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CO_2 Sequestration and Mineralization in Basalts in Eastern China: Prospects, Constraints and Challenges

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Abstract

Basalt-hosted CO_2 mineralization has emerged as a promising geological storage pathway due to its high storage permanence and low long-term leakage risk. In eastern China, widespread Cenozoic basalt formations are located close to major industrial emission clusters, providing favorable source-sink matching for near-source carbon storage. This study presents an integrated assessment of the prospects, constraints, and challenges of CO_2 sequestration and mineralization in eastern China basalts, with a site-specific investigation of the Bailonggang-Sanjiagang basalt system in the Shanghai coastal region. Geological characterization reveals strong vertical heterogeneity in lithofacies, mineralogical composition, and porosity-permeability properties, which fundamentally control reservoir accessibility and storage performance. Batch reaction experiments on representative basalt samples from Shanghai and Zhanjiang confirm effective CO_2 mineralization through carbonate precipitation, demonstrating strong mineralization potential in buried basalt reservoirs. Site-scale storage assessment under dissolved CO_2 injection indicates a realizable storage capacity of 75.10 Mt, while showing that practical storage capacity is governed primarily by effective pore accessibility and injectivity rather than by reactive mineral availability alone. Coupled reactive transport analysis further reveals dynamic porosity evolution during injection, characterized by an initial dissolution-enhanced stage followed by precipitation-induced self-sealing, which directly affects injectivity sustainability and mineral trapping efficiency. The results highlight that reservoir heterogeneity, reactive transport evolution, and mineralization-induced geomechanical responses represent critical constraints on field-scale deployment. Future development of basalt-hosted CO_2 mineralization in eastern China requires improved multi-scale THMC coupling, reliable upscaling from laboratory characterization to field deployment, and adaptive data-informed injection management to improve long-term storage efficiency and operational safety.

Keywords

CO_2mineralization, Basalt reservoirs, Geological carbon storage, Reactive transport.

1 Introduction

Geological carbon storage has been widely recognized as an essential pathway for mitigating anthropogenic carbon dioxide (CO_2) emissions and achieving carbon neutrality targets (IPCC, 2005). Among the various storage mechanisms, mineral trapping has attracted increasing attention because it offers the highest degree of storage permanence by converting injected CO_2into thermodynamically

stable carbonate minerals (Matter et al., 2016; Kelemen et al., 2019). Compared with conventional structural trapping in sedimentary reservoirs, where CO_2remains in mobile gaseous or supercritical phases and long-term containment depends strongly on caprock integrity, mineralization storage in mafic rocks provides an intrinsically safer alternative by immobilizing CO_2 through water-rock reactions (Gislason et al., 2010; Snæbjörnsdóttir et al., 2020). In particular, basalt formations are considered highly favorable for carbon mineralization because they are rich in Ca-, Mg-, and Fe-bearing silicate minerals, which can rapidly dissolve under CO_2-rich aqueous conditions and precipitate stable carbonate phases, thereby enhancing storage security and reducing long-term leakage risks.

Field-scale demonstrations have provided compelling evidence for the feasibility of basalt-based CO_2 mineralization storage. The CarbFix Project in Iceland showed that more than 95% of injected CO_2 could be mineralized within two years under favorable hydrogeochemical conditions (Matter et al., 2016), while pilot-scale injection tests at Wallula Basalt Pilot Project further demonstrated the operational viability of sustained injection and in situ carbonation (White et al., 2020).These successful cases have significantly advanced global interest in basalt-hosted CO_2 storage. In China, extensive Cenozoic basalt formations are distributed across the eastern coastal region, particularly within the Lower Yangtze and adjacent intraplate volcanic provinces (Zhang et al., 2023). Unlike the major sedimentary basins in northwestern China, which are geographically distant from major industrial emission sources, these eastern coastal basalt formations are located within densely industrialized and high-emission regions such as the Yangtze River Delta. This favorable source-sink spatial matching offers a strategic advantage for near-source CO_2 storage by reducing transportation distance, infrastructure requirements, and overall deployment costs (Zentou et al., 2025).

Despite these advantages, the deployment of CO_2 mineralization storage in eastern China basalts still faces several critical scientific and engineering challenges. First, basalt reservoirs are inherently heterogeneous, with strong vertical and lateral variations in lithofacies, pore-fracture connectivity, and permeability, which directly control injectivity and fluid accessibility. Second, CO_2 mineralization is governed by coupled reactive transport processes, in which mineral dissolution and carbonate precipitation continuously modify pore structures and permeability evolution (Ouyang et al., 2025). Third, mineralization-induced pore structure evolution and pressure perturbations may alter reservoir mechanical behavior and affect storage integrity (Xin et al., 2024). These coupled interactions form a strongly nonlinear thermo-hydro-chemo-mechanical (THMC) system, whose behavior remains insufficiently constrained under realistic geological conditions. In this paper, we provide an integrated assessment of CO_2 sequestration and mineralization in basalts in eastern China by combining regional geological analysis, site-specific characterization of the Bailonggang-Sanjiagang basalt system, experimental mineralization evidence, and coupled process-based interpretation. The paper focuses on three key questions: (1) what are the geological prospects for basalt-hosted CO_2 mineralization in eastern China; (2) what are the major constraints controlling storage efficiency and injectivity; and (3) what are the key scientific and engineering challenges toward future field-scale deployment?

2 Prospects for CO_2 Mineralization in Basalts in Eastern China

2.1 Geological distribution and reservoir characteristics of Cenozoic basalts

The distribution of Cenozoic basalts in eastern China is primarily controlled by the tectonic interaction between the Eurasian and Pacific plates, particularly along the circum-Pacific structural belt and major fault systems such as the Tan-Lu fault zone. Under this extensional geodynamic setting, widespread intraplate volcanism formed discontinuously distributed basaltic successions across Shandong, Jiangsu, Zhejiang, and the Shanghai coastal region (see Fig. 1). These basalt formations constitute one of the most important geological resources for CO_2 mineralization storage in China.

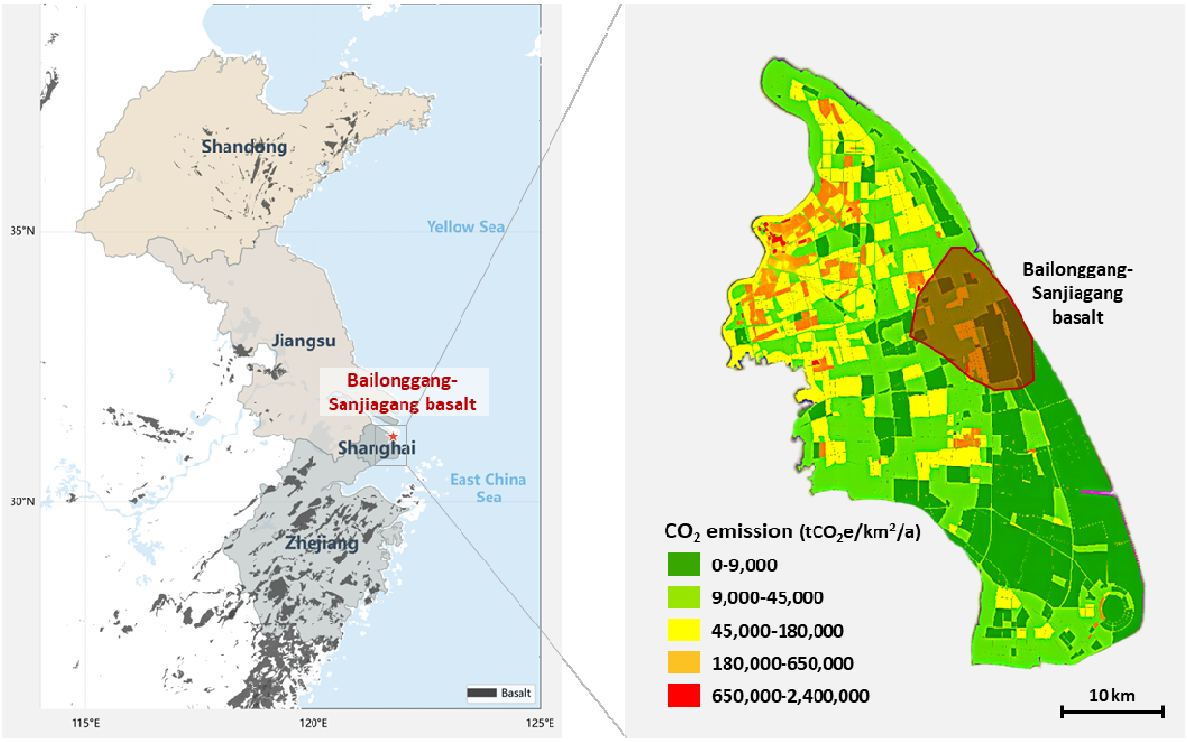


Fig. 1 Basalt reservoirs in Eastern China and Shanghai region.

Basalt reservoirs exhibit several favorable characteristics for CO_2 mineralization storage. They are rich in reactive Ca-, Mg-, and Fe-bearing silicate minerals, including plagioclase, pyroxene, and olivine, which provide essential cations for carbonate precipitation (Gislason et al., 2010; Matter et al., 2016). In addition, volcanic processes generate multi-scale pore-fracture systems, including vesicles, amygdales, cooling joints, and tectonic fractures, providing storage space and fluid migration pathways.

However, basalt reservoirs in eastern China also exhibit strong heterogeneity in thickness, pore structure, permeability, and alteration degree. Secondary mineral infilling and structural compartmentalization may significantly reduce effective pore connectivity, indicating that storage potential is controlled not only by mineral abundance but also by injectivity and fluid accessibility.

2.2 CO_2 mineralization mechanismsin basalt systems

The long-term security of CO_2 storage in basalt formations relies on in situ mineralization, where injected CO_2 is converted into stable carbonate minerals. Compared with conventional structural trapping, mineralization storage offers higher permanence and lower leakage risk (Snæbjörnsdóttir et al., 2020).

After injection, CO_2 dissolves into formation water and forms carbonic acid, initiating the acidification of the fluid system:

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \rightleftharpoons CO_3^{2-} + 2H^+ \#(1)$$

The decrease in pH promotes the dissolution of primary silicate minerals and basaltic glass, which constitutes the rate-limiting step in mineral carbonation. Representative dissolution reactions include:

$$Mg_2SiO_4 + 4H^+ \rightarrow 2Mg^{2+} + 2H_2O + SiO_{2(aq)} \#(2a)$$

$$CaAl_2Si_2O_8 + 8H^+ \rightarrow Ca^{2+} + 2Al^{3+} + 4H_2O + 2SiO_{2(aq)} \#(2b)$$

These reactions release divalent cations into solution while simultaneously consuming protons, thereby buffering the fluid acidity and sustaining further dissolution. The relatively fast dissolution kinetics of mafic minerals compared to more silica-rich phases make basalt particularly favorable for this process.

As cation concentrations increase, carbonate precipitation occurs through reactions such as:

$$(Me^{2+}) + CO_2 + H_2O \rightarrow MeCO_3 + 2H^+ \quad (Me = Ca, Mg, Fe) \#(3)$$

This process forms a dynamic feedback between mineral dissolution and carbonate precipitation. Dissolution enhances porosity and fluid accessibility, whereas precipitation progressively reduces pore space and permeability. The competition between these two processes controls injectivity, mineralization efficiency, and long-term storage performance (Ouyang et al., 2025).

2.3 Source-sink matching and deployment advantages in coastal eastern China

Eastern China is one of the largest industrial and CO_2-emitting regions in China, particularly the Yangtze River Delta, where fossil-fuel-intensive industries are highly concentrated (Liu et al., 2022). Developing near-source geological storage is therefore critical for regional decarbonization.Unlike conventional sedimentary storage targets in northwestern China, which are far from major emission sources, eastern coastal basalt formations are located close to industrial clusters. This favorable source-sink matching can significantly reduce transportation distance, infrastructure requirements, and deployment costs (Zhang et al., 2022; Zentou et al., 2025).

The Bailonggang-Sanjiagang basalt system (see Fig. 1) in Shanghai represents a typical near-source storage target, combining favorable geological conditions for mineralization with direct proximity to major emission sources. This makes it an ideal pilot-scale site for evaluating the feasibility of basalt-hosted CO_2 mineralization in eastern China.Overall, eastern China basalts provide a promising pathway for CO_2 mineralization storage due to their favorable mineral reactivity, reservoir distribution, and source-sink matching. However, their actual storage performance remains constrained by reservoir heterogeneity, injectivity limitations, and coupled reactive transport processes, which require site-specific assessment in the following section.

3 Site-Specific Assessment: The Bailonggang-Sanjiagang Basalt System

3.1 Geological architecture and reservoir stratification

The Bailonggang-Sanjiagang basalt system, located in the eastern Shanghai coastal region, represents a typical buried Cenozoic mafic reservoir in eastern China and serves as a representative pilot-scale site for evaluating CO_2 mineralization storage potential. Geologically, the reservoir is situated at the eastern termination of the Jiang-Shao fault zone within the Lower Yangtze tectonic domain, where the basement has experienced multiple stages of tectonic superposition associated with compression-extension transitions since the Mesozoic. This tectonic evolution controlled the emplacement, preservation, and subsequent structural modification of the Neogene basalt succession, resulting in a structurally complex and heterogeneous volcanic reservoir architecture(Li et al., 2016; Wang et al., 2014; Yang et al., 2016).

As shown in Fig. 2, the target reservoir corresponds to the Neogene Bailonggang-Sanjiagang basalt formation, which is widely distributed beneath Quaternary sedimentary cover in the eastern Shanghai coastal area. Based on regional geological mapping and borehole interpretation, the effective areal extent of the basalt reservoir is estimated to be approximately 86 km², forming one of the largest buried mafic reservoirs in the Shanghai region. Its location within the Yangtze River Delta industrial cluster provides a favorable near-source geological sink for CO_2 storage, where captured CO_2 can be transported over relatively short distances from major emission sources.

From an engineering perspective, the study site is strategically located between a volcanic center and an existing geothermal exploration well, providing valuable constraints on subsurface thermal-hydrological conditions and reservoir continuity. The proximity to the volcanic vent (~0.8 km) suggests relatively well-developed basalt thickness and eruptive facies preservation, while nearby geothermal exploration (~2.6 km away) provides additional hydrogeological constraints on reservoir temperature and fluid conditions.

To characterize the reservoir geometry and internal architecture, integrated geophysical surveys and deep borehole drilling were conducted. Surface-wave dispersion inversion reveals a distinct shear-wave velocity contrast at depths of approximately 350-400 m, corresponding to the top of the basalt formation. Localized velocity anomalies indicate structural discontinuities, likely associated with fault development, which may significantly influence reservoir compartmentalization and fluid migration pathways.

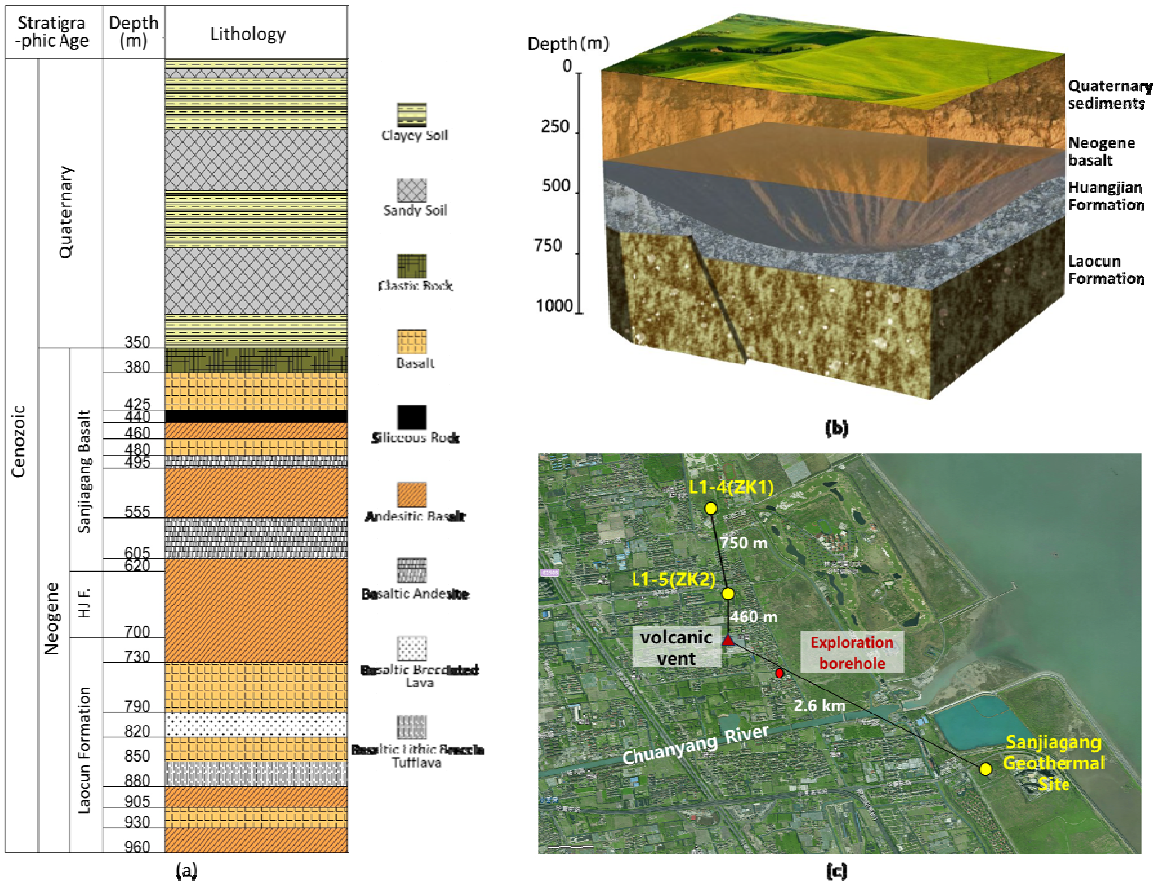


Fig. 2(a) Stratigraphy in theBailonggang-Sanjiagang basalt region, (b) Schematic diagram of the 3D stratigraphic distribution, and (c) Plan view of field borehole core sampling in the Shanghai region.

A deep exploration borehole (~970 m) further constrained the vertical architecture of the basalt reservoir. Core observations and integrated geological interpretation reveal pronounced vertical stratification and thickness variability, with the basalt formation generally thickening toward the volcanic center and thinning laterally. Based on lithological observations and petrographic characteristics, the reservoir can be subdivided into three major stratified intervals: a shallow interval (350-490 m), a middle interval (490-650 m), and a deep interval (650-960 m).

The shallow interval is dominated by vesicular and amygdaloidal basalt, characterized by well-preserved primary eruptive pore structures and locally developed fractures, providing favorable storage space and injectivity conditions. The middle interval is relatively denser and more structurally continuous, consisting mainly of basaltic andesite interlayered with localized pore-bearing facies, representing a relatively stable reservoir unit. In contrast, the deep interval exhibits stronger alteration and structural complexity, characterized by altered amygdaloidal basalt, brecciated lava, and extensive secondary mineral infilling, reflecting prolonged fluid-rock interaction and tectonic overprinting.

This vertically stratified architecture reflects the combined effects of primary volcanic facies distribution and secondary post-emplacement alteration, forming a strongly heterogeneous reservoir system. Such heterogeneity fundamentally controls the distribution of pore space, permeability, mineral accessibility, and fluid migration behavior, and therefore directly governs CO_2 injectivity and mineralization efficiency. The Bailonggang-Sanjiagang basalt system thus provides an ideal natural laboratory for evaluating the coupled geological constraints on CO_2 mineralization storage in eastern China.

3.2 Vertical heterogeneity in lithofacies and petrophysical properties

Core characterization, including petrographic observations, XRD/XRF analysis, and porosity-permeability measurements, reveals pronounced vertical heterogeneity in the Bailonggang-Sanjiagang basalt reservoir, reflecting the combined effects of primary volcanic emplacement and subsequent alteration.

As shown in Fig. 3, the reservoir can be divided into three vertically stratified intervals with distinct lithofacies characteristics. The shallow interval (350-490 m) is dominated by vesicular and amygdaloidal basalt, with abundant primary pore spaces and locally developed fractures, indicating favorable storage accessibility. The middle interval (490-650 m) is relatively denser and more structurally continuous, consisting mainly of basaltic andesite interlayered with localized pore-bearing facies. In contrast, the deep interval (650-960 m) exhibits stronger alteration and structural complexity, characterized by altered amygdaloidal basalt, brecciated lava, and extensive secondary mineral infilling.

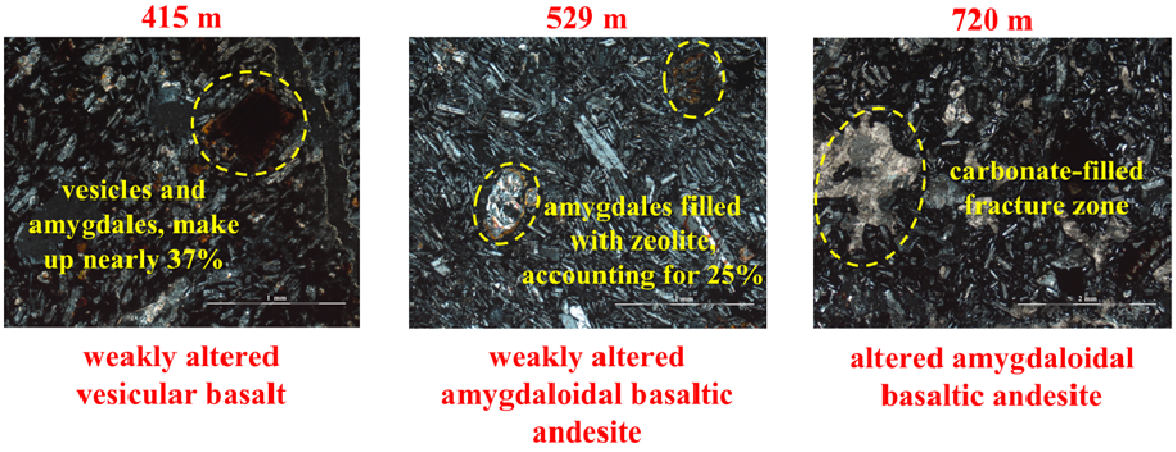


Fig. 3 Representative petrographic characteristics of the shallow, middle, and deep intervals of the Bailonggang-Sanjiagang basalt reservoir.

Mineralogical analysis (Fig. 4) further confirms clear vertical variation. The shallow and middle intervals are dominated by plagioclase and pyroxene, providing favorable reactive mineral sources for CO_2 mineralization. With increasing depth, pyroxene content decreases progressively and alteration minerals such as chlorite and montmorillonite become increasingly abundant, indicating stronger water-rock interaction and reduced reactive mineral preservation.

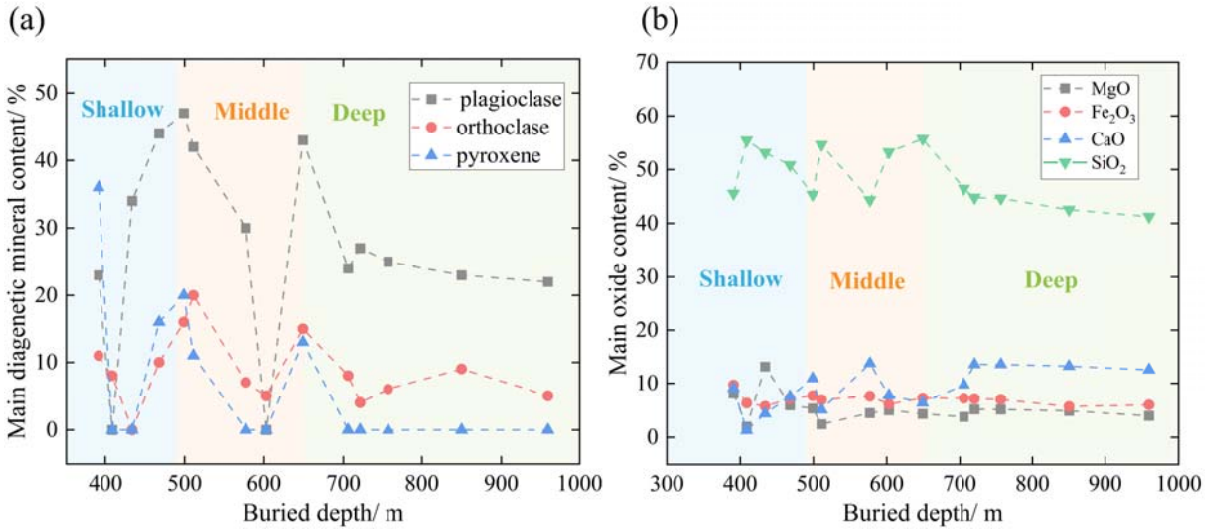


Fig. 4 Vertical variations in mineralogical and geochemical compositions of the Bailonggang–Sanjiagang basalt reservoir: (a) major mineral assemblages; (b) major oxide compositions.

The porosity-permeability measurements (Fig. 5) show strong depth-dependent variation. Porosity ranges from 1.894% to 25.464%, while permeability ranges from 0.671 to 33.437 mD. The shallow interval generally exhibits higher porosity and permeability, reflecting better preservation of primary pore structures and fracture networks. The middle interval shows relatively lower but more stable transport properties, suggesting better structural continuity and more predictable fluid migration behavior. In the deep interval, although some pore space remains locally preserved, permeability decreases significantly due to extensive secondary mineral infilling and reduced pore-throat connectivity.

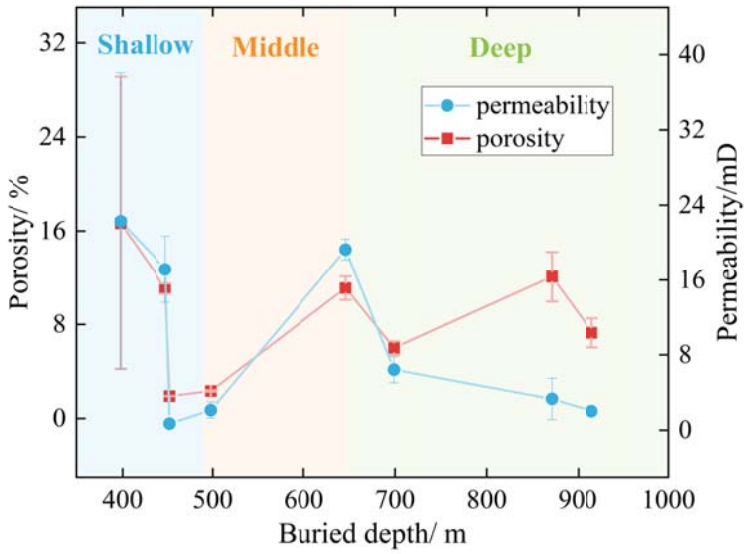


Fig. 5 Vertical distribution of porosity and permeability in the Bailonggang-Sanjiagang basalt reservoir.

These results demonstrate that the vertical heterogeneity of the basalt reservoir fundamentally controls CO_2 injectivity, fluid accessibility, and mineralization efficiency. The shallow interval offers favorable injectivity but stronger heterogeneity, the middle interval provides a relatively balanced reservoir condition, and the deep interval possesses large storage volume but stronger transport limitations. This heterogeneity forms the geological basis for evaluating mineralization potential and storage performance in the following sections.

3.3 Experimental evidence of mineralization potential

To evaluate the mineralization reactivity of the Bailonggang–Sanjiagang basalt reservoir toward CO_2 storage, a series of batch reaction experiments were conducted under simulated reservoir conditions using representative subsurface basalt samples from the Shanghai coastal basalt system. Core samples were collected from depths of approximately 396 m and 450 m (denoted as SH-396 and SH-450), corresponding to the middle reservoir interval. For comparison, basalt samples from Zhanjiang, including an outcrop sample (ZJ-O) and a subsurface sample at 450 m depth (ZJ-450), were also tested to provide additional constraints on mineralization behavior under different geological conditions.

All samples were crushed into powder to enhance reactive surface area and reacted under controlled conditions (60 °C, CO_2 pressure of 10 MPa, and water-rock ratio of 20) for 56 days. The objective was to assess mineral carbonation potential, reaction efficiency, and the influence of initial mineralogical states on CO_2 mineralization.Mineralogical analyses before and after reaction provide direct evidence of CO_2 mineralization. The Shanghai basalt samples are dominated by reactive silicate minerals, primarily plagioclase and pyroxene, together with varying amounts of clay minerals, indicating different degrees of pre-existing alteration. After reaction, newly formed carbonate minerals, particularly magnesite, were identified in the reacted samples, confirming effective mineral trapping through water-rock interaction (Fig. 6).

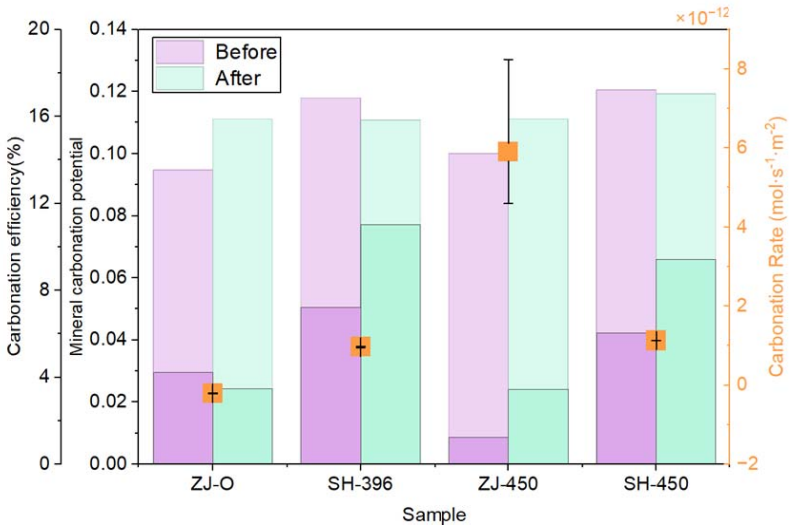


Fig. 6 Experimental evidence of CO_2 mineralization in representative basalt samples: mineralogical changes and carbonation efficiency before and after reaction.

Quantitative carbon analysis further confirms mineral carbonation by showing a clear increase in carbon content after reaction in all subsurface samples. Based on the measured carbon uptake, both carbonation extent and reaction rate were estimated. The results show that subsurface basalt samples exhibit significantly higher carbonation efficiency than the outcrop sample, indicating that buried basalt systems provide more favorable mineralization conditions than weathered surface-exposed basalts.

Notably, the Shanghai subsurface basalt samples (SH-396 and SH-450) consistently exhibit strong carbonation performance, demonstrating high reactivity under reservoir-relevant conditions. Although variations in carbonation rate are observed among the Shanghai and Zhanjiang samples, these differences are primarily related to variations in mineralogical composition and initial alteration states, rather than fundamental differences in mineralization mechanisms.

These experimental results provide direct evidence that buried basalt reservoirs in eastern China possess strong CO_2 mineralization potential. More importantly, the comparison between the Shanghai and Zhanjiang samples demonstrates that mineralization efficiency is highly sensitive to the initial reservoir conditions, including mineral preservation state and reactive surface accessibility. This experimental evidence supports the feasibility of basalt-hosted CO_2 mineralization in eastern China and provides important constraints for the site-scale storage assessment in the following section.

3.4 Storage potential assessment under dissolved CO_2 injection

To evaluate the practical storage potential of the Bailonggang-Sanjiagang basalt reservoir, a site-scale assessment framework was established under a dissolved CO_2 injection scenario, where CO_2 is injected in carbonated water rather than as a separate supercritical phase. This strategy can reduce buoyancy-driven migration and minimize the risk of caprock disturbance, while promoting direct water-rock interaction and accelerating in situ mineralization.

The storage assessment integrates two capacity limits: (1) the dissolution-based storage capacity constrained by effective pore volume and fluid transport accessibility, and (2) the mineralization-based storage capacity constrained by the availability of reactive Ca- and Mg-bearing minerals. To account for the strong vertical heterogeneity of the reservoir, the shallow, middle, and deep intervals were evaluated separately using representative petrophysical and mineralogical parameters.

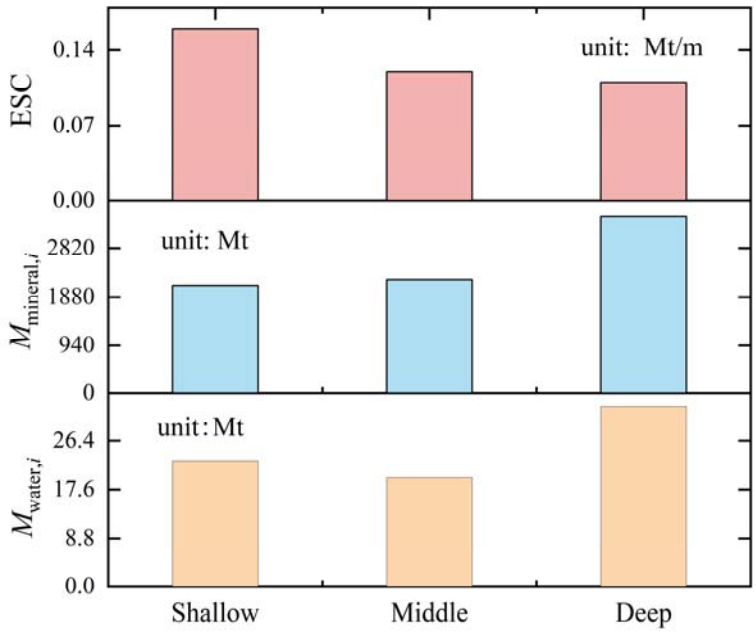


Fig. 7 Site-scale assessment of CO_2 mineralization storage potential in the Bailonggang-Sanjiagang basalt reservoir: dissolution-based capacity and mineralization-based capacity for different stratified intervals.

The results show that the dissolution-based storage capacities of the shallow, middle, and deep intervals are estimated at 22.76 Mt, 19.77 Mt, and 32.57 Mt, respectively, yielding a total realizable storage capacity of 75.10 Mt (Fig. 7). In contrast, the corresponding mineral reaction capacities are significantly higher in all three intervals, indicating that reactive mineral availability is not the limiting factor for storage.

The deep interval contributes the largest absolute storage capacity due to its greater thickness and higher CO_2 solubility under elevated pressure conditions. However, its lower permeability and stronger secondary alteration impose significant injectivity constraints. In contrast, the shallow interval exhibits the highest effective storage contribution per unit thickness, benefiting from better pore preservation and higher injectivity accessibility, although it also shows stronger local heterogeneity. The middle interval provides relatively balanced storage performance, combining moderate storage capacity, better structural continuity, and more stable transport properties.

These results indicate that the effective storage potential of basalt reservoirs is governed primarily by pore accessibility, fluid transport capacity, and injectivity, rather than by mineral reaction capacity alone. From an engineering perspective, the shallow and middle intervals represent the most favorable target horizons for pilot-scale CO_2 mineralization storage, while the deep interval may serve as a secondary storage target with larger capacity but stronger operational constraints.

4 Coupled Constraints on CO_2 Mineralization in Basalts

4.1 Reactive transport and porosity evolution

Reactive transport processes fundamentally control reservoir evolution during CO_2 mineralization in basalt systems. During injection, mineral dissolution and carbonate precipitation occur simultaneously, continuously modifying pore structures and fluid flow pathways, and thereby directly controlling injectivity and mineralization efficiency.

At the early stage of injection, CO_2-rich acidic fluids promote the dissolution of primary silicate minerals, leading to local pore enlargement and increased porosity. This dissolution-enhanced stage improves fluid accessibility and facilitates further water-rock interaction. As the reaction progresses, dissolved cations accumulate and carbonate precipitation gradually intensifies, progressively occupying pore space and reducing effective porosity.

As shown in Fig. 8, the coupled reactive transport simulations capture both the spatial distribution of carbonate precipitation and the associated porosity evolution during CO_2 injection. The results show that carbonate precipitation is concentrated near the injection zone and progressively expands outward,

while the surrounding reservoir undergoes heterogeneous pore structure changes. The reservoir near the injection well initially experiences pore expansion dominated by dissolution, followed by localized pore reduction associated with carbonate precipitation. This transition reflects the evolution from a self-enhancing regime to a self-sealing regime, which fundamentally controls the sustainability of fluid injection and mineral trapping.

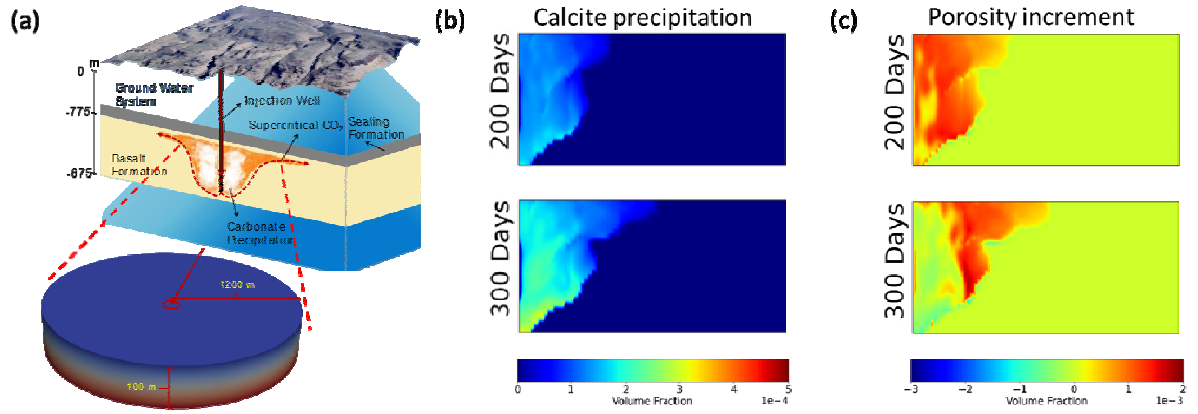


Fig. 8 Reactive transport evolution during CO_2 mineralization in basalt reservoirs: (a) conceptual and numerical model; (b) spatial distribution of calcite precipitation; (c) spatial evolution of porosity showing the transition from dissolution-enhanced pore development to precipitation-induced self-sealing.

Such dynamic porosity evolution represents a key constraint on basalt-hosted CO_2 mineralization. While dissolution improves injectivity and reaction accessibility, excessive precipitation may reduce effective pore connectivity and restrict fluid migration. Therefore, successful mineralization storage requires balancing reaction efficiency and long-term transport sustainability.

4.2 Reservoir accessibility and injectivity constraints

Although basalt reservoirs contain abundant reactive minerals for CO_2 mineralization, their effective storage performance is fundamentally constrained by reservoir accessibility and injectivity. As demonstrated in the site-scale storage assessment, the theoretical mineral reaction capacity of all stratified intervals significantly exceeds the dissolution-based storage capacity, indicating that reactive mineral availability is not the primary limiting factor for mineralization storage. As shown in Fig. 7, the large discrepancy between the mineralization-based capacity and the dissolution-based capacity directly reflects the practical limitation imposed by effective pore accessibility and fluid transport capacity.Instead, the practical storage capacity is governed by the effective pore volume and the ability of CO_2-rich fluids to access and circulate within the reservoir.

Reservoir accessibility is strongly controlled by pore connectivity, permeability distribution, and structural continuity. In heterogeneous basalt systems, effective fluid migration pathways are often highly localized due to the coexistence of vesicular zones, dense lava interiors, fracture networks, and secondary mineral infilling. Even in intervals with relatively high porosity, poor pore-throat connectivity may significantly restrict fluid transport and reduce effective mineral accessibility.

Injectivity constraints become increasingly important during long-term operation. As discussed in Section 4.1, reactive transport continuously modifies pore structures through the competing effects of dissolution and precipitation. Although early-stage dissolution may improve injectivity locally, progressive carbonate precipitation near the injection well may reduce effective permeability and restrict fluid penetration into the broader reservoir volume. This localized self-sealing effect may significantly reduce storage efficiency by limiting the effective sweep volume of reactive fluids.

The vertical heterogeneity of the Bailonggang-Sanjiagang basalt reservoir further amplifies these constraints. The shallow interval provides favorable injectivity due to better preserved pore-fracture systems, while the middle interval offers relatively stable transport conditions with improved structural continuity. In contrast, the deep interval possesses larger storage volume but is more strongly constrained by permeability reduction and alteration-induced pore isolation. These differences indicate that reservoir selection for CO_2 mineralization storage must balance storage capacity and injectivity accessibility.

Therefore, improving storage accessibility and maintaining sustainable injectivity represent critical engineering challenges for basalt-hosted CO_2 mineralization. Effective injection design, interval selection, and operational control are essential to maximize fluid-rock contact and enhance the realizable storage potential.

4.3 Injection strategy impacts on mineralization efficiency and storage security

Injection strategy plays a critical role in controlling both mineralization efficiency and storage security in basalt-hosted CO_2 sequestration. In heterogeneous basalt reservoirs, variations in injection location and injection rate directly affect fluid accessibility, reaction distribution, and pressure evolution, thereby influencing the overall storage performance.

Table 1Effects of injection rate and location on porosity and CO_2 sequestration efficiency.

Scenario	Injection Location	Injection Rate	Porosity Changes Near Wellbore	Sequestration Efficiency
1	Bottom	3 kg/s	-6.4×10^{-4}	10.3%
2	Bottom	5 kg/s	-5.4×10^{-4}	9.6%
3	Top	5 kg/s	-1.5×10^{-4}	8.4%

As summarized in Table 1, both injection location and injection rate significantly affect porosity evolution near the wellbore and final sequestration efficiency. Under the bottom injection condition, increasing the injection rate from 3 kg/s to 5 kg/s results in less porosity reduction near the wellbore, but also slightly decreases the final mineralization efficiency. In contrast, top injection at the same rate further reduces porosity reduction near the injection zone, indicating improved injectivity preservation, although the final sequestration efficiency becomes lower.

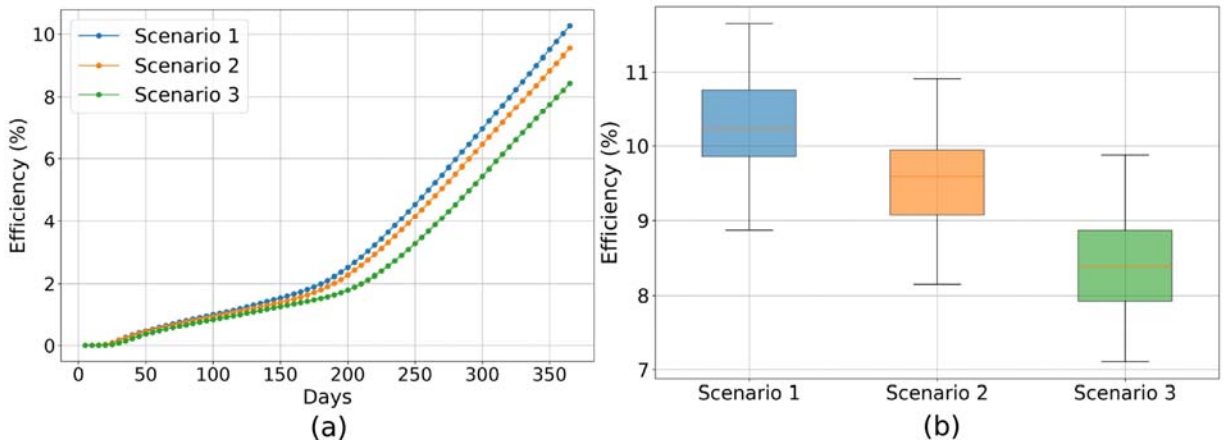


Fig. 9 Temporal evolution of CO_2 mineralization efficiency under different injection strategies.

The temporal evolution of sequestration efficiency shown in Fig. 9 further illustrates the dynamic effects of injection strategy on mineralization performance. In all scenarios, sequestration efficiency increases progressively with time, reflecting the gradual development of mineralization reactions. A clear acceleration of mineral trapping is observed after approximately 150 days, coinciding with significant magnesite precipitation, indicating that the availability of dissolved cations has reached a critical threshold for large-scale carbonate formation.

These results indicate an important operational trade-off. Bottom injection tends to achieve higher mineralization efficiency due to longer fluid-rock interaction pathways and stronger fluid retention, but may also induce stronger local porosity reduction and potential injectivity loss. In contrast, top injection may better preserve injectivity and fluid accessibility, but may reduce effective mineral trapping efficiency.

Therefore, effective injection strategies for basalt-hosted CO_2 mineralization should balance mineralization efficiency, injectivity sustainability, and storage security. Adaptive injection design, including interval selection and injection rate control, is essential for improving long-term storage performance while minimizing operational risks.

5 Challenges and Future Directions

5.1 Multi-scale THMC coupling and uncertainty

One of the most critical challenges for basalt-hosted CO_2 mineralization is the strong thermo-hydro-mechanical-chemical (THMC) coupling that governs reservoir evolution during injection. Unlike conventional geological storage, mineralization storage involves continuous interactions among fluid flow, heat transfer, geochemical reactions, and mechanical responses, forming a highly nonlinear coupled system.

At the pore scale, mineral dissolution and carbonate precipitation dynamically modify pore geometry and reactive surface accessibility, directly affecting local transport properties and reaction kinetics. At the reservoir scale, these local changes may progressively alter permeability distribution, fluid migration pathways, and pressure evolution. Meanwhile, mineralization-induced pore structure evolution may further affect rock stiffness, deformation behavior, and fracture stability, creating feedback between geochemical evolution and geomechanical responses.

A major challenge lies in bridging these coupled processes across scales. Laboratory experiments provide direct constraints on reaction kinetics and mineralization behavior, but their representativeness at reservoir scale remains limited. Conversely, field-scale simulations often rely on simplified assumptions regarding reaction kinetics, permeability evolution, and mechanical property changes, introducing substantial uncertainty into long-term storage predictions.

Reducing these uncertainties requires improved multi-scale THMC coupling frameworks that integrate laboratory observations, site-specific characterization, and field-scale reactive transport modeling. Developing robust predictive models for coupled reservoir evolution will be essential for improving storage performance evaluation and operational risk assessment in future basalt-hosted CO_2 mineralization projects.

5.2 Upscaling from laboratory characterization to field deployment

Bridging the gap between laboratory characterization and field-scale deployment remains a major challenge for basalt-hosted CO_2 mineralization. Laboratory experiments provide direct evidence of mineral carbonation potential and reaction pathways under controlled conditions, but their results are often obtained under simplified physical and chemical environments that differ significantly from in situ reservoir conditions.

At laboratory scale, crushed rock samples and controlled reaction conditions can greatly enhance fluid-rock contact and reaction efficiency, often leading to accelerated mineralization rates compared with natural reservoir systems. In contrast, field-scale reservoirs are characterized by strong lithological heterogeneity, variable pore-fracture connectivity, and complex fluid transport pathways, which may substantially limit effective mineral accessibility and reaction extent.

The site-specific assessment of the Bailonggang-Sanjiagang basalt system demonstrates that effective storage capacity is governed primarily by reservoir accessibility and injectivity rather than by reactive mineral abundance alone. This highlights the importance of integrating laboratory observations with realistic reservoir characterization and field-scale transport constraints when evaluating practical storage performance.

Future field deployment requires improved upscaling strategies that link laboratory-derived reaction kinetics, reservoir-scale heterogeneity, and operational conditions. Pilot-scale injection tests, integrated monitoring, and continuous model calibration will be essential for reducing scale-dependent uncertainty and improving the reliability of field-scale mineralization storage assessment.

5.3 Toward adaptive and data-informed injection management

The strong heterogeneity and dynamic reservoir evolution of basalt-hosted CO_2 mineralization require more adaptive injection management strategies than conventional geological storage operations. Because injectivity, fluid accessibility, and mineralization efficiency may evolve continuously during injection, static operational designs may become suboptimal or even increase storage risks over time.

Adaptive injection management aims to adjust operational parameters, such as injection interval, injection rate, and injection duration, based on the evolving reservoir responses. Continuous

monitoring of pressure evolution, fluid migration, and geochemical changes can provide important constraints on reservoir behavior and help identify early signs of injectivity reduction, localized self-sealing, or abnormal pressure buildup.

The integration of site monitoring data with predictive reservoir models offers a promising pathway toward data-informed operational control. By continuously updating reservoir conditions and reducing model uncertainty, adaptive strategies can improve fluid-rock contact efficiency, maintain sustainable injectivity, and reduce geomechanical risks.

Future basalt-hosted CO_2 mineralization projects will increasingly rely on integrated monitoring, dynamic model updating, and adaptive operational decision-making. Such data-informed injection management will be essential for improving long-term storage efficiency, operational safety, and field-scale deployment reliability.

6 Conclusions

Eastern China basalts represent a promising pathway for CO_2 mineralization storage due to their favorable mineralogical reactivity, widespread regional distribution, and advantageous source-sink matching with major industrial emission clusters. Compared with conventional sedimentary storage systems, basalt-hosted mineralization provides enhanced long-term storage security through permanent carbonate trapping, offering important opportunities for regional carbon mitigation.

The site-specific assessment of the Bailonggang-Sanjiagang basalt system demonstrates strong storage feasibility and mineralization potential. Integrated geological characterization, mineralogical analysis, petrophysical measurements, and batch reaction experiments confirm that buried basalt reservoirs in eastern China possess favorable reactive mineral assemblages and effective carbonation capacity. The site-scale storage assessment under dissolved CO_2 injection further indicates a realizable storage capacity of 75.10 Mt.

However, the effective performance of basalt-hosted CO_2 mineralization is fundamentally constrained by reservoir accessibility, injectivity sustainability, and coupled reactive transport evolution. The results show that practical storage capacity is controlled primarily by effective pore accessibility and fluid transport capacity rather than by reactive mineral availability alone. In addition, mineralization-induced porosity evolution and geomechanical responses introduce further uncertainty in long-term reservoir performance and storage security.

Future development of basalt-hosted CO_2 mineralization in eastern China requires improved multi-scale THMC coupling, more reliable upscaling from laboratory characterization to field deployment, and adaptive data-informed injection management. Integrating site-specific characterization, coupled process modeling, and dynamic operational control will be essential for advancing pilot-scale demonstration and future industrial-scale deployment of CO_2 mineralization storage in basalt systems.

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