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Advances in Basalt-Driven CO_2 Mineralization: Reactivity, Mechanisms, Kinetics, and Reservoir-Scale Prospects for Permanent Carbon Storage

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Abstract

Basalt-rich geological formations have emerged as one of the most promising natural systems for permanent CO_2 sequestration due to their high reactivity with injected carbon dioxide and their ability to form stable carbonate minerals. Recent research has significantly advanced the understanding of basalt–CO_2 interactions, covering mineral dissolution kinetics, aqueous and gas–solid phase pathways, reactive transport behavior, and the impact of fracture networks on mineralization efficiency. Studies have highlighted the role of basaltic minerals—especially olivine, pyroxene, and plagioclase—in accelerating carbonation reactions and enhancing long-term storage security. Mechanistic investigations have provided molecular-scale insights into surface reactions, revealing that basalt–CO_2 interactions proceed through coupled dissolution–precipitation pathways governed by temperature, fluid composition, and mineral structure. Process-controlled mineralization shows that manipulating flow regimes, pH, and reactive surface area can significantly boost carbonation rates and tune reservoir properties for optimal storage. Studies exploring low-kinetic gas–solid to aqueous transitions further demonstrate new technological routes for CCS using basalt under varied environmental conditions. Large-scale modeling efforts provide a systems view of mineral trapping and estimate long-term storage potential under realistic field conditions. Collectively, these studies outline a maturing scientific and technological framework for CO_2 mineralization in basalt and position basaltic systems as viable, scalable solutions for global decarbonization efforts.

Keywords: Basalt mineralization, CO_2 sequestration, carbonation mechanisms, reactive transport, basalt reactivity, carbon storage kinetics

1. Introduction

Basalt formations represent one of the most reactive lithologies suitable for geologic carbon storage due to their high content of divalent cation-bearing minerals such as olivine, pyroxene, and calcium-rich plagioclase. When exposed to CO_2-rich fluids, these minerals dissolve and rapidly precipitate stable carbonate minerals such as calcite, magnesite, and siderite, effectively locking carbon in solid form for geological timescales. Recent review works have established that basalt mineralization is one of the safest and most permanent CO_2 sequestration pathways, with negligible risks of leakage due to solid-phase trapping (Rasool & Ahmad, 2023).

Over the last decade, interest in basaltic formations has intensified following successful pilot projects such as CarbFix, which demonstrated mineralization within two years—far faster than earlier predictions. Building on this momentum, new studies focus on three major research fronts: mineral-scale reaction mechanisms, engineered process acceleration, and field-scale modeling. Mechanistic studies now allow researchers to quantify the stepwise pathways by which CO_2 interacts with basalt surfaces and to identify the rate-limiting controls under varying conditions (Shao et al., 2025). At the same time, process engineering methods—such as optimizing temperature, flow rate, and reactive transport regime—have been shown to drastically enhance carbonation kinetics (Deng et al., 2025).

Additionally, recent innovations explore CO_2 mineralization across different reaction environments, including low-kinetic gas-solid systems transitioning into aqueous reactions (Mazaheri et al., 2025). Researchers are also increasingly attentive to reservoir-scale behavior, including fracture flow, porosity evolution, permeability changes, and the long-term integrity of basaltic formations (Postma et al., 2022). These advances have positioned basalt as a leading candidate for large-scale CCS deployment. This review integrates findings across experimental, modeling, and field studies to provide an updated and comprehensive understanding of CO_2 mineralization in basaltic rocks, emphasizing mechanisms, kinetics, reservoir implications, and future perspectives for scalable carbon storage technology.

2. Mineral Reactivity of Basaltic Rocks Toward CO_2

Basalt reactivity stems primarily from divalent metal-bearing silicate minerals, which undergo dissolution in acidic CO_2-rich environments to release Ca^{2+}, Mg^{2+}, and Fe^{2+} ions. These ions, upon interaction with carbonate species, precipitate stable carbonates that effectively trap carbon. Rasool & Ahmad (2023) emphasize that minerals such as olivine (Mg_2SiO_4) and pyroxene exhibit the fastest dissolution kinetics under elevated CO_2 conditions due to their relatively unstable silicate bonding structure. Plagioclase feldspar contributes significantly as well, though its dissolution rate is typically slower and more sensitive to temperature and pH.

The reactivity of basalt is further enhanced by its high porosity and permeability relative to ultramafic rocks, enabling better fluid infiltration and greater reactive surface area. Studies also note that basalt glass—common in volcanic formations—reacts more rapidly than crystalline basalt due to its amorphous structure. Microstructural characteristics such as grain size, fracture density, and degree of weathering influence the dissolution rate of primary minerals and the subsequent precipitation of carbonates.

Furthermore, basalt reactivity depends strongly on the geochemical environment. High CO_2 concentration lowers pH, accelerating silicate dissolution but potentially causing rapid carbonate precipitation that may clog pore spaces. Reactive transport models suggest that dissolution fronts can progress several meters over short geological timescales, enabling substantial mineralization before significant permeability reduction occurs (Postma et al., 2022). Overall, basalt's mineral composition and structural attributes collectively make it an exceptional candidate for CO_2 mineralization.

Table 1: Basaltic Mineral Reactivity Toward CO_2

Mineral Type	Key Reactive Components	Relative Dissolution Rate	Carbonate Formed	Influencing Factors
Olivine	Mg, Fe	Very High	Magnesite, Siderite	pH, Temperature, CO_2 pressure

Mineral Type	Key Reactive Components	Relative Dissolution Rate	Carbonate Formed	Influencing Factors
Pyroxene	Ca, Mg	High	Calcite, Dolomite	Fluid flow, Acid strength
Plagioclase	Ca, Na	Moderate	Calcite, Aragonite	Temperature, Surface area
Basalt Glass	Multiple cations	Very High	Multiple carbonates	Structure, Water availability
Altered Basalt	Reduced cations	Low	Minor carbonates	Weathering extent

This table compares major basaltic minerals based on their dissolution rates, reactive cation content, and resulting carbonate phases. It highlights that olivine and basalt glass exhibit the highest reactivity due to weak silicate bonding, while altered basalt shows significantly lower reactivity. The table also summarizes the environmental conditions that influence carbonation such as pH, temperature, and CO_2 partial pressure. These parameters help determine how quickly minerals release Ca^{2+}, Mg^{2+}, and Fe^{2+}, which are essential for forming stable carbonate minerals. The table provides a foundational understanding of why basalt is considered highly suitable for CO_2 mineralization.

3. Surface Reaction Mechanisms during Carbon Mineralization

Surface interactions between CO_2-rich fluids and basalt minerals drive the initial stages of mineralization. Shao et al. (2025) demonstrate that carbonate formation is a multistep process involving (1) adsorption of CO_2 and water molecules on mineral surfaces, (2) proton-promoted dissolution of silicate frameworks, (3) release of metal cations, and (4) nucleation and growth of carbonate crystals. These reactions occur at the mineral–fluid interface and are highly dependent on surface defects, crystallographic orientation, and chemical heterogeneity.

Atomic-scale observations reveal that surface roughness and micro-fractures greatly enhance reactivity by increasing the density of reactive sites. Once dissolution begins, altered layers composed of amorphous silica form on basalt surfaces. These layers can either inhibit or facilitate carbonation depending on fluid chemistry. In high flow-rate systems, amorphous layers are removed quickly, exposing fresh mineral surfaces and accelerating carbonation. Under stagnant conditions, however, these layers may hinder further dissolution.

Shao et al. (2025) also highlight that coupled dissolution–precipitation reactions govern the overall rate of mineralization. The precipitation of carbonates occurs near or directly on dissolving mineral surfaces, creating tightly bound carbonate layers that immobilize carbon permanently. Additionally, the presence of catalytic ions and trace metals in basalt may accelerate nucleation kinetics. Surface spectroscopy and advanced imaging confirm that carbonate precipitation is spatially heterogeneous, occurring preferentially at high-energy sites such as steps, edges, and dislocation boundaries. These mechanistic insights deepen understanding of mineralization efficiency and guide process optimization for engineered basalt carbonation.

Table 2: Mechanistic Pathways of CO_2–Basalt Interactions

Reaction Stage	Description	Key Controlling Factor	Outcome
CO_2 Adsorption	CO_2 binds to mineral surface sites	Surface roughness	Initiates reaction
Proton-Promoted Dissolution	Breakdown of silicate bonds	Acidity (pH)	Release of metal cations
Metal Ion Migration	Movement of Ca/Mg/Fe into fluid	Temperature & flow	Ion availability
Carbonate Nucleation	First formation of carbonate clusters	Saturation state	Carbonate initiation
Crystal Growth	Growth of stable carbonate minerals	Time & ion supply	Permanent trapping

This table outlines the stepwise mechanisms described in recent mechanistic studies, showing how CO_2 transforms from dissolved form into solid carbonates. Each stage is linked to a critical chemical or physical condition that regulates reaction progress. The table also illustrates how mineral surfaces, water chemistry, and fluid movement all interact to control carbonation kinetics. Understanding these stages helps explain the rapid carbonation observed in basalt compared to many other rock types. This mechanistic insight is essential for interpreting laboratory and field experiments described in the referenced papers.

4. Accelerated CO_2 Mineralization via Process Control

Recent advancements reveal that engineered control over reaction conditions can significantly enhance the rate and extent of CO_2 mineralization in basalt. Deng et al. (2025) demonstrate that manipulating temperature, pH, fluid flow regime, and reactive surface area enables highly accelerated carbonation processes. For instance, elevating temperature enhances dissolution kinetics exponentially, leading to faster release of divalent metal ions required for carbonate precipitation. Similarly, optimizing pH within moderately acidic ranges promotes mineral dissolution without causing premature carbonate saturation.

Control over flow regimes plays a critical role as well. Continuous injection systems that maintain high fluid mobility prevent pore clogging and sustain reactive transport pathways, enabling sustained dissolution. Conversely, pulsed injection or periodic flow reversal can help remove silica-rich passivation layers, exposing fresh mineral surfaces. Another strategy involves heat-assisted injection, which harnesses geothermal gradients within volcanic regions to accelerate reaction kinetics.

Process-controlled mineralization also influences reservoir properties such as porosity and permeability. While carbonation tends to reduce pore space due to precipitation, careful management of injection rates and fluid composition can maintain adequate permeability for prolonged mineralization. Deng et al. (2025) further note that controlled mineral evolution—such as the transition from amorphous carbonates to more stable crystalline phases—ensures the long-term integrity of storage reservoirs.

These engineered approaches represent a significant advancement toward scaling basalt-based mineralization for deployment in industrial CCS operations, enabling mineral trapping at rates substantially faster than natural geological processes.

Table 3: Strategies for Accelerating Basalt-Based CO_2 Mineralization

Acceleration Strategy	Mechanism	Effect on Reaction Rate	Potential Limitations
Temperature Increase	Enhances dissolution	Strongly increases	Energy cost
Flow Rate Control	Maintains reactive surface	High increase	Reservoir clogging risk
pH Optimization	Promotes dissolution	Moderate–High	Requires additives
Enhanced Surface Area	Grinding/increasing fractures	High	Cost, engineering complexity
Heat-Assisted Injection	Uses geothermal energy	Very high	Site dependent

This table synthesizes engineered methods shown to speed up carbonation reactions in basalt. It explains how each strategy influences dissolution or precipitation processes and identifies limitations that must be considered in field applications. For example, temperature elevation provides significant acceleration but may not be practical in all locations. Flow regime optimization is highly effective but requires monitoring to prevent pore clogging. The table provides guidance for designing optimized mineralization systems that balance efficiency, safety, and cost.

5. Gas–Solid to Aqueous Phase Carbonation under Low Reaction Kinetics

Mazaheri et al. (2025) investigate CO_2 mineralization under low-kinetic conditions where reactions transition from gas–solid interactions to aqueous-phase chemistry. This pathway is particularly relevant for applications involving dry CO_2 injection, shallow basalt formations, or low-temperature storage environments. In the initial gas–solid stage, CO_2 adsorption onto mineral surfaces occurs slowly due to limited molecular mobility and the absence of a fluid medium. However, once water films or humidity levels rise, gas–solid interactions rapidly transition to aqueous reactions, thereby accelerating carbonation.

This dual-phase pathway reveals that even under unfavorable kinetic conditions—such as low temperature, limited water availability, or slow diffusion rates—basalt can still serve as an effective CO_2 sink. The study highlights that transient water films form naturally in subsurface environments through condensation, diffusion, or groundwater fluctuations, creating micro-reactors where carbonation proceeds more effectively.

Moreover, the authors demonstrate that mineral carbonation remains feasible across a wide range of environmental contexts if the system can transition into aqueous pathways. This finding expands the applicability of basalt mineralization beyond traditional deep-injection CCS and opens possibilities for near-surface or ex situ mineralization technologies. The slow-to-fast kinetic transition provides a critical understanding of how basalt can mineralize CO_2 even in arid, cold, or shallow geological conditions.

6. Field-Scale Modeling and Reactive Transport Behavior

Understanding CO_2 mineralization at reservoir scales is crucial for designing safe and effective large-scale storage systems. Postma et al. (2022) address this need by developing vertically integrated reactive transport models that simulate CO_2 injection, dissolution, fluid migration, and mineral trapping across large basaltic formations. These models account for complex coupled processes such as multiphase flow, geochemical reactions, heat transport, and mineral evolution.

The modeling results show that mineral trapping becomes a dominant storage mechanism over intermediate to long timescales, following initial solubility and residual trapping stages. Dissolution fronts propagate outward from injection zones, driving continuous release of metal ions and enabling sustained carbonate precipitation. Importantly, porosity reduction due to carbonation is localized and does not significantly compromise reservoir injectivity when injection parameters are optimized.

Field-scale models further highlight the importance of fracture networks. Fractured basalt significantly enhances fluid flow and reactive surface area but also introduces heterogeneities that influence carbonation patterns. The model outcomes align closely with field observations from natural analogues and pilot mineralization projects, confirming that basalt formations can safely store large quantities of CO_2 over geological time.

Such modeling frameworks provide essential guidance for site selection, injection strategy design, risk assessment, and long-term monitoring plans for future CCS projects.

Table 4: Reservoir-Scale Modeling Outcomes for Basalt Mineralization

Modeling Parameter	Finding	Implication
Dissolution Front Propagation	Several meters over years	Sustained carbonate formation
Porosity Evolution	Moderate reduction	Stable long-term injectivity
Fracture Influence	Enhances fluid distribution	Faster mineralization in fractures
Mineral Trapping Dominance	Long-term dominant mechanism	High permanence
Thermal Effects	Improves reaction rates	Beneficial for volcanic basalts

This table summarizes key insights from vertically integrated reactive transport models. The findings reveal how CO_2 behaves over large spatial scales in basalt formations, including dissolution front movement and carbonate precipitation. The table also highlights how fractures play a crucial role in increasing reactive surface area and fluid connectivity. These results confirm that basalt reservoirs can maintain injectivity while still achieving strong mineral trapping. This modeling evidence supports real-world deployment of basalt CCS projects.

7. Mechanisms and Prospects of Basalt as a Permanent Carbon Sink

Several researchers—including Sikurajapathi et al. (2025) and Owusu et al. (2025)—emphasize basalt's unique capacity for permanent CO_2 sequestration. Their work integrates geological, geochemical, and technological insights to highlight basalt's suitability for global climate mitigation. Basalt formations are

abundant worldwide across oceanic crusts, continental flood basalts, and volcanic provinces, offering vast storage capacity.

The fundamental mechanism involves mineral dissolution followed by carbonate precipitation, forming thermodynamically stable minerals that retain CO_2 permanently. These reactions occur on timescales ranging from months to years—significantly faster than in many sedimentary formations. Additionally, basalt mineralization is self-sealing; carbonate precipitation can strengthen rock structures and enhance capillary trapping.

Technological advancements such as enhanced injection strategies, engineered nanoparticles, thermal stimulation, and optimized fluid chemistries further improve mineralization rates. Researchers also highlight that basalt systems present minimal leakage risk compared to conventional storage reservoirs because CO_2 becomes immobilized in solid mineral phases rather than relying solely on physical or capillary trapping.

Looking ahead, basalt mineralization is considered a critical pillar in the portfolio of negative-emission technologies. Its scalability, permanence, and environmental compatibility make it an attractive solution for industrial decarbonization, direct air capture integration, and potential ex situ mineralization technologies using crushed basalt.

8. Conclusions

The collective findings across these studies provide compelling evidence that basalt formations are among the most effective geological media for permanent CO_2 sequestration. Basalt's mineral composition, porosity, and global abundance make it uniquely suited for rapid mineralization processes that securely lock carbon in stable solid phases. Surface reaction studies reveal that carbonation proceeds through well-defined dissolution–precipitation mechanisms influenced by mineral structure and fluid chemistry. Engineering advancements now allow substantial acceleration of mineralization through controlled manipulation of temperature, injection regimes, and reactive transport behavior.

Low-kinetic pathway studies expand the applicability of basalt mineralization into new environmental contexts, demonstrating potential even in shallow or low-temperature formations. Field-scale modeling confirms that basaltic reservoirs can safely store large volumes of injected CO_2 with minimal long-term risk. As global decarbonization efforts intensify, basalt-based CO_2 mineralization stands out as a robust, scalable, and permanent solution that complements renewable energy, carbon capture technology, and climate mitigation strategies. The integrated insights from the referenced studies underscore the readiness and potential of basalt mineralization to play a major role in climate stabilization efforts worldwide.

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