Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Reframing Carbon Dioxide as a Geochemical Driver for Long-Term Nuclear Waste Isolation

Wang Han-Sheng

a0983780012@gmail.com

Taiwan Power (Taiwan) https://orcid.org/0009-0007-7938-0665

Data Note

Keywords:

Posted Date: September 16th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11021673/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: The authors declare no competing interests.

Reframing Carbon Dioxide as a Geochemical Driver for Long-Term Nuclear Waste Isolation

HanSheng Wang

Independent Researcher Taichung, Taiwan

Email：a0983780012@gmail.com

Abstract

The safe long-term isolation of high-level nuclear waste remains a critical challenge for nuclear energy systems. Geological repositories rely on multiple engineered and natural barriers to prevent radionuclide migration over geological timescales. In most repository safety assessments, carbon dioxide (CO_2) is typically regarded as a potential geochemical disturbance that may influence corrosion processes or alter groundwater chemistry.

This study presents a conceptual framework that reinterprets CO_2 as a potential geochemical driver capable of enhancing fracture sealing through carbonate mineral precipitation. Drawing on knowledge from geological carbon sequestration research, the framework suggests that CO_2-induced mineralization may gradually reduce fracture permeability in suitable host rocks.

By bridging research fields between nuclear waste management and carbon capture science, this study introduces a novel interdisciplinary perspective and highlights potential pathways for future modeling and experimental investigation.

1 Introduction

The long-term management of high-level nuclear waste is one of the most significant challenges facing nuclear energy systems worldwide. Deep geological repositories are widely regarded as the most feasible solution for isolating radioactive materials from the biosphere for hundreds of thousands of years.

These repository systems typically rely on a **multi-barrier concept**, including

engineered barriers such as waste canisters and bentonite buffers, as well as natural geological barriers provided by host rock formations. Safety assessments focus on long-term stability, radionuclide migration, groundwater flow, and geochemical evolution within the repository environment.

In conventional safety analyses, carbon dioxide (CO_2) is often considered a geochemical factor that may influence corrosion processes or alter groundwater chemistry. However, studies in geological carbon sequestration have demonstrated that CO_2 can react with host rocks and groundwater to produce stable carbonate minerals. These reactions may lead to mineral precipitation and long-term immobilization of carbon within geological formations.

While extensive research has examined CO_2-induced mineralization in the context of carbon capture and storage (CCS), and numerous studies have investigated the safety of nuclear waste repositories, **these research domains have rarely been integrated**.

This study proposes a conceptual framework that explores the possibility that CO_2-driven mineralization could contribute to fracture sealing within deep geological repositories. By linking carbon sequestration geochemistry with repository science, this work aims to highlight a potential new interdisciplinary research direction. **A conceptual model illustrating this coupled process of CO_2-induced mineralization and subsequent fracture sealing is presented in Fig. 1.** Recent comprehensive evaluation of subsurface reactor-scale systems underscores that fracture occlusion through localized carbonate crystallization provides a crucial geochemical mechanism for fluid containment, transforming the understanding of mineral trapping from passive diffusion to active structural barrier engineering (Nisbet et al., 2024; Miller et al., 2026).

Figure 1

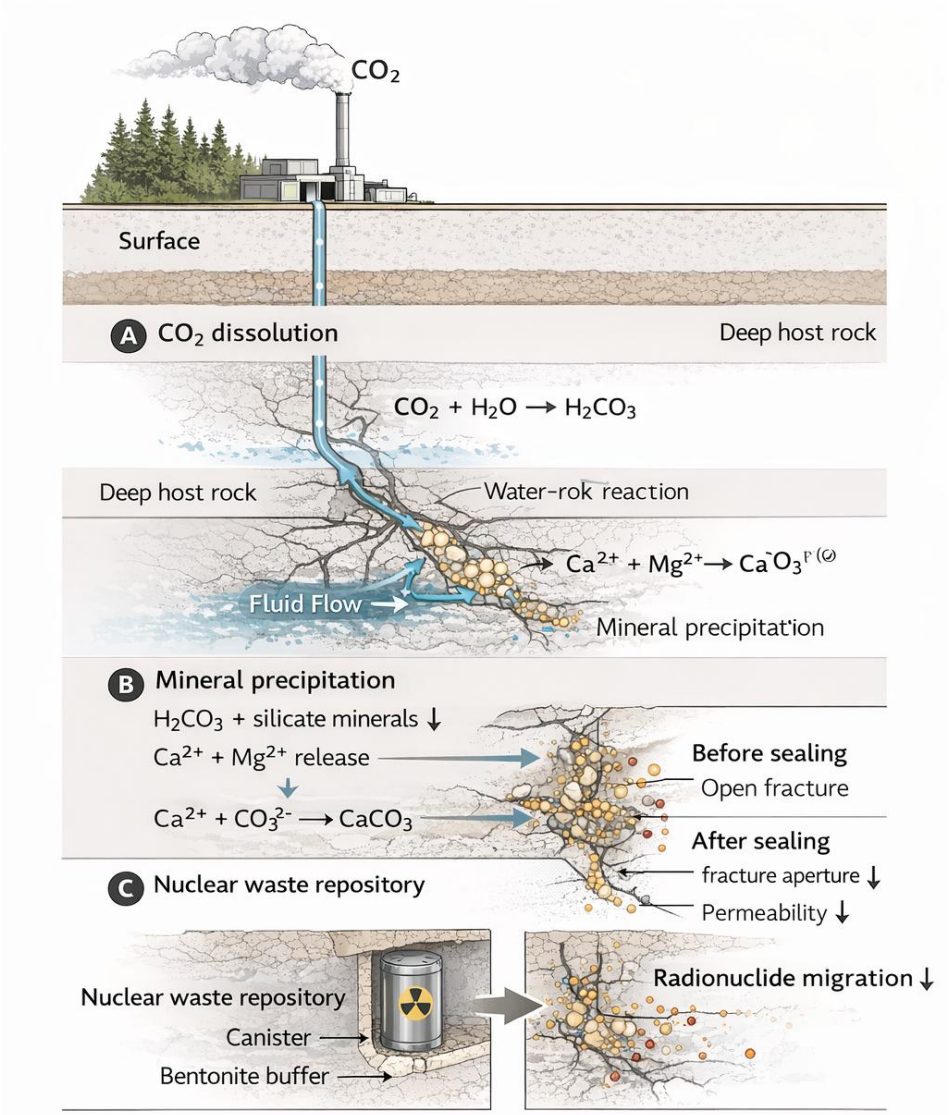


Figure 1 | Conceptual model of CO_2-induced mineralization and fracture sealing in a deep geological repository.

Injected or naturally occurring CO_2 dissolves in groundwater to form carbonic acid, which reacts with host rock minerals and releases divalent cations such as Ca^{2+} and Mg^{2+}. Subsequent carbonate mineral precipitation gradually fills fractures and pore spaces, potentially reducing permeability and enhancing long-term containment of nuclear waste canisters within the repository system.

2 Conceptual Framework

The conceptual framework proposed in this study considers the potential interaction between carbon dioxide, groundwater, and host rock minerals within a deep geological repository environment.

When CO_2 is present within subsurface systems, it can dissolve in groundwater to form carbonic acid. This weak acid reacts with silicate and carbonate minerals present in host rocks, releasing cations such as calcium, magnesium, and iron into solutions. These ions may subsequently recombine with dissolved carbonate species to form stable carbonate minerals.

Over geological timescales, these reactions may lead to **carbonate mineral precipitation within fractures and pore spaces**. The accumulation of mineral deposits can progressively reduce permeability and potentially contribute to fracture sealing.

This water-rock carbonation pathway mimics the fluid-dissolved \(\text{CO}_{2}\) injection mechanisms deployed in reactive subsurface formations, demonstrating that accelerated mineralization can bypass standard supercritical thermodynamic constraints via rapid kinetic deposition along conduit geometries **(Snæbjörnsdóttir et al., 2020; Shao et al., 2026)**

In the context of nuclear waste repositories, such mineralization processes may provide an additional geochemical mechanism that complements existing engineering and geological barriers. While this concept remains theoretical, it highlights a possible interaction pathway between CO_2 geochemistry and long-term repository evolution.

3 Theoretical Model

To conceptually describe the potential influence of mineral precipitation on fracture permeability, a simplified relationship between permeability and mineral accumulation can be proposed.

Fracture permeability can be expressed as:

$$k(t) = k_0 \cdot \exp(-\alpha M(t))$$

Where:

$k(t)$ = fracture permeability at time t
k_0 = initial permeability
$M(t)$ = cumulative mineral precipitation

α = empirical sealing coefficient

This expression reflects the idea that increasing mineral precipitation may progressively reduce available flow pathways within fractures. **The dynamic simulation profiles of fracture permeability evolution under this mathematical assumption are conceptually illustrated in Fig. 2.** Mineral accumulation may be described as a function of precipitation rate:

$dM/dt = R_{precip}(CO_2, T, P)$

Where:

R_{precip} = mineral precipitation rate

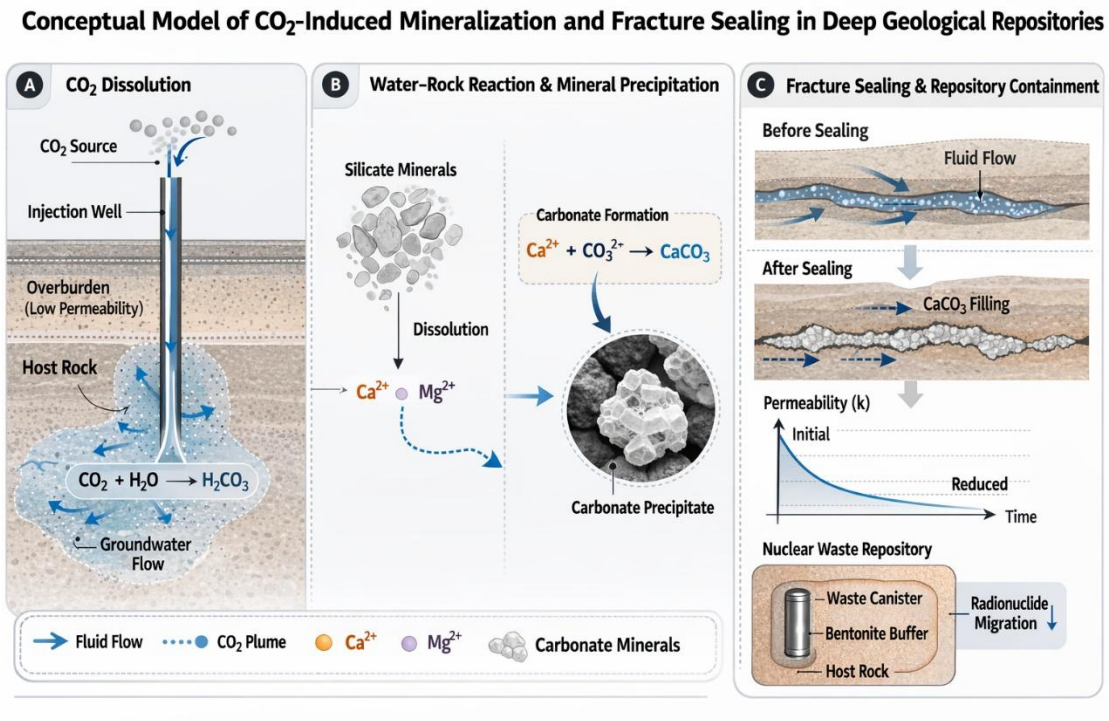
CO_2 = carbon dioxide concentration

T = temperature

P = pressure

Although simplified, this formulation provides a conceptual representation of how CO_2-induced mineralization could influence long-term permeability evolution in subsurface systems.

Figure 2



Conceptual simulation of fracture permeability evolution during CO_2-induced

mineralization.

A simplified exponential model illustrates the progressive reduction of fracture permeability due to carbonate mineral precipitation within fracture networks. The simulation assumes that cumulative mineral precipitation increases over time, leading to an exponential decline in permeability.

4 Discussion

The conceptual framework suggests that CO_2-driven mineralization may influence fracture evolution within geological formations over long timescales. In suitable geological conditions, carbonate precipitation could gradually reduce permeability and enhance natural sealing processes.

Host rock types that may be particularly reactive with CO_2 include basaltic formations, in highly reactive basaltic and mafic lithologies characterized by substantial divalent cation release, engineered in-situ mineralization presents an unprecedented self-sealing efficiency that enhances the long-term containment integrity of the deep repository footprint over geological epochs **(Kelemen et al., 2020; Schaef et al., 2025)**silicate-rich rocks, and certain sedimentary lithologies containing reactive minerals. In such environments, water-rock interactions could potentially lead to progressive mineral deposition along fractures and pore networks **, as diagrammed in the conceptual reactive transport model (Fig. 3)**. However, several important uncertainties remain. The kinetics of mineral precipitation under repository conditions are not well constrained, and the influence of temperature, pressure, and groundwater chemistry may vary significantly across geological settings. Additionally, CO_2-induced geochemical changes may influence corrosion processes or radionuclide mobility.

Therefore, further research is necessary to determine whether such mechanisms could play a meaningful role in repository evolution.

Figure 3

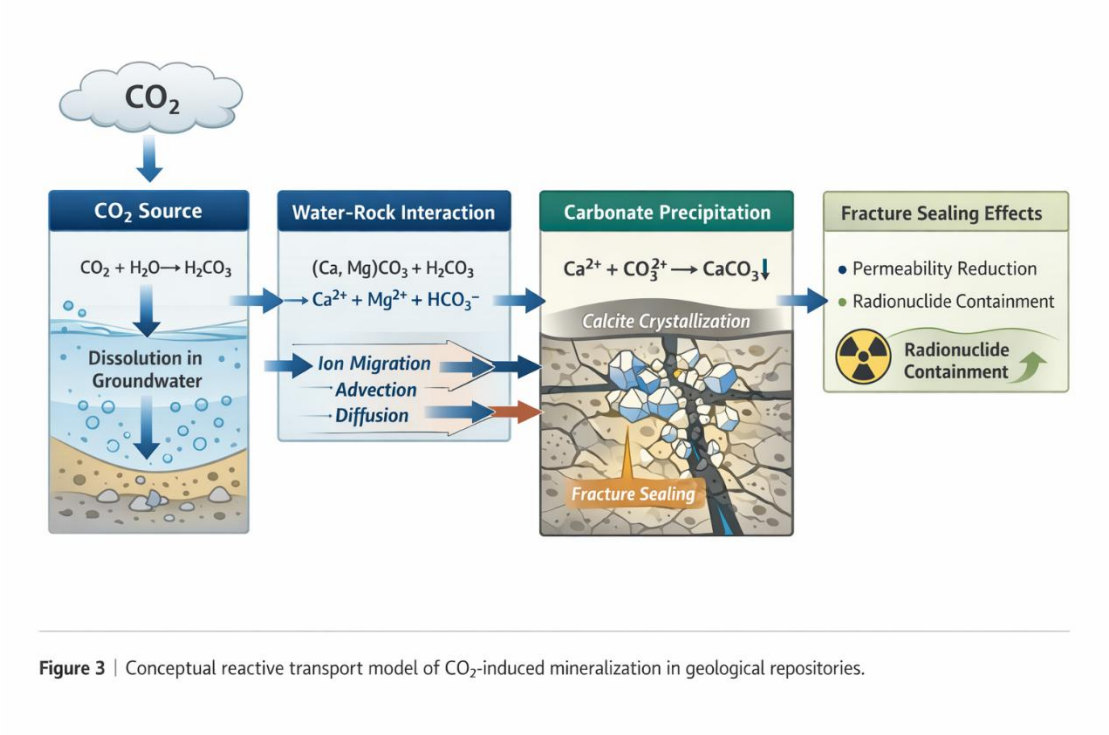


Figure 3 | Conceptual reactive transport model of CO_2-induced mineralization in geological repositories.

Conceptual reactive transport model of CO_2-induced mineralization in geological repositories.

The diagram illustrates the coupled processes of CO_2 dissolution, water–rock interaction, ion transport, and carbonate mineral precipitation. These processes collectively contribute to fracture filling and permeability reduction, potentially enhancing radionuclide containment in deep geological repository systems.

5 Limitations

The framework presented in this study is conceptual in nature and is not supported by direct experimental data. Several limitations should be acknowledged.

First, the kinetics of carbonate mineral formation under repository conditions remain uncertain. Second, the simplified permeability model does not account for complex fracture geometries or heterogeneous mineral distributions. Third, the potential influence of CO_2-driven geochemical changes on radionuclide transport requires further investigation.

Consequently, the proposed framework should be regarded as a conceptual starting point rather than a predictive model.

6 Future Research Directions

Future research should focus on experimental, numerical, and field-based studies to evaluate the feasibility of CO_2-induced mineralization within repository environments.

Laboratory experiments simulating CO_2-rock-water interactions under representative pressure and temperature conditions could help determine mineralization kinetics. Reactive transport simulations may also provide insight into long-term permeability evolution and geochemical interactions.

Field observations from geological carbon sequestration projects may offer valuable analogues for understanding mineralization processes in subsurface environments.

7 Conclusion

This study introduces a conceptual framework that reinterprets carbon dioxide as a potential geochemical driver capable of promoting fracture sealing through mineral precipitation. By connecting insights from carbon sequestration research with nuclear waste repository science, the framework highlights a novel interdisciplinary perspective.

Although the proposed mechanism remains theoretical, it suggests that CO_2-induced mineralization may represent a previously underexplored factor in repository evolution. Further experimental and modeling studies are required to assess its feasibility and potential implications for long-term nuclear waste isolation.

Author Contributions

The author conceived the research concept, developed the theoretical framework, and wrote the manuscript.

Declarations

Funding

The author received no specific funding for this work.

Ethics Approval and Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

Data Availability

No datasets were generated or analyzed during the current study.

Competing Interests

The author declares no competing interests.

References

Kelemen, P. B., McQueen, N., Wilcox, J., Renforth, P., Dipple, G., & Vankeuren, A. P. (2020). Engineered carbon mineralization in ultramafic rocks for CO_2 removal from air: Review and new insights. *Chemical Geology, 550*, 119628. https://doi.org/10.1016/j.chemgeo.2020.119628

Miller, Q. R. S., Bartels, M. F., Chopra, H., Depp, C. T., DiRaddo, S. G., Gibson, M. N. M., Lahiri, N., Lamberti, V. R., Rivera, N. L., Maier, K. L., Murchland, M. A., Nienhuis, E. T., Parisi, J., Polites, E. G., Stanfield, C. H., Steup, K. J., Teng, Y., Villante, M. A., Yan, K., & Schaef, H. T. (2026). Earth as a reactor: Carbon mineralization geochemistry in the context of emerging subsurface energy and resource technologies. *Chemical Reviews, 126*(10), 5713–5754. https://doi.org/10.1021/acs.chemrev.5c00716

Nisbet, H., Buscarnera, G., Carey, J. W., Chen, M. A., Detournay, E., Huang, H., Hyman, J. D., Kang, P. K., Kang, Q., Labuz, J. F., Li, W., Matter, J., Neil, C. W., Srinivasan, G., Sweeney, M. R., Voller, V. R., Yang, W., Yang, Y., & Viswanathan, H. S. (2024). Carbon mineralization in fractured mafic and ultramafic rocks: A review. *Reviews of Geophysics, 62*(4), e2023RG000815. https://doi.org/10.1029/2023RG000815

Schaef, H. T., Bartels, M. F., Davidson, C. L., DiRaddo, S., Lahiri, N., Lopez Rivera, N., Maier, K. L., Miller, Q. R. S., Nienhuis, E. T., Polites, E. G., Stanfield, C. H., & Villante, M. A. (2025). *Review of CO_2 storage via in-situ mineralisation in mafic-ultramafic rocks* (IEAGHG Technical Report 2025-03). IEA Greenhouse Gas R&D Programme. https://doi.org/10.62849/2025-03

Shao, Z., Liang, Y., Jo, G., Nakamura, K., & Tsuji, T. (2026). Interfacial mechanisms governing CO_2 mineralization: From reactivity origins of basaltic surfaces to engineering strategies. *Advances in Colloid and Interface Science, 356*, 103951. https://doi.org/10.1016/j.cis.2026.103951

Snæbjörnsdóttir, S. Ó., Sigfússon, B., Marieni, C., Goldberg, D., Gislason, S. R., & Oelkers, E. H. (2020). Carbon dioxide storage through mineral carbonation. *Nature*

Reviews Earth & Environment, 1(2), 90–102. https://doi.org/10.1038/s43017-019-0011-8