

Global Assessment of CO₂ Mineralization in Basaltic Formations: A Comprehensive Benchmark Analysis

Meriem Elhaouari

University of Boumerdes, Algeria

Corresponding authors

Meriem Elhaouari, University of Boumerdes, Algeria.

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Abstract

This comprehensive study presents a global assessment of CO₂ mineralization potential in basaltic formations. Through Monte Carlo simulations applied to terrestrial basalts, providing precise estimates of storage capacities for both carbonated water injection (P50: 20.89 tons) and direct CO₂ injection methods. The research evaluates key basalt regions worldwide, comparing onshore versus offshore storage potential, geological suitability parameters, and storage efficiency. Our analysis identifies optimal injection platforms based on multiple criteria including mineral composition, proximity to major emission sources, and storage security mechanisms. The results provide a robust framework for selecting promising basalt reservoirs for large-scale carbon sequestration initiatives.

Keywords: CO₂ Storage, Basalt Mineralization, Global Benchmark, Monte Carlo, Carbon Sequestration.

Introduction

The CO₂ Emissions Challenge

Global carbon dioxide (CO₂) emissions are projected to reach a record of 41.6 billion metric tons in 2024, up from 40.6 billion tons in 2023, primarily due to fossil fuel combustion China being the biggest emitter (Fig.1). Accurate assessment of anthropogenic carbon dioxide (CO₂) emissions and their redistribution in a changing climate is critical to better understand the global carbon cycle, support the development of climate policies, and project future climate change [1,2]. CO₂ mineralization is the safest CO₂ geosequestration method with the highest sequestration capacity Since Basalts contain a lot of carbon-fixing minerals which can achieve the fast mineral trapping of CO₂ [3,4].

Innovative Recommendations

Our innovative recommendations include exploring advanced monitoring technologies, optimizing injection techniques, and enhancing collaborations. Additionally, geophysical modeling provides more accurate capacity predictions. Exploring the potential of old oil and gas reservoirs for CO₂ injection is also

an innovative approach that can maximize the use of existing infrastructure.

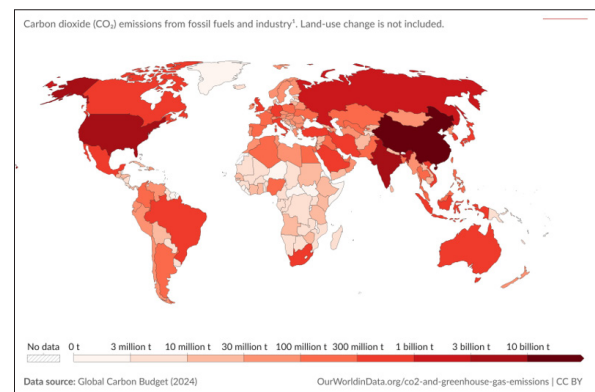


Figure 1: Global Map of Annual CO₂ Emissions from Fossil Fuels and Industry (2023) Source: Global Carbon Budget (2024). OurWorldInData.org/co2-and-greenhouse-gas-emissions

Worldwide Benchmark

Basalt, a type of volcanic rock, contains a high concentration of carbon-fixing minerals, making it an excellent candidate for CO₂ sequestration. The advantages are:

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1. The theoretical CO₂ mineral trapping capacity per unit volume of basalt can reach up to 378–680 kg/m³ [5].
2. Basalt has high reactivity, enabling it to rapidly convert most of the injected CO₂ into stable carbonate minerals. This reduces the dependence on the sealing conditions of the geological structures [5].
3. Basalt is widely distributed, covering 10% of the land area and most of the ocean floor [6].

Key Basaltic Regions

- **Island-Arc Basalts:** These basalts are located in subduction zones and are abundant in elements that enhance CO₂ sequestration [7].
- **Oceanic Island Basalts:** Commonly found in hotspots, they are distributed across the ocean floor and contain high silicate mineral content conducive to rapid CO₂ mineralization [7].
- **Mid-Ocean Ridge Basalts:** These form along tectonic plate boundaries, especially in mid-ocean ridges, and are characterized by young basalts with high porosity and permeability, making them favorable for CO₂ injection [7].

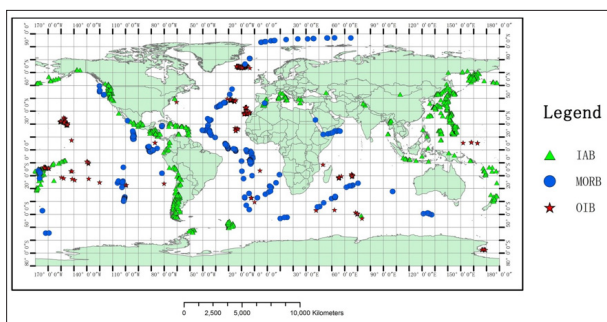


Figure 2: Global Distribution Map of Training Data Featuring 3,277 Island-Arc Basalt Samples, 5,920 Oceanic Island Basalt Samples, and 997 Mid-Ocean Ridge Basalt Samples (from “Formation of Tarim Large Igneous Province and Strengthened Lithosphere Revealed Through Machine Learning”)

Criteria for Basalt CCS Sites

The suitability of basalt formations for carbon capture and storage (CCS) depends on the following key criteria:

Structural and Geological Properties

- Adequate porosity and permeability to facilitate CO₂ injection.
- Presence of an impermeable caprock to prevent leakage.

Proximity to CO₂ Sources

- Sites should be located near major industrial CO₂ emitters to reduce transportation costs.

Water Availability:

- Essential for CO₂ injection, particularly if the CarbFix method (dissolution trapping) is used. Seawater is a potential alternative for offshore basalts.

Infrastructure and Social Acceptance:

- Accessibility for infrastructure development and public support are crucial for project feasibility.

Potential Sites for Basalt CCS

Australia

- **Antrim Plateau Volcanic Province:** Spanning over 12,000 km², this flood basalt province in Northern Australia has significant theoretical capacity. However, its remote location reduces its feasibility (*Earth Resources Victoria Government Website, 2016*).
- **Victoria Basalts:** Thin basalt flows (<50 m) limit storage potential in this region (*Earth Resources Victoria Government Website, 2016*). 2.3.2 India
- **Deccan Traps:** Covering 512,000 km², this extensive flood basalt formation has high potential. Features like vesicular-amygdaloidal zones and compound flows (450-710 m thick) enhance CO₂ injection efficiency. Proximity to major coal-fired power plants (e.g., Kahalgaon and Farakka) adds to its viability (*Mahoney, J.J., et al., 2000; IEAGHG, 2008*).
- **Rajmahal Traps:** Located in Jharkhand, these deposits (up to 608 m thick) are near coal-fired power plants, making them a promising candidate for CCS, pending further evaluation (*Geological Survey of India, 1954-55*).

South Africa

Karoo Basalts: Covering over 140,000 km², the Karoo basin includes basaltic lavas and ash beds. While its location near coal-fired power stations is advantageous, low porosity, permeability, and water scarcity present challenges (*Council for Geoscience South Africa, 2010; Ross, P.-S., et al., 2005*).

China

Basalt Deposits in China: The terrestrial basalts in China exhibit substantial CO₂ storage potential, as indicated by Monte Carlo simulations. These formations benefit from favorable geological conditions and proximity to large industrial CO₂ emitters. The effective mineral storage capacity of Chinese basalts highlights their promise as a CCS solution, though detailed site-specific assessments are necessary [04].

Basalt formations globally, including those in Australia, India, South Africa, and China, present immense potential for CCS due to their high reactivity and mineral trapping capacity. Pilot projects like CarbFix (Iceland) and Wallula (USA) have demonstrated the feasibility of basalt CCS. Further research and capacity assessments are critical to unlocking their full potential.

Basalt Quality Efficiency

Basalt Mineralisation offers an expanded geographic range of onshore (volcanic areas, large flood basalt provinces) and offshore (oceanic ridges) storage reservoirs and offers a global storage potential that exceeds anthropogenic emissions [8].

Offshore

Potential of Offshore Basalt Storage

Offshore basalt reservoirs are advantageous due to the large volumes of seafloor basalt and the availability of seawater. These reservoirs could address limitations associated with onshore carbon capture and storage (CCS) [9].

High Offshore Drilling Costs

Strategies to maximize CO₂ storage capacity per well are critical to offset the high costs of offshore drilling. Enhanced injection techniques, such as Water Alternating Gas (WAG) scenarios,

show variable performance metrics [9].

WAG Scenarios

Different WAG scenarios exhibit variability in injection rates, pressures, water demand, and injection duration. These factors directly impact well construction, maintenance costs, and energetic demands, particularly for CO₂-saturated seawater injection compared to seawater-only injection [10].

Cost Considerations

Offshore CCS incurs high initial investments, including drilling and site construction. Associated operational costs, although lower than initial investments, remain significant and require optimization [10].

Public Acceptance and Political Issues

Offshore storage minimizes public and political concerns often associated with onshore CCS projects. The overlying seawater and low-permeability sediment layers reduce leakage risks, enhancing the viability of offshore storage [10].

Emission Inventory Implications

Territorial emission inventories include emissions and removals from both national territories and offshore jurisdictions [10,11]. Consumption-based inventories adjust for exports and imports, ensuring accurate attribution of emissions to consumption patterns.

Risk Mitigation

The presence of natural barriers like low-permeability sediments near the seafloor adds a safety layer to offshore CCS systems [10].

Onshore

Northern Lights Project

The Northern Lights project involves the capture of CO₂ onshore, which will then be injected and permanently stored 2,600 meters below the seabed of the North Sea. Phase one of the project is expected to be completed by mid-2024, with a capacity to store up to 1.5 Mt CO₂/yr [8].

CCS and Injection Techniques

CCS projects have primarily focused on the supercritical injection of CO₂ into deep saline formations, depleted oil or gas fields no longer viable for production, and as part of enhanced oil recovery (EOR) operations [5].

Abundant Flood Basalt Fields

Although the occurrence of basalts onshore is limited (approximately 5%), the weathering of basaltic rocks on continents and volcanic islands contributes to around 30% of the natural CO₂ draw down attributable to continental silicate weathering. This highlights the relative advantage of basalt compared to other terrestrial rocks for in-situ carbon mineralization [12,14].

Storage Potential in Geothermal Systems

Onshore geothermal systems in Iceland, which is located along the mid-oceanic ridges, hold significant storage potential. CO₂ bound in carbonates has been measured in drill cuttings from basalt-hosted geothermal fields.

While carbonates precipitate over long timescales (10,000–300,000 years) [12].

Uncertainty and Risk Analysis

A probabilistic analysis using 1,000 Monte Carlo simulations has been conducted to assess uncertainties in the data, particularly regarding fault slip potential. This analysis helps in understanding the risk involved and optimizing the viability of onshore CO₂ storage systems [13].

Public Acceptance and Political Issues

Onshore CCS projects face political and public acceptance challenges. The potential for offshore mineral carbon storage, particularly through CO₂-charged seawater injection, offers a solution to mitigate these issues and enhance the global relevance of CCS techniques [10].

Offshore vs Onshore

Onshore CO₂ storage is effective in regions with flood basalts, such as India, Siberia, and the United States, where basalt weathering accounts for 30% of global CO₂ drawdown. Geothermal systems in Iceland demonstrate the ability of young basalts to store over 100 kg of CO₂ per cubic meter, highlighting their efficiency. However, challenges like limited basalt coverage (5%) and variability in porosity hinder scalability.

Offshore storage leverages vast subsurface basalt reservoirs and abundant seawater, offering immense potential. Despite high initial costs, techniques like Water Alternating Gas (WAG) injection optimize per-well storage. Additionally, offshore locations reduce risks and public concerns due to overlying seawater and impermeable sediment layers, making them suitable for large-scale CCS deployment.

Impact of Geochemistry

Basalt's porosity is mostly 5–20%, and the permeability is from several md to several thousand md. The main components of basalt include plagioclase, pyroxene, olivine, hornblende, and biotite [21-23]. Among them, the content of silicate minerals of calcium, magnesium, and iron with the ability to fix carbon can be as high as 40–70 wt%, associated with the content of Ca, Mg, and Fe oxide in basalts can reach 25 wt%. When CO₂ is injected into the basalt formation, it first dissolves in the formation water to produce carbonic acid [04,21].

Then the carbon-fixing minerals in basalts react with the H⁺ to release divalent cations Ca²⁺, Mg²⁺, and Fe²⁺.

Finally, the released divalent cations react with the HCO₃⁻ to produce carbonate precipitation to complete the carbon mineral trapping process.

During the entire process of carbon fixation, CO₂ dissolves in the formation water and reacts with divalent cations to form carbonate precipitation rapidly. This is a long-term thermodynamically stable process. The interaction of CO₂ with basalt and formation water determines the time for its safe storage [4].

Trapping Mechanisms

Trapping mechanisms enhance storage capacity and minimize leakage risk:

- **Structural and Stratigraphic Trapping:** CO₂ is confined beneath impermeable rock layers, ensuring containment in geological formations.
- **Residual Trapping:** CO₂ is trapped in pore spaces of the basalt matrix by capillary forces, preventing migration.
- **Solubility Trapping:** CO₂ dissolves into the formation's brine, reducing its volume and further preventing leakage.
- **Mineral Trapping:** The reaction between CO₂ and the minerals in basalt forms stable carbonates, effectively locking CO₂ in place over the long term.

The Monte Carlo method can be used to determine the variation range of CO₂ storage capacity in basalts.

Case Study

This study aims to significantly reduce China's emissions, which are the highest globally at 11.9 billion tons annually, by leveraging basalt reservoirs immense storage potential [15].

This report focuses on applying the Monte Carlo method to estimate the effective CO₂ storage capacity of a basalt formation near a hypothetical industrial plant emitting 1 million tons of CO₂ annually over 30 years. The simulation replicates the approach presented by Zhang et al. (2023), utilizing key parameters such as mineral composition, reservoir porosity, and effective storage coefficients [04]. By performing thousands of iterations, the study aims to quantify the potential range of storage capacities and derive statistically significant results, such as P10, P50, and P90 values.

Distribution and Geological Conditions of Terrestrial Basalts China

Volcanic rocks are widely distributed in and around China's sedimentary basins. [7] The Cenozoic volcanic rocks in the northeast, east, and southeast, as well as the Paleozoic volcanic rocks in the southwest and northwest, are either exposed or shallowly buried. These basalts provide ideal sites for CO₂ geological storage. [5] See figure 2.

Wu et al. pointed out that the basalt oil and gas reservoirs not only contain a large amount of carbon-fixing minerals but also have good cap conditions. They are good sites for carbon sinks, easy implementation, low cost, and high safety. The CO₂ storage capacity of the basalt gas reservoir in the Xujiaweizi fault depression in the Songliao Basin was estimated to be 9.553 Gt, while the CO₂ storage capacity of the basalt oil and gas reservoirs in the Jiyang Depression was predicted to be 3.968 Gt. The storage capacity contributed by the mineral trapping mechanism is as high as 90% or more [18,19].

Methodology

The methodology for this study utilizes a Monte Carlo simulation to estimate the effective CO₂ storage capacity of a basalt formation, accounting for uncertainties in key geological parameters such as mineral composition, porosity, and CO₂ sweep efficiency.

The Monte Carlo simulation is implemented using Python, with the following libraries:

- NumPy
- Matplotlib

Key Equations

- Theoretical Storage Capacity (MCO₂)
- Theoretical mineral storage capacity of CO₂
- Effective Storage Capacity (MCO₂eff)

Simulation Process: The simulation is run for 5000 iterations to ensure a statistically significant sample. In each iteration, random values are assigned to the parameters, and the CO₂ storage capacity is recalculated using the equations outlined earlier.

Statistical Analysis: After running the simulation, the 10th percentile (P10), 50th percentile (P50), and 90th percentile (P90) of the effective storage capacity are calculated. These values represent the range of possible storage capacities under different parameter scenarios.

For more details, access the files on: [Google Drive Link](#)

Results and Discussion Methods P10, P50, and P90 Results:

Injection Method	P10	P50	P90
Carbonated water Injection	12.81 tons	20.89 tons	30 tons
Direct Injection	12.67 tons	17.70 tons	23.04 tons

Understanding the Monte Carlo Results

- **P10:** Represents a scenario where the outcome is better than 90% of the simulations, indicating an optimistic scenario with lower likelihood.
- **P50:** Represents the median or most likely outcome; half of the simulations predict higher results and half predict lower.
- **P90:** Represents a scenario where the outcome is better than only 10% of the simulations, indicating a conservative or pessimistic scenario.

Innovative Recommendations

Innovative Approaches in CO₂ Storage

1. Utilization of Old Oil and Gas Reservoirs:

- Incorporates the use of *old oil and gas reservoirs* for CO₂ injection and storage, maximizing resource efficiency.
- Evaluates suitability for direct CO₂ injection and carbonated water injection in these reservoirs.

2. Advanced Capacity Estimation:

- Utilizes the *Monte Carlo method* to calculate theoretical and effective CO₂ mineral storage capacities.

3. Optimized Injection Techniques:

- Explores both direct CO₂ injection and carbonated water injection.
- Tailored for efficient storage in basalt reservoirs.

4. Geological Risk Mitigation:

- Applies the FSP tool to analyze pore pressure changes.
- Evaluates risks of fault slip during CO₂ injection to ensure reservoir stability.

5. Carbon Source-Sink Alignment:

- Addresses mismatches between CO₂ storage capacities and emission sites.
- Proposes carbon source-sink optimization to reduce transportation challenges.

6. Enhanced Monitoring and Modeling:

- Incorporates real-time geophysical monitoring for tracking CO₂ injection and mineralization.
- Proposes Geophysical modeling for precise capacity predictions and optimization.

Economic Analysis

There is great economic potential of injection in basalt especially oil and gas reservoirs [20]. These reservoirs feature substantial CO₂ storage capacities and favorable geological conditions, enabling efficient and cost-effective implementation.

Breakdown of Costs per Ton of CO₂

- **CO₂ Capture and Compression:** \$30–\$60/ton.
- **Carbonated Water Preparation:** \$5–\$10/ton.
- **Transportation and Injection:** \$10–\$20/ton.
- **Monitoring and Maintenance:** \$5/ton.

Total Cost per Ton of CO₂:

Total Cost = 30–60 + 5–10 + 10–20 + 5 = 50–95\$/ton.

- **Emissions Scenario:** A plant emitting 1 million tons of CO annually (1 MTPA) over 30 years is targeted for carbon capture and storage.
- **Total Project Cost for 30 Years:** For 1 MTPA over 30 years, the estimated cost is approximately \$1.5–2.85 billion USD for capturing and storing the emissions of the plant.

CO₂ Tax Avoidance Savings

Avoid carbon taxes imposed by governments on CO₂ emissions.

- **Annual CO₂ Emissions:** 1,000,000 tons.
- **Carbon Tax Rate:** \$50/ton.
- **Tax Avoidance Savings:** 1,000,000 tons × 50\$/ton = 50 million USD/year.

Scaling this across industries and regions demonstrates the potential for substantial financial savings while achieving environmental compliance.

Comprehensive Monitoring

During the project life, most of the CO₂ is contained by the first trapping mechanism and specific tools have been developed to characterize and monitor the integrity of the caprocks. Seismic, gravity, or electromagnetic tools are utilized to monitor the CO₂ plume migration to confirm containment by the caprock.

- **Emergency Preparedness:** Establish leak detection, alarm systems, and evacuation protocols [16].
- **Post-Injection Care:** Monitor site for 50 years to ensure CO₂ containment and plug wells [17].
- **Induced Seismicity:** Induced Seismicity and Geophysical Assessment: Induced seismicity occurs when CO₂ injection increases pore pressure on faults, potentially triggering slip. Site characterization [13].

Conclusion

This study investigates CO₂ sequestration in basaltic formations as a method to reduce atmospheric emissions. Using Monte Carlo simulations, we evaluate storage capacity for a Chinese industrial plant emitting 1 million tons annually over 30 years, incorporating mineral composition, porosity, and storage coefficients. Carbonated water injection proves superior, with average storage capacity of 249.50 Gt (P50). Terrestrial oil reservoirs offer proven stability, while basalt reservoirs provide

large capacity, permanent mineralization, easy implementation, and proximity to emission sources. The project follows UNFC sustainability frameworks with geophysical monitoring for containment assurance.

Onshore basalt formations in India and Siberia show promise despite limited coverage and porosity constraints, with Icelandic geothermal systems demonstrating efficient storage in young basalts. Offshore reservoirs offer greater potential through vast subsea volumes and seawater availability, with Water Alternating Gas injection optimizing capacity, though initial costs are higher. Natural barriers and reduced public concerns enhance offshore viability. Economic assessment considers capture, transport, and injection costs alongside revenue from carbon credits and green taxes, confirming basalt mineralization as a safe, permanent, and viable climate solution.

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