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Review of CO2 storage via in-situ mineralisation in mafic-ultramafic rocks

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IEAGHG

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IEAGHG

Report Overview:

Review of CO_2 storage via in-situ mineralisation in mafic-ultramafic rocks

Introduction

Mafic and ultramafic rocks, such as basalt and peridotite, are widely distributed across the globe and can be generally associated with: oceanic crust; large igneous provinces, such as the Deccan traps (India), the Columbia River Basalt Group (USA) and the Parana-Etendeka province (Brazil, Namibia); ophiolitic complexes e.g. Samail ophiolite (Middle East) and Coast range ophiolite (California); exhumed mantle assemblages; subduction zones and volcanic arcs; and layered intrusions. Their widespread distribution offers an alternative storage opportunity for the permanent sequestration of CO_2 compared to storage in a conventional sedimentary basin setting (i.e. saline aquifers or depleted oil and gas reservoirs). They largely rely on rapid in-situ mineralisation of injected CO_2.

Recent field experiments in mafic-ultramafic rocks demonstrate the potential for such storage opportunity, and IEAGHG felt it timely to commission a critical evaluation of the technology at this point, to understand the progress made to date and some of the factors necessary to scale up to industrial volumes necessary to impact climate targets. Despite growing research, total injected CO_2 through subsurface mineralisation remains around 100,000 tonnes, primarily from CarbFix projects, but claims of total storage resources range upwards of gigatons to teratons.

This report evaluates progress, barriers, and knowledge gaps, and provides stakeholders, regulators, and investors with a comprehensive summary of current knowledge and understanding of subsurface carbon mineralisation in mafic-ultramafic reservoirs.

Key Messages

- Current storage of mafic and ultramafic remains underdeveloped with large resource potential. To date ~100,000 tonnes of CO_2 have been injected into mafic-ultramafic reservoirs globally, with the majority at CarbFix.
- A consistent approach to storage resource estimation is needed to support more accurate assessments of resource potential. Current storage resource estimates, from 10 countries, range from gigatons to teratons (and vary depending on the approach taken).
- 31 reactive transport models to predict the fate of injected CO_2 in mafic and ultramafic reservoirs were reviewed. The accuracy of the models depends on rock properties, selection of primary minerals, accurately predicting secondary mineralization and scale of the model (pore versus reservoir scale).
- 10 active or completed CO_2 injection field sites have been reviewed from the literature and discussions with industry experts, across the USA, Iceland, Oman, Saudi Arabia and the UAE.
- The growing commitment to CO_2 mineralization as a scalable carbon storage solution is reflected in the development of 17 planned and prospective CO_2 injection sites across nine countries and six continents. Of these, seven sites are preparing for future injections, while the remaining ten are in the feasibility, drilling, or permitting phases. These projects aim to expand carbon mineralisation into diverse mafic and ultramafic formations.
- A variety of injection schemes are possible with pros and cons to each. For example, aqueous injection demands high levels of water resources which may inhibit scale-up to commercial volumes. Recent water usage estimates from the Coda Terminal in Iceland state that approximately 3000 Litres per second (greater than 1.63 million barrels per day) will be required for a 3 million metric tonnes per year (MMT/yr) CO_2 injection scenario.
- If properly selected and characterized, mafic-ultramafic reservoirs pose no greater risk (potentially less) of harmful reaction products (e.g. to potable water sources) than sedimentary reservoirs.
- Injected CO_2 may be converted to microbial biomass or methane, and requires further work to evaluate potential consequences.
- In theory any subsurface injection, including CO_2 sequestration, can trigger seismic activity due to increased reservoir pressures and resulting fault activation. Thus far, field projects have not seen induced seismicity as a result of CO_2 injection given the care taken in site selection, monitoring and stepwise development of storage sites. However, large-scale projects will increase uncertainty in pressure dynamics and mineralisation effects, possibly raising seismic risks.
- The complex, fractured, and heterogeneous nature of mafic-ultramafic formations, along with CO_2 -fluid-rock interactions which drive mineral trapping, require tailored

monitoring technologies to ensure storage security. These rely increasingly on geochemical rather than geophysical methods.

- Regulatory clarity is critical for scaling CO_2 mineralisation projects. While no major legal barriers exist under current CCUS regulations, targeted guidance and incentives could further accelerate deployment. Early projects will help navigate regulatory gaps and challenges under different frameworks.
- Scaling CO_2 mineralisation storage requires overcoming technical, economic, and potential regulatory hurdles. Lessons from the hydrocarbon, mining, and geothermal industries can help optimize processes, while stable revenue models and improved site characterization and MRV will be key to commercial success

Scope

The scope of this study covered the following topics, which are arranged as chapters to the report:

- A full assessment of screening, simulations and field studies of in-situ CO_2 mineralisation in mafic and ultra-mafic rocks from across the globe (chapter two)
- Evaluation of reactions and relevance to CO_2 mineralisation , as evidenced from field and simulation studies, what factors influence carbon mineralisation kinetics and summaries of reactions and relevance (chapter three)
- Subsurface risks were considered including an overview of the key subsurface parameters, evaluating the risks of harmful reaction products, and seismic risks (chapter four)
- Monitoring for CO_2 storage in mafic-ultramafic reservoirs was covered including overall monitoring objectives and requirements and descriptions of potential monitoring tools and technologies (chapter five)
- Global regulations and legal barriers to storage is a tackled in chapter six
- Moving from field studies to commercial deployment of this technology is explored via scale up challenges and cost and resource requirements (chapter seven)
- Finally, challenges and opportunities for CO_2 storage in mafic and ultramafic reservoirs in chapter 8

An appendix is supplied, which comprises a review of the reactive transport models.

Conclusions

This report undertakes a review of the current state of knowledge of CO_2 storage via in-situ mineralisation in mafic and ultramafic rock affinities. The promise of rapid mineralisation may ultimately reduce site monitoring costs and further reduce leakage risks. However, limited experience in mafic-ultramafic CO_2 storage poses a scaling risk. Adapting techniques from mining & geothermal industries could improve drilling efficiency and costs, although there are multiple unknowns such as the impact of secondary mineral formations and increased pore pressure at scale.

Mafic-ultramafic reservoirs, unlike well-studied sedimentary formations, lack extensive characterization data, and as yet the necessity and reliability of an aquitard is yet to be determined. Reactive transport modelling is essential to predict CO_2 trapping rates and kinetics, and an extensive review of known models and their inputs is provided.

If mineralisation can be accurately modelled, a smaller storage footprint(in the case of sCO2 injection) and shorter post-injection monitoring may make mineralisation projects more cost-effective. However, access to water resources may ultimately limit the scale up of projects.

Scaling CO_2 mineralisation storage requires overcoming technical, economic, and regulatory hurdles. Lessons from the hydrocarbon, mining, and geothermal industries can help optimize processes, while stable revenue models and improved site characterization will be key to commercial success.

Expert Review

The first draft of this report was reviewed by 15 expert reviewers from eight organisations (industry, academia, and research organisations), which generated a wide range of commentary and suggestions in the text. It also generated many follow-on ideas that are beyond the scope of this report but would be valuable follow-up.

Most reviewers felt it was well written, structured and rich in relevant references, and provides an excellent starting point for anyone wanting to know more about the current state of research and development in the emerging CO_2 storage play of mafic-ultramafic rocks. The report provides a solid overview of reactions, modelling codes and databases, experimental work and field studies.

It was felt that the final risk assessment relied on available information from small-scale injection projects and potentially overlooks the unforeseen challenges in scale-up, particularly water availability, mineralisation rates, pressure connectivity, and induced seismicity.

Chapter 6 (Global regulations) was reviewed twice, and careful wording has been introduced to highlight that the European CCS Directive Guidance Documents are legally non-binding.

Almost 700 comments in the report have been addressed by the authors and were gratefully received.

Recommendations

- There is a need to standardise storage resource estimation calculation methods to improve accuracy. A standardized approach incorporating updated thermodynamic and kinetic data could improve the reliability of CO_2 storage predictions in mafic-ultramafic reservoirs.
- The study highlights the need for more standardized kinetic parameters and better documentation of reaction pathways in CO_2 mineralisation models.
- Future research could focus on whole-rock experiments, deep biosphere assessments, and secondary mineral interactions to improve carbon mineralisation predictions. Whilst pressure, temperature, and salinity are well-understood factors in CO_2 solubility, these three less-explored factors require further study.
- Baseline assessments are needed prior to field-scale CO_2 injection, thorough sampling and deep biosphere characterization are essential.
- Based on current understanding, mafic-ultramafic reservoirs pose no greater risk of harmful reaction products than sedimentary reservoirs, However, additional research is needed to understand long-term formation water evolution. Ultramafic reservoirs remain underexplored and may contain higher concentrations of potentially harmful trace elements.
- The paucity of commercial scale mineralisation storage projects, and, in general, the lack of mafic-ultramafic injection experience, warrants additional fieldwork and research to evaluate the efficacy of monitoring techniques, especially for commercial-scale (e.g., >1 MMT per year) injections.

Review of CO_2 Storage via In Situ Mineralization in Mafic-Ultramafic Rocks

By

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Abbreviations

AoR	area of review
$CO_2(aq)$	aqueous carbon dioxide (dissolved in water)
ARPA-E	Advanced Research Projects Agency – Energy (United States)
BECCUS	bioenergy carbon capture storage
BOEM	Bureau of Ocean Energy Management (United States)
BSEE	Bureau of Safety and Environmental Enforcement (United States)
CARB	California Air Resources Board (United States)
CAPEX	capital expenditure
CCUS	carbon capture, utilization, and storage
CCS	carbon capture and storage
CDR	carbon dioxide removal
CO_2	carbon dioxide
CRBG	Columbia River Basalt Group
CSII	CarbonSAFE Phase II
DAC	direct air capture
DAS	distributed acoustic sensing
DInSAR	Differential Interferometric Synthetic Aperture Radar
DOE	Department of Energy (United States)
DWD	Drinking Water Directive (European Union)
EC	European Commission
EEA	European Economic Association
EOR	enhanced oil recovery
EPA	Environmental Protection Agency (United States)
ETS	Emissions Trading System (European Union)
EU	European Union
GD	Guidance Document
GGS	greenhouse gas storage
GHGRP	Greenhouse Gas Reporting Program
Gt	gigaton
IEAGHG	International Energy Agency Greenhouse Gas
InSAR	interferometric synthetic aperture radar
IRS	Internal Revenue Service (United States)
ISO	International Organization for Standardization
LCFS	Low Carbon Fuel Standard (United States)
MCL	maximum containment level
MEMR	Ministry of Energy and Mineral Resources (Indonesia)
METI	Ministry of Economy, Trade and Industry (Japan)
MMT	Million metric tons (tonnes)
MRV	measurement, reporting, verification
PNNL	Pacific Northwest National Laboratory (United States)
OGA	Oil and Gas Authority (United Kingdom)
OPEX	operating expenditure
ROP	rate of penetration
$scCO_2$	Supercritical carbon dioxide
SDWA	Safe Drinking Water Act (United States)

Tt	Teratons
TLS	seismic traffic light system
UAE	United Arab Emirates
UIC	underground injection control
USA	United States of America (also U.S.)
USDW	underground sources of drinking water
VSP	vertical seismic profile
VCM	voluntary compliance market
WAG	water alternating gas
WBSP	Wallula Basalt Sequestration Pilot
WHO	World Health Organization
XMT	X-ray Microtomography

Executive Summary

Recent carbon dioxide (CO_2) storage field experiments in mafic-ultramafic rocks, such as basalts and peridotites, demonstrate the potential for safe and efficient permanent CO_2 storage via in situ mineralization. Distributed in many areas that lack conventional CO_2 storage option, mafic-ultramafic rocks provide the potential for permanent storage through mineralization, and globally have the potential to store ~2.5-4.8 Teratons of CO_2. This review critically evaluates progress, barriers, and knowledge gaps of CO_2 mineralization in mafic-ultramafic reservoirs. The aim is to provide stakeholders, regulators, and investors with a comprehensive summary of current knowledge and offer an initial road map for evaluating subsurface carbon mineralization projects. We analyze feasibility, risks, and monitoring considerations, CO_2 mineralization processes, scaling up and cost analysis, evolving regulatory and monitoring frameworks, and comparison with conventional sedimentary basin storage paradigms.

Screening studies, reactive transport simulation studies, and field-based demonstrations in mafic-ultramafic reservoirs show increasing technical maturity of carbon mineralization technology around the world. Overall, field-based demonstration projects have shown rapid mineralization in mafic-ultramafic reservoirs, often faster than anticipated from laboratory and simulation studies. Screening studies have evolved from basic porosity and volume calculations to include mineralogy, bulk rock geochemistry, and pore surface area. Estimating mineralization storage potential is required to evaluate prospective injection sites, field study design, and climate mitigation plans, but no unified mineralization storage calculation method currently exists. Completed studies highlight the importance of field data to account for observed, in situ secondary mineralization and to inform both screening and simulation studies. Field-scale implementation and additional data collection will ultimately help validate laboratory and simulation experiments and drive the commercialization of carbon storage in mafic-ultramafic reservoirs.

We broadly address subsurface carbon mineralization processes by examining reactions and kinetics used in reactive transport simulations. Published simulations highlight compositional variability across 18 key phases, including olivine and basaltic glass, often influenced by prior studies or study locations. Three phenomena are identified with the potential to influence carbon mineralization rates, reaction extents, and phase outcomes: (1) Si-rich coatings have been implicated in simplified (e.g., monomineralic) studies as causing reaction passivation (i.e., armoring), but this behavior has not been observed in more realistic experiments or field studies; (2) natural and anthropogenic secondary minerals may influence carbonation by altering pore networks, reactive surface areas, and cation availability; and (3) inorganic to organic carbon partitioning in the deep biosphere after CO_2 injection may complicate mass balance calculations, underscoring the need for baseline assessments prior to field-scale tests followed by extensive downhole sampling and characterization.

Site-specific data for variable key parameters in mafic-ultramafic reservoirs, such as mineral composition, porosity, and permeability, are crucial to evaluating storage potential. Porosity values vary between mafic-ultramafic rocks, with values reported for mafic formations often higher than in ultramafic. Porosity and mineralogical composition make continental flood basalts favorable targets, but challenges remain in characterizing total connected porosity in laterally extensive basalt flows. In terms of contaminant risk, CO_2-water-rock interactions in mafic-ultramafic reservoirs promote dissolution and trace element/metal mobilization as reaction products. Experimental results show that there is no increased risk of generating harmful reaction products in basalts compared to sedimentary reservoirs. Induced seismicity due to injection and

geochemical reactions is another risk associated with CO_2 injection, but geomechanically coupled stochastic reactive flow modeling may aid in predicting plume evolution and proactively mitigating seismic risks. These same models may also help to determine the durability of the caprock ensuring long term containment of injected CO_2. Ultimately, a robust characterization and risk mitigation plan must be considered throughout the project development lifecycle and incorporated into key aspects of the design, construction, operation, and monitoring of the site.

Success of geologic carbon storage projects hinges on the application of robust monitoring systems—from pre-injection baseline monitoring, throughout the injection period, and post well-closure—to ensure safety, permanence, and regulatory compliance. Monitoring techniques implemented must measure CO_2 transport and containment while identifying and measuring potential leakages. Various regulatory frameworks, such as UIC (underground injection control) regulations in the U.S. and the EU CCS (carbon capture and storage) Directive 2009/31/EC with associated Guidance Documents dictate monitoring goals, without prescribing specific monitoring approaches. For mafic-ultramafic reservoirs, some monitoring technologies commonly used for CO_2 storage in sedimentary reservoirs could be applicable. However, the complex, layered structure and CO_2-fluid-rock interactions in mafic-ultramafic reservoirs require tailored monitoring technologies to ensure storage security. Continued advancements are essential to develop innovative techniques that enhance the predictive understanding of storage security risks, ensure regulatory compliance, and build public confidence in CCS projects.

Establishment of legal and regulatory frameworks for in situ mineralization storage enables commercial scale-up and deployment of these technologies by providing oversight and stewardship of these activities that ensure safe, secure, and permanent CO_2 storage. Moreover, development and implementation of these frameworks safeguards the protection of the environment and public health, clarifies the rights and responsibilities of stakeholders, and provides a legal foundation for the development, operation, and long-term management of CO_2 storage resources. Furthermore, evaluating the regulatory landscape in the context of CO_2 storage in mafic-ultramafic formations provides an overview of the viability of implementing carbon storge in these reservoirs and identifies regulatory guidance or additions that may accelerate CO_2 mineralization project deployment. There are no current regulatory barriers to permitting mineralization projects under the predominant CCS regulations covered in this report, but there could be opportunities to develop mineralization-specific guidance or incentives in future regulatory documents and/or revisions. Guidance for regulators on the science of in situ mineralization could continue to leverage and engage expertise developed through relevant research and development programs.

Scaling up CO_2 storage via mineralization in mafic-ultramafic formations poses several unique challenges compared to a pilot scale effort (tens to thousands of metric tons of CO_2). These challenges have direct and indirect impacts to local communities and economies, including potential CO_2 leakage, groundwater contamination, and induced seismicity. Models and measures for mitigation are important prior to the commencement of CO_2 injection at scale. Scaling up geologic carbon storage also introduces geochemical challenges, including loss of permeability leading to lower injectivity and the uncertainties associated with reaction rates at field scale. Thorough technical and economic assessment of the complete carbon capture and storage supply chain, as well as early and transparent engagement with local communities and stakeholders, are necessary for success of any full-scale project.

Challenges, opportunities, and associated risks are present in all aspects of in situ carbon mineralization and affect viability and feasibility. These include revenue streams, mineralization rates, injection/storage field development, upstream processes, site characterization, mineralization measurement, reporting, verification, and CO_2 transport. Stable revenue-generating mechanisms are needed for successful scale-up of CO_2 storage projects. New revenue-generating opportunities beyond carbon credits are being developed that rely on co-produced products required for the energy transition and may enhance adoption of in situ mineralization storage over conventional CO_2 storage. Limited data availability for mafic-ultramafic site characterization puts these reservoirs at an initial disadvantage to conventional sedimentary reservoirs, but new methods of site characterization developed to target highly reactive formations with large storage capacities could reduce costs. CO_2 in situ mineralization projects may require reactive transport modeling to accurately predict the extent and rate of mineral trapping. Public pushback against common transport methods (e.g., CO_2 pipeline) may hamper mineralization efforts, and carbon storage more broadly. However, given the well-established cost of transport, this risk is not unique or specifically detrimental to carbon mineralization. Overall, this report summarizes the status for in situ mineralization storage in mafic-ultramafic reservoirs and the key challenges and opportunities for future field-scale endeavors. The development of further field and commercial scale ventures for CO_2 storage in these reservoirs and the learnings from these projects will drive forward current and future work, allowing for implementation of durable and permanent storage of CO_2 around the world.

1 Introduction

1.1 Motivation

This report is motivated by the growing interest and promising results observed in recent carbon dioxide (CO_2) storage field experiments in mafic-ultramafic rocks, such as basalts and peridotites. These include the Carbfix project in Iceland[1-4] and the Wallula Basalt Sequestration Project (WBSP) in Washington State, United States of America (USA),[5-9] which have both demonstrated the potential for safe and efficient permanent CO_2 storage via mineralization. Bolstered by a confluence of incentives ranging from public investments to increased participation in compliance and voluntary offset markets, the present decade has witnessed rapid growth in the number of new carbon reduction and removal projects predicated upon safe, permanent storage of CO_2 in geologic reservoirs.[10] Accompanying this surge in interest from the investment community is a growing drive to differentiate market offerings, particularly in high-premium voluntary market sectors such as carbon dioxide removals (CDR), including direct air capture (DAC). This market pull for projects with unique value characteristics compared with more conventional compliance—or incentive-driven point source CO_2 capture and geologic storage (CCS) projects—helped generate interest in carbon mineralization, and continues to fuel growing demand to derisk and deploy mineralization-based CO_2 storage. Decades of experience continue to show that storing CO_2 in non-reactive reservoirs (i.e., conventional storage)—which currently accounts for nearly 100% of the injected volume currently hosted in geologic media—is both safe and effective for isolating CO_2 from the atmosphere. Although mineralization storage in mafic-ultramafic rocks is not necessarily more or less safe than conventional storage, the potential for transforming injected CO_2 into solid rock has an appeal to stakeholders more focused on long-term outcomes and liability. This includes developers, financers, communities, and—to the extent that risk reductions can be internalized in a way that meaningfully informs the permitting process—regulators. Additionally, mafic-ultramafic rocks have widespread distribution, and thus in situ mineralization storage may be an attractive alternative for investors in regions without conventional storage potential. However, the scientific basis for the potential benefits of mineralization storage, as well as key uncertainties including reservoir sustainability, variability in mineralization rates, characterization, monitoring and verification approaches, and lifetime project costs, is evolving.

This report evaluates progress, barriers, and knowledge gaps, and provides stakeholders, regulators, and investors with a comprehensive summary of current knowledge and understanding of subsurface carbon mineralization in mafic-ultramafic reservoirs. The review presents an in-depth examination of the feasibility, risks, and monitoring considerations associated with CO_2 storage in mafic-ultramafic rocks, such as those depicted in **Figure 1**. An analysis of how CO_2 mineralization storage can be scaled up in mafic-ultramafic formations, its relevance to other global resources, its place within an evolving regulatory and monitoring framework, and comparison with conventional sedimentary basin storage paradigms is included. This report provides an initial road map for evaluating subsurface carbon mineralization projects in a holistic context that includes geological storage potential, carbon source type and availability, water availability, reaction rates for specific lithologies, public acceptance, and regulatory environment.

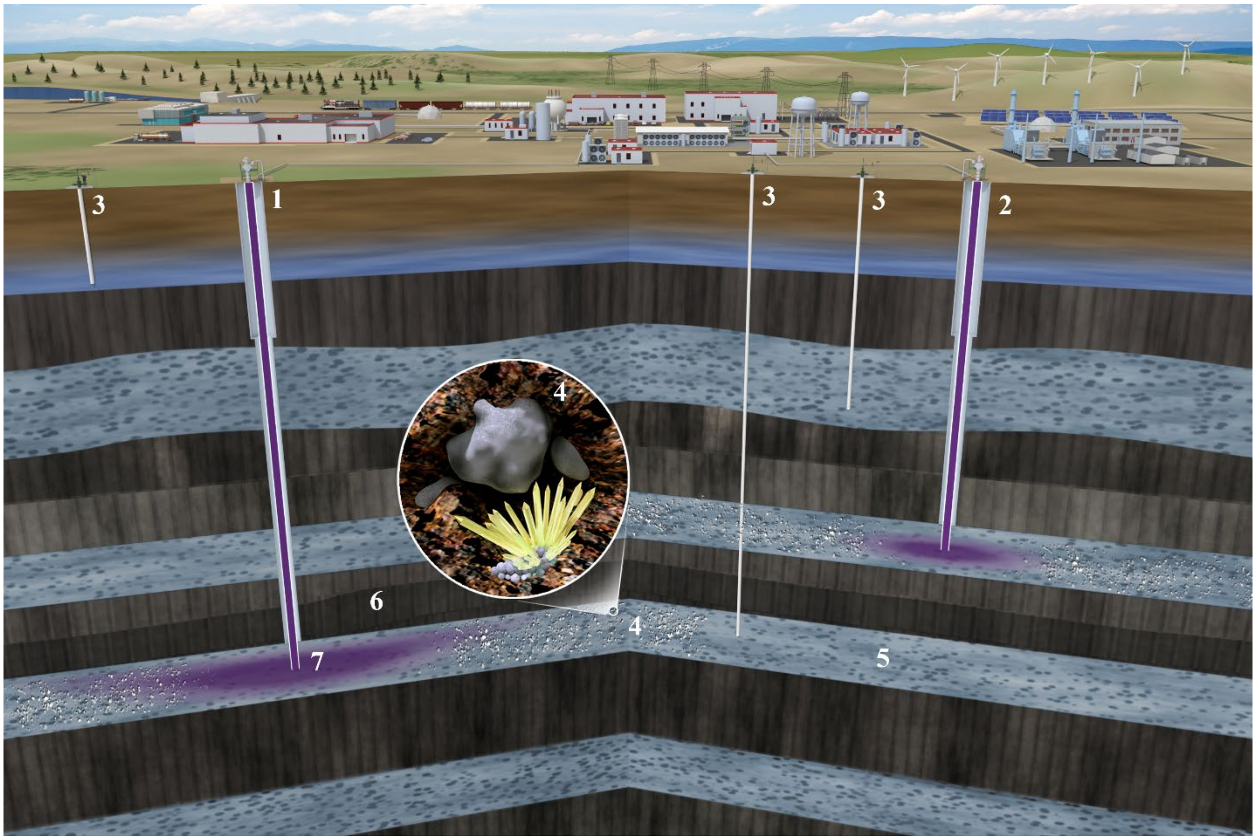


Figure 1. Illustration of carbon dioxide storage in mafic-ultramafic reservoirs within a layered continental flood basalt as an example. The wells show injection of CO_2 via supercritical (1) and aqueous (2) methods, along with monitoring wells (3). Mineralized CO_2 in the form of carbonates (4) are shown in the porous injection zones (5), below the confining, low-porosity layers (6). The CO_2 plumes for both injection strategies are also shown (7). Mafic-ultramafic reservoirs, such as the one shown here, have the potential of: (a) storing enormous amounts of CO_2, (b) containing multiple target zones within the same storage complex,(c) accepting injected fluids ranging between dry supercritical CO_2 to aqueous dissolved CO_2, and (d) mineralizing the CO_2 into a permanent solid carbonate for long term storage. This figure is not to scale (see **Figure 2**).

Herein, we gather and synthesize the extant literature evaluating the potential for subsurface mineralization to offer safe, secure, scalable solutions for permanent CO_2 storage. This summary includes experiences gained from field experiments, simulation studies, and feasibility assessments, including a compilation of completed, active, and prospective field sites (Section 2). Successes of pilot and commercial-scale projects around the globe are motivating investors to pursue projects in other mafic-ultramafic reservoirs (see Section 2.4). However, similar to other subsurface operations, geological and geochemical nuance underpin economic and technical feasibility uncertainties that may limit cloning success from pilot settings. To address this, Section 3 provides a review of the relevant geochemistry literature, an overview of reaction kinetics, and implications for pore- to field-scale impacts. A particular emphasis of Sections 2 and 3 is on evaluating reaction kinetics to determine potential changes in reactivity, and field site results. We also address subsurface and risk evaluation, including a compilation of key subsurface parameters for storage target formations, and risks from harmful reaction products and induced seismicity (Section 4). The review assesses monitoring and regulatory suitability for CO_2 storage in mafic-ultramafic reservoirs, including monitoring techniques for CO_2 storage and suitability for proving secure storage (Section 5). Together, Sections 4 and 5 examine logistical aspects, subsurface risks, and monitoring needs associated with commercial-scale mineralization storage deployment. Additionally, we explore global regulations and legal barriers for in situ mineralization storage in mafic-ultramafic reserovoirs, focusing on the EU Carbon Capture and Storage (EU CCS) 2009/31/EC Directive Guidance Documents and the USA Class VI regulations relevance for governing CO_2 storage in mafic-ultramafic reservoirs (Section 6). This review also analyses the challenges and costs of scaling up CO_2 storage in mafic-ultramafic rocks, including issues related to energy requirements, well construction, water consumption, regulations and permitting, and land/pore space considerations (Section 7). Lastly, we summarize the advantages and disadvantages of CO_2 storage in mafic-ultramafic rocks, highlighting technical and non-technical challenges along with strategies for risk mitigation (Section 8). In addition to identifying key knowledge gaps in each of the following sections, this report concludes with a set of suggested areas for international scientific collaboration focused on accelerating the commercial readiness of mineralization storage globally.

Each of these sections draw on analogous datasets associated with sedimentary storage operations while mining the few existing projects for mineralization-specific insights. This highlights the relative paucity of data, which differs significantly from available sedimentary storage work, upon which to base a comprehensive review needed by today's developers, investors, underwriters, and regulators. We envision that compiled knowledge and gaps in this review will be used to inform policymakers and industry stakeholders on the technical potential and regulatory considerations of using mafic-ultramafic rocks as CO_2 sinks for reducing carbon emissions. There is abundant opportunity for mineralization-based geologic CO_2 storage to benefit from a significant push for sustained, coordinated, outcome-focused research and development to accelerate the availability and widespread adoption of mineralization-based storage applications.

1.2 Background

During CO_2 injection into geologic formations, regardless of injection formation rock type, formation water reacts with CO_2 to generate carbonic acid as a reaction product through dissociation into H^+, HCO_3^-, and CO_3^{2-} ions, leading to a pH decrease (Eq. (1)). Silicate dissolution, if the appropriate silicate minerals are present, (Eq. (2)) then releases divalent cations M^{2+}(Ca^{2+}, Mg^{2+}, and Fe^{2+}) while consuming H^+ ions, increasing pH, and enhancing carbonate mineral precipitation (Eq. (3)).[11]

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

$$2H^+ + MSiO_3 \rightleftharpoons M^{2+} + SiO_2(aq) + H_2O \tag{2}$$

$$M^{2+} + CO_2 + H_2O \rightleftharpoons MCO_3 + 2H^+ \tag{3}$$

In situ mineralization describes technologies that leverage the geologic conditions (e.g., temperature, pressure, fluid, and rock composition) of the subsurface to accelerate mineralization and permanent storage of injected CO_2. This technology pathway includes two methods to inject

CO_2: Aqueous CO_2 (CO_2(aq)) injection and supercritical (or liquid) CO_2 ($scCO_2$) injection. These two storage mechanisms rely on similar trapping mechanisms (i.e., structural, residual, solubility, and permanent mineral trapping), but to varying degrees, with mineral trapping occurring on timescales of years to tens of years. It should also be noted that, injection of pure phase CO_2 is the rule rather than the exception for CCS, and only a subset of mineralization-based approaches rely on the co-injection of CO_2 and large amounts of water. Injection for in situ mineralization is usually done in mafic-ultramafic rocks, which are rich in magnesium (Mg), iron (Fe) and calcium (Ca), with low silica (Si) content. Mafic rocks, such as basalt or gabbro, contain reactive minerals like pyroxenes, plagioclase feldspar, olivine, and phases like glassy mesostasis (basaltic glass). Ultramafic rocks have higher concentrations of olivine, along with alteration products such as serpentine and brucite, resulting in a higher Mg and Fe content. These rock types are targeted due to these reactive minerals and thus a higher concentration of carbonate forming divalent cations (Mg^{2+}, Fe^{2+}, Ca^{2+}, Mn^{2+} [manganese]).

The CO_2(aq) mechanism involves dissolution of CO_2 into brine or water prior to, or during, injection. The fluid then reacts with formation minerals and glassy mesostasis to form stable carbonates in the subsurface. Due to the solubility trapping of CO_2 in this mechanism, the injection depth required can be much shallower compared to conventional geologic carbon storage, as shallow as 300 meters in certain settings, but typically greater than 400 meters[4] due to temperature and pressure constraints on the solubility of CO_2 in water. Advantages of the CO_2(aq) storage mechanism include immediate solubility trapping (i.e., the injected fluid is less mobile—and denser—than a buoyant single-phase $scCO_2$ fluid), and less reliance on a caprock to structurally trap the injected fluid. The flipside of this approach is a larger area of review (AoR) and the large volumes of water from fresh, ocean, deep saline, or recycled sources that need to be co-injected (~25:1 H_2O:CO_2) with the CO_2. Storage of 50 million metric tons (MMT) of CO_2 would require the injection of 1.25 gigatons (Gt) of water. This results in a less expensive well for CO_2(aq) due to the lower depth, but more wells are needed due to the large amount of fluid that needs to be injected.

The $scCO_2$ storage mechanism involves injection of dry gaseous or liquid CO_2 into reactive formations, where the CO_2-rich fluid becomes water-bearing and also dissolves into the formation water to form CO_2(aq), leading to carbonation of minerals already present in the reservoir. The injection depth for this mechanism is similar to conventional carbon storage, and typically requires a depth greater than ~800 m, due to temperature and pressure constraints, to maintain a favorable high-density CO_2 phase. This typically means more costly wells due to materials and depth, but each well can accommodate more CO_2 as it is injected as a pure phase. An illustration to represent the true scale of this injection depth is shown in **Figure 2**. Advantages of the $scCO_2$ method include no water requirements, a likely smaller AoR, and lower initial investment because of the ability to inject more CO_2 per well, thus allowing for larger scale injections and storage projects.

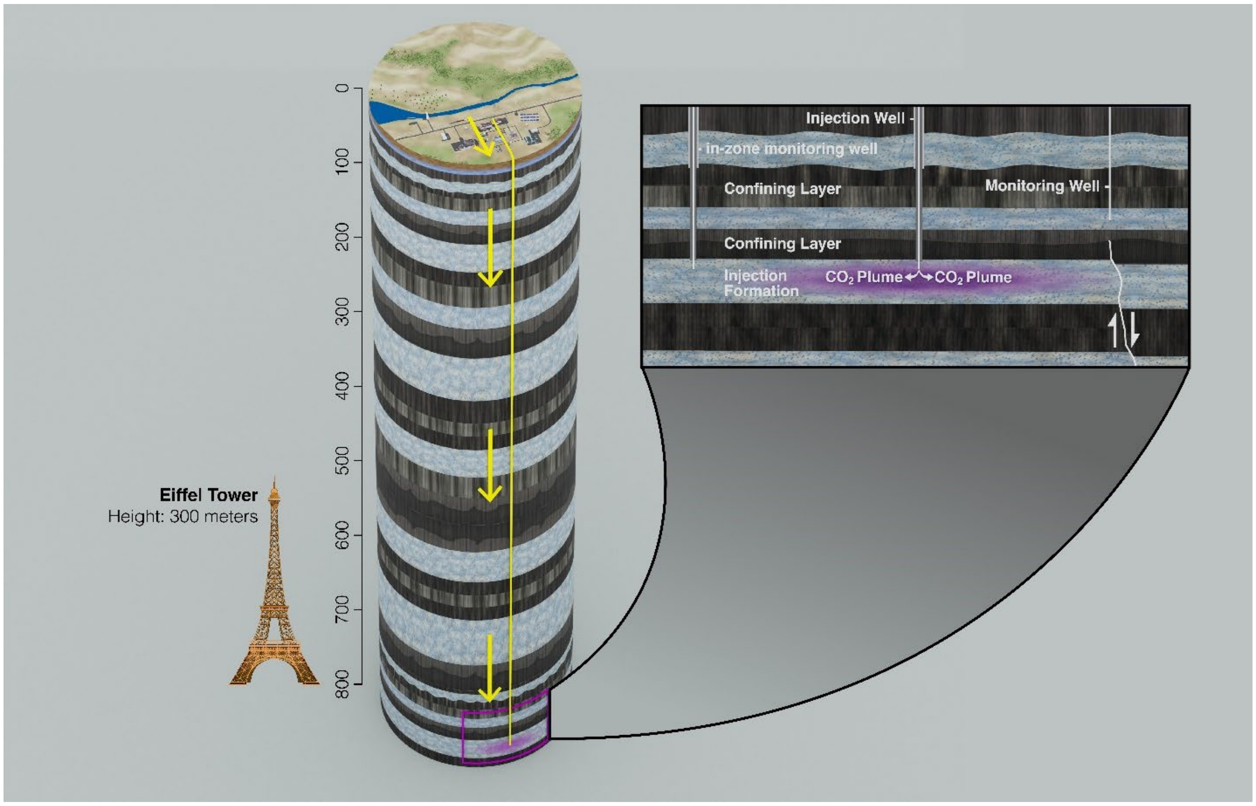
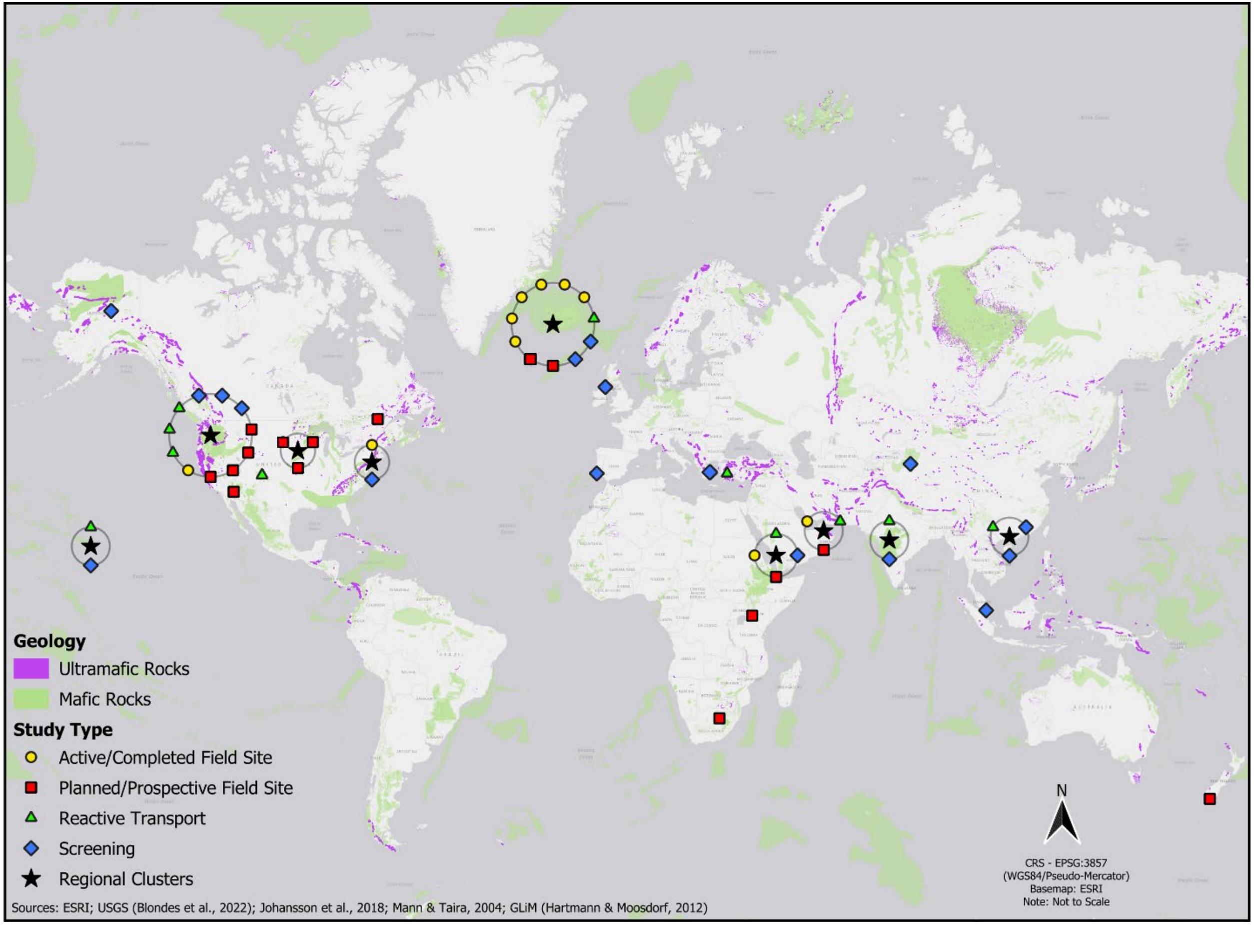


Figure 2. Illustration of the depth of geologic storage of carbon dioxide in a layered basalt. Injection zones for supercritical CO_2 injection in mafic-ultramafic reservoirs occur 800 m below the surface (at a minimum), as illustrated in this to-scale graphic. Injection of aqueous CO_2 can potentially be as shallow as 300 m but is typically injected between 400–500 m below the surface. As a reference, the Eiffel Tower (300 m) is shown alongside the scale to give a better perspective of the depths needed for geologic storage.

2 Summary of Screening, Simulation, and Field Studies

In this section, we synthesize and review existing public literature including peer reviewed publications, conference proceedings, and government reports, to examine carbon mineralization feasibility studies, reactive transport simulation studies, and field-based demonstrations in mafic-ultramafic reservoirs (**Figure 3**). We provide an evaluation of these studies and identify knowledge gaps. Section 2.1 defines those screening studies which estimate carbon storage potential of a country, region, or mafic-ultramafic reservoir. We compile key input parameters for these carbon storage calculations and describe the methodologies used for estimating the storage potential of mafic-ultramafic reservoirs. In Section 2.2, we review a total of 31 reactive transport studies that model carbon in situ mineralization in mafic or ultramafic formations. We also include a comparison and discussion of model parameters such as reactive transport coding software, thermodynamic and kinetic databases, and kinetic reaction rate equations along with identified limitations and challenges in reactive transport modeling. Lastly, in Section 2.3, we identify 27 completed, active, or planned/prospective field sites that have injected, or plan to inject, CO_2 for permanent storage in mafic-ultramafic lithologies. Prospective and planned pilot CO_2 field sites



Sources: ESRI; USGS (Blondes et al., 2022); Johansson et al., 2018; Mann & Taira, 2004; GLiM (Hartmann & Moosdorf, 2012)

Figure 3. Global overview of mafic-ultramafic formations and select studies documented in this report focused on mineralization. Study type differentiates active/completed field sites, planned/prospective field sites, reactive transport studies, and screening studies. For visualization purposes, locations with multiple studies (e.g., PNW USA, Iceland, Saudia Arabia, Oman, China, etc.) were grouped into 'Regional Clusters' symbolized with a black star surrounded by the relevant study type(s). Note: The individual project locations are not exact, and formation areas are not to scale.[12-15]

are split between studies with plans to inject and those that are drilling wells to complete feasibility and permitting stages of project development. Publicly available literature used for these sections was supplemented by 11 conversations with leaders of field-scale commercial or pilot carbon mineralization projects, including planned and developing projects. This section includes an overview of the existing literature including screening studies, reservoir simulation studies, and the evolving set of field projects—taken together, amounting to only about 100,000 tons of injected CO_2. Accounting for the vast majority of this injection total are the Carbfix projects.

2.1 Screening Studies

The total potential mass of CO_2 that can be mineralized in a mafic-ultramafic reservoir must be evaluated prior to the commencement of any commercial or pilot injection of CO_2. The feasibility of carbon mineralization depends on many factors including, but not limited to, the type of storage reservoir, proximity to CO_2 point sources, commercial opportunities, regulatory environment, and community engagement practices. In this section, we narrow the scope of in situ carbon mineralization screening studies to include only those studies considering regional lithology, mineralogical composition, and reservoir properties. Such studies estimate the potential carbon storage potential of a reservoir or region with simple algebraic equations where input parameters are obtained from laboratory studies, field observations, or commonly assumed values such as flow rate, dissolution kinetics, CO_2 solubility, and brine chemistry of the formation. Section 2.2 discusses reactive transport modeling as a valuable next step to numerical/analytical calculations of carbon storage potential.

Screening studies that calculate in situ carbon mineralization carbon storage potentials to assess feasibility have been completed across many different lithologies in 10 countries (**Table 1**). Two studies estimate storage capacities of offshore mafic-ultramafic resources. Out of 21 screening studies published in the peer-reviewed literature, 13 have been published in the last four years and 16 in the last ten years, at the time of writing this report. Fifteen studies calculate storage estimates for specific formations and reservoirs, while another six studies make global, regional, or national storage estimates (**Table 1**). Out of carbon mineralization sites assessed in all screening studies, nine are in North America, five in Europe, and six in Asia (**Table 1**). Compared to the global distribution of mafic-ultramafic reservoirs, it is notable that no screening studies have been conducted for formations in Africa, South America, Australia, or Oceania, despite the presence of large continental flood basalts in these regions.[3] However, there have been studies in these areas that would be considered “pre-screening” because they do not calculate CO_2 storage potential but still evaluate the potential for CO_2 for mafic-ultramafic reservoirs. There have been pre-screening studies in the Great Rift Valley in Kenya,[16] mafic-ultramafic rocks across Aotearoa/New Zealand and Australia,[17, 18], and the Serra Geral continental flood basalts in Brazil.[19, 20]

Over 75% of reservoir types investigated in all studies are basalt. Out of the three studies that estimate the CO_2 storage potential of ultramafic rocks, one focuses only on serpentinites, one includes dunite, and one includes ophiolites (**Table 1**). The skew of formations investigated in studies demonstrates a lack of work in understanding the carbon storage prospects of ultramafic reservoirs, which may be due to their limited distribution globally compared to mafic reservoirs.

Three of the screening studies listed in **Table 1** have directly preceded and enabled field injections of CO_2 into mafic-ultramafic reservoirs. These include McGrail et al. 2006[21] (Columbia River Basalt Group, USA), Snaebjornsdottir et al. 2014[22] (Icelandic basalts), and Oelkers et al. 2022[23] (Jizan Group, Saudi Arabia). The operating parameters and key findings of these completed field injections will be expanded upon in Section 2.3.

Most screening studies report carbon storage capacities on the order of gigatons (Gt) per formation. Three studies estimate the in situ mineralization storage potential of a country, concluding that hundreds of gigatons of carbon can be stored in China[24] and India[25], and Iceland.[22, 26] Deep sea basalts are estimated to store an additional 30–250 teratons (Tt) of CO_2[27] with ocean basalts closer to nearshore operation, like wind power generation, ranging from 4.3–196 Tt. The overall terrestrial storage potential in mafic-ultramafic reservoirs, from the studies presented without overlapping sites, is ~2.5–4,8 Tt (**Table 1**).

The complexity of analytical calculations used in screening studies has generally increased alongside the growth of the carbon mineralization field. Early research, dating back to 2000, estimated carbon storage potential using volume[21, 28] and porosity,[29, 30] the simplicity of which could lead to overestimated storage potential. Recent studies expand calculations to include parameters such as host rock reactivity and mineralization rates observed in Carbfix demonstrations,[23, 26, 31] however this method cannot be applied to all reservoirs, especially ultramafic ophiolites and serpentinites. Over the past 25 years, no standardized calculation has been established for mafic-ultramafic reservoir CO_2 storage potential. Although some studies expanded on methods used in conventional CO_2 storage in deep saline aquifers (e.g., the U.S. Department of Energy (DOE) methodology[32]) to include partial mineralization,[33] others developed their own equations.[21, 23, 24, 28-30, 34-37] The parameters most frequently incorporated in storage potential calculations are reservoir mineral volumes, porosity, and rock density. A limited number of studies incorporate parameters such as permeability, concentration of dissolved CO_2 in the injection fluid, and pH of formation brine.[21, 31] Several feasibility studies estimate storage potential by extrapolating from carbon mineralization potentials observed in laboratory experiments,[36] however, field-scale mineralization rates can often be much different than laboratory measured rates.[38, 39]

The carbon storage potential estimation method of each screening study generally falls into one of four approaches—the mineral replacement method, the pore filling method, the unit mineralization method, or the partial mineralization method, as adapted from the framework in Gao et al. 2023[46]

Table 1. Summary of screening studies that calculate CO_2 storage potential in mafic-ultramafic lithologies on the reservoir scale (top) and global, regional, and national scale (bottom).

Study	**Location**	**Formation / Type**	**Estimated CO_2 Storage Potential (Gt)**
Reservoir Scale			
Cao et al. 2024[40]	Washington and Oregon, USA	Grande Ronde (CRBG) / Basalt	40 [b]
McGrail et al. 2006[21]	Washington and Oregon, USA	CRBG / Basalt	100 [c]
Goldberg et al. 2008[30]	Washington and Oregon, USA and Vancouver Island, Canada	Juan de Fuca Plate / Basalt	250 [b]
Wiese et al. 2008[26]	Reykjanes, Krafla, and Hellisheiði , Iceland	Iceland's active high-temperature geothermal systems / Basalt	30–40 [e]
Snaebjornsdottir et al. 2014[22]	Iceland	Iceland / Basalt	953–2,470 [b,c]
Li et al. 2023[41]	Leizhou Peninsula, China	Leizhou Peninsula / Basalt	31–46 [a,b]
Stanfield et al. 2024[42]	Hawaii, USA	Mauna Kea & Mauna Loa Lava Flows / Basalt	>0.050 [d]
Steinthorsdottir et al. 2024[36]	British Columbia, Canada	Shulaps Complex, Coquihalla serpentine belt & Tulameen intrusion / Ultramafic	0.0028–0.141 [a,b,c]
Goldberg et al. 2010[29]	East Coast, USA	Sandy Hook Basin (CAMP) / Basalt	0.900 [b]
Oelkers et al. 2022[23]	Jizan region, Saudi Arabia	Jizan Costal Region / Basalt	1.4–10.2 [c]
Pereira and Gamboa 2023[31]	Portugal	Fontanelas Volcano / Basalt	1.2–8.6 [c]
Ayub et al. 2020[43]	Johor State, Malaysia	Segamat Basalt / Basalt	0.092 [b]
Tomsich et al. 2015[37]	Central Alaska, USA	Tozitna Terrance / Basalt & Gabbro	590 [a]
Andrews et al. 2023[44]	Northern Ireland	Antrim Lava Group Basalts / Basalts	0.008–0.012 [b]
Koukouzas et al. 2019[34]	Greece	Volos Basalts / Basalt	0.00011 [b]
Global, Regional, and National Scale			
Norton et al. 2024[35]	Global	Deep Ocean / Basalts	4,300–196,000 [b]
Zhang et al. 2023[24]	China	Volcanics Across China / Basalt	249.50–847.95 [a]
Goff et al. 2000[28]	Eastern US and Puerto Rico	Eastern United States / Ultramafic	170 [e]
Wang et al. 2023[45]	Northwest China	Northwest China / Ultramafic	96.3 [a]
Vishal et al. 2021[25]	India	India / Basalt	97-316 [c]
Snaebjornsdottir et al. 2014[22]	Ocean Ridges	Ocean Ridges / Basalt	2,000–40,000 [b,c]

[a] Mineral replacement method, [b] Pore filling method, [c] Unit mineralization method, [d] Partial mineralization method, [e] Their own unique method, [f] Non-reactive estimation method

and Lu et al. 2024[47]. The input parameters associated with each method can be found in **Figure 4**. In the mineral replacement method, it is assumed that the entire available surface area of reactive phases (i.e., olivine, basaltic glass) in a reservoir participates in carbonation reactions. The percentage of such minerals in the reservoir is coupled with the amount of reactive minerals required to produce one unit of carbonate mineral, along with parameters such as porosity and rock density, to achieve a final carbon storage potential estimate. In the pore filling method, it is assumed that a fraction to all volumetric pore space may be filled with CO_2(aq) or with secondary minerals precipitated because of CO_2 injection. If estimating storage potential for near-term mafic-ultramafic storage (before carbonate has mineralized), the weight percentage of CO_2 in the filling fluid is coupled with the assumption that all pore space is assumed to hold fluid. If estimating storage potential for long-term mineralization, the percentage of carbonate minerals in the secondary mineral matrix is obtained. This value is then integrated with secondary mineral densities and the mass fraction of CO_2 in carbonate minerals to yield an estimate of total reservoir CO_2 storage potential. Gao et al.[46] notes that the pore filling method should be chosen over the mineral replacement method when reservoirs have low porosity and high rock reactivity.

In the unit mineralization method, laboratory experiments are conducted to determine an amount of CO_2 mineralized per unit surface area of rock. This value is then coupled with reservoir volume, and in some cases, connected porosity, to obtain an estimated reservoir carbon storage potential.

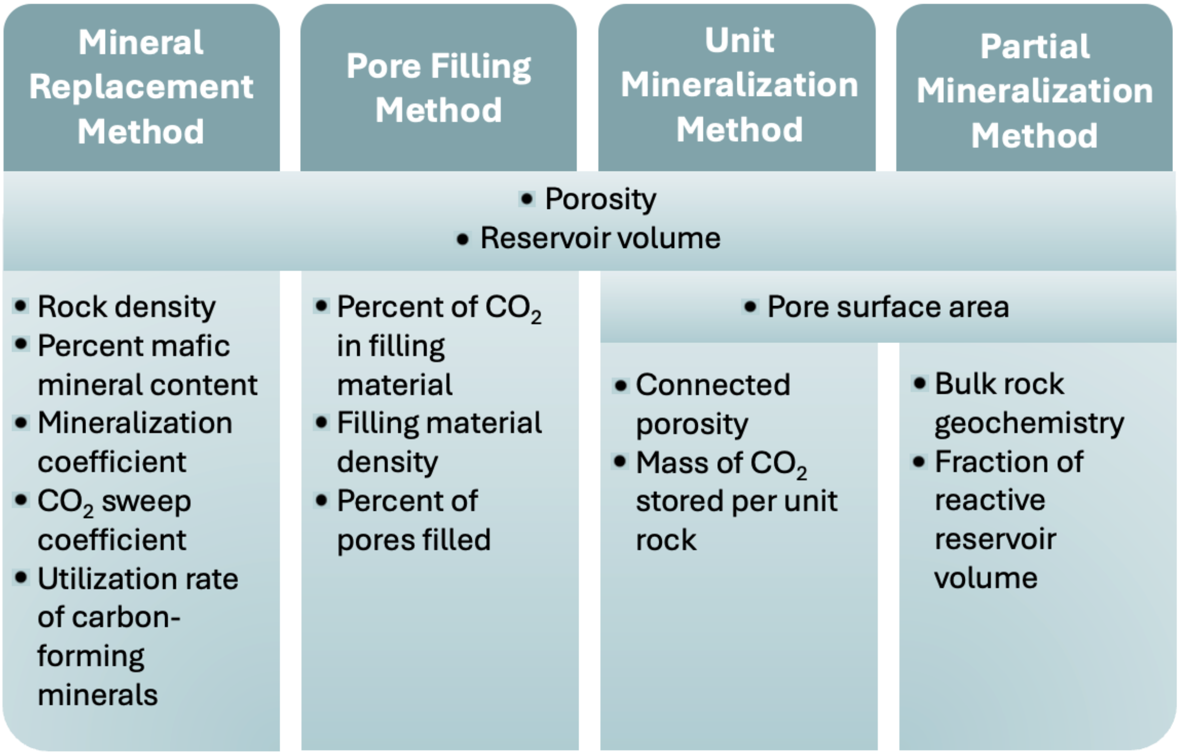


Figure 4. Primary storage potential estimate methodologies for mafic-ultramafic reservoirs and their respective input parameters. Adapted from Lu et al. 2024.[47]

Notably, this method requires a laboratory analysis of carbonation potential and, thus, may be more time-intensive and challenging than other estimation methods. However, some studies extrapolate laboratory results from previous feasibility work and apply them to their own sample compositions. Finally, the partial mineralization method considers the pore-surface area and bulk rock geochemistry of a reservoir, specifically quantifying the abundance of carbonate forming divalent cations. The volume of reactive rock is calculated by incorporating an estimated reaction depth into the pore walls, the pore surface area, and the total reservoir volume.[33] Finally, a mineralization storage estimation is achieved by coupling this value with the assumption that all the cations in the reactive volume fraction will react with injected CO_2 to form carbonate minerals. The mineralogy of the rock can also be considered in this calculation to ensure that only reactive phases are included in calculations.

When compared, different calculation methods result in drastically different storage potential estimates spanning over two orders of magnitude.[22, 36] Snæbjörnsdóttir et al. 2014[36] calculated the carbon storage potential of Icelandic basalts with three different methods, including a method reliant on extrapolations of pilot demonstration mineralization data, and they obtained results spanning from 1 to 175 Gt.[22] The study also estimates the storage potential of global mid-ocean ridge basalts using two methods, yielding estimates of 2,000 Gt and 40,000 Gt of CO_2 stored. Steinthorsdottir et al. 2024[36] used six different methods to calculate the carbon storage potential of the Shulaps complex, Coquihalla serpentine belt, and Tulameen intrusion in British Columbia and obtained results spanning two orders of magnitude for each formation.[36] These studies show evidence of a significant limitation in current carbon mineralization site screening and selection stage—mineralization storage potential estimations calculated via simple analytical approaches are highly method-dependent on, and influenced by, subtle changes in input parameters. Common uncertainties with feasibility and evaluating carbon mineralization potential in these reservoirs include the unknown composition and spatial distribution of rocks at relevant injection depths due to heterogeneity, and logistical challenges such as CO_2 transport, water access, and infrastructure (see Section 7 for further discussion).

Additionally, it has been cautioned that the total carbon mineralization potential observed in laboratory studies is generally higher than that observed in nature and at field sites due to an inability to artificially increase alkalinity.[48] Although total mineralization storage potential may be lower than predicted at field scale, rates of mafic mineral dissolution and carbonate precipitation are often faster than predicted in laboratory studies, as demonstrated by pilot injections of CO_2 into Columbia River Basalt Group (CRBG)[9] and Icelandic basalts.[49] This implies that methodologies dependent on extrapolations from laboratory studies run the risk of over- or underestimating the carbon storage potential of a reservoir. As more CO_2 storage projects in mafic-ultramafic reservoirs are considered around the world, a robust and unified storage potential calculation based on field site findings could produce more meaningful estimates.

2.2 Key Simulation Studies

Reactive transport models can predict the potential fate of injected CO_2-bearing fluids across different scales, from mineral-fluid interfaces to entire reservoirs. These models rely on key parameters such as reservoir mineralogy, porosity, permeability, formation conditions (e.g., temperature and pressure), formation brine chemistry, as well as kinetic and thermodynamic data (**Appendix Table**). Additionally, reactive transport models also rely on transition state equations within a chosen simulation program/code. In this section, we highlight the range of reactive transport modeling studies regarding CO_2 injection in mafic-ultramafic reservoirs from 31 relevant studies that were compiled (**Table 2; Appendix Table**). Basalt formations in Iceland[50-55] and the CRBG, USA[51, 56-65] are among the most extensively studied sites, as shown in **Table 3**. Other studies which have simulated carbon mineralization reactions in reservoirs include investigations of the Snake River Plains Basalt (Idaho, USA),[66] serpentinized basalt in Valmont Butte (Colorado, USA),[65] the Zingouzui Formation in the Jianghan Basin (China),[67] Deccan flood basalts (India),[68] the Samail Ophiolite (Oman),[69, 70] the Kizildere geothermal field (Turkey),[71] the Juan de Fuca Ridge (USA and Canada)[72], and the Mauna Kea and Mauna Loa pillow basalts (Hawai'i, USA)[73] (**Table 3**). A compilation of the key modeling parameters used for each of these studies is available in the **Appendix Table**.

Table 2. Reactive transport modeling codes identified in the literature relevant to mafic-ultramafic reservoirs and how many studies utilizing each code.

Reactive Transport Software	Number of Studies
TOUGHREACT	11
PHREEQC	6
Crunch Tope	4
STOMP	4
PFLOTRAN	3
TOUGH3	2
TOUGH2	2
Their Own Model	2
iTOUGH2	1

Table 3. Mafic-ultramafic reservoirs modeled in reactive transport modeling studies.

Location	Number of Studies
CRBG, USA	11
Iceland	6
Samail Ophiolite, Oman/UAE	2
Hawai'i, USA	1
Juan De Fuca, USA/Canada	1
Kizildere Geothermal Site, Turkey	1
Jizan Group, Saudi Arabia	1
Xingouzi Formation, China	1
Deccan Trap Basalts, India	1
Snake River Plain Basalts, USA	1
Valmont Butte, USA	1
Synthetic Reservoir	6

The various reactive transport modeling codes used to study carbon storage in mafic-ultramafic reservoirs in the literature are reported in **Table 2**. Common software packages and codes include ToughREACT, STOMP, CrunchTope, PHREEQC, and PFLOTRAN. ToughREACT and its related iTOUGH modules were developed by Lawrence Berkeley National Laboratory.[74] ToughREACT has capabilities to model in 1D, 2D, and 3D, while accounting for physical and chemical heterogeneities,[74] which is likely a reason it is the most used code in the current literature. STOMP was developed by the Pacific Northwest National Laboratory (PNNL),[75] has 3D modeling capabilities, and contains modules to introduce multiphase fluids like CO_2. STOMP studies in **Table 2** are represented solely by researchers at PNNL (**Appendix Table**). CrunchTope/CrunchFlow developed by Carl Steefel in the 1990's, is a software package used to develop and simulate reactive transport modeling under various conditions.[76]

Simulations built through CrunchFlow can be run on structured grids across 1D, 2D and 3D domains. This software package also supports both equilibrium and kinetic reactions, supporting simulations over long periods of time while capturing the reactions occurring during complex processes such as fluid-rock interactions. Open-source software, like PFLOTRAN[77] and PHREEQC by the USGS,[78] offer affordable options for reactive transport modeling, since high prices of licensed codes can be a barrier to entry. PFLOTRAN has capabilities to handle two phase flow with $scCO_2$, heterogeneities in permeability and porosity, and 3D model domains.[77] PHREEQC can be implemented for 1D and 2D diffusive, dispersive, or advective, reactive flow simulations.[78] Overall, choice of reactive transport code is dependent on the specific needs of each study including model domain, reservoir heterogeneities and complexities, the model's CO_2 capabilities, and sometimes budgetary restrictions.

A fundamental consideration for any geochemical model is the selection of initial solid phase mineral composition (primary minerals) and the minerals "allowed" to precipitate (secondary minerals) during fluid-rock interaction.[80-82] The accuracy of reactive transport models depends on its ability to capture complex initial mineralogical composition and small spatial variations in mineral phase abundance and surface area, as well as accurate thermodynamic and kinetic data. These factors become increasingly important when scaling the model domain to the reservoir level, where uncertainties can propagate significantly during large volume extrapolations. In our literature compilation (**Appendix Table**), 19 studies were designed to investigate reservoir scale carbon storage, while only eight studies were at the fracture scale and four at the pore scale. After relevant minerals are selected for a model, the accompanying thermodynamic and kinetic data (Section 3.1) must be chosen thoughtfully to ensure it aligns with the temperature and pressure conditions of the targeted reservoir. Additionally, it is important to keep in mind that non-carbonate mineral phases, such as zeolites and clays, may limit carbonate precipitation and overestimate the rate and extent of carbonate mineralization [8]. Therefore, a detailed understanding of potential secondary mineral phases for mafic-ultramafic formations is crucial and should be validated through laboratory and/or field experiments.

Compiled sources for thermodynamic data for all studies are shown in **Table 4**. 11 studies do not list their data used, which does a disservice to the reproducibility of these studies. Thermodynamic databases provide equilibrium data for a chosen code to use in calculating dissolution, precipitation, and the formation of aqueous complexes. They vary in source of experimentally or computationally determined equilibrium constants (log k) and Gibb's free energies (ΔG). Geochemical codes will use extrapolations to calculate log k's for a range of temperatures if the thermodynamic database being used does not already have data relevant to carbon storage in higher temperature reservoirs. In addition, many thermodynamic databases do not have data for minerals and phases commonly important to carbon storage in mafic-ultramafic reservoirs, such as glass and solid solutions carbonates. A modeler must either add missing mineral data

Table 4. Thermodynamic databases used in reactive transport modeling studies of mafic-ultramafic reservoirs and the number of studies that use each database.

Thermodynamic Database	Number of studies
EQ3/6	8
Carbfix.dat	5
V8.R6	3
THERMODEM	2
Kinec.dat	1
Aradóttir et al. 2012[79]	1
Phreeqc.dat	1
SUPRCRT92	1
Not Reported	11

manually, potentially from field and/or laboratory observations, or choose a database specifically designed for carbon storage. Aradóttir et al. 2012[79] developed a thermodynamic database to include minerals and aqueous complexes important for carbon storage in basaltic reservoirs. This database, used by one study in our literature search,[50] incorporated computations, experimental solubility values, and some data pulled from existing database EQ3/6.[79] Aradóttir et al. 2012[79] based the basaltic glass composition on Oelkers and Gislason 2001,[83] representing Icelandic basalts. The carbfix.dat thermodynamic database was also developed specifically for CO_2 and hydrogen sulfide (H_2S) storage in basaltic reservoirs,[84] making it a somewhat limited database. This database was designed for use with the PHREEQC code to improve calculations at high temperatures, add experimental solubility data for silicates and sulfides, and correct specific systematic mineral undersaturation problems.[84] The carbfix.dat database was developed using existing thermodynamic data primarily from core10.dat,[85] a derivative of phreeqc.dat[78] and llnl.dat,[78] of which only phreeqc.dat has been used in the studies compiled for this report (**Table 4**). As stated in Aradóttir et al. 2012,[79] thermodynamic data is constantly updated and improved, and the database a modeler chooses for CO_2 storage simulations in mafic and ultramafic reservoirs should reflect the current state of knowledge.

In reactive transport modeling simulations, thermodynamic data is coupled with kinetic rate data. Most of the reactive transport modeling studies presented in this report primarily relied on kinetic dissolution rate data from Palandri and Kharaka 2004.[86] This database compiles different dissolution rate constants. They do this by compiling available experimental data from which they then determine kinetic rate parameters by fitting rate equations and plotting via the concentration of catalyzing species or temperature. The dissolution rates from this database are largely far-from-equilibrium modeling at 25°C and near-neutral pH conditions, however there are some exceptions. The authors do note in their introduction that, in geological environments where fluid flows through porous media, in situ reactions are likely slower due to low chemical affinities resulting from the formation of concentration gradients at mineral-water interfaces.[86] Despite this caution, numerous field studies have shown faster-than-modeled rates of carbonate precipitation.[9, 87] Heřmanská et al. 2022 and 2023 [88, 89] recently published an updated kinetic rate database for primary silicates, secondary silicates, and glass material, to enhance modeling for mafic reservoirs and specifically Icelandic basalts. Further discussion of kinetic data is provided in Section 3.2.

Another important factor in these modeling codes is the use of transition state theory, which describes the progress of a chemical reaction through a transition state of highest potential energy, which is assumed to be rate-limiting in many cases. Ideally, the modeling programs should include affinity factors that account for evolving conditions such as changes in pH, mineral volume/surface area and porosity. Gislason & Oelkers 2003[90] developed such equations specifically for basalt glass dissolution. Some codes, like PFLOTRAN and CrunchFlow, can account for these multi-path transition state theories, while other codes, like STOMP, do not. Within transition state theory equations, the kinetic rate and surface area become the most important variables to assign for each individual mineral or “bulk” phase within the model.

2.3 Active and Completed Field Sites

A thorough review of the scientific literature, public reports, press releases, and discussions with operators and leaders in the field was conducted to assess completed, active, and planned and prospective field sites and operations for CO_2 injection in mafic-ultramafic formations. In total, 10 active or completed field sites were identified. To fill out information about these field sites that is not directly reported in the literature, 11 discussions were conducted with leaders in the field and operators of completed, active, or planned field sites. The completed and active field sites are compiled in **Table 5**, where specific parameters, such as CO_2 injection amount and rate, number of wells, and depth of injection are. Below we summarize the findings and status of these field studies and sites.

Completed field sites represent proof of concept, and active field sites are currently advancing carbon storage in mafic-ultramafic reservoirs as an impactful carbon storage technique. Field studies have been completed in the U.S., Iceland, Oman, Saudi Arabia, and the United Arab Emirates (UAE), and are currently ongoing in Iceland (**Table 5**). Early field demonstrations showed dissolution of host rock providing cations important for mineralization[91] and later studies resulted in faster than anticipated carbonate mineralization.[2, 9] These field-scale experiments have provided important insights into in situ secondary mineralization, groundwater chemistry,[2, 4, 91-93] reservoir porosity and permeability,[2, 9, 92], and timing[5, 8, 94-96] of mineralization. For further discussion of injection methodologies, strategies, technologies, and approaches, see Section 3.

Table 5. Completed and active pilot and field-scale injections of CO_2 into mafic-ultramafic formations for carbon storage via mineralization.

Project Name	**Location**	**Reservoir type**	**Wells (#)**	**CO_2 Injected (metric tons)**	**Total Average CO_2 Injection rate**	**Injection Type**	**Injection Timeframe**
Lamont Doherty Earth Observatory [91]	Palisades Sill, New Jersey, USA	Basalt-hosted aquifers (dolerite and underlying sedimentary rocks)	1	1.57	0.5 tons/hour	Aqueous (including NaCl and KBr)	3 hours
CarbFix1 [4] [2]	Hellisheiði , Iceland	Basalt-hosted low-temperature geothermal reservoir Depth: 400-800 m	1	175 55	0.25 tons/hr 0.0 4-0.18 tons/hr	Aqueous (downhole mixing)	3 months, 3 months
CarbFix2 [87, 97]	Hellisheiði , Iceland	Basalt-hosted high-temperature geothermal reservoir (highly altered due to high temperatures) Depth: >1000 m	4^a	Ongoing	---	Aqueous (surface dissolution)	June 2014 – present
Carbfix, Nesjavellir Geothermal Plant[98]	Nesjavellir, Iceland	Geothermal field near Hengill volcano (with alternating hyaloclastites) Depth: >950 m	1	Ongoing	Target of ~1kt/year	Aqueous (surface dissolution)	2022 – present
Wallula [5, 9]	Wallula, Washington, USA	Layered continental flood basalt Depth: 863 m	1	977	1.7 tons/hour	Supercritical (injected as liquid CO_2)	2 months
Saudi Aramco + KAUST [93, 99]	Saudi Arabia	Jizan Group (Altered bimodal volcanic and volcaniclastic rocks in a continental rift valley) Depth: 350 m	2^b	131	---	Aqueous	Summer of 2023
44.01 [100]	Oman	Hajar Mountains/Samail Ophiolite (Peridotite) Depth: N/A	3^c	10	---	Aqueous (mixed with seawater)	>100 days (2023-2024)
Orca DAC Plant[2, 101]	Hellisheiði , Iceland	Basalt-hosted low-temperature geothermal reservoir	9^d	Ongoing	Target of ~4 kt/year	Aqueous (downhole mixing)	2021-Present
Mammoth DAC Plant[102]	Hellisheiði , Iceland	Basalt-hosted low-temperature geothermal reservoir	3^e	Ongoing	Target of ~36 kt/year	Aqueous (surface dissolution)	2024-Present
Carbfix Project Seastone [103]	Helguyik, Iceland	Basalt-hosted low-temperature geothermal reservoir Depth: 400-800 m	4^f	Ongoing	Target of 1 kt/year	Aqueous (mixing with seawater)	2023-present

[a] 1 injection, 3 monitoring, [b] 1 injection, 1 production, [c] 1 injection, 2 monitoring, [d] 1 injection, 8 monitoring, [e] 2 injection, 1 monitoring, [f] 1 injection, 3 monitoring

Iceland. A series of CO_2 injections (**Figure 5**) have been completed in Iceland since 2012. The first of this series, CarbFix1, started with an injection of 175 tons of CO_2 followed by a mixture of 55 tons of CO_2 and 18 tons of H_2S into Icelandic basalt southwest of the Hellisheiði geothermal power plant.[4] Importantly, the Carbfix injection method is known for trapping CO_2 via dissolution in water before mineralization.[87] At CarbFix1, the mixing of gas and water was completed downhole, meaning that CO_2 dissolution in water was done via separated CO_2 and water streams that mixed downhole to form aqueous dissolved CO_2, using the hydrostatic pressure of the reservoir. The CO_2 was injected into a storage complex at depth between 400–800 m and temperatures at 20–50°C. The CO_2-H_2S mixture is representative of geothermal emissions and tests the ability to bypass costly gas separation processes.[4] This field demonstration used different approaches to calculate the storage efficiency: Mass balance calculations using both reactive (SF_6, SF_5F_3) and non-reactive (C-14) tracers confirmed that over 95% of the CO_2 injected was mineralized to carbonate minerals in less than 2 years.[4] This was further supported by calculation

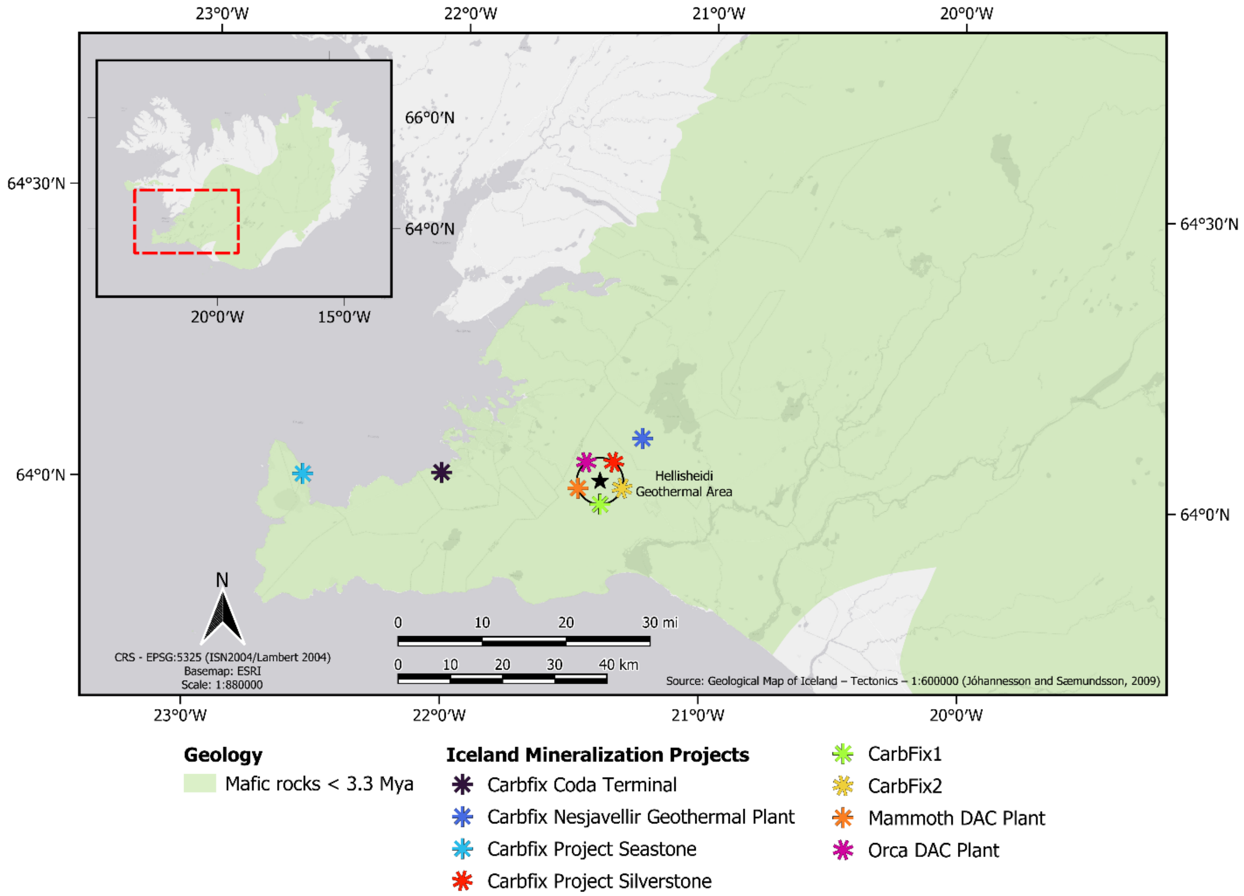


Figure 5. Map of Iceland showing young (i.e., <3.3 Mya) volcanic rocks alongside completed, active, and planned/prospective field sites shown in **Table 5** and **6**. Young volcanic rocks represent feasible areas for mineralization due to the likelihood of encountering more highly altered, lower injectivity and reactivity reservoirs in older rocks (See Snæbjörnsdóttir et al., 2014 for more detail[22]). Note: geologic age polygon based on data from The Icelandic Institute of Natural History's Geological Map of Iceland – Tectonics – 1:600000 for surface geology[104].

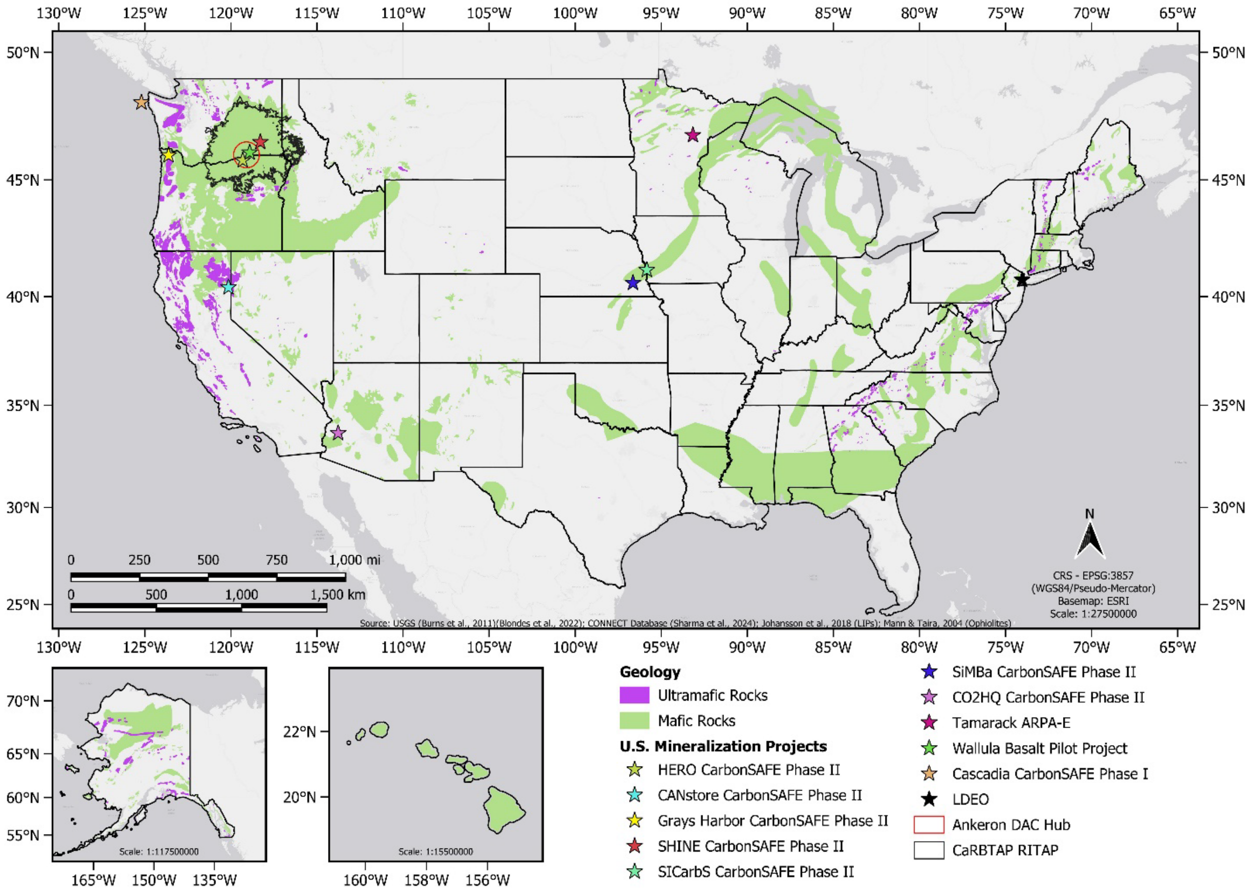
of saturation indices of carbonates and other secondary phases in samples from prior to, during and after injection[105] and geochemical modelling.[141] Finally carbon isotope ratios and calcite saturation indices of pre- and post-injection groundwater samples were used to estimate the amount of Ca lost from the groundwater due to carbonate formation, suggesting storage efficiency (% of injected CO_2 that was mineralized) of 72 ± 5% mineralized as calcite ($CaCO_3$).[2]

CarbFix2 also investigated the mixed CO_2-H_2S injections, but at a site north of the Hellisheiði geothermal power plant (**Figure 5**) and at a much greater depth with higher temperatures (>250 °C), in the reservoir where CO_2-enriched brine is also produced, and thus CO_2 is being recycled back into this reservoir that already contained this CO_2-bearing brine.[87] The temperature difference between the two sites has produced major differences in alteration minerals within the basalt reservoirs and spurs the need for different thermodynamic and kinetic considerations for CO_2 storage. Rather than downhole mixing, gas and water were mixed at the surface before injection. Like CarbFix1, this field study uses non-reactive tracers together with groundwater geochemistry and calculated saturation indices to determine percent mineralization of up to 60% within four to nine months.[49] One of the noted takeaways from the CarbFix2 project is that after 3.5 years of injection, there are no signs of decreased permeability in the basalt reservoir.[87]

There are four ongoing field-scale injection projects in Iceland that include the Orca DAC plant, Mammoth DAC plant, Nesjavellir Geothermal Plant,[98] and Project Seastone.[103] The Orca and Seastone projects, like CarbFix1, mix gases downhole while the other projects listed above are mixing gases at the surface like CarbFix2.[106] The Carbfix project in the Nesjavellir geothermal system (**Figure 5**) targets reservoirs at temperatures >200°C.[98] This Carbfix project is, again, injecting a mixture of CO_2 and H_2S from geothermal power emissions. Carbfix has partnered with Climeworks's Orca and Mammoth DAC plants to combine DAC technologies together with mineralization for capture and storage of the injected CO_2, with the potential to capture 4,000 and 36,000 tons of CO_2 per year, respectively.[101, 102] Another addition to Carbfix's portfolio is Project Seastone, which utilizes seawater for downhole gas dissolution.[103]

United States. In the U.S., two injections of CO_2 into mafic reservoirs have been completed. The first ever CO_2 injection documented in peer reviewed literature was completed by the Lamont Doherty Earth Observatory in 2004.[91] In the Palisades Sill (comprised of dolerite, pyroxene, and Ca-plagioclase) of the Newark Basin (**Figure 6**), 1.57 tons of CO_2 were injected in single-well push-pull tests over the span of seven days.[91] This experimental field study focused mainly on understanding bulk mineral dissolution using formation water sample geochemistry and calculating mineral reactivity using PHREEQC and mass balance calculations.[91]

About nine years later, the U.S.'s second field demonstration of CO_2 injection into basalt was completed at Wallula, Washington (**Figure 6**) by PNNL.[5] In 2013, 977 metric tons of liquid CO_2 ($scCO_2$ at reservoir depth) was injected into the CRBG over the course of three weeks, and closed for two years.[5] The novelty of this pilot study lies in the collection of post-injection data and the subsequent collection sidewall cores which were analyzed for secondary mineralization,[5, 8, 94-96] that can be used in future modeling and storage potential estimation efforts. Additionally, post-injection hydraulic testing and wireline geophysical surveys coupled with STOMP-CO2



Source: USGS (Burns et al., 2011)(Blondes et al., 2022); CONNECT Database (Sharma et al., 2024); Johansson et al., 2018 (LIPs); Mann & Taira, 2004 (Ophiolites)

Figure 6. Map of the United States showing mapped mafic-ultramafic formations alongside completed, active, and planned/prospective field sites shown in **Table 5** and **6**. Note: geologic formation borders were widened for ultramafic formations to increase visibility – formation areas not to scale and do not reflect thickness/depth of formations[12-14, 108, 109].

calculations simulated the resulting spatial distribution of CO_2 in the subsurface and enabled a calculation of 60% (~600 tons) CO_2 mineralization after two years.[107]

Middle East. Two pilot projects injecting CO_2 into mafic-ultramafic rocks have been conducted in the Middle East (**Figure 3**). A company named 44.01 announced the completion of their first pilot injection in late 2024.[100] They injected 10 tons of CO_2 in the Samail Ophiolite, located in Oman and the United Arab Emirates. 44.01 seeks to inject into fracture networks within peridotites,[69, 110, 111] as the majority of this formation contains overall less porosity in comparison to basalts in Iceland or the CRBG, but contains higher amounts of very reactive minerals, such as olivine. 44.01 announced in a press release that the 10 tons of injected were fully mineralized.[100] No formal scientific publication or evidence has been shown to support this claim.

Saudi Aramco, an oil and gas company in Saudi Arabia, partnered with King Abdullah University of Science and Technology (KAUST) for a pilot project injecting CO_2 into the Jizan Group basalts associated with continental rifting near the Red Sea.[23] The injection was done using CO_2-saturated brine, while the water is recycled using a production well which reduces the total amount of water needed for dissolving CO_2 for injection.[93] Overall, 131 tons of $CO_2(aq)$ were injected into this formation near Jizan in Southwest Saudi Arabia (**Figure 3**). Isotopic compositions of solids and water chemistries recovered from the production well equipment show ongoing mineral indicate the CO_2 was mineralized.[93]

2.4 Planned and Prospective Field Sites

Building on successful field demonstrations, there are currently 17 planned and prospective field sites (**Table 6**). Of these, seven are currently planning future injections, while the remaining 10 are in a feasibility, drilling, and/or permitting phase. These range across nine countries and six continents. While they are largely focused on basalts and other mafic formations, three of the 17 sites plan to store CO_2 in olivine-rich, ultramafic formations. The broad range of lithologies and rock types in comparison to completed field studies shows the diversification of reservoirs being targeted for carbon mineralization. These prospective sites are summarized below.

United States. There are currently seven U.S. DOE CarbonSAFE Phase II (CSII) projects that are focused on CO_2 storage via in situ mineralization in mafic reservoirs (**Figure 6**).[112, 113] The CarbonSAFE initiative began in 2016 with a goal of addressing the gaps and actions needed for CCS development and deployment.[114] The program is separated into four phases: (I) Integrated Carbon Capture and Storage Pre-Feasibility, (II) Storage Complex Feasibility, (III) Site Characterization and Permitting, and (IV) Construction. All the CarbonSAFE projects focused on mineralization as a storage mechanism are currently in phase II. Projects in this phase will evaluate the reservoirs characteristics via drilling, seismic surveys, core logs and/or well tests to determine if a reservoir is suitable for the storage of 50+ MMT of CO_2.[114] Five of the seven sites are in the western U.S., and the remaining two are found in the Midwest region.

There is a wide variance in reservoir lithology across these sites (**Figure 6**). The Hermiston Oregon (HERO)[122] Basalt CSII and the CO_2 Storage Hub for the Inland Northwest Economy (SHINE) CSII will evaluate the feasibility for CO_2 storage in layered continental flood basalts, specifically the CRBG in Oregon and Washington, respectively. The other CSII in the Pacific Northwest region of the U.S. is the Grays Harbor CSII located in southwestern Washington. This reservoir consists of basaltic sands, sediments primarily composed of grains from erosion and weathering of basalts, at the targeted injection depth. The California-Nevada CO_2 Storage Project (CANstore) CSII is located on the California-Nevada border and will evaluate the continental flood basalts of the Modoc Plateau. The final western CSII is the Southern Arizona CO_2 storage complex feasibility

Table 6. Planned and prospective sites for injection of CO_2 into mafic-ultramafic reservoirs for carbon storage via mineralization.

Project / Sponsor	Site Location	Site Description	Notes
Planning to Inject			
Cella Mineral Storage Inc [115]	Kenya	Kenyan Rift Basalts	CO_2 injection planned in 2025
Deep Sky One [116, 117]	Quebec, Canada	Ultramafic Peridotites	CO_2 injection planned for 2025
44.01[100]	Oman and UAE	Peridotites	Scale-up phase
Saudi Aramco[93, 118]	Saudi Arabia	Continental Rift Basalts	Scale-up phase
Carbfix Coda Terminal[119]	Straumsvik, Iceland	Stacked basaltic lavas reservoir	CO_2 injection planned for 2027
Carbfix Project Silverstone[120]	Hellishedi, Iceland	Basalt-hosted, high-temperature geothermal reservoir (highly altered)	Scale-up phase from CarbFix2. Injection planned for 2025
Council for Geoscience [121]	South Africa	Volcano-Sedimentary Successions	Tentative plan for 2025-2026
Drilling, Permitting, and Feasibility			
HERO [122] [113]	Oregon, USA	CRBG	CarbonSAFE Phase II
CANstore [113]	California, USA	Modoc Plateau Continental Flood Basalts	CarbonSAFE Phase II
Grays Harbor [112]	Washington, USA	Basaltic Sands	CarbonSAFE Phase II
SHINE [112]	Washington, USA	CRBG	CarbonSAFE Phase II
SICarbS [112]	Iowa, USA	Mid continental rift basalts	CarbonSAFE Phase II
SiMBa [112]	Nebraska, USA	Mid continental rift basalts	CarbonSAFE Phase II
CO2HQ [112]	Arizona, USA	Basin and Range Basalts	CarbonSAFE Phase II
ANKERON DAC Hub[123]	Washington, USA	CRBG	Design and feasibility
ARPA-E / Rio Tinto Tamarack Intrusive Complex[124]	Minnesota, USA	Poorly consolidated, olivine dominated peridotite	Multiple wells drilled into the peridotite “bowl”
Hardie Pacific / Weora LTD [125, 126]	Aotearoa/New Zealand	Ultramafic	Permitting, has drilled 5 holes in the Greenhills Complex

in Harquahala basin (CO2HQ). This project plans to evaluate basin and range basalts located within the Harquahala basin in southwest Arizona. The two CSII projects in the Midwest, Unlocking Scalable Carbon Capture and Storage in the Mid-Continent through Basalt Storage (SiMBa) and Southwest Iowa Carbon Storage Project (SiCarbS), both take advantage of the mid-continental rift basalts that span across Nebraska and Iowa, respectively.

The Rocky Mountain Institute (RMI) lead Ankeron DAC Hub, with PNNL, university, and industry partners, has the goal of creating a regional DAC and carbon management hub in the Pacific Northwest of the U.S.[123] It is the only DOE awarded regional DAC hub that uses carbon mineralization in a mafic reservoir as its storage mechanism. This hub seeks to take advantage of the ideal geology of the layered CRBG flood basalts and the region's commitment to low-carbon energy production.

The Tamarack Intrusive Complex, located in central Minnesota, is the proposed site of the next nickel mine in the U.S.[127-130] A team lead by Rio Tinto, one of the largest mining companies in the world, is seeking to take advantage of the world-unique, fine-grained olivine bowl[127] present at Tamarack for carbon mineralization. The project team is in the process of evaluating the potential site for mineralization with insights gained from PNNL's Wallula Basalt Pilot Project [124] and Carbfix's projects in Iceland.

Iceland. Coda Terminal, a project coordinated by Carbfix, will be the world's first carbon mineralization storage terminal.[131] The operation will receive CO_2 from hard-to-abate emitters in Northern Europe who wish to export their CO_2 for permanent sequestration in Icelandic basalts. The hub will be located in Straumsvík, SW-Iceland, where they will both receive and inject transported CO_2.[119] Carbfix plans to begin operations in 2027, with an annual injection of 0.7 MMT of CO_2 through a network of shallow (500–1000 m) injection wells. The full construction and implementation of the project is expected to be completed by 2032, with an annual injection of 3 MMT.[119] Project Silverstone, also operated by Carbfix, will seek to expand on the current operations at the Hellisheiði ON Power plant, the site of CarbFix2[120]. This project will increase the current annual injection rate from 12,000–34,000 tons of CO_2, capturing over 95% of the plant's emissions The project began in 2021 and injection is set to begin in early 2025.[120]

Other Global Locations. Cella Mineral Storage Inc., a company based in New York, USA, is planning a pilot injection of CO_2 into basalts in the Central Kenyan Rift Valley.[132] The reservoir contains flood basalts interlayered with trachytic basalts (high alkali metal content basalts), andesitic basalts, pyroclastics, and large sections of lake sediments.[16] The aim is to conduct a two-stage pilot, with a small injection of up to ~10 metric tons to validate storage, and then around 200 metric tons to follow. CO_2 will be injected via a water alternating gas (WAG) injection method[133, 134] at a depth of about 800 m.[115] Cella's aim is to integrate DAC sources for CO_2 in Kenya following the pilot injections, which are planned for 2025.[115]

In South Africa, the Council for Geosciences (CGS), is planning to begin a pilot injection of CO_2 into South African basalts in 2025 or 2026.[121] One of the reservoirs they are targeting for planned injection is the Ventersdorp Supergroup, one of the largest and oldest volcano-sedimentary successions on Earth.[121, 135] This massive formation extends across much of northeast South Africa, and underlies many large CO_2 producers in the nation. Targeting injection layers with 5–10% porosity in 300–500 m thick sections, the pilot plan would inject up to 10,000 metric tons of CO_2, and then keep the same well operational for use in possible commercial deployment in the future.[121]

Weora LTD in Aotearoa/New Zealand are in the process of evaluating the feasibility for carbon mineralization within the Greenhills ultramafic complex at the southern tip of the country. So far, five exploration and characterization wells have been drilled in the targeted area. CO_2 will be sourced from point source capture and will be injected as CO_2(aq) into fractured, serpentinized dunite. Feasibility assessments, reactive transport modeling, and technoeconomic analyses are ongoing. Additionally, Weora LTD plans to leverage assets from other ultramafic deposits across Aotearoa/New Zealand (Oreti, West Dome, Whakatū, Red Hills, King Country, Waikato, and Pokeno) for carbon mineralization.[125, 126]

There are additional companies around the world that have expressed plans to conduct pilot and scaled up injections of CO_2. Deep Sky, a company based in Quebec, Canada, plans to start a pilot injection into ultramafic peridotites in 2025.[117] Saudi Aramco in Saudi Arabia and 44.01 in Oman and the UAE are also both planning to scale up their mineralization projects in Jizan basalts and Samail ophiolite, respectively.[93, 100, 118]

2.5 Summary of Feasibility, Simulation, and Field Studies

Section 2 reviews relevant literature for three distinct facets of carbon mineralization investigations—screening, simulation, and field studies. These three areas of research have made significant advances through the past few decades and are often influenced by one another. Screening studies (**Table 1**) have evolved from basic porosity and volume calculations to include mineralogy and bulk rock geochemistry. Estimating storage potential is important for identifying prospective injection sites, field study design, and climate mitigation plans. Recognizing the importance of these calculations, researchers must choose parameters and methods that estimate CO_2 volumes as accurately as possible (**Figure 4**). Currently, no unified storage calculation method exists.

Similar to feasibility studies, accuracy of simulation studies is reliant on input data and model parameters. A variety of reactive transport modeling codes (**Table 2**), thermodynamic data, (**Table 4**) and kinetic data have been used in the current literature to evaluate carbon mineralization in mafic-ultramafic reservoirs in 11 countries (**Table 3**). Choosing mineralogy with accompanying thermodynamic and kinetic data can be a challenge when modeling basaltic reservoirs, since basaltic glass, solid solution carbonates, and some clays and zeolites are often difficult to characterize or include in a model. With the availability of new field data, models can be better designed to account for observed, in situ secondary mineralization. However, thermodynamic and kinetic data should be consistently updated and scrutinized to produce ever more accurate models.

Field projects have been the ultimate test of carbon mineralization storage in mafic-ultramafic reservoirs. Overall, these projects have shown rapid mineralization, faster than anticipated from laboratory and simulation studies. Completed studies on three continents highlight the importance of these field demonstrations to inform both feasibility and simulation studies. With seven planned, upcoming injections and ten studies in the drilling, permitting, and feasibility stage globally, private industry and government entities continue to push forward with carbon mineralization efforts.

All locations for the three categories of studies listed in this section are shown in **Figure 3**. Extending across six continents, this map shows the widespread extent of carbon mineralization technology for mafic-ultramafic reservoirs. Field-scale implementation and the collection of more data across a wide range of lithologies will ultimately help drive the commercialization of durable carbon storage in mafic-ultramafic reservoirs.

3 Evaluation of Reactions and Relevance to CO_2 Mineralization

This section presents an evaluation of claimed reactions and their rates, the degree of fixation over time, and whether reactivity drops with time. Determining reaction rates under in situ conditions is difficult and inherently complex, due to their dependence on pressure, temperature, fluid cation concentrations, phase assemblages, surface area, non-linear behavior (such as reaction rates under non-equilibrium conditions), complex fluid properties for CO_2 and water mixtures (**Figure 7**), and issues with lab-field scale-up based on small scale structures. Molecular level reaction rate determination, either through atomistic based experimental probes or reactive molecular dynamics, is relevant to the fate of CO_2 mineralization, both in water dominated systems and water lean fluids (e.g., hydrated liquid and supercritical fluids), as summarized by Qomi et al., in a recent review article.[136] Herein, we evaluate how published results parametrize their models and how relevant those values and results are for other common mineral compositions of basalts and similar rocks. This evaluation is based on laboratory testing, simulations, and field site tests that involve the full spectrum of multiphase CO_2-H_2O reactivity (**Figure 7**). Current carbon mineralization CO_2 injection strategies (i.e., CO_2 -saturated brine and free-phase CO_2 injection) [1-9] exist as end-

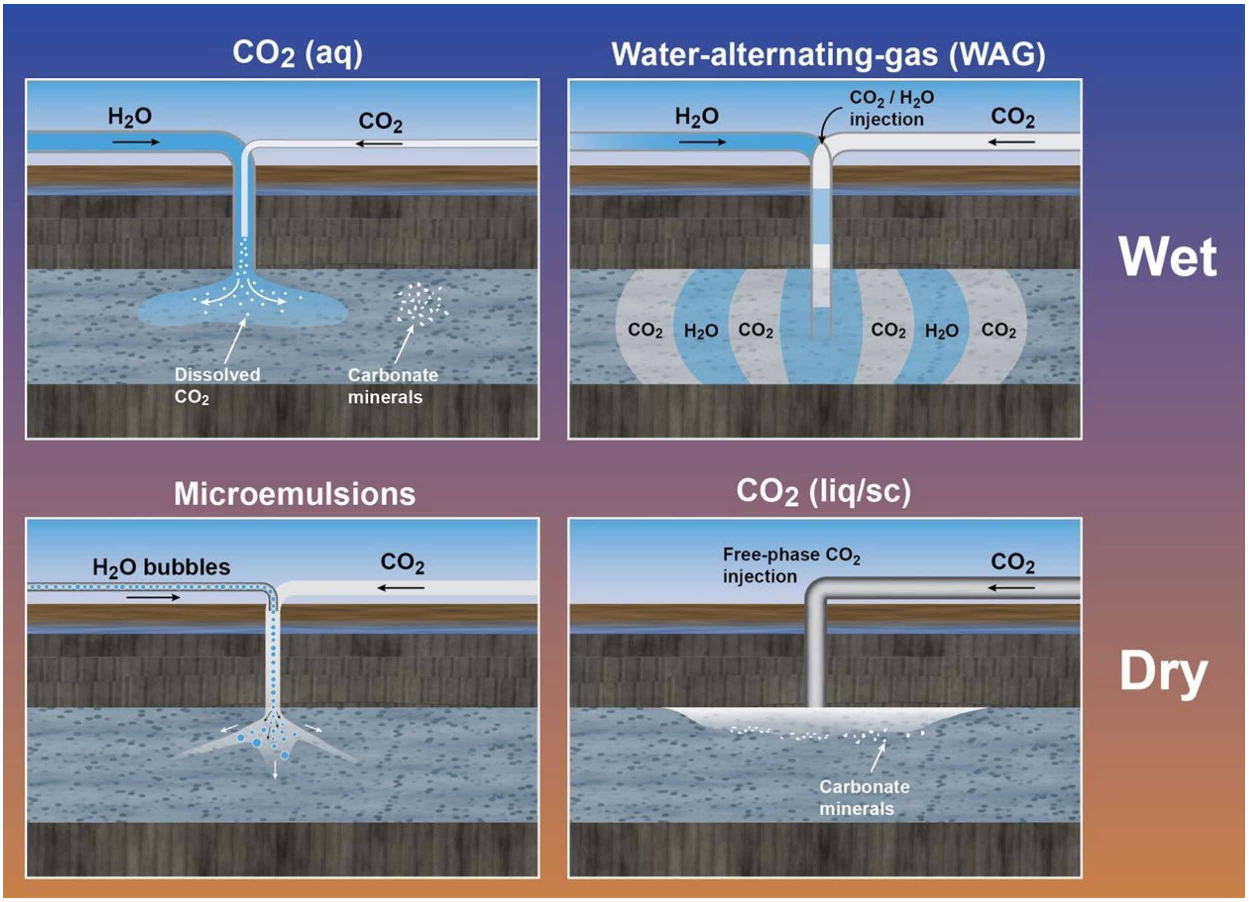


Figure 7. Summary of CO_2 subsurface carbon mineralization injection schemes. This illustration emphasizes that current injection strategies exist upon a spectrum, ranging from water-intensive to water-lean. These methodologies can be implemented depending on a variety of geologic, regulatory, climate, public acceptance, and technoeconomic constraints and opportunities. Multiple methods may be implemented in the same injection well and/or reservoir as needed to ensure injectivity, sustainability, efficiency, and durable storage security. The dark grey units in this conceptual schematic indicate impermeable units isolating injected CO_2 from shallow groundwater represented by the thin blue formation. Figure not to scale, see **Figure 2** for an illustration of the depth of CO_2 sequestration.

members on a spectrum of injection strategies that may also include WAG[137] and microemulsion[138] injection approaches to maximize safe storage potential in an increasingly water-constrained world.

3.1 Reactions from Field and Simulation Studies

Here we compile reactive transport modeling studies in mafic-ultramafic rocks, considering the reactions and kinetics used in the models and sources of these reaction pathways. We consider the ~70 mineral species accounted for in the reactive transport simulations compiled in Section 2, including chemical compositions, the source of the kinetic rate parameters, and relevant dissolution reactions. These reactions and the source of their kinetic rate parameters for dissolution and carbonation form the basis for the evaluation of the determined rates. We assess whether reaction pathways and kinetics are based on laboratory studies, a thermodynamic database, or studies on bulk rock or single minerals. We document how the surface area was evaluated for the material, parameters (pH, temperature, and pressure) used to determine kinetics, and what kinetic model was used to fit the data.

From the compiled field studies, key rock types and their simplified carbonation reactions are identified and provided in **Table 7**. Because field studies include both mafic and ultramafic reservoirs, phases like serpentine and brucite are included. Note that these are simplified reactions that assume end member compositions, which may not be representative of naturally occurring materials. For instance, we have included the pyroxenoid wollastonite, a common target in carbon mineralization studies,[141-151] given its utility as an analogue phase for calcic pyroxene.

Table 7. Simplified carbonate mineralization reactions for representative mafic-ultramafic minerals and basaltic glass.[139, 140]

Mineral or phase	Simplified reaction
Olivine	$Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2$
Plagioclase	$Ca_2Al_2Si_2O_8 + CO_2 + 2H_2O \rightarrow CaCO_3 + Al_2Si_2O_5(OH)_4$
Pyroxene	$CaMgSi_2O_6 + 2CO_2 \rightarrow CaMg(CO_3)_2 + 2SiO_2$
Basaltic glass	$(Mg, Fe, Ca)^{2+} + CO_2 + H_2O \rightarrow (Mg, Fe, Ca)CO_3 + 2H^+$
Serpentine	$Mg_3Si_2O_5(OH)_4 + 3CO_2 \rightarrow 3MgCO_3 + 2SiO_2 + 2H_2O$
Brucite	$Mg(OH)_2 + CO_2 \rightarrow MgCO_3 + H_2O$
Wollastonite	$CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2$

From the reactive transport simulations identified in Section 2.2, we compiled the phases utilized in these studies, their chemical compositions, the source of the kinetic data, and the number of studies utilizing each of the compiled phases to identify which are perceived to be the most relevant to the subsurface carbon mineralization community. Approximately 70 mineral phases were identified across 31 reactive transport simulations from Section 2.2. The top 17 compiled phases with the most relevance to mafic-ultramafic lithologies are listed in **Table 8** along with their corresponding chemical compositions utilized within the reactive transport simulation. In some cases, only the mineral name was directly provided, and readers are left to infer the chemical composition. Note that many of these phases/minerals are included in **Table 7**, although these simplified reactions do not capture the full mineralogical complexity in mafic-ultramafic reservoirs.

Table 8. Key minerals and phases utilized in reactive transport simulations for subsurface carbon mineralization. *Indicates mineral was utilized as a secondary mineral product in many of the simulations.

Phase/ Mineral	Composition(s)	# of Studies
Calcite*	$CaCO_3$[23, 50, 53, 57, 60, 62, 65, 66, 68, 70, 72, 152, 153]	23
Glass (Mesostasis)	$SiTi_{0.024}Al_{0.358}Fe_{0.188}Mg_{0.281}Ca_{0.264}Na_{0.079}K_{0.008}O_{3.370}$ [154] $SiAl_{0.36}Fe_{0.19}Mg_{0.28}Ca_{0.26}Na_{0.08}O_{3.31}$[50] $Ca_{0.015}Fe_{0.095}Mg_{0.025}Na_{0.025}K_{0.01}Al_{0.105}S_{0.003}Si_{0.5}O_{1.35}$[155] $SiAl_{0.358}Fe_{0.164}Mg_{0.094}Ca_{0.149}Na_{0.100}K_{0.034}O_{2.903}$[62] $SiAl_{0.358}Fe_{0.189}Mg_{0.281}Ca_{0.264}Na_{0.079}K_{0.008}O_{3.315}$ [53, 62, 64] $Si_{0.548}Al_{0.19}Ca_{0.102}Fe_{0.119}K_{0.006}Mg_{0.0826}Mn_{0.0015}Na_{0.0581}Ti_{0.017}O_{1.764}$[57, 58]	19
Feldspar / Plagioclase	$KAlSi_3O_8$[68, 72, 152] $Ca_{0.70}Na_{0.30}Al_{1.70}Si_{2.3}O_8$[50] $Ca_{0.5}Na_{0.5}Al_{1.5}Si_{2.5}O_8$[64, 155] $NaAlSi_3O_8$[57, 58, 68, 152]	17
Clinopyroxene and Orthopyroxene	$CaMgSi_2O_6$[57, 58, 65, 67-70] $Ca_{1.14}Fe_{0.64}Mg_{0.22}Si_2O_6$[155] $Ca_{0.5}Mg_{0.25}Fe_{0.25}SiO_3$[154] $Ca_{0.7}Mg_{0.84}Fe_{0.46}(SiO_3)_2$ [64] $Ca_{0.7}Fe_{0.6}Mg_{0.7}Si_2O_6$[155] $Ca_{0.35}Mg_{0.42}Fe_{0.23}SiO_3$[50] $Mg_2Si_2O_6$[69, 70]	16
Siderite*	$FeCO_3$[50, 57, 62, 68, 72, 152, 156]	16
Olivine	Fe_2SiO_4[60, 65, 67, 68, 70, 156] $(Mg_{0.43}Fe_{0.57})_2SiO_4$[60, 72] $Mg_{1.8}Fe_{0.2}SiO_4$[50, 154] Mg_2SiO_4[60, 65, 67-70, 82]	15
Amorphous silica*	SiO_2[50, 51, 62, 65-67, 69, 152, 156]	13
Magnesite*	$MgCO_3$[23, 50, 60, 62, 65-70, 72, 82, 152]	11
Magnetite	Fe_3O_4[23, 67, 68, 70]	10
Quartz*	SiO_2[50, 53, 69, 72]	9
Kaolinite	$Al_2Si_2O_5(OH)_4$[50, 67, 72, 152]	7
Dolomite*	$CaMg(CO_3)_2$[50, 57, 69, 70, 72]	7
Illite	$K_{0.85}Si_{3.15}Al_{2.85}O_{10}(OH)_2$[62]	6
Pyrite*	FeS_2[53, 57]	4
Brucite	$Mg(OH)_2$[69, 70]	2

Many of the phases showed compositional variance between studies, for example the glass phase showed variability within the reported composition. Many studies reported using olivine in their simulation as a starting component. In some cases, authors provide the end member olivine compositions: forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4) and utilize both in their simulation. Other studies provide an intermediate composition (e.g., $Mg_{1.8}Fe_{0.2}SiO_4$). This intermediate composition is not always reservoir specific, but instead is just an assumption or built upon previous simulation studies. In some instances, compositional variance is attributed to the location from which the study originated or the target reservoir. This becomes apparent when evaluating the selected compositions for the basalt glass or mesostasis. Three primary regions and corresponding compositions are listed when discussing basalt glass: Iceland Basalt (Stapafell glass),[50, 157] CRBG,[58, 158] and Mid-Ocean Ridge Basalt.[50, 157] Based upon the composition and corresponding structure, these materials will likely have distinct dissolution kinetics that may not be represented by one general dissolution reaction.

The reaction kinetics employed in the compiled simulation studies were often derived from outside literature sources. In some studies, there was no reference to the source of the kinetic data or original experimental derivation. Most of the studies utilized the reaction kinetics listed in Palandri and Kharaka.[86] Commonly utilized sources for kinetic data are also listed in the **Appendix Table**.

3.2 Potential Influences on Carbon Mineralization Kinetics

In this subsection, we identify and summarize three key factors that have potential to influence carbon mineralization kinetics, including the evolution of rates over time. These frontiers are 1) Si-rich alteration layer development, 2) the presence of naturally occurring or anthropogenic secondary minerals, and 3) the potential for organic-inorganic carbon transformations. These key examples were selected for further discussion due the relatively large knowledge gaps regarding their potential to exert first-order controls on reactive outcomes. Examples of better understood influences include pressure, temperature, and composition (e.g., salinity) of the reactive fluids, whose phase relationships are summarized in Bodnar et al.[159] These theoretically and empirically well-understood[160-171] relationships include decreased solubility of CO_2 in water with increasing temperature, increased solubility of CO_2 in water with increasing pressure, decreased solubility of CO_2 in water with increasing salinity, and decreased solubility of water in CO_2 with increasing salinity in the water reservoir. For the reactive water-bearing CO_2 phase, it has been recognized[172] that, along a typical geothermal-geopressure gradient, the concentration of water in CO_2 may change >10 times the concentration of CO_2 in water for the same change in depth. These changes in depth (pressure and temperature) and salinity have also been shown to influence carbon mineralization outcomes in interfacial water films by modulating overall system water activity.[173, 174]

One possible factor controlling overall carbon mineralization rates is the armoring of grains by emergent surface coatings. The potential formation of secondary Si-rich interfacial phases during mineral carbonation has been studied extensively, especially for olivine, due to the possibility of reaction inhibition or passivation via the development of coatings or armoring layers on silicate surfaces. As reviewed by Miller et al.,[175] Si-rich passivating layers may form on olivine through redeposition, limiting dissolution and, consequently, carbonate precipitation.[176-182] These secondary phases are spatially and temporally complex, as their properties vary with increasing reaction extent and associated interfacial and solution chemistry evolution.[176-183] Si-rich armoring layers on silicates are not simply amorphous silica and may also contain intergrowths of Fe/Mg/Al-rich phyllosilicates, Fe-oxyhydroxides, Fe-Si-rich phases, hematite, clinohumite, and carbonates.[143, 178, 180, 182-188] Importantly, studies that evaluate reaction potential passivation focus on simple solid compositions, primarily for monomineralic samples that are not representative of actual reservoir rocks. We are not aware of any study that demonstrates reaction passivating via surface coatings on whole rock samples, such as basalt or peridotite. Indeed, the Sissmann et al.[189] comparison of olivine carbonation behavior with an olivine-rich basalt revealed limited reactivity for the monomineralic reactivity but extensive carbonation for the olivine picrite. Overall, until a compelling experimental or field test campaign presents evidence of reaction rate decline in realistic lithologies, so-called armoring or passivation reactions will remain a theoretical concern only applicable to simplified single mineral systems rather than a serious concern for those actively scaling up the technology at the pilot and commercial scale.

Other key factors influencing mafic-ultramafic reactivity over time, especially at the incipient reaction stages, include the presence of naturally-occurring secondary minerals, including clay minerals, zeolites, and carbonates (**Figure 8**).[6, 26, 191-195] Lahiri et al.[6] revealed via comparisons of pre-injection and post-CO_2 injection Wallula sidewall cores that an important source of Fe and Mn for anthropogenic carbonate mineralization are the clay mineral-rich pore-lining phases (**Figure 8**). Laboratory-based comparisons of basalt reactivity as a function of alteration [191, 192] illustrated the nuance of comparing relative basalt dissolution rates, as secondary silicates could rapidly release certain cations via ion exchange and/or dissolution. It is difficult to conduct a meaningful "apples to apples" comparison of basalt reactivity given the differences in bulk composition, density, and reactive surface areas between samples of different ages. Additionally, not only is the primary basalt glassy mesostasis an important component to understand in basaltic settings, but it is also even more challenging to quantitatively characterize and understand the enigmatic phases formed over millions of years of glass alteration in these reservoirs.

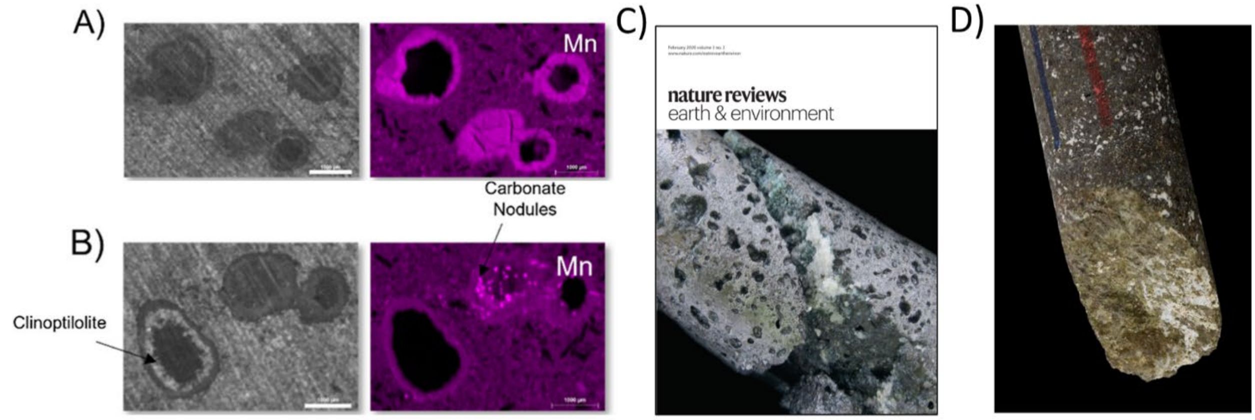


Figure 8. Images of carbon mineralization in basalts. Panels A and B show the Lahiri et al.[6] result indicating Mn mobilized from naturally-occurring pore-lining phases in the Columbia River Basalt sidewall cores recovered from Wallula contributed to anthropogenic carbonate mineral growth. Panels C[3] and D[190] how naturally-occurring carbonate minerals in Icelandic basalts from the CarbFix site.

Precipitation of secondary silicates induced by subsurface CO_2 injection also has the potential to influence carbonation rate by altering the pore network architecture, reducing reactive surface area, and incorporating cations that would otherwise be available for inclusion in carbonate minerals. Pogge von Strandmann et al.[2] attributed a portion of the Ca isotope fractionation observed during the CarbFix1 study to the precipitation of zeolite minerals, such as heulandite and stilbite. Evaluation of the Wallula sidewall cores revealed the formation of secondary aluminosilicates in the form of a fibrous zeolite-like phase.[8] Mg isotopic evolution in recovered water samples during the CarbFix1 study were deemed to be suggestive of clay mineral precipitation.[1] The overall picture of carbon storage reservoir lithologies detailed in Section 2 emphasizes the diversity of mineralogic compositions and ages, which influence the secondary mineral assemblages and overall structure (e.g., fractures). This global context also clarifies key knowledge gaps that experimental and simulation campaigns need to address. These knowledge gaps concern the degree of alteration of mafic-ultramafic rocks, which leads to pore/vein/fracture-lining phases (e.g., [65, 196, 197]), such as zeolites, carbonates, clay minerals, silica, and serpentine. These minerals or amorphous phases may play a controlling role in whole rock dissolution kinetics via their ability to dissolve and provide carbonate-forming divalent cations, or by their ability to limit access of fluid to fresh reactive interfaces. For projects in fractured peridotites and basalts which will rely on exploiting and/or enhancing (e.g., stimulating), preexisting flow paths in natural fracture networks, the reactivity of the serpentine-dominated host rock as a function of the geothermal and pressure gradients will need to be understood to accurately predict the fate and transport of CO_2 in these systems.

Lastly, the conversion of injected CO_2 into labile biologic carbon pools (i.e., not carbonate minerals) in stimulated biomass and/or microbial methanogenesis, as observed at CarbFix1 by Trias et al.[200] and in sedimentary hydrocarbon formations[201, 202] has the potential to obfuscate carbonate mineralization mass balance, as highlighted by Daval.[198] In Daval's perspective article, they illustrated this uncertainty (**Figure 9**) by juxtaposing the inferred Matter et al.[4] carbon sequestration trapping mechanism timeline with unconstrained fluxes for carbon between biomass and carbonate mineral reservoirs. Indeed, after the Daval[198] perspective was published, Pogge von Strandmann et al.[2] used Ca isotopes to determine the carbonation efficiency of the Carbfix1 test was only 72 ± 5% rather than the Matter et al.[4] value of 95±3%, indicating uncertainty in the carbon mineralization efficiency. This disparity in reported values from CarbFix1 may not necessarily be due to carbon fixation via biomass. As discussed in Oelkers and Gislason[203], the carbon isotope signatures reported in Matter et al.[4] are consistent with incorporation of carbon into calcite, and not necessarily due to the biomass, which caused clogging of the injection well and blocking of flow paths. Overall, based on these studies, it would be beneficial to have a baseline understanding of the deep biosphere at a field site of interest prior to CO_2 injection so the mass balance, containment risk, and injectivity may be better constrained.

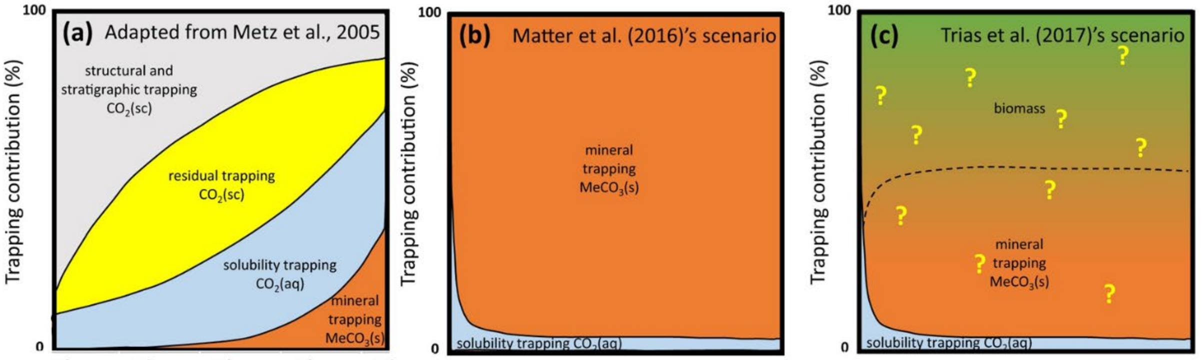


Figure 9. Reformatted from Daval[198] illustrating how CO_2-stimulated biomass changes in the subsurface creates uncertainty in the timescales and carbon sinks for CO_2 storage in reactive reservoirs[4, 199, 200].

Additionally, gas monitoring of methane[202] and hydrogen[204] may be undertaken to better understand abiotic and biotic reactions with the potential to compete with carbon mineralization or create additional containment hazards.

3.3 Summary of Reactions and Relevance

To provide a broad understanding of carbon mineralization processes in the subsurface, we examined reactions and kinetics used in reactive transport simulations, focusing on around 70 minerals and phases and their chemical compositions, kinetic rate parameters, and dissolution reactions. As part of our examination of reactions and kinetics collected from the key simulation studies in Section 2.2, we first evaluated whether reaction pathways are derived from laboratory studies, thermodynamic databases, or bulk rock and mineral analyses, documenting parameters that include surface area, pH, temperature, and pressure. Data from 31 simulations highlight compositional variability across 18 key phases, including olivine and basalt glass, often influenced by prior studies or study locations. While dissolution kinetics frequently rely on the well-cited compilation of Palandri and Kharaka,[86] some studies lack references to original experimental, thermodynamic, or kinetic data. We have also identified three phenomena with the potential to influence carbon mineralization rates, reaction extents, and phase outcomes. Si-rich coatings, often studied in olivine carbonation, can inhibit reactions but have not been proven to cause significant passivation in realistic lithologies including basalt or peridotite. Natural and anthropogenic secondary minerals such as clays, zeolites, and carbonates may influence carbonation outcomes and permeability by altering pore networks, reactive surface areas, and cation availability, with examples from field and laboratory illustrating these effects. Differences in basalt reactivity due to age and composition, as well as knowledge gaps regarding pore-lining and vein-filling phases in mafic-ultramafic rocks, may present challenges for accurately predicting carbonation potential and rates. Additionally, possible inorganic to organic carbon partitioning in the deep biosphere after CO_2 injection will complicate mass balance calculations, underscoring the need for baseline assessments prior to field-scale tests; all followed by extensive downhole sampling and characterization.

4 Subsurface and Risk Evaluation

This section provides an overview of unique characterization considerations and risks associated with mafic-ultramafic mineralization storage. Section 4.1 identifies key subsurface parameters within the target storage formations, including factors like fractures, porosity, connectivity, and permeability. In addition to providing a generic overview, we discuss characterization considerations related to containment, secondary minerals, and injectivity. Section 4.2 focuses on the identification of reaction products generated in water during the CO_2 storage process, with attention on assessing any potential harm if these products migrate into freshwater resources, water bodies, or surface environments. Considerations regarding the concentration of these substances in soils will also be explored. In tectonically active regions, a particular emphasis on seismic risk assessment is crucial, especially when dealing with mafic-ultramafic rocks, as addressed in Section 4.3. Lastly, findings and insights from this section are summarized and presented in Section 4.4, with further monitoring context in Section 5 and regulatory context described in Section 6.

4.1 Key Subsurface Parameters of Storage Target Formations

Key subsurface parameters for geological carbon storage in mafic-ultramafic formations include fractures, porosity, connectivity, and permeability, factors which are largely created during deposition. Generally, emplacement styles for mafic-ultramafic rocks are diverse and include intrusive igneous bodies, extrusive lava flows, and uplift or exhumation of subducted oceanic crust. Structural trapping capabilities of igneous sequences are controlled by formation continuity, which is a product of emplacement style and tectonic setting. The emplacement style and associated rock properties therefore influence the feasibility, implementation, and long-term injection strategies of CO_2 mineralization projects.

Internal structures of mafic formations: Continental flood basalts are of interest for in situ mineralization due to their geographical abundance, favorable mineral composition, layered flows, and vertically variable internal structures formed by differences in cooling rates.[206] For example, basalt flows in the CRBG are regionally continuous and typically extend over many thousands of square kilometers.[207] The feasibility of a prospective storage site depends on geological characterization that demonstrates sufficient injectivity, storage potential, and long-term containment of injected CO_2.

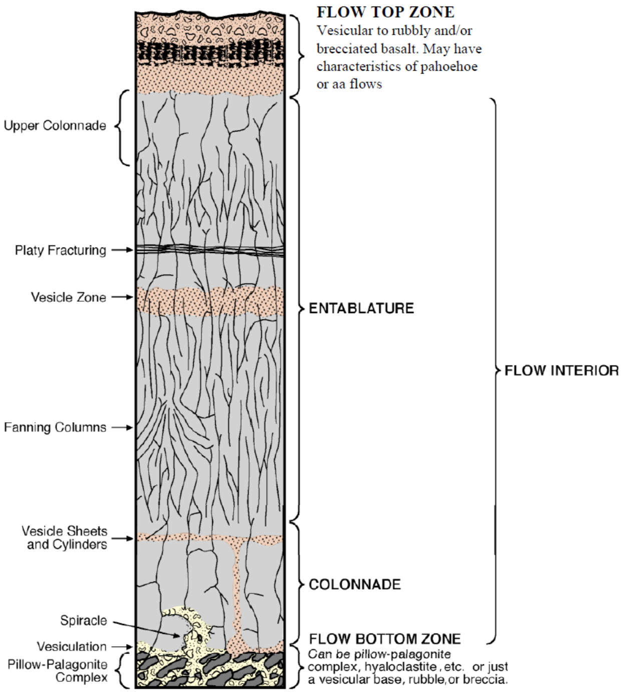


Figure 10. Graphical depiction of a typical basalt internal flow architecture in the CRBG, showing the dense flow interior and porous flow bottom and top zones. [205]

Internal structures of basalt flows (**Figure 10**), and the resultant petrophysical properties (e.g., porosity and permeability), are influenced by variable processes such as eruptive regime, cooling rates, magmatic viscosity, degassing, secondary mineralization, erosional processes, and environmental conditions.[21, 205, 208] Lateral variations in flow structures can be gradual or abrupt depending on environmental and structural controls, such as tectonics and paleo-topography[205].

Stacked flow units may create a series of discrete storage complexes by utilizing hydraulically isolated low-permeability flow interiors as confining intervals and brecciated flow tops as higher permeability injection zones. This concept has been reinforced through data released under the WBSP,[209] where wireline log responses show alternating high and low porosity and density across flow tops and flow interiors, respectively (**Appendix Figure**).[210] These flow top intervals at the WBSP were found to have 15–30% porosity and 75–150 mD permeability.[209] In addition, porosity and permeability generally decrease with increasing age of flows and depth due to alteration, formation of secondary minerals, and compaction trends.[22]

Containment characterization and risk. The process of defining containment and caprock for a mineralization storage complex may vary from the definition adopted in sedimentary basins. CO_2 storage projects in sedimentary basins typically utilize a regionally continuous, thick, impermeable shale free of faults and fractures. In mineralization storage, sedimentary interbeds are largely thin and discontinuous, controlled by depositional and tectonic environments. Different types of caprocks will exist in a mafic storage complex compared to an ultramafic storage complex. Caprock definition in mafic storage typically relies on low-permeability flow interiors. Flow interiors are composed of colonnade and entablature sections that exhibit primarily vertical fracturing (**Figure 10**). Field studies from the CRBG[205, 211, 212] have found that 1) flow interiors generally act as regional aquitards; 2) within flow interiors, as a function of compaction/depth, groundwater flow occurs along vertical fractures, but movement is largely isolated to the interior zone due to thickness of flow interiors, as well as the presence of secondary minerals; 3) sedimentary interbeds have been demonstrated to act as aquitards. Ultramafic formations are generally characterized by lower permeability, extensive fracturing, and abundant secondary minerals due to alteration as a result of natural carbonation and serpentinization.[213] Ultramafic mineralization storage projects may consider $CO_2(aq)$ injection to provide solubility trapping prior to injection, in lieu of low-permeability formations to act as caprocks. Fracture characterization, and integration of field and lab measurements with coupled geochemical and geomechanical flow simulation, will be important for demonstrating containment in both mafic and ultramafic mineralization storage operations.

Containment requirements of CO_2 in early stages of mineralization storage may be variable based on injection strategy. For example, CO_2 dissolved in brine prior to injection is no longer free-phase due to solubility trapping. Injection of $scCO_2$ requires a low-permeability caprock for containment. $CO_2(aq)$ injection will need to consider the lateral extent of pressure related to greater injection volumes in terms of containment risk. The current lack of commercial scale mineralization storage projects necessitates additional demonstration, at greater injection volumes and using variable injection strategies, to explore containment processes in mafic-ultramafic formations.

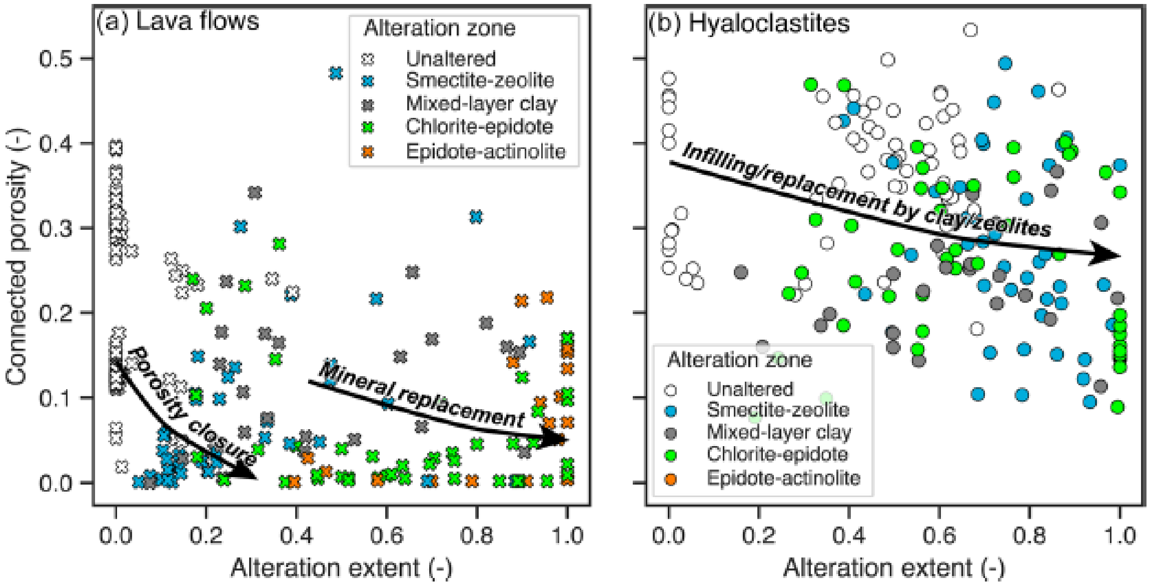


Figure 11. Connected porosity as a function of alteration extent in basalts ((a) lava flows, (b) hyaloclastites) can provide insights into types of minerals that are expected to limit fluid transmissivity in these formations. Reproduced from [208].

Porosity, permeability, and secondary minerals. Extensive characterization of mafic formations in Iceland have resulted in the culmination of a petrophysical library which includes over 1000 field and downhole samples, collected between 1970 and 2010.[208] Fossil and active geothermal systems, as well as young volcanic rocks, were analyzed for petrophysical, mineralogical, and geochemical properties. Lithologies include lava flows, hyaloclastite, pillow basalts, silicic volcanics, intermediate volcanics, basaltic intrusions, silicic intrusions, intermediate intrusions, and sedimentary rocks (clay, glacial, conglomerate, sandstone, and interbedded basalt). Overall, as shown in **Figure 11**, the correlation between connected porosity and alteration extent is dictated by initial emplacement conditions and native mineralogy because porosity is reduced by secondary minerals infilling.[208]

Figure 12. Example of vesicular variation, connected porosity (white arrows), and secondary mineral formation (white circle) in a sample of Grande Ronde basalt (Columbia River Basalt Group; CRBG) from outcrop, near Wallula Gap, WA.

Lateral vesicular variations and the presence of secondary minerals in basalt flows create characterization challenges in determining total connected porosity, well communication pathways, and how these variables impact storage potential. **Figure 12** depicts a hand sample from a CRBG outcrop showing variations in connected porosity, secondary mineral formation, and vesicular distributions and shapes. A quantitative mapping of pore volume networks in a Hawaiian lava flow core using x-ray microtomography (XMT) reveals the complexity of basaltic flow pathways which may be used to constrain storage potential estimates **Figure 13**.[33]

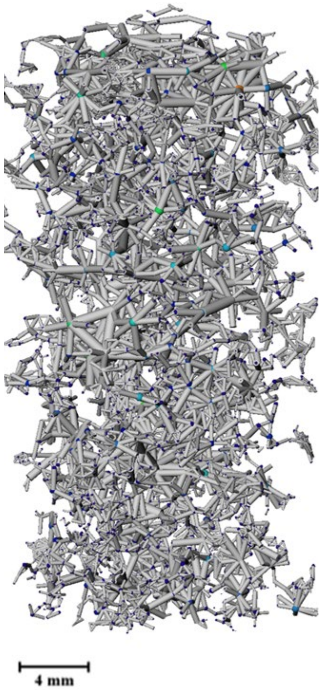


Figure 13. XMT derived pore network model from Hawaii lava flow core sample showing interconnectivity of pore structure, modified from [33].

In terms of permeability, vuggy and fractured basalt flow intervals may exhibit darcy or multi-darcy flow conditions.[42, 205, 214] To better understand the impacts of pore connectivity on flow, hydraulic testing (e.g., water injection, drill stem testing to collect in situ water samples for hydrochemical analysis, interference testing, and pressure fall-off testing) at individual flow units is commonly deployed to identify hydraulically isolated intervals, or lack thereof.[215] Extended hydraulic testing, which allows for sufficient aquifer development, along with bulk rock geochemistry is necessary to characterize flow intervals, zonal isolation, and far-field communication pathways.

Ultramafic rock types (e.g., peridotite and olivine) which typically have low porosity and extensive fracturing, present opportunities for in situ mineralization. Mineralization potential in ultramafic rock types is enhanced by rapid carbonation and reactive-driven fracturing (chemical fracturing), as observed in field outcrop and lab experiments.[222, 223] Mineralogy, natural fracture networks, surface area, and positive (cracking) and negative (clogging) reactivity loops that may influence pore volume will be key subsurface parameters to consider for mineralization storage in ultramafic rock types.[224]

Reported porosities (both averages and ranges) from mafic-ultramafic rock types across global locations are provided in **Table 9.** Reported values for porosity from open literature are a mixture of connected and total porosity values, as well as statistical reporting (average, maximum, range).

Table 9. Review of reported mafic-ultramafic porosity values obtained from the open literature. Porosity measurement methods vary across reported values.

Location	Lithology	Type	Porosity (%)	Ref
Iceland	Basalt	Mafic	13	[208]*
Iceland	Basalt	Mafic	22	[216]
U.S. CRBG	Basalt	Mafic	15–30	[209]*
U.S. CRBG	Basalt	Mafic	13	[107]*
India, Deccan Traps	Basalt	Mafic	20–40	[217]
Malaysia	Basalt	Mafic	16	[43]
Greece	Basalt	Mafic	15–23	[34]
Kenya Rift	Basalt	Mafic	1–30	[16]
Oman	Ophiolite	Ultramafic	1	[218]
New Zealand	Dunite	Ultramafic	0.5	[18]*
Australia	Serpentinite	Ultramafic	4	[18]*
Turkey	Ophiolite	Ultramafic	5	[219]
Atlantis Massif	Serpentinite	Ultramafic	3–13	[220]
Canada	Ophiolite	Ultramafic	1–4	[221]
*Permeability also reported				

The porosity of mafic-ultramafic reservoirs shown in **Table 9** are comparable to those of sandstone reservoirs. Overall, porosity values in mafic rocks are between 13–40%, apart from one outlying basalt sample from the Kenya Rift. Two flood basalts, CRBG and Deccan Traps, have the highest reported values of 30% and 40% respectively. For ultramafic formations, the values are significantly lower overall, with only one sample (Atlantis Massif) having a reported porosity of >10%.

Injectivity, capacity, and containment risks are key to evaluating the feasibility of CO_2 storage at prospective sites. **Table 10** summarizes subsurface parameters (depositional, structural, and chemical properties) of mafic-ultramafic rocks, mapped to injectivity, capacity, and containment. When considering mafic-ultramafic rock types for CO_2 storage, key considerations include (1) depth and thickness, (2) chemistry, and (3) connected porosity and natural fractures of target formations. Like sedimentary storage formations, heterogeneity may contribute to preferential flow pathways, and, for in-situ mineralization, heterogeneity may also impact reactivity away from the wellbore and overall injectivity and capacity.

In terms of historical geologic exploration, mafic-ultramafic rock types are generally under-explored compared to sedimentary formations, and therefore present unique challenges for drilling campaigns due to lack of operational experience. Not only are these rock types under explored, but also large-scale fluid injection in mafic-ultramafic rock types is not a common practice (outside of operations in Iceland). In terms of drilling hazards, highly fractured zones may contribute to lost circulation, wellbore stability, and cement quality issues, compromising containment integrity. Experiences and lessons learned from operations in vuggy carbonate formations, widely explored for hydrocarbon production and used in waste-water injection operations, may benefit characterization and operation in mafic-ultramafic rock types.

Table 10. Key subsurface parameter descriptions and their CO_2 storage impact.

Storage Criteria	Subsurface Parameter Description	Ref
Injectivity	Changes in porosity and permeability due to alteration effects, age, degassing, weathering	[22, 215]
	Characterizing flow and reactivity in naturally fractured flow tops as a result of flow top cooling/weathering	[56, 225, 226]
	Variable porosity and pore connectivity due to heterogeneity	[33, 227]
	Microporosity related to glass content	[228]
	Mapping internal architectural features (lobes, brecciated flow tops)	[229]
Capacity	In situ mineralization effects	[230]
	Alteration mapping to predict reactivity (less altered, more reactive, increased dissolution)	[229]
Containment	Coupled geomechanical and geochemical alterations to caprock	[226]
	Wellbore stability and cement quality	[231]

4.2 Risks of Harmful Reaction Products

As previously discussed (Section 2), when CO_2 dissolves in water a weak acid is created, leading to a reduction in pH in formation brine, which in early reaction stages may lead to mobilization of heavy metals native to the injection formation.[232-235] There is a risk that, if a leakage event occurs, mobilized heavy metals could unintentionally migrate into and damage USDWs, water bodies, or surface environments. Moreover, global regulatory frameworks (discussed in Section 6) advise storage facility operators to (1) conduct baseline testing, and injection and post injection monitoring of deepest USDWs (discussed in Section 5) and (2) conduct a risk assessment to inform an emergency remedial response plan, often supported by financial insurance instruments and long-term liability agreements. It should also be noted that brine or CO_2 (free-phase or dissolved in brine) migration into potable water sources or USDWs could result in water quality impacts such as acidification that may require remediation.[236] Conversely, a mine tailings example suggests that CO_2 mineralization of ultramafic rocks may sequester trace metals.[237]

Mobilized contaminants in potable aquifers can pose a significant risk to human health and the environment if injection causes leakage of injection formation fluids (formation fluid + injection fluid and reaction products). In addition, migration of heavy metals into soils can cause crop damage and broader ecological impacts. The risk of contamination can be evaluated based on drinking water regulation thresholds (i.e., maximum contaminant level – MCL) of the US Environmental Protection Agency (EPA), EU Drinking Water Directive (DWD), WHO guidelines, or other relevant regulatory frameworks. An overview of toxicologically relevant substances, regulatory MCLs, and the trace metal concentrations from Grand Ronde (CRBG) basalt carbon sequestration geologic formation is shown in **Table 11**.[233, 235]

Mobilization of contaminants in the injection formation does not imply leakage into USDWs, and it is pertinent to understand potential contaminant mobilization and impacts, particularly as

Table 11. Overview of values and limits for trace chemicals in potable aquifers.[235] Note: This table does not include other potential contaminants (Fe, Zn, Sr) which may lead to aesthetic and cosmetic issues. The basalt trace chemical mobilization potential is shown in column 5.[233]

Contaminant	**MCL[a] (mg/L)**				**Potential Health Effects**
	US EPA	**WHO**	**EU DWD[c]**	**Basalt[b]**	
Antimony	0.006	0.02	0.01	n/a	Increase in blood cholesterol; decrease in blood sugar
Arsenic	0.01	0.01	0.01	<MCL	Skin damage or problems with circulatory systems, and may have increased risk of getting cancer
Barium	2	1.3	n/a	n/a	Increase in blood pressure
Beryllium	0.004	n/a	n/a	n/a	Intestinal lesions
Cadmium	0.005	0.003	0.005	<MCL	Kidney damage
Chromium	0.1	0.05	0.25	<MCL	Allergic dermatitis
Copper	1.3	2.0	2.0	<MCL	Short term: Gastrointestinal distress Long term: Liver or kidney damage
Lead	0.015	0.01	0.005	<MCL	Children: Delays in physical or mental development; learning ability deficits Adults: Kidney problems; high blood pressure
Manganese	n/a	0.08[d]	0.05	>MCL	Possible health and aesthetic impact
Mercury	0.002	0.006	0.001	n/a	Kidney damage
Nickel	0.1[e]	0.07	0.02	n/a	Allergic contact dermatitis
Selenium	0.05	0.04[d]	0.02	n/a	Hair or fingernail loss; numbness in fingers or toes; circulatory issues
Thallium	0.002	n/a	n/a	n/a	Hair loss; changes in blood; kidney, intestine, or liver problems
Uranium	0.03	0.03	0.03	n/a	Increased risk of cancer, kidney toxicity

a – MCL refers to Maximum Contaminant Level from US Environmental Protection Agency (EPA).
b – Heavy metal mobilization results reported for Grand Ronde basalt lithologies from [233]
c – EU Drinking Water Directive: 2020/2184, Appendix 1
d – Provisional guideline due to uncertainty around health impacts
e - No current MCL is listed at the US EPA, but an outdated value is available, which is the same as the limit value of the California Code of Regulations, 2018

commercial-scale CO_2 mineralization projects develop. A 2013 study evaluated the possible release of trace metal concentrations due to CO_2 leakage and CO_2-water-rock interaction within a variety of geologic storage reservoirs based on experimental data.[238] Based on the data presented, the amounts of trace metals that could be leached from rock types are generally higher for sandstone and shale, followed by cement, and then carbonate, evaporite, and basalt. The Grand Ronde basalt experimental results stood out as releasing less primary and secondary contaminants than other rock types, staying below the US EPA MCL for most contaminants except Mn and Fe during CO_2-water-basalt experiments.[233] Despite the potential Mn and Fe mobilization increasing above the MCL, mineralization of Mn- and Fe-carbonates (in addition to Ca- and Mg-carbonates) can potentially neutralize this risk in the injection formation, reducing the impact of a leakage event. However, despite the potential for toxic metal leaching, field observations from monitoring data have not indicated an increase in toxic metal contamination.[97]

Additional supporting data for the low risk of mafic-ultramafic reservoirs for mobilizing harmful reaction products can be deduced from natural analogues where CO_2-water interacts with mafic or ultramafic rock (e.g., peridotite exposed at surface, volcanic systems). In Oman, surface water, spring, and well water samples, in contact with natural weathering of ultramafic rocks, were not observed to have increased levels of nickel or chromium.[223] In mafic rocks, a study of natural groundwater compositions near Mt. Hekla volcano in Iceland found that concentrations of Cd, As, and Pb were below the US EPA MCL and WHO/EU guidelines (**Figure 14**). This suggests that despite initial metal mobilization from basalt dissolution, these metals are reincorporated into solid phases (e.g., Sr and Ba into carbonates and Pb, Zn, and Cd into Fe(oxy)hydroxide phases) as continued dissolution and mineralization neutralizes the groundwater (i.e., away from a CO_2 injection well).[239] An assessment of groundwater at Mt. Vesuvius, Italy found similar trends for trace element mobilization due to CO_2-water-rock interaction and identified a trend of increasing trace element concentration with increasing bicarbonate.[240]

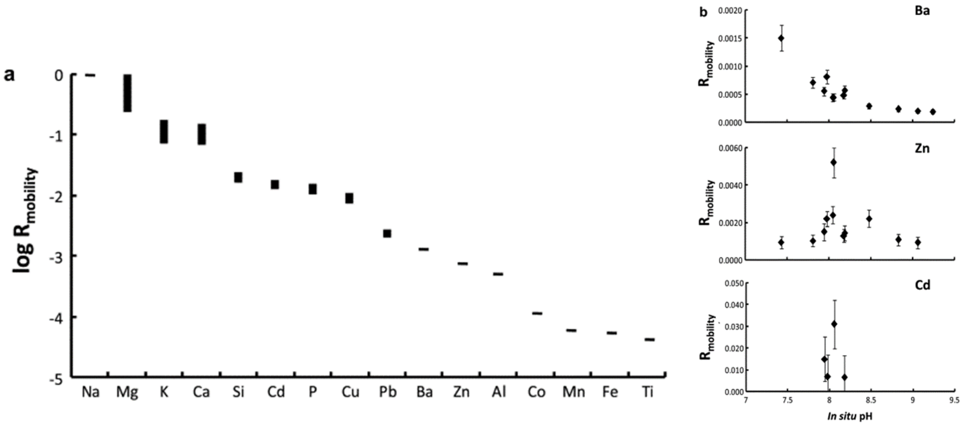


Figure 14. Plots of mobility of elements in groundwater. (a) The logarithm of the relative mobility of major and trace elements in Mt. Hekla groundwater. Concentrations of Fe, Al, Mn, Cd, Co, Pb, and Zn were below detection limits in some samples. (b) The mobility of trace metals ($R_{mobility}$) in Mt. Hekla groundwater versus pH. The sequence of relative mobility is Cd>Cu>Zn>Ba>Al>Ti>Mn>Co>Fe. Figure from Flaathen, Gislason [239] .

In summary, while CO_2-water-rock interactions in mafic-ultramafic reservoirs promote dissolution and trace element/metal mobilization as reaction products, there is no significant difference between the risk of generating harmful reaction products in these reservoir types compared to CCS in sedimentary reservoirs. Additional research is needed to better understand formation water evolution over time as it relates to in situ mineralization. This is particularly needed in other potentially feasible ultramafic reservoirs that have not been studied in as much detail as basalt reservoirs and could contain higher concentrations of potentially harmful trace elements or reaction products.

4.3 Seismic Risks

This section provides an evaluation of seismic risks from the perspective of CO_2 mineralization in mafic-ultramafic target reservoirs. Induced seismicity is a risk for any subsurface injection operation, including oil and gas wastewater injection, geothermal brine re-injection, and geological CO_2 sequestration.[241] Basement-fault interactions, fault seal and stability, native formation pressures, vertical and lateral variations of in situ stresses, and planned injection parameters (density, rate, pressure) may contribute to seismic risks.[242] Induced seismicity as a result of CO_2 injection may lead to storage complex integrity risks and may prove a significant challenge when planning and developing a commercial scale CO_2 injection.[243] Injection volume and rate play a significant role in pore-pressure and state-of-stress conditions and have been correlated to induced seismicity events.[244] When considering scale up of mineralization storage projects (e.g., >25 years injection, >1 million tons per year per well, multiple injection wells), uncertainty in near- and far-wellbore carbonation effects (and well-to-well interactions) could lead to an increased risk of induced seismicity as reactivity-driven changes in porosity and connectivity produce dynamic pressure environments. The ability to mitigate induced seismic events primarily relies on detailed fracture characterization and incorporation of fractures into models to understand pressure communication pathways in the context of geochemical and geomechanically coupled multi-phase flow environments, as discussed in Section 4.1. For monitoring, early detection of induced seismicity risks may be informed by water evolution and availability in the injection formation. In-zone water composition monitoring may be used to inform dissolution and mineralization rates, evaluate reactive feedback loops, and assess spatial distribution of reactive processes in fracture-controlled environments (in both injection and caprock formations). This analysis will be evaluated against model predictions and used to help determine the influence of reactive processes on geomechanical responses related to pore-pressure and state-of-stress. Safe and permanent storage of CO_2 into basalts will necessitate a comprehensive understanding of regional stresses, and coupled geomechanical and reactive transport modeling, due to high heterogeneity related to fracture controlled reservoir properties.[59] Developing induced seismicity monitoring and risk mitigation plans is a key technical undertaking for any CO_2 injection program and required under various regulatory frameworks (discussed further in Sections 5 and 6).

Regardless of injection formation rock type, increasing reservoir pressures during CO_2 injection can lead to fault reactivation and induced seismicity resulting from geomechanical changes in the storage complex and increased pressure along faults. Precipitation of carbonates and the replacement of mafic minerals can result in up to ~44% increase in solid molar volume, potentially leading to reduction of porosity and permeability. Increases in pore pressure may result in additional fluid pathways created by reaction-induced fracturing.[230] In situ mineralization pilot projects documenting monitoring efforts and post-injection reservoir changes (such as pressure, porosity, and permeability) include the WBSP (2013)[9] and CarbFix2 Pilot (2020)[49]. Post-injection hydrologic testing results from WBSP indicate that two years after injection (~1000 tons CO_2 over 30 days) 60% of the injected CO_2 was mineralized, with resulting carbonates occupying <2.5% of the initial pore space.[9] No induced seismicity was reported for the WBSP.[9] At the CarbFix2 project, CO_2 and hydrogen sulfide (H_2S) were dissolved in water prior to injection in basalt formations.[245] Tracer tests performed at the Carbfix Húsmúli re-injection site report a change in flow paths, requiring twice the porosity (from 5% to 10%) to properly history match, and may be related to induced seismicity, near-wellbore dissolution of basalt, thermal alteration, mineralization of carbonates, or a combination of these factors.[246] The same publication considers that 10% of the available pore space may be filled (i.e., carbonated) by 2050 at the theoretical maximum reservoir storage capacity of 300 megatons CO_2.

In Iceland, induced seismicity was observed at the Húsmúli geothermal brine reinjection site related to well drilling and brine reinjection activities (2007–2012) to support operations at the Hellisheiði Geothermal Field.[245, 247] However, later injection of CO_2 dissolved in condensate (beginning in 2014) indicated no clear correlation of $CO_2(aq)$ reinjection with induced seismicity.[245]

CO_2-water-ultramafic rock reactions (as opposed to mafic basalts described above) also result in chemical alterations to porosity and permeability. Chemical or reaction-driven cracking, as observed in serpentinized olivine outcrops and experimental lab testing, can lead to the creation of fractures.[222]

Induced seismicity risk mitigation for in situ mineralization is similar to other underground injection operations. Mitigation is supported by pre-injection subsurface characterization, operational strategies, injection monitoring, and post-injection site monitoring (**Table 12**). First and foremost, accurate site characterization and understanding of the storage complex and associated reservoirs, seals, and leakage pathways is critical to mitigating seismic risk and understanding natural seismicity (or induced seismicity from other activities) prior to injection. At the WBSP, a novel three-component 2D seismic swath profile was acquired to characterize first order subsurface stratigraphy and inform fault detection, greatly reducing overall project uncertainty[209].

Operational strategies should consider baseline seismicity data collected during site characterization in order to accurately assess the potential risk (i.e., frequency and magnitude) of possible induced seismic events due to CO_2 injection. Moreover, injection strategies may incorporate gradual scale-up of injection rates in order to minimize risk associated with large-scale injection by providing time for continuous monitoring, assessment and decision-making regarding the long-term injection strategy.[248]

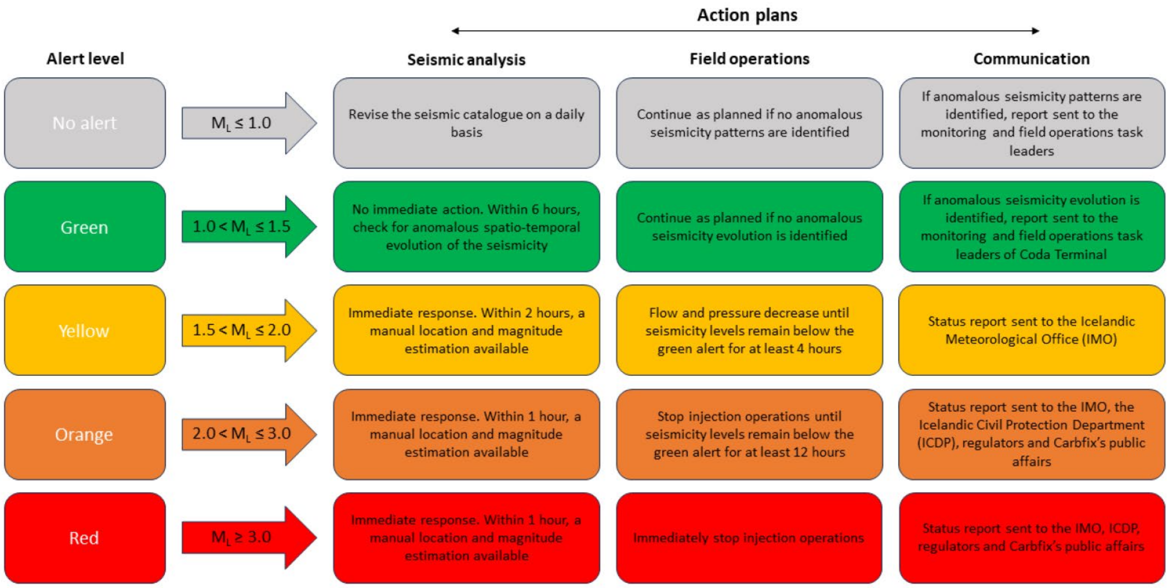
Table 12. Project life cycle activities that can be levered for seismic risk management and mitigation strategy. See Section 5.1 for review of monitoring techniques for CO_2 storage.

Project Life Cycle	Seismic Risk Management Mitigation Strategy
Characterization (pre- and post-injection)	Fault and fracture characterization, mineralogical, lab testing.
Modeling	Uncertainty and sensitivity modeling for: reactive transport, geomechanical modeling, injection strategy, mineralogy, CO_2 stream composition.
Risk Identification & Assessment	Project team and stakeholders identify surface and subsurface risks which may lead to induced seismicity and develop mitigation strategies.
Operational - Emergency Remedial Response Plan	Prescriptive operational responses to seismicity, based on magnitude, that exceeds natural baseline. Phase-up strategy to increasing injection rates incrementally over time.
Monitoring - Baseline	Site-specific seismic monitoring data (USGS, geophone arrays, etc.) used to inform natural seismicity profile. Baseline 3D seismic survey and pressure profiles.
Monitoring - Injection	Pressure gauges installed in monitoring wells to detect changes in injection formation pressures. Distributed acoustic sensing (DAS) fiber and/or geophone arrays to detect induced seismicity. 4D seismic survey to evaluate mineralization extent.[249]
Monitoring - Post-injection	Continued monitoring described above, conversion of injection well to monitoring well.

A site-specific monitoring plan that considers key seismic risks assessed during site characterization and design of the operational strategy is important for quickly identifying and mitigating risks. While the specific techniques to be employed in the monitoring plan depend on the injection method and site considerations, the monitoring plan should be designed to passively and actively collect geophysical data that can inform the reservoir models used to evaluate reservoir behavior, pressure dynamics, and potential induced seismicity. For example, extensive site characterization was conducted at the planned Carbfix Coda Terminal site to characterize baseline seismicity and seismic risk. This data is being used to inform operational strategies, injection and post-injection monitoring, and seismic risk mitigation through development of a seismic traffic light system (TLS) to facilitate thorough analysis, safe operations, and effective public communication/engagement with stakeholders. An example of a traffic light system from the Carbfix Coda Terminal project in Straumsvik, Iceland is shown in **Figure 15**. Seismic risk tools and threshold values are likely to be site-specific and may vary by jurisdiction. Monitoring and risk mitigation strategies are discussed further in Section 5. In addition, the findings and insights derived in this section concerning soil and groundwater risk are further connected with their regulatory context in Section 6.

4.4 Summary of Subsurface Risks and Evaluation

Key parameters in mafic-ultramafic reservoirs such as mineral composition, porosity, and permeability may be highly variable because of original emplacement conditions and secondary processes. Because of this, site-specific data is needed to build a comprehensive understanding of risk when evaluating potential storage sites. Porosity values range significantly between mafic-ultramafic rocks, varying from 1% to as high as 40%. In addition, laboratory measurements on basalt cores have shown a direct correlation with secondary minerals and fluid flow. In this context,



Action plans

Alert level		Seismic analysis	Field operations	Communication
No alert	$M_L \le 1.0$	Revise the seismic catalogue on a daily basis	Continue as planned if no anomalous seismicity patterns are identified	If anomalous seismicity patterns are identified, report sent to the monitoring and field operations task leaders
Green	$1.0 < M_L \le 1.5$	No immediate action. Within 6 hours, check for anomalous spatio-temporal evolution of the seismicity	Continue as planned if no anomalous seismicity evolution is identified	If anomalous seismicity evolution is identified, report sent to the monitoring and field operations task leaders of Coda Terminal
Yellow	$1.5 < M_L \le 2.0$	Immediate response. Within 2 hours, a manual location and magnitude estimation available	Flow and pressure decrease until seismicity levels remain below the green alert for at least 4 hours	Status report sent to the Icelandic Meteorological Office (IMO)
Orange	$2.0 < M_L \le 3.0$	Immediate response. Within 1 hour, a manual location and magnitude estimation available	Stop injection operations until seismicity levels remain below the green alert for at least 12 hours	Status report sent to the IMO, the Icelandic Civil Protection Department (ICDP), regulators and Carbfix's public affairs
Red	$M_L \ge 3.0$	Immediate response. Within 1 hour, a manual location and magnitude estimation available	Immediately stop injection operations	Status report sent to the IMO, ICDP, regulators and Carbfix's public affairs

Figure 15. Example of a seismic risk mitigation 'traffic light system' (TLS) for the Carbfix Coda Terminal project in Straumsvik, Iceland [250] modified from [251].

continental flood basalts are favorable targets due to their high porosity and mineralogical composition. However, challenges remain in characterizing total connected porosity in laterally extensive basalt flows. In terms of contaminant risk, it is true that CO_2-water-rock interactions in mafic-ultramafic reservoirs promote dissolution and trace element/metal mobilization as reaction products. Results of an experimental study from Grand Ronde basalt show that there is lower generation of trace metal reaction products in mafic rocks (basalts) as compared to CCS sedimentary reservoirs. However, CO_2 mineralization may sequester trace metals.[237] Another risk associated with CO_2 injection is induced seismicity, which arise from factors such as increased reservoir pressure, fault reactivation, and geochemical changes that typically occur due to mineralization. When designing monitoring plans (Section 5), developers may consider geomechanically coupled stochastic reactive flow modeling to better predict plume evolution overtime and mitigate seismic risks proactively.

It is important to address challenges such as trace metal mobilization and seismic risk through careful site characterization and monitoring. Identifying sites with multiple low-permeability barriers, evaluating heterogeneity, and potential compartmentalization, are all key to developing seismicity monitoring and risk mitigation plans for any CO_2 injection program and to meet the requirements and regulations described in Section 6. Prior to injection, regional background seismic monitoring, periodic groundwater sampling, and geophysical characterization is encouraged to detect changes in baseline conditions and evaluate if refinements to operational strategy are needed during injection. Mitigation is supported by pre-injection subsurface characterization, operational strategies, injection monitoring, and post-injection site monitoring. Ultimately, a robust characterization and risk mitigation plan must be considered throughout the project development lifecycle and incorporated into key aspects of the design, construction, operation, and monitoring of the site.

5 Monitoring for CO_2 Storage in Mafic-Ultramafic Reservoirs

In this section, we review the monitoring techniques applicable to CO_2 storage in mafic-ultramafic rocks, evaluating their effectiveness in ensuring secure storage. Conventional storage settings that rely primarily on physical trapping mechanisms (i.e., structural or residual trapping) mostly utilize geophysical methods, while geochemical monitoring may play a secondary role. In comparison, in mafic-ultramafic storage settings that rely primarily on mineralization trapping, geochemical methods are essential to monitoring. The monitoring techniques examined include direct geochemical sampling through monitoring wells, the utilization of tracers, and the application of various geophysical methods, such as active seismic, electro-magnetic surveys, and surface leakage detection. Specifically, we will review monitoring objectives for CO_2 storage (Section 5.1), describe monitoring techniques used to prove secure storage (Section 5.2), and provide a summary of mineralization monitoring suitability from a regulatory perspective (Section 5.3). We also discuss the challenges related to monitoring during project scale up (further discussed in Section 7.1), the role of monitoring in evaluating seismic risk (Section 4.3), and the role of monitoring in regulations (Section 6) in other chapters.

5.1 Monitoring Objectives and Requirements

Monitoring is an important component of CCS projects to verify the effective, safe, and long-term storage of CO_2, and to avoid adverse impacts to human health and the surrounding environment. Examples of monitoring techniques and how they would be deployed in a stacked layered continental basalt storage complex are graphically depicted in **Figure 16**. For geologic storage

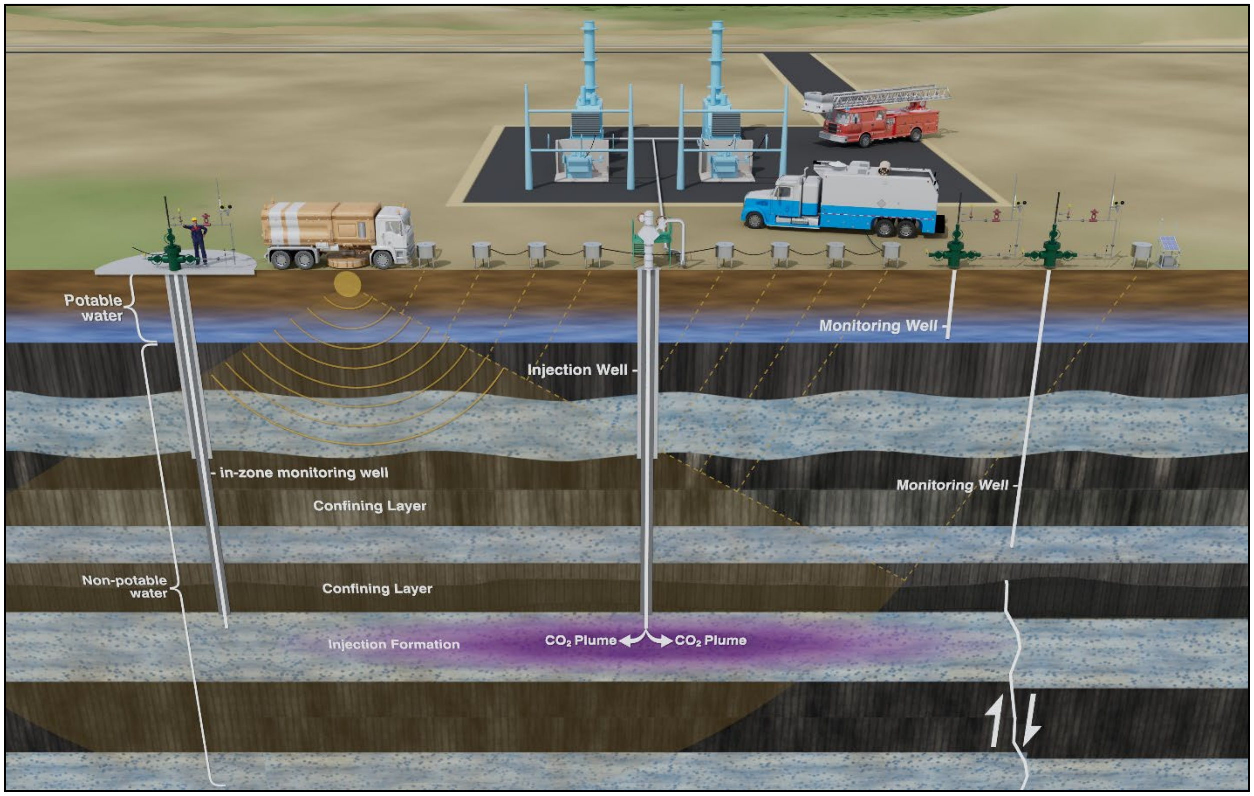


Figure 16. Overview of key monitoring, reporting, and verification technologies relevant to in situ mineralization. Figure not to scale, see **Figure 2** for an illustration of the depth of CO_2 sequestration.

projects, objectives of monitoring include 1) reliably quantifying the amount of CO_2 stored, 2) ensuring containment of CO_2 through direct and indirect monitoring tied to model validation, 3) ensuring conformance with expected CO_2 behavior, 4) compliance with permitting and environmental protection requirements, 5) identifying and alerting to increased risk of adverse events (e.g., leakage, contamination), and 6) optimizing injection and storage operations. Monitoring plans are designed to address these objectives through risk identification and assessment across all phases of the project (i.e., pre-construction through post-injection and site closure).[252-254] Once key risks are identified, a measurement-based monitoring methodology can be defined to mitigate any potential impacts.

Monitoring is built into existing regulatory frameworks for CCS that are described in Section 6. Typical regulations, however, do not prescribe specific monitoring technologies that are required for compliance, but rather the monitoring goals and data that must be collected through various techniques to ensure safe, secure, and long-term CO_2 storage (**Table 13**). Moreover, efficacy of monitoring technologies depends on the geology and possible leakage pathways at the given CO_2 storage site and must be determined on a site-specific basis. Ultimately, it is the combination of all

Table 13. Key regulatory/legal requirements for select regulatory frameworks (i.e., EU CCS Directive and US EPA UIC Class VI) covered in Section 6. Note: the regulatory examples provided are not exhaustive and intended to represent the general requirements for subsurface mineralization projects, regardless of jurisdiction. Adapted from [255-258]

Requirement	EU CCS Directive Example	US EPA Example
The legal framework is designed for **permanent** storage of CO_2.	Article 1.2	40 CFR 146.81(b)
The legal framework requires a **permit**, authorization, license, or equivalent regulatory control document for the operation of the storage site.	Article 6.1	40 CFR 144.11
The legal framework requires **storage site characterization** or other similar determination of minimum criteria of suitability for geological storage.	Article 4.3	40 CFR 146.83
The legal framework includes a **characterization of an eligible CO_2 stream**.	Article 12.1	40 CFR 146.81(d)
The legal framework requires appropriate **monitoring** of the injection facilities, the storage complex and the surrounding environment to ensure that the geologic storage project is operating as permitted and is not causing significant adverse effects.	Article 13	40 CFR 146.90
The legal framework requires at least periodical **reporting** to a competent authority to ensure that the geological storage project complies with storage permit conditions.	Article 14	40 CFR 146.91
The legal framework includes requirements for **emergency and remedial response** in case of leakage or other significant irregularities.	Article 16	40 CFR 146.94, 146.88(f)
The legal framework includes requirements for storage **site closure and post-closure site management**.	Article 17	40 CFR 146.92, 146.93
The legal framework includes requirements for **financial responsibility** or other comparable mechanisms (e.g., transfer of responsibility to a competent authority) to ensure that the obligations arising under the issued geological storage permit can be met.	Article 18, 19, 20	40 CFR 146.85

monitoring activities in the monitoring plan that deliver actionable data and information regarding site-specific risks (e.g., leakage).

The Intergovernmental Panel on Climate Change originally defined ‘leakage’ as a transfer of CO_2 from beneath the ground surface or seabed to the atmosphere or ocean, but defines ‘migration’ as the movement of CO_2 within and out of the geological storage reservoir while remaining below the ground surface or the seabed.[259] Now, ‘leakage’ includes any unexpected movement of injected fluids (i.e., CO_2) and/or injection formation brine into overlying sealing formations and aquifers, sources of potable water, or to the atmosphere/hydrosphere at the surface. Depending on the regulatory framework, temporal monitoring requirements vary but generally cover 1) the baseline, or ‘pre-injection’ period, 2) active CO_2 injection period, and 3) post-injection period of ~10–100 years,[260] unless the permanent containment of injected CO_2 can be sufficiently proven sooner. In some cases, monitoring and quantification of leakage serves as the basis for estimates of total carbon stored for incentive programs (e.g., U.S. Internal Revenue Service (IRS) 45Q tax credit) and compliance markets (e.g., EU Emissions Trading System (ETS)).

Regardless of the regulatory framework under which monitoring is taking place (**Table 13**), a general approach to measurement-based monitoring, such as that proposed by Dixon and Romanak[254] is capable of addressing the large variability and site-specific nature of storage geology.[261] The general components of such a system, shown in **Table 14**, would include site characterization combined with modeling of CO_2 behavior in the subsurface to specifically address potential leakage pathways. In addition, monitoring of these leakage pathways and tracking of CO_2 behavior during injection would be used to update models. The last component of the methodology is reporting of the total mass of CO_2 injected and any emissions from the storage complex. The general process for estimating emissions from a CO_2 storage site (**Table 14**; **Figure 17**) is initiated under the site characterization and flows down through assessment, monitoring, and reporting.[259] Quantification, reporting, and validation guidelines for monitoring data are provided through relevant authorities, such as the EU Monitoring and Reporting Regulation[262] and US EPA Greenhouse Gas Reporting Program (GHGRP).[263]

Table 14. Components of proposed measurement-based monitoring for CO_2 sequestration storage operations.[254]

	Measurement-based Monitoring Components
1	Site characterization and identification of potential leakage pathways.
2	Assessment of risk of leakage by combining site characterization and modeling of CO_2 behavior.
3	Monitoring of leakage and of CO_2 behavior during injection and subsequent updating of models.
4	Reporting of CO_2 injected and emissions from storage.

With a risk-based approach to monitoring, CO_2 mineralization projects must develop monitoring plans based on specific measurement and detection technologies capable of addressing the following general activities:[254]

1) measurement of background CO_2 fluxes through the ground surface and/or seabed

2) measurement of CO_2 injected

3) monitoring of emissions from the injection system

4) monitoring to determine fluxes through the ground surface and seabed (excluding background)

5) Post-injection monitoring

6) incorporation of improvements in monitoring techniques/technologies

7) periodic verification of emissions estimates.

Monitoring technologies included in a site-specific monitoring plan largely depend on the phase of the project (i.e., site characterization vs post-injection), site geology, and expectations for the rate, extent, and impacts of CO_2-water-rock interactions in the mineralization storage reservoir. Ultimately, project-specific decisions on appropriate monitoring techniques will need to be made on a case-by-case basis, taking into account potential tradeoffs of individual monitoring technologies and their ability to identify, mitigate, or reduce risk.[264]

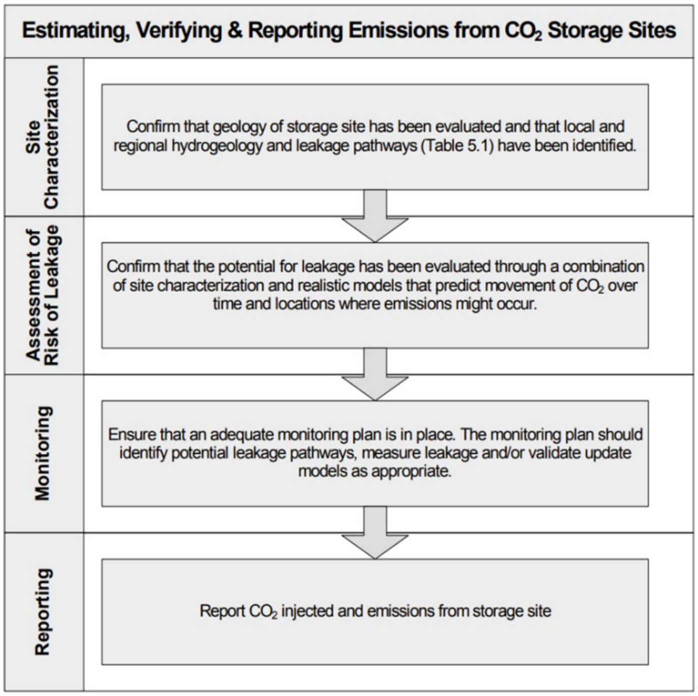


Figure 17. General process for estimating emissions from CO_2 storage sites. Figure reproduced from [259].

5.2 Description of Monitoring Techniques for Mineralization Storage

Diverse monitoring techniques exist to address specific monitoring and regulatory requirements throughout the duration of a CO_2 mineralization project (i.e., for site characterization, pre-injection, injection, and post-injection phases). For mafic-ultramafic reservoirs, monitoring techniques that are relevant to CO_2 storage in sedimentary reservoirs could, in some cases, be applicable. Unique monitoring to capture signatures of geochemical reactions are needed to measure and validate mineralization, as well as demonstrate the absence of leakage. As shown in **Table 15**, a number of techniques can be used to directly and indirectly monitor injected CO_2 in the subsurface.[199] The applicability and sensitivity of these techniques may be site specific as well as specific to certain injection strategies. In general, most techniques are suitable for proving secure storage and can be matrixed into monitoring plans suited to in situ mineralization. The following discussion is framed around a non-exhaustive selection of various relevant monitoring techniques for CO_2 storage in mafic-ultramafic rocks.

Fluid Geochemistry. Monitoring of fluid geochemistry evolution during CO_2 mineral storage is an essential tool to assess trapping security and identify leakage. Establishing a well-distributed baseline fluid geochemistry dataset across the storage field (including injection zone(s), confining zone(s), and potable water sources) is necessary to accomplish both purposes—and typically required in established regulatory frameworks. Sampling of groundwater from injection zones, above zone aquifers, and potable water aquifers can monitor CO_2 migration and carbonate precipitation through changes in pH, salinity, quality/chemical composition, and concentrations of dissolved inorganic/organic carbon (DIC/DOC), divalent cations (e.g., Ca^{2+}, Mg^{2+}, Fe^{2+}), and other major ions. Other parameters like baseline isotopic ratios, minor ions, and microbial content are important for isotopic tracer tests (see below), assessing contamination via trace metals (see Section 4.2), and changes to organic carbon.[200, 202] The same indicators can be used to detect potential leakage into overlying aquifers, so long as well-established baseline formation fluid chemistry is available.[265] Changes in DIC, DOC, salinity, pH, and quality/chemical composition of potable water sources outside of the storage formation—and in the absence of alternative natural sources (e.g., volcanic degassing)—may be indicative of potential leakage of CO_2 and/or brine. Fluid geochemistry datasets serve a valuable function for monitoring throughout all phases of a project, but particularly for developing reactive transport simulations to predict mineralization and to identify leakage. Collecting fluid samples in situ may even provide valuable evidence of mineralization on downhole sampling equipment.[4]

Rock Characterization. Acquiring whole rock geochemistry, petrophysical, and geomechanical data for mafic-ultramafic storage reservoirs and overlying seals is necessary for development of a site-specific monitoring plan, reactive transport simulation, and assessment of mineral trapping. In addition to being a standard regulatory requirement, acquiring representative samples (e.g., cuttings, sidewall core, slimhole core) of both the injection and confining zone will support validation of logging data, reservoir calibration, and geochemical assessment. This includes measurements of porosity, effective porosity, and permeability to ensure the capacity of the injection zone to store the CO_2 and for the confining zone to contain the CO_2. Additional focus should be placed on adequately characterizing reactive surface area and geochemical characterization (e.g., baseline mineralogy cation availability, and reactivity under expected injection conditions) to estimate mineralization potential and parameterize reactive transport simulations. Standard measurement procedures like X-ray diffraction, X-ray fluorescence, scanning electron microscopy with energy dispersive X-ray spectroscopy, electron probe microanalysis, and thermogravimetric analysis with mass spectrometry[266] are useful characterization methods for establishing divalent cation availability for mineralization. As a tool for monitoring during post-injection site closure, collecting samples from the injection zone that confirm mineralization is occurring provide valuable evidence that may inform closure and transfer of liability.

Table 15. Summary of possible monitoring techniques for CO_2 storage in mafic-ultramafic reservoirs. Modified from [199].

Measurement category	Measured parameters	Example applications
Fluid geochemistry	Dissolved inorganic carbon (DIC): CO_2, HCO_3^-, CO_3^{2-}	Quantifying CO_2 dissolution (solubility trapping) and mineralization (mineral trapping)
	pH	Detecting presence of dissolved CO_2 and quantifying dissolution and mineralization reactions
	Non-reactive tracers	Tracking CO_2 and/or fluid travel times and migration in the storage reservoir
	Major ions	Quantifying CO_2-water-rock interactions
	Isotope tracers	Quantifying CO_2 dissolution (solubility trapping), mineralization (mineral trapping), and biogeochemical reactions
	Trace elements	Detecting leakage into shallow groundwater aquifers, contamination identification
	Salinity	Detecting leakage into shallow groundwater aquifers
Rock Characterization	Reservoir parameters (porosity, effective porosity, permeability, etc.)	Establishing integrity of reservoir and confining zone, parameterizing models
	Geochemical parameters (mineralogy, cation availability, etc.)	Establishing mineralization capacity of reservoir, parameterizing models
Subsurface pressure	Formation pressure	Ensure formation pressure remains below the fracture pressure
	Annulus pressure	Assessing wellbore and injection tube condition
	Groundwater aquifer pressure	Detecting leakage from the storage formation
Well logs	Brine salinity	Tracking CO_2 movement in and above the storage formation
	Resistivity	Tracking the migration of reservoir fluid into shallow aquifers
	Sonic velocity	Calibrating seismic velocities for 3D seismic surveys
	CO_2 saturation	Indicating CO_2 is being trapped residually
	Temperature	Tracking injected CO_2 through temperature differentials between the CO_2 and formation fluid
Time-lapse 3D seismic imaging	P- and S-wave velocities	Tracing free phase CO_2 movement in and above storage formation
	Reflection horizons	Fluid distribution in the storage formation
	Seismic amplitude attenuation	Detecting geomechanical changes
Passive seismic	Location, magnitude, and source of seismic events	Detect development of micro fractures in the formation or caprock
		Identification of reactivated faults or fractures which may act as CO_2 leakage paths
Time-lapse gravity measurements	Density changes caused by fluid displacements	Detecting free-phase CO_2 movement in or above the storage formation
		CO_2 mass balance in the subsurface
Surface deformation	Tilting	Detecting surface flux which may indicate geomechanical changes
	Vertical/horizontal displacement	Identification of CO_2 leakage paths
Soil gas sampling	Soil gas composition	Detecting elevated levels of CO_2
	Isotopic analysis of CO_2	Identifying the source of elevated gas in soil
	Infrared detectors	Evaluating ecological impacts

Tracer Tests. Reactive (e.g., ^{14}C) and nonreactive (e.g., SF_6) tracers can be added to injected CO_2 to deduce the amount of CO_2 stored through mineralization using mass balance calculation. [4, 267] Isotopic tracers (e.g., $\delta^{44/40}Ca$, $\delta^{13}C$, $\delta^{18}O$) can be used to track mineralization by comparing pre- and post-injection ratios because isotopes will fractionate between mineral (i.e., carbonate) and non-mineral (i.e., dissolved CO_2) phases in proportion with the extent of mineralization, which can be determined from reservoir fluid samples obtained from monitoring well(s).[2, 268] Purpose-built piston-type bailers have been built to facilitate sampling of CO_2- and tracer-rich fluids from the deep subsurface.[269]

Subsurface Pressure and Temperature. Variations in pressure may indicate CO_2 or brine movement in the subsurface and can be continuously monitored to validate reservoir models.[270] Pressure sensors in injection and monitoring wells—both within the injection zone, in confining zone(s), and at the surface—can inform whether there is pressure communication between the storage reservoir and overlying formations, indicating the potential for CO_2 plume and/or brine migration.[271] Temperature logging provides valuable information about mineralization conditions to parameterize reactive transport models and can support calibration of monitoring data based on temperature differences between injection and formation fluid.

Well Logs and Testing. Well logging suites acquired during drilling are typically deployed during the site characterization phase of any storage or drilling project. Wireline logging tools may also be used to assess injection wells during scheduled downtime for maintenance. Moreover, during the post-injection period, well logs can provide early detection of leaks through real-time data acquisition, identifying potential CO_2 leakage issues early and verify the continued integrity of storage. Well logging includes geological, geophysical, and engineering logs, and should be part of a monitoring plan from site characterization through site closure. Well logs measure physical properties of formations (**Table 16**). Detailed logging programs for checking wellbore integrity (i.e., through use of temperature log/sensor, oxygen activation log, caliper, etc.) should be conducted by the operator to protect formations, prevent unintended lateral migration in reservoirs, and ensure protection of potable water sources. In addition to well logging, well testing (i.e., hydraulic tests) provide valuable evidence of reservoir parameters and may be used to conduct pilot CO_2 injections to verify reactivity of the injection zone (e.g., via push-pull or small-scale injection).[5, 272]

Table 16. Examples of common logs used to characterize a carbon storage reservoir.

Log Type	Formation Characteristic
Gamma ray	Rock formations and their boundaries
Density	Porosity
Sonic	Identification of potential fractures
Electrical	Formation resistivity for fluid movement
Temperature	Detect changes in temperature (CO_2 migration)
Pressure	Pressure changes within the reservoir

Time-lapse 3D Seismic Imaging. Seismic imaging (i.e., 3D or 4D seismic) is a commonly used technology for imaging sedimentary storage reservoirs and injected $scCO_2$ plumes. In the site characterization phase, seismic may be a suitable tool for identifying reservoirs between seal formations through surficial or borehole imaging—particularly in homogenous eruptive settings like massive flood basalt provinces.[249, 273] 4D or time lapse seismic may be used to assess the extent of CO_2 injection, migration, leakage into overlying aquifers, and to validate modeled CO_2 plume predictions..[274, 275] Although seismic monitoring may be more difficult in mafic-ultramafic reservoirs compared to sedimentary reservoirs due to strong scattering caused by the impedance contrasts between basalt flows and sedimentary interbeds,[276] studies have shown that seismic imaging may be able to ascertain P- and S-wave velocity changes due to mineral precipitation and fluid replacement.[274, 275] However, the application of seismic imaging for monitoring depends on the injection method (i.e., CO_2(aq) vs. $scCO_2$ injection) since standard 2D/3D seismic surveys or vertical seismic profiles (VSP) cannot be applied to CO_2(aq) injections.[277] Seismic imaging to monitor CO_2(aq) injection may be useful to detect exsolution of CO_2 if free phase CO_2 saturation is above seismic resolution. Notably, time lapse seismic for mineralization storage has not been tested in the field and therefore applicability is largely theoretical. The efficacy of time lapse seismic to image injected CO_2 is likely to depend on 1) the thickness of injection zone, and 2) the extent of brine saturation/mineralization.

Passive Seismic Monitoring. Passive seismic monitoring is different than controlled-source techniques such as continuous recording and near real time data analysis. For example, passive seismic monitoring can only record events between where microseismic events are occurring and where receivers are located.[278] Passive seismic monitoring detects microseismic events induced in the reservoir by dynamic responses to the modification of pore pressures or the reactivation or creation of small fractures. Microseismic events are extremely small (i.e., <2.0 on the Richter scale), but monitoring these events may allow the tracking of pressure changes and, possibly, the movement of gas in the reservoir or saline formation.[199] This data will also be essential to capture possible induced seismicity correlated with injection activities (see Section 4.3).

Time-lapse Gravity Measurements – Magnetic & Gravity Methods. Carbonation and serpentinization reactions may be detectable through aeromagnetic or gravity surveys given the distinct changes in magnetic susceptibility and density induced by mineralization processes.[279] These approaches are particularly suited to identifying appropriate mineralization storage targets (i.e., through magnetic surveys of reactive ultramafic formations) during site characterization.

Surface Deformation. Interferometric synthetic aperture radar (InSAR) measurements of ground surface deformation can be used to estimate areas of pressure build-up.[280] Deformation monitoring is conducted using space-borne Differential Interferometric Synthetic Aperture Radar (DInSAR), capable of achieving millimeter precision and meter spatial resolution over the entire monitored area.[281] These monitoring techniques require a robust baseline dataset to differentiate between project-induced impacts and background natural variations (e.g., through volcanic activity, other subsurface activities).

Electrical Methods. Complex resistivity measurements in cross-well, inter-wellbore, surface, or integrated system arrangements can be used to monitor CO_2 leakage and geochemical transformations [282] by tracking changes in pH and bicarbonate-carbonic acid formation. This method may be able to identify mineral dissolution and ion exchange due to surface charge density changes and corresponding electrical phase decrease, thus provide a pathway to monitoring in situ mineralization. pH, bulk electrical conductivity, and bulk dielectric permittivity may also be used simultaneously as an approach to monitor CO_2 leakage in basalts.[283]

Atmospheric. Atmospheric monitoring of CO_2 storage is essential to ensure the safety of public health and the environment due to the significant risk associated with exposure to CO_2. Typical methods for CO_2 detection at the surface are often derived from techniques developed for studying the carbon cycle (e.g., infrared detectors).[178, 179] Soil gas and/or surface flux measurements are the standard approach to monitoring potential surficial leakage and require extensive baseline data for comparison.[284]

5.3 Summary of Monitoring and Regulatory Suitability

Geologic carbon storage projects require robust risk-based monitoring plans that encompass all periods of the project from site characterization and construction through the injection period and post-injection to ensure safety, permanence of storage, and regulatory compliance. Monitoring techniques implemented must measure CO_2 migration and containment in the injection zone, while identifying and measuring potential leakages into overlying aquifers, potable water sources, or to the surface. Various regulatory frameworks, such as the EPA UIC regulations in the U.S. and the EU CCS Directive dictate monitoring goals (as discussed in Section 5.1), without prescribing specific monitoring approaches. In this regard, a flexible, risk-based monitoring approach is outlined, that would be capable of addressing the large variability and site-specific nature of storage geology while focusing on techniques well-suited to mineralization storage.

For mafic-ultramafic reservoirs, monitoring technologies commonly used for other CO_2 storage reservoirs (e.g., sedimentary reservoirs) could, in some cases, be applicable. However, the complex, fractured, and heterogeneous nature of mafic-ultramafic formations, along with CO_2-fluid-rock interactions which drive mineral trapping, require tailored monitoring technologies to ensure storage security. Several promising testing and monitoring tools have been proposed, and some initially tested (e.g., in-zone fluid sampling, tracer tests, side-wall coring, geophysical testing, etc.), and from these, a fit-for-purpose monitoring program can be devised. The paucity of commercial scale mineralization storage projects, and, in general, the lack of mafic-ultramafic injection experience, warrants additional field work and research to evaluate the efficacy of monitoring techniques, especially for commercial-scale (e.g., >1 MMT per year) injections. Continued innovations in this field are essential to develop techniques that enhance the predictive understanding of storage security risks, ensuring regulatory compliance and public confidence in mineralization storage projects.

6 Global Regulations and Legal Barriers for CO_2 Storage

This section identifies and reviews global regulations for CO_2 mineralization (Section 6.1), regulatory considerations for the US EPA Class VI program (Section 6.2), EU Directive on Geologic Carbon Storage (2009/31/EC, known as the EU CCS Directive) and associated Guidance Documents (GDs) (Section 6.3), and an assessment of whether regulations or guidance for regulations are required moving forward (Section 6.4).

6.1 Global Regulations for CO_2 Mineralization

Regulatory frameworks for CO_2 storage are being developed around the globe in response to increased deployment of CCS and CDR to meet net-zero goals. Regulations exist at both the national and sub-national (i.e., state or provincial) level, with sub-national regulation largely following industry interest or development in that locality. As of 2022, more than 20 national and sub-national jurisdictions had developed CCS laws and regulations.[260] Where there is no CCS precedent, new regulatory and legal frameworks are being developed out of existing climate, injection, or other industrial waste management laws (e.g., Mexico's development of a regulatory framework for CCS[285]), or CCS provisions are being incorporated into existing petroleum-related or environmental legislation. In addition, international standards developed under the International Organization for Standard (ISO)[286] and others[287, 288] provide a baseline framework for CO_2 storage regardless of jurisdiction. Typically, CO_2 sequestration regulations are written to address geological sequestration in sedimentary reservoirs and provide very little guidance or requirements specific to in situ CO_2 mineralization. Aspects of CO_2 mineralization storage that differ from sedimentary storage, such as the need for robust geochemical characterization to understand reactivity potential and support reactive transport modeling, may not be adequately covered by existing regulatory frameworks. However, most regulations appear to be technology agnostic which may provide pathways for CO_2 storage in mafic-ultramafic rocks, if relevant site characterization, monitoring, and operational requirements are met. Examples of existing global regulatory frameworks issued between 2006–2024 are provided in **Table 17**, including the country, regulatory agency, regulation, and date issued.

Of the 21 different regulatory frameworks identified, only a handful (~3) of guidance and/or regulatory frameworks address in situ CO_2 mineralization. Although not legally binding, recent (July 2024) updates to the GDs of the EU CCS Directive[256] from the European Commission briefly recognize mineralization topics on CO_2 trapping, volume-area definition, containment requirements, and geochemical and geomechanical modeling and monitoring guidance. The Norwegian Offshore Directorate implemented regulations pertaining to subsea reservoirs on the continental shelf for storage of CO_2 in 2014; the regulation includes language specifying that geochemical data is required to support storage complex characterization and determine potential mineralization rates.[289] Operators are required to assess dynamic conditions such as reactive processes and changes in formation brine chemistry, pH, and mineral formation, supported by reactive modeling. The California Air Resources Board (CARB) Carbon Capture and Sequestration Protocol under the Low Carbon Fuel Standard (LCFS) was established in 2018 and discusses incorporation of reactive transport models which use mineral precipitation kinetics parameters to predict mineral precipitation and permeability impacts in storage formations where CO_2 injection may result in reactivity.[290] The U.S. EPA introduced a new underground injection

Table 17. Non-exhaustive list of non-binding global guidance, regulations, and frameworks that may apply to CO_2 sequestration.

Country	Regulatory Agency	Laws, Regulations, and Frameworks	Date	Ref
Australia	Department of Industry, Science and Resources	Offshore Petroleum and Greenhouse Gas Storage Act	2006	[292]
Australia	State of Victoria Minister for Resources in Victoria; Environmental Protection Agency	Greenhouse Gas Geological Sequestration Act 2008	2008	[293]
Australia	State of Queensland Minister for Resources and Critical Minerals	Greenhouse Gas Storage Act (GGS Act) 2009	2009	[294]
Australia	State of South Australia Department of Energy and Mining	Petroleum and Geothermal Energy (Energy Resources) Amendment Bill 2023	2023	[295]
Australia	State of Western Australia	Petroleum Legislation Amendment Bill 2023	2023	[296]
Australia	Australian Government Department of Climate Change, Energy	Offshore Petroleum and Greenhouse Gas Storage (Environment) Regulations 2023	2023	[297]
Brazil	Brazil Environment Committee National Agency of Petroleum, Gas and Biofuels (ANP)	Law No. 1425/2022	2023	[298, 299]
Canada	Province of Saskatchewan	Disposal and Injection Well Requirements, The Oil and Gas Conservation Act	2023	[300]
Canada	Province of British Columbia, British Columbia Energy Regulator	Natural Gas Development Statutes Amendment Act, 2015	2015	[301]
Canada	Province of Manitoba	The Captured Carbon Storage Act	2024	[302]
Canada	Province of Alberta, Alberta Energy Regulator	Mines and Minerals Act Carbon Capture and Storage Statutes Amendment Act, 2010	2010	[303] [304]
EU/EEA Member States	European Commission (EC)	Directive on Geologic Carbon Storage 2009/31/EC and Guidance Documents	2009, 2024	[256]
Indonesia	Ministry of Energy and Mineral Resources (MEMR)	Regulation Number 2 of 2023 (MEMR 2/2023)	2023	[305]
Indonesia	Ministry of Energy and Mineral Resources (MEMR)	Presidential Regulation No. 14 of 2024 on the Organization of CCS Activities	2024	[306]
Japan	Ministry of Economy, Trade, and Industry (METI)	CCUS Business Act	2024	[307]
Malaysia	State of Sarawak Administration	Land (Carbon Storage) Rules, 2022	2022	[308]
Norway	Norwegian Ministry of Energy, Norwegian Ministry of Climate and Environment, Norwegian Offshore Directorate	The Petroleum Act The Pollution Control Act Continental shelf storage of CO_2	2010 1981 2014	[289, 309, 310]
United Kingdom	Oil and Gas Authority (OGA)	The Energy Act of 2008	2010 2023	[291, 311]
United States	California Air Resources Board (CARB)	Carbon Capture and Sequestration Protocol Under the Low Carbon Fuel Standard	2018	[290]
United States	United States Environmental Protection Agency	Underground Injection Control Class VI Well Program; Guidance Documents	2010	[257, 258, 263, 312]
United States	United States Environmental Protection Agency	Greenhouse Gas Reporting Program (GHGRP Subpart RR)	2010	[263]

control well type (Class VI) in 2010 for dedicated (non-enhanced oil recovery) CO_2 injection.[291] Both the U.S. EPA Class VI ruling and associated Class VI GDs mention requirements to describe trapping mechanisms, including mineralization.

6.2 US EPA Class VI Program: Relevance to CO_2 Mineralization

The U.S. EPA Class VI Rule was issued in 2010—prior to any field injection of CO_2 for mineralization storage (e.g., CarbFix1 Pilot in 2012 and WBSP in 2013). At the time, the predominant method of geologic sequestration of CO_2 involved injecting $scCO_2$ into deep saline aquifers, oil and gas reservoirs, and unmineable coal seams. Basalt is mentioned several times in the U.S. EPA Class VI guidance documentation in the context of storage capacity estimation, mineralogy as it relates to geologic storage reactivity, secondary porosity from fractures, and challenges related to seismic imaging. Mineralization can be applied as a storage approach in Class VI permits if performance of CO_2 storage can be justified based on the regulatory framework. However, prescriptive requirements or considerations for mineralization storage projects are not provided.

The U.S. EPA Class VI program focuses primarily on protection of USDWs in accordance with the Safe Drinking Water Act (SDWA). There are no specific mineralization requirements, except as required to assess the compatibility of the CO_2 injection stream with fluids/minerals in the injection and confining zone(s) (§146.82.c.3). As outlined in the U.S. EPA Class VI Well Site Characterization Guidance, geochemical modeling is strongly encouraged to evaluate potential reactivity within the storage complex. The guidance also discusses bench-top laboratory testing to simulate subsurface geochemical reactions using site-specific injection and confining zone core data, or samples with similar mineralogy where site-specific data is not available. If geochemical analysis (e.g., lab, modeling, literature) predicts significant mineral precipitation or dissolution, applicants are required to discuss reactive impacts to injectivity and containment. Mineralization projects may be eligible to receive reduced post-injection site care timeframes (default 50-yr) if they can effectively demonstrate to the Director that site-specific processes will result in CO_2 trapping via dissolution and mineralization (§146.93.c.1.iv and §146.93.c.1.v).

CO_2 mineralization storage projects include different approaches for characterization and monitoring. Challenges include: (1) tightly coupled reactive transport and flow modeling in fractured mafic-ultramafic rocks to predict the AoR, (2) reduced suitability of geophysical methods in mafic-ultramafic rocks, (3) well workover requirements to account for near-wellbore mineralization, (4) stimulation programs for mafic-ultramafic rocks with low porosity and permeability, (5) injection strategies not considered under the current EPA Class VI ruling, (6) stratigraphic test well requirements and appropriateness of designated testing requirements (e.g., additional core samples needed for carbonation experiments, applicability of specific wireline logging tools, etc.), and state-based permitting of wells, and (7) storage capacity calculations coupled to mineralization rates. Site characterization, injection, and monitoring requirements under the U.S. EPA Class VI ruling are informed by known risks associated with storing CO_2 in sedimentary formations; mineralization risks may require additional consideration and mitigation to comply with current regulatory frameworks.

6.3 EU CCS Directive and Guidance Documents: Relevance to CO_2 Mineralization

The European Commission released an update to its GDs on the CCS Directive, and specifically GD 2, in July 2024.[256] The update includes brief descriptive language for in situ mineralization, with most modifications being related to storage complex characterization, CO_2 stream composition, monitoring, and corrective measures. It also provides non-binding direction on the interpretation and implementation of the EU CCS Directive that is relevant to in situ CO_2 mineralization. These GDs also include a new section on evaluating storage capacity that is not specific to mineralization, and a new sub-section on evaluating legacy wells for site characterization (**Table 18**). Additional guidance is provided for topics related to CO_2 stream composition, depleted field storage, and induced seismicity. The EU CCS Directive GDs provide additional detail on trapping mechanisms, geomechanical characterization, legacy wells for site characterization, modelling contributions to uncertainty assessment, monitoring technologies, and planning. The updates to the GDs were largely made in response to advances and new activities in the European Economic Association (EEA), with a focus on removing ambiguity for new technologies, like in situ mineralization.[313] The GDs do not have a direct impact on operators unless EU Member States decide to directly implement guidance into their permitting frameworks.

The EU CCS Directive GD 2 contains language specifically for $CO_2(aq)$ injection mineralization storage on topics of storage site definition, geochemistry, geomechanics, $CO_2(aq)$ and CO_2 stream considerations, and monitoring (**Table 18**).[256] The GD reads that, "Mineralization projects have demonstrated that CO_2 can be stored safely provided all injected CO_2 is fully dissolved in water and maintained in dissolved form until CO_2 is mineralized through geochemical reactions with the host reservoir rock." The EU CCS Directive GD 2 notes geochemistry and geomechanics considerations of $CO_2(aq)$ moving in the subsurface or exsolving from solution, complicating hazards and CO_2 mineral formation. Language specific to $CO_2(aq)$ calls out that "ensuring the CO_2 remains dissolved in water is therefore essential to demonstrating containment." This requires "pressure and temperature monitoring of mineralization sites to ensure the CO_2 remains trapped in solution, unless a secondary (i.e., structural) trapping mechanism is also present."[256] The GD does not provide specific information about monitoring techniques for verifying the CO_2 remains dissolved until mineralization.

The European Commission's update to the CCS Directive GD 2 in July 2024 also includes non-binding guidance on caprock requirements for the storage complex (**Table 18**). Description of the CO_2 storage complex may include caprock, as well as seals, faults, facies changes, or other geologic features. In potential mineralization reservoirs where injected CO_2 is contained in the storage formation, per the non-binding guidance,[256] a caprock may not be required as part of the storage complex or in models of the storage complex. Models need to demonstrate that CO_2 will remain in the storage formation for the duration of the project (through post-closure) and does not lead to negative environmental effects. Ostensibly, the operator must demonstrate a caprock is 1) not required for ensuring CO_2 and CO_2-charged water stays within the storage complex and 2) does not leak into overlying drinking water formations or the atmosphere through reaction with the host rock to form stable carbonate minerals and/or 3) solubility trapping, as has been shown in field studies (see Section 2.3).

6.4 Summary and Recommendations to Global Regulations for CO_2 Storage

Currently, regulatory frameworks and guidance material specific to mineralization storage is sparse and, in most cases, non-existent. Establishment of legal and regulatory frameworks for CO_2

Table 18. Relevant language in the EU CCS GD 2, July 2024 for in situ CO_2 mineralization.[256]

Section	Topic	Non-Binding Language from the EU CCS Directive GD 2
Characterizing the storage complex and surrounding area	Storage site definition	"Caprocks and seals are not required components of the mineralization storage complex definition if it is demonstrated that they are not critical to ensure the containment of the injected CO_2 within the storage complex." (p. 14) "In these cases, the model(s) would need to provide sufficient evidence to demonstrate that the injected CO_2 remains in a non-free phase for the duration of the injection, closure, and post-closure periods and that pressures associated with the injection of CO_2 does not drive CO_2-bearing fluids to the atmosphere, the water column or to domains where negative effects to the environment may occur." (p. 30)
	Geochemistry	"Geochemical analysis can identify the propensity for mineralization reactions to take place, leading to mineral storage of CO_2. It may also identify the propensity of a geochemical system to result in precipitation of solids, which may be another indicator of mineral trapping or lead to a reduction in injectivity. A geochemical analysis may identify the likelihood of mobilization of other elements that could have site-specific environmental or health implications in the event of leakage." (p. 18) "Geochemical analysis and modeling will also help to identify capacity in systems that rely on geochemical interactions, such as mineralization projects." (p. 18) "The extent and nature of any geochemical changes that could occur will be site-specific and therefore appropriate sampling and assessment will need to be completed for each storage complex." (p. 18) "A geochemical analysis may include reactive transport modeling, reservoir simulation of pressure and temperature conditions, as well as chemical and mineralogical sampling of rock, reservoir fluids and injected fluids." (p. 18)
CO_2 composition	Aqueous CO_2 and CO_2 stream considerations	"Mineralization projects have demonstrated that CO_2 can be stored safely provided all injected CO_2 is fully dissolved in water and maintained in dissolved form until CO_2 is mineralized through geochemical reactions with the host reservoir rock. This typically involves injecting approximately 25 parts water per part CO_2 injected. 'Mineralization' CO_2 storage operations are also permissible under the CCS Directive since the water injected is not considered to be part of the CO_2 stream." (p. 36)
Monitoring	Mineralization sites	"Mineralization sites, for example, may require geochemical sampling and geochemical modelling to accurately evaluate containment and conformance." (p. 47)

mineralization storage in mafic-ultramafic reservoirs enables commercial scale-up and deployment of these technologies by providing oversight and stewardship of these activities that ensure safe, secure, and permanent CO_2 storage. Moreover, the frameworks being developed and implemented ensure the protection of the environment and public health, clarify the rights and responsibilities of stakeholders, and provide a legal foundation for the development, operation, and long-term management of CO_2 storage resources.[260] Furthermore, evaluating the regulatory landscape in the context of CO_2 storage mineralization provides an overview of the viability of implementing CO_2 storage in mafic-ultramafic reservoirs and identifies regulatory guidance or additions that may accelerate CO_2 mineralization project deployment.

The development of mineralization-specific guidance by the European Commission (Section 6.3) may benefit the commercialization and deployment of mineralization storage by clarifying key and distinct aspects of mineralization relative to traditional CCS in sedimentary reservoirs. In particular, the EU CCS GD 2 mentions the potential for assessing mineral storage potential using geochemical modeling, the definition of the storage complex with flexibility based on injection method (i.e., pure-phase vs. dissolved-phase CO_2), and monitoring requirements to prove mineralization.

This report highlights U.S. and EU frameworks and does not fully analyze the potential legal and regulatory barriers to CO_2 mineralization projects. Initial mineralization projects will test the pathways and barriers under differing regulatory frameworks and guidance. However, there could be opportunities to develop mineralization-specific guidance or incentives in future GDs and/or revisions. Guidance for regulators on the science of in situ mineralization could continue to leverage and engage expertise developed through federally funded research and development programs. Authorities that have not yet formalized their CCS regulatory framework with regard to mineralization, but have geologic potential for mineralization, could incorporate similar guidance, regulations, and technical learnings into their initial framework draft.

Establishment of legal and regulatory frameworks for CO_2 storage enables commercial scale-up and deployment of these technologies by providing oversight to ensure safe, secure, and permanent CO_2 storage. Moreover, these frameworks being developed and implemented ensure the protection of the environment and public health, clarify the rights and responsibilities of stakeholders, and provide a legal foundation for the development, operation, and long-term management of CO_2 storage resources. Furthermore, evaluating the regulatory landscape in the context of CO_2 storage in mafic-ultramafic formations provides insight into the technical and commercial viability of mineralization storage. The evaluation also enables identification of regulatory guidance or additions that may accelerate CO_2 mineralization project deployment. There are no current regulatory barriers to permitting mineralization projects under the predominant CCS regulations covered in this report, but there could be opportunities to develop mineralization-specific guidance or incentives in future regulatory documents and/or revisions. Guidance for regulators on the science of in situ mineralization could continue to leverage and engage expertise developed through relevant research and development programs.

7 Scale up and Cost Analysis

This section is dedicated to the evaluation of scale up challenges and considerations associated with in situ CO_2 storage via mineralization. These challenges encompass various aspects, including the assessment of geological and geochemical risk factors, logistical intricacies linked to the injection of significant fluid volumes (including volume requirements, fluid accessibility, subsurface constraints, and the implications of pressure dynamics, including injection pressure versus induced fracturing pressures), potential risks related to the contamination of potable water sources, energy demands, and a cost analysis of the major cost drivers for the development and operation of a commercial scale CO_2 storage facility. One aspect of this is evaluating the water requirements of different carbon storage mineralization injection strategies and approaches, given the reality that our carbon-constrained world is increasingly water-constrained, especially considering the feedback between CO_2, climate, and water availability. Any scale up approach with any form of geologic CCS will entail different challenges and risks that are specific to the geology, geochemistry, and geography of the location. This analysis of costs and challenges presents a broad overview mineralization focused carbon storage, but all individual scale ups will encounter their own specific opportunities, challenges, and costs.

The two sub-sections—Scale Up Challenges and Cost and Resource Requirements for Scaling Up—within this section provide a summary of scaling up CO_2 storage efforts within the context of mafic-ultramafic geological formations. The insights and findings derived from this assessment are integrated to highlight considerations and challenges associated with the expansion of in situ CO_2 mineralization storage operations.

7.1 Scale Up Challenges

Based on published literature, we identify and compile a set of technical challenges and considerations associated with scaling up mineralization-based carbon storage projects from pilot to commercial scale. A compiled list segmented into broader categories is presented in **Table 19**.

Geomechanical Implications. Geomechanical risks associated with injection of large volumes of aqueous dissolved or $scCO_2$ in mafic-ultramafic reservoirs are essential considerations for maintaining seal integrity and ensuring long-term storage security.[59, 314-316] The major geomechanical concerns during the scale up of CO_2 storage are the development of potential leakage pathways and induced seismicity.[317] Prior to injection operations, a comprehensive understanding of the site geology must be acquired, including detailed wireline logging and hydrologic testing to determine key geophysical parameters which can be incorporated to develop robust geologic models that enable the assessment of geomechanical risks, such as the presence of critically stressed faults. Here, delineating lateral continuity of the injection formation and the caprock is an important outcome of the initial assessment. A caprock is defined as a relatively impermeable rock that forms a barrier for vertical fluid migration. For example, in layered mafic formations, dense flow interiors can act as caprocks. This delineation is even more important for ultramafic formations that may lack similar lateral continuity for the caprock. The state of stress in both reservoir and caprock is another key factor, as it influences fracture behavior and propagation, and is influenced by both geological history and mechanical properties.[318-320] Hydraulic fracturing and hydraulic tests on pre-existing fractures must be conducted to determine the magnitude and orientation of principal stresses. Additionally, the presence of natural fractures can significantly impact the direction of fracture propagation for induced fractures. These insights, when coupled with geomechanical modeling, can provide a predictive understanding of the changes in stresses and rock properties as a result of CO_2 injection and can be utilized to mitigate geomechanical risk factors by optimizing site-specific CO_2 injection strategies. This could include the addition of production wells to modulate pore-space pressure, or the selection of optimal injection rates and strategies as shown in **Figure 7**.

Table 19. Key challenges for the scale up of in situ CO_2 storage via mineralization.

Scale Up Challenges	
Geomechanical	Fluid pressure build up at borehole (*Section 4.3*)
	Caprock integrity
	Natural and induced fracture network characterization
	Fault characterization and modeling transmissibility
	Seismic risks and data acquisition
Geochemical	Compatibility of CO_2 stream (pure vs impure) with formation brine and mafic-ultramafic host rock
	Pore clogging and permeability challenges from formation of clays/secondary minerals
	Water contamination concerns (*Section 4.2*)
Pore Space Management	Delineating pore space rights
	Basin-scale pressure interaction management
Public Perception	Induced seismicity concerns (*Section 4.3*)
	CO_2 pipeline and land rights
	CO_2 leakage and aquifer (USDW) protection concerns (*Section 4.2*)
Logistical and Technoeconomic	Water resource availability
	CO_2 availability and transport infrastructure
	Reactive transport modeling at basin scale and estimation of storage potential (*Section 2.2*)
	Monitoring, reporting, and verification (*Section 5.1)*

Geochemical Risks. As CO_2 storage is scaled up, there are several geochemical risk factors that need to be considered, such as caprock integrity, reservoir property changes, contaminant mobilization, and uncertainties with reaction rates.[314, 321] Specifically, for a $scCO_2$-based injection strategy, physical trapping mechanisms play an important role that allow for mineralization processes to occur over time. While in many cases, the interaction of CO_2 with the porous reservoir is well-studied, it is also important to delineate CO_2-brine-rock interactions with respect to the caprock, to prevent caprock failure over time.[322] The current state of practice for modeling fluid flow in fractured media is still under development and likely presents a geochemical and geomechanical risk.[82, 323] Another important factor to consider is the possibility for permeability reduction via pore clogging with time, resulting in lowered injectivity. This could be a result of the precipitation of carbonates and secondary minerals, such as clays, during injection, which is much more prevalent in mafic-ultramafic settings. Additionally, the possibility for salt precipitation near the wellbore during large volumes of dry $scCO_2$ injection[324, 325] must be considered and mitigated with altered injection strategies (e.g., WAG). Based on post-injection characterization efforts, no evidence of porosity or permeability reduction was observed at the Wallula pilot-scale injection.[5, 9, 326] Similarly, CarbFix2 found no evidence for permeability reduction.[49] Intermittent clogging of the injection well at CarbFix1 was observed where a drop in transmissivity was attributed to FeS precipitation and associated bacterial bloom blocked fluid flow paths near the injection well.[200, 203] Importantly, all field-scale demonstrations thus far have been small scale (**Table 5**) relative compared to planned commercial scale efforts (**Table 6**). Moreover, performing numerical simulations to understand the rates of formation of secondary minerals and to model flow characteristics, can be used to delineate changes in permeability over time. In addition to chemical processes, microbial growth as a result of impurities in CO_2 stream (e.g., O_2) may lead to injection well blockages and reduce overall injectivity over time.[327] Microbial conversion of CO_2 to CH_4 (methane) may also have significant impacts to storage potential, security, and injectivity.[3, 198, 200, 202, 327, 328]. Another important factor to consider is the potential for contaminant mobilization during CO_2 injection.[232-235] Development of leakage pathways into shallow aquifers (USDW) could release potential contaminants into groundwater sources and should be carefully considered during site selection and risk evaluation.[329] This aspect is described in detail in Section 4.2. For further review of changes in reactivity in mafic-ultramafic reservoirs, please see Section 3.2.

Public Perception. Successful clean energy projects globally have highlighted the importance of early, transparent, and open public participation, and community support. Numerous instances around the world have highlighted that inadequate community engagement can hinder energy deployment. Safety and environmental impact aspects specific to carbon storage, such as induced seismicity, aquifer contamination, pipeline failure, and gas leakage are some key areas for engagement. At this point in time, it is difficult to verify conformance and containment in mafic-ultramafic rocks (see Section 5 for further discussion). Additionally, construction of commercial scale carbon management infrastructure (e.g., pipelines) on private property comes with permitting and community opposition risks. These reservations are not insurmountable obstacles but opportunities for fostering innovation and economic growth (see Section 8).

Logistical and Technoeconomic Challenges. Developing an economical source-to-sink framework is key to any CCS deployment. An important consideration in the CCS supply chain is the development of a sustainable CO_2 transportation framework that will ensure a constant supply of CO_2 at scale for subsurface storage.[330] Onshore CO_2 storage efforts are likely to leverage pipeline-based transport to minimize additional environmental impacts due to vehicular emissions. Additionally, stranded sources could be serviced by trucks, train, or shipping linked to a pipeline network. However, there would be a requirement to understand the emissions related to the transport system so that there can be effective carbon accounting. In Europe, large-scale pipeline-based CO_2 transport infrastructure is still in its very early stages. In this regard, the US has an extensive CO_2 pipeline transport infrastructure primarily geared towards enhanced oil recovery (EOR), which could be repurposed for geologic storage in sedimentary formations. Currently, the U.S. has a total of 5200 miles of pipeline infrastructure, capable of transporting up to 66 MMT per annum of liquid CO_2, with an additional 4000 miles of pipeline development in planning stages. However, no pipeline infrastructure currently exists for CO_2 transport to mafic-ultramafic storage sites. Conventionally, mafic-ultramafic storage sites are not close to areas that contain extensive pipeline infrastructure compared to that which is typically found in oil and gas operations. Another consideration is the availability of freshwater resources for an aqueous dissolved CO_2 injection strategy. In an increasingly water-constrained world, acquiring large volumes of freshwater may be a significant challenge depending upon the location. Additionally, transporting large volumes of water, fresh or saline, would involve significant investments, making the technoeconomics of CCS deployment inefficient. Moreover, aqueous injection of CO_2 would require a significantly larger investment in well infrastructure and space requirements compared to $scCO_2$ injection[223] (e.g., 1 Gt CO_2 injection would require 26 Gt of injected $CO_2(aq)$ compared to 1 Gt for $scCO_2$). This aspect is discussed further in Section 7.2. Lastly, the implementation of adequate monitoring, reporting, and verification protocols is a key factor for large-scale carbon storage projects. This enables the creation of a transparent system for communicating data related to storage efficiency, and environmental impacts, thus developing community and stakeholder trust (see Section 5).

7.2 Cost and Resource Requirements for Scale up

This section presents an analysis of cost and resource requirements to scale up carbon storage in mafic-ultramafic reservoirs. We discuss the collection, evaluation, and ranking of scale up challenges associated with CO_2 storage. We also analyze resource requirements for multiple injection strategies ($CO_2(aq)$ vs $scCO_2$) at a commercial scale and provide a preliminary cost analysis. A summarization of findings is presented in **Table 20**.

Table 20. Summary of Cost and Resource Requirements for Scale Up

Primary Drivers for Cost and Resource Requirements	
Energy usage	- OPEX-compression, injection, and monitoring - CAPEX-Infrastructure development
Well Construction	- Drilling a single onshore injection well can range between USD 1 million to USD 10 million
Water Consumption	- Aqueous dissolved CO_2 injection requires ~25 tons of fresh water per ton CO_2 injected - CAPEX costs would be the water required for drilling purposes
Regulatory and Permitting	- Permit acquisition is estimated to be between USD 100,000 to USD 500,000[331] - Ongoing compliance monitoring involves regular inspections and reporting
Land and Pore Space Considerations	- Land acquisition for injection and MRV - Pore space ownership compensation USD 15/acre to USD 155/acre

To date, Carbfix (in Iceland) runs the only actively-injecting, commercial carbon mineralization enterprise across multiple facilities. In the context of other CO_2 storage operations (Sleipner, Snohvit, Decatur, Gorgon), Carbfix's average of 12,500 MT per year since 2014[332] is less than these operations and the >3 MMT per year[119] buildout projected. This scarcity of field data for commercial scale efforts introduces uncertainties in the costs to upscale carbon storage efforts. From 2018 to 2019, the average estimated cost of $CO_2(aq)$ storage in mafic reservoirs ranged between USD10/tCO_2 to USD25/tCO_2.[97, 314, 333] Additional costs including site characterization, adjustments for inflation, resource availability, source-sink matching, transport infrastructure, and monitoring needs are not including in this cost range. Although not an exhaustive list, we outline below the most significant factors affecting scale up costs.

Energy Costs. Primary capital expenditure (CAPEX) energy costs are related to development of infrastructure. This would primarily include costs associated with drilling wells (detailed below), water processing facilities, pipeline infrastructure, and facilities for CO_2 compression, and injection. Primary operational energy requirements can vary significantly based on the injection strategy (**Figure 7**), implementation, and location. For example, for supercritical phase injection, energy requirements for CO_2 compression/pumping would depend on the depth of injection and the injectivity of the reservoir. Estimates for levelized costs (including capital, power, power source, and maintenance) ranged between USD8/tCO_2 to USD15/tCO_2 in 2006 for scCO_2 depending on the final pressure and the mass flow rate of CO_2.[334] On the other hand, gas compression is not likely to be a significant energy requirement for an CO_2(aq) approach, however, water requirements will dominate energy costs in this scenario, as detailed below. Operational costs (OPEX), including energy usage, would also entail the cost of monitoring throughout the injection period, as well as post-injection. This is likely to require substantial resources as it involves the use of advanced technologies such as seismic surveys, satellite imaging, and ground-based sensors (refer to Section 6 for more details), and these costs will depend on the monitoring technique used.[335]

Well Construction. The cost of drilling makes up the large majority of well construction CAPEX costs for injection and monitoring wells. Drilling costs vary significantly depending on the geology, location (e.g., onshore vs offshore), injection technique, material selection, depth, and existing infrastructure. Drilling expenses in hard rock, such as mafic-ultramafic formations, may be higher than those of sedimentary formations.[231] Such formations often require specialized drilling techniques such as diamond core drilling or down-the-hole hammer drilling, with the need to frequently replace drill bits, therefore adding to the cost. Other primary cost components include the construction of corrosion resistant tubing/casing, CO_2-resistant cement, well-head pumps, and control equipment. Overall, the average cost of drilling a single onshore well can range between USD 1 million to USD 10 million.[333] Combined with the requirement for multiple injection wells and several monitoring or pressure management wells per storage site, the total well construction capital costs can be on the order of tens to hundreds of millions, depending on the scale of injection (e.g., the number, type, and spacing wells).

Water Consumption. The availability of water resources becomes an important factor to consider for in situ CO_2 mineralization storage, specifically for CO_2(aq) injection. For example, aqueous injection by Carbfix at Hellisheiði requires approximately 25 tons of water (condensate from the geothermal plant) per ton CO_2 injected.[4] Recent water usage estimates from the Coda Terminal in Iceland state that approximately 3000 liters per second (greater than 1.63 million barrels per day) will be required for a 3 MMT/year CO_2 injection scenario.[336] For context, BP's largest offshore oil project (Thunder Horse) processes 140,000 barrels of water per day, ~12 times less than the amount of water required for Coda Terminal. While CO_2(aq) may offer additional leakage security, acquiring, transporting, and pumping such large volumes of water will incur significant costs through the duration of the injection period. Production of brine from target injection formations and its reinjection could be a potential strategy to alleviate the need to source enormous amounts of freshwater, however, no published literature exists demonstrating this at a commercial scale. Alternatively, ongoing efforts to use seawater-dissolved CO_2 are being carried out by Carbfix, as part of their CO2Seastone project located in Helguvik, Iceland.[103] In addition to OPEX energy requirements, water resource availability is also a consideration for CAPEX costs, particularly during drilling in mafic-ultramafic reservoirs.

Regulatory and Permitting. Although there are gaps and uncertainties in regulatory frameworks for in situ mineralization, compliance with regulatory requirements is a critical component of any field-scale geologic carbon storage effort. The cost of obtaining permits can vary based on the respective regulatory framework and complexity of the project. For example, in the US, the combined cost of obtaining a Class VI well permit and an environmental impact assessment can range between USD100,000 to USD500,000 for initial CAPEX costs.[331] Additionally, ongoing compliance monitoring involves regular inspections and reporting that can add to OPEX costs for any type of geologic storage effort.

Land and Pore Space Considerations. In order to establish a commercial scale geologic carbon sequestration project, costs related to both above ground and below ground factors must be taken into consideration. For example, land will need to be acquired to accommodate the array of injection and monitoring wells in the area, as well as hosting compression and processing facilities.[337] However, the amount of area required below ground would be significantly larger than the above ground features. For $scCO_2$ injection in mafic-ultramafic reservoirs, the amount of pore space required will be similar to conventional storage and would likely be much lower as compared to $CO_2(aq)$.[338] The cost of land will vary based on the location, size, and existing land use. For example, in the US, landowner compensation could range between USD15/acre and USD155/acre.[339] Costs associated with pore space utilization tend to be less well defined, particularly for mineralization-based carbon storage applications. In many cases (including in the US), pore space ownership correlates with surface ownership, which can significantly elevate costs of carbon storage given several tens of thousands of acres in the subsurface would generally be required for commercial scale carbon storage.[340]

7.3 Summary of Scale Up and Cost Analysis

In summary, scaling up CO_2 storage via mineralization in mafic-ultramafic formations poses several unique challenges. Particularly important are those that directly or indirectly impact the local communities and economies near the project sites. These include, but are not limited to, ramifications due to potential CO_2 leakage scenarios, groundwater contamination, and induced seismicity (see Section 4 for subsurface risk evaluation). It is therefore important to model and understand the possibilities for such incidents and provide measures for mitigation prior to the commencement of CO_2 injection at scale. Scaling up geologic carbon storage also introduces specific geochemical challenges, including loss of permeability leading to lower injectivity, and the uncertainties associated with reaction rates at the field scale. A thorough technical and economical assessment of the complete CCS supply chain, including transport of CO_2 from source to sink, is also important for the success of a project. In many cases, the source and sink may be located in different countries (e.g., Northern Lights in Norway, which accepts and stores CO_2 from other countries). Lastly, it is of paramount importance to have early and transparent engagement with local communities and stakeholders to understand and address specific concerns related to the transport and storage of CO_2.

8 Challenges and Opportunities for CO_2 Storage in Mafic-Ultramafic Reservoirs

This section summarizes and assesses the documented advantages and disadvantages associated with the utilization of mafic-ultramafic rocks as geological reservoirs for CO_2 storage. Additionally, we summarize strategies for minimizing and effectively mitigating the inherent risks linked to CO_2 storage in geologic formations, and those unique to mafic-ultramafic rocks. By comparing benefits and drawbacks of CO_2 storage in mafic-ultramafic rocks while addressing overall risk management, we examine the overall potential for CO_2 storage in mafic-ultramafic reservoirs to scale-up and become a significant component of future global CO_2 storage strategy. Key technical challenges and opportunities for mineralization in mafic-ultramafic rocks can be broken down into project activities that impact cost or feasibility. The main technical challenges and opportunities for in situ mineralization are summarized in **Table 21**. These include revenue streams; mineralization rates; injection/storage field development; upstream processes; site characterization; mineralization measurement, reporting, and verification (MRV); and CO_2 transport. For each technical challenge, there is an associated risk placed on the challenge's expected impact to scale-up, and a mitigation potential assessed for the opportunity for innovations to mitigate that risk. These forward-looking statements are not all-encompassing and do not necessarily reflect near-term opportunities, but general opportunities for the broader mineral storage sector in the long-term. The end of Section 8 summarizes these challenges and opportunities.

8.1 Revenue Streams

Challenges. For all projects solely focused on storing CO_2, business models rely primarily on revenue from carbon credits generated under compliance (e.g., EU Emissions Trading System (ETS)) or voluntary carbon market (VCM) schemes and policy incentives such as the U.S. IRS Section 45Q tax credit. This reliance on policy incentives or voluntary markets creates long-term uncertainty and risk for development of any CO_2 storage project, where shifts in policy or market perception of the need for CO_2 storage could mothball projects that may already face low margins from subsidies and high risks during development. Because CO_2 storage projects are inherently long-term and high capital expense projects, stable financing mechanisms are needed for successful scale-up. In the absence of a carbon tax/accepted social cost of carbon emissions, carbon storage would require additional revenue from co-production of a beneficial product. However, these challenges are not unique to mineralization storage. For example, CO_2-EOR has enabled CCS for the past 50 years, but dedicated storage did not develop until more recently. Therefore, we assign these challenges a high risk, because under current policy and market structures, there is no universal "product" from CO_2 storage, except the value placed on it for climate change mitigation.

Table 21. Summary of technical challenges and opportunities for in situ mineralization and associated risk and mitigation assessment. The risk assessment is tied to the 'challenge' described and reflects the risk it may present to scale up, and the mitigation potential refers to the likelihood of the 'opportunity' described in mitigating that challenge. Both risk and mitigation potential assessments are ranked qualitatively as Low, Med, or High.

Challenges and Opportunities	Description of Challenge and Opportunity	Risk	Mitigation Potential
Revenue Streams	**Challenge:** CO_2 storage business models rely heavily on policy incentives like the U.S. IRS 45Q tax credit, and voluntary or compliance carbon markets (e.g., VCM or EU ETS). **Opportunity:** Innovations to co-produce subsurface resources, energy, or other revenue streams to supplement CO_2 storage incentives (e.g., CO_2 enhanced critical mineral recovery (CO_2-EMR), producing subsurface fluids for pressure management/critical mineral extraction from brines/formation water).	**High**	**High**
Mineralization Rates	**Challenge:** Mineralization rates may vary from expected: ultramafic rocks > mafic rocks > intermediate/felsic rocks > sedimentary/metamorphic rocks. **Opportunity:** Enhancing reactivity or mineralization rates through use of pre-treatments, catalysts, and biological additives to injection fluid. Development of catalysts to make non-reactive rocks reactive or as emergency remediation for leakage.	**Low**	**Med**
Injection/Storage Field Development	**Challenge:** Hard-rock drilling challenges (e.g., rate of penetration, fluid losses, drill bit sticking) may increase costs. Commercial-scale operations may require pressure management, pore space optimization, and more wells to mitigate loss of injectivity. Induced seismicity due to injection volumes may also cause public perception risks in addition to realized hazards. **Opportunity:** Technologies designed to optimize per well injection capacity (e.g., WAG, microemulsion) may reduce operational costs. Transfer of learnings from other hard-rock drilling industries (e.g., mining, geothermal) may decrease drilling/field development costs.	**Med**	**Med**
Upstream Processes	**Challenge:** Energy consumption for capture and conditioning may reduce net carbon emission removal/reduction. High water requirements for $CO_2(aq)$ injection may reduce scale up potential in water limited regions. **Opportunity:** Innovations to integrate capture with injection (e.g., use of downhole dissolution/mixing) may reduce energy consumption. Re-use of produced water, seawater, or brine from other sources may reduce freshwater requirements (for $CO_2(aq)$ injection) and water costs.	**Low**	**Low**
Site Characterization	**Challenge:** Traditional site characterization techniques (e.g., seismic) may be more challenging for mafic-ultramafic reservoirs. **Opportunity:** Developing characterization methods well-suited to these lithologies can reduce characterization cost; establishment of baseline mineralization capacity in key target reservoirs can improve characterization.	**High**	**High**
Mineralization MRV	**Challenge:** Some MRV techniques used in sedimentary basins may not be appropriate for monitoring phase changes or dissolved CO_2, while direct sensing of mineral trapping may be costly (i.e., core retrieval) or reliant on modeling. Difficulty monitoring loss of containment (leakage) of dissolved CO_2 with existing methods may increase costs for monitoring. **Opportunity:** Application of existing technologies (e.g., seismic, gravity, aqueous geochemistry) with new interpretation, modeling, or processing methods to verify mineralization. Significant opportunity to reduce post-injection site care monitoring timeframe.	**Low**	**Med**
CO_2 Transport	**Challenge:** Transport costs are relatively constrained, while public perception of common transport methods (i.e., CO_2 pipeline) may limit scale-up. **Opportunity:** Optimal siting of CO_2 sources (or DAC) with high-potential mineralization sites can reduce transport costs, while co-location with clean energy sources (e.g., geothermal/BECCS) may encourage deployment.	**Low**	**Low**

Opportunities. Diversification of revenue streams through delivery of co-products or co-benefits may provide an opportunity to reduce the overall cost of in situ mineralization, or even provide a pathway to generate profit. Injection of CO_2 into reactive mafic-ultramafic formations for in situ mineralization could produce economically viable quantities of critical minerals, extracted through monitoring or production wells to produce fluids for surface critical mineral extraction. In situ solution mining using CO_2 may be able to offset most of the cost of CO_2 capture via enhanced recovery of critical minerals (i.e., Ni or Co from olivine).[33, 341-363] Given the demand for significantly greater production of critical minerals necessary for the clean energy transition,[364, 365] in situ mineralization combined with enhanced critical mineral recovery could drive greater adoption of mineralization storage as a more profitable alternative to standalone CO_2 storage in non-reactive formations. Unique storage field/reservoir development strategies including stacked storage reservoir utilization, cyclic injection into multiple reservoirs (i.e., injecting CO_2 for a period, then allowing time for dissolution and critical mineral separation to take place prior to production), and horizontal drilling could maximize the critical mineral recovery potential of this technology. In addition to producing revenue from sale of mineral resources, this method of in situ solution mining could reduce land use impacts and tailings waste from conventional mining techniques. Depending on the reservoir fluid chemistry, there may be additional opportunities to produce critical minerals out of formation brines produced to the surface for reservoir pressure management. Overall, we assign this set of opportunities a high potential to mitigate the risk associated with the previously described challenges.

8.2 Mineralization Rates

Challenges. In situ mineralization relies on engineering the natural reactivity of mafic-ultramafic rocks to enhance mineralization. While this mimics naturally occurring processes,[26, 223, 366, 367] mineralization rates in engineered systems may be different than expected (e.g., field heterogeneity, secondary mineralization) and cause problems for predicting mineralization extent, reservoir changes to porosity/permeability over time (e.g., clogging/cracking), and monitoring requirements. Moreover, mineralization rates vary significantly depending on rock type, even for igneous rocks. Reactivity trends for common rock types indicate ultramafic > mafic > intermediate/felsic > sedimentary/metamorphic rocks. However, mineralization rates in mafic-ultramafic rocks remain orders of magnitude faster than non-reactive sedimentary formations where the majority of CO_2 storage to date has taken place.[140, 224] While the rate of mineralization can impact the overall long-term post-injection site care and monitoring timeframes, the observed rapid mineralization will reduce the need for enhancing this rate further. Moreover, for both injection strategies utilized to date (i.e., $scCO_2$ and $CO_2(aq)$), secondary trapping mechanisms of structural and solubility trapping prevent the risk of relying solely on mineral trapping. Thus, we assign a low risk to these challenges because prior mineralization projects have indicated rapid mineralization into permanent carbonates in sub-decadal timeframes.[2, 4, 9, 87]

Opportunities. Enhancing reactivity or mineralization rates through use of pre-treatments, catalysts, and organic or inorganic additives to injection fluid may enhance reservoir dissolution rates, accelerate mineralization, improve reservoir management capabilities, or improve critical mineral recovery potential in mafic-ultramafic rocks. For example, extremophile microbes have shown promise as a potential additive that could accelerate mineralization timeframes from years to months or less. Specifically, recent advancements have identified microbes that may accelerate the conversion of CO_2 into carbonate minerals that could be catalytic under common in situ conditions (e.g., temperatures of 20 to 150 °C and pressures of 250 to 900 bar).[368] The inclusion of microbial or inorganic additives into a CO_2 injection strategy could enhance the rate of mineralization, providing pathways to more rapid permanent storage, leading to reduced post-injection site care requirements, reduced risk of leakage and CO_2 credit return, and increased public acceptance.[368] Furthermore, under certain conditions (e.g., WAG or enhanced critical mineral recovery), it may be desirable to accelerate mineralization in stages to increase control over reservoir dynamics in relation to injection timing. In addition, developing technologies such as catalysts or additives that provide the capability to 'induce' mineralization on demand could provide an extremely valuable remediation tool (e.g., if monitoring picks up a potential leakage event). Finally, development of techniques to 'pre-seed' non-reactive or low-reactivity reservoirs for mineralization could expand the reach of in situ mineralization beyond just mafic-ultramafic rocks (e.g., through co-injection of colloidal iron).[369-372] Overall, we assign this set of opportunities a medium potential to mitigate the risk associated with the previously described challenges.

8.3 Injection/Storage Field Development

Challenges. Key technical challenges for injection/storage field development of in situ mineralization in mafic-ultramafic rocks include hard-rock drilling challenges (e.g., slow rate of penetration (ROP), loss of circulation, drill bit sticking, etc.),[231] costs associated with commercial-scale injection (e.g., well construction/completion costs), and storage field development (e.g., scale-up of injection rates, monitoring well construction, reservoir pressure management, backup injection wells, etc.). In addition to challenges with economically drilling to total depth, completing the well (e.g., casing and cementing) may also require specific well construction requirements to reduce risk of corrosion that may increase cost (e.g., use of stainless steel for $CO_2(aq)$ injection). Spatial and temporal evolution of porosity, permeability, and fracture networks in the reservoir are also key concerns for mineralization projects, where dissolution and precipitation reactions may increase or decrease these key storage parameters during injection.[373, 374] Lack of subsurface exploration data and experience operating in these rock types may also hinder development rates and increase cost. Available data from similar industries may be regionally limted (e.g., geothermal) or proprietary (e.g., mining). This not only places a data constraint on site selection and characterization, but also an operational constraint on the drilling and wellfield services providers capable of operating in mafic-ultramafic rocks. While many of these challenges are not unique to CO_2 storage in mafic-ultramafic reservoirs (e.g., scale-up of injection rates, reservoir pressure management, well completion, etc.), challenges such as hard-rock drilling, operator experience, completion requirements tied to specific injection strategies (e.g., $CO_2(aq)$), and reservoir injectivity changes may be more challenging in mafic-ultramafic reservoirs. The individual risks associated with these challenges may also not be equivalent. For example, the risk associated with loss of containment (i.e., leakage) due to corrosion in the wellbore could lead to significant costs associated with stopping injection or permit revocation. On the other hand, risks associated with injectivity decline may be more easily mitigated through reservoir stimulation techniques.

Overall, the technical challenges associated with injection/storage field development create commercialization challenges that may pose risk to scale-up. Individual challenges presented here (i.e., drilling, completion, injectivity) may present different individual risks, but when combined with the lack of commercial experience developing and operating CO_2 storage in mafic-ultramafic rocks, we estimate these challenges may pose a medium risk to scale-up.

Opportunities. For in situ mineralization, technologies that can maximize the per well injection rate capacity (e.g., tons CO_2/well/year) such as the pilot-proven scCO_2 injection strategy[5] and novel strategies like WAG[133, 134] or microemulsion injections[138] may reduce capital costs associated with drilling more wells and operating costs associated with servicing a greater number of wells. Introducing nanoparticles into the injection fluid may also enhance the efficiency of CO_2 trapping and the solubility of CO_2 in the aqueous phase, leading to greater injection capacity for a single well and enhanced mineralization in the reservoir as more CO_2 could enter the aqueous phase and drive the dissolution-precipitation feedback cycle.[375] While hard-rock drilling brings unique challenges, there is opportunity to transfer industry knowledge and capabilities from other industries frequently operating in mafic-ultramafic rocks, such as the mining and geothermal industry[376], and potentially repurposing decommissioned exploration and production wells. For example, drilling for enhanced geothermal system development has utilized data-driven decision making to significantly improve drilling performance.[377] The learning-by-doing strategy can be combined with site-specific drilling optimization to significantly improve the drilling efficiency to reduce costs.[378] While porosity and permeability reduction is a key concern for storage field management, utilization of reservoir stimulation techniques developed in the oil & gas and geothermal industries could provide an opportunity to engineer suitable storage sites in any mafic-ultramafic formation.[379] Overall, we assign this set of opportunities a medium potential to mitigate the risk associated with the previously described challenges.

8.4 Upstream Processes

Challenges. Technical challenges for upstream processes such as CO_2 purification and compression vary depending on the injection method (i.e., scCO_2 vs. CO_2(aq)) and contents of the CO_2 stream (i.e., concentration of impurities like CO, O_2, SO_x, NO_x, H_2S, etc.), but generally focus on optimizing CO_2 capture for integration with injection systems to reduce energy and resource requirements. The net storage or removal efficiency (i.e., tons permanently stored/tons captured) declines when accounting for lifecycle greenhouse gas emissions (e.g., from energy or water usage), so reducing energy and other key process resource requirements is essential. Injection of impure CO_2 stream may also reduce mineralization efficiency or complicate storage field management by precipitating non-carbonate minerals in pore space and potentially clogging permeable pathways.[380] However, since typical upstream processes like purification and compression utilize relatively mature technologies, there is less room for optimization or innovation. Moreover, while these technical challenges still exist, they are not central to the risks associated with mineralization as a storage technology. Water availability, or lack thereof, also poses a potential challenge, especially for the CO_2(aq) method. As discussed previously, the higher water-to-CO_2 ratio needed for this injection method may limit the potential for Gt project scale up in water-limited locales. Thus, we estimate these challenges pose a low risk to scale-up.

Opportunities. Although upstream processes are a low-risk challenge, there are still opportunities for innovation that could reduce the energy or resource consumption upstream of the injection well. Cost reductions through strategic integration with CO_2 sources could drive down energy or water consumption costs depending on the injection method used and potential to utilize co-produced process water (e.g., subsurface brine, cooling water condensate, wastewater, or other water slated for subsurface injection). For example, designing injection systems—as done at CarbFix1/Orca in Iceland—that can be directly integrated with the CO_2 source (e.g., wellbore dissolution of CO_2 in water at depth prior to entering storage reservoir)[381] could reduce energy costs by leveraging the downhole pressure of the reservoir. In addition, in situ mineralization using $CO_2(aq)$ could integrate CO_2 absorption in water-scrubbing towers—as done at CarbFix2, Nesjavellir, and Mammoth—that utilize medium or low pressure to dissolve CO_2 for injection, reducing overall energy requirements for compression by avoiding the energy penalty of CO_2 compression.[382, 383] Additional innovation may focus on using seawater to dissolve CO_2 to reduce freshwater procurement costs.[384, 385] While utilization of seawater for aqueous-dissolved injections may clog pore space due to anhydrite precipitation at higher temperatures (>150 °C),[386] there is an opportunity to strip sulphate out of the seawater prior to injection, as practiced in the oil and gas industry.[387] However, this would not be an issue in most settings with average geothermal gradients. Similar to the challenge with utilizing seawater, impure CO_2 streams with co-contaminants like SO_x, NO_x, or H_2S may reduce the efficiency of carbon mineralization. However, opportunities exist to reduce the energy consumption of pre-treatments[388, 389] and co-inject impurities where additional mineralization of impurities (e.g., H_2S into FeS_2) may be a desirable co-benefit, or even the primary goal of the operation (i.e., sour gas disposal) given the high cost of sulfur removal which can exceed $300/ton.[97] Overall, we assign this set of opportunities a low potential to mitigate the risk associated with the previously described challenges.

8.5 Site Characterization

Challenges. Traditional site characterization techniques (e.g., seismic) may be more challenging for mafic-ultramafic formations. Additionally, well logging techniques optimized to characterize traditional sedimentary CO_2 storage formations may not be optimized for mafic-ultramafic rocks. Difficulty with site characterization and the lack of existing data (see Section 8.3) may require more stratigraphic wells to be drilled to collect the same quantity and quality of data that CO_2 storage projects in sedimentary reservoirs may have. Additionally, these formations are typically fractured which presents challenges for characterizing and modelling them as well as for identifying potential leakage pathways in the storage complex. Therefore, we estimate these challenges pose a high risk to scale-up.

Opportunities. Site characterization can reduce costs if more effective, rapid, and accurate methods of characterization are developed to target highly reactive formations with large storage capacities. Moreover, establishing baseline mineralization reservoir parameters from targeted exploration in high storage potential locations could accelerate parameterization of reservoir models. Collecting and benchmarking experimental data (e.g., dissolution rates, precipitation rates) to easily translate this data into reactive reservoir models could also support a streamlined modeling process for assessing mineral trapping. Development of new data collection techniques or interpretation methods specific to mafic-ultramafic rocks may reduce characterization uncertainty. For example, existing subsurface characterization techniques (e.g., seismic, gravity, magnetics) could be leveraged through new approaches [249, 279, 390, 391] that can overcome typical challenges with imaging mafic-ultramafic rocks.[276, 277] Prior work to establish seismic characteristics and best practices for interpretation of seismic data in basalts was gathered under the Big Sky Carbon Sequestration Partnership,[273] and many other characterization techniques (see Section 2.3) were employed in the CarbFix1/2 projects to assess mineralization security and storage.[4, 49, 105, 157] The learning-by-doing strategy invoked by the Wallula Basalt Pilot Project and CarbFix1/2 has already led to significant discoveries in site characterization techniques (e.g., seismic and geochemical characterization) well-suited to mineralization storage and future project experience can improve this further. Overall, we assign this set of opportunities a high potential to mitigate the risk associated with the previously described challenges.

8.6 Mineralization Monitoring, Reporting, and Verification (MRV)

Challenges. Some MRV techniques used in sedimentary basins may not be appropriate for monitoring phase changes or dissolved CO_2, while direct sensing of mineral trapping may be costly (i.e., core retrieval) or overly reliant on modeling. Relative to CO_2 storage projects in sedimentary or non-reactive reservoirs that do not require reactive transport modeling, in situ mineralization projects require reactive transport modeling to predict the extent and rate of mineral trapping. This may be timely, costly, and could place these projects at a competitive disadvantage to projects that only model stratigraphic, residual, or solubility trapping. Additionally, in fractured basalts and peridotites, fluid flow will be primarily influenced by fractures, and thus accurate modeling and characterization is necessary to properly understand the fate of injected CO_2. Although there are similar challenges for traditional CCS sites (i.e., leakage out of storage reservoir, groundwater contamination, trace metal mobilization, induced seismicity), rapid mineralization can largely reduce some of these risks—particularly over long-term operation. Thus, when considering the permanence and security provided by mineralization, we estimate these challenges pose only a low risk to scale-up.

Opportunities. In situ mineralization projects may find cost savings relative to traditional geologic CO_2 storage by reducing the footprint of the AoR due to comparatively rapid reactions and reducing the timeline of post-injection monitoring if mineralization can be accurately modeled and proven.[198] Verification of mineralization of injected CO_2 will require new modeling and sensing capabilities, building upon traditional geochemical monitoring most commonly used in mineralization pilot studies. Advanced remote sensing and geophysical monitoring technologies to track and characterize subsurface changes due to mineralization in real time could streamline MRV and reduce field sampling and monitoring well drilling costs. Methods may include development of additives to injection fluid that enhance geophysical signals received at surface (i.e., acoustic contrast nanofluid)[392] or processing techniques that can detect acute geophysical property changes due to mineralization (e.g., gravity inversion techniques that can pick up changes in layer density due to mineralizing a fraction of the formation porosity with a carbonate mineral of differing density).[197, 199] Overall, innovations that reduce MRV costs by minimizing operating and maintenance costs, increasing accuracy of mineralization monitoring, reducing timeframes for post-injection site care and monitoring, and developing remote or autonomous sensing protocols will reduce monitoring requirements and cost. Thus, we assign this set of opportunities a medium potential to mitigate the risk associated with the previously described challenges.

8.7 CO_2 Transport

Challenges. Transportation costs are challenging to reduce because of the relatively established cost curves for pipeline-, maritime-, rail-, or truck-based CO_2 transport. Additionally, public pushback against common transport methods (i.e., CO_2 pipeline) may limit scale-up.[393, 394] Given that this technical challenge is mostly unrelated to the CO_2 storage formation, we estimate these challenges pose only a low risk to scale-up.

Opportunities. There are minor opportunities to alleviate some of the transport challenges for CO_2 storage in mafic-ultramafic rocks, which lie in creative identification/siting of CO_2 sources co-located with short-range transportation networks and in situ CO_2 storage sites. For example, on-site use of clean and cheap electricity from a bioenergy with a carbon capture and storage (BECCS) plant co-located with in situ storage could reduce energy costs for compression needed for pipeline transport to injection wells. Additionally, pairing DAC with geothermal energy could provide low-carbon electricity and heat, utilization of existing pipeline and injection well infrastructure, and leveraging existing subsurface characterization data necessary to CO_2 storage site development. Some existing geothermal sites may also operate in reservoirs with mineralization potential, delineating a clear path to scale-up. DAC combined with geothermal has been piloted and proven commercially in Iceland, and research indicates significant OPEX savings potential in the U.S. when co-locating geothermal and DAC.[395] Intermodal transportation (i.e., combination of pipeline, rail, ship, barge, or truck) may optimize cost of transport for specific locations, while centralized transport and mineral storage hubs will develop economies of scale and drive transport costs down through shared infrastructure for intermediate storage, purification, conditioning, etc.[396] Finally, identification of point-source emissions proximal to mafic-ultramafic formations will also support early-stage project development and impact CO_2 transportation costs. However, given the well-established cost of transport, we assign this set of opportunities a low potential to mitigate the risk associated with the previously described challenges.

8.8 Summary of Challenges and Opportunities

The technologies for injecting and monitoring CO_2 in the subsurface stand on the shoulders of the hydrocarbon exploration and development industry of the early 20th century. Similarly, most of today's new CCS project developments owe their improved economics and reduced risks to projects like Sleipner and Snøhvit, whose early efforts moved us farther along the learning curve. According to the Global CCS Institute's 2022 fact sheet,[397] over 300 million tons of CO_2 was injected in geologic reservoirs around the world that year—each million tons further derisking those that would follow. However, of this global storage total, reactive reservoir storage accounts for only about 0.3 percent (approximately 100 thousand tons); nearly all of it in basalts. Said another way, 99.7 percent of the learning-by-doing inherent in derisking geologic CO_2 storage to date has happened in non-reactive reservoirs. While much of the experiential knowledge gained across all storage projects provides invaluable insights into operating and managing large-scale CO_2 injection, a significant, sustained effort is needed to develop and derisk a set of best practices to characterize, simulate, test, and pilot mineralization storage across a variety of relevant geological and geochemical settings.

Challenges, opportunities, and associated risks are present in all aspects of carbon mineralization, including revenue streams, mineralization rates, injection/storage field development, upstream processes, site characterization, MRV, and CO_2 transport. As CO_2 storage projects are long term projects with high capital expenses, stable revenue-generating mechanisms are needed for successful scale-up. This revenue may primarily be from carbon credits associated with compliance, incentives, or voluntary carbon market schemes. New revenue-generating opportunities are being developed that rely on co-produced products required for the energy transition, and in situ mineralization combined with enhanced critical mineral recovery may promote the adoption of mineralization storage. Demonstrated rapid mineralization would have an associated rapid critical mineral extraction rate, and rapid mineralization is providing pathways to more rapid permanent storage, leading to reduced post-injection site care requirements, reduced risk of leakage and CO_2 credit return, and increased public acceptance. Although a lack of commercial experience developing and operating CO_2 storage in mafic-ultramafic rocks may pose a risk to scale-up, a learning-by-doing approach adapted from mining and geothermal industries may help improve drilling efficiency and reduce cost. Technical challenges for upstream processes such as CO_2 purification and compression vary depending primarily on the type of CO_2 stream, but there are opportunities to reduce the energy consumptions of CO_2 pre-treatments, and the most important constraint will be what regulators allow in terms of impurities. Additionally, operators would need to ensure pipelines and wells can handle the new stream composition. The limited data availability for mafic-ultramafic site characterization puts these reservoirs at an initial disadvantage to conventional well-characterized sedimentary systems, but site characterization can reduce costs as new methods are developed to target highly reactive formations with large storage capacities. Establishing baseline mineralization reservoir parameters from targeted exploration in high storage potential locations could accelerate parameterization of reservoir models. Relative to CO_2 storage projects in sedimentary or non-reactive reservoirs that do not require reactive transport modeling, in situ mineralization projects require reactive transport modeling to accurately predict the fate and transport of CO_2, including the extent and kinetics of mineral trapping. For example, in situ mineralization systems may find cost savings relative to traditional geologic CO_2 storage by potentially reducing the footprint of the AoR and reducing the timeline of post-injection monitoring if mineralization can be accurately modeled. Lastly, public pushback against common transport methods (e.g., CO_2 pipeline) may hamper mineralization efforts, and carbon storage more broadly. However, given the well-established cost of transport, this risk is not unique to carbon mineralization, but may still be present if CO_2 transport to a site is necessary.

9 Conclusions and Outlook for In Situ Mineralization in Mafic-Ultramafic Reservoirs

In summary, this report documents the potential for large-scale, durable carbon storage in mafic-ultramafic reservoirs around the world, which is currently estimated at ~2.5–4.8 Tt of CO_2. Currently, there are planned or prospective projects on five continents. These new projects will likely face challenges during commercial scale up, but learnings from these field sites, such as those from pilot projects like Wallula[5] and CarbFix[4], can be integrated into these ongoing field and future operations. The current lack of legal and regulatory guidance specific to mafic-ultramafic mineralization storage does not appear to present a barrier to field implementation, and in fact further demonstrations nearing commercial scale and across different reservoir geologies are likely needed to develop regulatory frameworks. Additionally, many of the associated risks related to scale up and commercial operation can often be seen as opportunities rather than roadblocks. The lack of revenue streams beyond tax credits is a risk for all CCS operations, but mafic-ultramafic rocks may provide pathways for the generation of value-added products like critical minerals or geologic hydrogen. And while traditional site characterization techniques may not be suited for these unconventional reservoirs, the development of novel techniques and establishment of mineralization capacity calculations based on field-validated results may reduce site characterization costs. Overall, this report outlines key knowledge gaps and opportunities for in situ mineralization storage in mafic-ultramafic reservoirs, and how the field can benefit from sustained, coordinated, and outcome-focused research that accelerate the availability and widespread adoption of carbon storage.

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Appendix

Review of CO_2 Storage via In Situ Mineralization in Mafic-Ultramafic Rocks

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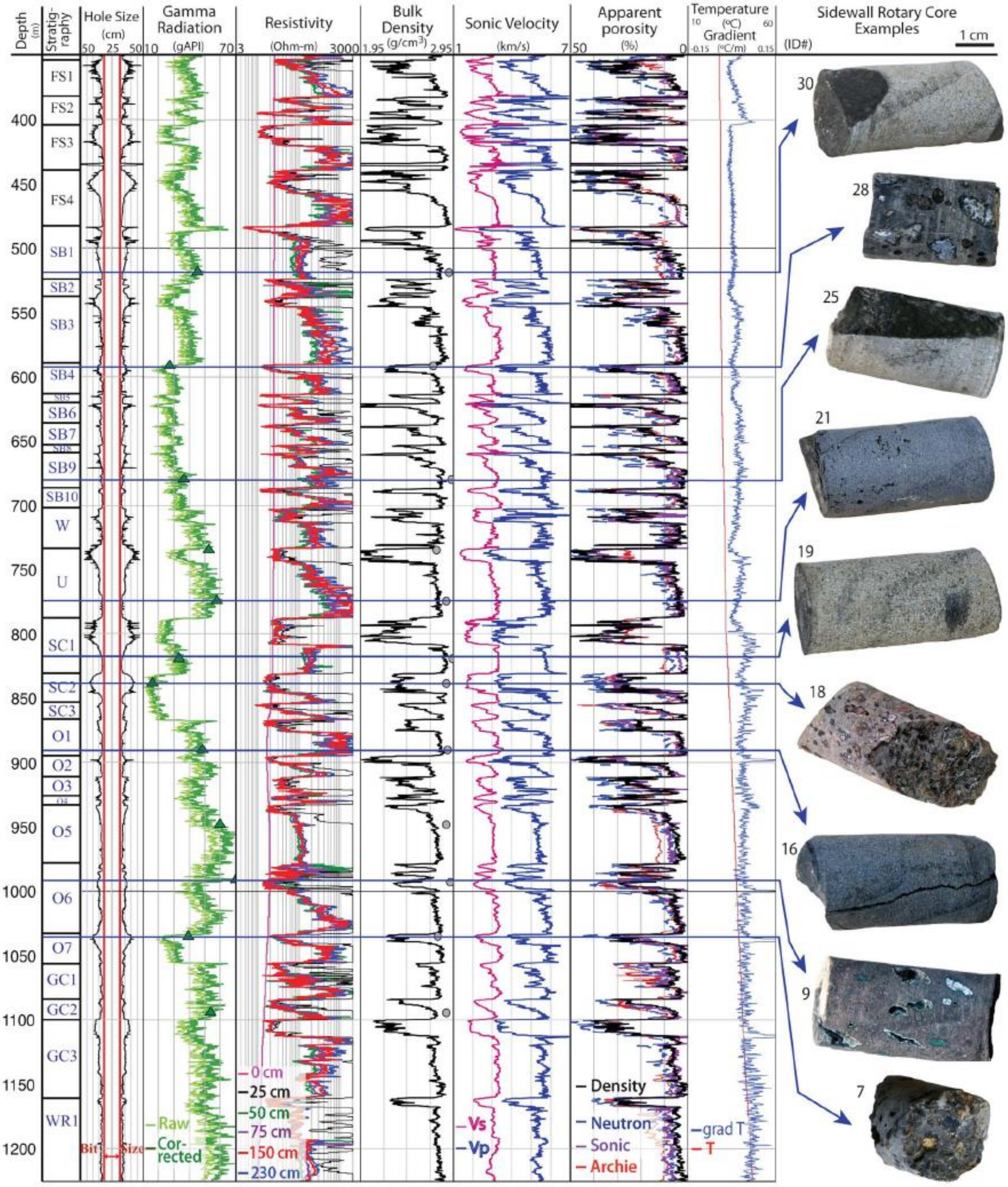

Appendix Figure. Wireline results and sidewall rotary core examples from the Wallula Basalt Sequestration Pilot Project showing numerous alternating flow top (high porosity) and flow interior (low porosity) stacked flows over 400-1200 m [1]

Appendix Table. Summary of reactive transport simulation studies in mafic-ultramafic rock types.

Authors	Location	Minerals	Kinetic data sources	Reactive Transport Modeling Software	Thermodynamic Database
Addassi et al. 2024[2]	---	Basaltic glass, olivine, pyroxene, plagioclase, chamosite, epidote, ankerite, calcite, hydromagnesite, magnesite, siderite, diaspore, hematite, Ca-beidellite, Fe-beidellite, Mg-beidellite, Na-beidellite, Ca-montmorillonite, K-montmorillonite, Mg-montmorillonite, Mg-Fe-saponite, Mg-K-saponite, Mg-Mg-saponite, analcime, Ca-mordenite, stilbite, kaolinite, chalcedony, amorphous silica	---	PRHEEQC 3.6.2	KINEC.dat database from Voigt et al. 2018
Aradottir et al. 2012[3]	CarbFix	Basaltic glass, plagioclase, pyroxene, olivine, allophane, amorphous silica, p-antigorite, Ca-montmorillonite, celadonite, Fe-Celadonite, Fe-chlorite, imogolite, kaolinite, K-montmorillonite, Mg-chlorite, Mg-montmorillonite, moganite, Na-montmorillonite, quartz, amorphous Al hydroxide, Fe(II) hydroxide, Fe(III) hydroxide, dolomite, magnesite, siderite, analcime, ca-chabazite, Ca-heulandite, laumontite, mesolite, Na-chabazite, Na-heulandite, natrolite, Stellerite, stilbite	Palandri and Kharaka 2004, Gislason and Oelkers 2003, Gislason et al. 1997, Rimstidt and Barnes 1980, Knauss et al. 2005	TOUGH2, iTOUGH2, TOUGHREACT	Aradottir et al. (2012) database: Development and evaluation of a thermodynamic dataset for phases of interest in CO_2 mineral sequestration in basaltic rocks
Awolayo et al. 2022[4]	Offshore Cascadian Basin, eastern flank of the Juan de Fuca Ridge	Olivine, plagioclase, clinopyroxene, magnetite, analcime, ankerite, calcite, diaspore, dolomite, gibbsite, hematite, illite, K-feldspar, kaolinite, magnesite, quartz, siderite, montmorillonite	Palandri and Kharaka 2004, Rimstidt et al 2012, Carrol and Knauss 2005, Rimstidt and Barnes 1980, Yang and Steefel 2008, Arvidson and mackenzie 1996, 1999, Saldi et al. 2009, Golubev et al. 2009.	PFLOTRAN	---
Bacon and Murphy 2011[5]	CRBG	Albite-high, anorthite, diopside, hedenbergite, mesostasis, magnetite, anatase, anhydrite, Ca-adelite, K-adelite, Mg-adelite, calcite, chalcedony, dawsonite, dolomite, pyrite, rhodochrosite, siderite	Palandri and Kharaka 2004	STOMP-CO2-R simulator with the add on batch geochemistry solution module ECKEChem	EQ3/6 version 8.0 COMP database
Bacon et al. 2014[6]	CRBG	Albite, anorthite, diopside, hedenbergite, mesostasis glass, magnetite, anatase, anhydrite, beidellite, calcite, chalcedony, dawsonite, dolomite, pyrite, rhodochrosite, siderite	Palandri and Kharaka 2004, Xu et al. 2005	STOMP-COMP	EQ3/6 version 8.0 COMP database
Boampong et al. 2024 [7]	---	Olivine, gypsum, wollastonite	Johnson et al. 2014 Daval et al .2009	PFLOTRAN	---

DePaolo et al. 2021[8]	Hawai'i - Mauna Kea and Mauna Loa Pillow Basalts	Plagioclase, clinopyroxene, orthopyroxene, magnetite, quartz, calcite	Palandri and Kharaka 2004	TOUGHREACT	---
Gierzynski and Pollyea 2017[9]	CRBG	---	---	Monte Carlo numerical model, TOUGH3 with ECO2M module	---
Jayne et al. 2019[10]	CRBG, Grande Ronde	---	---	TOUGH3 with ECO2M module	---
Liu et al. 2019 [11]	CRBG and CarbFix	Diopside, hedenbergite, albite, anorthite, antigorite, greenalite, forsterite, fayalite, K-feldspar, calcite, magnesite, siderite, amorphous silica	Palandri and Kharaka 2004, Knauss et al. 2005, Xiong et al. 2020	TOUGHREACT	---
Menefee & Ellis 2021[12]	CRBG	Olivine, wollastonite, calcite, magnesite, antigorite, and amorphous silica	Palandri and Kharaka 2004, Pokrovsky et al. 2005, Rimstidt and Dove 1986, Teir et al. 2007, Orlando et al. 2011, Tester et al. 1994, Carroll et al. 2013	CrunchTope	EQ3/EQ6
Menefee et al. 2017[13]	---	Diopside, albite, anorthite, antigorite, forsterite, fayalite, K-feldspar, calcite, magnesite, siderite, amorphous silica, kaolinite	Palandri and Kharaka 2004, Knauss et al. 2005, Pokrovsky et al. 2005, Pokrovsky et al. 2002, Golubev et al. 2009, Teir et al. 2007, Orlando et al. 2011, Tester et al. 1994, Carroll et al. 2013, Huertas et al. 1999	CrunchTope	---
Van Pham et al. 2012 [14]	CRBG	Augite, pigeonite, feldspar, glass, magnetite	Palandri and Kharak 2004, Gislason and Oelkers 2003	PHREEQC	V8.R6.230
Postma et al. 2021[15]	CarbFix	Fayalite, siderite, silica	Palandri and Kharak 2004, Knauss et al. 2005	Created their own which was adapted from Gasda et al 2011	Voigt et al, 2018 - carbfix.dat
Schwartz 2022[16]	CRBG	Calcite, siderite, magnesite, amorphous silica, montmorillonite, illite, continental flood basalt glass, mid ocean ridge basalt glass	---	TOUGHREACT V3	THERMODDEM
Wu et al. 2021 [17]	---	Basalt, calcite, magnesite, siderite, Mg, Ca-montmorillonite, Fe (II) illite, amorphous silica	Pollyea and Rimstidt 2017, Palandri & Kharaka 2004	TOUGHREACT v3.2-OMP, complied with the equation of state module ECO2N	based on Thermodemm v.1.10 (Blanc et al. 2012) and modified by Pollyea and Rimstidt (2017).

White et al. 2006[18]	CRBG	CRBG composition instead of mineralogy + lab-derived kinetics. Secondary Minerals: calcite, chalcedony, illite, kaolinite, magnesite, Ca-nontronite, Mg-nontronite	Schaef and McGrail 2009	STOMP-CO2	EQ3/6 (Wolery and Jarek, 2003
Cao et al. 2023[19]	CRBG	Plagioclase, clinopyroxene, glass, phyllosilicates, carbonates	Palandri and Kharaka 2004, Xu et al. 2005, Alemu et al. 2011	STOMP-CO2 with ECKEChem	modified V8 R6 thermo database
Gunnarsdóttir et al. 2020[20]	Nesjavellir,Iceland	Basaltic glass, calcite, pyrite, chamosite, and quartz	---	TOUGHREACT	carbfix.dat
Ratuois et al. 2022[21]	CarbFix2	Calcium, aluminum pyroxene, diopside, hedenbergite, ferrosilite, enstatite, albite, K-feldspar, hematite, magnetite, calcite, chamosite, clinochlore, quartz, epidote	Palandri and Kharaka 2004, Gislason et al. 1997, Knauss et al. 2005, Rimstidt and Barnes 1980	TOUGHREACT	carbfix.dat
Erol et al. 2023[22]	Kizildere Geothermal Site, Turkey	Albite, andalusite, calcite, chlorite, dolomite, epidote, hematite, paragonite, pyrite, montmorillonite, muscovite, quartz, siderite, talc	Palandri and Kharaka 2004	PHREEQC and TOUGHREACT	EQ3/6
Farshidi 2016 [23]	Samail Ophiolite, Oman	Olivine, forsterite, enstatite, diopside, fayalite, magnesite, hydromagnesite, calcite, dolomite, chrysotile, brucite, magnetite, quartz, halite	Palandri and Kharaka 2004, Oelkers and Schott 2001, Knauss et al. 1993, Paukert et al. 2012	Stanford's Automatic Differentiation-based General Purpose Research Simulator (AD-GPRS)	EQ3/6 and SUPCRT92
Paukert 2014 [24]	Samail Ophiolite, Oman	Forsterite, enstatite, diopside, chrysotile, brucite, talc, montmorillonite, calcite, dolomite, magnesite, quartz, amorphous silica	Palandri and Kharaka 2004	TOUGH2 and TOUGHREACT	EQ3/6
Steefel and Hsu 2022 [25]	---	Magnesite, forsterite	Giammar et al. 2005, Steefel and Yang 2021, Xiong and Giammar 2014.	CrunchTope	---
Hoteit and Addassi 2021[26]	Stapafell Mountain, Iceland	Basaltic glass	---	PHREEQC	phreeqc.dat with selected aqueous solubility constnats from Gysi and Stefansson 2011 added
Liu et al. 2022 [27]	Deccan flood Basalts, India	Diopside, hedenbergite, albite, anorthite, forsterite, fayalite, magnetite, glass, K-feldspar, aragonite, calcite, magnesite, ankerite, siderite, chlorite, Ca-smectite, Na-smectite, Mg-smectite, amorphous silica	Palandri and Kharaka 2004, Liu et al. 2019, and Xiong et al. 2017.	TOUGHREACT	---
Zhao et al. 2024 [28]	Xingouzui formation, Jianghan Basin	Diopside, hedenbergite, albite, anorthite, forsterite, fayalite, magnetite, glass, K-feldspar, aragonite, calcite, magnesite, ankerite, siderite, chlorite, Ca-smectite, Na-	Liu et al. 2019, Liu et al. 2022, Hsieh et al. 2017 and Xiong et al. 2017	TOUGHREACT	---

		smectite, Mg-smectite, amorphous silica, antigorite, greenalite, kaolinite, hematite			
Oelkers et al. 2022 [29]	Jizan region, Saudi Arabia	Ankerite, aragonite, calcite, magnesite, siderite, goethite, hematite, ilmenite, magnetite, titanite, albite, K-feldspar, Fe-Fe-saponite Fe-K-saponite, Mg-Mg-saponite, Mg-K-saponite, Mg-Fe-saponite, Ca-beidellite, Fe-beidellite, K-beidellite, Mg-beidellite, Na-beidellite, celadonite, clinochlore, Analcime, Ca-chabazite, Na-chabazite, laumontite, Ca-mordenite, Ca-Stilbite, thomsonite, wairakite, epidote, kaolinite, quartz, chalcedony, amorphous silica, prehnite	Hermanska et al. 2022	PHREEQC	carbfix.dat
Xiong et al. 2017[30]	CRBG	Diopside, hedenbergite, albite, anorthite, antigorite, greenalite, forsterite, fayalite, K-feldspar, calcite, magnesite, siderite, SiO_2(am), gibbsite	Palandri and Kharaka, 2004, Orlando et al. 2011, Teir et al. 2007, Knauss et al. 2005, Golubev et al. 2009, Carroll et al. 2013	CrunchTope	EQ3/EQ6
Dou et al. 2024 [31]	Snake River Plains	Olivine, pyroxene, plagioclase, Ca-montmorillonite, Na-montmorillonite, illite, calcite, magnesite, siderite, amorphous silica	carbfix.dat, Marty 2015, Palandri & Kharaka 2004	PHREEQC coupled with "Ideal Spheres Model" designed in Matlab	carbfix.dat, V8.R6.230 for illite, augite, and labradorite
Neil et al. 2024[32]	---	Gypsum, calcite	---	PFLOTRAN coupled with dfnWorks	---

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