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Regulatory Considerations for Mineralization Storage

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Abstract

The commercial-scale deployment of in-situ mineralization necessitates a comprehensive understanding of near and far field CO_2-water-rock interactions to ensure storage permanence and alignment with regulatory requirements through detailed characterization, construction, injection, and monitoring activities. Site characterization plans designed to emphasize site-specific geochemical and hydraulic data collection will allow developers to appropriately parameterize reactive transport simulations, meaningfully resolve mineral trapping behaviors, and guide operational strategies. Commercial projects will benefit from monitoring techniques uniquely designed to measure reservoir changes identified as signatures of carbon mineralization, including geochemical and pressure evolution. Identifying and operationalizing these unique signatures to develop quantitatively rigorous monitoring and verification strategies will be key to reducing barriers to investment, permitting, and broad deployment of mineralization storage.

Introduction

Permanent CO_2 sequestration can rely on a variety of trapping mechanisms including structural, residual, solubility, and mineral trapping.[1] CO_2 storage in sedimentary formations typically relies on a combination of all of these trapping mechanisms. However, because these reservoir rocks are almost entirely composed of non-reactive silica sand, they lack the geochemistry needed to drive mineralization at rates or volumes relevant to the 50- to 100-year timeframes typically associated with projects developed under regulatory frameworks (e.g., U.S. Environmental Protection Agency (EPA) Class VI regulations).[2-4] Mineralization occurs much more rapidly in mafic and ultramafic systems (~10^1 years),[5-7] which are highly enriched in calcium, iron, magnesium, manganese, and other elements necessary for the formation of carbonate minerals. The affinity of CO_2 to form carbonates in these conditions offers an attractive opportunity to quickly trap carbon in these mineralization-dominated storage systems, while also requiring novel approaches to project design and implementation. Compared to the physical trappingdominant nature of sedimentary storage reservoirs, mafic and ultramafic systems that exhibit more rapid and sustained mineral trapping present unique technical considerations within established regulatory frameworks related to characterization, modeling, injection, and monitoring.

The potential for rapid CO_2 mineralization in mafic and ultramafic rocks has attracted significant public and private investment. Since 2007, twelve projects related to mineralization storage (Figure 1) have been selected for Department of Energy (DOE) funding, with 83% of projects selected since 2020. This growing interest extends beyond government-funded initiatives, as evidenced by numerous commercial announcements. Notable examples include the offshore CarbonStone project led by TotalEnergies[8], private equity investments secured by 44.01[9], Carbfix and Deep Sky's mineralization evaluation project in Quebec[10], and agreements to explore North American mineralization opportunities by CarbonQuest and Carbfix[11]. Growing interest in mineralization storage warrants a comprehensive understanding of regulatory frameworks and how such frameworks can support the unique aspects of mineralization storage.

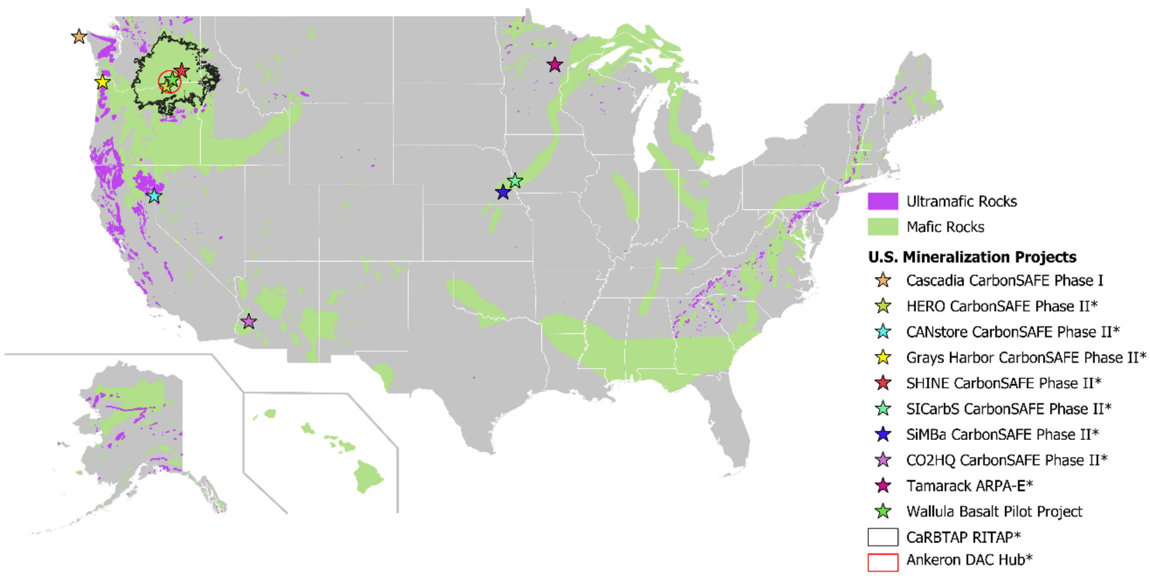

Figure 1. Overview of DOE-funded mineralization storage projects across the U.S and suitable mineralization formations (mafic and ultramafic rocks).[12] 83% of projects shown on the map were awarded since 2020, denoted by an asterisk.

Background

When CO_2 is injected into mafic/ultramafic formations, the CO_2 (pre-dissolved or upon mixing with formation brine) creates a lower pH environment. This acidic condition leads to dissolution of the host rock, releasing divalent cations (Ca^{2+}, Mg^{2+}, and Fe^{2+}). The elevated concentrations of these cations in solution paired with elevated CO_2 concentrations facilitate the rapid formation of stable carbonate minerals, permanently trapping CO_2 in a solid form.[13, 14] Given that mineralization storage predominantly depends on this rapid mineralization trapping mechanism, rather than structural or residual trapping, holistic consideration of mineralization effects is needed across all aspects of permanent storage. This includes tailoring site characterization, injection strategies, monitoring plans, and risk assessments to account for the distinct chemical and physical processes involved in mineralization trapping.

Mature and developing regulatory frameworks provide compliance mechanisms to support the safe and permanent storage of CO_2 in subsurface formations. In the U.S., EPA Class VI guidelines[4] contain broad language to support mineralization storage. The EU CCS Directive[15], revised in 2024, includes language pertaining to storage estimation, caprock definition, and monitoring requirements for aqueous CO_2 mineralization storage projects.

U.S. EPA Class VI guidelines require project developers to computationally model the predicted Area of Review (AoR), which is defined by the area where CO_2 and displaced brine may endanger underground sources of drinking water (USDWs).[16] AoR determination guides characterization, injection, monitoring, and post-injection site care activities. For sedimentary injection formations, AoR modeling may involve limited geochemical evaluation and 3D reactive transport modeling due to a primary reliance on structural and residual trapping mechanisms. Both the U.S. EPA Class VI ruling and the EU CCS Directive call for project developers to utilize appropriate modeling to numerically predict all phases of CO_2 during injection and post-injection time frames.

Key Considerations for Mineralization Storage Deployment

Primary technical considerations for mineralization storage include injection and seal characterization, mapping heterogeneity characteristic of mafic/ultramafic rock types, evaluating changes in pore pressure and pore space availability due to in-situ mineralization, and appropriate deployment of direct and indirect monitoring techniques to assess injection zone carbonation. Table 1 summarizes key technical areas of interest for mineralization storage projects.

From a characterization standpoint, mafic/ultramafic formations are generally less explored compared to sedimentary basins and therefore deep subsurface data is typically sparse. Drilling in mafic/ultramafic rock environments can present operational challenges such as reduced rates of penetration and fluid losses.[17] Geophysical characterization (e.g. land seismic surveys) in mafic/ultramafic formations is a challenge due to velocity variations resulting in scattered amplitudes which require extensive post-processing.[18, 19] The operational goals of mineralization storage stratigraphic test wells and associated sampling plans may prioritize activities to better quantify formation reactivity through specific requirements for hydraulic flow testing, coring, and fluid samples collection. Emplacement histories and internal structure mapping (e.g. flow top, flow interiors, trends related to secondary minerals) present major controls on formation heterogeneity and require geochemical, geomechanical, and hydraulic evaluation for potential near and far-field impacts to injectivity and containment. Storage estimation which incorporate in-situ mineralization effects and reservoir reactivity potential is an area of active research.[20, 21] Site-specific reactive transport modeling to demonstrate reactive processes like dissolution, mobilization, and precipitation of minerals is critical to understanding

Table 1. Key technical areas of interest for mineralization storage.

Mineralization Storage – Technical Areas of Interest	
Characterization	Geophysical, geochemical, geomechanical, and hydraulic data collection
	Emplacement history, internal structure mapping, caprock definition, reservoir reactivity potential
	Natural fracture network and fault characterization, seismic data acquisition
	Identification of non-potable aquifers
	3D reactive transport modeling to evaluate and optimize injection strategies
Well Design	Well design considerations based on injection strategy
	Injection well redundancy, well workovers or maintenance considerations to support injectivity
	Stacked injection strategies and pressure management considerations
Injection	Injection strategy (e.g., aqueous dissolved CO_2, supercritical CO_2, water-alternating-gas (WAG))
	Geochemical and geomechanical considerations related to passivation, pore clogging, and dissolution and/or formation of clays/secondary minerals
	CO_2 stream pre-treatment needs to ensure compatibility with formation brine and injection formation
Monitoring	Consider in-zone monitoring techniques to sample formation fluid chemistry and monitoring well spacing
	Effects of injection strategy on plume evolution, migration, and extent
	Induced seismicity and aquifer protection
	Post-injection site monitoring and closure timeframes

CO_2-rock interactions over time. Reactive transport simulations are used to evaluate AoR geometry due to pressure variations related to mineralization or uncertainties around mineralogic distributions in the subsurface.

Well configuration design considerations will vary based on operation strategy, and the injection may include Water Alternating Gas (WAG)[22, 23], supercritical CO_2 (e.g., Wallula Pilot)[24], or aqueous dissolved CO_2 (e.g., Carbfix Pilot)[25]. Project developers pursuing WAG or aqueous dissolved CO_2 injection strategies will not only have to consider well design, workover, and redundancy to support injectivity rates, but also water availability and related environmental and monitoring impacts of increased water usage. Dynamic pore pressure regimes due to injection strategy, heterogeneity, and in-situ mineralization may necessitate consideration of pressure management solutions such as stacked injection strategies.

Monitoring strategies for mineralization storage are anticipated to mirror monitoring for dedicated CO_2 storage in sedimentary basins. A notable difference relates to in-zone monitoring techniques and the ability to obtain water, tracer, or core samples directly from the injection formation to assess carbonation rates and extent. Typically, in-zone monitoring wells in sedimentary storage formations are cased off from the injection formation to mitigate out of zone migration of free-phase CO_2. The spacing of in-zone monitoring wells for mineralization storage may also vary from sedimentary storage monitoring strategies. Far-field in-zone monitoring wells may be desired to appropriately sample water evolution at the pressure front. Geophysical monitoring methods including baseline and co-injection microseismicity monitoring are expected to mirror strategies for sedimentary basins. The opportunity for reduced post injection site care and closure timelines may be possible if operators can demonstrate earlier plume stabilization based on mineralization findings.

Discussion

Technical and commercial opportunities exist within the mineralization storage landscape. Ongoing and future work related to dual-use pore space applications such as enhanced mineral recovery (EMR) via CO_2 mineralization and CO_2 plume geothermal (CPG) will benefit from a fundamental understanding of large-scale CO_2 rock interactions in mafic and ultramafic formations. Learnings from mineralization storage can support other subsurface storage use cases such as hydrogen storage. Workforce development related to mafic/ultramafic rock characterization, as well as geochemical, geomechanical, and modeling expertise will be needed to facilitate the adoption of large-scale mineralization storage. 3D reactive transport modeling which considers multi-scale geochemical and geomechanical interactions will be needed to support adoption of commercial mineralization storage projects. Building a fundamental understanding of mineralization storage through the lens of existing regulatory frameworks presents an opportunity to enable commercialization of future mafic/ultramafic subsurface activities.

Conclusions

In-situ CO_2 mineralization projects may offer storage solutions to stranded emissions sources where traditional sedimentary basins are not available for geological CO_2 storage. Technical considerations related to reservoir reactivity potential, injection strategy, caprock definition, and carbonation monitoring are key to understanding storage integrity and permanence due to the process of rapid carbonation of CO_2 in mafic/ultramafic rock environments. Due to the paucity of large-scale commercial projects, early pilot projects and the scale up of those pilot projects may inform new technical challenges or opportunities related to regulatory frameworks. The rapid transformation of free-phase CO_2 into stable carbonates via mineralization storage, and the verification of mineralization through monitoring techniques, will enable project developers to build confidence among community and industry stakeholders while permanently storing CO_2 in the subsurface.

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