



The Overlooked Magnesium Advantage in Enhanced Rock Weathering

How Magnesium-Rich Silicates Like Olivine Resist Carbonate Formation and Are More Efficient Per Tonne as Compared to Calcium-Based Minerals

Eric Matzner¹

¹ Chief Technology Officer and Co-Founder of Metalplant PBC

ABSTRACT Enhanced rock weathering (ERW) leverages the chemical breakdown of silicate minerals to remove atmospheric CO₂. While much attention has been given to calcium-rich minerals, magnesium-rich silicates present important chemical advantages. Magnesium's strong hydration shell creates significant kinetic barriers that prevent it from forming solid carbonates easily under typical environmental conditions, resulting in more durable carbon sequestration as dissolved bicarbonate and reliable pathways for carbon transport from soils to the ocean. This inherent chemical resistance to carbonate precipitation ensures that magnesium remains mobile and less likely to be locked into solid phases that could prematurely curtail the carbon removal process or later release CO₂. These properties simplify monitoring and verification, help sustain soil structure, and enhance long-term storage of alkalinity in marine environments. Among magnesium-rich minerals, olivine stands out for its natural abundance and high magnesium content, offering exceptional carbon removal potential per unit mass. While concerns about its nickel content have historically limited olivine's widespread adoption, prompting many ERW initiatives to focus instead on basalt, Metalplant's patent-pending recent advances in combining phytoremediation with ERW technology has opened new possibilities. The integration of nickel hyperaccumulator crops in phytomining operations, particularly on existing serpentine soils, provides a pathway to simultaneously manage nickel concentrations and achieve carbon removal. This development potentially unlocks olivine's full potential as an ideal mineral feedstock for ERW applications, enabling more efficient and reliable carbon removal while generating valuable nickel byproducts. As olivine becomes increasingly viable for large-scale deployment, it becomes crucial to understand the fundamental chemical properties that make magnesium-rich minerals generally superior to calcium-based alternatives for durable carbon dioxide removal, primarily through the generation and transport of dissolved bicarbonate alkalinity.

KEY WORDS enhanced rock weathering; magnesium silicates; olivine; carbon dioxide removal; soil enhancement; calcium carbonate; mineral weathering; carbon sequestration; ocean alkalinity; nickel phytomining

I. INTRODUCTION

Enhanced rock weathering (ERW) relies on the chemical dissolution of silicate minerals to sequester atmospheric CO₂, primarily by converting it into dissolved bicarbonate ions (HCO₃⁻); the fate of these weathering products is crucial for the long-term effectiveness of carbon removal (1). Current efforts to harness ERW as a carbon dioxide removal strategy have often concentrated on basalt, a calcium- and magnesium-bearing

silicate rock that can be sourced widely. This focus partially arises from practical constraints, despite the fact that olivine, one of the most abundant magnesium silicates, has exceptional potential due to its high magnesium content and reactivity. While olivine's carbon removal efficiency is superior, it is frequently set aside due to environmental and health concerns posed by associated elements like nickel when applied to coastal shorelines or arable farmland. As a result, basalt's relative safety profile and availability have often made it a more common choice, even though magnesium-rich minerals like olivine offer more favorable chemistry for durable carbon sequestration.

The behaviors of magnesium (Mg^{2+}) and calcium (Ca^{2+}) ions in soils create distinct advantages for Mg-rich minerals in ERW. A fundamental chemical difference is that magnesium is far less prone to precipitating as a carbonate mineral (e.g., magnesite, $MgCO_3$) in typical soil environments compared to calcium, which readily forms calcium carbonate ($CaCO_3$, e.g., calcite) (2, 3). This distinction is critical because the precipitation of carbonate minerals directly in soils can lead to less efficient net removal of atmospheric CO_2 . Specifically, if Ca^{2+} reacts with two bicarbonate ions (from prior CO_2 drawdown) to form $CaCO_3$ in an open soil system, one molecule of CO_2 can be released back to the atmosphere ($Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3(s) + CO_2(g) + H_2O$), effectively halving the sequestered carbon and immobilizing the remainder locally (4). Magnesium's strong tendency to remain as a dissolved ion in soil solutions, primarily due to the high energetic barrier for dehydrating the Mg^{2+} ion, ensures that the captured carbon (as HCO_3^-) remains mobile. This allows dissolved carbon and alkalinity to continue moving through the soil profile to deeper storage and ultimately to the ocean, rather than becoming trapped in potentially unstable or less effective carbonate minerals near the surface (1).

II. COMPARATIVE ANALYSIS OF CARBONATE PRECIPITATION

A. Understanding Carbonate Formation: Beyond Simple Solubility

The distinct behaviors of magnesium and calcium in typical agricultural soils are often initially considered through their solubility products (Ksp), which indicate

the thermodynamic tendency of their respective carbonates to precipitate from solution (2). Under standard farming soil conditions (around 25°C), calcium carbonate (as calcite) exhibits a Ksp of approximately $10^{-8.48}$ (3). Magnesium carbonate (as magnesite, the anhydrous form) shows reported Ksp values ranging from $10^{-7.52}$ to $10^{-10.3}$ (2). While these values might suggest that thermodynamically, magnesite could also precipitate if solutions become sufficiently supersaturated, the observed rarity of magnesite formation in common soil environments, compared to the ubiquity of calcite, points to factors beyond simple equilibrium solubility. The critical difference lies in the *kinetics* of precipitation, governed largely by ion-water interactions (5).

Both calcium and magnesium ions are surrounded by water molecule shells (hydration shells) in solution. However, magnesium ions, being smaller and having a higher charge density than calcium ions, bind these water molecules much more strongly. This strong hydration creates a significant kinetic barrier to the formation of anhydrous magnesium carbonate (magnesite), even when its precipitation is thermodynamically favorable.

B. Energy Requirements for Dehydration and Temperature Effects

The formation of crystalline magnesium carbonate (magnesite) requires overcoming a significant energy barrier associated with the removal of water molecules from the Mg^{2+} ion's primary hydration shell. For magnesium to form an anhydrous carbonate, it must shed this tightly bound water shell, a process that demands considerably more energy than for calcium. Specifically, the Gibbs free energy of hydration for Mg^{2+} is much more negative (e.g., Mg^{2+} approx. -1908 kJ/mol) than for Ca^{2+} (approx. -1577 kJ/mol) (4). This difference of roughly 330 kJ/mol represents a substantial energetic hurdle. Although the numerical difference might appear modest in absolute terms, it creates a significant activation energy threshold that typical ambient soil conditions cannot easily overcome.

This disparity in dehydration energy requirements manifests distinctly in soil environments, particularly at typical soil temperatures (5-30°C). At these temperatures, calcium ions can relatively easily shed their more loosely bound water molecules, explaining the com-

mon occurrence of calcium carbonate (e.g., limestone, calcite) formation in soils. In contrast, magnesium ions remain firmly bound to their water molecules, as the thermal energy available at these temperatures is generally insufficient to overcome magnesium's much higher dehydration energy barrier for magnesite formation (6).

This fundamental kinetic difference explains why anhydrous magnesium carbonates like magnesite are rarely found in normal soils and typically form only in specific geological settings where conditions (such as elevated temperatures, high pH, high salinity, or very long timescales) can overcome these energy barriers. For instance, magnesite deposits are predominantly found in arid environments with intense evaporation, hot spring settings, sabkha environments, and ancient marine deposits that underwent specific diagenetic conditions (7). The restricted occurrence of significant magnesite deposits to these environments, contrasted with the ubiquity of calcium carbonates, provides compelling real-world evidence for the kinetic difficulty of magnesium carbonate formation under normal earth surface conditions.

Even at higher ambient temperatures, such as in hot summer soils, magnesium maintains its resistance to forming anhydrous carbonates. While calcium continues to readily form carbonates, magnesium strongly resists relinquishing its water shell, with typical soil thermal energy being insufficient to efficiently break magnesium-water bonds for magnesite formation. The requirement that all six water molecules in the inner hydration sphere surrounding the magnesium ion be removed for incorporation into the magnesite structure further complicates the process (4). This temperature resistance proves advantageous for ERW carbon removal applications, as it ensures magnesium carbonates (especially magnesite) won't readily form even during hot periods, keeping captured carbon as mobile dissolved bicarbonate rather than forming potentially less stable or less mobile solid carbonates.

C. Kinetic Barriers and Structural Constraints to Magnesite Formation

The formation of magnesium carbonate (magnesite) encounters several kinetic challenges beyond the high overall dehydration energy. For carbonate mineral formation, the carbonate ion (CO_3^{2-}) must effec-

tively displace water molecules from the cation's hydration shell and form bonds with the cation. This process is energetically unfavorable for magnesium due to its tight hold on its water molecules, which typically prevents effective competition from carbonate ions. The energy required to remove even a single water molecule from magnesium's primary hydration shell creates a significant step in the activation energy barrier (5).

This limitation kinetically impedes the formation of long-range ordered structures – the regular, repeating patterns of atoms necessary for stable anhydrous carbonate minerals like magnesite. Without overcoming this dehydration barrier, magnesium and carbonate ions cannot easily organize themselves into the crystalline arrangements required for stable mineral formation. The process is analogous to attempting to construct a precise brick wall when the bricks (ions) cannot properly align due to their thick, tightly-held water molecule padding that resists removal.

The dehydration step represents a critical rate-limiting process in magnesite formation. Even under conditions that are thermodynamically favorable for carbonate formation (i.e., supersaturation), the extremely slow rate of water molecule removal from the Mg^{2+} ion creates a kinetic bottleneck (5). This process operates similarly to an assembly line where, regardless of downstream efficiency, progress depends entirely on the slow step of magnesium shedding its water shell. Consequently, anhydrous magnesium carbonate precipitation in soils remains severely limited. Even when magnesite formation is theoretically possible, the rate-limiting dehydration step prevents significant precipitation, keeping magnesium in its hydrated form and mobile as dissolved ions (primarily Mg^{2+}) along with the sequestered carbon as dissolved bicarbonate (HCO_3^-) through soil solutions. (Note: Metastable hydrated magnesium carbonates can form more readily but are not the focus here regarding long-term stable sequestration pathways).

III. IMPLICATIONS FOR ENHANCED ROCK WEATHERING

A. Advantages for Carbon Sequestration Permanence and Mobility

The lower precipitation tendency of anhydrous magnesium carbonates (like magnesite) under typical soil conditions provides several crucial benefits for ERW applications. Most significantly, the reduced carbonate precipitation directly in soils diminishes the risk of CO₂ re-release that can occur during calcium carbonate formation in open systems, and it avoids immobilizing alkalinity near the surface. This helps maintain the permanence of the net carbon sequestration intended for ocean storage (1). This characteristic is particularly valuable when considering long-term carbon storage stability and maximizing the efficiency of transporting alkalinity to the ocean.

The high mobility of magnesium in soil solutions, due to its resistance to forming these carbonate precipitates, is one of its most significant advantages for carbon removal. Because magnesium strongly prefers to maintain its hydrated form rather than precipitating as magnesite, it remains dissolved in soil water. This enables the free movement of Mg²⁺ ions and associated bicarbonate alkalinity through soil pores and groundwater systems. This behavior contrasts sharply with calcium, which tends to form CaCO₃ and become immobilized in surface soils, while magnesium and its captured carbon continue their journey towards oceanic reservoirs.

B. Ocean Transport and Storage Mechanisms

The pathway to ocean storage represents a particularly robust aspect of magnesium-based carbon sequestration. The dissolved magnesium, along with its associated bicarbonate alkalinity (representing captured CO₂), can travel through multiple environmental compartments: soil layers, groundwater systems, streams, and rivers, eventually reaching the ocean (8). This transport chain creates a highly secure carbon storage pathway because once in the ocean, the magnesium and associated alkalinity contribute to increasing the ocean's capacity to absorb atmospheric CO₂, a state which remains stable on timescales of hundreds of thousands of years. The vast volume of the ocean

provides enormous storage capacity for CO₂, and importantly, the same kinetic properties that prevented magnesite formation in soils continue to work advantageously in the ocean environment. Magnesium's high hydration energy maintains its resistance to forming anhydrous carbonates, making it far less likely to precipitate compared to calcium, even under typical oceanic conditions (2).

Ocean carbonate chemistry reveals striking differences between magnesium and calcium behavior. In seawater, calcium readily participates in carbonate mineral formation, serving as a primary component of coral reefs and marine shells (biogenic CaCO₃), and can precipitate directly as calcium carbonate in warm, shallow waters (abiotic CaCO₃). These calcium carbonates contribute to the oceanic carbon cycle, but their formation can also mean that calcium's contribution to dissolved alkalinity can be "locked up" in solid phases more readily. Magnesium, despite being the second most abundant cation in seawater, rarely forms pure magnesium carbonates (magnesite) in ocean conditions, even in warm surface waters where calcium readily precipitates. When magnesium does become incorporated into carbonate minerals, it typically occurs in mixed calcium-magnesium carbonates (e.g., high-magnesium calcite), but its overall tendency to remain dissolved and contribute to persistent alkalinity is much greater than calcium's (5).

The behavior of these ions varies across different ocean environments, each with distinct implications for carbon storage. In warm surface waters (0-200m), where most biological carbonate formation occurs, calcium readily forms carbonates while magnesium largely stays dissolved, maintaining alkalinity. The temperature and pressure conditions at these depths remain insufficient to overcome magnesium's kinetic barrier to magnesite precipitation. In continental shelf regions, areas of high biological activity, calcium carbonate precipitation is common, but magnesium maintains dissolved alkalinity, playing a crucial role in coastal carbon cycling. Deep ocean environments (>1000m), characterized by higher pressure and lower temperature, tend to keep both ions dissolved (and CaCO₃ becomes more soluble), though magnesium's inherent resistance to precipitation ensures its reliable stability, critical for long-term carbon storage. In upwelling zones, where deep waters rise to the surface and undergo rapid chemical changes, magnesium's stability helps maintain consistent alkalinity, providing critical

ocean carbon buffering capacity.

This stability of dissolved magnesium across varying ocean environments makes it particularly valuable for long-term carbon storage. It maintains alkalinity in actively cycling surface waters, provides consistent carbon buffering capacity, and remains less affected by biological and physical processes that might rapidly remove calcium from the dissolved pool. Its persistent resistance to precipitation enables continued contribution to ocean carbon uptake over extended time periods (8).

C. Soil Process Benefits and Water Movement

The resistance of magnesium to forming extensive secondary carbonate precipitates significantly impacts soil structure and water movement dynamics. In soil systems, the preservation of pore networks plays a crucial role in maintaining healthy soil function. While significant calcium carbonate formation can lead to blockages or narrowing of pore spaces, creating mineral crusts that seal off pathways and cement soil particles together in ways that restrict water flow, magnesium's tendency to remain dissolved helps maintain these pathways in their functional state. It should be noted, however, that very high magnesium concentrations relative to calcium (high Mg:Ca ratios) in certain soil types, particularly those with high smectite clay content, can potentially cause clay dispersion and negatively affect soil structure; therefore, application rates must be managed with soil type in mind (9).

Hydraulic conductivity, which determines how easily water moves through soil, represents another critical aspect of soil function. This property affects various processes including rainfall infiltration, groundwater recharge, and the transport of dissolved minerals. By resisting precipitation, magnesium helps maintain this conductivity by preventing the formation of extensive mineral blockages and keeping pore spaces open, thereby allowing for consistent water movement. Over extended periods, excessive calcium carbonate precipitation can create hardpans (dense, impermeable layers), reduce soil drainage capacity, and lead to waterlogging or runoff problems. In contrast, magnesium's mobility helps prevent these issues by maintaining soil structure (assuming balanced cation ratios), preserving natural drainage patterns, and supporting consistent transport of weathering products, including the

vital dissolved bicarbonate.

IV. TECHNICAL CONSIDERATIONS FOR ERW IMPLEMENTATION

A. Design Implications

Understanding magnesium carbonate precipitation behavior (or lack thereof under typical conditions) significantly influences ERW design considerations. In terms of material selection, magnesium-rich silicates (like olivine or dunite) offer distinct advantages over calcium-rich alternatives by largely avoiding the risk of extensive secondary carbonate precipitation at the soil surface or within the application zone (1). This reduces concerns about surface passivation of the applied mineral grains (where newly formed carbonates coat the mineral, slowing further weathering) and the premature immobilization of captured carbon. This characteristic allows implementation strategies to focus primarily on optimizing mineral dissolution rates and the transport of dissolved products, without needing to manage extensive local carbonate formation.

B. Monitoring Considerations

The monitoring of enhanced rock weathering effectiveness differs markedly between magnesium- and calcium-based feedstocks, with magnesium-based systems offering several distinct advantages for verifying the transport of dissolved alkalinity. In terms of solution chemistry monitoring, magnesium-based systems provide more straightforward interpretation of soil solution and drainage water measurements, as dissolved magnesium concentrations and associated alkalinity changes more directly indicate weathering progress and carbon capture destined for long-term storage. There is less concern about "missing" magnesium due to widespread precipitation as magnesite, and changes in solution chemistry more reliably reflect actual weathering rates and the mobilization of alkalinity (6).

In contrast, calcium-based systems require more complex interpretation due to CaCO_3 precipitation effects. Monitoring must account for calcium lost to solid carbonate formation, potentially requiring sampling and analysis of both dissolved and solid phases. This carries the risk of underestimating weathering rates or overestimating mobile alkalinity if "hidden" precipitated CaCO_3 is not accurately quantified.

Measurements of pH and alkalinity also demonstrate significant differences. Magnesium-based systems are expected to maintain more stable pH readings over time in leachate, with alkalinity measurements better reflecting total weathering and experiencing less interference from secondary precipitation reactions within the soil. This results in a clearer relationship between measured alkalinity in drainage waters and the carbon capture that is being transported away from the site. Calcium-based systems, however, can experience pH fluctuations associated with CaCO_3 precipitation/dissolution, and alkalinity measurements become complicated by carbonate formation (which consumes alkalinity from solution if it precipitates from bicarbonate). This requires careful accounting for alkalinity effectively trapped in solid precipitates, creating a more complex relationship between measured dissolved alkalinity and actual net carbon capture.

Carbon accounting (specifically, tracking dissolved inorganic carbon, DIC) presents another area where magnesium-based systems show advantages for assessing ocean-bound carbon. These systems provide more directly interpretable DIC profiles in solution, with better correlation between DIC changes and actual carbon removal transported from the weathering site. There is less need to account for solid-phase carbon within the soil itself if the goal is to quantify alkalinity export. Calcium-based systems, conversely, must rigorously account for carbon in precipitated carbonates, monitor potential re-release from these carbonates, perform more complex carbon mass balance calculations at the site, and face greater challenges in tracking the ultimate fate of the carbon through the system.

C. Practical Implementation Considerations

The practical implications of these chemical differences manifest in several key areas for monitoring, reporting, and verification (MRV). Regarding monitoring costs and effort for tracking alkalinity export, magnesium systems generally allow for more direct measurement of the key parameters in soil water and runoff. Verification reliability for carbon transported off-site is enhanced in magnesium systems, which provide more direct evidence of dissolved carbon removal, higher confidence in measurements of mobile alkali-

linity, and easier establishment of clear cause-effect relationships for carbon being leached from the system. This can result in more reliable long-term monitoring data for carbon destined for oceanic storage. System understanding is also improved, as magnesium systems offer a clearer picture of weathering dynamics without the confounding factor of extensive local carbonate precipitation, making it easier to optimize application rates and conditions, troubleshoot more straightforwardly, and better predict system performance regarding alkalinity export.

D. Efficiency Considerations

While the chemical advantages of magnesium in ERW are substantial, there is another significant practical advantage that merits attention: the superior carbon dioxide removal efficiency of magnesium-rich minerals like olivine compared to many calcium-rich alternatives like basalt, *per ton of rock*. Olivine can offer 2-5 times more CO_2 removal potential per ton of material than typical basalts, primarily due to its higher molar proportion of reactive magnesium. For instance, some olivine-rich minerals used in research contain up to 79.8% olivine. This dramatically higher efficiency is due to olivine's high magnesium content and the stoichiometry of its weathering reactions. The enhanced carbon removal capacity per ton of rock translates into numerous practical benefits throughout the implementation chain.

Recent lifecycle analysis (LCA) provides concrete validation of these efficiency advantages. (10) found that olivine-bearing rocks achieved *net* carbon dioxide removal potentials of approximately 760 kg CO_2 /metric tonne of rock applied (after accounting for emissions from mining, grinding, transport, etc.). In contrast, calcium-rich alternatives like dacite and andesite only achieved net removals of 125-160 kg CO_2 /metric tonne under similar conditions. This nearly 5-fold difference in net carbon removal potential per unit mass has profound implications for implementation costs and scalability. Their analysis of Northern California operations showed that only olivine-bearing minerals could achieve the U.S. Department of Energy's "Carbon Negative Shot" target of \$100/tonne CO_2 removed, reaching costs as low as \$96/net tonne CO_2e . In contrast, meta-andesite and meta-dacite applications resulted in costs of \$174-235/tonne CO_2e even under favorable conditions.

Notably, the analysis demonstrated that even if

calcium-based minerals were available at no material cost, the higher material volumes required (due to their lower CO₂ removal efficiency per tonne) still prevented achieving the \$100/tonne CO₂ target due to the increased lifecycle burdens of transportation, handling, and application. This highlights a fundamental economic and logistical advantage of magnesium-rich minerals: their higher carbon removal potential per unit mass reduces material handling requirements throughout the entire implementation chain, making cost targets more achievable.

The reduced material requirements represent a primary advantage. Less total rock mass is needed for the same carbon removal potential. This reduction cascades through the entire process:

- Lower mining volumes: Less material to extract.
- Reduced grinding energy and costs: Less rock to process.
- Decreased transportation requirements: Lower fuel consumption and emissions for transport.

The monitoring process also benefits from this efficiency. A smaller applied mass (for equivalent CO₂ removal) or a more concentrated effect from the same mass means weathering effects become more pronounced and easily measured above background noise.

The monitoring efficiency advantages are particularly noteworthy. With higher carbon removal potential per unit of mineral applied, magnesium-rich minerals achieve more carbon removal per site, leading to stronger, more measurable signals (e.g., of Mg²⁺ and HCO₃⁻ in leachate) in each monitored location. This increased efficiency means more carbon removal can be robustly verified. The higher effective mineral concentration in soil makes changes more detectable, resulting in a stronger signal-to-noise ratio in measurements and more reliable distinction between weathering effects and background variations. These characteristics make it easier to establish clear cause-and-effect relationships in the monitoring process.

From a sampling economics perspective, this increased efficiency means more carbon removal can be verified per sampling point, leading to more efficient use of monitoring resources and a better value proposition for verification efforts. The stronger statistical confidence in results due to larger effects per site further enhances the reliability of measurements. Field implementation benefits from achieving more carbon removal within the same monitored area, po-

tentially allowing for more efficient use of monitoring equipment and reduced travel and labor for sampling.

These efficiency gains extend to the overall implementation process, resulting in lower logistical complexity, a reduced operational footprint, more efficient use of available land, and better cost-effectiveness per ton of CO₂ removed.

V. CONCLUSIONS

Magnesium-rich minerals emerge as highly advantageous candidates for enhanced rock weathering, underpinned by a combination of fundamental chemical properties and practical efficiencies that often make them superior to calcium-based alternatives for achieving durable, ocean-based carbon sequestration. The core chemical advantage lies in magnesium's high hydration energy, creating a significant kinetic barrier to the formation of anhydrous magnesium carbonates (like magnesite) under typical soil conditions. The approximately 330 kJ/mol higher energy requirement for Mg²⁺ dehydration compared to Ca²⁺ ensures that magnesium predominantly remains as a dissolved ion, keeping the captured atmospheric CO₂ (as dissolved bicarbonate alkalinity) mobile within the soil-water system. This inherent resistance to premature precipitation acts as a built-in benefit, operating continuously and passively.

Recent lifecycle analyses, such as (10), have compellingly demonstrated that these chemical advantages translate into economic and operational viability. While many calcium-based minerals may struggle to meet stringent cost targets (e.g., <\$100/tonne net CO₂ removed) due to their lower CO₂ removal efficiency per tonne, magnesium-rich minerals like olivine can achieve these thresholds precisely because of their superior efficiency (e.g., 760 kg net CO₂/tonne rock). This economic advantage is compounded by the reliable transport of magnesium-derived alkalinity to the ocean. Unlike calcium, which can precipitate as CaCO₃ at various points, potentially reducing alkalinity transport, magnesium cations maintain exceptional mobility, ensuring a more complete journey for the sequestered carbon to oceanic reservoirs.

The benefits extend to soil systems, where the persistence of dissolved magnesium (assuming balanced soil chemistry) helps maintain open soil pore networks and hydraulic conductivity, crucial for efficient transport of weathering products. In the ocean, the same kinetic stability that prevents magnesite formation in

soils continues to operate. While calcium readily forms marine carbonates, magnesium largely remains dissolved, contributing to a more stable and persistent increase in ocean alkalinity, which is vital for long-term carbon storage and mitigating ocean acidification.

Furthermore, the verification of carbon removal is often more straightforward with magnesium-based systems due to predictable solution chemistry and less interference from local precipitation. This suite of reinforcing advantages—from fundamental chemical stability and high efficiency per tonne to reliable transport and robust verification—makes magnesium-rich minerals particularly well-suited for ERW. They address key challenges at every stage: resisting local carbonate formation that could reduce effectiveness or permanence, maintaining reliable transport pathways for dissolved bicarbonate, enabling confident verification, ensuring stable long-term ocean storage, and minimizing risks of CO₂ re-release often associated with less stable carbon forms.

This combination of characteristics establishes enhanced rock weathering with magnesium-rich minerals as one of the most promising and scientifically robust approaches to carbon dioxide removal available. The fact that these benefits arise from magnesium's inherent chemical properties provides a strong foundation for developing credible, scalable, and economically viable carbon removal projects.

REFERENCES

1. Jens Hartmann and Stephan Kempe. What is the maximum potential for weathering induced carbonate formation to sequester atmospheric CO₂. *Geochemical Transactions*, 9:5, 2008. doi: [10.1186/1467-4866-9-5](https://doi.org/10.1186/1467-4866-9-5).
2. John W. Morse and Fred T. Mackenzie. *Geochemistry of Sedimentary Carbonates*, volume 48 of *Developments in Sedimentology*. Elsevier, Amsterdam, 1990. doi: [10.1016/S0070-4571\(08\)70001-9](https://doi.org/10.1016/S0070-4571(08)70001-9).
3. Friedrich Lippmann. *Sedimentary Carbonate Minerals*. Springer-Verlag, Berlin, Heidelberg, 1973. doi: [10.1007/978-3-642-65474-9](https://doi.org/10.1007/978-3-642-65474-9).
4. Klaus S. Lackner. Carbonate chemistry for sequestering fossil carbon. *Annual Review of Energy and the Environment*, 27(1):193--232, 2002. doi: [10.1146/annurev.energy.27.122001.083433](https://doi.org/10.1146/annurev.energy.27.122001.083433).
5. Vasileios Mavromatis, Quentin Gautier, Pascale Bénézech, Jörgen Hovelmann, and Eric H. Oelkers. Magnesium isotope fractionation during magnesite precipitation. *Geochimica et Cosmochimica Acta*, 114:188--203, 2013. doi: [10.1016/j.gca.2013.03.029](https://doi.org/10.1016/j.gca.2013.03.029).
6. Alexander P. Gysi and Andri Stefánsson. CO₂--water--basalt interaction. Numerical simulation of low temperature CO₂ sequestration into basalt. *Geochimica et Cosmochimica Acta*, 75(17):4728--4751, 2011. doi: [10.1016/j.gca.2011.05.037](https://doi.org/10.1016/j.gca.2011.05.037).
7. Karl B. Föllmi. A synchronous N--P--Zn enrichment in the ocean during the Cambrian explosion and its implications for the origin of life. *Geological Society of America Bulletin*, 120(9--10):1221--1233, 2008. doi: [10.1130/B26273.1](https://doi.org/10.1130/B26273.1).
8. Richard E. Zeebe and Dieter A. Wolf-Gladrow. *CO₂ in Seawater: Equilibrium, Kinetics, Isotopes*, volume 65 of *Elsevier Oceanography Series*. Elsevier, Amsterdam, 2001. doi: [10.1016/S0422-9894\(01\)80002-7](https://doi.org/10.1016/S0422-9894(01)80002-7).
9. Elena M. Bennett, Garry D. Peterson, and Line J. Gordon. Understanding relationships among multiple ecosystem services. *Ecology Letters*, 12(12): 1394--1404, 2009. doi: [10.1111/j.1461-0248.2009.01387.x](https://doi.org/10.1111/j.1461-0248.2009.01387.x).
10. Hanna M. Breunig, Peter Fox, Jeremy Domen, Raj Kumar, Ricardo J. E. Alves, Kateryna Zhalnina, Anja Voigtländer, Hannah Deng, Bhavna Arora, and Peter Nico. Life cycle impact and cost analysis of quarry materials for land-based enhanced weathering in Northern California. *Journal of Cleaner Production*, 476:143757, 2024. doi: [10.1016/j.jclepro.2023.143757](https://doi.org/10.1016/j.jclepro.2023.143757).