

Experimental evidence of reaction-driven fracturing and ultramafic rock weakening induced by CO₂ mineralization

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Key Points:

- Ultramafic core plugs in carbonated Mg-rich brine at 90 °C undergo systematic damage and disaggregation within 1 month.
- X-ray scans and digital volume correlation reveal significant volumetric expansion along brucite veins after 11 days of soaking.
- Scanning electron microscopy and Raman spectroscopy show evidence of magnesite formation and expansion in fractures.

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Abstract

Carbon sequestration in mafic and ultramafic rocks offers a pathway to mitigate CO₂ emissions, while mineralization could mechanically precondition deposits for critical mineral extraction. However, reaction-driven fracturing processes necessary to increase permeability and weaken rock remain underexplored. Here, we expose serpentinized dunite rock samples to CO₂-brine at 90°C and 3.5 MPa for up to 32 days, employing X-ray computed tomography and digital volume correlation to quantify morphological evolution and 3D solid displacements. Results reveal tensile microfractures nucleating within 11 days, progressing to core disaggregation, with localized expansion concentrated along pre-existing veins and flaw tips. Calculated crystallization pressures over 100 MPa and a fracture mechanics model supports magnesite's volumetric expansion inside of brucite-filled veins as the main cause for reaction-driven fracturing. Raman spectroscopy and scanning electron microscopy help identify mineral changes. These constraints on spatiotemporal dynamics provide evidence and guidelines for injecting and mineralizing CO₂ in ultramafic formations.

Plain Language Summary

This study investigates how magnesium-rich igneous rocks absorb carbon dioxide and concurrently weaken, thereby facilitating metal extraction. Both result from carbon dioxide-rocks chemical reactions, which induce fracturing within the rock body. Magnesium-rich igneous core samples were reacted with carbon dioxide-rich brine under temperature and pressure conditions representative of the deep subsurface for up to one month. Advanced X-ray microscopy methods, similar to medical computed tomography scan, combined with image analysis were used to quantify three-dimensional deformation and fracture evolution. We observed microfractures developing within ~11 days and progressed to significant disaggregation of the rock, with cracking strongly localized along pre-existing mineral veins and grain-scale flaws. The main mineral responsible for expansion is magnesium carbonate, generating internal pressures that readily exceeded rock strength and in-situ confining stress. These internal pressures generated by mineral precipitation explain the rapid onset of mechanical damage. The results support the hypothesis that carbon dioxide mineralization can mechanically precondition magnesium-rich igneous rock formations for both permanent carbon dioxide sequestration and more energy-efficient mining.

1 Introduction

Carbon capture, utilization, and storage (CCUS) technologies seek to control carbon dioxide emissions (Bashmakov et al., 2022). Concurrently, the global demand for critical minerals has increased with booming electrification/electronics infrastructure and consumer products (International Energy Agency, 2021; Reich & Simon, 2025; Shi et al., 2025; DiCarlo et al., 2026). However, high-profit deposits are rapidly depleted, resulting in ore grade degradation and increased extraction costs (Calvo et al., 2016; Mudd, 2010). Simultaneous carbon sequestration in mafic and ultramafic formations combined with facilitation of critical mineral extraction, through mechanical pre-conditioning by reaction-driven fracturing to reduce the comminution energy, could tackle two major societal priorities.

In-situ carbon mineralization via the injection of CO_2 dissolved in water or as a free phase in mafic and ultramafic rocks exploits the exothermic reactions between CO_2 and silicate minerals rich in divalent cations Mg^{2+} , Fe^{2+} , and Ca^{2+} , such as olivine and pyroxene, to precipitate stable carbonates, including magnesite, calcite, and dolomite (Kelemen et al., 2020). This process not only sequesters CO_2 in solid form but also induces coupled chemo-mechanical alterations and reaction-driven fracturing that could control rock permeability, well injectivity, and ultimately rock mechanical strength. Field observations substantiate carbon mineralization and coupled hydro-mechanical processes across diverse geological settings. Natural peridotite carbonation in the Samail Ophiolite, Oman, induced carbonate veining with zones indicative of episodic crack-seal driven by chemical saturation gradients (Kelemen & Hirth, 2012; Menzel et al., 2022). Recently, field tests demonstrated the delicate balance between the fluid chemistry and stress state that control clogging by precipitation, or permeability changes by mineral dissolution/precipitation. At the CarbFix project in Iceland, the injection of CO_2 into permeable basaltic formations achieved mineralization rates exceeding 95% within two years, forming calcite precipitates that locally reduced porosity (Matter et al., 2009; Gunnarsson et al., 2018). The Wallula Basalt Pilot site in the United States documented 60% conversion of supercritical CO_2 to ankerite nodules along pre-existing fractures, facilitating reactive transport (McGrail et al., 2017). Mineral precipitation and phase change not only induce porosity and permeability changes but may also trigger ground deformation and seismicity. Microseismic monitoring at the Trans-Atlantic Geotraverse hydrothermal mound reveals mineral precipitation-induced fracturing, where the formation of anhydrite triggered mi-

croearthquakes corresponding to discrete injected volume increments, underscoring how reaction fronts can self-accelerate permeability enhancement (Pontbriand & Sohn, 2014).

Laboratory experiments and numerical models provide a tool to help explain and predict these complex coupled hydro-chemo-mechanical phenomena. Core-scale carbonation experiments in fractured basalts have demonstrated that carbonates can fill up to 15% of the fracture volume within weeks with non-uniform precipitation fronts locally nucleating tensile cracks (Xiong et al., 2017). Microfluidic observations support advective flow control on morphology: higher rates promote denser calcite growth into dead-end pores, mitigating surface passivation (Menefee et al., 2018; Nisbet et al., 2025). Mineral dissolution increases porosity and reduces Young’s modulus and shear strength, while subsequent mineral precipitation imposes differential stresses that promote fracture nucleation and propagation (Zhu et al., 2016a; Shovkun & Espinoza, 2019b, 2019a). Synchrotron X-ray tomography of olivine carbonation captures this reactive feedback: initial etch-pit formation induces surface perturbations that evolve into polygonal crack networks (Plümper, Røyne, Magrasó, & Jamtveit, 2012; Lisabeth et al., 2017). Reactive transport models suggest that flow-reaction coupling can sustain permeability despite volume expansion from mineral growth (Paukert et al., 2012). Notwithstanding these insights, spatiotemporal quantification of strain during incipient carbonation in ultramafic rocks under reservoir conditions remains limited, with prior efforts often relying on proxies over extended timescales (Zhu et al., 2016b; Lisabeth et al., 2017; Noiriel & Renard, 2022; van Noort et al., 2017).

The objective of this paper is to demonstrate reaction-induced fracturing in brucite-rich ultramafic rocks from the Crawford Ultramafic Complex in Ontario, Canada, triggered by carbonate mineral precipitation from CO₂-rich brine. We conduct experiments on miniature ultramafic core plugs exposed to carbonated water mixed with Mg(OH)₂ at 3.5 MPa and 90 °C for up to 32 days, employing X-ray computed tomography to resolve morphological evolution. First, we present the experimental methods used. Second, the results summarize observations from visual inspection, X-ray tomography, SEM-EDS, and Raman spectroscopy that provide evidence for CO₂ mineralization and reaction-induced fracturing. Last, we discuss the genesis of fractures, the applicability of kinetics and fracture mechanics models, and chemo-mechanical dynamics and implications for field-scale CO₂ mineralization applications in mining.

2 Materials and Methods

2.1 Sample Preparation and Experiment Setup

Rock samples were provided by Canada Nickel Company (Ontario, Canada) and collected from the Crawford Ultramafic Complex, part of the Deloro Assemblage, 2730 – 2724 Ma. Five 9.5 mm in diameter and 21 mm in length cylindrical cores were drilled from serpentinized dunite, an ultramafic rock. All samples (A-J) were prepared from a single borehole core segment, which was originally at 129.8 – 132.0 m depth. After the extraction from the subsurface, the sample was preserved in a vacuum-sealed bag before sub-coring into miniature plugs (henceforth referred as “mini plugs” in agreement with the literature (Gu et al., 2025)). A 1.6 mm-diameter, 9.5 mm-deep blind hole was drilled in each mini plug to increase the reactive surface and residence time, thereby promoting reaction within pre-existing heterogeneities, veins, and pores.

A series of stainless-steel reactor vessels were constructed and placed in a temperature-controlled bath. Each reactor vessel is 15 cm long and 1 cm inner diameter and is connected to a CO₂ tank (Supporting Information (SI), Section S1). All reactor vessels were maintained at a constant pressure of 3.5 MPa and a temperature of 90° C for varying periods of time. Mini plugs were introduced into the vessels, submerged in brine, and the vessels were sealed and pressurized by research-grade CO₂ gas (SI, Section S1). Density-driven convection facilitates aqueous CO₂ dissolution and mixing in the brine (Kneafsey & Pruess, 2010). To simulate the aqueous chemistry in the field far from the injection borehole, the brine consisted of magnesium hydroxide (Mg(OH)₂, the equivalent of brucite), pre-mixed with deionized water (DI, 18.2 MΩ·cm) at a concentration of 2.9 g/L. To ensure supersaturation during testing, the powder was stirred in a beaker at 90°C for 15 minutes. The mini plugs were “unjacketed”; thus, under zero Terzaghi effective stress, as soon as their pore pressure equilibrated with the reactor internal pressure. The presence of undissolved magnesium hydroxide at the bottom of the reactor was verified at the end of the experiment, indicating that it acted as a chemical buffer, that maintained supersaturated conditions in the brine.

Samples A, B, C, D, and E were reacted for 2, 4, 11, 18, and 32 days, respectively (SI, Section S1). During these periods, pressures were monitored and maintained at a constant ~3.5 MPa, supplied with CO₂ from the reservoir tank. After the samples reacted for their respective times, the reactor was depressurized at approximately 0.7–1 MPa

per hour to prevent tensile fracture formation due to gas expansion during depressurization. Additionally, two control experiments were conducted with a residence time of 11 days for the following conditions: sample I was reacted in a carbonated deionized water solution (no brine) at 90° C and sample J was reacted in a carbonated brine at 20° C (low temperature). The control cores were used to assess the isolated effects of $\text{Mg}(\text{OH})_2$ and temperature on microstructural and mineralogical changes.

2.2 X-ray Tomography and Digital Image Analysis

Sample cores were imaged before and after reaction by means of micro-computed X-ray tomography (CT) using a Nikon XT-H 225 ST scanner at 115 kV and 195 μA and 2984 projections averaged 4 times. The resulting CT volumes have a voxel resolution of 12.7 μm corrected for beam-hardening effects. The post-reaction X-ray volumes were registered relative to the pre-reaction volumes and analyzed for tracking displacement fields using Software for Practical Analysis of Materials (SPAM) (Stamati et al., 2020). The software-specific parameters used for displacement field computations are provided as SI (Section S2).

2.3 Raman Spectroscopy and SEM-EDS

To identify the mineralogical and textural changes associated with the observed reaction-induced damage, Raman spectroscopy and scanning electron microscopy-based energy-dispersive X-ray spectroscopy (SEM-EDS) imaging were performed on representative locations of samples A – C. For SEM-EDS analyses, the sample was embedded in epoxy, sectioned into a radial slice (15 mm from base), and two longitudinal slices (perpendicular to the brucite vein), polished with alumina, and then carbon-coated. Additional details are provided as SI, Section S3.

3 Results

3.1 Morphological Observations

Prior to reaction, the samples were composed primarily of serpentine (lizardite and chrysotile)-dominated mesh texture, relict olivine ($<10\%$), brucite ($\sim 5\text{-}10\%$), and trace magnetite. The samples also contained prominent planar veins filled mainly with brucite, with or without serpentine. In most cases, the blind holes drilled to increase reactive sur-

face area intersected brucite-rich veins of various apertures (Figure 1). No carbonate minerals were present. After 2 and 4 days of residence time, samples A and B exhibit only subtle exterior alterations, characterized by darkened pre-existing brucite-rich veins and minor reddish-brown discoloration. Additionally, white-colored minerals appeared along and immediately adjacent to these veins.

The sample retrieved after 11 days of reaction (sample C) shows significant exterior alteration, where brucite-rich veins turned reddish-brown in color and flanked by newly-formed white minerals (Figure 1C). Furthermore, there are prominent morphological changes and fracturing, cracks propagating outward from the blind hole and rock fragments that have broken off the sides. Closer inspection reveals white minerals that have precipitated on the mini-plug exterior and newly broken surfaces.

The samples retrieved after 18 and 32 days (samples D and E) were disaggregated into smaller pieces, rendering the cores unrecoverable for post-reaction CT scanning. Sample D exhibits fragmentation into pieces smaller than ~ 5 mm, while sample E disintegrated into mm-sized fragments. Both samples' pieces had little cohesive strength and the tendency of breaking apart upon manual handling. For both samples, exposed surfaces exhibited significant alteration, coated with white minerals and changed in color to reddish-brown where brucite-rich veins were present.

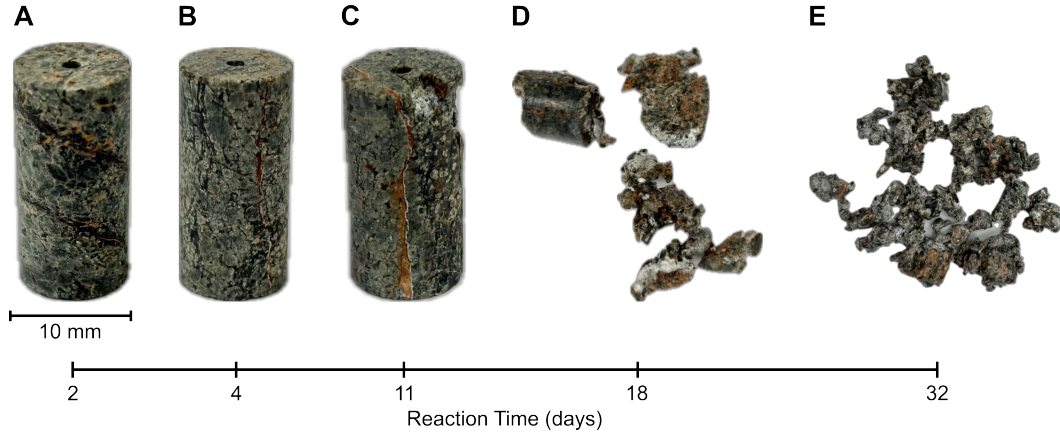


Figure 1. Sequence of ultramafic mini-plugs after retrieval from reaction vessels in CO_2 -rich brine. Samples A and B show minimal visible exterior alteration. Sample C exhibits exterior color alteration and fracturing. Samples D and E underwent disaggregation into progressively smaller fragments.

3.2 X-ray Microstructural Characterization and Evolution

For samples A and B (2 and 4 days of reaction, respectively), we quantified X-ray intensity changes by computing voxel-wise differences between the pre-reaction and post-reaction CT volumes, $\Delta I = I_{\text{post}} - I_{\text{pre}}$, after affine registration of the datasets. Histograms and maps of ΔI show only minor, spatially scattered intensity variations with no coherent patterns above the background noise level, indicating that bulk density changes due to dissolution or precipitation are negligible at these early times (see Supplementary Information, Section S2). Consistent with this, displacement fields derived from DVC for samples A and B exhibit no systematic deformation: displacements are extremely small in magnitude and lack any organized localization along veins, fractures, or other heterogeneities, suggesting that reaction-induced strain is minimal during the first 2–4 days of exposure to CO₂-rich fluid (Figures in SI, Section S4).

Figure 2 illustrates the microstructural evolution for sample C through representative slices in the **XY**, **XZ**, and **YZ** planes of the X-ray tomography. Panels a-c in Figure 2 show the X-ray intensity prior to reaction: gray phase $I \approx 0.5$ is predominantly serpentine/olivine, while the bright phase $I \approx 1$ represents magnetite and other heavy minerals. The CT images reveal the initial heterogeneous microstructure characterized by mineral grains, veins, and the drilled blind hole. Post-reaction intensities in Figure 2 (d-f) highlight the prominent displacements that occurred during reaction, marked by the detachment of large fragments, and also localized changes along veins, and the formation of new fractures. These localized changes are highlighted in Figure 2 panels g-i with the difference in X-ray intensity (ΔI), where positive ΔI values indicate regions of increased density and negative values correspond to decreased density. While visually striking, the computed differences in X-ray intensity cannot unequivocally distinguish between displacements/or void creation, or mineral precipitation.

We employed SPAM to compute three-dimensional digital volume correlation (DVC) and obtain displacement fields u_x , u_y , and u_z defined along the CT volume axes, with the z -axis approximately aligned with the cylindrical core axis. We plot the scalar field $u_x + u_y$ in x - y cross-sections (planes orthogonal to the z -axis), so that u_x and u_y represent the in-plane displacement components within each slice and range between -0.2 mm and $+0.2$ mm (Figure 2j-l). The out-of-plane component u_z is computed but not shown since its magnitude is small relative to u_x and u_y . The $u_x + u_y$ displacement field shows

macroscopic morphological changes resulting from the geochemical reactions and exhibit three notable zones of interest: (1) the **XY** slice in Figure 2j shows displacement away (blue magnitudes) from a vertically-aligned vein in quadrant III, also prominent between $\approx 0 - 2$ mm along the x-axis in Figure 2k; (2) roughly half of the sample volume exhibits negligible displacements (u_x and u_y), seen in Figure 2k and Figure 2l; (3) there is significant displacement field away from (red magnitudes) another newly formed vertically-aligned fracture in quadrants I and II of Figure 2j. Overall, these features are consistent with the X-ray intensity features in Figure 2g-i, but clearly show the extent of mechanical damage over the 11 days of reaction.

Additional constraints on the role of temperature and fluid composition come from the control experiments. The 11-day control core reacted with CO_2 and deionized water at 90°C (sample I) shows intensity-difference maps and DVC displacement fields that are similar in character to those of samples A and B, with very small, spatially uncorrelated ΔI and displacement magnitudes, and no evidence for pervasive or localized cracking (see Supplementary Information, Section S2). In contrast, the 11-day control core reacted with CO_2 , deionized water, and magnesium hydroxide brine at 20°C (sample J) displays modest but coherent deformation in the DVC displacement fields and notable changes in X-ray intensity, dominated by regions of negative ΔI relative to the pre-reaction state, indicating that even at lower temperature reaction with CO_2 can drive mineralogical changes, mostly dissolution, and measurable microstructural evolution, albeit without the extensive fracture networks observed in the fully buffered 90°C experiments (see SI, Section S4).

3.3 Mineralogical Characterization

To identify the mineralogical and textural changes associated with the observed reaction-induced damage, we combined targeted Raman spectroscopy with scanning electron microscopy-based energy-dispersive X-ray spectroscopy (SEM-EDS) imaging, guided by the CT/DVC results. Raman spectroscopy was performed on exterior surfaces adjacent to pre-existing veins in samples A–C and also on newly formed fracture surfaces in sample C. In addition, SEM–EDS maps were acquired on representative regions of sample C that coincide with zones of large local expansion identified by the DVC analysis, allowing direct comparison between mineralogy, vein geometry, and localized deformation.

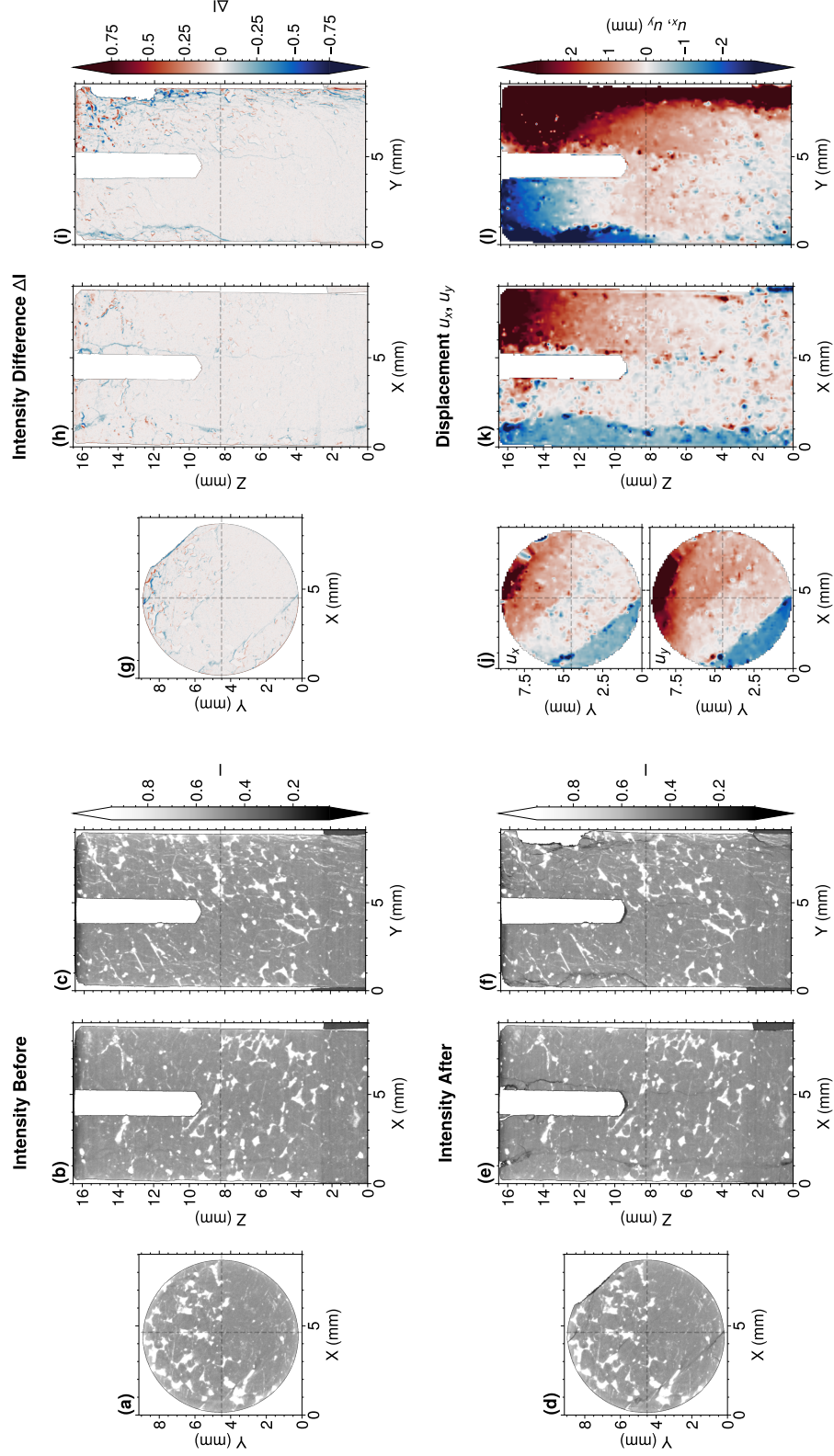


Figure 2. Planar slices from X-ray CT volumes before (a-c) and after (d-f) reaction for sample C (11 days). (g-i) Slices from intensity difference (ΔI) for sample C. Blue corresponds decreased intensity (lost material) and red corresponds to increased density. (j-l) Slices from displacement fields, $u_x + u_y$, computed from digital volume correlation. Note the significant displacements adjacent to fractures and veins, consistent with volumetric expansion of the reacted minerals.

Raman spectroscopy on the altered exterior surfaces of samples A and B confirms the presence of newly formed chrysotile and nesquehonite adjacent to pre-existing veins. For sample C, regions of interest were selected along an altered vein and on a newly formed fracture surface where the CT images show morphological changes and DVC indicates local expansion. An optical overview image marks these locations and the corresponding Raman sampling points on the fracture surface and along the vein (Figure 3a–c). Spectra collected on the newly formed fracture surface show peaks characteristic of chrysotile, whereas spectra from the bright carbonate immediately adjacent to the brucite vein show peaks characteristic of magnesite when compared with reference spectra, confirming the presence of magnesite next to the vein and chrysotile on the fracture surface (Figure 3d). Full Raman spectra are shown in SI (Section S5).

The corresponding composite SEM-EDS image from the region of interest near the bottom of the longitudinal cut is shown in Figure 3f. SEM-EDS imaging and spectral analyses reveal three main changes along the preexisting brucite and serpentine-filled vein: (i) elevated concentration of Mg and Fe within the brucite vein which we identify as spherules rich in Mg and Fe made of magnesite; (ii) a reaction front of carbonates (magnesite) that extends from the sample base upward along the brucite vein, meeting the unaltered brucite (brighter green) at ~ 1 mm from the bottom of the sample; and (iii) extensive fracturing around the reacted brucite vein.

Sample C was cut into a longitudinal slice (Figure 3e) and one radial slice, approximately 1 mm from the top, Figure 3g. The longitudinal cut in particular highlights alteration into the miniplug rock matrix, characterized by mineral bleaching ~ 1 mm into the interior on the sides and adjacent to the blind hole. The corresponding composite SEM-EDS map from the region of interest near the bottom of the longitudinal cut is shown in Figure 3f. Along this section, the pre-existing vein is largely continuous and, over most of its length, is dominated by brucite, which appears as a relatively bright, compositionally homogeneous band. In the lowermost part of the sample, however, the vein contains a distinct altered segment: within approximately the first ~ 1 mm from the base, the original brucite fill is largely absent and is instead occupied by discrete, rounded features that show Fe-enriched cores surrounded by Mg-rich rims in the SEM-EDS maps, consistent with Fe-bearing carbonate (magnesite) spherules that were not present in images taken before the reactions. The transition between this carbonate-bearing segment and the overlying, still brucite-filled portion of the vein suggests a reaction front located at

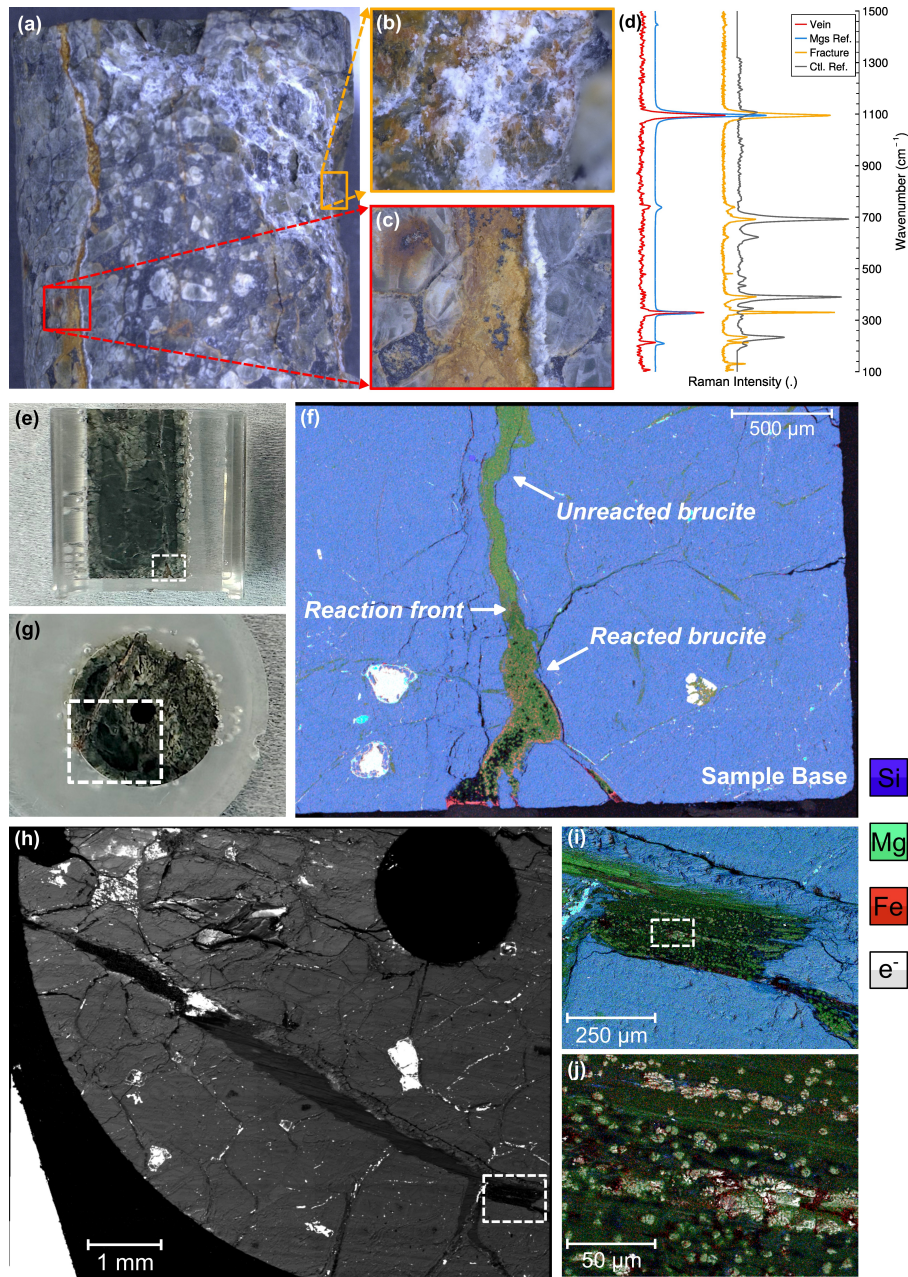


Figure 3. (a–c) Reference locations for Raman spectroscopy of sample C on a newly formed fracture surface (b) and adjacent a brucite vein (c). (d) Spectral signals from locations (b) and (c), respectively; reference mineral spectra are overlain: magnesite (Mgs) and chrysotile (Ctl). Magnesite is observed on newly formed fracture surface. (e–j) Optical and SEM-EDS images of sample C highlighting the inside of newly formed fracture showing Fe-bearing magnesite. Progressive zoom is shown in panels e → f, g → h → i → j.

~ 1 mm above the sample base. In and around the altered segment, the composite map also shows an increased density of fractures both within the vein and in the adjacent host rock, whereas the predominantly brucite-filled portion of the vein higher in the sample is comparatively less fractured. A similar increased fracture density pattern is observed in the radial slice of sample C near the blind hole at the top of the sample, where zones of reduced X-ray intensity and changes in backscatter contrast extend from veins into the surrounding matrix and toward the sample edges, indicating mineralogical modification of the host rock adjacent to fluid pathways (Figure 3g).

The radial slice shown in Figure 3g is located near the blind hole toward the top of sample C, where X-ray intensity and DVC indicate localized opening. Within this slice, SEM-EDS mapping of the selected area in the bottom-left quadrant (Figure 3h) shows a diagonal Mg-rich, Si-poor vein consistent with brucite, cutting through a serpentized matrix. In the lower right portion of this mapped area, the vein hosts a patch in which the original brucite-filled fabric is disrupted and replaced by Mg- and Fe-rich material with limited Si, identified by Raman spectroscopy as magnesite (Figure 3i). Higher magnification of this patch reveals rounded features with Fe-enriched cores and Mg-rich rims, consistent with Fe-bearing magnesite spherules, surrounded by a network of microfractures that extend into the adjacent matrix (Figure 3j). Once again, these features are not observed in pre-reaction CT images at the same locations and are spatially restricted to regions that remained saturated during the experiment, indicating that they formed during exposure to CO₂ and brine rather than during sample preparation and handling.

4 Discussion: Integrating Microstructural and Mineralogical Observations

Mineralogical analyses corroborate preferential reactivity at veins (Figure 3). Raman spectroscopy reveals the presence of magnesite spherules with Fe-rich cores within veins that were previously primarily filled with brucite. These new minerals, spatially aligned with an area exhibiting $\Delta I < 0$ and displacement discontinuities, indicate precipitation-induced expansion rather than dissolution. We interpret these observations as manifestations of reaction-driven cracking, wherein fracture nucleation and propagation arise primarily from stresses induced by mineral replacement and volume expansion in confined geometries, rather than external mechanical loading (Kelemen et al., 2013). The underlying mechanism involves a chemical free-energy decrease from brucite carbona-

tion, manifesting as fluid supersaturation with respect to product phases (magnesite), which generates crystallization pressures transmitted to the host rock. In natural settings, reaction-driven cracking has been inferred from textural evidence in peridotite massifs and ophiolites, such as crack-seal textures in carbonate and serpentine veins, reaction fronts, and dilation zones that enhance reactive surface area (Jamtveit et al., 2009; Putnis, 2009; Beinlich et al., 2010). For instance, in the Samail Ophiolite (Oman), episodic veining driven by saturation gradients produces microcrack networks that sustain carbonation of olivine and pyroxene, with molar volume increases (e.g., forsterite to magnesite: $\approx 20\%$) promoting permeability evolution (Mervine et al., 2014; Menzel et al., 2022). Laboratory studies have replicated these dynamics under controlled conditions. In olivine carbonation experiments, initial etch-pit formation evolves into polygonal crack networks via self-propagating fronts, with crystallization pressures exceeding host tensile strength ($\sigma_t \approx 10\text{--}50$ MPa) to drive vein-parallel opening and permeability gains (Plümper, Røyne, Malthe-Sørensen, et al., 2012). Synchrotron X-ray tomography shows evidence of reactive feedback in olivine, where surface perturbations amplify into fracture networks over the period of months (Lisabeth et al., 2017). These works, while insightful, predominantly rely on proxies for strain (e.g., etch morphology or inferred pressures) or 2D imaging, precluding full spatiotemporal quantification of 3D deformation fields during incipient carbonation in ultramafic rocks under reservoir conditions.

The present study advances beyond previous studies by providing direct, volumetric quantification of strain via DVC on time-resolved X-ray CT data, co-registered with in-situ mineralogical mapping, in brucite-rich ultramafic cores at 90°C and 3.5 MPa fluid pressure. This approach resolves localized expansion ($\approx 35\%$ for magnesite relative to brucite) and displacement discontinuities within 11 days—a rapidity not previously documented—revealing how reaction fronts along thermodynamically favorable veins self-accelerate fracturing. The inferred stresses from this expansion ($\sigma_c > 100$ MPa, modeling in SI, Section S6) exceed typical tensile strengths for serpentinized dunite, in the range of 2.5–25 MPa (Al Kalbani et al., 2024; Breuninger et al., 2021; Diamantis & Fereidooni, 2023) and, when intensified at flaw tips, yield stress intensity factors K_I are sufficient to surpass fracture toughness $K_{Ic} \approx 1 \text{ MPa}\sqrt{\text{m}}$ (measurements in SI, Section S6), driving fracture propagation without external loading. Thus, these experiments elucidate the chemo-mechanical feedback essential for permeability enhancement in CO_2 mineralization, offering predictive constraints absent in prior proxy-based inferences. While laboratory precedents es-

353 tablish reaction-driven cracking via volume expansion in olivine systems (e.g., (Plümper,
 354 Røyne, Mølle-Sørensen, et al., 2012)), they rely on 2D proxies or aggregate-scale strain,
 355 precluding 3D resolution of vein-localized dynamics under reservoir conditions. In con-
 356 trast, our DVC-CT approach quantifies spatiotemporal strain accumulation (± 50 μm dis-
 357 placements) co-registered with magnesite phases, revealing rapid (11-day) propagation
 358 from pre-existing flaws—advancing beyond indirect attributions in prior ultramafic tests
 359 (van Noort et al., 2017; Lisabeth et al., 2017). This integration elucidates self-accelerating
 360 permeability enhancement, providing empirical bounds for kinetic-fracture models that
 361 forecast injectivity in field-scale carbonation. Results also highlight the role of brucite
 362 veins and magnesite as precursors in reaction-driven cracking.

363 5 Conclusions

364 This study provides experimental evidence for reaction-driven fracturing in brucite-
 365 veined ultramafic rock induced by CO_2 mineralization under simulated reservoir condi-
 366 tions ($T = 90^\circ \text{C}$, $P = 3.5 \text{ MPa}$). Mini plugs exposed to carbonated Mg-rich brine ex-
 367 hibited systematic damage, progressing from localized microfractures (nucleating within
 368 11 days, as quantified by X-ray CT and DVC) to full disaggregation by 32 days. Dis-
 369 placement fields revealed local volumetric expansions of 35–50% along pre-existing veins,
 370 with controls confirming the necessity of elevated temperature and brucite availability.
 371 Mineralogical analyses (SEM-EDS and Raman) identified magnesite spherules in reac-
 372 tivated veins, corroborating precipitation as the dominant expansion driver over disso-
 373 lution.

374 Calculated crystallization pressures exceeding 100 MPa from magnesite’s volume
 375 mismatch relative to brucite, applied to a coupled kinetic-fracture mechanics model, yields
 376 stress intensity factors sufficient for fracture propagation at flaw sizes of $\sim 10 \mu\text{m}$. This
 377 calculation supports vein-centric chemo-mechanical feedback, advancing beyond prior
 378 proxy-based inferences by providing direct 3D strain quantification in intact ultramafic
 379 cores.

380 These findings constrain the spatiotemporal evolution of fracture porosity/connectivity
 381 enhancement and reaction-driven rock weakening during carbon mineralization in ultra-
 382 mafic rocks under low effective stress conditions. More broadly, the results demonstrate
 383 that CO_2 mineralization can simultaneously promote permanent carbon sequestration

and mechanically precondition ultramafic ore bodies through fracturing, softening, and progressive disaggregation. This coupling between carbonation reactions and mechanical weakening has important implications for mining and enhanced critical mineral extraction, as it may reduce the energy required for blasting, comminution, and beneficiation while improving fluid access to reactive and metal-bearing phases (SI, Section S8).

Open Research Section

Experimental data presented in this study is available at the Digital Porous Media portal: <https://www.doi.org/10.17612/njh2-s034>. Numerical codes for DVC are available at: <https://www.spam-project.dev/>.

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