Geo-processes in Mineral Carbon Storage (GMCS)
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Class: 2022 – 2026

Mission Statement: *To develop the fundamental science that will lead to realizing the potential for the large-scale subsurface storage of CO_2 via mineralization.*

A promising strategy to reduce anthropogenic CO_2 is to permanently mineralize carbon in mafic and ultramafic geologic reservoirs. These rock masses are advantageous due to their prevalence in the earth's subsurface and their ability to rapidly store CO_2 through mineralization. Recent successful pilot-scale mineral carbon storage projects in mafic rock, including CarbFix and CarbFix2 in Iceland and the Wallula basalt sequestration site in Washington State, have demonstrated storage via mineralization on a time scale of a few years. However, storing the levels of CO_2 needed to address the present climate crisis requires (i) a significant up-scaling of these operations and (ii) the ability to predict the impact of long-term, large-scale CO_2 mineralization on the geologic reservoir.

For mafic and ultramafic rocks such as basalt and peridotite, efficient mineralization of the rock mass requires the existence or development of a penetrating fracture network that accommodates the flow and reaction of CO_2-bearing fluids. This involves optimizing fully coupled thermal, hydrological, mechanical, and chemical processes that can sustain flow for long-term carbon mineralization. Complex feedbacks exist among fracture propagation, fluid flow, dissolution, precipitation, and fracture closure, including phenomena such as passivation of mineral surfaces that reduce reactive surface area, carbonate precipitation that can clog pores and fractures, and reaction-driven cracking. These questions require a coupled understanding of fluid flow and transport in fractured media and the chemical and mechanical processes that occur during carbon mineralization. Such a coupled understanding does not currently exist, since the fields of fracture mechanics, fluid flow in fractures, and geochemistry are often studied separately for other subsurface applications such as hydrocarbon extraction, nuclear waste storage, or traditional carbon sequestration where caprocks and seals are used to prevent CO_2 leakage. However, carbon mineralization requires a coupled understanding of reaction rates, feedback between geomechanics and geochemical reactions, and the influence of flow and transport. By expanding the frontiers of interdisciplinary research, GMCS aims to evaluate, for a given CO_2 storage operation within a given reservoir, the evolution of the amount of carbon $\mathrm{M(t)}$ mineralized:

$$M(t) = \int_V m(\boldsymbol{x}, t) dV(\boldsymbol{x}), \tag{1}$$

where V is the volume of the rock mass and $m(\boldsymbol{x}, t)$ is the mineral carbon density (mass of carbon stored per unit volume of rock). All GMCS efforts are anchored by equation (1), with the aim to determine how different mechanisms affect the amount of CO_2 mineralized with time so that the operation can be optimized and up-scaled.

The research GMCS is pursuing aims to fill the knowledge gaps that are the result of this highly coupled fracture mechanics, fluid flow, and geochemical problem. Our research revolves around (i) unlocking the mechanisms behind reaction-driven cracking and fracture, (ii) understanding dissolution and precipitation regimes and their effect on fracture flow, and ultimately combining this knowledge with (iii) continuum and discrete modeling of fracture networks to determine the rate and mass of CO_2 mineralized. The study of these processes is not restricted to a single research thrust and a full understanding is not contained within a single knowledge domain. Indeed, maximizing the success of our research thrusts involve a subtle combination and coupling of the disciplines of geomechanics, geochemistry, porous media flow, and sensing technology. Thus, the research is organized around three thrusts (Fig. 1):

1. Reaction-driven cracking and fracture: elucidate the coupled chemo-hydro-mechanical processes leading to the formation of a microcrack network in the rock matrix.
2. Dissolution and precipitation regimes: understand how mineral carbonation is affected by reactive transport and the interaction between fracture flow and the surrounding rock matrix.
3. Continuum and discrete modeling of fracture networks: develop capabilities to predict and monitor capacity of a mafic or ultramafic reservoir for carbon storage and design optimal solutions for reservoir stimulation.

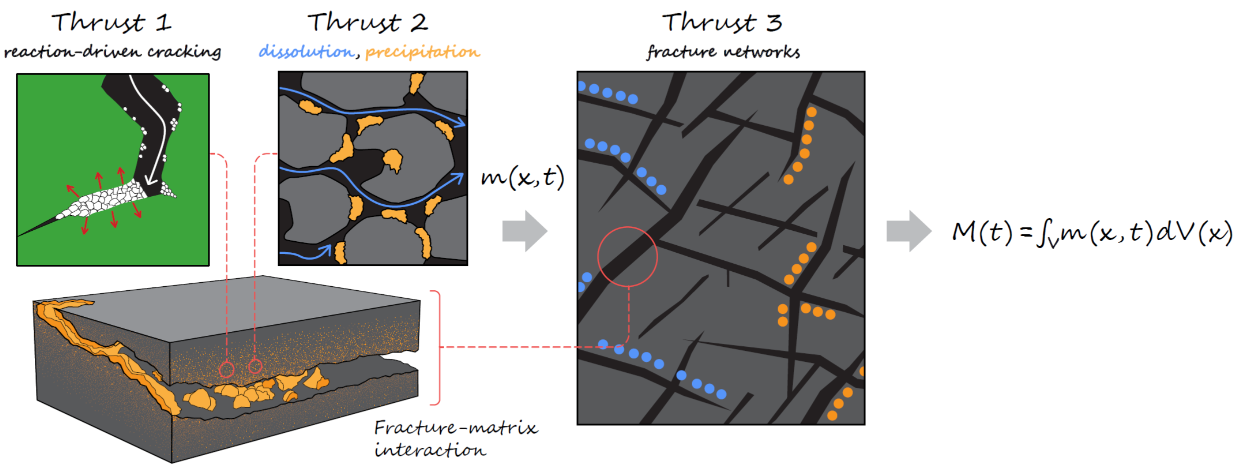

Figure 1. The three thrusts target different aspects of mineralization and share the common goal: the amount of mineralized carbon M(t) will ultimately emerge as a result of competition among the underpinning physical and chemical processes in mafic and ultramafic rocks.

GMCS has launched numerous interdisciplinary projects crucial to the advancement of carbon mineralization. Further, to understand the current state of the science, knowledge gaps, challenges and opportunities, the GMCS team authored a comprehensive review: "Carbon Mineralization in Mafic and Ultramafic Rocks," *Reviews in Geophysics,* submitted. The review covers field studies, laboratory experiments, and numerical simulation, emphasizing that a multidisciplinary approach is required to advance our understanding of what mechanisms control *in situ* carbon mineralization.

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