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CO_2 Sequestration in Basalt Formations

FWP-73235

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Management Project Review Meeting
August 5 – 9, 2024
Carbon Transport and Storage Breakout Session 2
Wednesday 1:50 pm, 304/305

H. Todd Schaef

Photo: Andrea Starr (PNNL

Presentation Outline

- Project Overview
  - Key Project participants, Project objectives, Project performance dates, Funding summary
- Project Background
  - Brief Project history, Project location(s), Importance of project towards advancing DOE Program Goals
- Technical Approach/Project Scope
  - High-level Project execution plan, Project schedule summary including key milestones, Project success criteria/ expected outcomes, Summary of high probability and/or high impact project risks, with mitigation strategies
- Current Status of Project and Accomplishments (*Focus of the presentation*)
  - Status of project objectives and tasks, Summary of significant accomplishments / key findings and their impact, Summary of significant challenges and mitigations
- Summary of Community Benefits / Societal Considerations (CB/SCI) and Impacts
  - Summarize CB/SCI efforts planned or undertaken as part of the project, Summarize progress towards CB/SCI SMART milestones
- Next Steps
  - For Project, After Project/ Scale-up potential

Five Key Takeaways: Project Review for CO_2 Sequestration in Basalts

1) Do not ignore pre-existing secondary minerals associated with basalt weathering. These alteration products have a role in 1) how fast mineralization occurs and 2) what type of carbonates form.
2) Carbonation products forming from CO_2-Basalt interactions are complicated and not easily understood.
3) Glass chemistry, structure, and degree of weathering appear to be major contributors to the overall bulk reaction rate of a basalt in the presence of $CO_{2.}$
4) Deployment of carbon storage mineralization should involve site-specific injection strategies for carbonation and pore space optimization
5) Impacts to water quality is a key concern of carbon storge developers and hosting communities. We need to better understand post-injection reservoir formation water quality.

Health, Safety, and Environment Share: Mentoring

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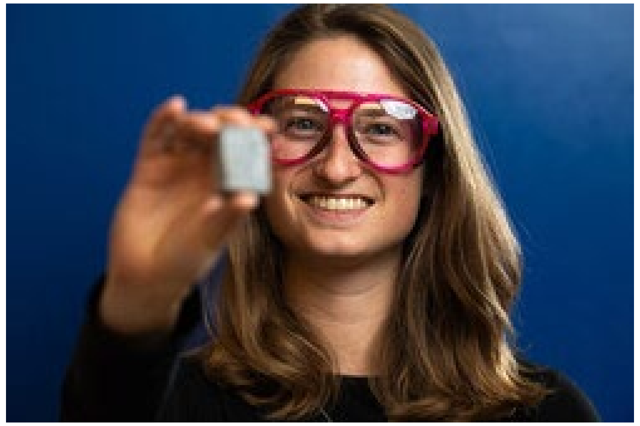
- ➢ A Big Source of Knowledge
- ➢ Help Setting Achievable Goals
- ➢ Valuable Connections
- ➢ Help With Your Growth

5 Guiding Principles for Mentors

- Availability: the open door
- Balancing direction and self-direction
- Celebration
- Publish
- Networking

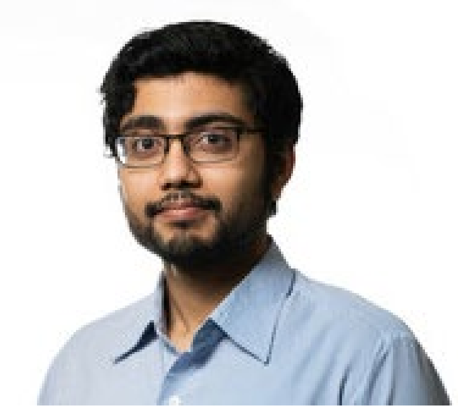


Lee, A., Dennis, C. & Campbell, P. *Nature*'s guide for mentors. *Nature* **447**, 791–797 (2007).

PNNL Carbon Mineralization Team is Working to Advance Low-Carbon Technologies and Accelerate Development of Commercial-Scale Solutions

Emily Nienhuis
Fluid-Rock Interactions Chemist/PI

Quin Miller
Carbon Mineralization Geochemist



Nabajit Lahiri
DAC and Carbon Storage Geochemist

Stephanie DiRaddo
Class VI Permitting Geologist

Matt Villante
CDR/Mineralization Geologist

Seunghwan Baek
Reservoir Modeling Reservoir Engineer

Katie Muller
Reservoir Modeling Environmental Engineer

Janie Vickerman
Contracting and Project Management

Ross Cao
Carbon Storage Geologist

Casie Davidson
FECM Manager Economic Geologist

Todd Schaef
Scientist

Early Career Contributions Driving Low-Carbon Technology Advances

Maddie Bartels (SULI)

Madeline Murchland (MLEF)

Ellen Polites (MLEF/SCGSR)

- Outreach and community engagement are keystones of our program
- Early career researchers include interns, postdocs, staff, visitors
- Product-driven research experience cultivates and unleashes talent
- Diversity and inclusion enables innovation and creativity, breadth of perspectives needed for global challenges

Arianna Morfin (CCI)

Heath Stanfield (SULI)

Charlie Depp (SULI)

Jade Holliman (MSIPP/GEM)

Julian Stapper
Visiting PhD Student

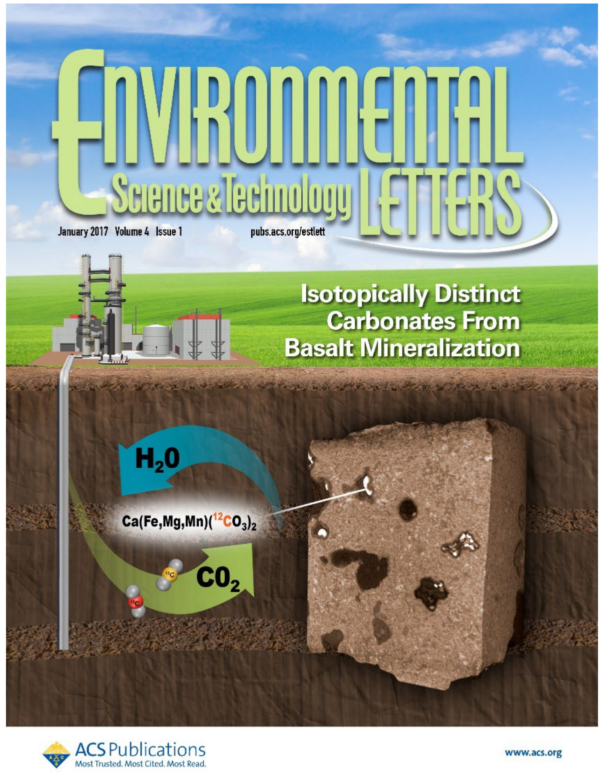
Prof. Briana Aguila (VFP)

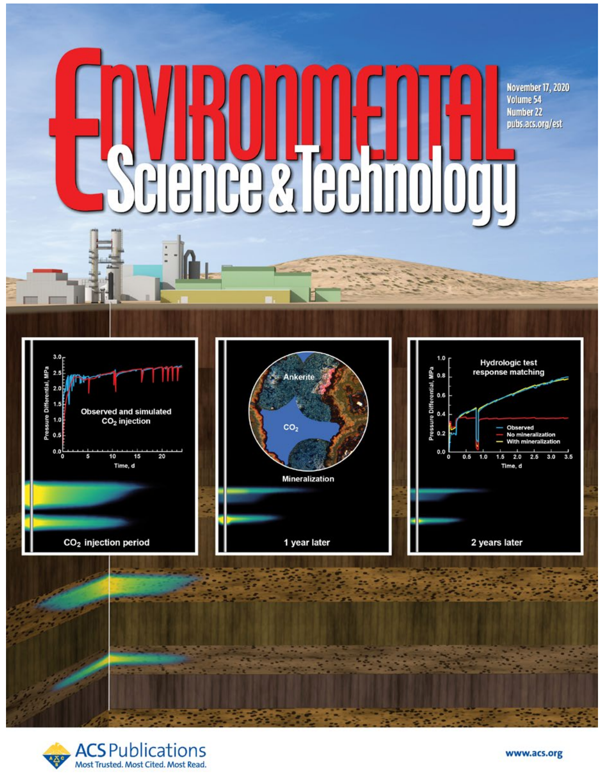
Landon Hardee (VFP)

Joey Jacobs (ARPA-E)

Project Overview

- Key Project Participants
  - State/Federal, National Lab, Universities, and Industry
- Project Objectives: **Address key knowledge gaps to enable commercial scale CO_2 sequestration in basalts:**
  - Provide support for post-closure characterization activities associated with the Wallula Basalt Pilot Well.
  - Sensitivity analysis and parameterization of reactivity of basalt in CO_2-bearing fluids for reactive modeling tools
  - Reservoir formation water quality evolution post-injection
  - Role of flow regimes and porosity changes on carbon mineralization
  - Create and disseminate reactive modeling tools that can simulate interactions of $scCO_2$ fluids in basaltic reservoirs.





Technical Approach/Project Scope For FY24 (by task)

Task 1: Complete Wallula Post-Injection Characterization

- Explore chemical zonation and mineralogy in Wallula post-injection cores to improve current understanding of plausible carbonation pathways for future reservoir storage estimates, modeling efforts.

Task 2: Basalt Reactivity in CO_2 Fluids

- Benchmark the reactivity of the glassy mesostasis for input into reservoir simulations, including a sensitivity analysis related to composition, abundance, and weathering.

Task 3: Post-Injection Reservoir Formation Water Quality

- Estimate timeline for reservoir water recovery post injection using laboratory-based experiments with insights from pre- and post-injection Wallula water chemistry and the baseline water chemistry of other basalt wells in the PNW.

Task 4: Flow Regimes in Basalt Reservoirs

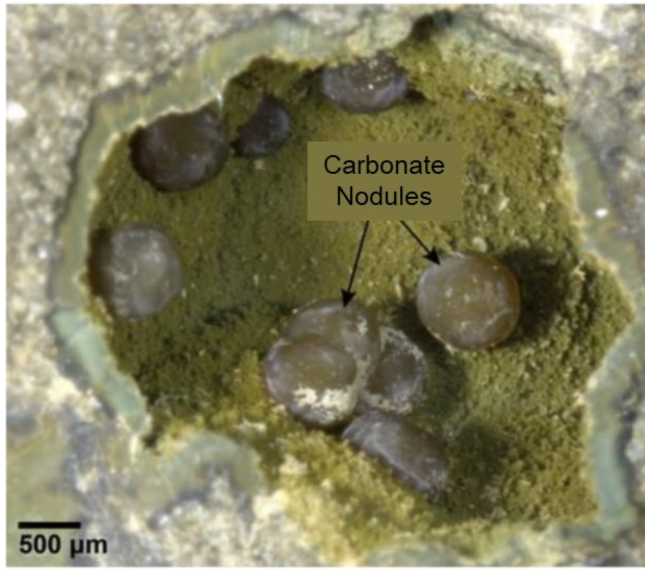
- Determine the role of flow and transport regimes in a reservoir on carbon mineralization using engineered microfluidics and basalt cores.

Task 5: Reactive Transport Module for Water Bearing Fluids

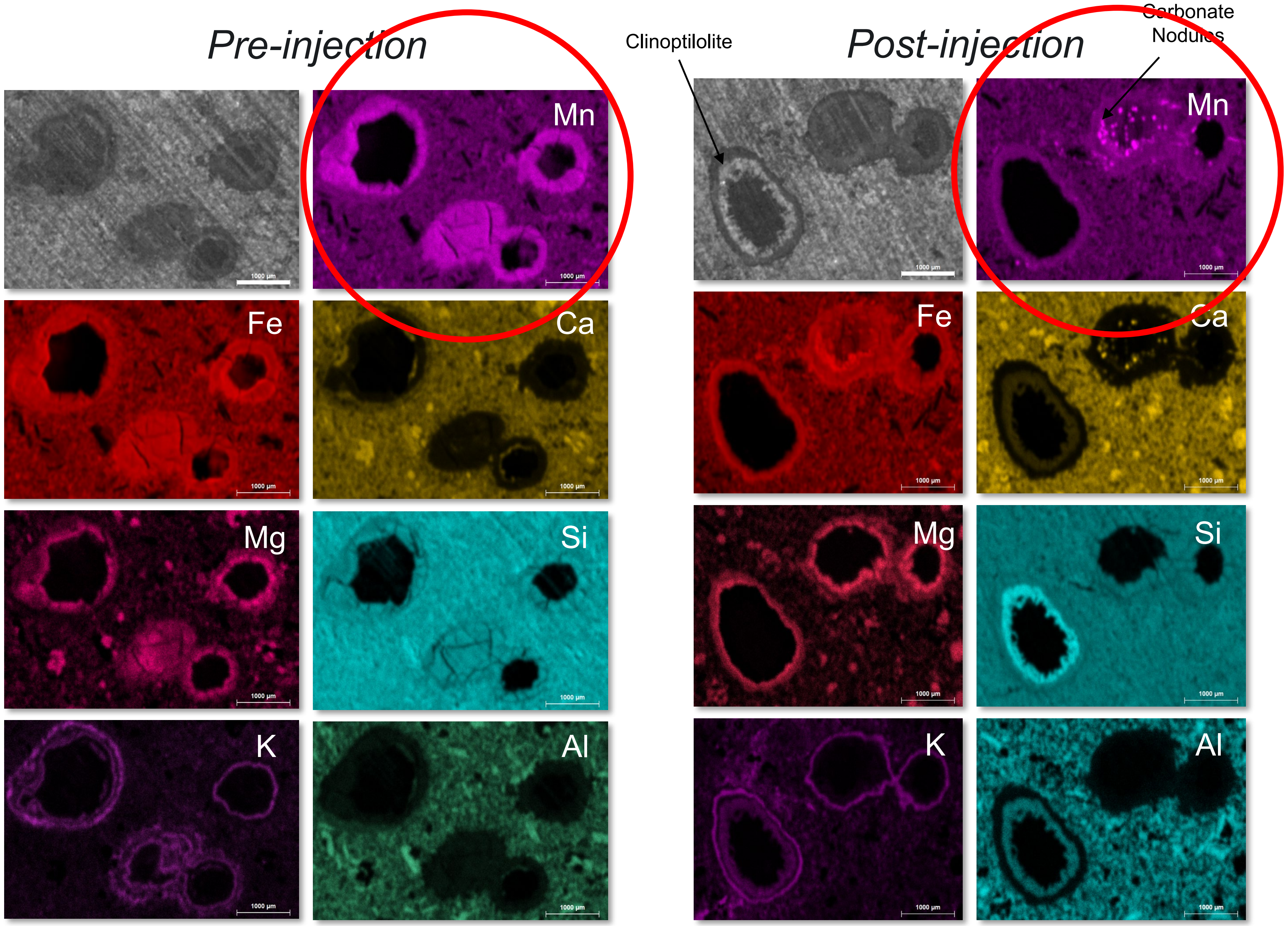
- Develop modeling tools to account for the reactivity of water bearing fluids and mineralization of CO_2 in basalt, using insights from Tasks 1-4.

Key Objectives: Solving knowledge gaps to enable commercial scale subsurface carbon mineralization in basalts

Pore Lining Secondary Mineral Phases are the Source of Mn^{2+} in Carbonates from Wallula



Core-scale XRF chemical maps highlight the source and fate of critical cations

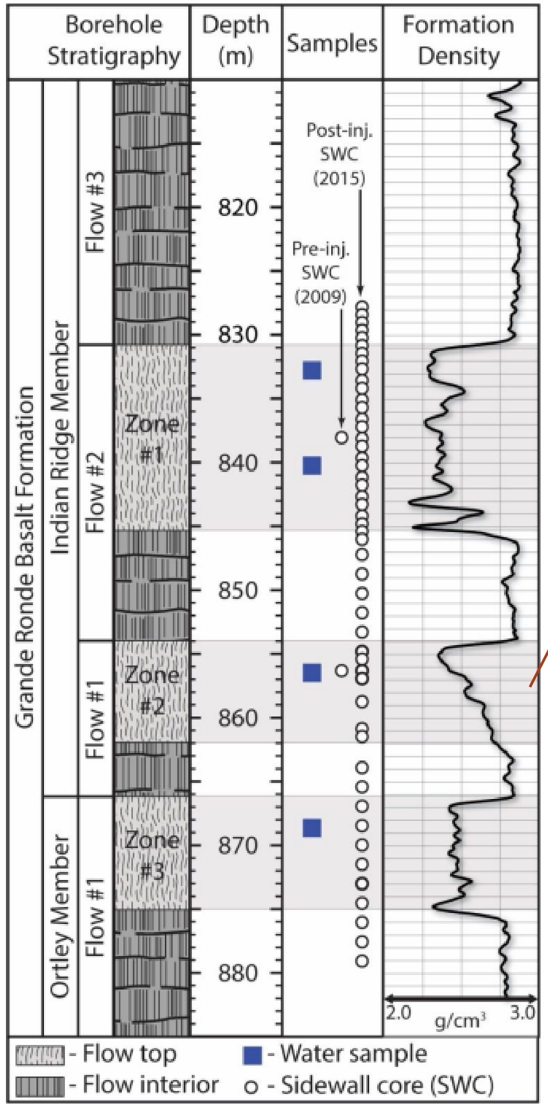


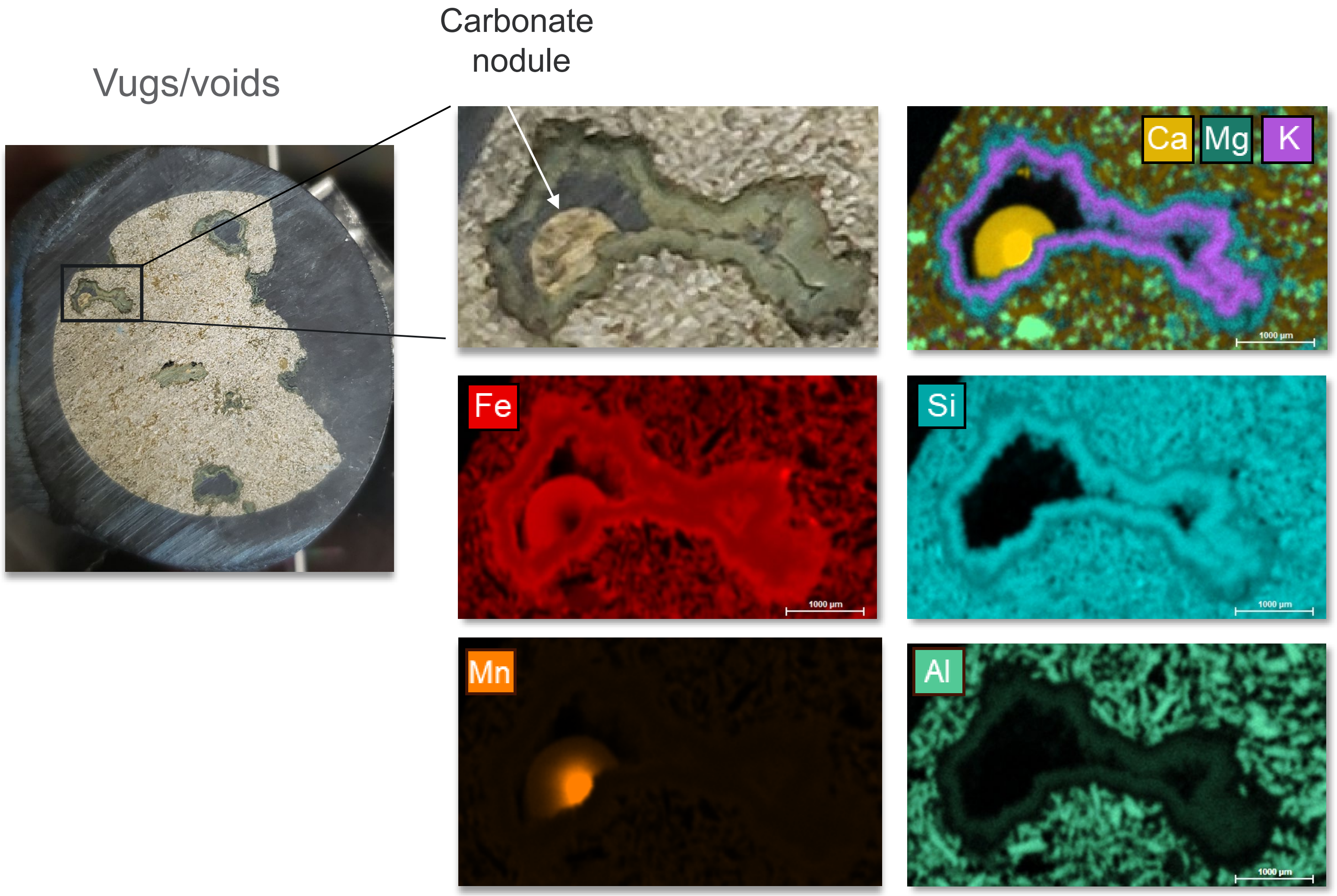
Key Findings: CO_2 injection leads to

1) Release of Mn from pore-lining phases (Mn-oxide/oxyhydroxides)
2) Redistribution of other cations (Si, Al, Fe, etc.)

Lahiri et al., "Facile Metal Release from Pore-Lining Phases Enables Unique Zonation in a Basalt Carbon Mineralization Demonstration", *Environ. Sci. Technol.* 2023, *57*, 11843

Carbonation products forming from CO_2-Basalt interactions are complicated and not easily understood





X-Ray Fluorescence (XRF) chemical mapping shows that the nodules have a **Ca/Mn-rich interior with an Fe-rich outer rim.**

Lahiri et al., "Facile Metal Release from Pore-Lining Phases Enables Unique Zonation in a Basalt Carbon Mineralization Demonstration", *Environ. Sci. Technol.* 2023, *57*, 11843

Nanoscale Analysis Reveals Complex Nature of Mineralization Products

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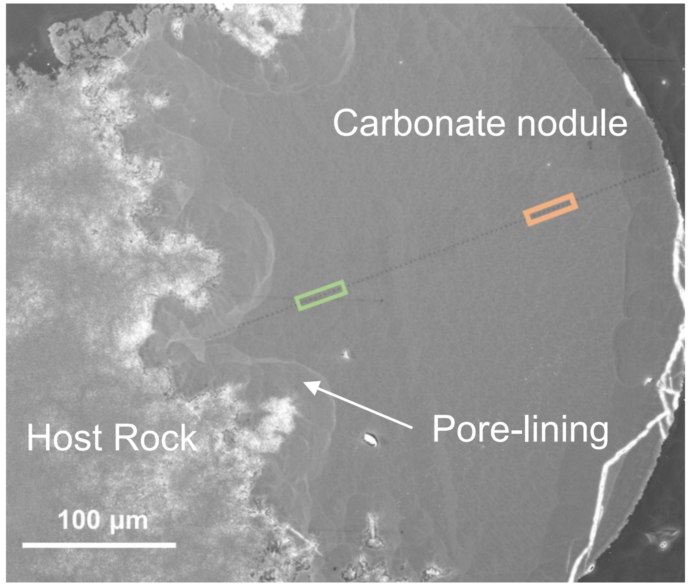
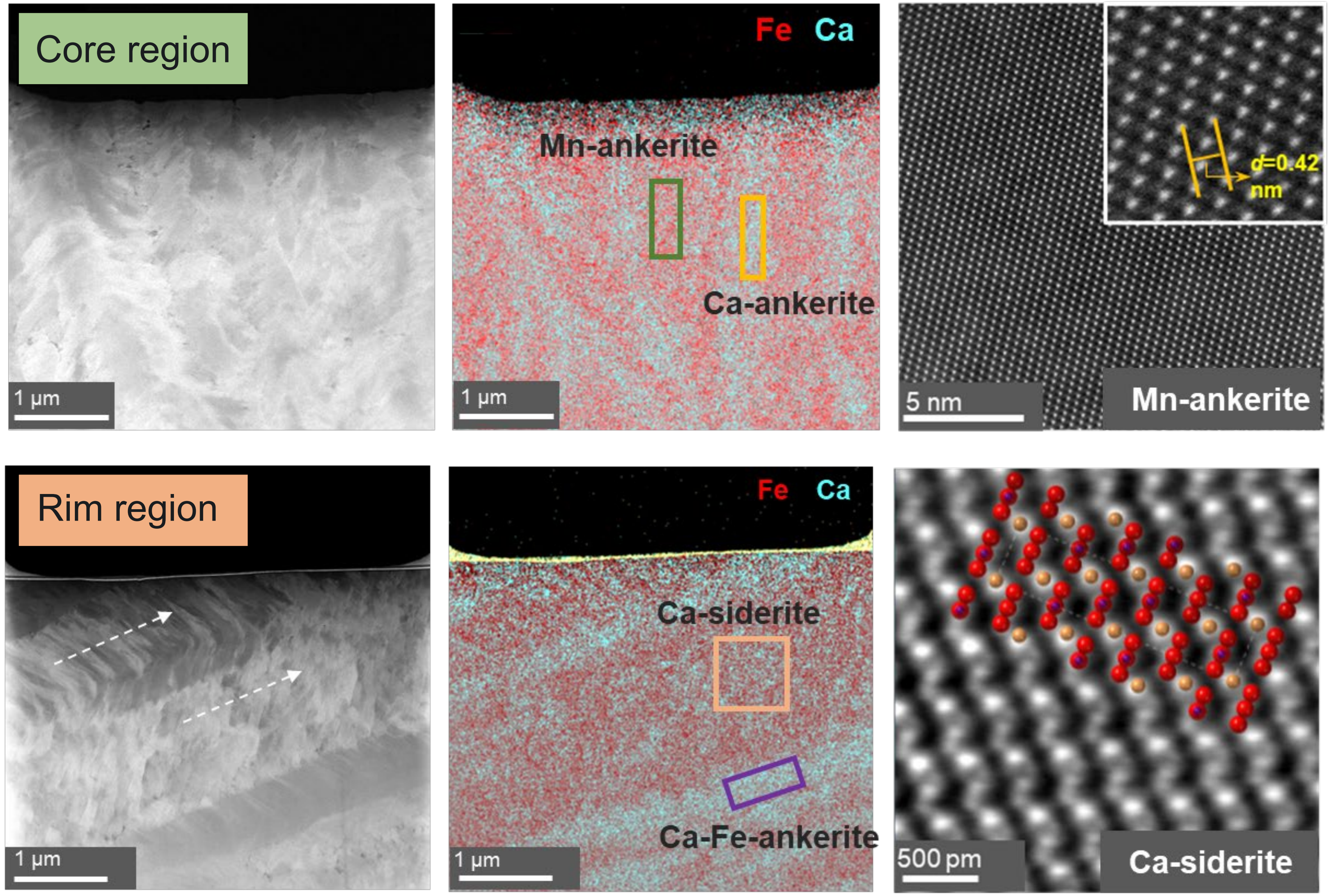
Lahiri et al. **2024**, "Unveiling Complex Carbonate Phases that Drive Geologic CO_2 Mineralization", *Submitted*





Characterization at the nanoscale reveals:

- Four distinct carbonate phases
- Ordered Mn-ankerite and Ca-Fe ankerite not found in nature or synthesized in the laboratory
- Mg is absent in the carbonates

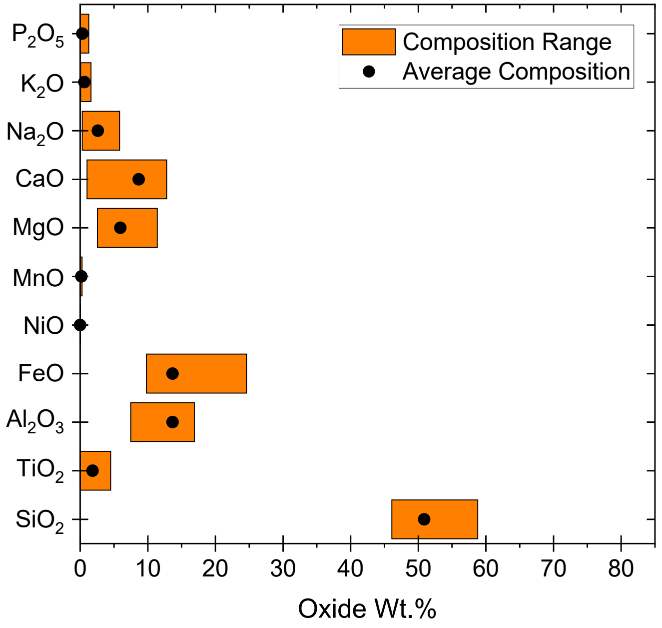
Key Outcomes:
Accurate identification of carbonate phases enables better predictive geochemical modeling and refinement of capacity estimates for future sequestration efforts in reactive reservoirs.

Basalt Glass Chemistry, Structure, and Degree of Weathering Influence Bulk Reaction Rates

For reactive reservoirs, we need to account for CO_2 – fluid – rock reactivity.

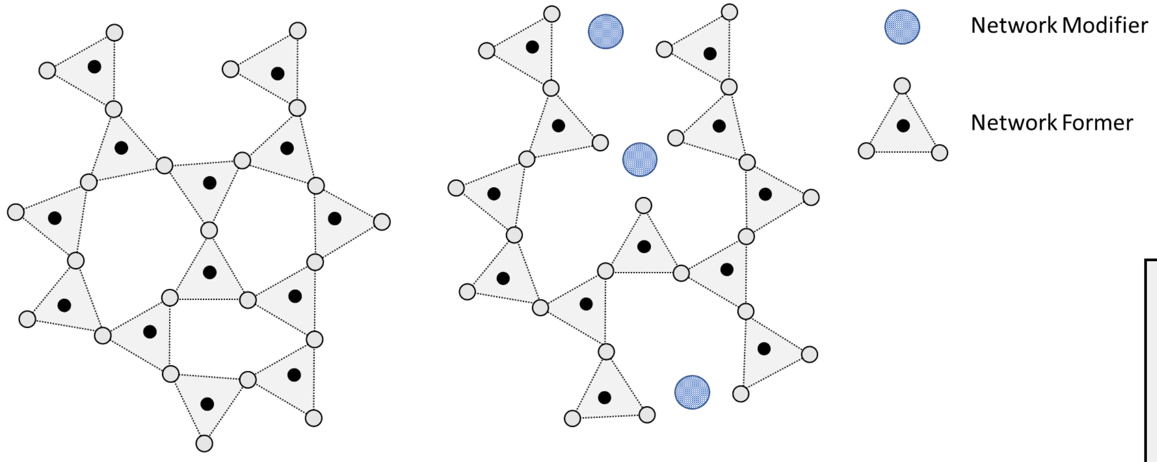
- What reactivity matters when scaled from laboratory to reservoir?
- What variability in laboratory scale reactivity needs to be reflected in reservoir simulations?

Variable Compositions → Variable structure → Variable reactivity



Current reactive simulations use one glass composition while a range of compositions exist globally in basalts. Is this enough?

Structural Roles of Glass-Forming Oxides	
Network Formers:	SiO_2, P_2O_5
Network Modifiers:	ZrO_2, Na_2O, **MnO**, **MgO**, K_2O, Cr_2O_3, **CaO**
Network Intermediates:	TiO_2, **FeO**/Fe_2O_3, Al_2O_3

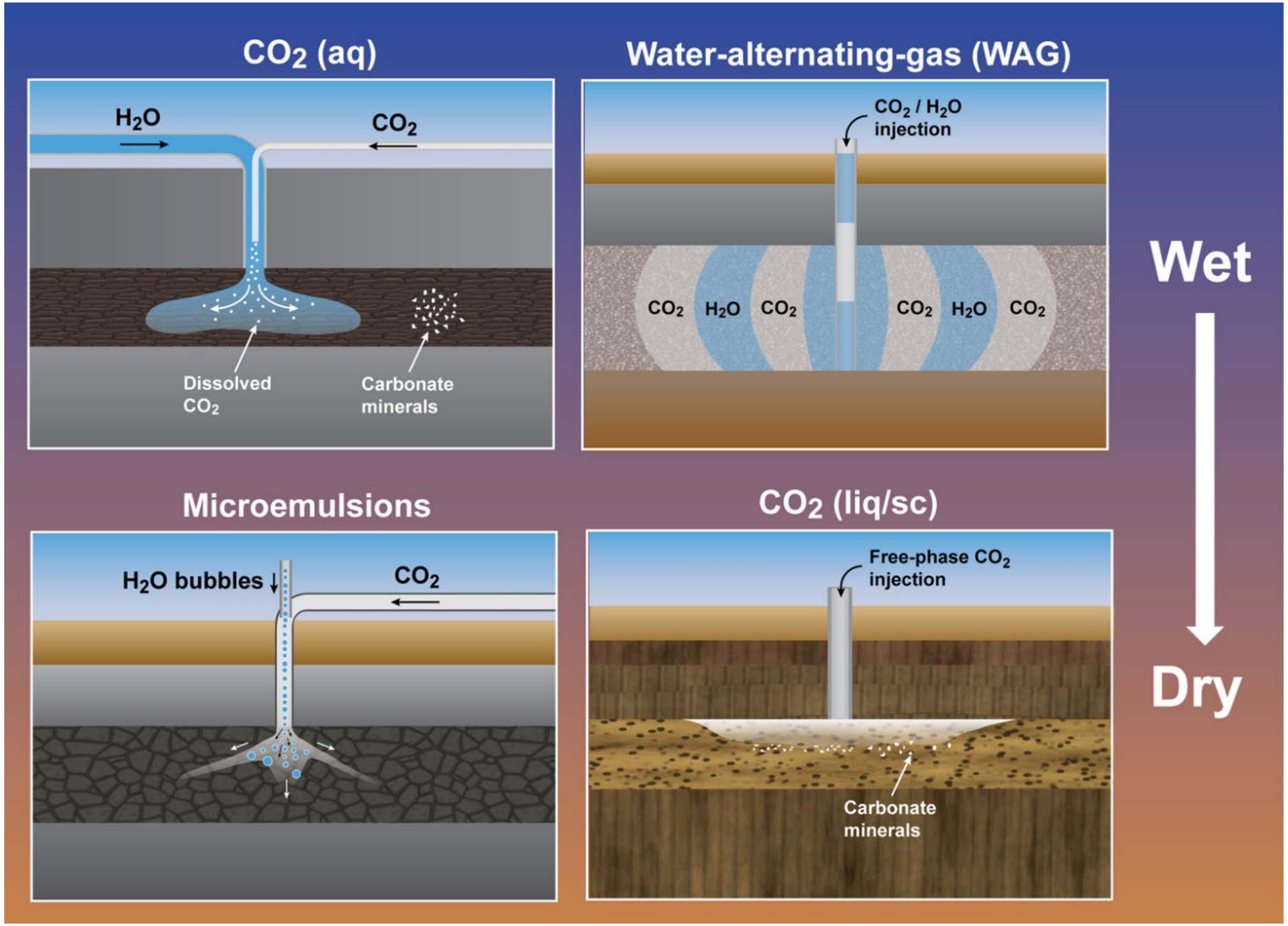


Ginkgo hyaloclastite cuttings from well near Zillah, WA

Use of synthetic and natural glass analogues to explore composition-structure-reactivity relationships in basalt glass.

Aqueous-Dissolved CO_2 and Pure CO_2 are End Members for the Spectrum of CO_2-H_2O Injection Strategies

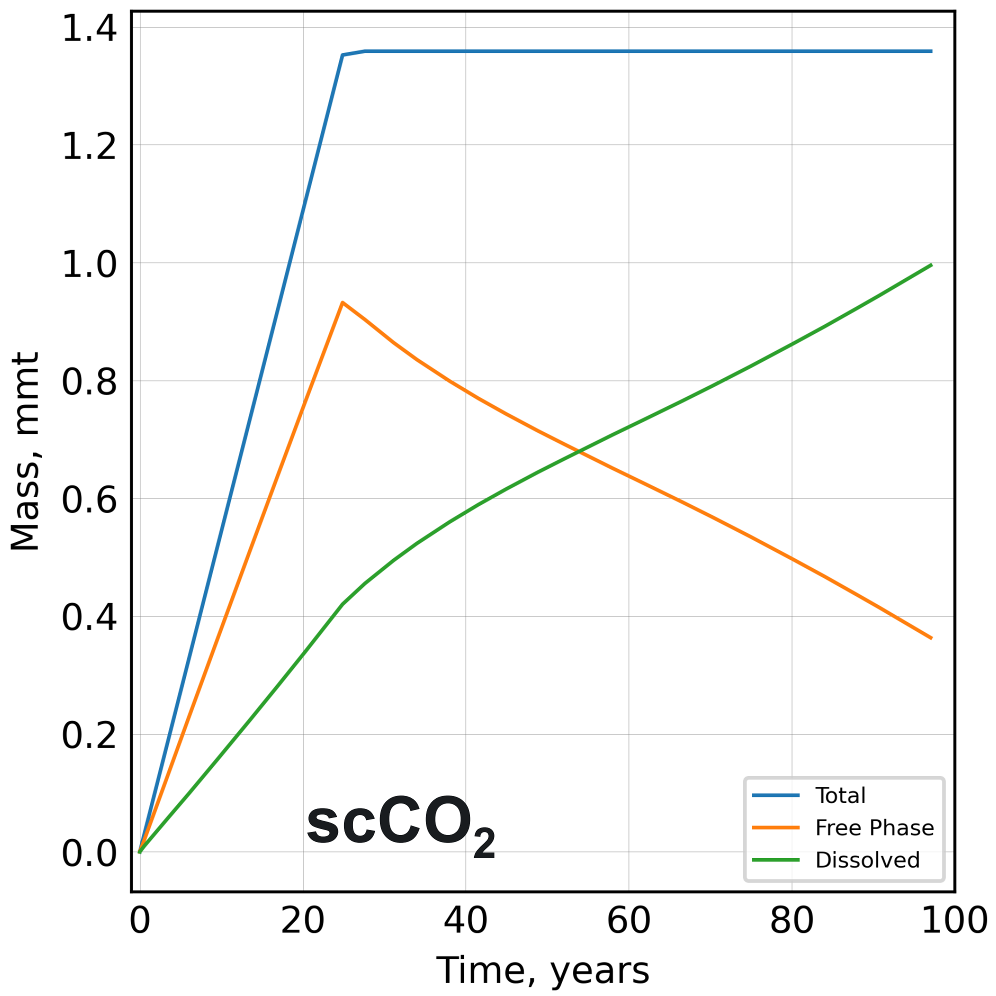
- Potential for tailoring reservoir water content and optimizing carbonation efficiency through hybrid approaches
- Advanced injection strategies allow for H_2O and/or CO_2 microemulsions for controlling the hydration of reservoirs
- Inclusion of engineered additives to enhance mineralization
- Multiphase injection strategies will be catalyzed by advances in drilling technologies and approaches

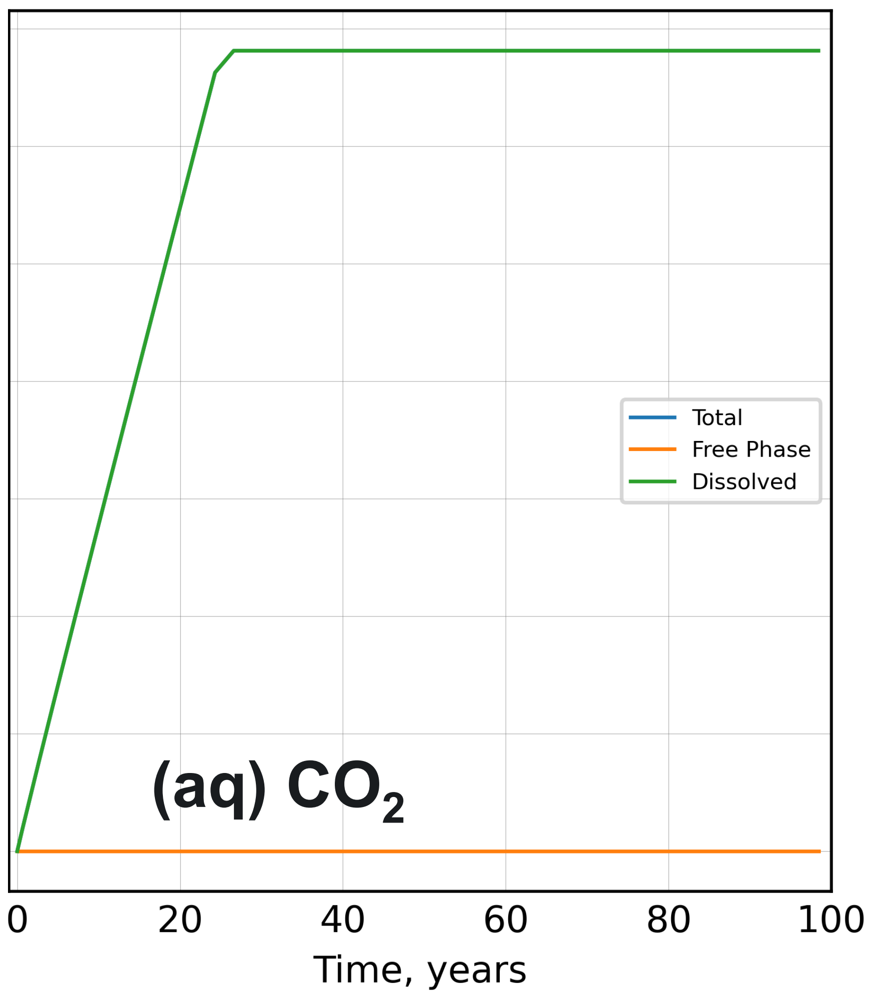


Deployment of carbon storage mineralization should involve site-specific injection strategies for pore space optimization

For Carbon Mineral Storage Performance Optimization, we need to consider impacts of injectant phase/properties

Case Study: Inject 1.35 MMT of CO_2 as (1) aqueous dissolved and (2) $scCO_2$ phase, over 25 years. For $aqCO_2$, 31.6 MMT of water was injected [generic sandstone, 25% porosity, 500mD].





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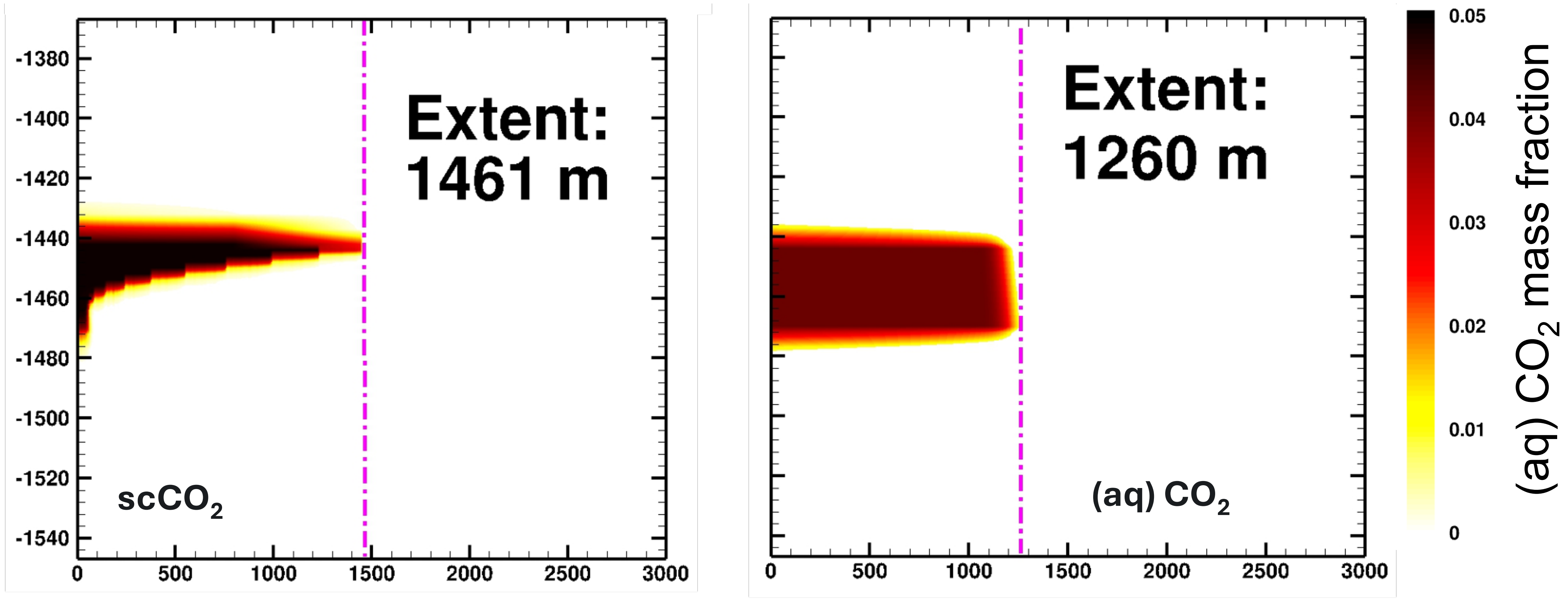
(aq) CO_2 Mass Fraction (25 years)



Distance from the well, m

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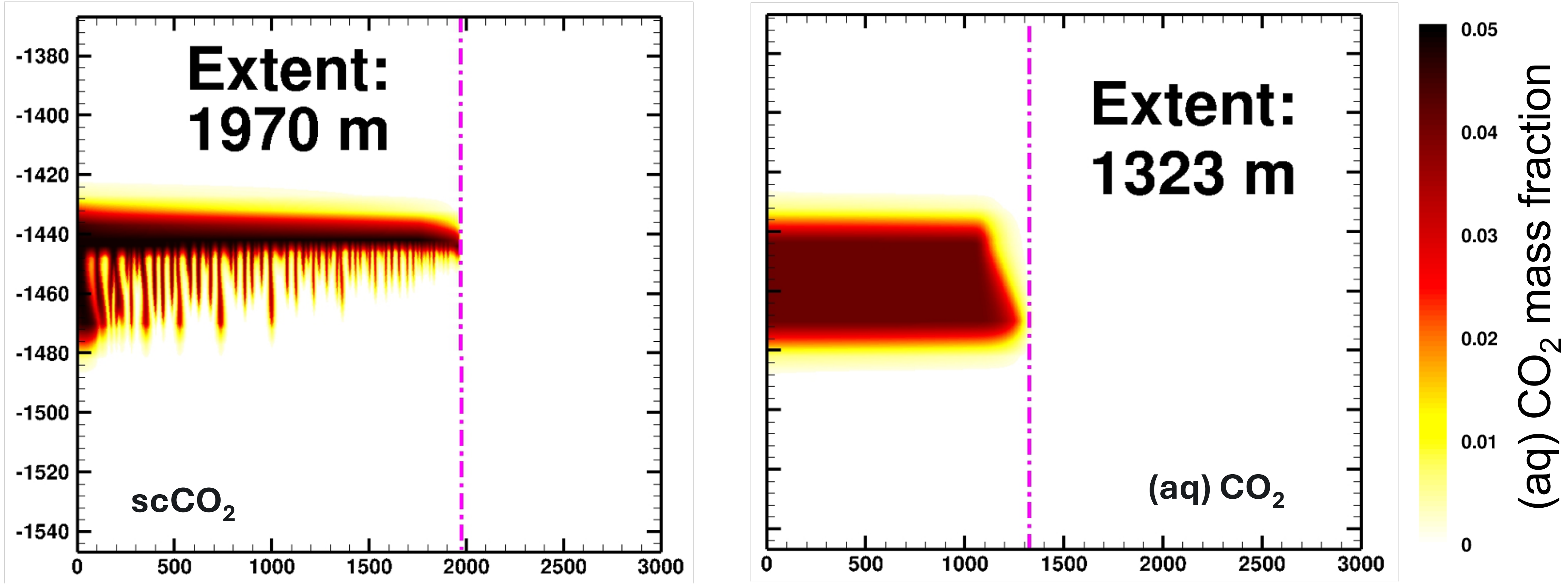
(aq) CO_2 Mass Fraction (100 years)



Distance from the well, m

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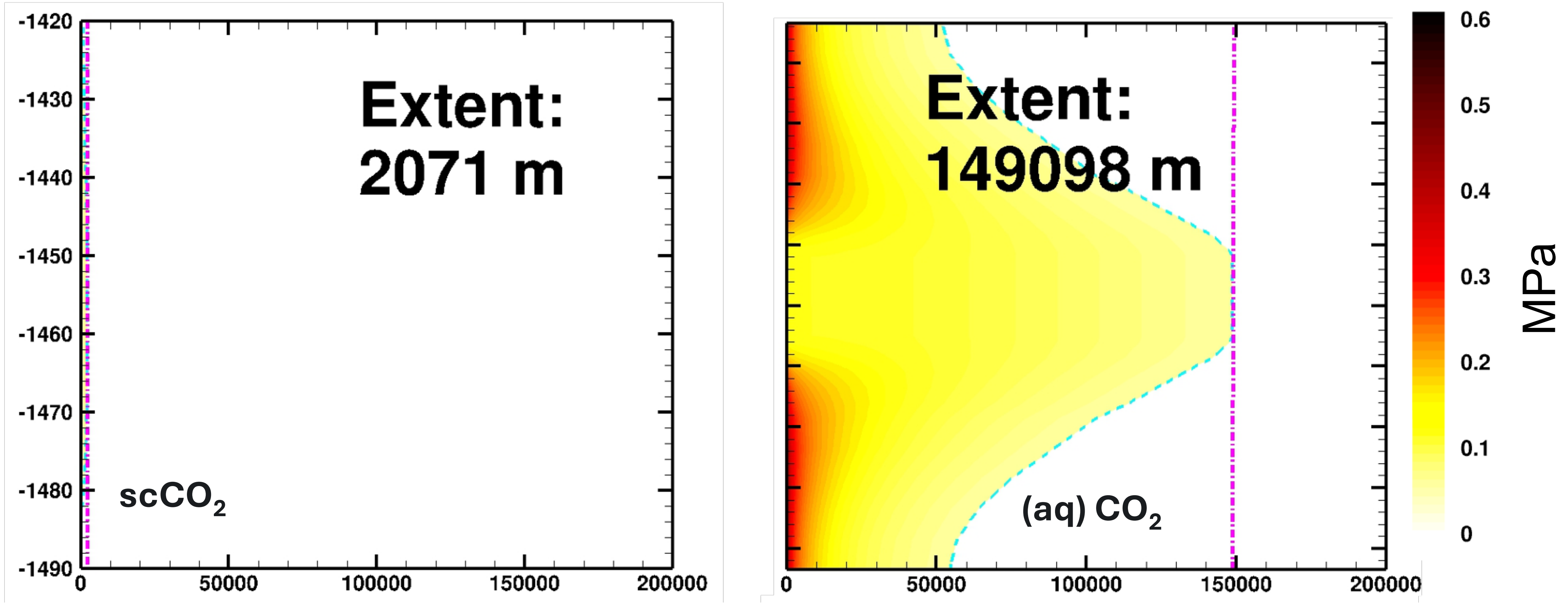
Pressure Extent (AoR) (25 years)

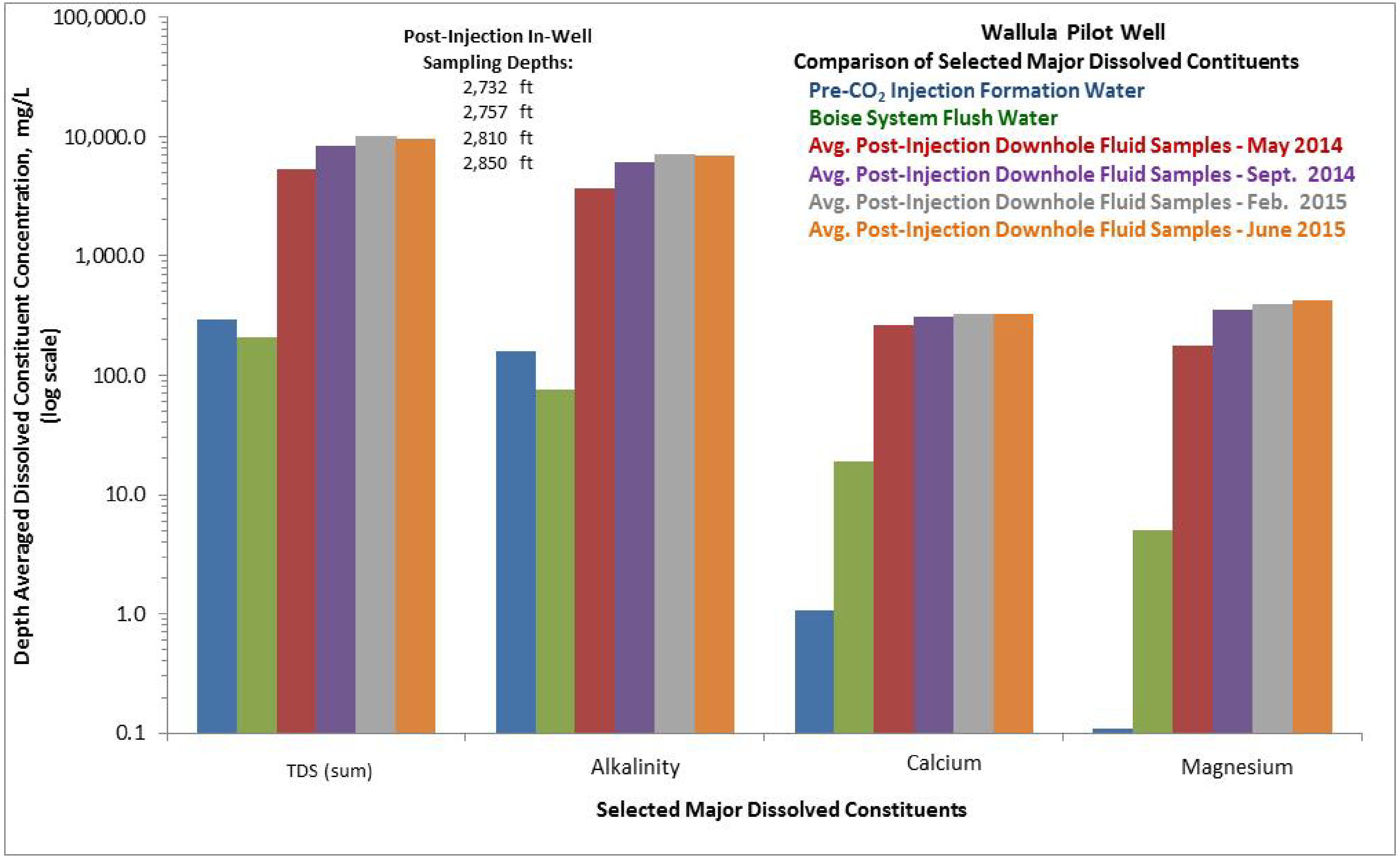


Distance from the well, m

What Do We Know About Reservoir Quality Water Post CO_2 Injection?

Water Sampling Data from Wallula

- Downhole water sampling (2-year span)
- Significant increases (factor of 10 to 100X higher) concentrations
- TDS shows a plateau trend after two years.
- Concentrations continued to increase post injection



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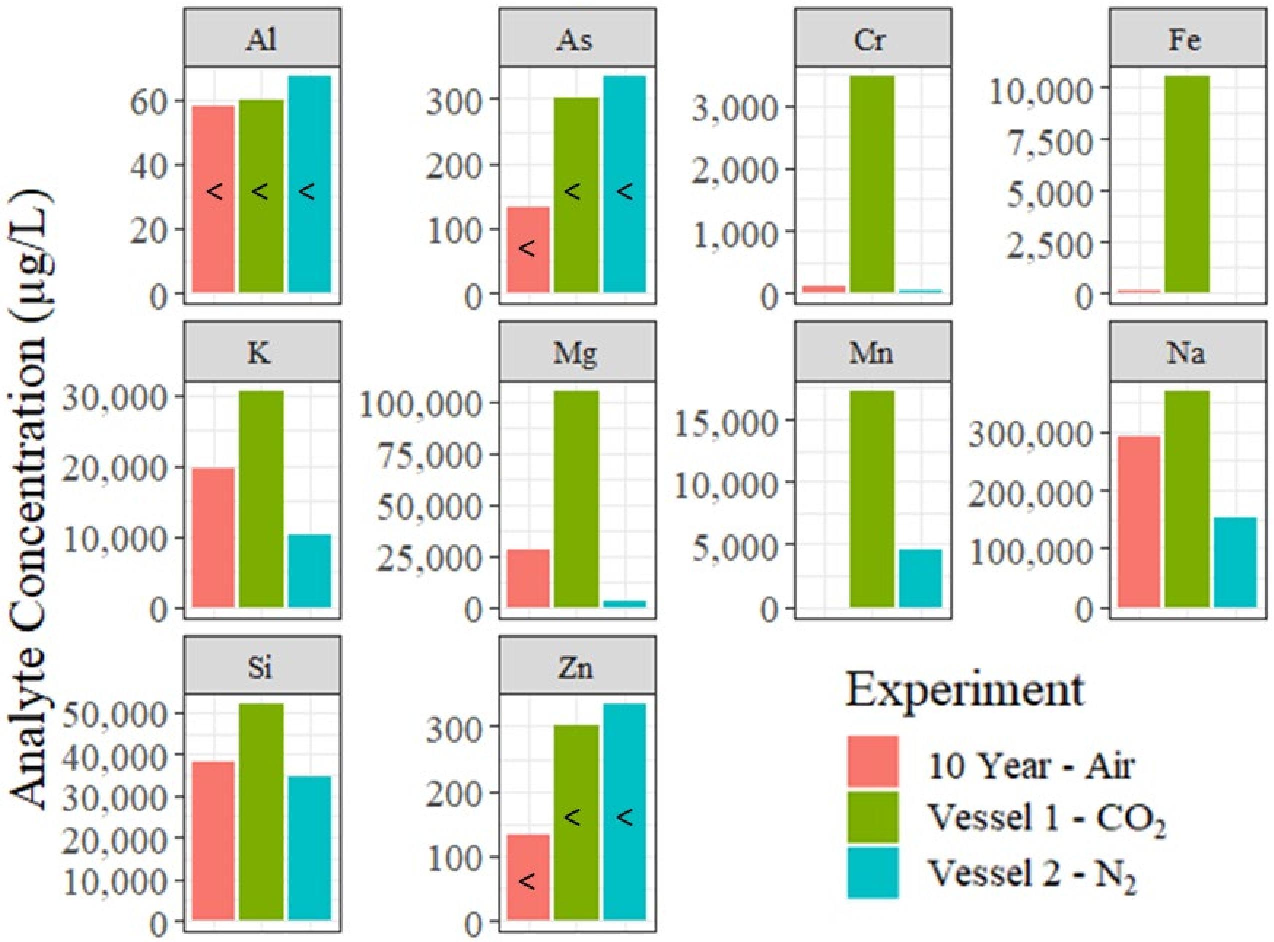
- Significant increases (factor of 10 to 100X higher) concentrations
- TDS shows a plateau trend after two years.
- Concentrations continued to increase post injection
- Laboratory testing will provide insights into groundwater impacts.

Results of fluid sampling after 45 days of reaction in (aq)CO_2 (Vessel 1) and N_2 (Vessel 2) at 90 bar and 90 °C, compared to a 10-year compressed air experiment.



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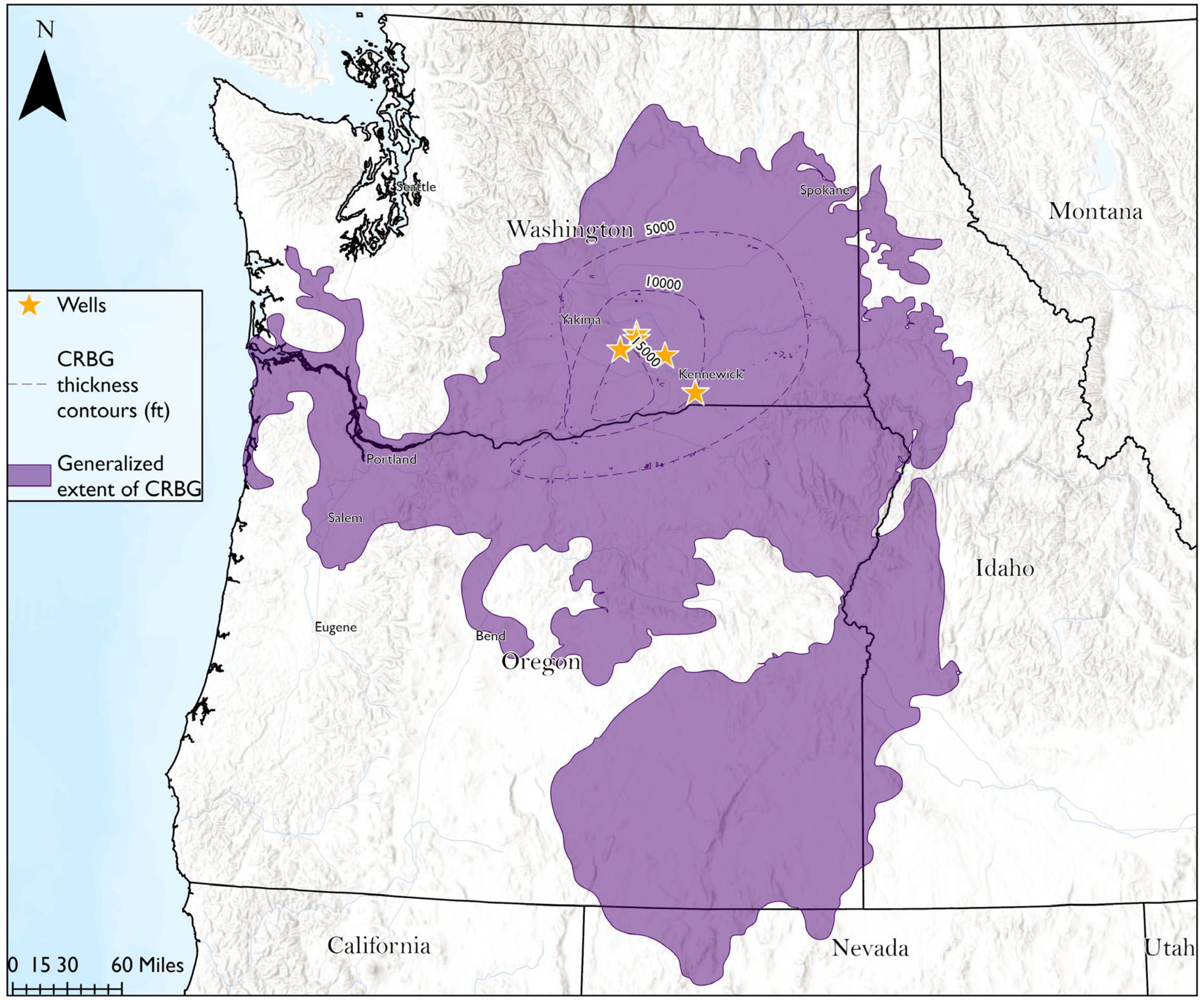
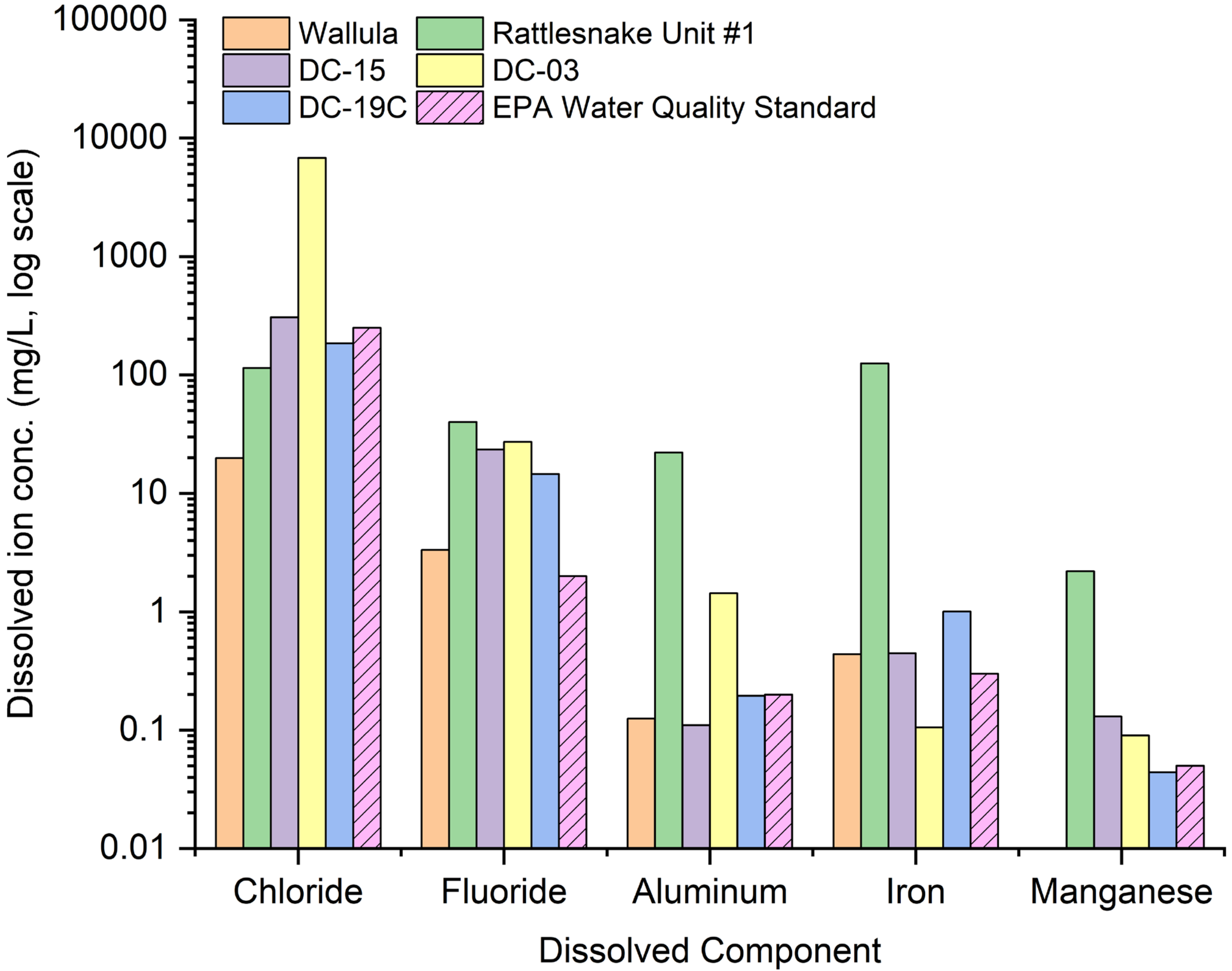
Water Quality Is a Key concern of Carbon Storge Developers and Hosting Communities

For reservoir characterization, we need to understand hydrochemical constituents and zonal isolation

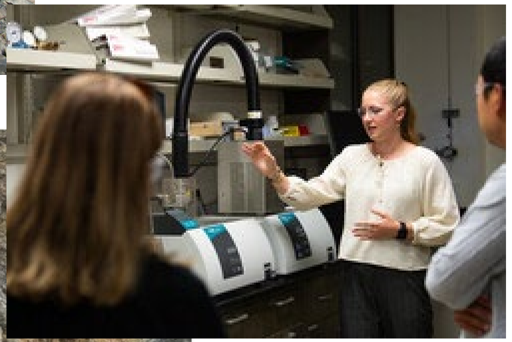
- What are the structural and stratigraphic controls for zonal isolation?
- What is the chemical composition of deep basalt aquifers and what is the recharge mechanism?
- What community benefit collaboration opportunities exist for water reuse?

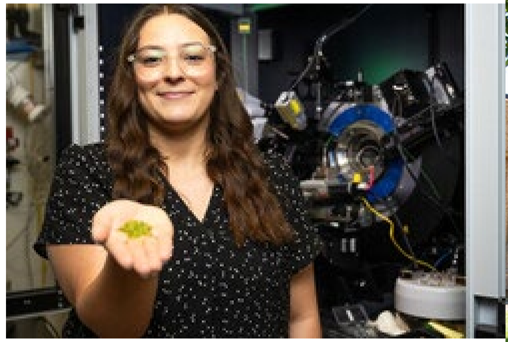


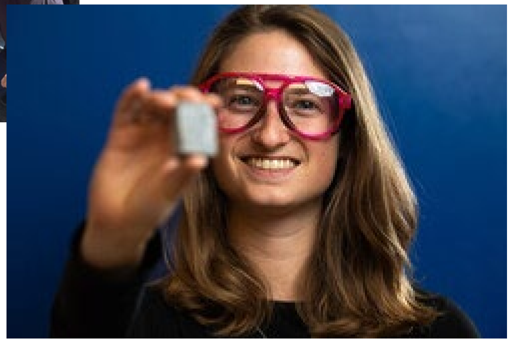


Stakeholder and Community Outreach is Strategic for Clean Energy Project Acceptance and Developing STEM Pipeline

- Early inclusion of communities and stakeholders in clean energy projects is vital
- Early career researchers (e.g., interns, PDs, staff, visitors, etc.)
- DOE synergy: FECM (MLEF), SC (VFP, SULI, SCGSR), NNSA (MSIIP), CCI, GEM
- Nurturing sustainable STEM pipeline that fosters diversity and inclusivity







Next Steps (FY25)

- Develop modeling approaches that incorporate critical insights from field and laboratory studies
- Identify dominate fluid flow regimes to better minimize impacts to porosity and permeability
- Establish a baseline modeling approach, benchmarked by laboratory studies, to:
  - Simulate formation water recovery post CO_2 injection,
  - Support permitting efforts (e.g., class VI),
  - Develop engineered injection strategies (e.g., WAG, additives, critical mineral extraction, etc.) for optimizing mineralization and minimize impacts to ground water.

Carbon Mineralization Research Portfolio at PNNL connects Fundamental Processes to Field Scale Deployment

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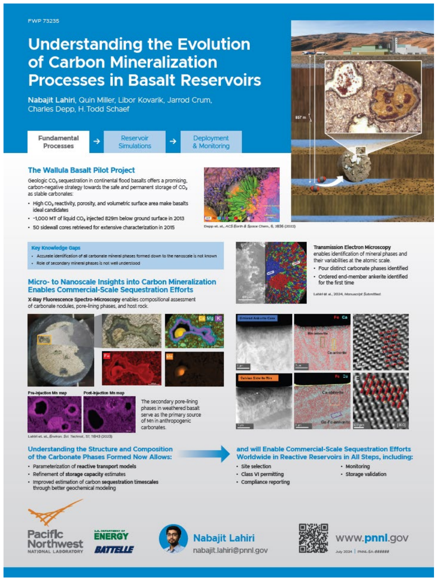

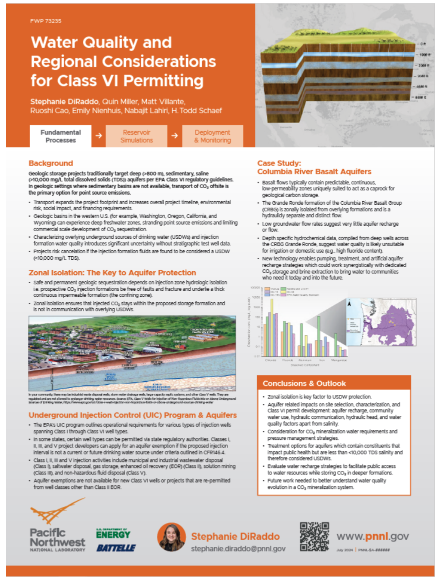

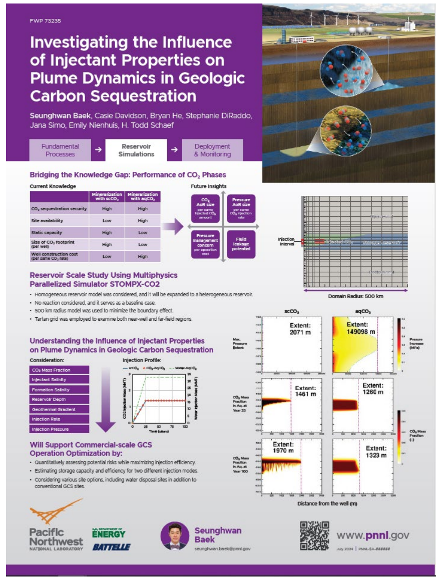

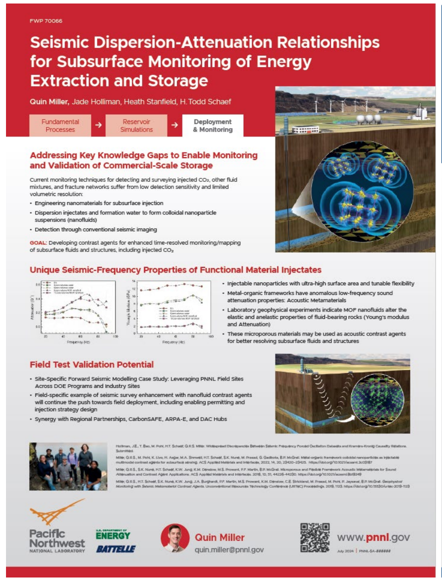

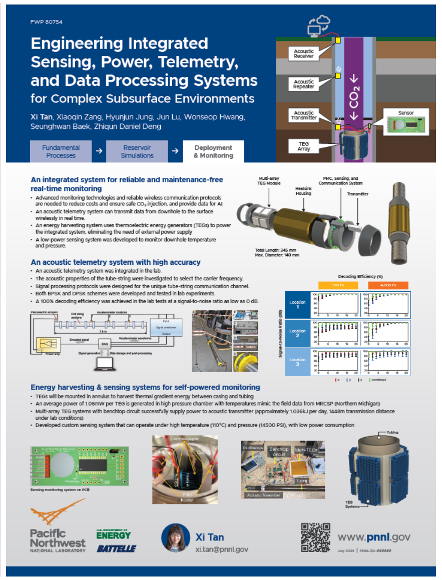

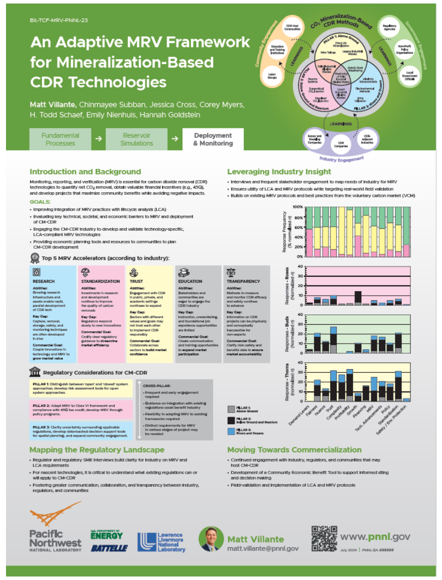

Pore-scale to nanoscale studies inform molecular mechanisms of carbonate nucleation and growth

Reactive Transport Simulations help derisk permitting and deployment of carbon storage at the field scale

Advanced **subsurface monitoring** and **deployment** technologies enable commercial-scale carbon sequestration in reactive reservoirs, including community and stakeholder engagement

Tuesday (Aug 6) at 5:45pm at the Ballroom Gallery!

DOE Office of Fossil Energy Carbon Management (FECM)
Darin Damiani (DOE HQ)
Carbon Utilization and Storage Partnership (CUSP)

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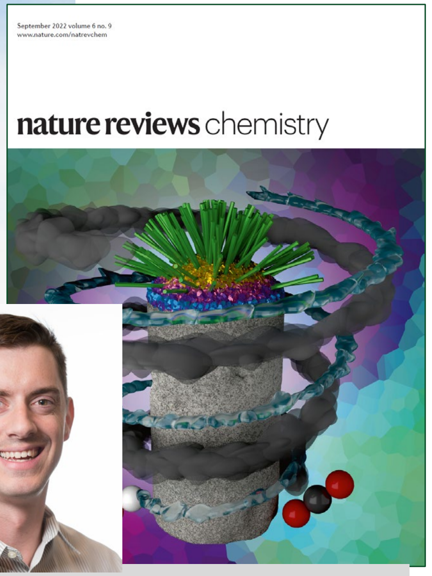
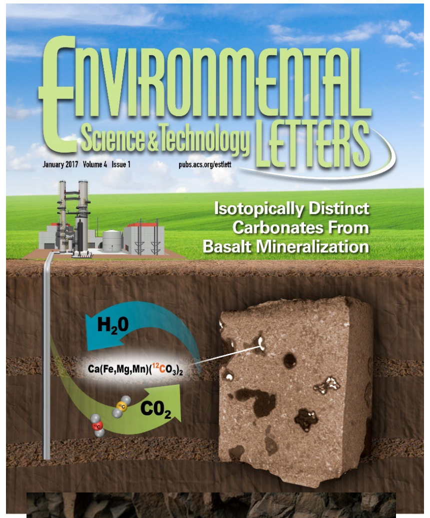
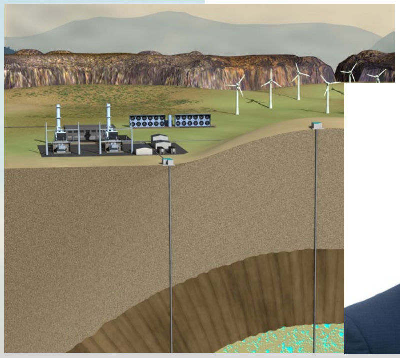
U.S. DEPARTMENT OF ENERGY Fossil Energy and Carbon Management



Qomi, Miller, Schaef et al. 2022 Molecular-Scale Mechanisms of CO_2 Mineralization in Nanoscale Interfacial Water Films, Nature Reviews Chemistry

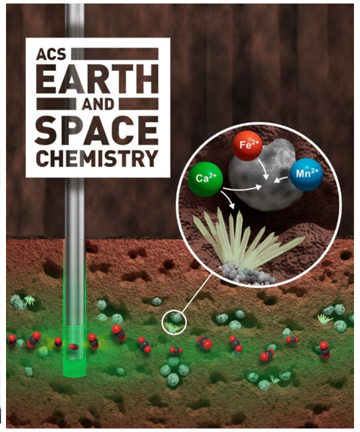


Miller and Schaef, 2022 Activation Energy of Magnesite ($MgCO_3$) Precipitation: Recent Insights from Olivine Carbonation Studies. Environmental Science: Advances

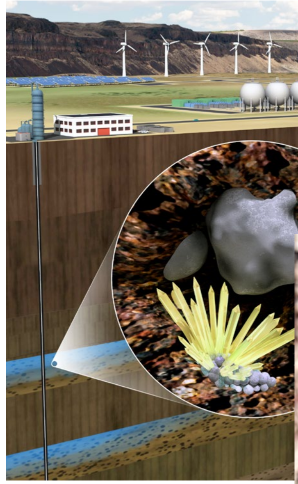


Cao et al, 2024, Gigaton Commercial-Scale Carbon Storage and Mineralization Potential in Stacked Columbia River Basalt Reservoirs, Int. J. Greenhouse Gas Control.

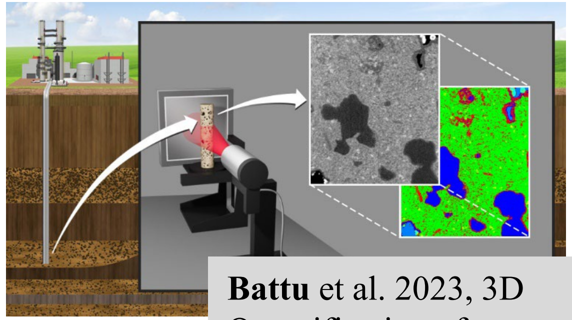
Stanfield et al. 2024, Carbon Mineralization and Critical Mineral Resource Evaluation Pathways for Mafic–Ultramafic Assets, ACS Earth & Space Chem.



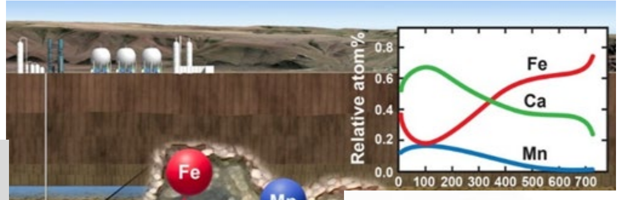
Depp et al., 2022, Pore-scale Microenvironments Control Anthropogenic Carbon Mineralization Outcomes in Basalt, ACS Earth & Space Chemistry

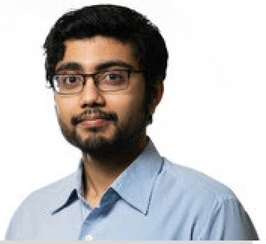


Polites et al. 2022, Exotic Carbonate Mineralization Recovered from a Deep Basalt Carbon Storage Demonstration, ES&T

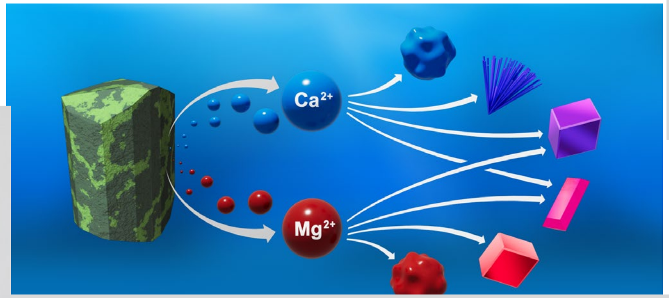


Battu et al. 2023, 3D Quantification of Anthropogenic Carbon Mineralization and Pore Networks in Stacked Basalt Reservoirs, ES&T





Lahiri et al. 2023, Facile Metal Release from Pore-lining Phases Enables Unique Carbonate Zonation in a Basalt Carbon Mineralization Demonstration, ES&T.



Aguila et al. 2023, Kinetics of Diopside Reactivity for Carbon Mineralization in Mafic-Ultramafic Rocks, Environmental Science: Nano.

Acknowledgements

Thank you Nicholas Means and Darin Damiani for supporting this research. This material is based upon work funded by the U.S. Department of Energy Office of Fossil Energy Carbon Management at PNNL through the National Energy Technology Laboratory, Morgantown, West Virginia.