



**Pacific  
Northwest**  
NATIONAL LABORATORY

# Sequestration in Basalt Formations

FWP-73235

U.S. Department of Energy  
National Energy Technology Laboratory  
Carbon Management Project Review Meeting  
August 28 – September 1, 2023  
Carbon Transport and Storage Breakout Session 2  
Tuesday 1:10pm, 315/316

H. Todd Schaefer



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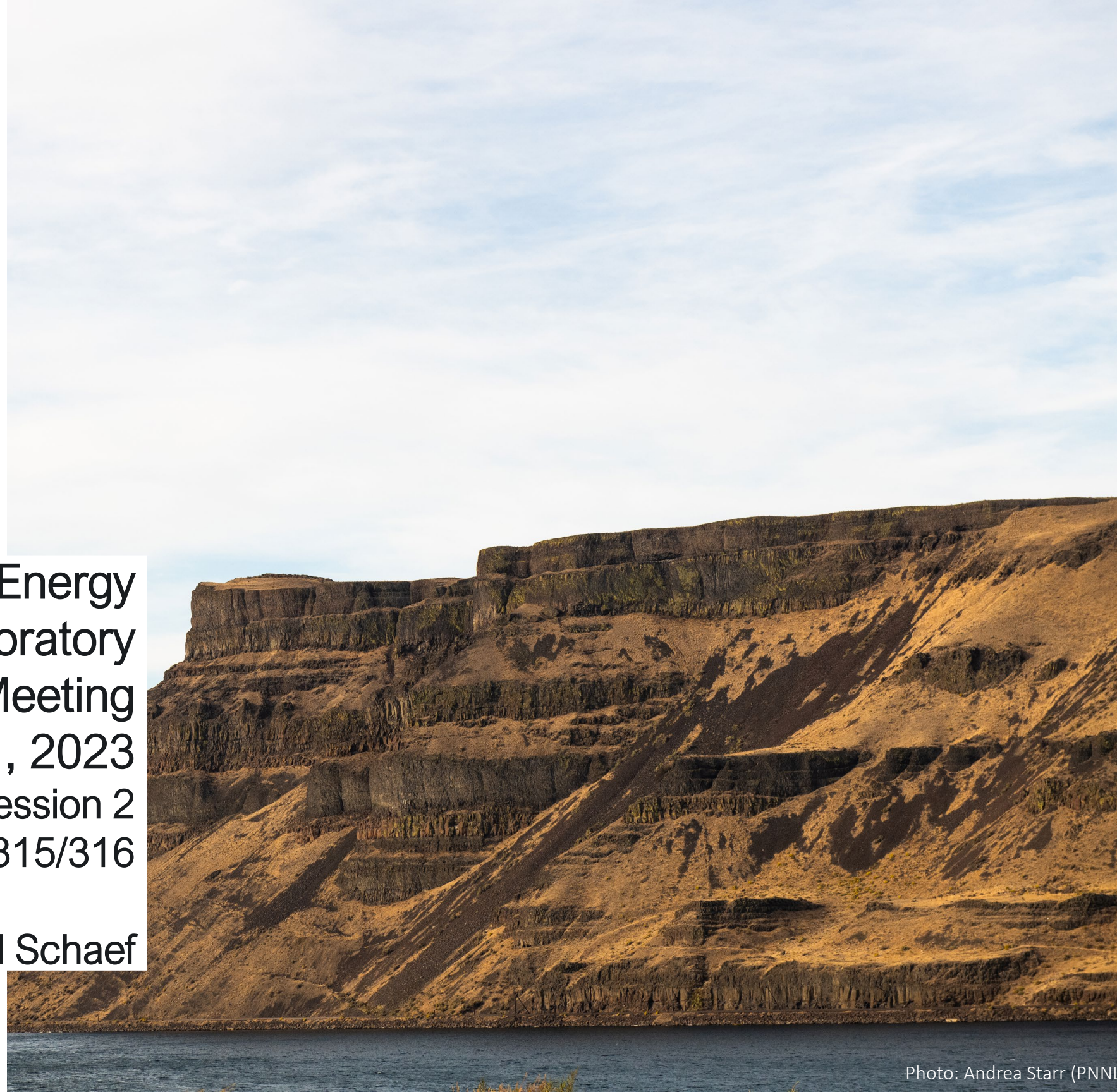


Photo: Andrea Starr (PNNL)

# 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

## ➤ Summary of Lessons Learned to date



# Health, Safety, and Environment Share: Everyday Respect

- Leaders need to be the shining examples of everyday respect
- Caring, courageous and curious leadership
- Elevate process over results
- Cultivating talent, not teams

## 5 Ways To Promote Respect In The Workplace

- Choose Your Words Carefully
- Make Soft Skills a Priority
- Resist All Forms of Exclusion
- Clearly Articulate Zero Tolerance for Harassment
- Get Transparent



# Project Overview

- Key Project Participants
  - State/Federal, National Lab, Universities, and Industry

## Collaboration Development

state/federal    national labs    universities    industry

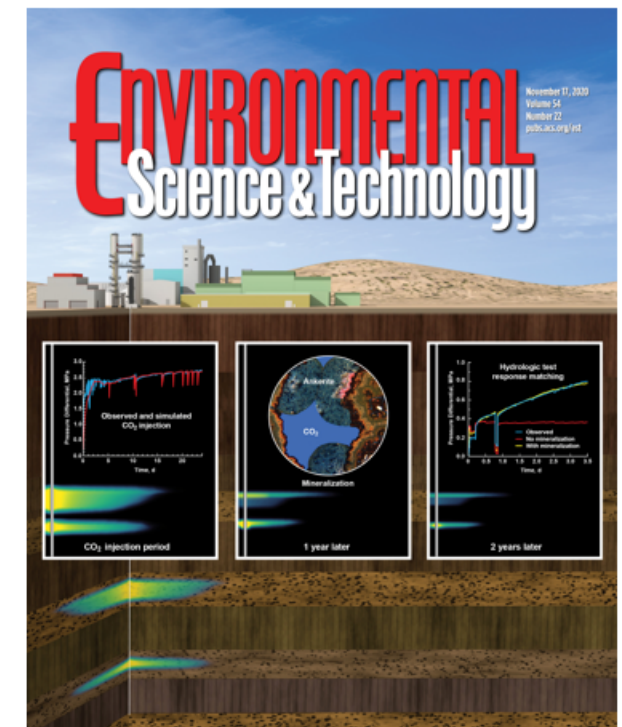
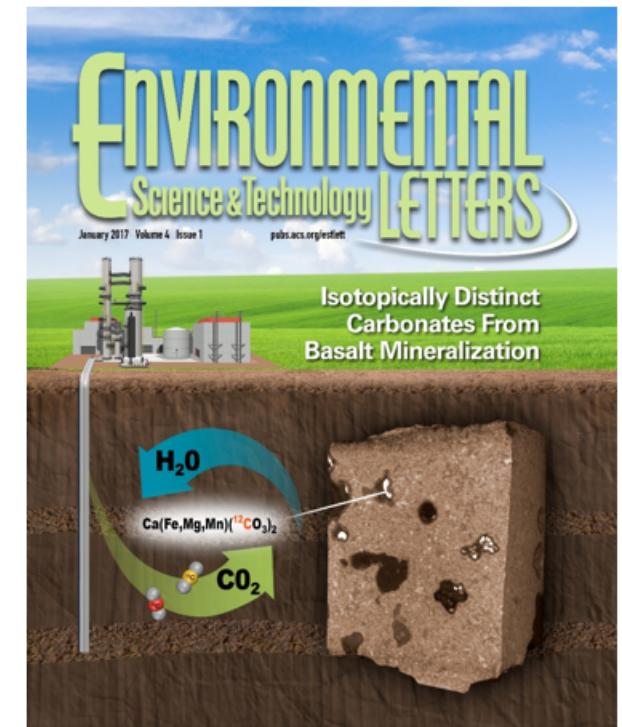


The collage includes logos for the following organizations:

- State/Federal:** Washington Department of Natural Resources, U.S. Department of the Interior Geological Survey, WI DNR, State of Oregon.
- National Labs:** National Energy Technology Laboratory, Oak Ridge National Laboratory, Sandia National Laboratories.
- Universities:** Columbia University, Harvard University, Colorado School of Mines, Massachusetts Institute of Technology, University of California, Cornell University, University of Minnesota, Washington University in St. Louis, University of Wyoming, Francis Marion University, Yale University, University of Minnesota Duluth.
- Industry:** Aramco, Mitsubishi, Eden, Rio Tinto, Schlumberger, Talon Metals Corp, Carbon Capture, Oxy, Calpine, Sibanye Stillwater, Carbfix, EnerPlus.

# Project Overview

- Key Project Participants
  - State/Federal, National Lab, Universities, and Industry
- Project Objectives
  - Provide support for post-closure characterization activities associated with the Wallula Basalt Pilot Well.
  - Biomineralization reactions affecting the effectiveness of CO<sub>2</sub> injection, stability of primary minerals in the reservoir and caprock, precipitation of secondary carbonate minerals, and potential impacts to associated critical minerals (e.g., release rates, precipitation products, etc.)
  - Create and disseminate reactive modeling tools that can simulate interactions of scCO<sub>2</sub> fluids in basaltic reservoirs.
- Project Performance Dates and Funding Summary
  - FY21 \$200K; FY22 \$150K; FY23 \$250K



# Project Background

## MINERALIZATION SETTINGS

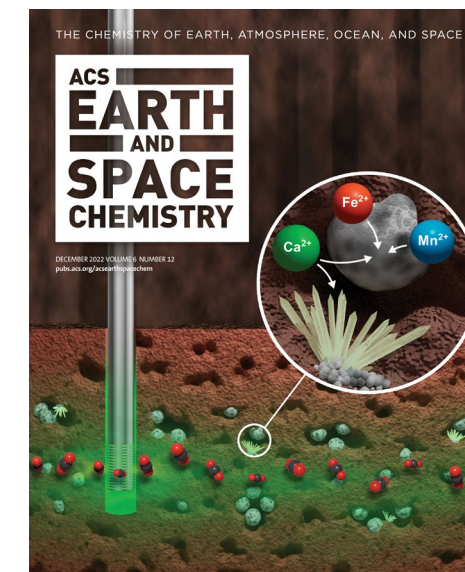
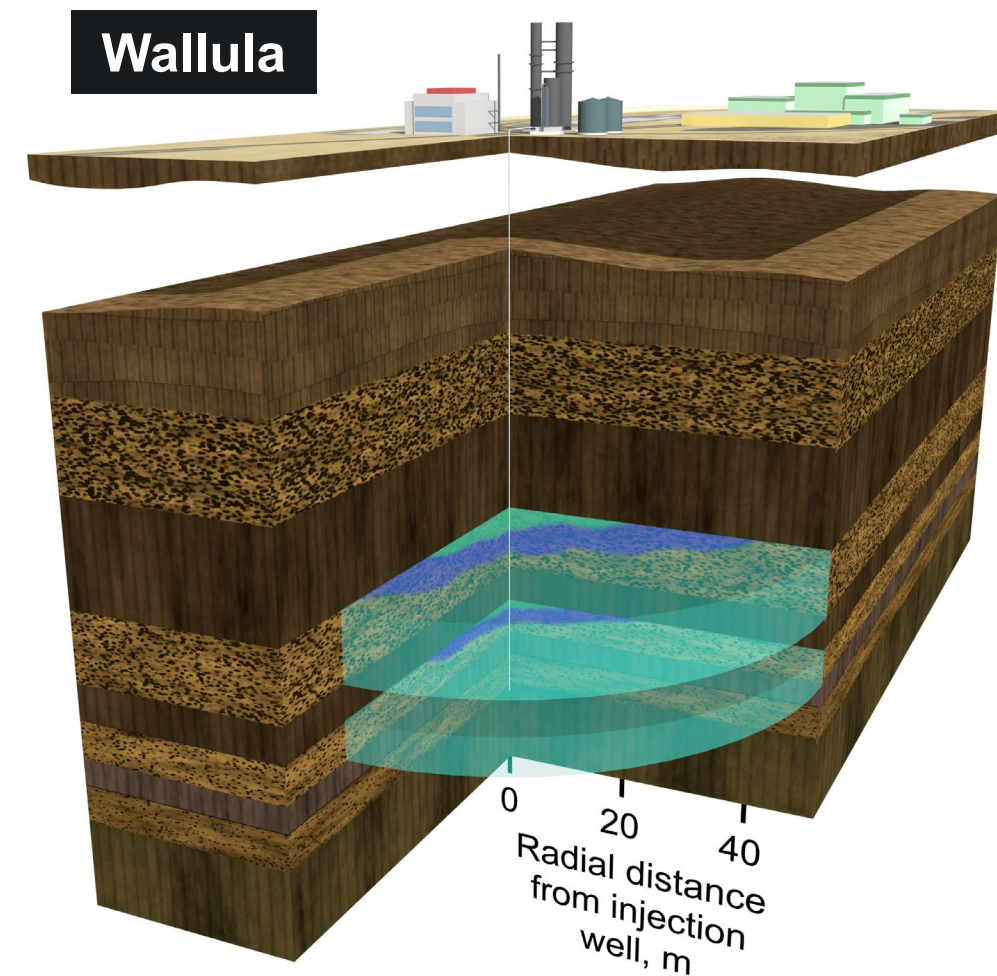
- Targets for in situ CO<sub>2</sub> mineralization include:
  - Porous reservoirs (e.g., basalts)
  - Fractured reservoirs (e.g., peridotite, serpentinite)
  - Hybrid systems (e.g., fractured basalt-hosted geothermal reservoirs, basalt-rich sandstones)
- Ex situ mineralization efforts focus on mine tailings, soil amendments, and engineered systems that leverage non-ambient conditions

## BASALT GEOCHEMISTRY

- Basalts are comprised of crystalline minerals (feldspars, pyroxenes, olivine) within a highly reactive glassy matrix
  - carbonate-forming cations (e.g., Ca<sup>+2</sup>, Fe<sup>+2</sup>, Mg<sup>+2</sup>, and Mn<sup>+2</sup>)
- Carbonate type controlled by depth, temperature, surface area, pre-existing secondary minerals, pressure, & water chemistry

### Opportunities to Solve Challenges:

- Assessing mineral carbonation processes from the SWCs retrieved post CO<sub>2</sub> injection, providing a unique perspective on subsurface carbon mineralization.
- Develop modeling tools that incorporate critical insights from field and laboratory studies to advance CO<sub>2</sub> mineralization storage





# Technical Approach/Project Scope For FY22 & FY23 (by task)



## FY22 (FY23-24) Scope

**Task 1:** Post-closure characterization activities associated with the Wallula Basalt Carbon Sequestration Pilot Well

## FY23 Scope

**Task 1:** Biomineralization Literature Review

- Review biomineralization in ultra mafic and mafic rocks and minerals, guiding Task 3, 4

**Task 2:** Biosignatures of Natural and Anthropogenic Wallula Carbonates

- Evaluate role of biogenic carbon cycles on carbon mineralization at the Wallula site

**Task 3:** Biomolecule Enhancement of Carbonation

- Explore role of biomolecule proxies on carbonate precipitation in mafic and ultramafic rocks and minerals.

**Task 4:** CM Outcomes During Carbonation

- Fate of CM in the presence of biomineralization

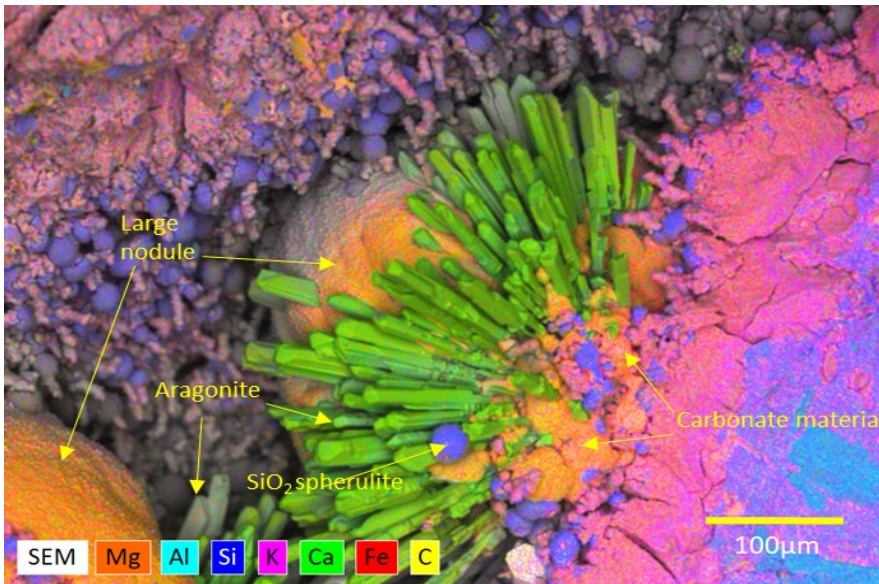
### **Key Objectives:**

- Extracting key information from the post-injection/pre-closure phase of the basalt pilot project, with a focus on assessing mineral carbonation processes from the SWCs retrieved post CO<sub>2</sub> injection.
- Enhancing carbonation of basalt through biomineralization and determining the fate of critical minerals in these formations.
- Provide to the mineralization community key data to advance CO<sub>2</sub> mineralization in reactive reservoirs.
- Support and advance MRV for mineralization.

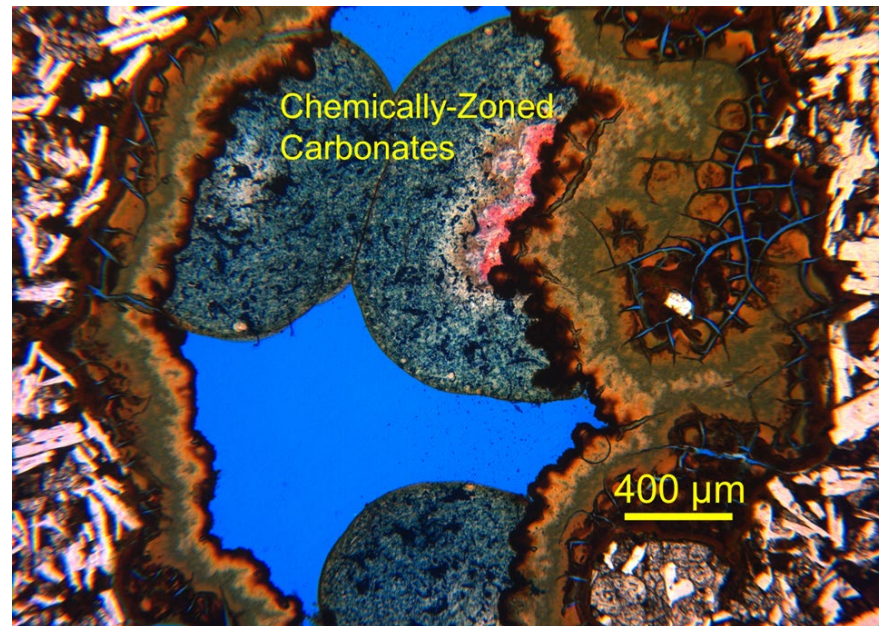
# Predicting CO<sub>2</sub> Mineralization Requires Understanding Reaction Pathway Endpoints

CO<sub>2</sub> mineralization processes are overlapping and complex

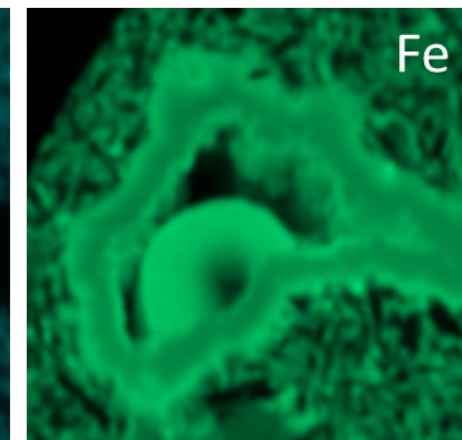
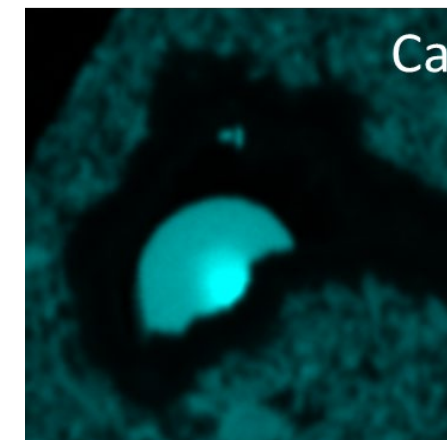
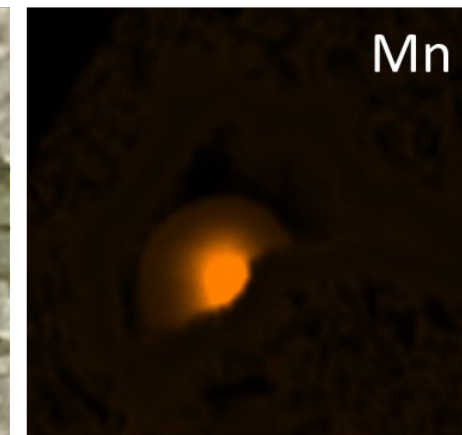
- Observed carbon mineralization assemblages at Wallula include aragonite (CaCO<sub>3</sub>), siderite (FeCO<sub>3</sub>), ankerite [Ca(Fe,Mn)(CO<sub>3</sub>)<sub>2</sub>], and non-carbonate minerals
- Chemically-zoned carbonate nodules (Ca, Mn, and Fe)
- Unique chemistries directly correlated to pre-existing pore-lining minerals.



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



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

## Key Questions and Knowledge Gaps:

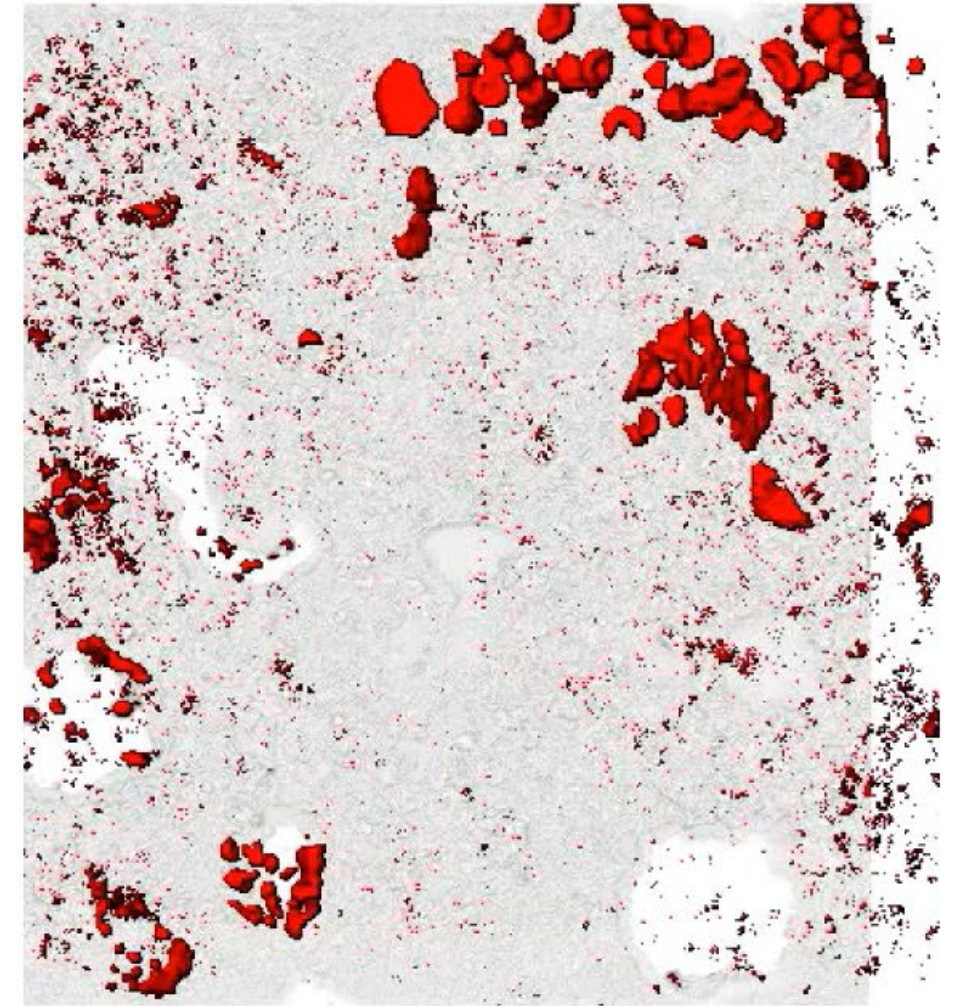
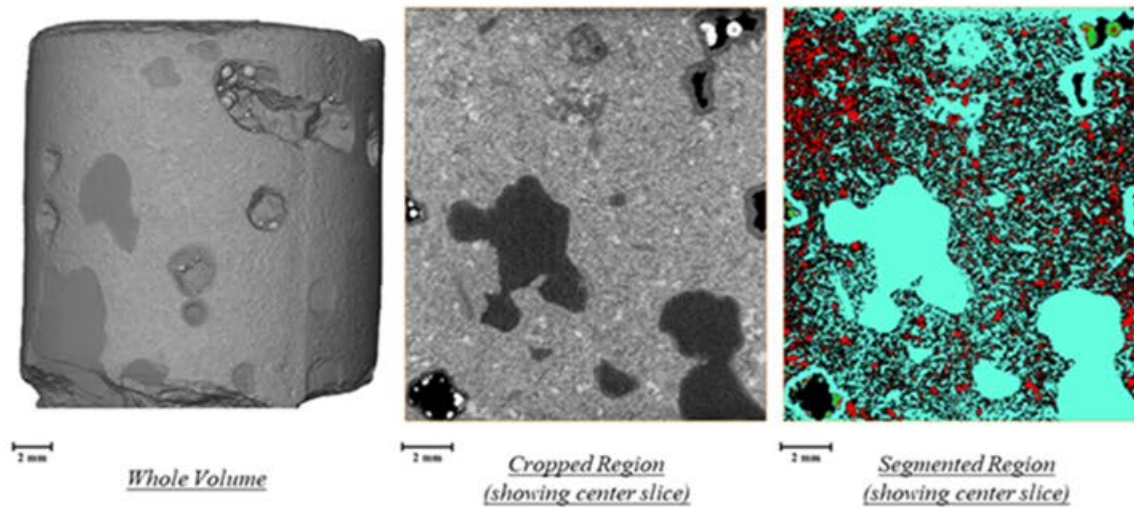
- What types of realistic parameters and sensitivity analysis are needed to establish mineral transformation rates?
- Robust characterization criteria/methodologies for pre-and post-CO<sub>2</sub> injection are needed
- Existing databases do not contain new exotic carbonate mineral compositions and structures observed at Wallula
- **How can we establish a predictive understanding of complex carbon mineralization outcomes in subsurface conditions?**





# Quantification of Basalt Pore Network Architecture and Carbon Mineralization Extent

- X-ray microtomography allows for pore network quantification and determination of phase abundances and spatial associations
- XMT captures internal zonation of carbonate nodules
- Information is being used to parametrize reservoir models (e.g. reactive surface area) and quantify degree of carbon mineralization at Wallula



2 mm

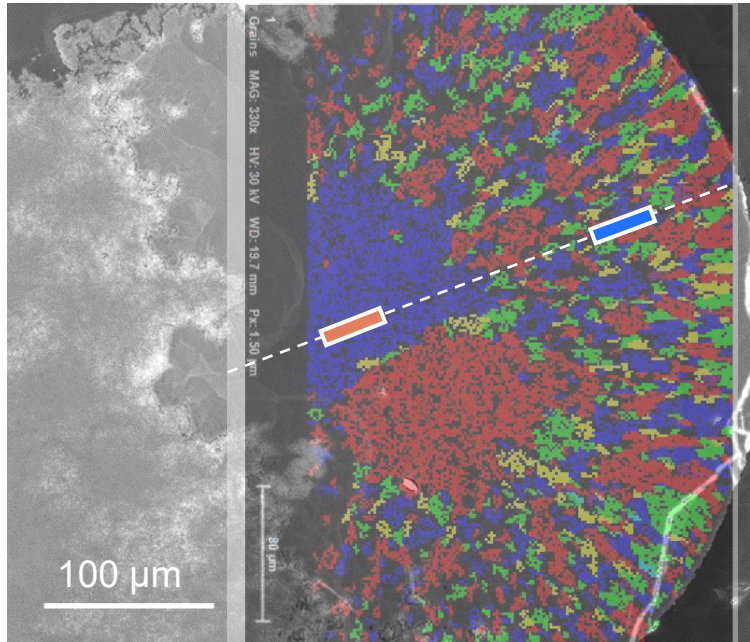
## Key Outcomes:

- Quantify impacts to porosity (pre and post CO<sub>2</sub> injection)
- Carbonate morphology, carbonation quantification (post injection)

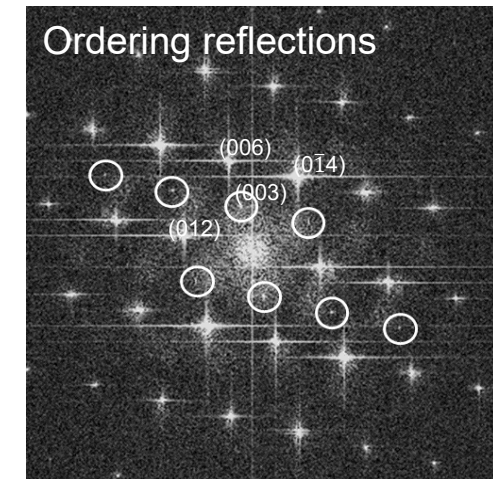
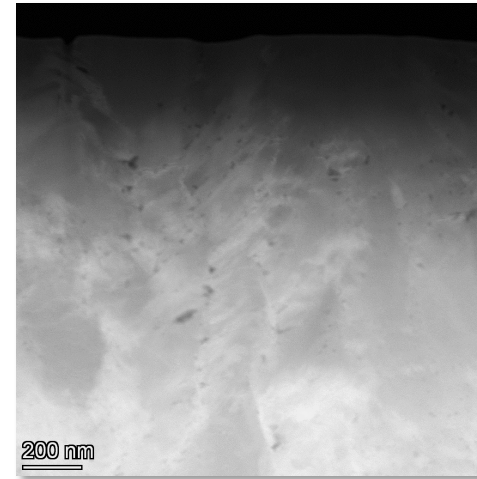
# Nanoscale Insights Enable Refinement of Predictive Geochemical Modeling



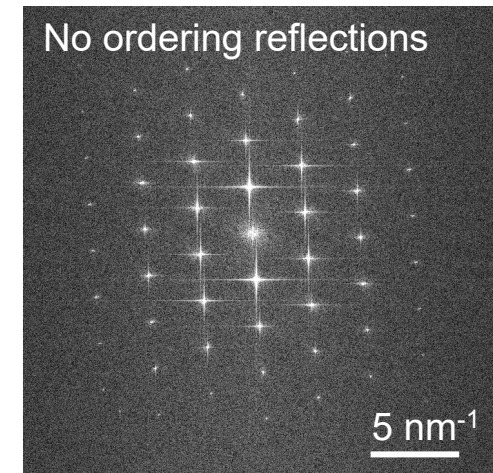
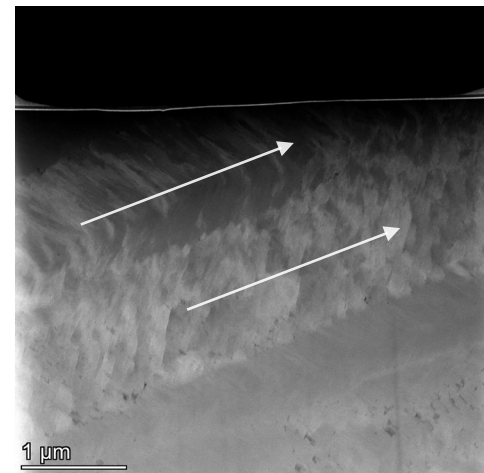
- Electron backscatter diffraction reveals a large uniform core and a granular rim
- Exotic Mg-deficient and ordered ankerite structure observed in the core region surrounded by spherulitic siderite
- Mg in all natural ankerite samples
- Ordered Mg-deficient ankerite not known synthetically or naturally.



## Ordered Ankerite Core Region



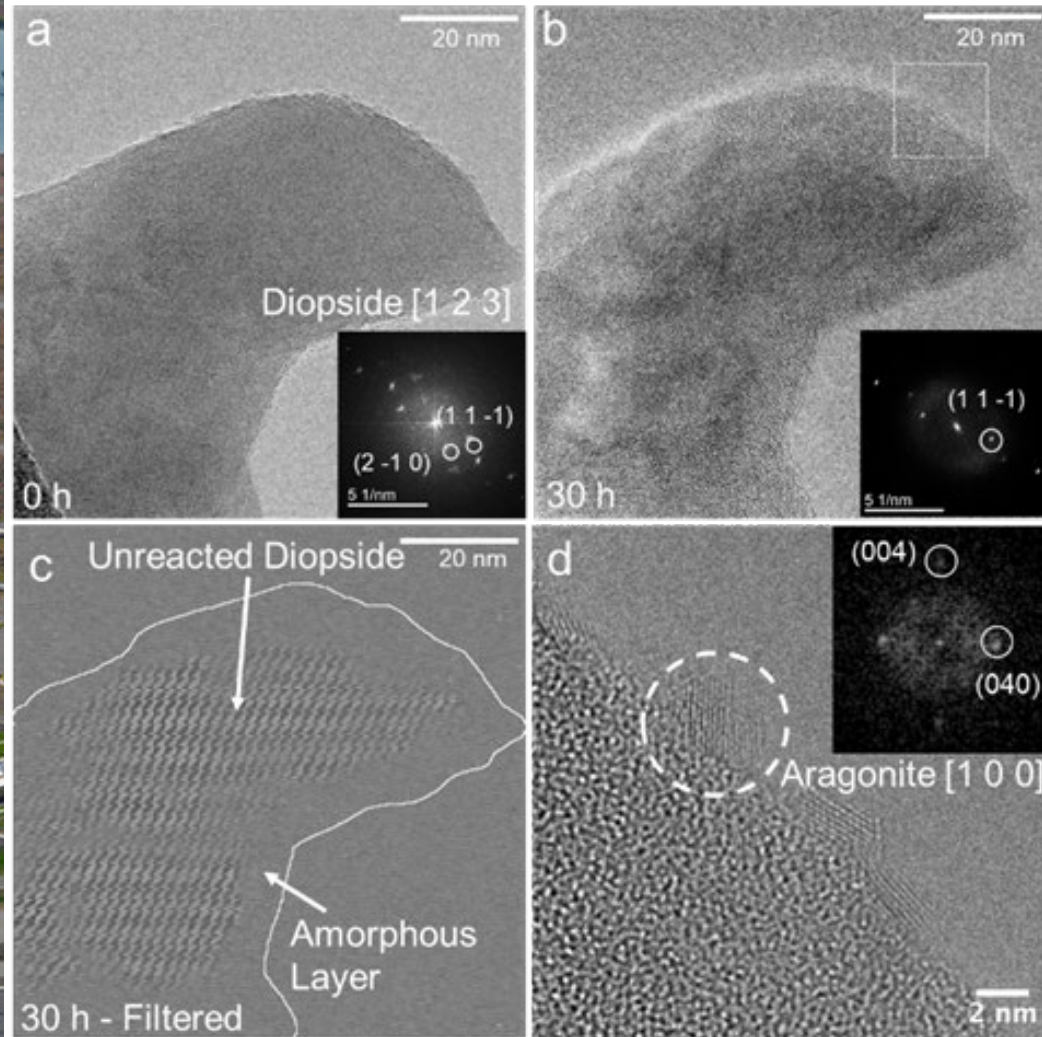
## Calcian Siderite Rim Region



### Key Outcomes:

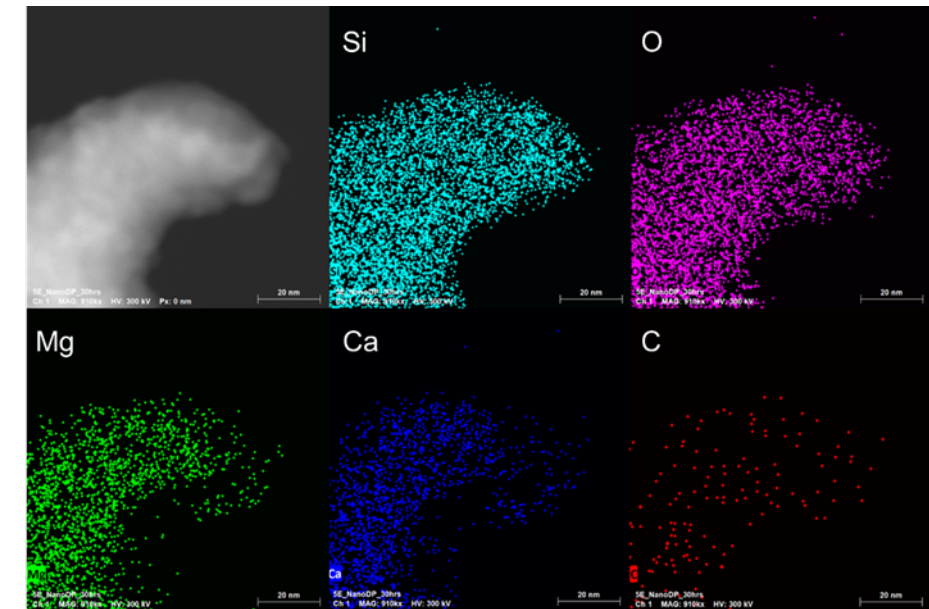
Accurate identification of carbonate phases enables better predictive geochemical modeling and refinement of capacity estimates for future sequestration efforts in reactive reservoirs.

# Nanoscale Amorphous Phases Control Carbon Mineralization in Basalts



Identical location TEM methodology reveals importance of amorphous precursors in carbon mineralization

- Diopside ( $\text{MgCaSi}_2\text{O}_6$ ) [and Forsterite ( $\text{Mg}_2\text{SiO}_4$ )] show initial formation of amorphous material and volume expansions following reaction with  $\text{scCO}_2$  (50 °C, 90 bar)
- Nanoscale aragonite ( $\text{CaCO}_3$ ) then crystallizes on amorphous material, not directly from crystalline diopside.
- The amorphous layer is depleted in carbonate-forming cations compared to unreacted mineral.
- Mg is not incorporated into carbonate phases, consistent with previous lab- and field-scale data.

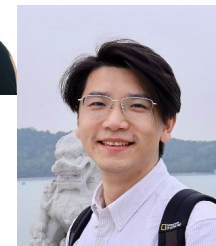


Li et al., 2023, Identical location transmission electron microscopy reveals nanoscale intermediates during silicate carbonation in wet supercritical  $\text{CO}_2$ , *in preparation*.

## Key Findings:

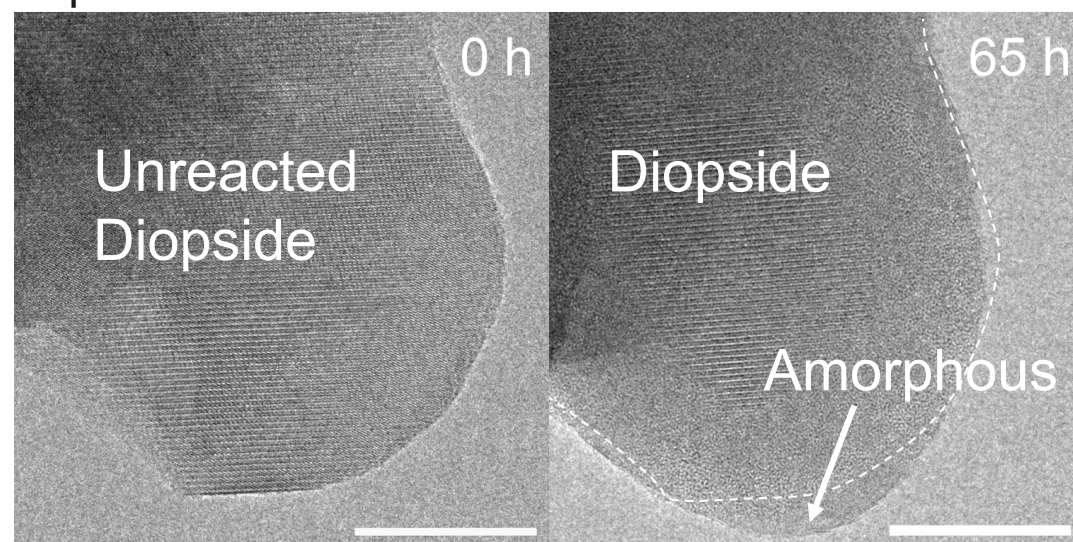
- An amorphous phase depleted in cationic species is formed following reaction with wet supercritical  $\text{CO}_2$ .
- Nanoscale aragonite subsequently crystallizes on the reactive amorphous phase

# Influence of Biomineralization on Mineral Carbonation and Fate of Critical Materials



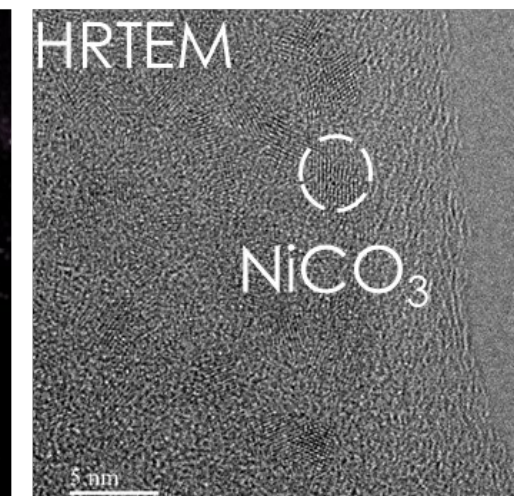
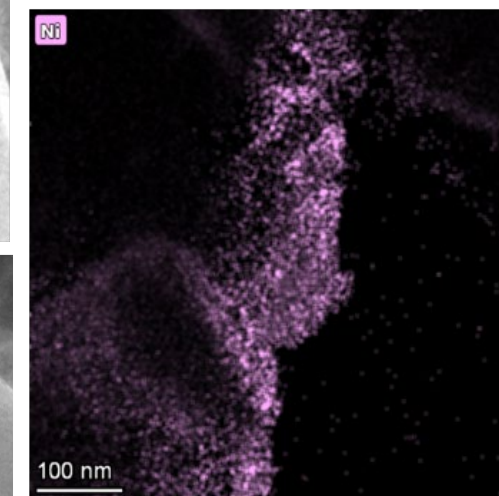
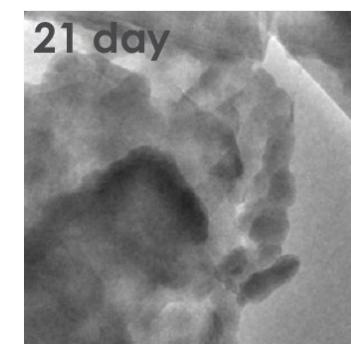
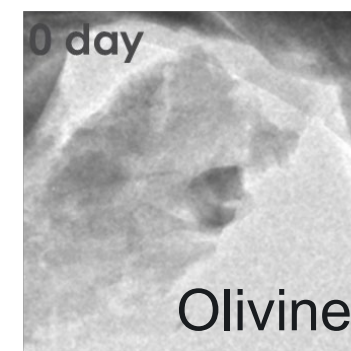
The use of biomolecule proxies do not alter the short time scale and molecular mechanisms behind carbon mineralization in silicate minerals

- Formation of amorphous layer on the surface of diopside is unchanged with the addition of citrate.
- Limited evidence of enhanced leaching of Mg and Ca from amorphous material.



Identical location TEM reveals the fate of Ni in olivine following reaction with scCO<sub>2</sub>

- Olivine forms a Ni-enriched amorphous layer upon reaction with scCO<sub>2</sub> (50°C, 90 bar).
- Ni is then incorporated into crystalline NiCO<sub>3</sub>.



## Key Findings:

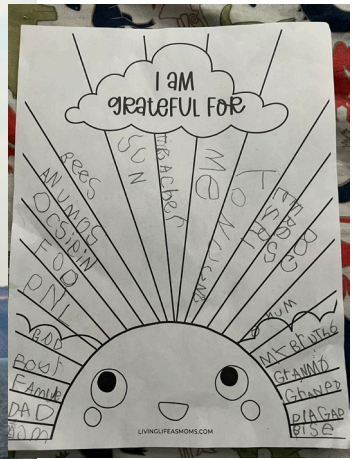
- Primary formation of an amorphous material on mineral surface is common among all minerals tested, with secondary formation of crystalline carbonates, including those containing critical materials.
- Biomineralization does not appear to initially alter the mechanisms behind carbon mineralization.



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

PNNL

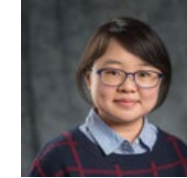
- Early inclusion of communities and stakeholders in clean energy projects is vital
- Early career researchers (e.g., interns, PDs, staff, visitors, etc.)
- DOE synergy: FECM (MLEF), SC (VFP, SULI, SCGSR), NNSA (MSIPP), CCI, GEM
- Nurturing sustainable STEM pipeline that fosters diversity and inclusivity



## Next Steps (FY24)

- Develop modeling tools that incorporate critical insights from field and laboratory studies
- Identify dominant 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<sub>2</sub> injection,
  - Support permitting efforts (e.g., class VI),
  - Develop engineered injection strategies (e.g., WAG, additives, critical mineral extraction, etc.) for restoring ground water chemistry to the natural state.
- Create and disseminate a reactive modeling tool that can simulate reactivity of water-bearing scCO<sub>2</sub> fluids in a reactive reservoir.

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



### Sequestration in Basalt Formations: Molecular Scale Mechanisms Behind Carbon Mineralization

Emily Nienhuis, Xiaojin Zang, Quin Miller, H. Todd Schaeff

**Addressing Key Knowledge Gaps to Enable Commercial Deployment**

- Molecular mechanism of carbon sequestration in basaltic reservoirs incorporating critical insights from field and laboratory studies
- Nanoscale CO<sub>2</sub> fluid-rock interactions
- Reaction rates of key mineral phases
- Fate of dissolved carbon and reaction products

**Identical Location TEM Studies Enable a Nanoscale Mechanical Understanding of Carbon Mineralization**

Identical TEM of dissolved  $\text{Mg}(\text{Mg})_2$  in well  $\text{MCO}_2$  reveals:

- Formation of reactive amorphous intermediates
- Preferential release of the Ca from diopside
- Aragonite formation on amorphous layer + CO<sub>2</sub> fluid interface

**Determination of Mineral-Specific Kinetics of Dissolution and Carbon Mineralization through Nanoscale TEM Studies, Synthetic Basalt Glasses, and Natural Basalt**

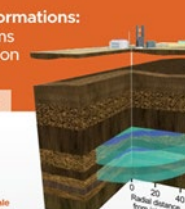
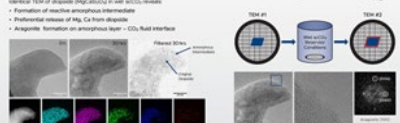

- Thickness of amorphous layer and thickness can be measured as a function of reaction time or reactive mineral phase and related to core scale studies using identical location TEM
- Computational studies on carbon sequestration in synthetic basalt glasses analyzed in terms from scale
- Ultimately, determine the key controls on mineral carbonation in basaltic reservoirs

**MOLECULAR SCALE MECHANISMS PROVIDE:**

- Superior CO<sub>2</sub> fluid mineral capacity input for reactive transport models
- Mechanisms controlling reaction rates and rate controlling steps
- Fate of dissolved carbon for storage capacity estimates

**ENABLING COMMERCIAL SCALE CARBON MINERALIZATION EFFORTS:**

- Reaction kinetics identified/estimated
- Clear CO<sub>2</sub> permeability/porosity simulation

### Unraveling the Structure and Composition of Anthropogenic Carbonates from a Geologic Carbon Storage Demonstration

Nabajit Lahiri, Quin Miller, Libor Kovarik, Sandra Taylor, Javed Qureshi, Chiranjeev Dey, H. Todd Schaeff

**Introduction and Background**

- Geologic CO<sub>2</sub> sequestration in natural reservoirs offers a promising carbon-sequestration strategy towards the safe and permanent storage of CO<sub>2</sub> in their subsurface
- High CO<sub>2</sub> reactivity, permeability, and viscous surface area near basaltic mineral assemblages
- $\sim 1000$  m<sup>3</sup> of artificial CO<sub>2</sub> trapped in EOR under ground surface in 2010
- 100% of CO<sub>2</sub> captured by mineral sequestration in 2018

**Micro- to Nanoscale Insights into Carbon Mineralization Enables Commercial Scale Sequestration Efforts**

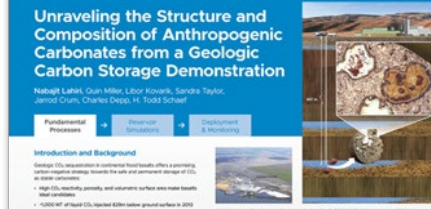

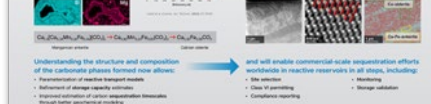
- In-situ fluorescence spectroscopy reveals compositional evolution of carbonate minerals during CO<sub>2</sub> sequestration
- Micro- to nanoscale insights into carbon mineralization and the evolution of mineral phases and their composition over time
- Control and reaction kinetics identified for the first time

**Understanding the structure and composition of the carbonates formed over decades**

- Identification of reactive transport models
- Influence of storage capacity estimates
- In-situ estimation of carbon sequestration through reactive transport simulations

**and will enable commercial-scale sequestration efforts worldwide in reactive reservoirs in all stages, including:**

- Monitoring
- Data management
- Compliance reporting

### Accelerating Carbon Storage Commercialization in Basalt via Reactive Transport Simulation and Stakeholder Engagement

Ruoshi Cao, Katherine A. Miller, Quin R.S. Miller, H. Todd Schaeff

**Knowledge Gaps and Opportunities for Commercial Scale Carbon Mineralization Storage**

- Strategic and structural controls on reactivity in basaltic
- Sustainability and management of high volume injection of CO<sub>2</sub>
- Continuity and connectivity of deep basalt flows from site- to regional scale
- Reaction rate evolution during high volume CO<sub>2</sub> injection
- Accuracy of structural and physical trapping security of wells (integrity), basalt flow integrity
- Efficacy of standard geophysical, remote sensing, hydrogeologic, and other tools for characterizing structure and tracking fluid movements in deep basalt

**Reactive Transport Simulation Leadership: Enabling Permitting, MRV, Injection Strategy Optimization, and Storage Efficiency**

- Numerical simulation of CO<sub>2</sub> storage in basaltic
- Reveals full carbon mineralization rate
- Are parameterized and validated by experiments and field data
- Predicts CO<sub>2</sub> transport and quantifies mineralization extent
- Optimizes injection and development strategies
- Supports permitting and MRV

**Setting the Stage to Accelerate Commercial Scale Carbon Storage Deployment**

- Build advocacy and address non-technical barriers
- Continued engagement with:
  - State agencies
  - Private industry
  - City, state, tribal, federal agencies
  - Workshops, citizens, field trips, career fairs, and lab tours





### Seismic Dispersion-Attenuation Relationships for Subsurface Monitoring of Energy Extraction and Storage

Quin Miller, Jade Holliman, Heath Starfield, H. Todd Schaeff

**Addressing Key Knowledge Gaps to Enable Monitoring and Validation of Commercial-Scale Storage**

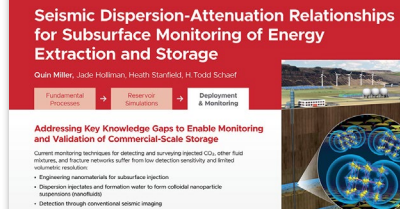
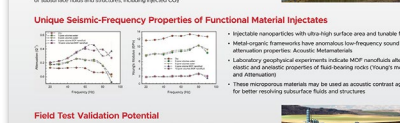

- Current monitoring techniques for detecting and surveying reservoir CO<sub>2</sub> other fluid features, and tracking reservoirs offer low resolution sensitivity and energy resource resolution
- Engineering materials for subsurface injection
- Dispersion spectra and formation water to form colloidal nanoparticle suspensions (nanoparticles)
- Detection through conventional seismic imaging

**Unique Seismic-Frequency Properties of Functional Material Injectates**

- Injectable nanoparticles with ultra-high surface area and tunable flexibility
- Metal-organic frameworks have anomalous low-frequency sound attenuation properties, Acoustic Metamaterials
- Laboratory geophysical experiments include MPP nanoparticles after the elastic and anisotropic properties of fluid-bearing rocks (change modulus and attenuation)
- These responsive materials may be used as acoustic contrast agents for better resolving subsurface fluids and structures

**Field Test Validation Potential**

- Site Specific Forward Seismic Modeling Case Study: Leveraging PNNL Field Sites (Bioscience Resource and Laboratory Sites)
- Field-specific examples of seismic survey enhancement with nanofluid contrast agents will continue the path towards field deployment, including enabling permitting and reactive strategy design
- Synergy with Regional Partnerships, CarbonSAFE, ASPX, E, and DAC Hubs

### Engineering Integrated Sensing, Power, Telemetry, and Data Processing Systems for Complex Subsurface Environments

Xiaojin Zang, Hyunjun Jung, Jun Lu, Jeyagan J. Marthandam, Brianna Friedman, Wonsup Hwang, Zhuojun Daniel Deng

**Integrating Energy Harvesting, Sensing, and Data Communication Systems for Reliable, Low-Power, and Maintenance-Free Real-Time Monitoring**

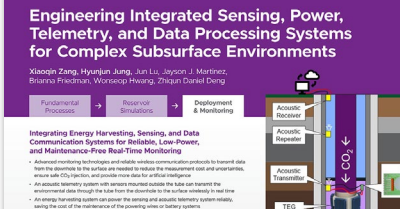
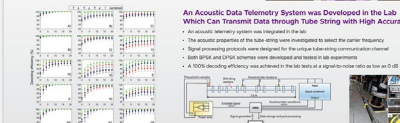
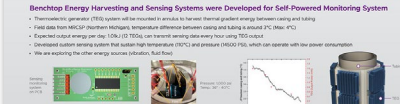
- Advanced monitoring techniques and reliable wireless communication systems to transmit data from the subsurface to the surface are needed to realize the environmental data and operational insights from subsurface CO<sub>2</sub> injection and provide real-time data for critical decisions
- An acoustic telemetry system can transmit real-time data from the subsurface to the surface wirelessly by using time-varying frequency spectrum to overcome the complex subsurface environment, using the loss of the transmission of the power line or battery systems
- A low-power sensing system for distributed temperature and pressure monitoring and control in the well

**An Acoustic Data Telemetry System was Developed in the Lab Which Can Transmit Data through Tube Spring with High Accuracy**

- An acoustic telemetry system was designed in the lab
- The acoustic properties of the tube spring were investigated to assist the carrier frequency
- Signal processing protocols were designed for the unique laboratory communication channel
- Both BPSK and QPSK schemes were developed and tested in lab experiments
- A 100% accuracy efficiency was achieved in the lab for a 100m-long tube spring in the lab

**Benchtop Energy Harvesting and Sensing Systems were Developed for Self-Powered Monitoring System**

- The benchtop energy (TEG) system will be used in the field to harvest thermal gradient between casing and tubing
- Field data from wellbore pressure monitoring systems using data logging and storage (DC Power, CPU)
- Expected output energy per day: 100s (10 TWh) can harvest energy data every hour using TEG module
- Operational status: wellbore pressure monitoring (100% TEG) and pressure (1000 PSI) which can operate with the power consumption
- We are exploring other energy sources (solar, fuel, etc.)

### Critical Mineral Recovery and Carbon Mineralization from Mafic-Ultramafic Rock Formations

Alle Nagourney, Quin Miller, Nabajit Lahiri, H. Todd Schaeff

**Supercritical CO<sub>2</sub> (sCO<sub>2</sub>)-Based Mining for Developing a Domestic Supply of Critical Minerals**

- Green energy transition requires an increased demand for mineral resources and critical mineral mining
- Ni and Co are key for electric car batteries, solar panels, and wind turbines – but have a high supply risk
- Ultramafic rocks like Ni, Co, etc. are used to generate a domestic source of critical minerals

**Key Knowledge Gaps**

- Understanding the role of CO<sub>2</sub> in mineral recovery and storage
- Research needed to assess CO<sub>2</sub> mineral recovery and storage potential from mafic/ultramafic rocks

**Supercritical CO<sub>2</sub>-Based Mining**

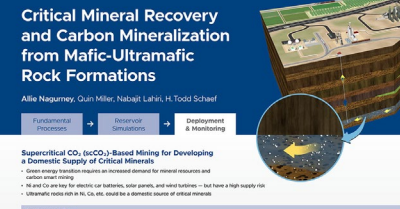
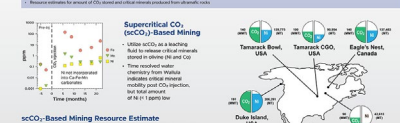

- Unlike sCO<sub>2</sub> as a working fluid, supercritical CO<sub>2</sub> is used to extract critical minerals from mafic/ultramafic rocks
- This method can be used to extract critical minerals from mafic/ultramafic rocks and CO<sub>2</sub> recovery and storage
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**sCO<sub>2</sub>-Based Mining Resource Estimate**

- Determine the amount of CO<sub>2</sub> stored and all produced from U.S. ultramafic deposits: 7.0% of the total CO<sub>2</sub> is a total mass of 100 TWh with various CO<sub>2</sub>
- Calculate the total amount of Ni and Co stored in U.S. ultramafic rocks
- 100,000 MMT Ni and 10,000 MMT Co in U.S. ultramafic rocks
- 100 MMT Ni and 7.7 MMT Co stored in high-grade basaltic rocks

**Understanding the Potential for CO<sub>2</sub> Mineralization and Critical Mineral Recovery in Ultramafic Rocks**

- Will Enable Commercial-Scale CO<sub>2</sub>-EHR Efforts, including:
  - Site selection for CO<sub>2</sub>-EHR
  - Financial incentives for CO<sub>2</sub>-EHR through selling critical minerals, CO<sub>2</sub> credits
  - Synergy with CarbonSAFE and ASPX-E

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

**Tuesday (Aug 29) at 5:45pm at the Ballroom Foyer!**

# Appendix



# Gantt Chart and Milestones for FY23

Milestone	Description	QRT
M1	Downselect biomolecules to test in experiments based on the results of the critical literature review.	Q1
M2	Initiate nano/micro-analysis of biogenic influences of Wallula carbonates	Q2
M3	Compare experimental determinations of mineral carbonation kinetics with the compiled literature	Q3
M4	Submit journal article detailing critical mineral behavior and reaction rates for carbon biomineralization at subsurface conditions in the context of the broader critical literature review and Wallula SWC insights. This milestone will be produced using information from all four tasks.	Q4

Task	Milestone	Title	G/N	Begin	End	FY23			
						Q1 1	Q2 2	Q3 3	Q4 4
		<b>Sequestration in Basalt Formations FWP 73235</b>		0	4				
Task 1		<i>Biom mineralization Literature Review</i>							
	M1	Downselect biomolecules to test in experiments based on the results of the critical literature review.		1	1	▲			
Task 2		<i>Biosignatures of Natural and Anthropogenic Wallula Carbonates</i>							
	M2	Initiate nano/micro-analysis of biogenic influences of Wallula carbonates		2	3		▲		
Task 3		<i>Biomolecule Enhancement of Carbonation</i>							
	M3	Compare experimental determinations of mineral carbonation kinetics with the compiled literature		3	3			▲	
Task 4		<i>Critical Mineral Outcomes During Carbonation</i>							
	M4	Submit journal article detailing critical mineral behavior and reaction rates for carbon biomineralization at subsurface conditions in the context of the broader critical literature review and Wallula SWC insights.		4	4				▲

# Summary of Lessons Learned

Lesson Learned	Supporting Information
<p>Injected supercritical CO<sub>2</sub> (dry) in contact with water is reactive.</p>	<p>Findings from WBPP reveal carbonation occurred during the 24-month period that was directly linked to the injected CO<sub>2</sub>. Minerals identified in the sidewall cores include ankerite, siderite, aragonite, and zeolite.</p>
<p>Pre and post comprehensive hydrogeological characterization conducted on the target injection zones is critical.</p>	<p>Detailed analysis of pre- and post-injection hydrologic tests that capitalizes on the difference in fluid properties between scCO<sub>2</sub> and water can be used to assess changes in near-field, wellbore, and reservoir conditions.</p>
<p>Reactive reservoir simulations of CO<sub>2</sub>-water-basalt interactions at WBPP are complex and rely on post carbonate characterization.</p>	<p>Paragenetic insights for the timing of aragonite, silica, and fibrous zeolites are captured in sidewall cores retrieved post CO<sub>2</sub> injection. These samples provided clarification, based on mineral texture and spatial relationships, along with time-resolved downhole fluid sampling, on the mineralogy, chemistry, and paragenesis of carbon mineralization.</p>