Regional Carbon Initiative for CO_2 Management in Basalt: *CaRBTAP*

Richard Middleton | CARBON SOLUTIONS

Houston CCUS, 3–5 March 2025

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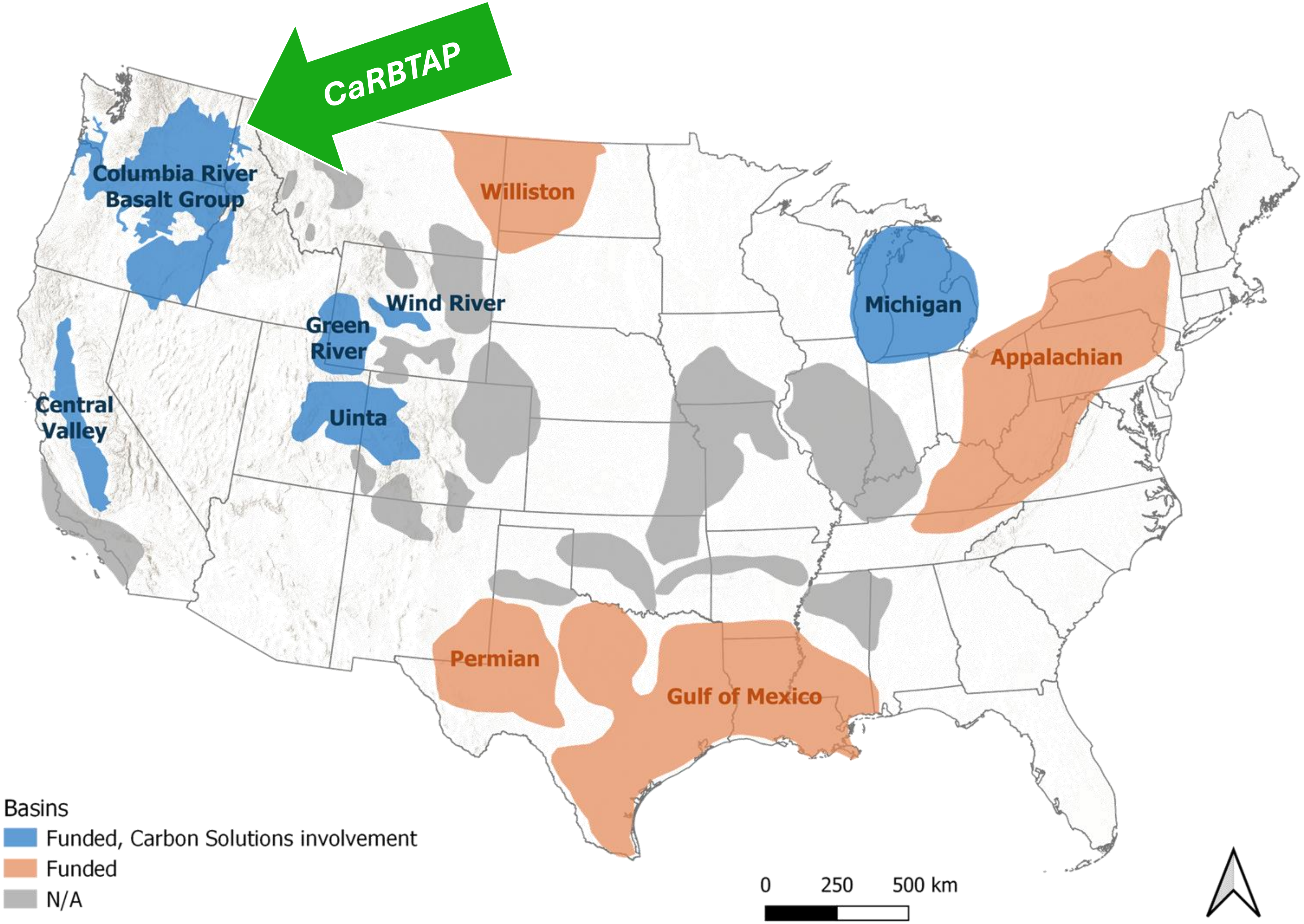
DOE Initiative

- Regional Initiative for Technical Assistance Partnerships (RITAP).
- *Accelerate the understanding of specific geologic basins to enable the permanent storage of CO_2.*

#	Basin	Prime
1	Appalachian Basin	Battelle
2	Central Valley	Stanford
3	Columbia River Basalt Group	Carbon Solutions
4	Permian Basin	Texas Tech University
5	Williston Basin	University of North Dakota
6	NW Gulf of Mexico Basin	The University of Texas at Austin
7	Uinta Basin	The University of Utah
8	Green River and Wind River Basins	University of Wyoming
9	Michigan Basin	Western Michigan University



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Regional Carbon Initiative for CO_2 Management in Basalt: *CaRBTAP*

Research team

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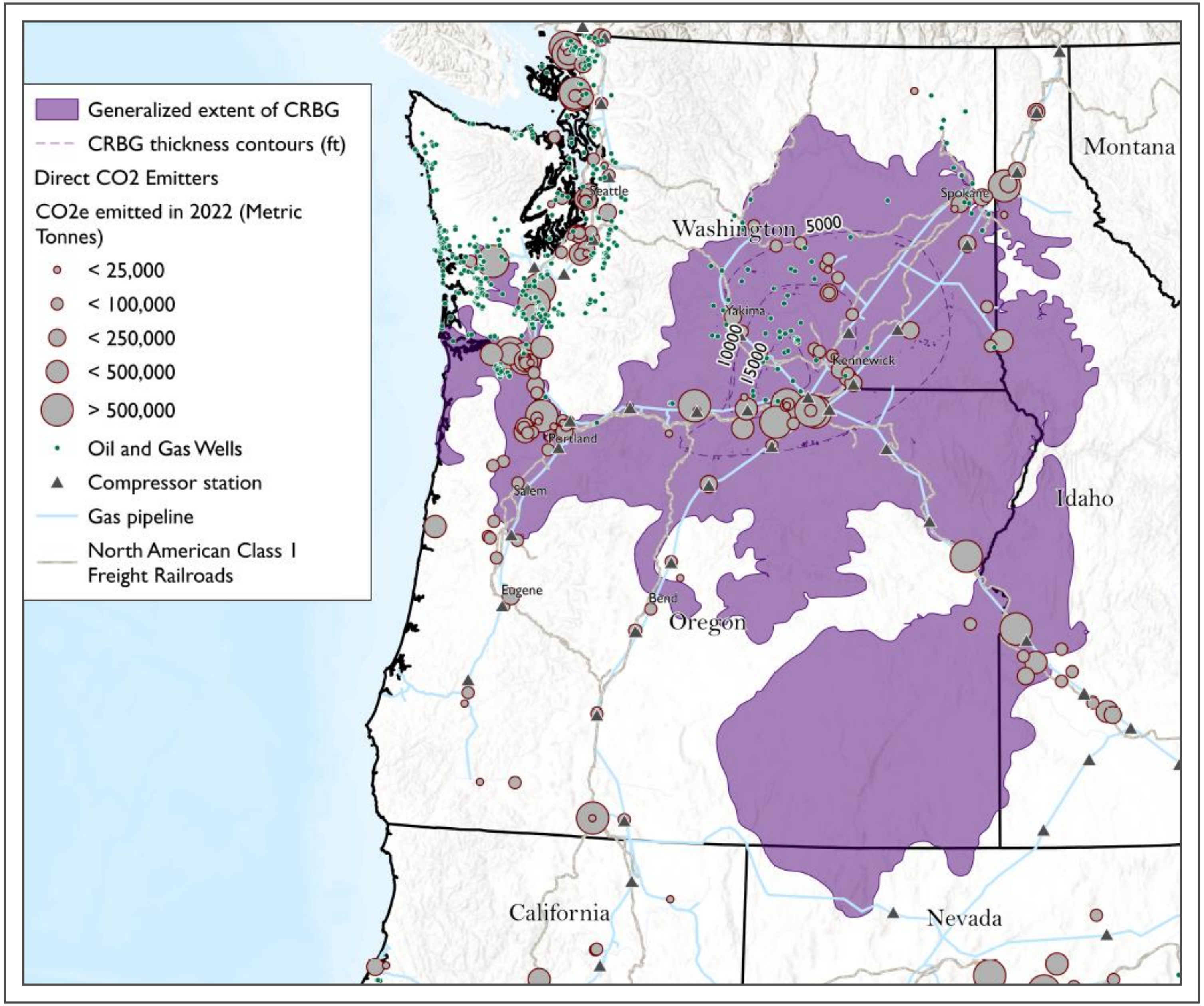
- **Carbon Containment Lab (CCL)** | Anastasia O'Rourke.
- **Idaho National Laboratory (INL)** | Trevor Atkinson.
- **Oregon Department of Geology and Mineral Industries (DOGAMI)** | Ruarri Day-Stirrat.
- **Pacific Northwest National Laboratory (PNNL)** | Todd Schaef.
- **Washington Geological Survey (WGS)** | Lee Florea.
- **Washington State University (WSU)** | Zoe Strong.

Industry Board

- Carbfix | CRC/TerraVault | Cella | Addis Energy...

Why *CaRBTAP?*

1. Storage potential of basalt.
2. Hard-to-decarbonize region.
3. Motivated region.
4. Multiple CO_2 projects.



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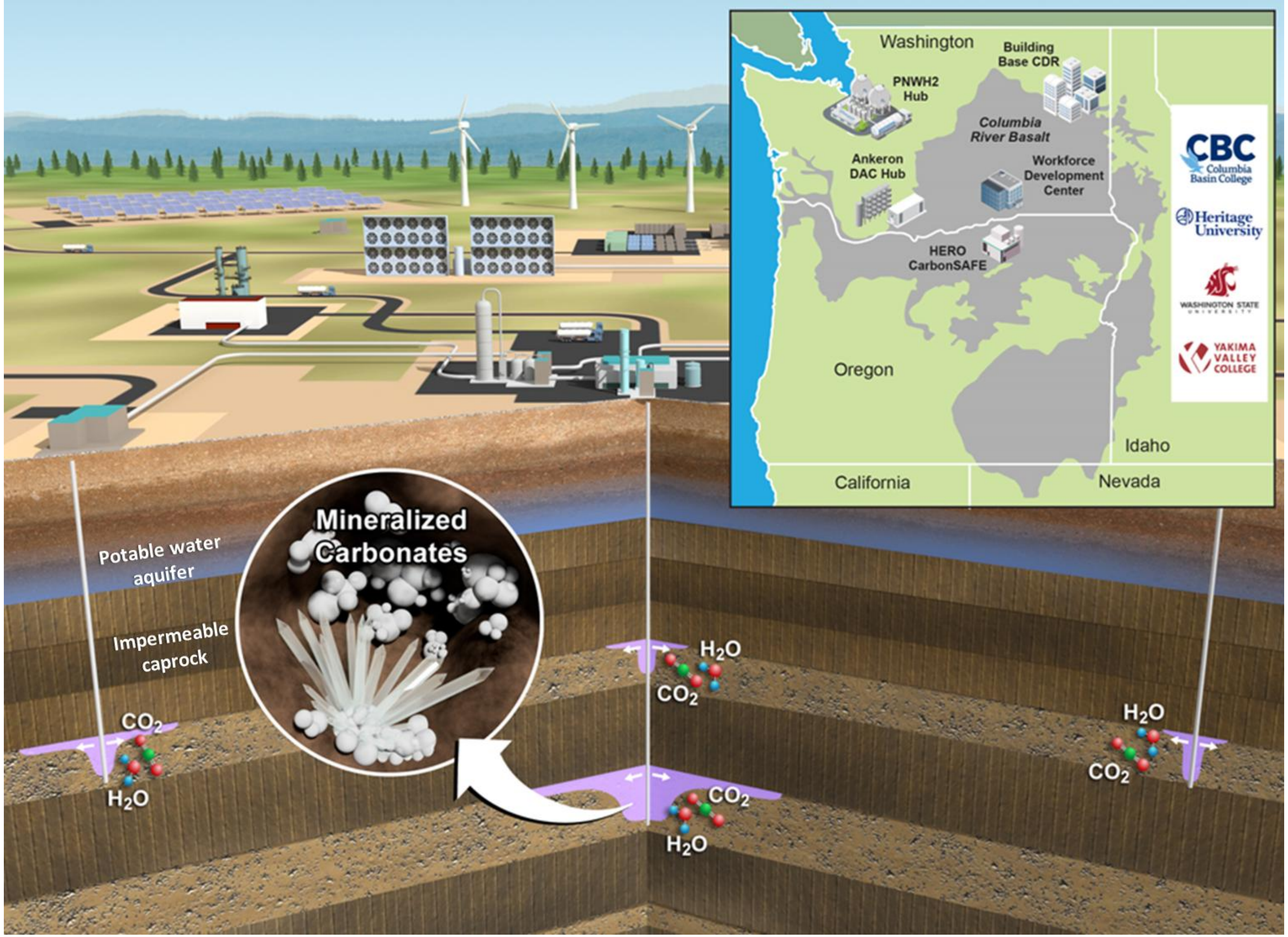


What *CaRBTAP?*

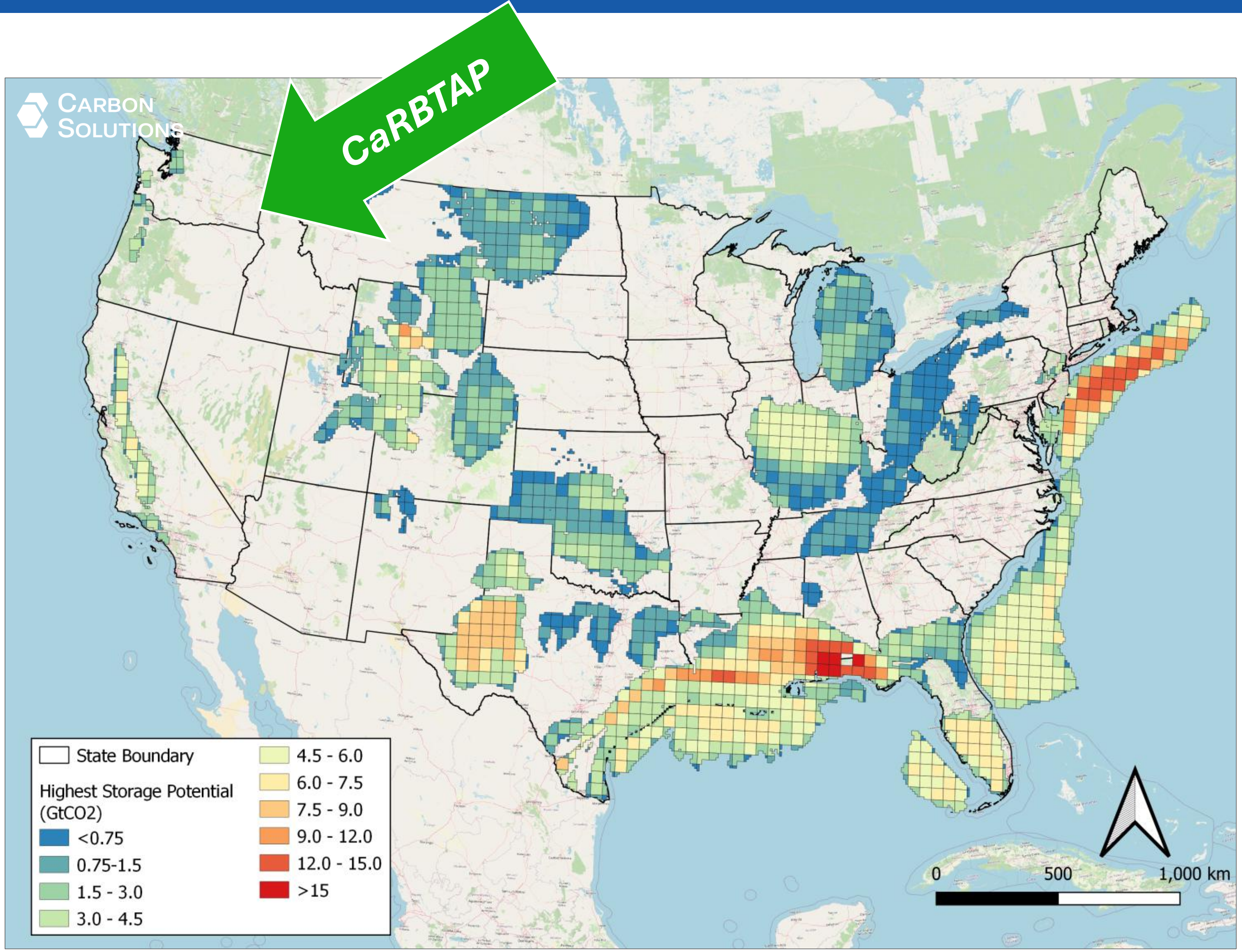
1. Geologic Challenges.
2. Carbon Management Infrastructure.
3. Policy and Regulatory Framework.
4. Commercial Acceptance.

Carbon Solutions

Task 1: Storage Resource Assessments

Focus

- Regional Geologic Characterization.
- Regional Reservoir Model.
- Regional Storage Potential Estimates.
- Regional Geologic Database Development.
- Cross-Cutting Opportunities.



SCO_2T^{PRO}: Nationwide saline storage potential

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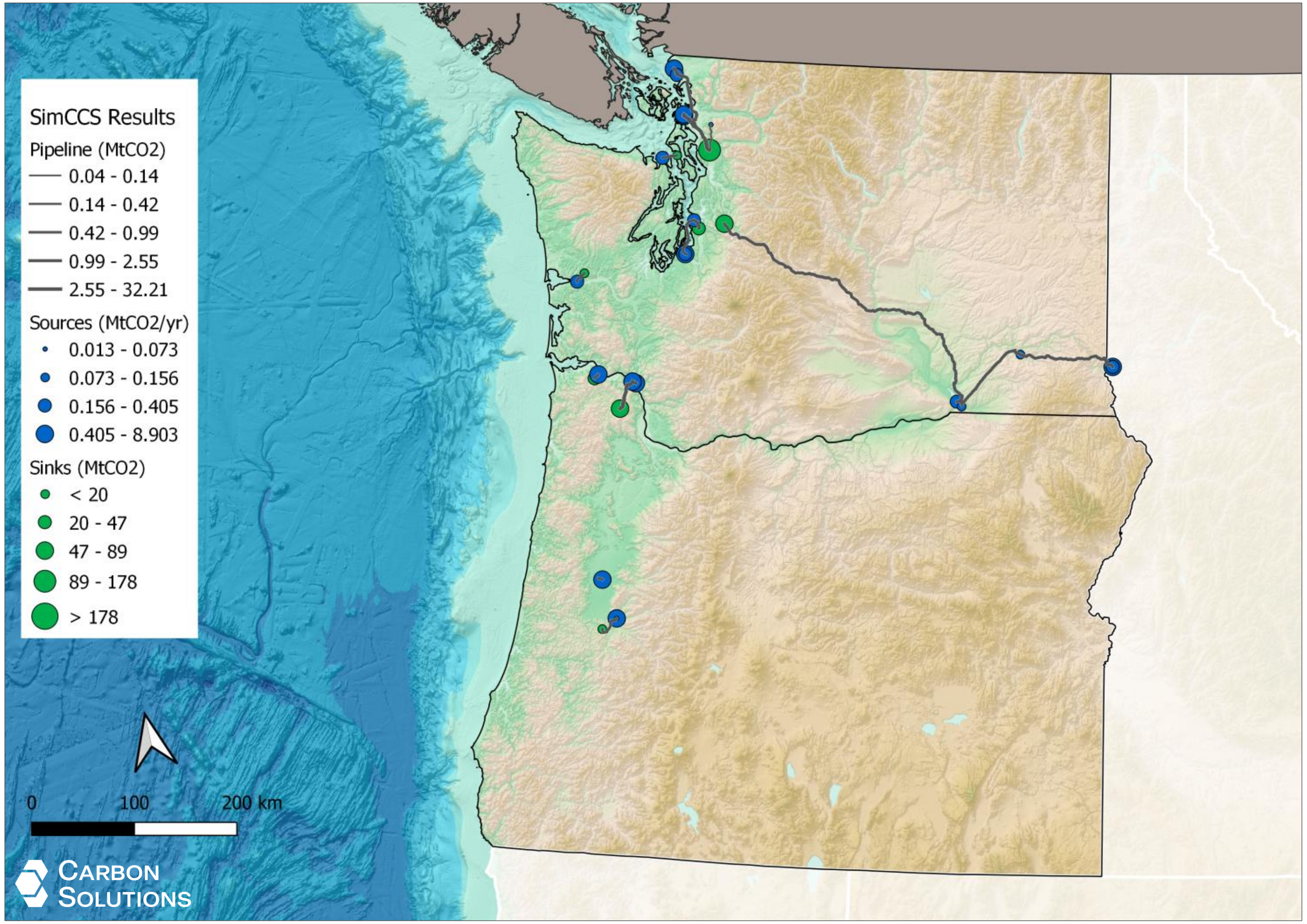
Task 2: Technical Assistance

Focus

- Project Development.
- Monitoring, Reporting, & Verification (MRV).
- Pore and Pressure Space Management and Optimization.
- Legal and Regulatory Assessments and Strategies.
- Carbon Transport, Planning, & Safety Assistance.



SimCCS^{PRO}: Industrial emissions & CCS infrastructure

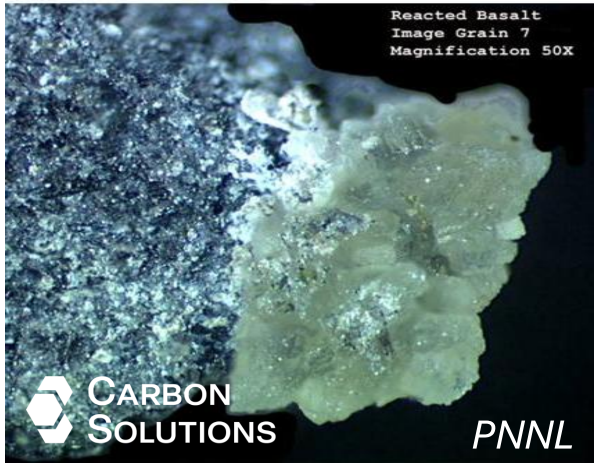
Carbon Solutions

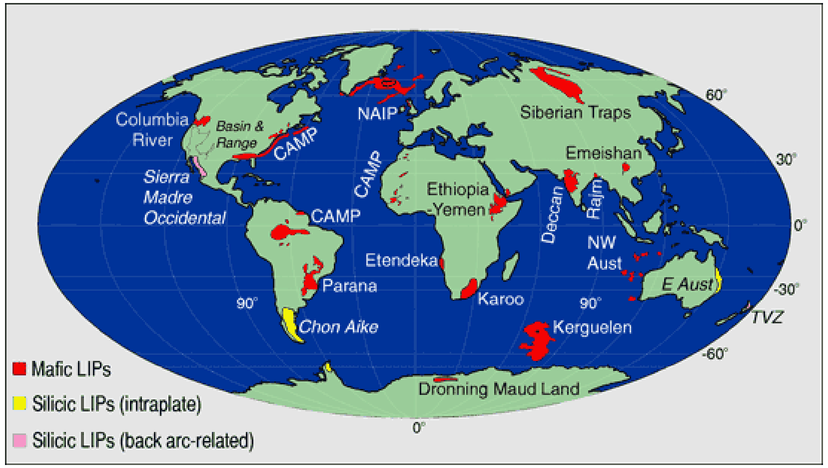
CO_2 & Basalts 101

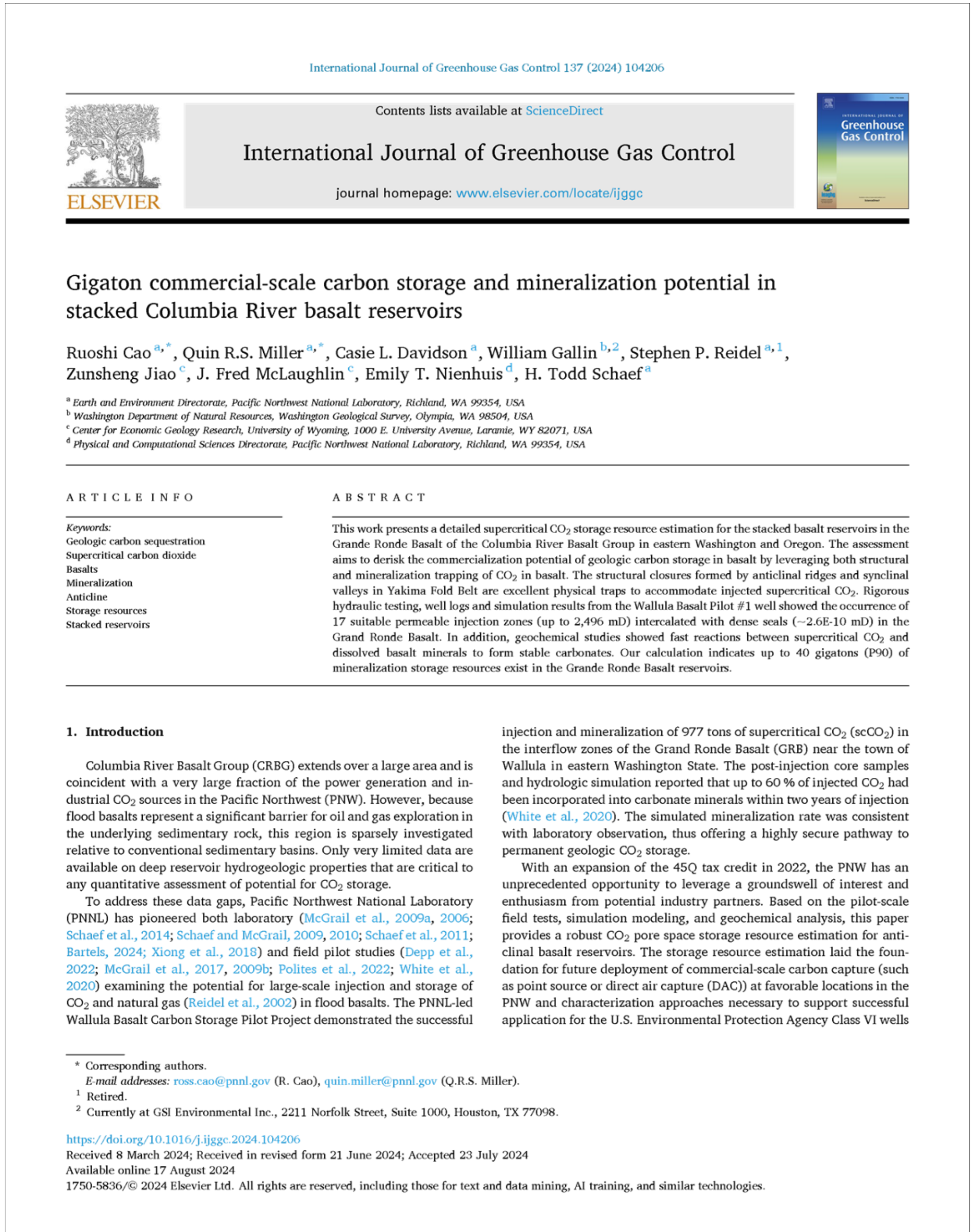
A primer

Why Basalts?

- Mineralization & storage.
- Highly reactive with supercritical CO_2.
- Self-sealing for leakage scenarios.
- Gigatonne-storage in the Columbia River.
- Common rock type with worldwide distribution.
- Few/no other co-located storage options.







International Journal of Greenhouse Gas Control 137 (2024) 104206

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

ELSEVIER

Gigaton commercial-scale carbon storage and mineralization potential in stacked Columbia River basalt reservoirs

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ARTICLE INFO

Keywords:
Geologic carbon sequestration
Supercritical carbon dioxide
Basalts
Mineralization
Anticline
Storage resources
Stacked reservoirs

ABSTRACT

This work presents a detailed supercritical CO_2 storage resource estimation for the stacked basalt reservoirs in the Grande Ronde Basalt of the Columbia River Basalt Group in eastern Washington and Oregon. The assessment aims to derisk the commercialization potential of geologic carbon storage in basalt by leveraging both structural and mineralization trapping of CO_2 in basalt. The structural closures formed by anticlinal ridges and synclinal valleys in Yakima Fold Belt are excellent physical traps to accommodate injected supercritical CO_2. Rigorous hydraulic testing, well logs and simulation results from the Wallula Basalt Pilot #1 well showed the occurrence of 17 suitable permeable injection zones (up to 2,496 mD) intercalated with dense seals (~2.6E-10 mD) in the Grand Ronde Basalt. In addition, geochemical studies showed fast reactions between supercritical CO_2 and dissolved basalt minerals to form stable carbonates. Our calculation indicates up to 40 gigatons (P90) of mineralization storage resources exist in the Grande Ronde Basalt reservoirs.

1. Introduction

Columbia River Basalt Group (CRBG) extends over a large area and is coincident with a very large fraction of the power generation and industrial CO_2 sources in the Pacific Northwest (PNW). However, because flood basalts represent a significant barrier for oil and gas exploration in the underlying sedimentary rock, this region is sparsely investigated relative to conventional sedimentary basins. Only very limited data are available on deep reservoir hydrogeologic properties that are critical to any quantitative assessment of potential for CO_2 storage.

To address these data gaps, Pacific Northwest National Laboratory (PNNL) has pioneered both laboratory (McGrail et al., 2009a, 2006; Schaef et al., 2014; Schaef and McGrail, 2009, 2010; Schaef et al., 2011; Bartels, 2024; Xiong et al., 2018) and field pilot studies (Depp et al., 2022; McGrail et al., 2017, 2009b; Polites et al., 2022; White et al., 2020) examining the potential for large-scale injection and storage of CO_2 and natural gas (Reidel et al., 2002) in flood basalts. The PNNL-led Wallula Basalt Carbon Storage Pilot Project demonstrated the successful injection and mineralization of 977 tons of supercritical CO_2 ($scCO_2$) in the interflow zones of the Grand Ronde Basalt (GRB) near the town of Wallula in eastern Washington State. The post-injection core samples and hydrologic simulation reported that up to 60 % of injected CO_2 had been incorporated into carbonate minerals within two years of injection (White et al., 2020). The simulated mineralization rate was consistent with laboratory observation, thus offering a highly secure pathway to permanent geologic CO_2 storage.

With an expansion of the 45Q tax credit in 2022, the PNW has an unprecedented opportunity to leverage a groundswell of interest and enthusiasm from potential industry partners. Based on the pilot-scale field tests, simulation modeling, and geochemical analysis, this paper provides a robust CO_2 pore space storage resource estimation for anticlinal basalt reservoirs. The storage resource estimation laid the foundation for future deployment of commercial-scale carbon capture (such as point source or direct air capture (DAC)) at favorable locations in the PNW and characterization approaches necessary to support successful application for the U.S. Environmental Protection Agency Class VI wells

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https://doi.org/10.1016/j.ijggc.2024.104206
Received 8 March 2024; Received in revised form 21 June 2024; Accepted 23 July 2024
Available online 17 August 2024

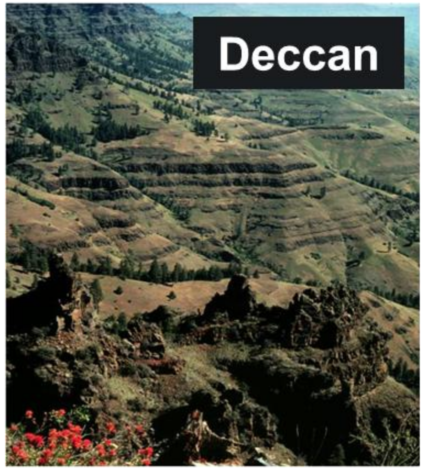
Setting the Stage for CO_2 Mineralization

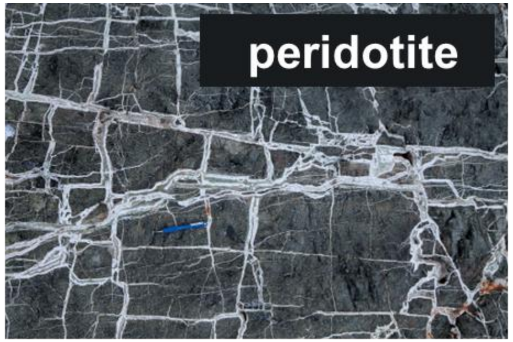
Mineralization settings

- **In situ** mineralization:
  - 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.
  - Mine tailings, soil amendments, & engineered systems that leverage non-ambient conditions.

Basalt chemistry

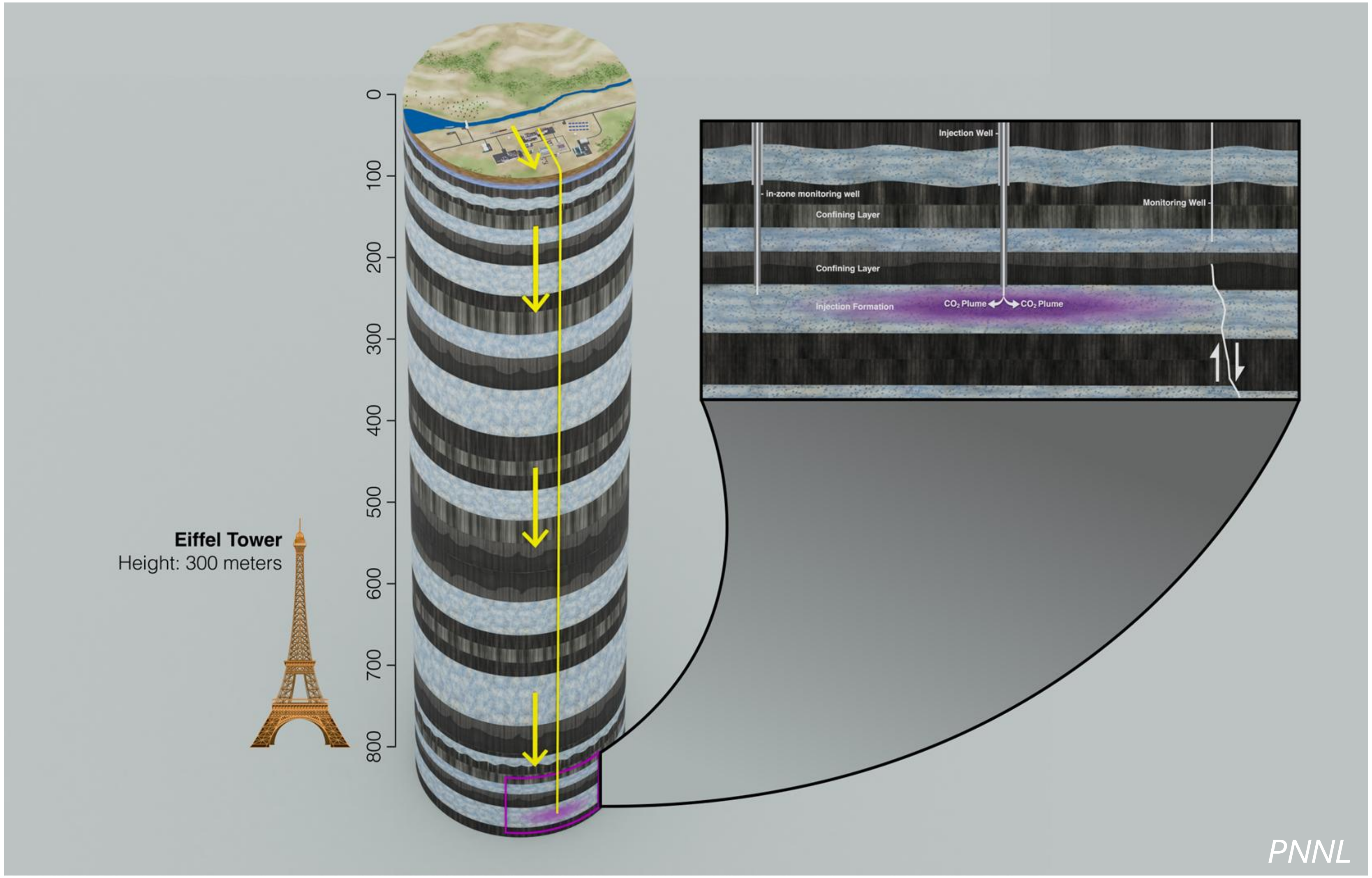
- Crystalline minerals (feldspars, pyroxenes, olivine) within a highly reactive glassy matrix
- Carbonate type controlled by depth, temperature, surface area, pre-existing secondary minerals, pressure, & water chemistry.





In Situ Geologic Storage of CO_2 in Basalts

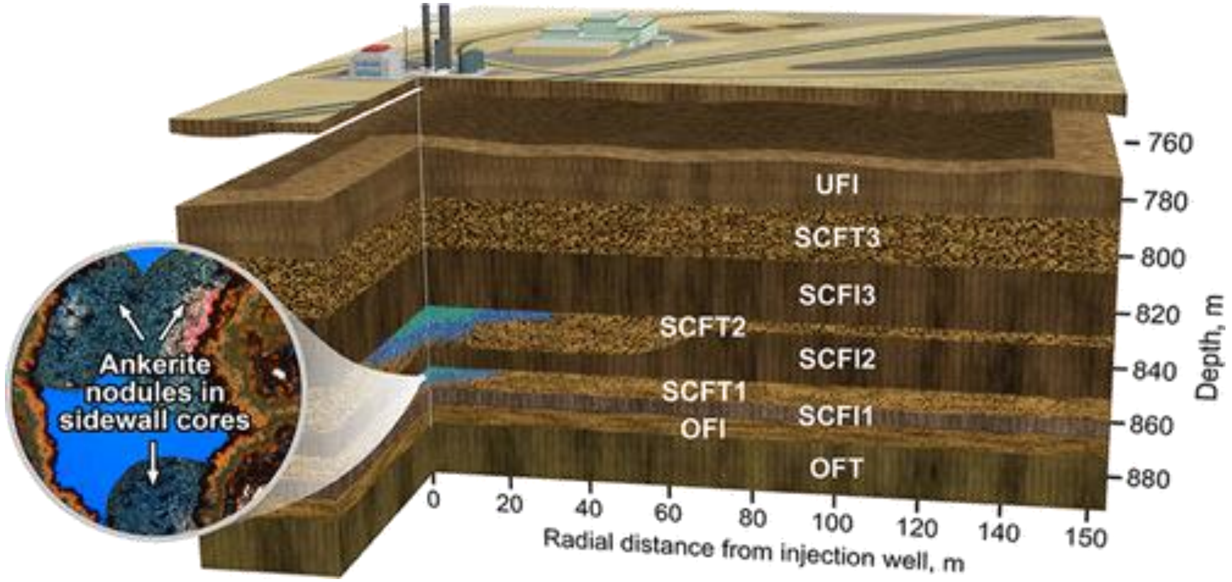
- Illustration of the depth of geologic storage of carbon dioxide in a layered basalt.
- Mafic-ultramafic reservoirs occur 800 m below surface.
- As a reference, the Eiffel Tower (300 m) is shown alongside for scale.



Pure Phase vs. Dissolved Phase

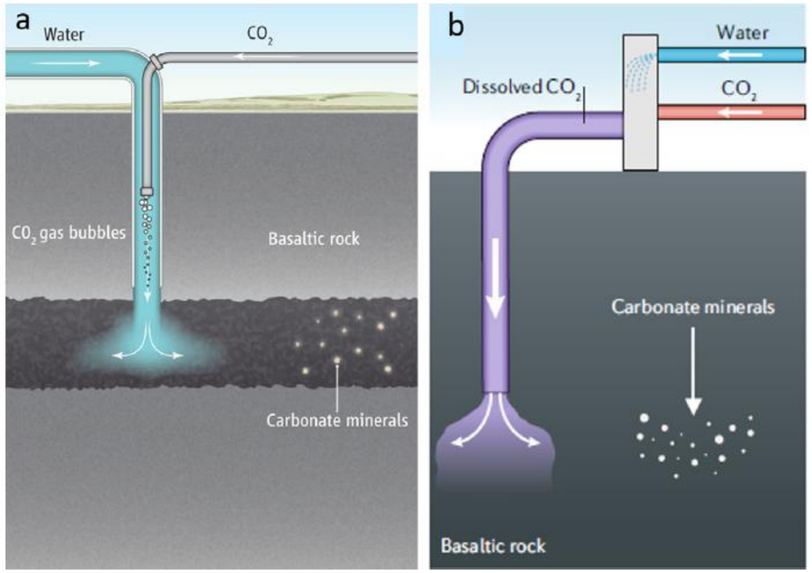
Pure phase

- Free-phase supercritical CO_2 ($scCO_2$).
- 800 m & deeper to remain $scCO_2$.
- High-storage density, no water use.



Dissolved phase

- CO_2 dissolved in water (~1:25).
- Suitable above 800 m.
- Low-storage density, high water use.



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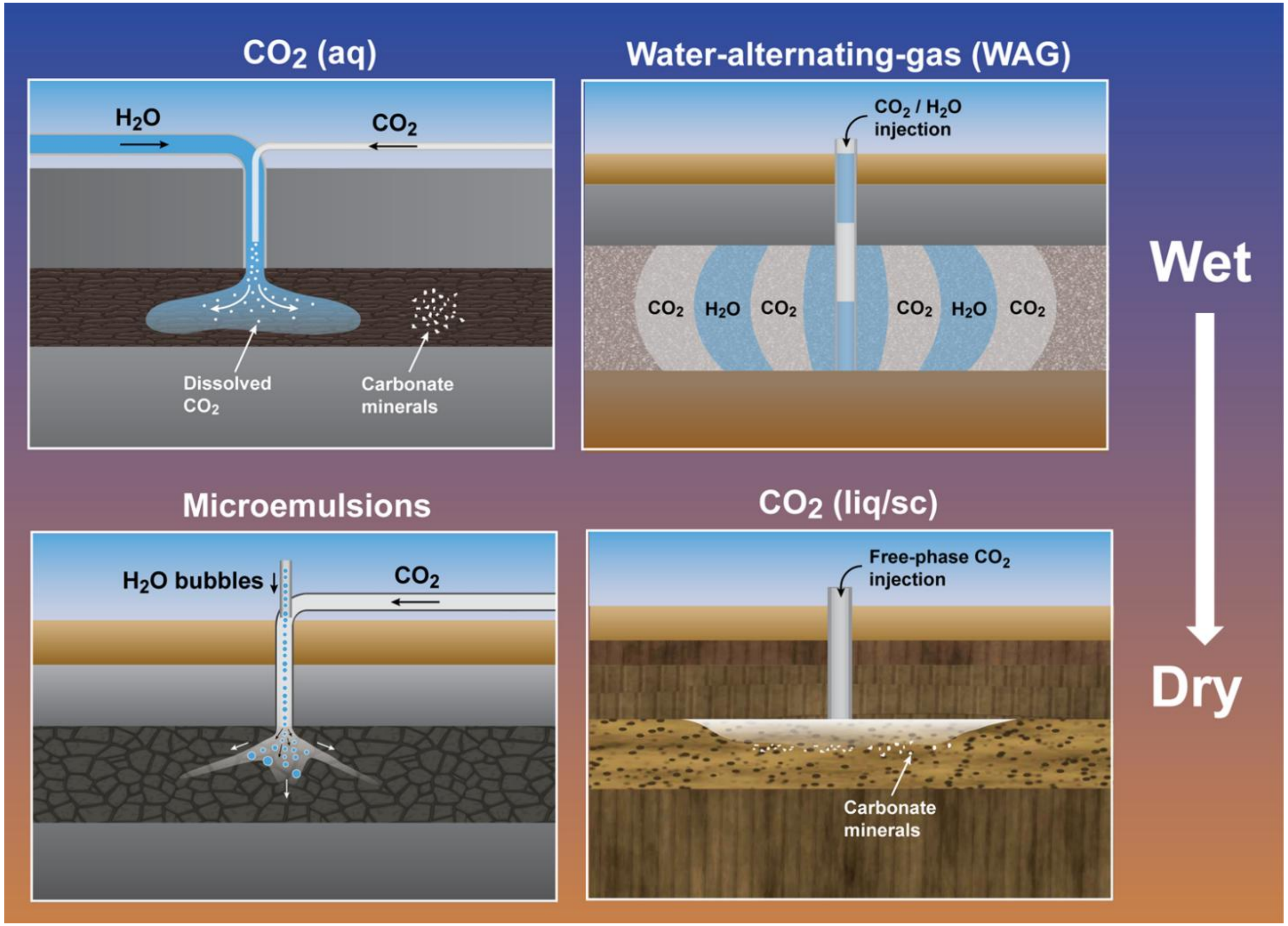
Injection Strategies: Pure vs. Dissolved

- Pure-CO_2 vs. Aqueous-CO_2: End members on a spectrum.
- Hybrid approaches to storage efficiency & sustainability.
- Customization: water content & optimizing carbonation efficiency.
- Engineered additives to enhance mineralization.
- Multiphase injection strategies with drilling technologies & approaches.



Carbon Solutions

Basalts tested in the field

Project: Wallula Basalt Carbon Sequestration Pilot

- Pacific Northwest National Laboratory (PNNL).
- Test characterization well: (2009).
- Injection permit issued (2011).
- Extended hydraulic test characterization (2012).
- Injection: ~1,000 tonnes of CO_2 (2013).
- Final characterization/decommissioning (2015).
- Sidewall core characterization (2017).
- Reservoir Simulations (2020).

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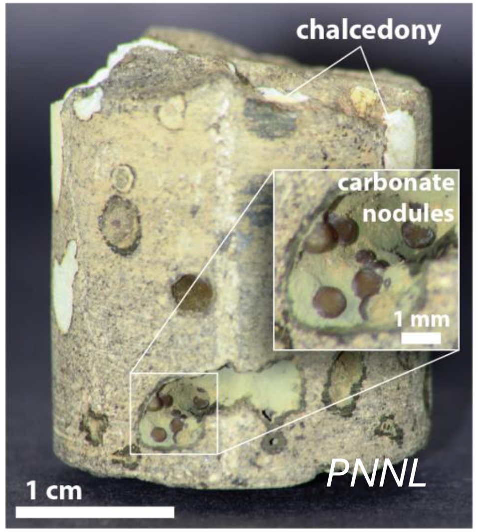
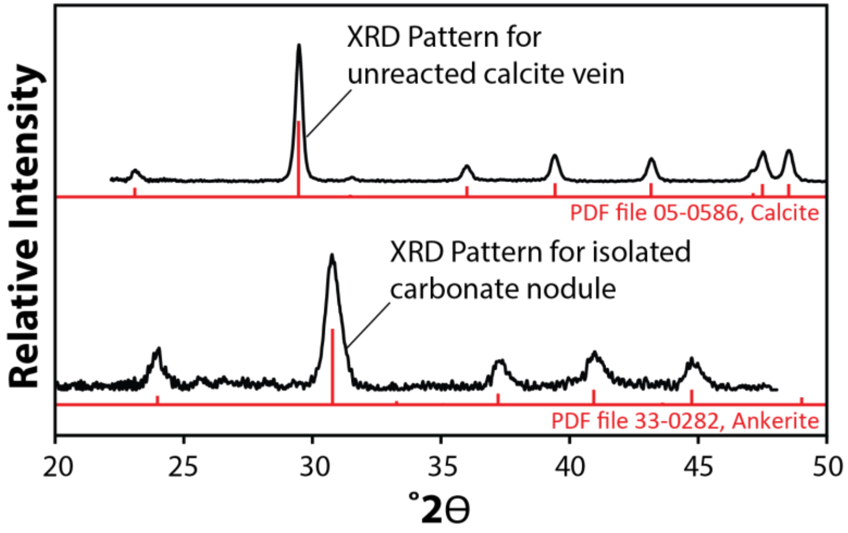
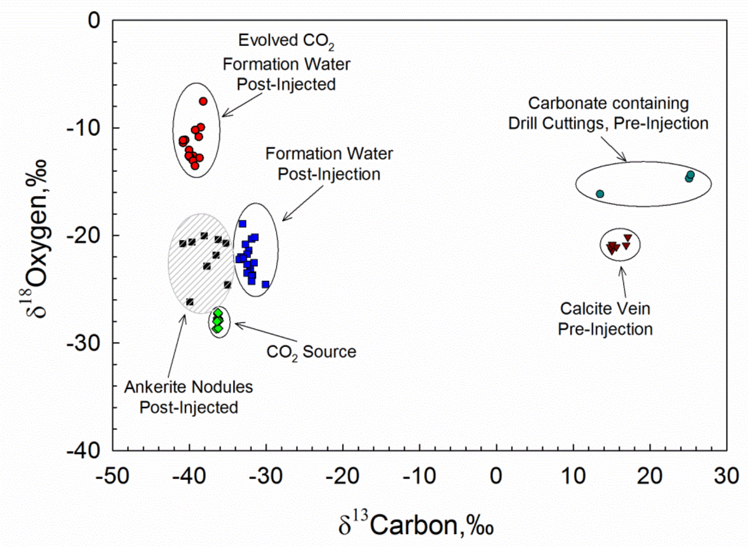
Basalts tested in the lab

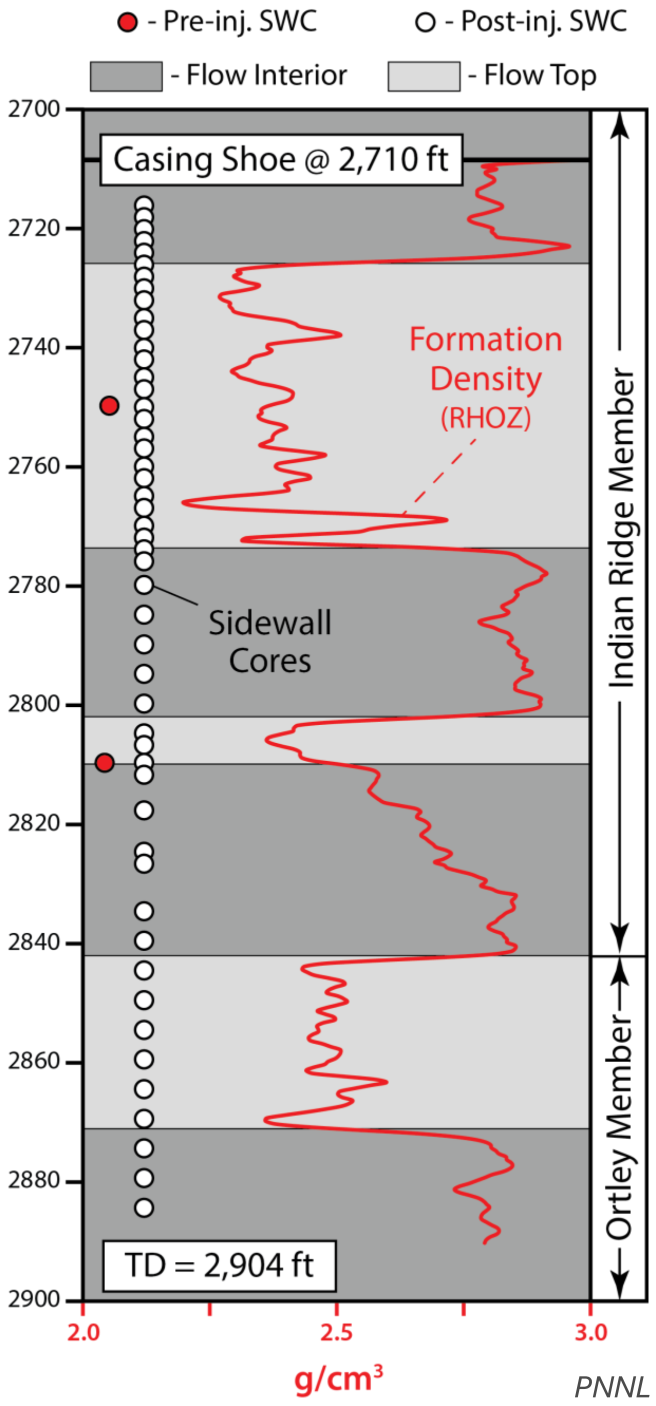
Wallula findings

- 50 sidewall cores (SWC).
- Carbonate nodules observed.
- XRD of nodule material identified ankerite.
- Isotopic signature confirmed the injected CO_2 was mineralized.



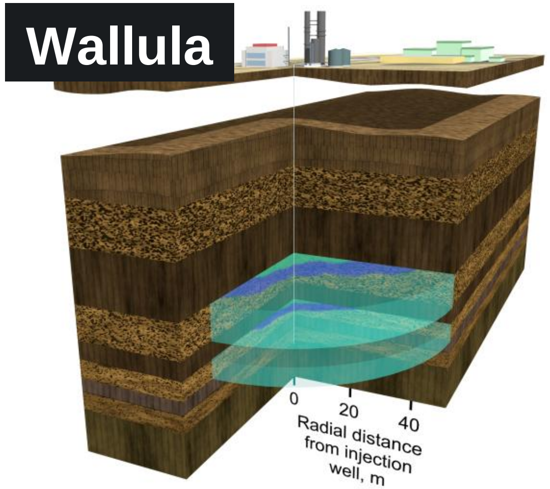


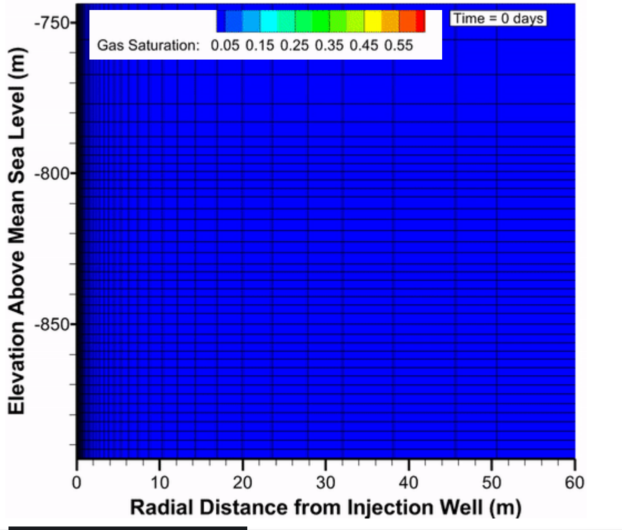


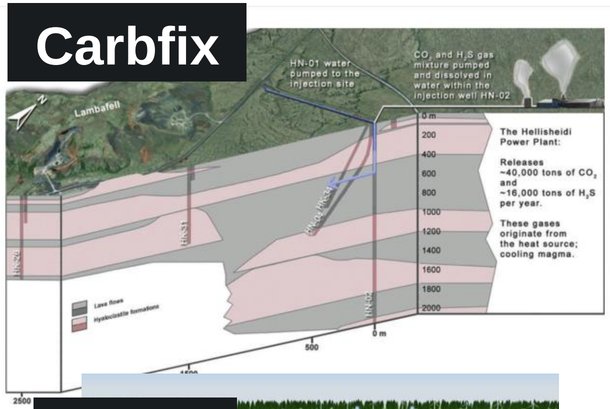


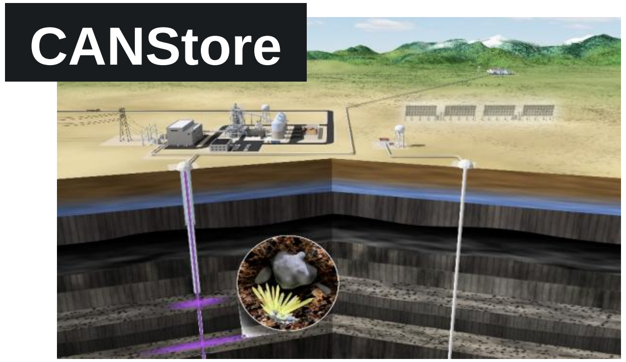
Field to Simulations

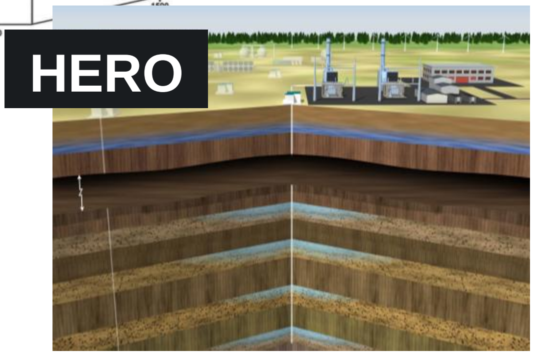
- Reservoir simulations: history matching and forecasting
  - Data representing before, during, and after injection.
  - Simulations for ground-truthing CO_2 mineralization.
- Rates and mechanisms of mineralization in multiphase CO_2-H_2O fluids
  - Mineral-specific reactive surface areas.
  - Upscaling reactive MD to derive rates.
  - Parameterizing wet CO_2 in reactive transport codes.
- Holistic understanding of CO_2 mineralization for all divalent cations, Al, Si, Fe3+, etc.
  - Net porosity/permeability generated during reactive crystallization, or only maintenance.
  - No measurable decreases in porosity, permeability, or injectivity at Wallula.











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Take home message

Photo: Andrea Starr (PNNL)

Why basalts?

- Vast storage potential in the US & globe, particularly in underserved areas.
- Mineralization & conventional storage.
- Risk minimization, storage paradigm.
- Field, lab, & simulation testing.

CaRBTAP

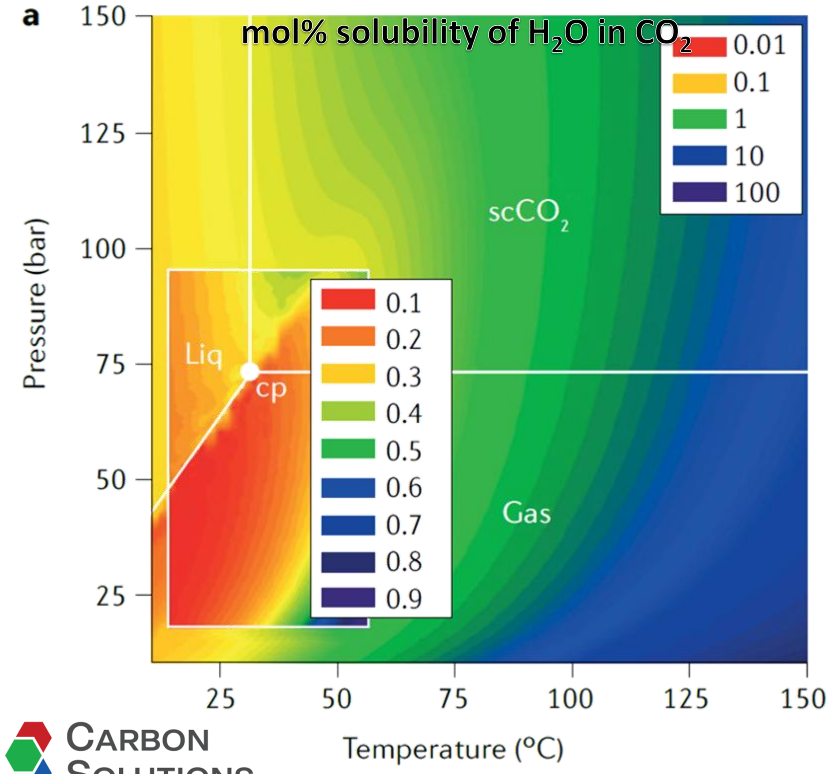
- Motivated region, for energy solutions.
- Industry & government investments.
- Experienced *CaRBTAP* team.
- Roadmap for commercial success.

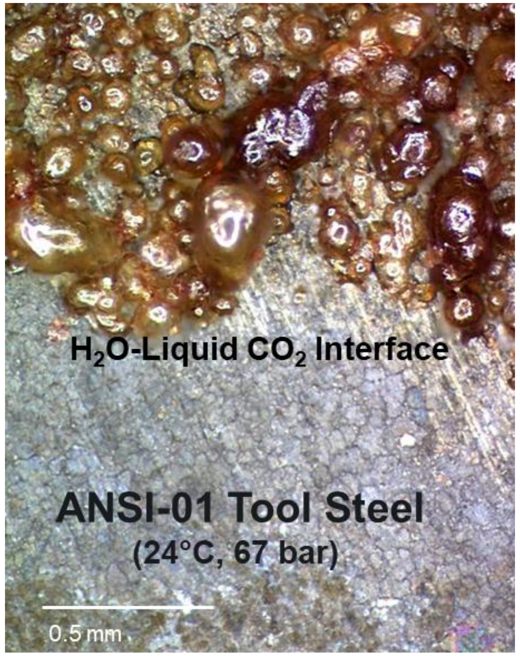
Pacific Northwest NATIONAL LABORATORY
WASHINGTON STATE DEPT OF NATURAL RESOURCES
Carbon Containment Lab
CARBON SOLUTIONS
INL Idaho National Laboratory
WASHINGTON STATE UNIVERSITY

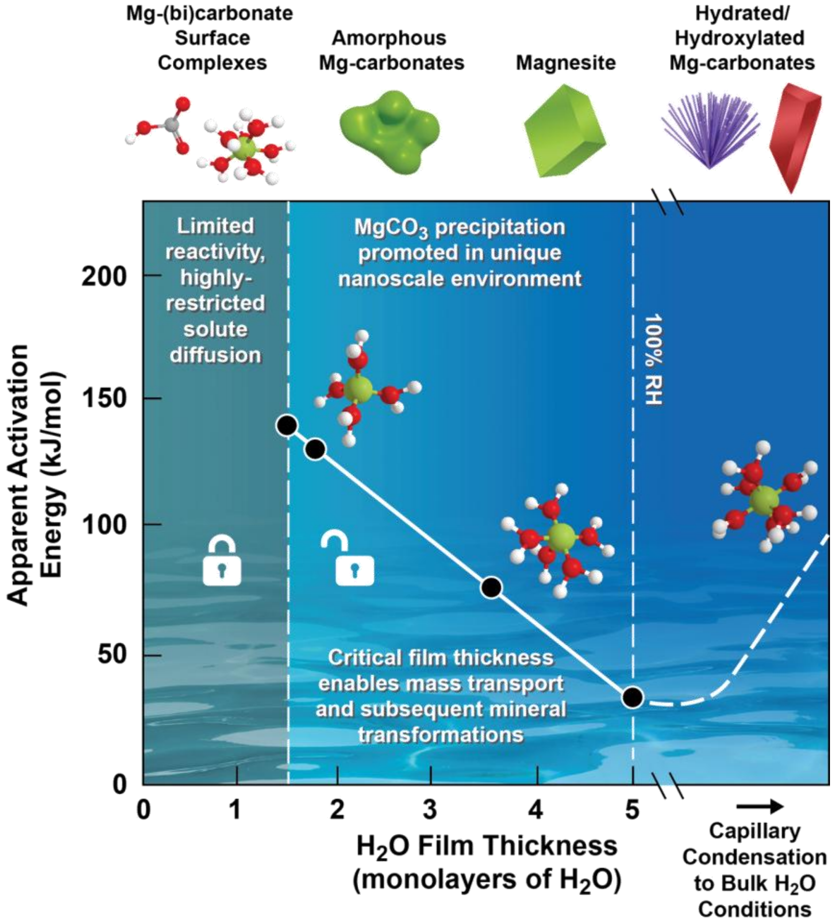
Additional material

Phase Behavior of CO_2-H_2O Mixtures

- Up to ~5 mol% H_2O solubility in CO_2 at prototypical carbon storage conditions.
- Water-bearing CO_2 is more reactive than aqueous-dissolved CO_2.
- Nanoscale water films control unique mechanisms and anomalous energy barriers.
- Accessing new carbon mineralization routes.







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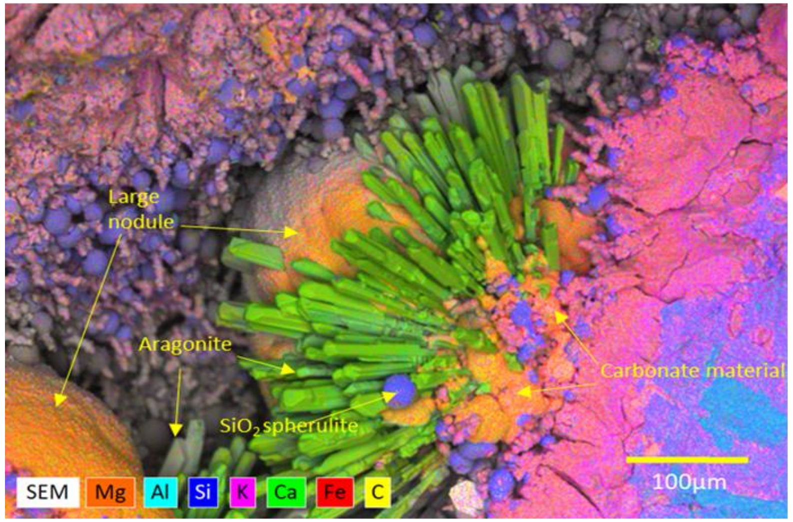
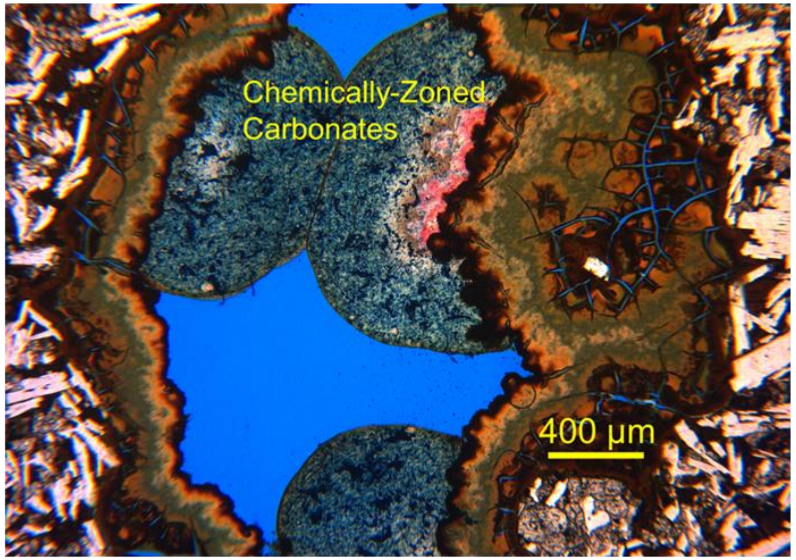
CO_2 Mineralization Reaction Pathway Endpoints

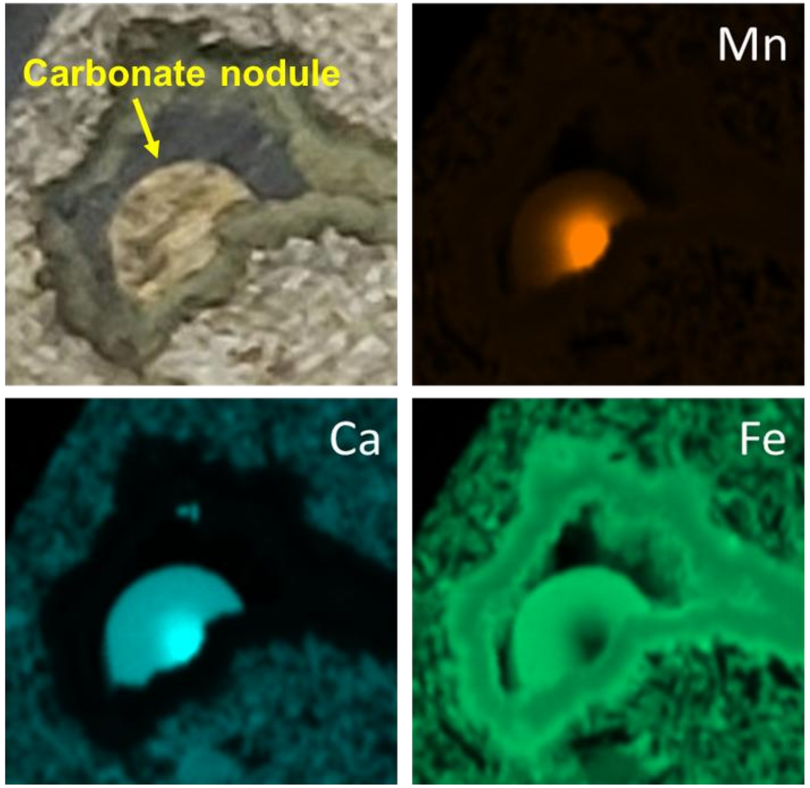
- CO_2 mineralization processes are overlapping and complex.
- Observed carbon mineralization assemblages at Wallula include aragonite ($CaCO_3$), siderite ($FeCO_3$), ankerite [$Ca(Fe,Mn)(CO_3)2$], and non-carbonate minerals.
- Chemically-zoned carbonate nodules (Ca, Mn, & Fe).
- Unique chemistries 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



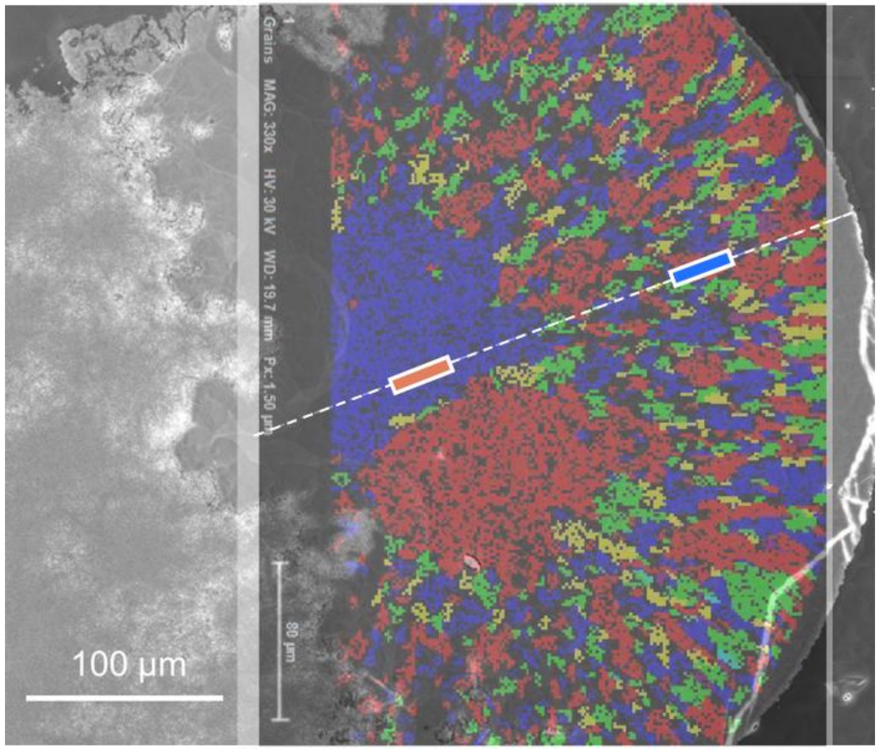
Polites et al. 2022, Exotic Carbonate Mineralization Recovered from a Deep Basalt Carbon Storage Demonstration, ES&T

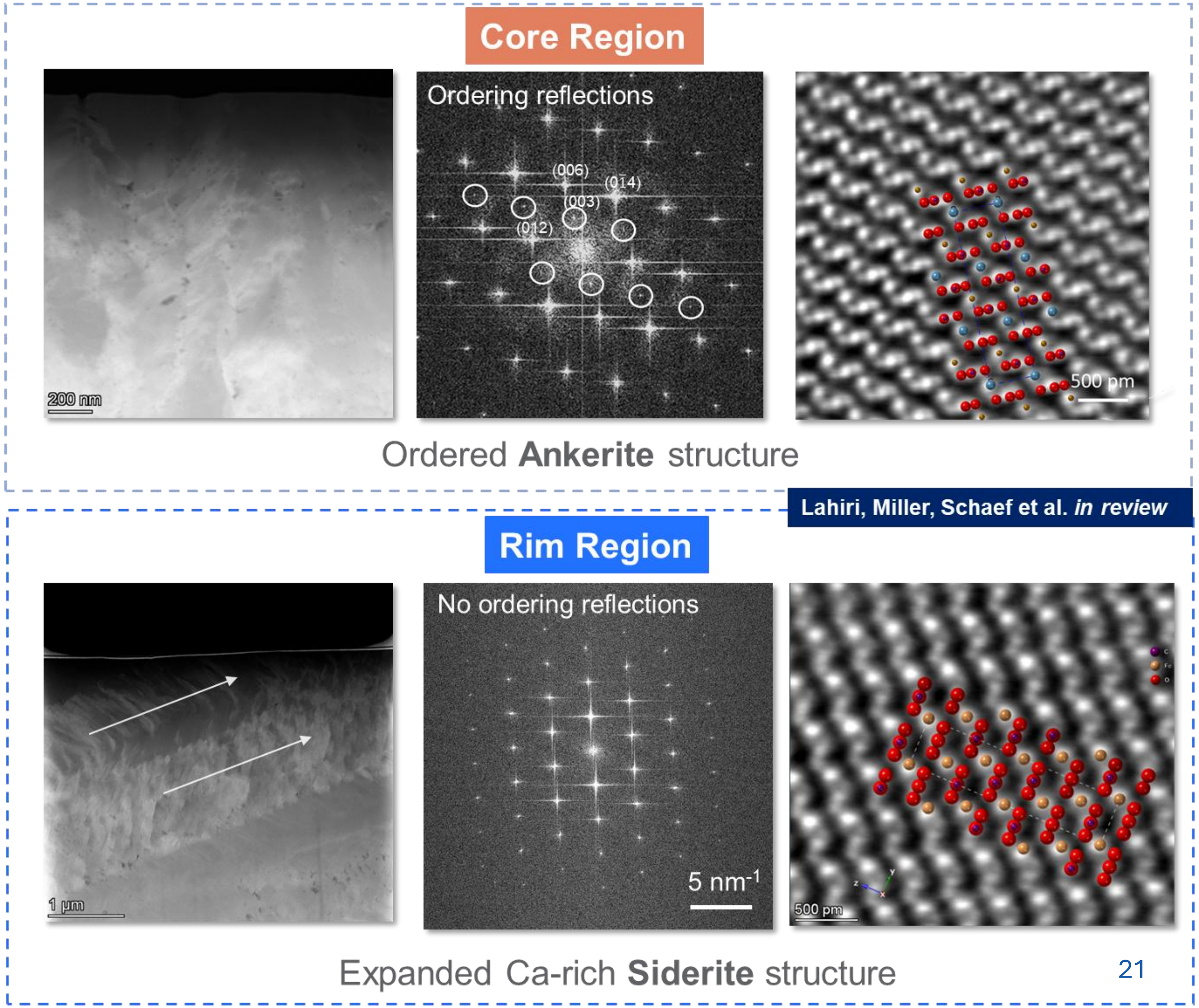


Lahiri et al., 2023, Facile Metal Release from Pore-lining Phases Enables Unique Carbonate Zonation in a Basalt Carbon Mineralization Demonstration, ES&T

Reservoir Simulator Parameterization

- Mg-deficient, ordered ankerite structure.
- Rim region expanded siderite structure.
- Differential phase contrast imaging techniques further confirm the structure of the carbonate.
- No synthetic or natural ankerite ever observed.





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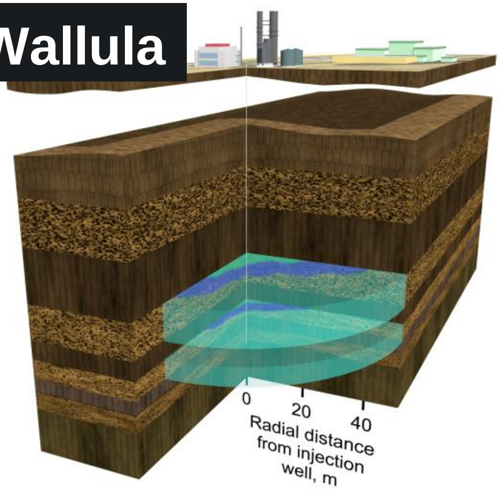
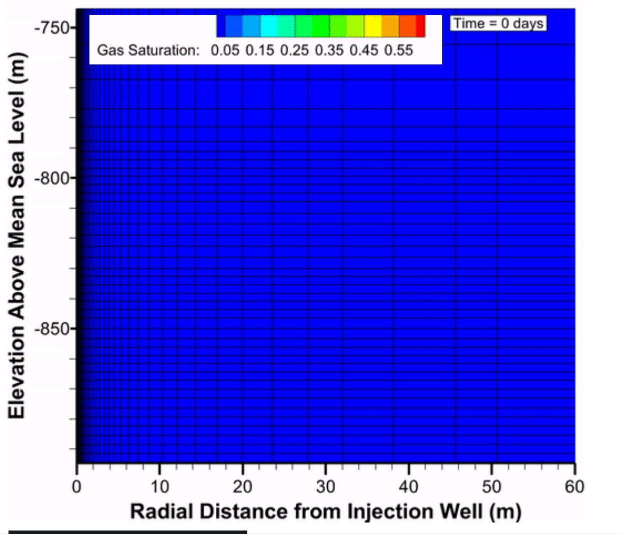
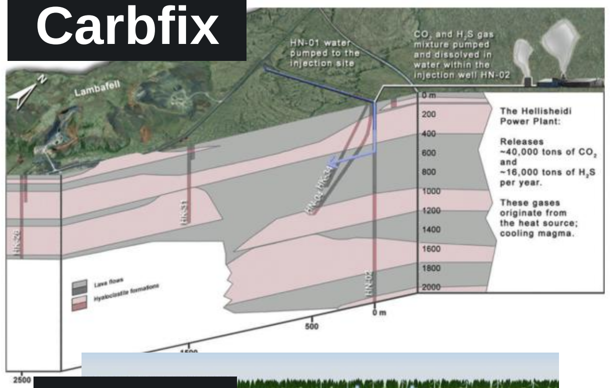
Wallula



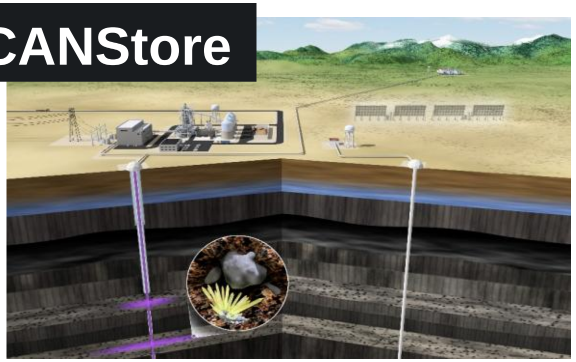


Tamarack

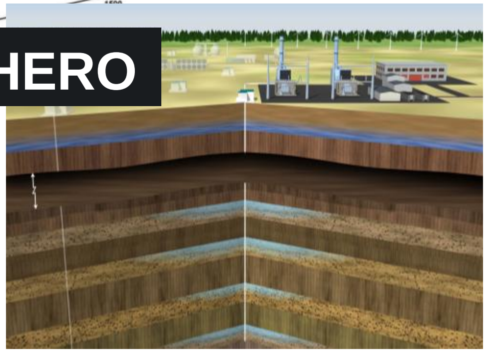
Carbfix



CANStore



HERO



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