Utilization of CO_2 in Unconventional Reservoirs

Project Number 58159

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Collaborating Institutions
University of Wyoming
University of Hawaii

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the
Infrastructure for CO_2 Storage
August 18-21, 2015

Presentation Outline

- Program Focus Area and DOE Connections
- Goals and Objectives
- Scope of Work
- Technical Discussion
- Accomplishments to Date
- Project Wrap-up
- Appendix (Organization Chart, Gantt Chart, and Bibliography

Benefit to the Program

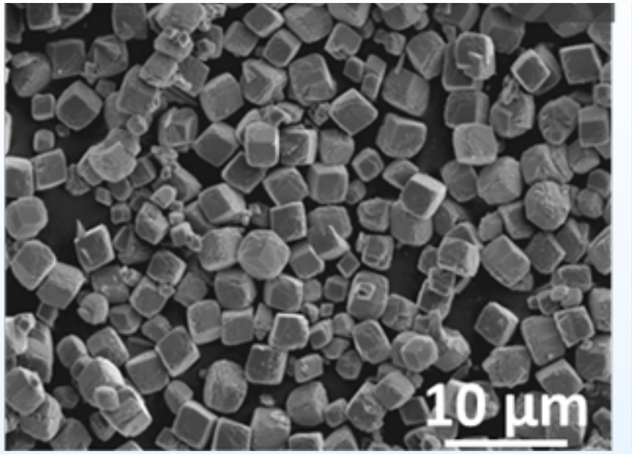
- Program goals addressed:
  - Technology development to predict CO_2 storage capacity
  - Demonstrate fate of injected CO_2 and most common contaminants
- <u>Project benefits statement</u>: This research project conducts modeling, laboratory studies, and pilot-scale research aimed at developing new technologies and new systems for utilization of CO_2 in unconventional geologic formations (basalts and shales) for long term subsurface storage and enhanced gas recovery. Findings from this project will advance industry's ability to predict CO_2 storage capacity in geologic formations.

Basalt Project Overview:
Goals and Objectives

- Goal: Provide a path forward for commercial use of deep basalt formations for CO_2 sequestration
- Objective: Address key challenges associated with utilization of basalt formations as CO_2 storage units
  - Conduct laboratory research that addresses commercial-scale injection strategies
  - Provide laboratory measurements for predicting CO_2 fate and transport
  - Improved seismic imaging methods for basalt characterization

Basalt Project Overview:
Scope of work

- Carbonate Mineralization of Basalts in Aqueous-Dominated Fluids
  - Carbonation rates and key variables important to evaluating long term storage of CO_2
  - High pressure $scCO_2$ batch experiments
    - Low temperature magnesite
    - Aqueous dominated reactions, long-term testing



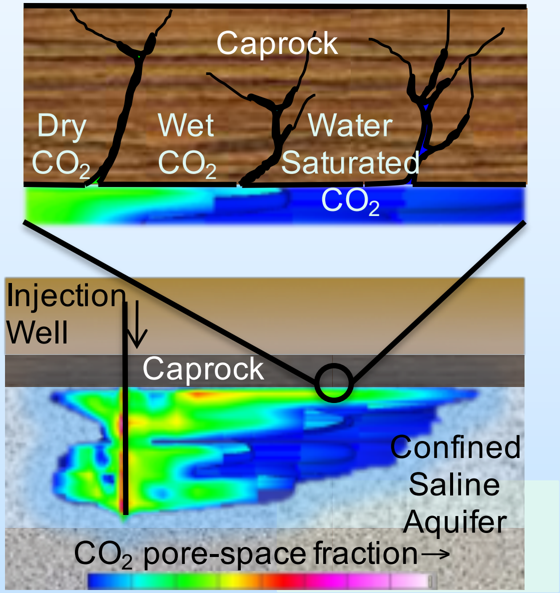
Magnesite particles forming after 56 days at 50°C and 90 bar.

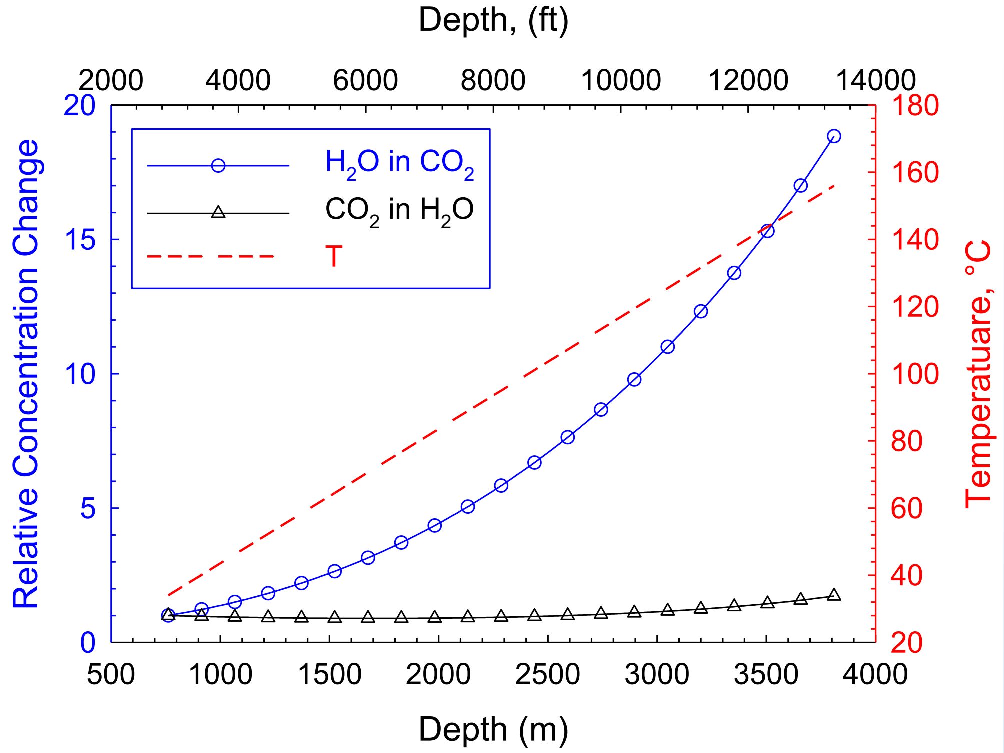
- Basalt Reactions with Wet $scCO_2$
  - Dynamic geochemistry occurring in adsorbed H_2O films.
  - Visualization of Mineral Carbonation in Wet $scCO_2$
  - Impacts of Organic Ligands on Carbonation
  - Modeling Silicate Surfaces in Contact with $scCO_2$ using AIMD Simulations

Phase Behavior of CO_2-H_2O Mixtures in Geological Sequestration

CO_2-H_2O Mixtures

- CO_2 solubility in water varies little with pressure and temperature
- H_2O solubility in $scCO_2$ is strongly dependent on depth
- An equivalent geochemical framework for chemical reactivity in wet $scCO_2$ does not yet exist





Mineral transformation kinetics is potentially as great or greater in wet $scCO_2$

Dynamic mineral reactivity and crystalline product formation in H_2O films

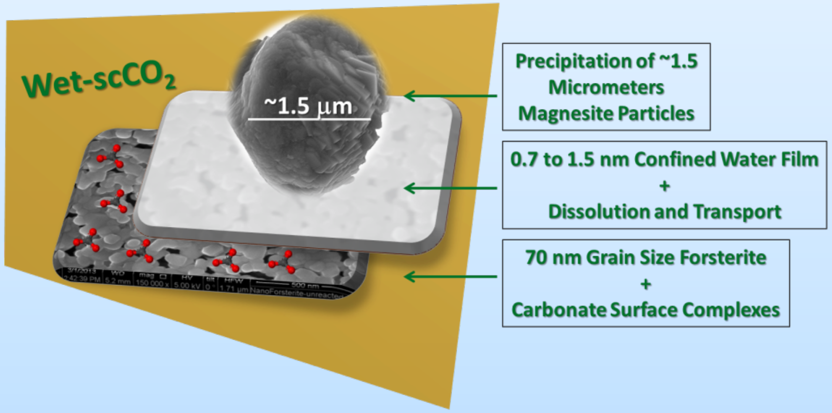
Water film Growth

Goal: Characterize the dynamic geochemistry occurring in adsorbed H_2O films.

Experimental Conditions: Constant temperature (50°C) and pressure (90 bar), with dry to variable wet $scCO_2$.

Results: Mg-carbonate surface complexes predominate before a threshold adsorbed H_2O concentration. Beyond the threshold adsorbed H_2O concentration, magnesite precipitates.

Carbonate Precipitation



Precipitation of ~1.5 Micrometers Magnesite Particles

0.7 to 1.5 nm Confined Water Film + Dissolution and Transport

70 nm Grain Size Forsterite + Carbonate Surface Complexes

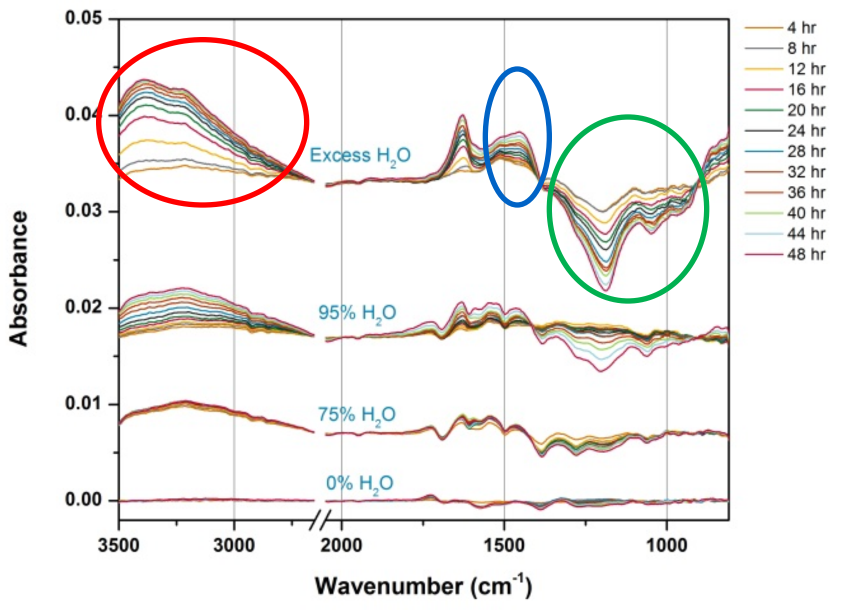
Wet $scCO_2$ and Mineral Surface Interactions

Goal: Characterize the dynamic geochemistry occurring in adsorbed H_2O films

- Water film growth (OH stretch)
- Carbonate precipitation (Asymmetric CO stretching bands)
- Mineral dissolution and precipitation of amorphous silica (SiO stretching bands)

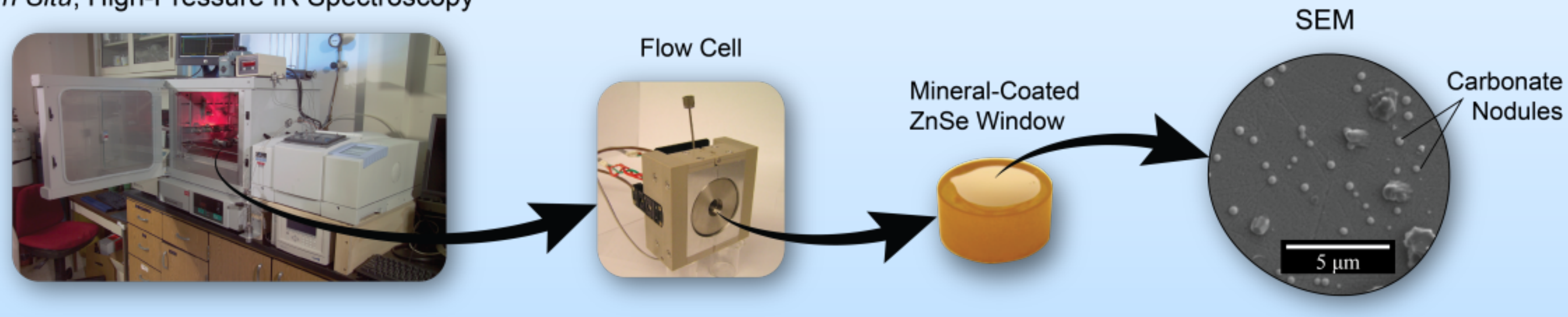
Implications: Significant reactivity highlights need for reservoir simulators to account for reaction kinetics in wet $scCO_2$ fluids.

Plagioclase [$(Ca,Na)(Al,Si)_4O_8$]



Other minerals studied: forsterite, albite, brucite, antigorite, and enstatite, and microcline

In Situ, High-Pressure IR Spectroscopy

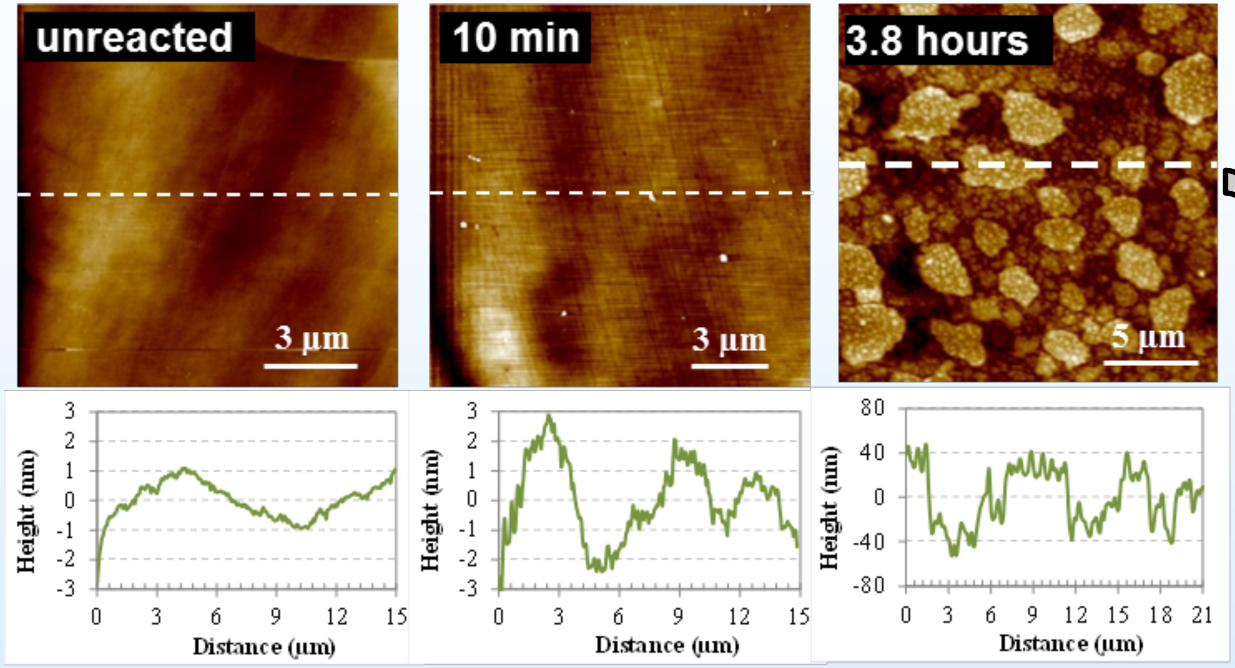


Visualizing Mineral Carbonation in Wet $scCO_2$

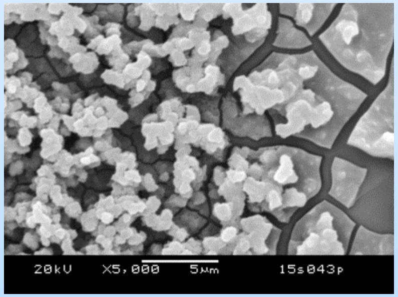
Pressurized Atomic Forced Microscopy

- Carbonation in wet $scCO_2$
  - Controlling factors
  - Modeling parameters
- Carbonation Products
  - Nucleation sites
  - Growth habits and morphologies
- Intrinsic Rate Constants
  - Water concentrations in $scCO_2$
  - Variability in water film thickness

Experimental Approach: Brucite, when exposed to a steady stream of humid $scCO_2$ at 50°C and 90 bar, forms islands of nesquehonite clearly visible on the brucite surface.

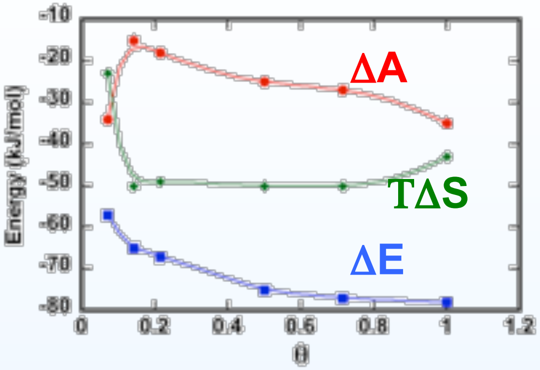


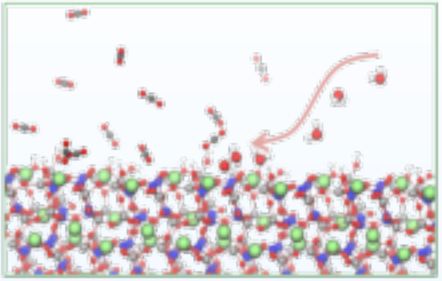
Mineral Carbonation: *in-situ* AFM images of brucite surface, 1) unreacted, and after contact with wet $scCO_2$ for 2) 10 minutes and 3) 3.8 hours (50 °C, 90 bar).

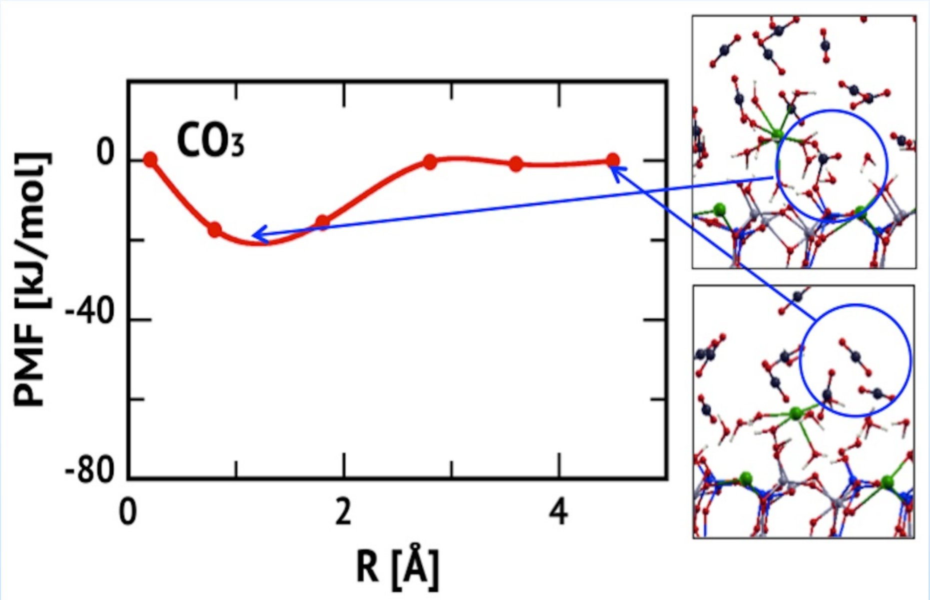


AIMD Simulations Designed to Model Water film Growth on Silicate Surface in Contact with Wet $scCO_2$

- AIMD simulations of free energy of adsorption and reactivity at a Mineral/H_2O/$scCO_2$ interface
  - Mechanism of water layer nucleation and growth at solid/liquid interfaces occurs even at the low (10^{-4}) water solubility in $scCO_2$.
  - Water facilitates reactivity to form cation vacancies on the surface, leading to carbonate formation, in agreement with exp. observations.
- Wet $scCO_2$ can lead to unique speciation, structural transformations, and unexpected reactivity at solid/liquid interfaces.







Basalt Project Overview:
Scope of work

- Wallula Basalt Pilot Project Support
  - Field Activities
    - Detailed wireline survey characterization
    - Groundwater sampling
    - Targeted side-wall coring
    - Extended hydrologic tests
    - Final well decommissioning/site demobilization.
  - Laboratory Activities
    - Side wall core characterization.

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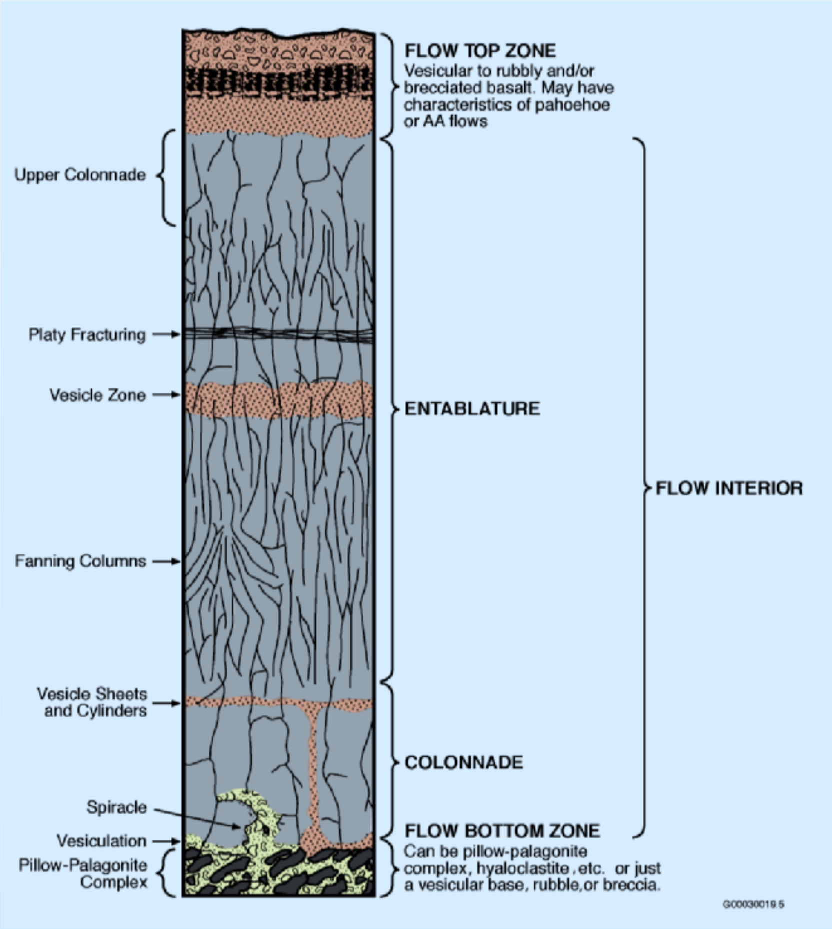
Flood Basalt Features Relevant to CO_2 Sequestration

- Formation process
  - Giant volcanic eruptions
    - Low viscosity lava
    - Large plateaus
  - Multiple layers
- Primary structures
  - Thick impermeable seals
    - Caprock (flow interior)
    - Regional extensive interbeds
  - Permeable vesicular and brecciated interflow zones
    - Injection targets
    - 15-20% of average flow

Deccan Trap Basalts

Layered Basalt Flow



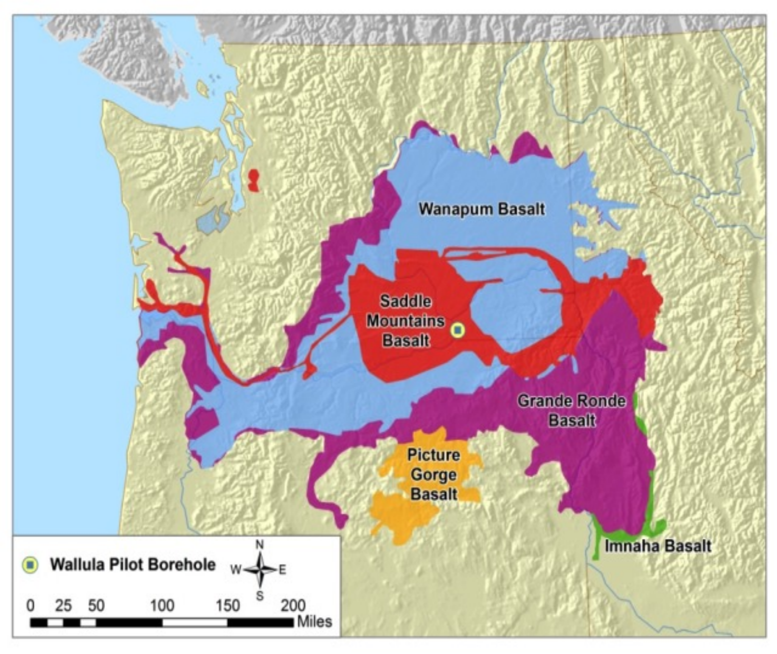
Wallula Basalt Carbon Sequestration Pilot Project

Project Background:

- Drilling initial test characterization and well completion: Jan. – May 2009
- Extended hydraulic test characterization: Feb. – March 2011 and Sept. – Nov. 2012
- ~1,000 MT CO_2 injection: July 17th – August 11th, 2013
- Post-injection air/soil monitoring and downhole fluid sampling performed for ~2 years following injection

Current Status:

- Final well characterization activities: June – July 2015
- Detailed wireline survey
- Targeted sidewall coring
- Extended hydrologic tests
- Final well decommissioning/site demobilization: August 2015



Wallula Basalt Pilot Well: Final Wireline and Hydrologic Characterization

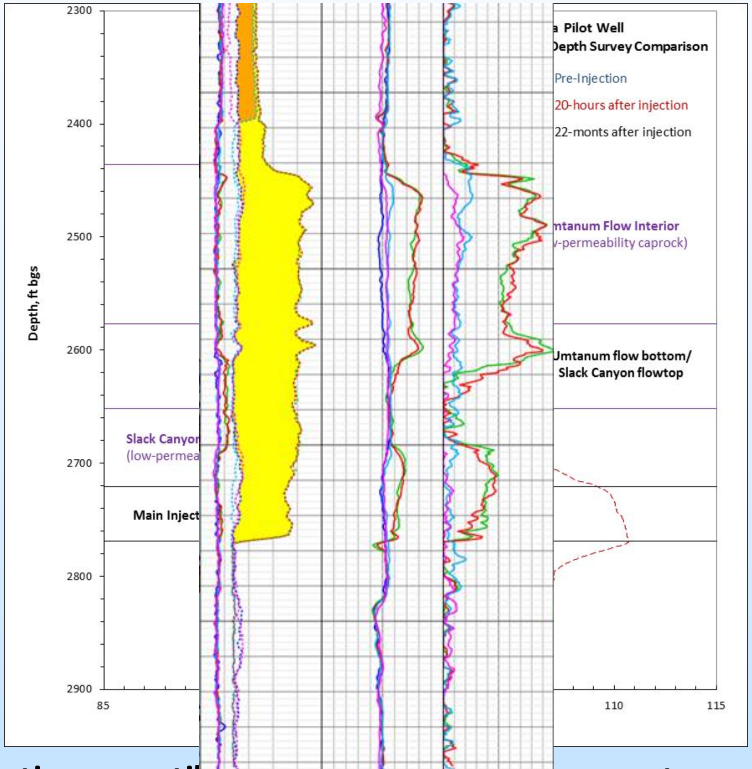
- **Extended duration hydrologic injection test**
  - Assess large scale changes in aquifer reservoir hydraulics
  - 18,000 gallons of water was injected over 3.7 days (avg. rate of ~3.4 gpm).
  - Post injection recovery was monitored over a 5 day period
- **7 low-stress (i.e. ΔP ≈ 13 psi), near-field pressurized slug tests (i.e. pulse tests)**
  - Near-field reservoir hydraulic properties immediately surrounding the open borehole
- **Short-duration constant rate drawdown and recovery test**
  - Near-field reservoir hydraulic properties extending a few 10’s of feet from the borehole

Detailed wireline survey for detecting CO_2 and geochemical and physical property changes (porosity) in injection zone basalt flow tops:

- Fluid temperature/pressure/gamma (4-2,901 ft)
- Platform Express logging suite (2,400 – 2,904 ft)
- Formation Micro Imager (2,720 – 2,904)
- Residual Saturation Tool – Sigma (100 – 2,904 ft)
- Residual Saturation – Carbon/Oxygen (2,710 – 2,904)

Fluid Temperature Survey Results

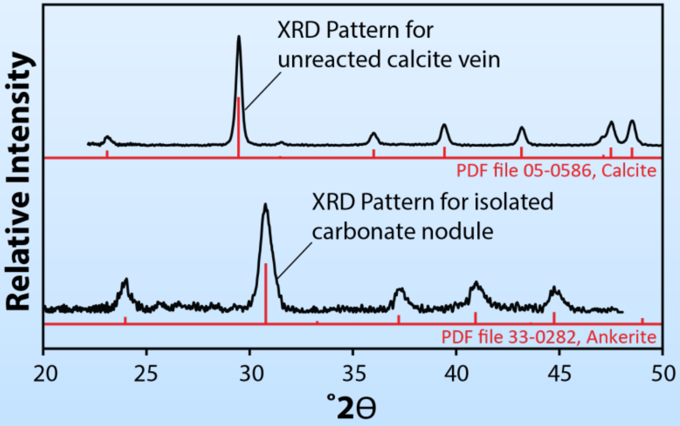
Well Logging Results



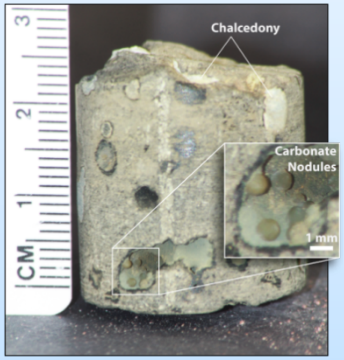
Injection zone still exhibits a well-defined temperature signature (+4 °F) 22-months after injection termination.

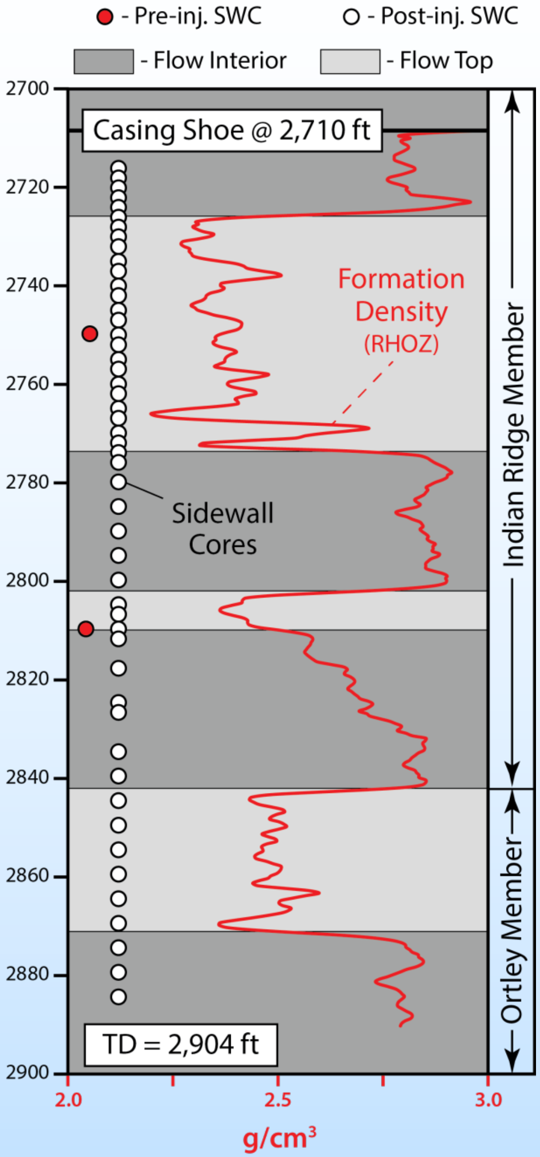
Wallula Basalt Pilot Well: Initial Sidewall Core Characterization

- 50 sidewall cores were collected across the open borehole section between 2,716 – 2,900 ft bgs
- Potential carbonate reaction products observed on SWC samples occur both as large (up to ~1mm) nodules within open vesicles and as a coating on the borehole wall face of a few core samples
- XRD analysis of selected carbonate nodules identified ankerite as the only carbonate mineral present



2,810 ft Core Sample (Post-injection)

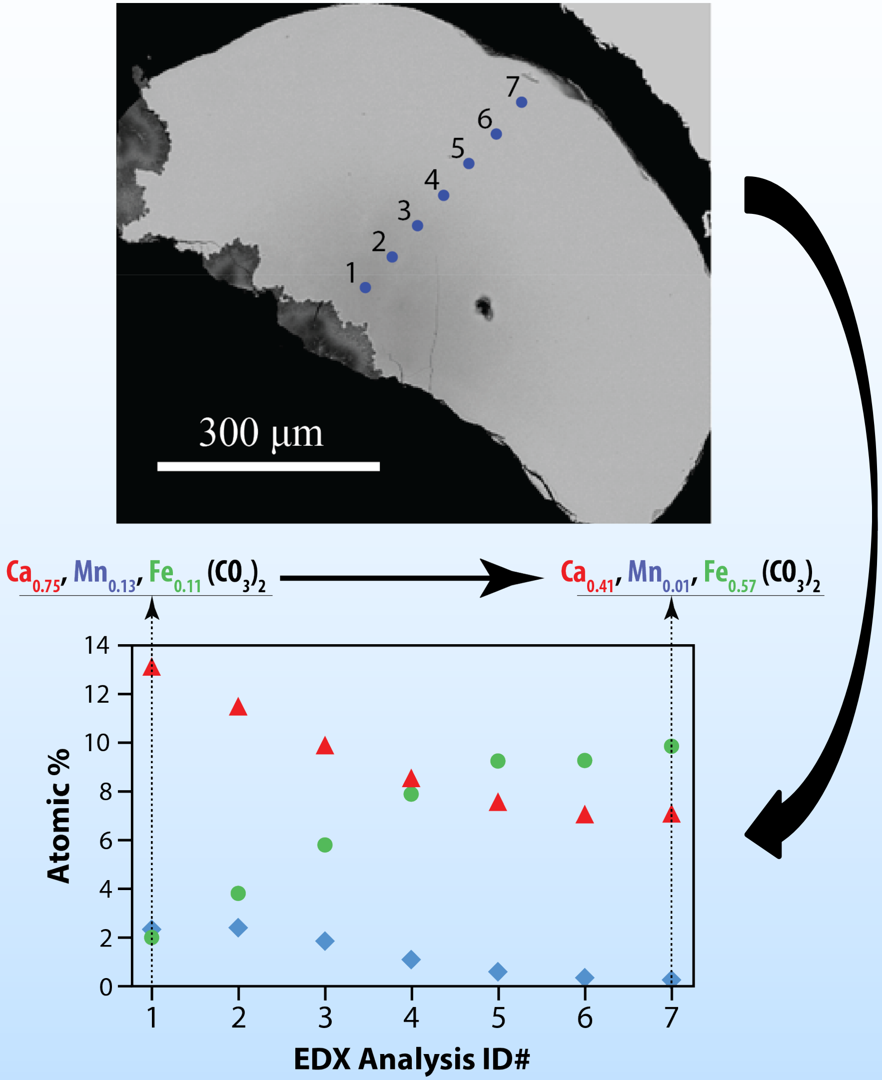




Wallula Basalt Pilot Well: Initial Sidewall Core Characterization

XMT imaging of post-injection sidewall core sample collected from 2,810 ft bgs

SEM micrograph of polished cross section of ankerite nodule (EDX analysis ID #)

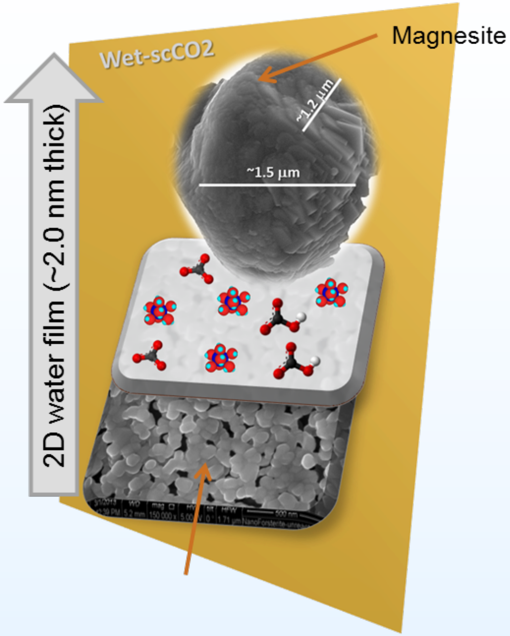


- XMT imaging shows likely ankerite nodules existing throughout core
- Chemically, these ankerite nodules are initially dominated by Ca, but become Fe rich as the precipitation progresses.

Summary

- **Key Findings**
  - Reactions occurring between silicate minerals and H_2O-$scCO_2$ fluids produce well crystallized carbonate minerals at laboratory time scales.
  - Carbonation occurs after adsorbed water films become thick enough to solvate and transport cations and bicarbonate ions.
  - Atomistic modeling provides insights into dynamic chemical environment occurring in thin water films.
  - Basalt Pilot Project providing first time evidence of *in situ* carbonation analogous to laboratory results

"CO_2 storage in basalt formations is also a potentially important option for regions like the Indian subcontinent " IEG Technology Roadmap, 2009.



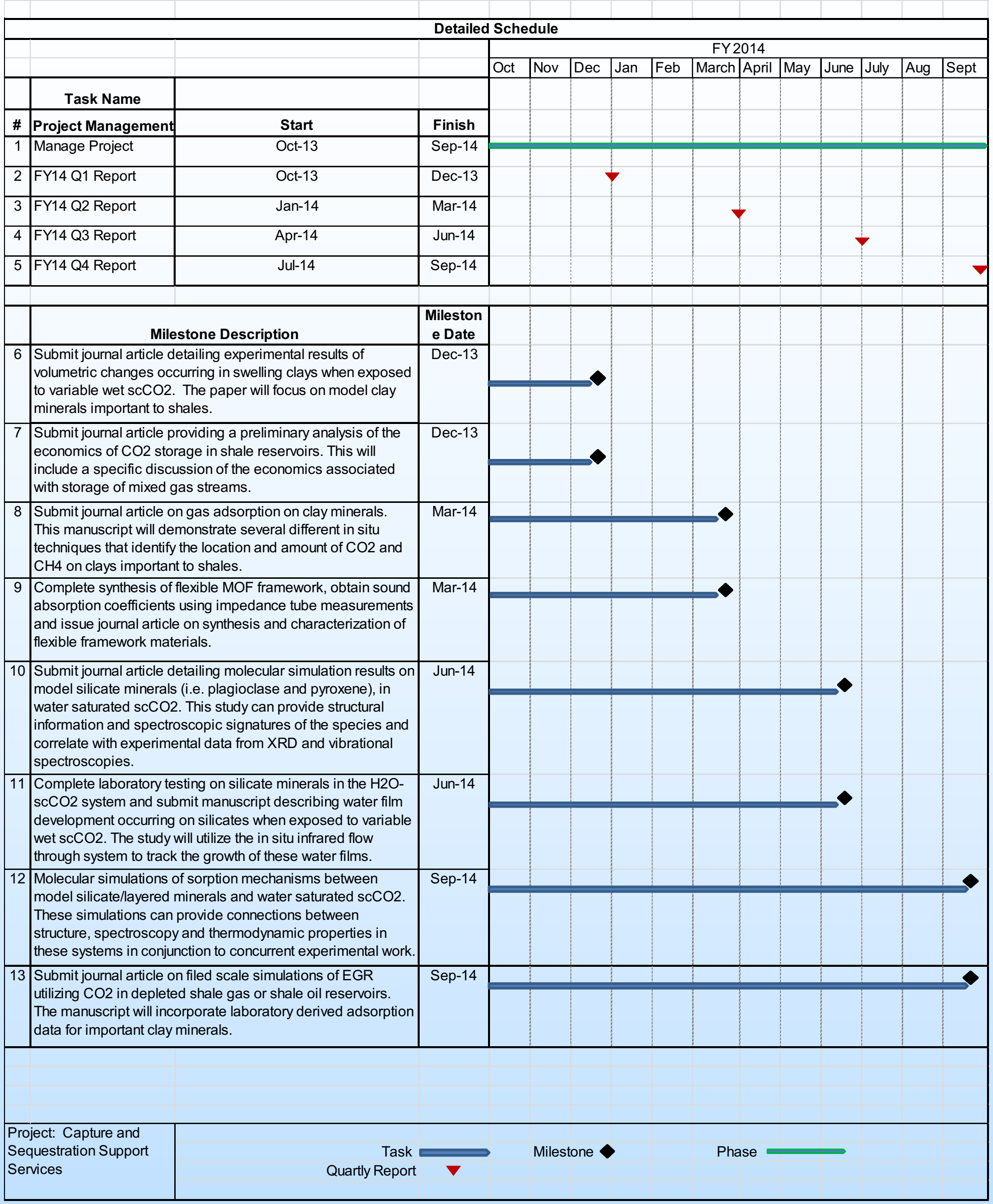
Transport of Aqueous Species
(water-film diffusion mechanism)

- **FY 16 Planned Activity**
  - Expanded scope to examine importance of water bearing $scCO_2$ on relevant silicate minerals
  - Continued laboratory support for basalt pilot project including isotopic characterization of carbonate precipitates

Organization Chart

- Project team has participants that cut across the Energy & Environment and Fundamental Sciences Directorates at PNNL
- Pacific Northwest National Laboratory is Operated by Battelle Memorial Institute for the Department of Energy

Gantt Chart



Detailed Schedule

#	Task Name Project Management	Start	Finish
1	Manage Project	Oct-13	Sep-14
2	FY14 Q1 Report	Oct-13	Dec-13
3	FY14 Q2 Report	Jan-14	Mar-14
4	FY14 Q3 Report	Apr-14	Jun-14
5	FY14 Q4 Report	Jul-14	Sep-14

#	Milestone Description	Milestone Date
6	Submit journal article detailing experimental results of volumetric changes occurring in swelling clays when exposed to variable wet scCO2. The paper will focus on model clay minerals important to shales.	Dec-13
7	Submit journal article providing a preliminary analysis of the economics of CO2 storage in shale reservoirs. This will include a specific discussion of the economics associated with storage of mixed gas streams.	Dec-13
8	Submit journal article on gas adsorption on clay minerals. This manuscript will demonstrate several different in situ techniques that identify the location and amount of CO2 and CH4 on clays important to shales.	Mar-14
9	Complete synthesis of flexible MOF framework, obtain sound absorption coefficients using impedance tube measurements and issue journal article on synthesis and characterization of flexible framework materials.	Mar-14
10	Submit journal article detailing molecular simulation results on model silicate minerals (i.e. plagioclase and pyroxene), in water saturated scCO2. This study can provide structural information and spectroscopic signatures of the species and correlate with experimental data from XRD and vibrational spectroscopies.	Jun-14
11	Complete laboratory testing on silicate minerals in the H2O-scCO2 system and submit manuscript describing water film development occurring on silicates when exposed to variable wet scCO2. The study will utilize the in situ infrared flow through system to track the growth of these water films.	Jun-14
12	Molecular simulations of sorption mechanisms between model silicate/layered minerals and water saturated scCO2. These simulations can provide connections between structure, spectroscopy and thermodynamic properties in these systems in conjunction to concurrent experimental work.	Sep-14
13	Submit journal article on filed scale simulations of EGR utilizing CO2 in depleted shale gas or shale oil reservoirs. The manuscript will incorporate laboratory derived adsorption data for important clay minerals.	Sep-14

Project: Capture and Sequestration Support Services

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Utilization and Storage of CO_2 in Unconventional Reservoirs

Project Number 58159 Task 2

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Pacific Northwest National Laboratory

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Benefit to the Program

- Program goals addressed:
  - Technology development to predict CO_2 storage capacity
  - Demonstrate fate of injected CO_2
- Project benefits statement: This research project conducts modeling and laboratory studies to lower cost and to advance understanding of storing pure CO_2 and mixed gas emissions produced from post- and oxy-combustion flue gas in unconventional geologic reservoirs.

Project Overview:
Goals and Objectives

- Goal: Development of geologic storage technology with a near zero cost penalty goal – a grand challenge with enormous economic benefits.
- Objective: Employ a multidisciplinary approach for identifying key sequestration opportunities and for pursuing major research needs in:
  - Identifying R&D needs and pursuing R&D on promising low-cost technologies for utilizing CO_2 and CO_2 containing other constituents in depleted shale gas and shale oil reservoirs.
  - phase behavior and fate and transport of supercritical gas mixtures in fractured geologic formations.
  - casing material studies with water and mixed gas systems
  - development of acoustically responsive contrast agents for enhanced monitoring of injected CO_2.

Project Overview:
Scope of work

- Task 2 – Utilization in Unconventional Reservoirs
  - 2.1 Storage in Depleted Shale Gas Reservoirs
    - Economics of Utilizing CO_2 in Depleted Shale Gas Reservoirs
    - Laboratory Studies
      - Probing structural changes on natural shale samples during $scCO_2$ exposure
      - Characterizing Water Film Development and Mineral Stability during exposure to wet acid gases
      - Quantify water solubility in CH_4/CO_2 gas mixtures at reservoir conditions
      - Distinguish interactions between metal cations and $scCO_2$: chemical reactivity versus physisorption processes
    - Molecular Dynamics Modeling
      - Independent check on the sorption behavior of CO_2 on the external surfaces of minerals
      - Provide mechanistic insight into CO_2 intercalation
    - Reservoir Modeling
      - Field scale simulation utilizing CO_2 in a depleted fractured shale reservoir utilizing CO_2
      - Incorporate laboratory findings to optimize methane production
  - 2.2 Enhanced Monitoring Agents
    - Synthesis methods and performance testing in a laboratory setting
    - Newly developed laboratory technique for low frequency measurements

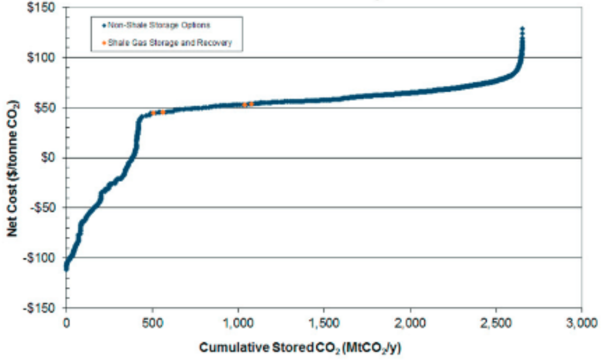
Costs, Offsetting Revenues, and Deployment Potential of EGR in Gas Shales

- Using three CO_2:CH_4 recovery relationships taken from the literature, Davidson & McGrail (2015) developed revenue estimates associated with the CO_2 injection phase of a shale-based CCS project
- These three revenue cases were used to parameterize scenarios evaluated via least-cost optimized source-sink pairing to generate cost curves for CCS in the U.S. to illustrate the impact of CO_2:CH_4 response on the potential for shale-based CCUS deployment
- Variation in the final cost curves suggests that resolving uncertainty around reservoir response is necessary to understanding the commercial potential of shale-based storage, and to help identify lower cost targets for deployment
- This work has been used to help focus current and future experimental efforts to allow for refinement of resource estimates and operational costs. Specific areas of interest include:
  - Bulk incremental recovery response
  - Relative sorption of CO_2 and CH_4 on mineral and organic shale components
  - Compositional effects on swelling and permeability changes
  - Efficacy of fractures and diffusion processes for CO_2 and CH_4 transport
  - Storage mechanisms (sorption vs free-phase)

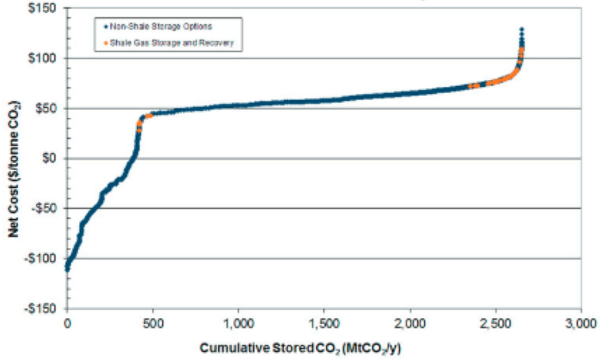
Case	**Revenue ($/t$CO_2$)**	**Shale-based Projects (#)**	**Storage (MtCO_2/y)**
Low Gas Recovery	$0.52	5	1
Moderate Gas Recovery	$11.44	44	20
High Gas Recovery	$18.46	303	600

from CL Davidson, RT Dahowski, JJ Dooley, BP McGrail. 2014. Modelling the deployment of CO_2 storage in U.S. gas-bearing shales. *Energy Procedia.* Volume 63, pages 7272-7279.

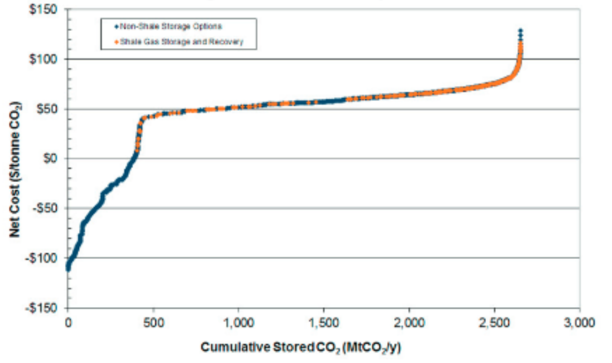
Low Recovery Case



Moderate Recovery Case



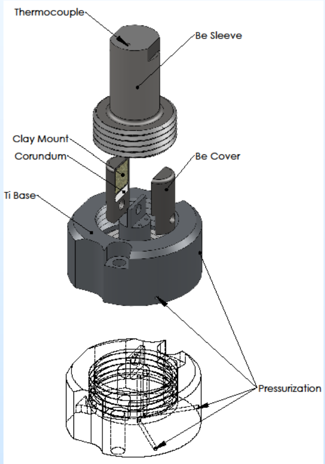
High Recovery Case



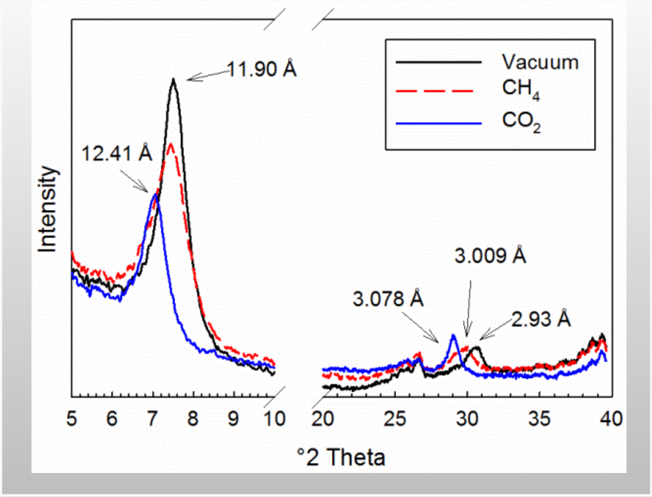
Laboratory Studies: Probing Structural Changes with HXRD

Goal: Characterize shale stability (i.e., swelling, shrinking) in the presence of $scCO_2$ and water

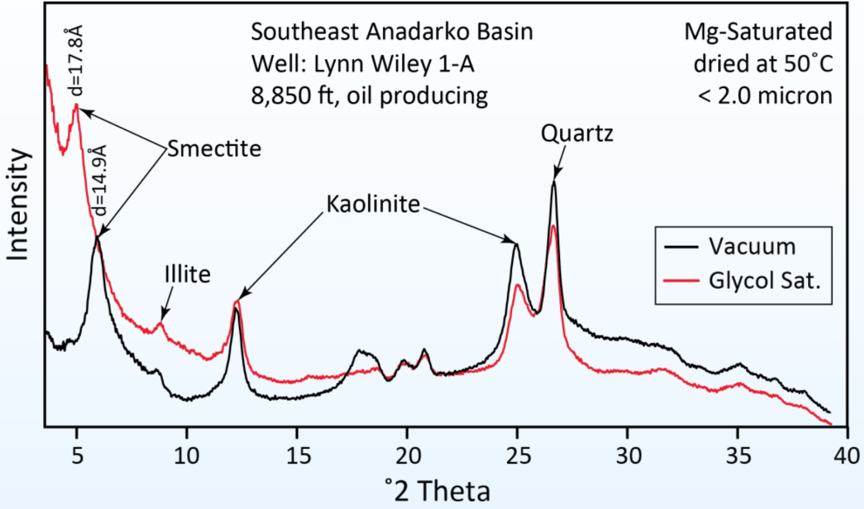
- Woodford shale contains quartz, illite, kaolinite, and smectite
- No observable instability when in contact with anhydrous $scCO_2$
- Minor amount of swelling during exposure to $scCO_2$

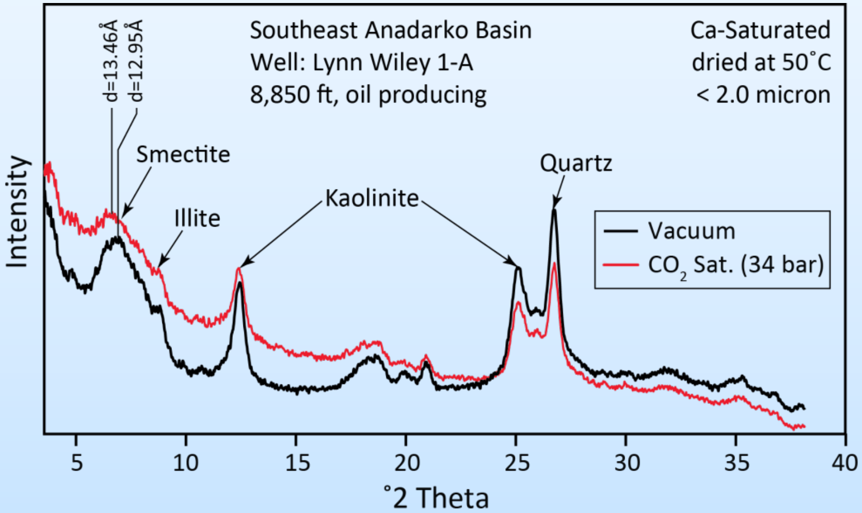


Montmorillonite (SWy-2) swells with $scCO_2$, but not with CH_4.



Woodford Shale



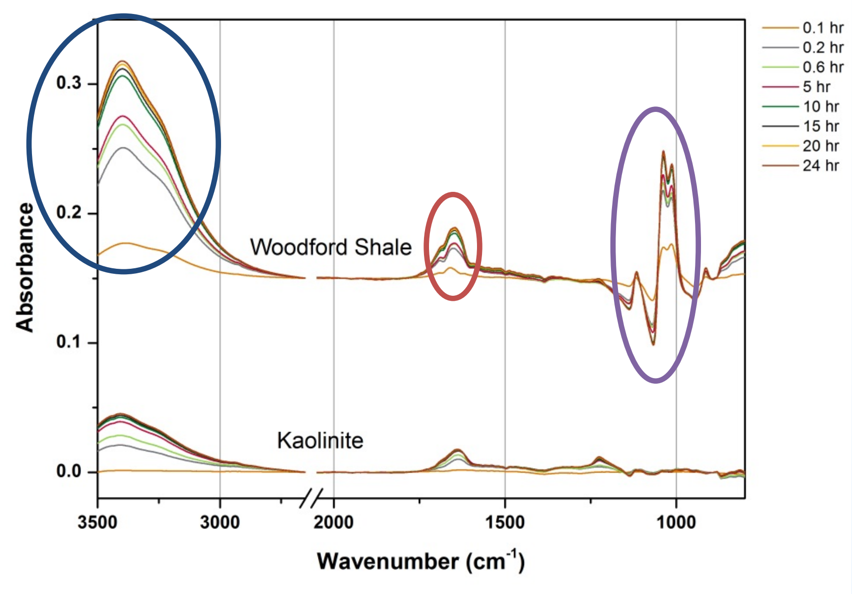


Technique Reference : Schaef, H. T., E. S. Ilton, O. Qafoku, P. F. Martin, A. R. Felmy and K. M. Rosso (2012). "In situ XRD Study of Ca^{2+} Saturated Montmorillonite (STX-1) Exposed to Anhydrous and Wet $scCO_2$." IJGGC, 220-229.

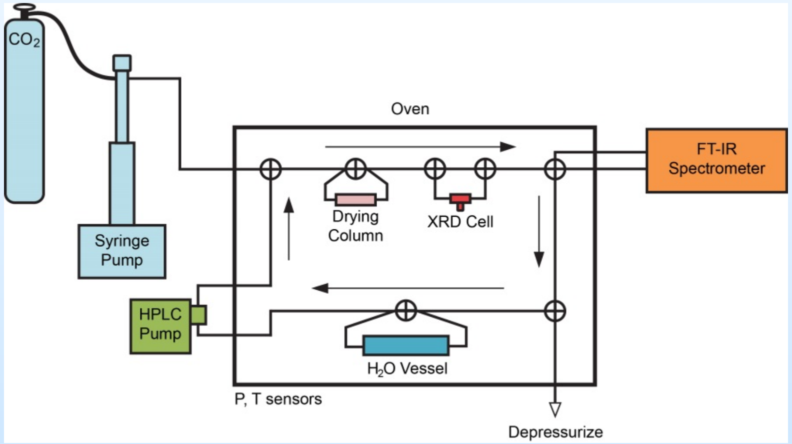
Tracking Water Film Development and Mineral Stability with *In Situ* IR Spectroscopy

High-pressure *in situ* IR spectroscopy study of Woodford Shale and Kaolinite exposed to water-saturated $scCO_2$ (50 °C, 90 bar) for 24 hr

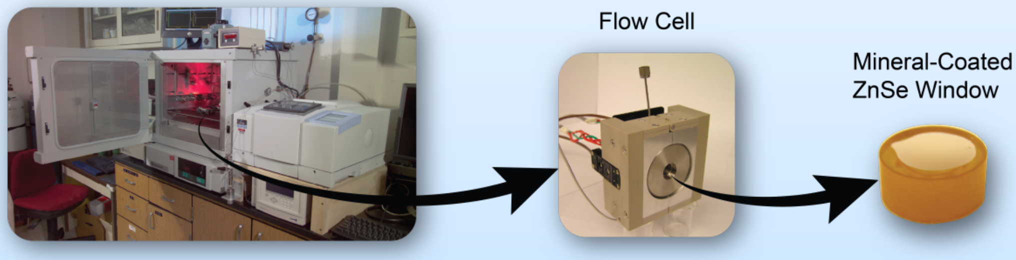
- Water film growth (OH stretch)
- Water film growth (HOH bend)
- Structural changes (expansion) with varying hydration (SiO and AlO stretching bands)



Water partitions between wet $scCO_2$ and shale, resulting in water films, structural changes, and possible changes in strength and porosity.



In Situ, High-Pressure IR Spectroscopy

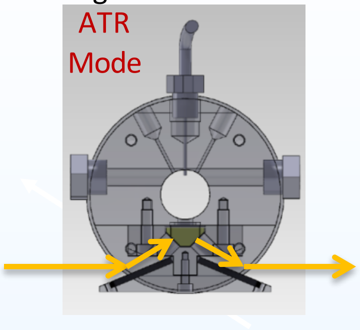


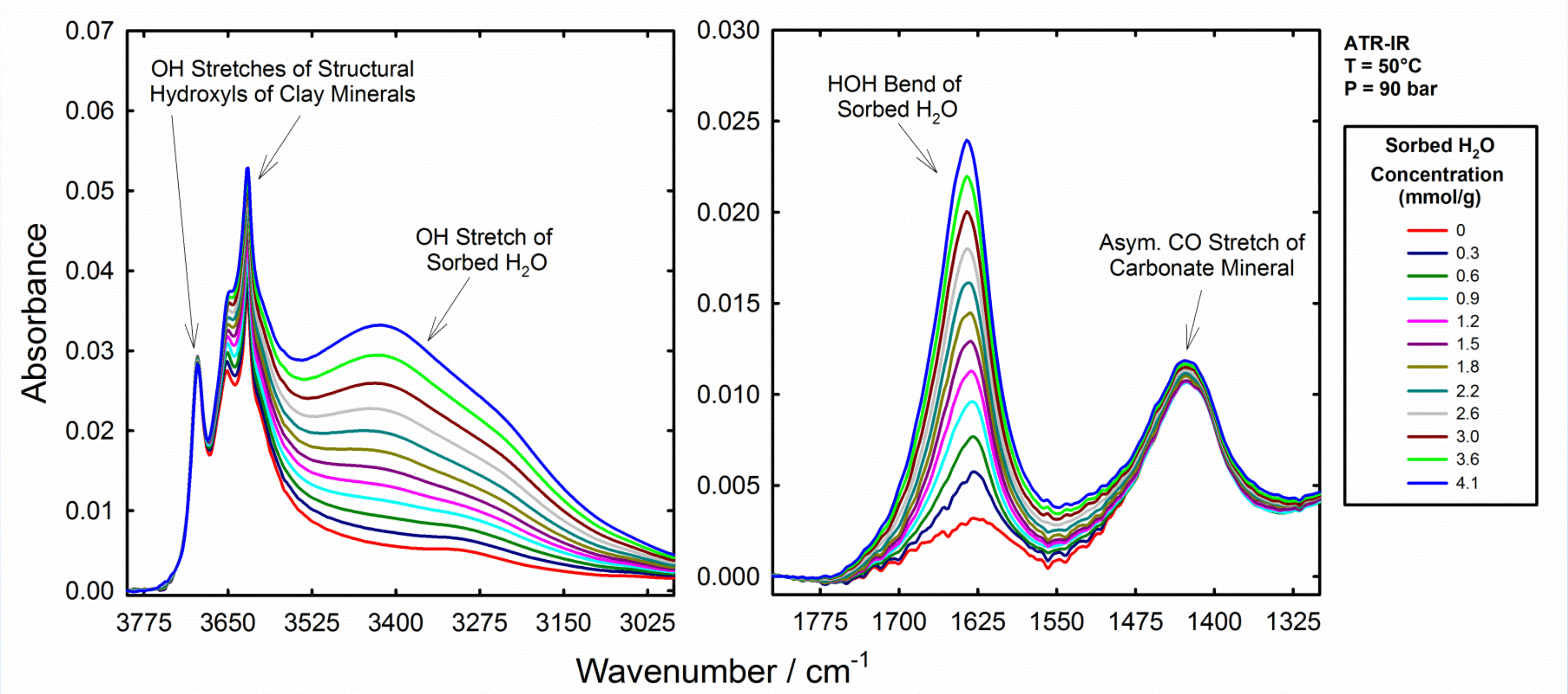
Technique Reference Thompson, C. J.; Loring, J. S.; Rosso, K. M.; Wang, Z. M., (2013). "Comparative Reactivity Study of Forsterite and Antigorite in Wet Supercritical CO_2 by *In Situ* Infrared Spectroscopy." IJGGC, vol. 18, 246–255.

IR Spectroscopic Titrations of a Woodford Shale Sample: ATR-IR Data

- ATR-IR data provides molecular-level information about the water and CO_2 interactions with clays.
  - Chemometric analysis indicates H_2O molecules exist in multiple chemical environments as a function of total water concentration.
- Mineral stability as a function of dissolved H_2O
  - Precipitation and dissolution
  - Intermediate metastable phases

Cross Section of High Pressure Cell

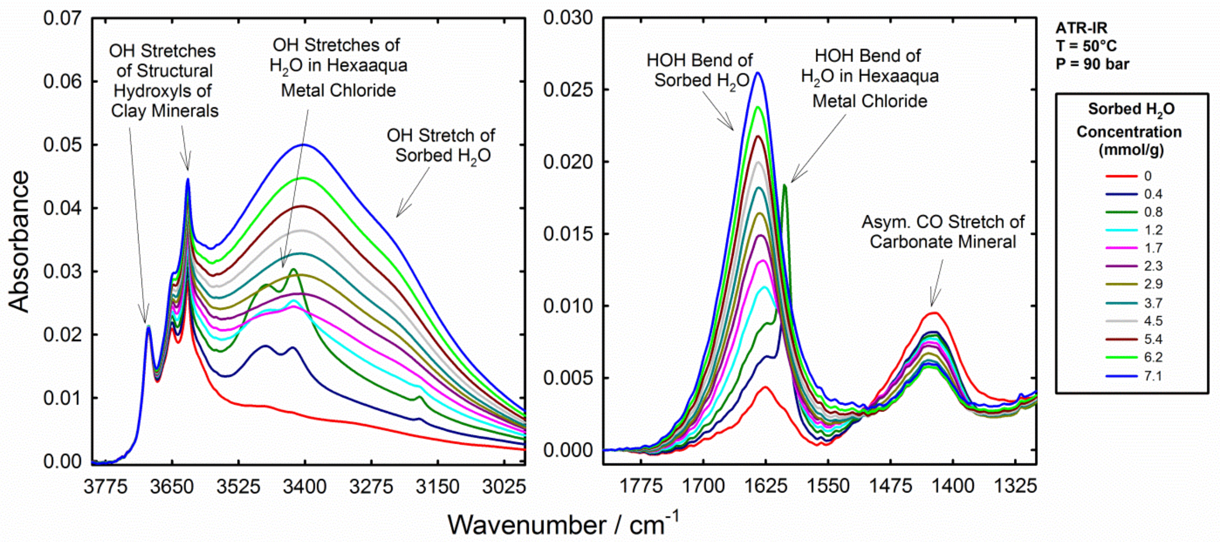




Technique Reference: Thompson, C. J., et al, (2014). "Automated high-pressure titration system with in situ Infrared spectroscopic detection." Review of Scientific Instruments vol 85, issue 4, 044102.

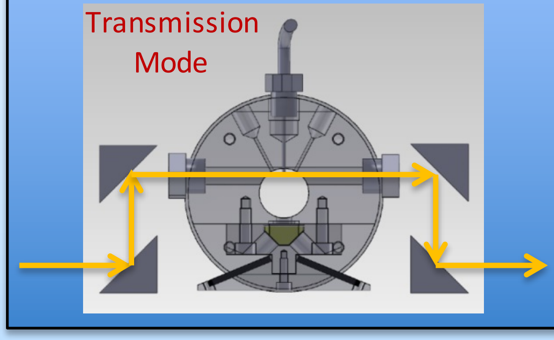
IR Spectroscopic Titrations of a Woodford Shale Sample in a CO_2-HCl Mixture

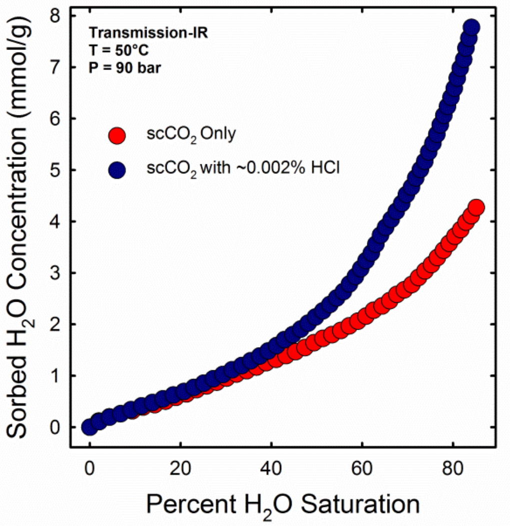
- **Objective**: Investigate Woodford shale reactivity in a CO_2-HCl-H_2O mixed gas system
- **Observations:**
  - Before H_2O addition, no observable differences compared to the pure CO_2 system
  - Initial H_2O uptake indicates a secondary phase (hydrated metal chloride)
  - Carbonate mineral begins dissolving
  - Higher water content dissolves metal chloride
- **Implication**: Tracking mineral-fluid interactions at reservoir conditions provides insight into geochemical processes.



Transmission IR: Quantitative information on H_2O partitioning onto mineral surface.

Cross Section of High Pressure Cell



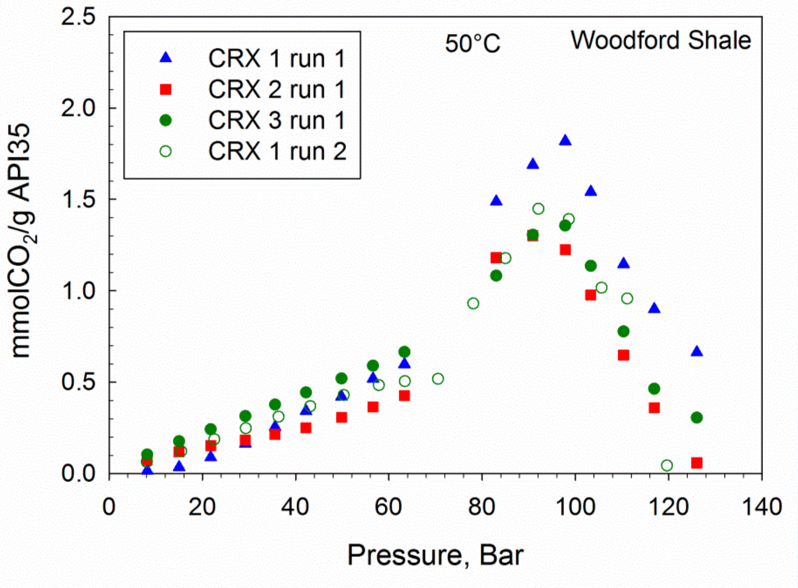


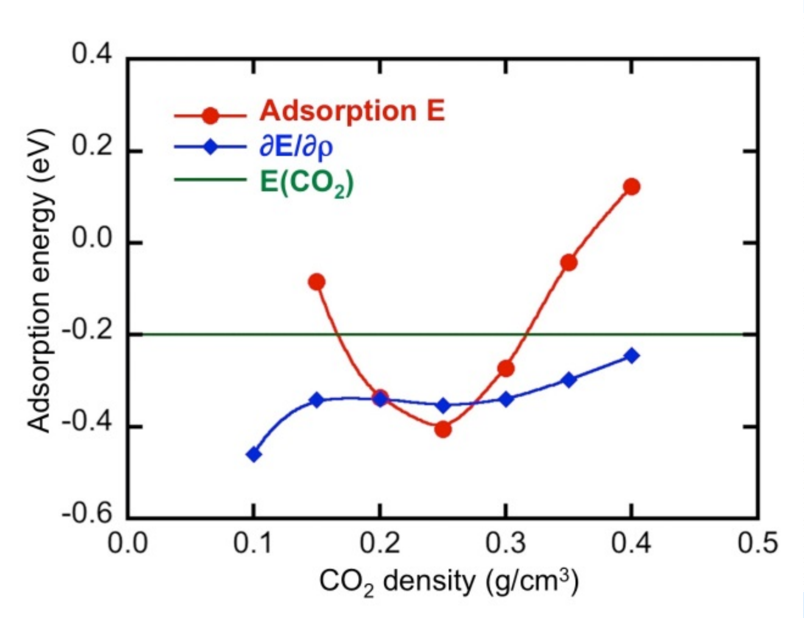
Surface Condensation of CO_2 on Minerals

Goal: Quantify unusual behavior of CO_2 sorption on important shale minerals

In situ quartz crystal microbalance technique used to determine CO_2 sorption on clay fraction of Woodford shale sample

- Absolute mass change
- High mass sensitivity for micro weighing in pressurized environments
- Use N_2 to establish surface roughness correction factors (i.e. N_2 ~0.2 mmol/g clay)
- Sorption was nearly linear on shale through the gaseous phase, but increased dramatically in the supercritical phase and peaked at ~90 Bar before desorbing.
- Molecular simulations describe adsorption as initially driven by CO_2 film formation on the surface, resulting in adsorption energies more favorable than the average CO_2-CO_2 interaction in bulk $scCO_2$.
- At higher pressures, the interactions in bulk CO_2 become more energetically favorable.



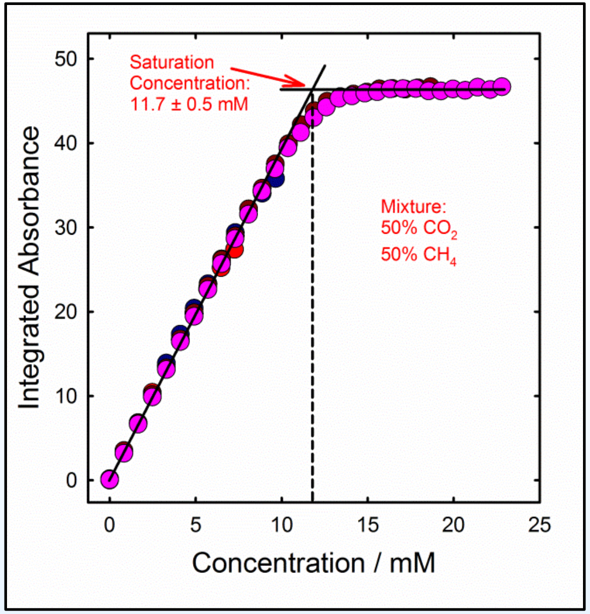


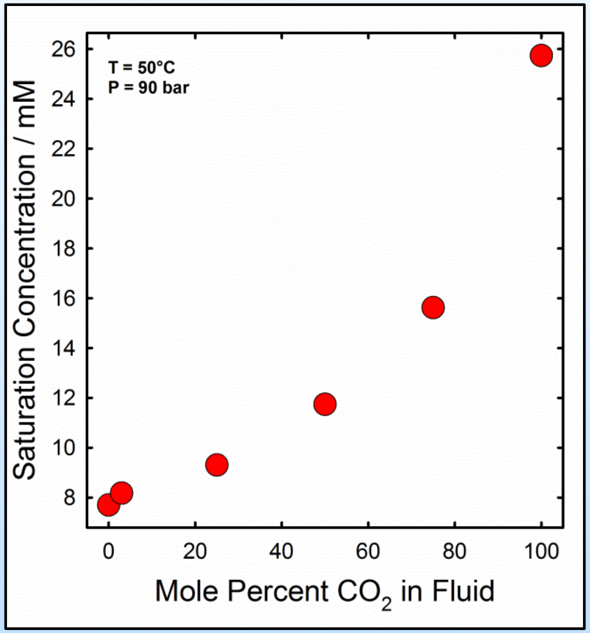
Characterizing Mixed Gas Systems ($H_2O/CO_2/CH_4$)

Experimental water solubility data for mixed gas systems are scarce.

- Gas mixtures with compositions between pure methane and pure carbon dioxide were titrated with water at 50°C and 90 bar using an in situ IR spectroscopic titration capability.
- Each gas mixture shows a linear increase of dissolved water until saturation is reached, indicated by a plateau in the data (top graph).
- Overall, these titration results show an increase in water solubility that correlates with CO_2 concentrations (bottom graph).

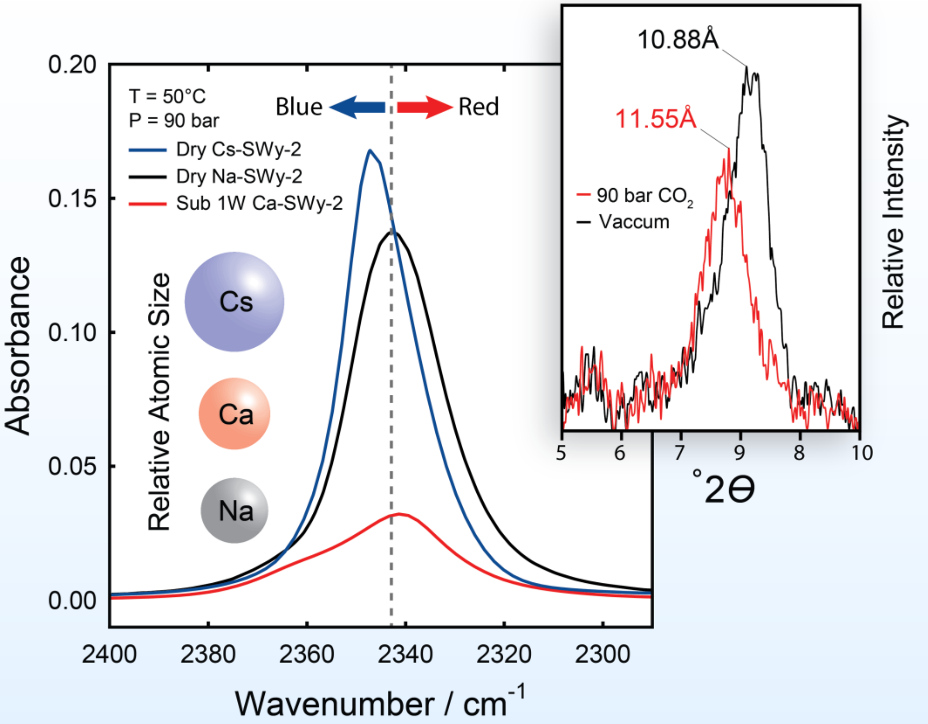
Application: These data are necessary to understand competitive gas sorption processes and clay hydration and expansion mechanisms occurring in shales.

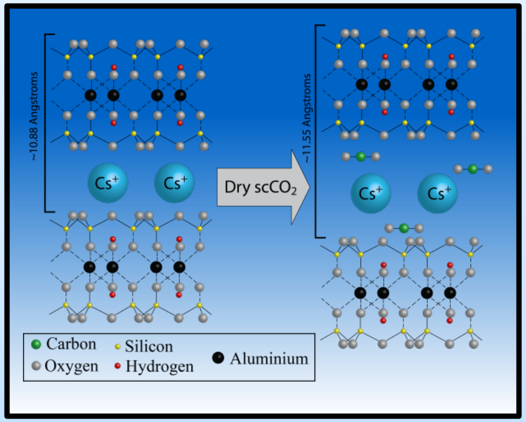


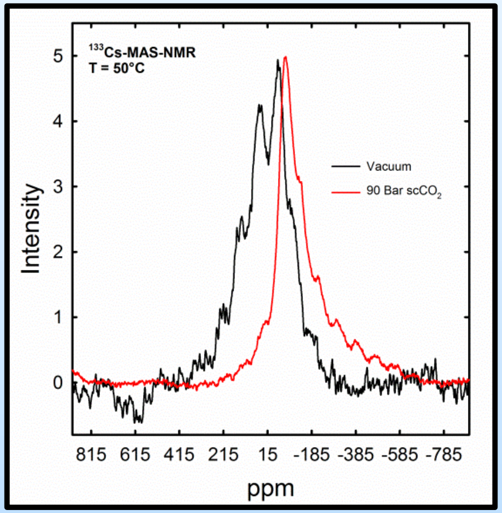


Distinguishing CO_2 Interactions in Model Clay Systems During Exposure to CO_2 and H_2O

- Interaction between CO_2 and interlayer Cs^+ cations
  - HXRD shows a large basal spacing shift from 10.88Å (anhydrous) to 11.55Å in the presence of dry $scCO_2$
  - No expansion with dry N_2
  - IR spectroscopy reveals a blue shift of the asymmetrical CO shift of the CO_2 molecule
  - No measurable IR shifts with hydrated metal cations (i.e. Ca, Na, and Mg)
  - MAS-NMR indicates a large shift for the ^{133}Cs in the presence of $scCO_2$
- Theory predicts measureable CO_2 and cation interactions
  - Cryscenti and Cygan, 2013
  - Myshakin et al., 2013
  - Glezakou et al., 2014



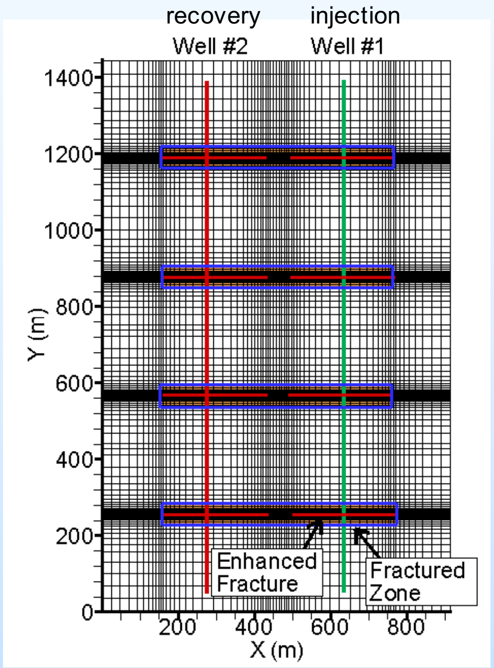




Modeling Enhanced Recovery of Methane with CO_2

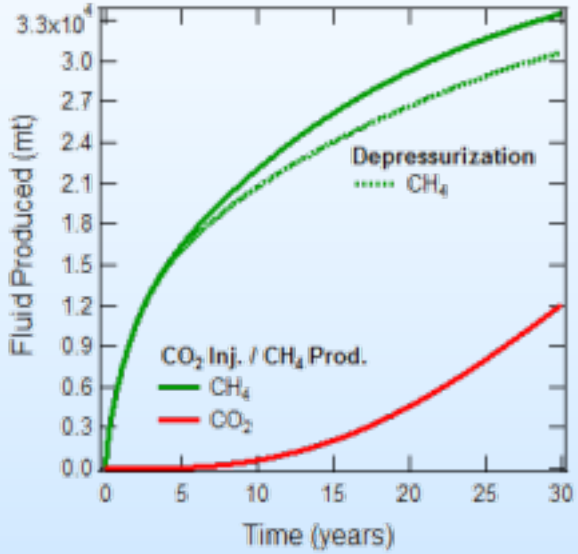
- STOMP-EOR simulates multiphase, multicomponent flow and transport of CO_2, methane and oil components coupled with geochemical reactions
- Simulations are used to investigate methane release via competitive CO_2 adsorption at the field scale by injecting CO_2 while producing CH_4.

Scenario: Hydraulic fracture stages in CO_2 injection and CH_4 production wells



- Advection through hydraulic and natural fractures
- Diffusion and desorption from the shale matrix

Results: Methane recovery with and without simultaneous CO_2 injection



- With CO_2 injection, CH_4 production increased after 3 years
- Desorbed CH_4 increased from 5 to 31%
- Clay minerals and organics adsorbed similar amounts of CO_2
- Stored 80 metric kilotons of CO_2

Accomplishments to Date

- Key *in situ* measurements conducted with field samples provide insights into gas sorption processes
- Laboratory studies coupled with atomistic simulations are essential to deriving fundamental geochemical information at reservoir conditions.
- Building a data base for reaction mechanisms and dominant geochemical processes for formulation and incorporation into reservoir simulators.
- Incorporating results from fundamental studies on competitive CH_4/CO_2 adsorption in shales into reservoir simulators to model at the field scale CH_4 production enhanced by injecting CO_2

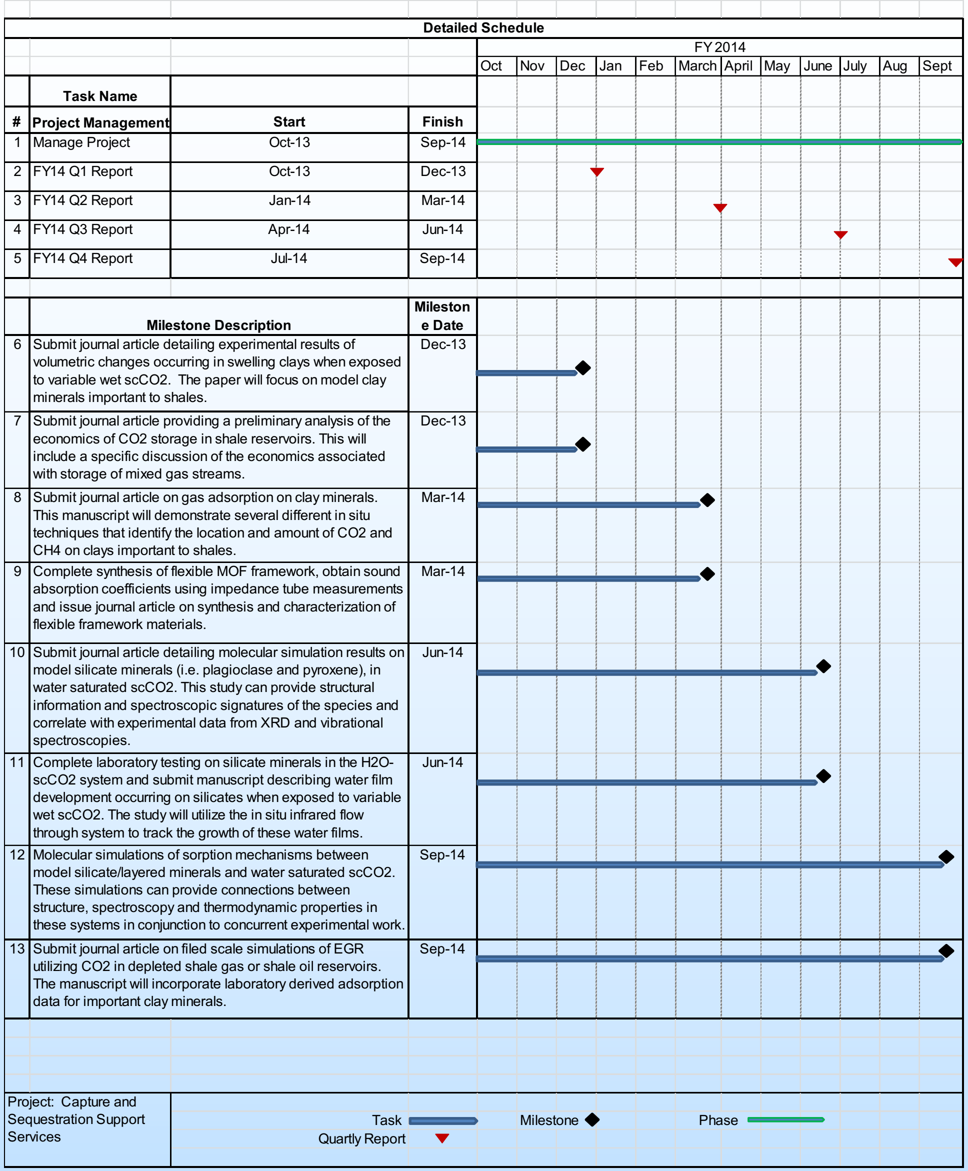
Appendix

- These slides will not be discussed during the presentation, but are mandatory

Organization Chart

- Project team has participants that cut across the Energy & Environment and Fundamental Sciences Directorates at PNNL
- Pacific Northwest National Laboratory is Operated by Battelle Memorial Institute for the Department of Energy

Gantt Chart



Detailed Schedule

FY 2014: Oct | Nov | Dec | Jan | Feb | March | April | May | June | July | Aug | Sept

#	Task Name Project Management	Start	Finish
1	Manage Project	Oct-13	Sep-14
2	FY14 Q1 Report	Oct-13	Dec-13
3	FY14 Q2 Report	Jan-14	Mar-14
4	FY14 Q3 Report	Apr-14	Jun-14
5	FY14 Q4 Report	Jul-14	Sep-14

#	Milestone Description	Milestone Date
6	Submit journal article detailing experimental results of volumetric changes occurring in swelling clays when exposed to variable wet scCO2. The paper will focus on model clay minerals important to shales.	Dec-13
7	Submit journal article providing a preliminary analysis of the economics of CO2 storage in shale reservoirs. This will include a specific discussion of the economics associated with storage of mixed gas streams.	Dec-13
8	Submit journal article on gas adsorption on clay minerals. This manuscript will demonstrate several different in situ techniques that identify the location and amount of CO2 and CH4 on clays important to shales.	Mar-14
9	Complete synthesis of flexible MOF framework, obtain sound absorption coefficients using impedance tube measurements and issue journal article on synthesis and characterization of flexible framework materials.	Mar-14
10	Submit journal article detailing molecular simulation results on model silicate minerals (i.e. plagioclase and pyroxene), in water saturated scCO2. This study can provide structural information and spectroscopic signatures of the species and correlate with experimental data from XRD and vibrational spectroscopies.	Jun-14
11	Complete laboratory testing on silicate minerals in the H2O-scCO2 system and submit manuscript describing water film development occurring on silicates when exposed to variable wet scCO2. The study will utilize the in situ infrared flow through system to track the growth of these water films.	Jun-14
12	Molecular simulations of sorption mechanisms between model silicate/layered minerals and water saturated scCO2. These simulations can provide connections between structure, spectroscopy and thermodynamic properties in these systems in conjunction to concurrent experimental work.	Sep-14
13	Submit journal article on filed scale simulations of EGR utilizing CO2 in depleted shale gas or shale oil reservoirs. The manuscript will incorporate laboratory derived adsorption data for important clay minerals.	Sep-14

Project: Capture and Sequestration Support Services

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