NETL RIC Carbon Storage FWP
Task 2 – Reservoir and Seal Performance
Task 3 – Shales as Seals and Unconventional Repositories

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National Energy Technology Laboratory

Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 1-3, 2017

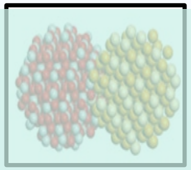
Presentation Outline

- FWP and task overview
- Technical status
  - $scCO_2$ contact angle → k_r
  - $scCO_2$ interactions with reservoir and sealing formations
- Accomplishments
- Lessons learned
- Summary

NETL RIC Carbon Storage Portfolio

Enhancing Effectiveness and Reducing Uncertainty in Long-Term CO_2 Storage and Efficiency

CO_2 Reuse
- Novel Systems for CO_2 Conversion

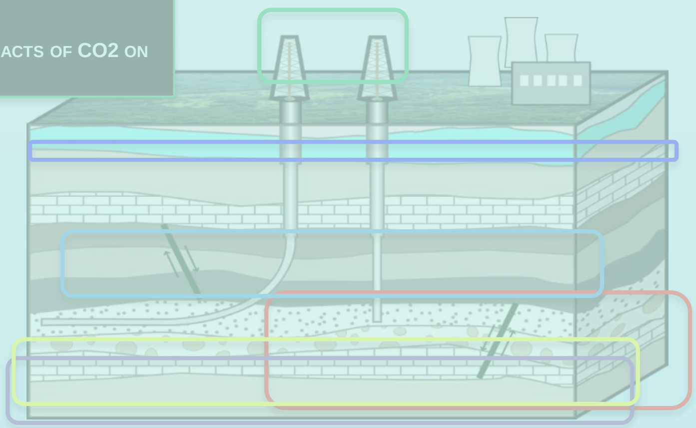


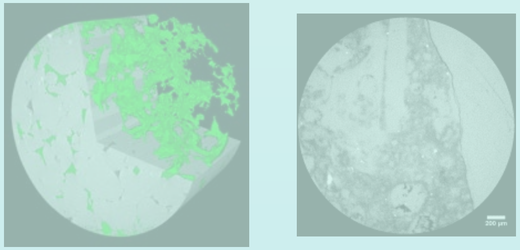
Monitoring CO_2/Brine Plumes and Groundwater Impacts
- Develop and Demonstrate Tools and Protocols for Detection of CO2/Brine Interface and Groundwater Monitoring

MVA Field Activities
- Support Large-Scale Field Activities

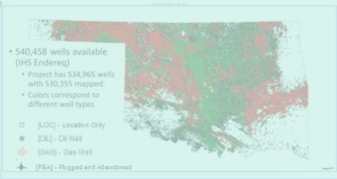
Reservoir Performance
- Experimental measurements of Relative Permeability, Residual Saturation, and Porosity needed For Reservoir simulations

Wellbore Integrity and Mitigation
- Evaluate Geochemical Impacts of CO2 on Cement





SubTER
- DOE Crosscutting Subsurface Technology



Shales as Seals and Unconventional Reservoirs
- Improve characterization of shales as seals and storage reservoirs

Resource Assessments and Geospatial Resources (EDX and NATCARB)
- Develop Defensible DOE Storage Methods for the Onshore and OffShore
- Develop, Maintain, and Utilize Geospatial Platforms to Support CO2 Storage research

Energy Data eXchange

Overall FWPs

Task 2

- 2.1 Fluid Interactions
  - $scCO_2$/brine k_r
  - $scCO_2$/brine contact angle
- 2.2 $scCO_2$ Induced Changes to Rock
  - Seal and reservoir rocks
- 2.3 Microbial Induced Changes
  - Characterizing subsurface systems in response to $scCO_2$

Task 3

- 3.1 Macroscopic Interactions
  - Laboratory core floods
  - Literature review of CO_2/shale interactions
- 3.2 Microscopic Interactions
  - $scCO_2$ exposure batch reactions
  - FIB/SEM – umCT
- 3.3 Field and Core
  - Describe and distribute core

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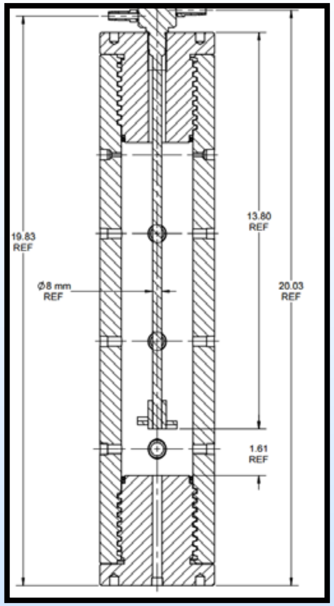
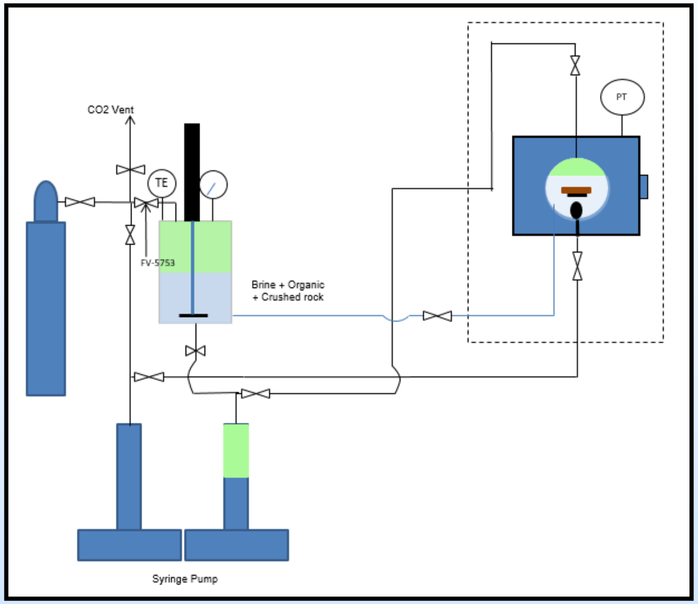
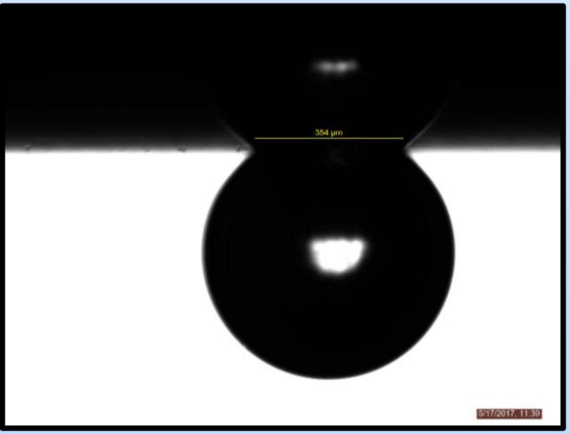
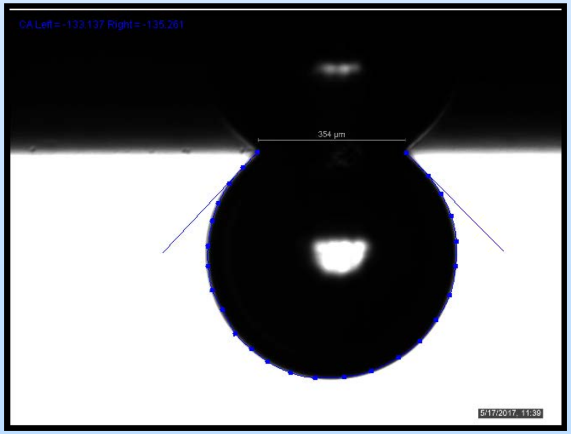
Traditional Contact Angle Setup

- Sessile drop measurements of $scCO_2$/brine/solid contact angles (θ) in a controlled system
- Device to measure three locations on a substrate developed and functional
- System operational and baseline measurements being collected



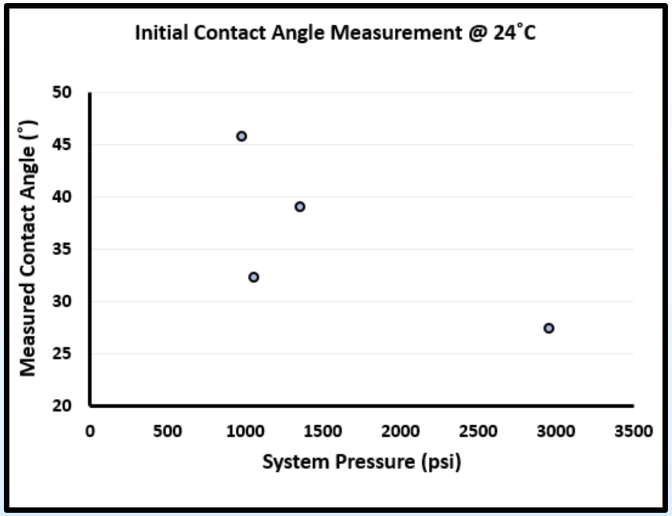


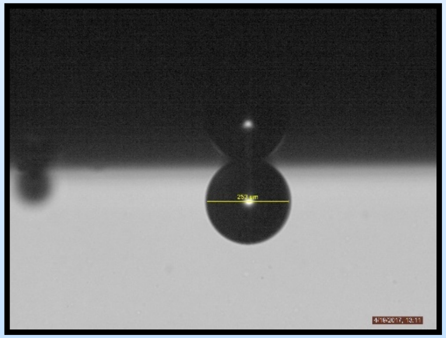


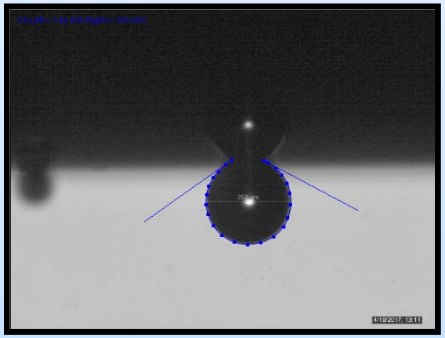


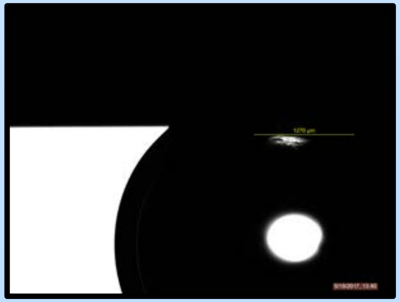
Traditional θ Progress

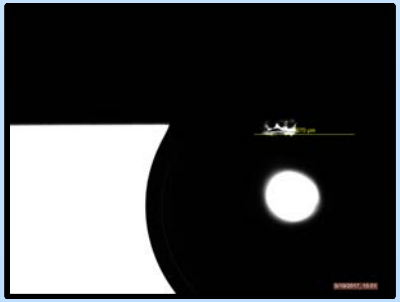
- Initial measurements on quartz plates have been performed
- Roughness, impact of temperature, pressure, and material being examined





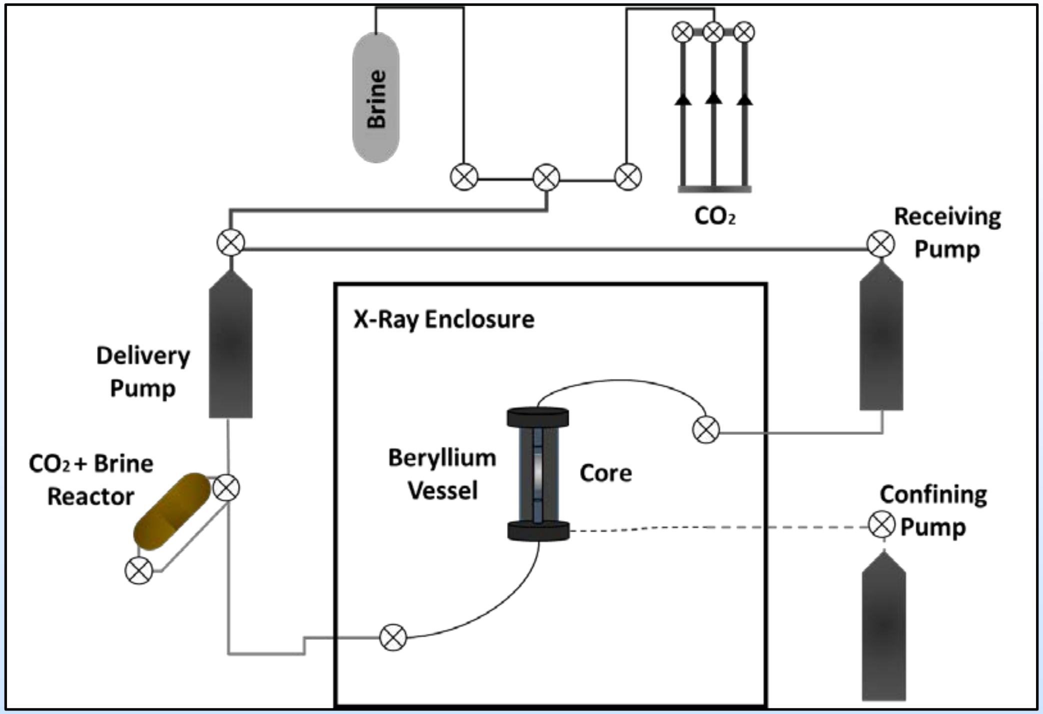


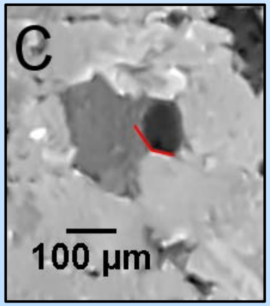


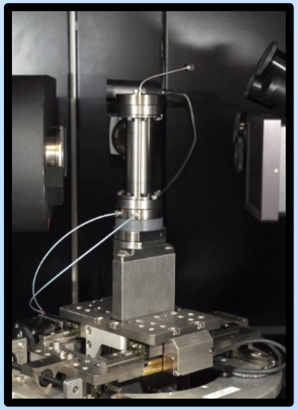


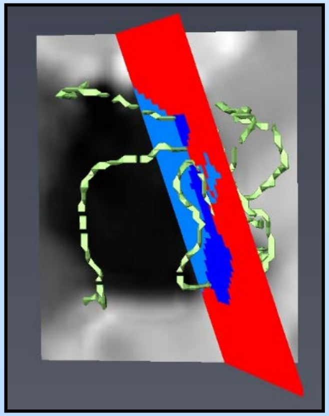
In-situ θ Setup

1. Berea cored to 1.6 inch long by 0.25 inch diameter.
2. Flood system with gas CO_2 at low pressure to remove air.
3. Raise pore and confining pressures to 1800 and 2100 psi.
4. Injected CO_2-saturated brine, liquid CO_2, CO_2-saturated brine sequentially.
   - Each injection step was scanned.
5. Raised temperature (115°F) and equilibrated for 24 hours.
6. Followed by two high magnification scans.





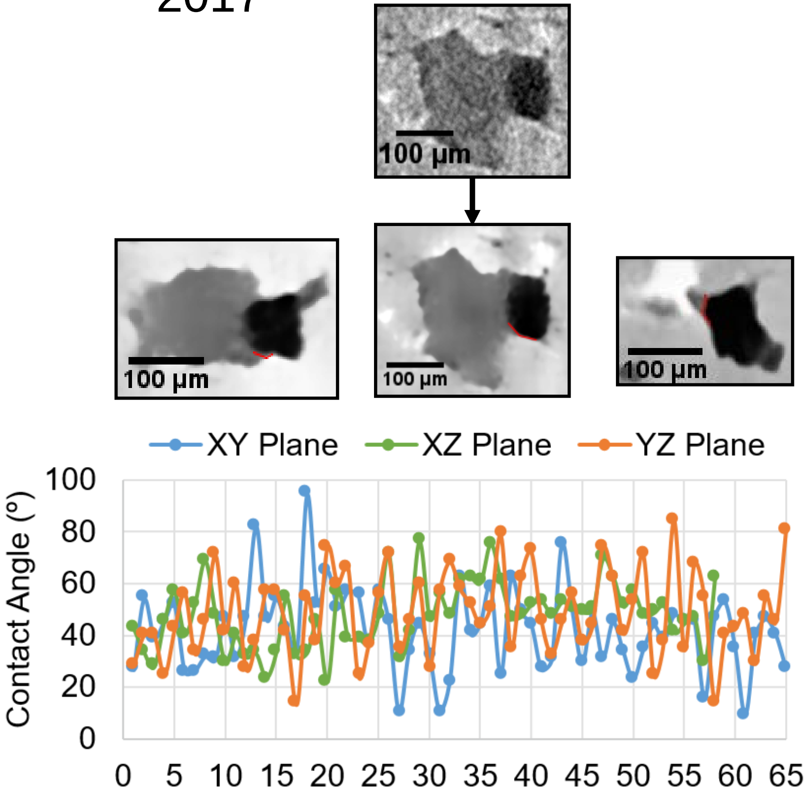




In-situ θ Methods

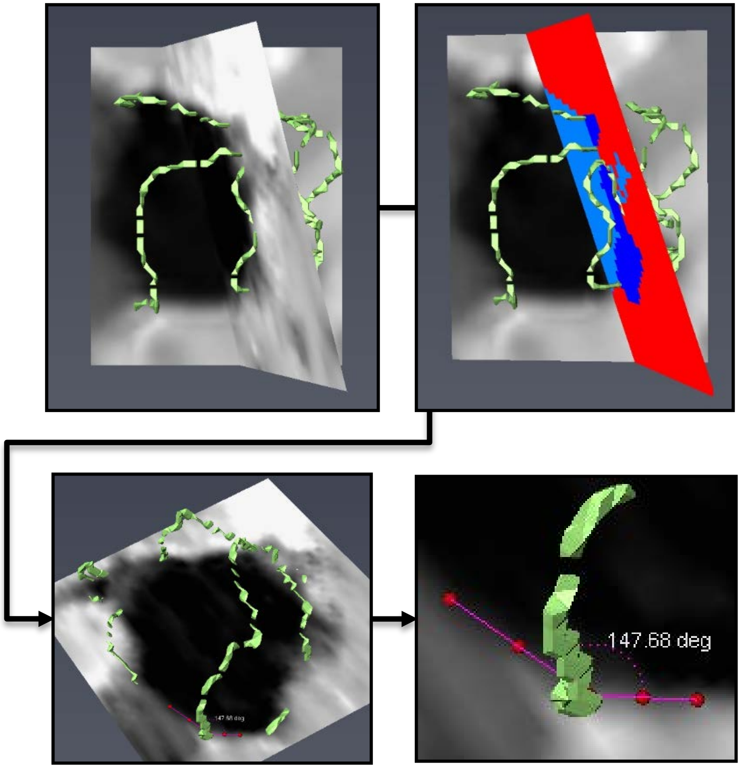
2D ImageJ Angle Tool:

- XY, XZ, YX-Planes
- Tudek et al. 2017; Dalton et al 2017



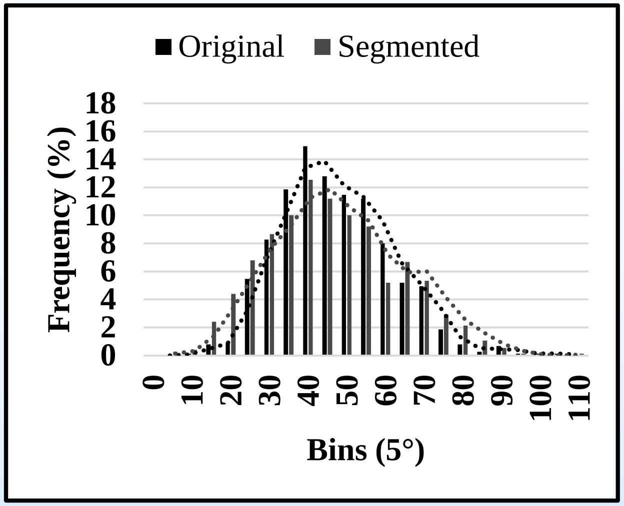
PerGeos® 3D Contact Line Method:

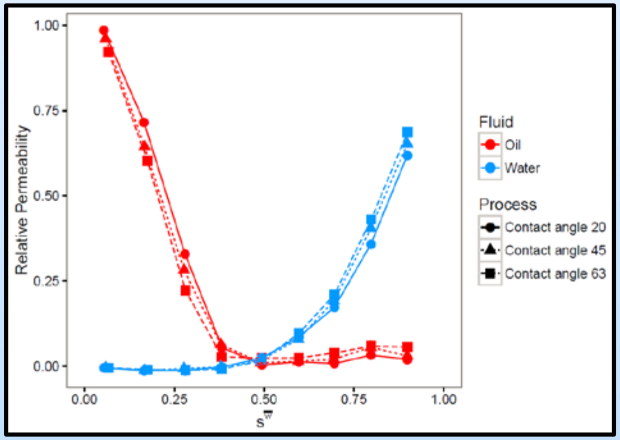
- Andrew et al. 2014, Scanziani et al. 2017, and Lv et al. 2017



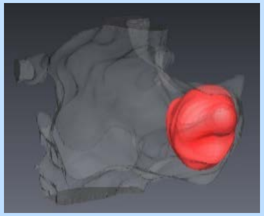
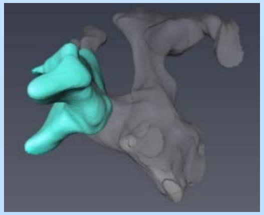
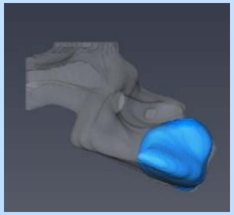
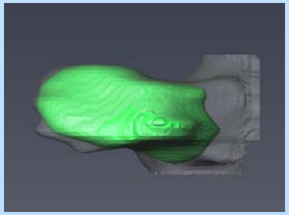
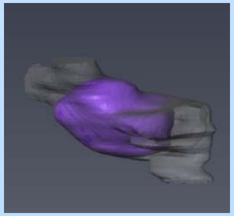
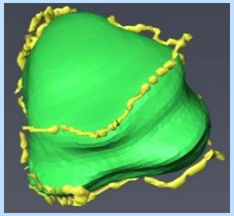
In-situ θ Comparisons

- Measurement of contact angle varies depending on method
- Automated processes are being developed, but consistency across labs needed
- Impact of θ differences being evaluated in LBM models



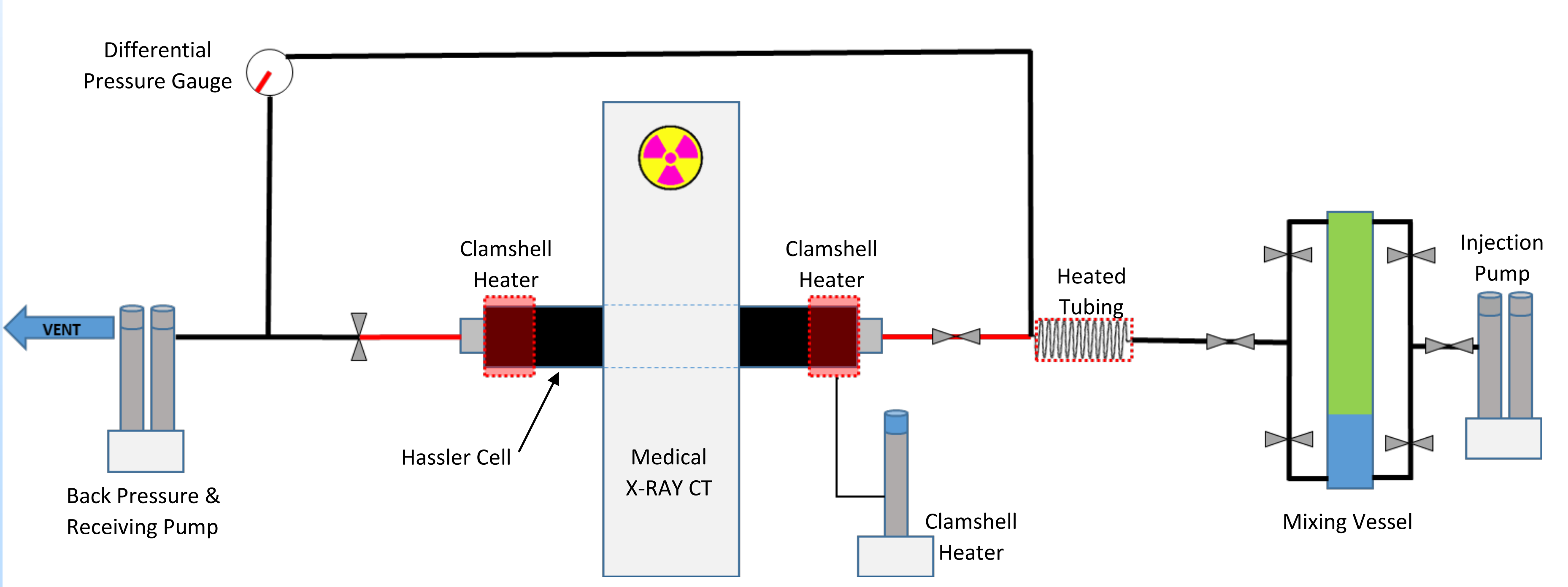


Method	θ per ROI	θ Range	Average
1	20	30° - 80°	57.2° ± 13.0°
2a	150	10° - 105°	44.4° ± 14.3°
2b	150	5° - 110°	43.5° ± 17.0°
3	~180	10° - 105°	46.2° ± 15.9°

$scCO_2$ Relative Permeability

- Evaluating variation in $scCO_2$ k_r of different depositional environments
- Constant $scCO_2$ flow, controlled P & T.



$scCO_2$ k_r Progress

- Dynamic measurement of change in ...ion with CT scanning
- ...ne CO_2 saturation and calculate k_r

$$\overline{S_d} = \frac{\frac{V_i(t)}{V_p}}{a + b\frac{V_i(t)}{V_p}} + S_{d,i}$$

$$S_{d,2} = b\left[\frac{\frac{V_i(t)}{V_p}}{a + b\frac{V_i(t)}{V_p}}\right]^2 + S_{d,i}$$

$$M_{d,2} = \frac{\left[a + b\frac{V_i(t)}{V_p}\right]^2}{a} - 1$$

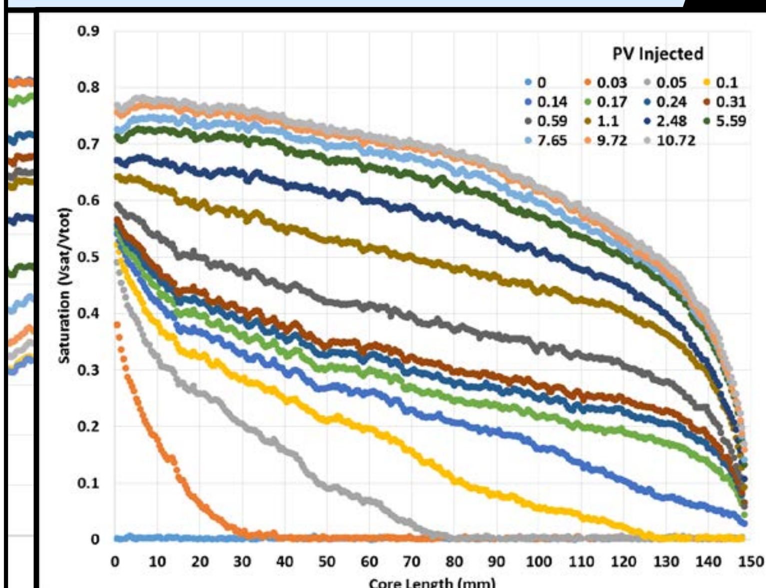
$$f_{d,2} = \frac{M_{d,2}}{M_{d,2} + 1}$$

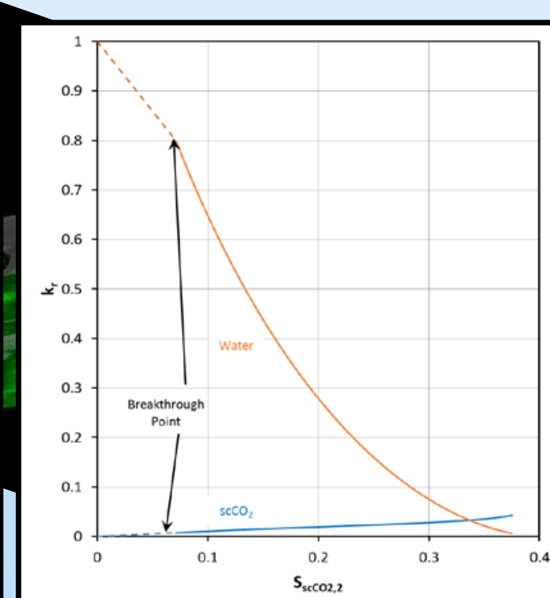
$$f_{k,2} = \frac{1}{M_{d,2} + 1}$$

$$Y(S_{d,2}) = \frac{q_i L}{kAa_1 + (1 - b_1)\left(\frac{V_i(t)}{V_p}\right)^{b_1}}$$

$$k_{r,d} = \mu_d f_{d,2} Y(S_{d,2})$$

$$k_{r,k} = \mu_k f_{k,2} Y(S_{d,2})$$





CO_2 interactions with shale

- Literature review of CO_2-Shale interactions from various disciplines
- Available as Technical Reports
  - Review of the Effects of CO2 on Very-Fine-Grained Sedimentary Rock/Shale - Part I: Problem Definition (June 2016) link
  - Review of the Effects of CO2 on Very-Fine-Grained Sedimentary Rock/Shale - Part II: Clay Mineral & Shale Response to Hydration (Aug 2016) link
  - Review of the Effects of CO2 on Very-Fine-Grained Sedimentary Rock/Shale - Part III: Shale Response to CO2 (In review)
- Combined, over 400 pages with ~200 citations

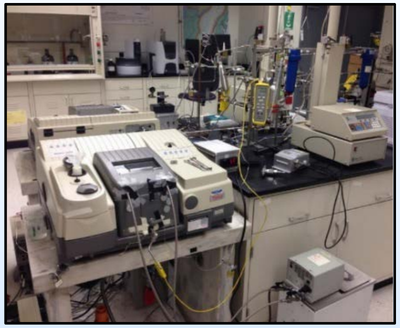
CO_2 interactions with shale

- Condensing to a easier to access base document for peer-review
- Using knowledge gained to develop ‘best practices’ for describing shale research across different laboratory spaces

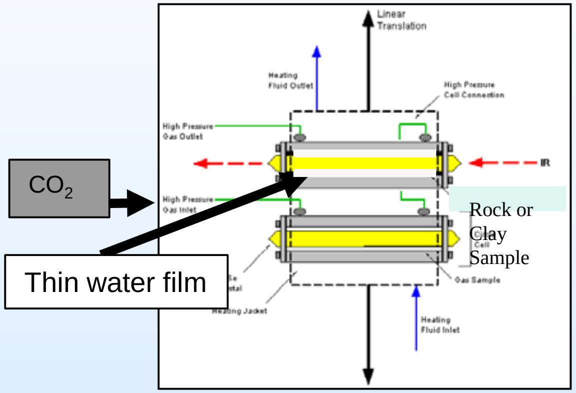
Shale Reactions with CO_2/Water

Long-Term - effects of carbon dioxide and fluid on Utica shale

- Utica Shale: Flat Creek Member exposed to CO_2 under dry and wet conditions
- Change in shale measured with *in-situ* FT-IR, SEM with feature relocation, and BET surface area/pore size analysis
- Kerogen and clays studied independently to understand influence
- Dry results shown in following slides



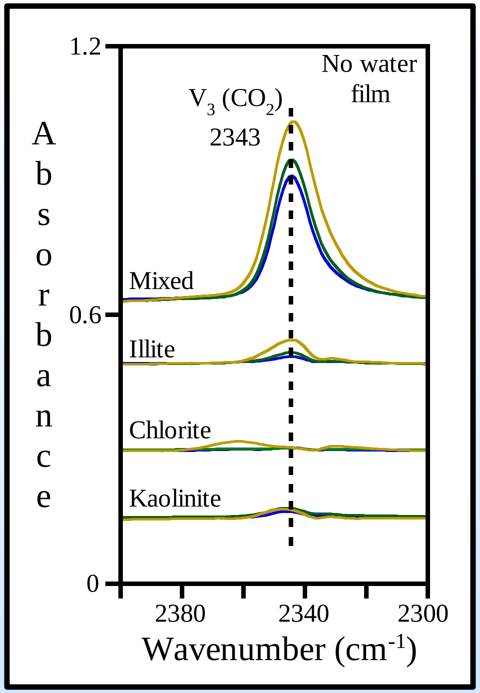
FT-IR Spectrometer

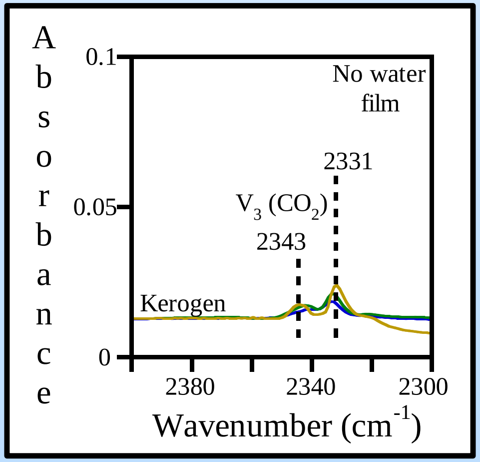


Sample holder set up for FT-IR. Note water film

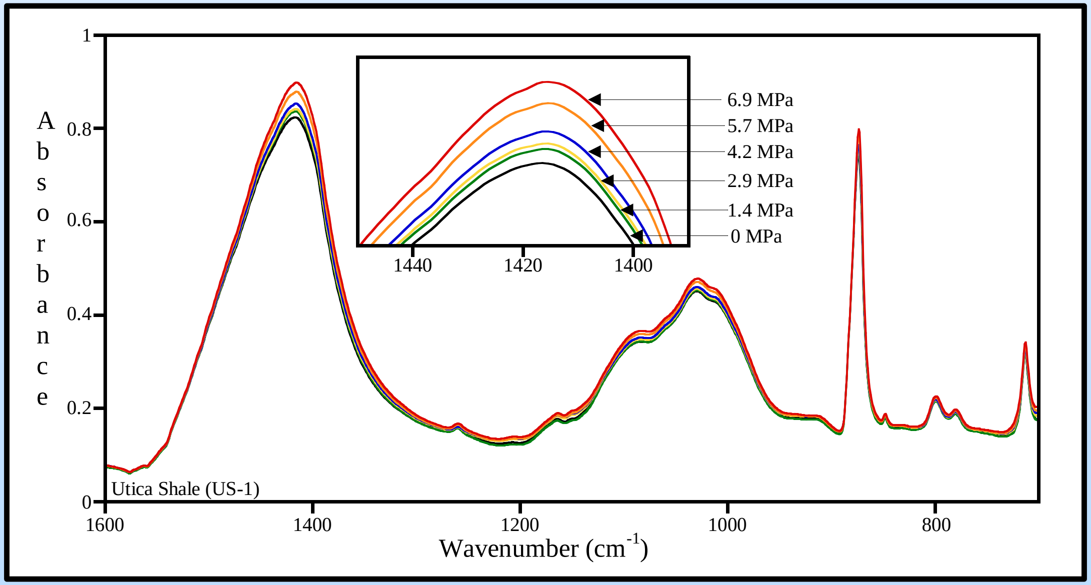
SEM used for feature relocation before and after dry/wet CO_2 exposure.

Shale Reactions with CO_2



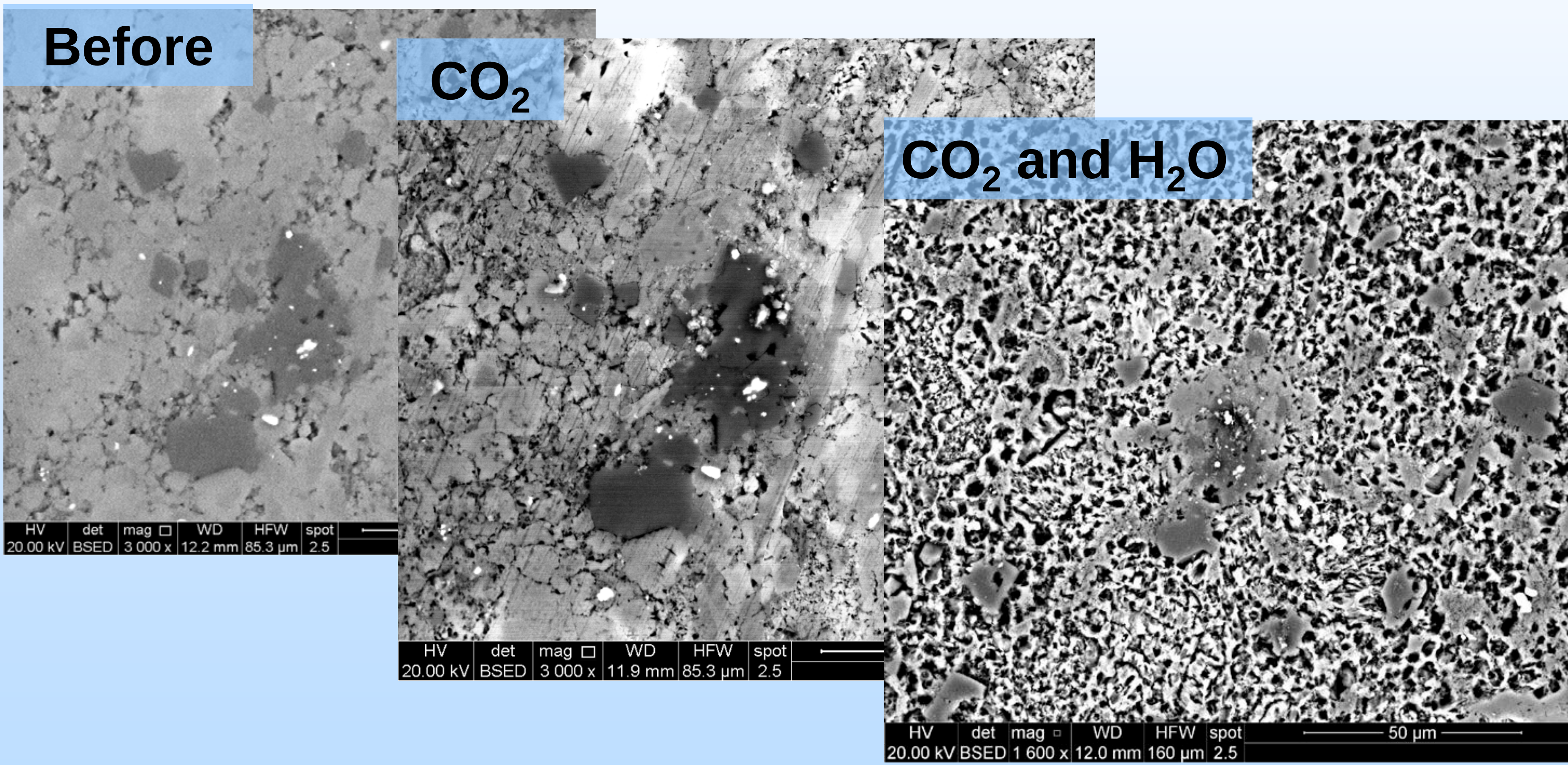


- Clays: adsorption at ν_3 2343 cm^{-1} observed
- Kerogen: shoulder at ν_3 2343 cm^{-1} and weak adsorption between 665 to 645 cm^{-1}
- Utica Shale: combined clay and kerogen adsorption, in addition to carbonate-like band interactions



Shale Reactions with CO_2/Water

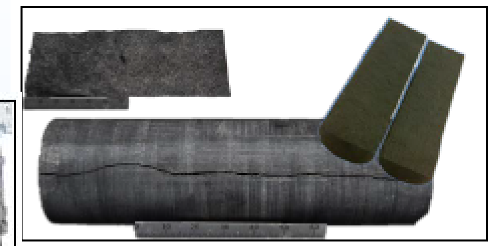
Long-Term - effects of carbon dioxide and fluid on Utica shale

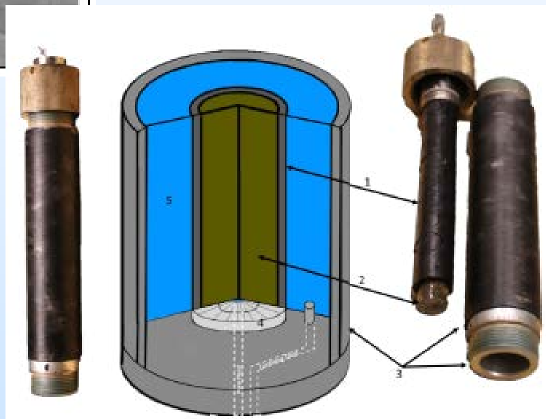


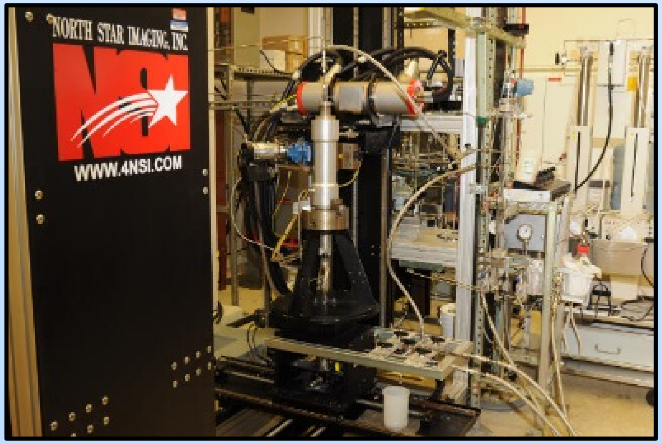
<u>Mineral dissolution and etching was observed</u>

Shale Swelling Setup

- Fractured Middle Bakken and calcite rich Marcellus samples exposed to CO_2 at elevated pressure (13.8 MPa) for several weeks.
- CT imaging of structure to observe changes taken intermittently with permeability measurements more frequently.

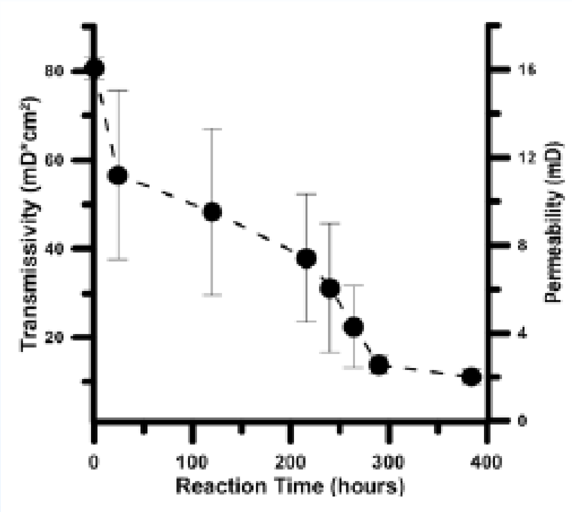


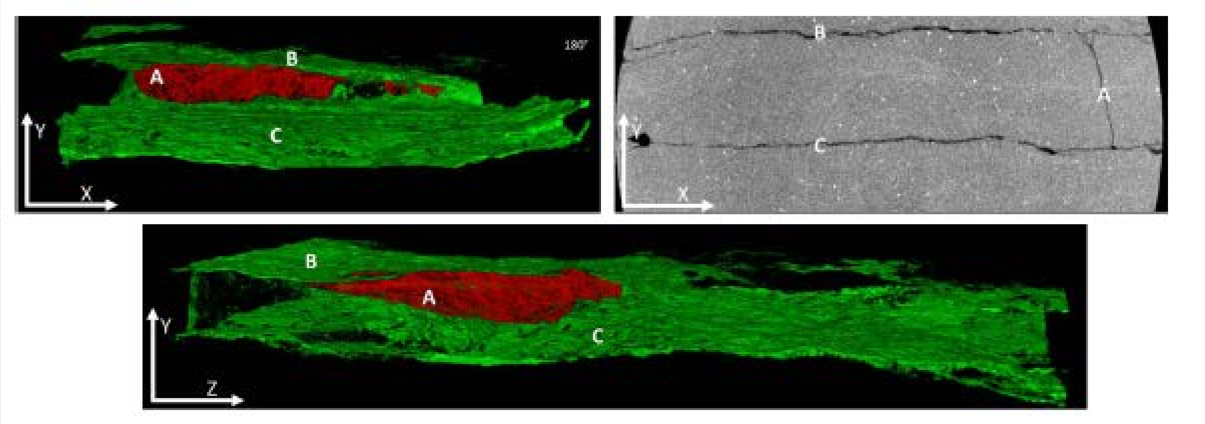




Shale Swelling Results

- Fractured Bakken reduction in k, slight geometric change.
- Fractures in Marcellus, complex structure difficult to identify changes and fluctuating changes in permeability.

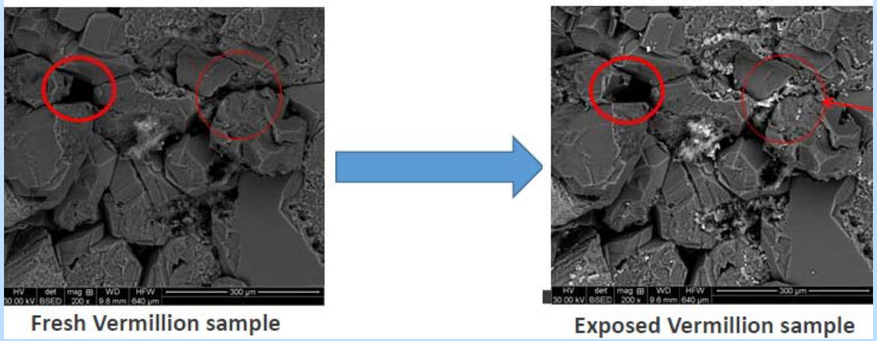




- Moore, J. E.; Crandall, D.; Lopano, C. L.; Verba, C. A. Carbon Dioxide Induced Swelling of Unconventional Shale Rock and Effects on Permeability; NETL-TRS-9-2017; NETL Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Morgantown, WV, 2017; p 28. (link)

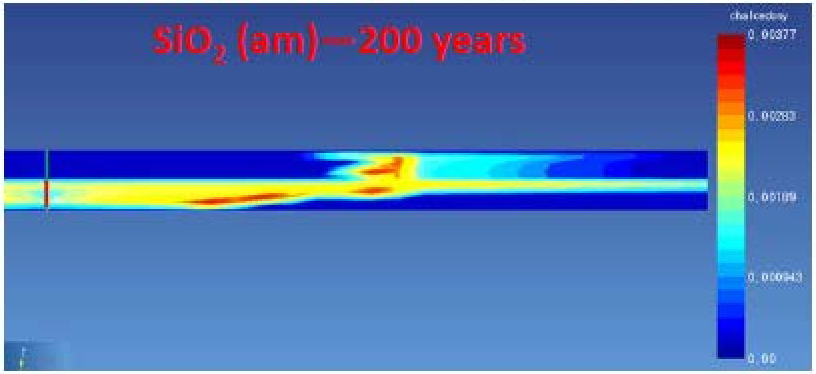
$scCO_2$ changes to reservoir rock

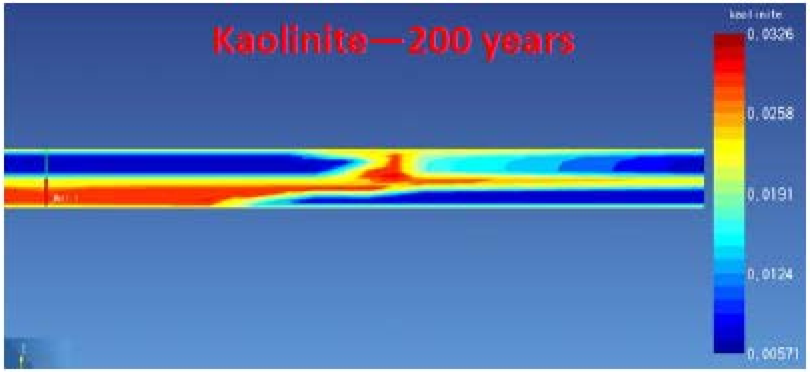
- Long term reaction studies on the impact of $scCO_2$/brine at elevated T&P continue.
  - Plant Daniel, Mount Simon, and TECo samples studied
  - SEM, CT, rock properties, brine chemistry
- Cover of GHG, Dec 2016
- Extending results to TOUGHREACT



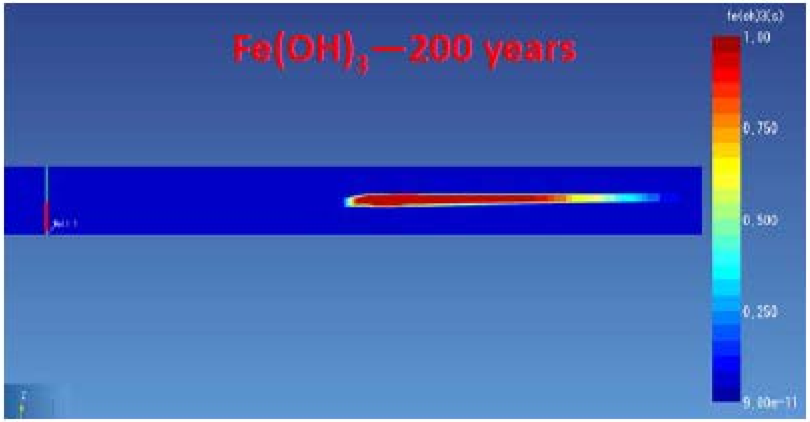
$scCO_2$ changes to reservoir rock

Lower Tuscaloosa formation: observable precipitations of SiO_2 (am) and kaolinite in regions with high concentration of dissolved CO_2





Selma Chalk formation: dissolution of calcite and precipitation of $Fe(OH)_3$ near the high-permeability zone



Accomplishments to Date

- Pore to core experimental systems developed to test $scCO_2$/brine/rock interactions
- Contact angle of CO_2 measured on simple and in complex surfaces at representative T&P
- Long term and short term reactions of $scCO_2$ with reservoir and seal rocks analyzed
  - Upscaling and development of databases underway

Lessons Learned

- Shale != Shale
  - Multi-scale analysis, including detailed characterization of shale features required to have unity across lab studies

- Complexity of nature is difficult to upscale without analogues
  - OK, so θ in pore space is higher… so what? Is this impacting k_r in a meaningful way?

Synergy Opportunities

- Within the NETL-RIC infrastructure, there are multiple teams working on these problems and synergy between the work presented here in the Carbon Storage FWP and ongoing work in the Onshore Unconventional FWP.

- The imaging and analysis capabilities provide use to external projects to NETL-RIC, including
  - EERC FE-SEM Shale Characterization project
  - ASSET Collaborations within Onshore Unconventional FWP
  - Energy Frontier Research Consortium GSCO2
  - RCSPs

Project Summary

This research plan supports DOE Core R&D goals of developing and advancing the Carbon Capture and Storage (CCS) technologies necessary for widespread commercial deployment. R&IC's Carbon Storage projects support the Storage Core Research Program's high level goals of developing technologies to allow the ability to (1) develop and validate technologies to ensure for 99 percent storage permanence, (2) develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness, and (3) support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.

Appendix

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

Benefit to the Program

Program goals addressed:

- Develop technologies that ensure safe, secure, efficient, and cost effective CO_2 containment in diverse onshore and offshore applications, protecting the environment for commercial readiness by 2030.

Project benefits statement:

- These research projects includes basic research to understand the interaction of CO_2 in geologic storage applications.
  - Long term exposure tests on reservoir and seal formations, analysis of the impact of CO_2 plumes on microbiological communities, and reductions in efficiency factor uncertainty are the primary thrusts of Task 2.
  - Direct measurements of shale properties, analysis of interactions of fractured shale with CO_2, and an in-depth review of shale interactions with CO_2 are the primary thrusts of Task 3.
- This research contributes to the Carbon Storage Program’s efforts of to develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness and support industry’s ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.

Project Overview

Goals and Objectives

Task 2: Improve assessments of CO_2 storage for key reservoir classes by providing experimental measurements of critical properties at *in situ* conditions and characterizing critical property changes as CO_2 interacts with the reservoirs and seals.

1. Uncertainties in CO_2 migration properties being quantified experimentally
   Relative permeability & wettability measurements of CO_2/brine/reservoir rock is ongoing with improved NETL infrastructure to accurately measure these poorly understood, yet critical, characteristics of GCS.
2. Impact of CO_2/brine exposure on seal/reservoir rock examined
   Long term interaction experiments continue to yield results/publications on real rock at real conditions.
3. Subsurface microbial community resilience to CO_2 injection studied
   The ability to analyze metagenomics and perform genomic sequencing of subsurface microbial communities in CO_2 enriched environments is now possible at NETL, and the results are providing insight into the impact of CO_2 on various subsurface environments.

Task 3: Improve the characterization of shales as both seals for CO_2 containment and as reservoirs for geologic storage of CO_2

1. Technical reports on shale interactions with CO_2/water released
   A detailed review of the state of knowledge of CO_2/shale interactions across multiple disciplines to guide future research questions.
2. Shale swelling of fractured cores observed
   Core scale experimental work is showing interactions of shale/CO_2 reducing fracture permeability and accurate permeability equipment is being calibrated.
3. Variations in pore structure of different shales imaged
   Nano and Micro-scale research into the pore structure, and CO_2 interactions, with shale are revealing the wide range of structures and behaviors of the motley substance we call shale.

Organization Chart

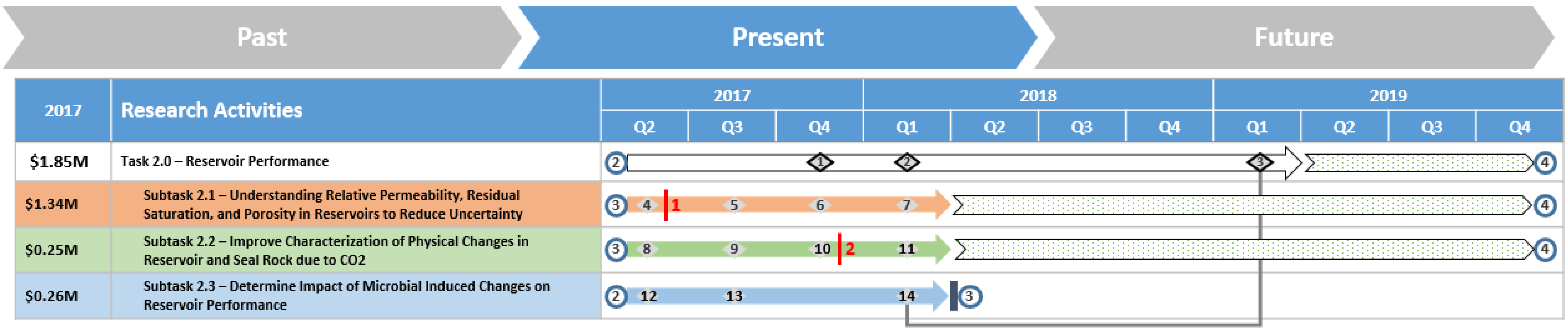
Task 2

- Team Portfolio Lead – Angela Goodman
- Task Technical Lead – Dustin Crandall
- Subtask PIs, planners, and participants
  - Yee Soong, Djuna Gulliver, Jim Fazio, Sean Sanguinito, Thomas McGuire, Deepak Tapriyal, Jeong Choi, Johnathan Moore, Karl Jarvis, Bryan Tennant, Roger Lapeer, Magdalena Gill, Mathew Stadelman, Jerry Boyle, Dustin McIntyre, Bret Howard, Kevin Shanley, Goodarz Ahmadi, Neal Sams, Liwei Zhang, Igor Haljasmaa, Lyanda Dudley, Brian Ellis, Cheng Chen, Kyle Bibby, Daniel Lipus …

Task 3

- Team Portfolio Lead – Angela Goodman
- Task Technical Lead – Dustin Crandall
- Subtask PIs, planners, and participants
  - Christina Lopano, Ernest Lindner, Circe Verba, Igor Haljasmaa, Bob Dilmore, Johnathan Moore, Karl Jarvis, Bryan Tennant, Yee Soong, Igor Haljasmaa, Lei Hong, Scyller Borglum, Michael Hannon, Jan Goral, Alex Washburn, Mary Tkatch, Barbara Kutchko, Jeffery Culp, Sittichai Natesakhawat, Sean Sanguinito …

Gantt Chart - Task 2



Milestones

1. M1: Develop draft tool to distribute/access the relative permeability results via EDX.
2. M2: Publish database of relevant changes in storage and flow properties of reservoir and seal formations due to CO_2 exposure.
3. M3: Relative permeability database with selection tool for determining inputs to CO_2 injection simulations for improving prediction of trapping mechanisms in reservoirs.

2.1

4. Develop depositional environment list for cores to be tested. Prepare NETL-MGN CT facility to run tests and coordinate with NETL-PGH flow facility to run duplicates. Working with the Energy Frontier Research Center (EFRC) Center for Geologic Storage of CO2 (GSCO2) scan cores from Mount Simon VW1 for characterization.
5. Perform full relative permeability tests of two depositional environments at $scCO_2$ conditions. Perform minimum one CO_2/brine flood in the umCT at elevated P&T.
6. Identify next six depositional environments to study in FY18 and begin procurement of materials. Perform full relative permeability tests of two more depositional environments at $scCO_2$ conditions. Develop draft tool to distribute/access the relative permeability results via EDX.
7. Perform full relative permeability tests of two more depositional environments at $scCO_2$ conditions. Continue population of draft tool to distribute/access the relative permeability results via EDX. Report on results from CO_2 flooding tests along with comparison and contrasting results to contact angle measurements performed in the NETL-PGH FIRE laboratory.

2.2

8. Start 6 month exposure of TECo samples.
9. Draft manuscript of combined reactive work completed for internal review.
10. Draft manuscript of TECo results submitted.
11. Start 6 month exposure of new and relevant samples.

2.3

12. Isolate and characterize draft genome of abundant microorganisms from CO_2 exposed fresh water aquifer.
13. Investigate future collaborations for microbial experiments with new CO_2 exposed system.
14. Present results from metagenomics analysis of CO_2 exposed systems at national conference.

Chart Key

- # TRL Score
- Go / no-go Timeframe
- Task Stopping Point
- Milestone
- M1 Milestone

Go / No-Go

1. In order to move past this milestone, NETL's MGN CT facility needs to be fully prepped and coordination needs to take place with the NETL-PGH facility as well as with the Energy Frontier Research Center. This type of coordination takes time to prep.
2. The drafting of these associated manuscripts from Subtask 2.2 is directly linked to the completion of other key Task 2.0 milestones. Therefore, work should not be continued until these manuscripts have been drafted before moving onto assessing other research samples.

Deliverables

1. Continued publications

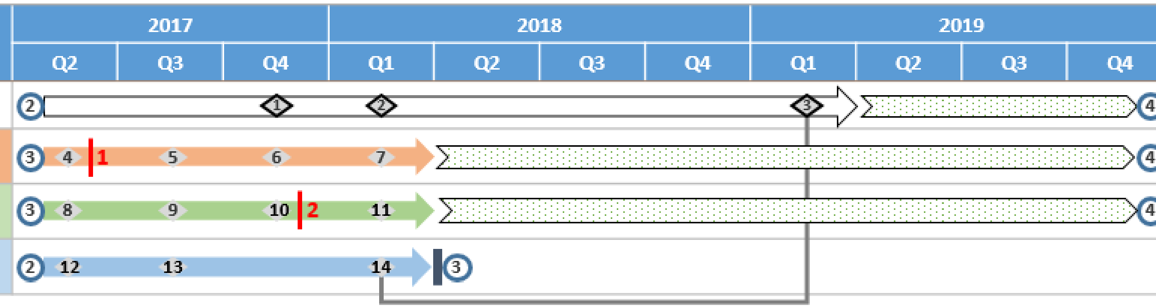
NATIONAL ENERGY TECHNOLOGY LABORATORY

Thank you to Brian Plowman and Budd Schaffer (Deloitte) for assisting with these!

Gantt Chart - Task 3

Past | Present | Future

2017	Research Activities
$1.85M	Task 2.0 – Reservoir Performance
$1.34M	Subtask 2.1 – Understanding Relative Permeability, Residual Saturation, and Porosity in Reservoirs to Reduce Uncertainty
$0.25M	Subtask 2.2 – Improve Characterization of Physical Changes in Reservoir and Seal Rock due to CO2
$0.26M	Subtask 2.3 – Determine Impact of Microbial Induced Changes on Reservoir Performance



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Deliverables

1. Continued publications

NATIONAL ENERGY TECHNOLOGY LABORATORY

Thank you to Brian Plowman and Budd Schaffer (Deloitte) for assisting with these!

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Journal, multiple authors:

- Crandall, D.; Moore, J.; Gill, M.; Tudek, J. (2017) **Understanding micro-to-macro scale control on multiphase phenomena in CO_2 reservoir rock**, NETL-TRS-3-2017; Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Morgantown, WV, 2017; p 24.

Publication:

- Dalton, L., Crandall, D., Goodman, A. (August 2017) **In situ contact angle measurements of supercritical CO2, brine, and sandstone cores using micro-CT imaging**, Microscopy and Microanalysis 2017, August 6-10, St. Louis, MO
- Menefee, A., Crandall, D., Giammar, D. E., Ellis, B.R. (August 2017) **Characterization of reaction fronts associated with mineral carbonation of fractured basalts**, Goldschmidt 2017, August 13-18, Paris France
- Dalton, L.E., Crandall, D., Goodman, A. (March 2017) **In situ contact angle measurements of supercritical CO_2, brine, and sandstone cores using micro-CT imaging**, 3rd Annual review meeting of the Energy Frontier Research Consortium GSCO2, March 29-30, Champaign IL
- Tkach, M., Goodman, A., Kutchko, B., Crandall, D., Spaulding, R., Harbert, B., Werth, C., Akono, A.-T., Druhan, J., Jessen, K., Tsotsis, T. (March 2017) **Addressing geochemical alterations in reservoir rock and the impacts in seismic properties**, 3rd Annual review meeting of the Energy Frontier Research Consortium GSCO2, March 29-30, Champaign IL
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Journal, multiple authors:

- Tudek, J., Crandall, D., Fuchs, S., Werth, C.J., Valocchi, A.J., Chen, Y., and Goodman, A. (*accepted*) ***In situ* contact angle measurements of liquid CO_2, brine, and Mount Simon sandstone core using micro-CT imaging, sessile drop, and lattice Boltzmann modeling**, J. Petrol Science special edition "Energy Frontier Research".
- Delaney, D., Purcell, C., Mur, A., Haljasmaa, I., Soong, Y, Crandall, D., and Harbert, W. (*accepted*) **Dynamic Moduli and Attenuation: Rhyolite and Carbonate Examples,** The Leading Edge
- Crandall, D.; Moore, J.; Rodriguez, R.; Gill, M.; Soeder, D.; McIntyre, D.; Brown, S. (*2017*) **Characterization of Martinsburg Formation using Computed Tomography and Geophysical Logging Techniques**; NETL-TRS-4-2017; Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Morgantown, WV, 2017; p 68.

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- Carr, T.R., Wilson, T.H., Sharma, S., Hewitt, J., Costello, I., Carney, B.J., Jordon, E., Yates, M., McPhil, K., Uschner, N., Thomas, M., Akin, S., Magbagbeola, O., Morales, A., Johansen, A., Hogarth, L., Anifowoshe, O., Naseem, K., Hammack, R., Crandall, D., Kumar, A., Zorn, E, and Vagnetti, R. (Accepted) **Marcellus Shale Energy and Environment Laboratory: Subsurface Reservoir Characterization and Engineered Completion** submitted to the Unconventional Resources Technology Conference, 24-26 July 2017, Austin TX
- Verba, C., Crandall, D., Moore, J., and Lopano, C. (Accepted) **Petrophysical Characterization of the Bakken Shale for Carbon Storage Investigation** *to be presented at* the Unconventional Resources Technology Conference, 24-26 July 2017, Austin TX
- Hakala, J.A., Moore, J.E., Phan, T.T., Crandall, D., Lopano, C.L., Sharma, S. (Accepted) **Laboratory-scale studies on chemical reactions between fracturing fluid and shale core from the Marcellus Shale Energy and Environmental Laboratory (MSEEL) site,** *to be presented at* the Unconventional Resources Technology Conference, 24-26 July 2017, Austin TX
- Kavousi, P., Carr, T., Wilson, T., Amini, S, Wilson, C., Crandall, D. (accepted) **Correlating distributed acoustic sensing (DAS) to natural fracture intensity for the Marcellus Shale,** 87th annual meeting of the society of exploration geophysicists, 24-29 September, Houston TX
- Verba, C., Montross, S., Spaulding, R., Dalton, L., Crandall, D., Moore, J., Huerta, N., and Kutchko, B. (April 2017) **Petrophysical Characterization of Foamed Cement for Potential Carbon Storage Initiatives** submitted to the 2017 Carbon Capture, Utilization, and Storage Conference, 10-13 April 2017, Chicago IL.