Reservoir Performance

FWP-ORD-FY15 Task 2
1022403

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Office of R&D, Predictive Geosciences Division/ U.S. D.O.E. National Energy Technology Laboratory

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Transforming Technology through Integration and Collaboration
August 18-20, 2015

Benefits to the Program

- Primary program goal being addressed
  - Support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30%

- Project benefits statement
  - Through an improved understanding of the micro-to-core scale phenomena impacting CO_2 migration through reservoir rocks, we are developing improved methods for predicting CO_2 transport.

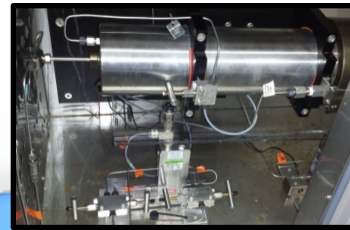
Presentation Outline

- Project Overview
  - Introduction to our group philosophy and facilities
  - Project description
  - What, don’t we already know this?!?

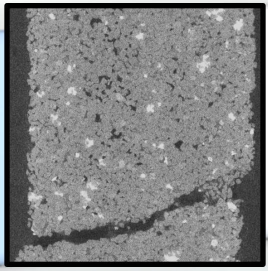
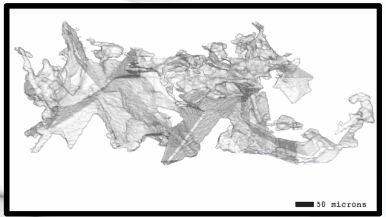
- Progress to Date on Key Technical Issues
- Plans for Remaining Technical Issues
- Project wrap-up

Multiscale/Multiphase Group Philosophy

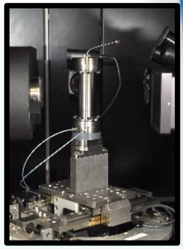
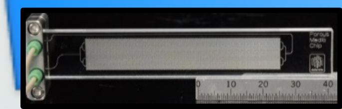
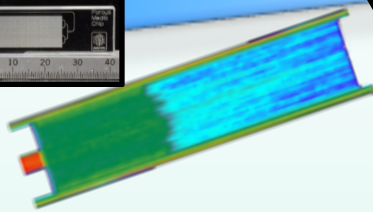
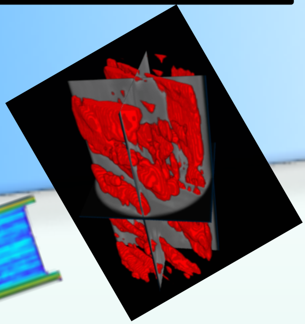
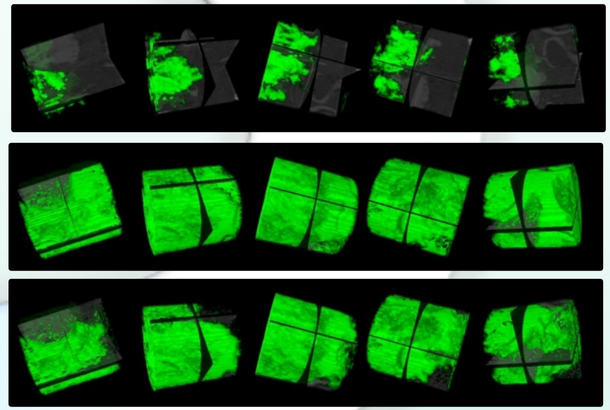
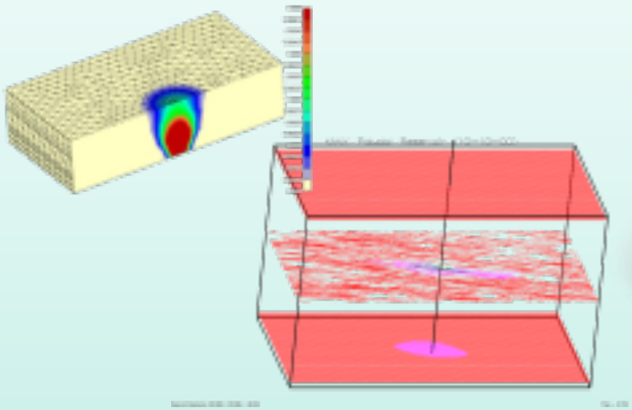




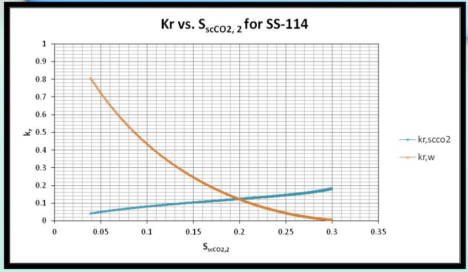
Data Conversion and CFD

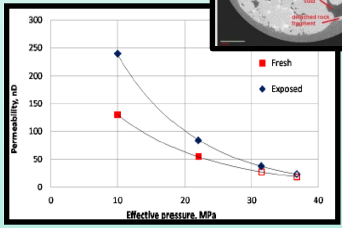



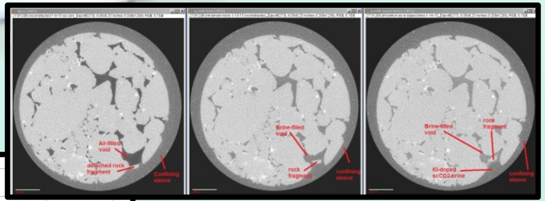
Micro-Scale Data Collection

Multiscale Data Analysis







Reservoir-Scale Application

FWP-ORD-FY15 Task 2 Overview: Goals and Objectives

Primary program goal being addressed:
"Support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30%"

- Subtask 2.1 – Understanding Relative Permeability, Residual Saturation and Porosity in Reservoirs to Reduce Uncertainty
  - Evaluate k_r in the depositional environments listed in the Carbon Sequestration Atlas to improve prediction of CO_2 migration efficiency.
    - Success is developing a tool that can be used to link reservoir characteristics to improved k_r models.
  - Quantify the changes of contact angle and organic contamination on wettability of reservoirs.
    - Success is reporting improved lab procedures for measuring $scCO_2$ θ and influence of organics.
- Subtask 2.2 – Improve Characterization of Physical Changes in Reservoir and Seal Rock
  - Compare/contrast physical changes to reservoir and seal rocks after exposure to CO_2+brine at *in situ* conditions to understand impacts on rock properties.
    - Success is publishing multiple peer reviewed reports of long term changes to rock structure.
- Subtask 2.3 – Determine Impact of Microbial Changes on Reservoir Performance
    - Success is a comprehensive report describing the impacts on microbial communities due to CO_2 storage.

k_r etc. in CO_2 Reservoirs

- What, don't we already know this?!?
  - With 15+ years of active research on k_r in rocks, there are still some very fundamental questions that remain unanswered.
    - How do we determine geologic properties that can be measured to the physical parameters needed to describe k_r?

- Let's examine the NETL CO_2 Storage Atlas methodolgy for estimating storage resources in
  - $G_{CO2} = A_t \, h_g \, \phi_{tot} \, \rho \, E_{saline}$
    - » $E_{saline} = E_{An/At} \, E_{hn/hg} \, E_{\phi e/\phi tot} \, E_v \, E_d$

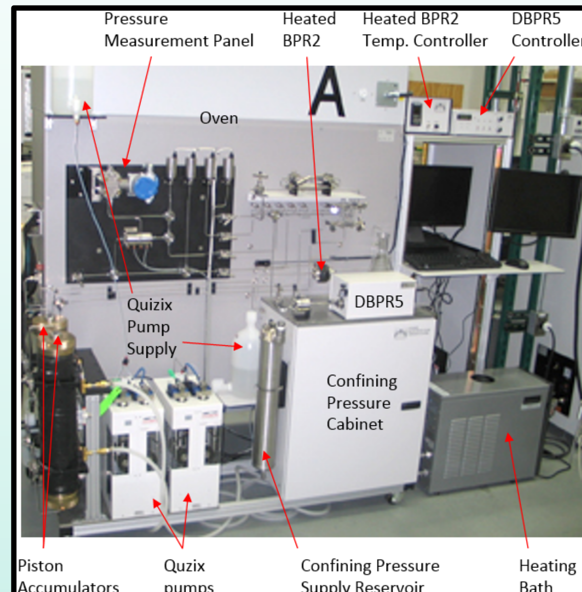
Table 4: *Parameters for Saline Formation Efficiency*

Term	Symbol	P_{10}/P_{90} Values by Lithology			Description
		Clastics	Dolomite	Limestone	
Displacement terms used to define the pore volume immediately surrounding a single well CO_2 injector					
Volumetric Displacement Efficiency	E_v	0.16/0.39*	0.26/0.43*	0.33/0.57*	Combined fraction of immediate volume surrounding an injection well that can be contacted by CO_2 and fraction of net thickness that is contacted by CO_2 as a consequence of the density difference between CO_2 and in situ water.
Microscopic Displacement Efficiency	E_d	0.35/0.76*	0.57/0.64*	0.27/0.42*	Fraction of pore space unavailable due to immobile in situ fluids.

*Values from IEA (2009)

k_r etc. in CO_2 Reservoirs

- Displacement efficiencies are described with reservoir models using k_r curves.
  - Measurement of k_r in the laboratory is difficult.
- But we've built up the capabilities



CFS-839Z Core Flow System redesigned to enable $scCO_2$/brine relative permeability measurements at the core scale.

Replaced seals/o-rings, viton to EPDM

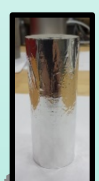
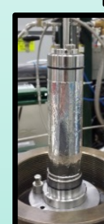
PEEK pistons replaced with SS pistons

Reduce swelling due to adsorption

Upgraded mass flow meters

Multiphase high temp/pressure Coriolis mass flow meters

Improved Core Wrapping Process

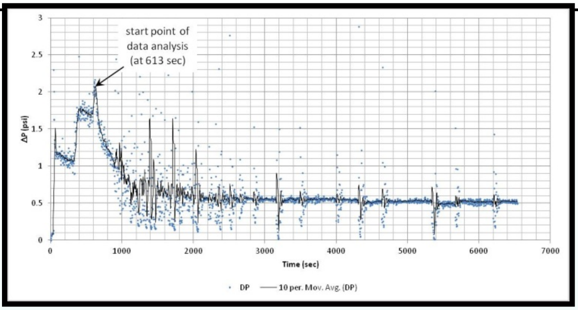




k_r etc. in CO_2 Reservoirs

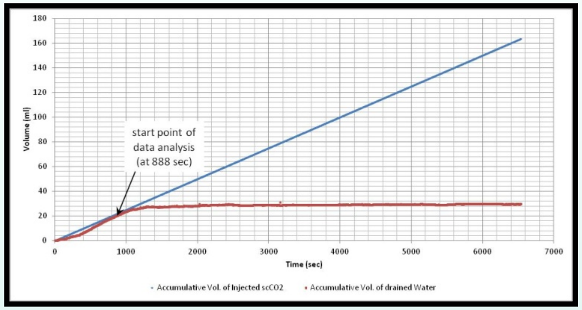
- With all of this, we (*finally*) have confidence in our methodology.

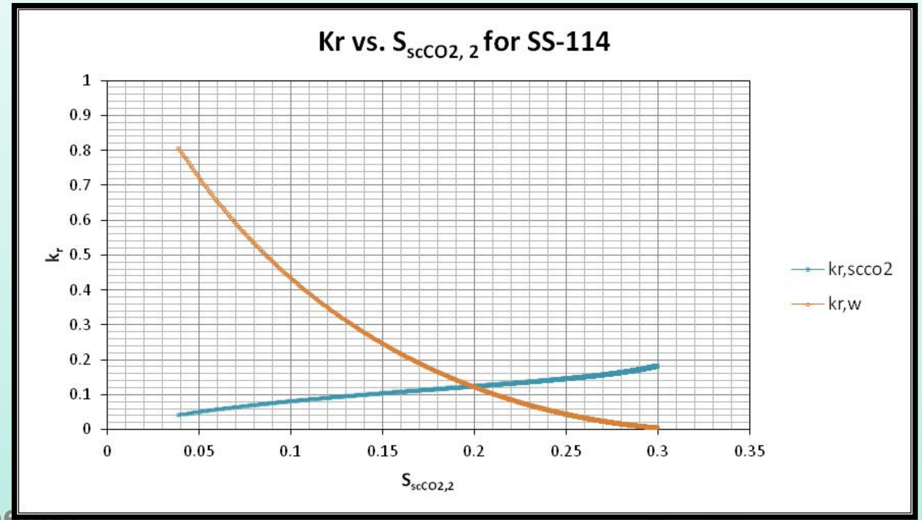
- Results shown for case of $scCO_2$ injection to replace water
  - P_{pore} = 1500 psi
  - $P_{confining}$ = 3000 psi
  - Core temperature = 50 ^oC

Pressure across Core



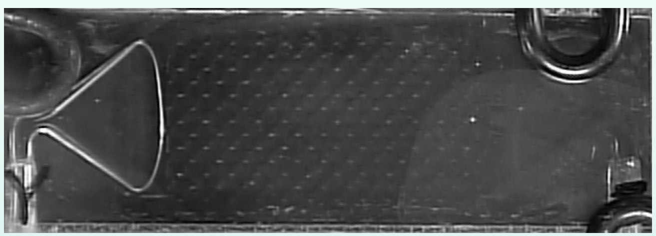
Volume Of Fluids

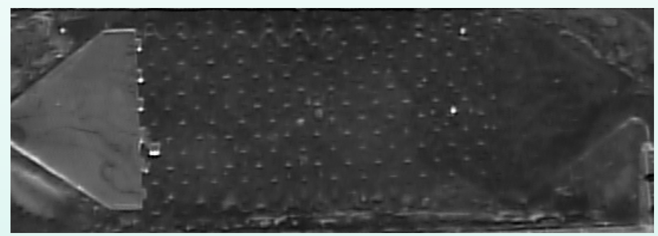




k_r etc. in CO_2 Reservoirs

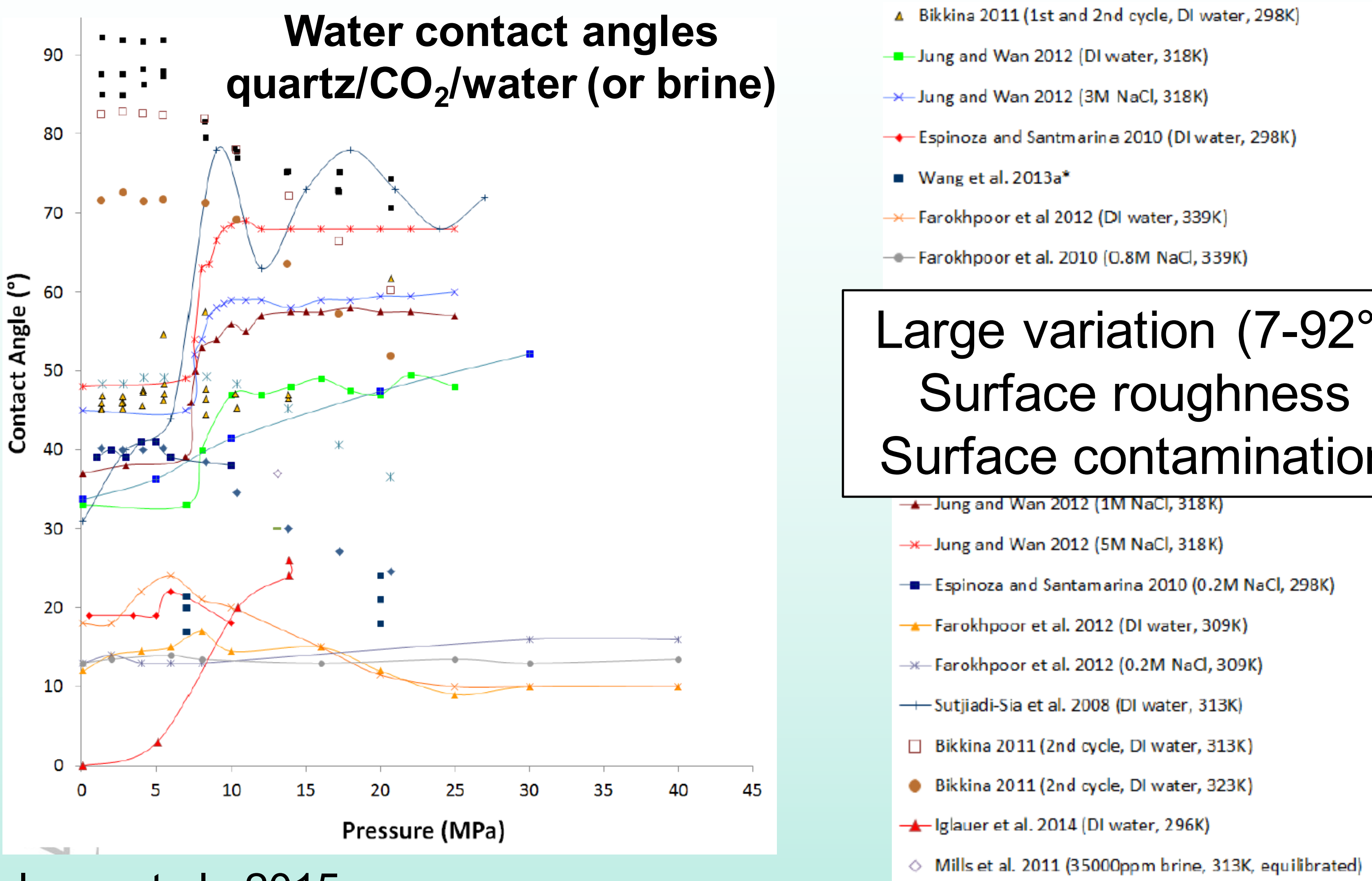
- Are there simpler measurements that we can use to deduce changes in the k_r curve properties (i.e. residual saturation) that we're most interested in?
  - Contact angle of $scCO_2$/brine?





- Iglauer, Pentland and Busch WRR 2015 Review on CO_2 wettability of reservoir rocks
  - Large range of contact angles measured in various lab studies

k_r etc. in CO_2 Reservoirs

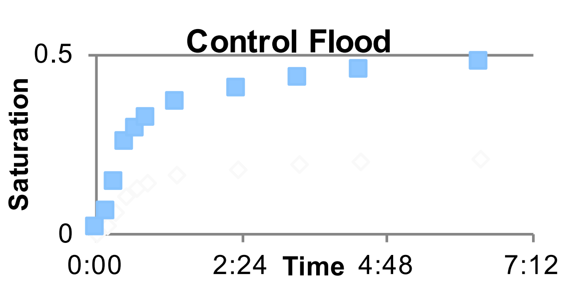


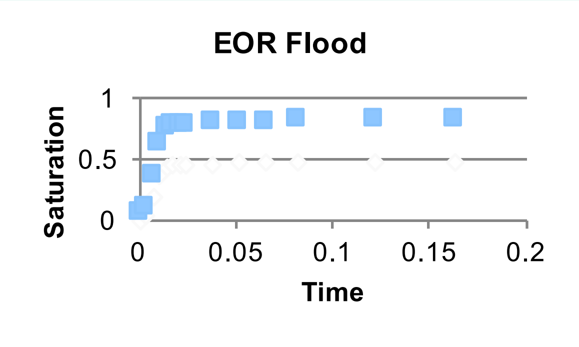
Large variation (7-92°)
Surface roughness
Surface contamination

Iglauer et al., 2015

k_r etc. in CO_2 Reservoirs

- So, what are we doing about this?
  - Taking what we've learned from k_r measurement process and transferring it to the industrial CT scanner for improved ability to measure saturation.
    - » Previous work with the medical CT scanner illustrates ability to accurately measure CO_2 saturation
  - Transforming unused lab space to contact angle measurement facility to evaluate materials under various contamination levels.





Ethanol/acetone commonly used Insufficient to remove all organics

Table 4. "Reality Check": Sessile Drop Water Contact Angles θ Measured on an α-Quartz Single Crystal in CO_2 Atmosphere at Varying Cleanliness States and Ambient Conditions[a]

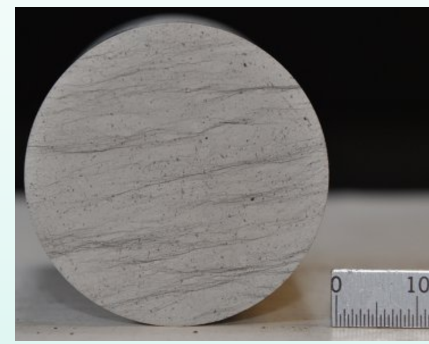
Surface Cleanliness State	Cleaned With Piranha Solution	Cleaned With Piranha Solution, Then a "Clean" Paper Towel	Cleaned With Piranha Solution Then Exposed to Laboratory Atmosphere for ~8 Weeks
θ	0°	25°	70°

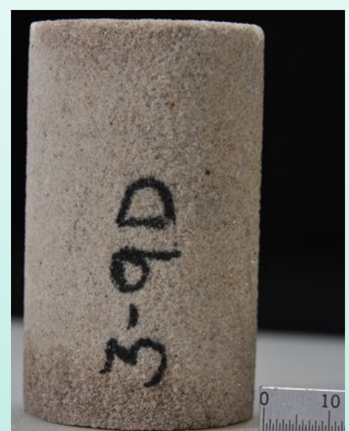
[a]Piranha solution comprises 5vol:1vol H_2SO_4:H_2O_2.

Iglauer et al., 2015

Changes to Reservoir Rocks and Seals

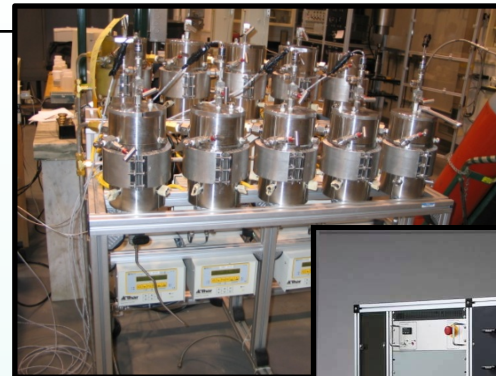
- Examination changes to reservoir and seal rocks from SECARB site
  - Plant Daniel, Jackson County Mississippi
  - Selma Chalk (1-14D) 6212.2 ft
    - 90 % Calcite, 3% Chlorite, 2 % Kaolinite, 3 % Quartz and 2% Illite
  - Lower Tuscaloosa Massive Sand (3-39D) 8539.35 ft
    - 92% Quartz, 2% Chlorite, 3% Feldspar, 1% each for Kaolinite, Illite, and Carbonate.

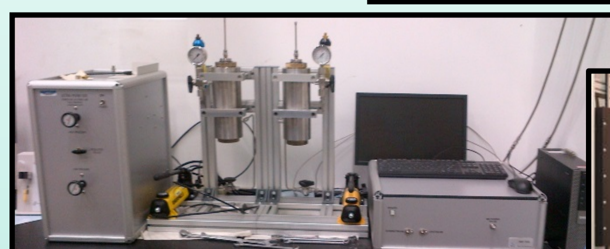


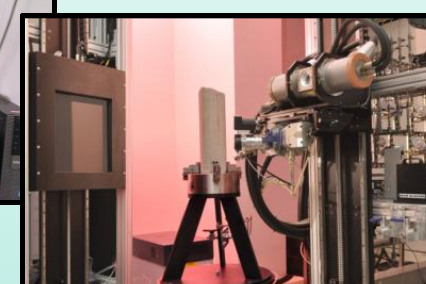


Changes to Reservoir Rocks and Seals

- 6 month exposure in high-pressure vessels
  - 23.8 Mpa (3450 psi)
  - 85 °C (185 °F)
- CT, XRD, SEM, petrography, porosity, and permeability analyses were conducted before and after the six month exposure experiment.

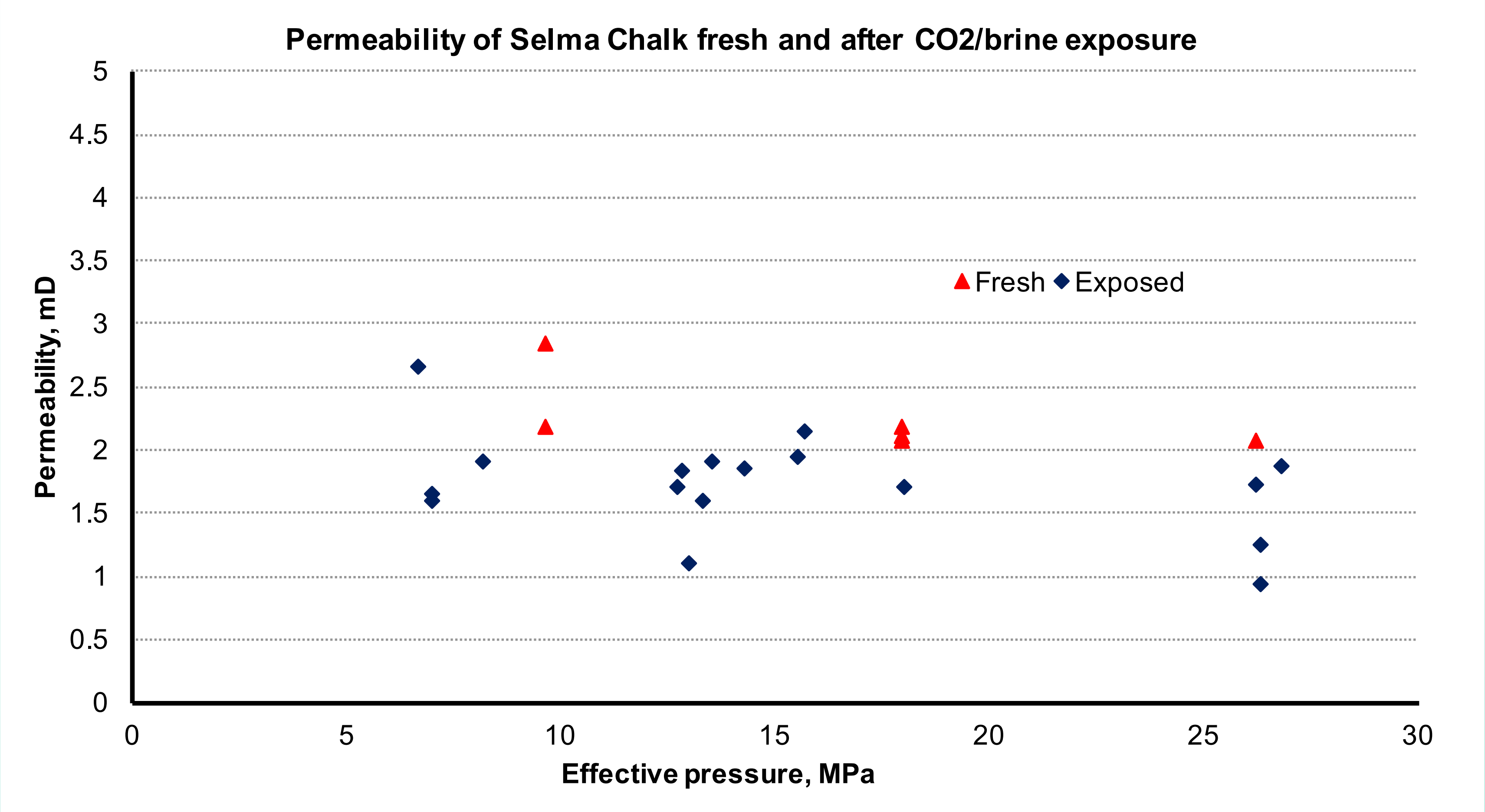






Changes to Reservoir Rocks and Seals

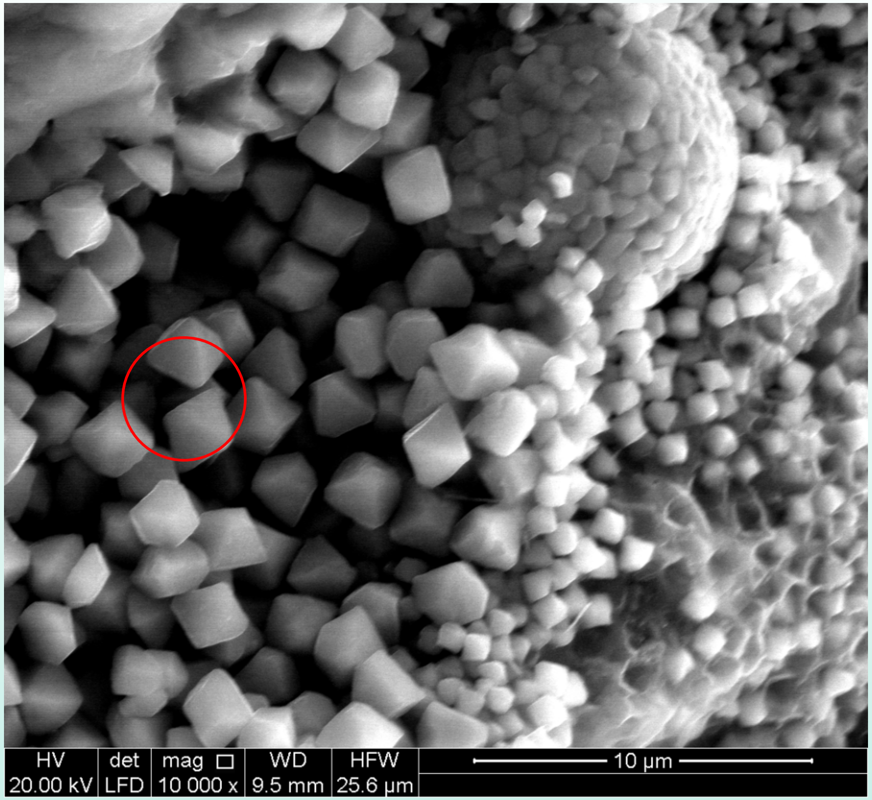
- Selma Chalk, permeability



Changes to Reservoir Rocks and Seals

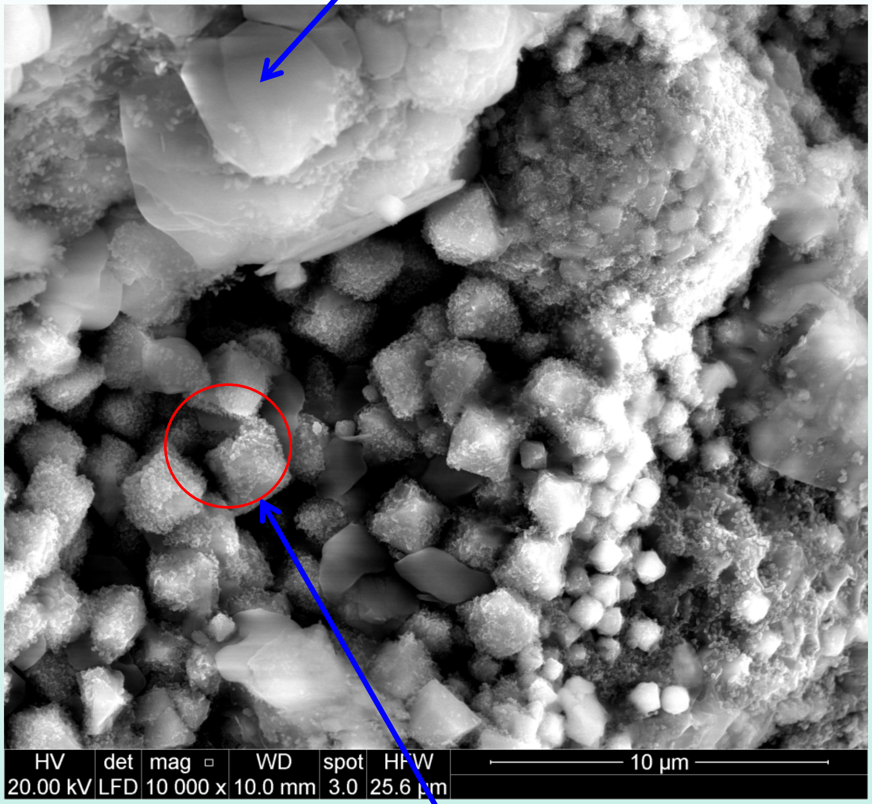
- Selma Chalk, SEM revealed NaCl residue

Fresh



Exposed

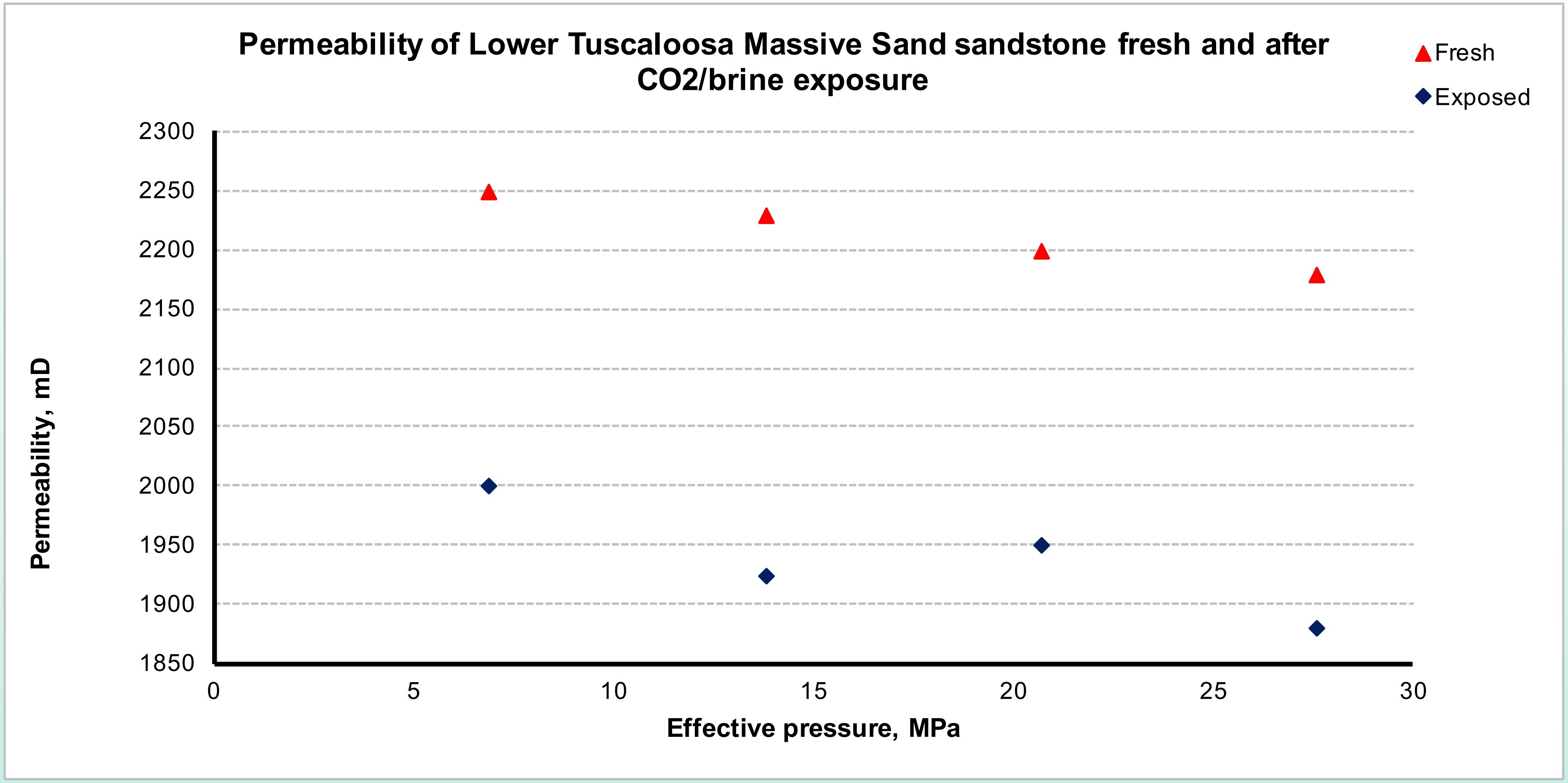
NaCl



Particles on pyrite

Changes to Reservoir Rocks and Seals

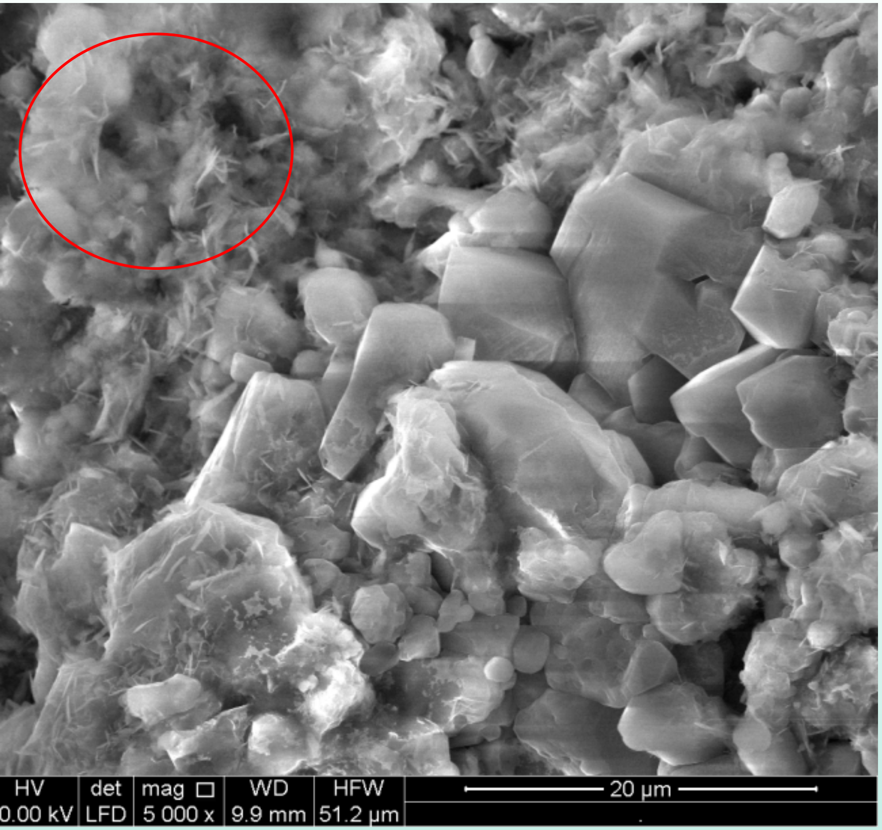
- Tuscaloosa Sand, permeability



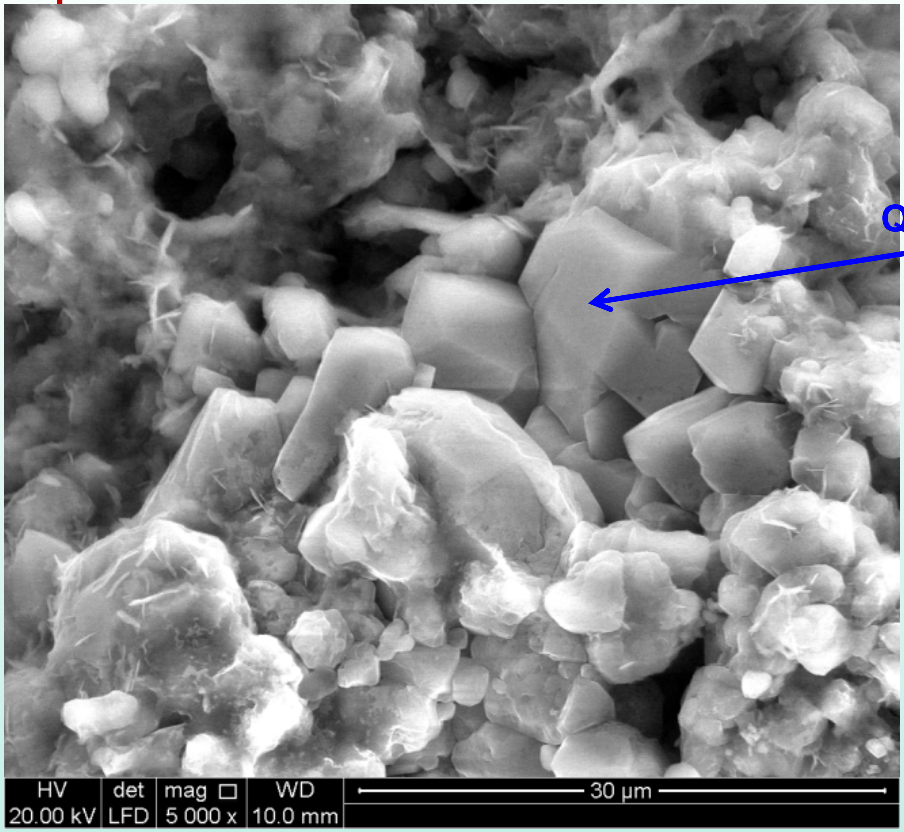
Changes to Reservoir Rocks and Seals

- Tuscaloosa Sand, SEM revealed NaCl residue

Fresh



Exposed

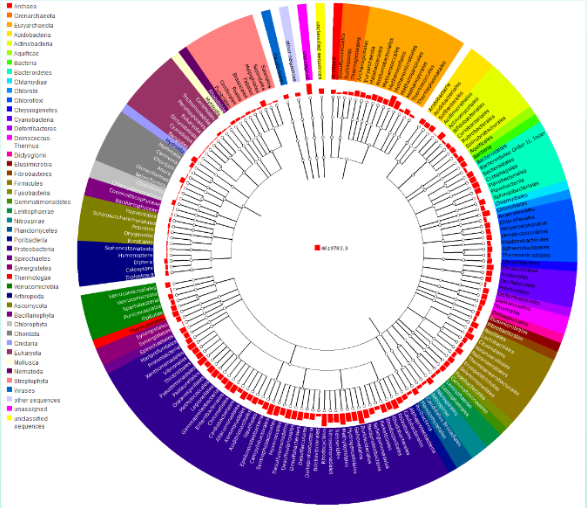


Changes to Reservoir Rocks and Seals

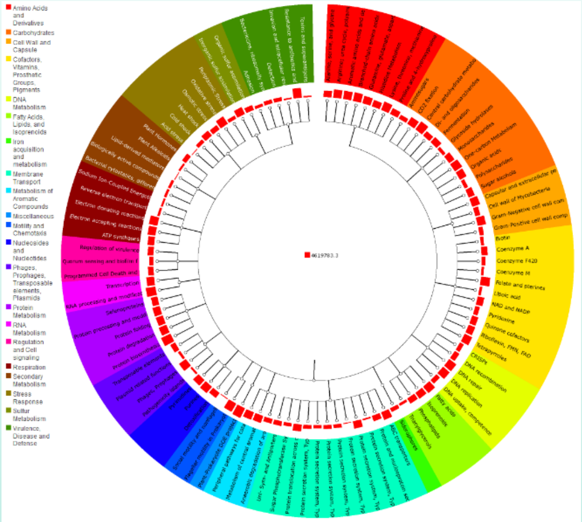
- CT and SEM showed little change to the structure, but with a 13% increase in the permeability of sandstone brine analysis was performed as well
  - Increased conc. of Ca, Fe, K, Mg, Na, S and Si in the reacted brine may suggest some dissolution of carbonate (Selma Chalk)
  - Increased conc. of Al, Ca, Fe, K, Mg, Mn, Na and Si in the reacted brine may suggest the dissolution of Feldspar and chlorite (Massive Sand)

Determine Impact of Microbial Changes on Reservoir Performance

- This year's primary focus was to setup the metagenomics lab at NETL
  - Mission accomplished!
  - All training for metagenomics capabilities has been completed.
  - Metagenomic analysis of CO_2 exposed freshwater microbial communities began this year and metagenomic profile completed.
  - Analysis underway!

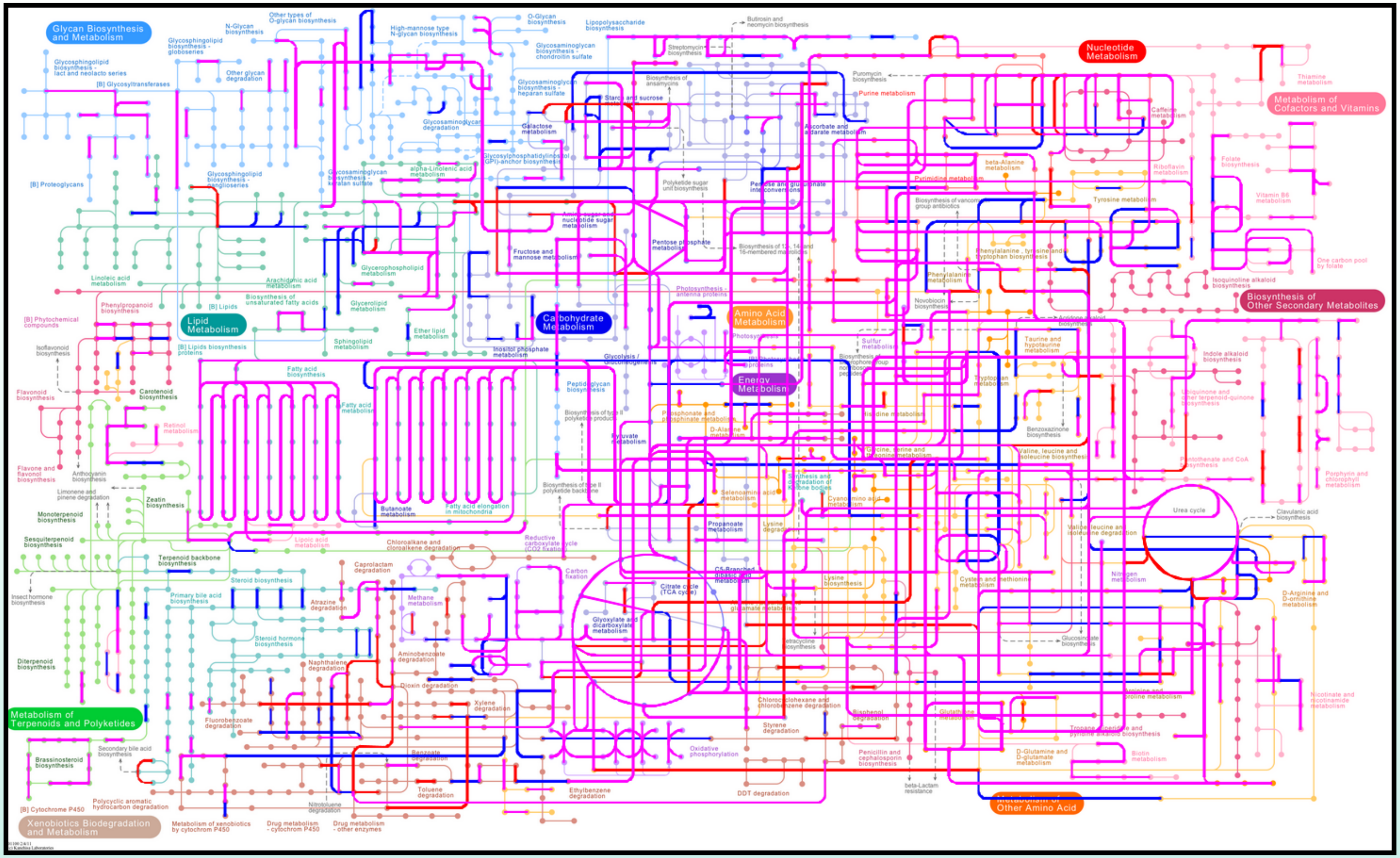


16 S Illumina Sequencing to determine types of microorganisms



Shotgun Illumina Sequencing to determine microbial processes

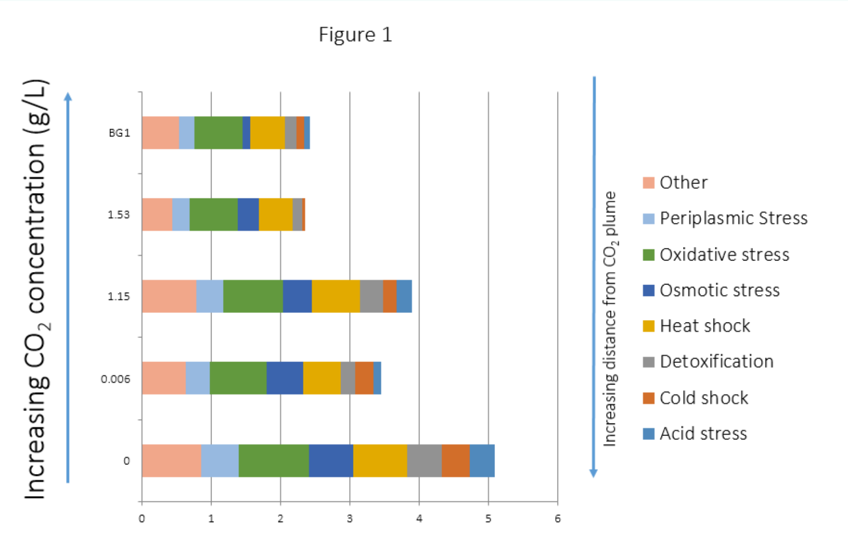
Microbial Activity in CO_2 Exposed Brine



- Full metagenomics pathway. Each line demonstrates a microbial metabolic pathway occurring in CO_2 exposed environments. Each node is a chemical being produced.

Metagenome in CO_2 exposed systems

- Metagenomic capability is being developed for future analysis of microbial communities in CO_2 exposed systems
- Metagenomic analysis of the microbial community in a controlled CO_2 leakage scenario is underway
  - Wells downgradient to CO_2 plume appear to have increase stress response mechanisms and increase mobility (Figure 1)



Synergy Opportunities

Mandate: Discuss how collaboration among projects could have a synergistic effect on advancing the carbon storage technology described during the session in which you are presenting.

- Well, this project may be the odd one out in today's session, little hard to predict a priori…
- But hopefully the multiscale laboratory analysis capabilities at within NETL ORD presented here are of interest to the attendees to further examine some of the small changes in storage formations that may have a large impact on successful carbon storage.

Accomplishments to Date & Summary

– scCO2 Relative permeability curves obtained (2.1)
  - Equipment for CT + high precision flows purchased for FY16
  - Micro-CT scans of displacement in Mt Simon obtained

– SECARB reservoir & seal rock exposure to $scCO_2$ + brine completed
  - Analysis wrapping up and manuscript drafted
  - Mount Simon exposure underway

– Metagenomics lab set up
  - CO_2 reservoir brine analysis to be started shortly

NETL Research Presentations and Posters

TUESDAY, AUGUST 18, 2015

- **2:15 PM** Resource Assessment - Angela Goodman
- **5:10 PM** Catalytic Conversion of CO_2 to Industrial Chemicals - Doug Kauffman
- **6:00 p.m. Poster Session (CORE R&D, NRAP, and RCSPs)**
  1. Dave Blaushild - Perfluorocarbon Tracer (PFT) Analysis to Support the South West Partnership,
  2. Liwei Zhang - Numerical simulation of pressure and CO2 saturation above the fractured seal as a result of CO2 injection: implications for monitoring network design
  3. NRAP, EDX, and NATCARB Grant Bromhal, Bob Dilmore, Kelly Rose, Maneesh Sharma

WEDNESDAY, AUGUST 19, 2015

- **1:15 PM** Monitoring the Extent of CO_2 Plume and Pressure Perturbation - Bill Harbert
- **2:05 PM** Reservoir and Seal Performance - Dustin Crandall
- **3:45 PM** Monitoring Groundwater Impacts - Christina Lopano
- **5:30 p.m. Poster Session (SubTER, NRAP, and EFRCs)**
  1. Kelly Rose - Evaluating Induced Seismicity with Geoscience Computing & Big Data – A multi-variate examination of the cause(s) of increasing induced seismicity events
  2. NRAP, EDX, and NATCARB Grant Bromhal, Bob Dilmore, Kelly Rose, Maneesh Sharma
  3. John Tudek- *Preliminary results of 3-D Micro-CT imaging of Mt. Simon reservoir rock.* EFRC
  4. Sean Sanguinito NETL CO2 SCREEN

THURSDAY, AUGUST 20, 2015

- **11:25 AM** Shales as Seals and Unconventional Reservoirs for CO_2– Robert Dilmore

Appendix

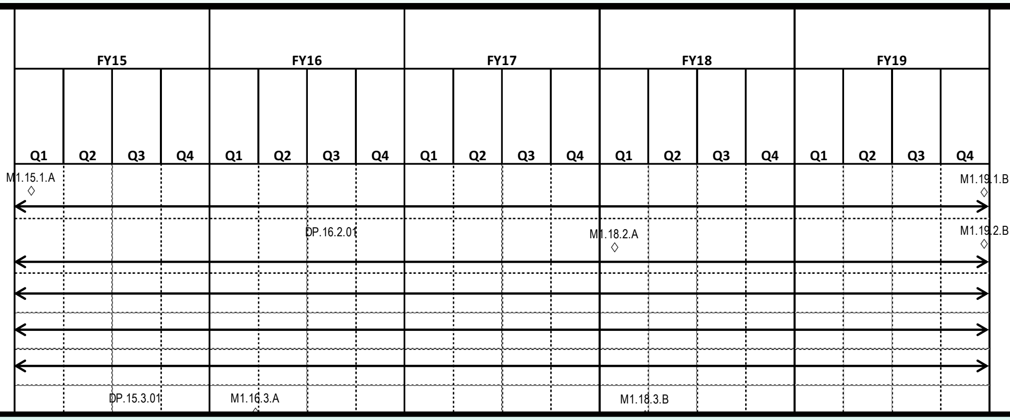
– These slides will not be discussed during the presentation, but are mandatory

Organization Chart

- Task 2.0 – TTC Dustin Crandall
  - Subtask 2.1 – Understanding Relative Permeability, Residual Saturation and Porosity in Reservoirs to Reduce Uncertainty
    - PI Grant Bromhal
  - Subtask 2.2 – Improve Characterization of Physical Changes in Reservoir and Seal Rock
    - PI Yee Soong
  - Subtask 2.3 – Determine Impact of Microbial Changes on Reservoir Performance
    - PI Djuna Gulliver

Gantt Chart

FY15 Carbon Storage (Project Period: 10/01/14 – 09/30/19)	Project Dates For each Task, Subtask, Sub-subtask of your WBS **Start** Reflects the date the work is scheduled to begin	 **Finish** Reflects the date the work is scheduled for completion
1. Project Management and Planning	**10/1/2014**	**9/30/2019**
2. Reservoir and Seal Performance	**10/1/2014**	**9/30/2019**
2.1 Understanding Relative Permeability, Residual Saturation, and Porosity in Reservoirs to Reduce Uncertainty in Long-Term CO_2 Storage and Efficiency	10/1/2014	9/30/2019
2.2 Improve Characterization of Physical Changes in Reservoir and Seal Rock due to CO_2	10/1/2014	9/30/2019
2.3 Determine Impact of Microbial Induced Changes on Reservoir Performance	10/1/2014	9/30/2019



- Gantt Chart from current FY15 FWP, detailed chart to be constructed from work plans. – DC 8/12/15

Bibliography

- Peer reviewed journal articles:

  - Deng, H., Fitts, J., Crandall, D., McIntyre, D. and Peters, C.A., (available online) **Alterations of fractures in carbonate rocks by CO_2-acidified brines**, Environmental Science & Technology.
  - Alexis, D., Karpyn, Z.T., Ertekin, T. and Crandall, D. (*2015*) **Fracture permeability and relative permeability of coal and their dependence on stress conditions**, *J Unconventional Oil and Gas Resources,* 10, 1-10.
  - McLendon, W.J., Koronaios, P, Enick, R.M., Biesmans, G., Salazar, L., Miller, A., Soong, Y., McLendon, T., Romanov, V., and Crandall, D. (2014) **Assessment of CO_2-soluble Non-ionic Surfactants for Mobility Reduction Using Mobility Measurements and CT Imaging.**, *J. Petroleum Sci. & Eng.,* 119, 196-209.
  - Gulliver, D.M., Lowry, G.V., and Gregory, K.B. (2014) **CO_2 concentration and pH alters subsurface microbial ecology at reservoir temperature and pressure**, *RSC Advances,* 4, 17443-17453.
  - Gulliver, D.M., Lowry, G.V., and Gregory, K.B. (2014) **Effect of $CO_{2(aq)}$ Exposure on a Freshwater Aquifer Microbial Community from Simulated Geologic Carbon Storage Leakage** *Environ. Sci. Technol. Lett*., 2014, 1 (12), 479–483
  - Soong, Y., Howard, B.H., Dilmore, R.M., Haljasmaa, I., Crandall, D., Zhang, L., Irdi, G., and McLendon, T.R. (*in progress*) **CO2/Brine/Rock interactions in Lower Tuscaloosa Formation**

Bibliography

- Conferences and Posters:

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