Understanding of Multiphase Flow for Improved Injectivity and Trapping

4000.4.641.251.002

Dustin Crandall, URS

PI: Grant Bromhal, NETL ORD

Morgantown, West Virginia

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 21-23, 2012

Presentation Outline

- Benefit to the program
- Project overview
- Breakdown of FY12 project tasks
- Facilities and personnel
- Task progress to date
- Planned task successes
- Tech transfer and summary

Benefit to the Program

- Program goal being addressed
  - Develop technologies that will support industries' ability to predict CO_2 storage capacity in geologic formations to within ±30%.
- Project benefits statement
  - This research project is an examination of pore scale multiphase flow behavior, in the lab and with micro-scale simulations, to inform key processes of reservoir-scale simulations (e.g. capacity & injectivity prediction, sweep efficiency, storage permanence). This insight contributes to the Carbon Storage Program's effort of ability to predict CO_2 storage capacity in geologic formations to within ±30%.

Project Overview: Goals and Objectives

- Numerical modeling, laboratory measurements, and field samples to focus on the key processes that will allow more accurate prediction of CO_2 capacity, injectivity, sweep efficiency and storage permanence.
- **Objectives for FY12:**
  - Make measurements of key parameters for injectivity, sweep efficiency, and trapping
  - Perform simulations to investigate the effects of parameter variability
  - Develop a framework for understanding "atypical" CO_2 migration

Project Tasks for FY12

- Task 2.5.1- Measurement of pore geometries and residual saturation/relative permeability in cores
- Task 2.5.2 - Immiscible flow scaling relationship
- Task 2.5.3 - Reservoir scale impacts of relative permeabilities and residual saturations on injectivity and capillary trapping
- Task 2.5.4 - Estimation of CO_2 losses along leakage pathways between the reservoir and the near-surface
- Task 2.5.5 - CO_2 trapping mechanisms in clay materials

Project Tasks for FY12

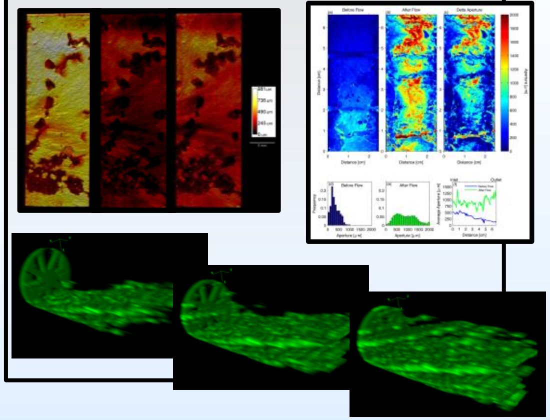
- Task 2.5.1- Measurement of pore geometries and residual saturation/relative permeability in cores
- Task 2.5.2 - Immiscible flow scaling relationship
- Task 2.5.3 - Reservoir scale impacts of relative permeabilities and residual saturations on injectivity and capillary trapping
- Task 2.5.4 - Estimation of CO_2 losses along leakage pathways between the reservoir and the near-surface
- Task 2.5.5 - CO_2 trapping mechanisms in clay materials

Collaboration Is Key

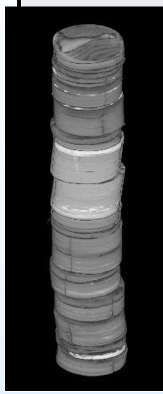
- **Team Members/Collaborators:**
  - Grant Bromhal – NETL-ORD
  - Dustin McIntyre – NETL-ORD
  - Martin Ferer – ORISE
  - Dustin Crandall - URS
  - W. Neal Sams – URS
  - Shahab Mohaghegh – WVU
  - Donald Gray – WVU
  - Egemen Ogretim – WVU
  - Jeong Choi – ORISE
  - Eugene Myshakin – ORISE
  - Vinod Kumar – UTEP
  - Ale Hakala – NETL-ORD
  - Christina Lopano – NETL-ORD
  - Robert Warzinski – NETL-ORD
  - Kathy Bruner – URS
  - Corinne Disenhof – URS
  - Igor Haljasmaa – URS
  - Magdalena Gill – URS
  - Yongkoo Seol – NETL-ORD
  - Ken Jordan – Pitt
  - Dan Mareno - WVU
  - Paul Delgado – UTEP

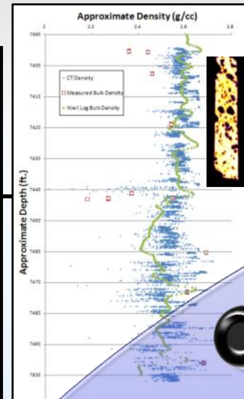
Multi-Scale CT Scanning

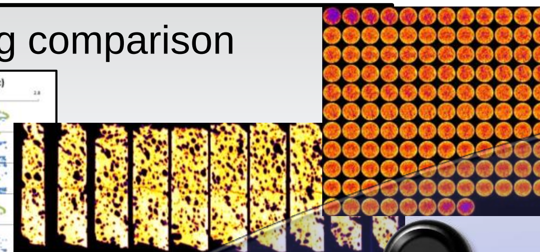
Measuring flow at in situ P, T, stress, and geochemical conditions



CT/well log comparison

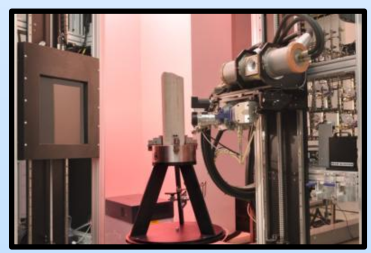




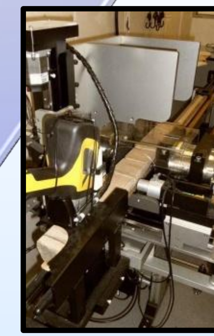


Micro CT Scanner
- Resolution 10^{-6} to 10^{-5} m
- Pore scale

Industrial CT Scanner
-10^{-6} to 10^{-3}m
- Pore & core scale
- Pressure & flow controls

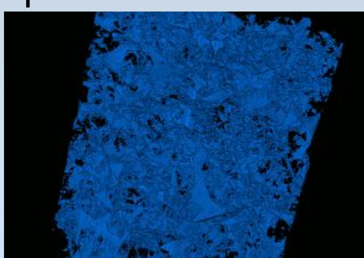


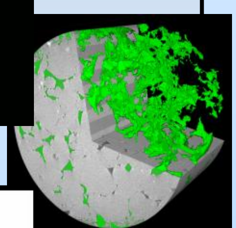
Medical CT Scanner
-10^{-4} to 10^{-2}m
- Core scale
- Pressure, temperature, and flow controls

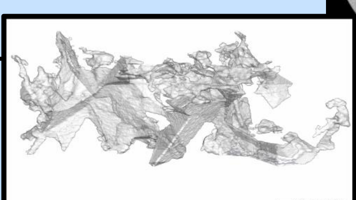


MSCL for geophysical logging

Simulating flow through pore and fracture networks





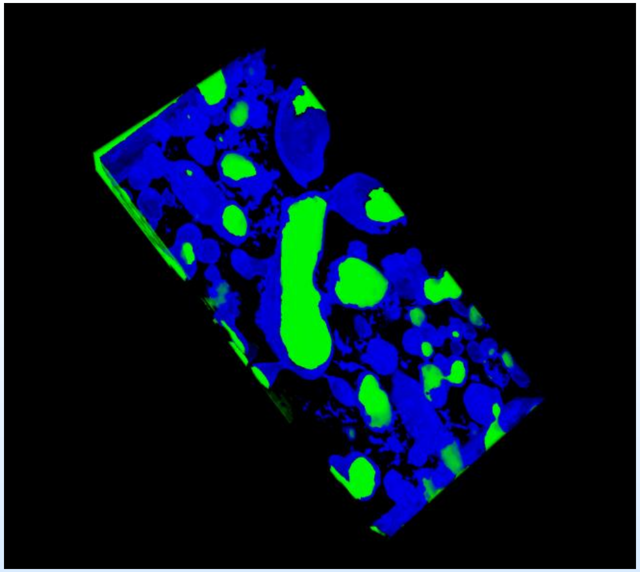


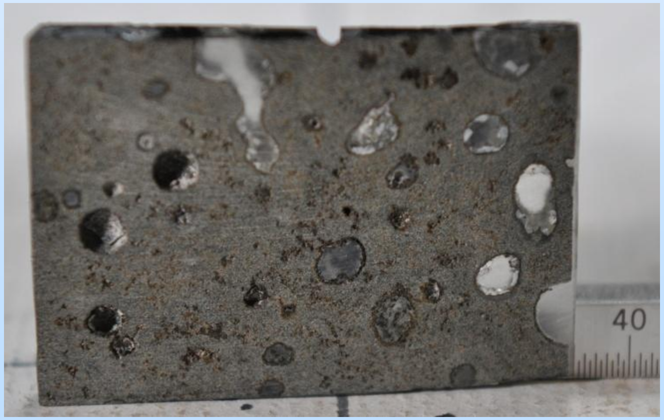
Current Collaborations

Los Alamos National Laboratory EST. 1943
BR Petrobras
glori energy
Pacific Northwest National Laboratory
Princeton University
NETL-RUA Regional University Alliance
The University of Texas at Austin
中國科學院 Chinese Academy of Sciences
ORMAT
URS
Schlumberger
Lawrence Livermore National Laboratory

Pore Geometry Measurement

- Isolation and measurement of pores within various pertinent formations within the industrial and micro CT scanners has been performed
- Example: CO_2 reacted Wallua Gap basalts





Task 2.5.1 - Measurement of pore geometries and residual saturation/relative permeability in cores

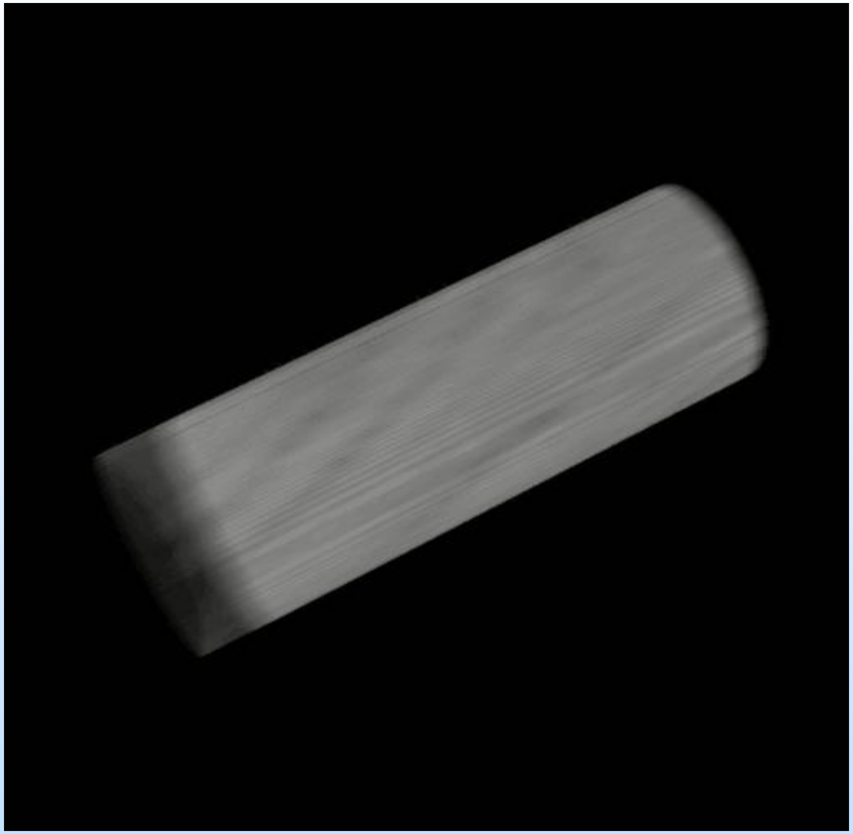
Residual Saturation: Core Scale

- Ordos Basin core samples procured from Chinese Academy of Sciences (CAS)
- Core sub-sampled for multiple scales of analysis: micro to core-scales

Task 2.5.1 - Measurement of pore geometries and residual saturation/relative permeability in cores

Residual Saturation: Core Scale

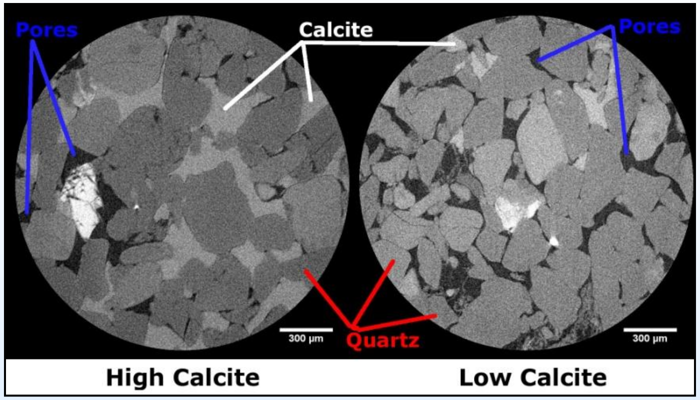
- Dynamic flow in medical scanner
  - $k_{int} \approx 6.4$mD & $\phi_{int} \approx 7\%$
  - $Q = 0.02\ {}^{ml}/_{min}$
  - P_{conf} = 2450 psi
  - P_{inj} = 2200 psi
  - CO_2 displacing 5wt% KI brine
    - Angled bedding planes!

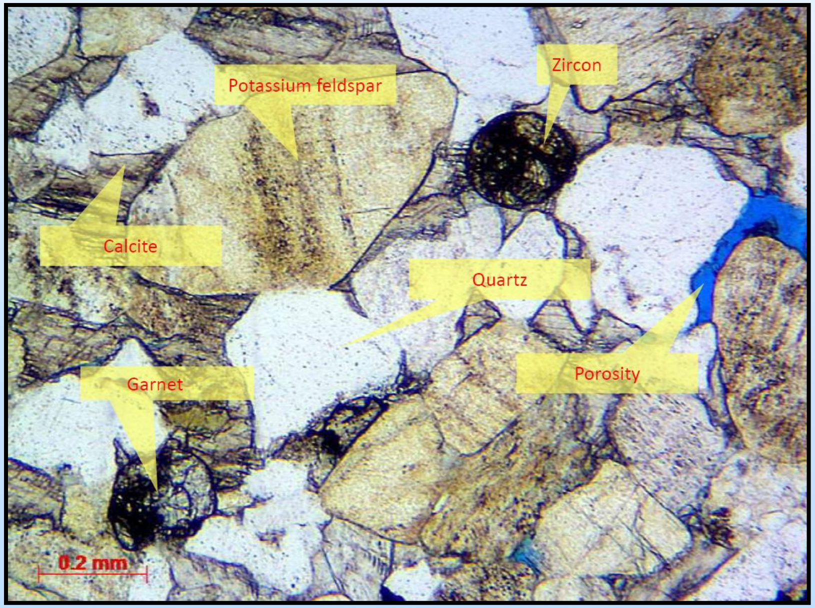


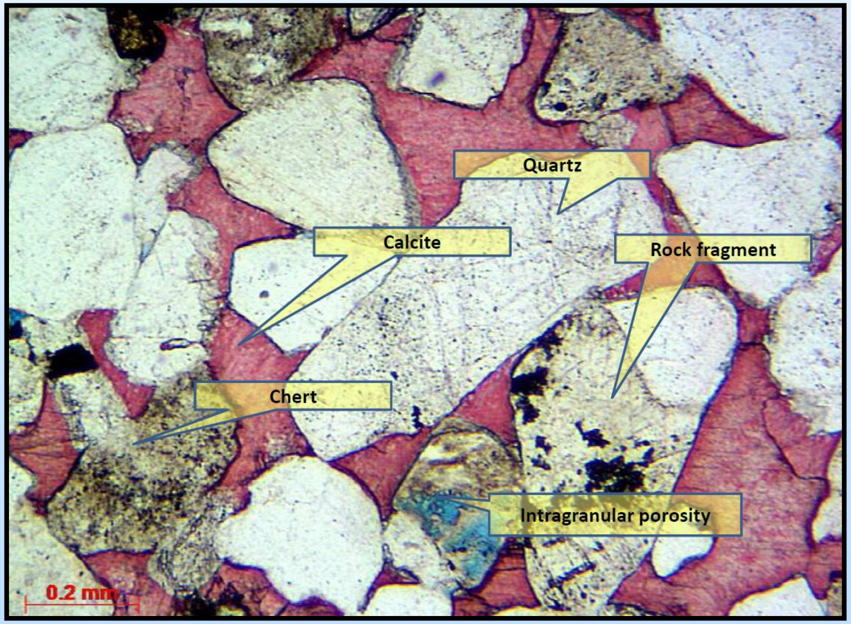
Task 2.5.1 - Measurement of pore geometries and residual saturation/relative permeability in cores

Residual Saturation Micro-Scale

- Arkosic arenite Q/F/RF = 51/32/17
- Calcite ~16%; main cementing agent
- Porosity of ~10%
- Permeability in the range of 50mD







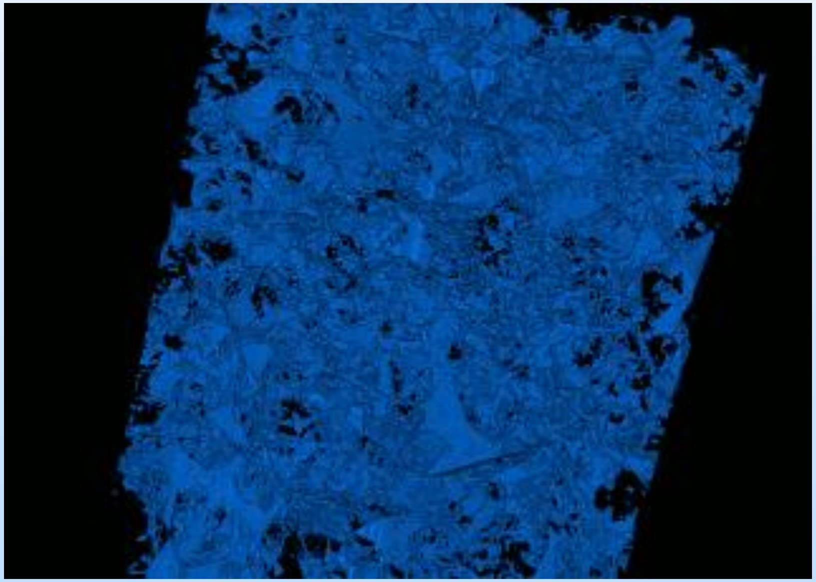
Task 2.5.1 - Measurement of pore geometries and residual saturation/relative permeability in cores

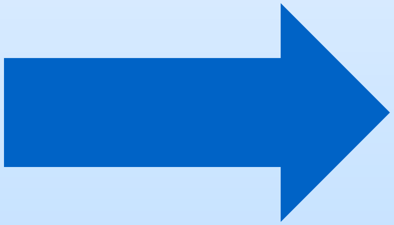
Immiscible flow relationship

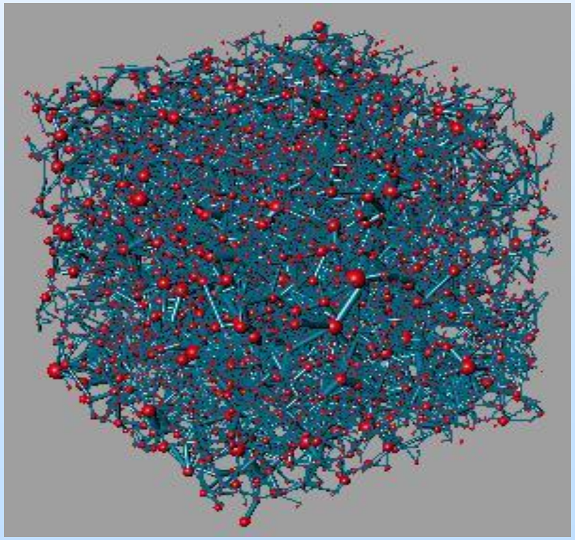
- Pore-scale simulation of two-phase flow for the purpose of being able to generate relative permeability “data” without needing large numbers of experiments
  - Multiple techniques have been used for multiphase flow simulations in pore scale
    - Lattice Boltzmann
    - Navier-Stokes with Volume-of-Fluid
    - Pore-Network modeling

Pore Geometry Extraction

- Generation of irregular pore network from CT images
- Initial network has been generated

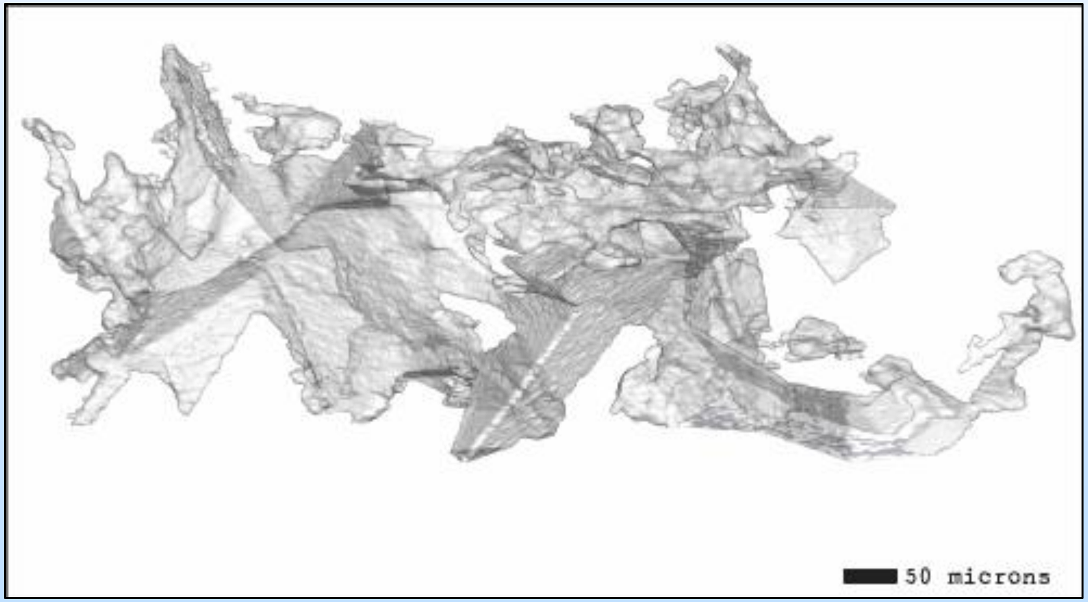






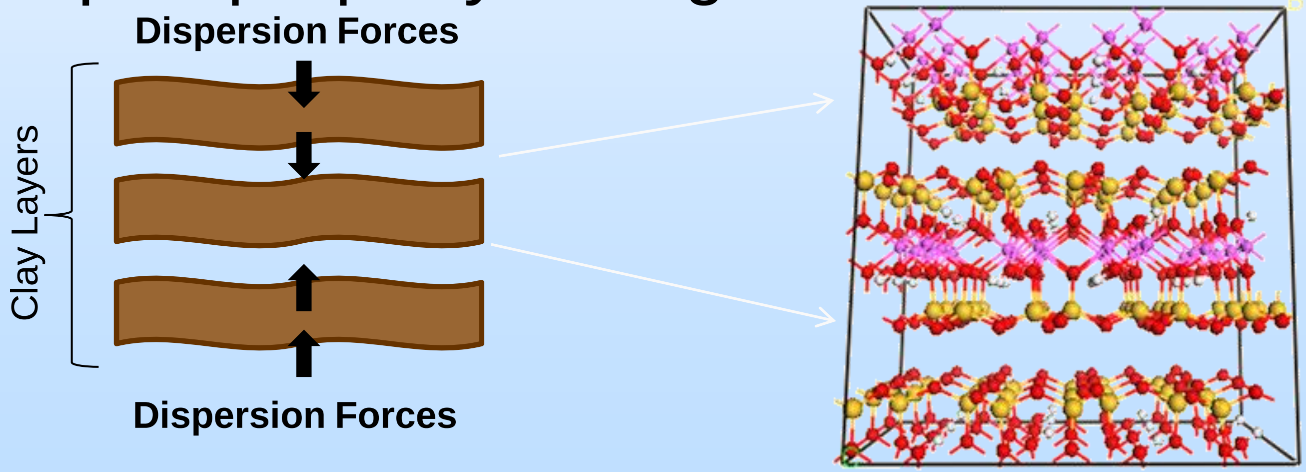
Small NS-VOF Models Run

- Mt Simon sandstone pores
  - 1 x 1 x 3.5 mm domain. CO_2 & brine properties at a depth approximate of 5800 ft
  - Ran a series of variations to complement flow through tests in the medical scanner performed
  - Increased saturation of CO_2 with increased CO_2 viscosity



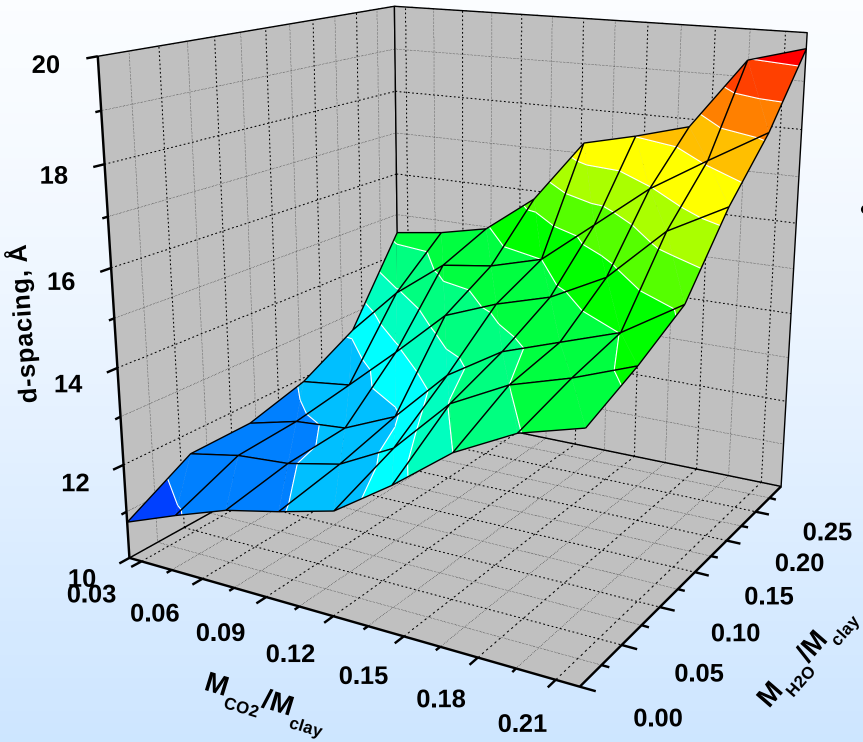
Molecular Modeling of CO_2/Clay

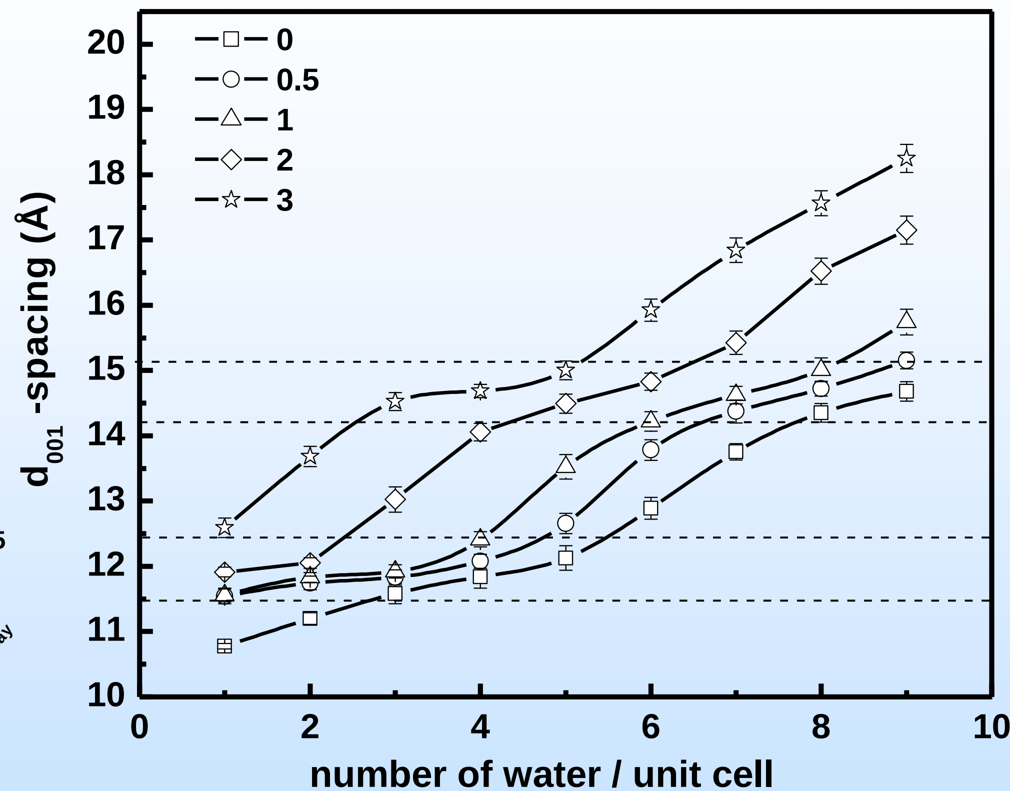
- Using molecular modeling to understand CO_2 trapping in clays:
  - Amount of CO_2 trapped
  - Clay volume changes
  - Clay transport property changes



Task 2.5.5 - CO_2 trapping mechanisms in clay materials

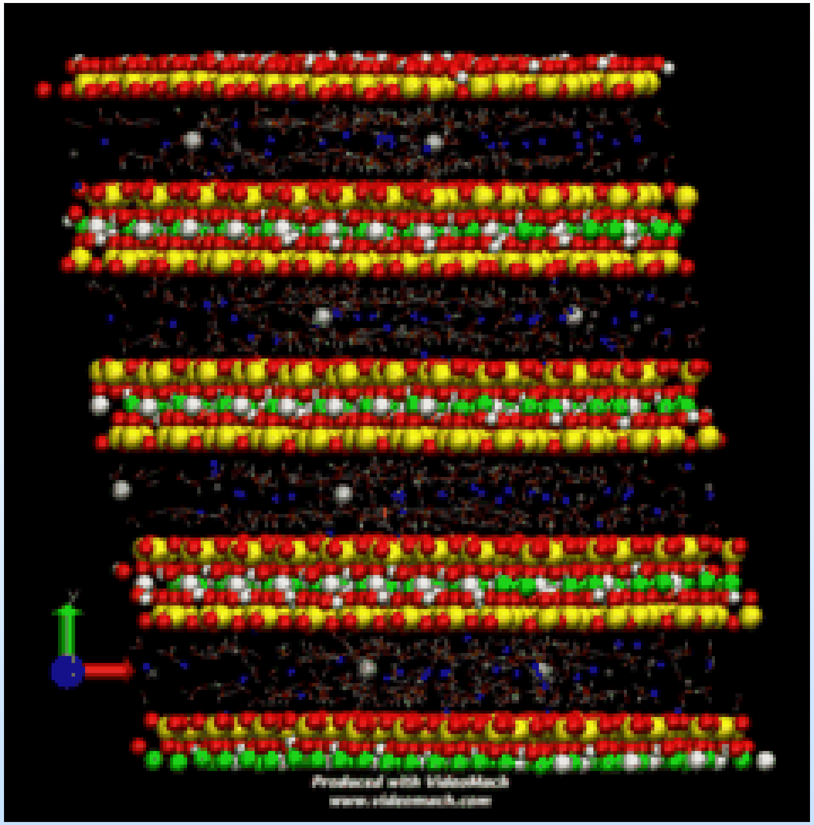
Molecular Modeling Results





3D plot and 2D map of basal spacing dependence on initial water content and amount of intercalated carbon dioxide.

Molecular Modeling Results



Sodium ions are migrating over the internal montmorillonite surfaces, the small blue balls are sodium ions, the big cyan ones are Ca2+. CO_2 and H_2O are represented by sticks.

Reservoir Modeling

- At the small scale we can determine relationships applicable to flow at the field-scale results. Relative permeability is chief among these.
- Reservoir modeling with appropriate k_r

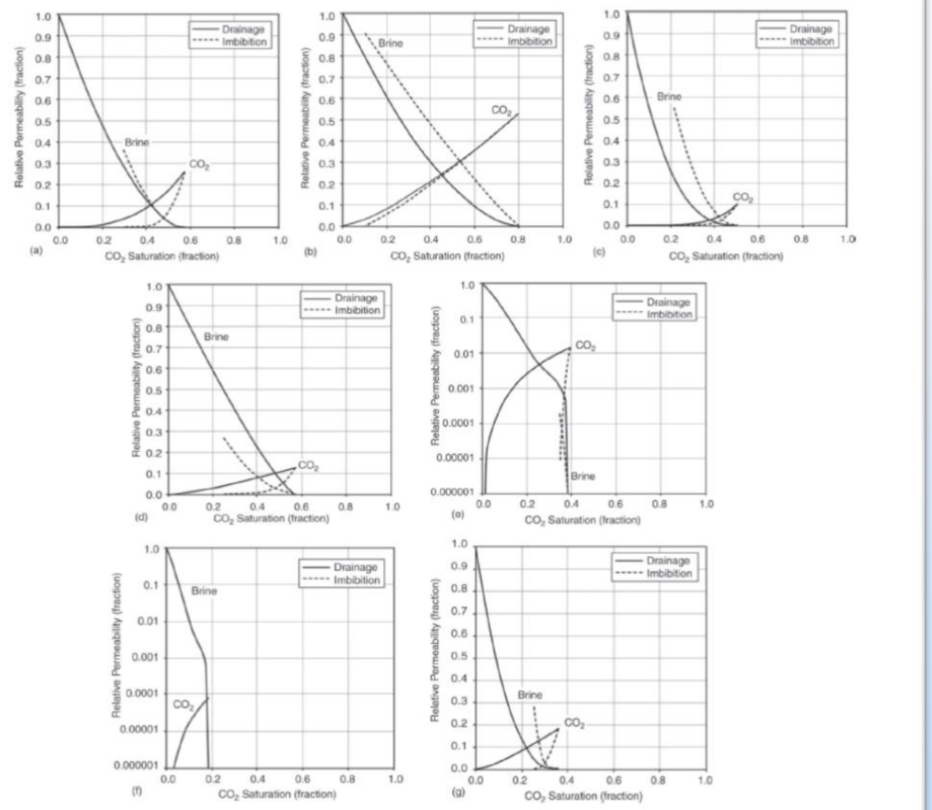


Fig. 4—Relative permeability data (drainage and imbibition) for CO_2/brine systems at in-situ conditions for the following core samples: (a) Viking #2, (b) Nisku #2, (c) Cardium #1, (d) Cardium #2, (e) Colorado, (f) Muskeg, and (g) Calmar. Note that the vertical scale for the very-low-permeability Colorado and Muskeg rocks is logarithmic.

SPE 99326 Bennion D., Bachu S. "Drainage and imbibition relative permeability relationship for supercritical CO_2/brine systems in intergranular sandstones, carbonate, shale and Anhydrite rocks"

Task 2.5.3 Reservoir scale impacts of relative permeabilities and residual saturations on injectivity and capillary trapping

Reservoir Modeling of Citronelle

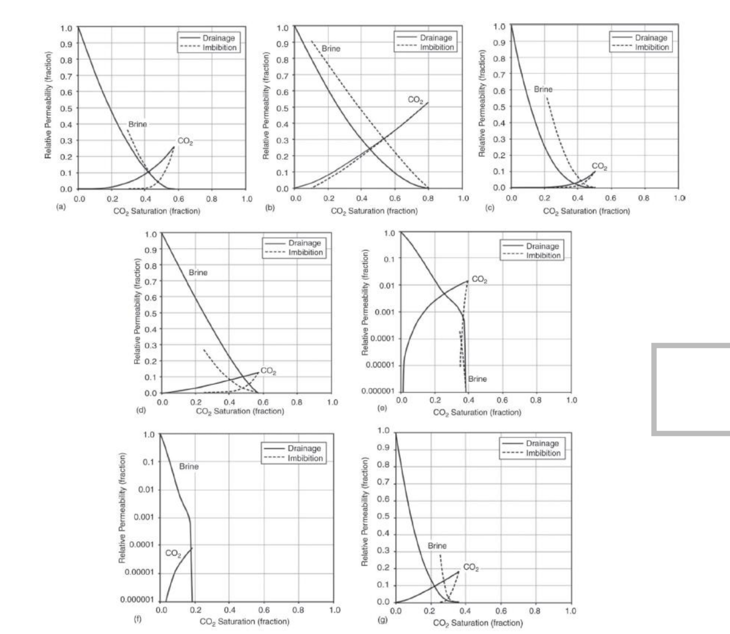
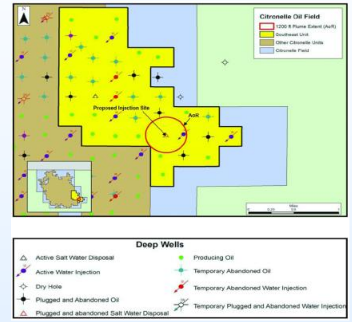


Fig. 4—Relative permeability data (drainage and imbibition) for CO_2/brine systems at in-situ conditions for the following core samples: (a) Viking #2, (b) Nisku #2, (c) Cardium #1, (d) Cardium #2, (e) Colorado, (f) Muskeg, and (g) Calmar. Note that the vertical scale for the very-low-permeability Colorado and Muskeg rocks is logarithmic.

SPE 99326 Bennion D., Bachu S. "Drainage and imbibition relative permeability relationship for supercritical CO_2/brine systems in intergranular sandstones, carbonate, shale and Anhydrite rocks"

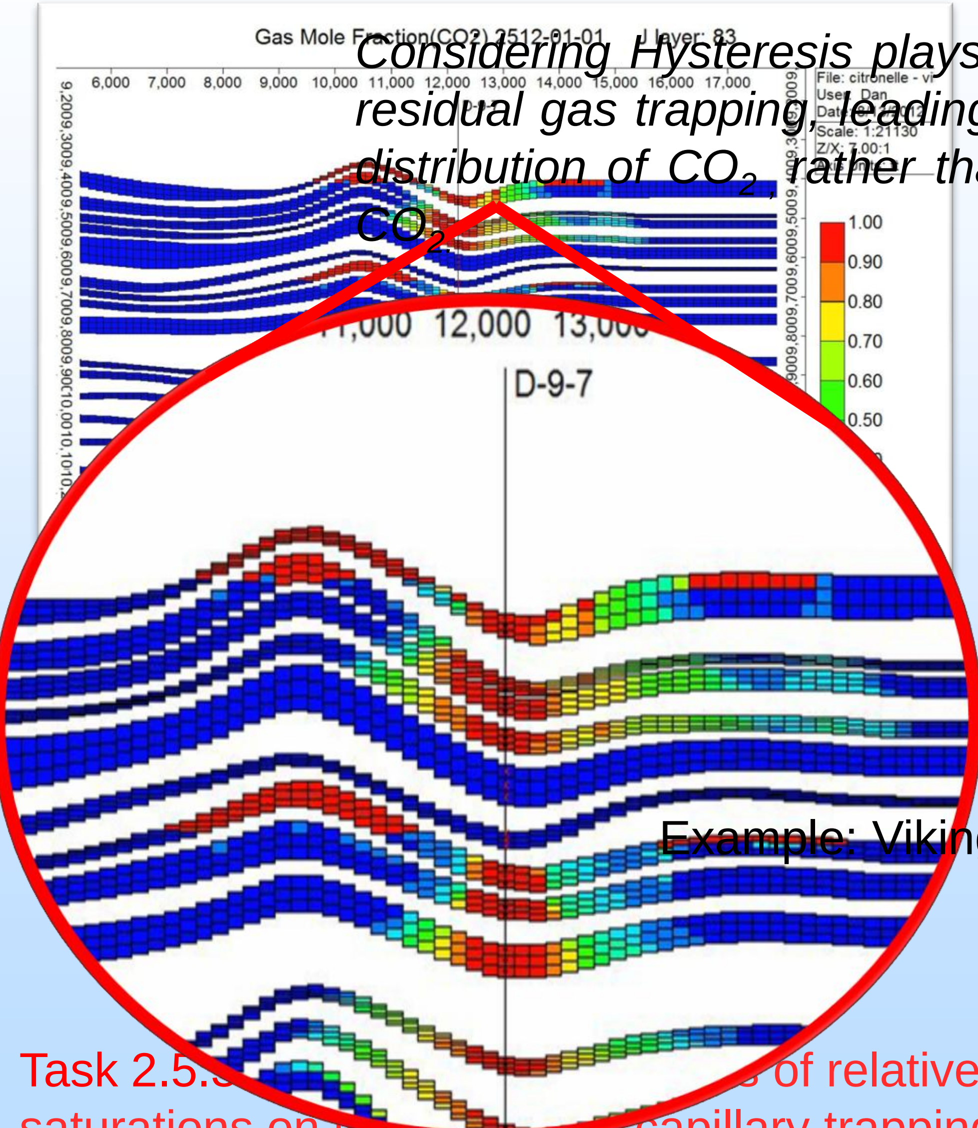


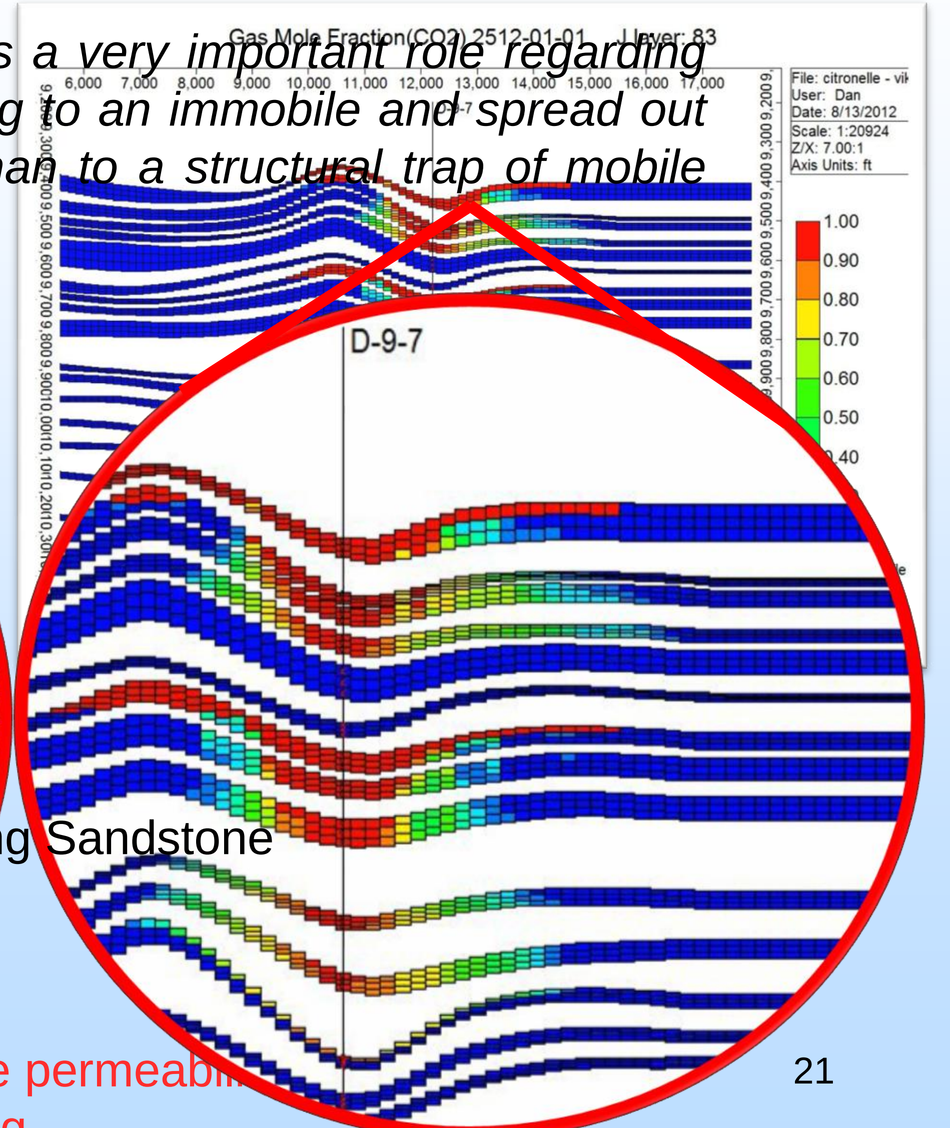
- Type of Waste:
  Carbon Dioxide
- Depth of Well: **11,800 feet**
- Depth and Geological Name of Injection Zone:
  Paluxy Formation
- Depths and Geologic Name of Injection Interval:
  9,400 – 10,500 feet below GL
  Paluxy Formation
- Injection Volumes:
  Average Daily Volume: **148,000 gal/day** (500 ton/day)-- 182500 ton/year

Task 2.5.3 Reservoir scale impacts of relative permeabilities and residual saturations on injectivity and capillary trapping

Modeling with Hysteresis

Considering Hysteresis plays a very important role regarding residual gas trapping, leading to an immobile and spread out distribution of CO_2, rather than to a structural trap of mobile CO_2.





Example: Viking Sandstone

Task 2.5.3 … s of relative permeabi… saturations on inj… capillary trapping

Task 2.5.1 – Future Plans

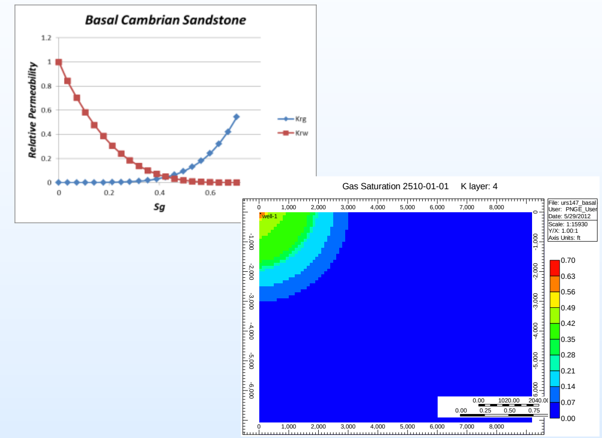
- Relative permeability and residual saturation values are keys to sweep efficiency and trapping
- Use regional partnership cores that have been collected
- Generate additional k_r relationships (FY13)
- Compare to pore-scale simulation results (FY14 with Task 2.5.2)

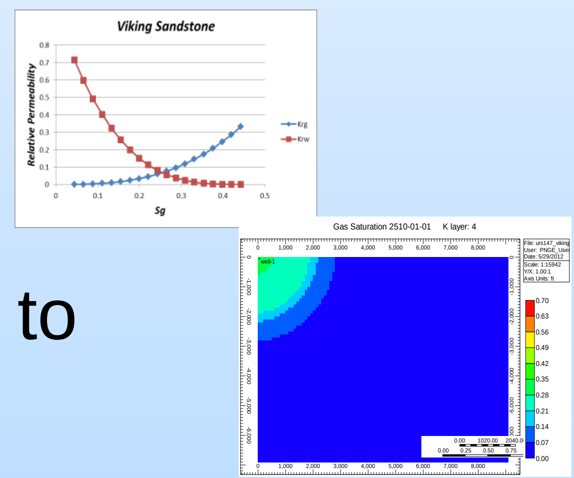
Combining measurements with CT images will provide significant enhancement to understanding of these fundamental phenomena

Task 2.5.1 - Measurement of pore geometries and residual saturation/relative permeability in cores

Task 2.5.3 – Future Plans

- Started in June
- Reservoir simulation model will be generated in CMG (by 10/12)
  - Modify solubility in brine
  - Use variety of relative permeability relationships
- Simulations will be performed for sensitivity analysis (FY13)
- Results will be compared for sweep efficiency (FY13)
- Longer simulations will be performed to study trapping mechanisms (FY14)





Task 2.5.3 - Reservoir scale impacts of relative permeabilities and residual saturations on injectivity and capillary trapping.

Task 2.5.4 – Future Plans

- Started March 1
- Begun work to develop framework for predicting non-continuous flow outside of reservoir
  - Literature survey, focused on oil and gas field experience
- Assessment of bubble flow rates (summer)
- Incorporate background aquifer flow (thru Q1 FY13)

Task 2.5.5 – Future Plans

- Refocus work on clays in caprock and volume changes that could effect seal integrity
  - Develop estimates of volumes of clays in caprock layers
  - Assess the stable states of clays in the presence of CO_2 and identify corresponding volume changes
  - Determine if volume changes will have an impact on seal integrity

Accomplishments to Date

- ✓ **Milestone Q1: CT imaged flood of CO_2 into brine-saturated permeable rock core from potential sequestration field site.**
- ✓ **Milestone Q2: Completed simulations of CO_2 injection into brine-filled sample based on actual pore geometry.**
- ✓ **Milestone Q3: Complete modeling of CO_2 intercalation in smectite clay minerals in presence of brine to elucidate the trapping mechanism and the chemical environment favorable for permanent retention of carbon dioxide in the interlayer space.**
- Milestone Q4: Completed reservoir model of synthetic site.
- Milestone Q4: Calculation of percentage of CO_2 that reaches the surface through a permeable wellbore as a function of bottomhole pressure.

Published Accomplishments

- Peer Reviewed Publications
  - Cygan, R.T., Romanov, V.N., and Myshakin , E.M. **Molecular Simulation of Carbon Dioxide Capture by Montmorillonite Using an Accurate and Flexible Force Field,** Journal of Physical Chemistry C 2012, 116 (24), pp 13079–13091
  - Zhang, G., Al-Saidi, W. A., Myshakin, E. M., and Jordan, K. D., **Dispersion-Corrected DFT and Classical Force Field Calculations of Water Loading on a Pyrophyllite(001) Surface**, Journal of Physical Chemistry C, 2012, 116 (32), pp 17134–17141

- Conference Presentations
  - Bromhal, G. et al. (May 2012) **CAS-NETL-PNNL collaboration to evaluate CO_2 storage potential in the Ordos basin.** *11th Annual Conference on Carbon Capture Utilization & Sequestration.* Pittsburgh PA.
  - Dahowski, R.T., et al (May 2012) **CAS-NETL-PNNL U.S.-China Clean Energy Partnership: Progress and Early Results from CCUS Tasks.** *11th Annual Conference on Carbon Capture Utilization & Sequestration.* Pittsburgh PA.

- Conference Poster
  - Crandall, D., Warzinski, R.P. and O'Connor, W.K. (May 2012) **Examining How CO_2 Displaces Brine at the Pore Level** International Society of Porous Media 2012 Annual Meeting, West Lafayette IN.

Summary

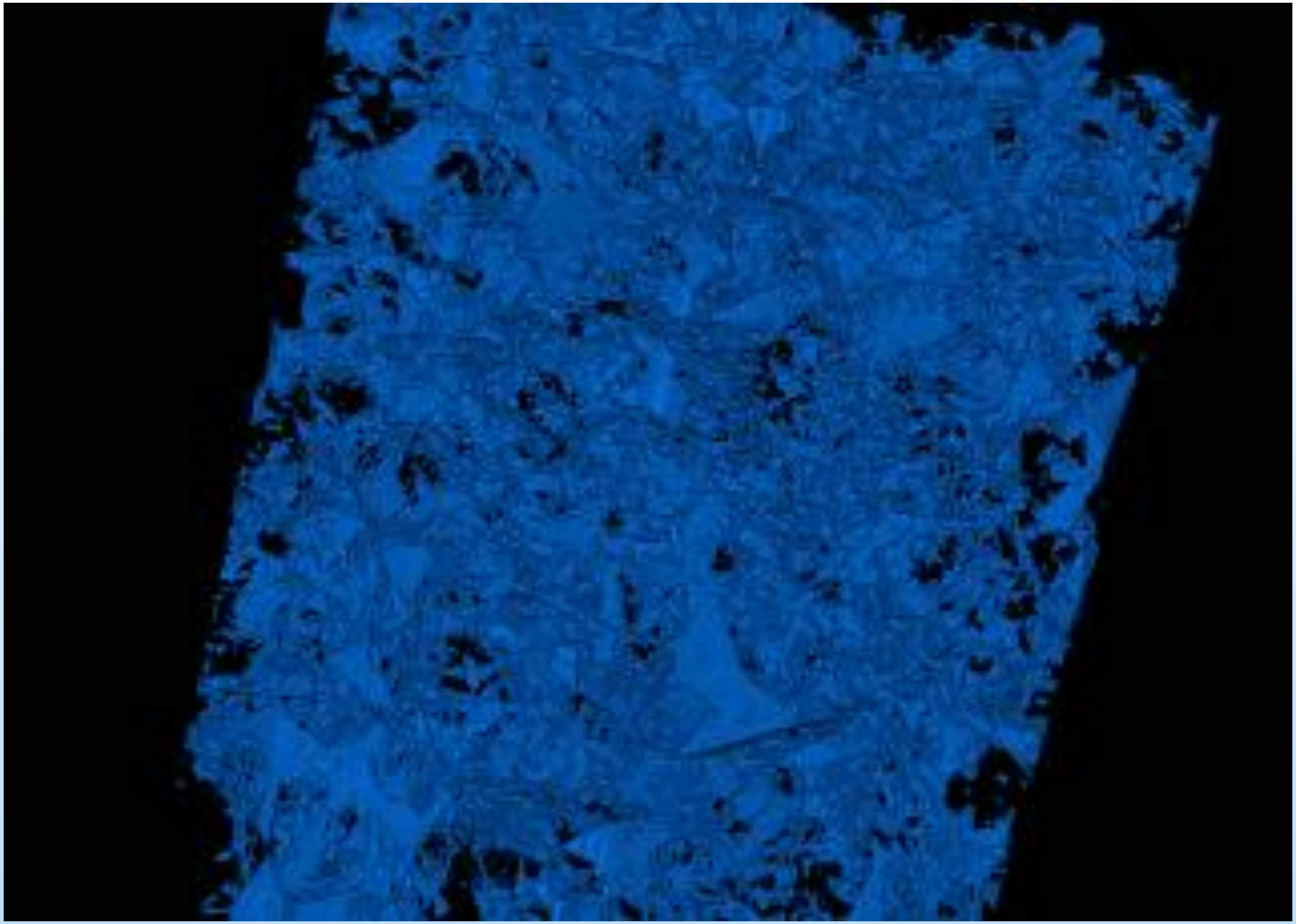
– Key Findings

- We are able to view experimental multiphase flows on multiple scales to isolate pertinent relationships
- Simulations at the small-scale are in good agreement with the experiments to date
- Shale swelling is likely to have little effect on reservoir behavior for reservoirs with small volumes of clay, but it may have an effect on seals

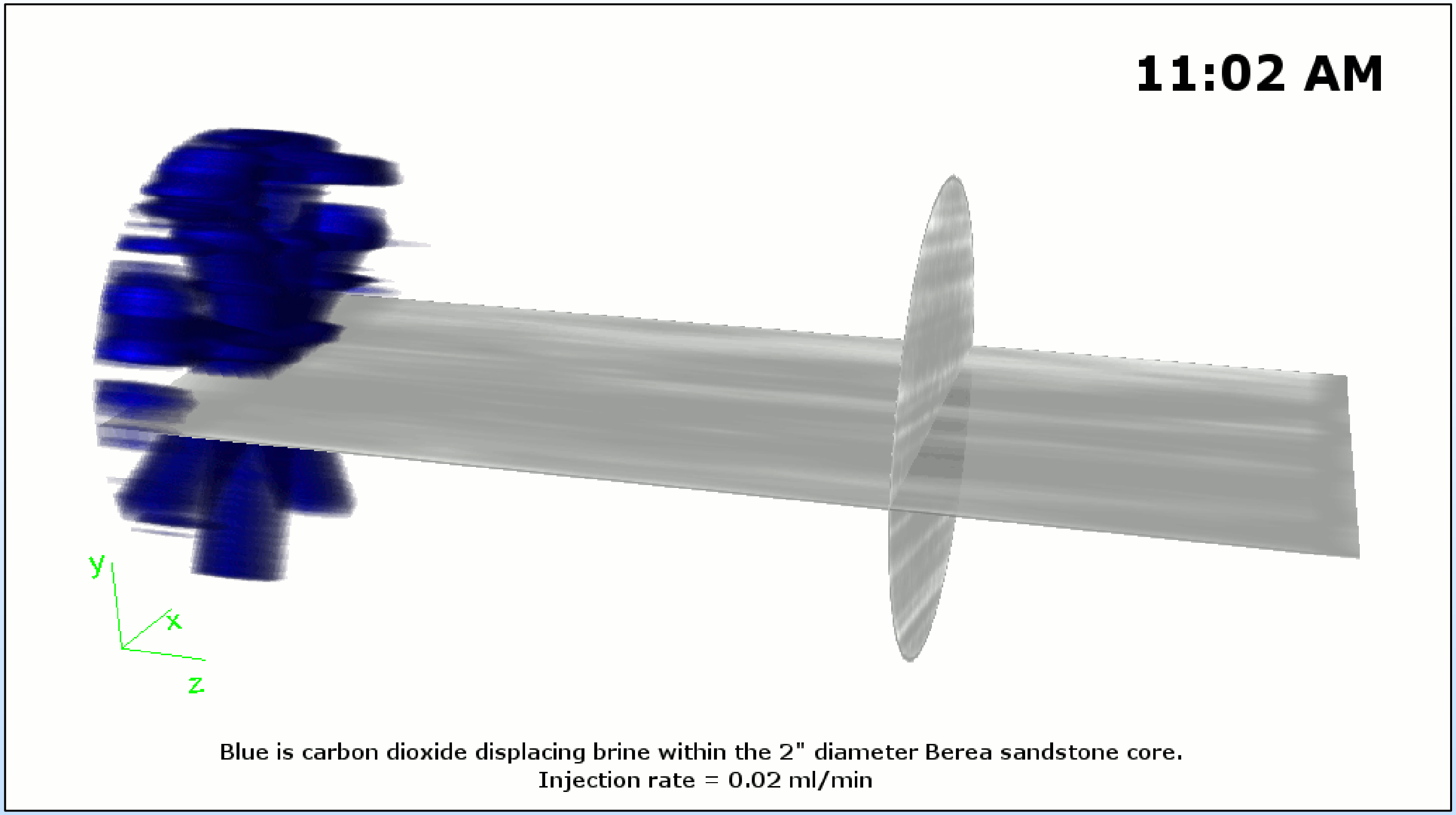
– Lessons Learned

- Involving simulation in experimental planning and vice-versa at the earliest possible times improves efficiency and effectiveness

Thank you



Visualization of Liquid CO_2 Flow



CO_2 displacing brine within sandstone

These tests performed in April as part of our Pitt/RUA collaboration