SHALES AS SEALS AND UNCONVENTIONAL STORAGE RESERVOIRS

Project Number 1022403

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Benefit to the Program

• Carbon Storage Program Goals Addressed:
  – Support industry’s ability to predict CO$_2$ storage capacity in *(unconventional)* geologic formations to within ± 30 percent
  – Ensuring 99 percent storage permanence.

• Project Benefits:
  – Improve understanding of injection/storage performance of unconventional formations
  – Inform efficiency estimation for resource assessment
  – Insights feeding to seal characterization in integrated assessment of risk
Presentation Outline

• Project Overview
  – Introduction to research area
  – Project Description
• Progress to Date on Key Technical Issues
• Plans for Remaining Technical Issues
• Tie in with other work
• Project wrap-up
Project Overview:
Goals and Objectives

• Project Objectives
  – Evaluate matrix response to CO$_2$ exposure (sorption, swelling/shrinkage, geochemical interactions)
  – Characterize effective permeability and porosity of shale to CO$_2$
  – Experimental and simulation-based performance of CO$_2$ storage in/transport through shale with natural and engineered fractures
  – Reduced order characterization to improve resource estimation and quantitative risk assessment of geologic CO$_2$ storage
Technical Scope

Shales as Seals

Shales as Storage Reservoirs

Considering shale matrix and fracture dynamics

Building on previous related work evaluating potential for CO$_2$ storage and enhanced recovery in depleted shale gas formations.
Representing Fracture Networks

- Discrete Transverse Fracture Planes
- Crushed Zone Representation
- Semi-stochastic fracture Network

Discrete Fracture Modeling coupled with conventional reservoir simulation

Modified dual porosity, multiphase, compositional, multidimensional flow model

Semi-stochastic fracture network and flow modeling
Multiple influences contribute to shale response to CO₂ exposure.
Single and MultiPhase Flow from Micro to Reservoir Scale

MICRO-SCALE DATA COLLECTION (CT, SEM, ETC)

Flow in fractures and pore space

100 μm

RESERVOIR-SCALE MODELING

DATA CONVERSION AND COMPUTATIONAL FLUID DYNAMICS

Relative Permeability in a Fracture

Shale Density from CT Scan vs Well Log

Shales as Seals and Unconventional Reservoirs

• **Subtask 3.1 Understanding Permeability, Residual Saturation, and Porosity in Shale to Reduce Uncertainty in Long-Term CO$_2$ Storage and Efficiency**
  – Understanding permeability, porosity in unfractured shale matrix
  – Characterize the influence of shale swelling in response to CO$_2$ uptake on fracture conductivity in shales
  – Simulation of fractured shale formation response to CO$_2$ uptake

• **Subtask 3.2 Improve Characterization of Physical Changes in Shale with Exposure to CO$_2$**
  – Sorption and Characterizing Mechanisms of CO$_2$-Shale Interactions
  – Swelling and Shrinkage in Shale Matrix in Response to CO$_2$ Uptake
  – Mineralogical, Geochemical, and Pore Characteristics of Shales

• **Subtask 3.3 Field Activity to Obtain, Log, Ship, and Store Shale Core from South Dakota**
MEASURING EFFECTIVE PERMEABILITY, POROSITY, AND CAPILLARY ENTRY PRESSURE

Effective porosity and permeability of shale to CO$_2$/CH$_4$ over range of effective stress, capillary entry pressure, gas slippage, and strain measurements.


Subtask 3.1 Understanding Permeability, Residual Saturation, and Porosity in Shale to Reduce Uncertainty in Long-Term CO₂ Storage and Efficiency

- Steady-state flow measurement, research quality data
- Capable of reproducing in-situ net stress, and measuring gas flow under partial liquid saturation.
- Can also measure pore volume to gas, sorption isotherms and PV compressibility using N₂, CH₄ or CO₂
- Uses stable gas pressure as a reference for flow measurement
  - Temperature controlled
  - Stable to one part in 500,000
  - Target flow measurement is 10⁻⁶ standard cm³ per second
Shale matrix response to CO₂ exposure

Autolab 1500 – strain measurements with CO2 uptake
- Storage capacity of geologic samples
- Permeability of tight or moderately permeable samples
- Elastic constants via strain gages and linear variable differential transducers
- Sonic velocity and resistivity - unique “sonic/ resistive fingerprints” of the representative samples for remote “on-site” monitoring of subsurface fluid storage and motion.
Swelling of smectite clay

Observing bulk mechanical swelling of unconfined clays and shales (3.2)

Vac ~900psia CO$_2$ ~1500psia CO$_2$

Swelling of Texas montmorillonite (Hong et al.)
Isolating Fractures

- Fracture in shaly limestone
- Used for looking at changes in fracture topography and aperture under cyclic pressure
- Flow in fracture (DI H₂O)
- Utilize isolated fracture image to calculate apertures (bᵥ, bₑᶠᶠ & b₉)
  - Isolation via imageJ
    - Typically can use Otsu thresholding
    - In complex fractures use manual thresholding via selective histogram
Fracture Hysteresis Under Cyclic Pressure

Characterize fracture conductivity change in response to shale swelling with CO$_2$

Does CO$_2$ sorption lead to swelling in shales, reducing effective fracture aperture and fracture hydraulic conductivity?

Fractured shale response to CO$_2$ exposure

Lower Bakken shale
TOC >20 wt%

Shale core without confining pressure. Fractures still present. (Scale in millimeters.)
Permeability evolution calculations for the top portion of the fracture.

Sample courtesy of UND EERC; data generated by Moore, Crandall et al.
Modeling CO$_2$ Flow in Fractured Shale
Incorporating matrix swelling/shrinkage effects

FRACGEN stochastically generates fracture networks

NFFLOW models flow in discrete fracture networks

Images from: Sams, N. Overview of NFFLOW & FRACGEN. June 3, 2013
Dynamic permeability model to account for clay swelling during CO$_2$ invasion into shale reservoir

- based on the induced strain – effective horizontal stress relationship
- Applies a transmissivity modifier to the fracture segment transporting the CO$_2$
Subtask 3.3 South Dakota Core Acquisition and Logging

North American shale plays
(as of May 2011)

Source: U.S. Energy Information Administration based on data from various published studies. Canada and Mexico plays from ARI.
Updated: May 9, 2011
Subtask 3.3 South Dakota Core Acquisition and Logging

- MOU between DOE and South Dakota School Mines &Technology and South Dakota Geological Survey.

**Treedam core (Pierre shale)**
- Treedam core from South Dakota shipped from Rapid City, SD to Morgantown, WV (January)
- Logging using Multi-Scanner Core Logger (MSCL) complete, source rock analysis tests complete
- Preliminary tests in core-flooding unit

**Presho core**
- Completed coring in South Dakota
  - Pierre Shale section, and all of Niobrara Formation below it.
  - total of about 900 feet of core available for processing.
- Brought to NETL and scanning with MSCL
- SDGS is going to try to log the hole at Presho; MSCL data on the core will provide tie point back to the rock (or, If the field logging attempt fails, the MSCL scan will be the only petrophysical data)
- Thin section billets, source rock analysis chips, and a dozen or so core plugs will be available

Dr. Foster Sawyer of SDSM&T pointing to the Pierre-Niobrara contact at an outcrop location along the Missouri River south of I-90.
Relationship to Other NETL ORD Research

- CO₂ Storage Task 4: National-Scale Resource Estimation Methodology Development
- National Risk Assessment Partnership – NSealR fractured seal model
- NETL discrete fracture flow simulator – NFFLOW – shale storage and seal performance
Tie in: Storage Resource Assessment Methodology for Unconventional Formations

Prospective Storage Resource for CO$_2$ storage in shale at the national scale at the Exploration Phase.

- Develop National Scale Prospective Method
- Builds upon existing Volumetric Approach
- Based on highly-limited data availability

- Produce a universally-applicable method capable of being applied to all U.S. shale basins — even pre-production formations lacking detailed geophysical data — to provide prospective CO$_2$ resource at a national level.

DOE CO$_2$ Storage Classification

- Prospective Resources: Prospect, Lead, Play
- Prospective Storage Resources: Qualified Site(s), Selected Areas, Potential Sub-Regions
Tie in: NRAP Seal Leakage Characterization
Tool for estimating leakage through fractured seal (NSealIR)

- Estimate flux through a fractured or perforated seal
- Account for storage outside of primary target zone

- Uses inputs of pressure and saturation at the reservoir/seal interface
- Computes two-phase (brine and supercritical CO₂) flux and includes fluid thermal/pressure dependence
- Module to compute leakage through a Barrier (Seal) Layer
- Various levels of complexity to model barrier response
- Accounts for effective stress dependence of aperture
Accomplishments to Date

- Established workflow and demonstrated capability to measure change in fracture aperture and permeability in response to stress cycling and matrix volumetric change.
- Commissioned a high resolution steady state permeameter to collect research-quality permeability measurements in shale matrix.
- Initiated development of matrix shrinkage/swelling and fracture aperture dynamics model in NFFLOW/FRACGEN.
Synergy Opportunities

– Continued collaboration with South Dakota School Mines & Technology and South Dakota Geological Survey, RCSPs, industry collaborators

– Suggest interlab comparison as a means of cross-validation and method refinement
**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- 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
Thanks for listening!

Shaly limestone Marcellus sample (F2HB) from Facies 2, with several dense bivalve fossils in its interior.

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