SHALES AS SEALS AND UNCONVENTIONAL STORAGE RESERVOIRS

Project Number 1022403

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Office of R&D, Predictive Geosciences Division
U.S. DOE, 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

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

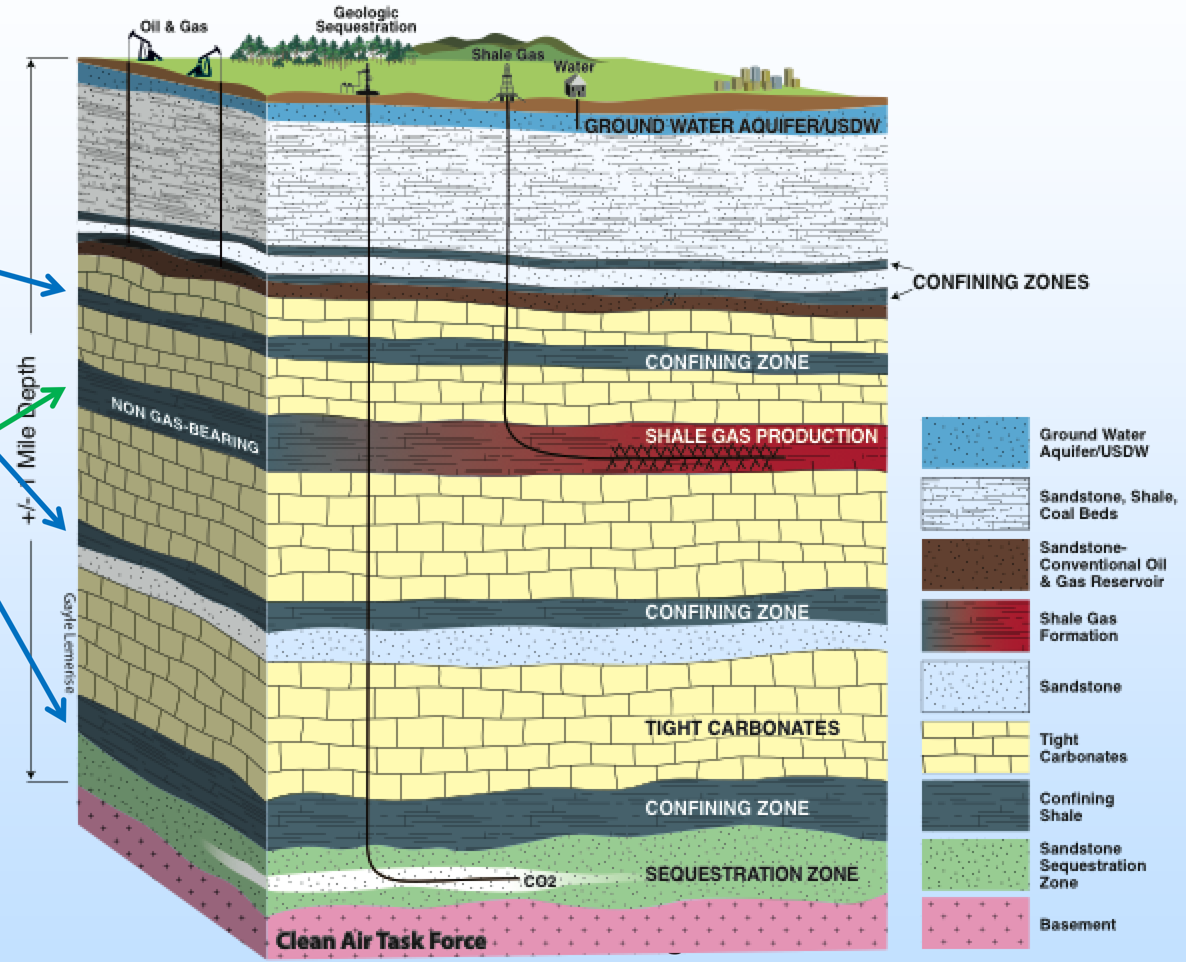
Project Overview:
Goals and Objectives

- 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

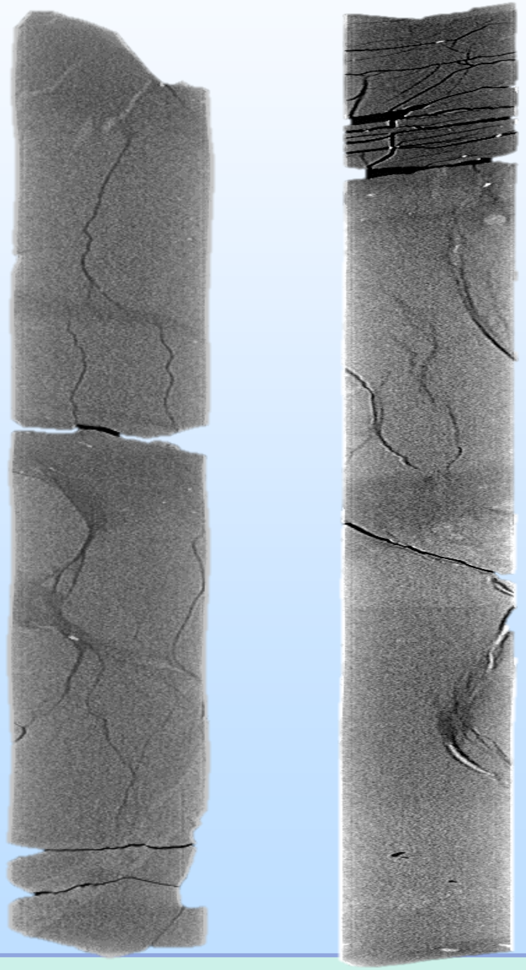
Shales as Seals

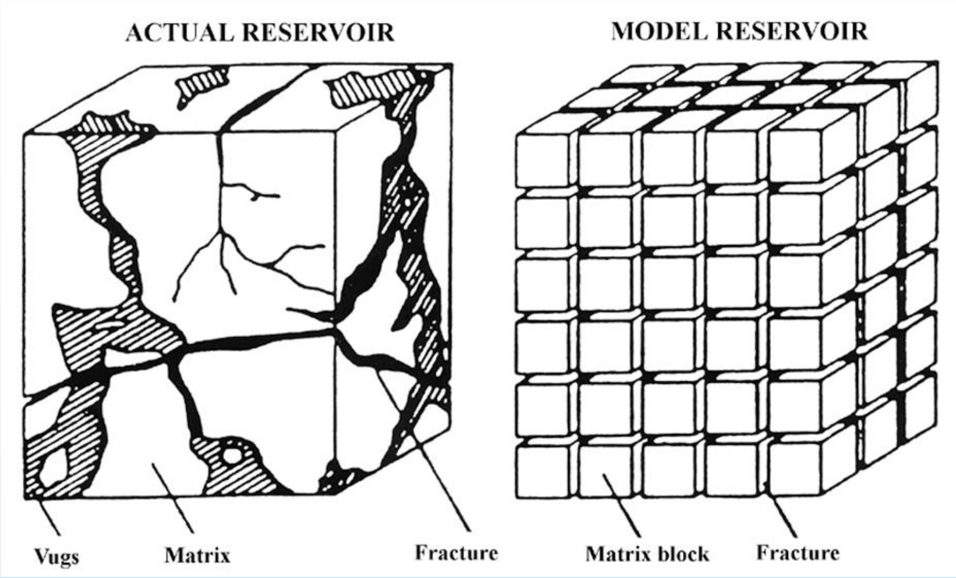
Shales as Storage Reservoirs



*Sources: **HF illustration from National Energy Technology Laboratory (NETL), 2011),** Micro CT images by Rebecca Rodriguez, ORISE; Shale image from Reference: Lacazette , A. and Engelder, T. (1992) Fluid-driven cyclic propagation of a joint in the Ithaca Siltstone, Appalachian Basin, New York: p. 297 - 323 in B. Evans and T.-F. Wong (editors): Fault Mechanics and Transport Properties of Rocks; a festschrift in honor of W. F. Brace: Academic Press, San Diego.; NETL Carbon Storage Atlas IV (2012)*

Considering shale matrix and fracture dynamcis





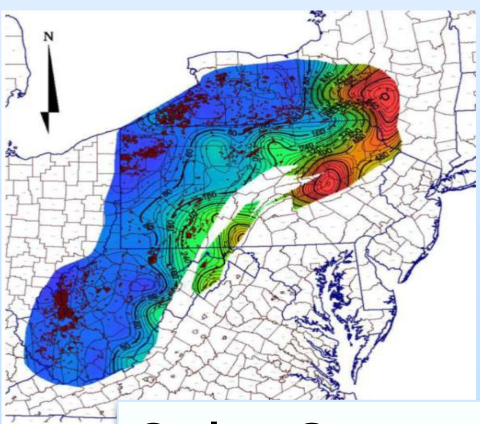
SOURCE: Warren, J.E. and Root, P.J.: "The Behavior of Naturally Fractured Reservoirs," *SPEJ (Sept.*1963) 245-255.

Building on previous related work

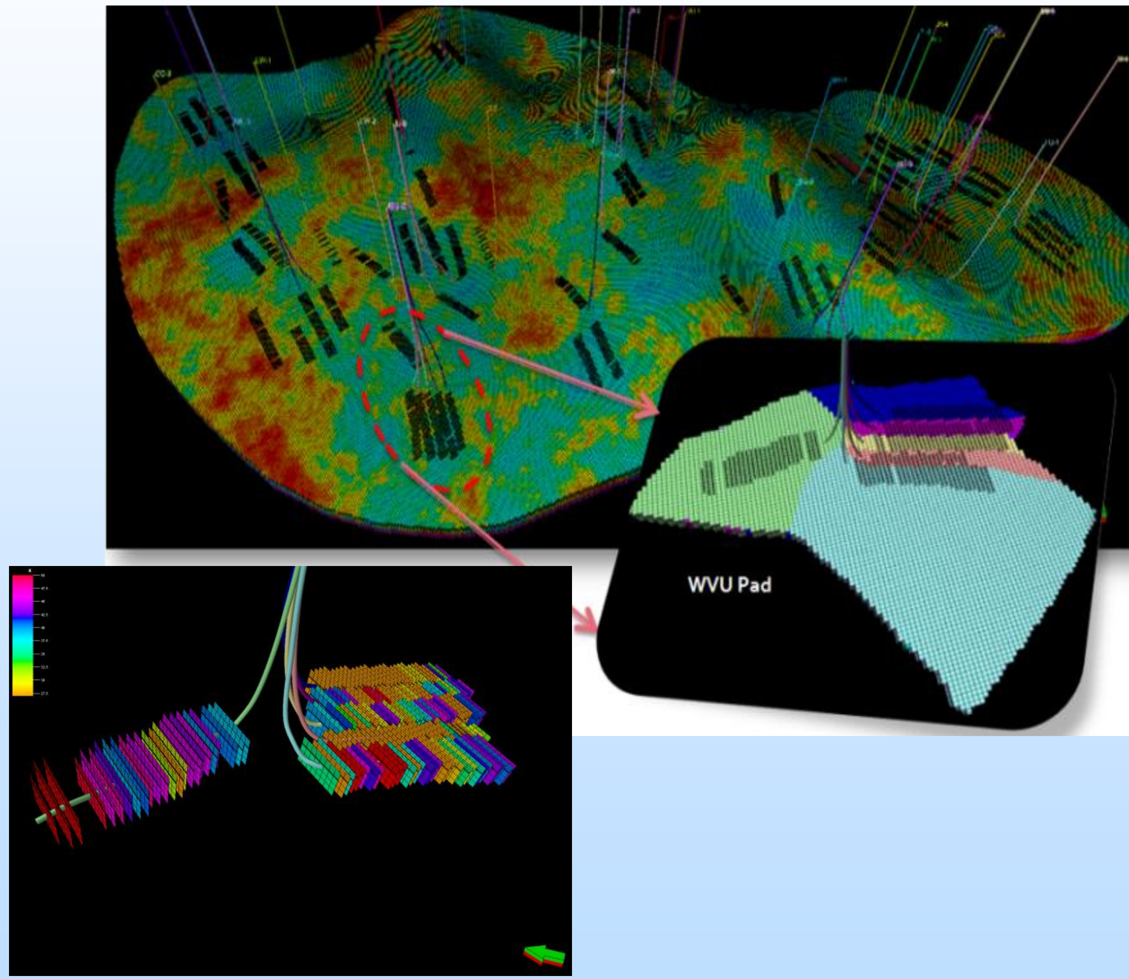
evaluating potential for CO_2 storage and enhanced recovery in depleted shale gas formations

ICMI

Industrial Carbon Management Initiative

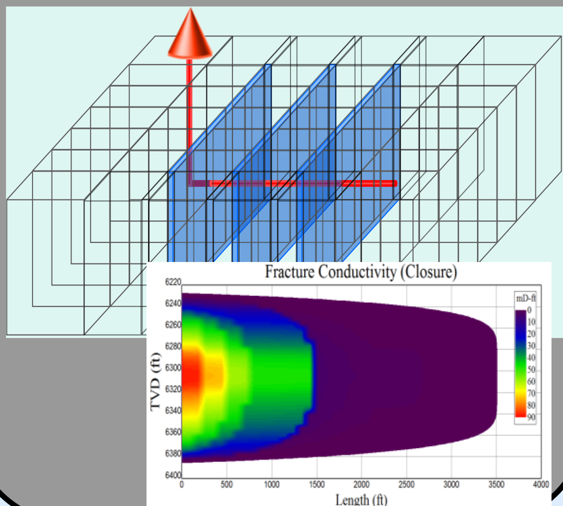


Carbon Storage
Depleted Shale Fields

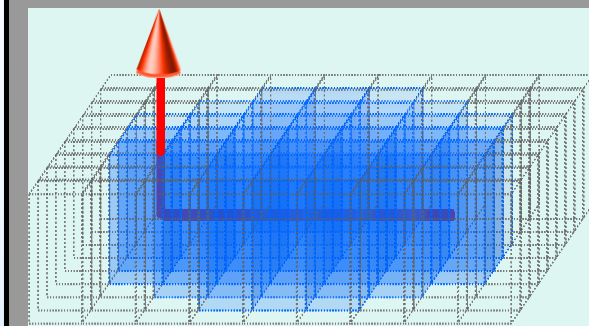


Representing Fracture Networks

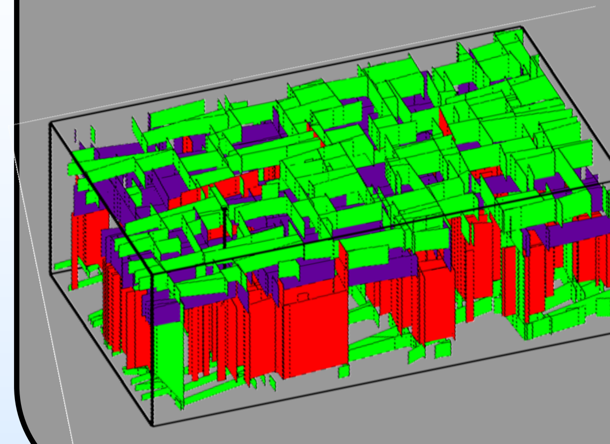
Discrete Transverse Fracture Planes



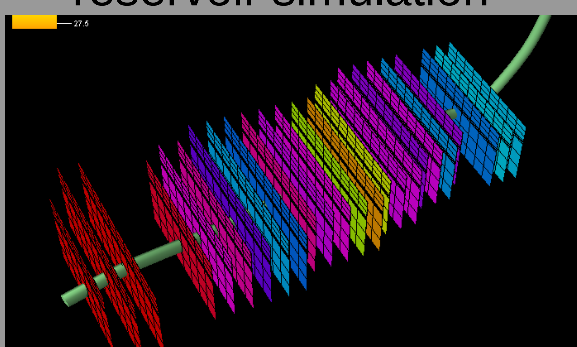
Crushed Zone Representation



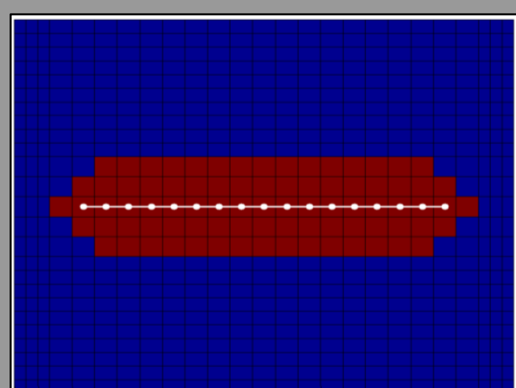
Semi-stochastic fracture Network



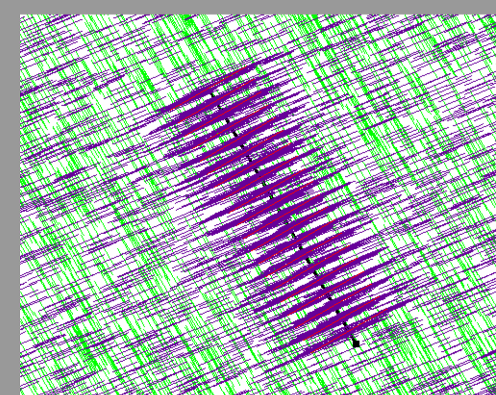
Discrete Fracture Modeling coupled with conventional reservoir simulation



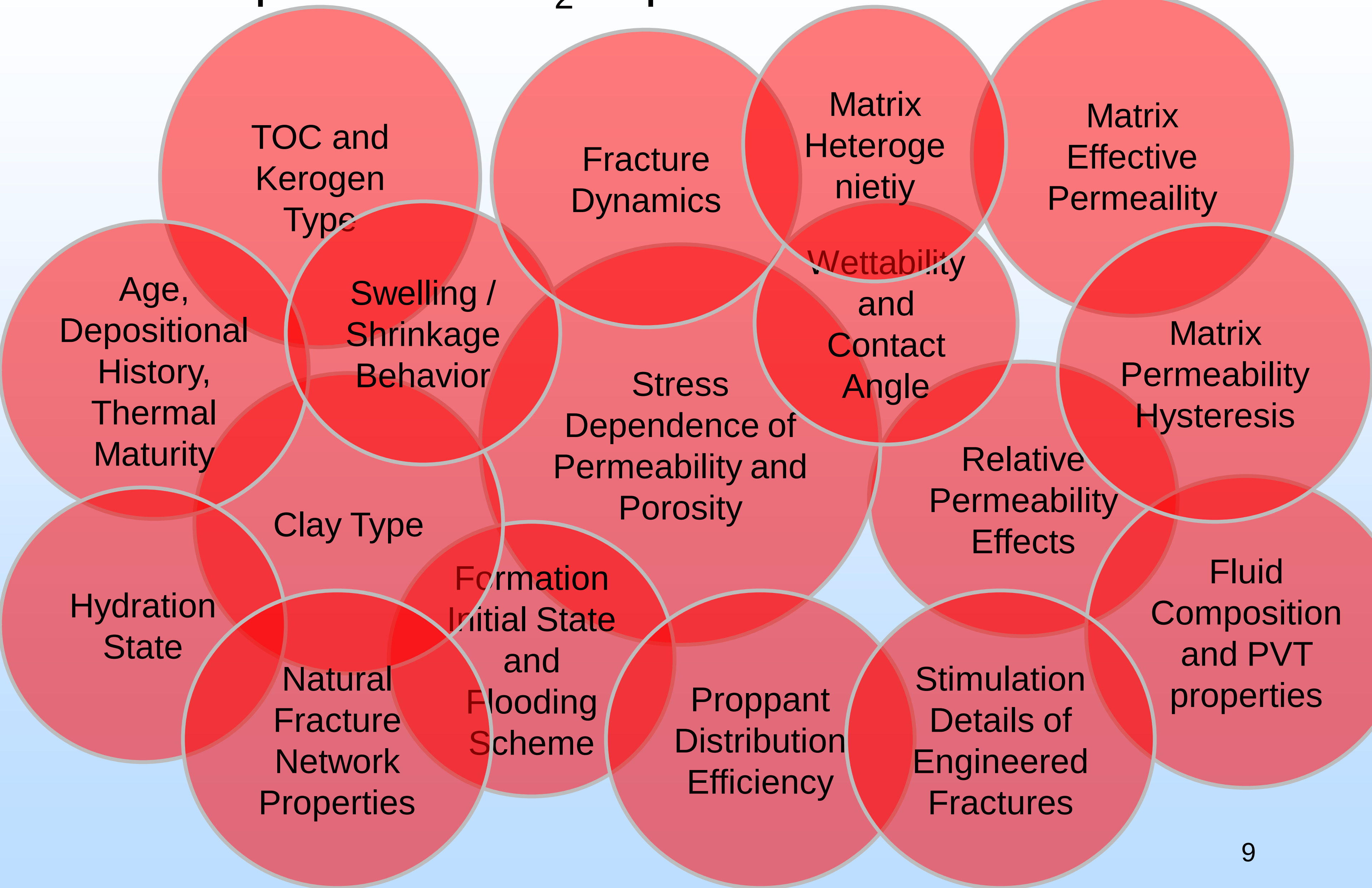
Modified dual porosity, multiphase, compositional, multidimensional flow model



Semi-stochastic fracture network and flow modeling

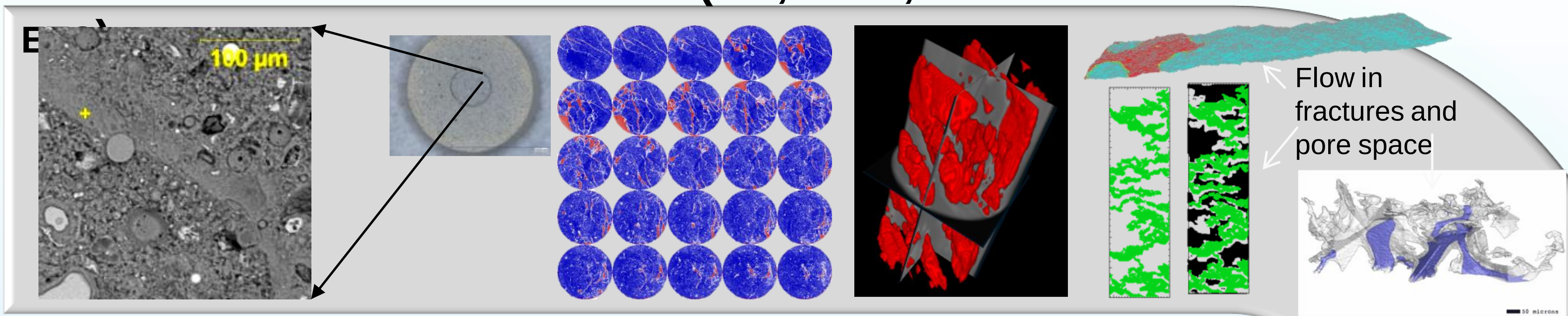


Multiple influences contribute to shale response to CO_2 exposure

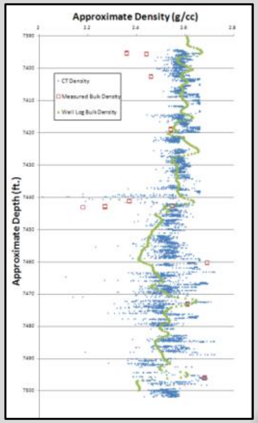


Single and MultiPhase Flow from Micro to Reservoir Scale

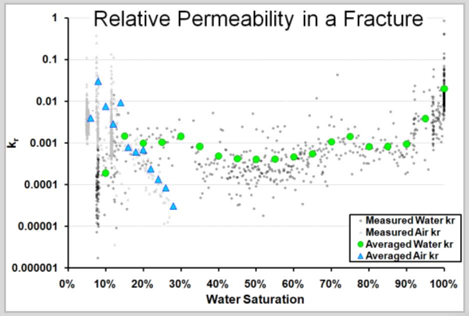
Micro-Scale Data Collection (CT, SEM, E…)



Data Conversion and Computational Fluid Dynamics

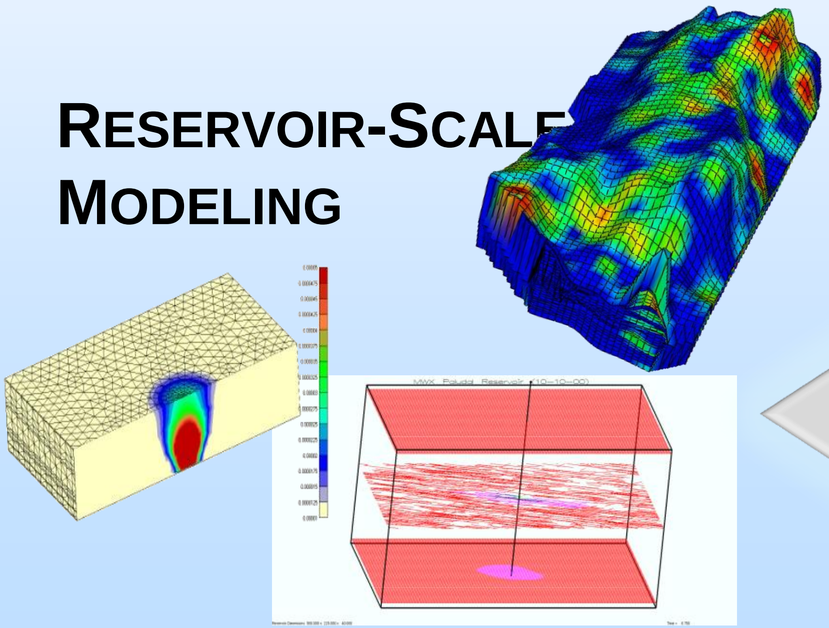


Shale Density from CT Scan vs Well Log



Multiscale Data Analysis

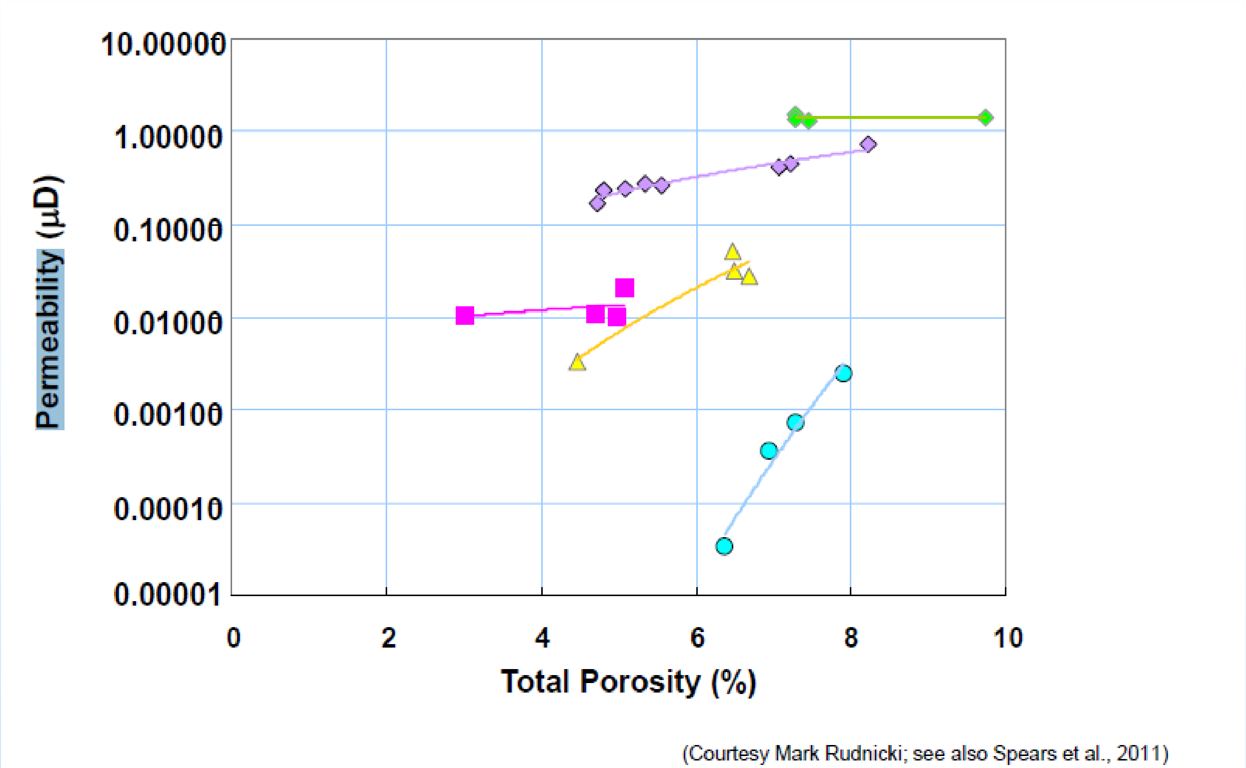
Reservoir-Scale Modeling



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

Precision Petrophysical Analysis Laboratory (RaSSCAL prototype)

Source: Q.R. Passey, K.M. Bohacs, W.L. Esch, R. Klimentidis, and S. Sinha. My Source Rock is Now My Reservoir - Geologic and Petrophysical Characterization of Shale-Gas Reservoirs. Search and Discovery Article #80231 (2012AAPG Discovery Pages

GRI Method: Walls, J.D., Nur, A.M., and Bourbie, T., 1982, Effects of pressure and partial water saturation on gas permeability in tight sands: experimental results: Journal of Petroleum Technology, v. 34, No. 4, p. 930-936 (April)

Subtask 3.1 Understanding Permeability, Residual Saturation, and Porosity in Shale to Reduce Uncertainty in Long-Term CO_2 Storage and Efficiency

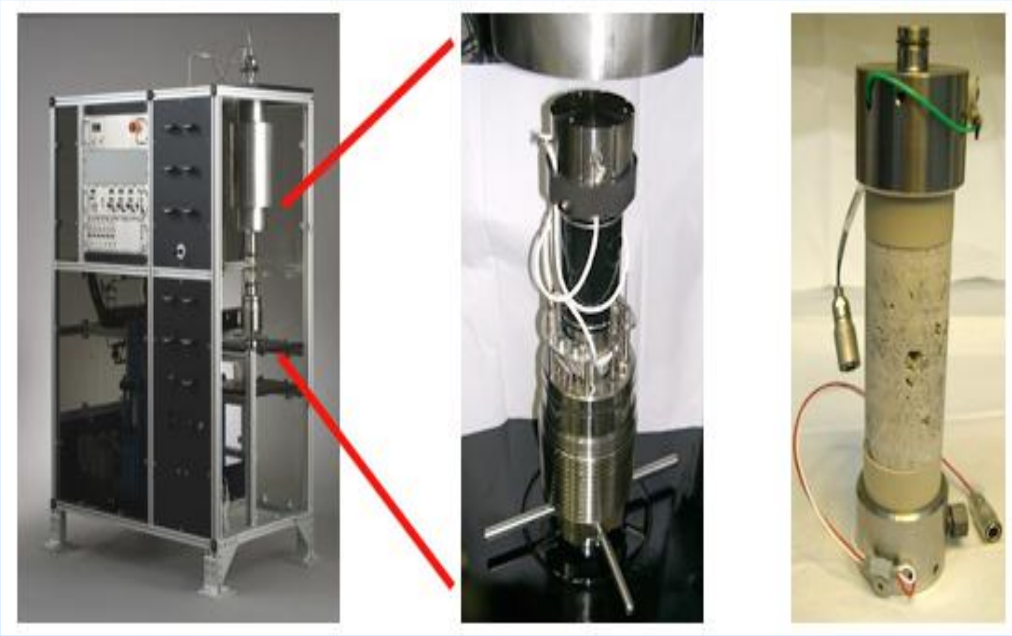
Randolph stead-state core analysis laboratory (RaSSCAL) apparatus

- 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 N_2, CH_4 or CO_2
- 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 cm^3 per second

Shale matrix response to CO_2 exposure

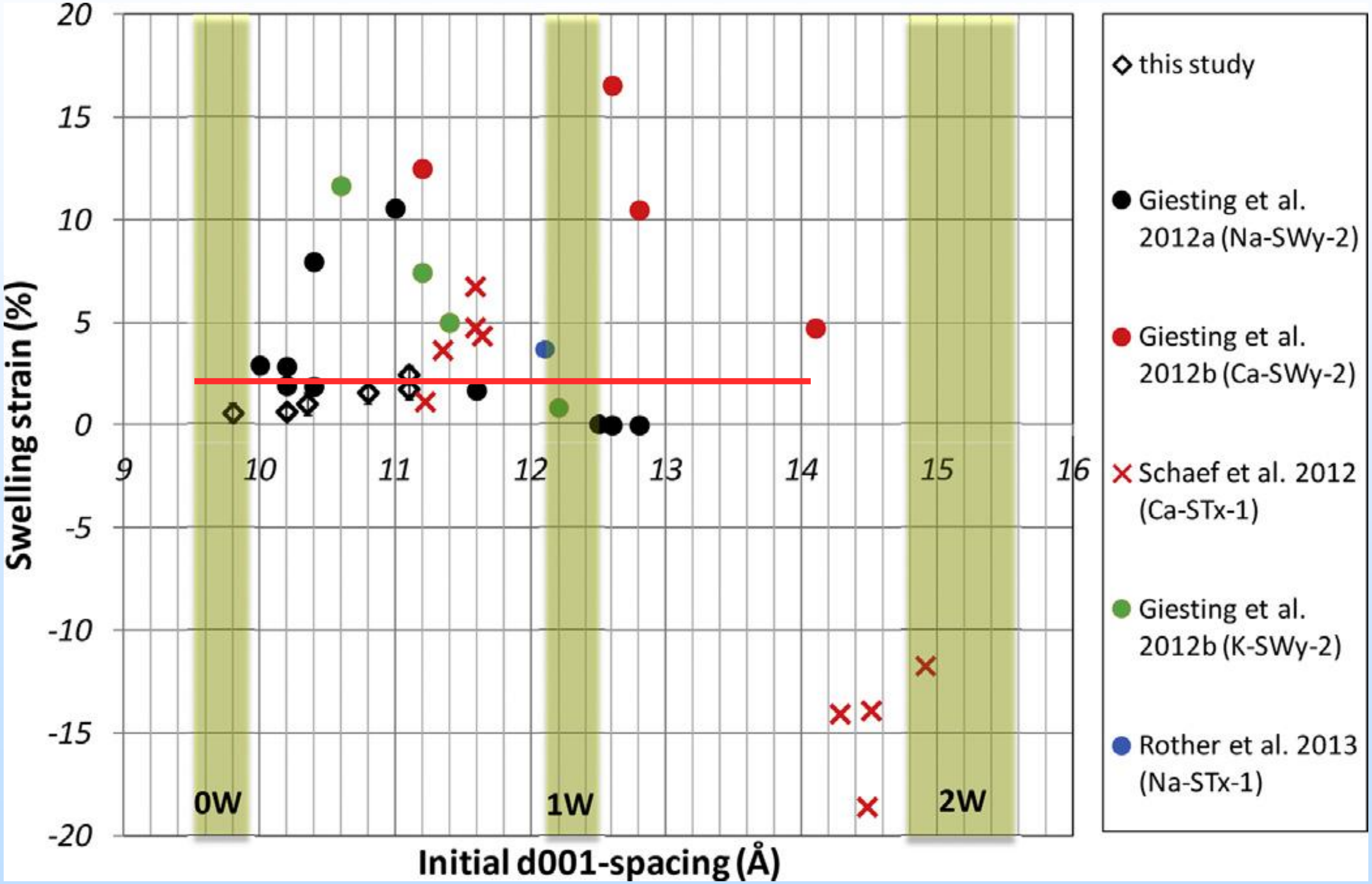
Autolab 1500 – strain measurements with CO2 uptake

- 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.



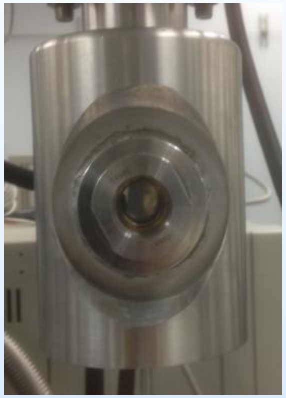
Autolab 1500 (NER, Inc.)

Swelling of smectite clay

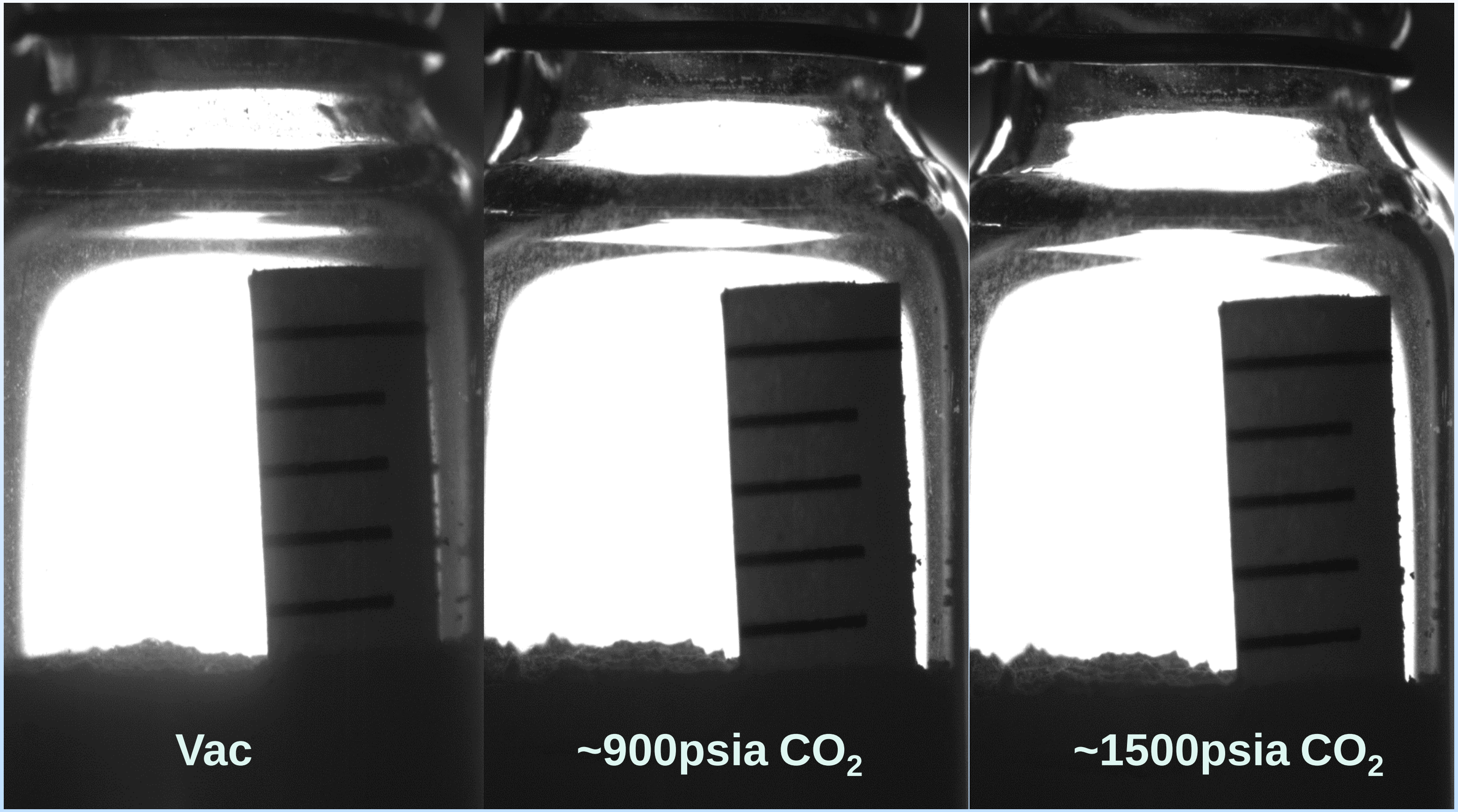


REFERENCE: de Jong, S.M., Spiers, C.J., Busch, A. Development of swelling strain in smectite clays through exposure to CO2. International Journal of Greenhouse Gas Control 24(2014) 149-161.

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



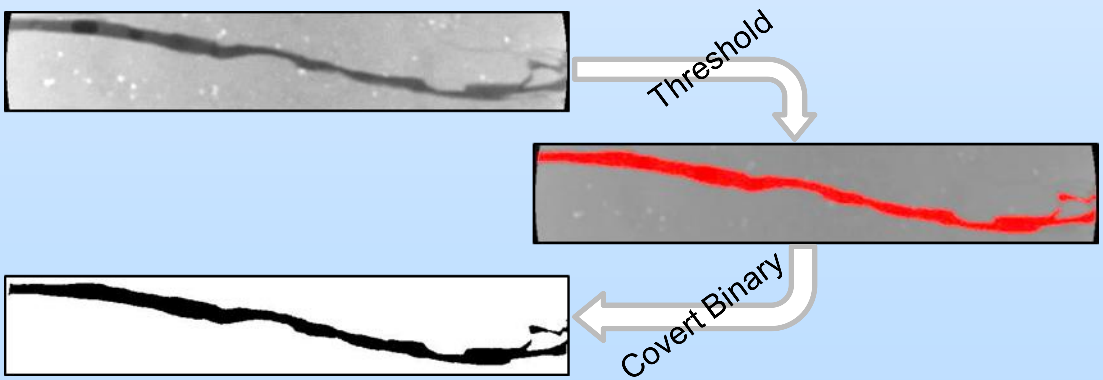
STx-1b



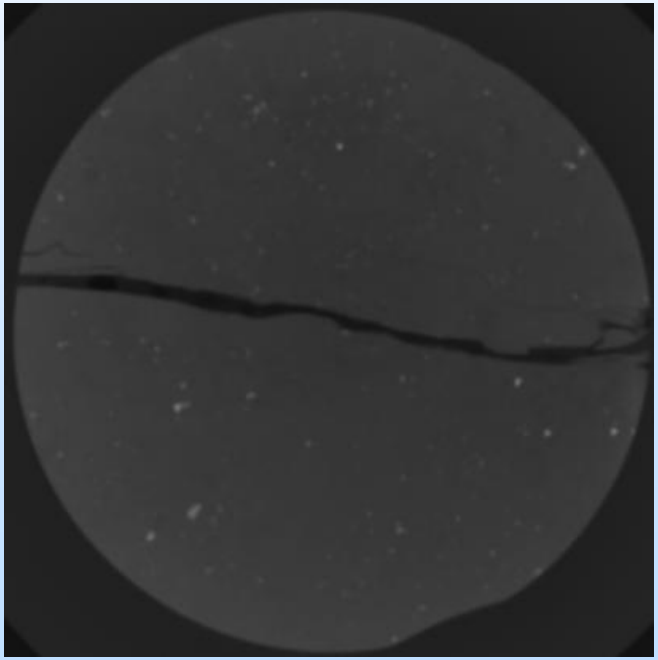
Swelling ofTexas montmorillonite **(Hong et al.)**

Isolating Fractures

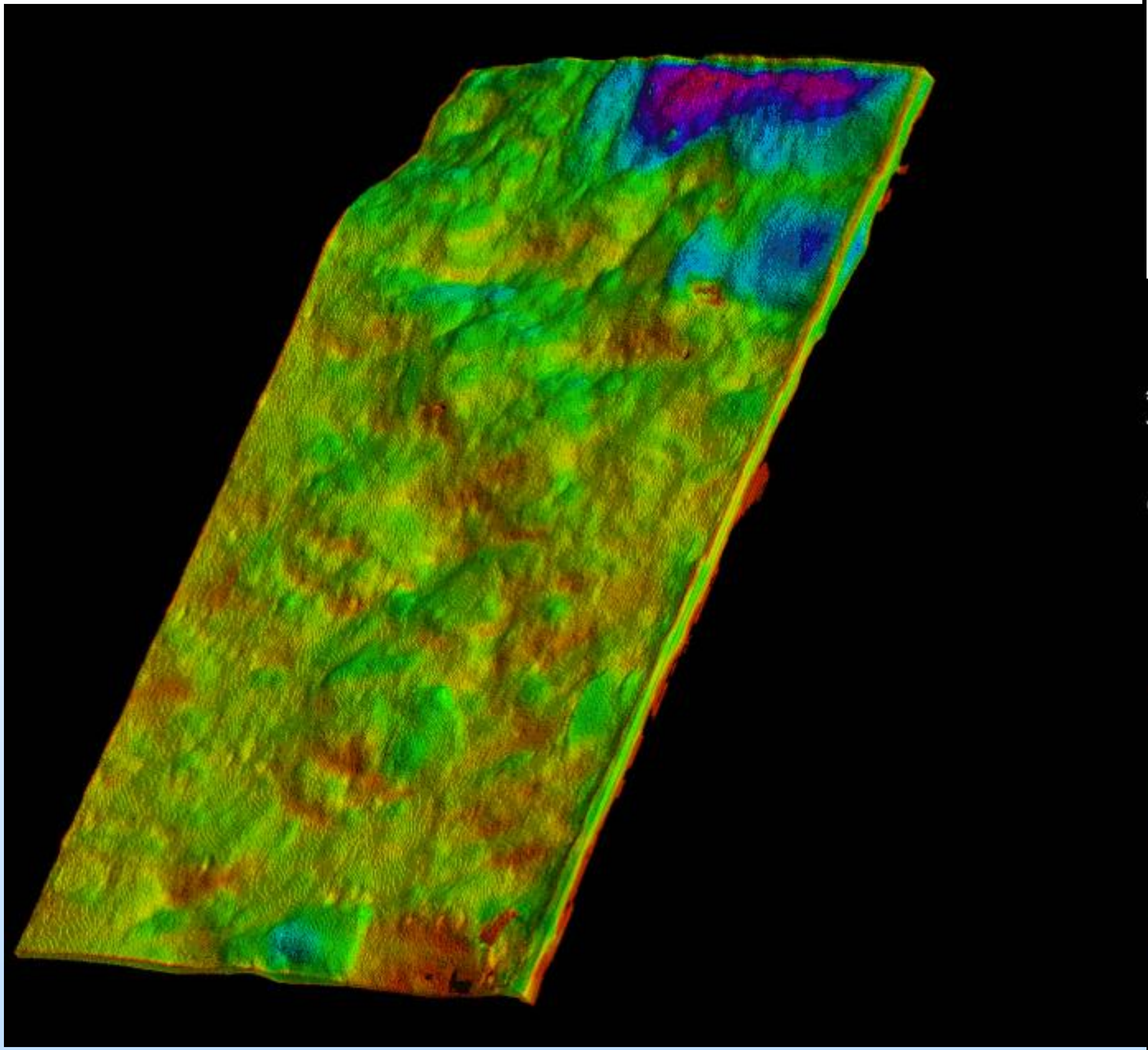
- Fracture in shaly limestone
- Used for looking at changes in fracture topography and aperture under cyclic pressure
- Flow in fracture (DI H_2O)
- Utilize isolated fracture image to calculate apertures (b_V, b_{eff} & b_H)
  - Isolation via imageJ
    - Typically can use Otsu thresholding
    - In complex fractures use manual thresholding via selective histogram

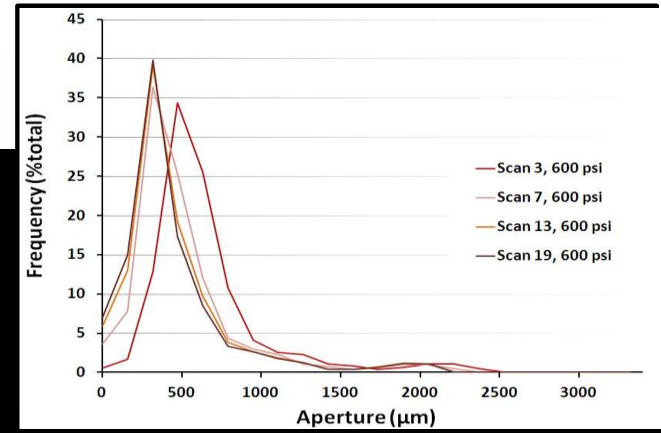


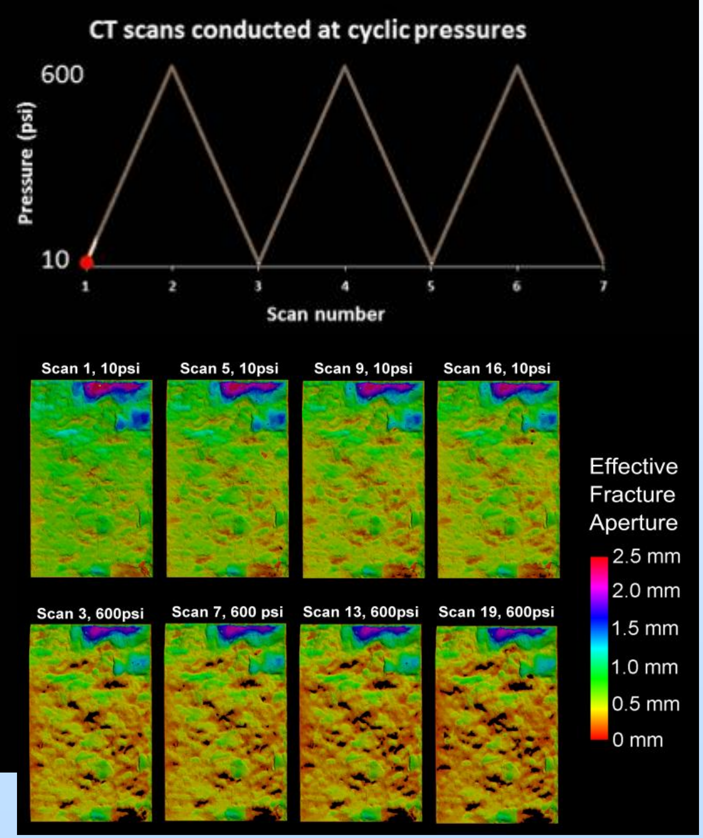
Fracture in Shaley Limestone



Fracture Hysteresis Under Cyclic Pressure



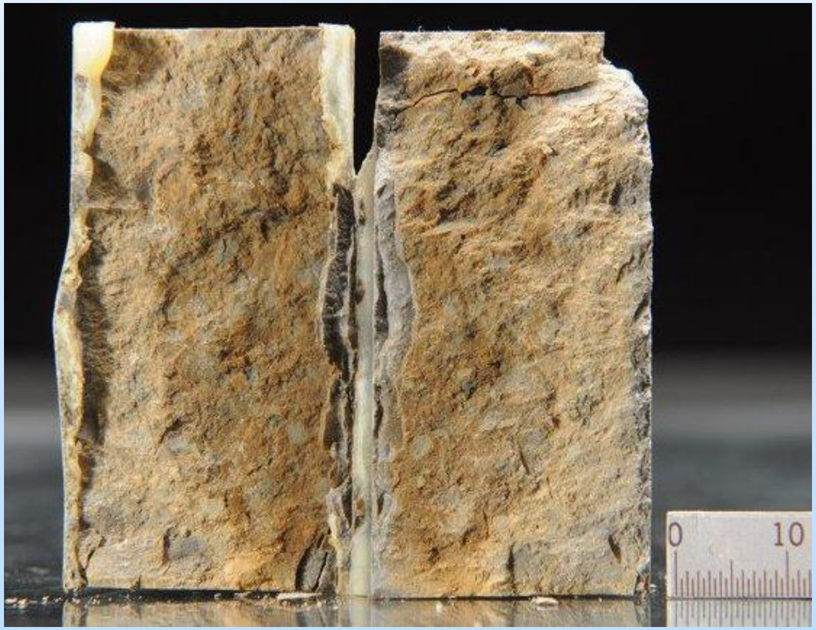


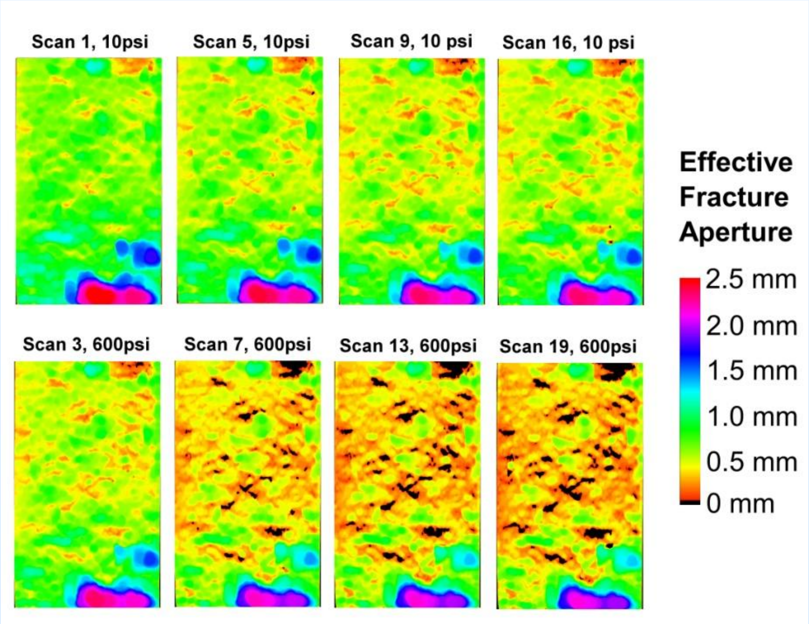


Source: Moore – Shales at All Scales – June 9th, 2015

Characterize fracture conductivity change in response to shale swelling with CO_2

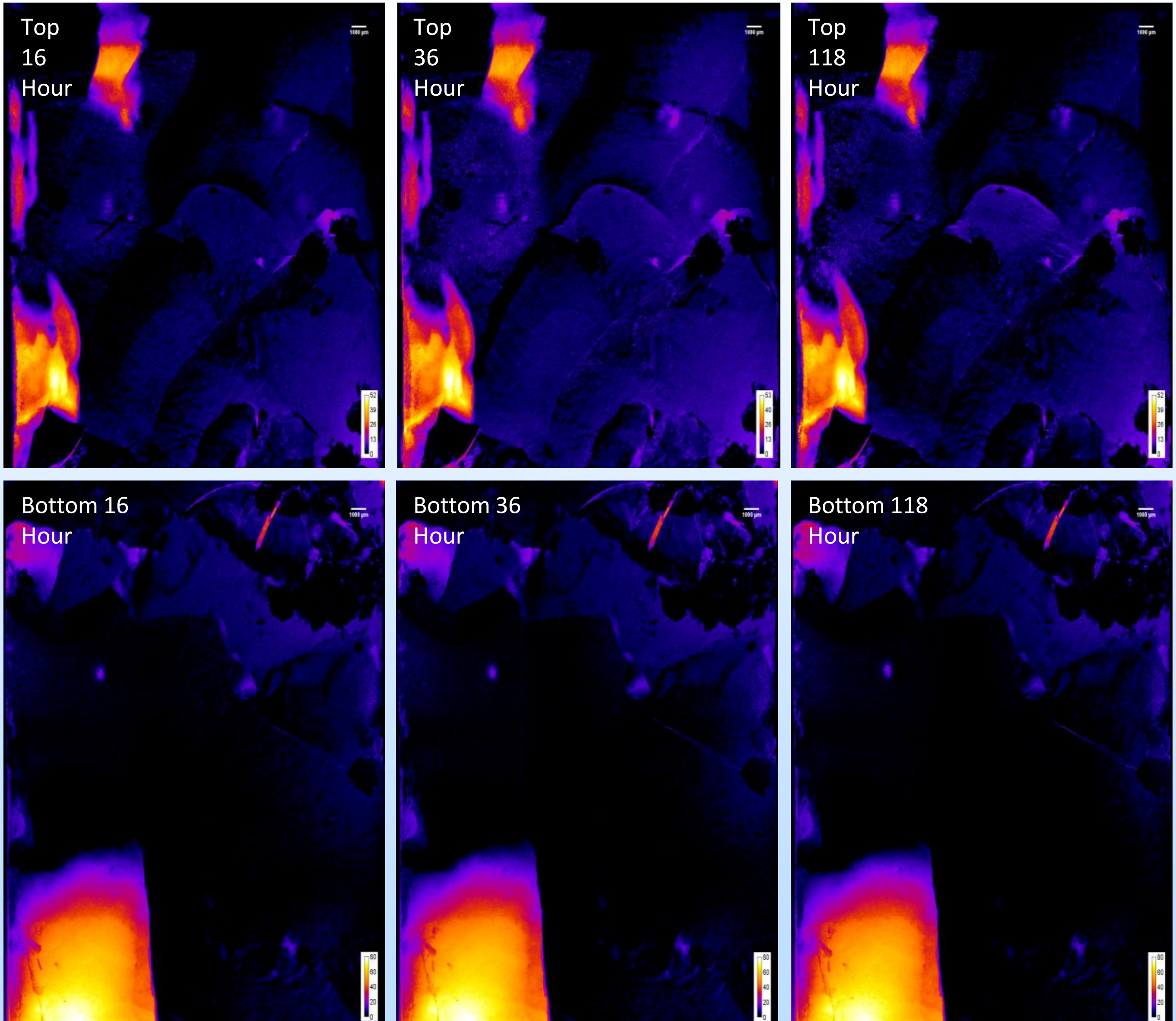
Does CO_2 sorption lead to swelling in shales, reducing effective fracture aperture and fracture hydraulic conductivity?





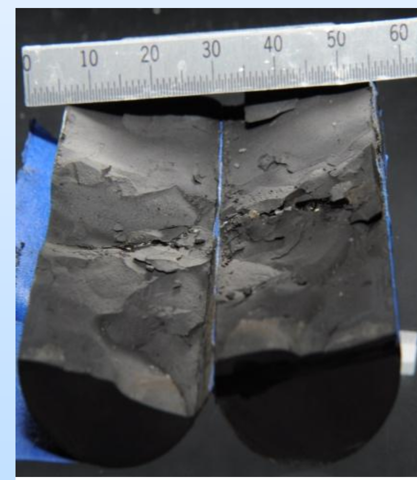
Source: *Crandall, D. Gill, M., McIntyre, D.L., and Bromhal, G.S. (2013)* ***Coupling Mechanical Changes of a Fracture to Hydraulic Changes*** *SPE 165695-MS. prepared for SPE Eastern Regional Meeting held in Pittsburgh, Pennsylvania, USA, 20–22 August 2013. © 2013, SPE*

Fractured shale response to CO_2 exposure



Lower Bakken shale

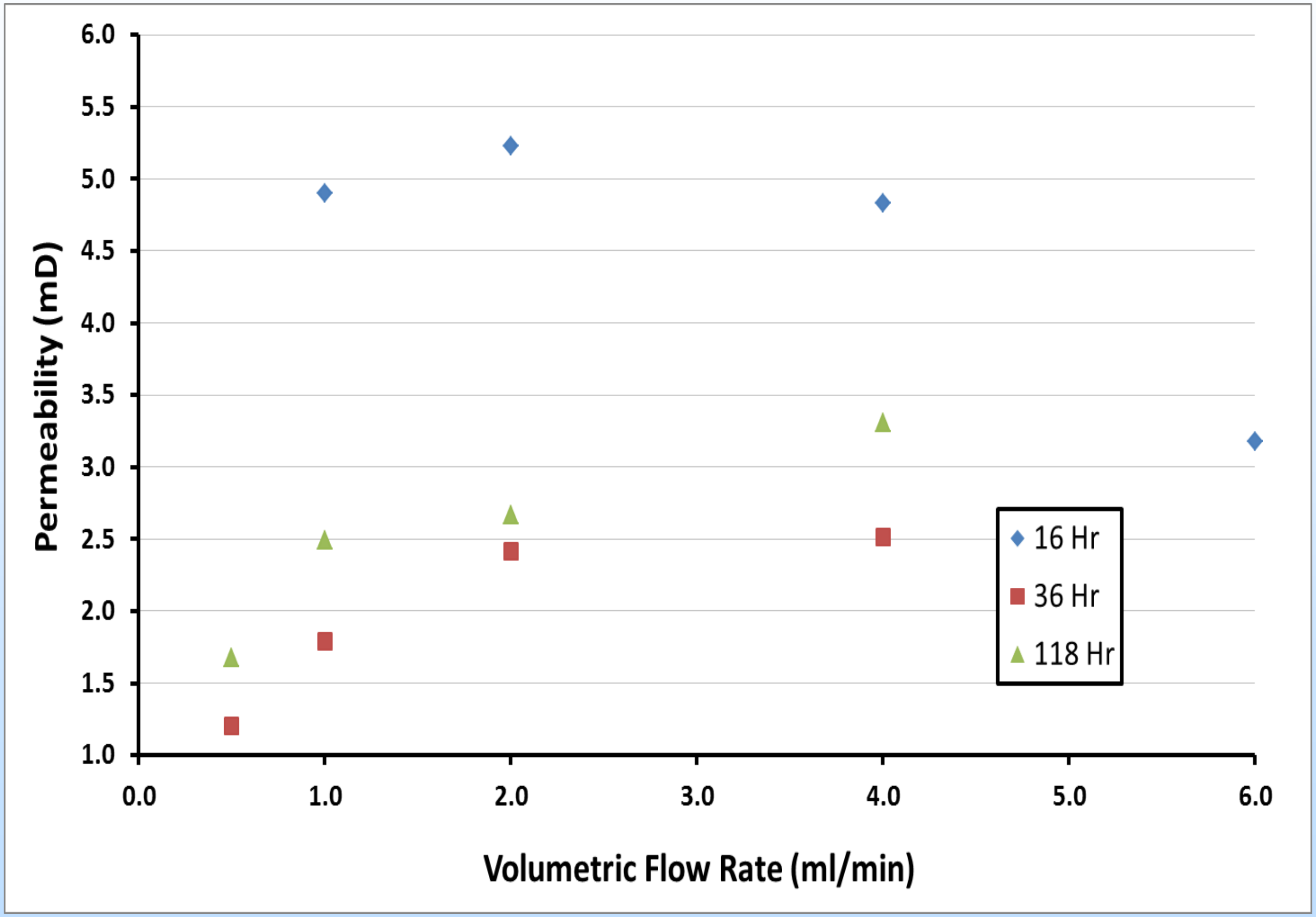
TOC >20 wt%



Shale core without confining pressure. Fractures still present. (Scale in millimeters.)

Sample courtesy of UND EERC

Permeability evolution calculations for the top portion of the fracture.

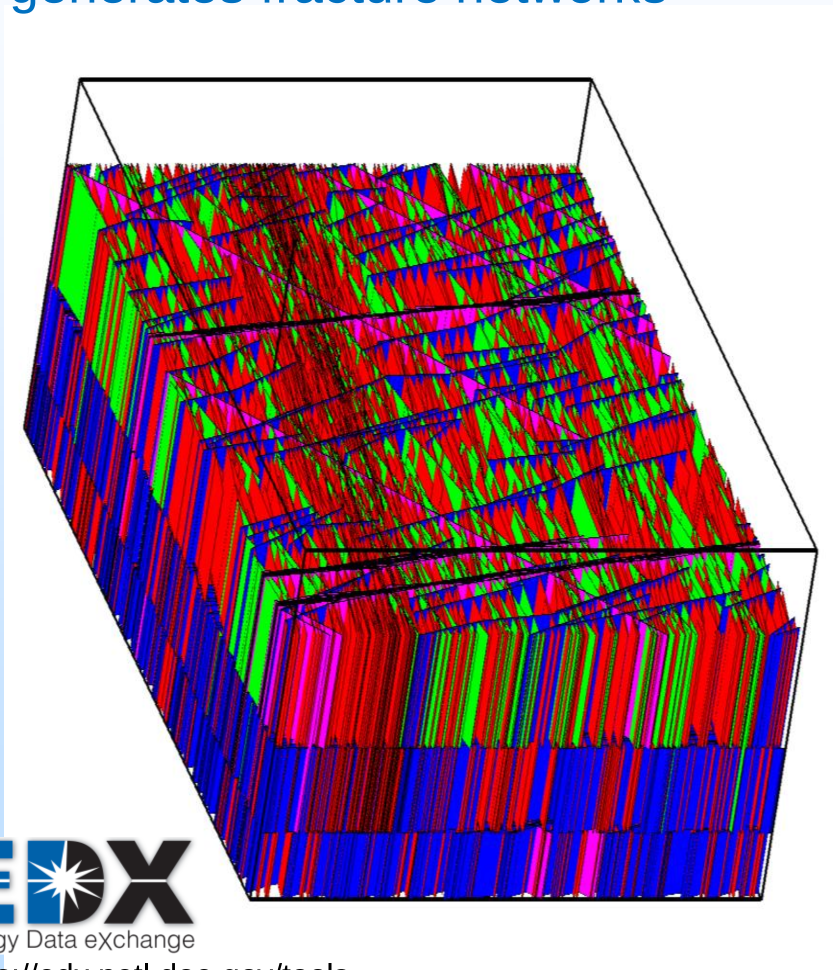


Sample courtesy of UND EERC; data generated by Moore, Crandall et al.

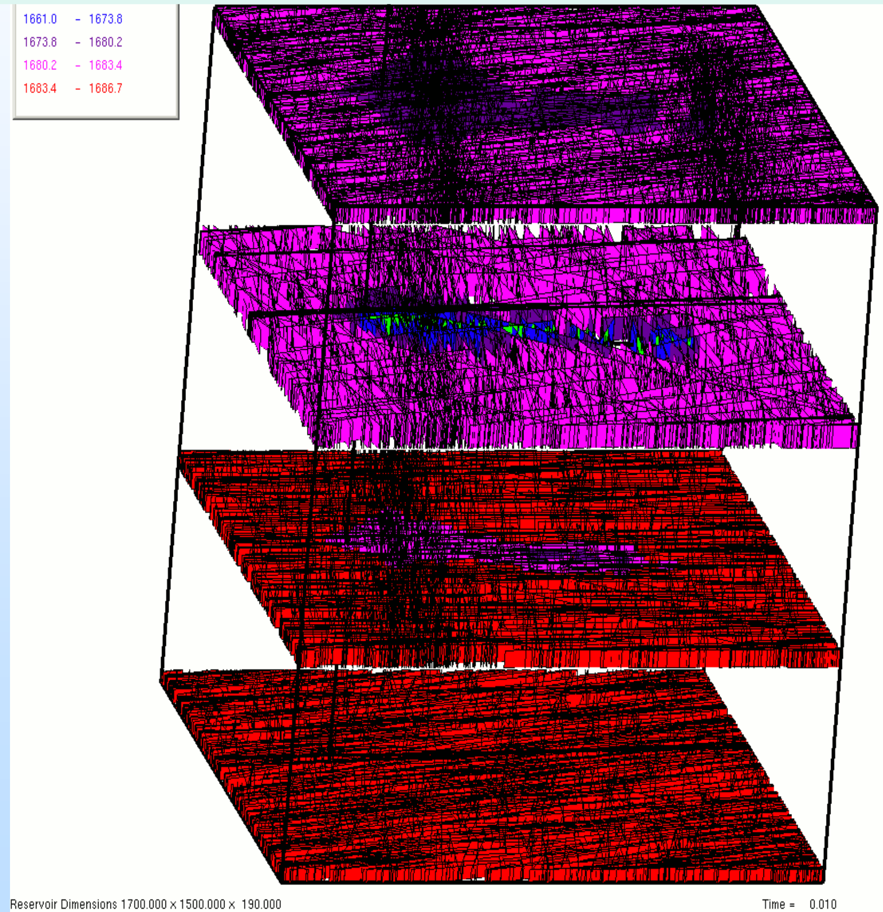
Modeling CO_2 Flow in Fractured Shale

Incorporating matrix swelling/shrinkage effects

FRACGEN stochastically generates fracture networks



NFFLOW models flow in discrete fracture networks



Energy Data eXchange

https://edx.netl.doe.gov/tools

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

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

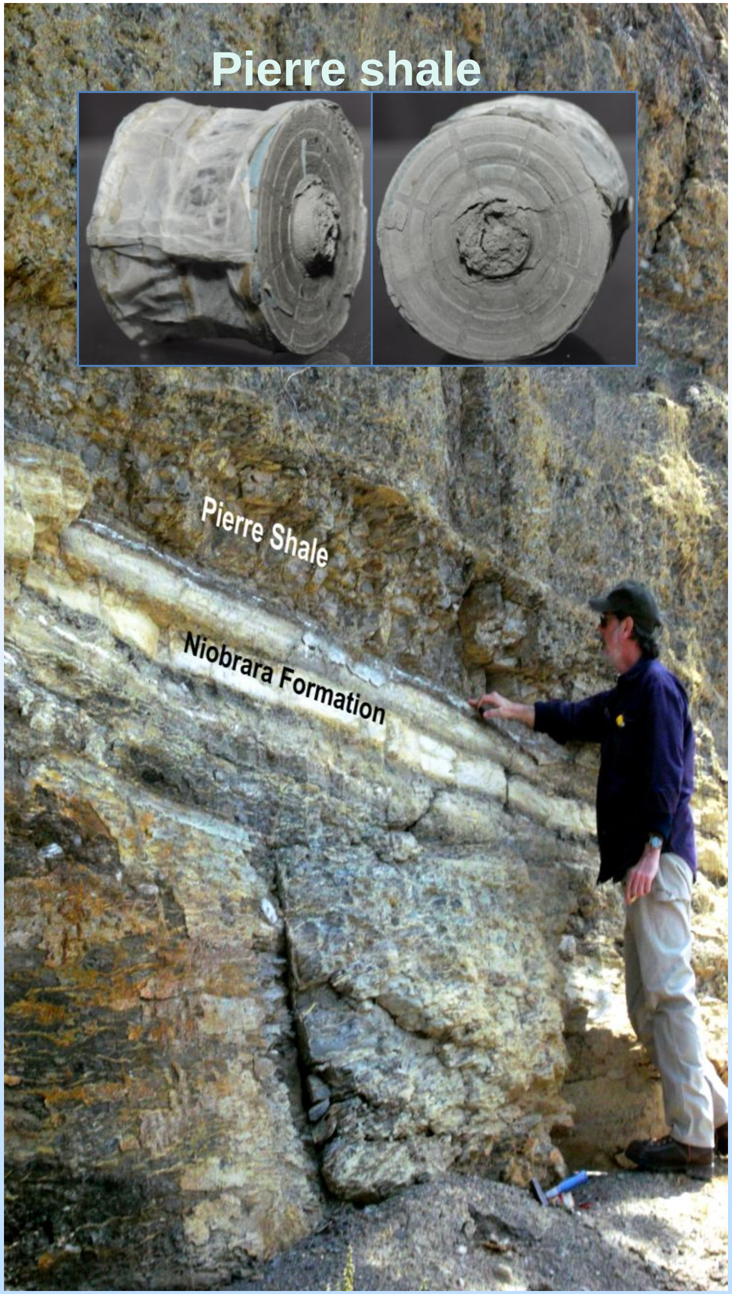
- MOU between DOE and South Dakota School Mines &Technology and South Dakota Geological Survey.

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

- CO_2 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

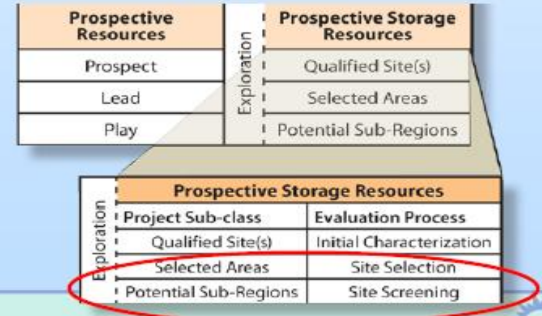
Prospective Storage Resource for CO_2 storage in shale at the *national scale at the Exploration Phase*.

- 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.

Pierre Shale core recovered at the surface in SD
Photo by Dan Soeder, 2014

DOE CO_2 Storage Classification

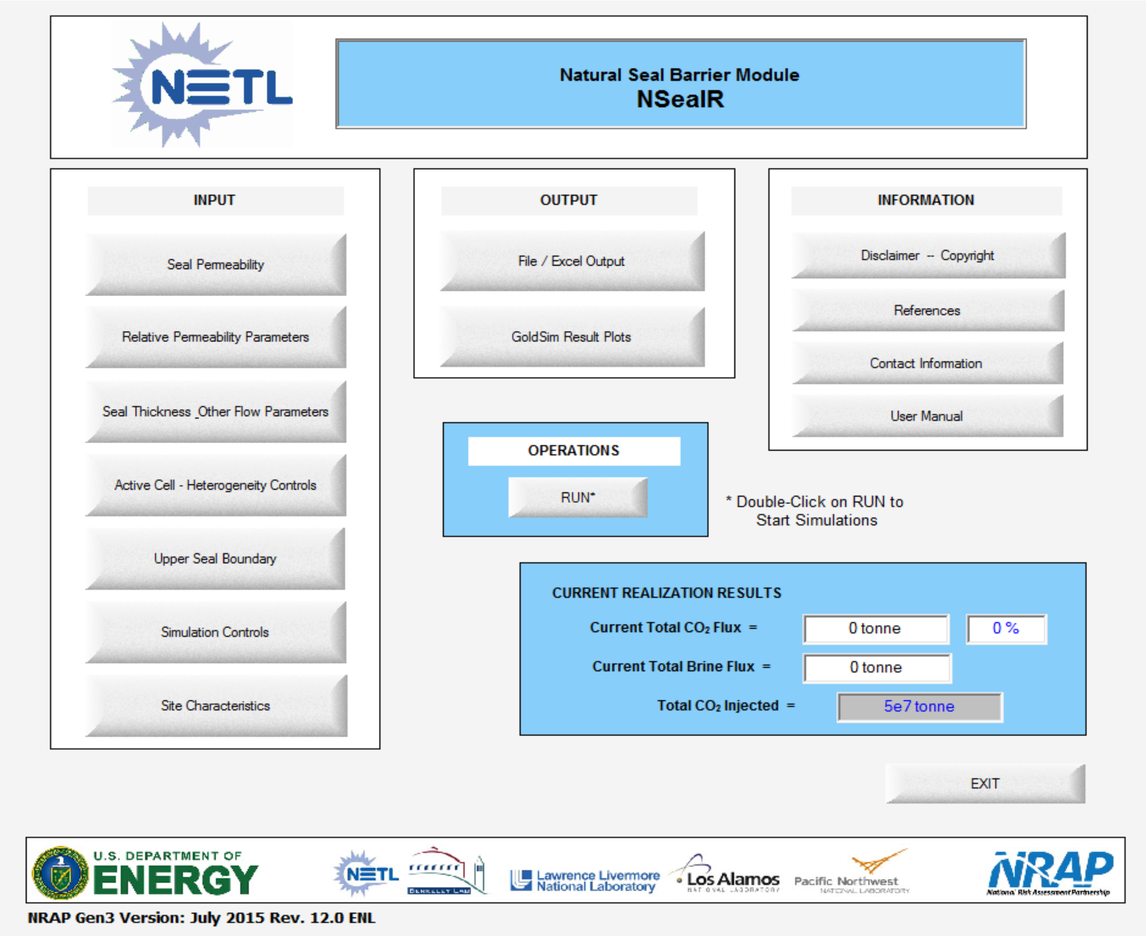


Tie in: NRAP Seal Leakage Characterization

Tool for estimating leakage through fractured seal (*NSealR*)

- 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 CO_2) 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

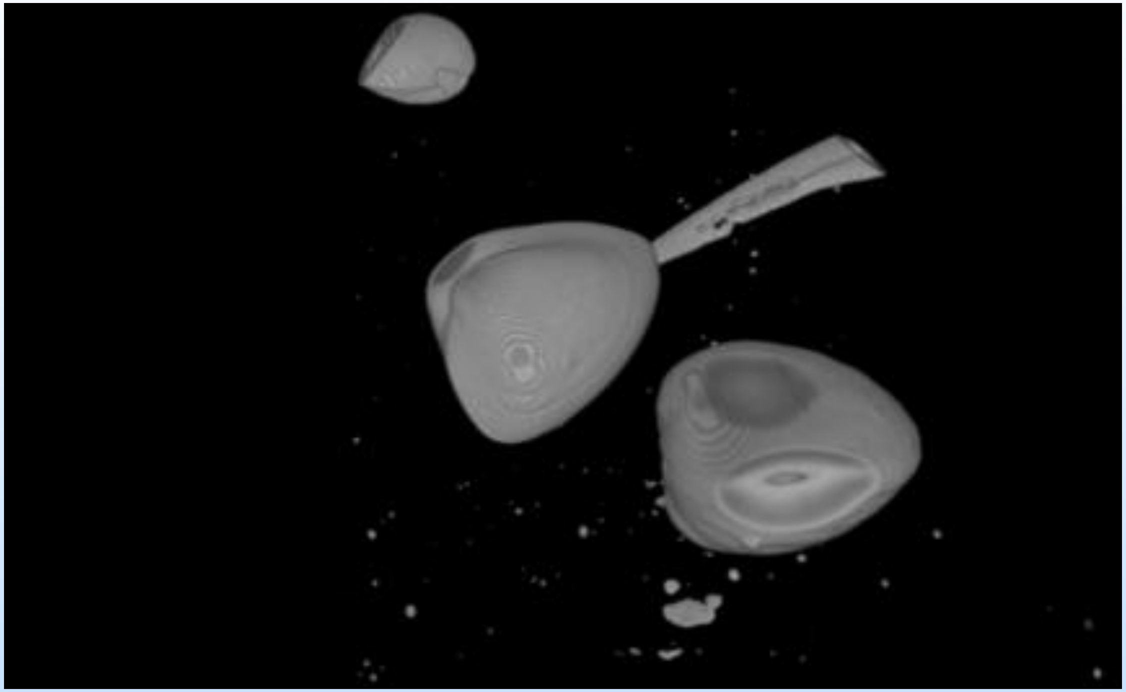
WEDNESDAY, AUGUST 19, 2015

- **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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