Methodology for Assessing CO_2 Storage Potential of U.S. Gas Shale Formations

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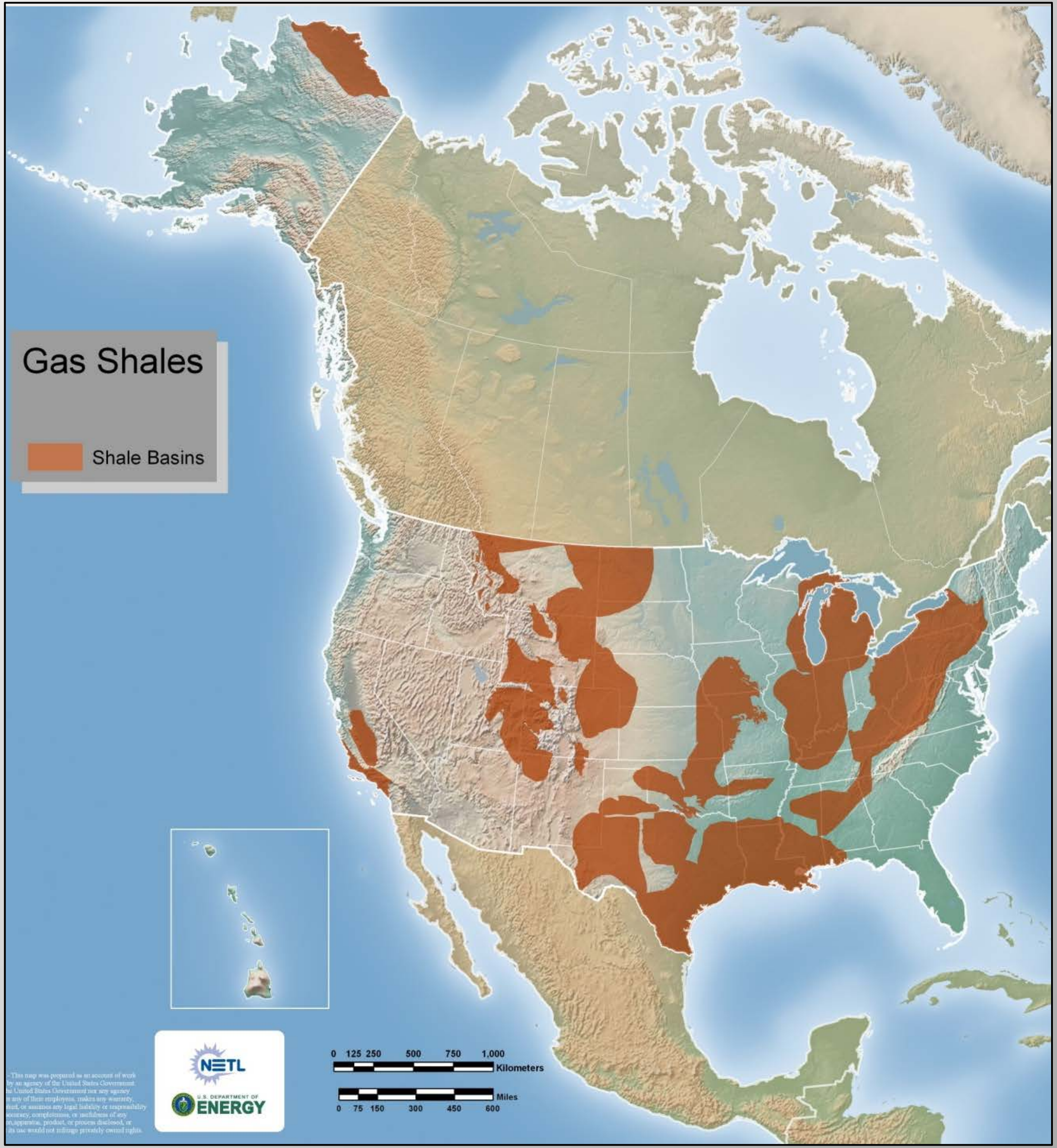
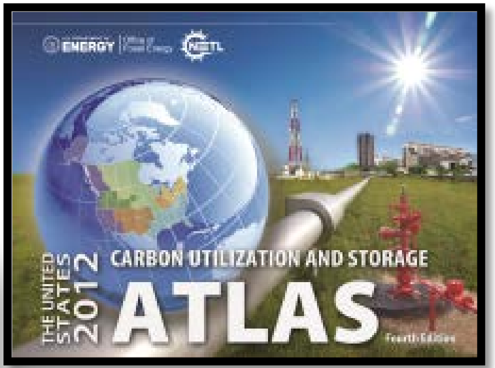


Focus of Gas Shale Research

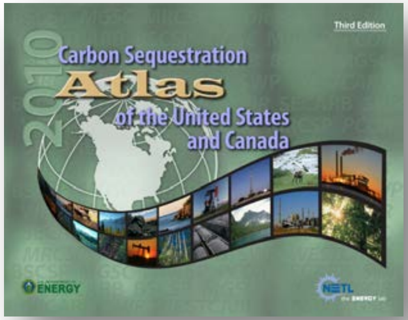
Adapt existing DOE-NETL CO_2 Storage Methodology to gas shales

Purpose of Research:

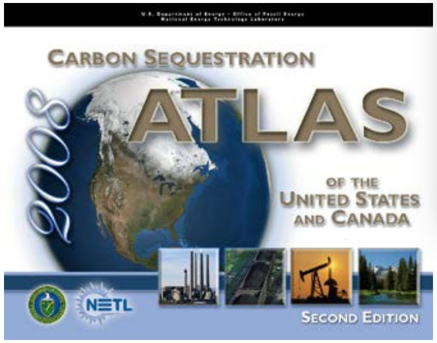
Develop a method to estimate CO_2 storage resource for gas shales in United States and Canada



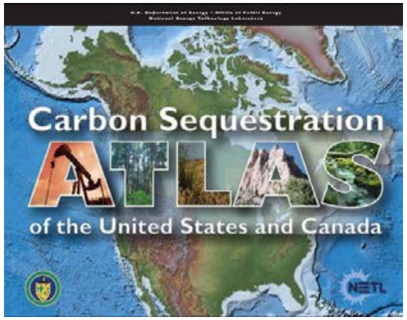
Atlas IV – November 2012



Atlas III - November 2010



Atlas II - November 2008



Atlas I - March 2007

Extending Existing Methods to Other Formations

Volumetric approach: *geologic properties & storage efficiency*

Geologic Formation	Mass Resource Estimate	Storage Efficiency
(1) Saline	$G_{CO2} = A_t\, h_g\, \phi_{tot}\, \rho\, E_{saline}$	$E_{saline} = E_{An/At}\, E_{hn/hg}\, E_{\phi e/\phi tot}\, E_v\, E_d$
(2) Oil and Gas	*(in progress)*	*(in progress)*
(3) Coalseams	$G_{CO2} = A_t\, h_g\, C_s\, \rho\, E_{coal}$	$E_{coal} = E_{An/At}\, E_{hn/hg}\, E_A\, E_L\, E_g\, E_d$
(4) Shale	***(in progress)***	***(in progress)***

total pore volume

fluid properties

efficiency

% of volume that is amenable to CO_2 sequestration

effective CO_2 plume shape

accessible pore volume

- Simple Geometric-Based Formula
- Extensive Peer-Review
- Extensive Statistical Rigor

Stochastic Treatment of Storage Efficiency

A **fraction of the total** volume of the formation that will effectively store CO_2

Represents **variability** in geologic parameters used to calculate G_{CO_2}

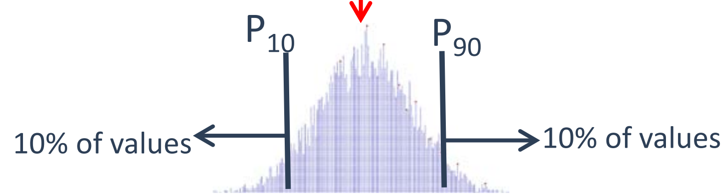
$$E_{saline} = \underbrace{E_{An/At}\, E_{hn/hg}\, E_{\phi e/\phi tot}}_{\text{\% of volume that is amenable to } CO_2 \text{ sequestration}}\ \underbrace{E_v}_{\text{effective } CO_2 \text{ plume shape}}\ \underbrace{E_d}_{\text{accessible pore volume}}$$

Saline Formation Efficiency Factors		
Lithology	**P_{10}**	**P_{90}**
Clastics	0.51%	5.4%
Dolomite	0.64%	5.5%
Limestone	0.40%	4.1%

Log Odds Method applied with *Monte Carlo* sampling

$E_{An/At}$ $\quad E_{hn/hg}$ $\quad E_{\phi e/\phi tot}$ $\quad E_v$ $\quad E_d$

$$E = \left(\frac{1}{1+e^{-X(E_{An/At})}}\right)\left(\frac{1}{1+e^{-X(E_{hn/hg})}}\right)\left(\frac{1}{1+e^{-X(E_{\phi e/\phi tot})}}\right)\left(\frac{1}{1+e^{-X(E_v)}}\right)\left(\frac{1}{1+e^{-X(E_d)}}\right)$$



Source: Goodman, A., Hakala, A., Bromhal, G., Deel, D., Rodosta, T., Frailey, S., Small, M., Allen, D., Romanov, V., Fazio, J., Huerta, N., McIntyre, D., Kutchko, B.,and Guthrie, G. "U.S. DOE methodology for the development of geologic storage potential for carbon dioxide at the national and regional scale. International Journal of Greenhouse Gas Control (2011)

U.S. Gas Shales: *Geologic Properties*

Fine-Grained, Organic-Rich, Fissile Sedimentary Rocks

Total Organic Content (TOC) ≥ 0.5 wt. %

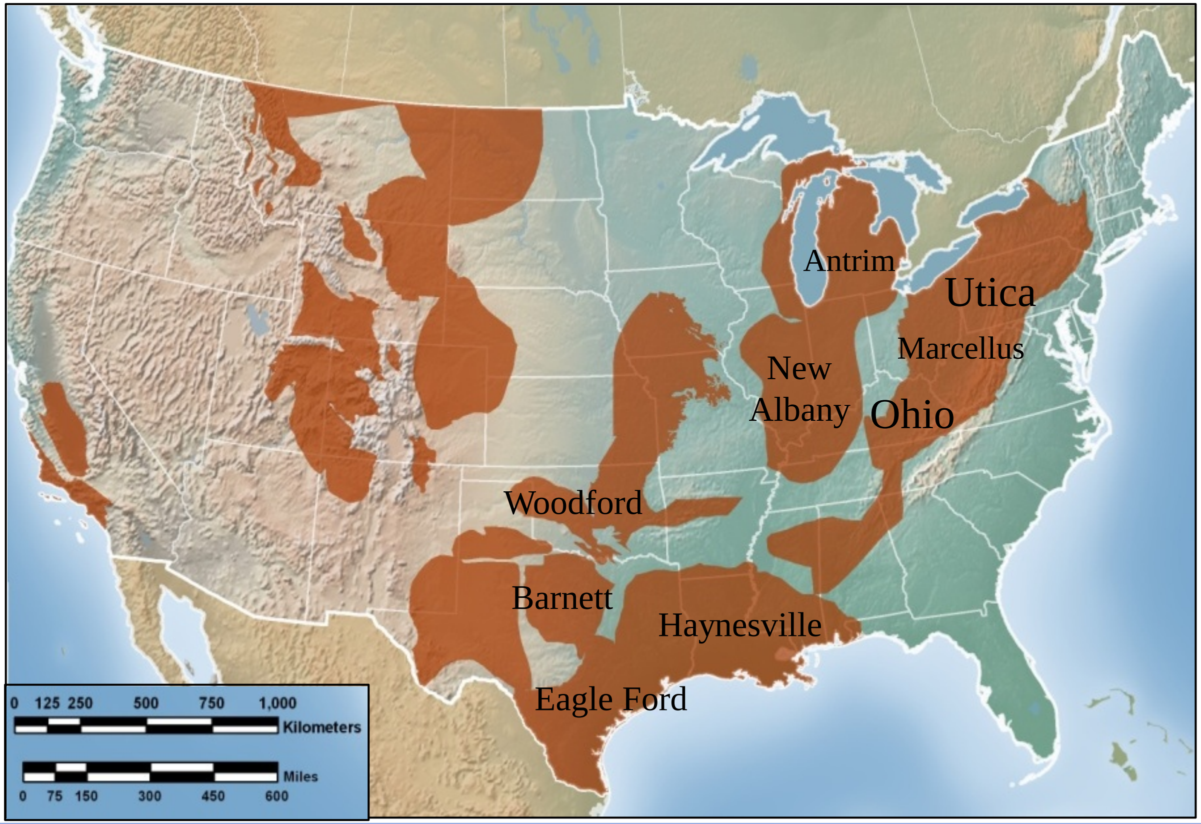
- black shale TOC ≥ 2.0 wt. %, grey shale TOC ≤ 2.0 wt. %

Thermally Mature: Depths of 3-6 km, Temps of 100-200+ °C

Thick: ~ 30.5-100m (100-328+ ft)

~777,000 km^2 of Contiguous U.S.

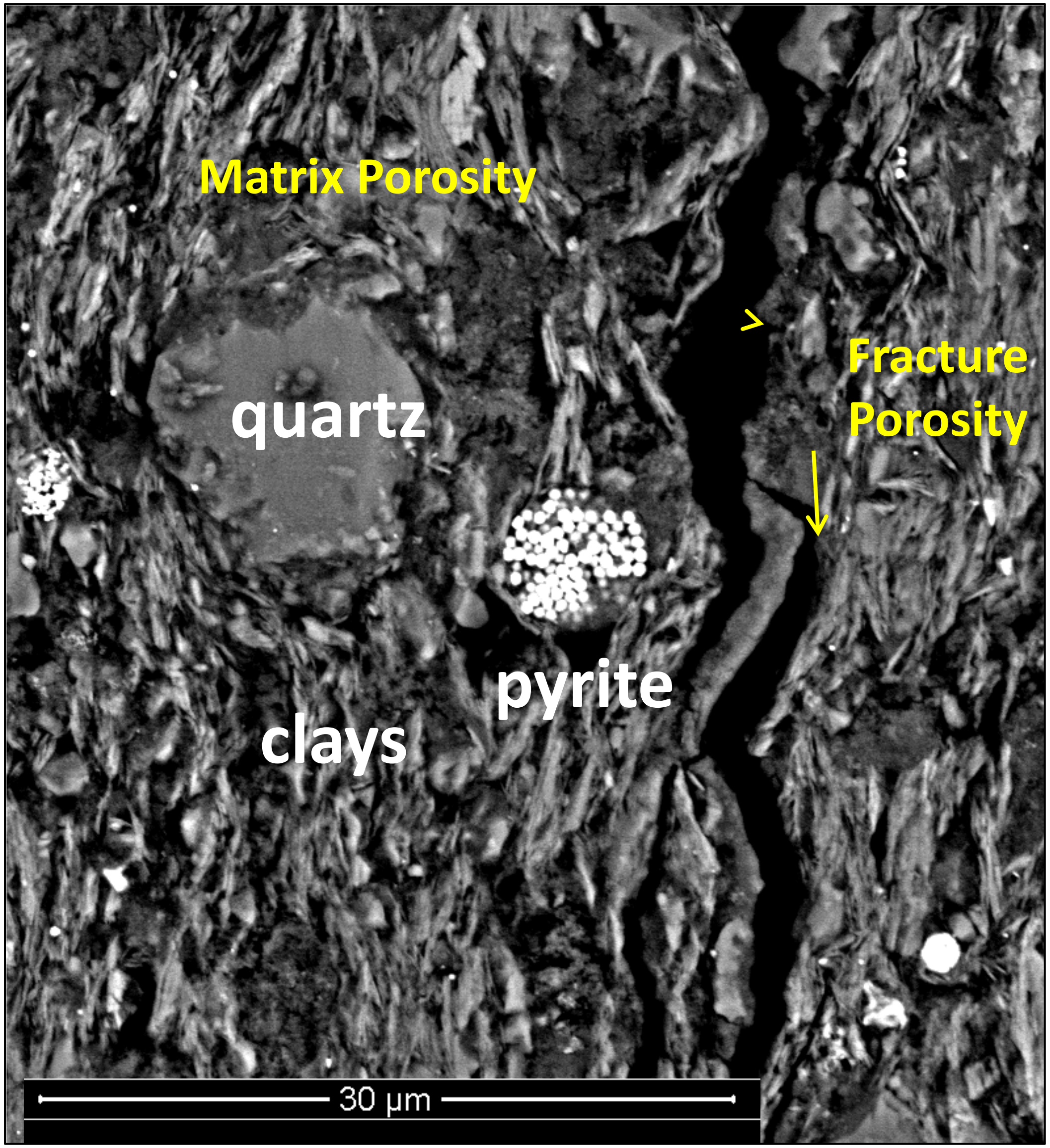
Methane-bearing: Stored as adsorbed & free gas; ~25% of natural gas production



Map of U.S Gas shales (after NETL-NATCARB 2013)

Potential Storage Mechanisms in Gas Shales

Fractures > adsorption > matrix porosity



E-SEM: Back-scattered-electron image

7798 ft; **side-cut, parallel to layering** before exposure

Proposed Shale Method

Geologic Criteria for CO_2 Sequestration in Gas Shales

1) Depleted, black gas shales w/ (TOC) ≥ 2.0 %

prolific reservoirs for natural gas- therefore more geologic, reservoir data, more known about storage mechanisms/capacity relative to other shales

2) A combination of hydro-geologic conditions restricts migration of the CO_2 to within the formation

- e.g. Presence of a seal to limit vertical flow of the CO_2 to the surface; via **hydrodynamic, structural trapping, adsorption**
- ***assuming an upper portion of the shale formation will remain intact and act as a seal -or- there is a redundant, secondary seal*

3) Depths exceeding ~800 m: *P & T adequate for $CO_{2\ supercritical}$*

Proposed Shale Method

Mass Resource Estimate

$$G_{CO_2} = \underbrace{A_t \, h_g \, \phi_t}_{\text{total pore volume}} \; \underbrace{C_s \, \rho_{CO_{2res}}}_{\text{fluid properties}} \; \underbrace{E_{shale}}_{\text{efficiency}}$$

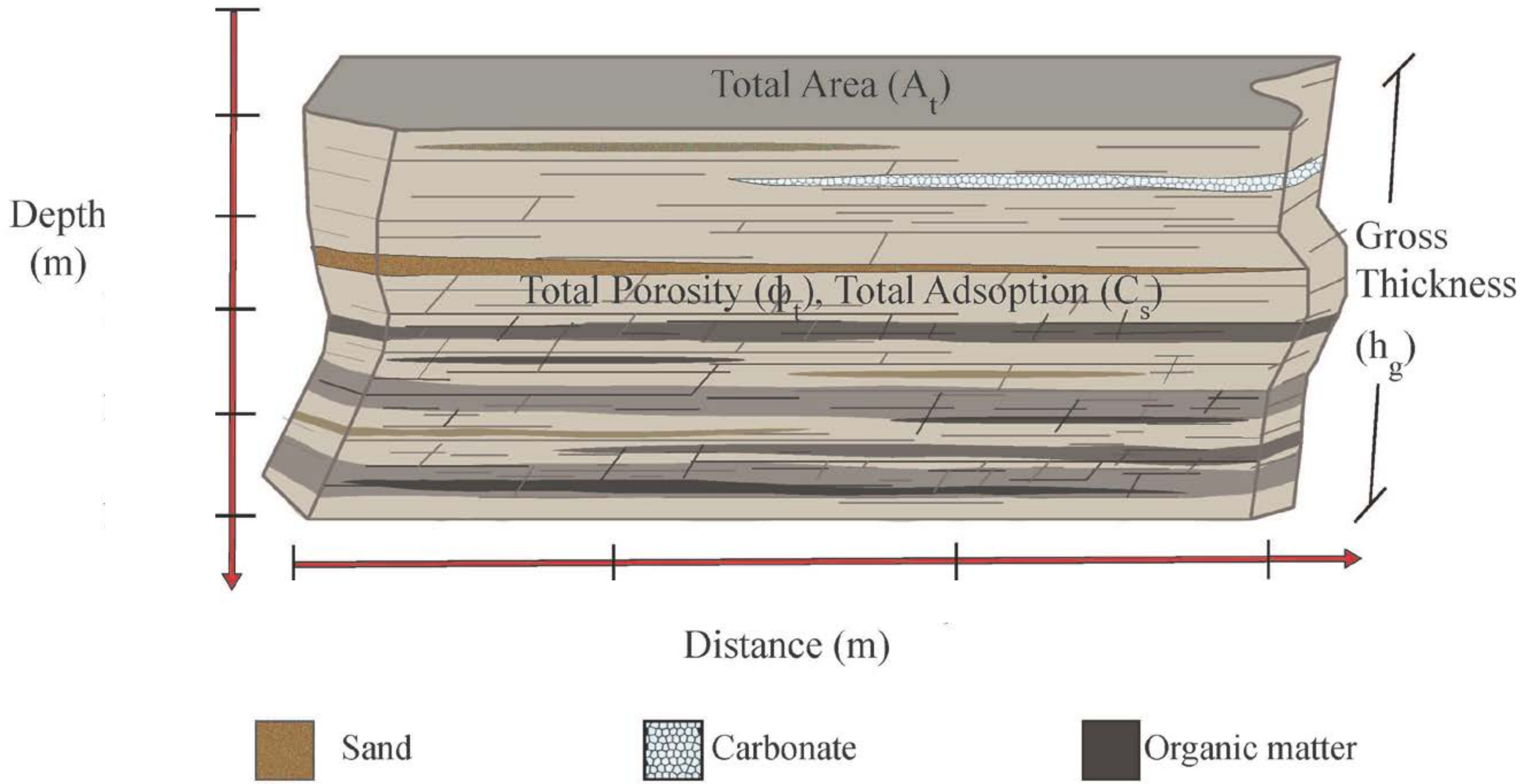


Figure of a simplified, prospective gas shale basin illustrating terms in GCO2 equation

Storage Efficiency Values

Shale Properties that Influence Efficiency

Efficiency Factors For Saline and Coal Formations				
Lithology	Limestone	Clastics	Dolostone	Coal
Low (P_{10})	0.40%	0.51%	0.64%	21.0%
High (P_{90})	4.10%	5.40%	5.50%	48.0%

Efficiency Properties	Low/High (P_{10}/P_{90})				
	Clastics	Dolomite	Limestone	Coal	Shale
Net-to-Total Area	0.2/0.8	0.2/0.8	0.2/0.8	0.6/0.8	Under development
Net-to-Gross Thickness	0.2/0.8	0.2/0.7	0.1/0.6	0.8/0.9	
Effective-to-Total Porosity	0.6/0.8	0.5/0.7	0.6/0.8		
Effective-to-Total Sorption					
Areal Displacement	0.2/0.4	0.3/0.4	0.3/0.6	0.7/0.9	
Vertical Displacement				0.8/0.9	
Gravity Displacement				0.9/1.0	
Microscopic Displacement	0.4/0.8	0.5/0.6	0.3/0.4	0.8/0.9	

Gas Shale

Shale Formation Efficiency Factors	
P_{10}	Low
P_{90}	High

U.S. Gas Shales: Potential to Sequester CO_2

Advantages

1. TOC-rich layers are thick (>65 m) & at lower-mid portion of basins

2. CO_2: CH_4 adsorption ≈3:1 *(at 7Mpa)*

3. Close proximity to CO_2 sources

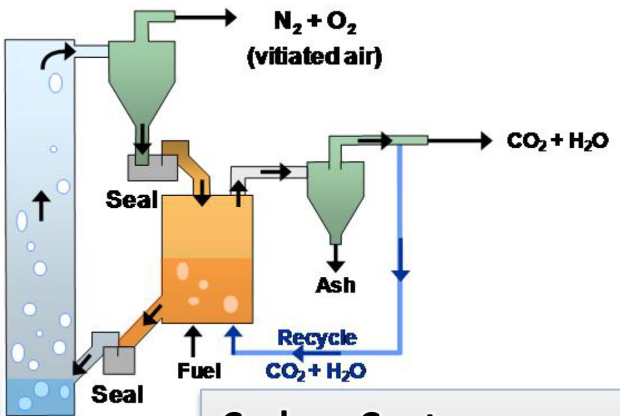
Challenges

1. Low permeability: *100-500 nanodarcys*
2. Matrix porosity: *accessible?*
3. Heterogeneity
4. Sensitivity to stress
5. Fracture variability: *reservoir vs. seal, natural vs. induced*

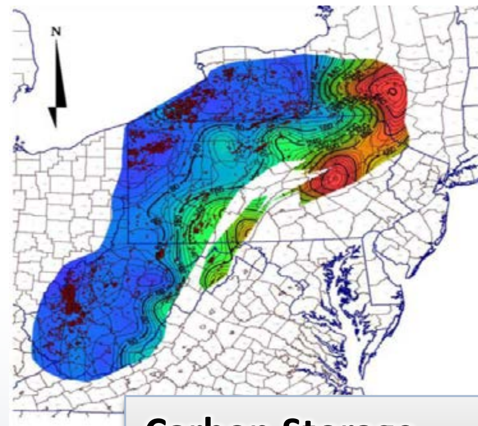
Picture of Utica Shale from the Ohio Oil and Gas Association

ICMI

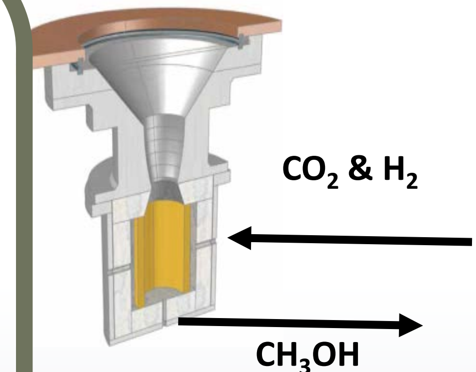
Industrial Carbon Management Initiative



Carbon Capture
Chemical Looping Combustion

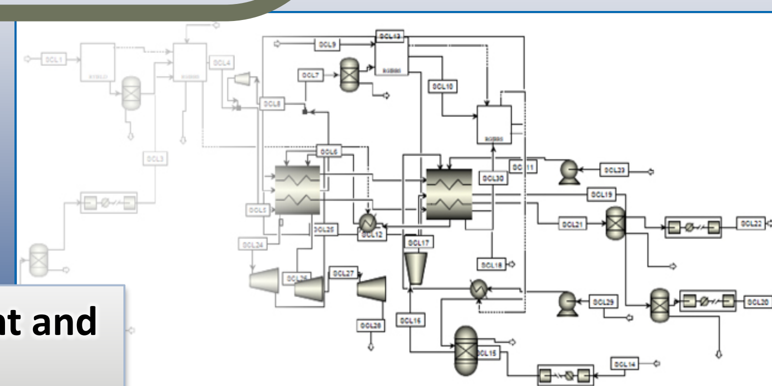


Carbon Storage
Depleted Shale Fields



Carbon Utilization
Photocatalytic Conversion

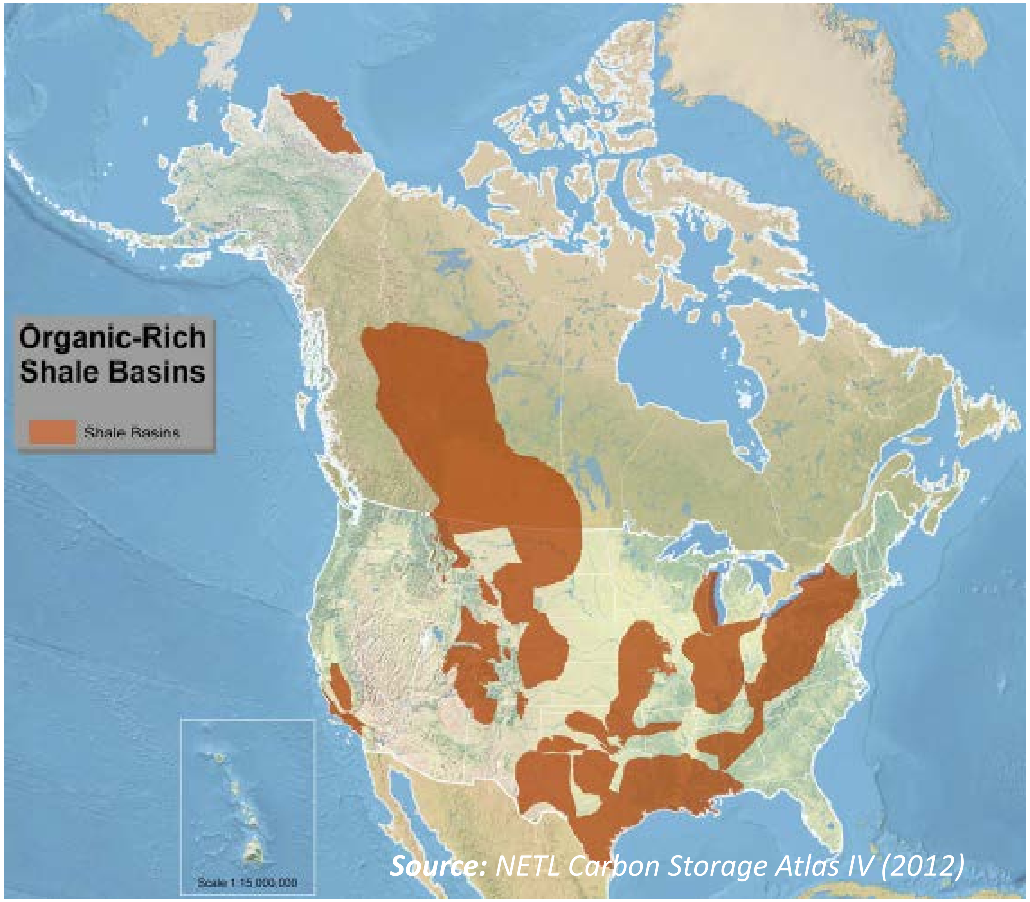
CCUS for Industrial Applications



Industrial assessment and systems analysis

Problem Statement

Objective: Develop a robust characterization of site-scale technical CO_2 storage and EGR potential of gas-bearing shale formations and preliminary assessment of potential economic viability



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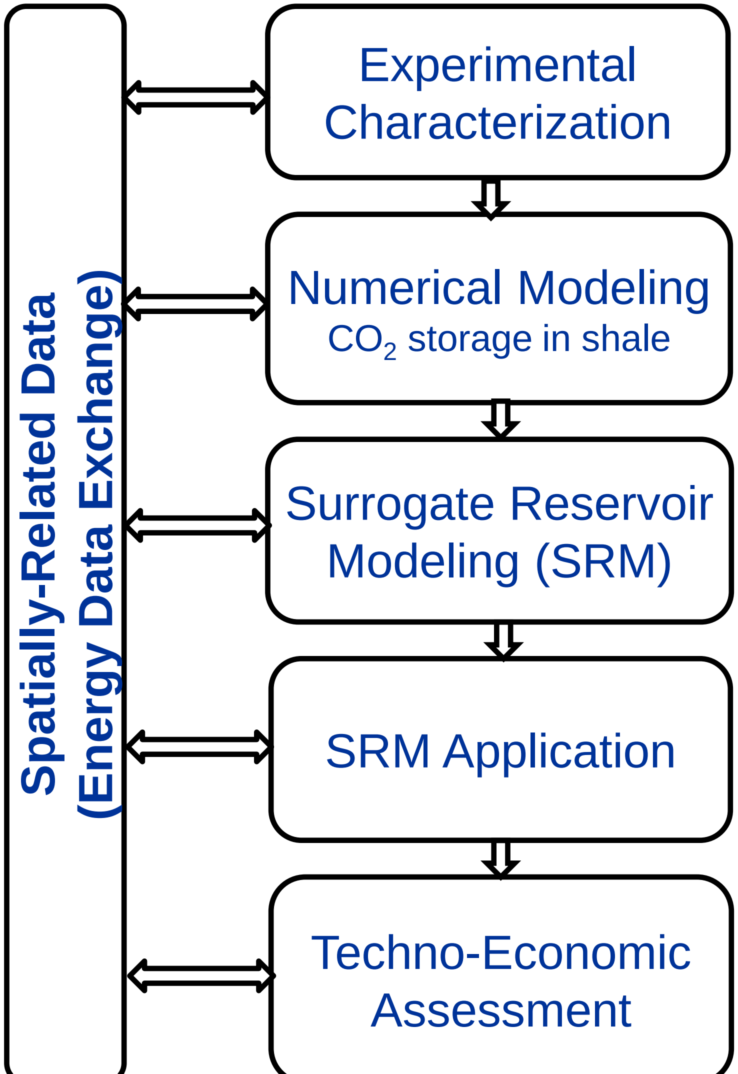
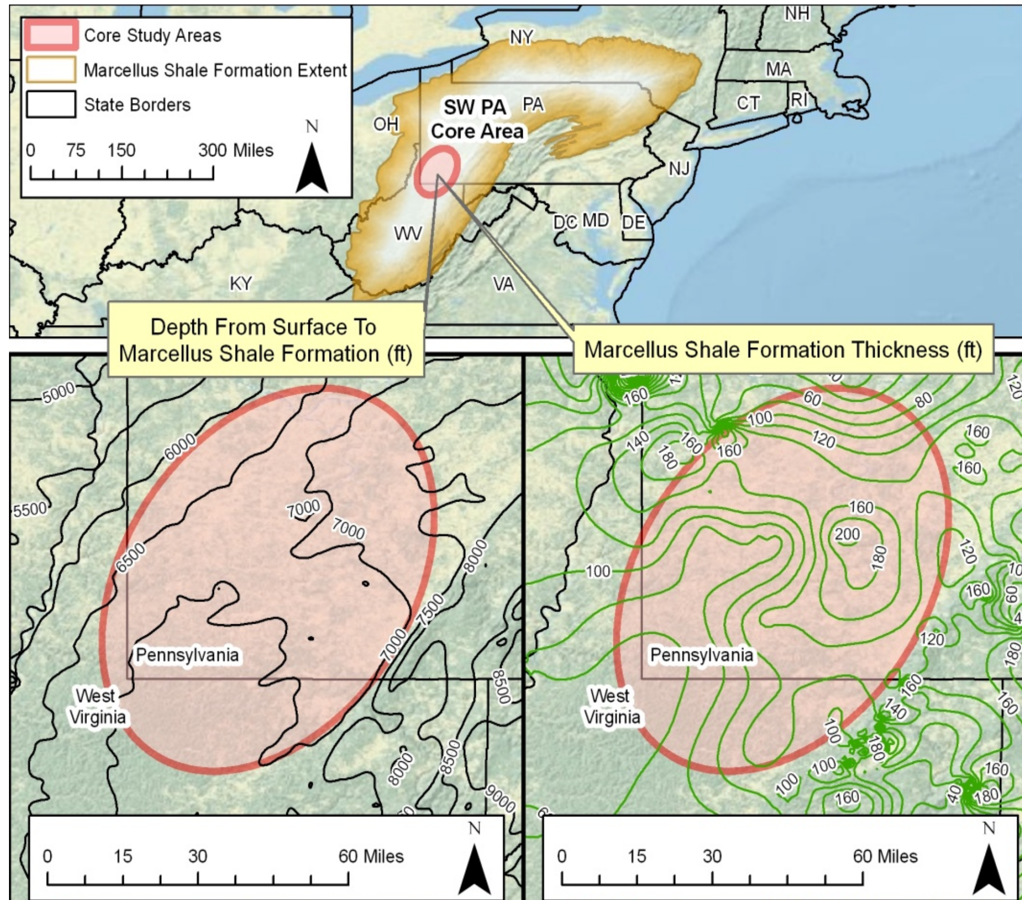
NETL-RUA Regional University Alliance

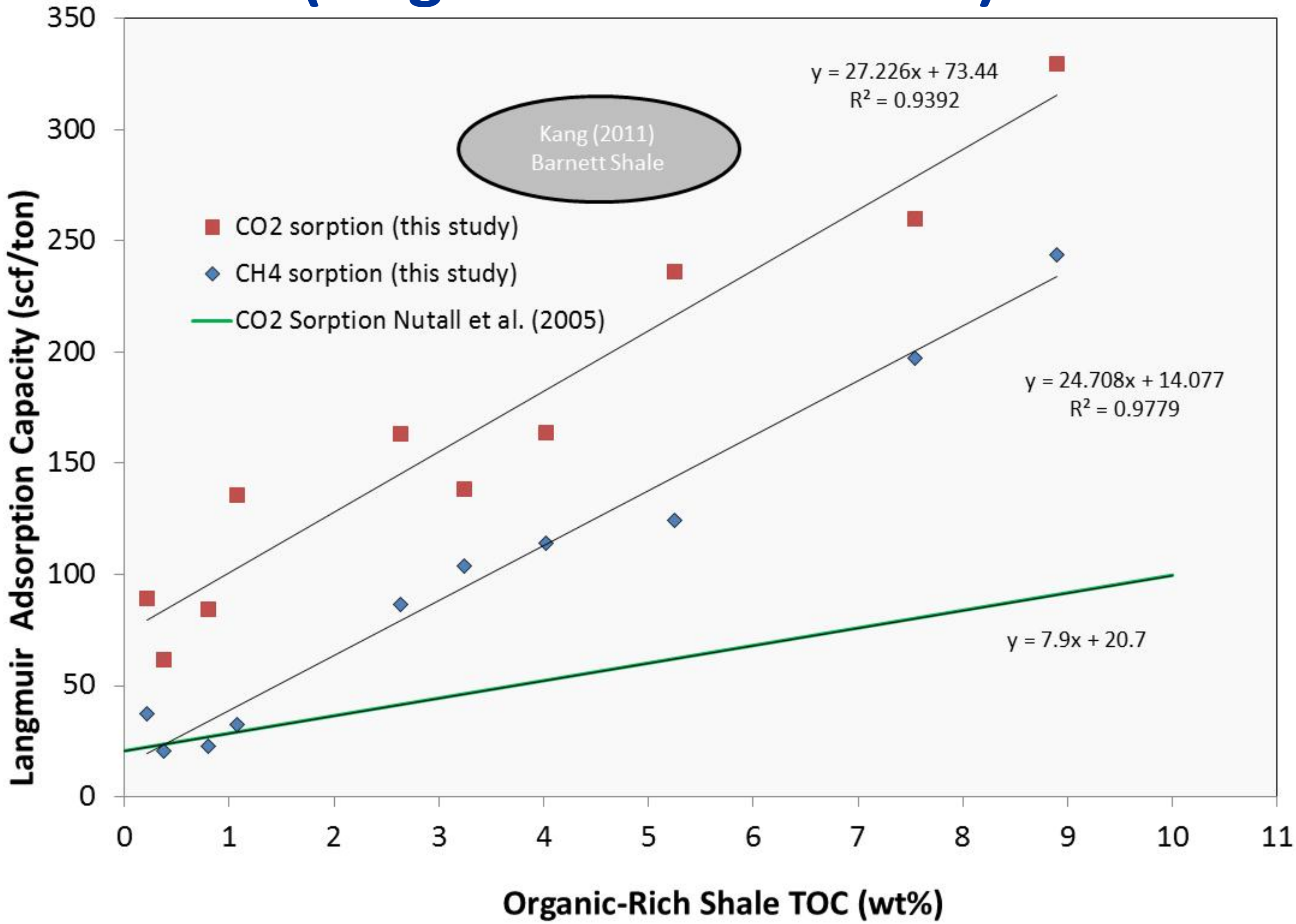
CO_2 Storage in/Enhanced Gas Recovery from Shale Gas Formations



Scenario Definition

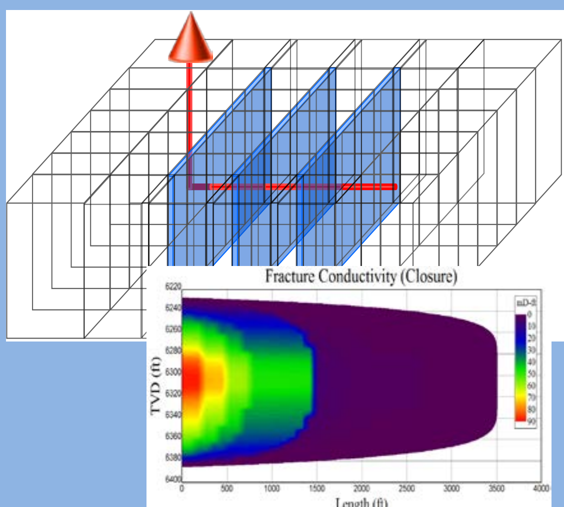


Sorption capacity as function of %TOC (single-fluid isotherms)

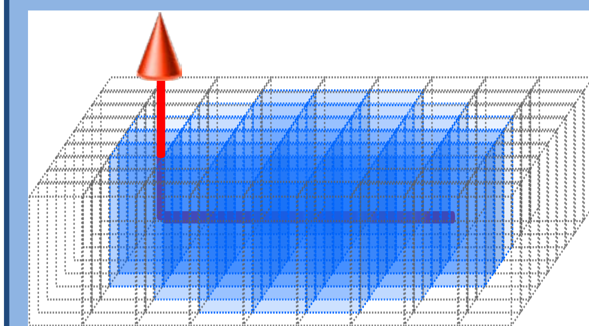


There are different ways to represent Networks of Engineered Fractures

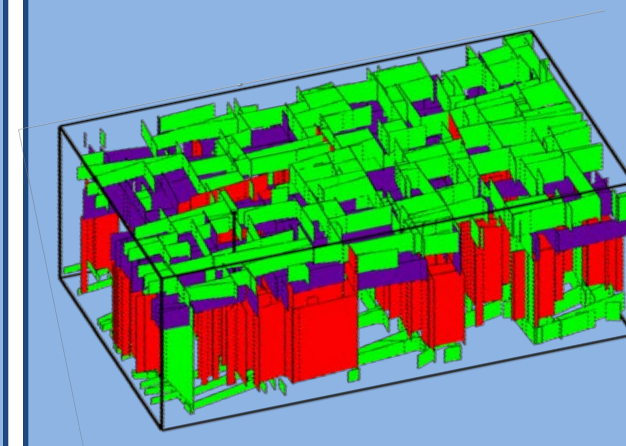
Discrete Transverse Fracture Planes



Crushed Zone Representation

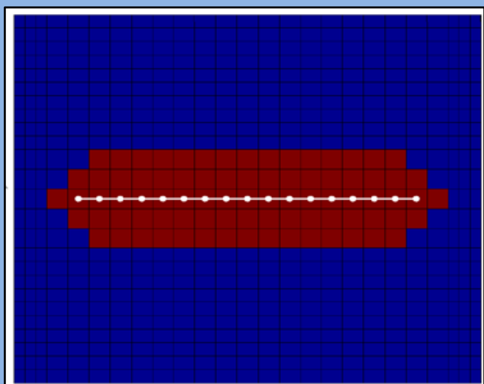


Semi-stochastic fracture Network

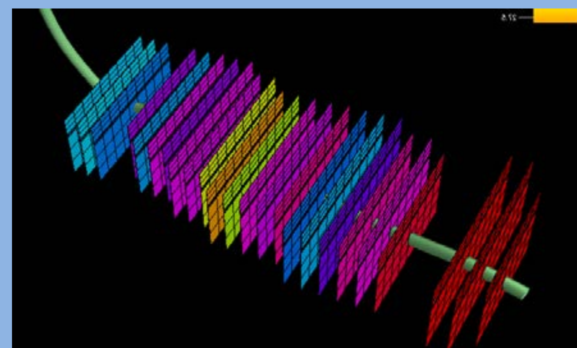


Reservoir Simulation – Gas Depletion

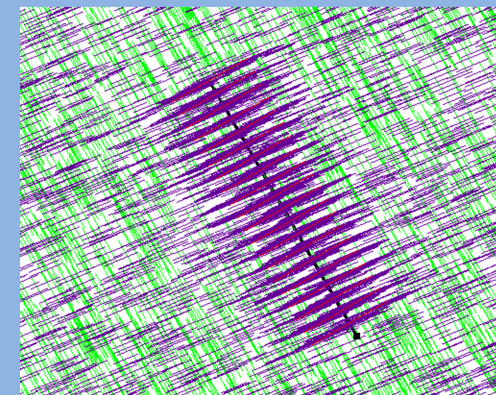
Modified dual porosity, multiphase, compositional, multidimensional flow model



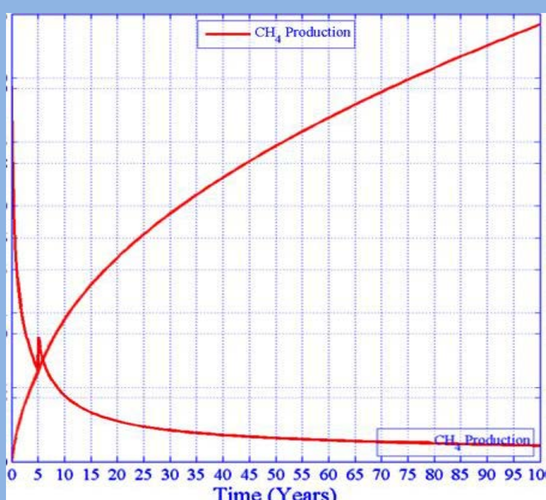
Discrete Fracture Modeling coupled with conventional reservoir simulation

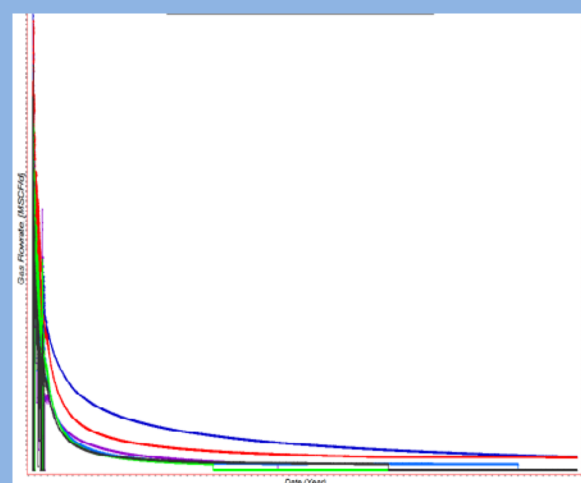


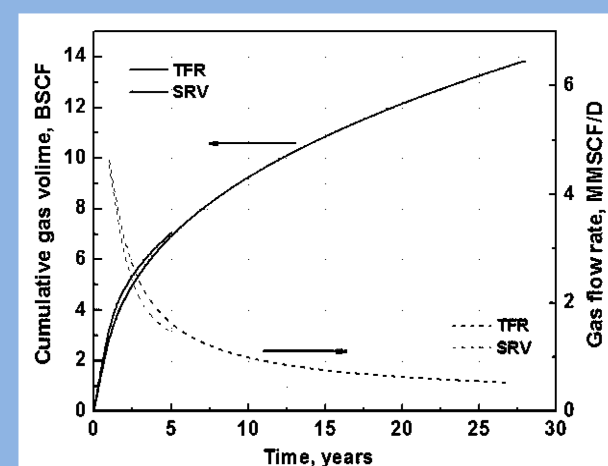
Semi-stochastic fracture network and flow modeling



Single Lateral Depletion Gas Production and Pressure Field

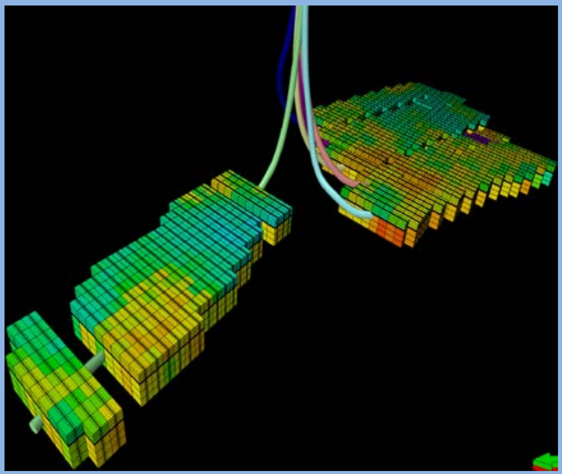


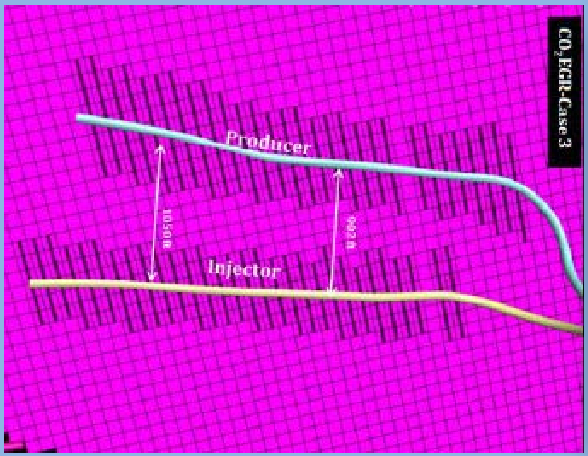


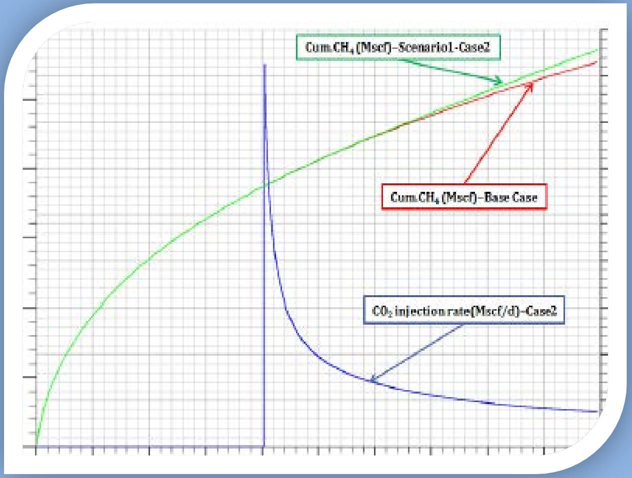


CO_2 Injection Scenario Evaluation

Example: Discrete Fracture Modeling coupled with conventional reservoir simulation





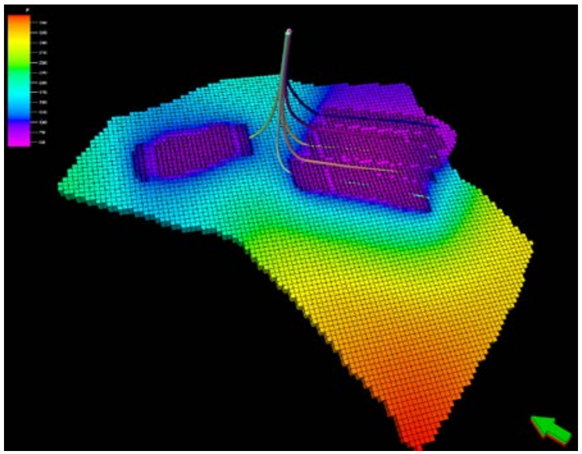


Sensitivity of CO_2 storage/EGR models to:

- Injector/producer configuration (length and distance between)
- Matrix and fracture permeability
- Matrix CO_2 and CH_4 sorption characteristics
- Fracture network characteristics
- Duration of injection

Developing Tool for Techno-Economic Screening

Full-Field Numerical Model

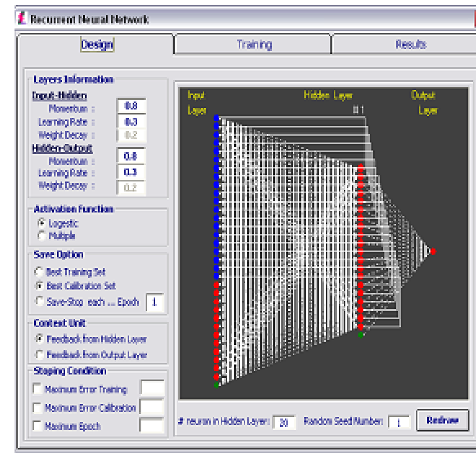


Database of 10-20 Simulation Runs

SRM Training

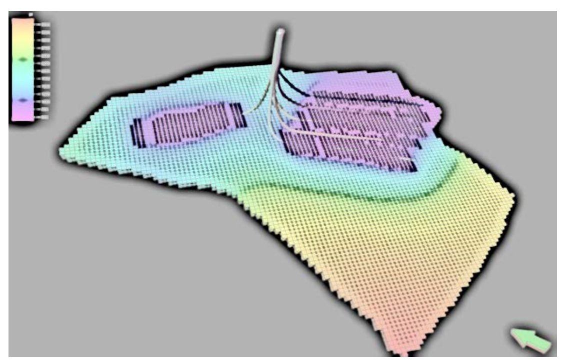
Pattern Recognition

(fuzzy set theory and Artificial Neural Networks)



SRM validation

SRM Mimics Behavior of Full-Field Model



Explore Storage Technical and Economic Performance

NETL

Carbon Storage Initiative

Shales as Seals

Shales as Storage

DATA GAPS

Daniel J. Soeder

Research Scientist, Geology and Environmental Systems

August 21, 2013

U.S. DEPARTMENT OF ENERGY | National Energy Technology Laboratory

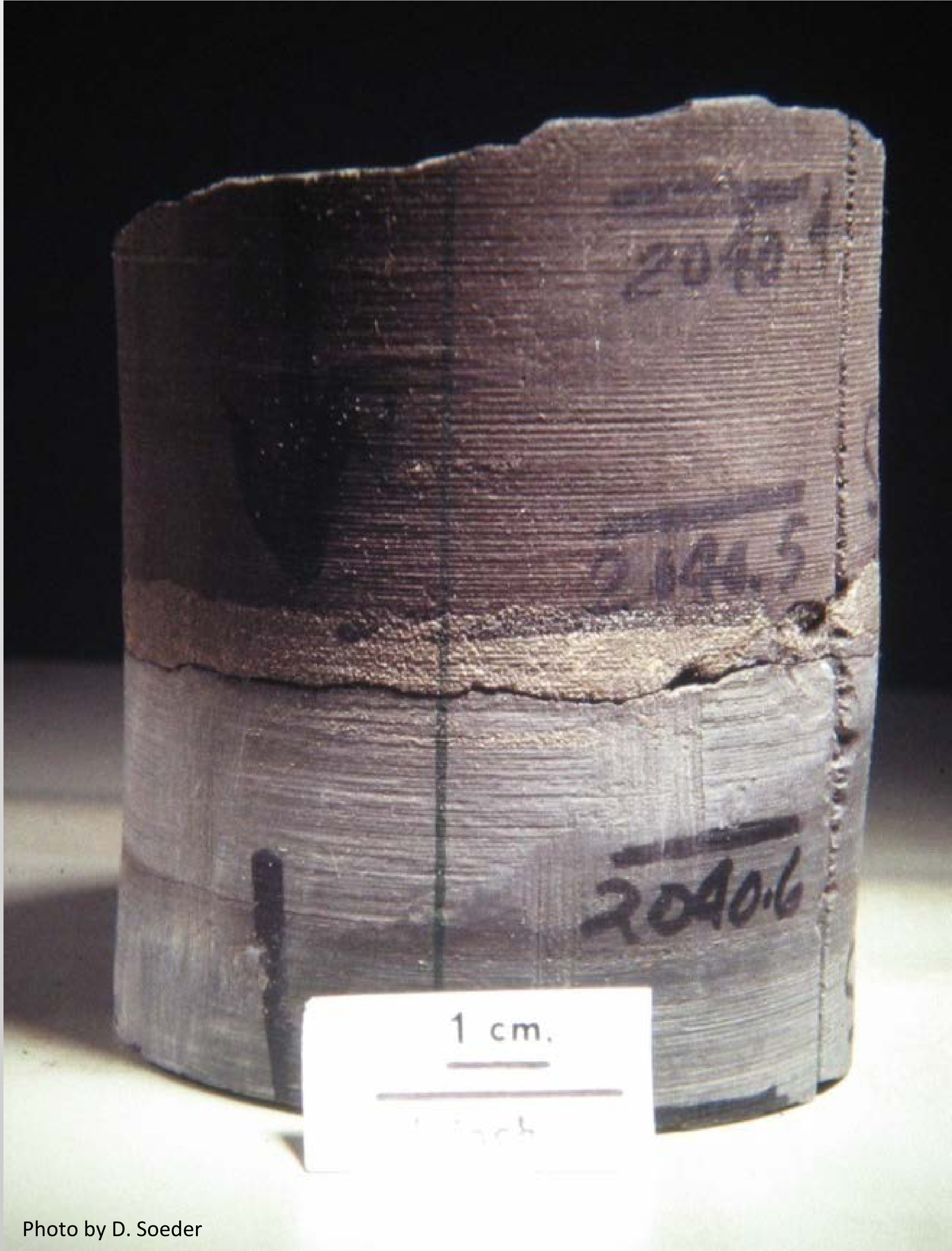


Photo by D. Soeder

1. Understanding Shale Pore Structure

- **Shale pore types (simplified categories after Loucks et al*)**
  - Inter-granular: between mineral grains
  - Intra-granular: within mineral grains
  - Intra-organic: nanotubes within organic carbon fragments
  - Gas can also be adsorbed on organics and clays or dissolved into organics
- **How are these pores connected?**
  - Horizontal versus vertical anisotropy of flowpaths
  - Sensitivity to stress
- **Pores and fluids**
  - High capillary entry pressure of liquid in shale pores
  - Relative permeability of gas versus liquid: mobile phase and non-mobile phase; irreducible water saturation
  - Liquid phase behavior in oil-wet versus water-wet shales
  - Behavior of methane versus CO_2 – molecule size, chemical properties
  - Devonian shales have pores in the 5 to 15 nm range

Loucks, Robert G, Stephen Ruppel, Robert M. Reed, and Ursula Hammes, 2011, Origin and classification of pores in mudstones from shale-gas systems, Search and Discovery Article #40855, posted December 19, 2011, http://www.searchanddiscovery.com/documents/2011/40855loucks/ ndx_loucks.pdf

Pore Sizes (Nelson, 2009)

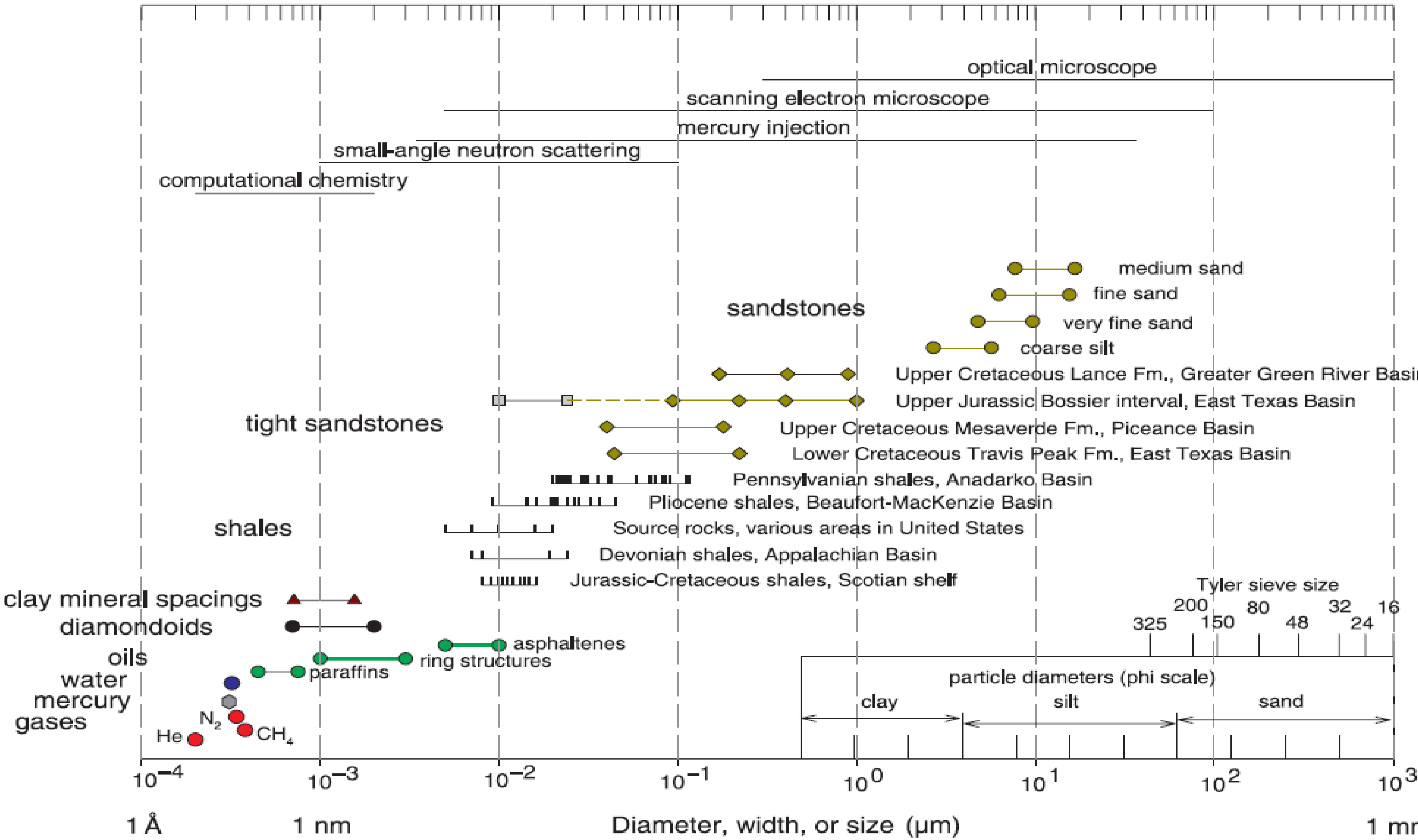
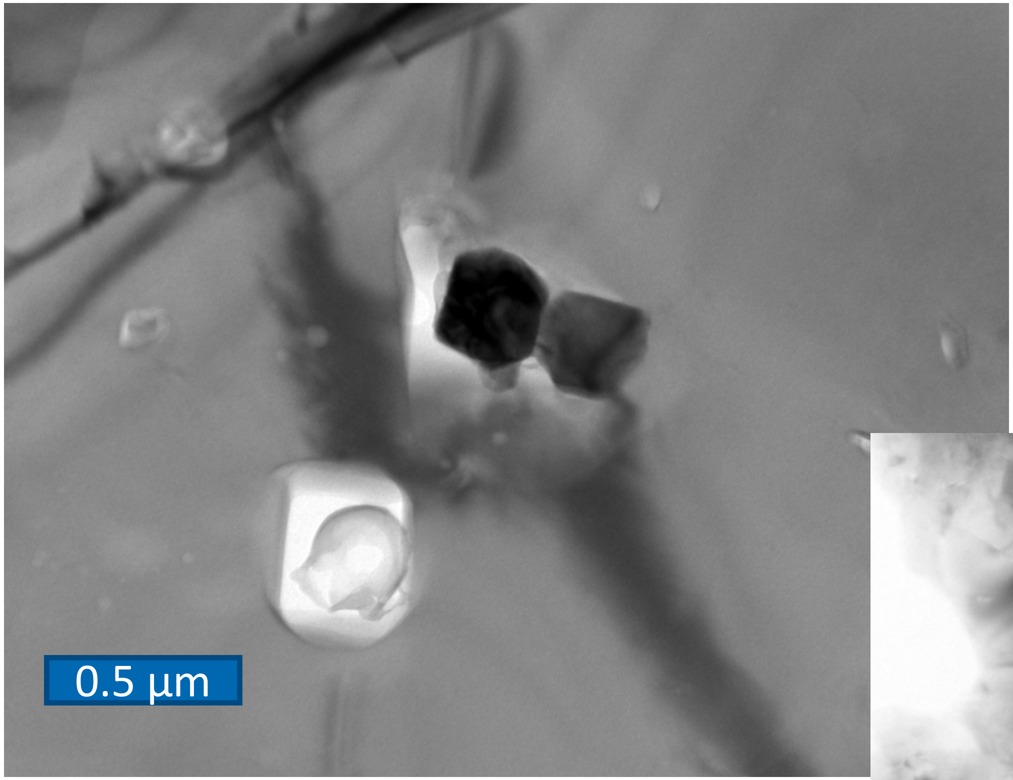


Figure 2. Sizes of molecules and pore throats in siliciclastic rocks on a logarithmic scale covering seven orders of magnitude. Measurement methods are shown at the top of the graph, and scales used for solid particles are shown at the lower right. The symbols show pore-throat sizes for four sandstones, four tight sandstones, and five shales. Ranges of clay mineral spacings, diamondoids, and three oils, and molecular diameters of water, mercury, and three gases are also shown. The sources of data and measurement methods for each sample set are discussed in the text.

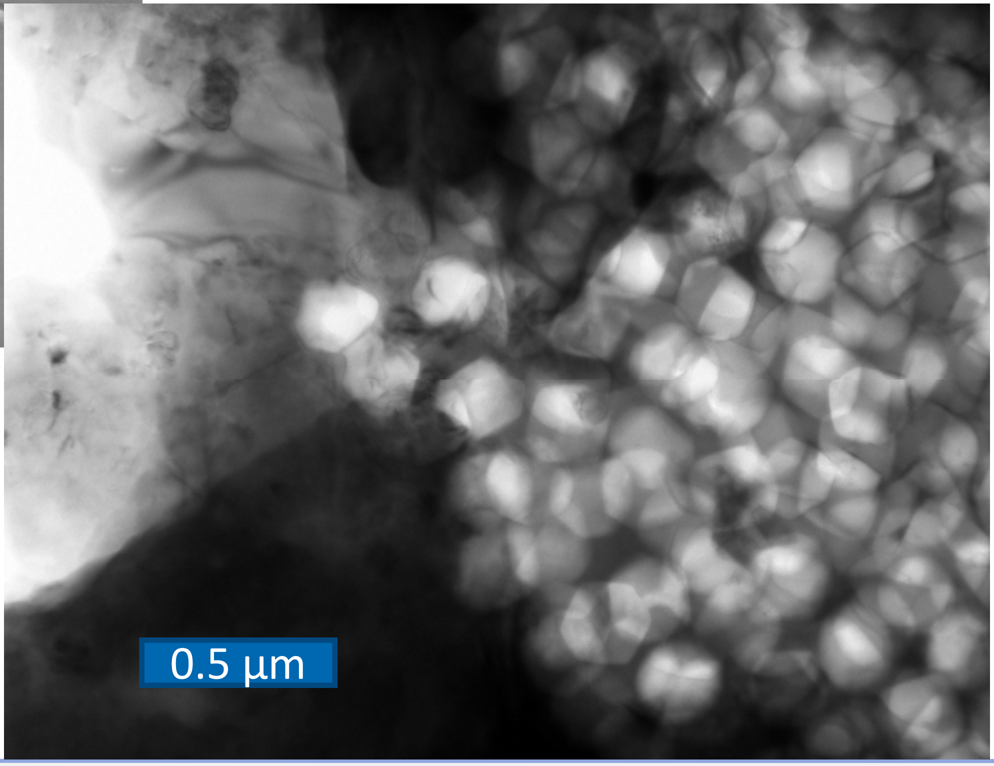
Nelson, Philip H., 2009: Pore-throat sizes in sandstones, tight sandstones, and shales: AAPG Bulletin, v. 93, no. 3 (March 2009), pp. 329–340

Shale Pores under TEM



Dr. Xueyan Song at WVU has been experimenting with a TEM on shale.

Resolution of these images far exceeds any other technology.



Dr. Song has a TEM stage that can tilt up to 60 degrees.

We can obtain axial images with this stage, and do 3-D reconstructions using CT software.

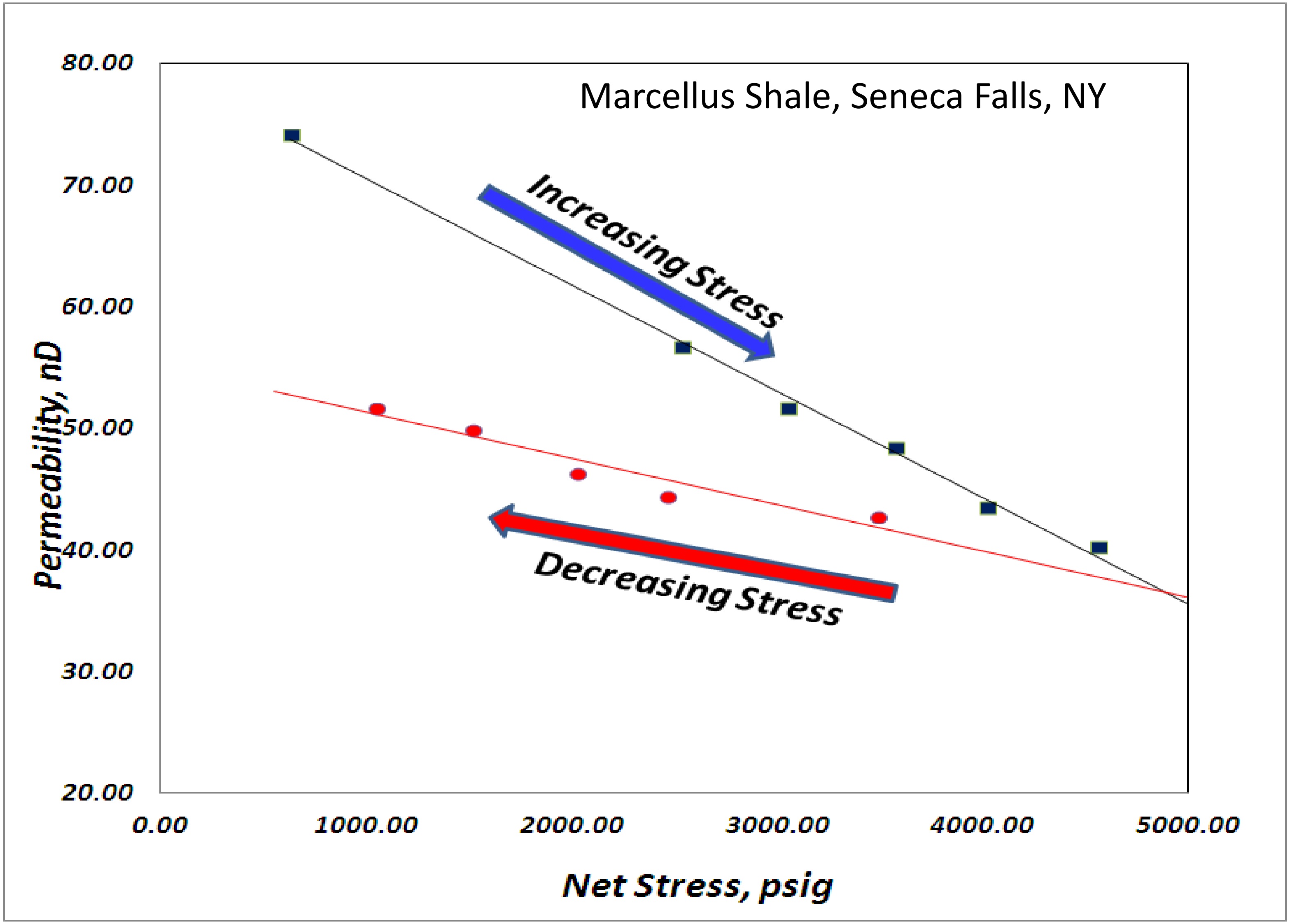
TEM images by Xueyan Song, West Virginia University

2. Understanding the Petrophysical Behavior of Shale

- **Behavior of porosity in shale**
  - How does total pore volume equate to gas storage potential?
  - The CO_2 molecule is larger than CH_4 and may behave differently in nano-scale pores
  - Are there volume changes in shale when CO_2 is added (i.e. swelling)?
  - Importance (or not) of adsorption phenomena for gas storage?
- **CO_2 physical and chemical reactions with the shale**
  - Reaction to oil-wet versus water-wet shales
  - Reaction to mineralogy (clays, carbonate, sulfides, etc.)
- **Core sample bias?**
- **Permeability challenges**
  - Mass flow versus diffusion; movement of gas through nanopores on a molecular scale
  - Importance of the Klinkenberg effect and gas slippage
  - Exactly how low is a permeability of one nanodarcy?
  - Loss of permeability at higher net stress; hysteresis
  - Changes in flowpath aperture and tortuosity due to increased net confining stress*

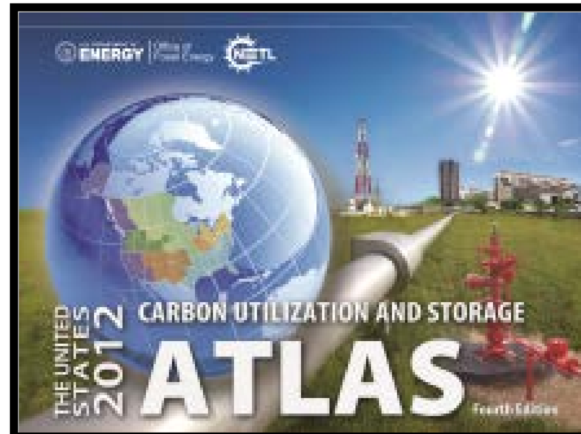
**Soeder, D. J., 1988, Porosity and permeability of eastern Devonian gas shale: SPE Formation Evaluation, Vol. 3, No. 2, p. 116-124, DOI 10.2118/15213-PA.*

Hysteresis in Shale



3. What is the correct efficiency factor for shale?

- **A bulk volume of shale has a porosity of about 10%**
- **Assuming it is 100% filled with gas, operators report a recovery rate of about 10% of the gas-in-place***
- **This results in a storage volume of 1% of the bulk volume – pretty low.**
- **In reality, it is probably even lower**
  - Not all of the porosity will be accessible
  - There are likely other fluids in the pores
  - Hysteresis may close pore throats



- **Understanding how and where gas is contained in shale is critically important to evaluating the potential of this rock for the long-term storage of carbon dioxide.**

**Engelder, T., and G.G. Lash, 2008, Marcellus Shale play's vast resource potential creating stir in Appalachia: The American Oil and Gas Reporter, May 2008, 7 p. (www.aogr.com)*