Stanford University

Global Climate & Energy Project

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On Carbon Capture & Sequestration
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CO_2 Sequestration: What have we found? What should future priorities be?

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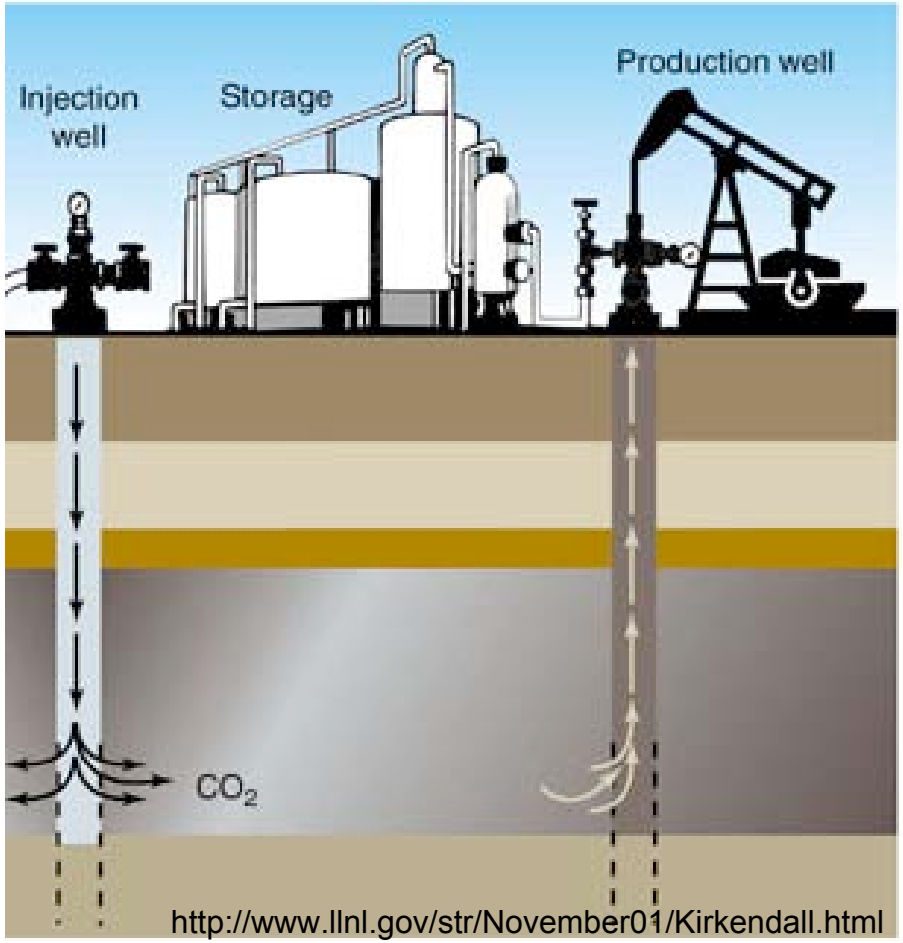
My Opinion…

- Today, we can
  - select sites
  - drill and complete wells for CO_2 injection
  - manage the subsurface flows
  - monitor the progress of CO_2 migration
  - plug and abandon wells



http://www.llnl.gov/str/November01/Kirkendall.html

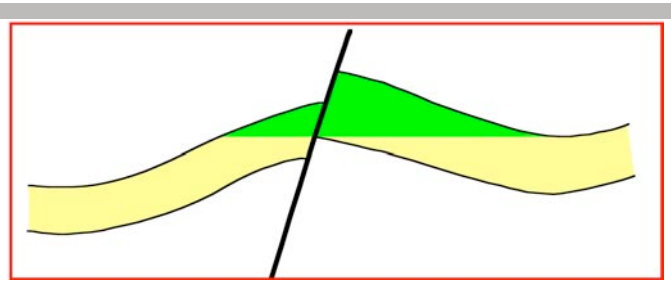
My Opinion…

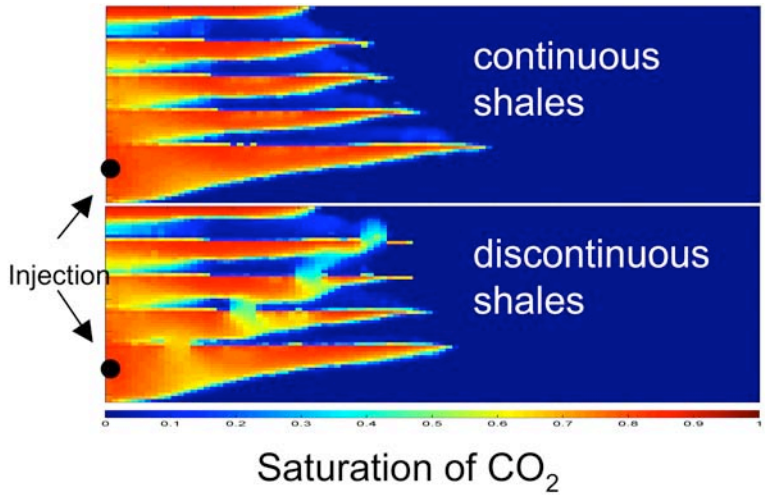
- But, we are not ready to answer the hard questions, such as
  - 90-99% of all organic matter deposited was never captured by a trap
  - oil seeps are common
  - leakage from gas caps in the North Sea is documented
  - CO_2/water, CO_2/oil displacements are unstable => how to predict
  - cartoon understanding, at best, of physics for coalbed and ocean sediment settings

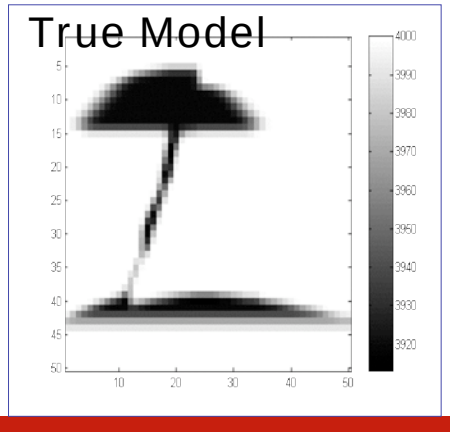
GCEP: CO_2 Storage Efforts

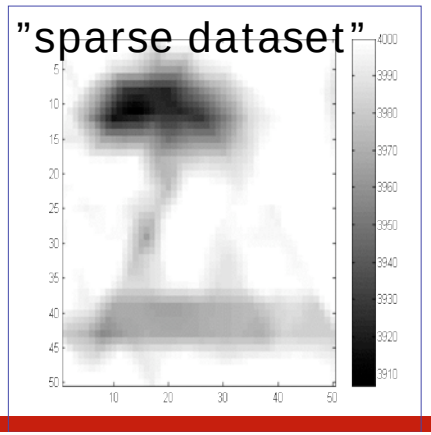
Project Components:

- **Site selection and evaluation: effective methods to assess the integrity of geologic seals that limit CO_2 migration.**
- **Fluid migration: efficient methods for predicting the flow paths and long-term fate of injected CO_2.**
- **Monitoring: appropriate tools for monitoring the state of injection projects at each stage.**





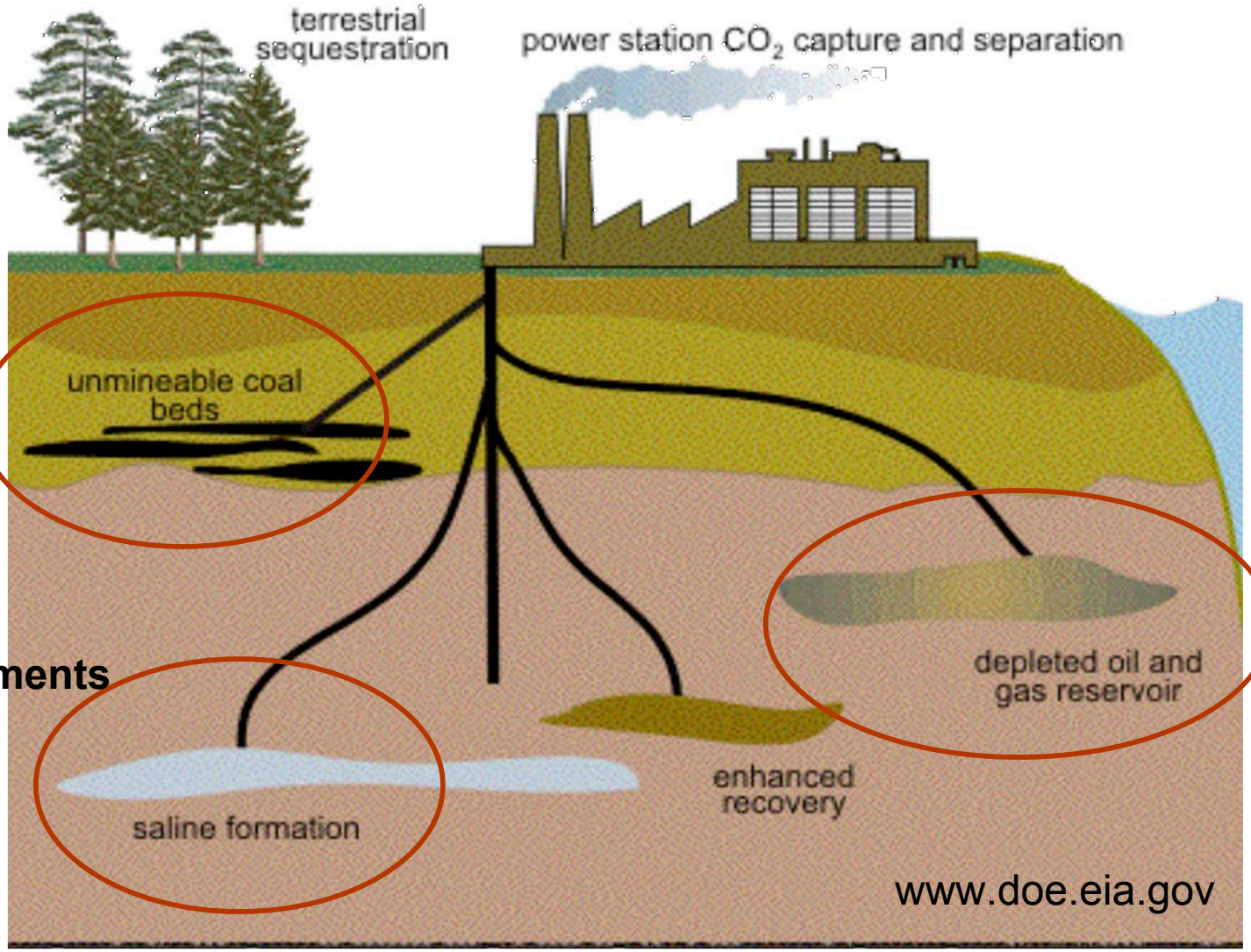




3 GCEP Vignettes

ECBM Physics

Unstable Displacements

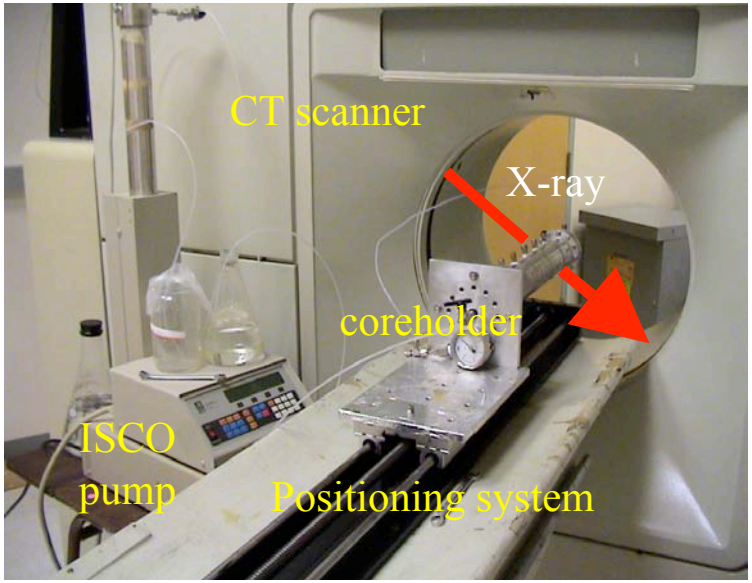


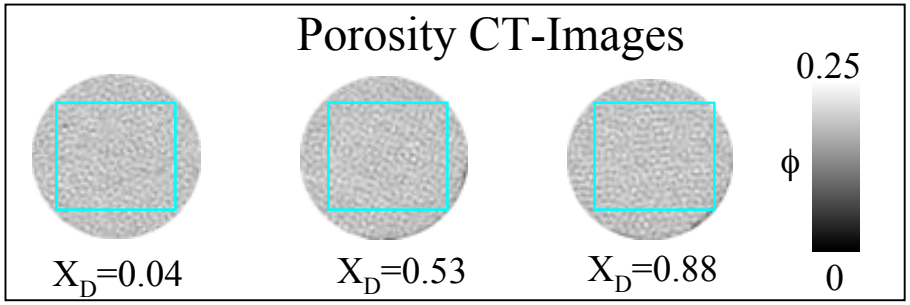
Traps and Seals

www.doe.eia.gov

Unstable Displacements

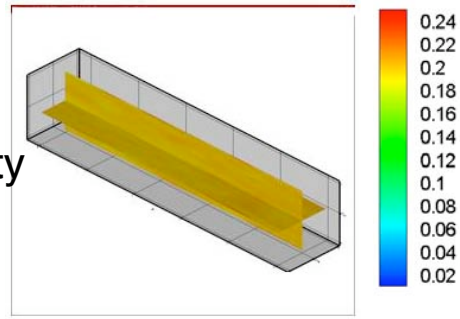
Experimental Set up



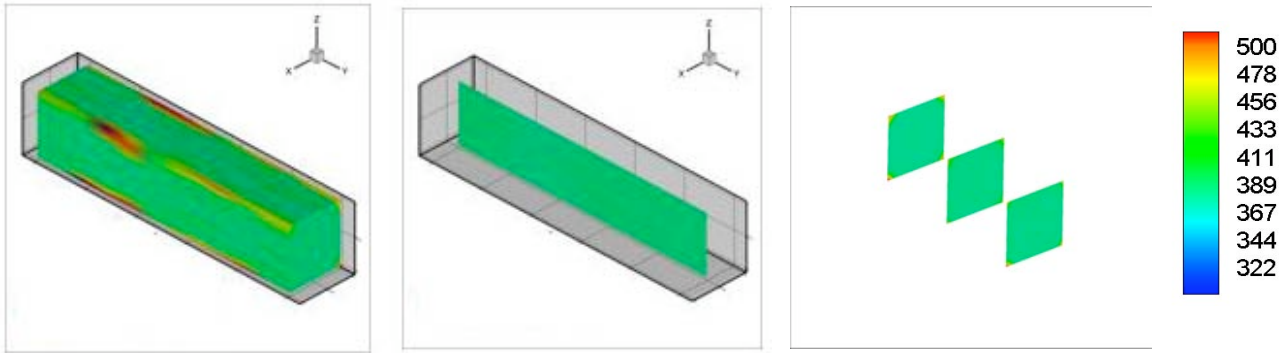


With 26 porosity/perm CT images

3D-porosity



3D-permeability



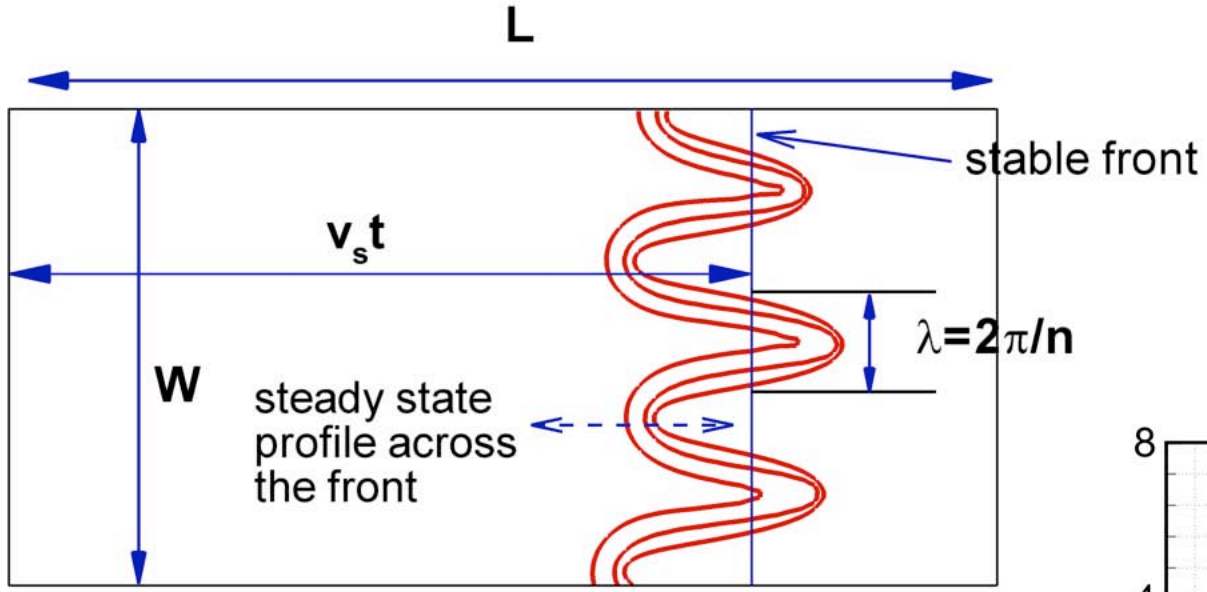
Rock: Berea Sandstone
Length: 52 cm
Diameter: 5.05 cm
Permeability: 377 md
Porosity: 0.205 PV
Orientation: horizontal

Neutral buoyancy

Tang and Kovscek, 2004

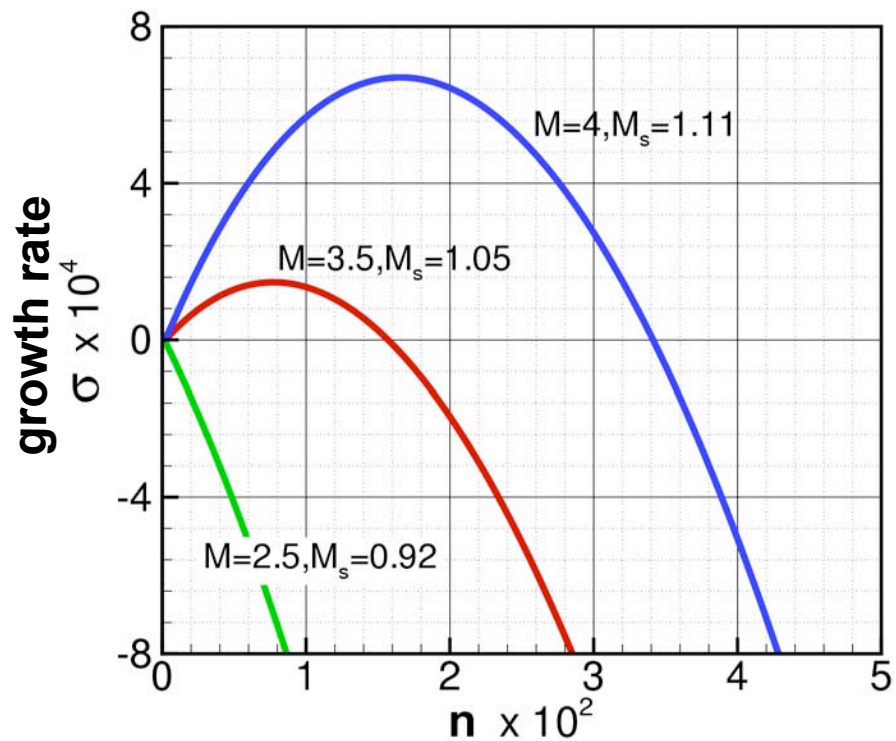
Unstable Displacements

Direct Numerical Simulation



Shock mobility ratio :

$$M_s = \frac{\lambda(s_{sf})}{\lambda(0)}$$

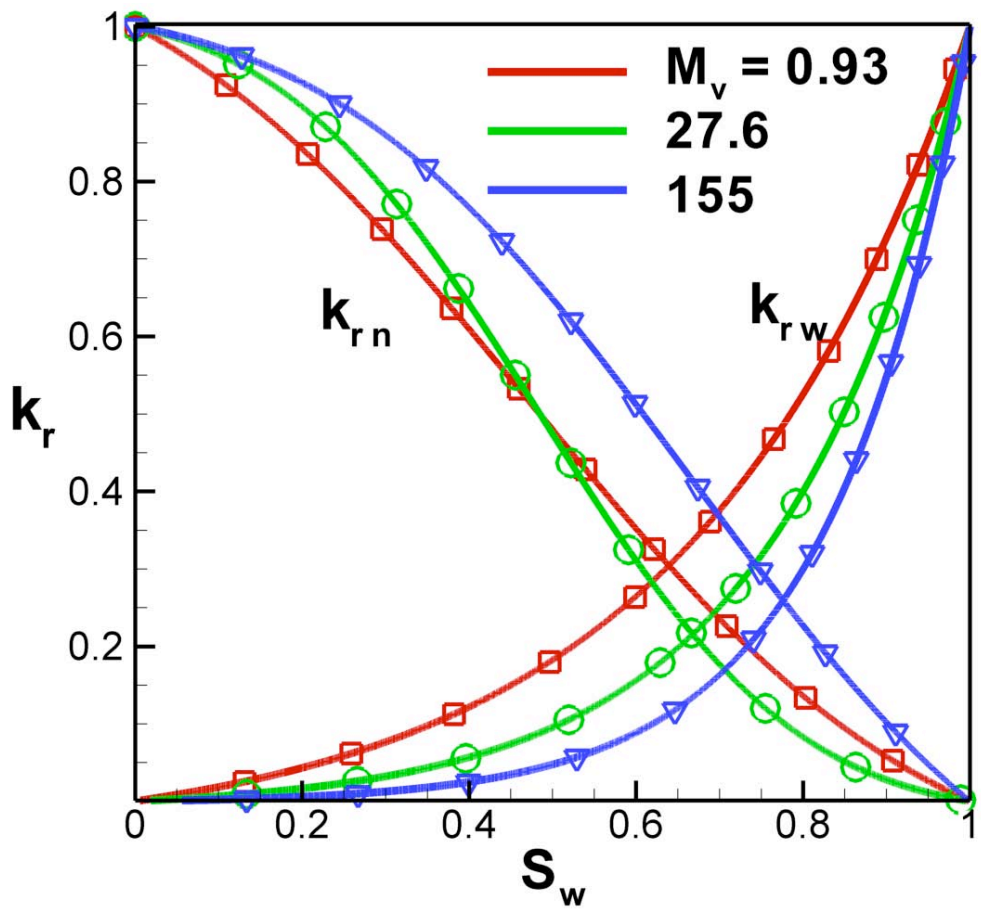


- **Growth rate positive, $M_s > 1$**
- **Growth rate negative, $M_s < 1$**

Riaz and Tchelepi, 2005

Completely Determined Rock Properties

Steady-state
Relative permeability



$$\mathbf{u}_w = -\frac{Kk_{rw}}{\mu_w}(\nabla P_w - \rho_w \mathbf{g})$$

$$\mathbf{u}_n = -\frac{Kk_{rn}}{\mu_n}(\nabla P_n - \rho_n \mathbf{g})$$

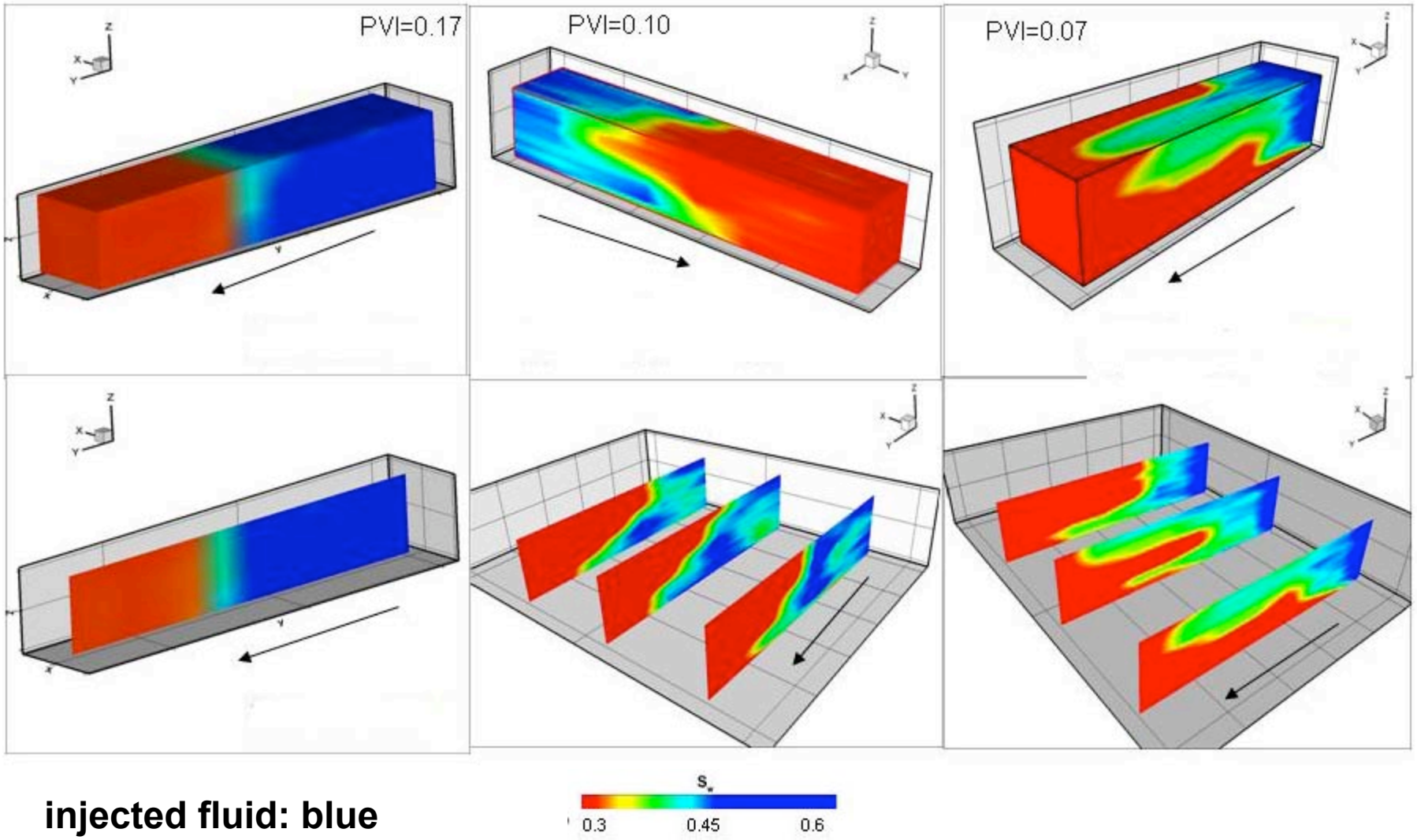
$$\phi\frac{\partial S_w}{\partial t} = -\nabla \cdot \mathbf{u}_w$$

$$\phi\frac{\partial S_n}{\partial t} = -\nabla \cdot \mathbf{u}_n$$

3D-distribution: u=1.05 m/d

neutral buoyancy

M^0=0.07~0.91 | M^0=2 | M^0=12~22

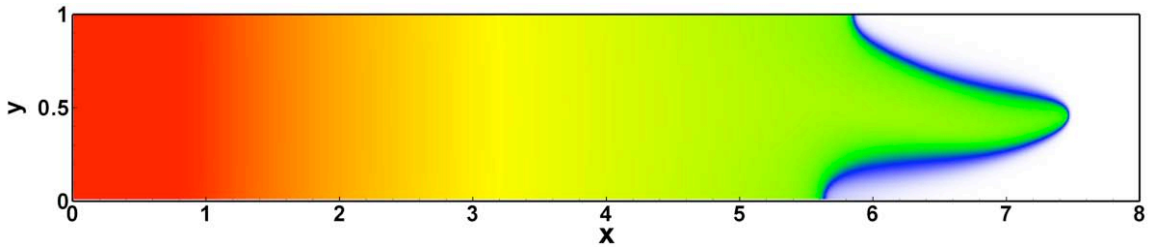


injected fluid: blue

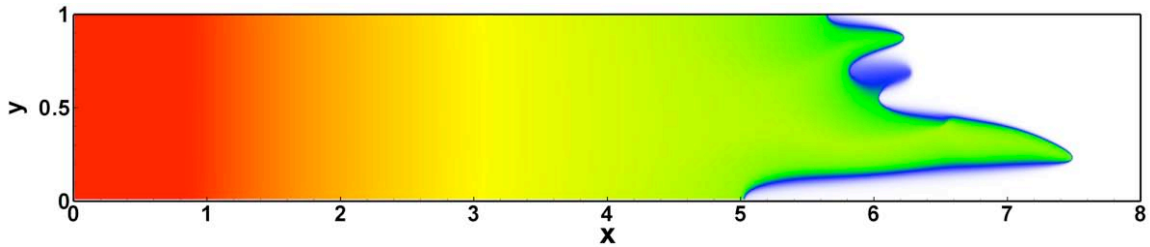
DNS versus Experiments

Riaz, Tang, Tchelepi, and Kovscek, 2006

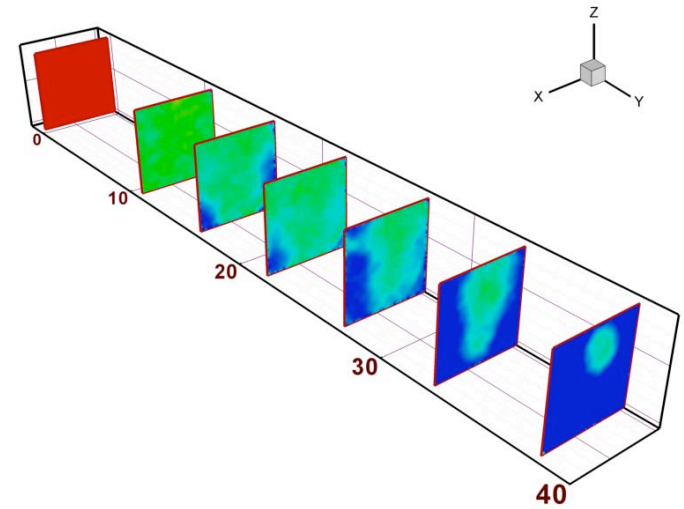
M_v=155

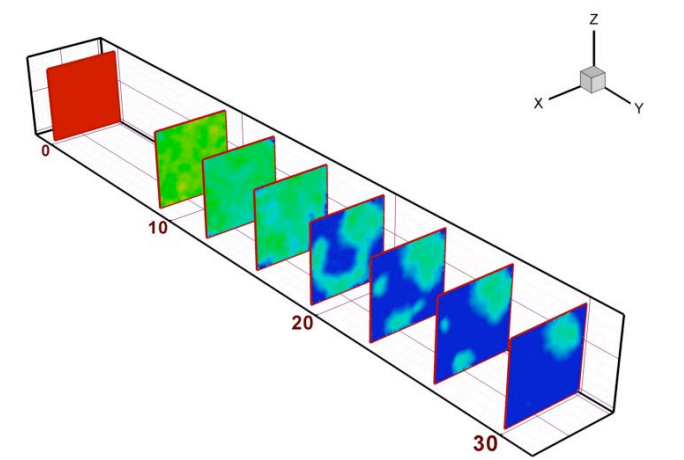


M=155, Ca=2x10^{-7}



M=155, Ca=6x10^{-7}

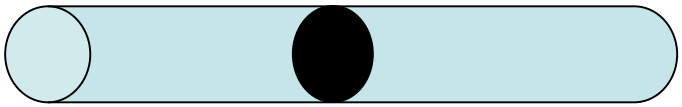


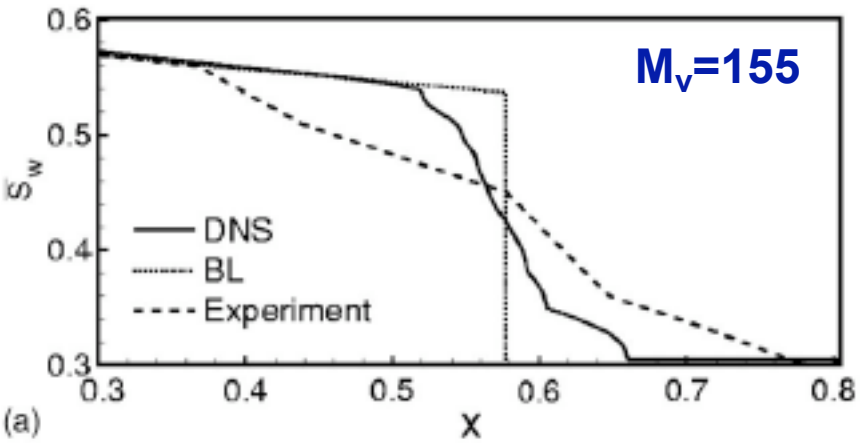


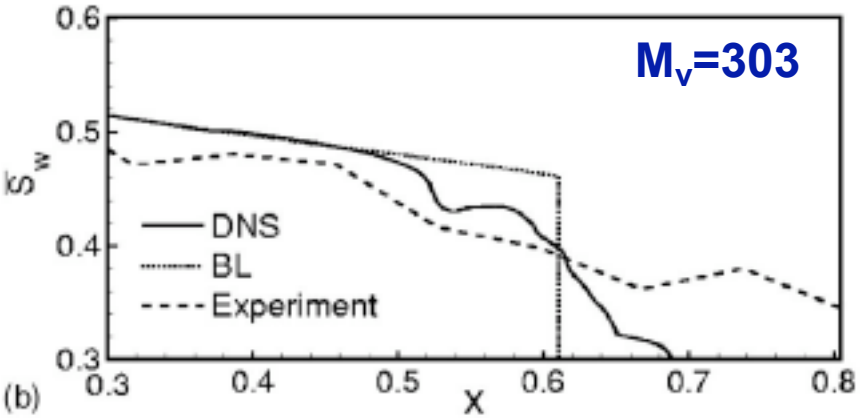
injected fluid: red

Summary: Unstable Flows

- relative permeability applicable to stable flows
- qualitative agreement only for M > 1
- onset of instability marks the threshold of validity of rel-perm approach
- a fundamental problem that we have not solved, but wave our hands at a lot

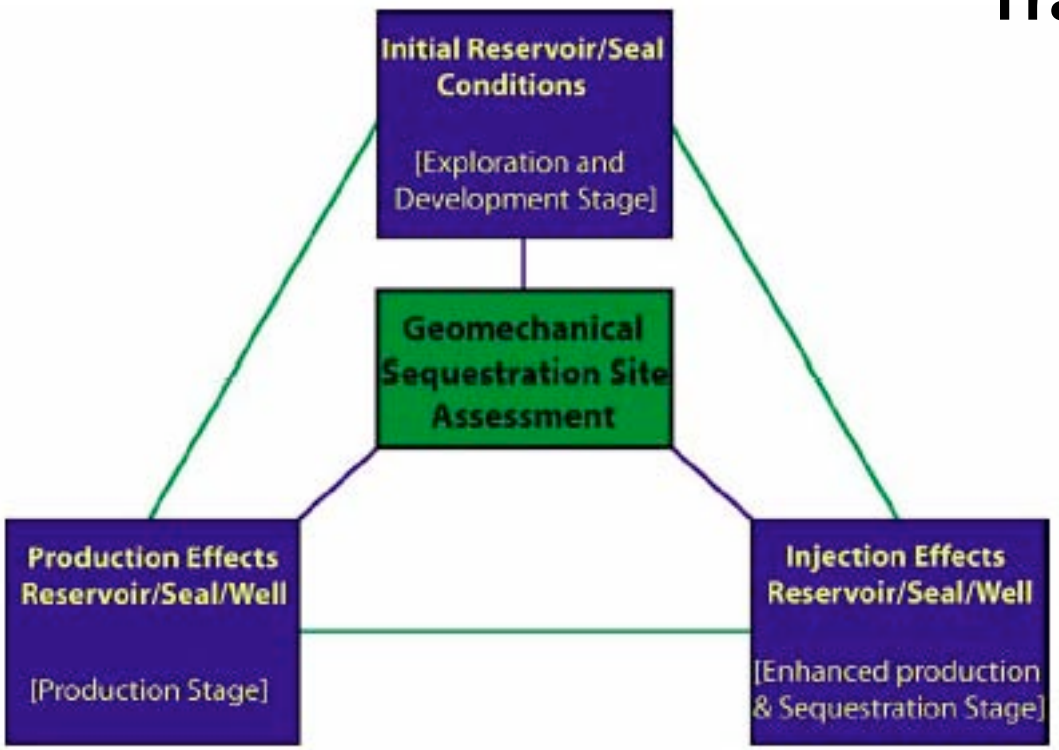






Riaz, Tang, Tchelepi, and Kovscek, 2006

Geomechanics and Seal Capacity



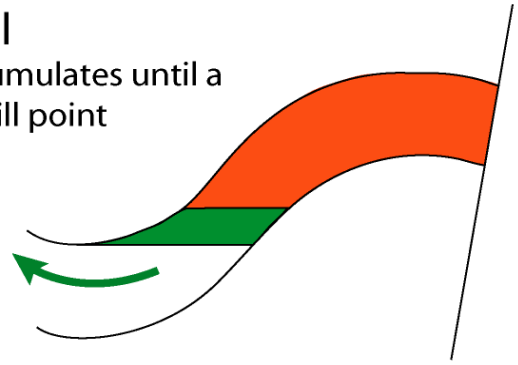
Trap and Seal Framework

- How will CO_2 injection affect the reservoir seal?
- Did production and depletion affect the seal?
- What are the geomechanical mechanisms governing capacity?

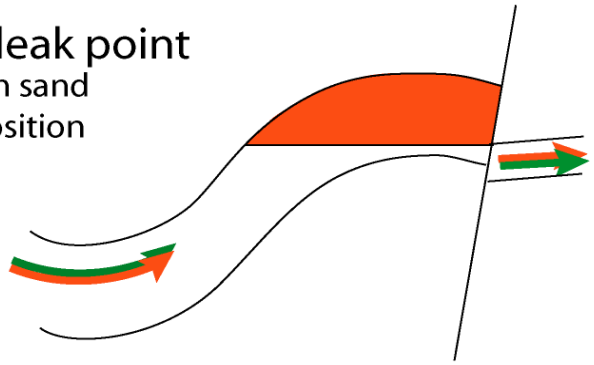
Hydrocarbon Fill Controls

Structural Controls

Fill to Spill
Column accumulates until a structural spill point is reached

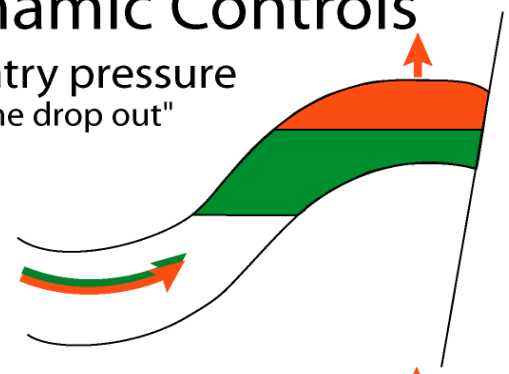


Fault leak point
Sand on sand juxtaposition

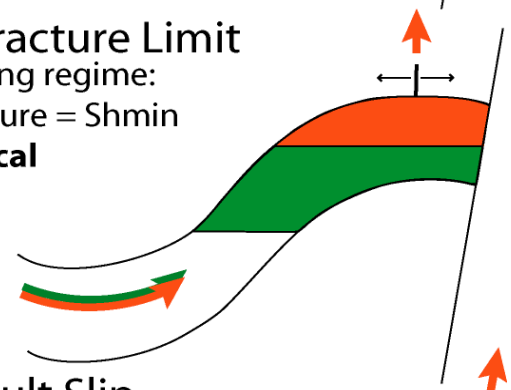


Dynamic Controls

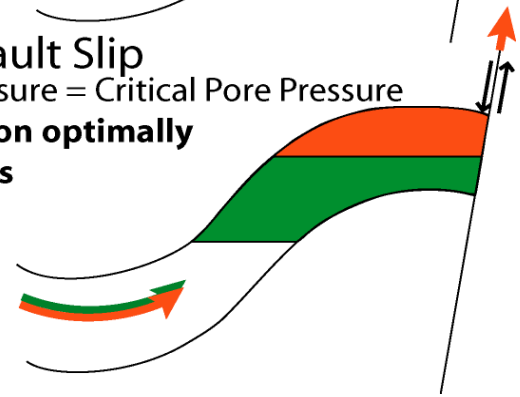
Capillary entry pressure
"One drop in one drop out"



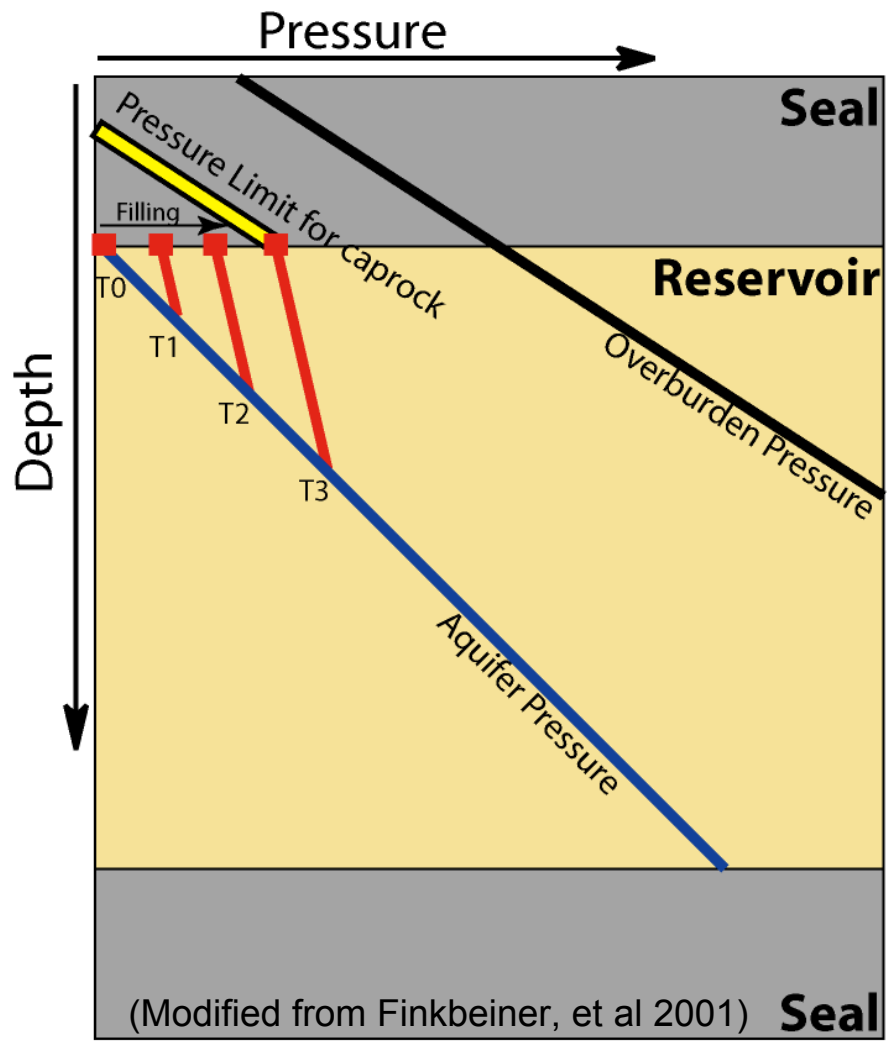
Hydraulic Fracture Limit
In normal faulting regime:
Buoyancy Pressure = Shmin
Results in **vertical hydrofracture**



Dynamic Fault Slip
Buoyancy Pressure = Critical Pore Pressure
Results in **slip on optimally oriented faults**



Dynamic Controls on CO_2 Capacity



- When pressure limit is reached, the seal cannot support any additional CO_2
- Pressure released through:
  - Capillary entry
  - Hydraulic fracturing
  - Dynamic fault slip

CO_2 Sequestration Seal Integrity Research Projects

Powder River Basin

- CBM Production
- Collaboration with Western Res. Foundation

Mountaineer, West Virginia

- Deep aquifer injection
- Collaboration with DOE, NETL, Battelle, AEP, BP, Schlumberger, Ohio Coal Development Office

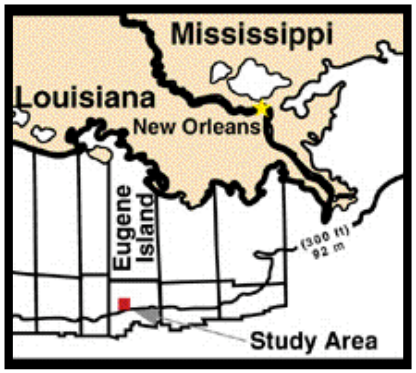
South Eugene Island

- Depleted Oil and Gas Reservoir
- Sequestration seal capacity
- Collaboration with ExxonMobil

Teapot Dome

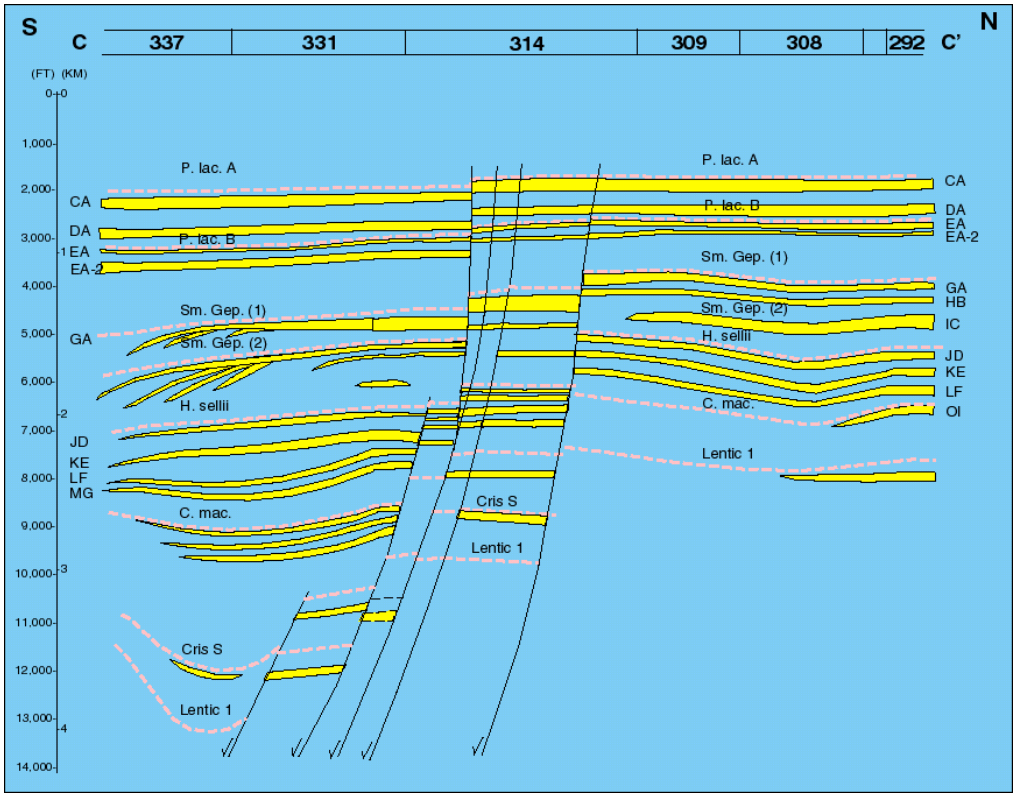
- Depleted Oil and Gas Reservoir
- Sequestration seal capacity
- Collaboration with DOE

South Eugene Island, Gulf of Mexico



•*Eugene Island Blocks 330 and 314 are excellent fields in which to examine CO2 sequestration potential in depleted oil and gas reservoirs in the Gulf of Mexico*

•

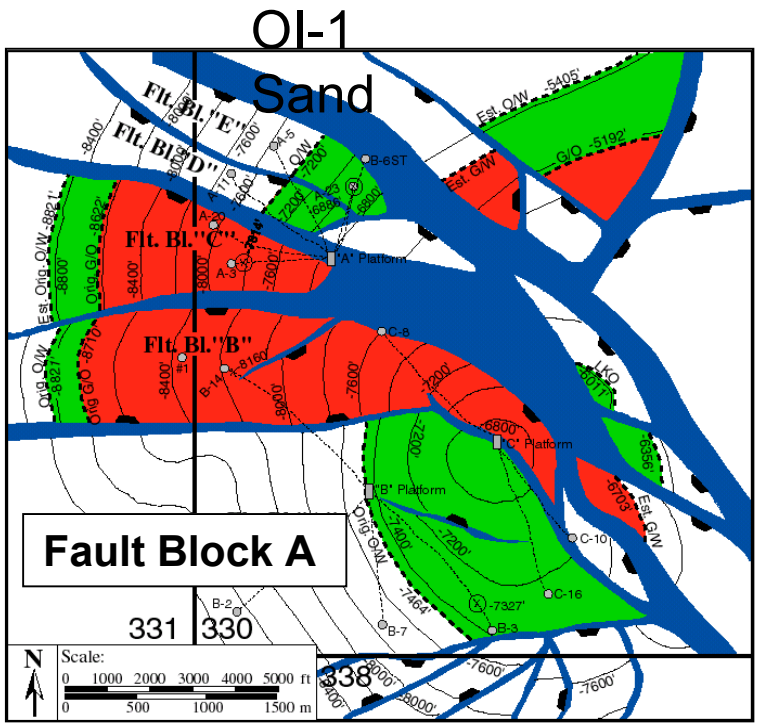


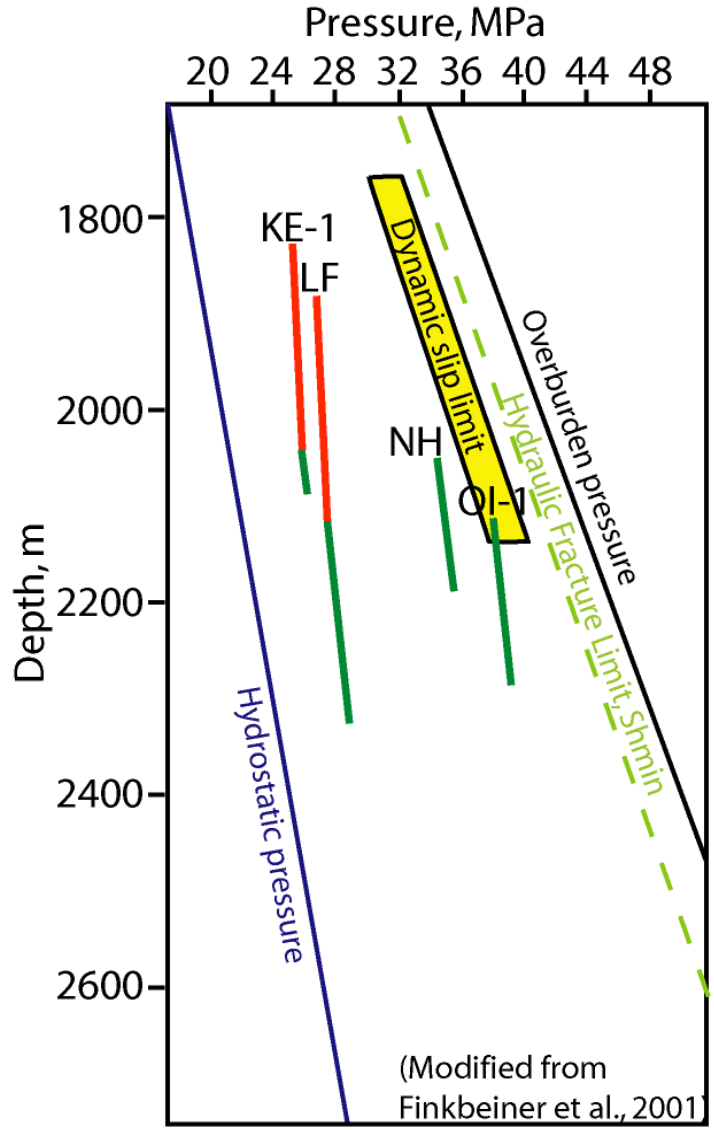
- Trap fill controlled by several different mechanisms

- Mature fields with substantial data available

- New 3D seismic interpretations are currently being performed at ExxonMobil

South Eugene Island 330
Fault Block A





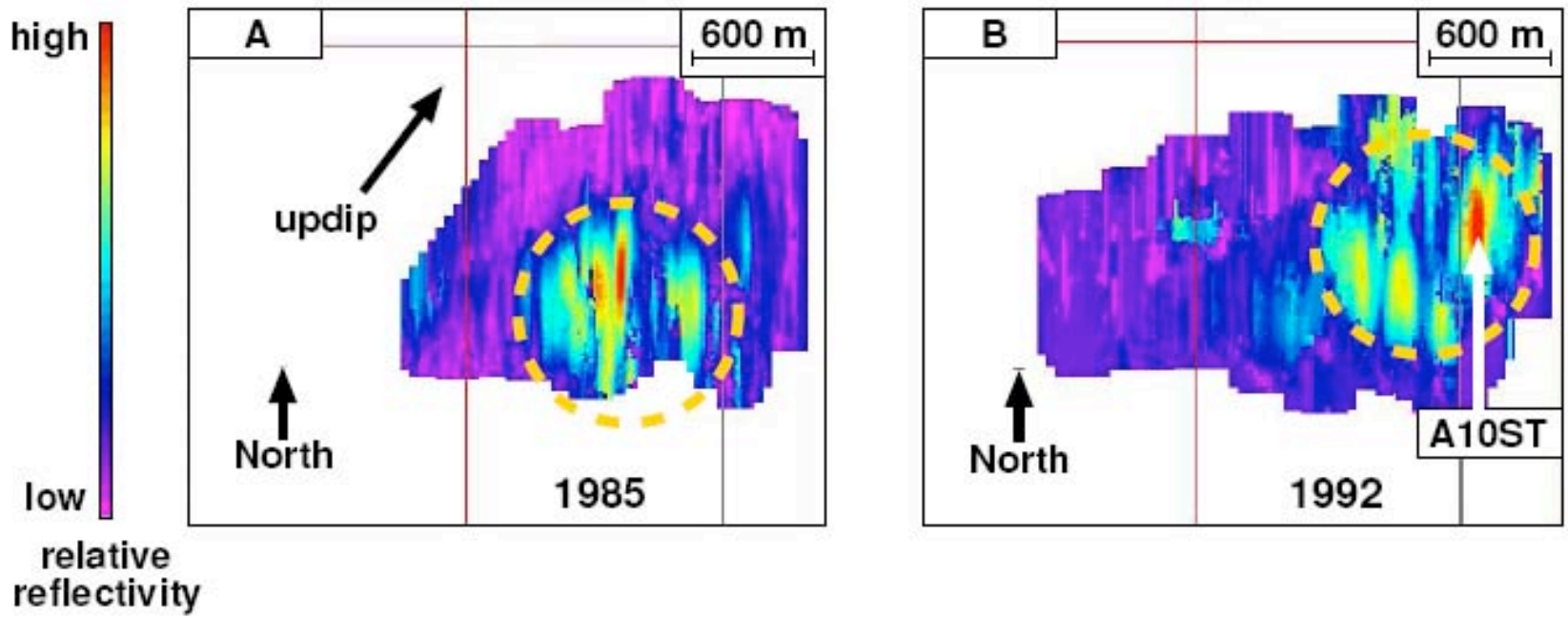
OI-1 Sand Fault Block A:

Small oil column

Highly over-pressure

Pressure at top reaches Dynamic fault slip limit

A "burp" of fluid moving up SEI fault?

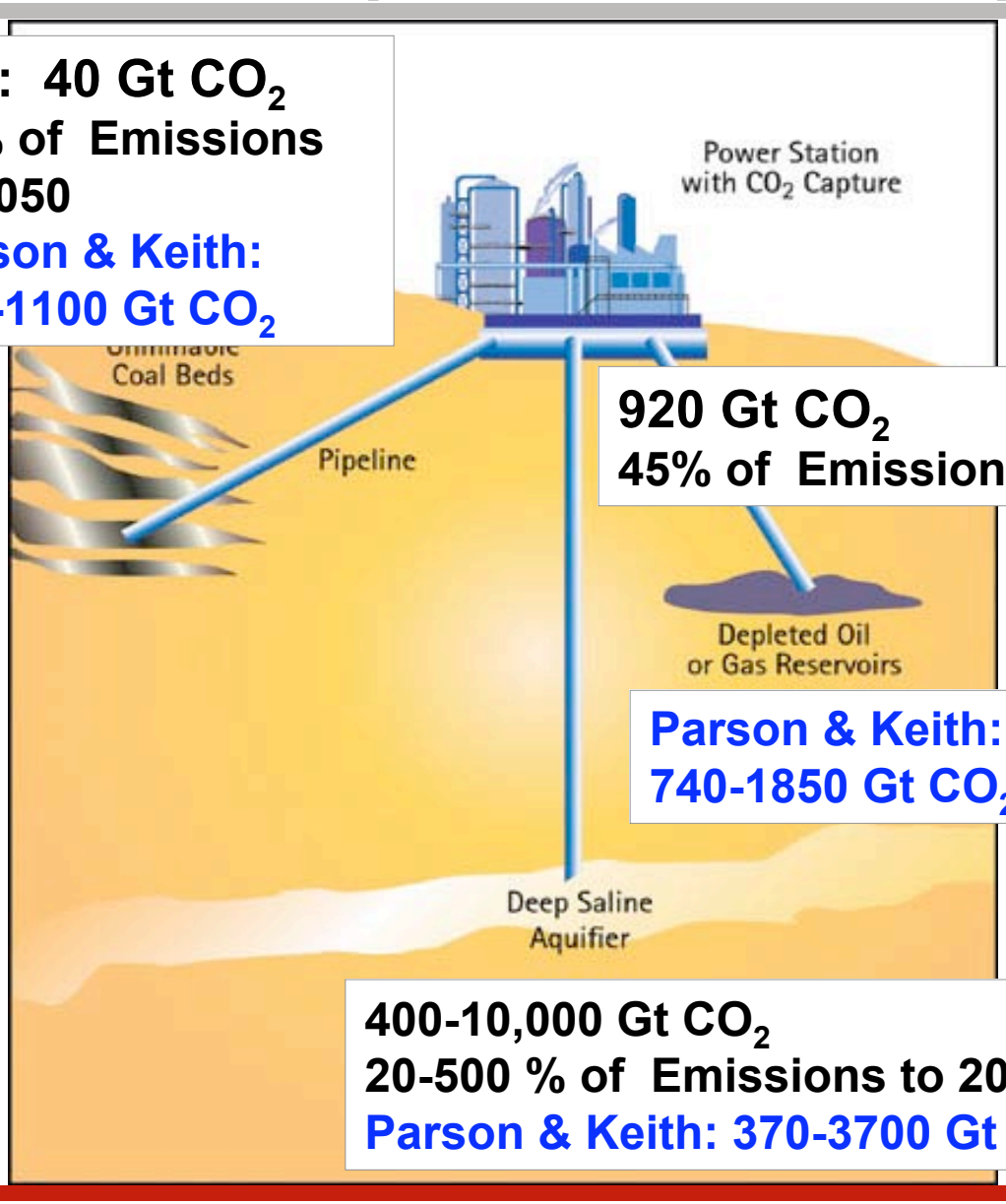


Haney et al. (2005)

Why study coalbeds?

IEA comparison at costs up to $20/t CO_2

IEA: 40 Gt CO_2
<2% of Emissions to 2050
Parson & Keith: 370-1100 Gt CO_2



920 Gt CO_2
45% of Emissions to 2050

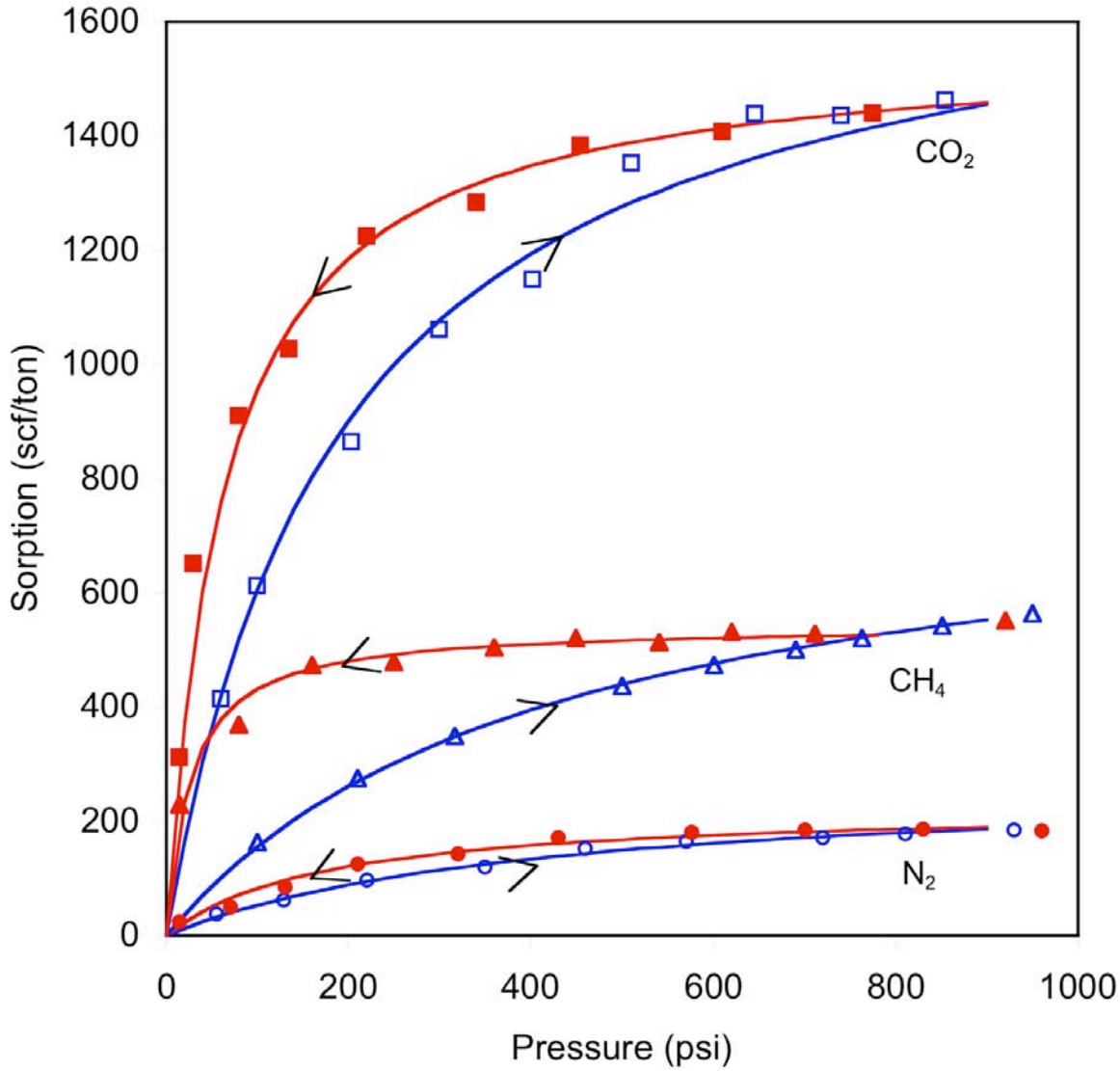
Parson & Keith: 740-1850 Gt CO_2

400-10,000 Gt CO_2
20-500 % of Emissions to 2050
Parson & Keith: 370-3700 Gt CO_2

- add certainty to volume estimates
- store other contaminants
- smother fires
- significant challenges for monitoring
- coal is intrinsically interesting

CO_2, CH_4, N_2 Sorption
Dry Powder River Basin (WY) Coal

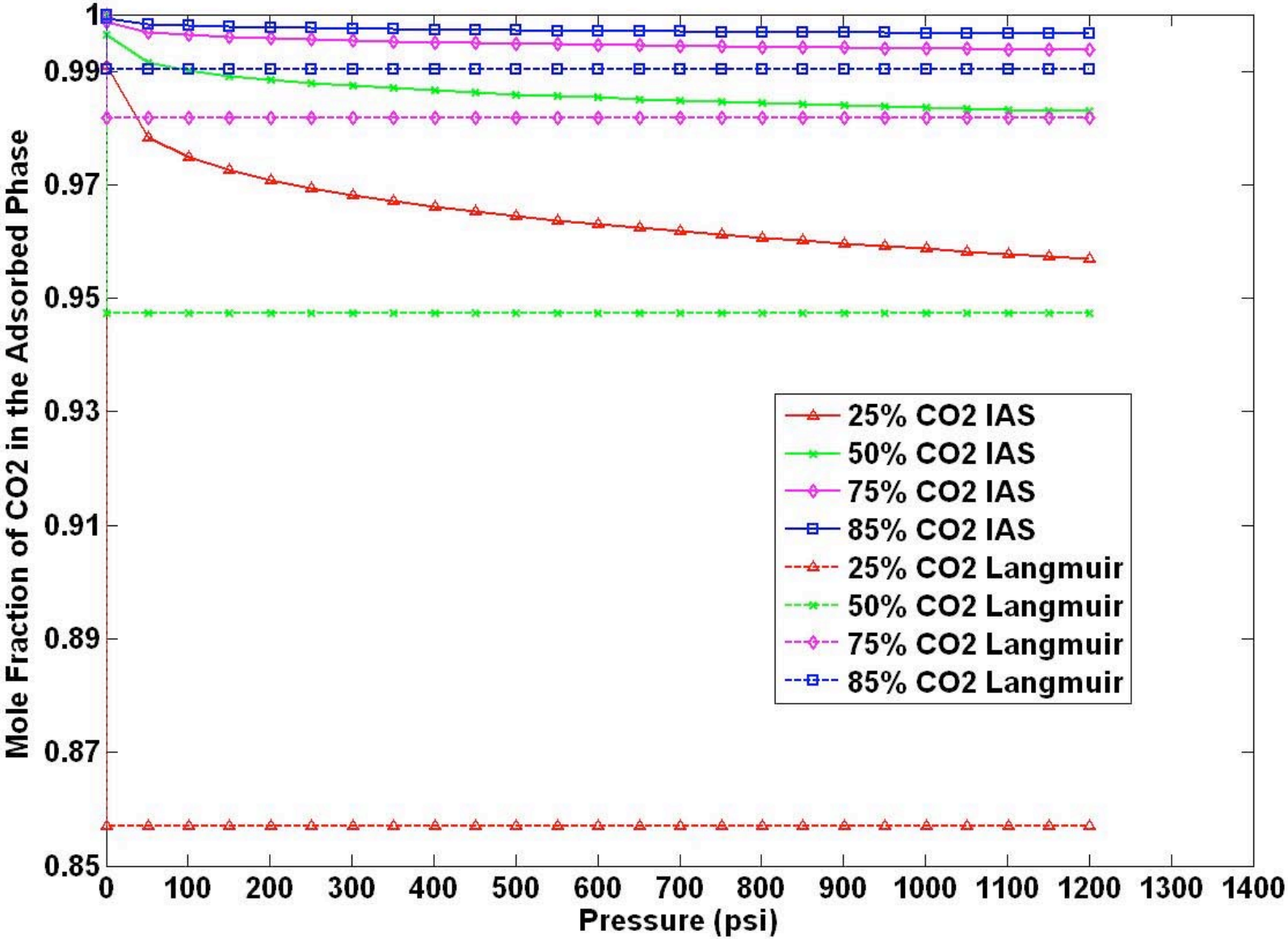
- Pure components are well fit by Langmuir isotherm
- CO_2 adsorbs preferentially
- adsorption hysteresis for all gases
- scanning loops are evident



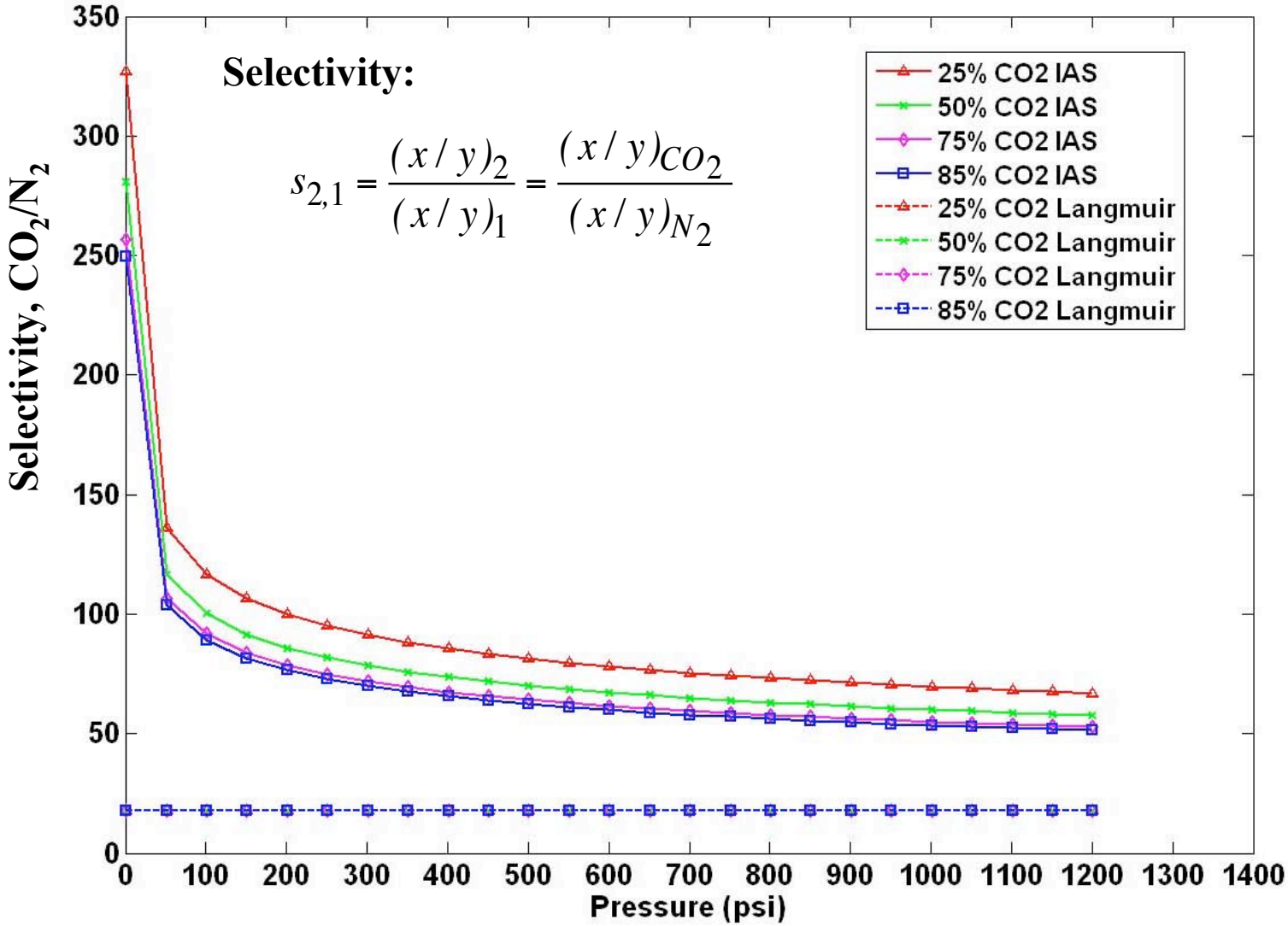
Tang, Jessen, and Kovscek, 2005

IAS vs Extended Langmuir

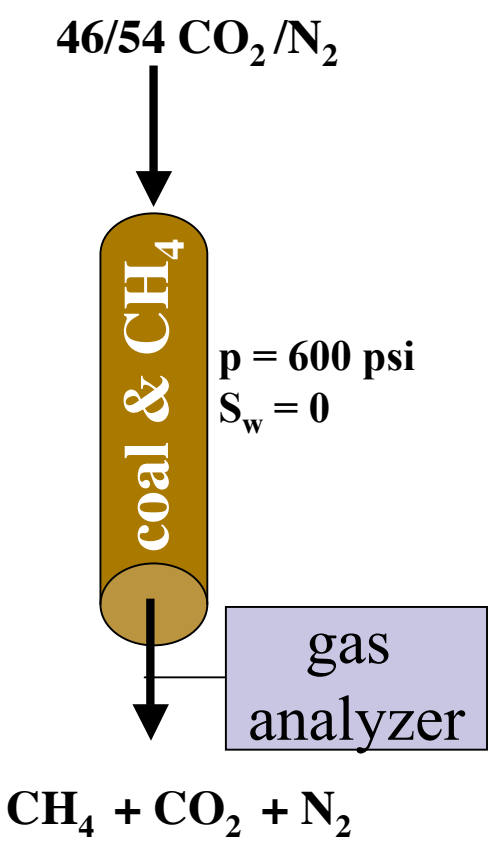
IAS = Ideal Adsorbed Solution



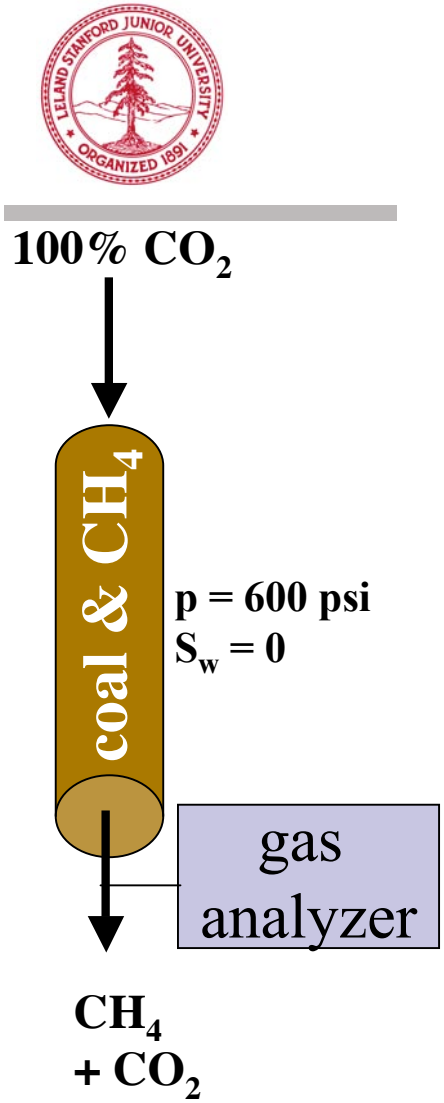
IAS vs Langmuir Adsorption

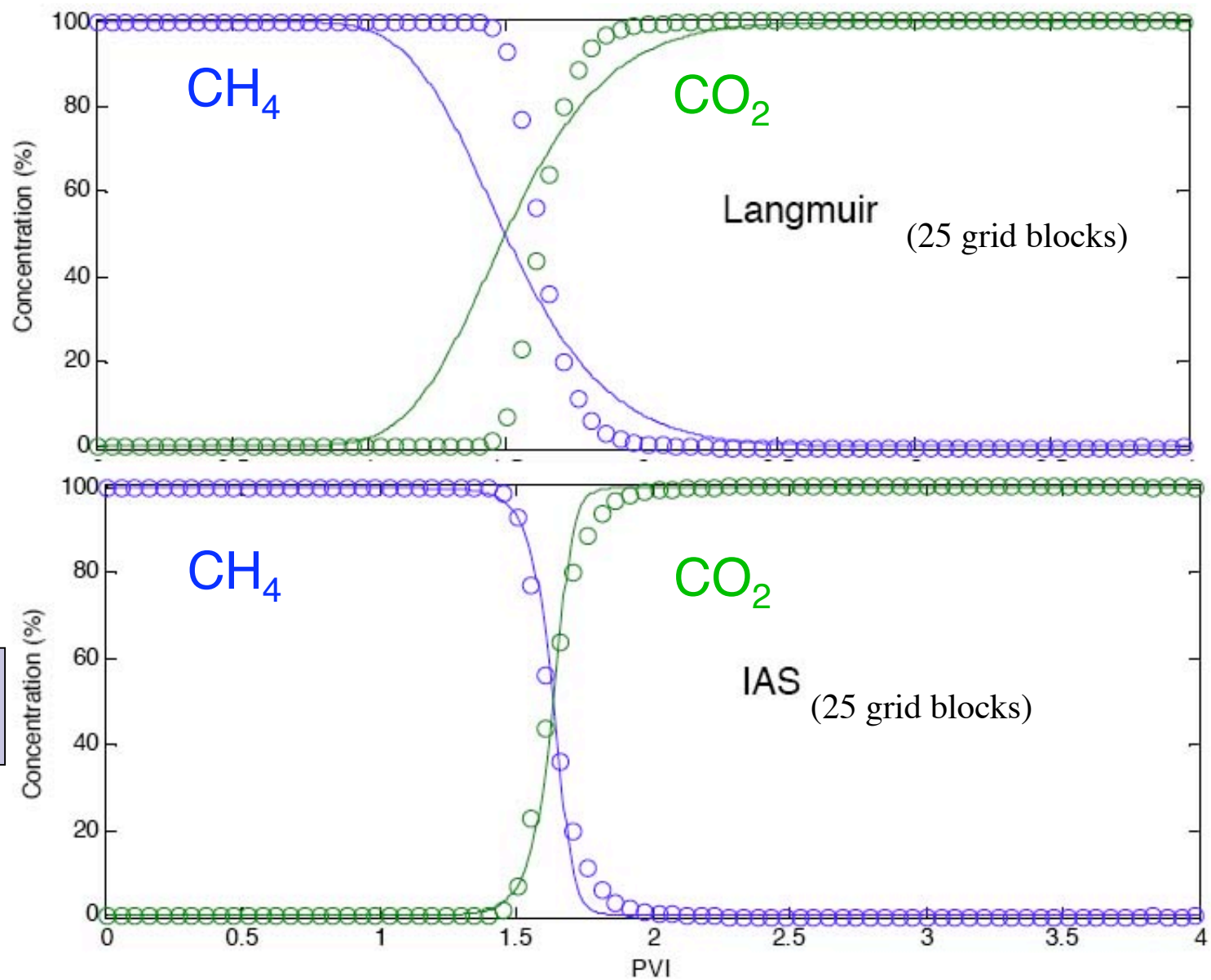


Adsorption/Desorption/Transport Modeling

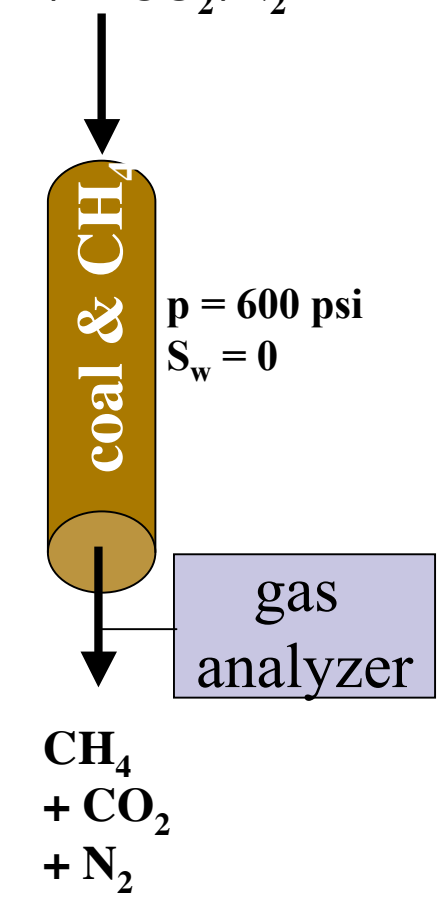


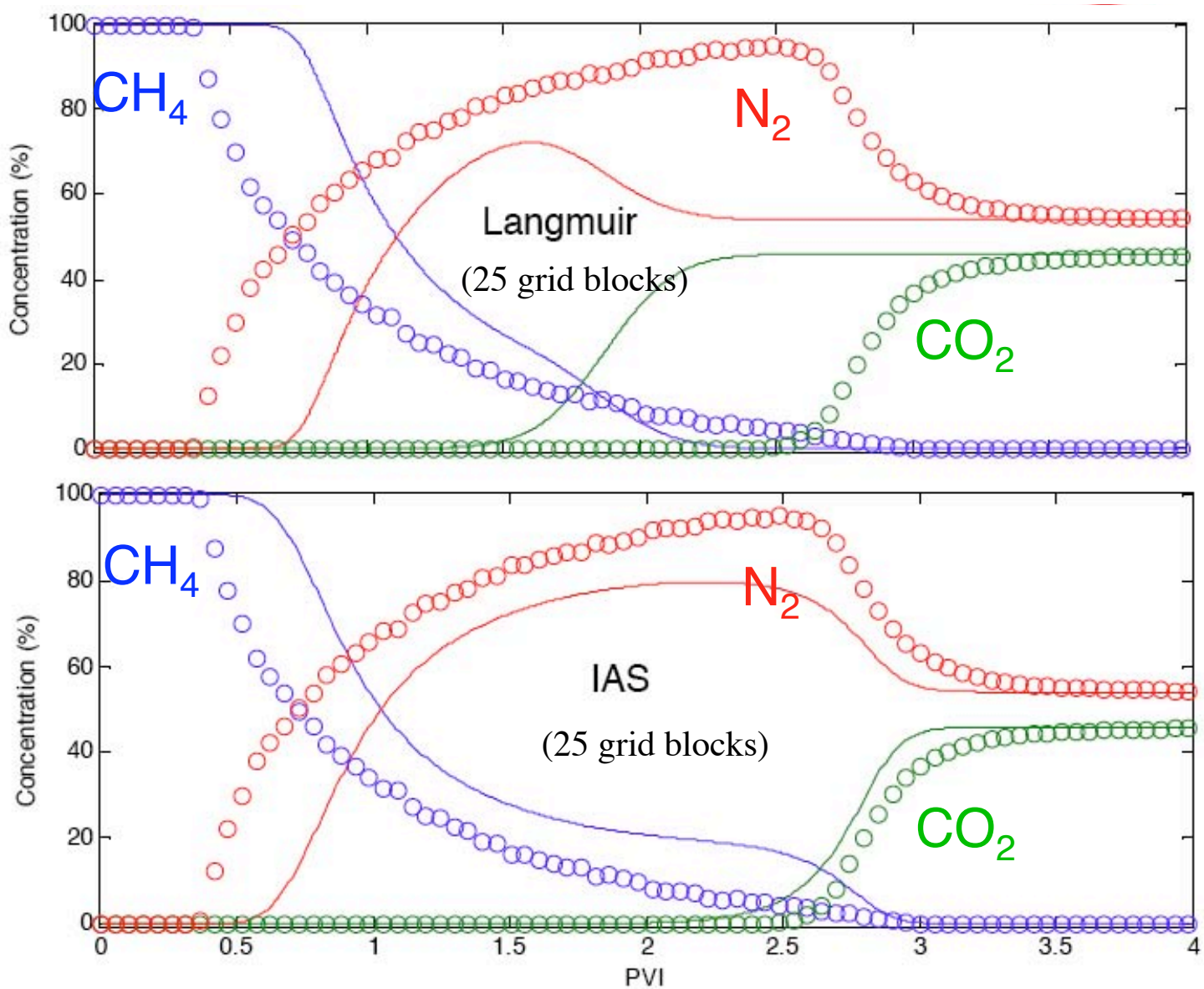
- **1D:** $$\phi \frac{\partial C_i}{\partial t} + (1-\phi)\frac{\partial a_i}{\partial t} + \nabla \cdot (\underline{v} C_i) = q_i$$
- **a_i: extended Langmuir vs ideal adsorbed solution (IAS)**
- **dual porosity**
  - **primary and secondary (grain): $\phi = \phi_1 + \phi_2$**
  - **instantaneous equilibrium**
  - **2%< ϕ_2 <8%**
- **PR-EOS with** $$V_{ads} = \sum_i z_i b_i$$
- **Finite difference solution**





no parameter adjustment

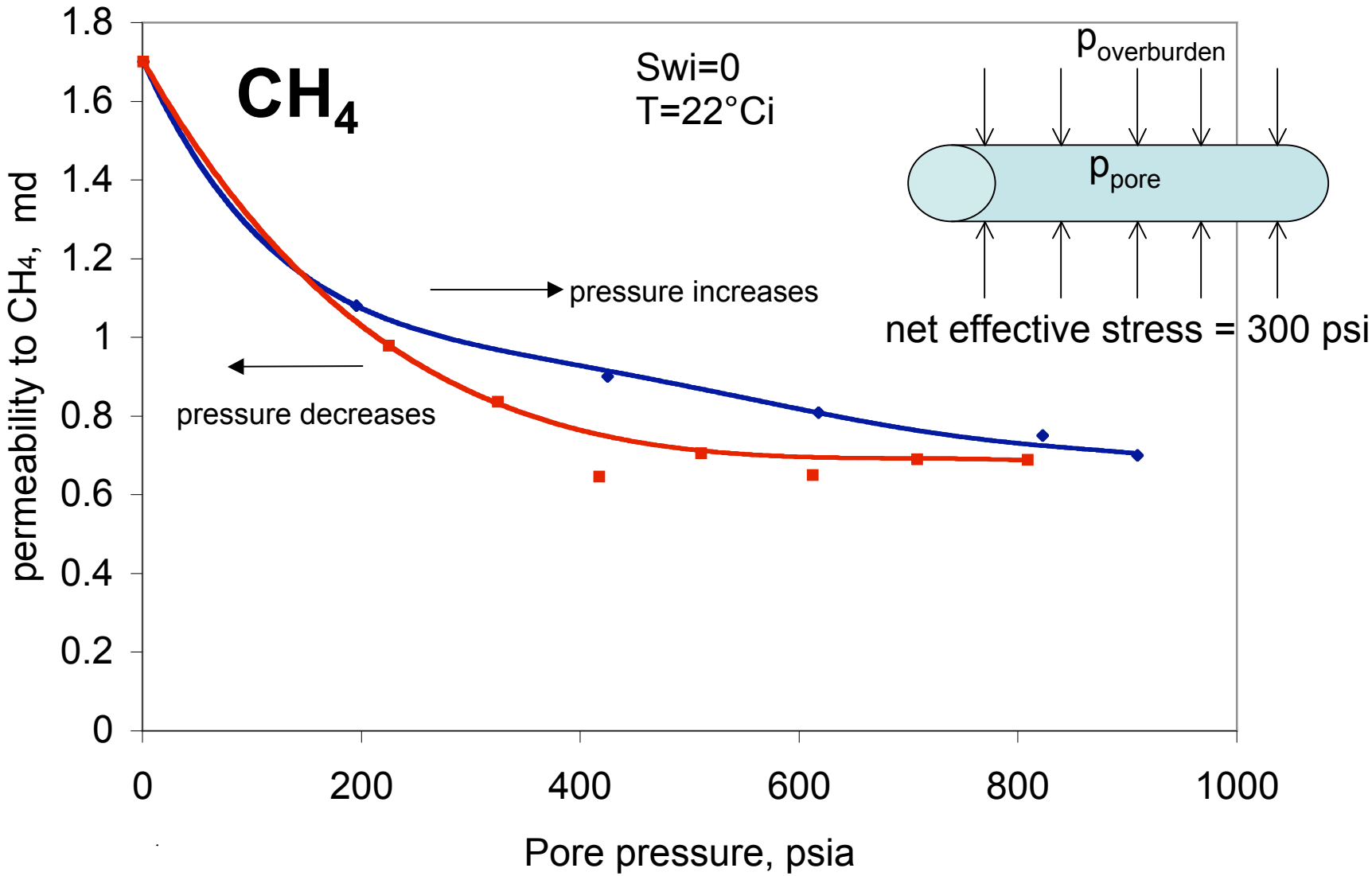




no parameter adjustment

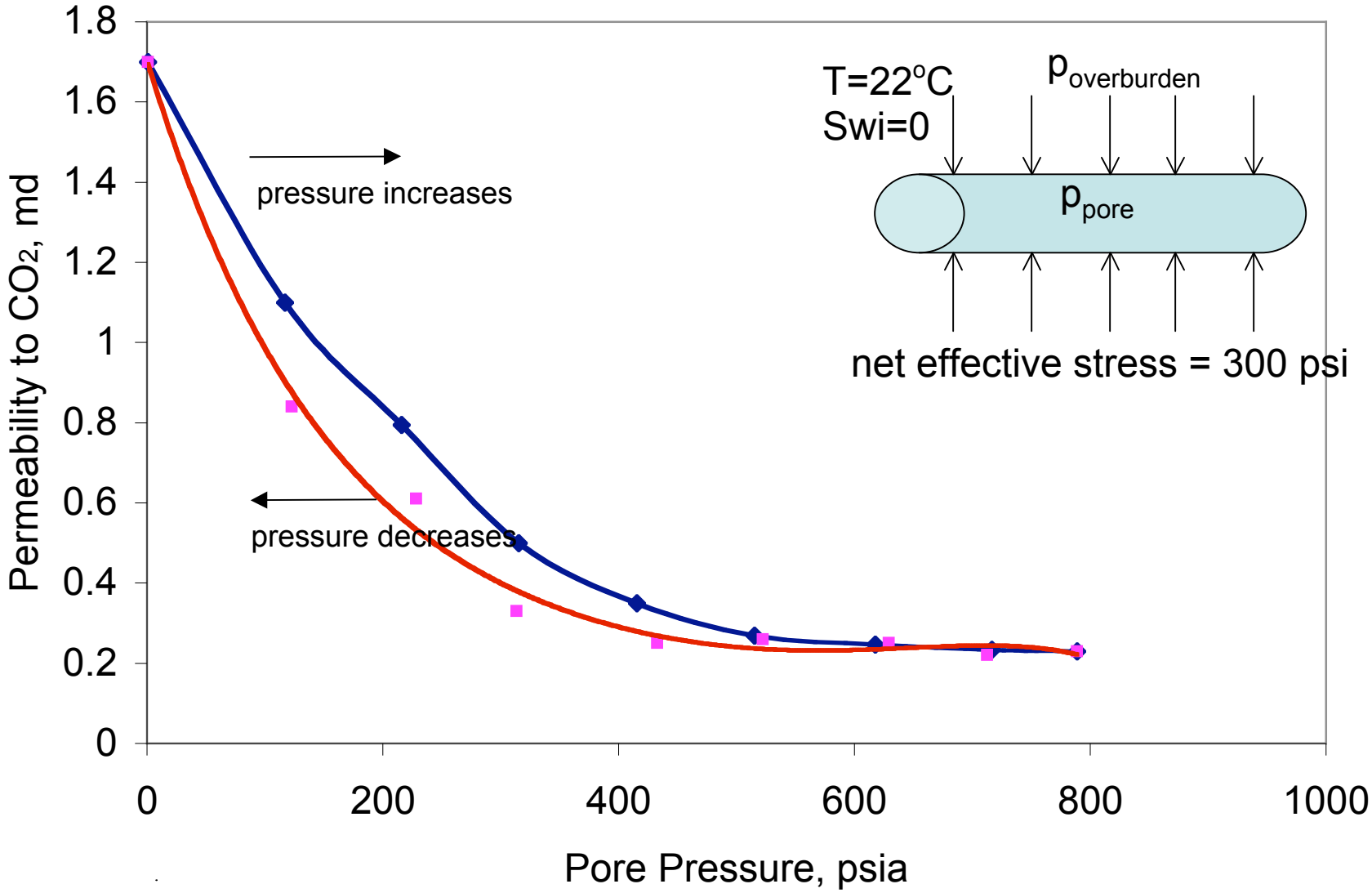
Is permeability sensitive to gas?

hysteresis loading/unloading



Permeability to CO_2

hysteresis loading/unloading



Summary: Coalbeds

- Current Activities
  - hysteresis
  - nonideal, multicomponent sorption
  - dispersion
  - swelling and permeability reduction
- Cartoon understanding?
  - yes
- Quantitative/mecha-nistic understanding?
  - no

Conclusion

What have we found?

- Knowledge:oil/gas > aquifers > coalbed > ocean sediments
- unstable displacements not described well by Darcy's law
- reservoir seals can be dynamic
- Coals demonstrate rich dynamical behavior
  - gas adsorption
  - adsorption hysteresis
  - temperature
  - water pH

Future Priorities?

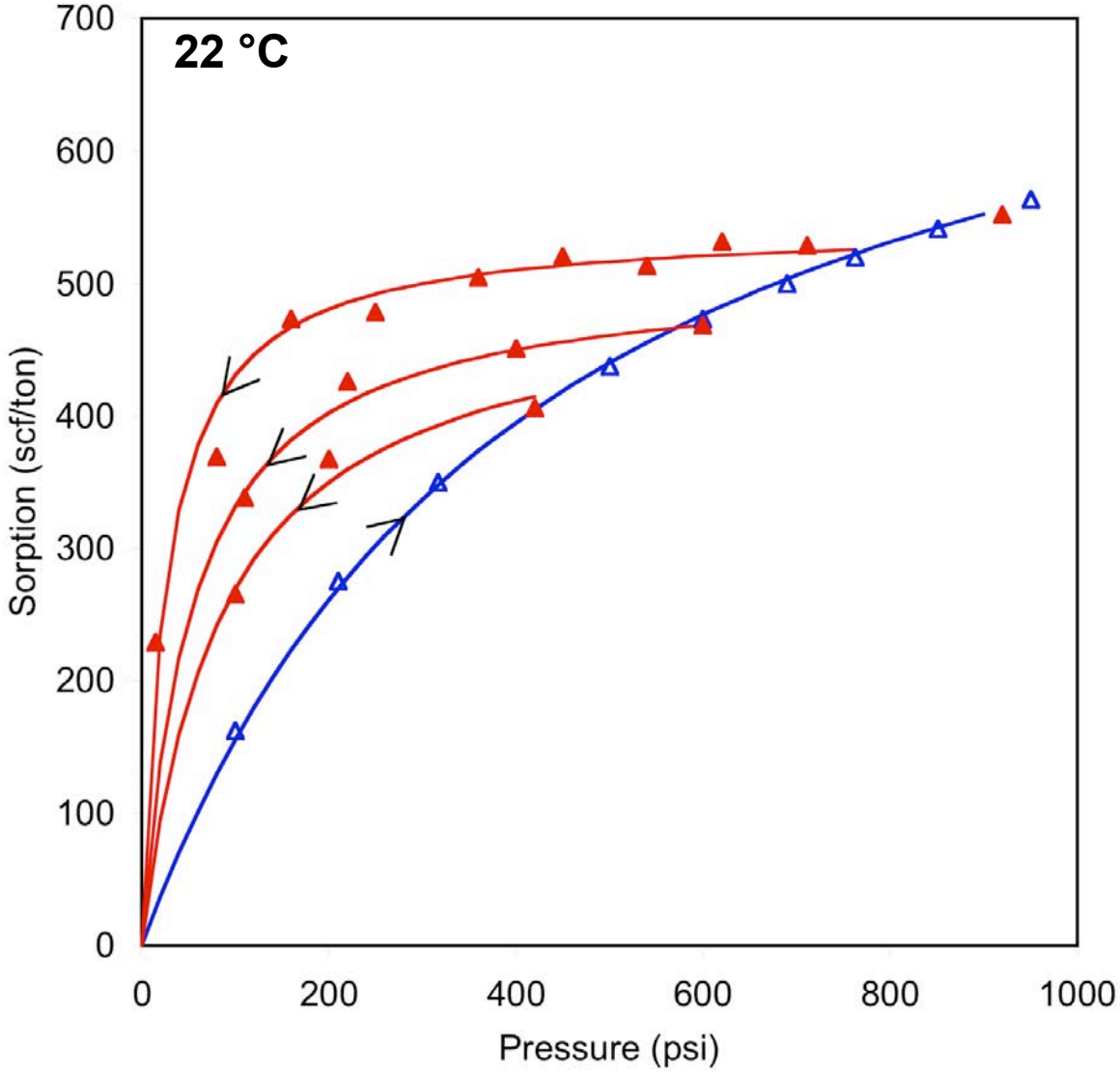
- world class science and engineering science
- further fundamental understanding of transport and geomechanics:T&E
- assess through field tests and simulation, methods to access low perm systems
- injectivity in coals as a function of gas type, stress, and temperature

Acknowledgement

- **GCEP**
- **Collaborators: Khalid Aziz, Lou Durlofsky, Paul Hagin, Marc Hesse, Wenjuan Lin, Lynn Orr, Amir Riaz, Hamdi Tchelepi, Jerry Harris, Mark Zoback, Paul Hagin, Youli Quan, Tom Tang, Eduardo Santos, Adeyemi Arogunmati, Laura Chiaramonte, Jolene Robin-McCaskill, Hannah Ross, Chun-tang Xu, Taku Ide, Wenjuan Lin, Carolyn Seto, Kristian Jessen**

CH_4 Scanning Loops

Initial pressure influences desorption hysteresis



Composite Coal

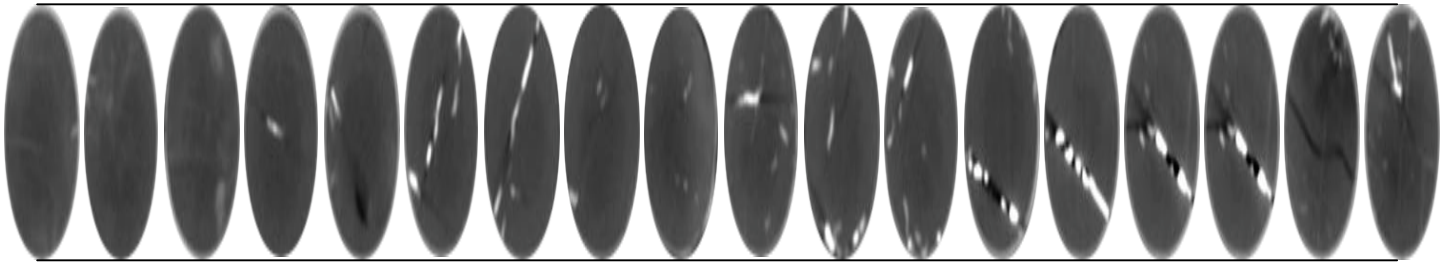
Total length: 21.17 cm

Diameter: 2.79 cm

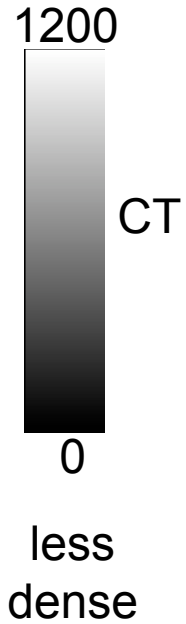
Porosity: 7%

Permeability to He: 1.7 md

Intact composite coal plugs

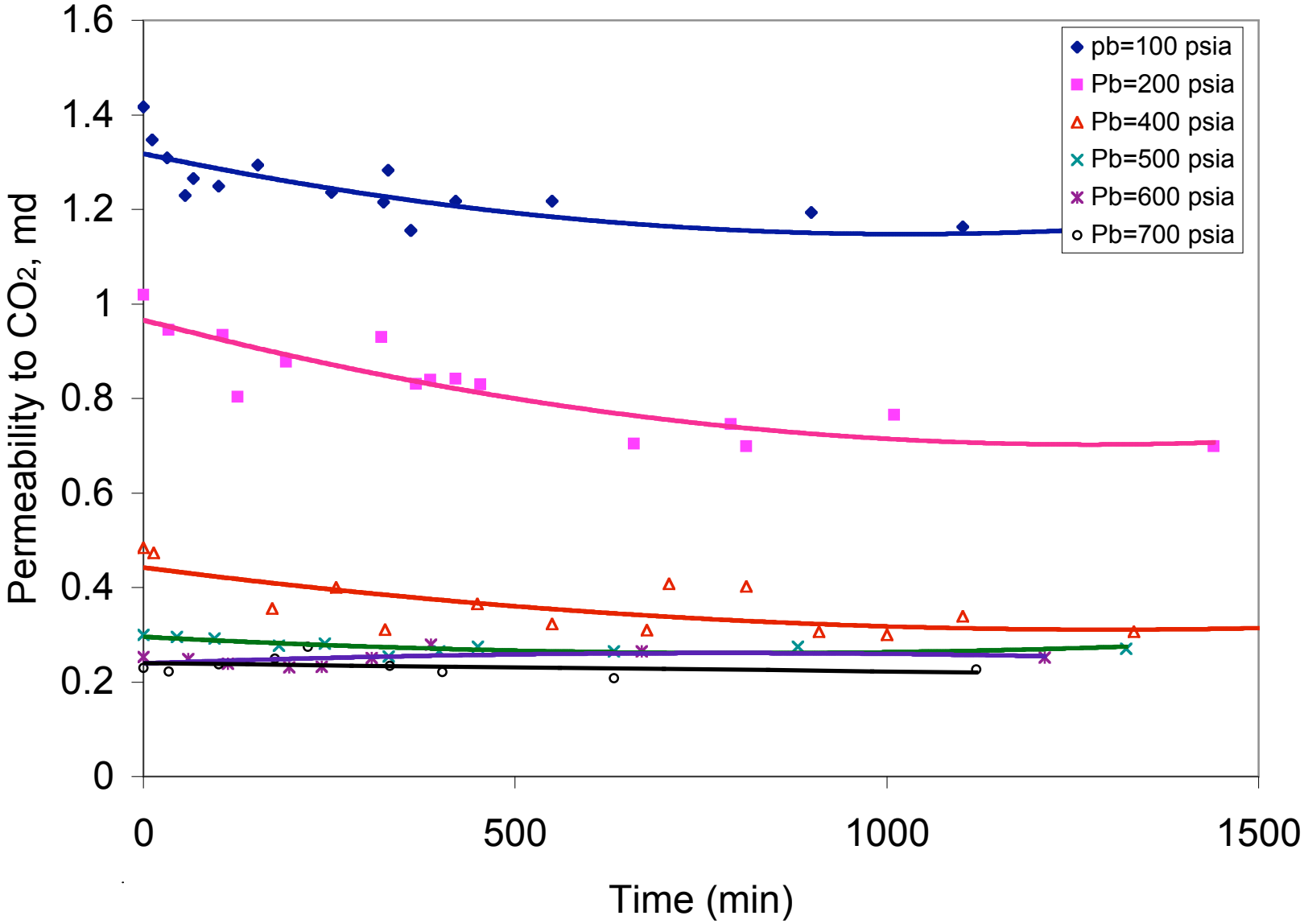


Corresponding CT-images



Time to Steady Flow

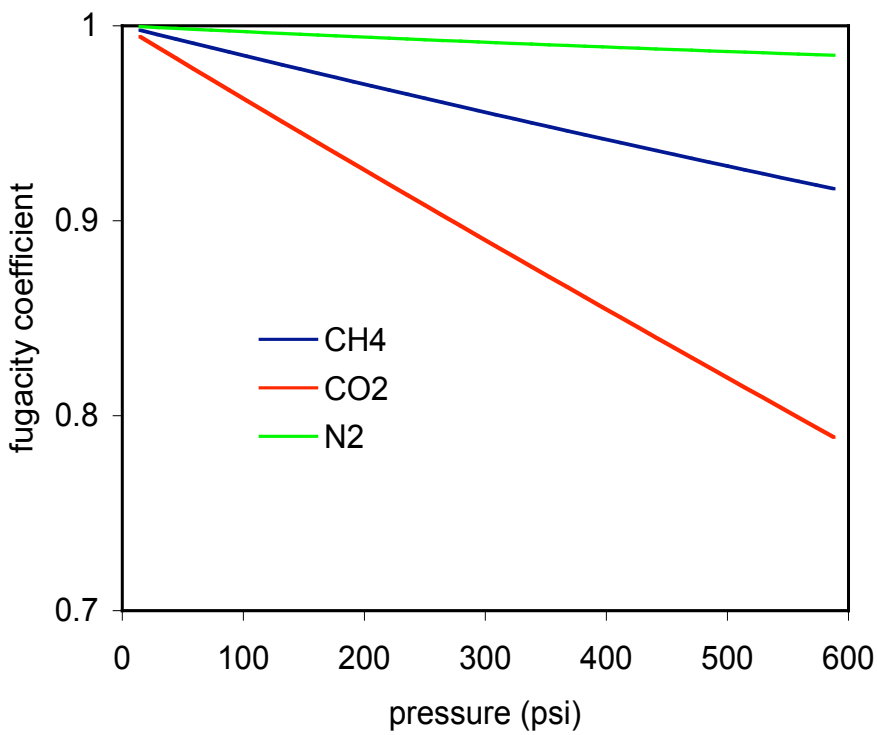
increasing pressure



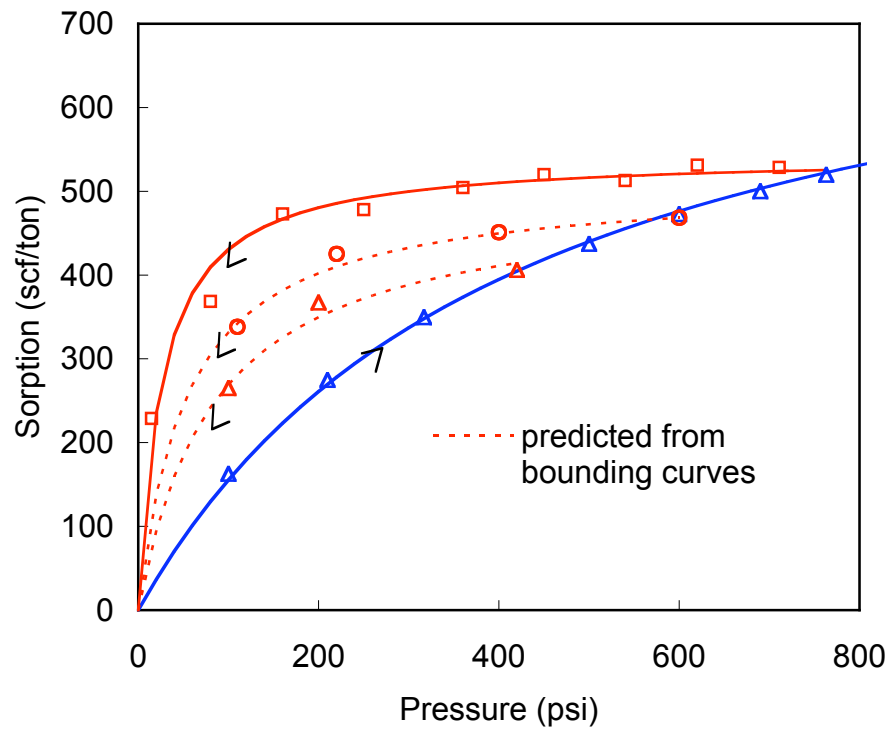
Summary: Coalbeds

Current Modeling Activities

dispersion, non-ideal behavior, and hysteresis



$$y_i P \Phi_i = x_i \pi_i \gamma_i$$



Methane sorption