Geomechanics of Coal and Gas Shales

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G3 CENTER FOR GEOMECHANICS, GEOFLUIDS & GEOHAZARDS

Outline

Science Questions and Objectives

- First Order Observations – Similarities Coal/Shale Gas
- Shale Gas – Similarities/Differences

Permeability Evolution

- Mechanistic Models – Dual Porosity Models with Deformation
  - Geometric Attributes
  - Mechanistic Features
- Swelling Response
  - Theoretical Response – single porosity
  - Constrained Crack Model – dual porosity

Experimental Observations

- Apparatus
- Capabilities and Experimental Suites
- **Coals**
- **Shales**

Field-Scale Response

- ECBM and Optimization
- Well Survivability
- Gas Outbursts

Summary

CBM - Science Questions

Applications

CBM and ECBM

CO_2 sequestration

In situ combustion

Coal bumps and bursts

Principal Questions

How do stresses and deformation and gas and water saturations control:

Permeability – rates of injection and recovery

Sorption – capacity and the influence of stress and swelling

} **i.e. Optimize recovery**

Science Questions

What are processes and rates of sorption and desorption?

What are rates and magnitudes of swelling strains and related stresses?

How do these affect permeability and sorption capacity?

How does coal respond to methane/CO_2/N_2 injection/adsorption?

How does sequencing of these binary/ternary mixtures influence injectivity/recovery?

What are relative permeabilities to water and binary diffusion?

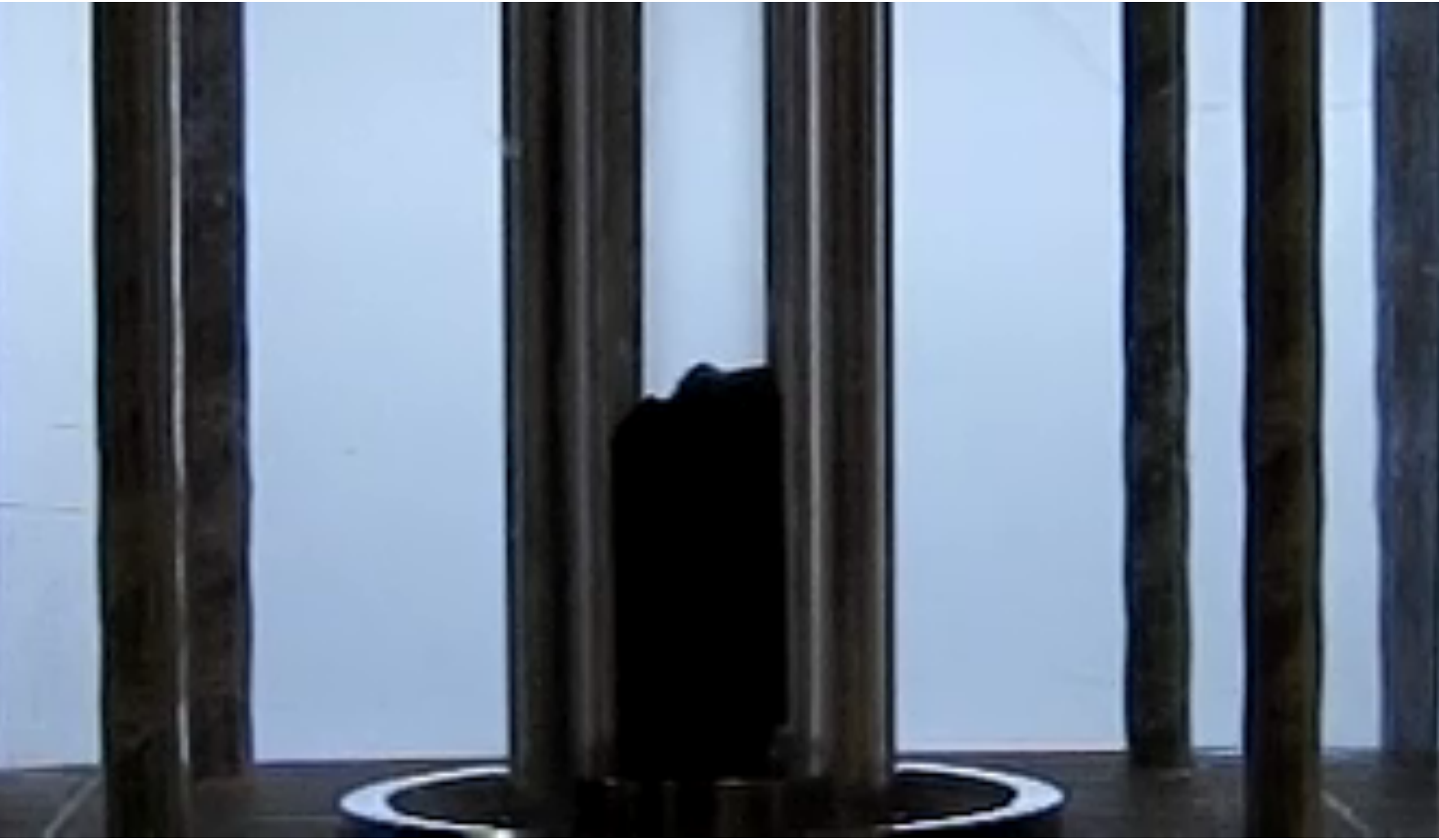
What poromechanics of coal influences desorption and failure?

How do loading rates and magnitude influence failure style and mode?

What is the role of methane desorption in the failure of coal?

What are anticipated acoustic signals of desorption and failure?

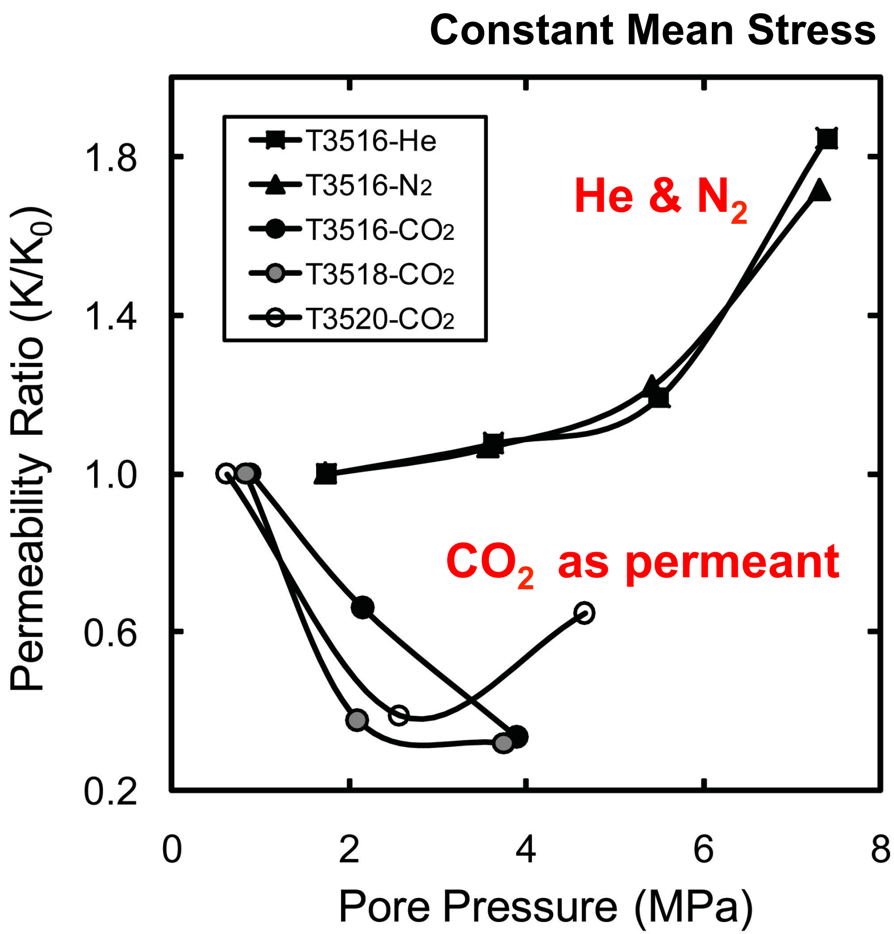
Rapid Desorption of CO_2



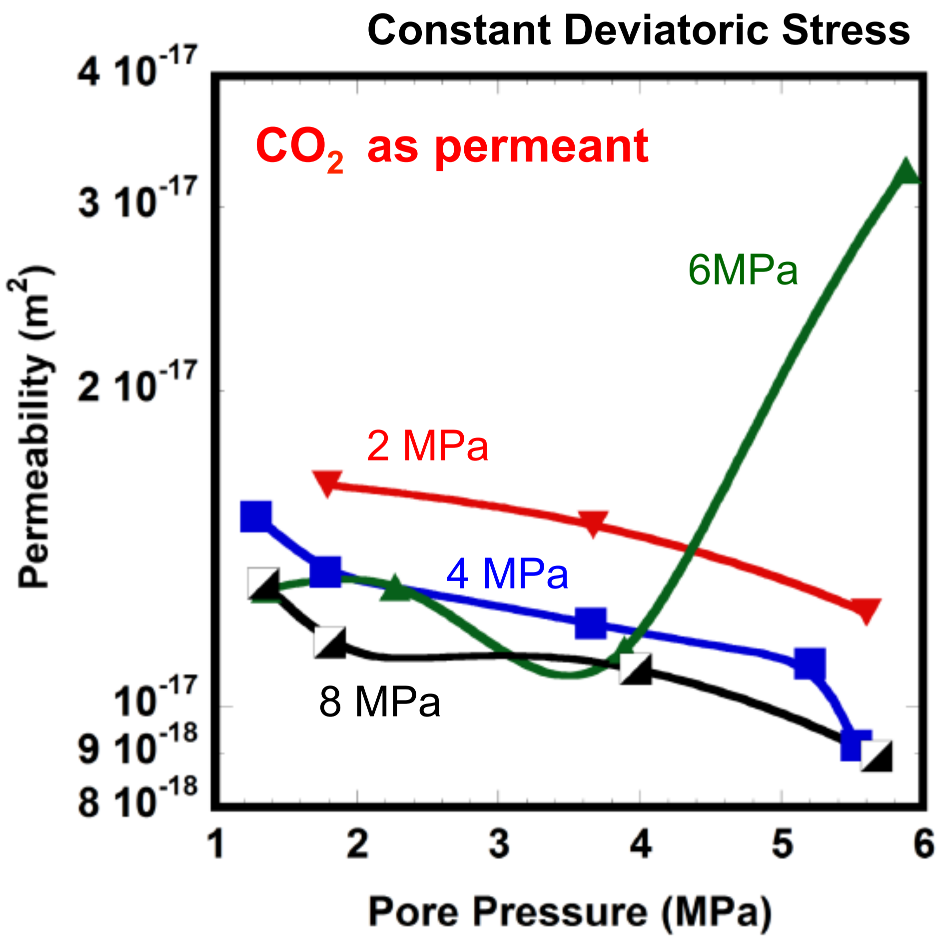

Huainan Coal Company, Huainan
1MW Coal-gas drainage generator
On 5%-30% CH_4

Permeability Evolution – Observations

Coal-unconstrained



Gas Shale - unconstrained



CO_2 as permeant - Analogous to CH_4

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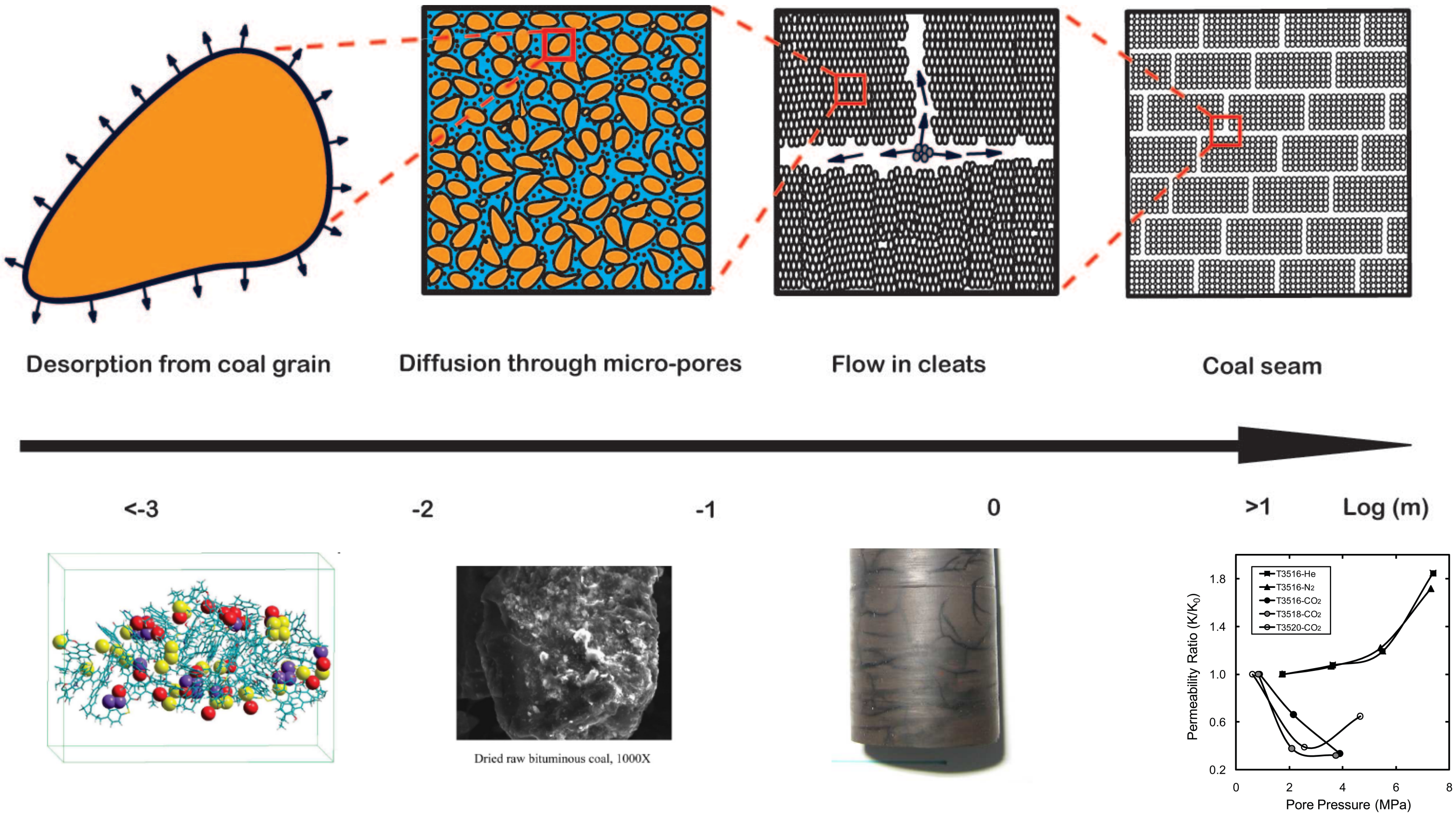
Multi-Porosity Multi-Permeability and Multi-Scale Medium



Overlapping Continua

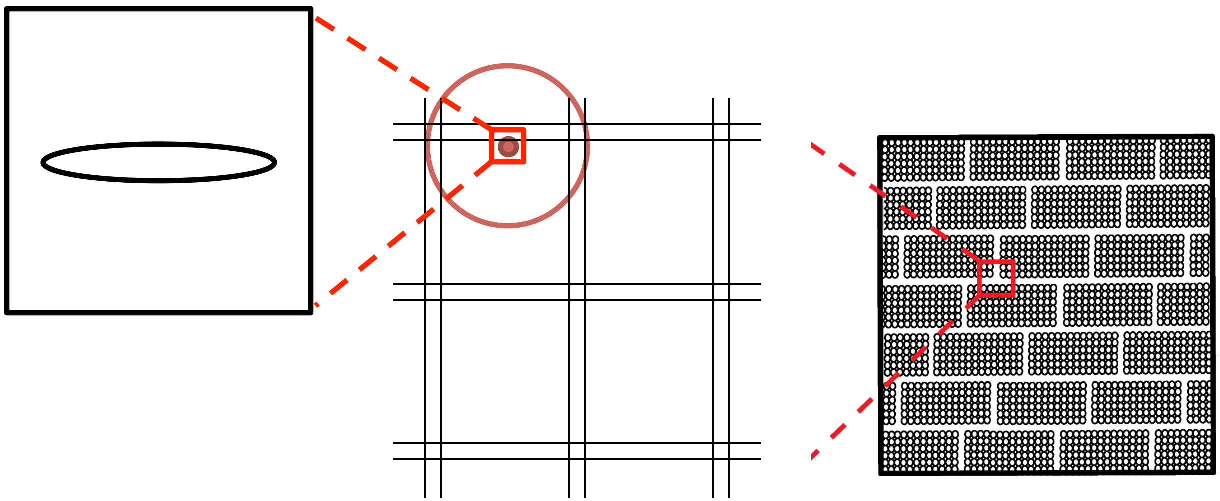
Transport
- Multi porosity/permeability
- Matrix interchange
- Fickian diffusion
- Advection

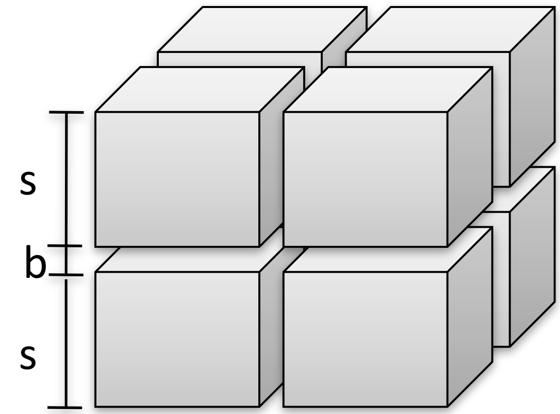
Deformation
- Aggregate response
- Strain partitioning
  - Fluid pressures
  - Compliances

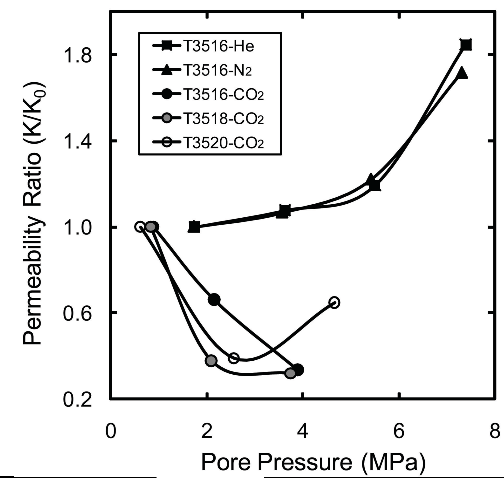
Geometric Model – Principal Features

How does sorption- or desorption-induced strain of the coal matrix influence porosity and the permeability evoluton?

Enigma: Swelling (at low gas pressures) results in permeability loss







change in pore pressure → changes effective stress → deformation

sorption of gas into the coal matrix → changes volume of the matrix → swelling

Key Mechanistic Features [1] - Deformation

Mechanical Behavior with fluid pressure and sorption effects

$$\varepsilon_{ij} = \frac{1}{2G}\sigma_{ij} - \left(\frac{1}{6G} - \frac{1}{9K}\right)\sigma_{kk}\delta_{ij} + \frac{\alpha}{3K} p_m \delta_{ij} + \frac{\beta}{3K} p_f \delta_{ij} + \frac{\varepsilon_s}{3}\delta_{ij}$$

Where

$$\alpha = 1 - \frac{K}{Ks}$$

$$\beta = 1 - \frac{K}{Kn \cdot s}$$

$$\varepsilon_s = \varepsilon_L \frac{p_m}{p_m + p_L}$$

K	Bulk modulus
K_s	Grain elastic modulus
K_n	Normal stiffness of individual fractures
ε_s	Gas sorption-induced strain
ε_L	Langmuir volumetric strain
p_L	Langmuir pressure
p_m	Matrix Pressure

Key Mechanistic Features [2] - Permeability

Permeability Model:

Fracture permeability

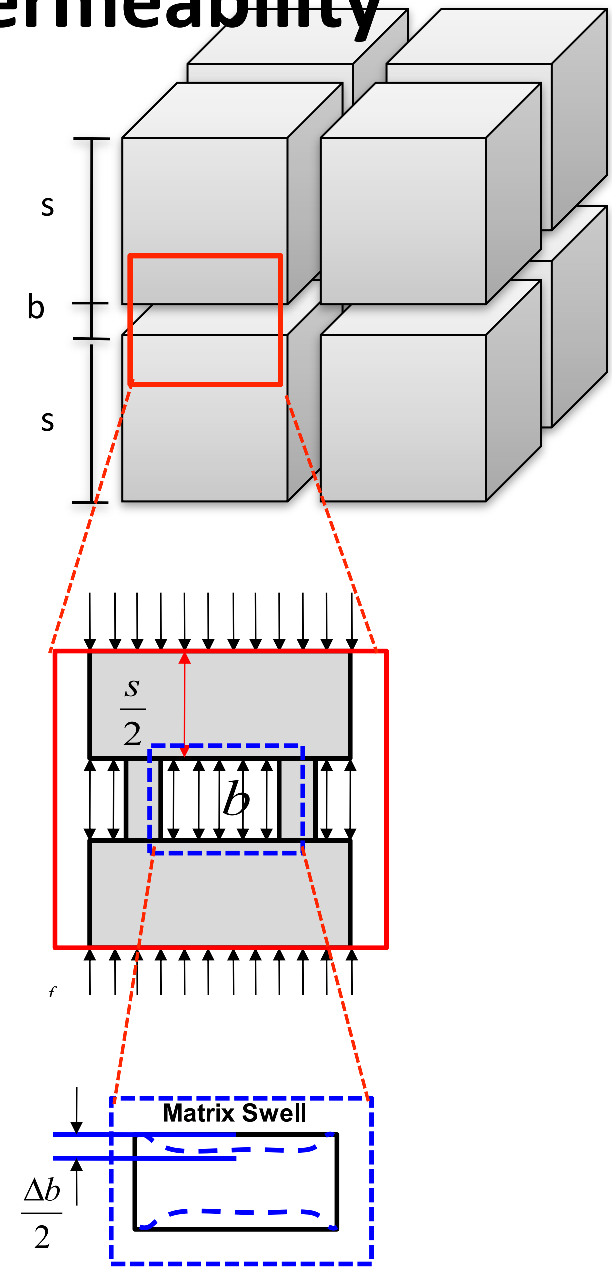
$$k = \frac{b^3}{12s}$$

Initial aperture

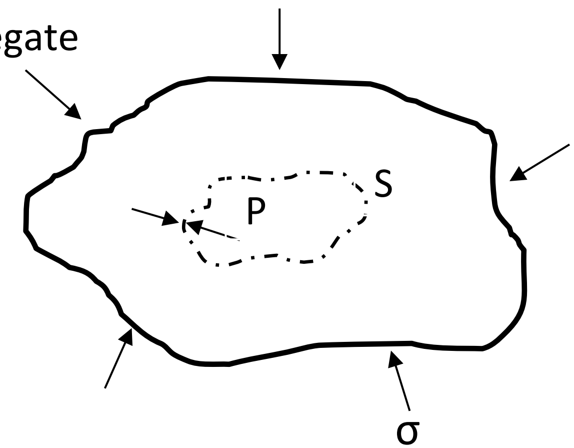
$$b_0 = \sqrt[3]{12ks}$$

Dynamic permeability of the cracked system:

$$\frac{k}{k_0} = (1 + \frac{\Delta b}{b_0})^3 \sim (\frac{\phi}{\phi_0})^3$$



Porosity Evolution - Swelling-Induced Deformation



Apply loading in two steps:

Uniform stress (P) to the un-perforated sample:

$$\frac{\Delta V_1}{V} = \frac{1}{K_s} P - \varepsilon_s$$

Uniform stress (*σ*-*P*) to the perforated sample:

$$\frac{\Delta V_2}{V} = \frac{1}{K} (\sigma - P)$$

Total volume strain:

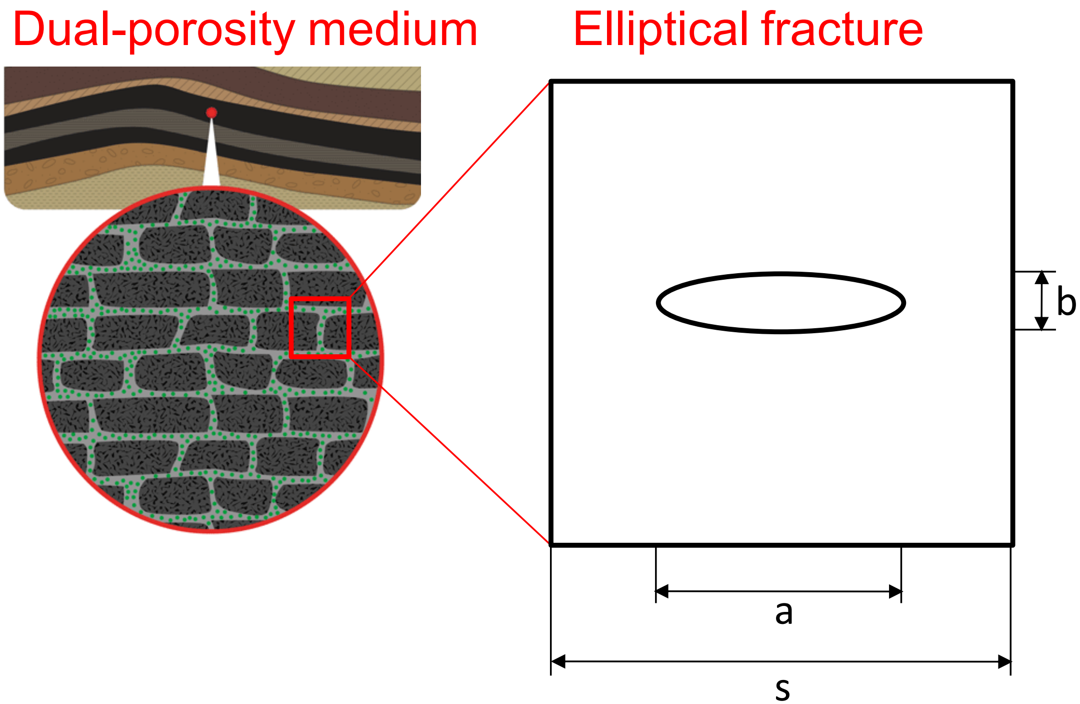
$$\frac{\Delta V}{V} = \frac{\Delta V_1}{V} + \frac{\Delta V_2}{V}$$

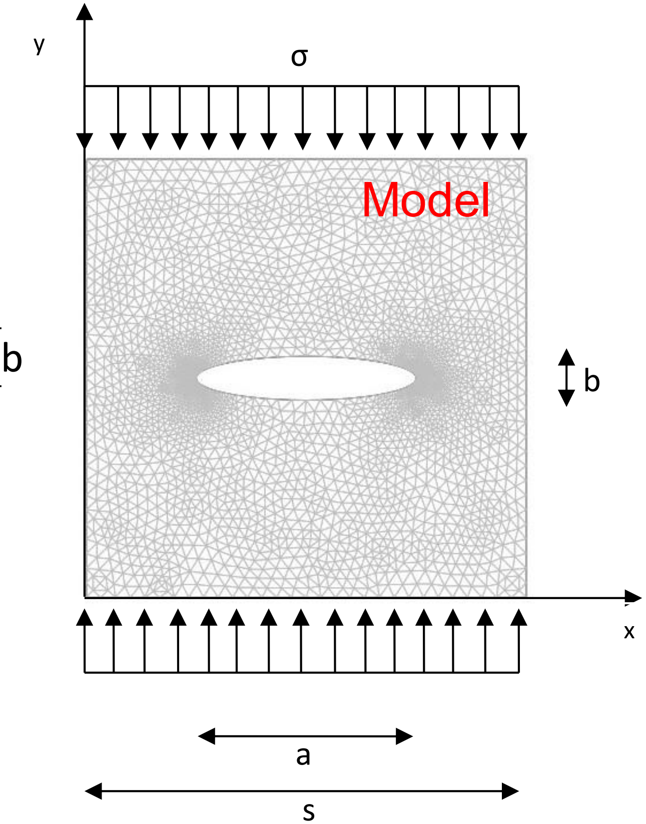
Change in volume of pore:

$$\frac{\Delta V_p}{V} = \frac{1}{K} (\sigma - \alpha P) - \phi \varepsilon_{Sc} P$$

[e.g. Nur and Byerlee, 1971]

Model to Replicate Observed Permeability Response





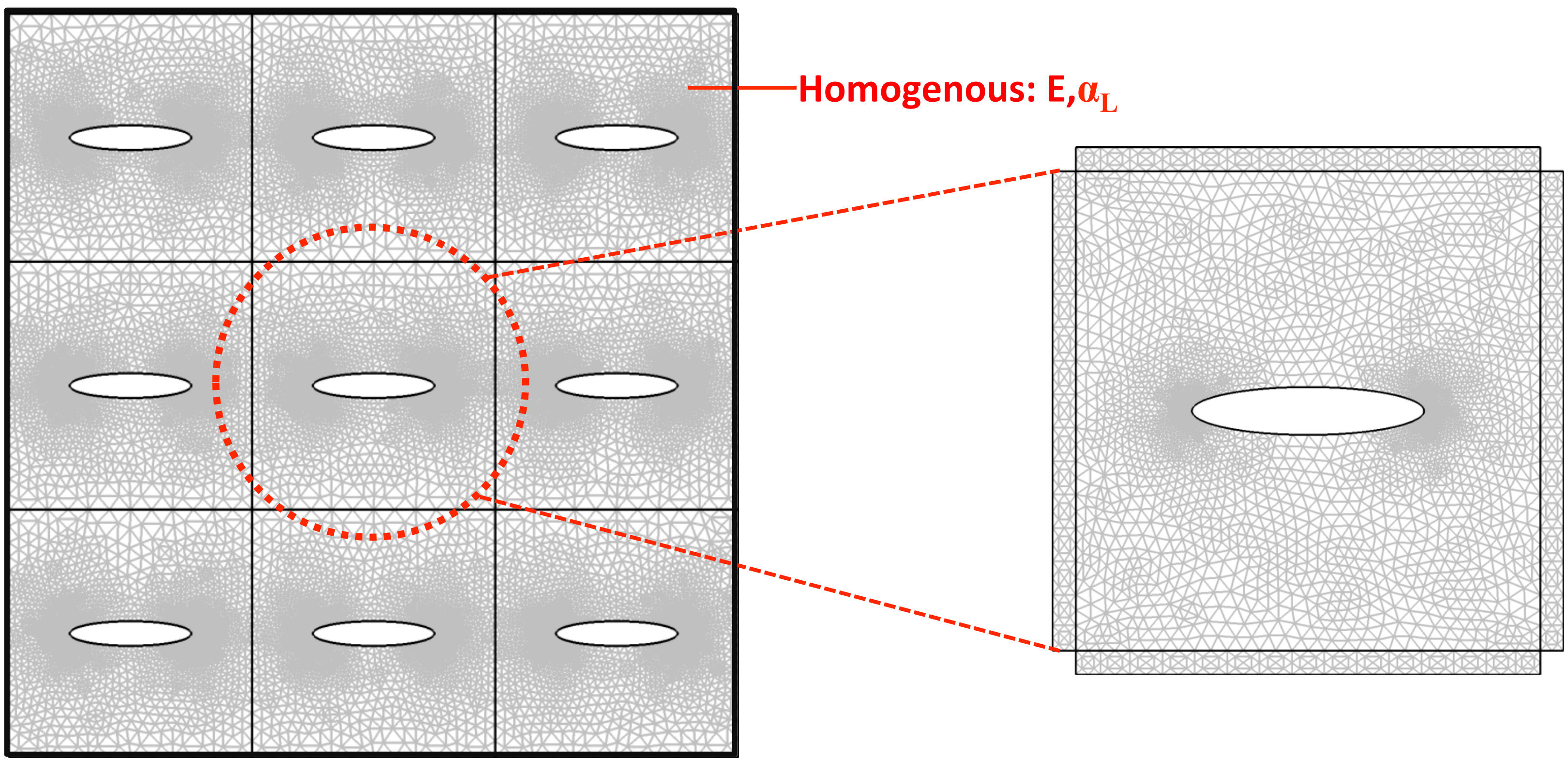
S=0.01(m) **a**= 0.005(m) **b**=10×10^{-6}(m)

Boundary and initial conditions

$$
\begin{cases}
u_i = \tilde{u}_i(t) \quad \sigma_{ij} n_j = \tilde{F}_i(t) \\
u_i(0) = u_0 \quad \sigma_{ij}(0) = \sigma_0 \\
p_m = \tilde{p}_m(t) \quad \vec{n} \cdot \dfrac{k_m}{\mu} \nabla p_m = \tilde{Q}_s^m(t) \\
p_m(0) = p_{m0}
\end{cases}
$$

Repeating Geometries and Boundary Conditions

Response of Cracked Continuum with Interacting Flaws

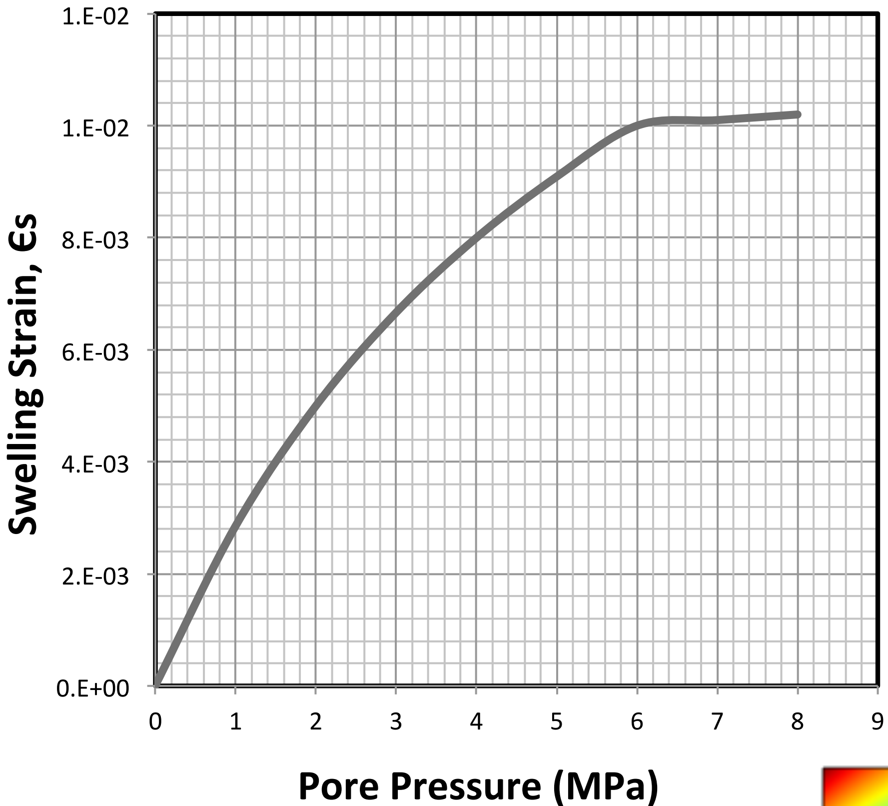


Homogeneous medium seeded with array of interacting cracks

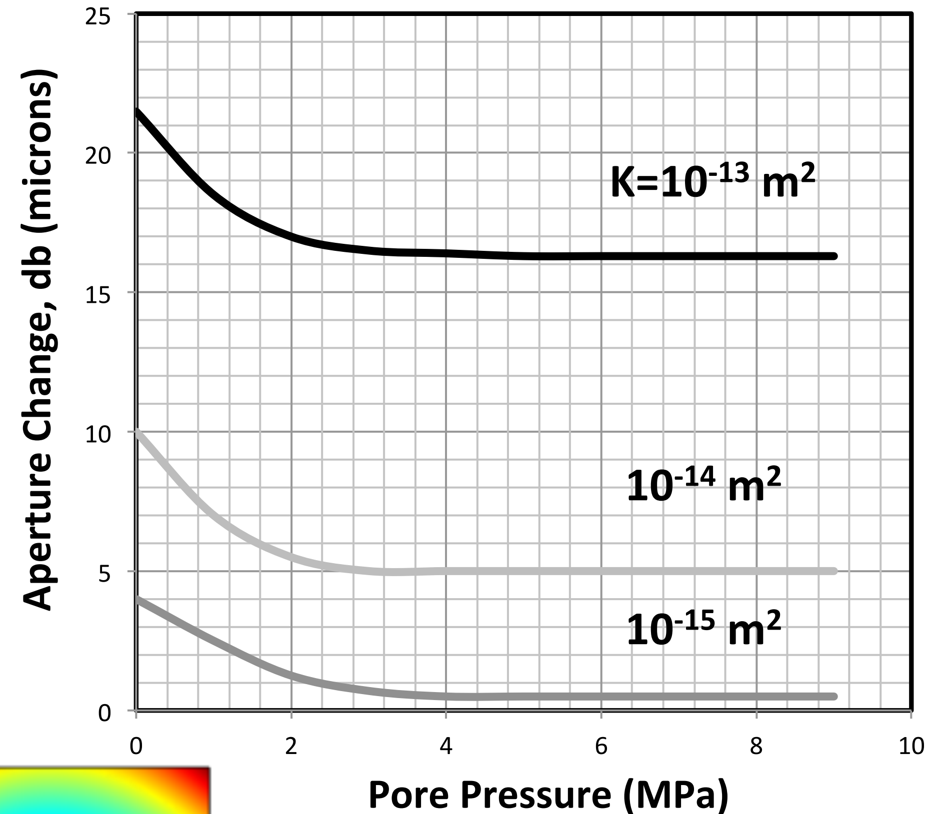
Single component part removed from the array

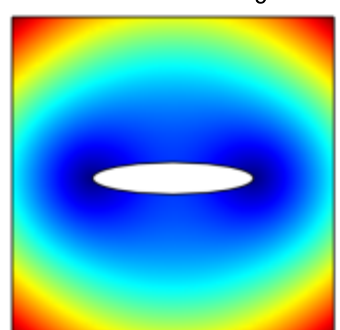
Mechanical Response - Free Swelling

Langmuir strain



Aperture change

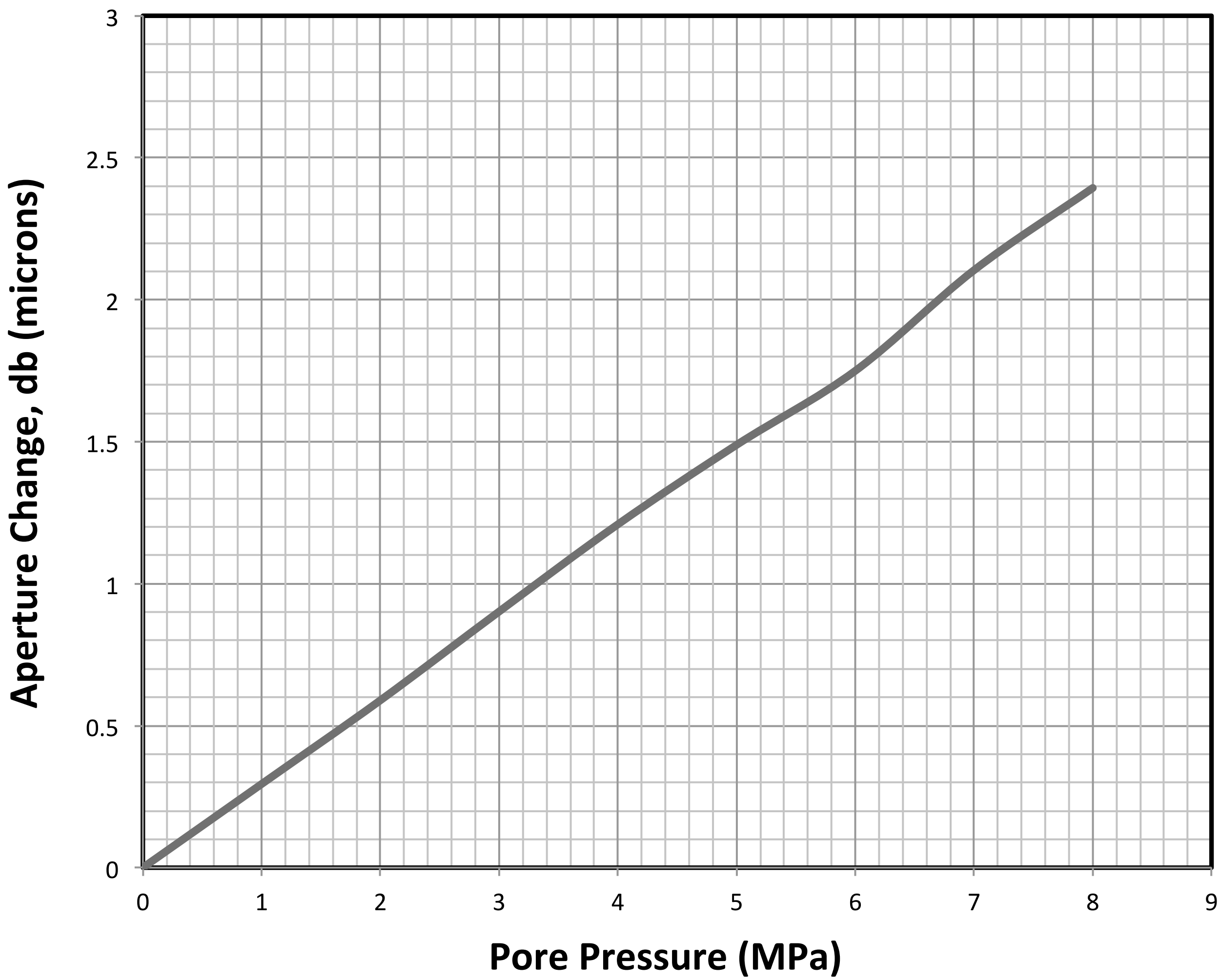


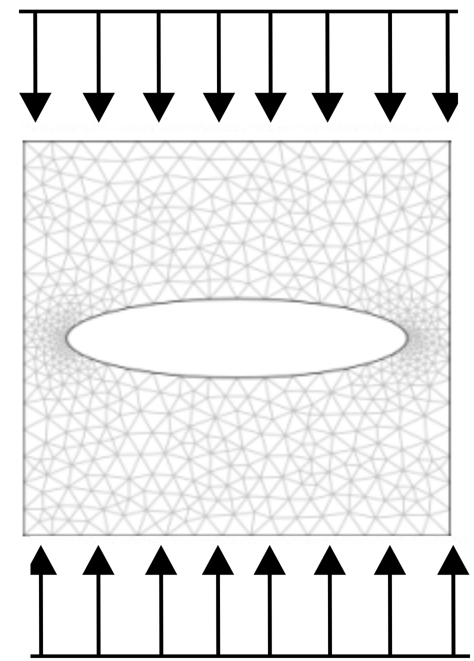


Swelling strain with pore pressure

Change in aperture with pore pressure

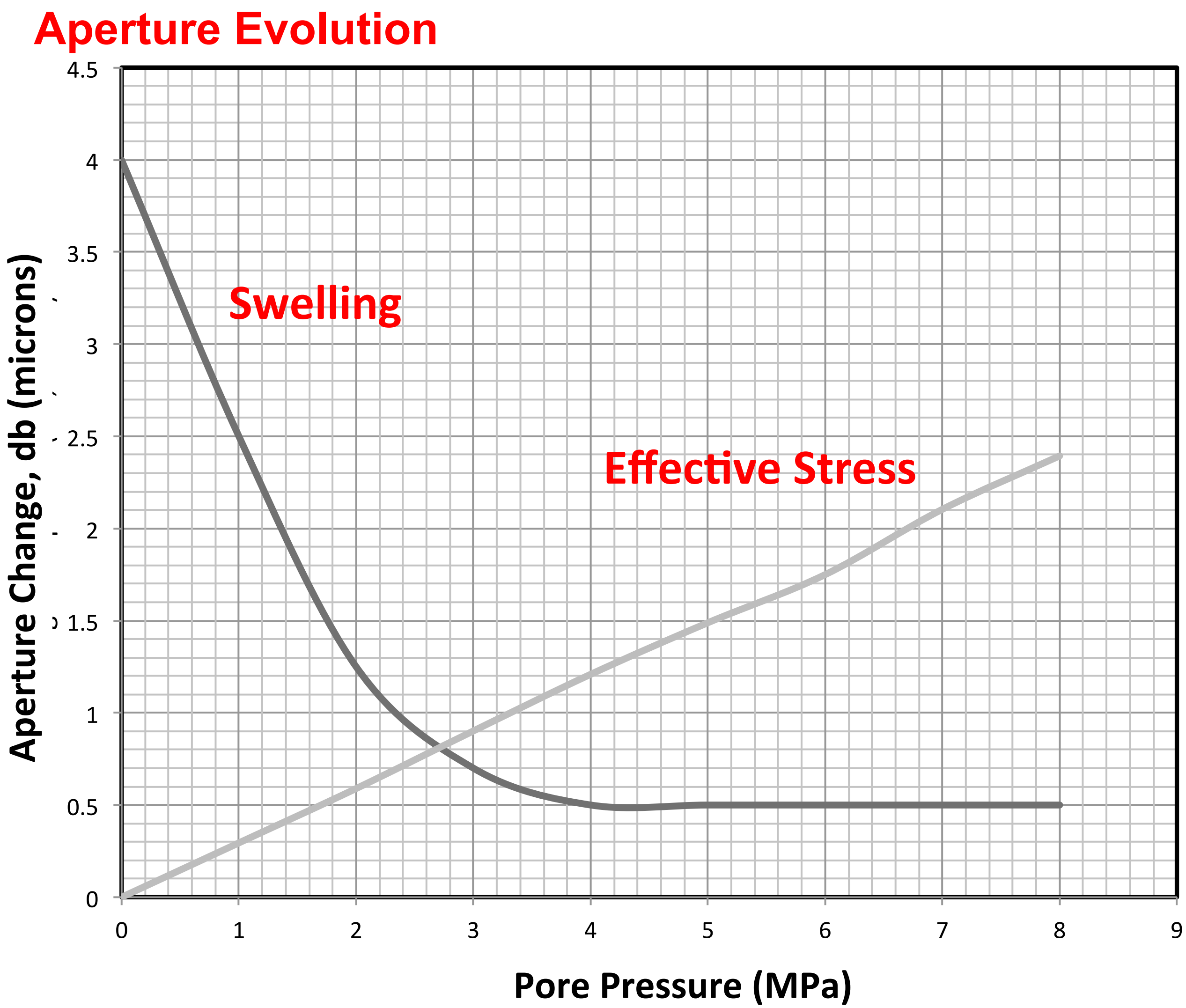
Mechanical Response – Effective Stress





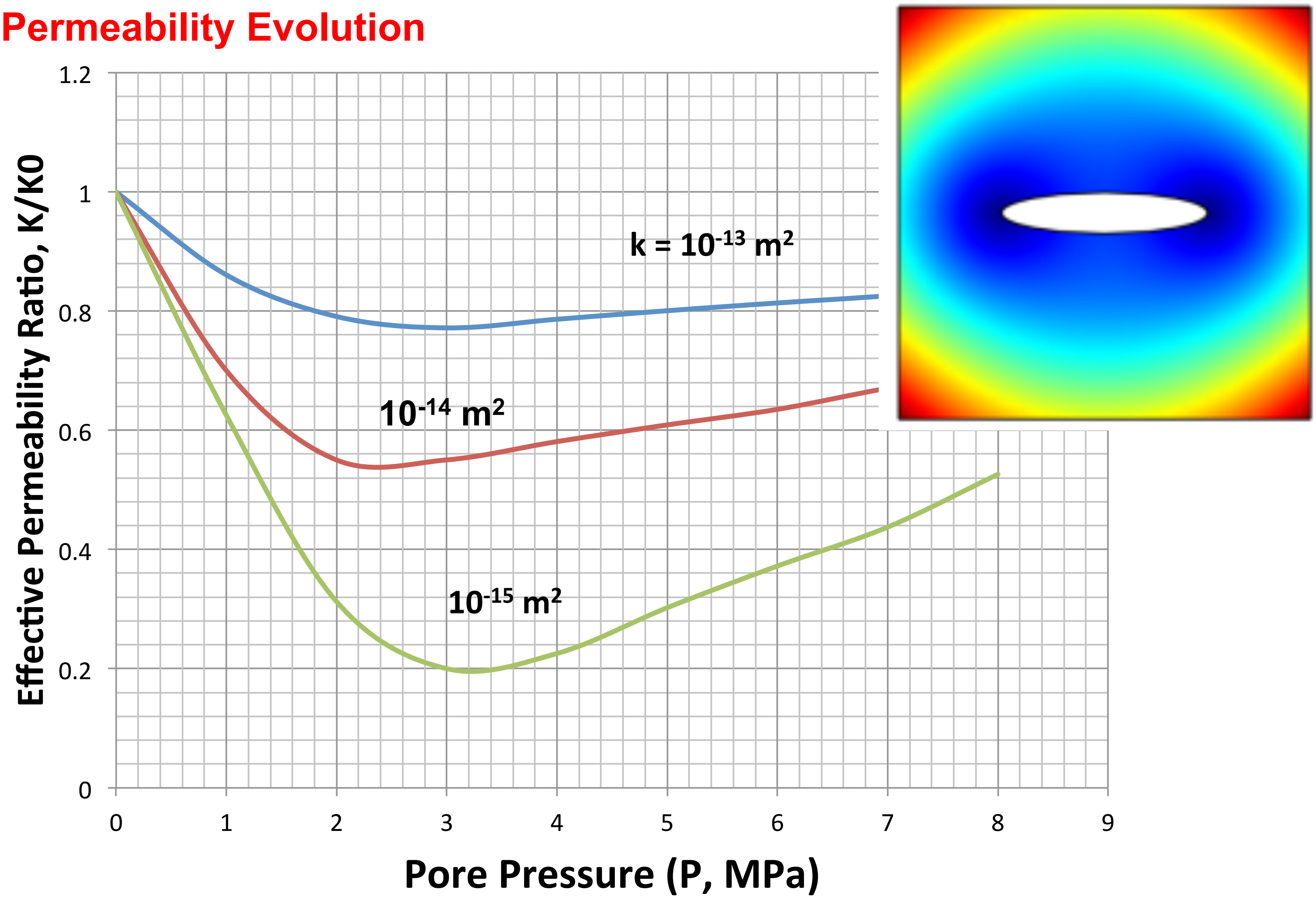
Change in aperture with pore pressure due to effective stress

Ensemble Response – Aperture Evolution



Combined effect of swelling and effective stress on aperture of the void

Influence of Initial Permeability



Effect of initial permeability on permeability evolution

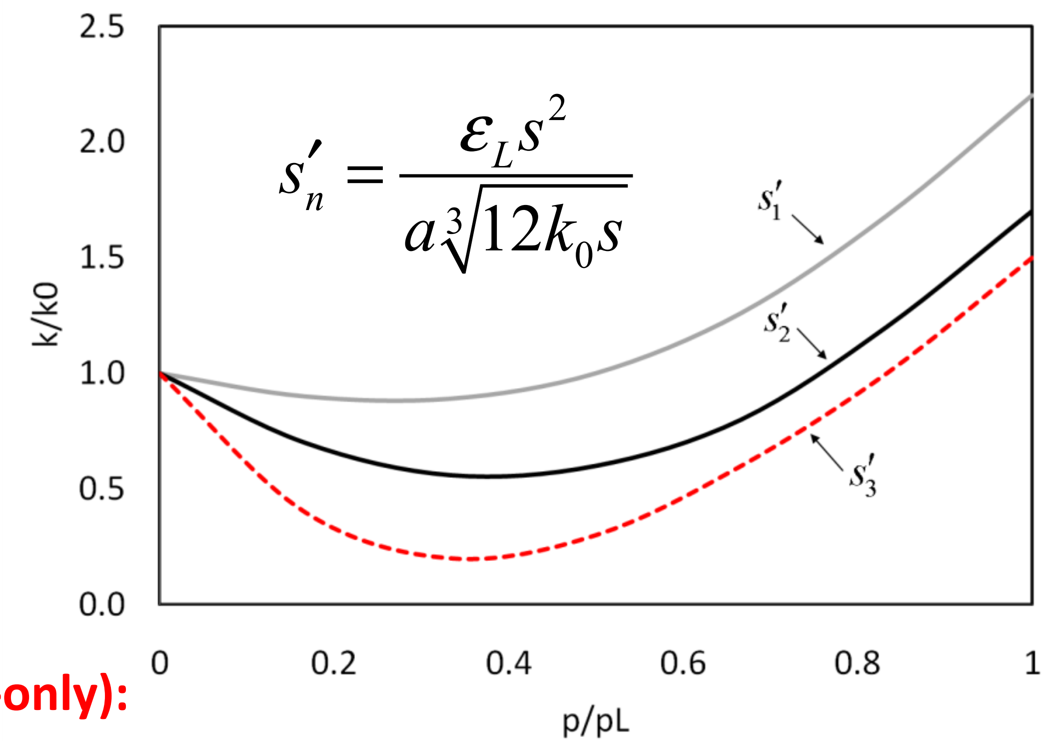
Generalized Response – Swelling Component

Permeability relationship:

$$\frac{k}{k_0} = \left(1 + \frac{\Delta b}{b_0}\right)^3$$

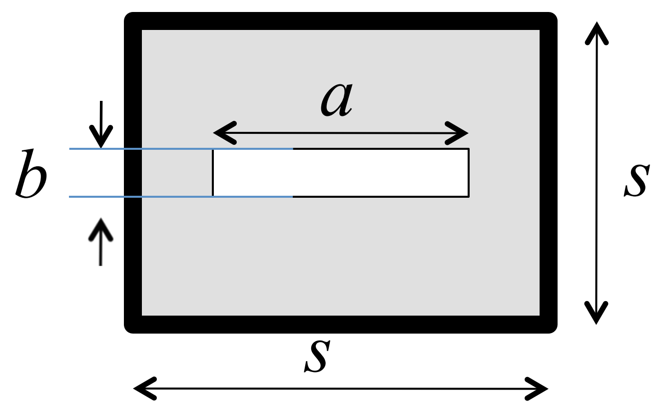
Assuming full restraint:

$$\frac{\Delta b}{b_0} = \frac{\varepsilon_s s^2}{a b_0}$$



Permeability evolution (swelling-only):

$$\frac{k}{k_0} = \left(1 + \frac{\varepsilon_s s^3}{a b_0}\right)^3 = \left(1 + \left(\frac{\varepsilon_L s^2}{a b_0}\right)\frac{p}{p + p_L}\right)^3$$



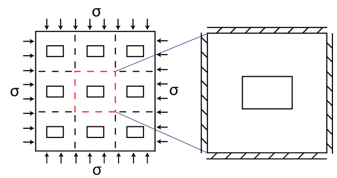
Non-dimensional variables:

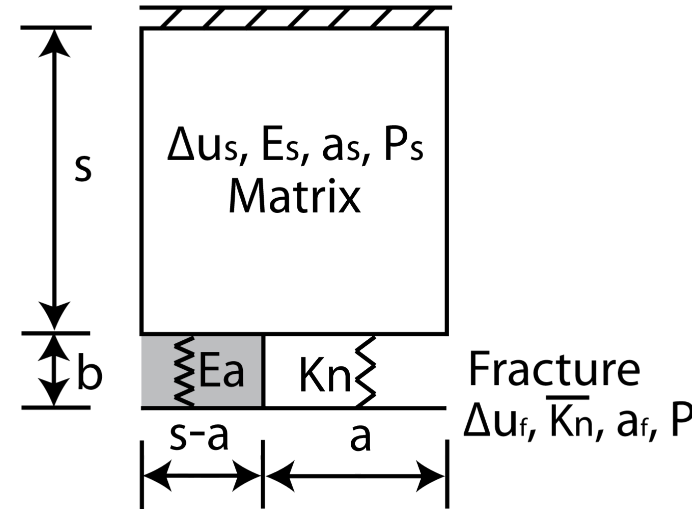
$$\frac{k}{k_0} = f\left(\frac{\varepsilon_L s^2}{a b_0}; \frac{p}{p_L}\right)$$

Ensemble Response

Permeability relationship:

$$\frac{k}{k_0} = (1 + \frac{\Delta b}{b_0})^3$$





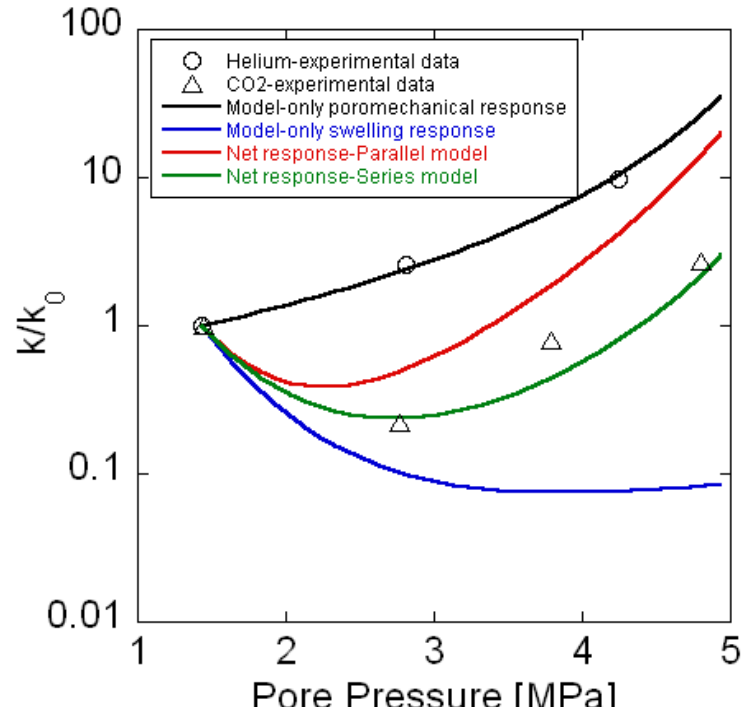
Fracture stiffness:

$$\overline{K_n} = \frac{E_a}{b}\frac{s-a}{s} + K_n \frac{a}{s}$$

Permeability evolution:

$$\frac{k}{k_0} = \left(1 + \frac{(\alpha_f - \alpha_s)}{\left(1 + \overline{K_n} s / E_s\right)} \frac{s(P - P_0)}{b_0 E_s} - \frac{3}{\phi_0} \frac{\varepsilon_L P_L \left(P - P_0\right)}{\left(P + P_L\right)\left(P_0 + P_L\right)}\right)^3 \quad [parallel]$$

$$\frac{k}{k_0} = \left(1 + \frac{(\alpha_f - \alpha_s)}{\left(1 + \overline{K_n} s / E_s\right)} \frac{s(P - P_0)}{b_0 E_s}\right)^3 \left(1 - \frac{3}{\phi_0} \frac{\varepsilon_L P_L \left(P - P_0\right)}{\left(P + P_L\right)\left(P_0 + P_L\right)}\right)^3 \quad [series]$$



[Wang et al., JGR, 2011]

Non-Dimensional Behavior

Non-dimensional variables:

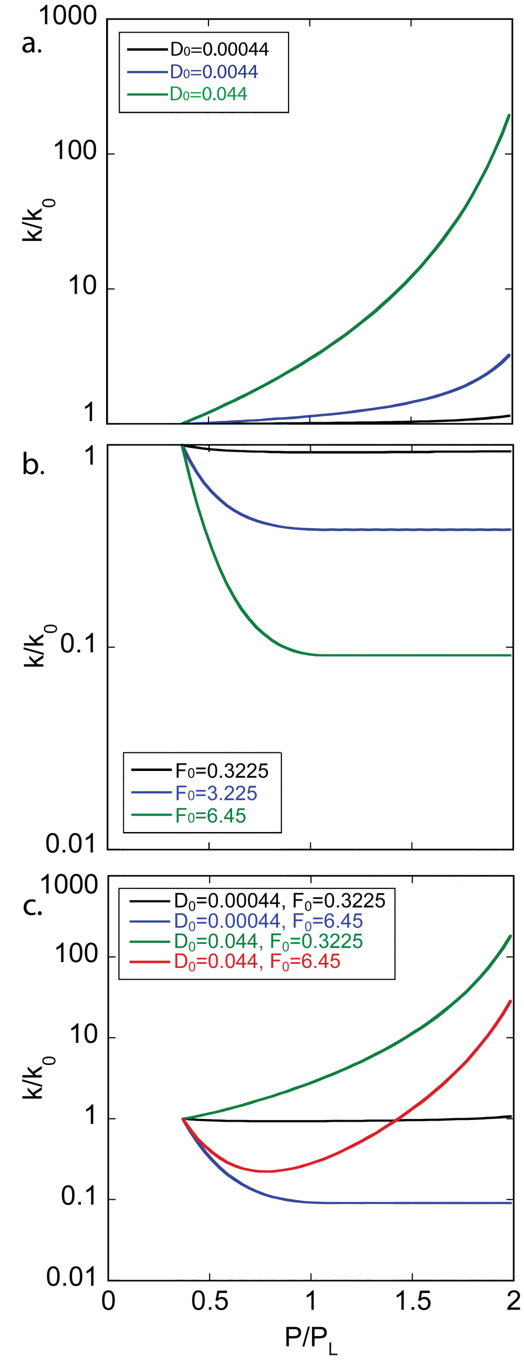
$$\frac{k}{k_0}=\left(1+\frac{(\alpha_f-\alpha_s)}{\left(1+\overline{K}_n s/E_s\right)}\frac{s}{\sqrt[3]{12k_0 s}}\frac{P_L}{E_s}\frac{P}{P_L}\right)^3\left(1-\frac{s}{\sqrt[3]{12k_0 s}}\varepsilon_L\frac{P/P_L}{\left(P/P_L+1\right)}\right)^3 \quad [series]$$

$$\frac{k}{k_0}=\left(1+D\frac{P}{P_L}\right)^3\left(1-F\frac{P/P_L}{\left(P/P_L+1\right)}\right)^3$$

Non-dimensional groups:

$$D=\frac{(\alpha_f-\alpha_s)}{\left(1+\overline{K}_n s/E_s\right)}\frac{s}{\sqrt[3]{12k_0 s}}\frac{P_L}{E_s}$$

$$F=\frac{s}{\sqrt[3]{12k_0 s}}\varepsilon_L$$



[Wang et al., JGR, 2011]

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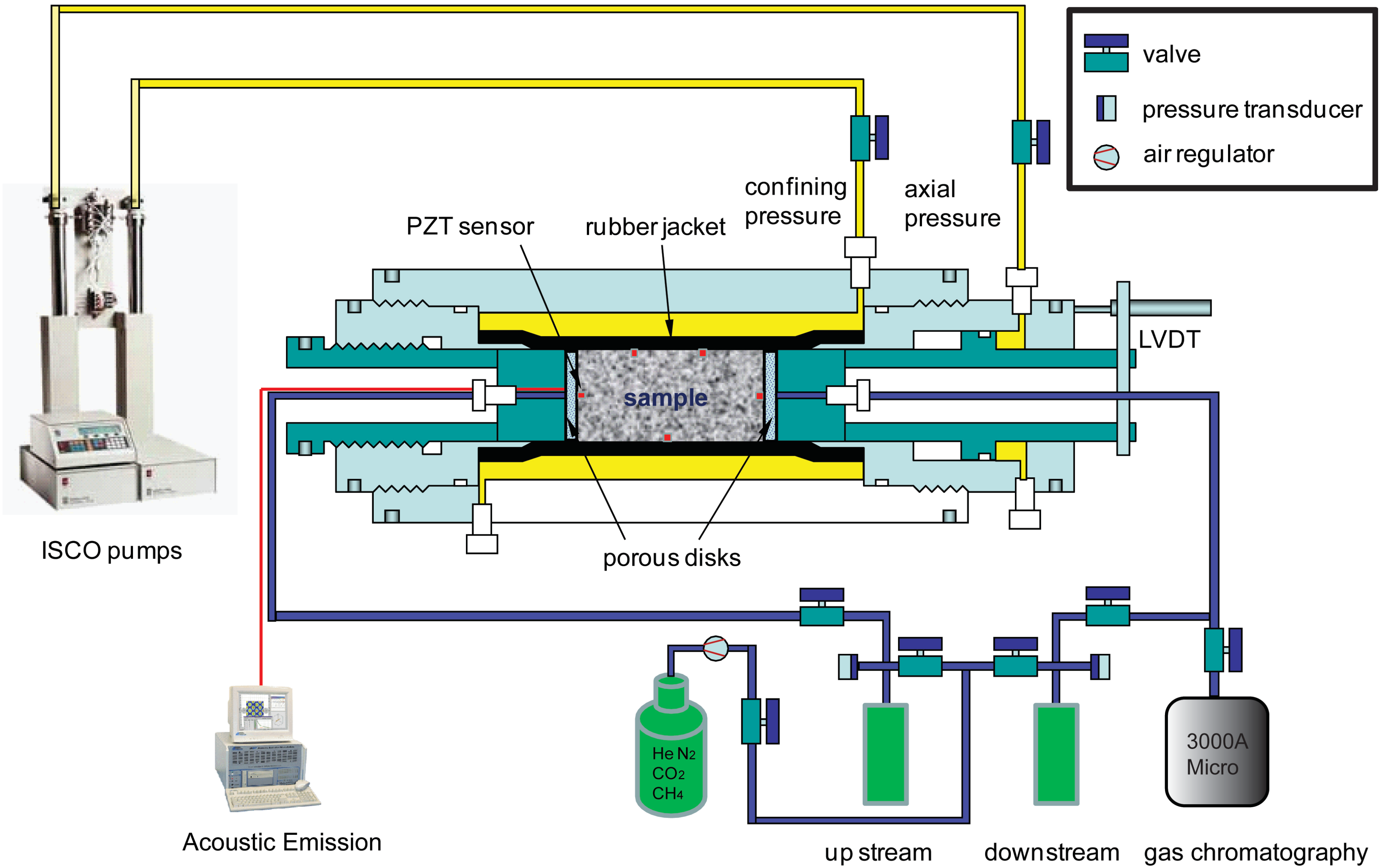
- **Shales**

Field-Scale Response – Optimization

Summary

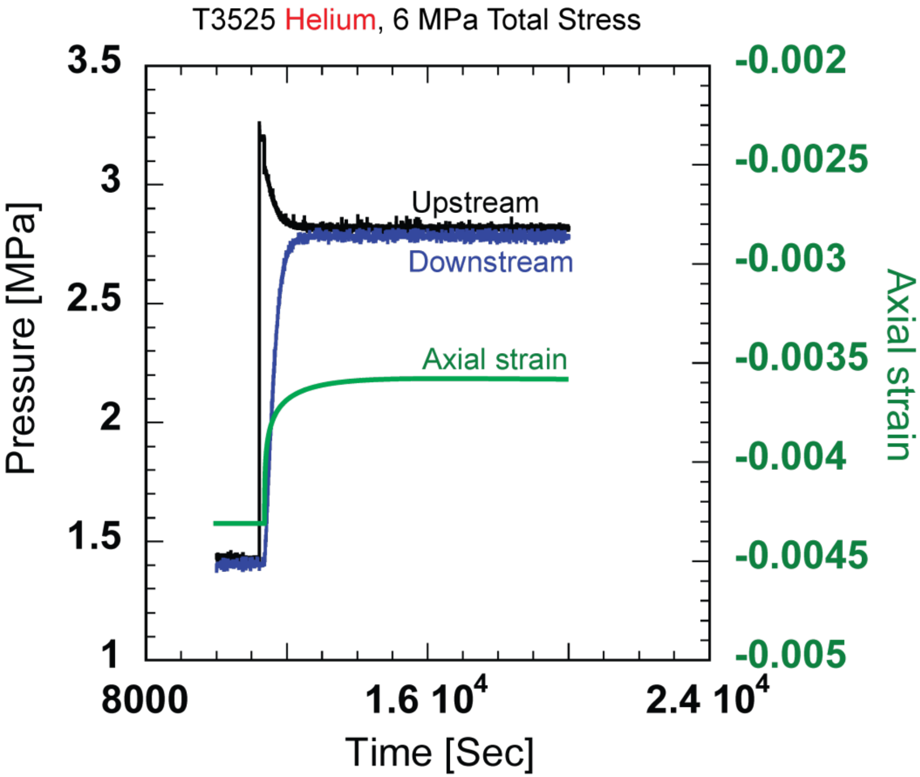
Experimental Apparatus [1]

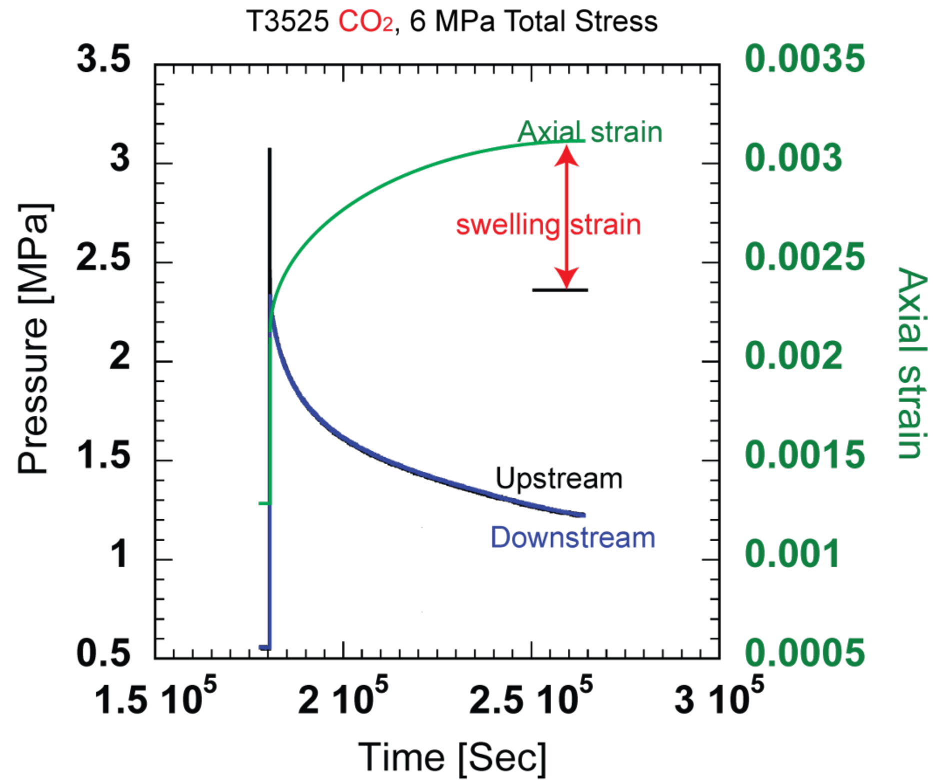
35 MPa Triaxial System



Experimental Apparatus [2]

Permeability measurement method 1:
pressure transient method

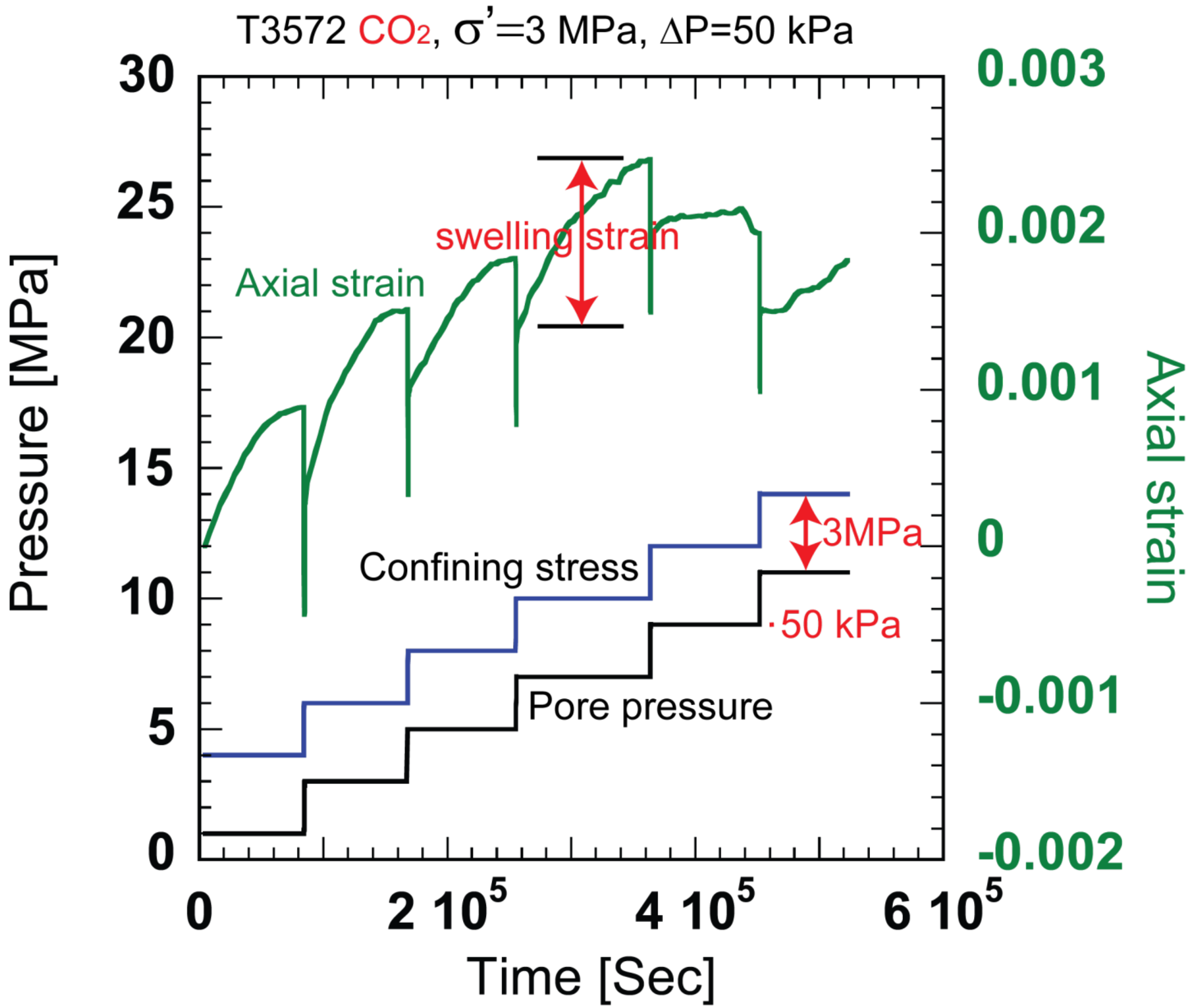




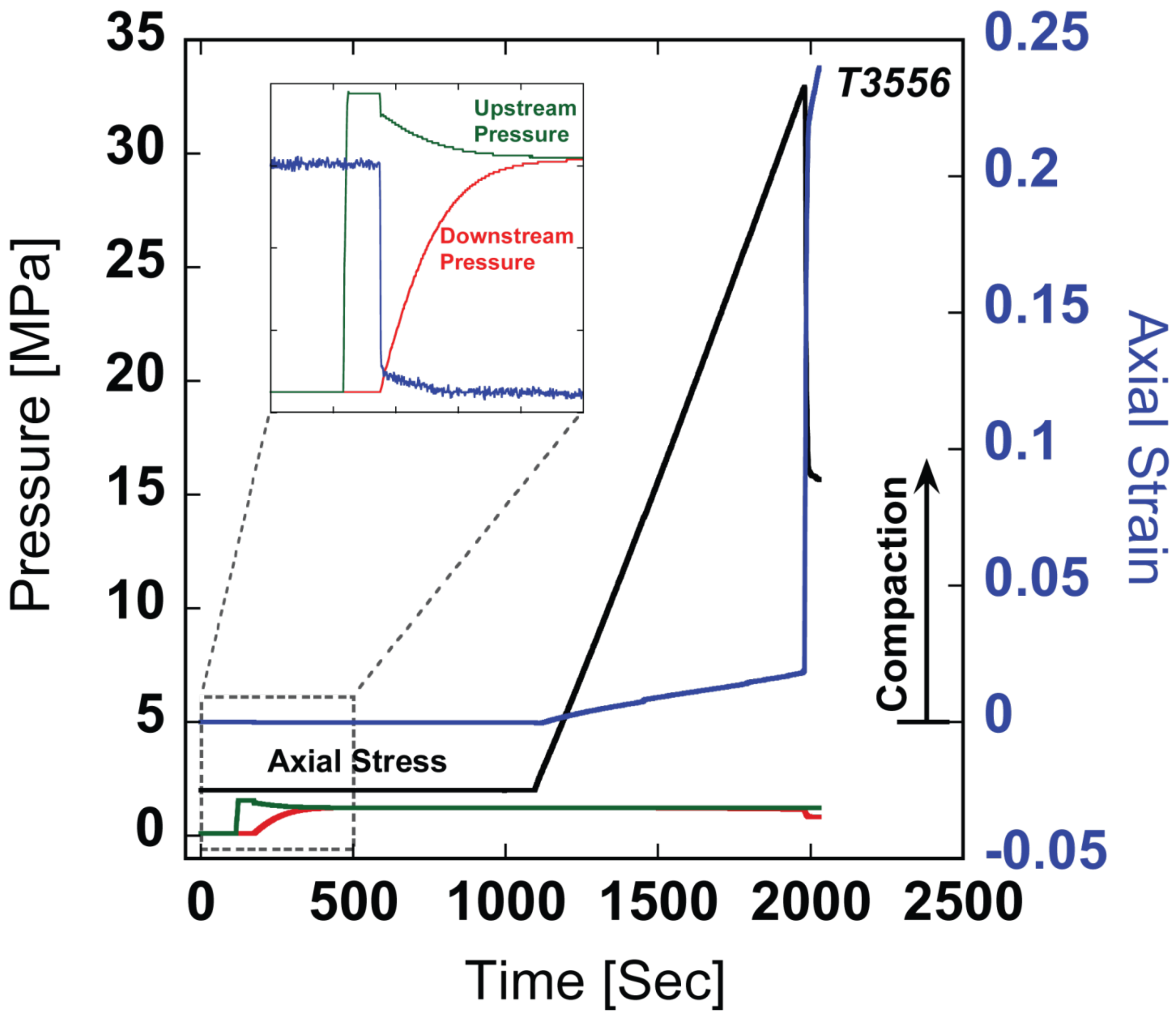
Inert

Sorbing

Permeability measurement method 2:
steady state method



A typical experiment for samples loaded to failure



Permeability Results– He, N_2, and CO_2 [1]

Invariant Total Stress

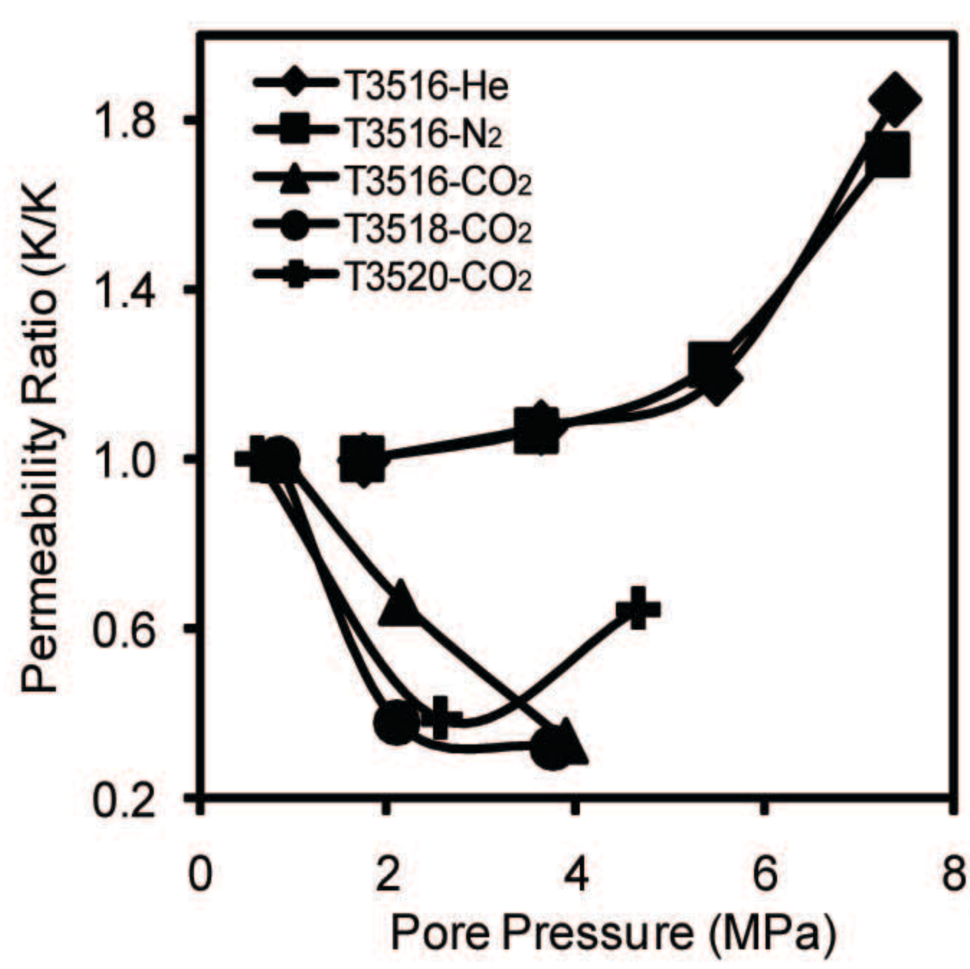
Observations

Varied: Pore pressure

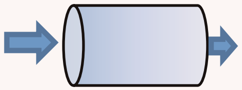
He is non-sorbing and follows effective stress path – nonlinear in permeability but could be linear in closure/compaction

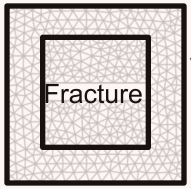
N_2 is slightly-sorbing but dominated by effective stress response

CO_2 has turnover at intermediate Langmuir pressure for 2 of 3 experiments



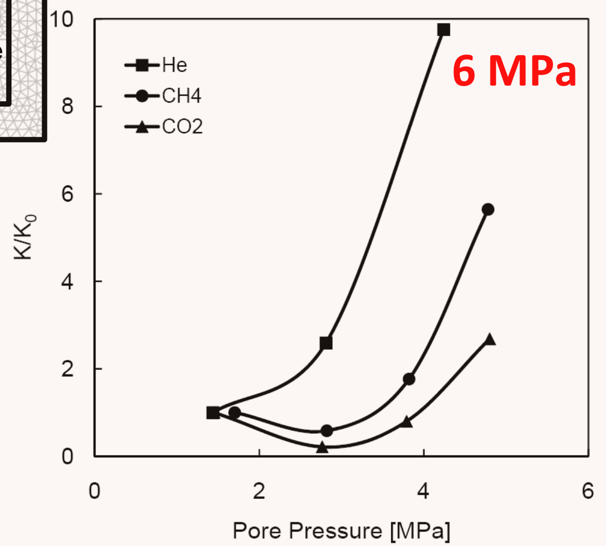
Permeability to Inert and Sorbing Gases



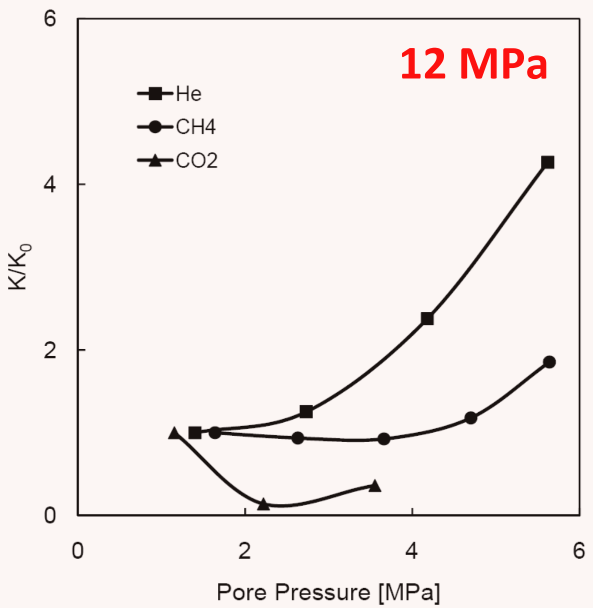


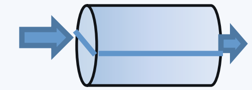
Intact Sample

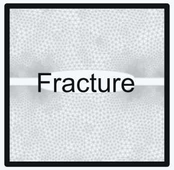
Intact sample under 6 MPa constant total stress



Intact sample under 12 MPa constant total stress

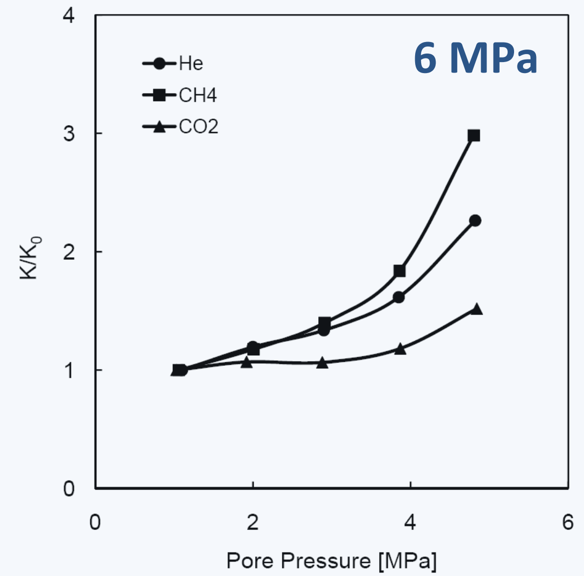




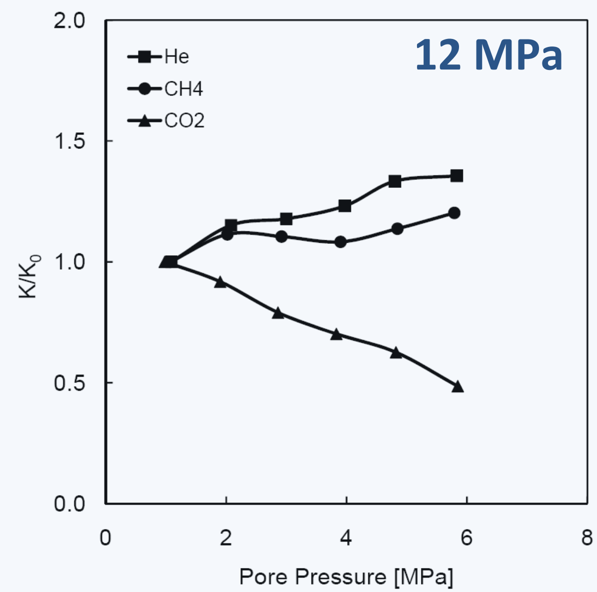


Split core

Single fractued sample under 6 MPa constant total stress

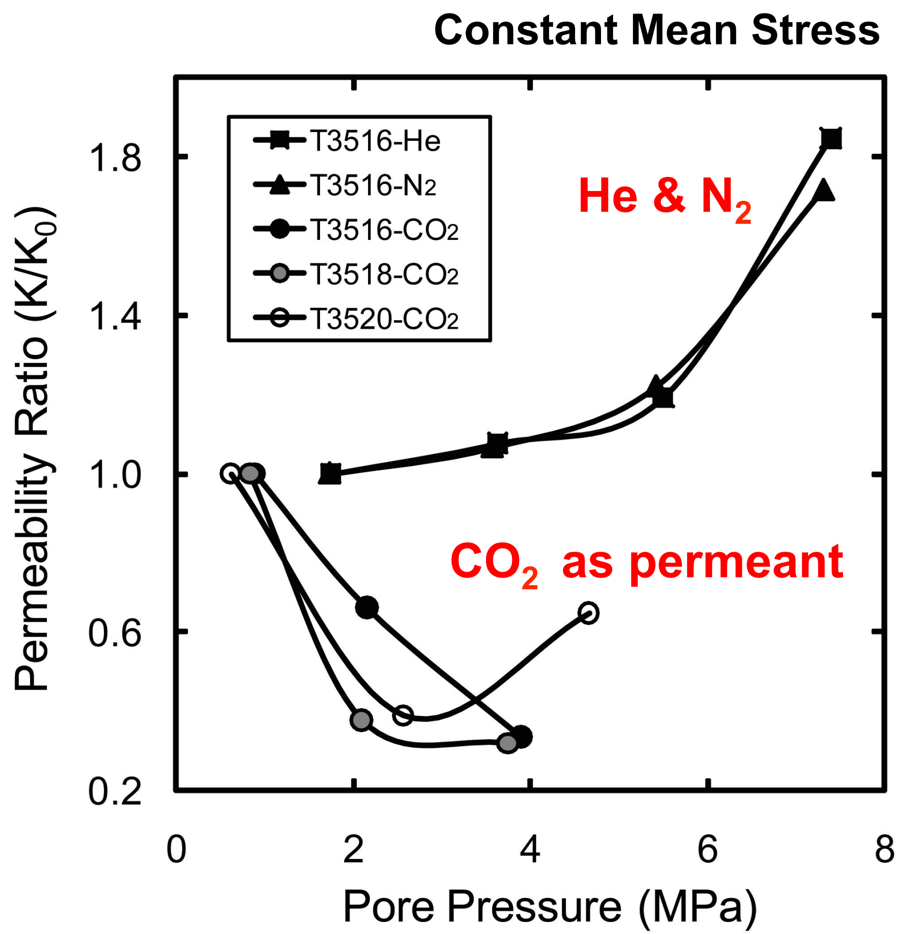


Single fractued sample under 12 MPa constant total stress

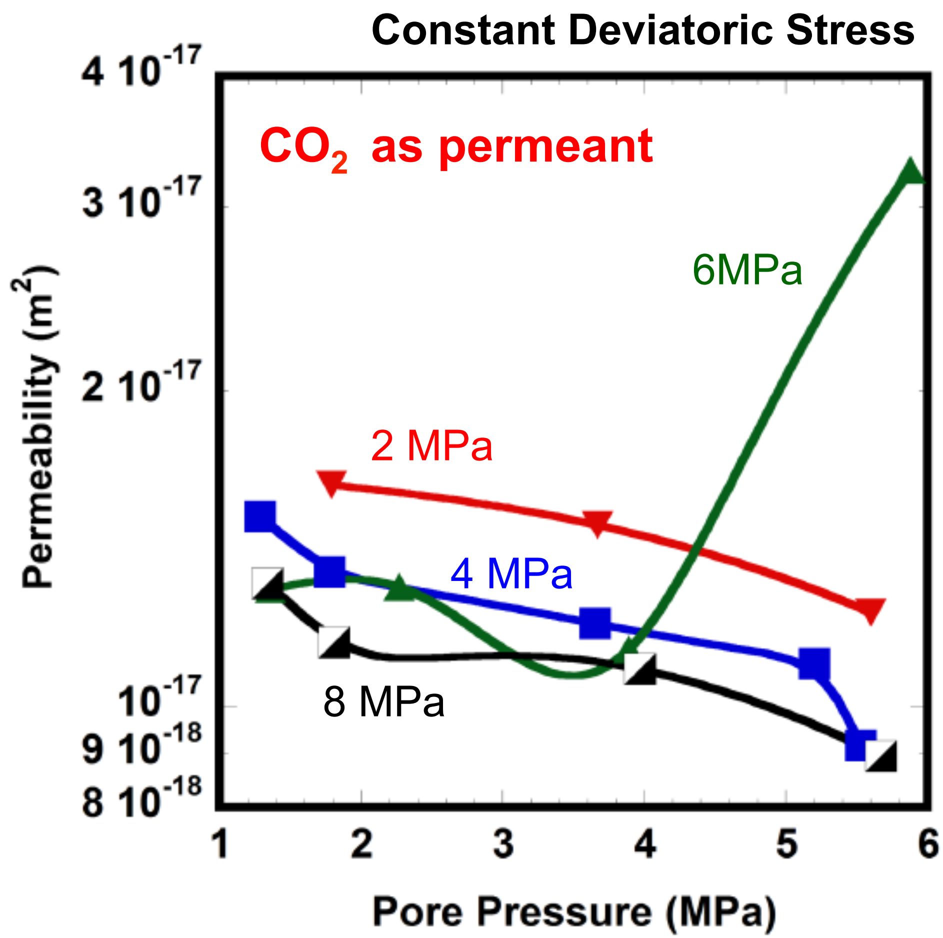


So What About Shales?

Coal



Gas Shale



CO_2 as permeant - Analogous to CH_4

Coal-Gas and Shale Gas: Contributing Similarities

	Coal-Gas	Shale-Gas
Relative carbon content	High	Low
Free gas content	Low	High
Bound gas content	High	Low
Sorptive strains	Large	Small
Fracture network geometry	Small spacing	Long spacing
Comparative permeability	High/Open fractures	Low/Tight fractures
Permeability sensitivity to deformation	Low	High
Linkage: Perm-to-Sorption	**Significant**	**Significant**
Stiffness	Low	High
Strength	Low	High

Why CO_2-Enhanced Recovery?

Statistics

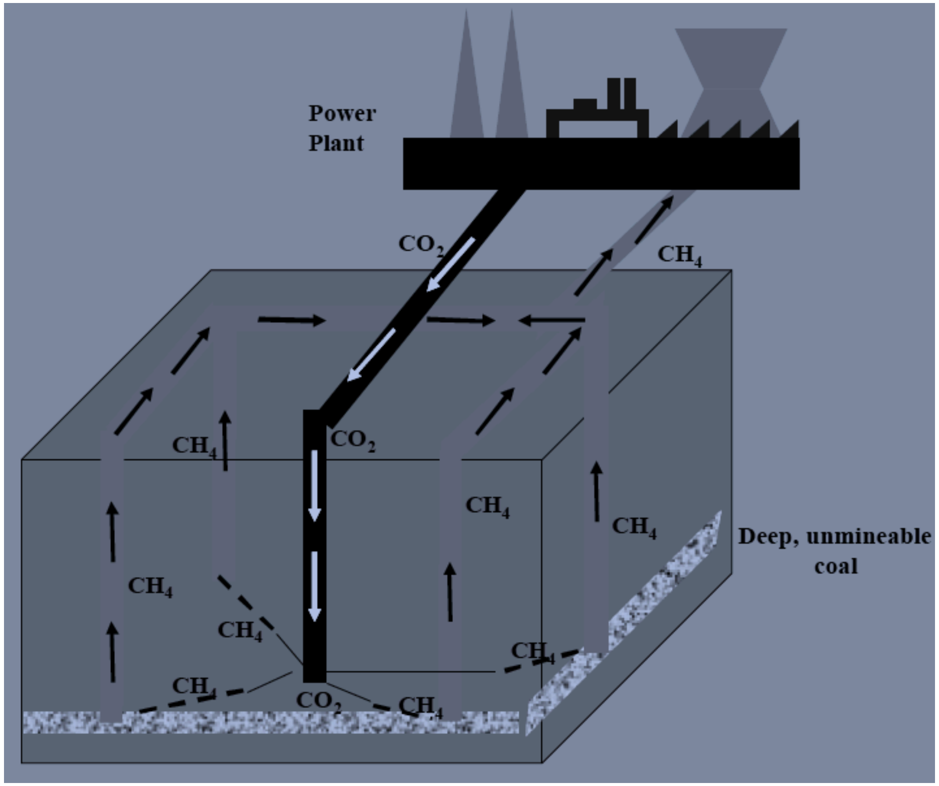
- US CO_2 emissions 100 TCF/yr (2010)

Enhanced Recovery

- Higher recoveries
  - 10-20% (Coalbed Methane)
  - 5-22 % (Enhanced Oil Recovery)
- CO_2 storage
  - Significant potential, unmineable coal and shale

Challenges

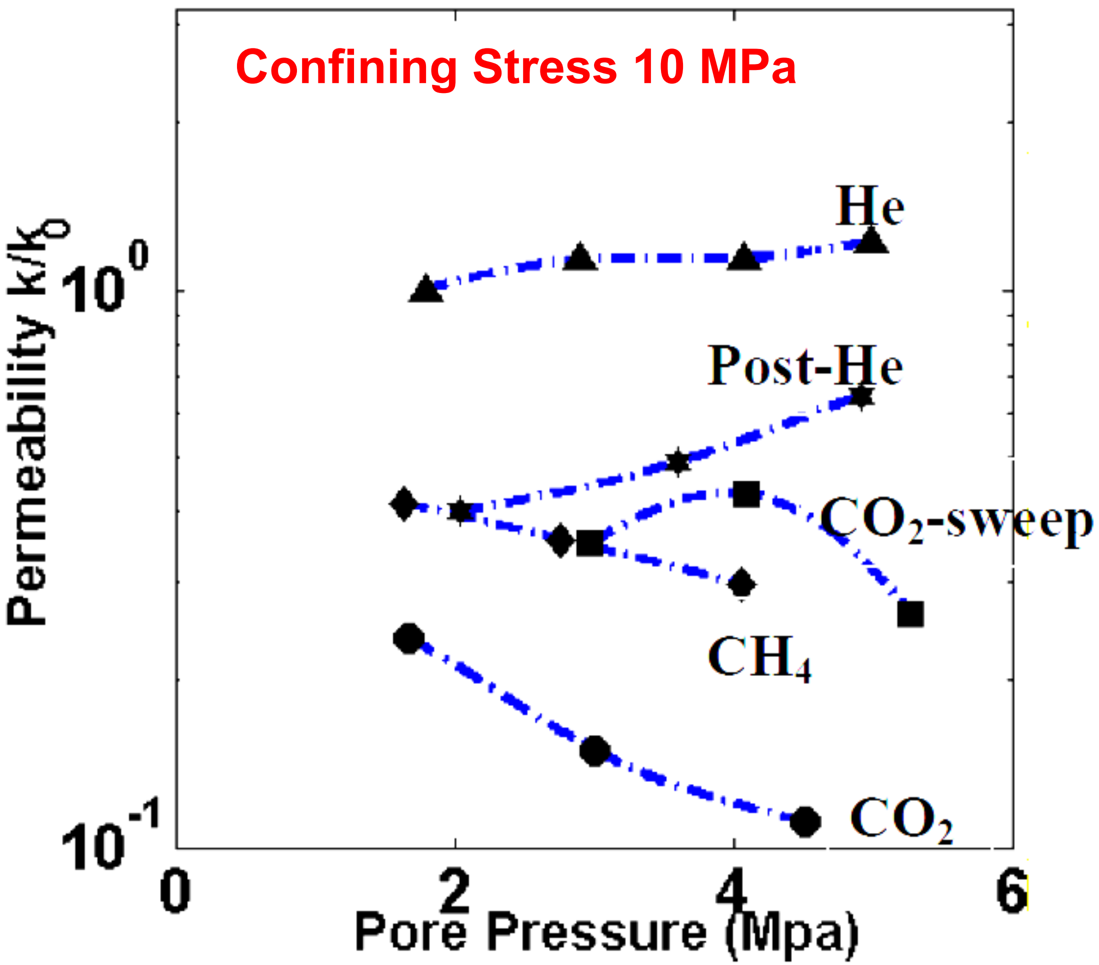
- Retaining permeability
- Preventing early CO_2 breakthrough



Source: Advanced Resource International, 2003, The coal-seq project: results of the Allison and Tiffany ECBM field studies

CO2- Enhanced Recovery is an attractive alternative

Permeability Evolution During Sweep Experiments - Dry



Experimental Sequence

- Helium
- Methane
- CO_2 sweep of Methane
- CO_2
- Helium sweep of CO_2

Observations

Pore Pressure Effects

- Non-sorbing (He) – effective stress
- Swelling (CH_4, CO_2) - Swelling effect
- Irrespective of displacement constraint

Effective Stress Effects

- K decreases with eff. stress increase

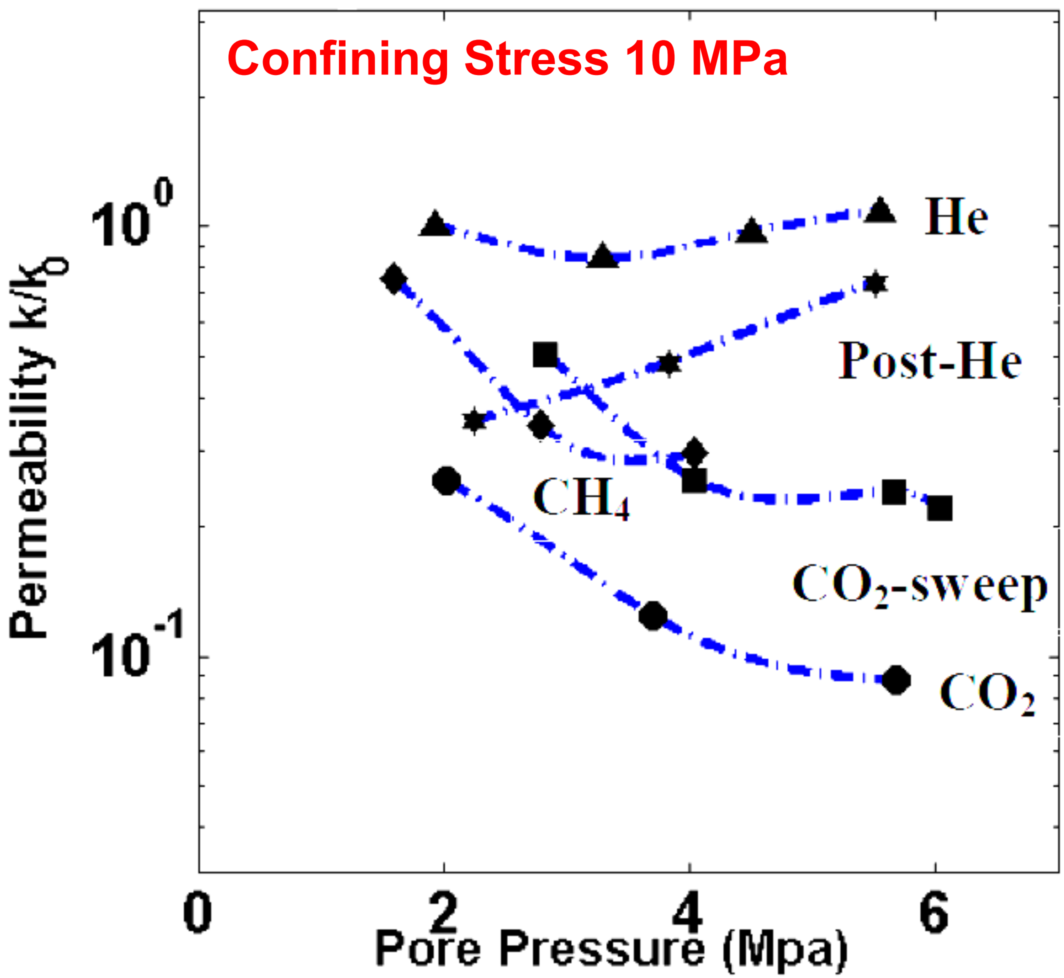
Gas Saturation

- Different affinities (not shown)
- K change He<CH_4<CO_2

CO_2 Sweep Effects

- Slight perm increase over displaced CH_4

Permeability Evolution During Sweep Experiments - Wet



Experimental Sequence

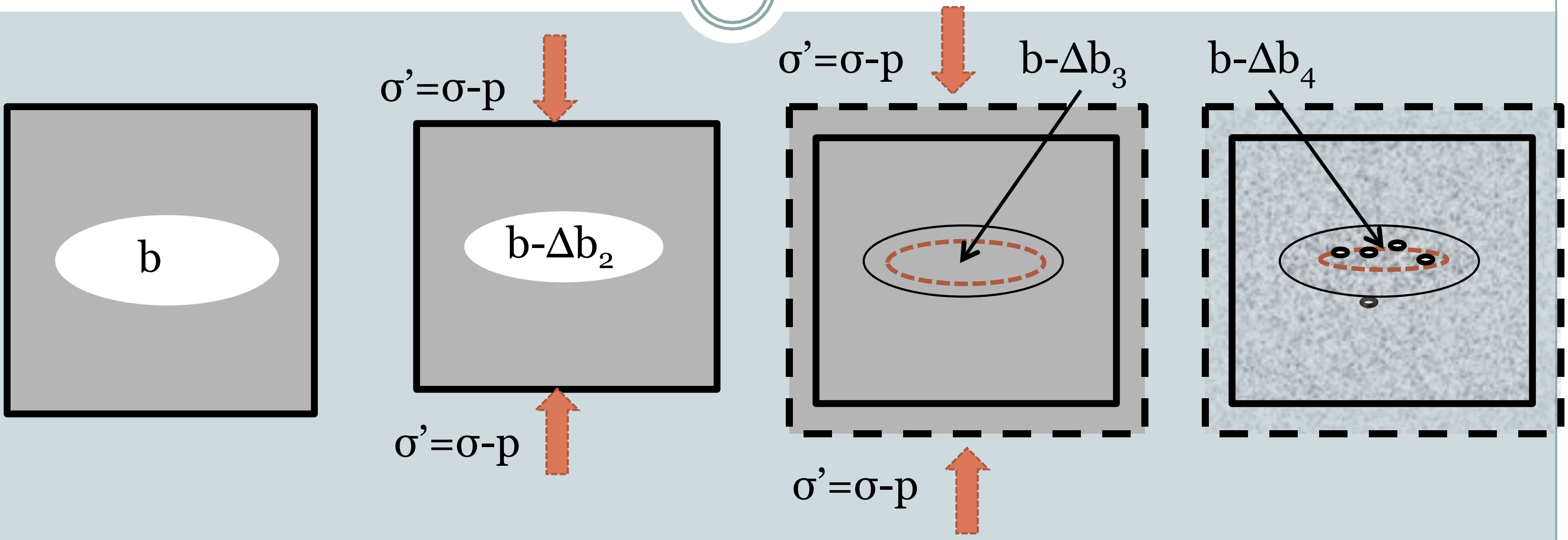
- Helium
- Methane
- CO_2 sweep of Methane
- CO_2
- Helium sweep of CO_2

Observations

Increased Water Saturation

- Perm changes in same order He<CH_4<CO_2
- Relative perm changes are of the same magnitude as dry
- But absolute perm is reduced x10 when wet
- Reduced sorption capacity (not shown)

Mechanistic model



$$\left(\frac{k}{k_0}\right) = \alpha \exp(-\beta\sigma')$$

Effective stress

$$\left(\frac{k}{k_0}\right) = \left(1 + C\left(\frac{p}{p+p_L}\right)\right)^3$$

Swelling

$$\left(\frac{k}{k_0}\right) = \gamma \exp(-\delta S_w)$$

Saturation

$$\left(\frac{k}{k_0}\right) = f(\sigma', p_{CO_2}, p_{CH_4}, p_{He}, S_w) = \left(\left(1 + C\left(\frac{p}{p+p_L}\right)\right)^3 + \exp(-\beta\sigma')\right) \times \exp(-\delta S_w)$$

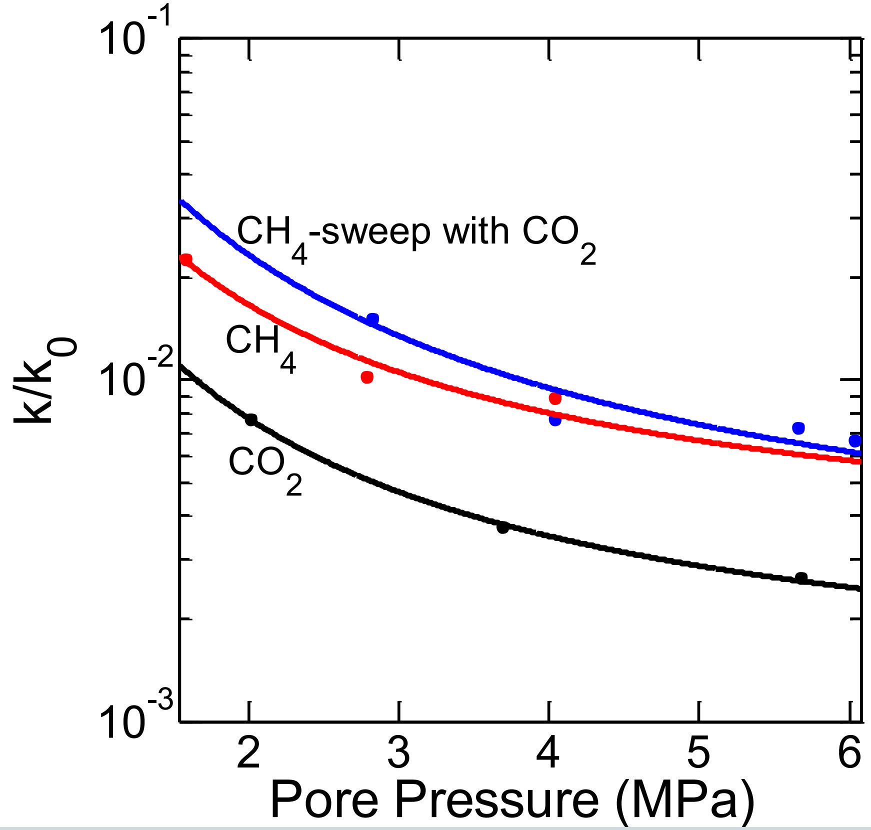
Mechanisms - Gas sorption

$$\left(\frac{k}{k_0}\right) = \left(1 + C\left(\frac{p}{p + p_L}\right)\right)^3$$

1. Isolate the effect of other two factors using constant water saturation and stresses

2. Use adsorbing gas (CH_4, CO_2)

3. C and P_L are fitting parameters

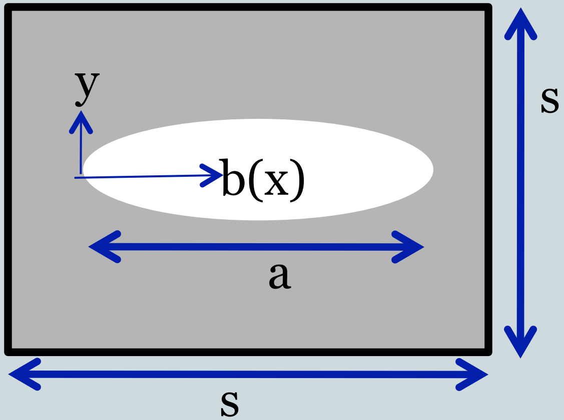


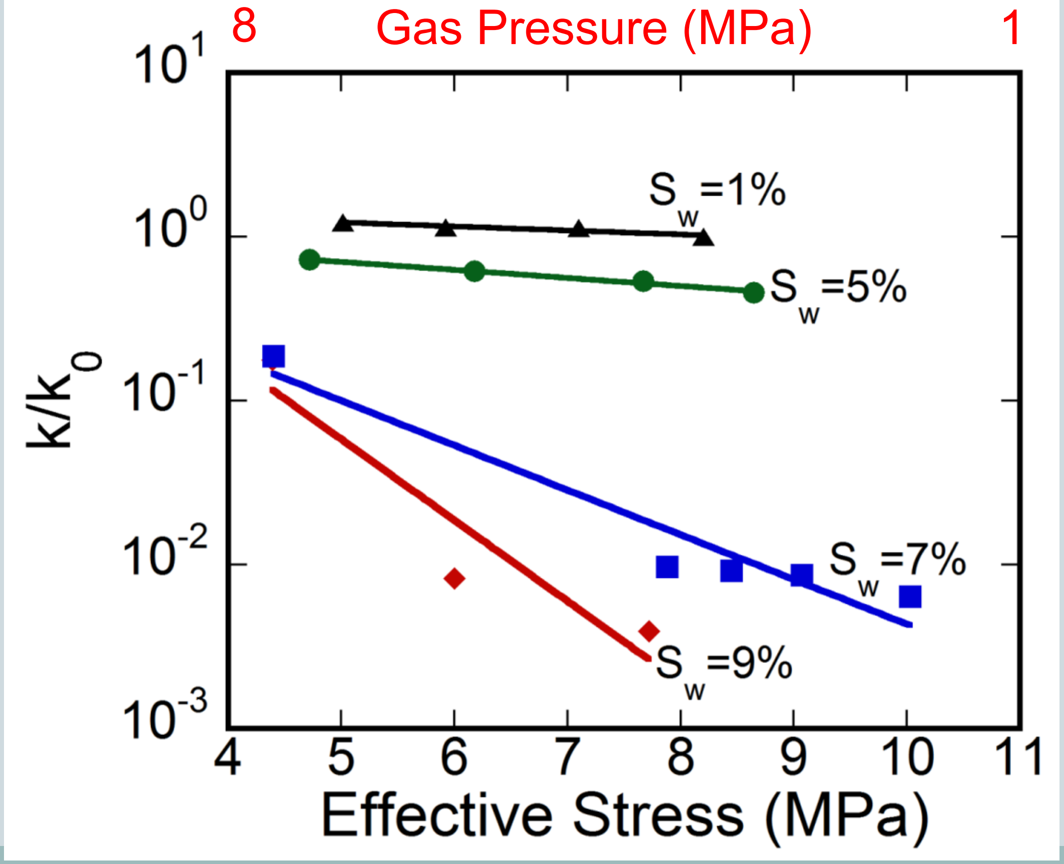
Mechanisms - Effective stress

1. Isolate the effect of other two factors by using constant water saturation and non-adsorbing gas, Helium
2. Use different water saturation levels
3. α, β are fit parameters

$$\left(\frac{k}{k_0}\right) = \alpha \exp(-\beta\sigma')$$

β, Stiffness coefficient



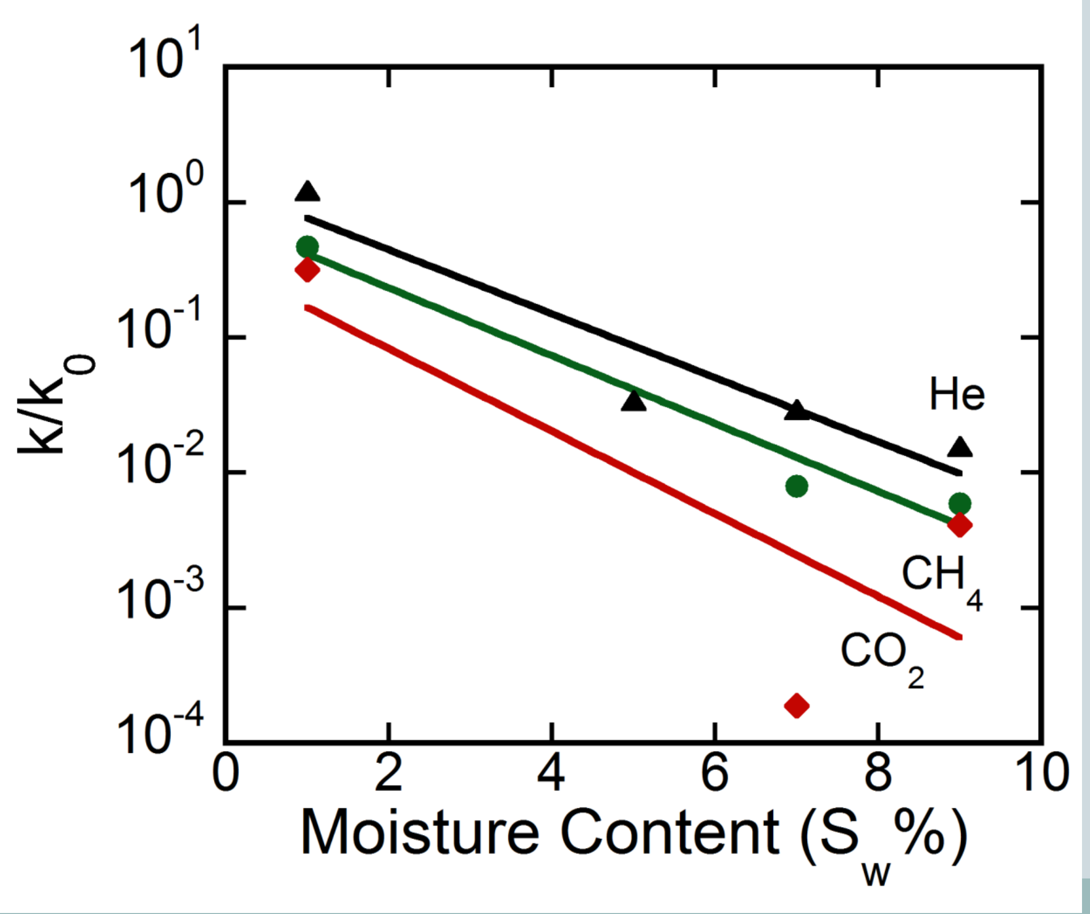


Mechanisms - Water content

$$\left(\frac{k}{k_0}\right) = \gamma \exp(-\delta S_w)$$

δ, Gas interaction coefficient

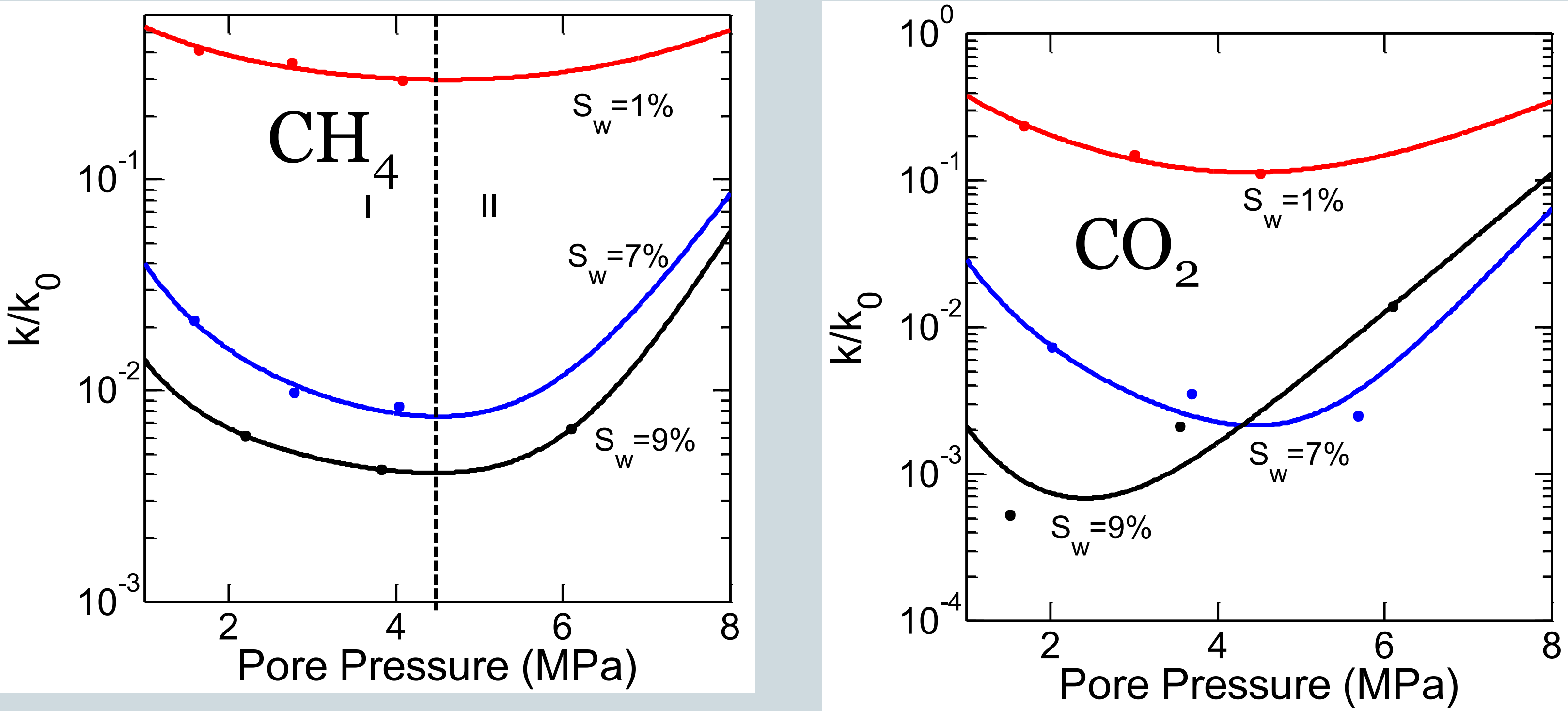
1. Isolate effect of other two factors using constant confining stress and non adsorbing gas helium
2. Various moisture saturation levels
3. γ, δ are fit parameters



Parameter Fits

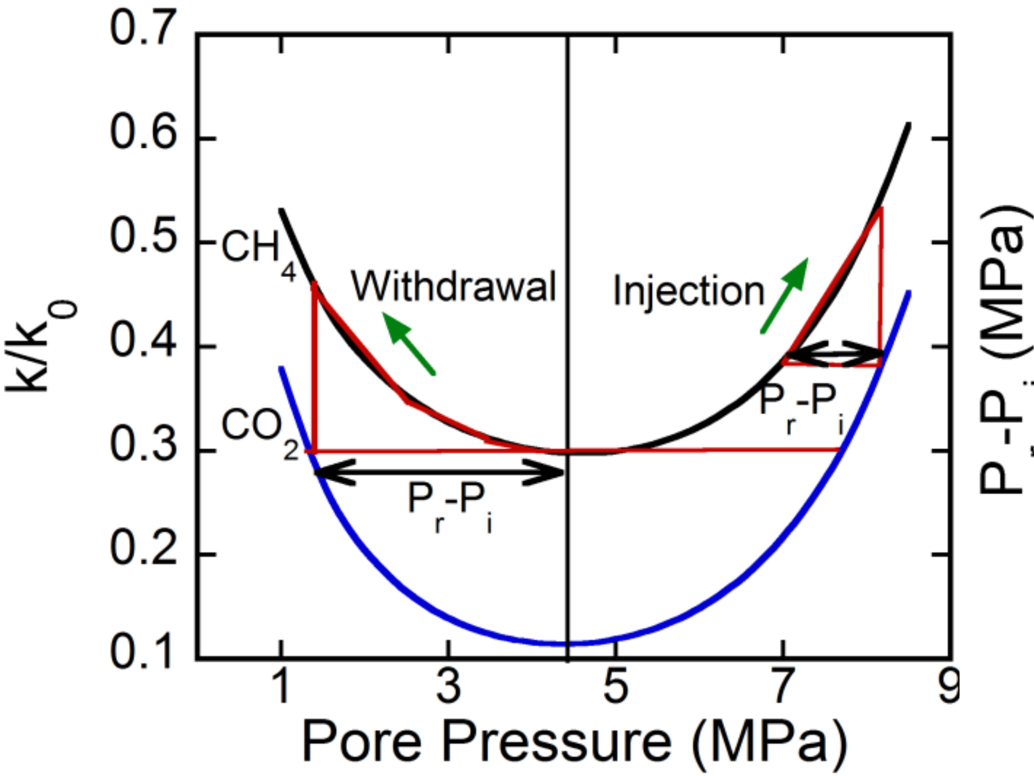
$$\left(\frac{k}{k_0}\right)=\left(\left(1+C\left(\frac{p}{p+p_L}\right)\right)^3+\exp(-\beta\sigma')\right)\times\exp(-\delta S_w)$$

C	Sorptive strain
$\boldsymbol{P_L}$	Langmuir pressure
$\boldsymbol{\beta}$	Stiffness coefficient
$\boldsymbol{\delta}$	Interaction coefficient

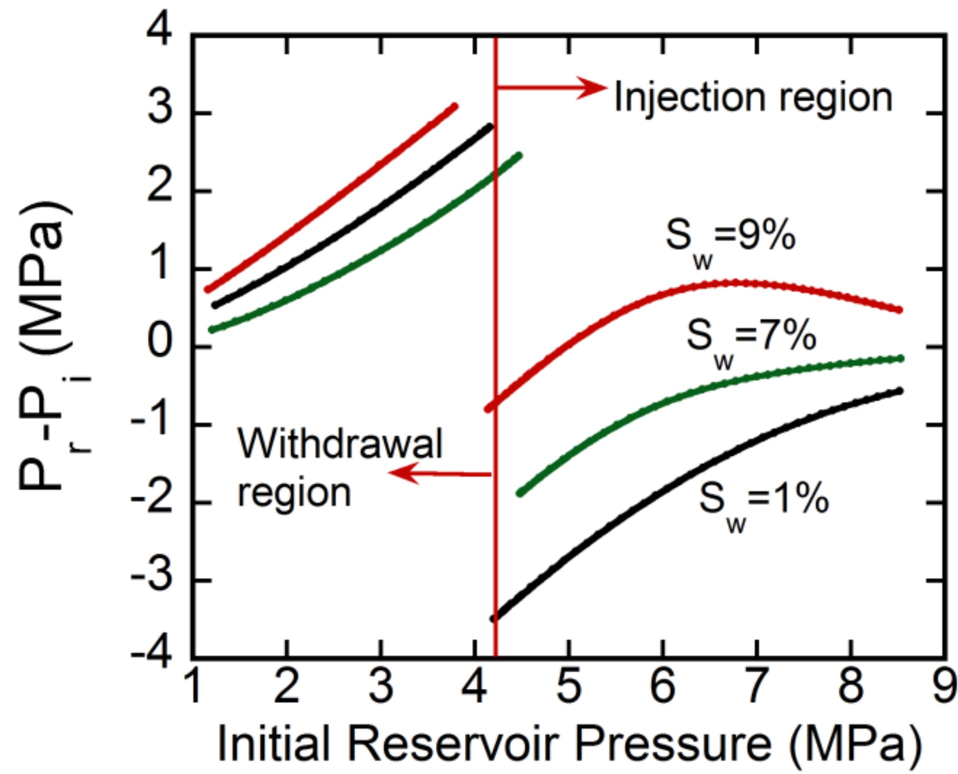


Optimization of Recovery with CO_2 Injection

Permeability Curves

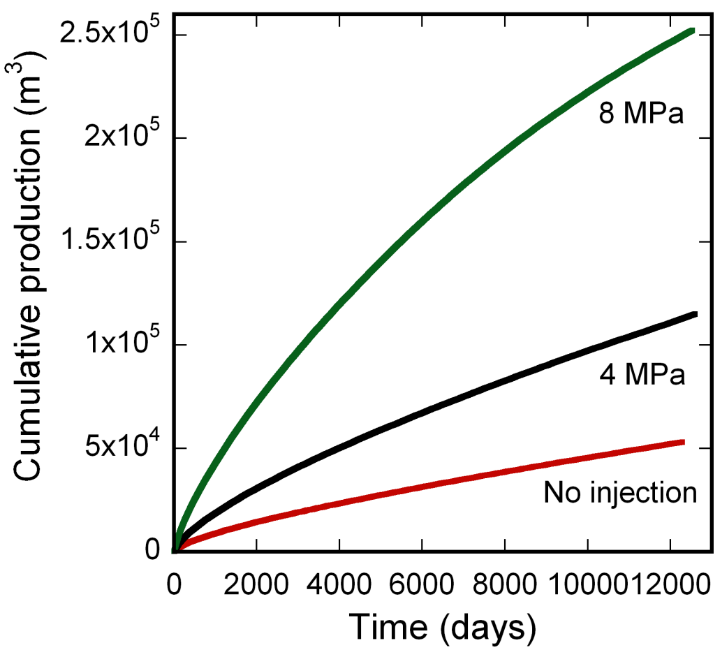


Pressure Needed to avoid Perm loss

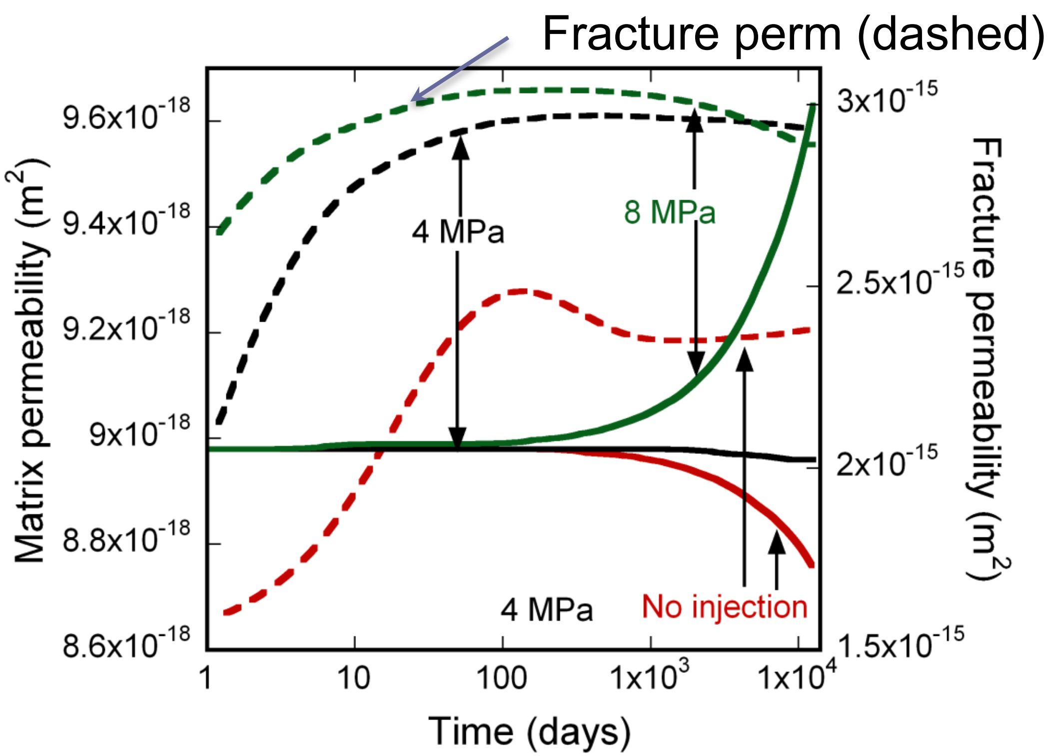


Injection Pressure – Homogeneous Perm.

Production



Permeability



Injection of CO_2 at higher pressures is advantageous

Kumar *et al.*, Effect of CO2 injection on homogeneously and heterogeneously permeable coalbed reservoir, In prep., Int. J G. Gas

Injection Pressure

Time (years)

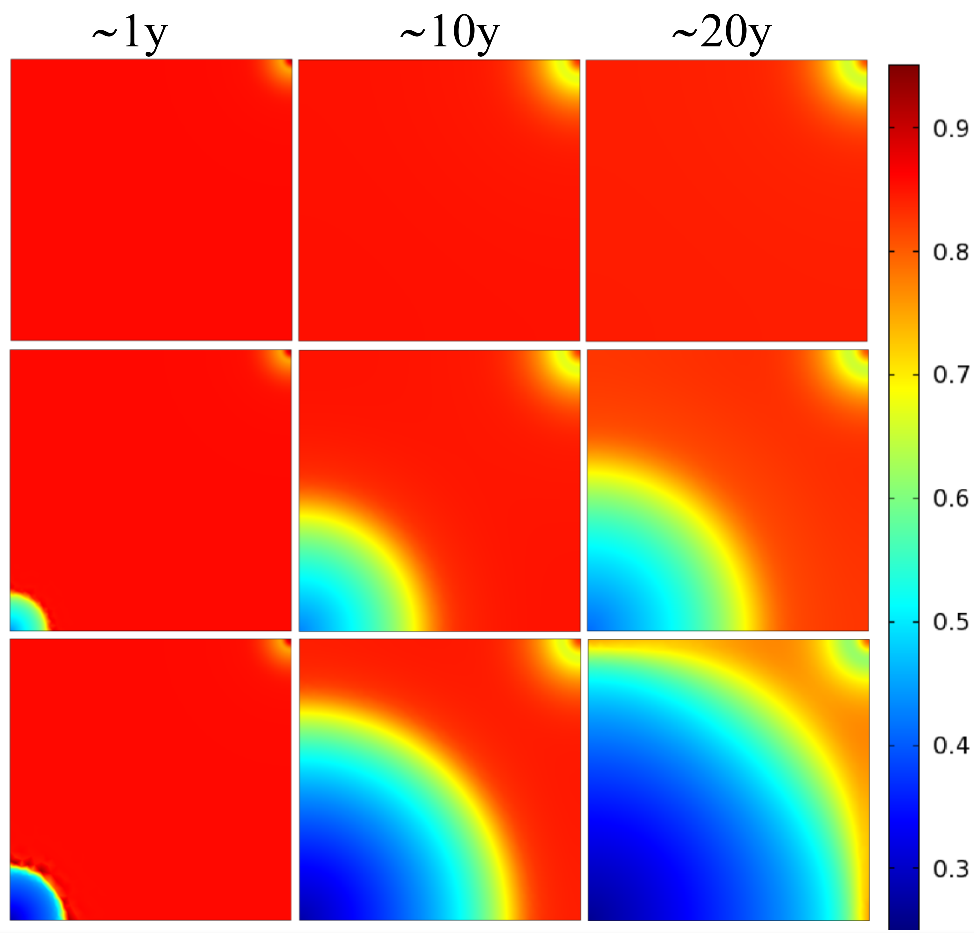
Mole Fraction of CH4

CO2 Injection (MPa)

No injection

4 MPa

8 MPa



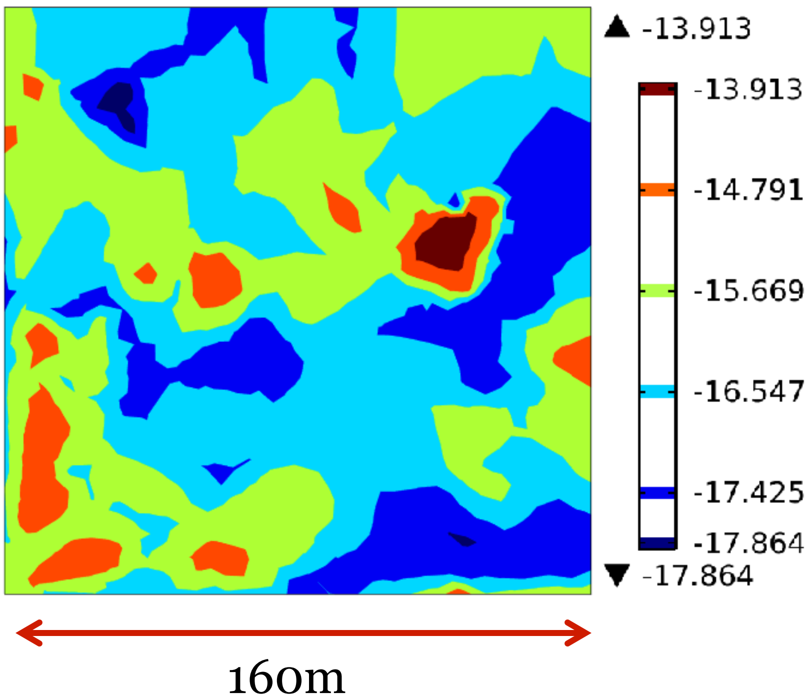
The injection of CO_2 rapidly reduces CH_4 mole fraction

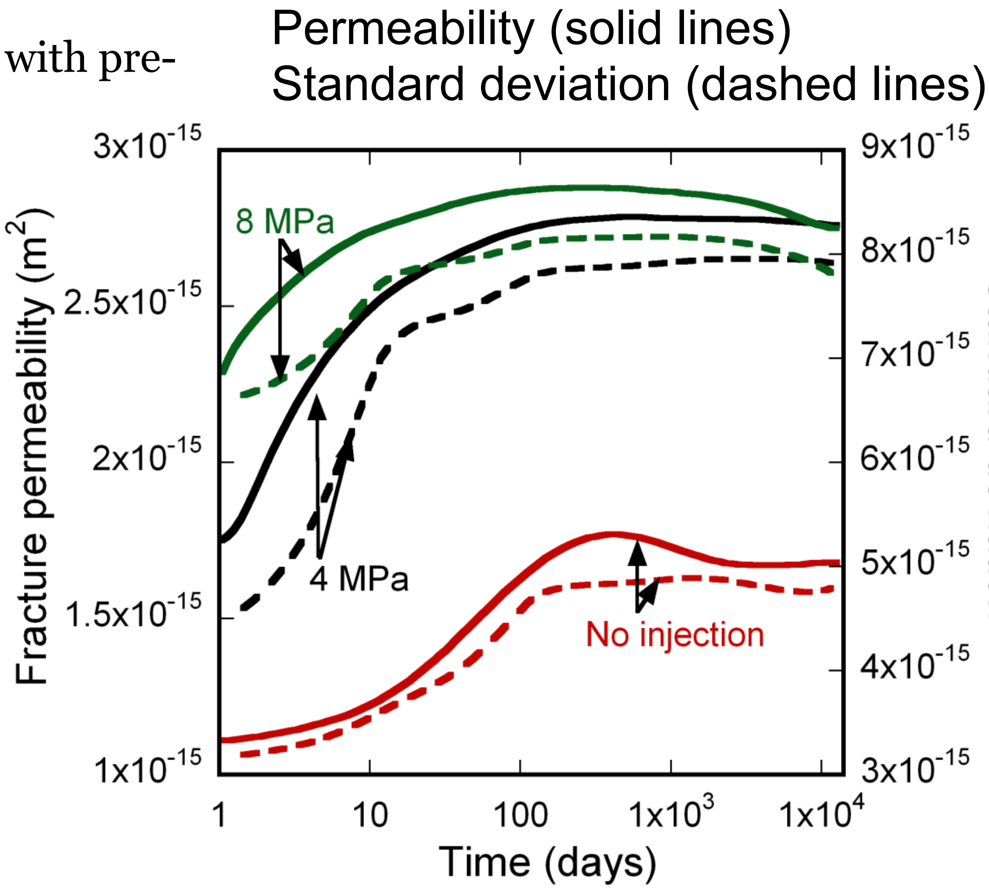
Kumar *et al.*, Effect of CO2 injection on homogeneously and heterogeneously permeable coalbed reservoir, In prep., Int. J G. Gas

Heterogeneity

Permeability configuration

- Gaussian distribution of permeability with pre-defined mean and range





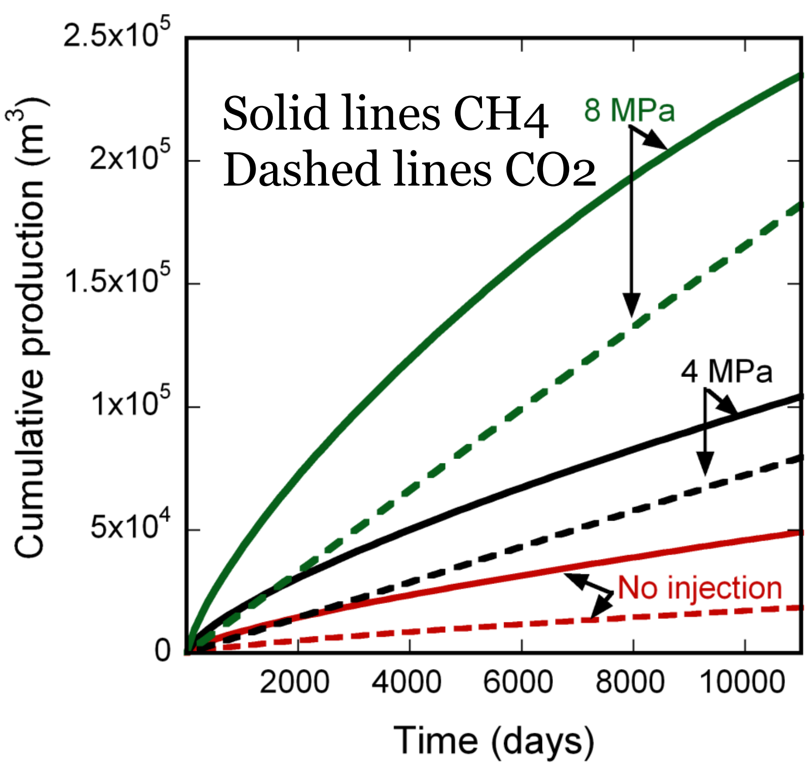
Heterogeneous regime shifts to homogeneous configuration with CO_2 injection.

Kumar *et al.*, Effect of CO2 injection on homogeneously and heterogeneously permeable coalbed reservoir, In prep., Int. J G. Gas

Heterogeneity

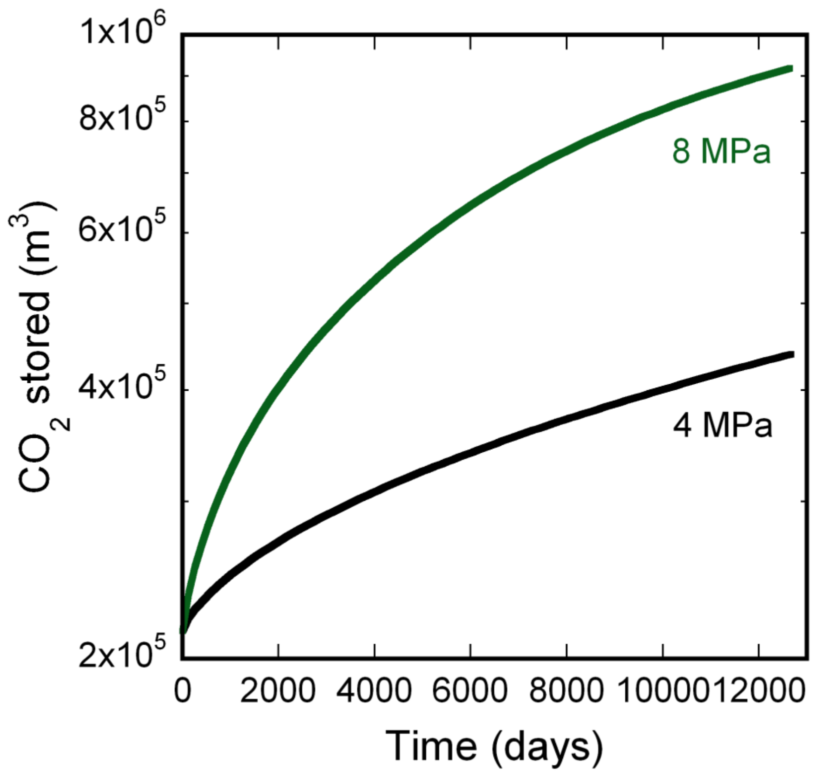
Earlier breakthrough

- When volume ratio:: CO2/CH4~1



Co2 stored

- Co2 sequestered in the process of enhanced recovery

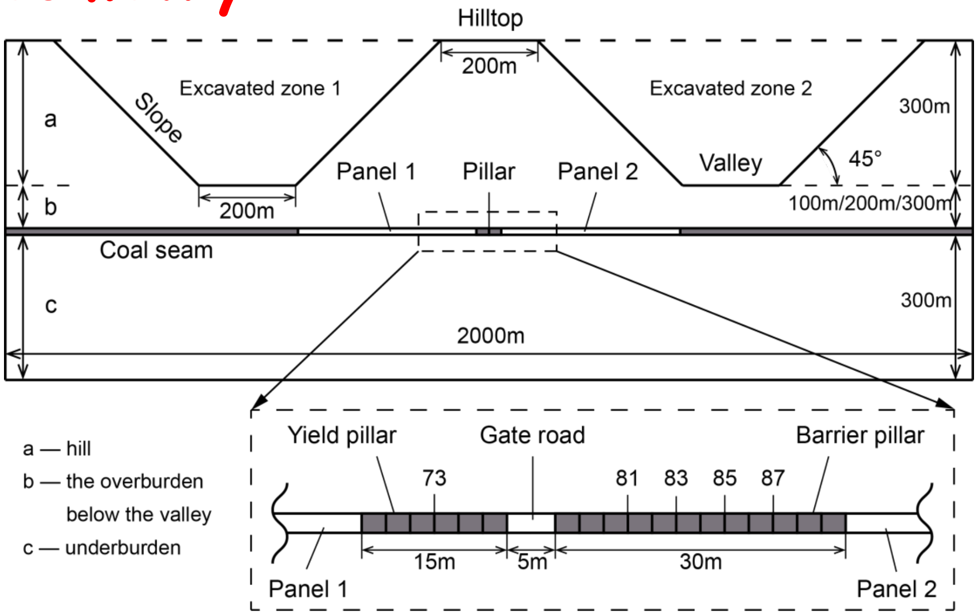


No scenario yields earlier breakthrough !!!

Kumar *et al.*, Effect of CO2 injection on homogeneously and heterogeneously permeable coalbed reservoir, In prep., Int. J G. Gas

Longwall Panel Well Survivability

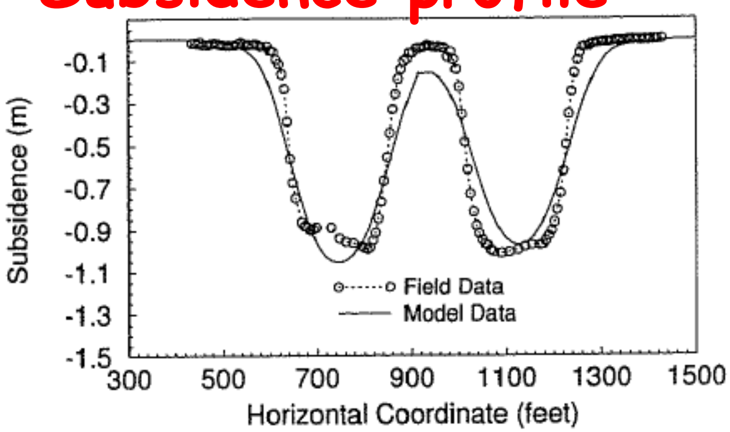
Geometry



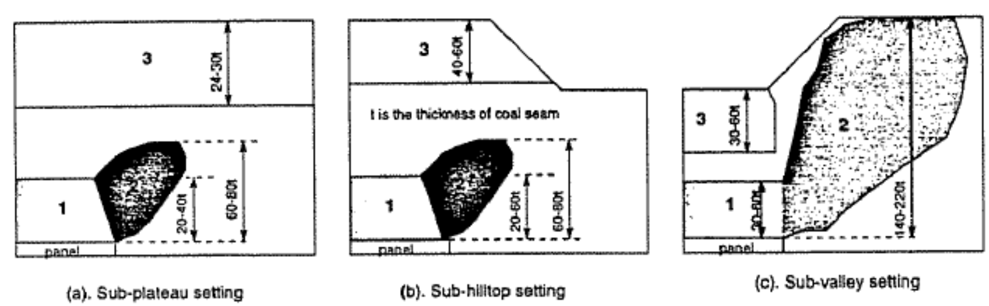
Issues

- Well deformation
  - Panel depth
  - Topography
  - Bedding slip
  - 3-D effects
  - Sequencing effects
- Permeability evolution analog

Subsidence profile

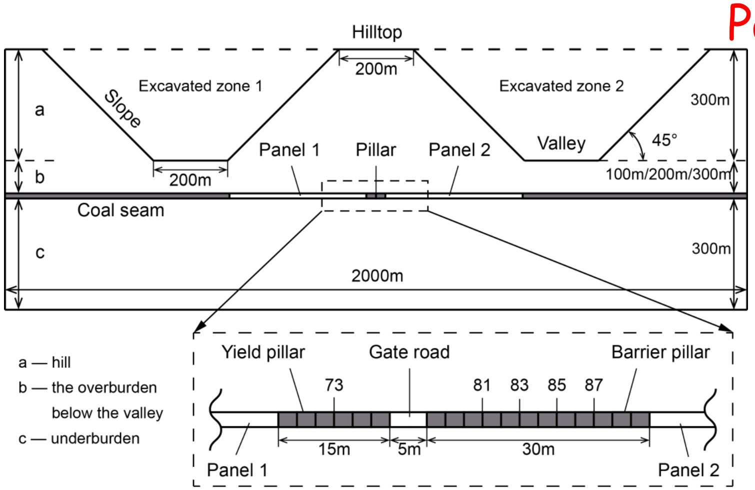


Zones of Observable Change



Longwall Panel Well - Shear Offsets

Geometry



First Left Panel Mined

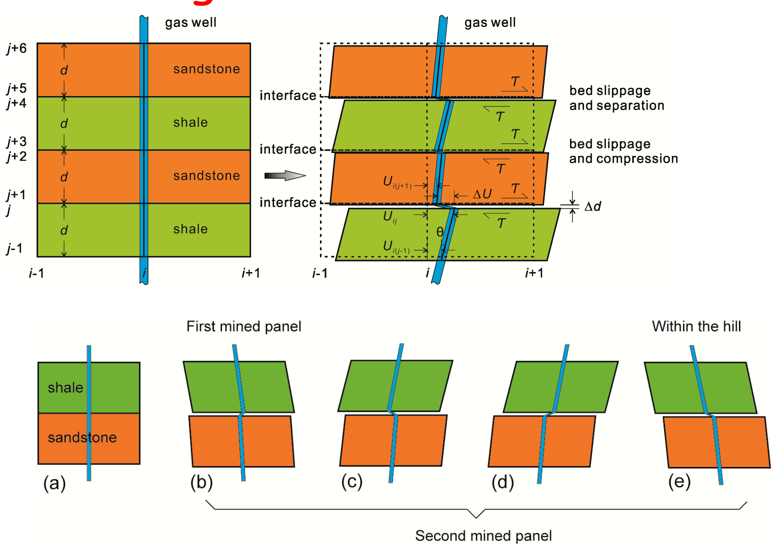
Second Right Panel Mined

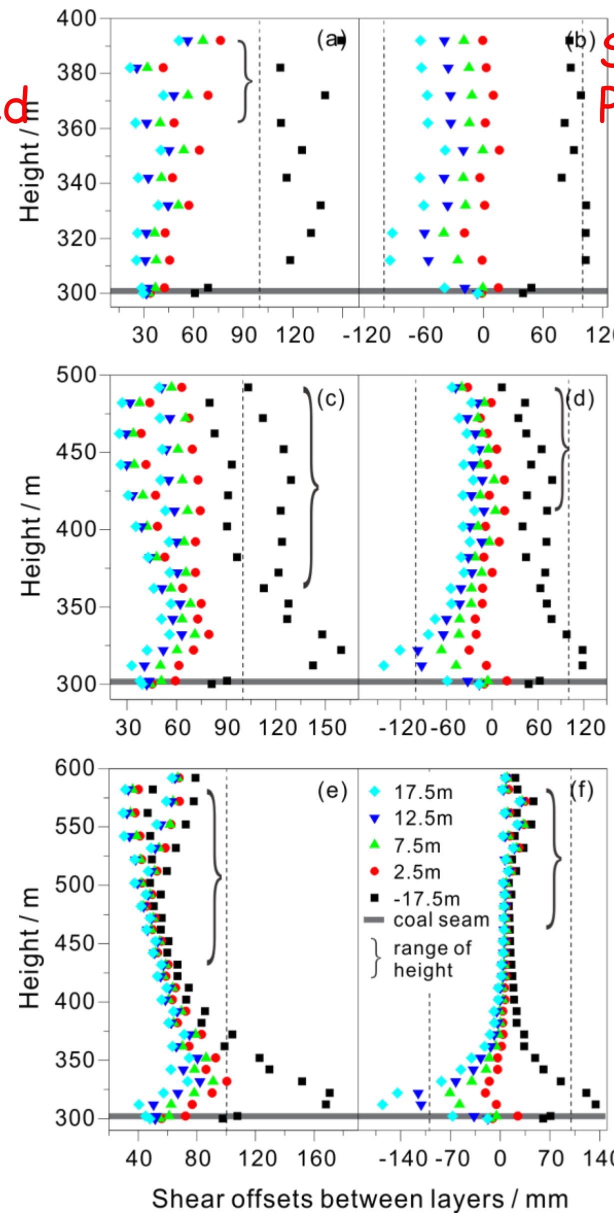
100m

200m

300m

Bedding Shear

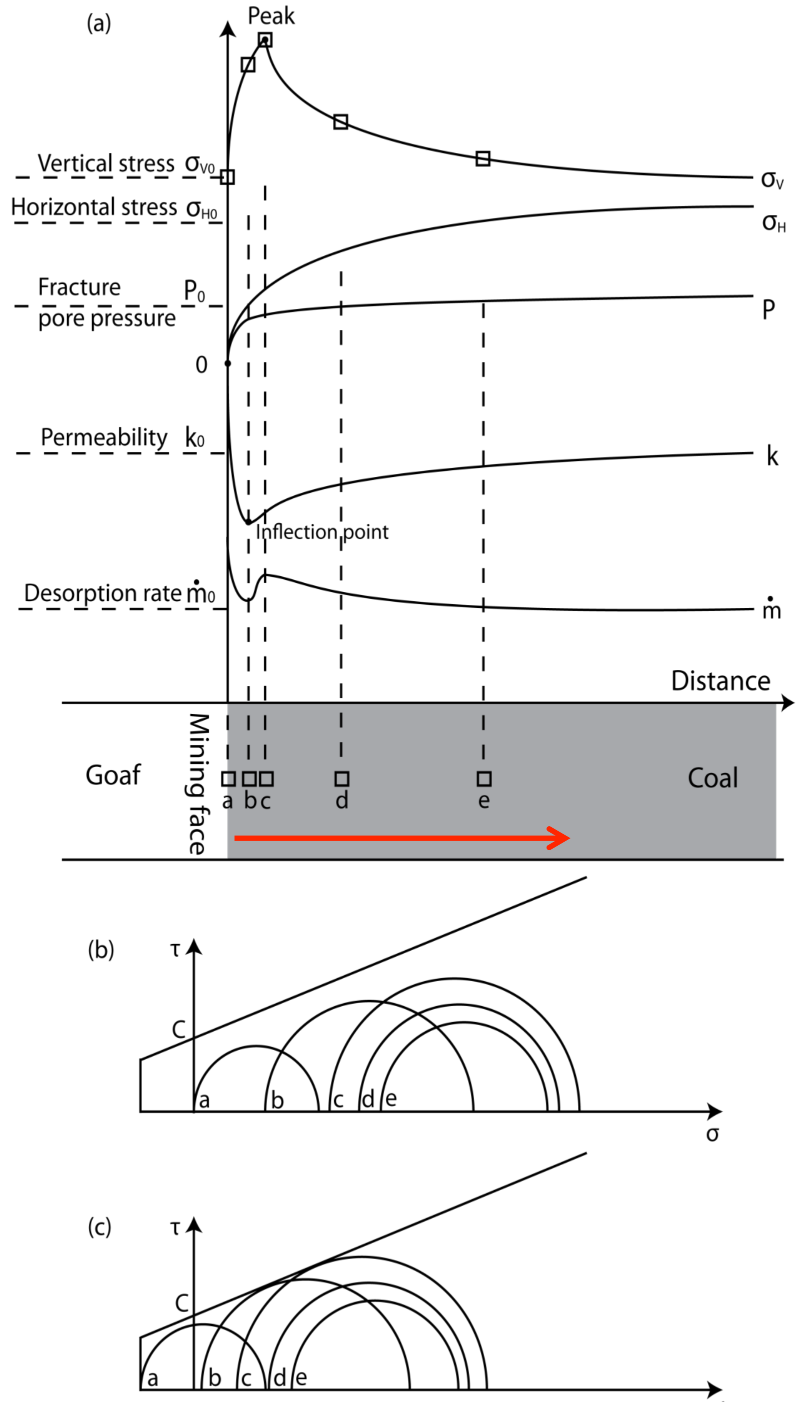




Gas Outbursts

Two Necessary Ingredients:

1. Failure driven by:
    1. Vertical stress
    2. Horizontal stress
    3. Excess pore pressure
2. Energy shedding driven by:
    1. Rock structure stiffness
    2. Gas stiffness/ compressibility

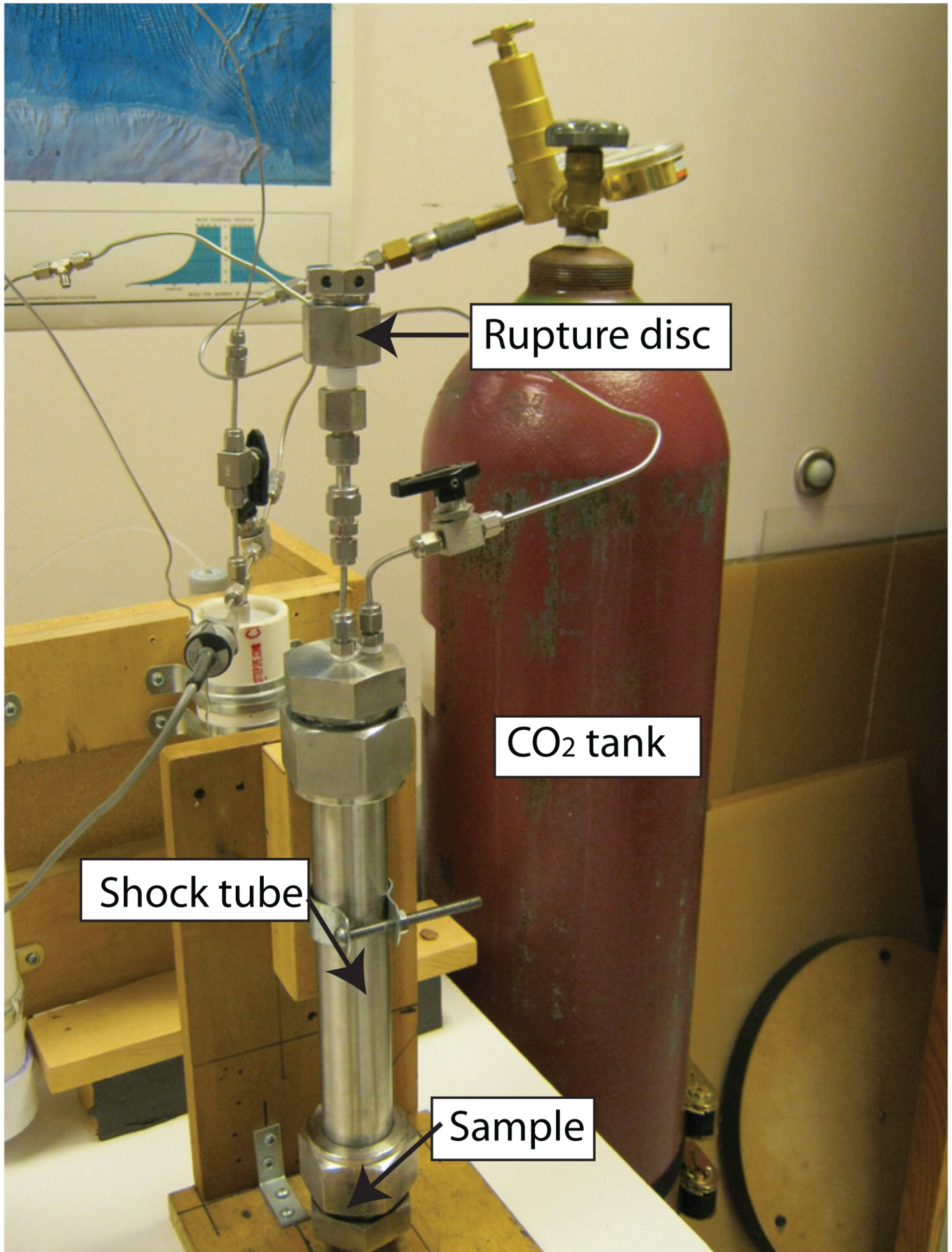


Moving ahead to the coal seams:

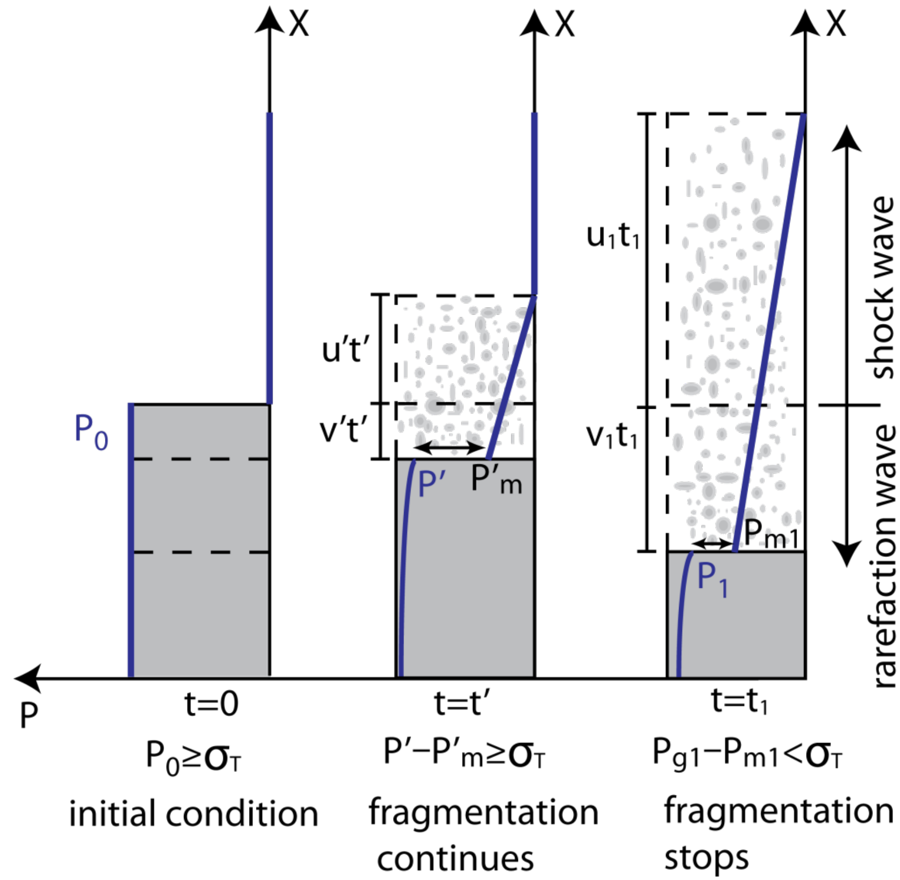
•tensile failure zone,

•gas overpressure induced shear failure zone (outbursts),

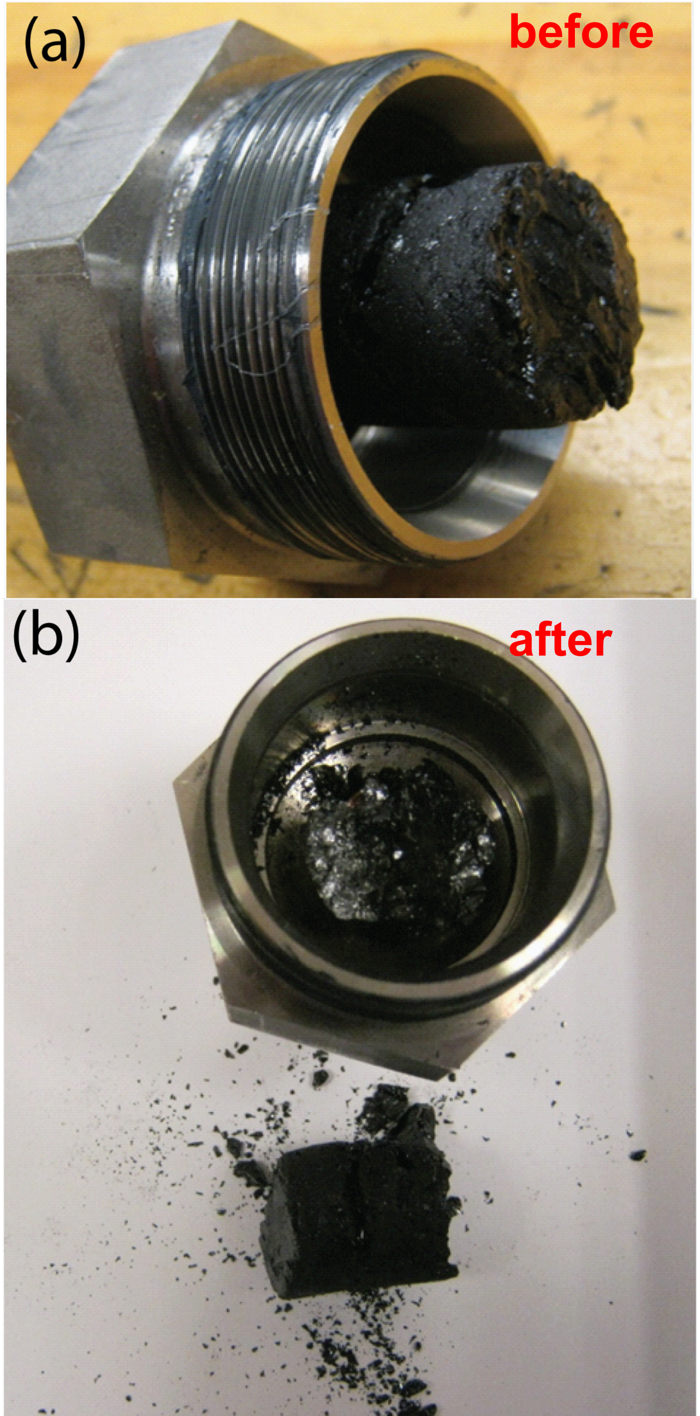
•vertical stress induced shear failure zone.

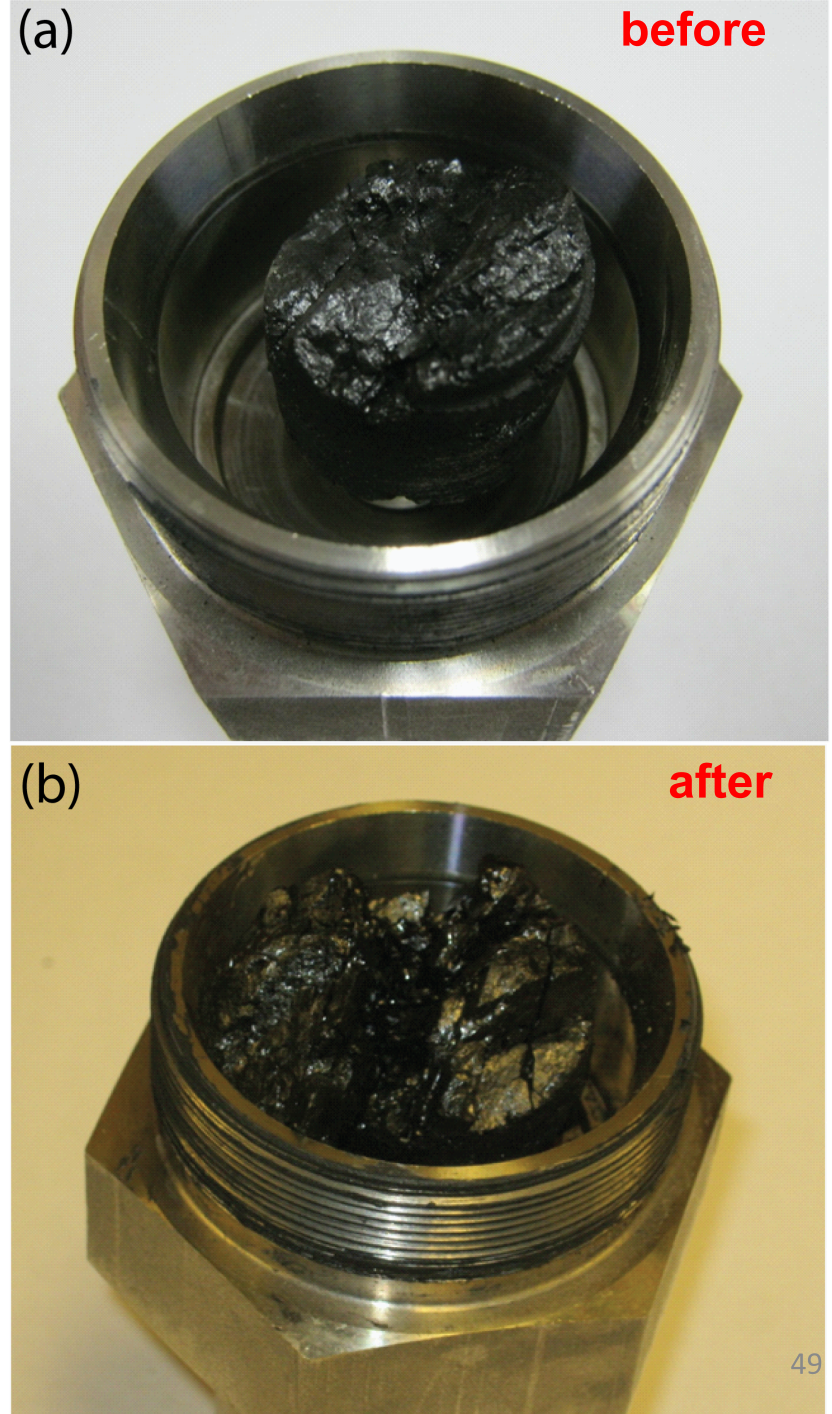


Rupture disc
CO2 tank
Shock tube
Sample

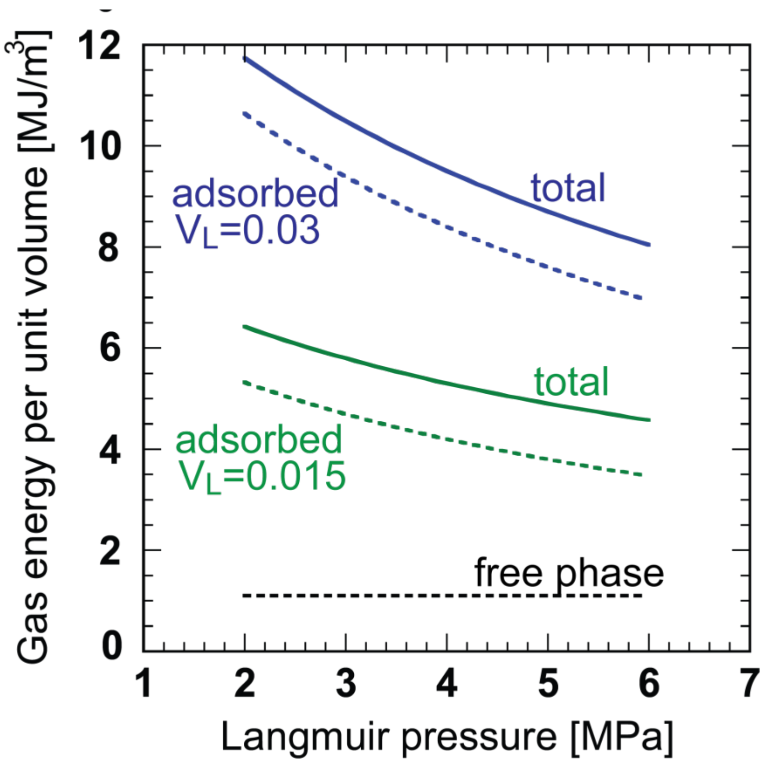


X
X
X
P0
u't'
v't'
P'
P'm
u1t1
v1t1
Pm1
P1
shock wave
rarefaction wave
P
t=0
P0≥σT
initial condition
t=t'
P'−P'm≥σT
fragmentation continues
t=t1
Pg1−Pm1<σT
fragmentation stops


(a)
before
(b)
after

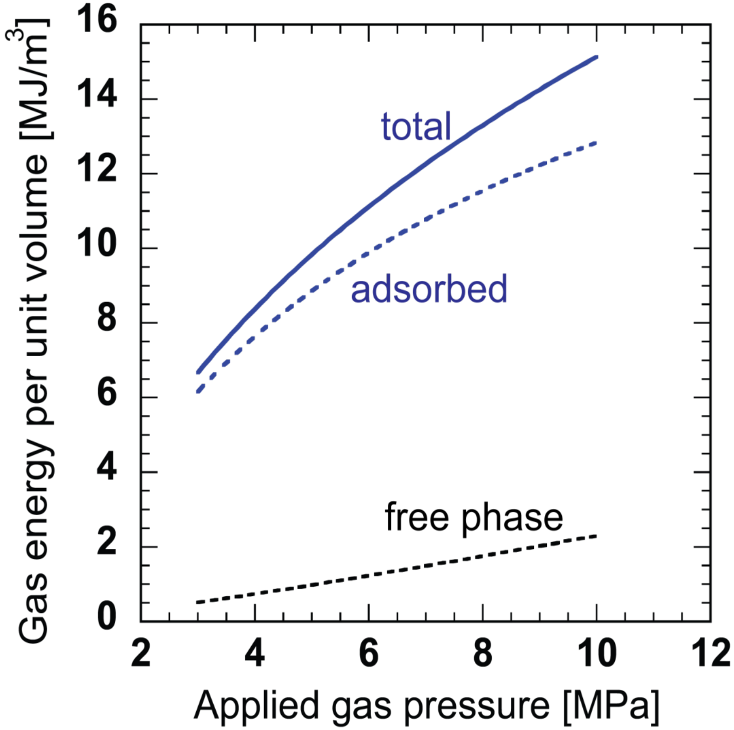

(a)
before
(b)
after

The role of Langmuir pressure



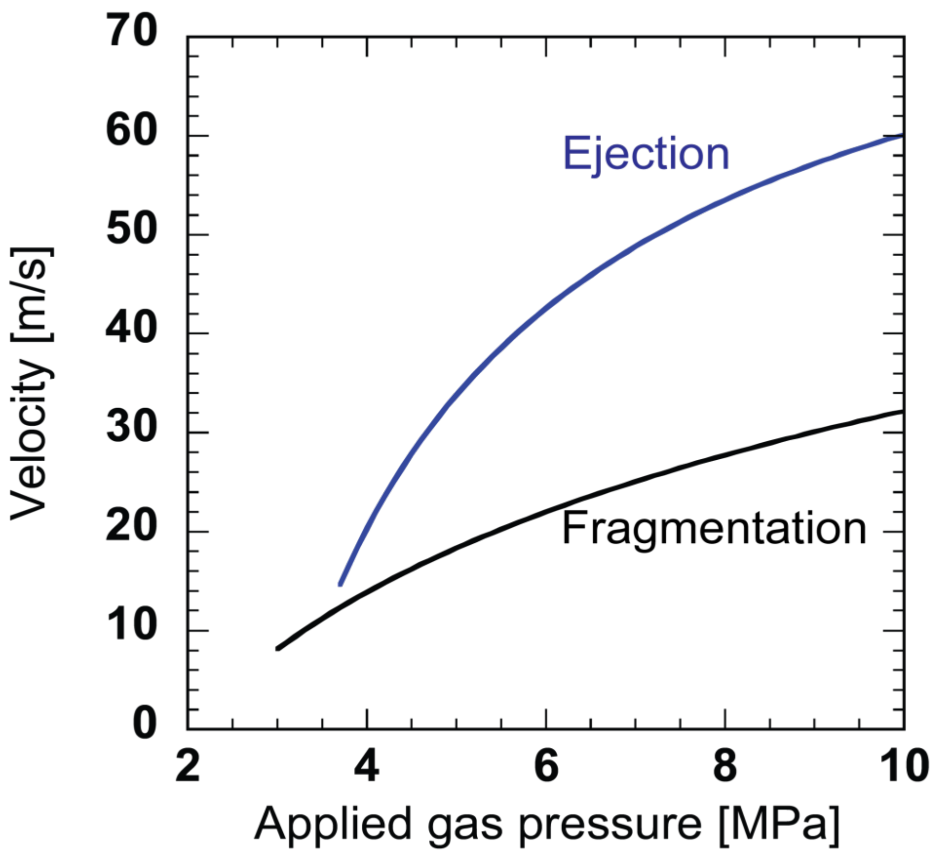
Most of the energy is in the adsorbed gas.

The role of initial gas pressure



Gas energy increases with pressure.

The role of initial gas pressure on the velocities



- The ejection velocity is larger than the fragmentation speed,
- Both velocities increase with increasing the applied gas pressure.

Summary

Poromechanical response of coals and shales have some similar attributes

- Role of fractures - high permeability but low storage
- Role of matrix – low permeability and high storage (pore and sorbed)
- Sorption – influence of swelling

Shown principally for coals but also germane to gas shales

- Swelling has significant but enigmatic influence on permeability evolution
- Role of Langmuir pressure
  - *Below* P_L - swelling influences deformation and permeability
  - *Above* P_L – effective stresses influence deformation and permeability

Attributes of using CO_2 as a displacing fluid

- Straightforwardly define pressures needed to retain permeability in the reservoir
- For CO_2 transmission:
  - No early breakthrough apparent – although CO_2 does dilute the methane flux throughout
  - CO_2 increases net production rate so economics is determined by:
    - Increased value of early time methane production
    - Increased cost of separating extra CO_2 from the reservoir (20% CO_2 present in reservoir)
  - CO_2 is net sequestered in the reservoir