A Scaling Study of Microbially-Enhanced Methane Production from Coal (MECBM): Optimizing Nutrient Delivery for Maximized Methane Production

Penn State (Derek Elsworth and Shimin Liu)
SIU-Carbondale (Yanna Liang and Satya Harpalani)

Background

Project Objective

Technical Approach

- Task 2 - Developing Nutrient Solutions for Sites #1 and #2
- Task 3 - Investigating Methane Productivity in a Core Holder Simulating In-Situ Conditions
- Task 4 – Characterizing Hydraulic Fracturing for Improved Bio-Gasification
- Task 5 – Determining In Situ Permeability Evolution
- Task 6 - Define the Viability of Bio-Gasification (MECBM) Systems

Project Structure

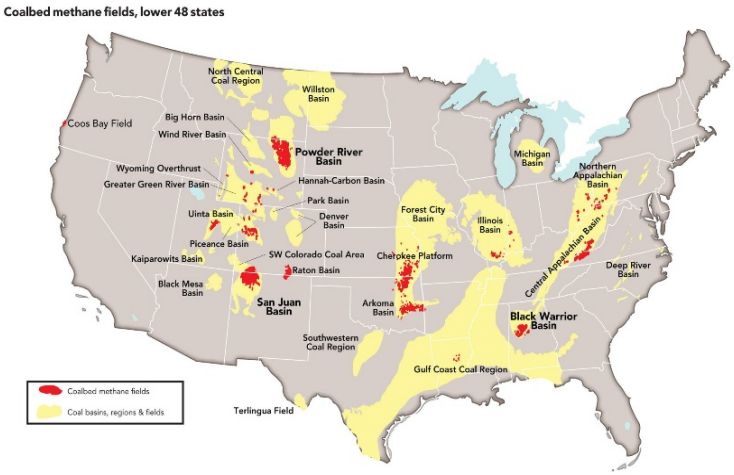
Project Schedule

Project Budget

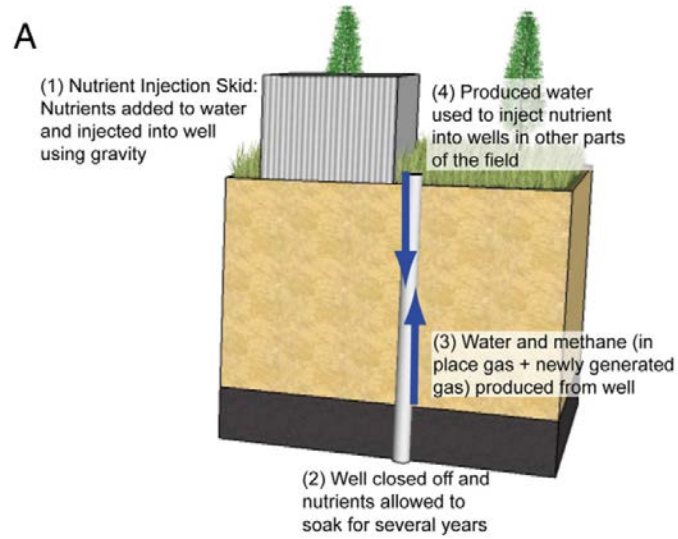
Project Management Plan and Risk Management

Background

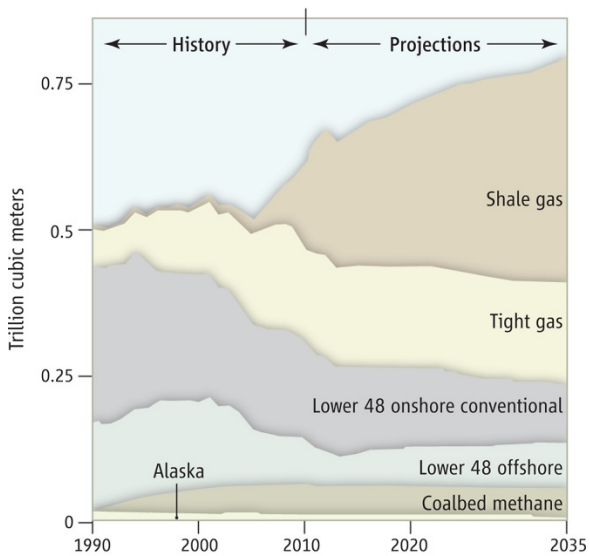
Geographic Distribution



Methods of production

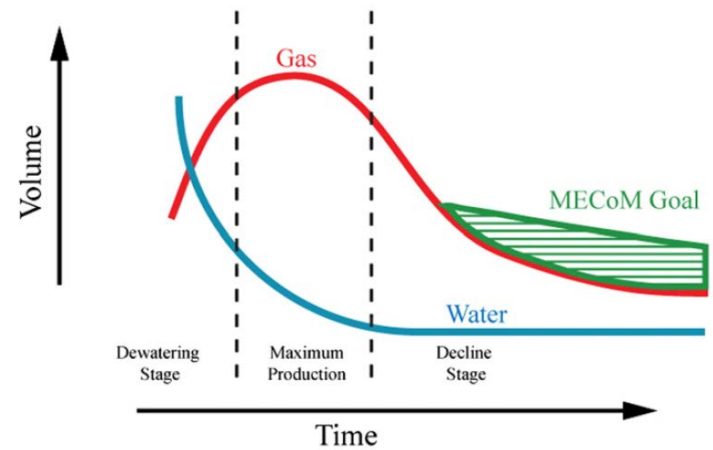


Projected US Gas Production



[Science, Oct 18, 2012]

MECBM Scheduling



[Nuccio, 2000]

Objectives

Develop Nutrient Solutions

- Extend work on Illinois Basin
- Initiate work on San Juan Basin

Optimize Methods of Delivery

- Explore hydraulic fracturing for improved sweep
- Define longevity of fracture treatment
- Permeability evolution – nutrient delivery & CH_4 productivity

Evaluate Potential Improvement

Synthesize Response

- Microbiology – improved productivity
- Geomechanics – delivery and longevity

Design Field Experiment

- Define/refine key questions
- Identify key location
- Identify unique tools/methods

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Rationale for Task 2

1. The nutrient solution we have developed for IL coal so far is tap water based without considering composition of the formation water.
2. For this project, we will test nutrient recipes based on the exact composition of the formation water at the two sites.
3. Composition and structure of the microbial community at the SJ basin is unknown.

Task 2: Accomplishments

1. Formation water collection

Two trips: IL basin: 10/14/2015

SJ basin: 10/23-27/2015

Procedure:

1) Water samples were added to containers containing: Na_2S (1 mM) and resazurin (2 mg/l).
2) During transportation, containers were kept on ice.
3) Upon arrival in the lab, part of water was filtered to collect microbial cells, part was centrifuged to obtain concentrated cells. One half gallon was sent for chemical analyses. All the others were stored in a freezer (-20°C) directly.

Results:

1) 200 frozen stocks (-80°C) of microbial community for each site.
2) 10 gallon of water frozen (-20°C) for each site.
3) Active cultures from each site are growing in our lab.

Task 2: Accomplishments- cont.

2. Chemical analysis

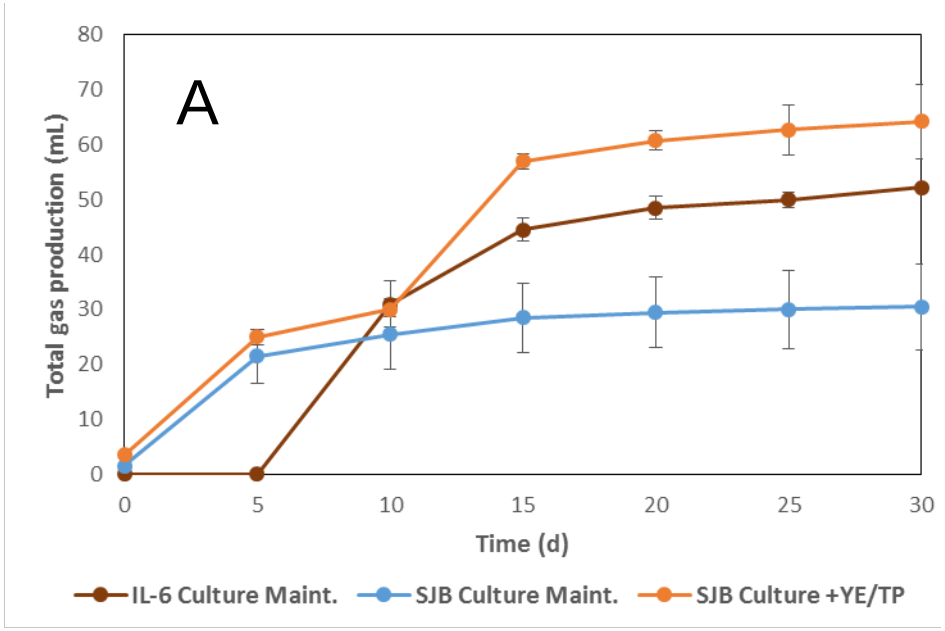
Parameter	Unit	IL basin	SJ basin
Temperature	(°C)	25-32	41-44
pH		7.65	8.19
Free ammonia	mg/l	0.012	0.23
Total ammonia	mg/l	9.05	1.78
Total Nitrogen-N	mg/l	<5.0	2.4
COD	mg/l	650	2497
H_2S	mg/l	**431**	33
Fluoride	mg/l	1.8	4
Nitrite	mg/l	<0.5	<0.5
Nitrate	mg/l	<0.5	0.2
Phosphate	mg/l	<0.75	<0.75
Total phosphate-P	mg/l	<5.0	0.171
Sulfate	mg/l	<0.75	<0.75
Chloride	mg/l	**21665**	161
Iron	mg/l	0.3	1.11
Total dissolved organic carbon	mg/l	0.44	1.15
Alkalinity as CaCO3	mg/l	400	1280
Heavy metals	ug/l	Pending	Pending

3. Microbial analysis

1. DNA was extracted from water samples from SJ basin.
2. Samples of DNA with good concentration and quality were sent for sequencing.

Task 2: Accomplishments- cont.

4. Active cultures in the lab



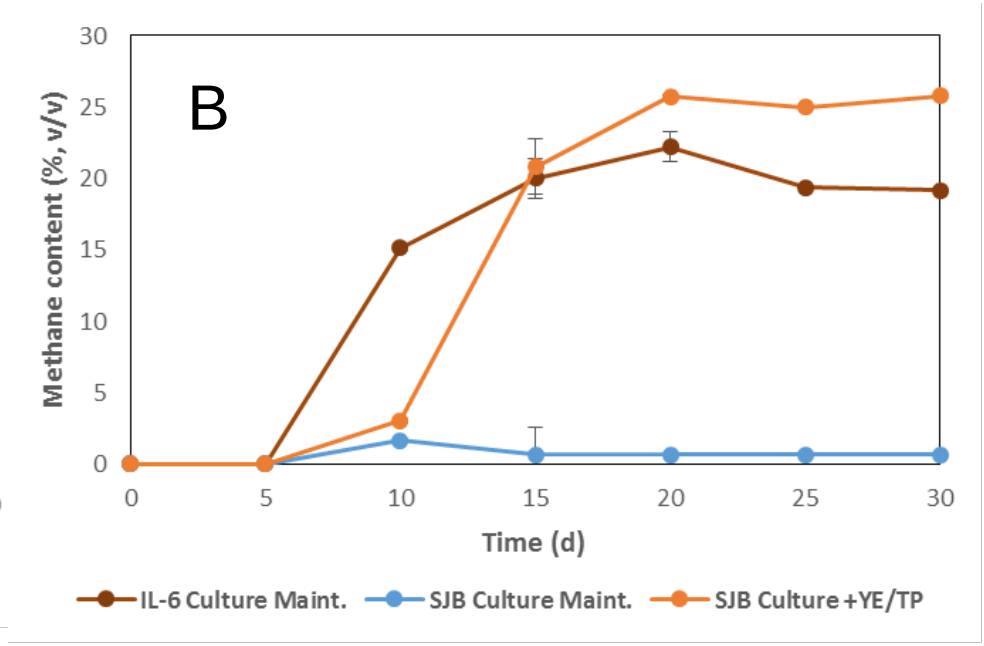


Fig. Cultures developed from frozen stocks from two sites. For IL basin, the microcosms contained: IL coal + one nutrient solution + cells and incubated at 28°C. For SJ basin, the microcosms contained: SJ coal + SJ formation water + cells and incubated at 43°C. YE: yeast extract, TP: trypticase peptone. A: total gas volume; B: methane content.

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Project Structure
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Rationale for Task 3

1. For fractured coal, we need to understand how often nutrients should be provided under in situ conditions and how methane yield can be affected by different fracturing.
2. Comparing methane yield between setups where nutrients are fed intermittently vs. continuously.
3. Understand changes made to coals at the two sites due to biogasification.

Future work

Task 2

- Subtask 2.2 – Analyzing DNA sequencing data and understanding microbial composition of formation waters from site #2
- Subtask 2.3 - Developing nutrient recipes for site #2

Task 3 - Investigating Methane Productivity in a Core Holder Simulating In-Situ Conditions (Satya, Yanna)

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Rationale for Task 4

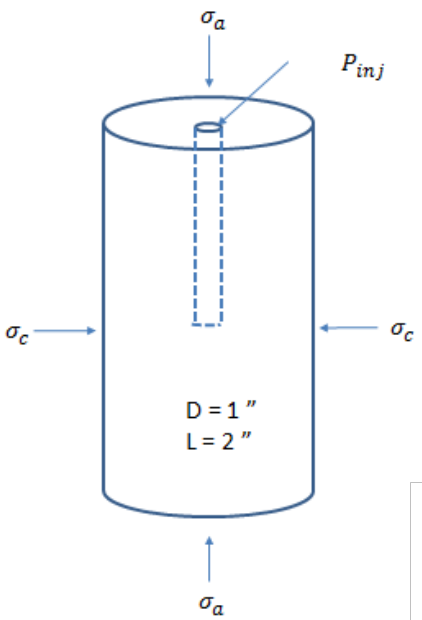
1. **One method to effectively sweep the entire reservoir is to use hydraulic fracturing.**

If we do this, we need to understand:

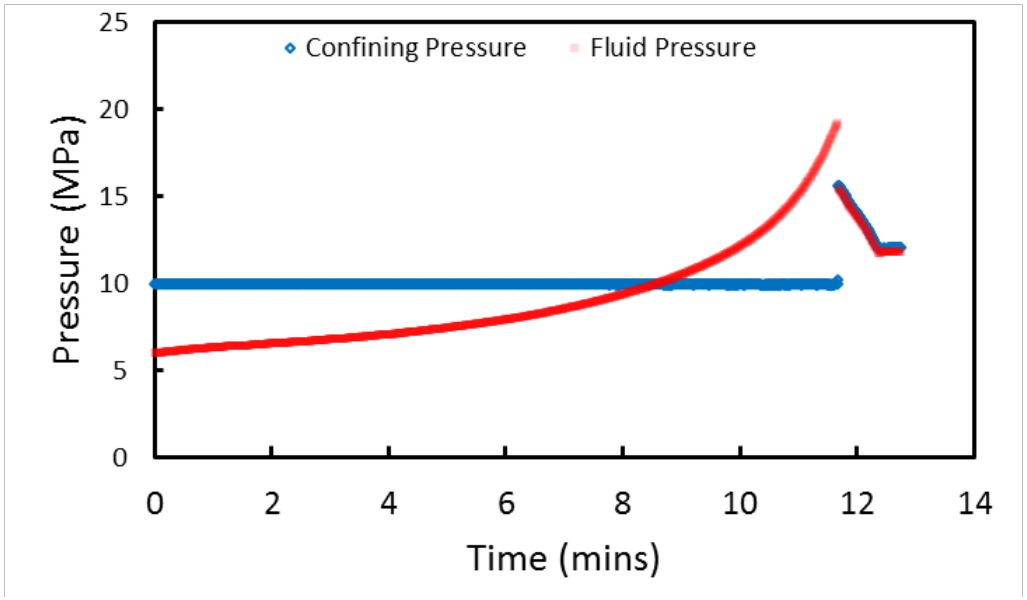
1. What will be the dimensions of the hydraulic fractures?
2. What will be the permeability – with proppants?
3. How will this permeability change with time?
4. How will permeability change away from the fracture?

Hydraulic Fracturing

Sample Geometry

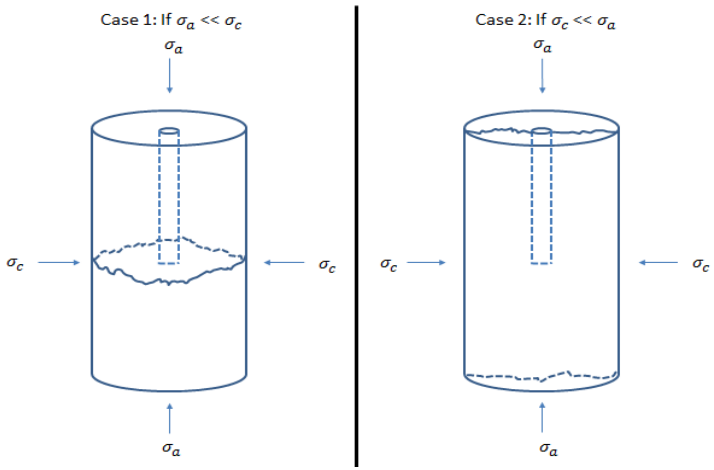


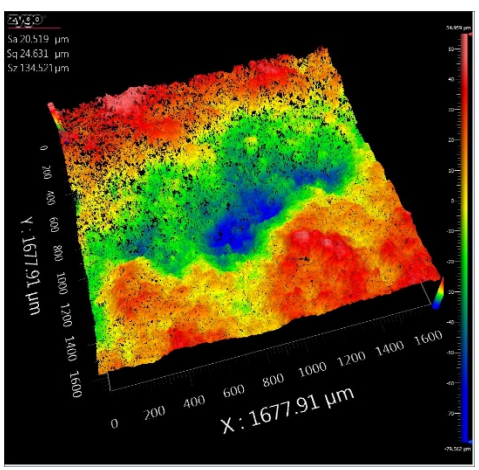
Sample Platens/Seals



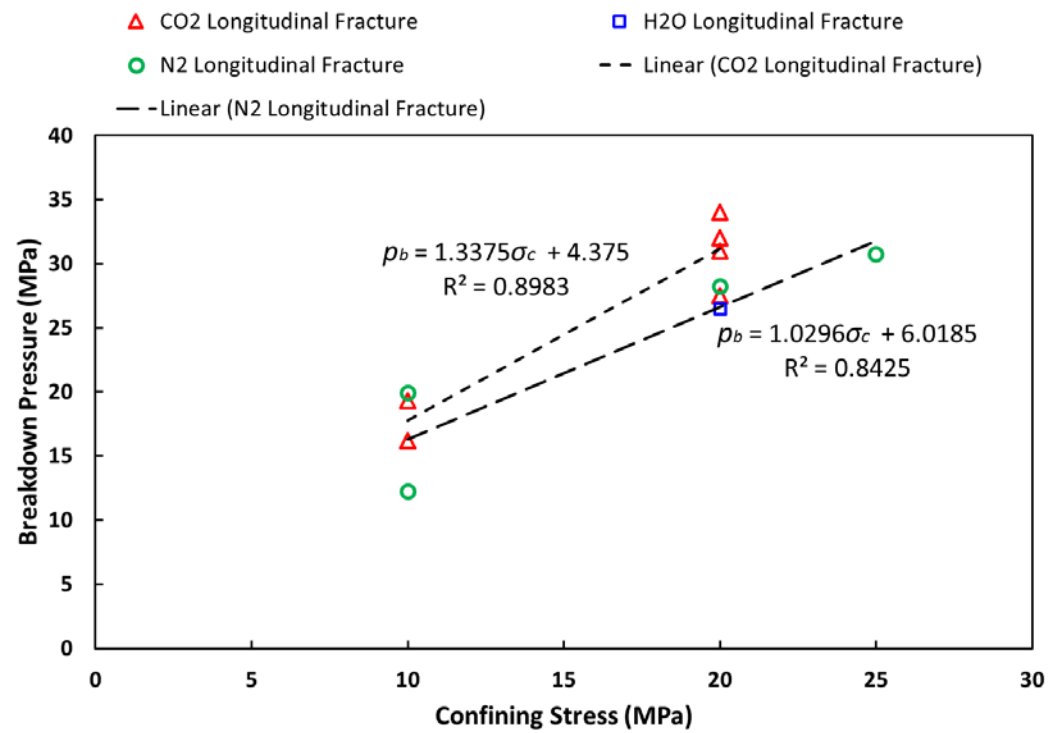
Results for Shales

Stress-dependent failure modes





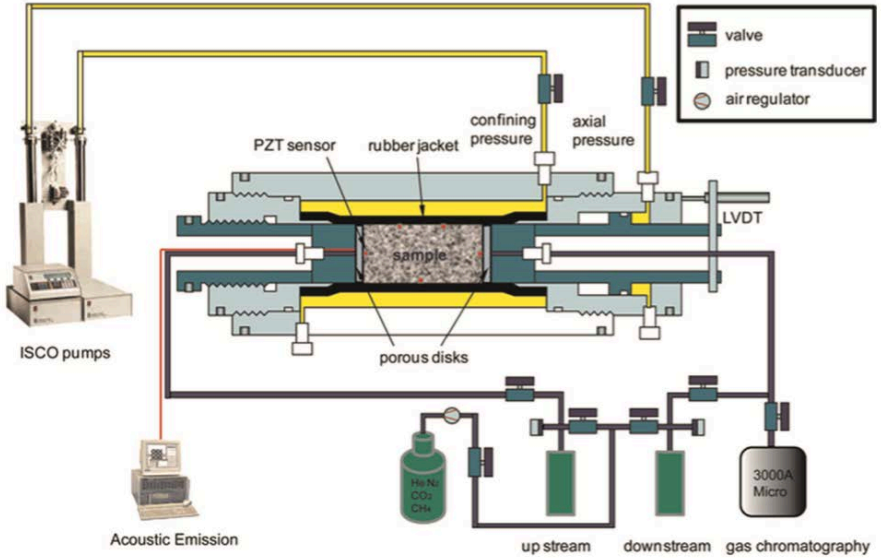
Breakdown pressures



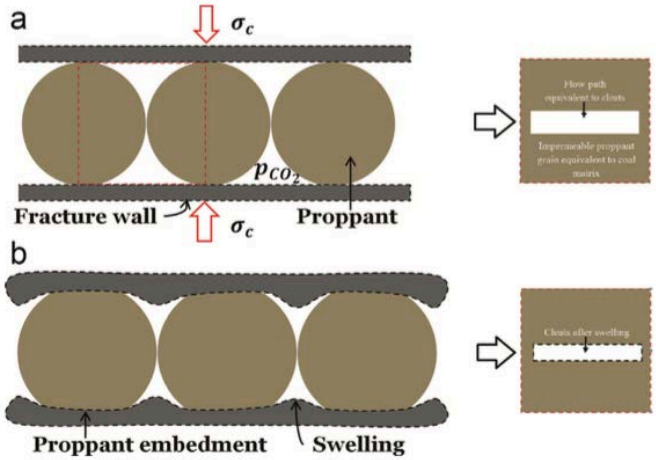
Proppant Embedment - Measurements

Split sample

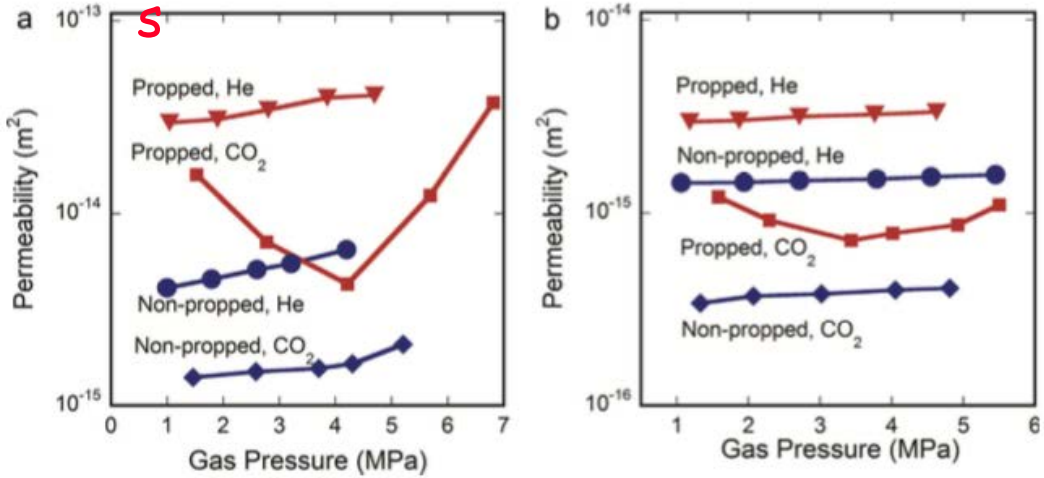
Apparatus



Embedment and swelling

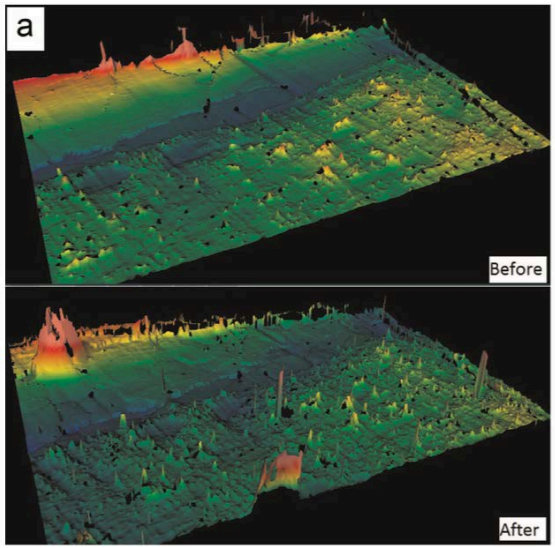


Observations

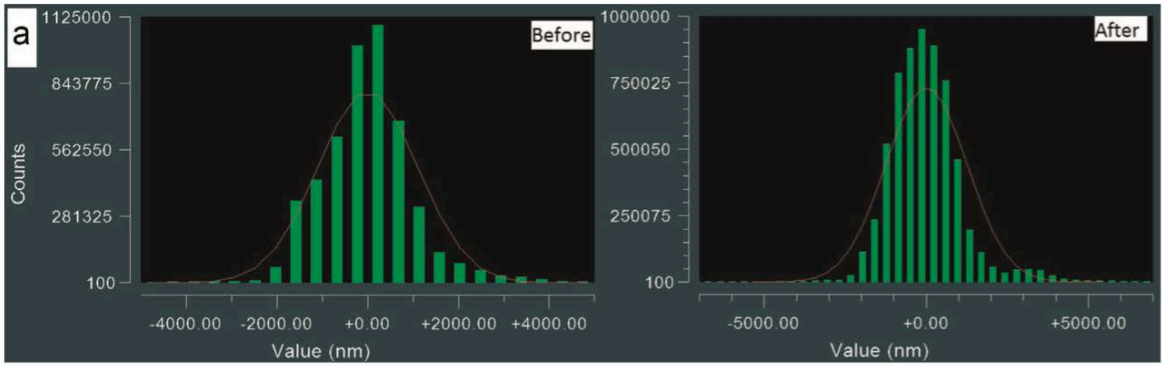


Proppant Embedment - Analysis

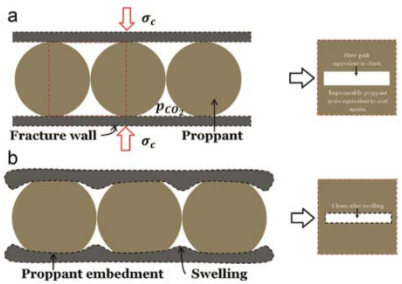
White light interferometry

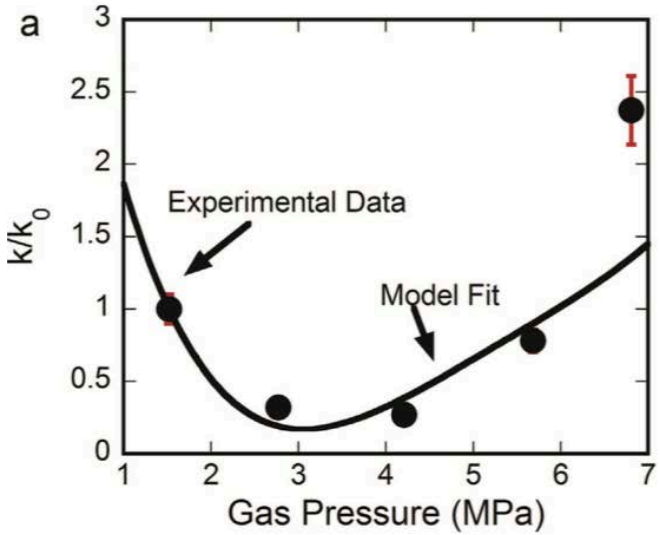


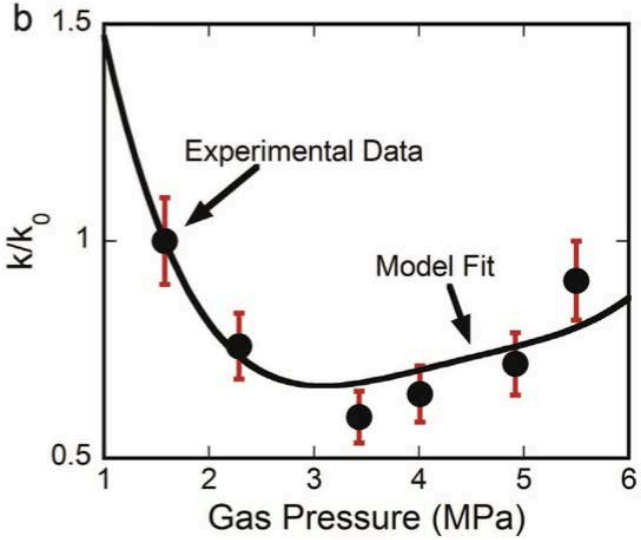
Irrecoverable embedment



Permeability model







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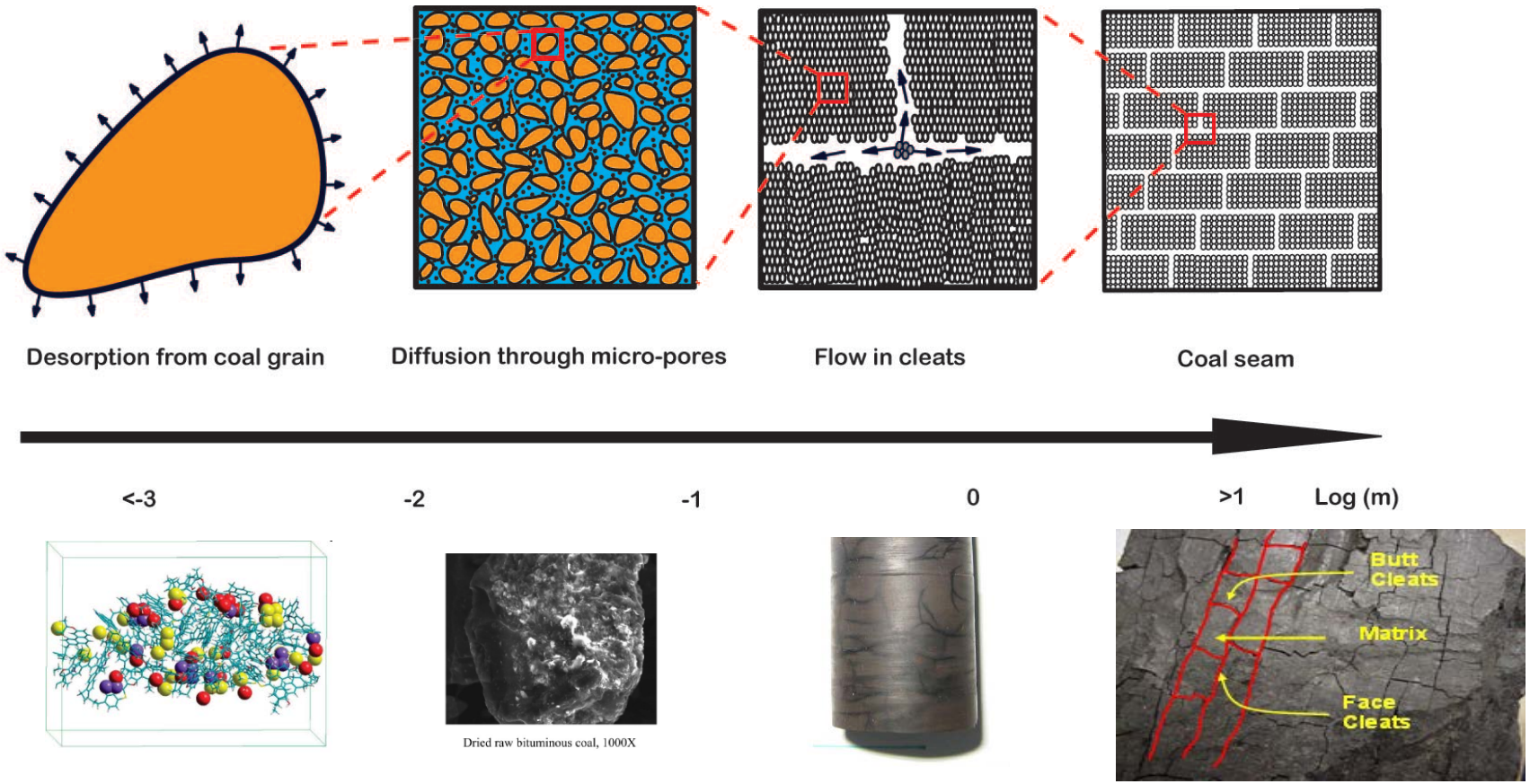
Rationale for Task 5

1. **Delivery of nutrients is dependent on changes in permeability with time**

We need to understand:

1. What is the initial permeability of coal?
2. How does this permeability change with nutrient delivery?
    1. Duration
    2. Concentration
    3. Gas production
3. How does gas recovery change with nutrient delivery – in situ?

Multi-Porosity Multi-Permeability and Multi-Scale Medium



Overlapping Continua

Storage
- Dissolved in water
- Free-gas
- Sorbed gas

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

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

Key Mechanistic Features [2] - Permeability

Permeability Model:

Fracture permeability

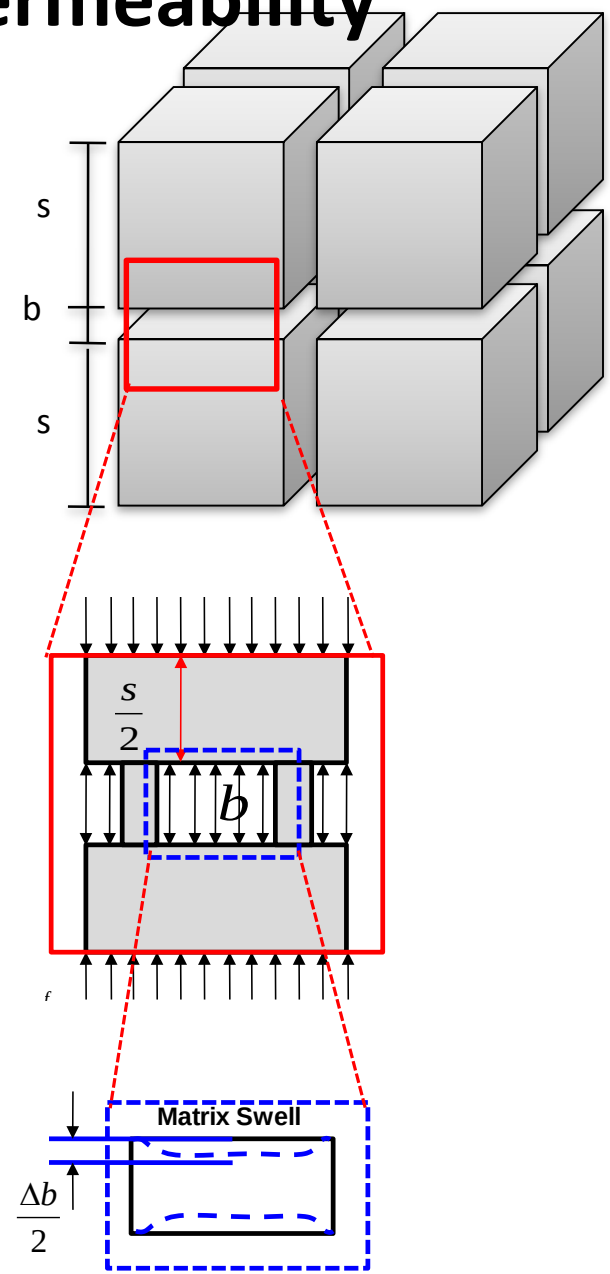
$$k = \frac{b^3}{12s}$$

Initial aperture

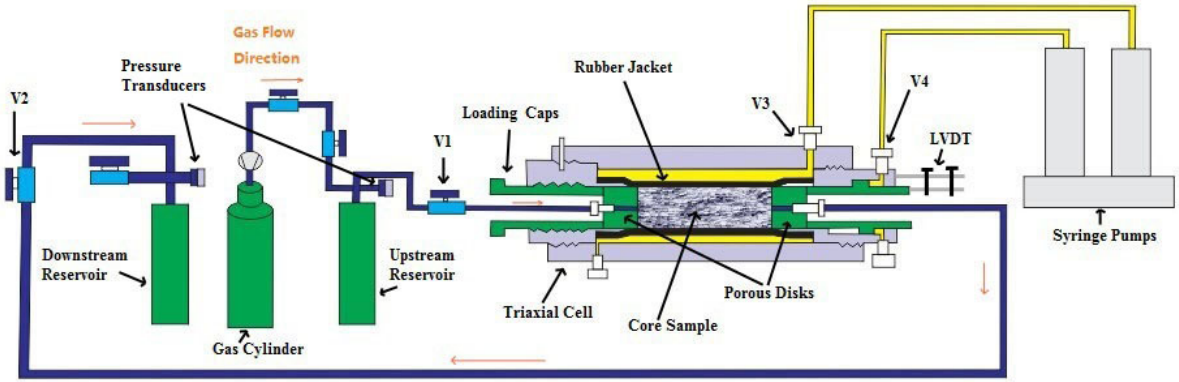
$$b_0 = \sqrt[3]{12ks}$$

Dynamic permeability of the cracked system:

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

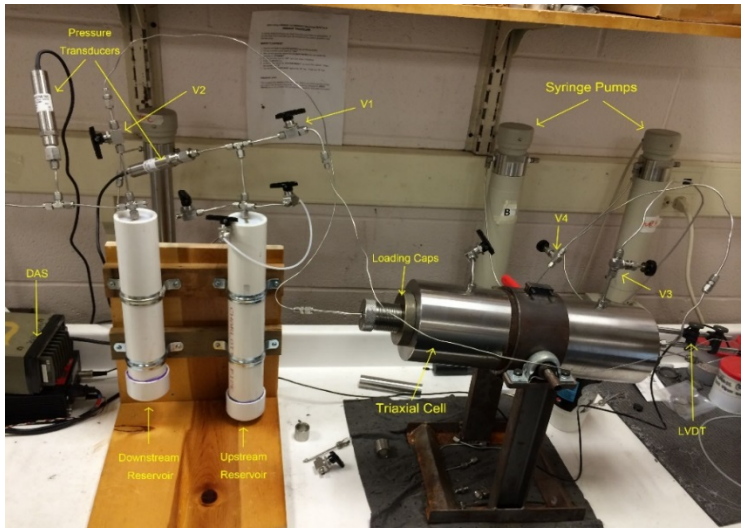


Experimental Investigation



Schematic of experimental setup

- Triaxial loading
- Temperature control
- Deformation monitoring
- High accurate pressure monitoring



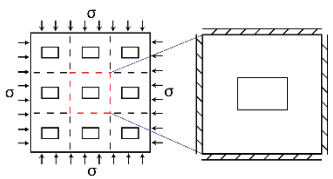
Experimental setup

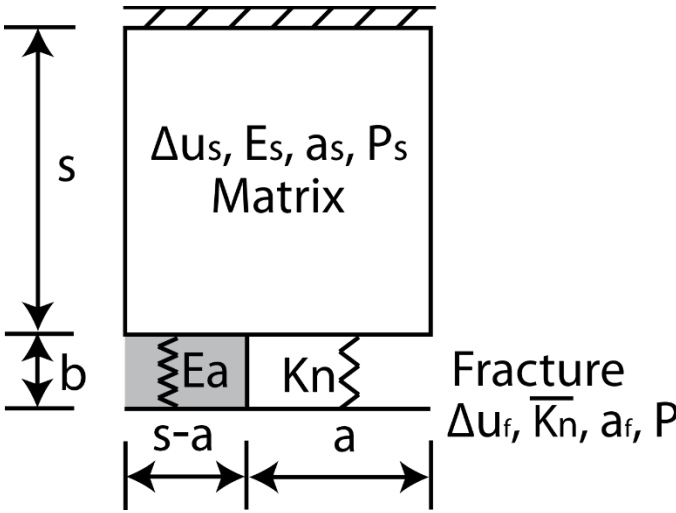
Coal Core samples

Ensemble Response

Permeability relationship:

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





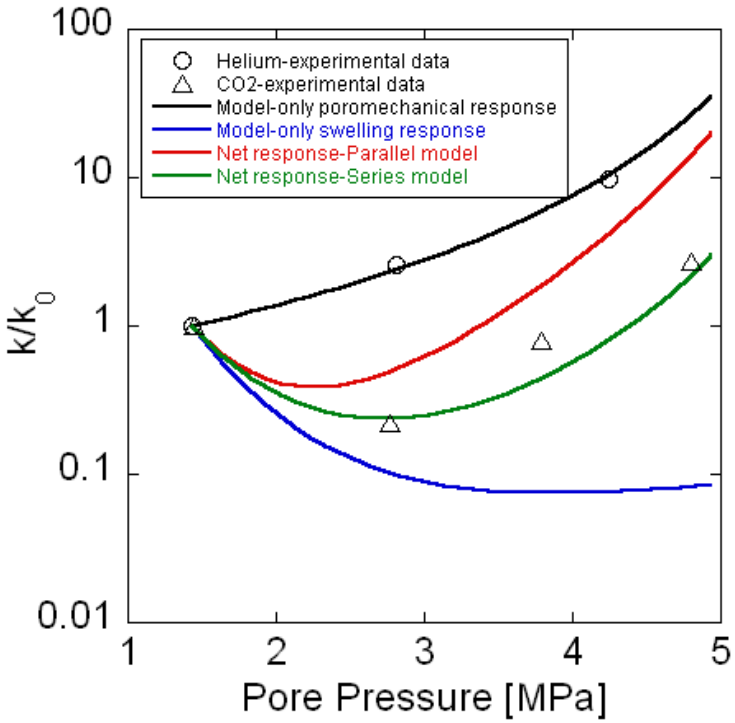
Fracture stiffness:

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

Permeability evolution:

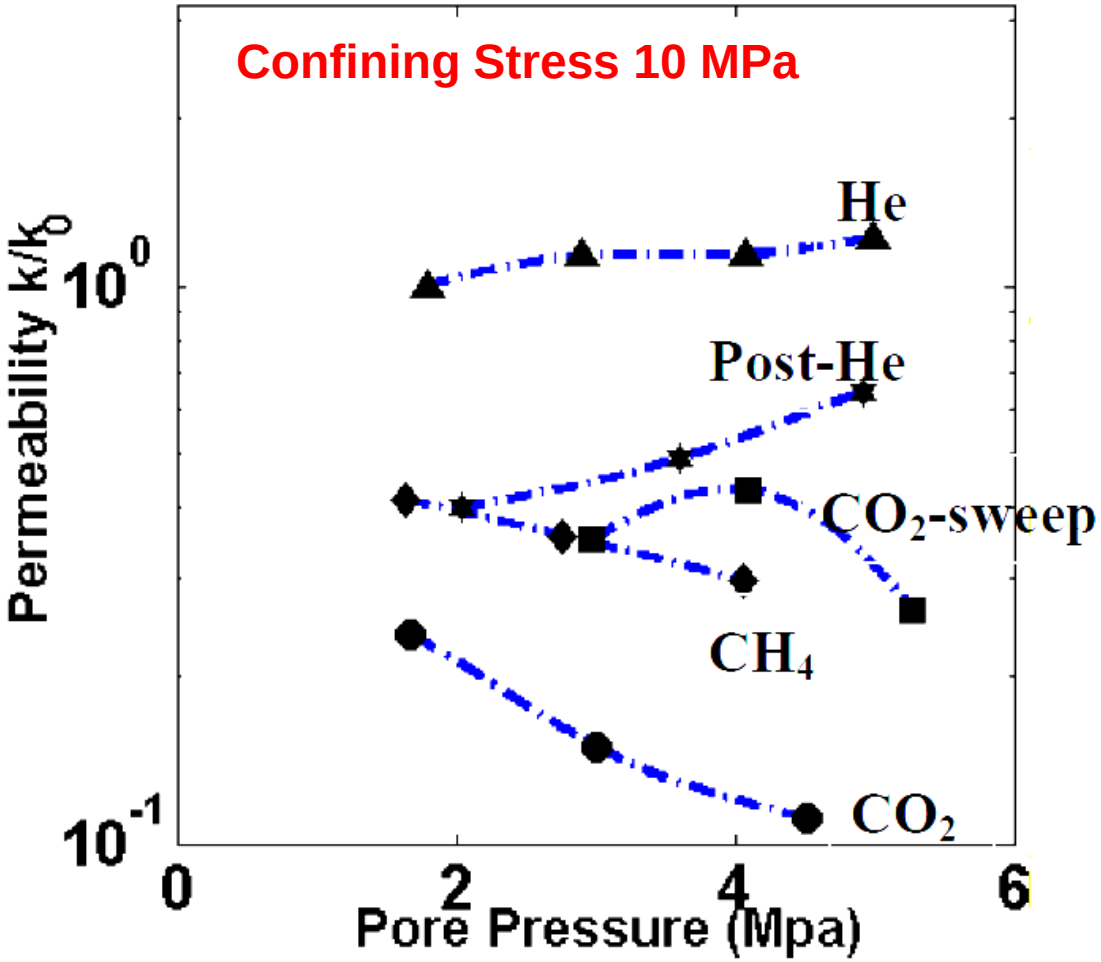
$$\frac{k}{k_0} = \left(1 + \frac{(\alpha_f - \alpha_s)}{\left(1 + \overline{K_n} s / E_s\right)}\frac{s(P-P_0)}{b_0 E_s} - \frac{3}{\phi_0}\frac{\varepsilon_L P_L (P-P_0)}{(P+P_L)(P_0+P_L)}\right)^3 \quad [parallel]$$

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



[Wang et al., JGR, 2011]

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

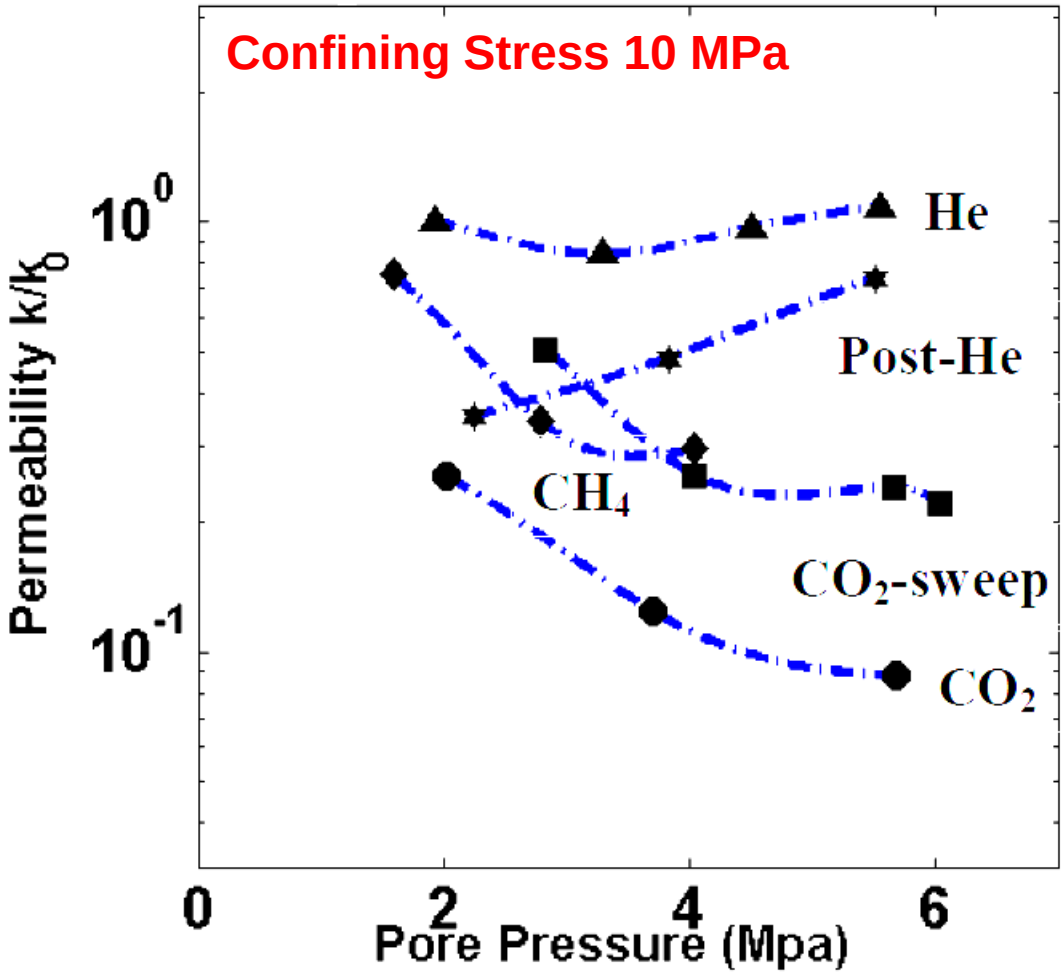
Gas Saturation

- 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

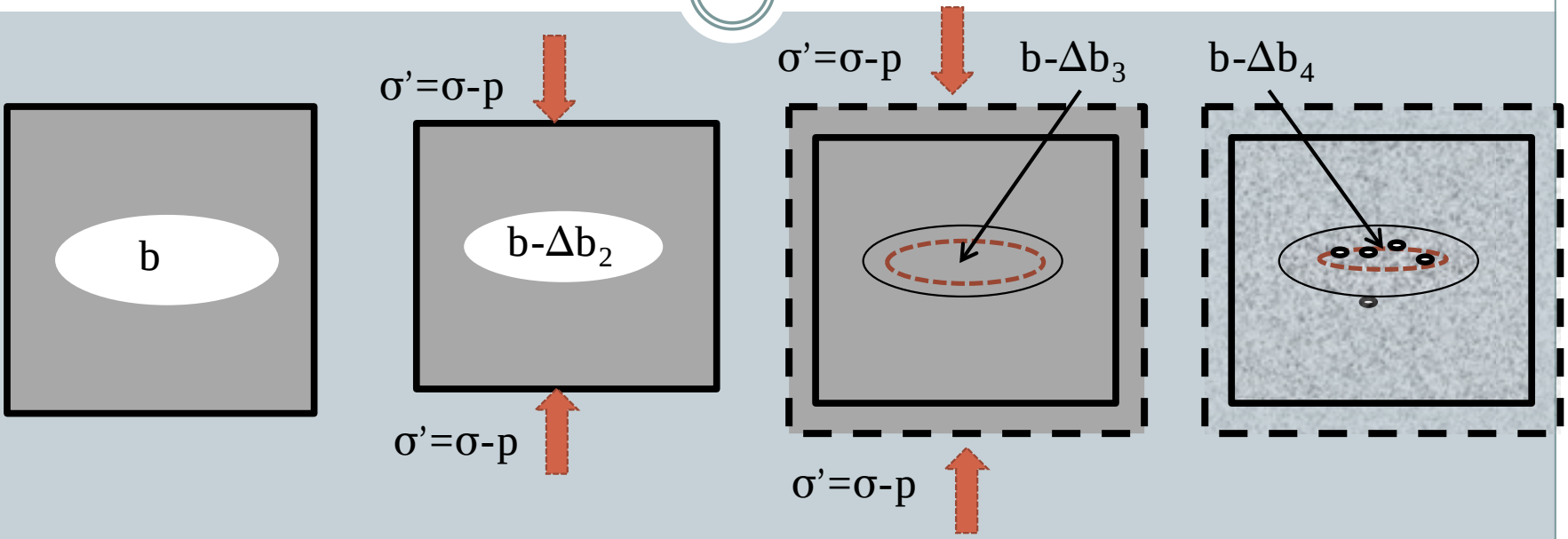
- Helium
- Methane
- CO_2 sweep of Methane
- CO_2
- Helium sweep of CO_2

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

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

A Scaling Study of Microbially-Enhanced Methane Production from Coal (MECBM): Optimizing Nutrient Delivery for Maximized Methane Production

Penn State (Derek Elsworth and Shimin Liu)
SIU-Carbondale (Yanna Liang and Satya Harpalani)

Background
Project Objective
Technical Approach
Task 2 - Developing Nutrient Solutions for Sites #1 and # 2 (Yanna)
- Subtask 2.1 - Characterizing chemical compositions of formation waters from site #1 and #2
- Subtask 2.2 - Characterizing microbial composition of formation waters from site #2
- Subtask 2.3 - Developing nutrient recipes for site #2

Task 3 - Investigating Methane Productivity in a Core Holder Simulating In-Situ Conditions (Satya)
- Subtask 3.1 - Evaluating methane yield from the core holder operated under fed-batch conditions
- Subtask 3.2 - Evaluating methane yield from core holders operated under continuous flow modes
- Subtask 3.3 - Evaluating properties of coal after bioconversion

Task 4 – Characterizing Hydraulic Fracturing for Improved Bio-Gasification (Derek)
- Subtask 4.1– Understanding hydraulic fracture characteristics
- Subtask 4.2 – Quantifying loss of permeability by proppant embedment and fracture diagenesis
- Subtask 4.3 – Developing models for field-scale permeability evolution of hydraulic fractures

Task 5 – Determining In Situ Permeability Evolution (Shimin)
- Subtask 5.1 – Quantifying permeability evolution with nutrient delivery and microbial growth
- Subtask 5.2 – Quantifying gas recovery after microbial growth
- Subtask 5.3 – Developing models for permeability evolution in the reservoir

Task 6 - Define the Viability of Bio-Gasification (MECBM) Systems (All)
- **Subtask 6.1 – Define upscaled bio-gasification productivity for field implementation**
- **Subtask 6.2 – Define timescales and bio-stimulation yields of prototypical field experiments**
- **Subtask 6.3 – Complete preliminary economic analysis**

Project Structure
Project Schedule (use Gantt chart)
Project Budget
Project Management Plan and Risk Management

Rationale for Task 6

1. **How do the gas production magnitudes from lab-batch reactors scale to field-scale?**

We need to understand:

1. What are the key microbial factors influencing gas-yield?
    1. Nutrient composition/type?
    2. Rate of supply?
    3. Duration of supply?
2. How are these factors aided by engineering?
    1. Hydraulic Fracturing versus no-HF?
    2. Dimensioning of fracture and complexity?
    3. Longevity of fractures?
    4. Evolution of permeability?
3. What are key measurements needed in a field project? Field-scale influences and scalability
    1. Nutrient delivery – key parameters?
    2. Gas recovery – key parameters?
    3. Roles of fracturing and field permeability evolution in these?
    4. Experimental design to probe these influences.

Project Structure and Management Plan

Background
Project Objective
Technical Approach
Task 2 - Developing Nutrient Solutions for Sites #1 and # 2 (SIU – Liang/Harpalani)
- Subtask 2.1 - Characterizing chemical compositions of formation waters from site #1 and #2
- Subtask 2.2 - Characterizing microbial composition of formation waters from site #2
- Subtask 2.3 - Developing nutrient recipes for site #2

Task 3 - Investigating Methane Productivity in a Core Holder Simulating In-Situ Conditions (SIU - Harpalani/Liang)
- Subtask 3.1 - Evaluating methane yield from the core holder operated under fed-batch conditions
- Subtask 3.2 - Evaluating methane yield from core holders operated under continuous flow modes
- Subtask 3.3 - Evaluating properties of coal after bioconversion

Task 4 – Characterizing Hydraulic Fracturing for Improved Bio-Gasification (PSU – Elsworth/Liu)
- Subtask 4.1 – Understanding hydraulic fracture characteristics
- Subtask 4.2 – Quantifying loss of permeability by proppant embedment and fracture diagenesis
- Subtask 4.3 – Developing models for field-scale permeability evolution of hydraulic fractures

Task 5 – Determining In Situ Permeability Evolution (PSU – Liu/Elsworth)
- Subtask 5.1 – Quantifying permeability evolution with nutrient delivery and microbial growth
- Subtask 5.2 – Quantifying gas recovery after microbial growth
- Subtask 5.3 – Developing models for permeability evolution in the reservoir

Task 6 - Define the Viability of Bio-Gasification (MECBM) Systems (All)
- Subtask 6.1 – Define upscaled bio-gasification productivity for field implementation
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Project Structure
Project Schedule
Project Budget
Project Management Plan and Risk Management

Project Schedule

Schedule of Tasks and Milestones	Year 1											
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
			Q1			Q2			Q3			Y1
Task 1: Project Management and Planning (PSU & SIUC)	x											
Task 2: Developing Nutrient Solutions for Sites #1 and # 2 (SIUC)												
2.1 Characterizing chemical compositin of formation waters for sites #1 and #2												
2.2 Characterizing microbial composition of formation waters from site #2												
2.3 Developing nutrient recipes for site #2							M2/NG					
Task 3: - Investigating Methane Productivity in a Core Holder Simulating In-Situ Conditions (SIUC)												
3.1 Evaluating methane yield from the core holder operated under fed-batch												
3.2 Evaluating methane yield from core holders operated under continuous mode												
3.3 Evaluating properties of coal after bioconversion												
Task 4: Characterizing Hydraulic Fracturing for Improved Bio-Gasification (PSU)												
4.1 Understanding hydraulic fracture characteristics						M1/NG						
4.2 Quantifying loss of permeability by proppant embedment and fracture diagenesis												
4.3 Developing models for field-scale permeability evolution of hydraulic fractures												
Task 5: Determining In Situ Permeability Evolution (PSU)												
5.1 Quantifying permeability evolution with nutrient delivery and microbial growth												
5.2 Quantifying gas recovery after microbial growth												
5.3 Developing models for permeability evolution in the reservoir												
Task 6: Define the Viability of Bio-Gasification (MECBM) Systems (PSU & SIUC)												
6.1 Define upscaled bio-gassification productivity for field implmentation												
6.2 Define timescales and bio-stimulation yields of prototypical field experiments												
6.3 Complete preliminary economic analysis												
Deliverables - Quarterly and Final Reports			Q1			Q2			Q3			F
Briefings/Technical Presentations	x											x
Group meetings						x						x