Core/Lab Studies in Support of CBM Operations:
Gas Content Measurement & Factors Influencing Production

CMPDI

September 29, 2020

a bit about myself

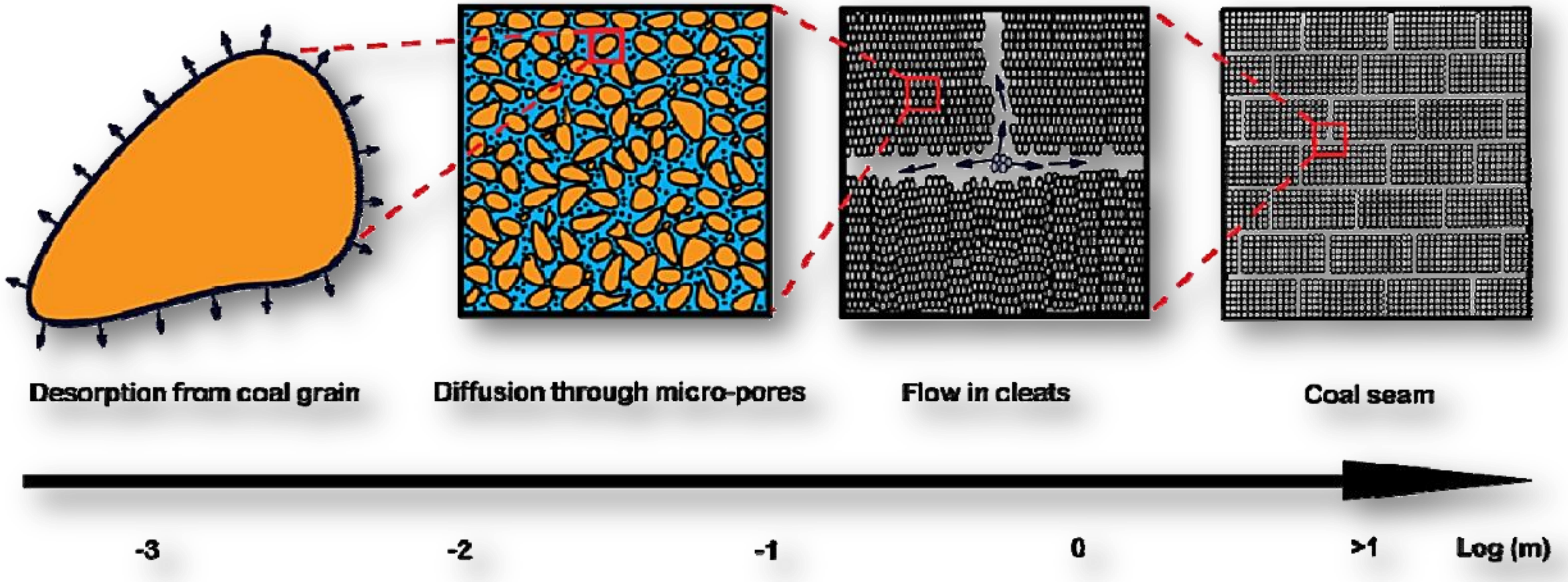
- Devoted my entire research career (>30+ years, including graduate school) to flow in porous media – gas flow in coal/sandstone/shale, flow of dilute acid flow in porphyry copper, coal bio-conversion.

- Major sources of funding – ConocoPhillips, British Petroleum (BP), Encana, VICO Indonesia, Gas Research Institute, US Federal Govt. agencies.

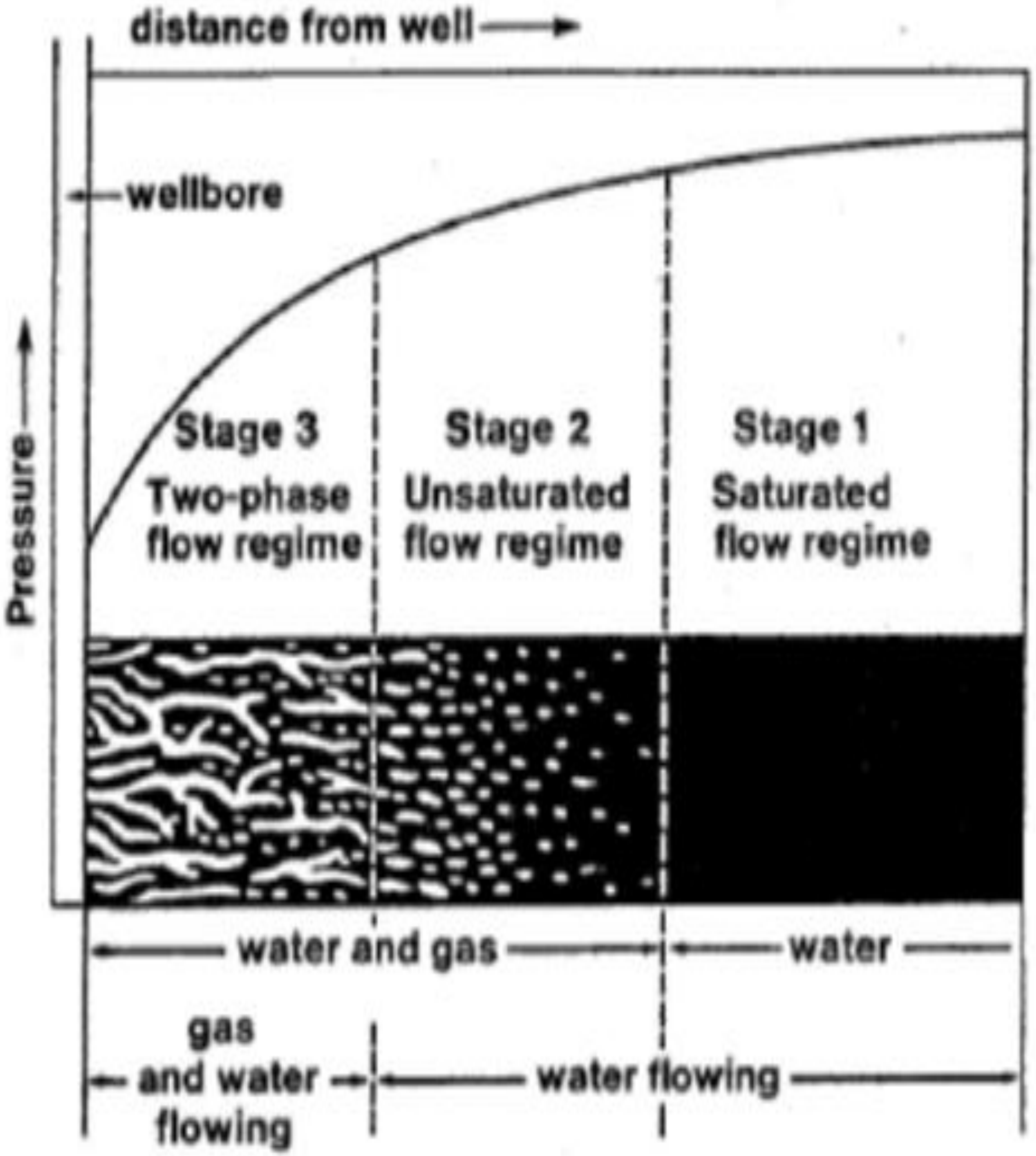
- Sabbatical leaves with BHP, BP America and ARI.

Gas Storage and Transport of Coal

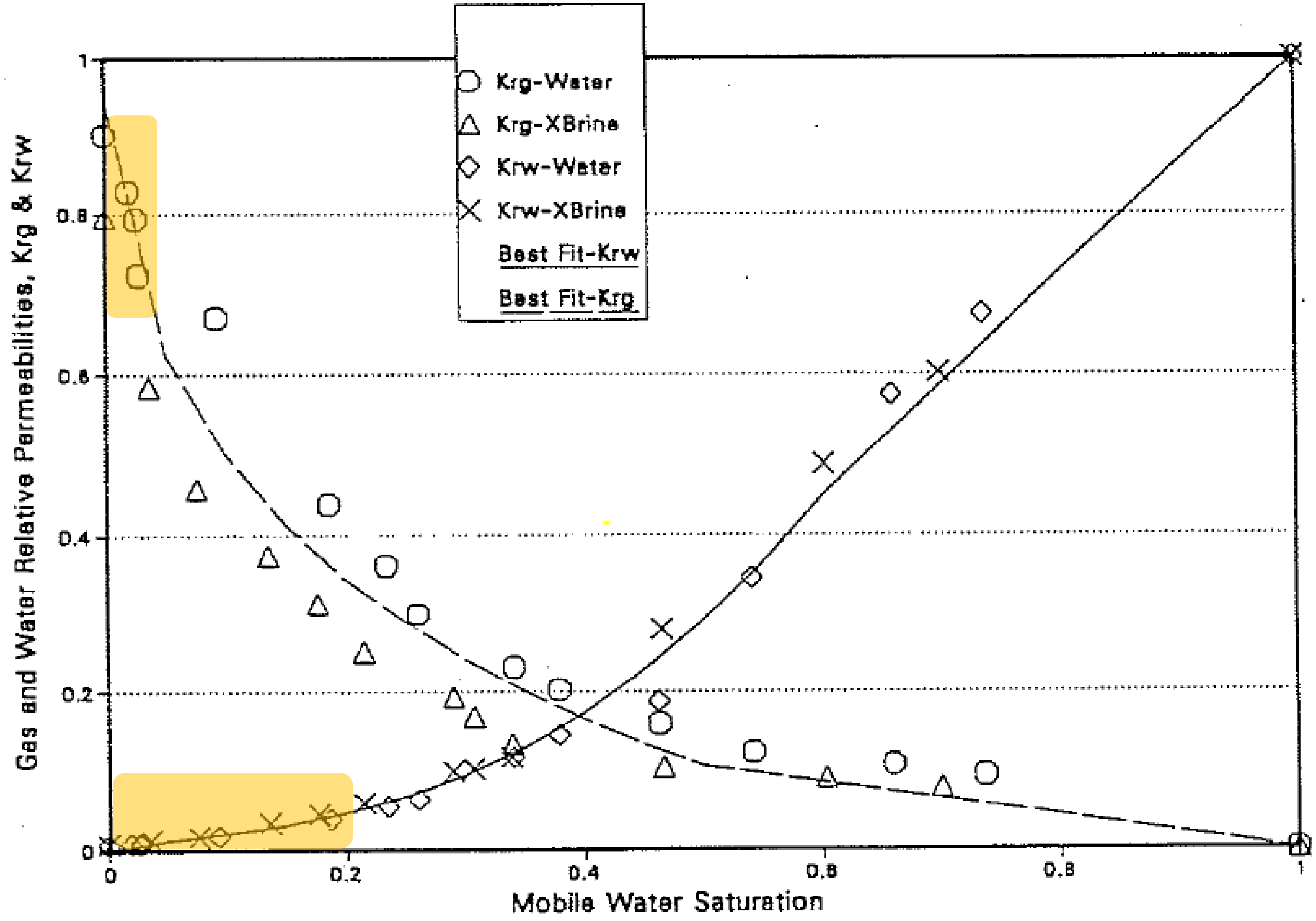
cleats are water saturated



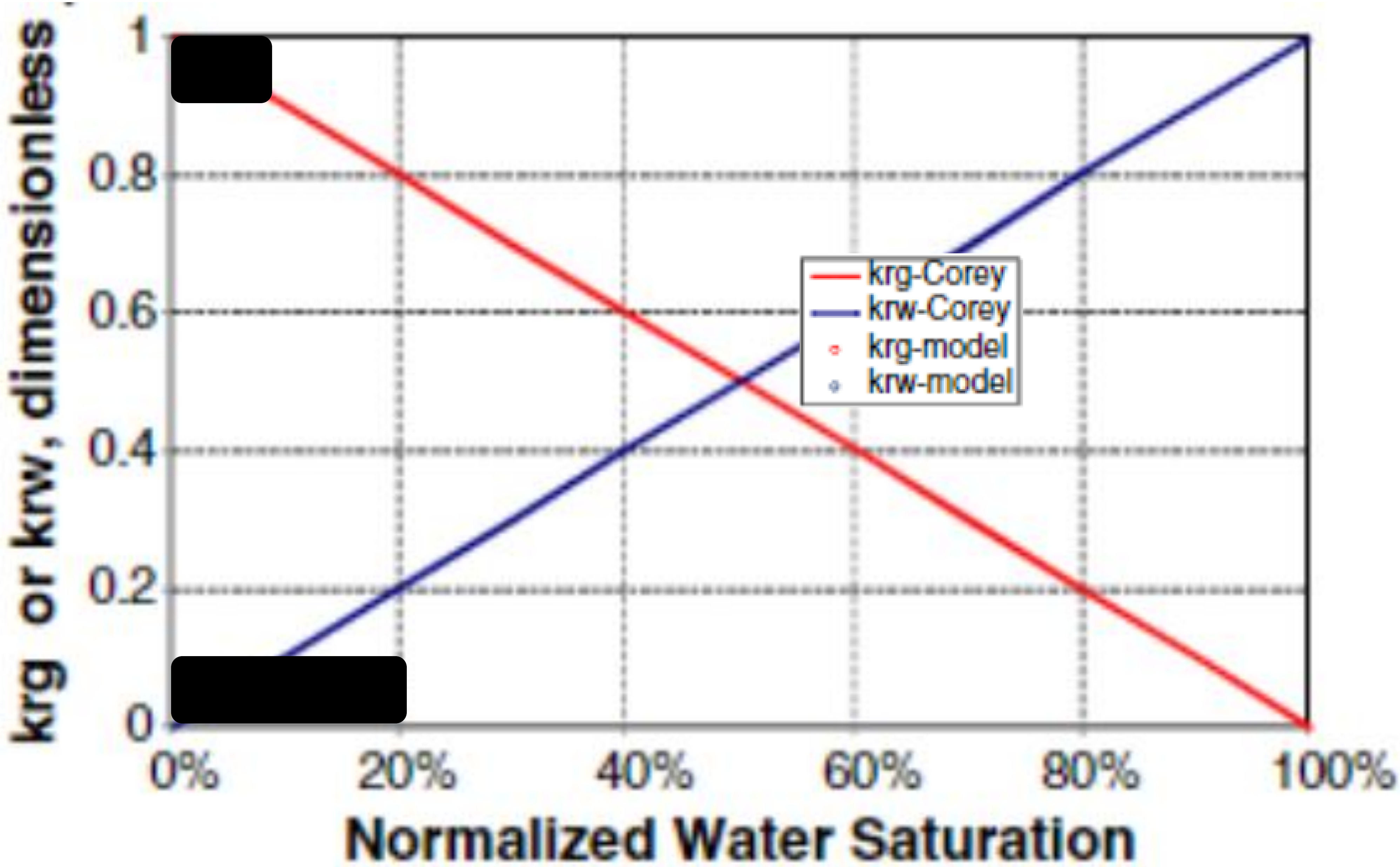
Three stages of coalbed gas production



Lab Measured Relative Permeability Curves (1991)

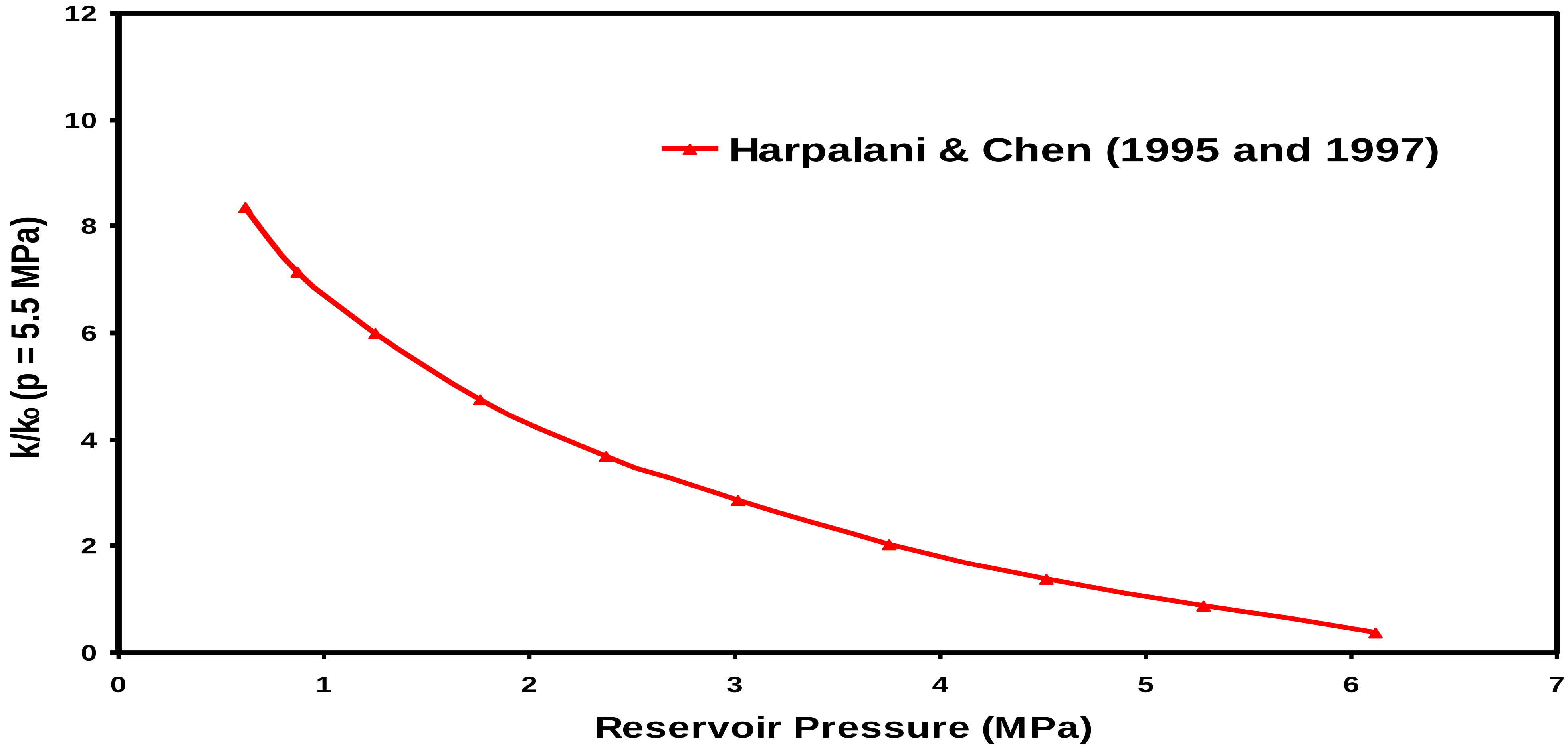


Relative Permeability Curve – by Corey

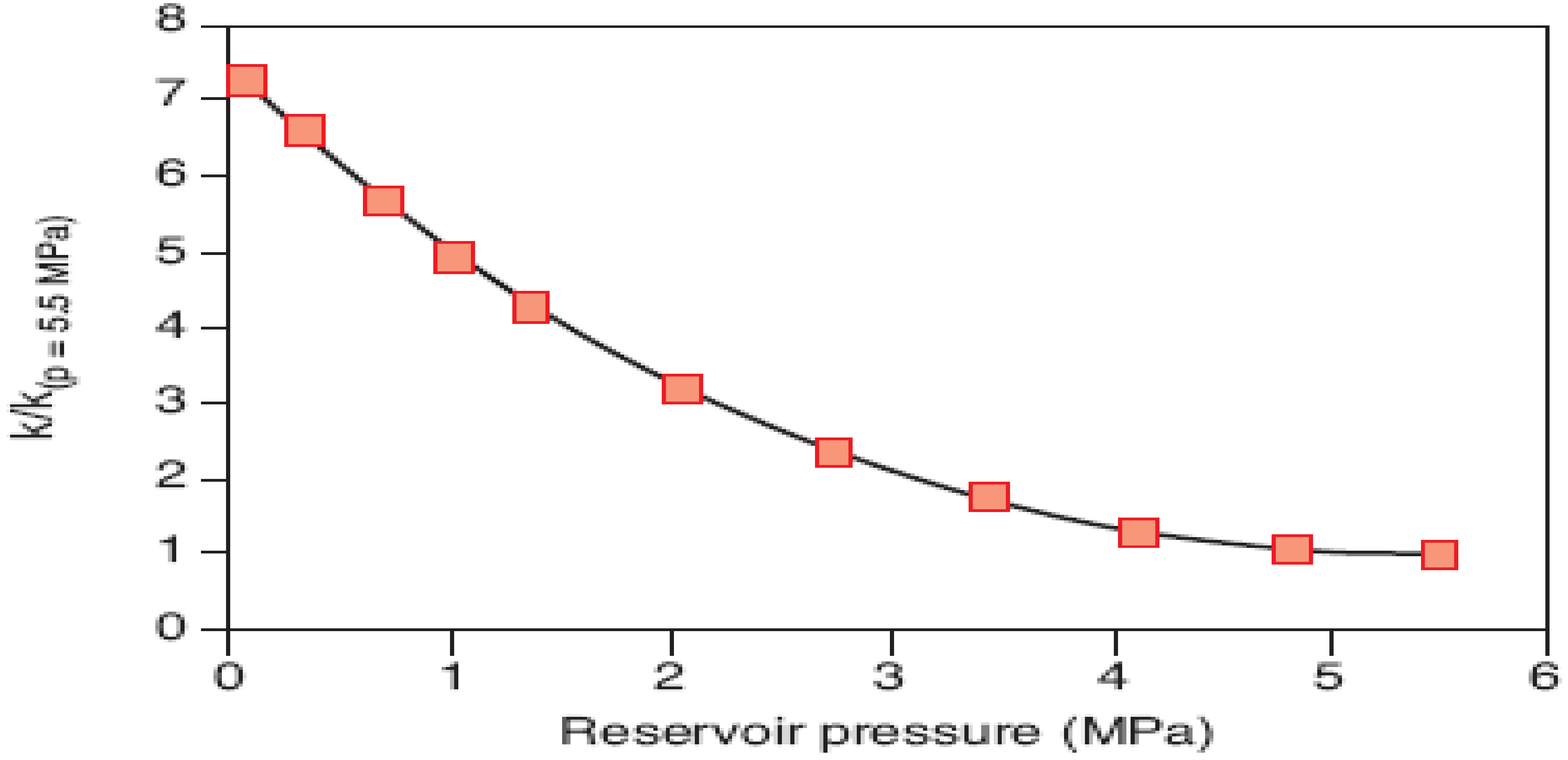


Lab *versus* Field Permeability

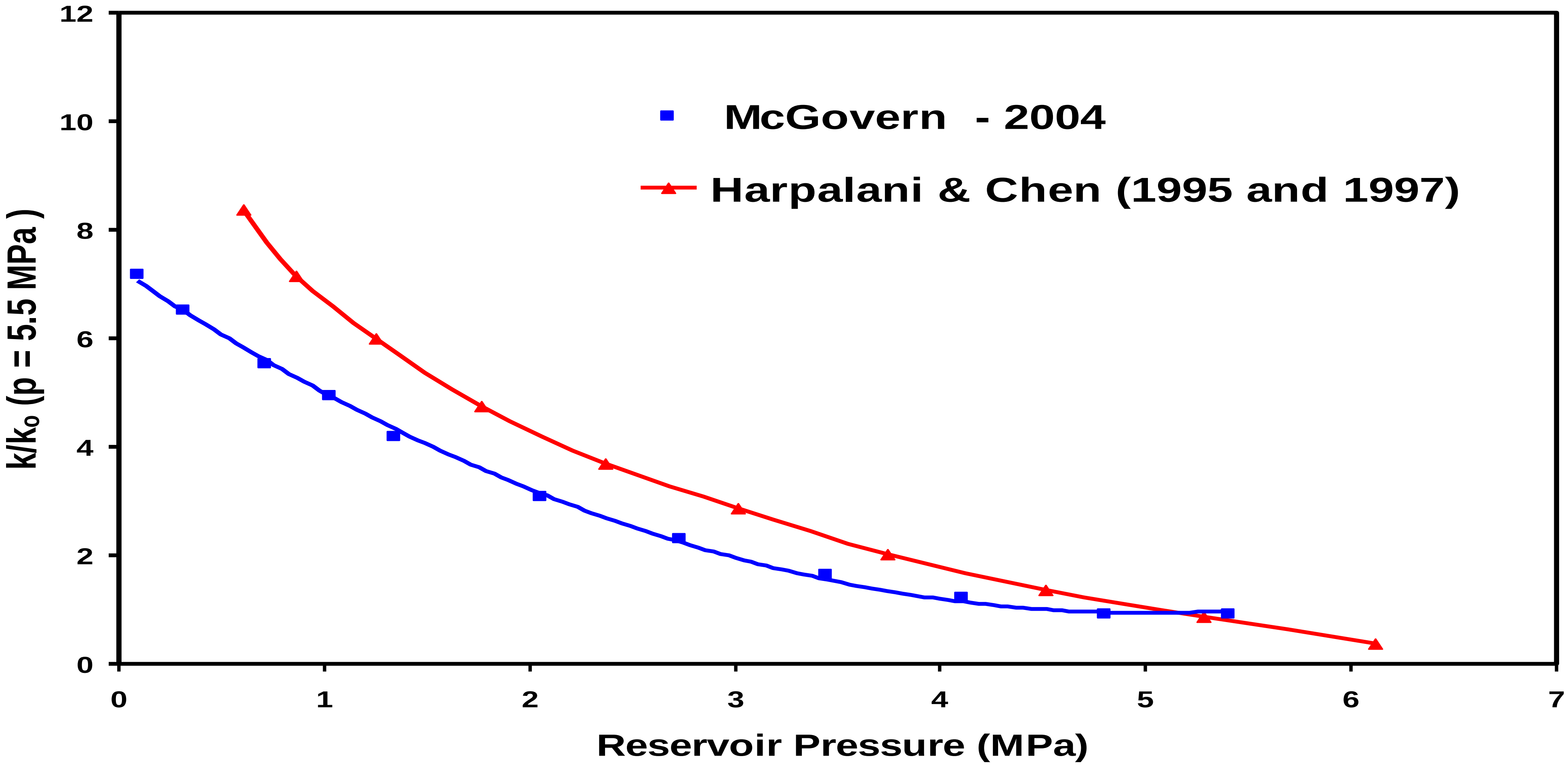
Pressure Dependent Permeability (PdK): Lab Measurement



PdK Multiplier – Field Results (ConocoPhillips, 2004)



Comparison of Lab and Field Results



Core Testing Plan

CORE TESTING PLAN

1. Gas Content & Isotherms

Evolution of Estimating Gas Content

- Amount of gas released from a weighed amount of recovered core over time; time taken for 63% of gas to come out = ***sorption time***.

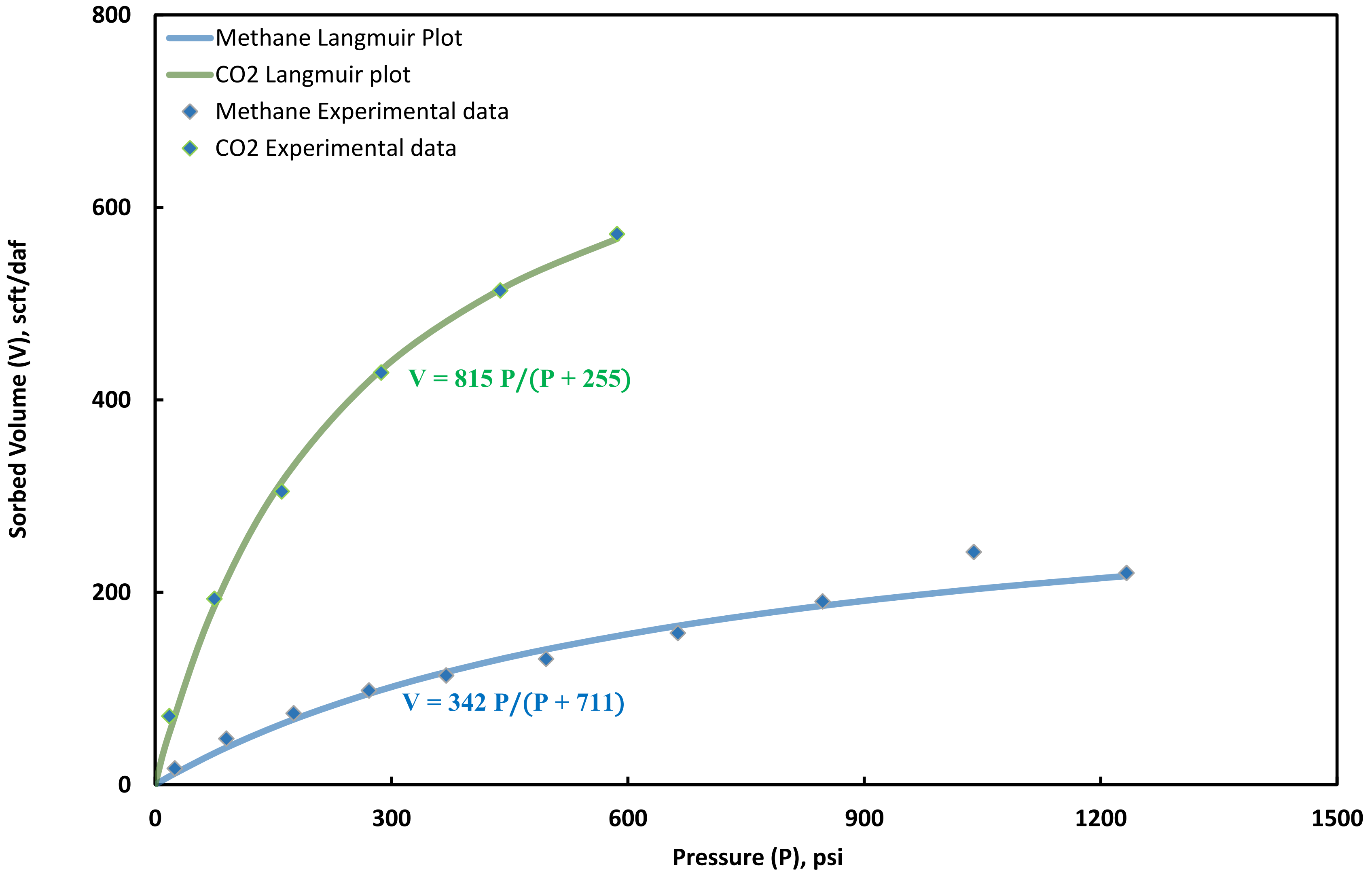
- *In situ* gas composition . . . gas chromatography.

- Carrying out canister tests under *in situ* temperature.

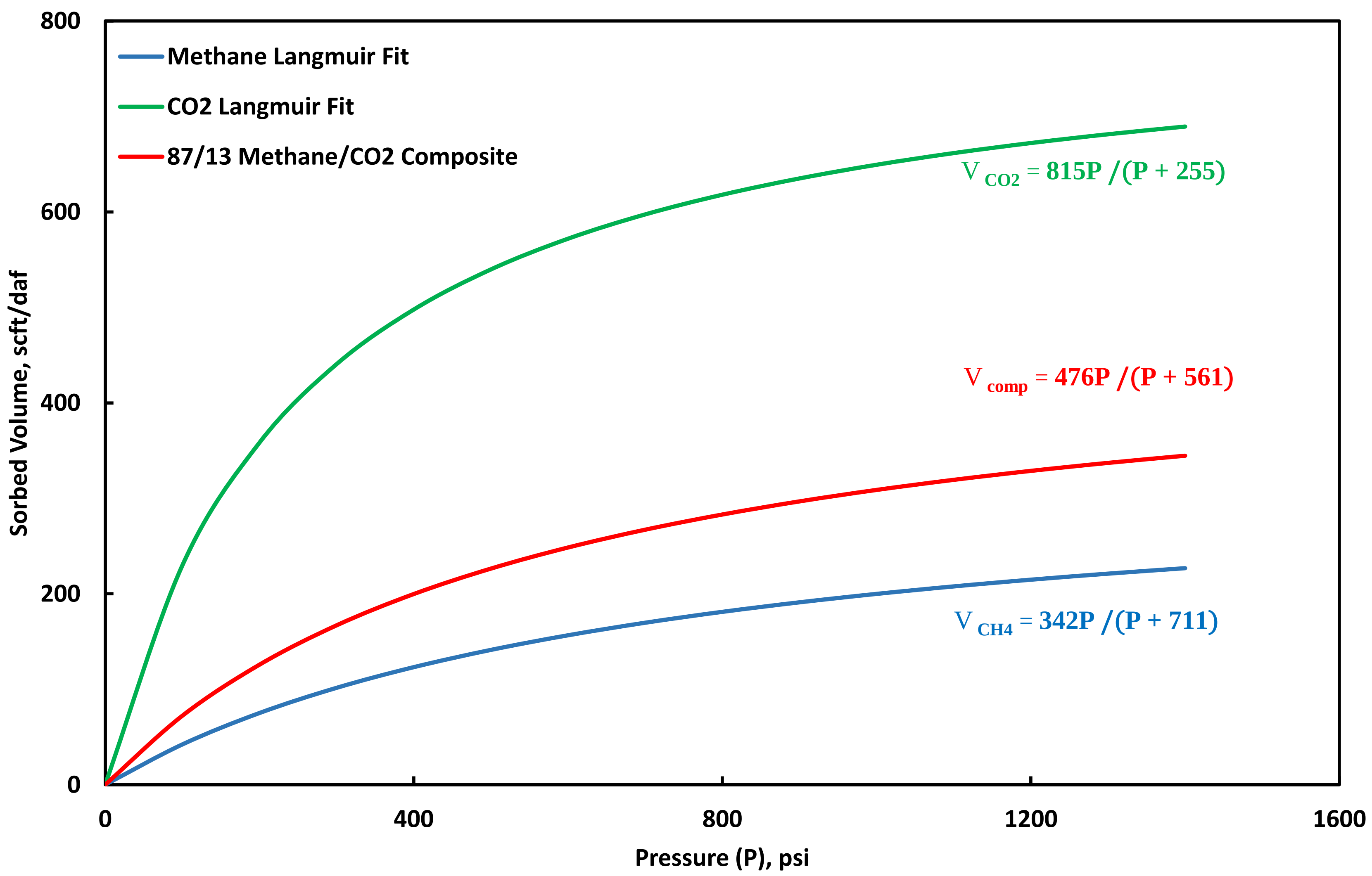
estimation of gas content, composition and sorption time are critical

(e.g., disappointment with San Juan south of fairway)

Methane and CO_2 Sorption Isotherms for . . Coal at 68°F



EL Isotherms for Methane, CO_2 and 83/17 Composite for . . Coal 68ºF



What do results tell us?

- Gas Content: ***potential/profitability***

  excellent description of procedure and technique

  Mavor . . . . Nelson

- Degree of under-saturation

  dewatering need/period, water disposal facility

- Sorption Time – ***indicator of diffusion***

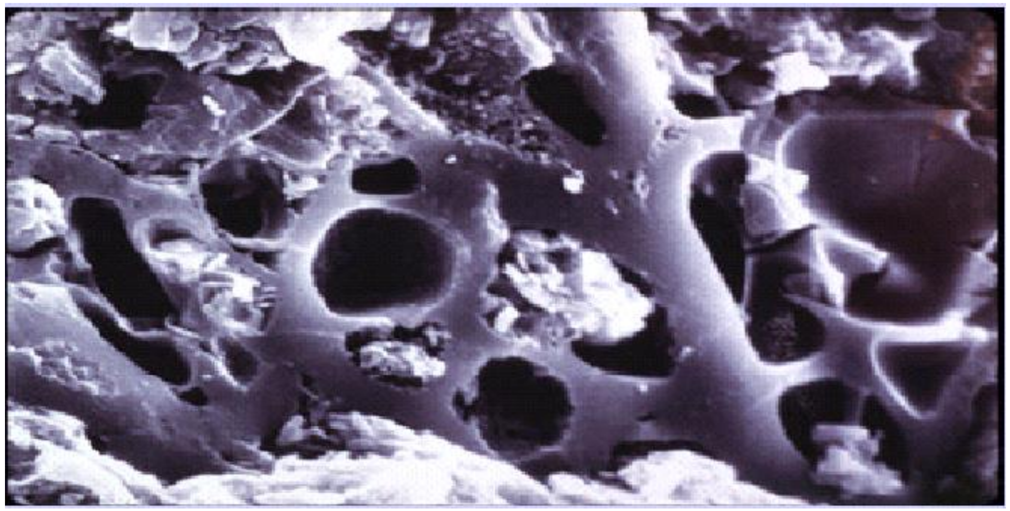
- Variation in composition of recovered gas, scrubbing needs

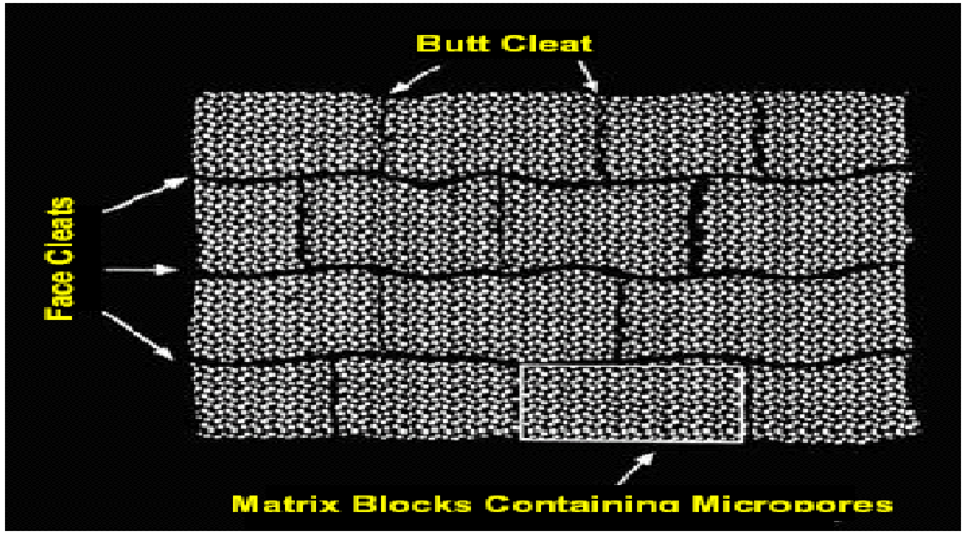
  N_2 and CO_2 removal prior to pipelining

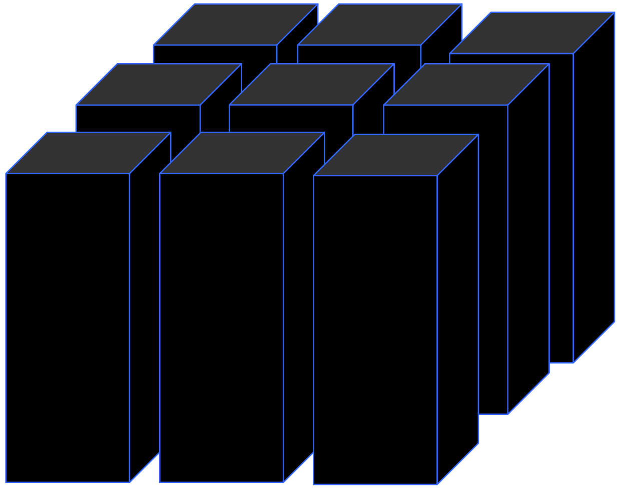
- P_L – slope of isotherm . . . indicative of when the production will become significant

2. Cleat Characterization

Magnified

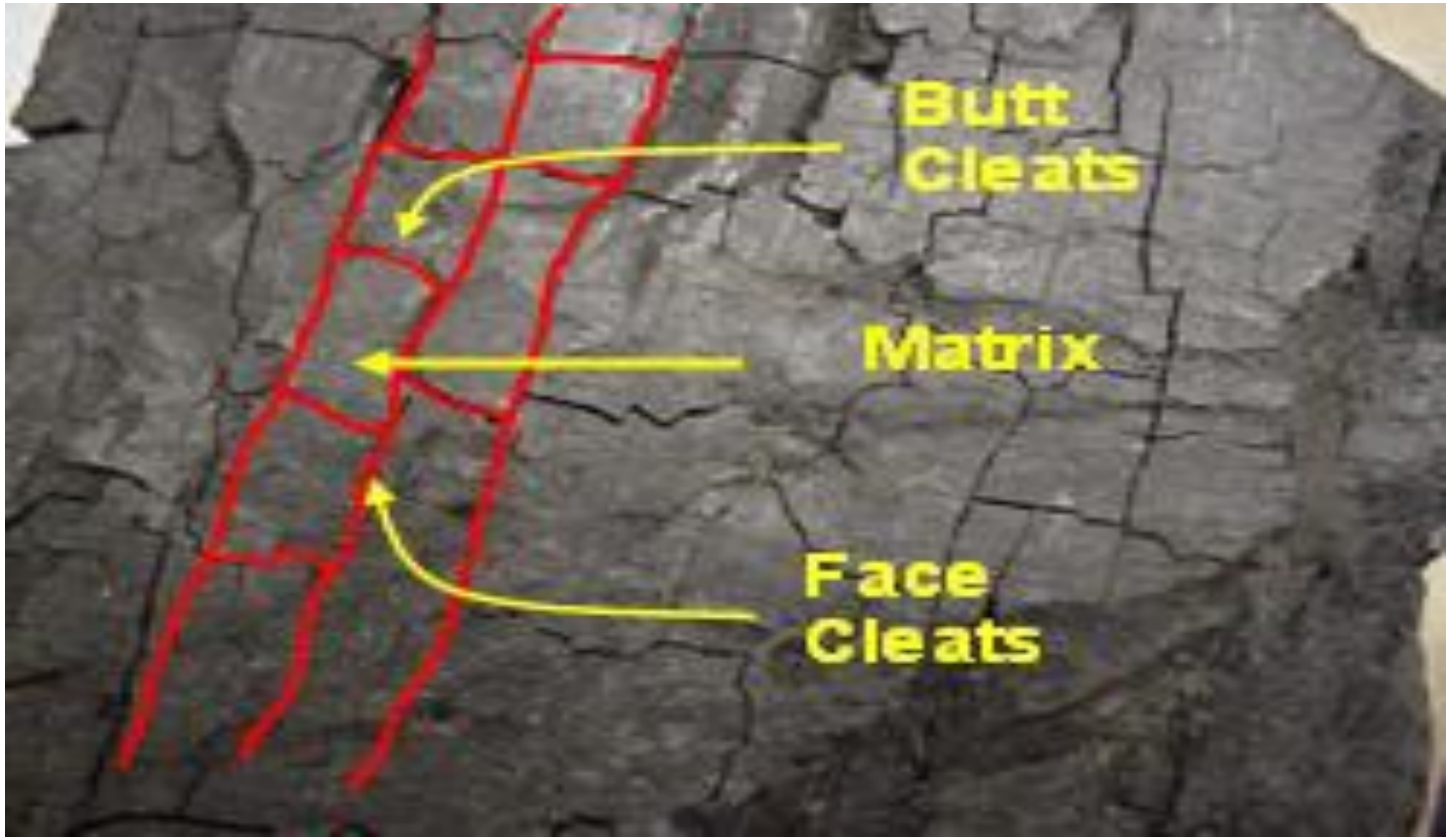






bundle of matchsticks geometry used for modeling

Section of coal *(visual examination and tracing)*

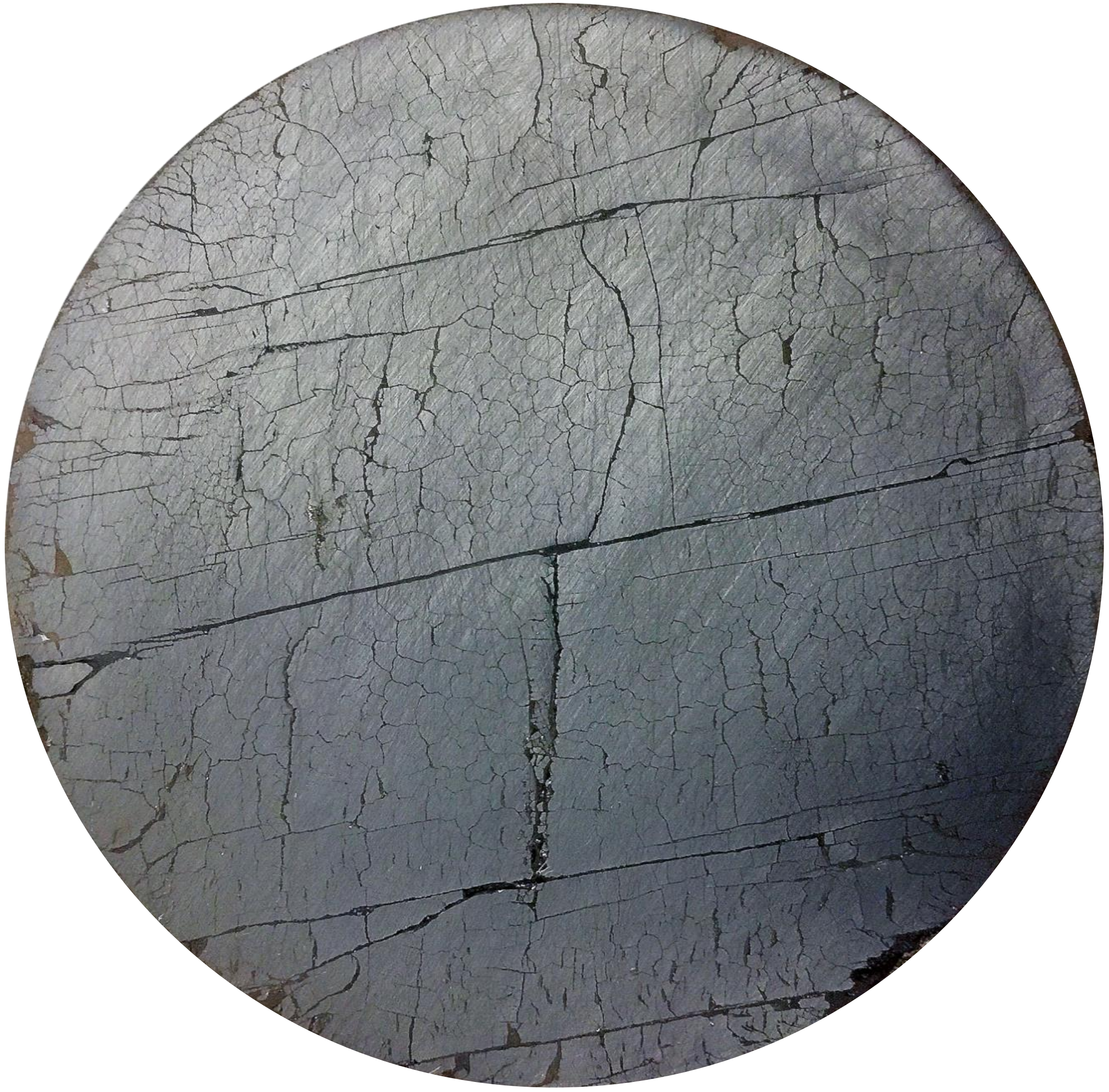


Cleat Characterization

- **CT-Scanning** – main features . . . integrity of core, cracks, etc., ***not cleats***
- **Polishing** . . . visible cleats
- **Scanning electron microscopy** imaging . . . finer cleats, spacing
- **Water permeability** . . . *in situ* cleat porosity (using Young's Modulus and Poisson's ratio)
- Filled cleats versus open

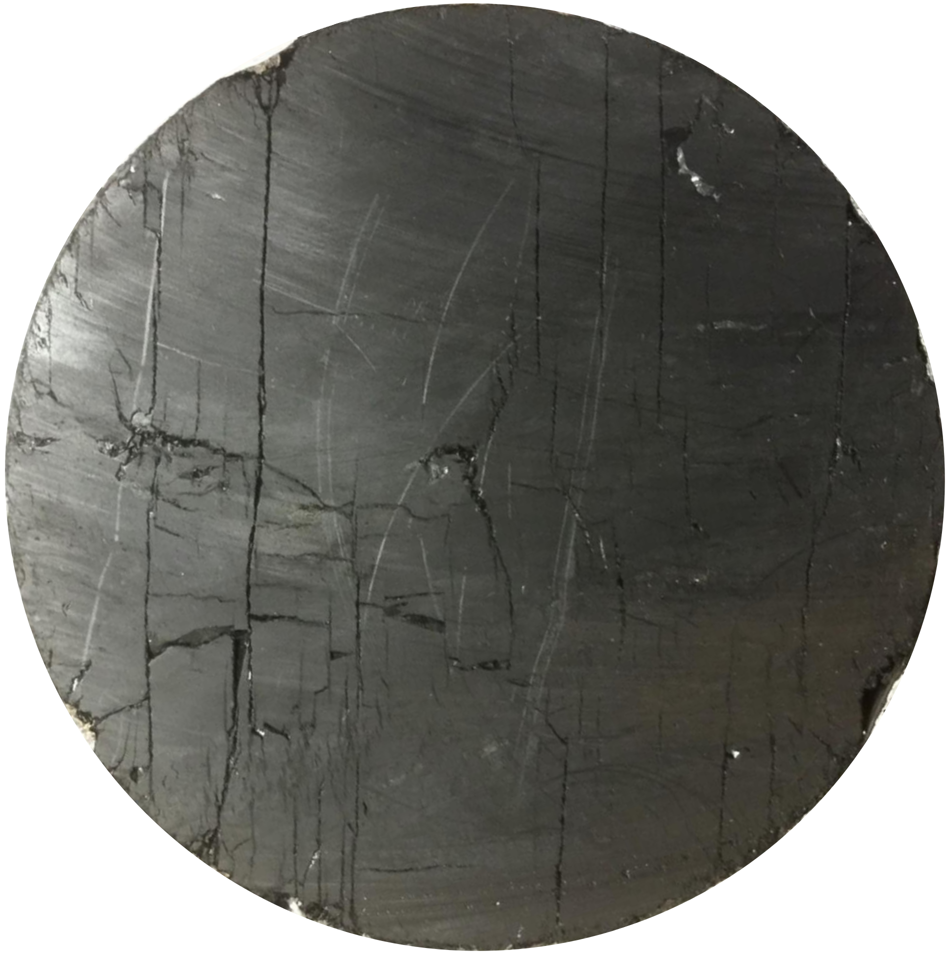
Sanga Sanga Core

Polished Core End

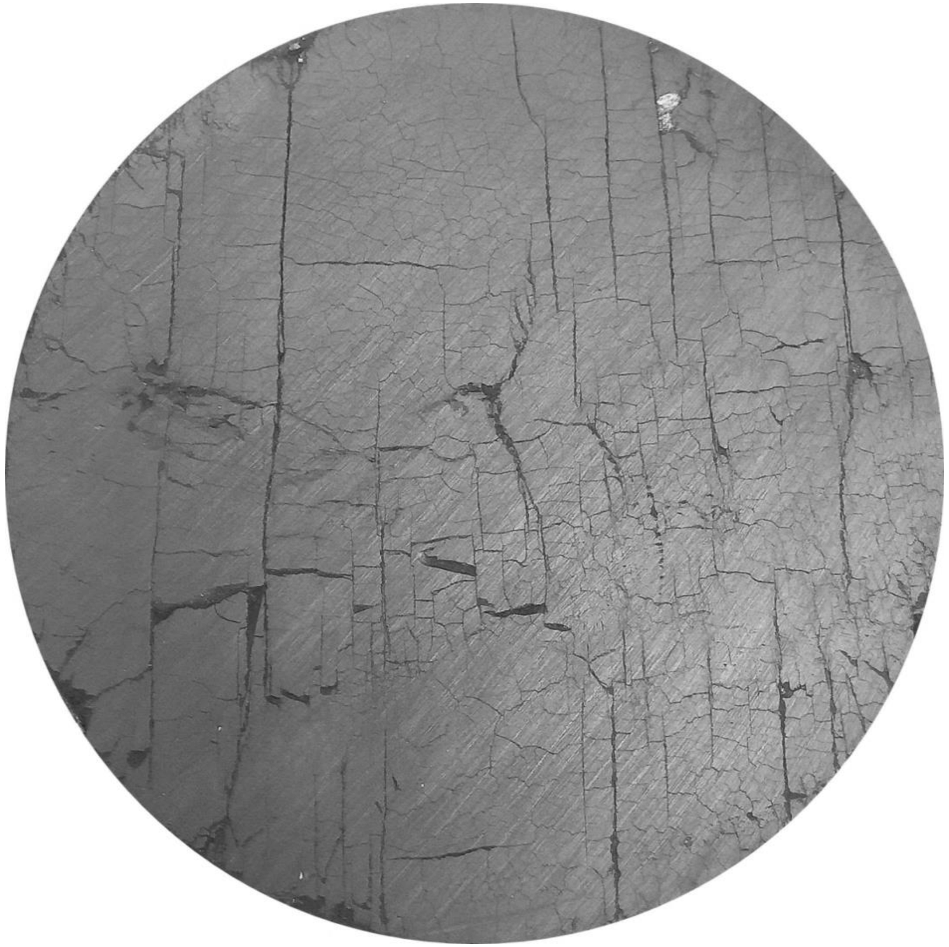


Cleats Show up when Cleaned and Polished

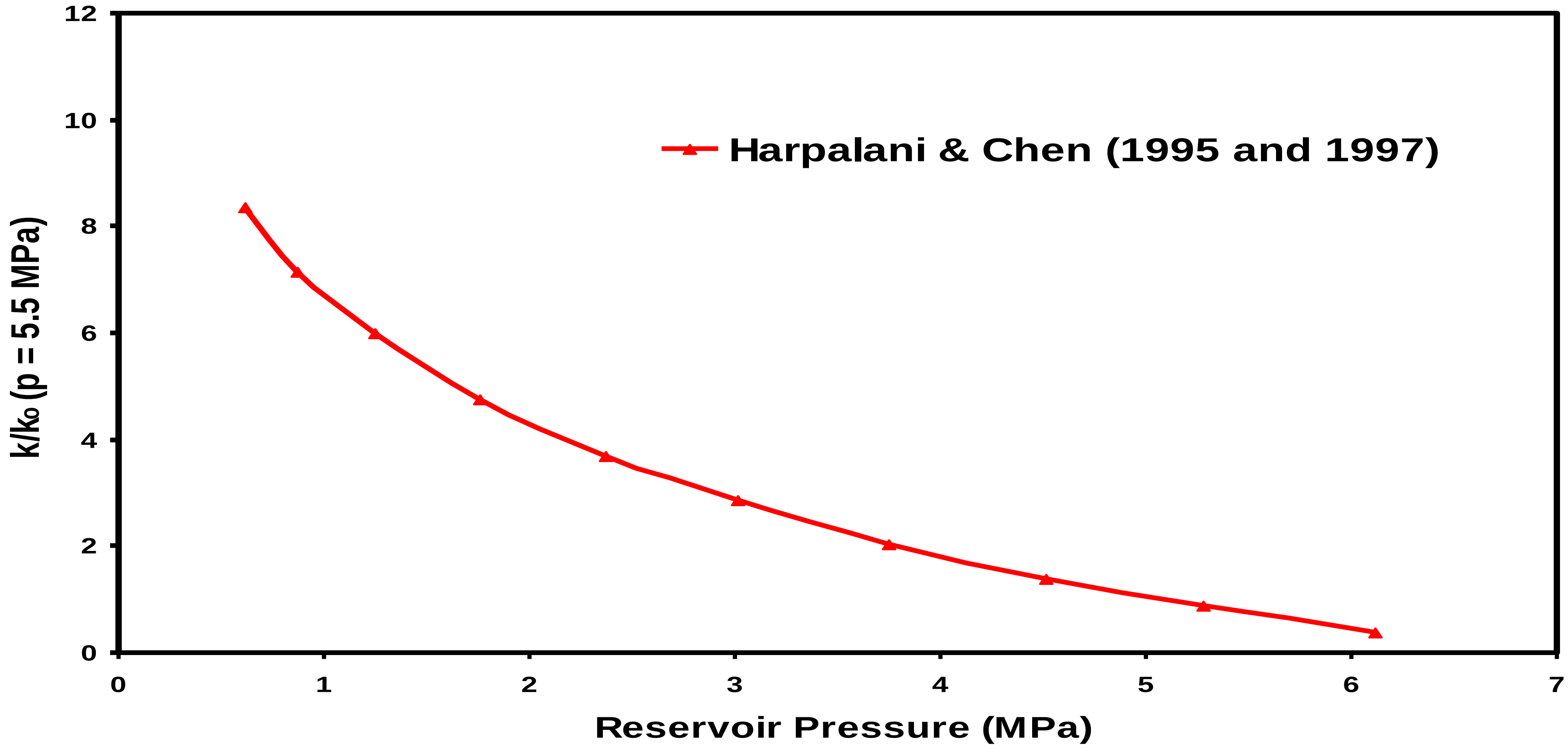
Unpolished Core End



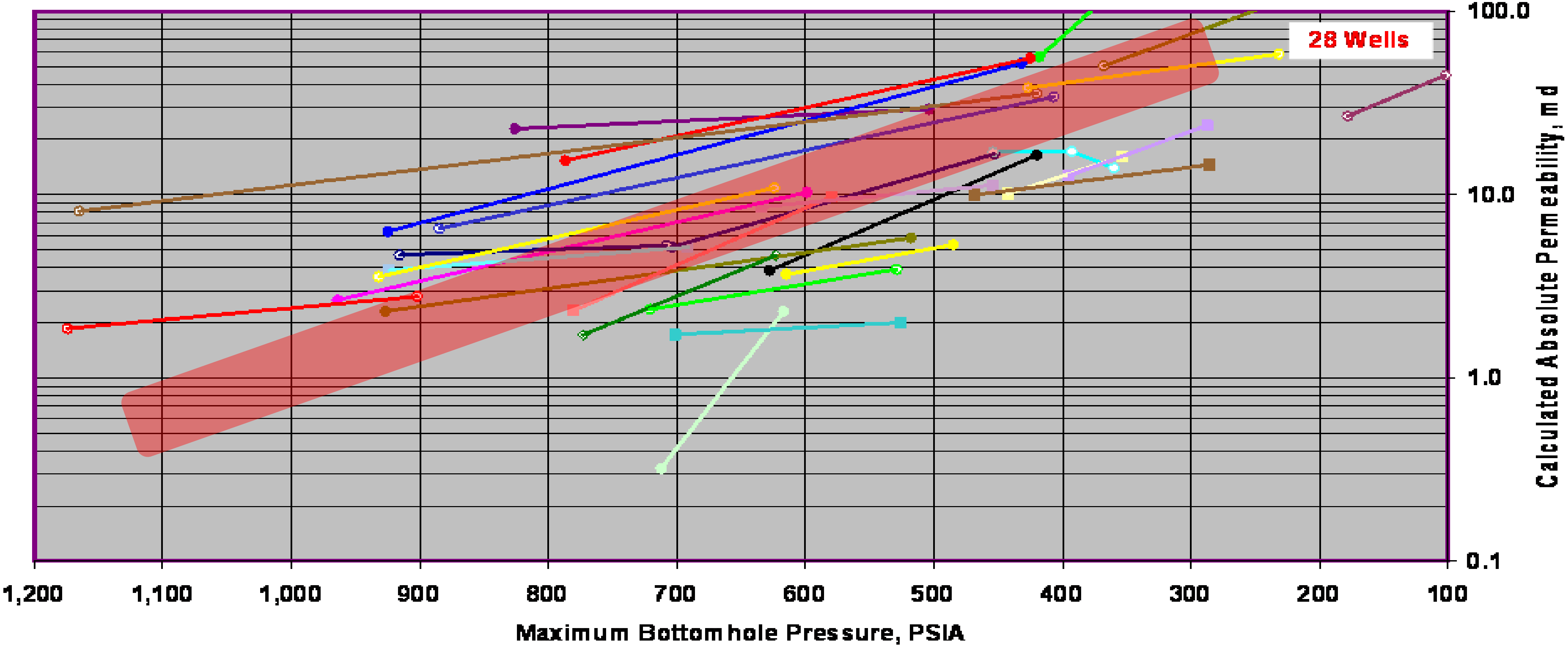
Polished Core End



What is Pressure Dependent Permeability?



PdK for Reservoir Depletion in San Juan Basin (BP, 2007)



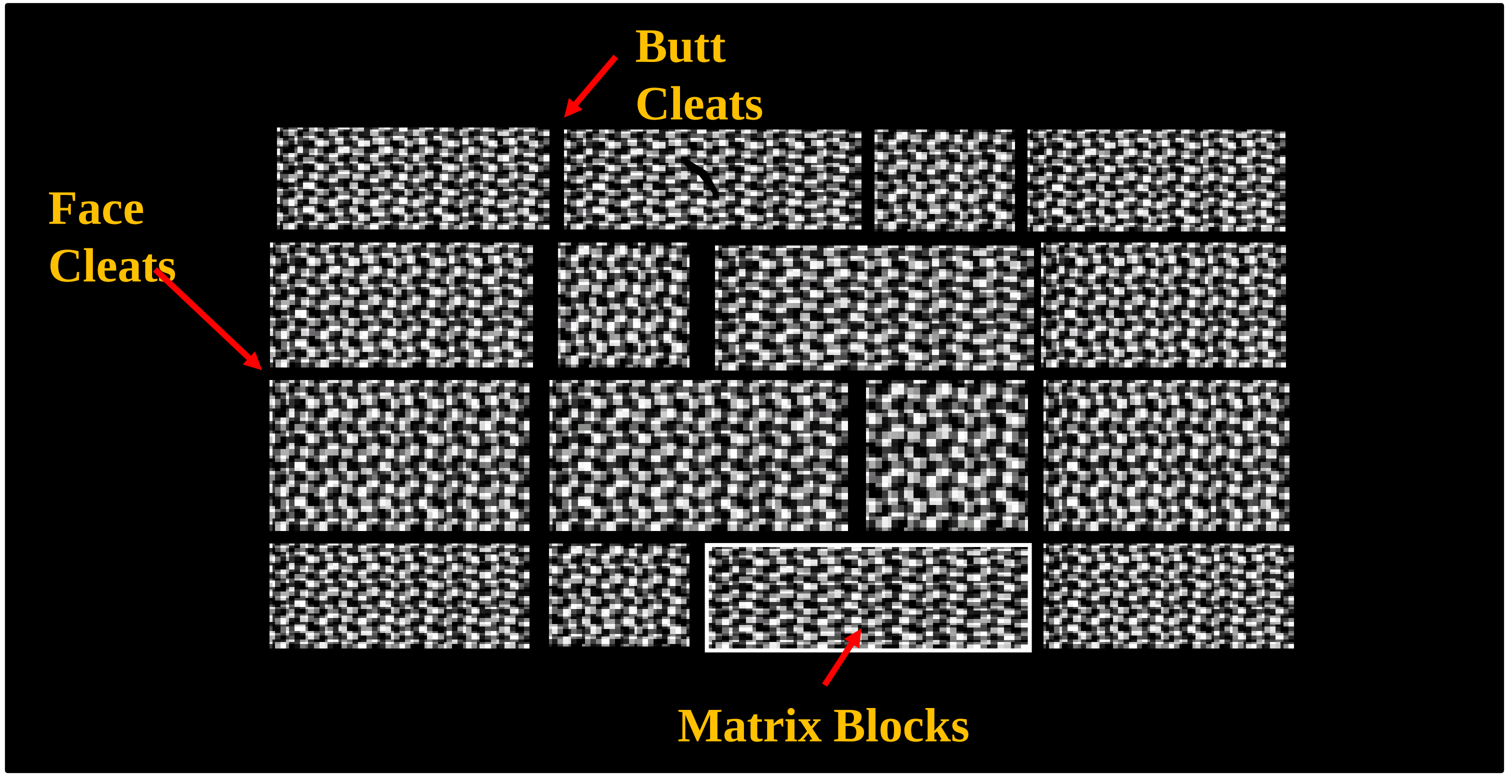
Why does permeability increase with depletion?

“Matrix Shrinkage”

“sakshat” Lakshmi

in the San Juan basin

how does matrix shrinkage affect permeability…



PdK Models

- Palmer et al (P&M . . P&H) – strain based under uniaxial strain
- Shi and Durucan (S&D) – stress based under uniaxial strain
- ARI Model – not based on geo-mechanics but has C_p and C_m as separate input parameters
- . . .
- . . .
- . . .
- . . .
- Harpalani et al – “***whole bunch***” of permeability models (2013, 2015, 2016, 2017, 2018)

Input Parameters for Permeability Modeling/Simulation

- Palmer and Mansoori Model (1997, 2005, 2007 and 2010)

  Required Parameters: E, ν, β/C_g, ϕ_o, ε_∞, P_ε [*f and g from fitting*]

- Shi and Durucan Model (2005)

  Additional Parameters Required: α (shrinkage/gas content) and C_p

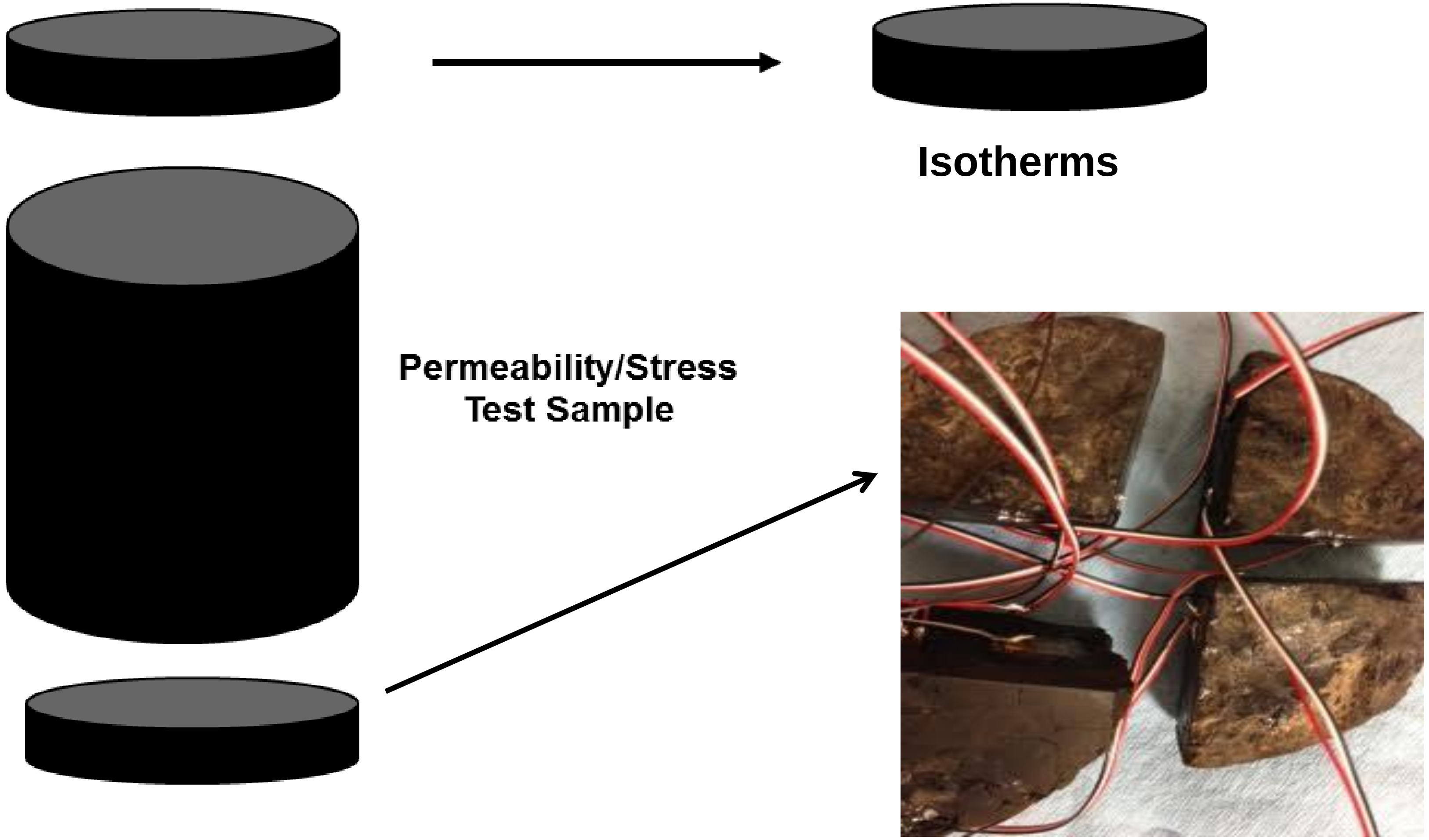
- Palmer and Higgs Model (2014)

  Additional Parameter : *Anisotropic Factor* ($g = E_Z/E_{x/y}$)

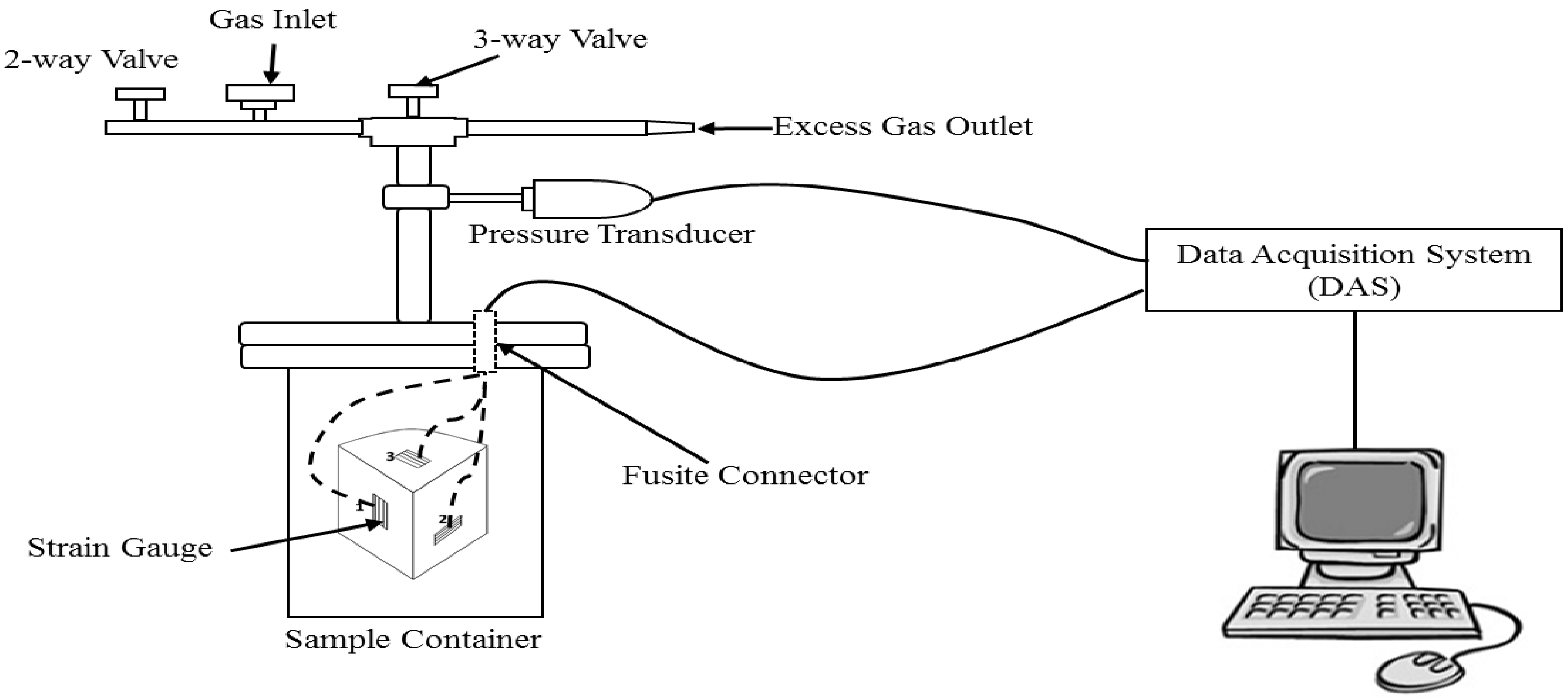
let us start with some "real" experiments (personal experience)

Environmental Chamber
(temperature and humidity controlled)

4. Matrix Shrinkage/Permeability Measurement



Flooding - Matrix Shrinkage Setup



5. Measurement (*estimation*) of Permeability Changes

little about experimental setup

Capable of controlling and monitoring:

- Vertical and horizontal stresses to replicate *in situ* conditions
- Vertical and horizontal strains – to monitor deformation
- Temperature – to maintain *in situ* condition
- Pore pressure – upstream and downstream to replicate depletion

Measurement of:

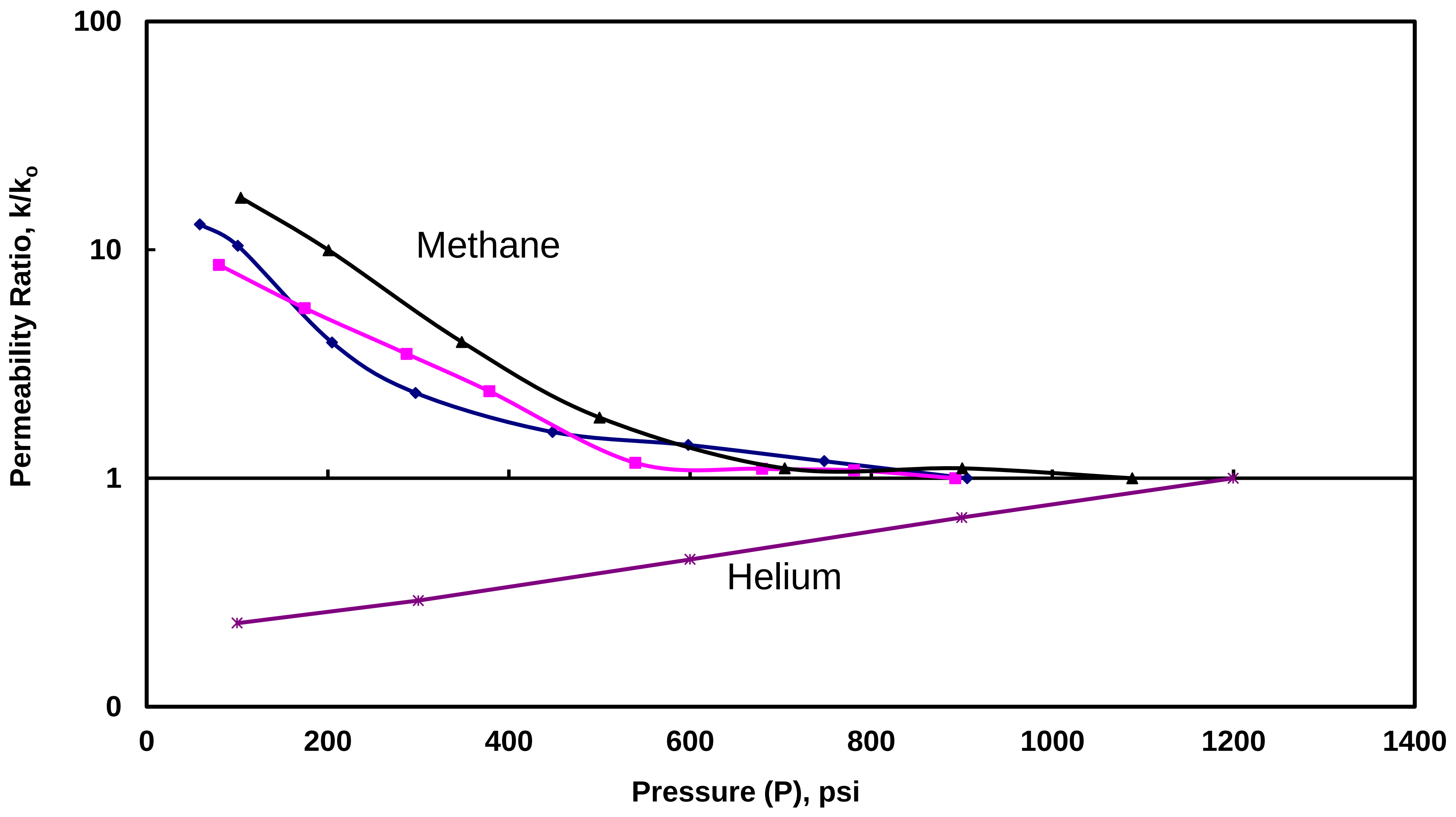
- Flowrate and strain
- Long. and shear velocities

Calculation of:

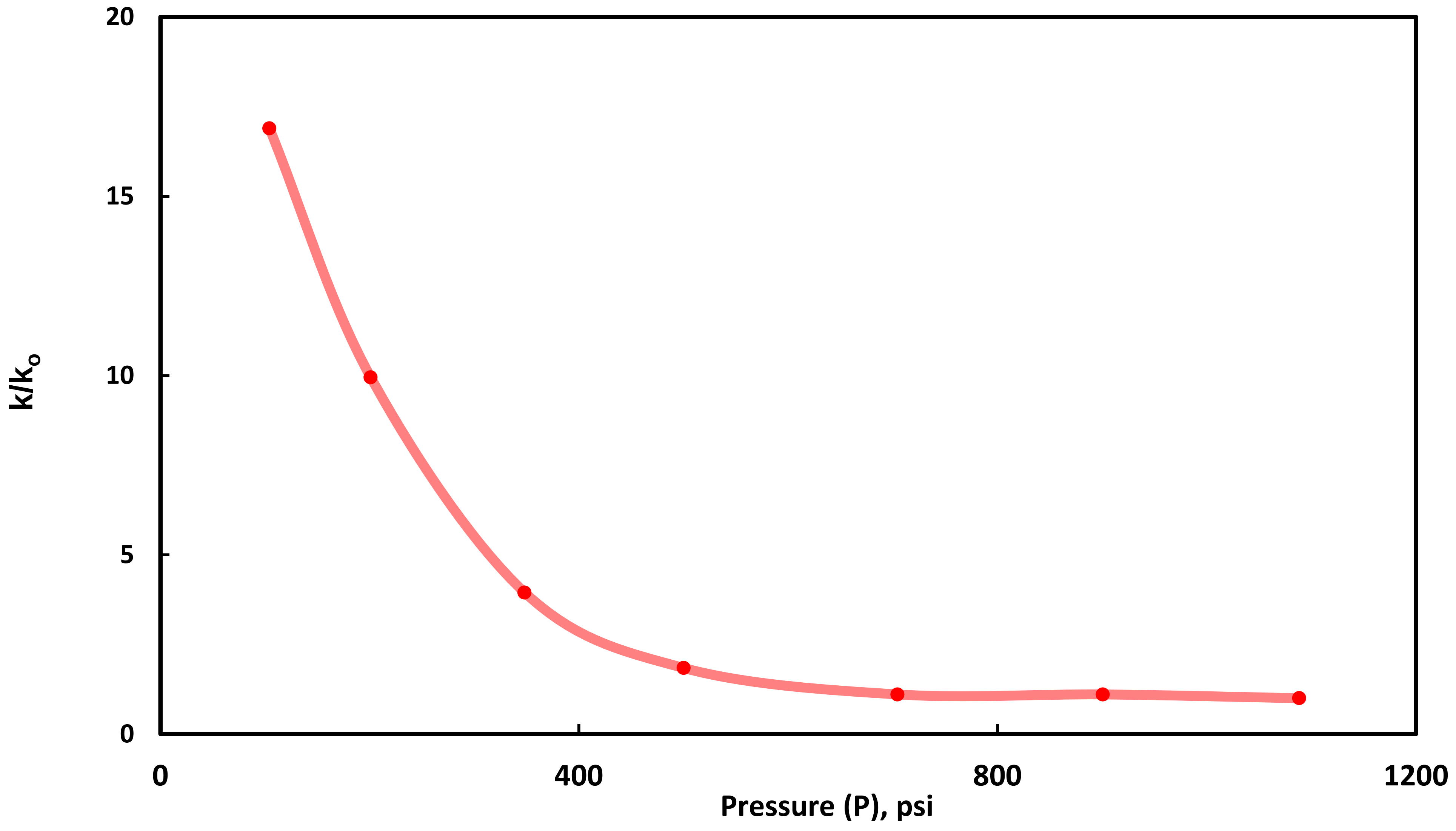
- Permeability and stress as a function of pressure (depletion)
- Strength, geo-mechanical parameters

PdK for Methane Depletion

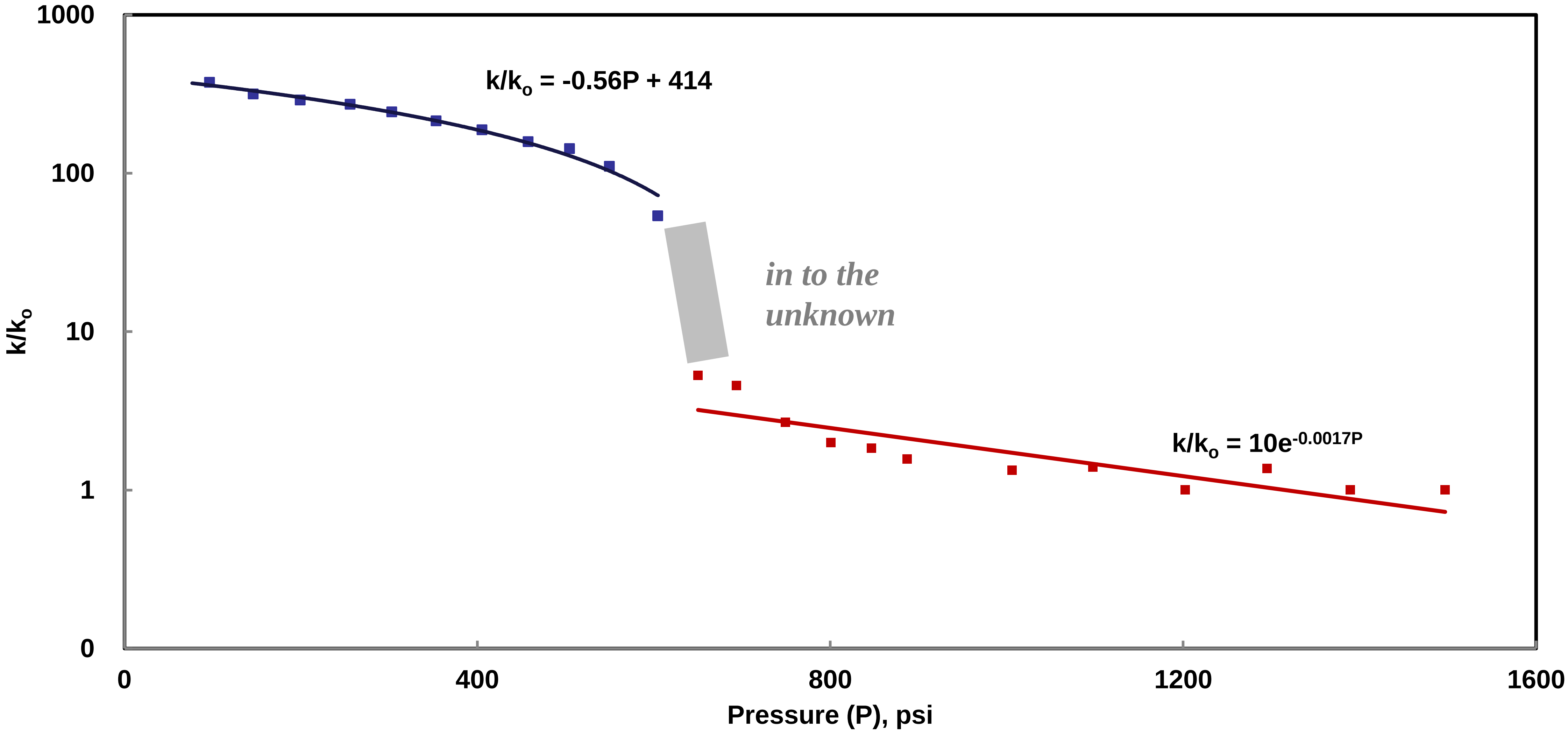
(*very first ever under u/a condition replicating ~1000 feet depth*)



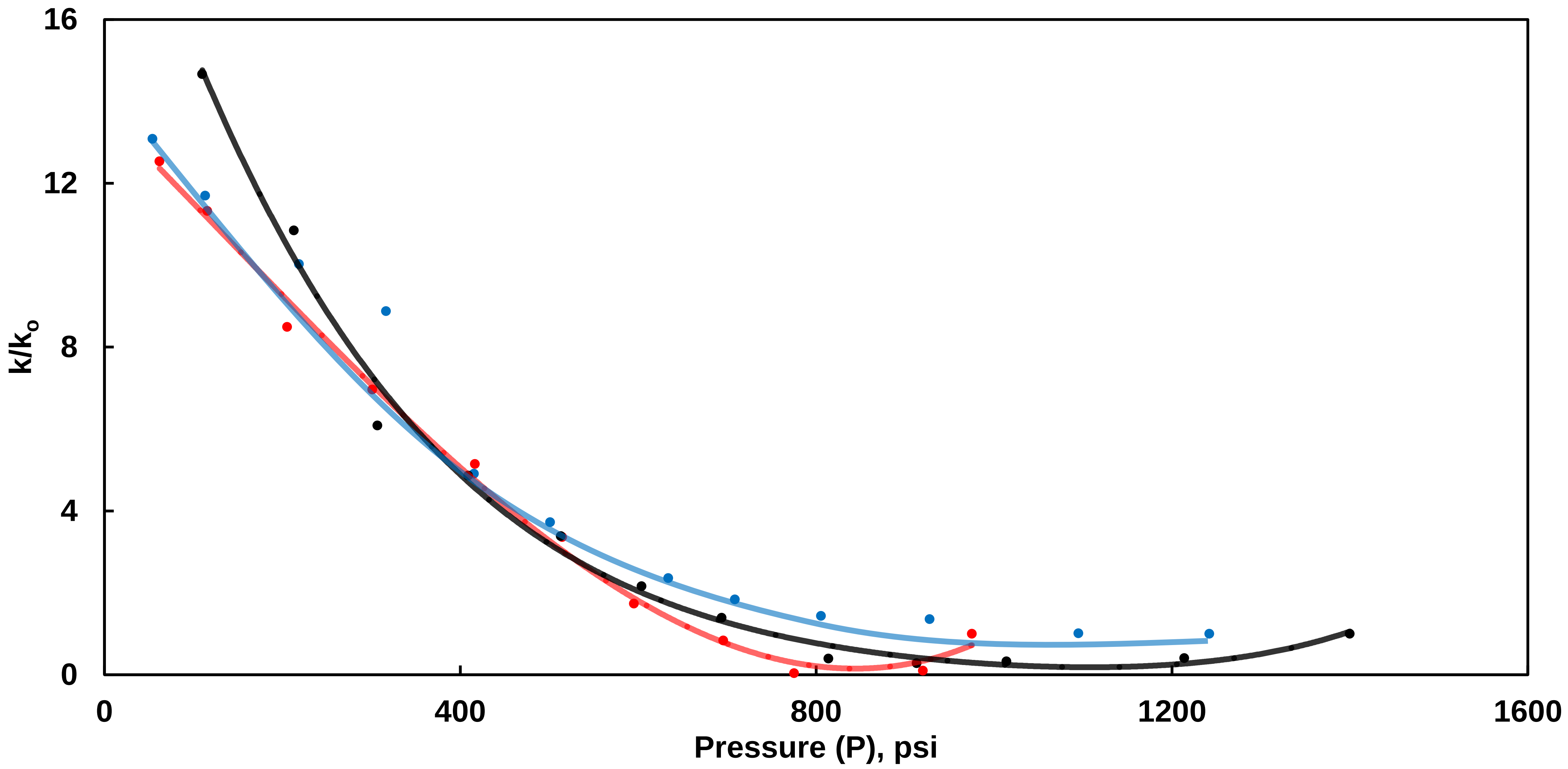
PdK for Methane Depletion ***replicating ~2500 feet depth***



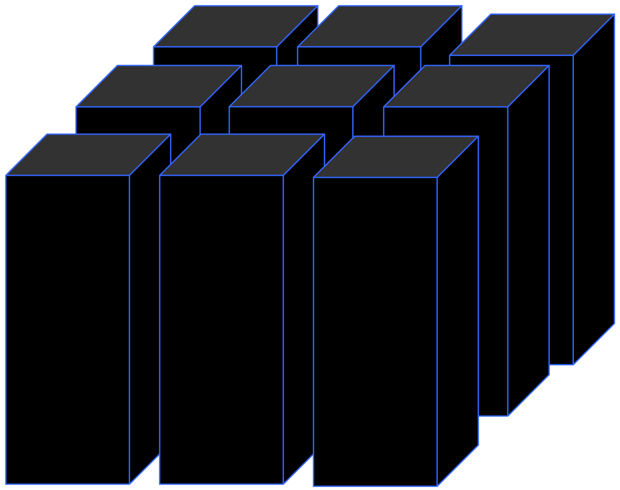
PdK for Methane Depletion *replicating 3500 feet depth*

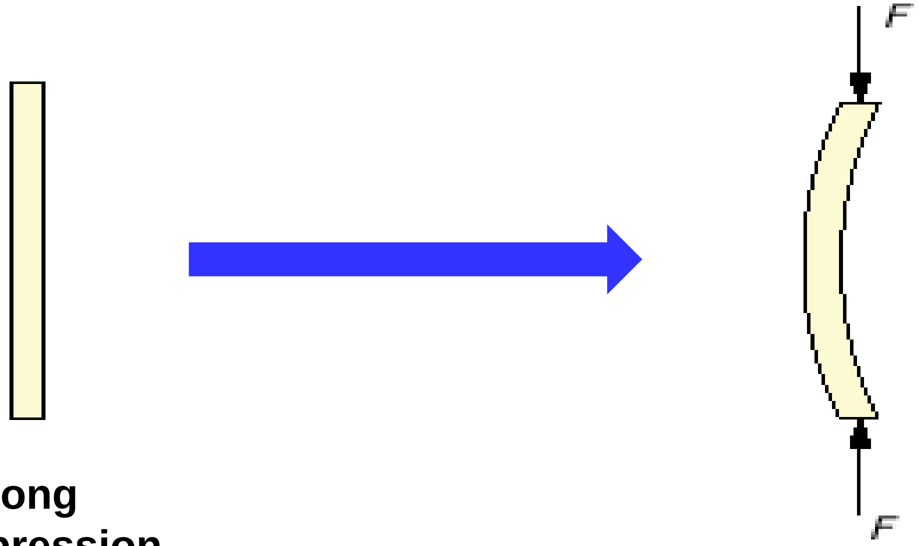


PdK Plots - Sanga Sanga Coal



Theory I: Buckling . . . *after Higgs*





Long Compression Member (matchstick)

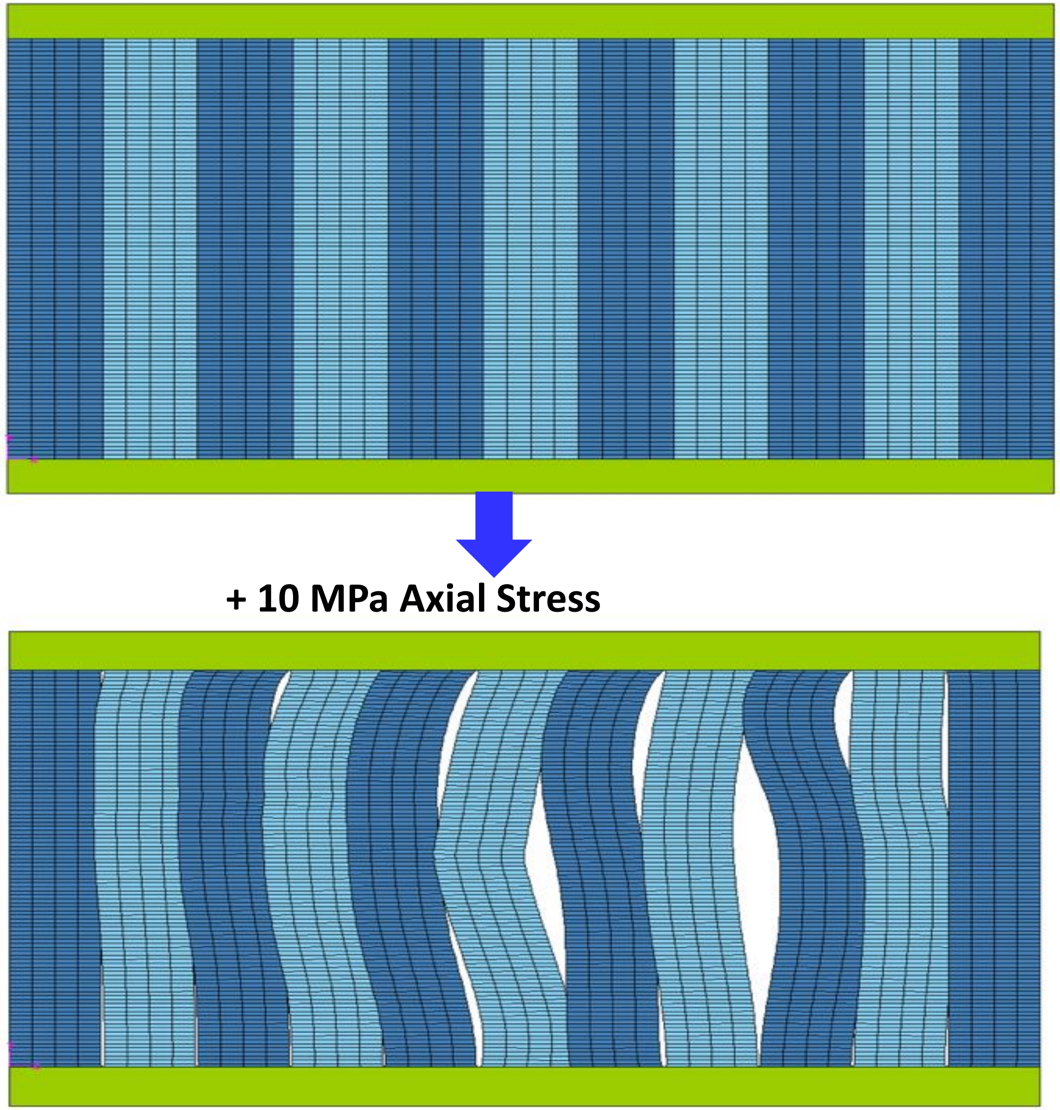
Buckling

Impact of Buckling

Initial cleat width cannot be seen even with expanded horizontal scale

Post Buckling

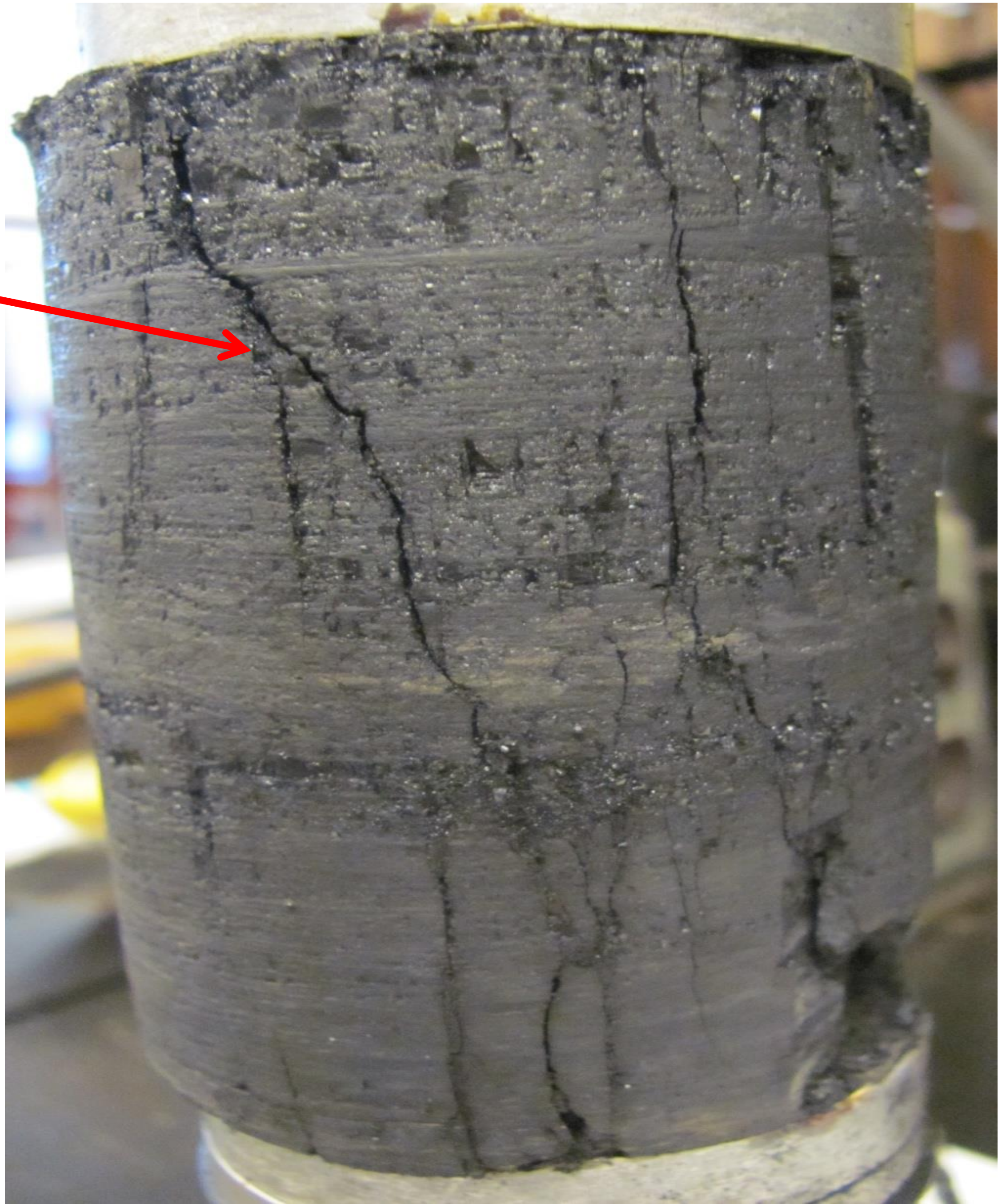
(expanded horizontally)



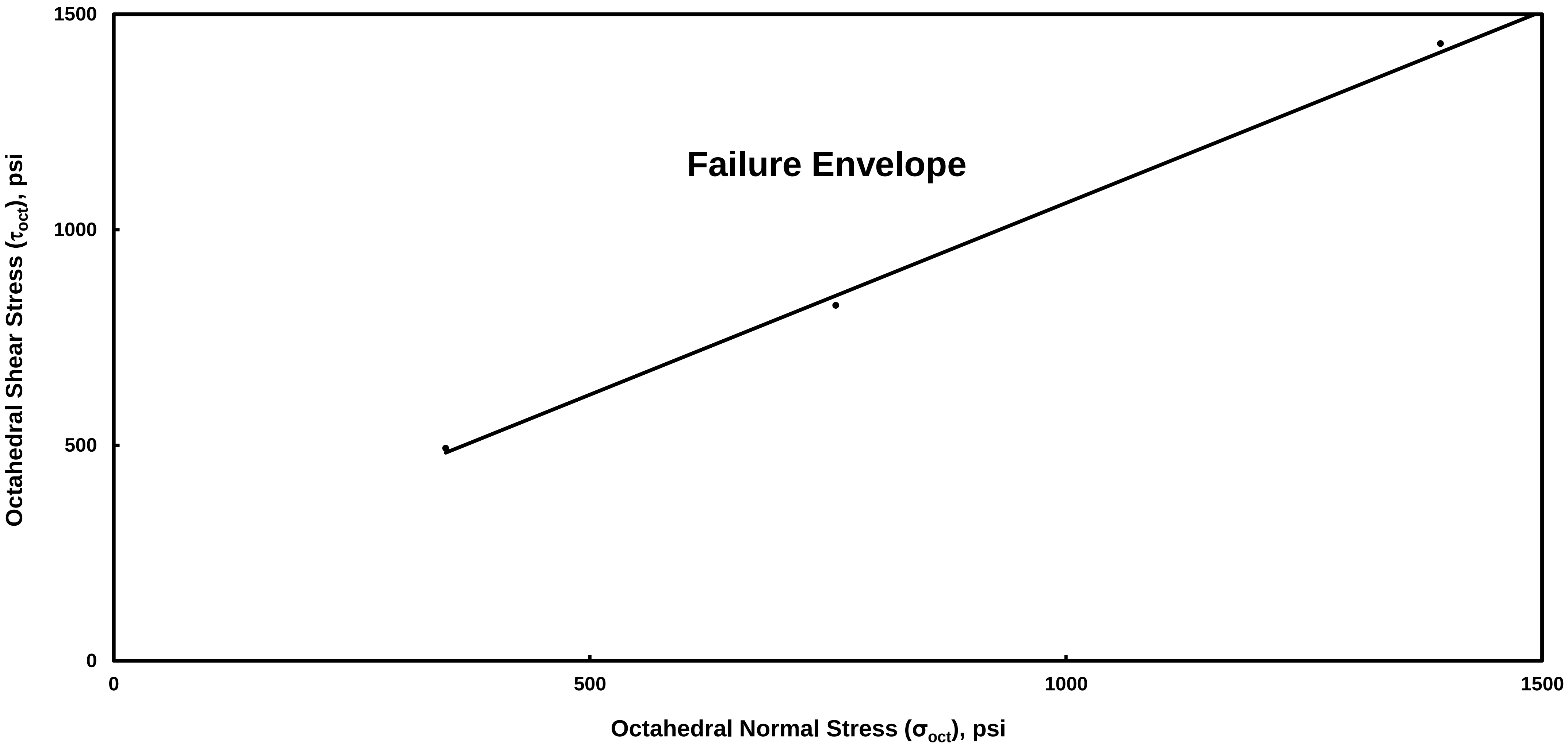
Theory II: Coal Failure post-depletion

Shear Failure

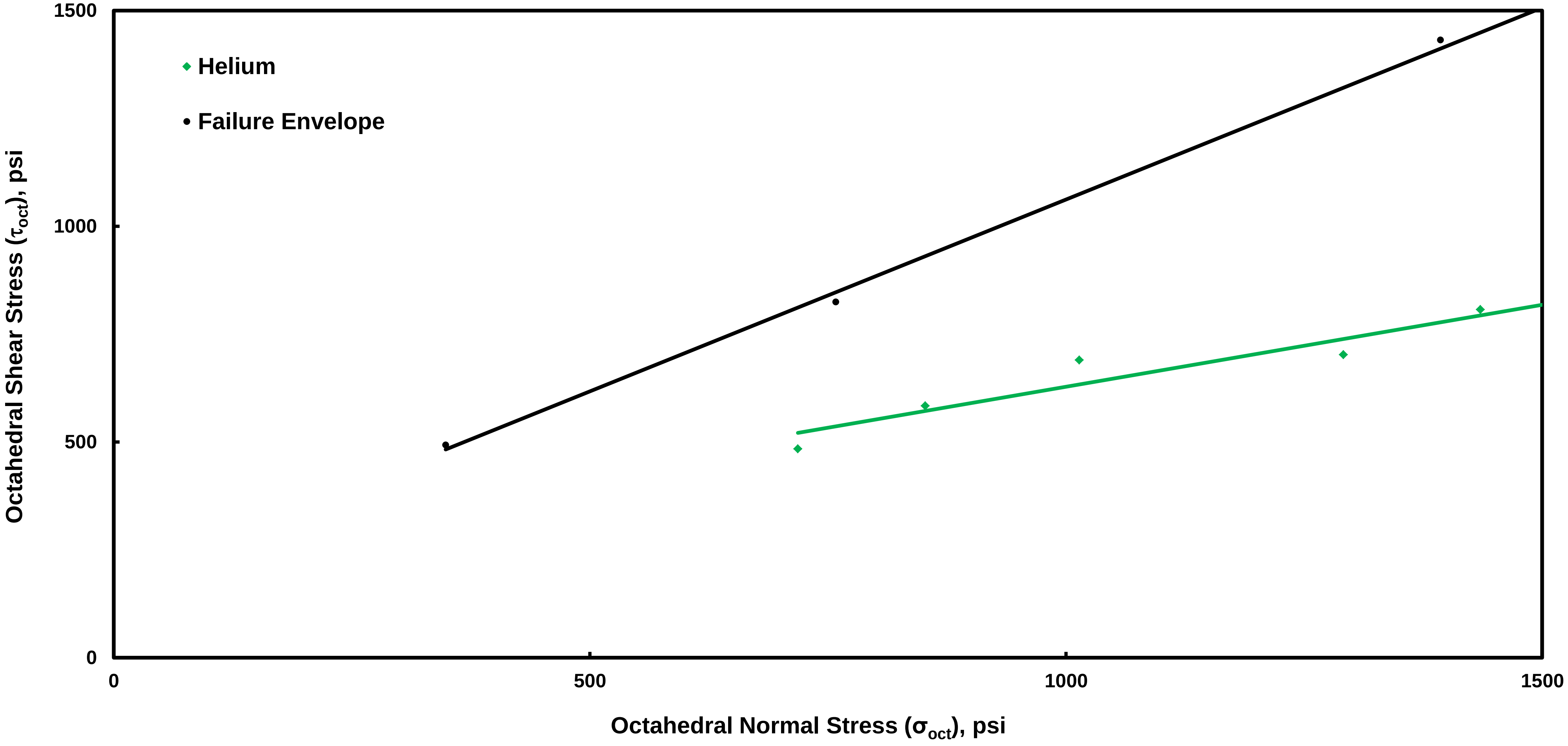
Post-permeability testing
with Methane



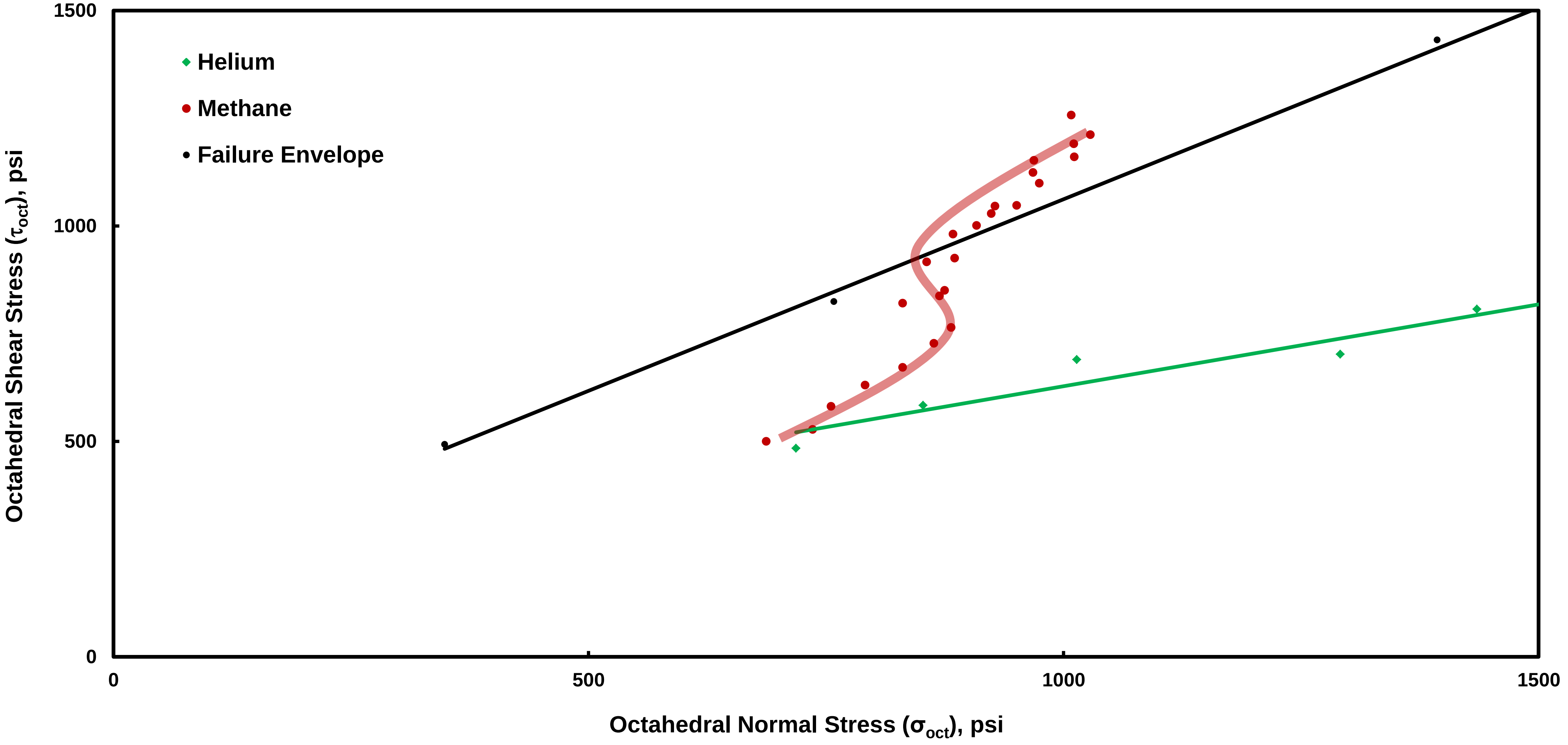
Stress Invariant Path with Helium *and* Methane Depletion



Stress Invariant Path with Helium *and* Methane Depletion



Stress Invariant Path with Helium *and* Methane Depletion



***6.** we need **geomechanical testing**:*

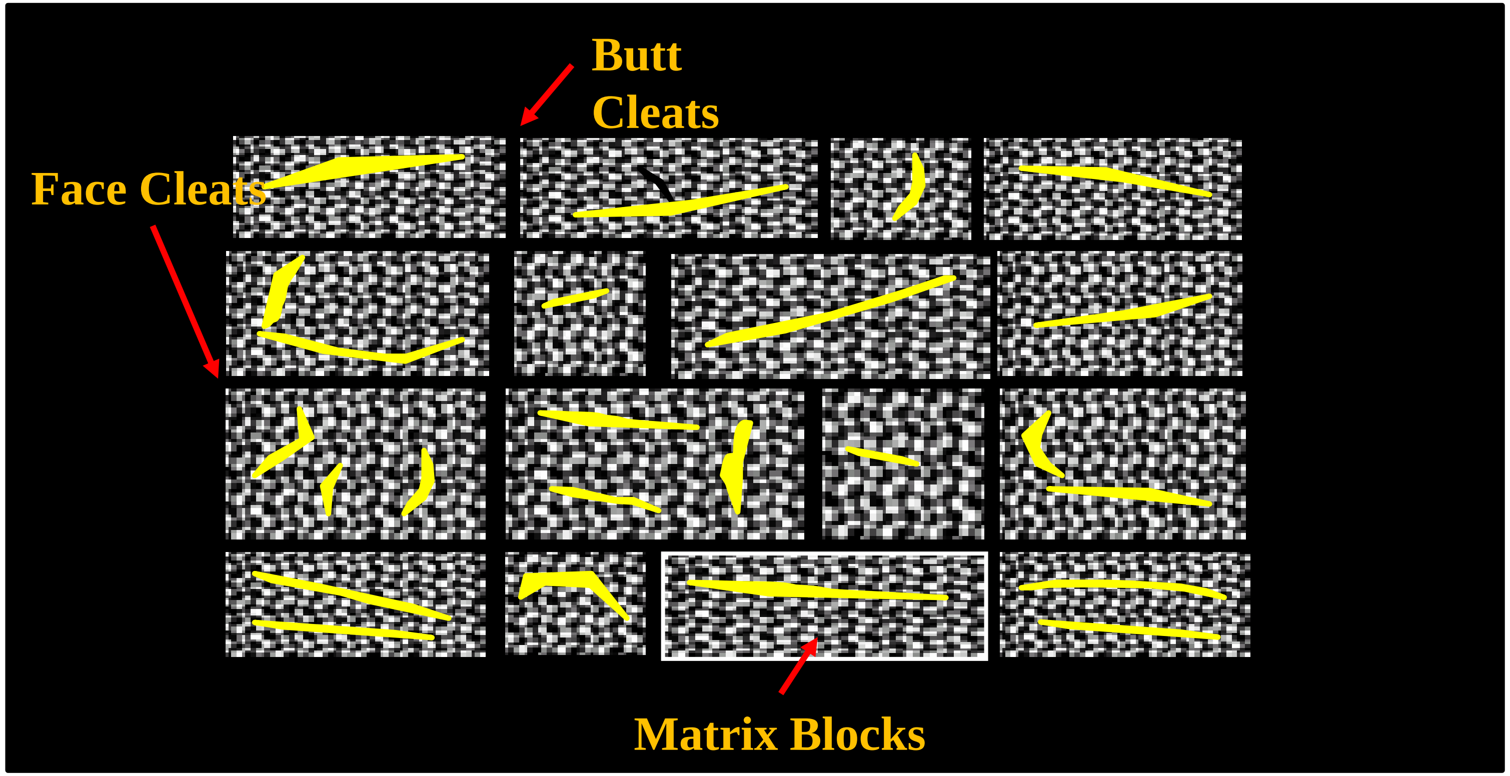
failure envelope for the coal type

(whether the coal will fail with depletion and at what stage)

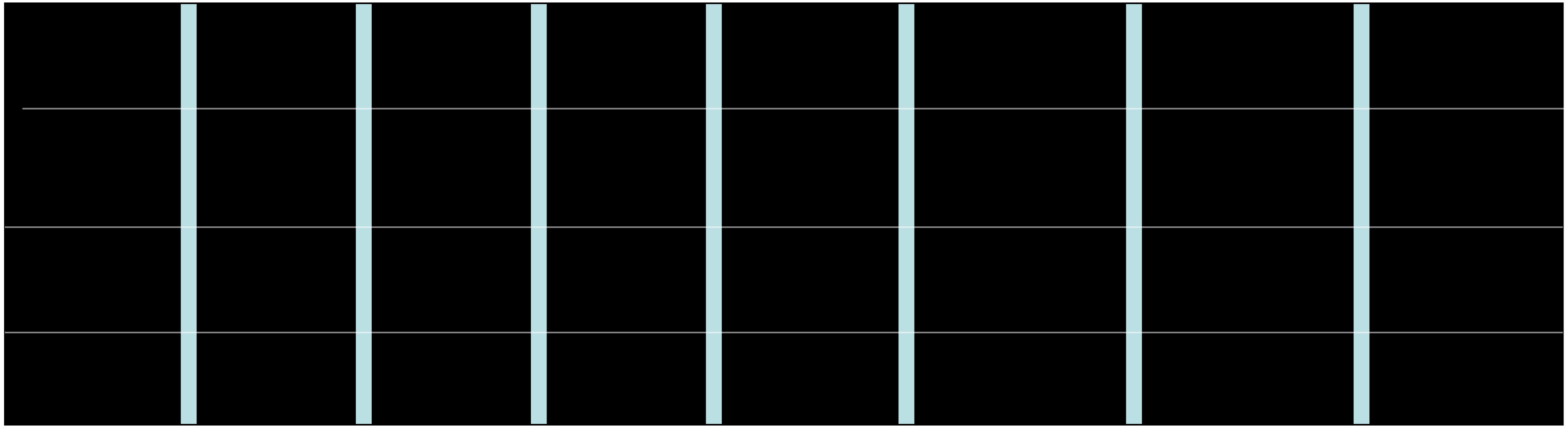
Young’s Modulus and Poisson’s ratio for modeling

fortunately, these are standard tests and can be carried out in most geomechanics lab

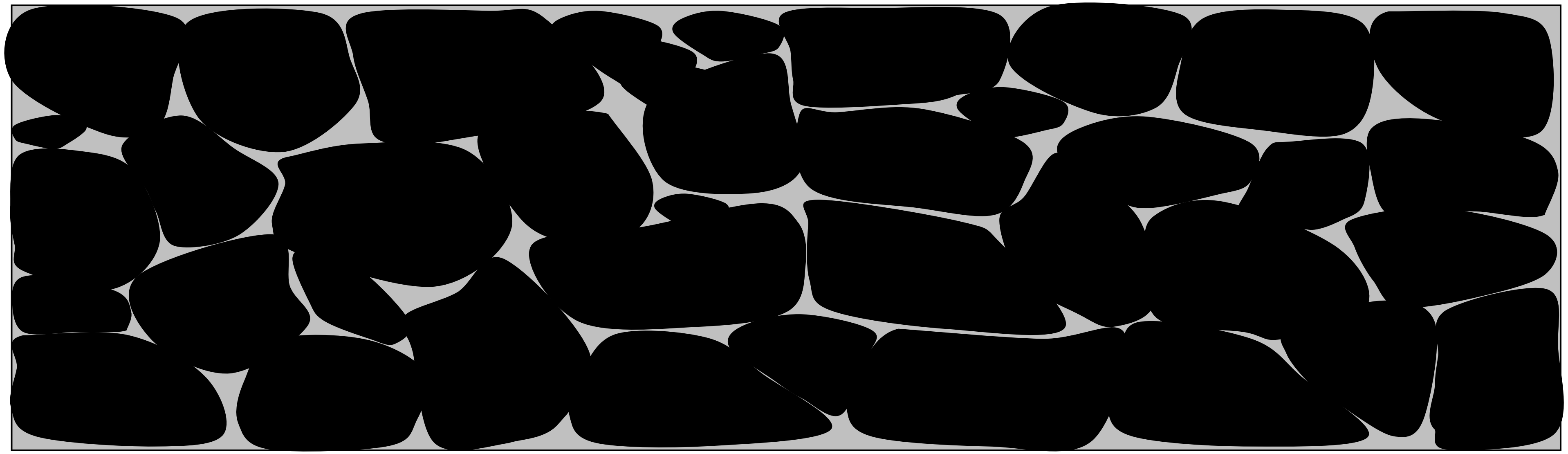
Matrix Shrinkage and Microfracturing



starts looking something like this . . . .



ends up looking like this after depletion . . .

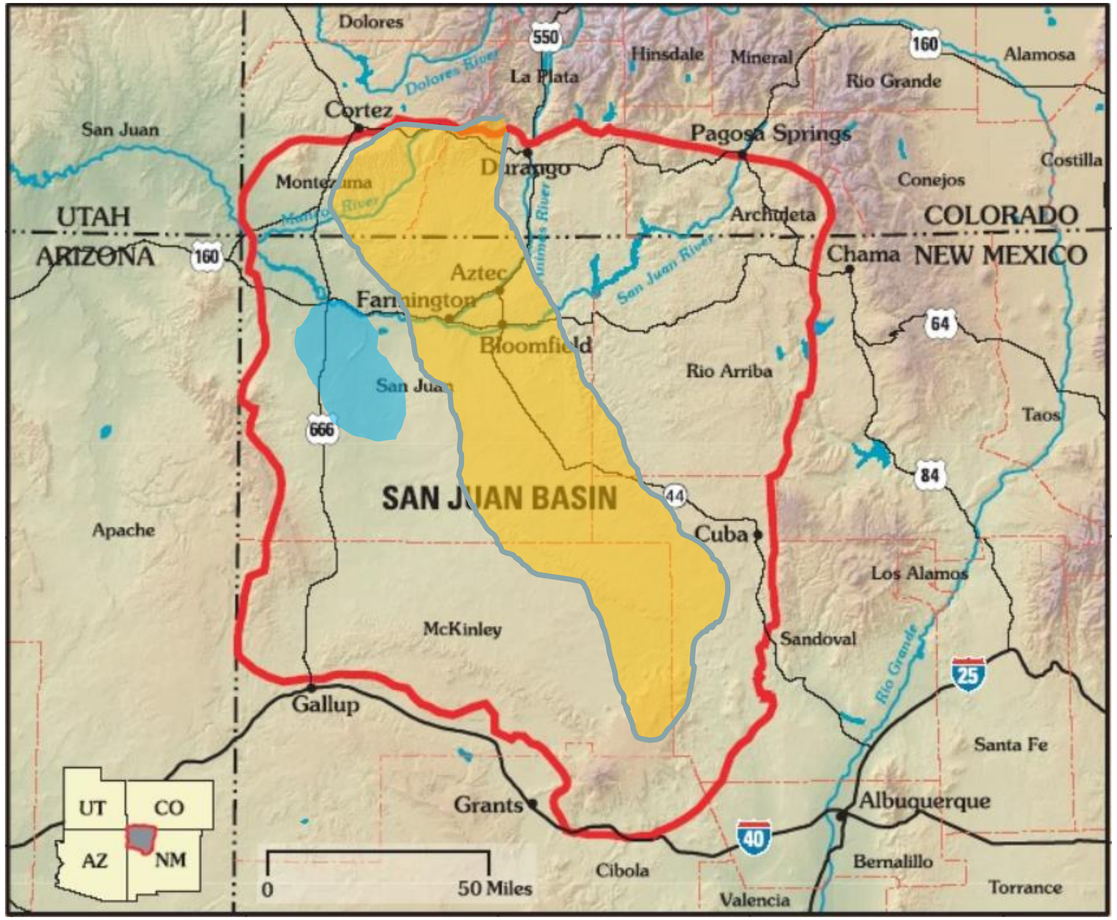


Summary: Typical Testing Plan

Intact Core

- ✓ Gas Content/Composition
- ✓ Isotherms – for gases present *in situ*
- ✓ Cleat Porosity (%): Estimated by measuring water permeability of stressed core
- ✓ Geomechanical Testing: Young's Modulus (E) and Poisson's ratio (ν), Failure Envelope
- ✓ Matrix Shrinkage: Grain Compressibility (C_g/β), Matrix Shrinkage Compressibility (C_m), Shrinkage Constants (P_ε and ε_∞), α (matrix linear strain)
- ✓ Stress- ***and*** Pressure- dependent-permeability (PdK and Pdσ with depletion)
- ✓ No. of Samples: Typically, two?
- ✓ Experimental Conditions: Uniaxial strain, helium and methane

San Juan Basin Fairway (*and just west of it*)



Ongoing Research in CBM

- Slow diffusing coals . . . . . . all modeling based on permeability-controlled production . . . . would require diffusion-controlled production modeling.

- Can diffusion process somehow be enhanced?

e-z stuff

e-z stuff

e-z stuff

Questions???

one email away: satya@siu.edu

e-z stuff

e-z stuff

e-z stuff