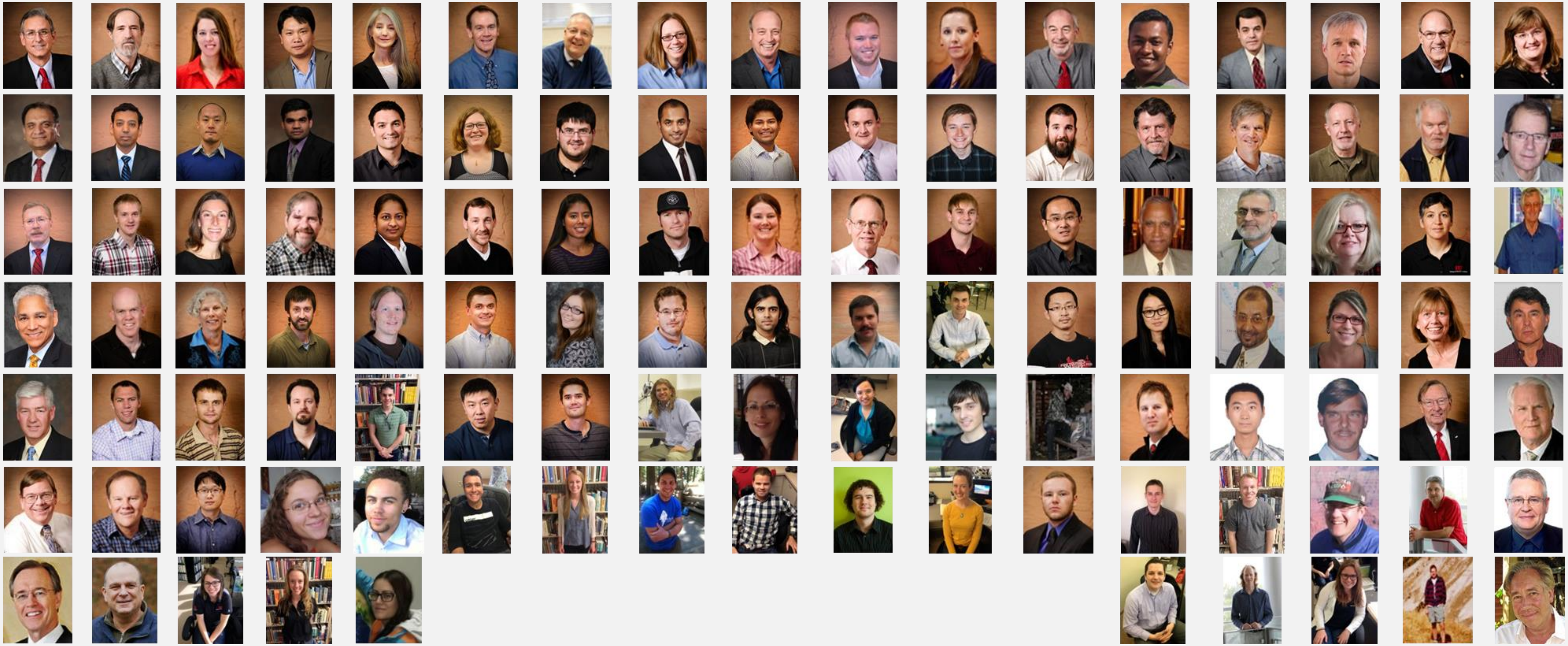
# Optimized Recovery from Unconventional Reservoirs: How Nanophysics, the Micro-Crack Debate, and Complex Fracture Geometry Impact Operations

Energy & Geoscience Institute
AT THE UNIVERSITY OF UTAH

EGI

## Salt Lake City | Bratislava | Calgary | Houston | Jammu | London | Sydney



*~120 EGI Staff & Affiliated Scientists*

Transcending Scale

Slow

Speed of process

Fast

Large

Scale of process

Small

Rasoul Sorkhabi | **Global Systems**

Michal Nemčok | **Orogenic Systems**

**2 New Books**

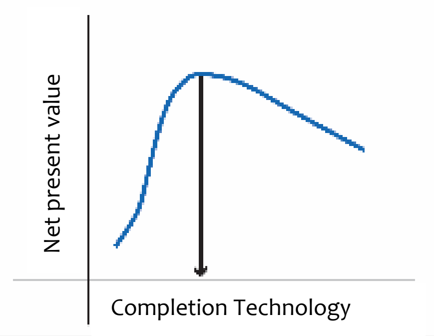
Lansing Taylor | **Prospect- to Seismic-scale Structure**

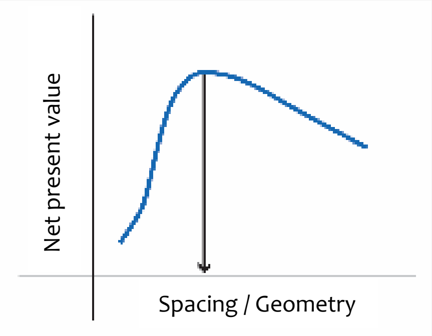
John McLennan | **Reservoir Geomechanics**

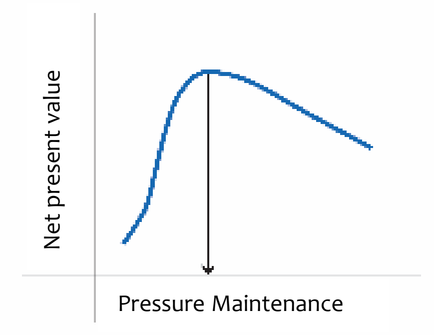
Ian Walton | **Well-bore Geomechanics**

Milind Deo | **Pore to Nano-scale Engineering**

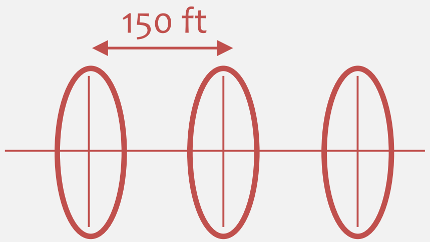
# Optimized Recovery from Unconventional Reservoirs



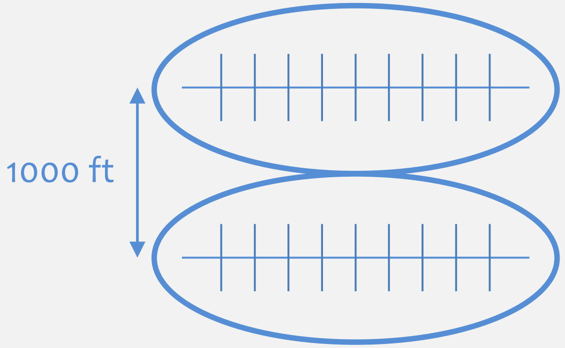




- **Near Wellbore**




- **Well-to-Well**

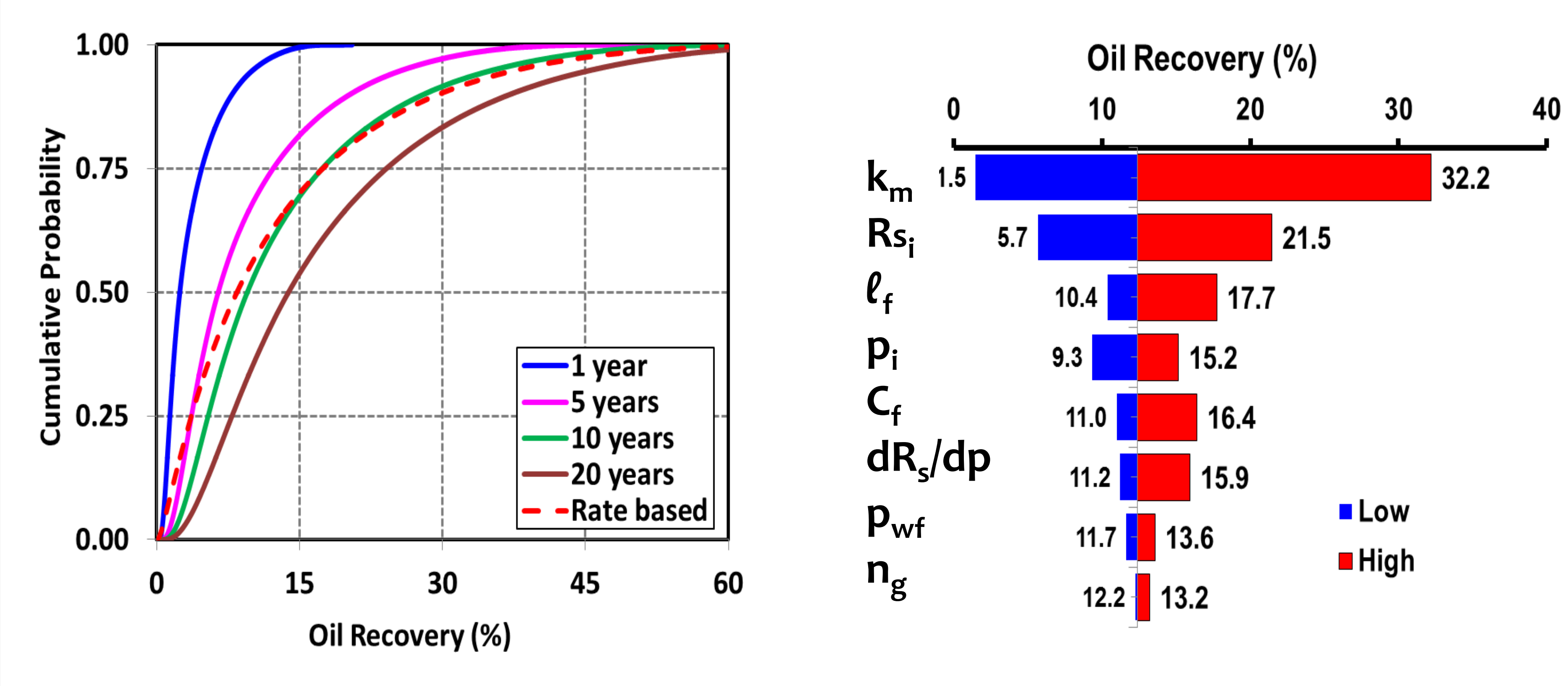



- **Field Development**

# Liquids from Shales

**Milind Deo, Ph.D.**
Professor and Chair
Chemical Engineering

**Palash Panja, Ph.D.**
Post-Doctoral Researcher
Energy & Geoscience Institute




- **Probability density functions (PDFs)**
- **Obtained using Monte Carlo simulations**

| Symbol | Property |
|---|---|
| $K_m$ | Matrix perm |
| $X_f$ | Hydraulic Fracture spacing |
| $Rs_i$ | Initial dissolved gas oil ratio |
| $dRs/dp$ | Slope of dissolved GOR |
| $P_i$ | Initial pressure |
| $n_g$ | Gas rel. perm exponent |
| $C_f$ | Compressibility |
| $P_{wf}$ | Producing BHP |

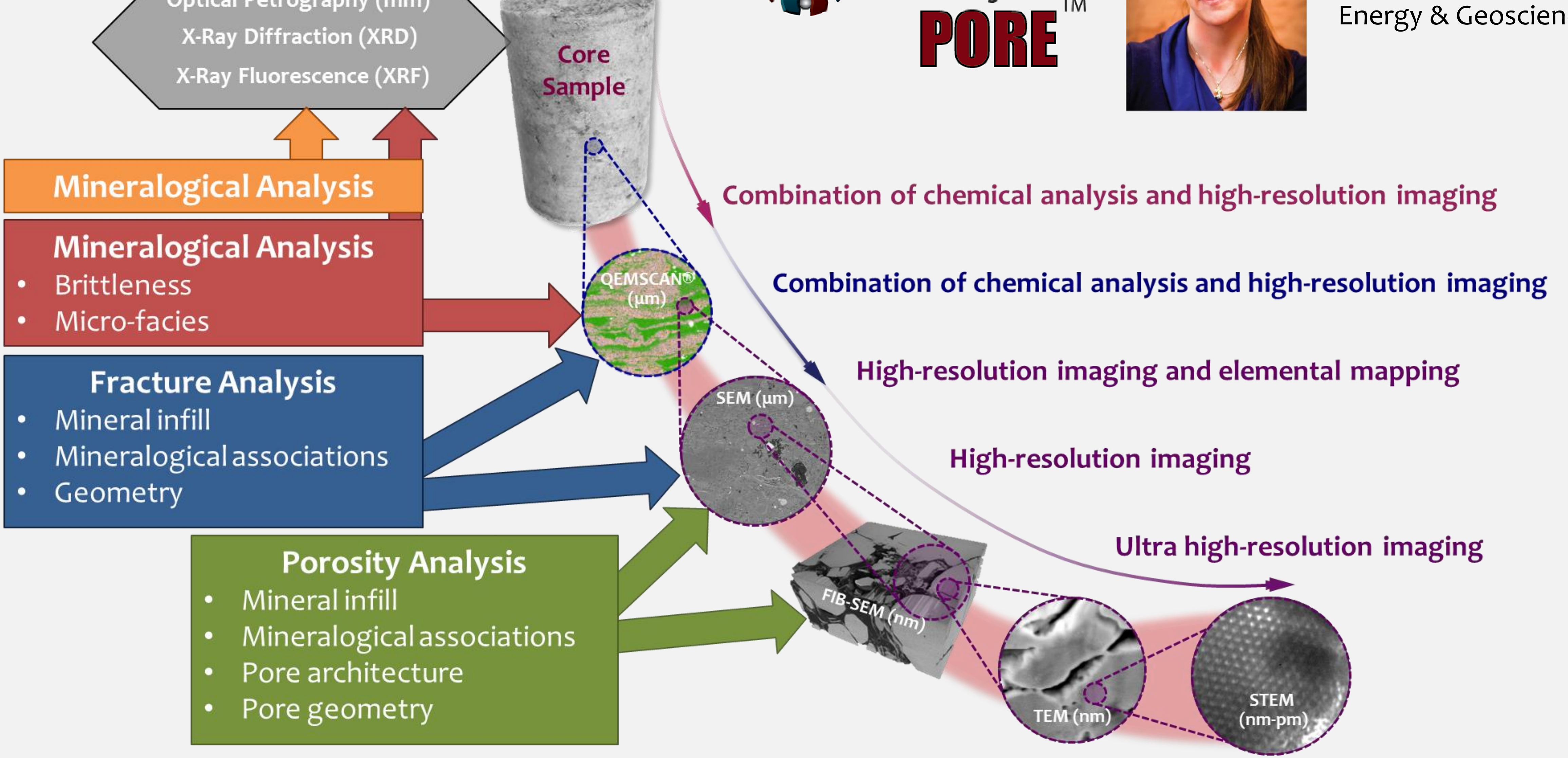
# Oil Recovery from Shales

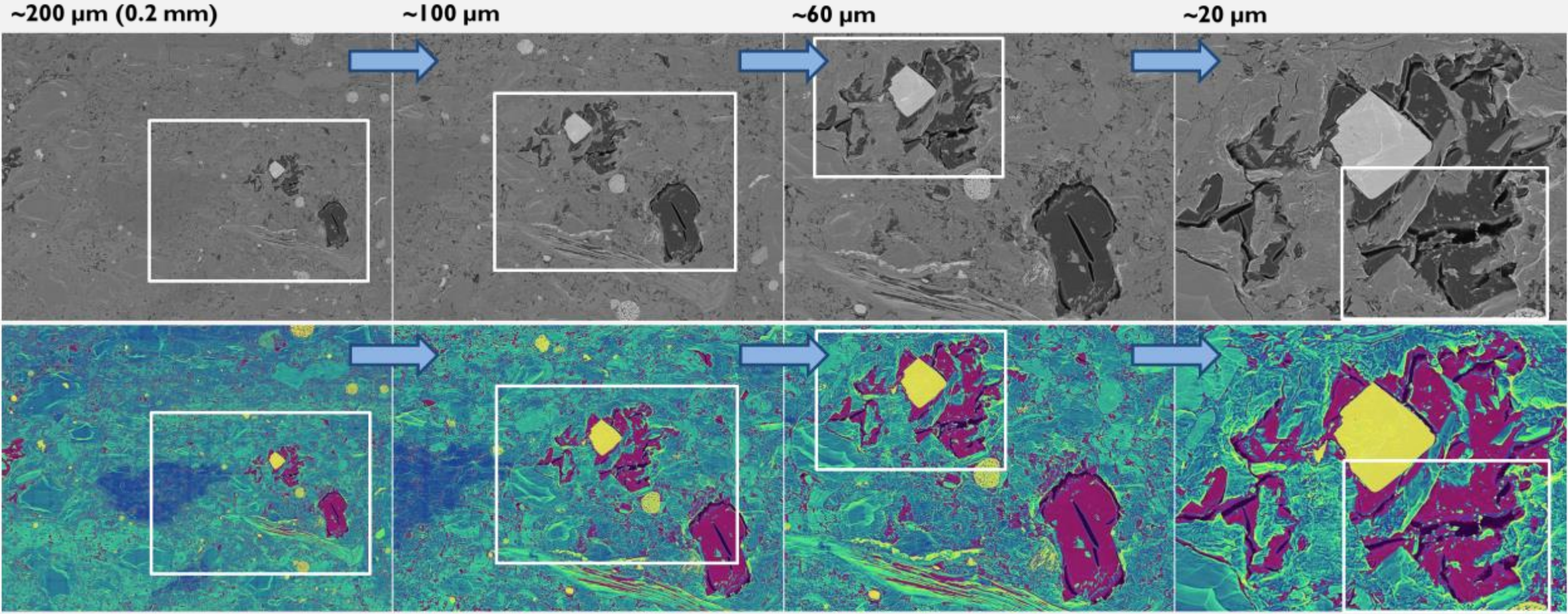
| 1 yr | 10 yrs | 20 yrs | Economic Rate 5 bbl/d/fracture | Ranking |
|---|---|---|---|---|
| $*X_f$ | $K_m$ | $K_m$ | $K_m$ | Most important |
| $K_m$ | $*X_f$ | $*X_f$ | $Rs_i$ | |
| $Rs_i$ | $Rs_i$ | $Rs_i$ | $*X_f$ | |
| $P_i$ | $dRs/dp$ | $dRs/dp$ | $P_i$ | |
| $dRs/dp$ | $P_i$ | $P_i$ | $C_f$ | |
| $*P_{wf}$ | $n_g$ | $C_f$ | $dRs/dp$ | |
| $n_g$ | $C_f$ | $*P_{wf}$ | $*P_{wf}$ | |
| $C_f$ | $*P_{wf}$ | $n_g$ | $n_g$ | Least important |

Only 2 of the variables are operationally controllable parameters

CORE through PORE™

**Bryony Richards, Ph.D.**
Senior Petrologist
Energy & Geoscience Institute

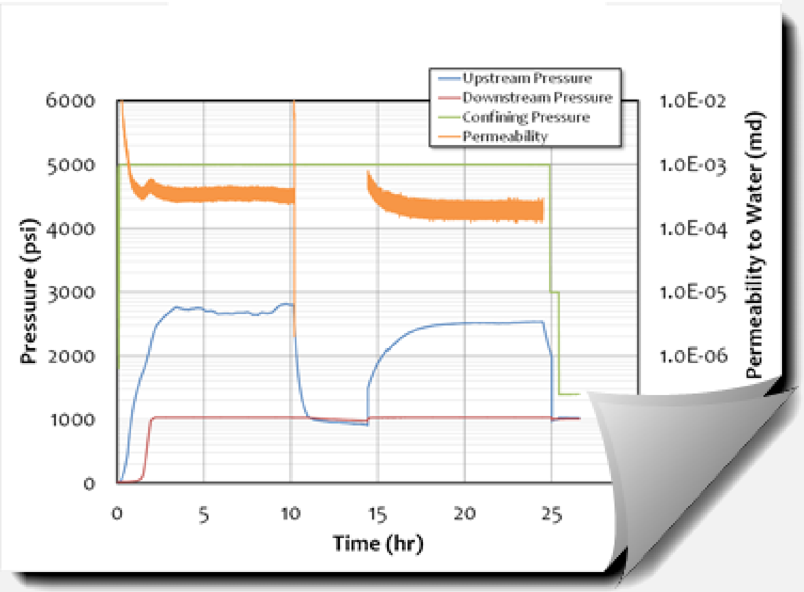



~200 µm (0.2 mm)
~100 µm
~60 µm
~20 µm

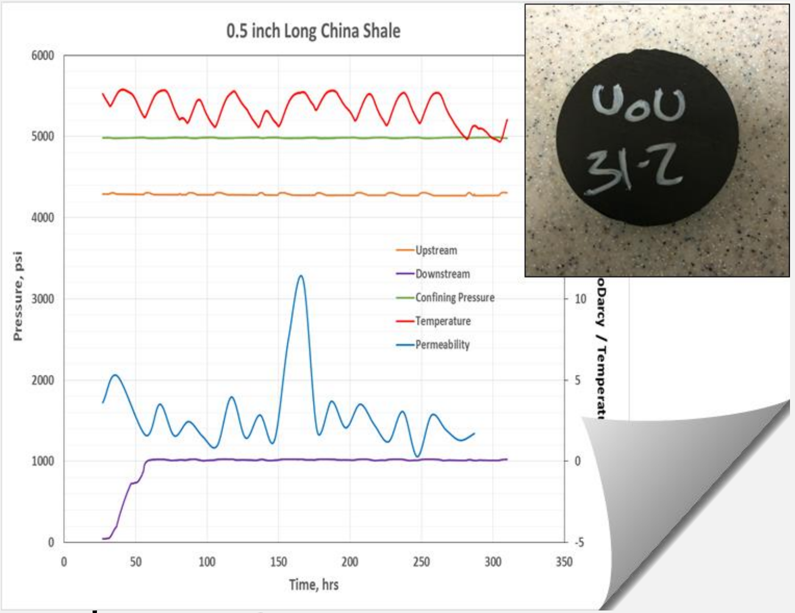
## Shale Interrogator

- Pressure – 15,000 psi
- Temperature 300°F
- High-resolution Volume and Pressure Measurements

## Absolute permeability

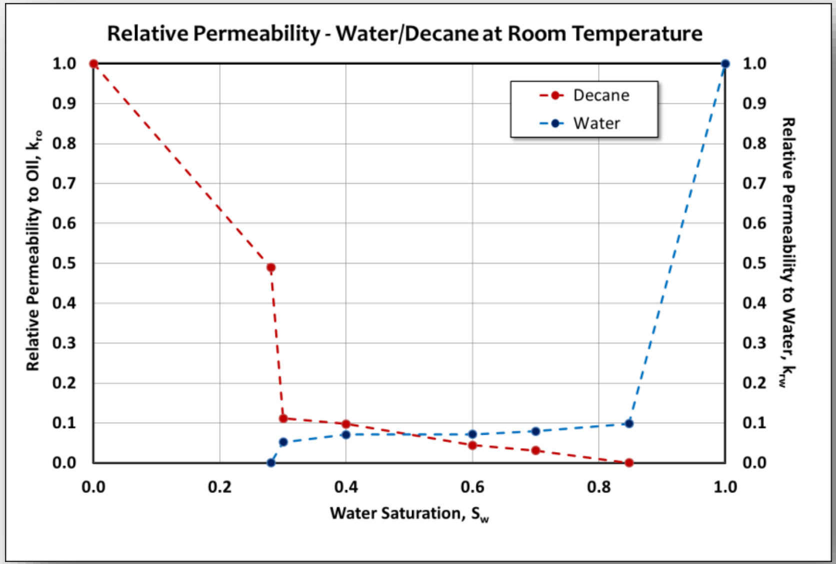


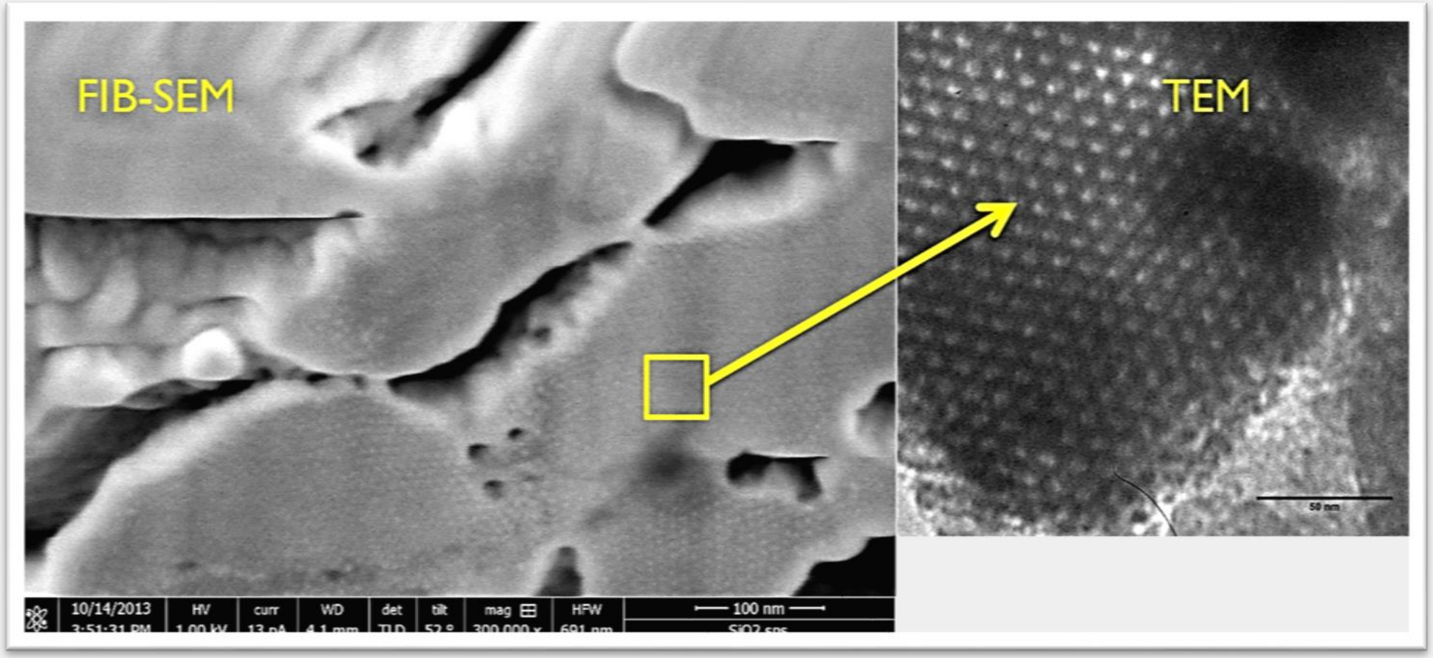

1 Day, 200 nD




14 days, 5 nD

## Relative permeability




**Manas Pathak, Ph.D.**
Energy & Geoscience Institute

## Darcy's Law Formula

$$Q = \frac{-kA(P_b - P_a)}{\mu L}$$

$Q$ – total discharge in $m^3/s$

$k$ – soil coefficient of permeability in $m^2$

$A$ – cross sectional area of flow in $m^2$

$P_b$ – initial pressure in $Pa$

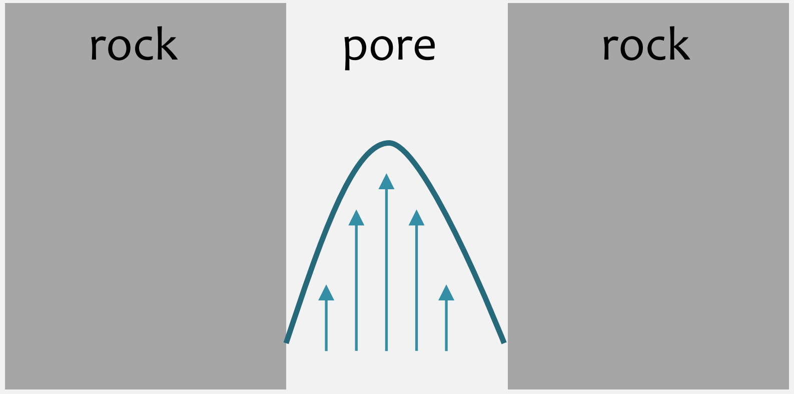
$P_a$ – final pressure in $Pa$

$\mu$ – viscocity in $Pa$

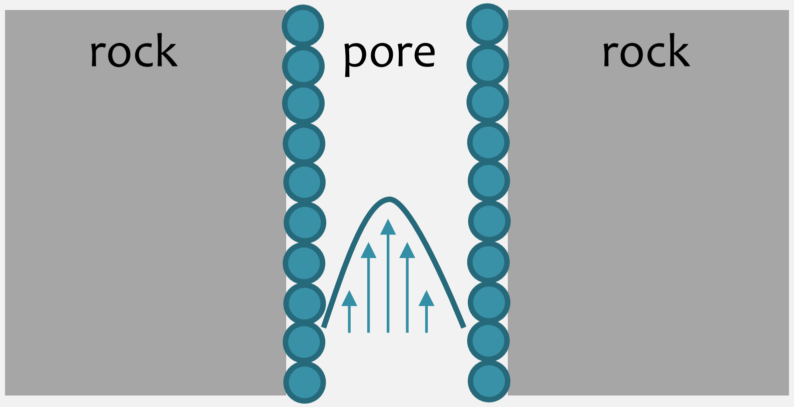
$L$ – length in $m$

At the Nano-scale, permeability is not a rock property but also depends on fluid-rock interaction

## Surface Interaction

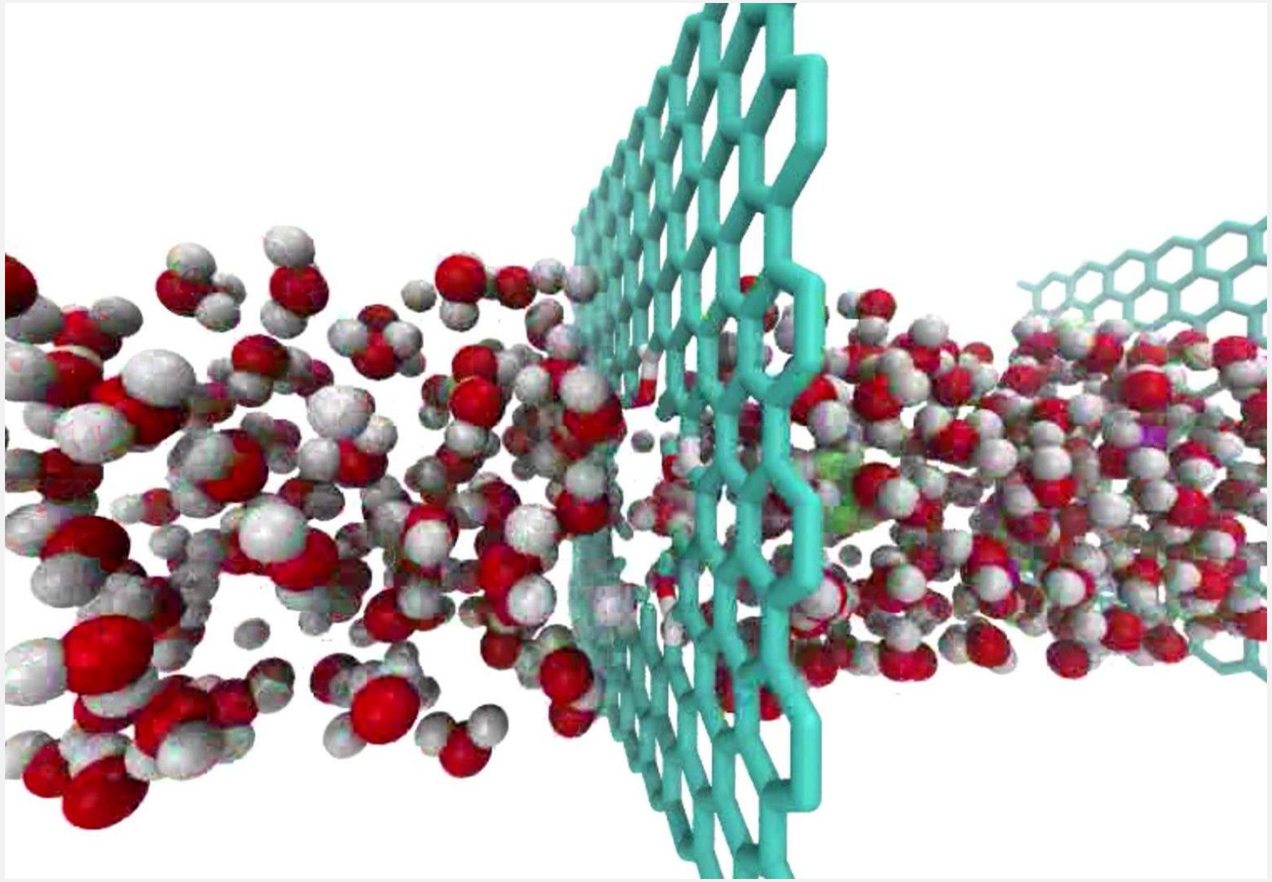



***Micro***

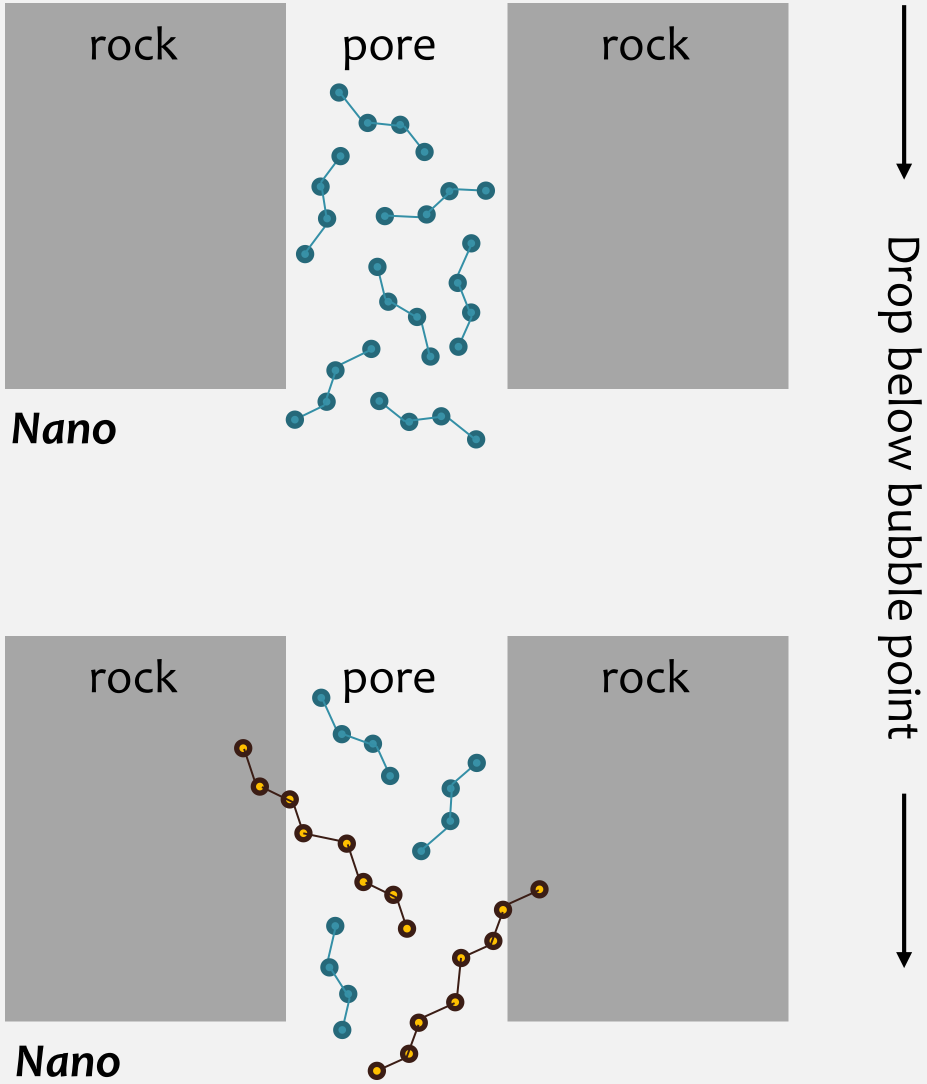



***Nano***

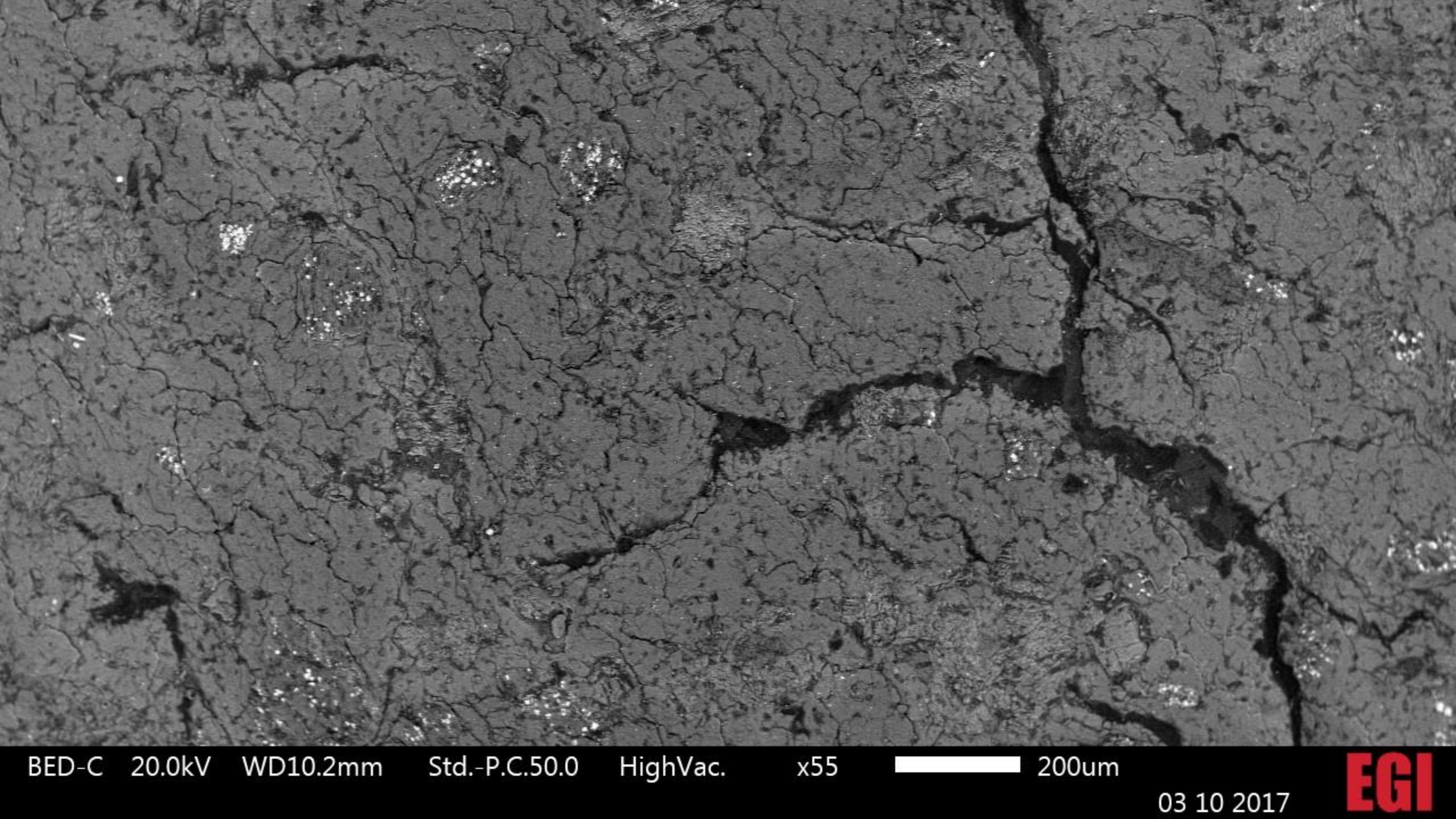
Molecular Dynamics



Restriction




Bubble point is suppressed in nano-pores

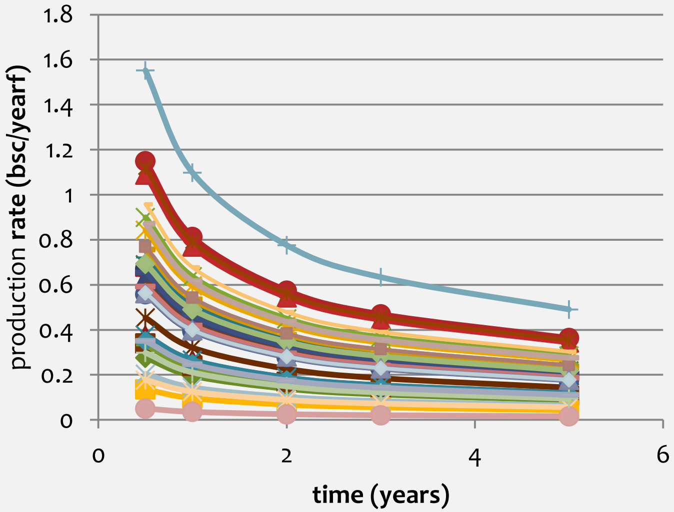

BED-C 20.0kV WD10.2mm Std.-P.C.50.0 HighVac. x55 200um
03 10 2017
EGI

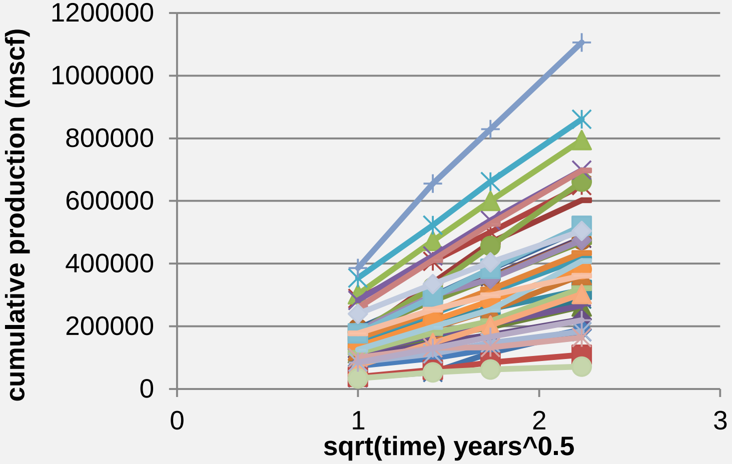
# Cumulative production and production rate

$$Q = C_p\sqrt{t}, \quad q = \tfrac{1}{2}\frac{C_p}{\sqrt{t}}$$

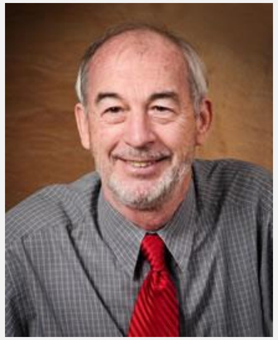
where $C_p$ depends on:

- Pressures (bhfp, pore or reservoir pressure)
- Reservoir quality/ GIP (permeability, porosity)
- Gas properties (viscosity, compressibility, equation of state)
- Productive fracture surface area



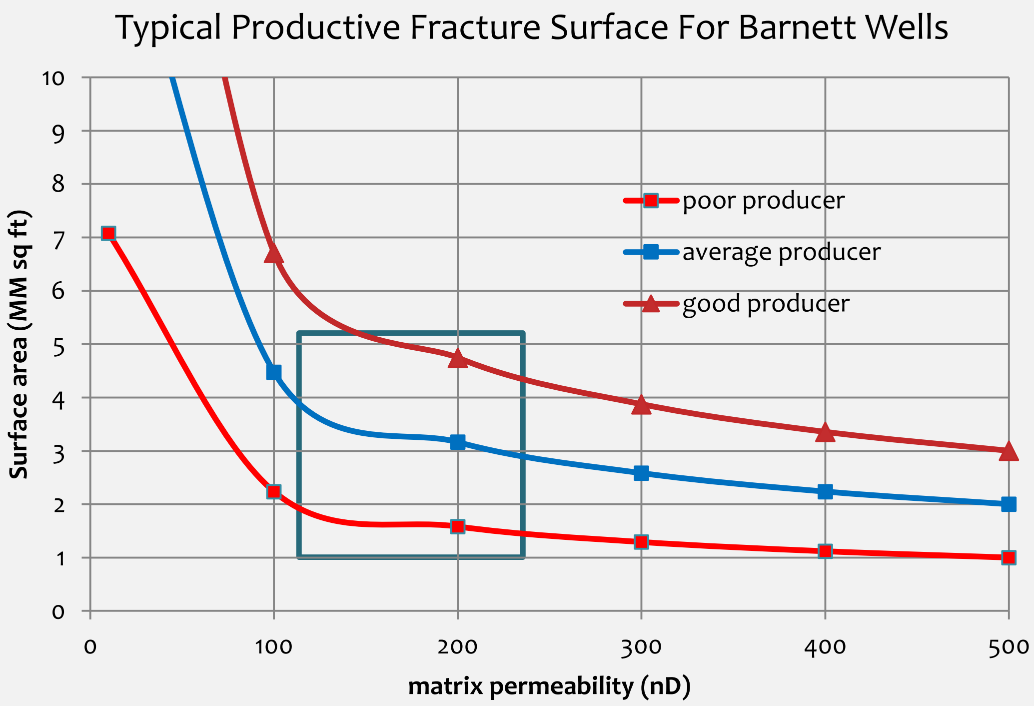

**Shale Gas Production Analysis**



**Ian Walton, Ph.D.**
Research Scientist
Energy & Geoscience Institute

# Estimate of Productive Fracture Surface Area

- Measure the production coefficient
- Estimate pressures, porosity etc
- Infer productive fracture surface area

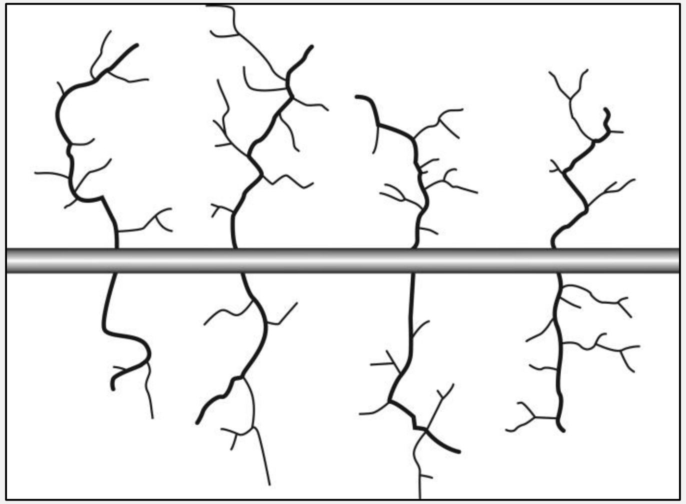



Productive fracture surface area in the Barnett: 1-5 MM sq ft.

# Estimate of Created Fracture Surface Area

## Mass balance

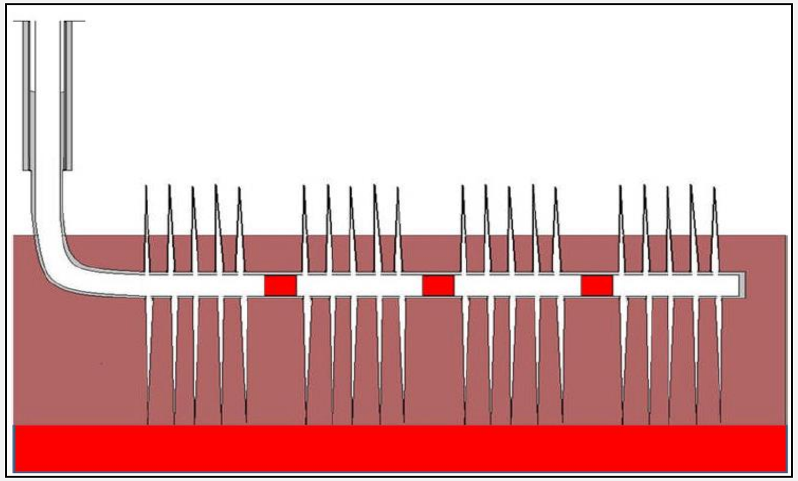
- Frac fluid:
  Frac surface area ~ 100 MM sq ft
- Proppant:
  Propped frac surface area
  ~ 1-5 MM sq ft



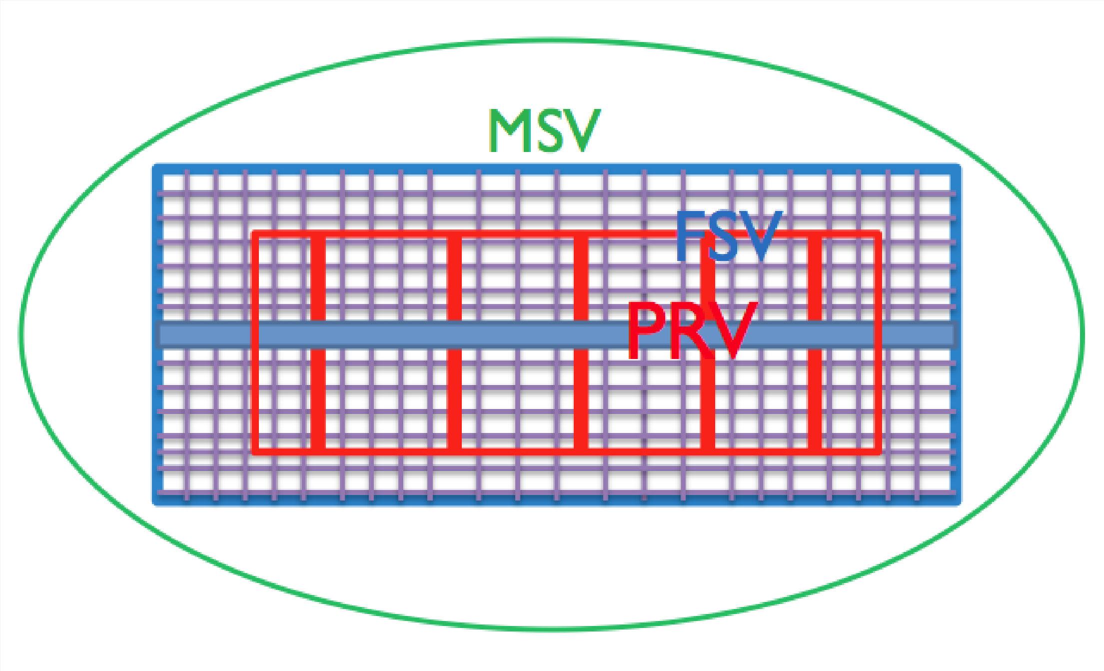
## Example

15 transverse hydraulic fracs each
200 ft high and 500 ft across

Frac surface area = 2*15*200*500 sq ft
= 3 MM sq ft

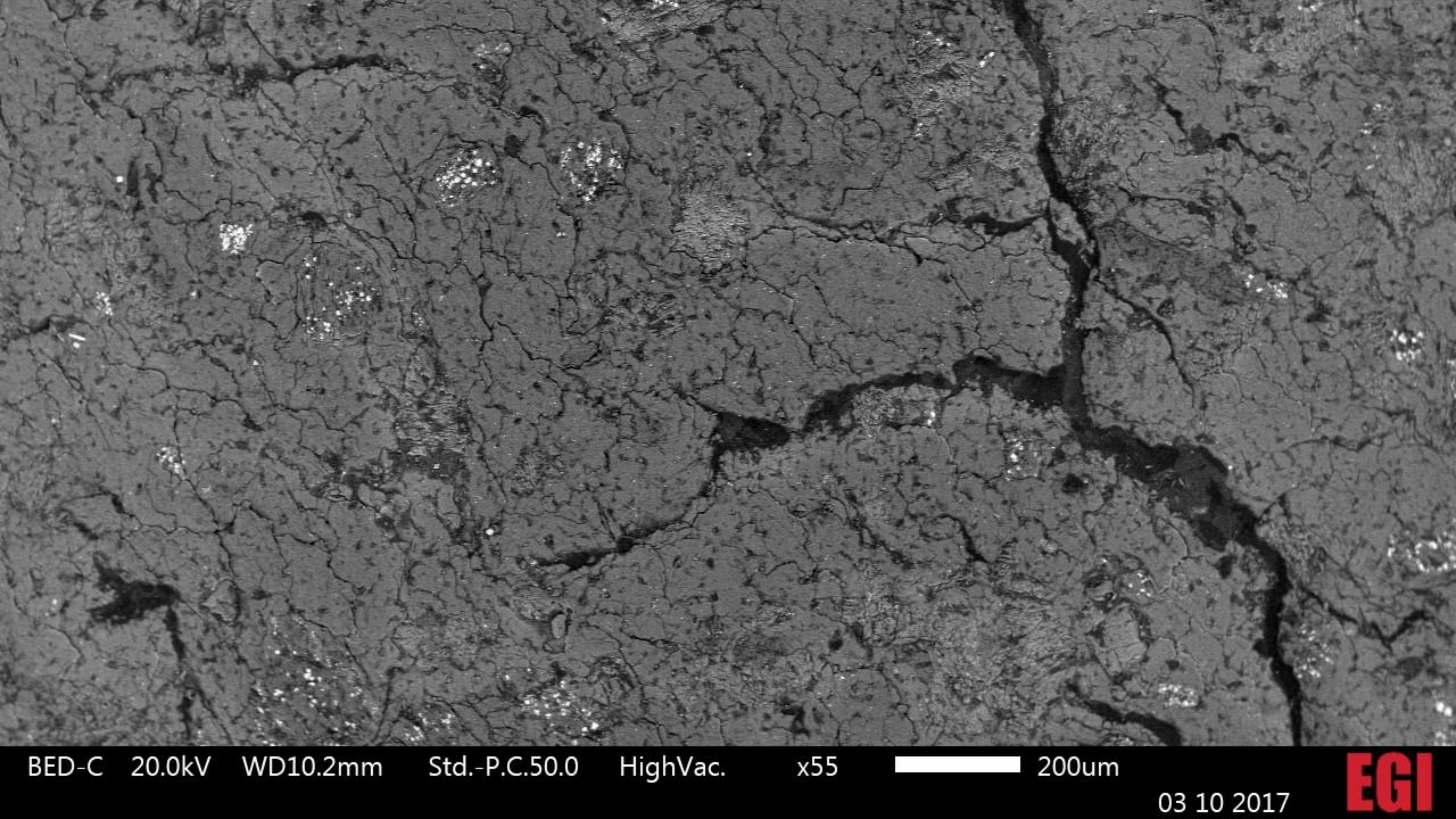


# Productive Reservoir Volume




- Gas is produced from the volume defined by extent of primary fracture network
- Most of the fracture fluid resides in the large secondary fracture network and is eventually imbibed into the matrix

Large scale slickwater fracturing is very inefficient: the volume of the productive fractures represents only a small percentage of the volume of the fluid pumped.


BED-C
20.0kV
WD10.2mm
Std.-P.C.50.0
HighVac.
x55
200um
03 10 2017
EGI

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| $K_m$ | *$X_f$ | *$X_f$ | $Rs_i$ | |
| $Rs_i$ | $Rs_i$ | $Rs_i$ | *$X_f$ | |
| $P_i$ | dRs/dp | dRs/dp | $P_i$ | |
| dRs/dp | $P_i$ | $P_i$ | $C_f$ | |
| *$P_{wf}$ | $n_g$ | $C_f$ | dRs/dp | |
| $n_g$ | $C_f$ | *$P_{wf}$ | *$P_{wf}$ | |
| $C_f$ | *$P_{wf}$ | $n_g$ | $n_g$ | Least important |

Only 2 of the variables are operationally controllable parameters

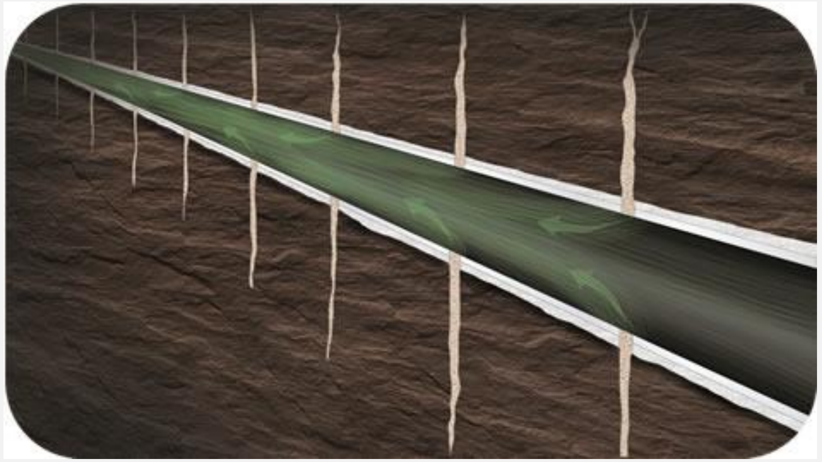
## Large Scale Geologic Controls on Hydraulic Stimulation

**John McLennan, Ph.D.**
Associate Professor of Chemical Engineering
Energy & Geoscience Institute

## Mechanical Stratigraphy for Hydraulic Stimulation

**Lans Taylor, Ph.D.**
Research Scientist
Energy & Geoscience Institute

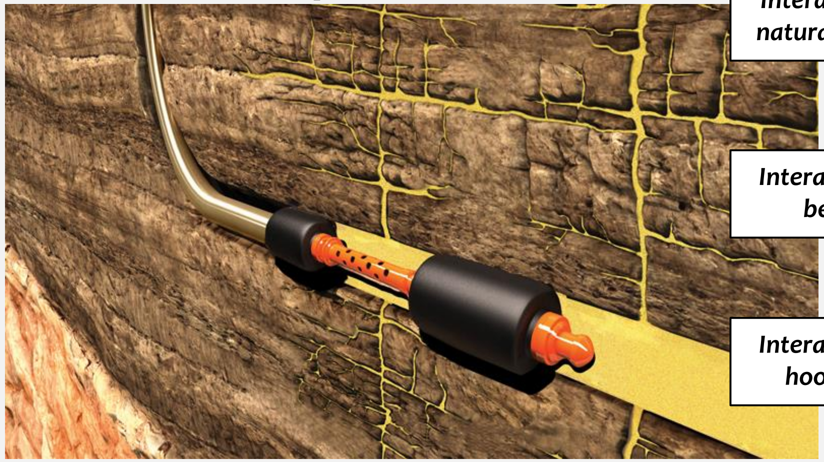
## Idealized Conception



*www.halliburton.com*

*Greater penetration, lower fracture density?*

## Plausible Complexity



***Interaction with natural fractures***

***Interaction with bedding***

***Interaction with hoop stress***

*www.drillingcontractor.org*

*Lower GRV, higher fracture density?*

*Does bedding plane slip explain diffuse zones of micro-seismicity during frac jobs?*

*Jim Rutledge, SLB Microseismic Services, "The Signature of Shearing Driven by Hydraulic Opening", HGS Mudrocks Conf. 2015*

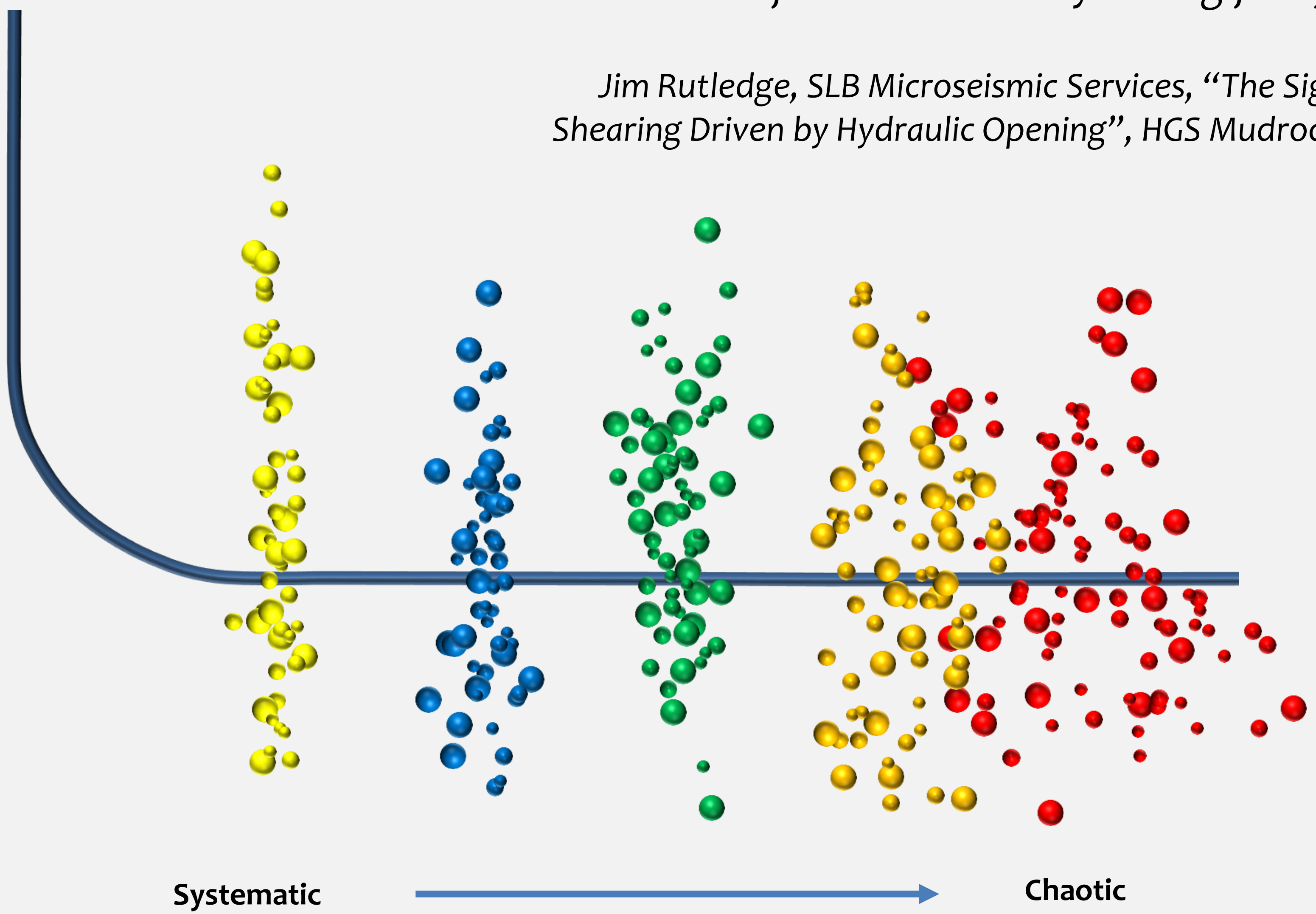
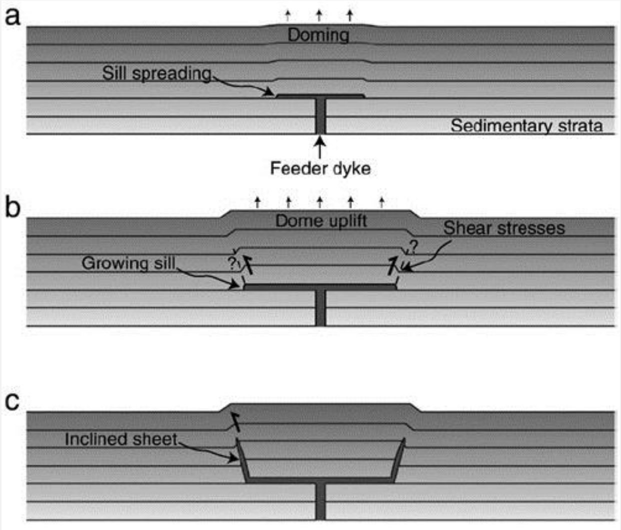
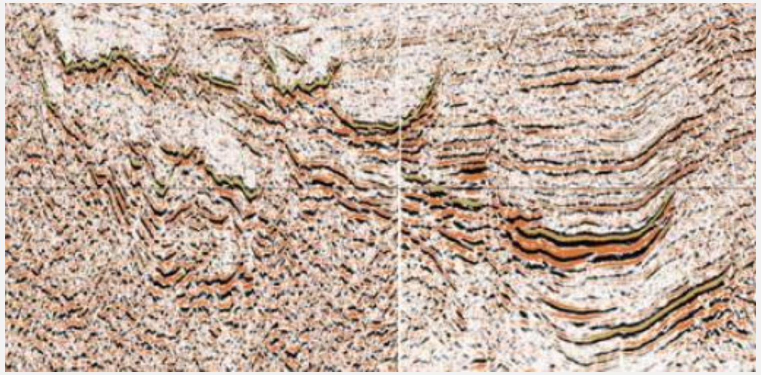
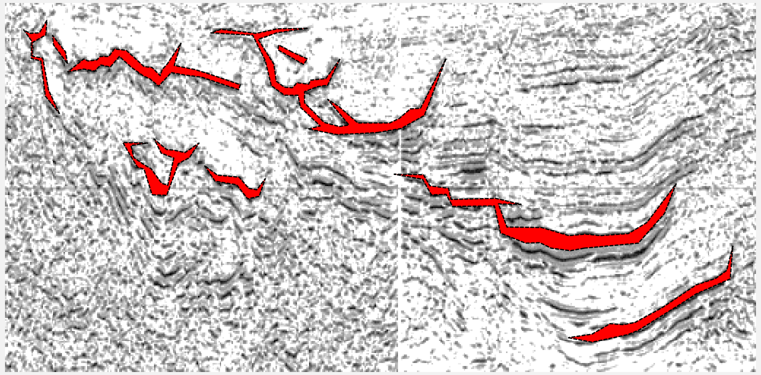


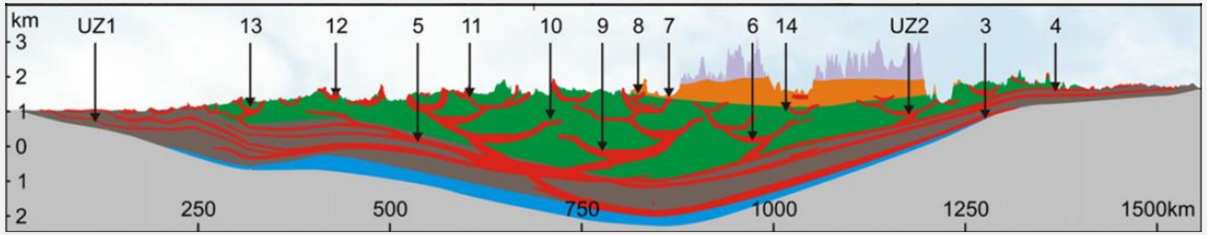
Photo: Alan Cooper, www.otago.ac.nz



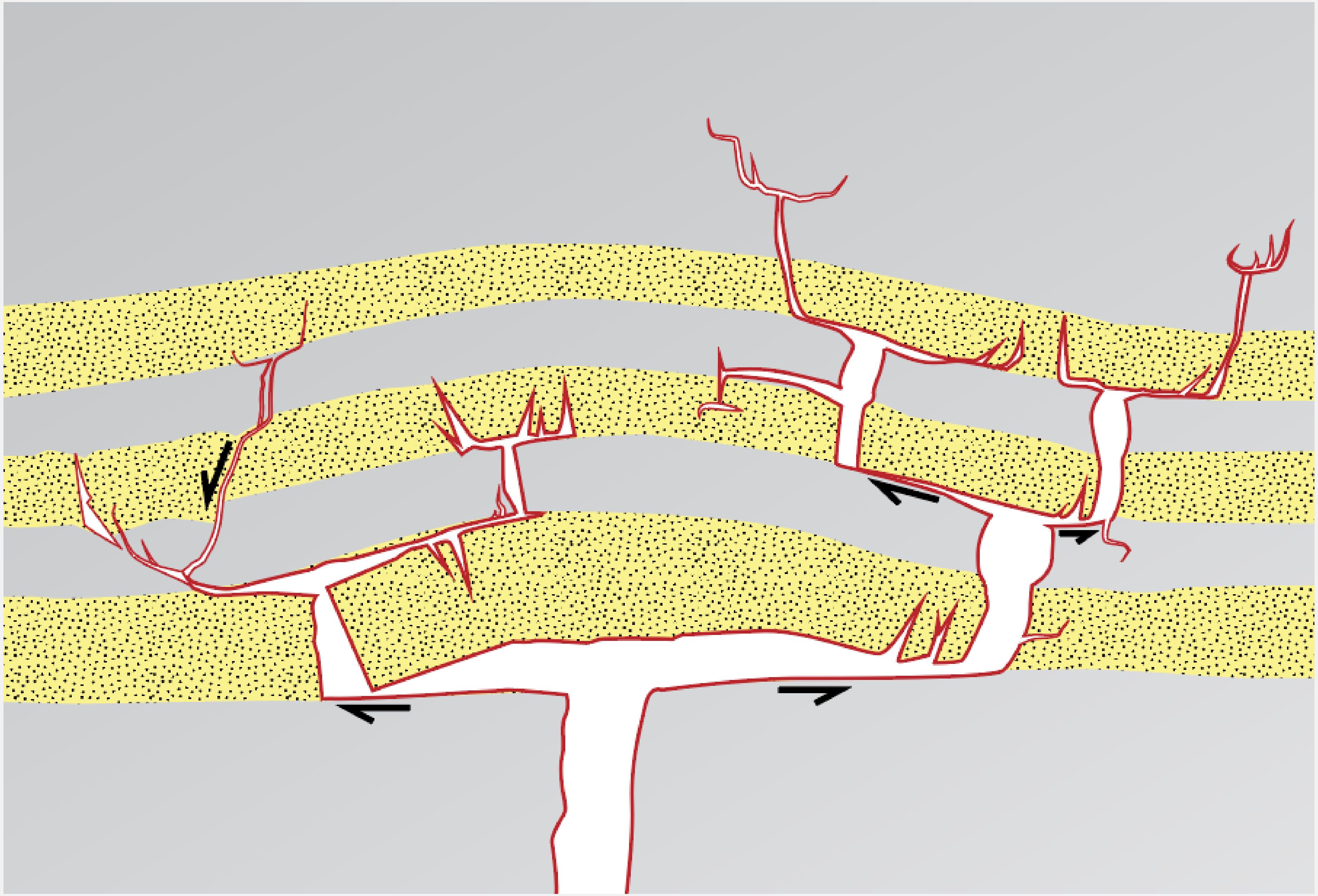





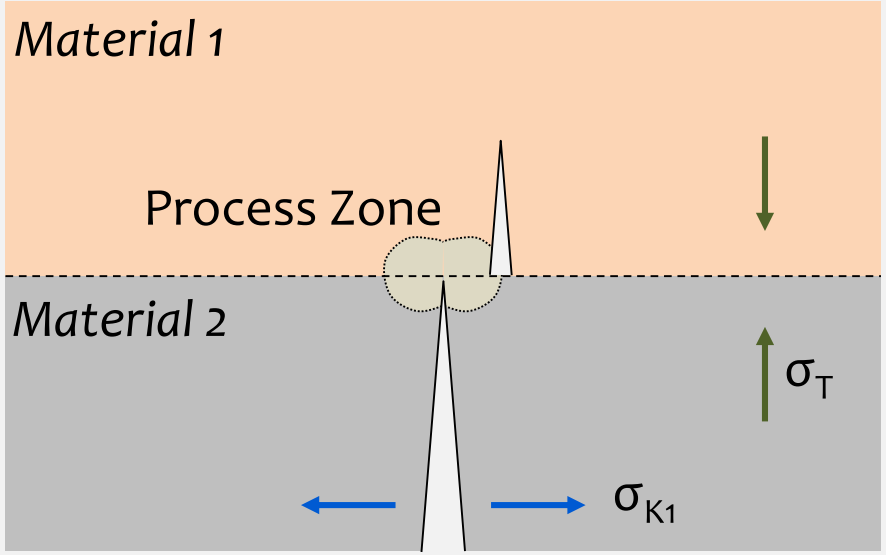
***North Sea***

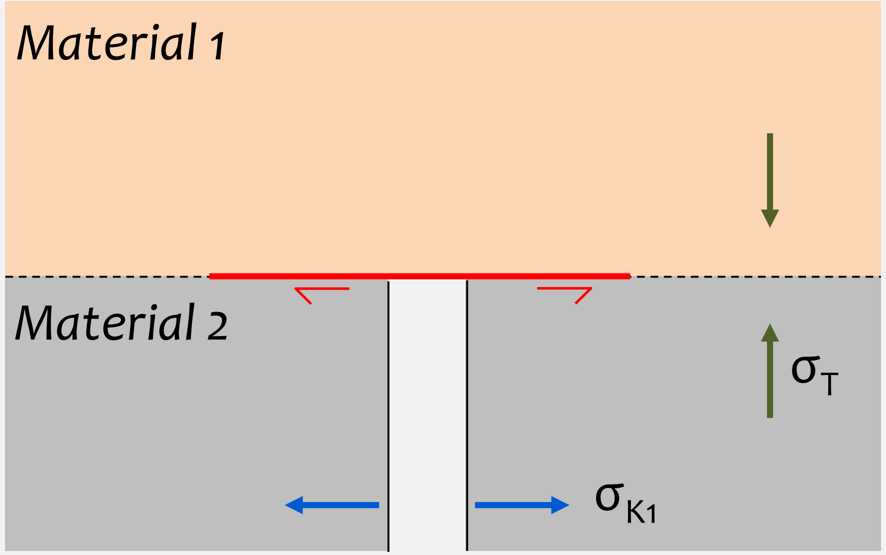



***Karoo, S. Africa***

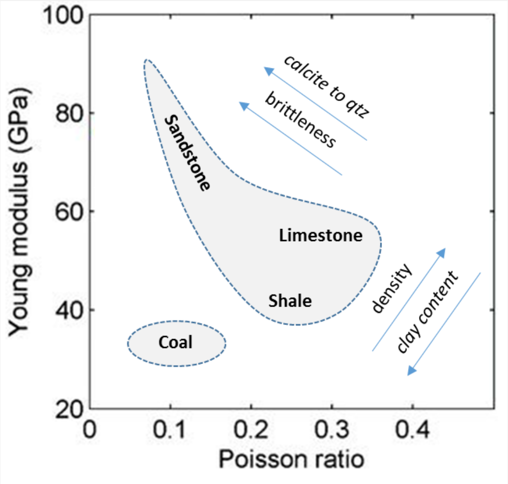


# Compressional Crossing

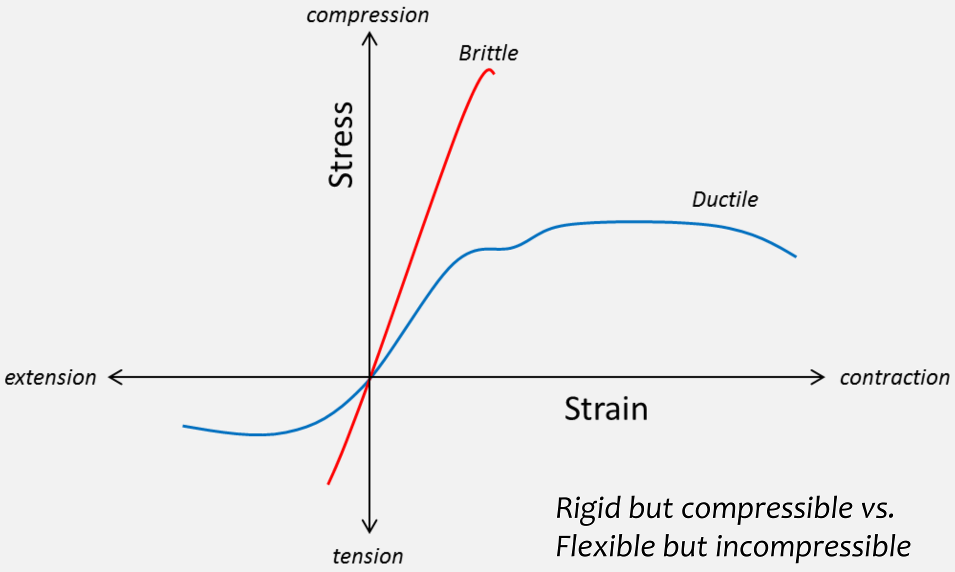


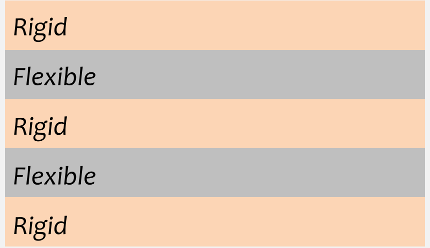

*Modified from Renshaw & Pollard, 1995*



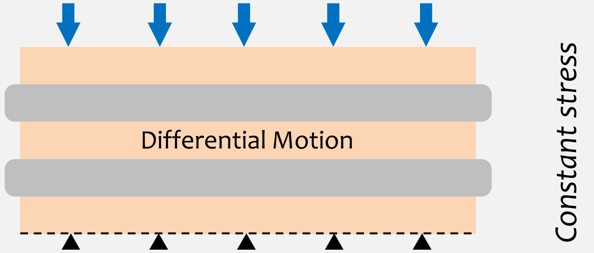

*as Poisson Ratio decreases, Young's Modulus increases*



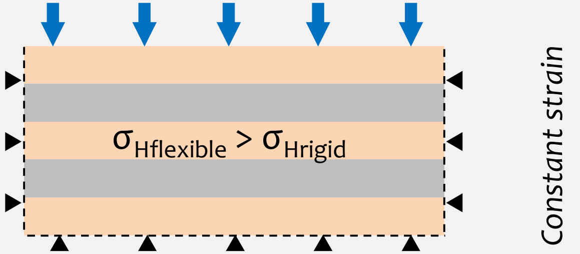

*Rigid but compressible vs. Flexible but incompressible*



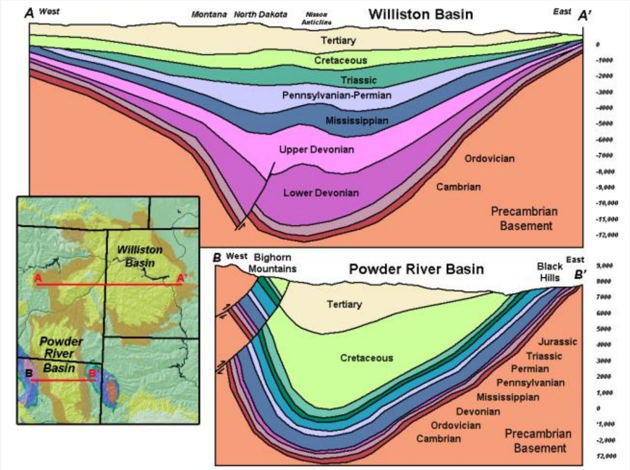

Initial condition

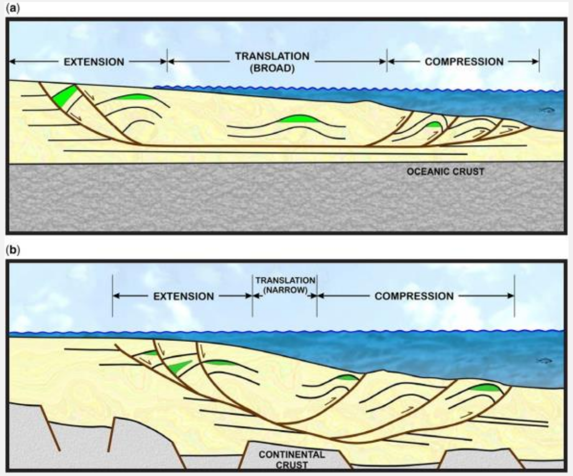



Vertical load unconfined

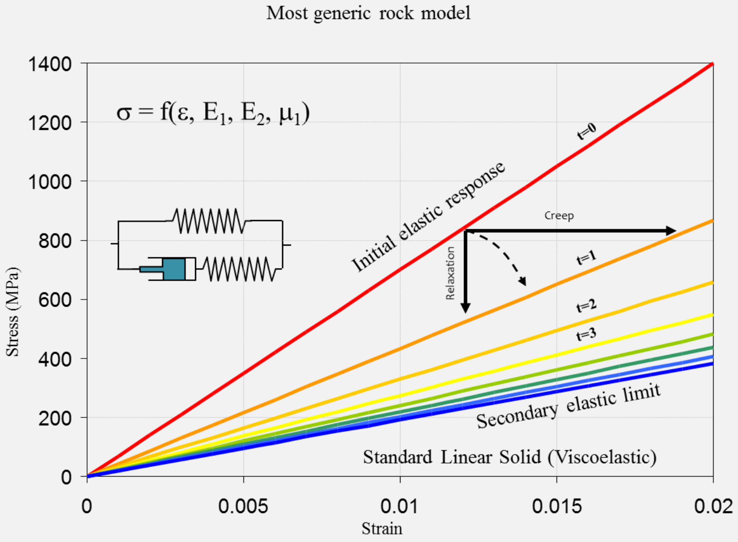



Vertical load lateral confinement



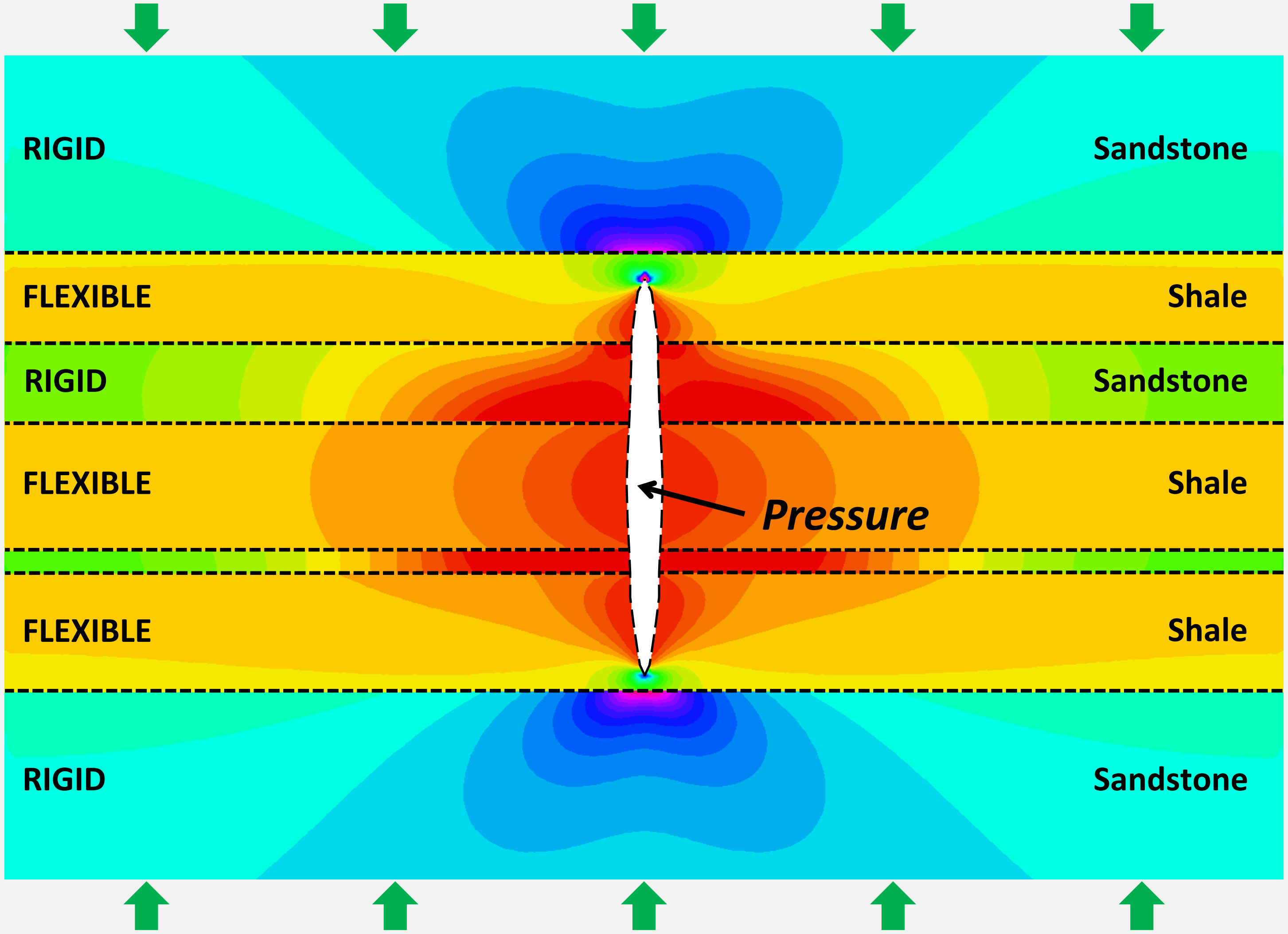




How is present day stress influenced by basin form and topography?




Does creep enhance stress heterogeneity?


Horizontal Stress Magnitude
Least
Compressive
Most
Compressive


RIGID
Sandstone
FLEXIBLE
Shale
RIGID
Sandstone
FLEXIBLE
Shale
Pressure
FLEXIBLE
Shale
RIGID
Sandstone

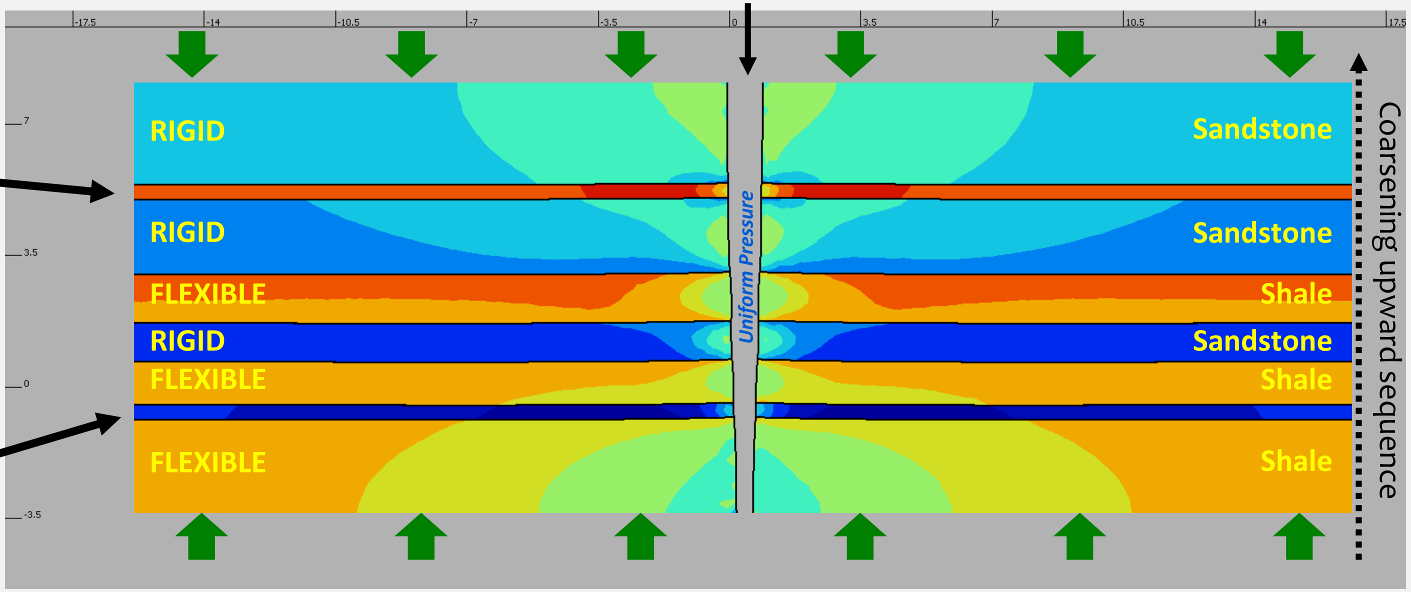
## Stratigraphic arrangement matters

Coarsening upward sequence

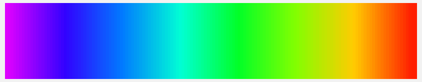
thin shale encased in sand

thin sand encased in shale

## Hydraulic Fracture



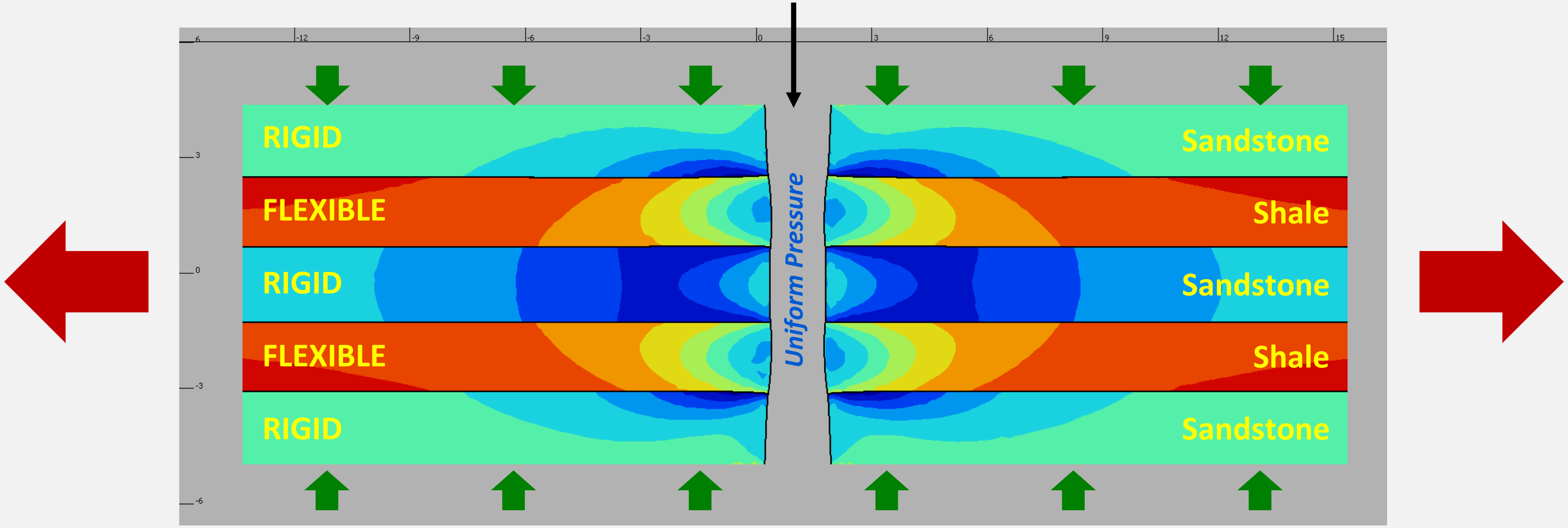

**Horizontal Stress Magnitude**



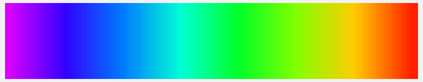
**Least Compressive**

**Most Compressive**

Hydraulic Fracture

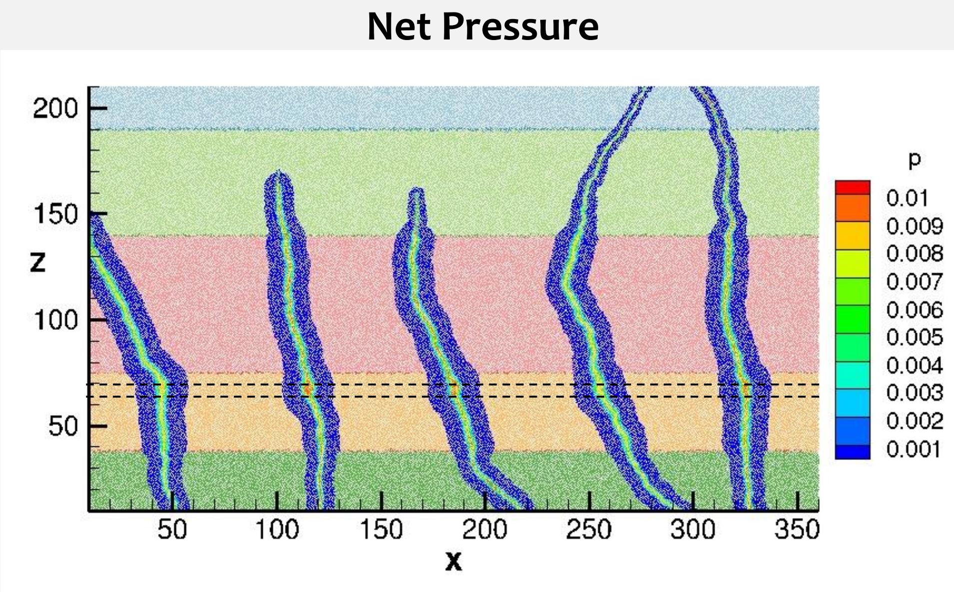


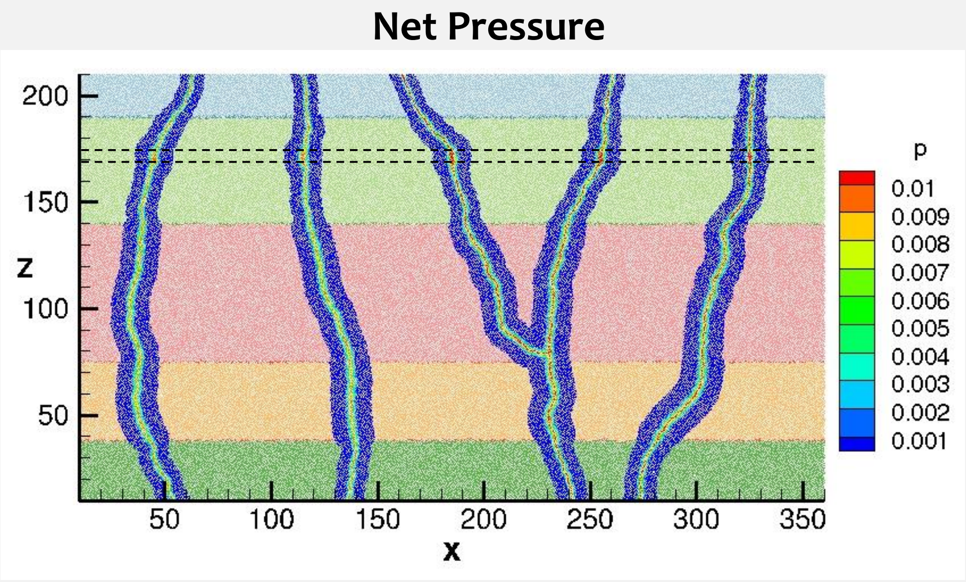

**Horizontal Stress Magnitude**



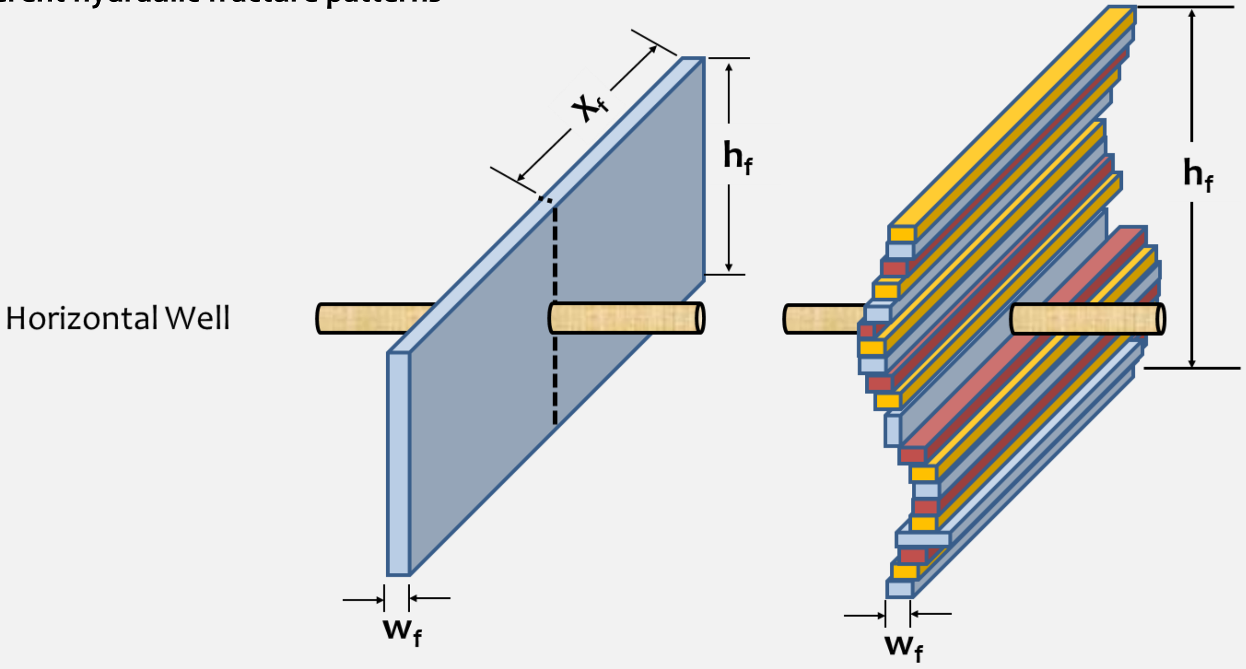
Least Compressive

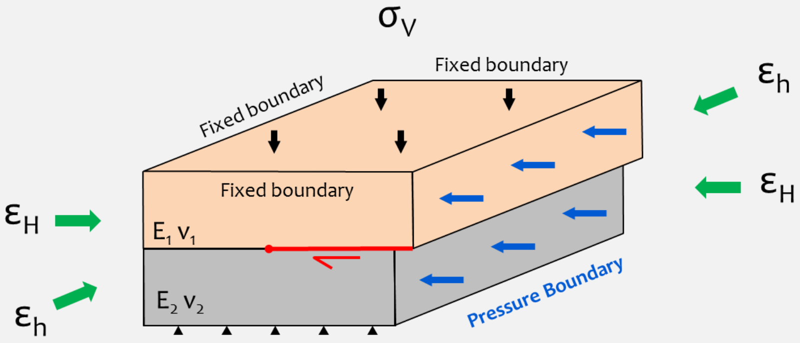
Most Compressive



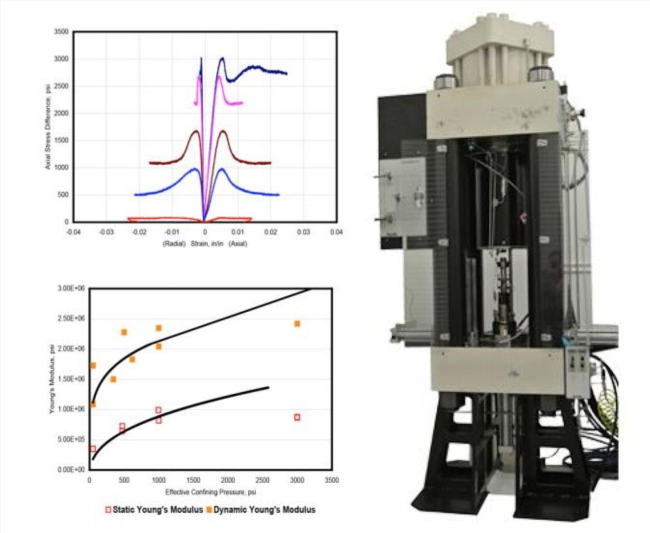




**Different placement of horizontal wells will lead to different hydraulic fracture patterns**

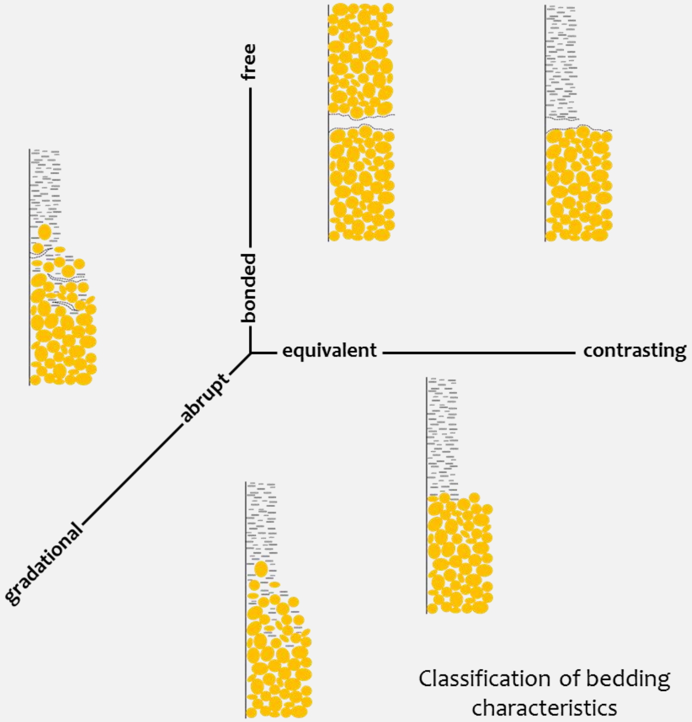





Finite Element

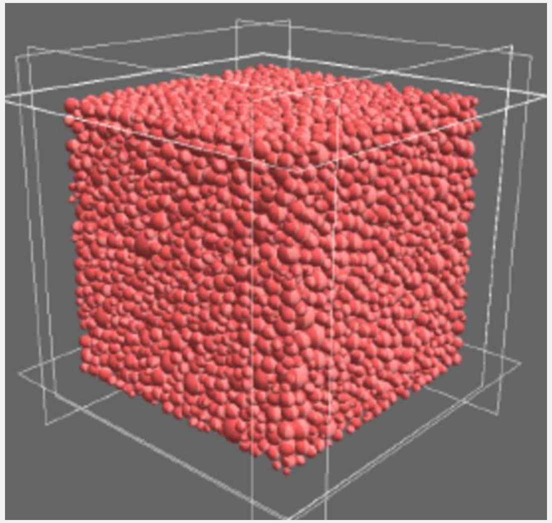



Direct measurement


Classification of bedding characteristics

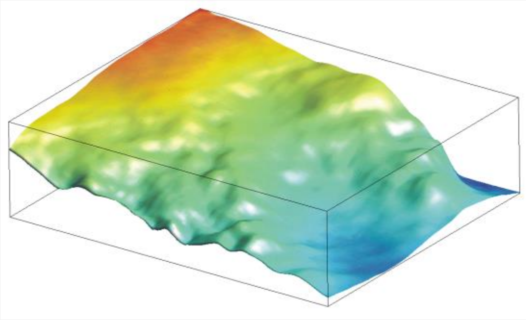
Behavior of gradational interfaces



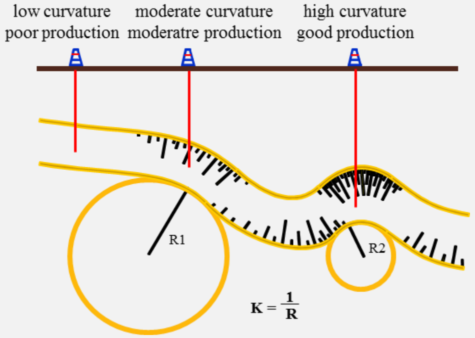
Discrete Element Models

# Curvature Analysis

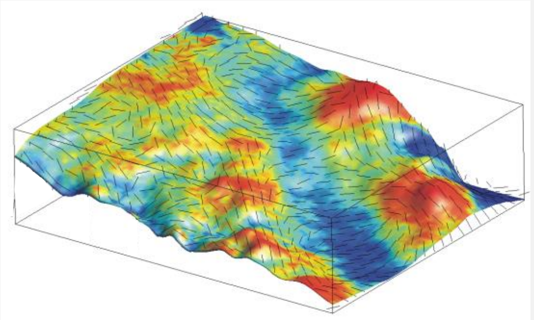
### 1) Input horizon

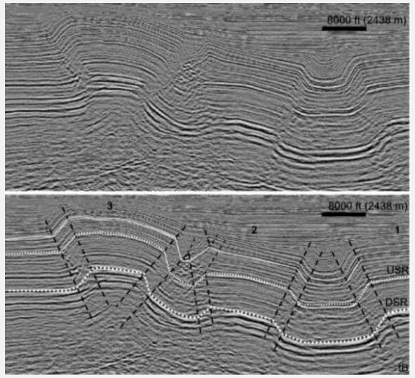


### 2) Bending model

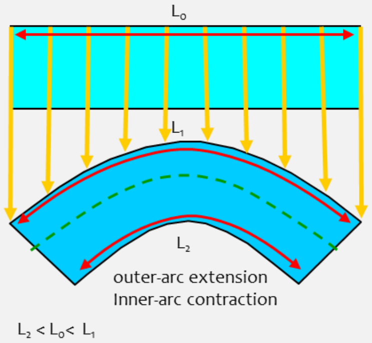



### 3) Stress prediction

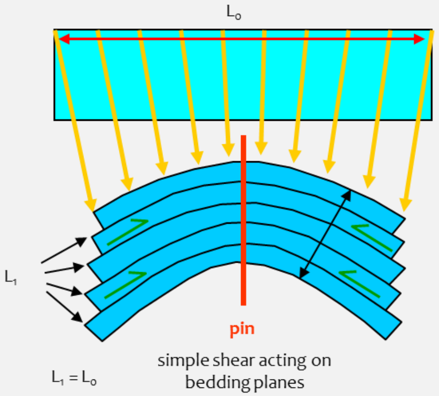


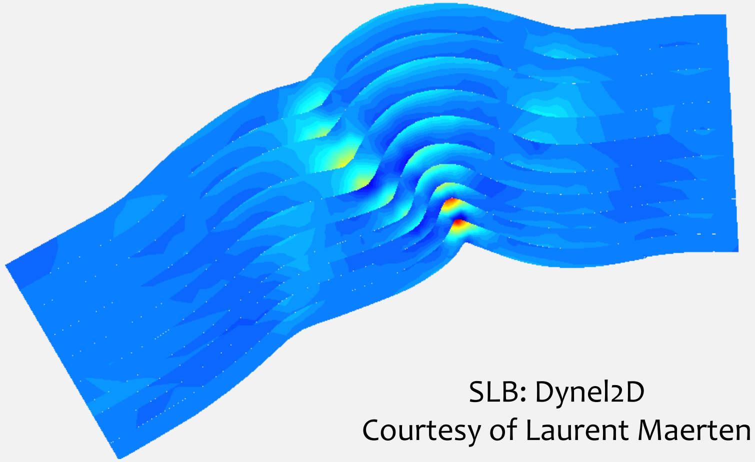


### Plate bending



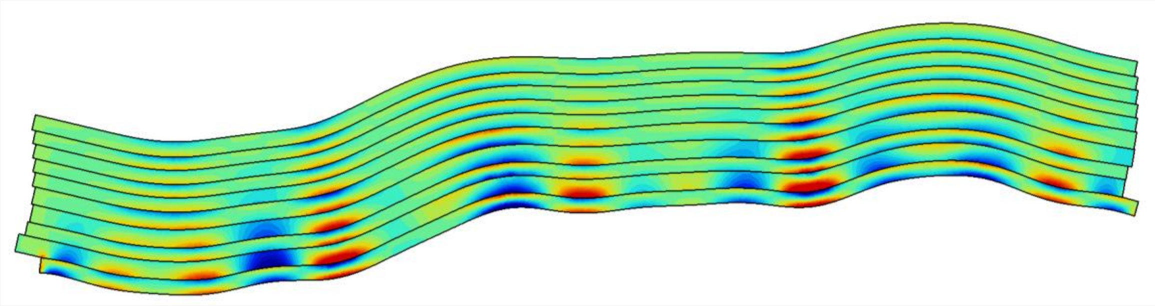

### Flexural slip

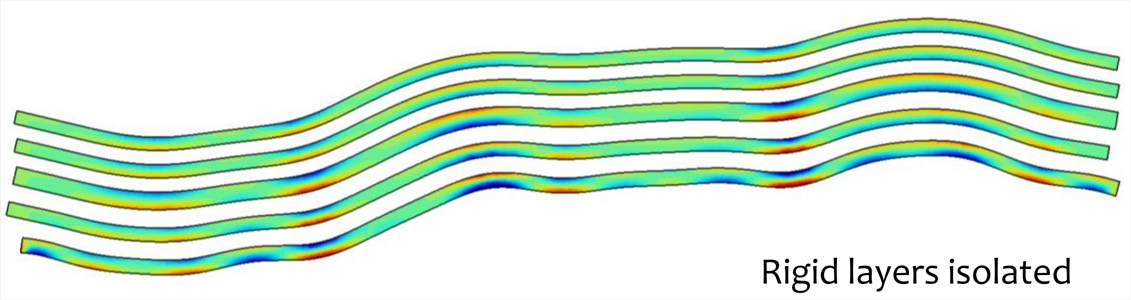


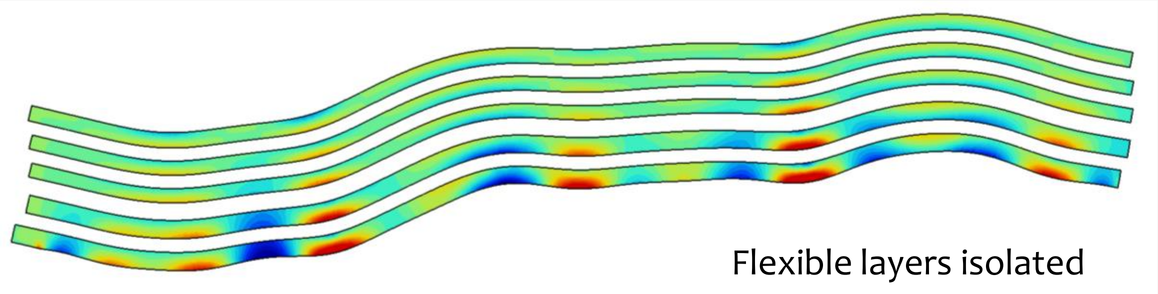



SLB: Dynel2D
Courtesy of Laurent Maerten

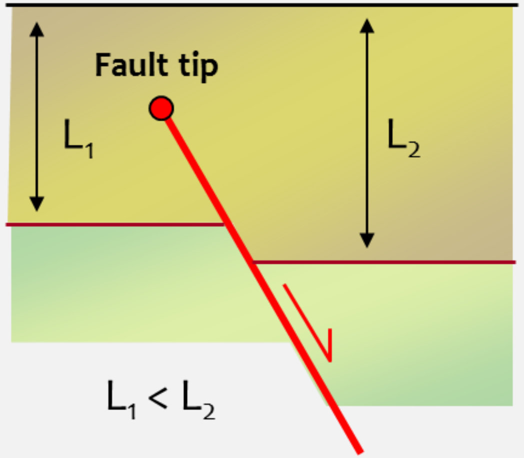
# Curvature for Unconventional Targets

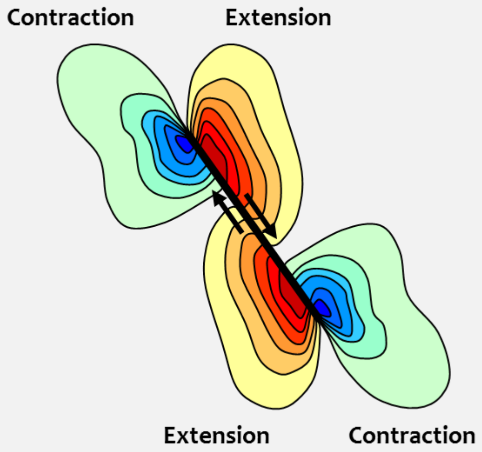



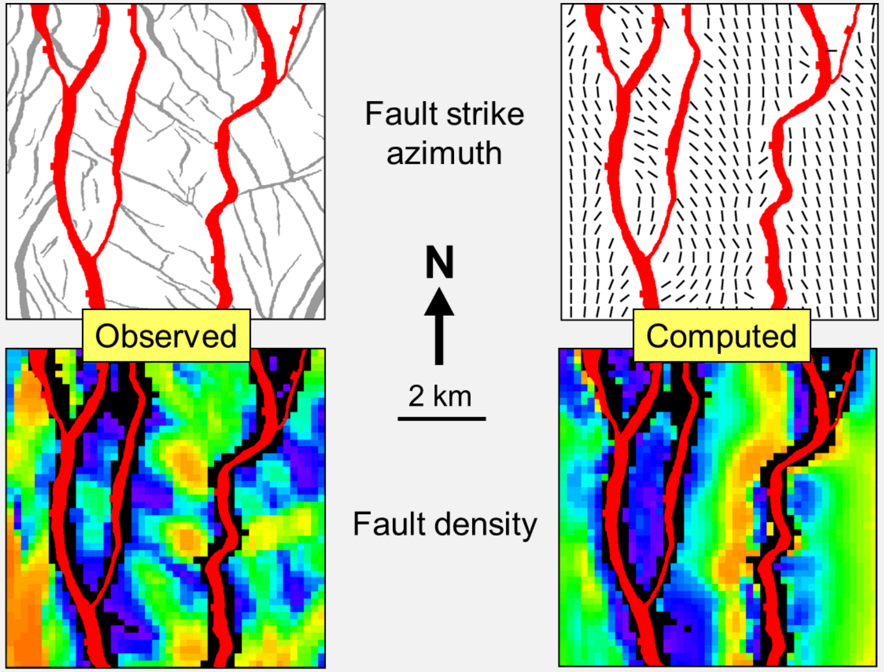


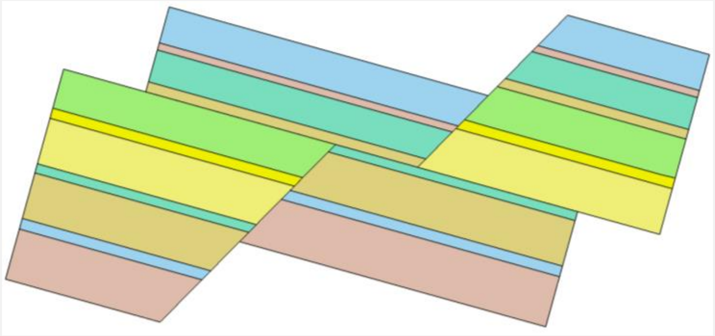
# Dislocation Analylsis



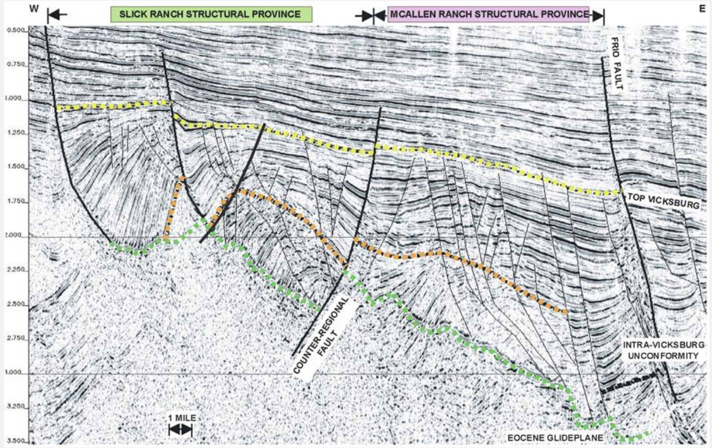



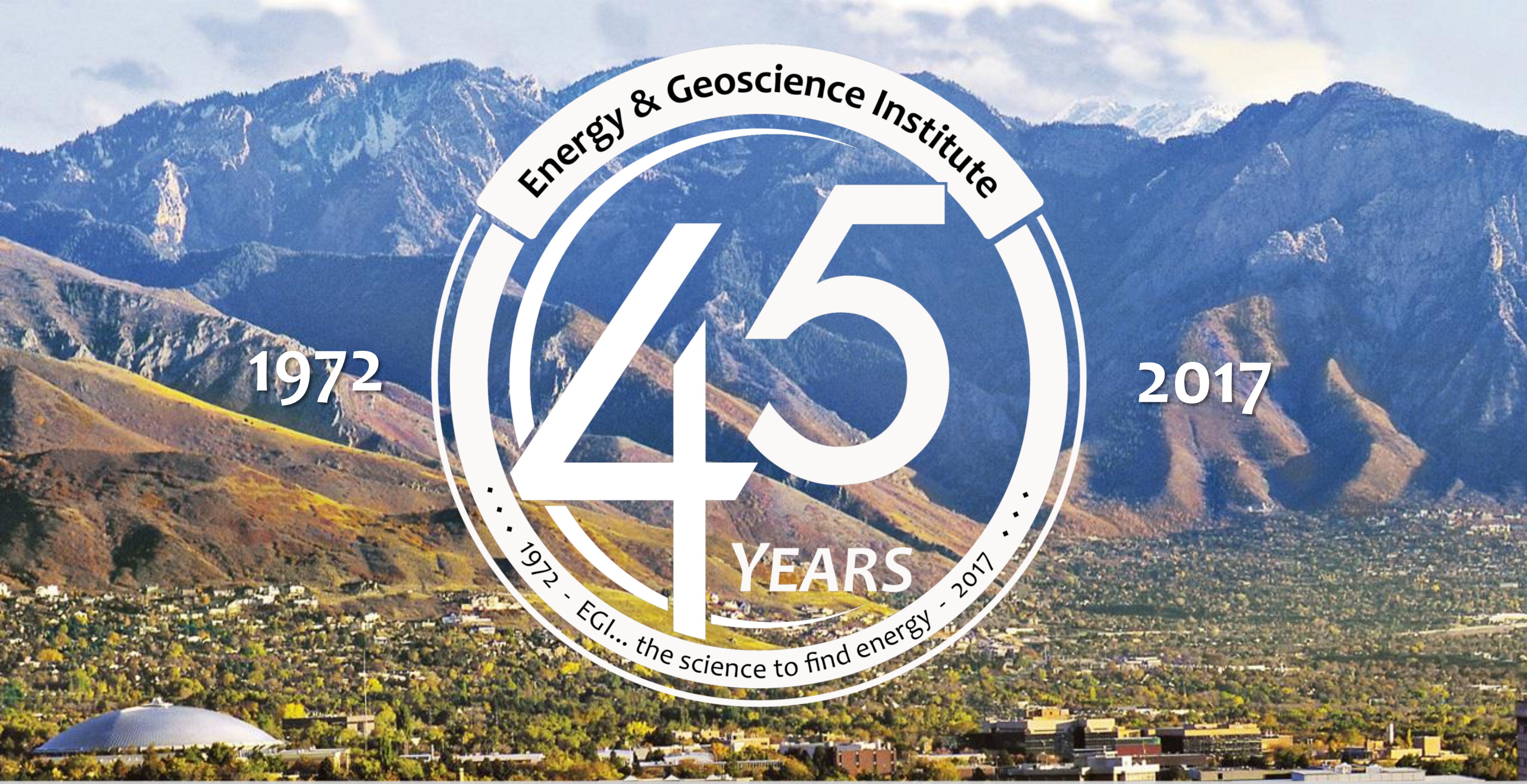

(Maerten, et al., AAPG Bull, 2006)



Fault Locking




Regional / Counter-regional Faulting

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