Hydraulic Fracturing Complexity: Interaction between Hydraulic and Natural Fractures*

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Abstract

The industry is beginning to use hydraulic fracturing simulations that consider the presence of subsidiary natural fractures or similar discontinuities, and in-situ stresses. The most sophisticated of these models are coupled thermo-hydro-mechanical formulations, where the deformation of natural fractures is contingent on material properties of natural fractures, local pressure and the far-field stresses.

These models provide insight into the complexity of the network of created, reopened and reactivated discontinuities that comprise the productive domain – that is often casually referred to as the stimulated reservoir volume. Progress is being made, industry-wide, in understanding the fracture complexity in different geologic domains – for example, geometric characteristics in a passive-margin setting can differ substantially from behavior in a strike-slip domain. Examples are provided, suggesting different geologically controlled morphologies resulting from the active interaction between the injected fluids, the pre-existing far-field stresses, and existing discontinuities –faults, fractures and bedding planes – and the consequences for microseismic activity.

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Hydraulic Fracture Complexity: Interaction Between Hydraulic and Natural Fractures

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Dan Potocki, EnCana Corporation, Calgary
July 16, 2013

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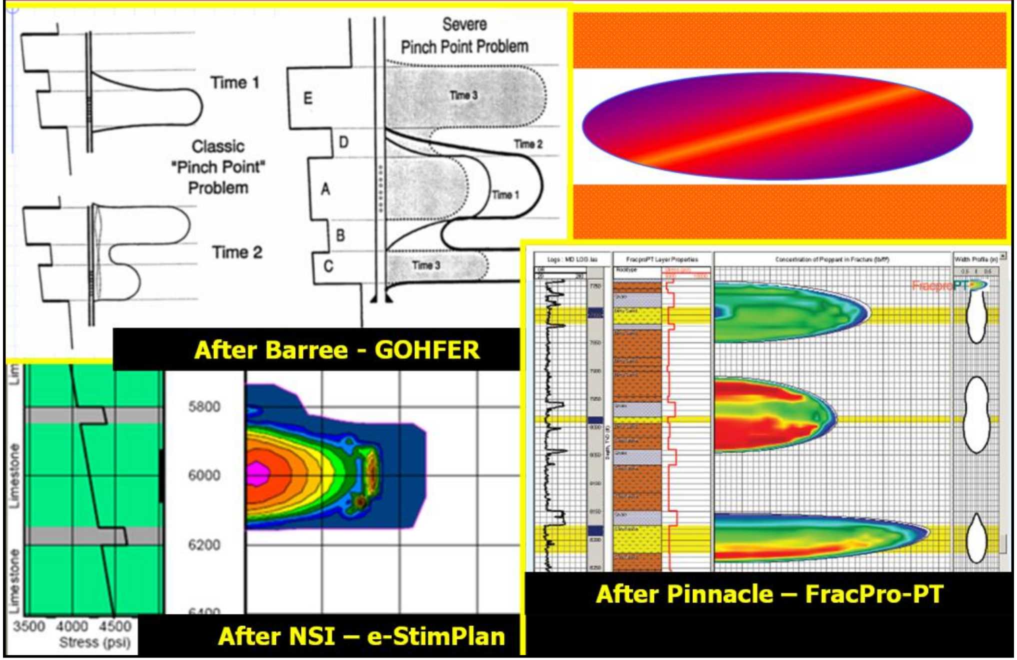
Numerous publications in the literature including:

- Abou-Sayed, Early 80s
- Murphy and Fehler, SPE 14088, 1986
- Warpinski and Teufel, 1987
- Shlyapobersky and Chudnovsky, USRM, 1992
- Mahrer et al., SPE 36441, 1996
- Barree, SPE 39932, 1998
- Cipolla et al., SPE 115771, 2008
- Meng and de Pater, SPE 140429, 2011
- Wu and Olson, SPE 163821, 2013
- And So On

How Have We Modeled Fracturing?

- Analytical, constant height, fracture mechanics relationships were formulated in the 1950s
- Coupled with one-dimensional fluid loss in the 1950s and 1960s
- Modified to approximate vertical, planar growth – the so-called pseudo-three-dimensional models (1980s, 1990s and onwards)
- Planar, three-dimensional models with rigorous mathematical basis were developed (1980s onwards)
- Modifications made to simulate fluid loss in more than one dimension, to provide more sophisticated coupling with the reservoir, and to at least conceptually consider out-of-plane events

For Many Situations These Fracturing Simulators Are Adequate



So, Why Are We Not Satisfied?

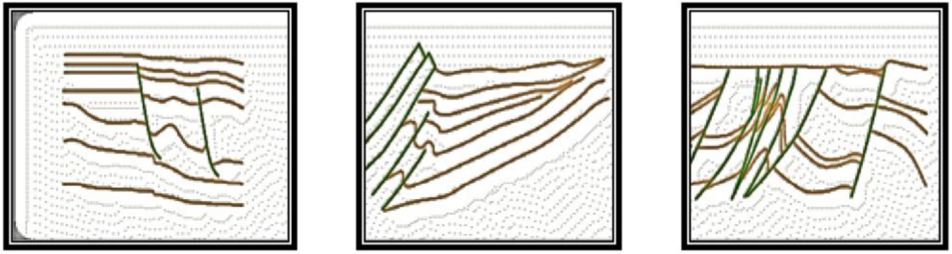
- Naturally fractured reservoirs
- Refracturing situations
- Where the stress field is relatively isotropic
- More sophisticated modeling may be valuable, particularly on a field-scale, overview basis – to minimize the inevitable learning curve.
- **Newer simulation techniques are evolving that may ultimately help to refine our appreciation of fracture complexity**

Variations In Fabric

Hypothesis 1 –
Key to Future Modeling is Discontinuities

- **Using Current Stimulation Technology Production (As Represented by NPV) Productivity Decreases With Increasing Tectonic Complexity**

Increasing Complexity --- Tectonic Regime and In-Situ Stresses

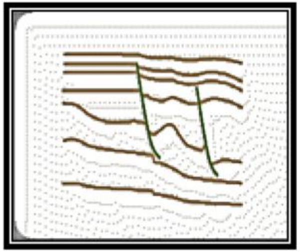


After Potocki, 2012, SPE 162814

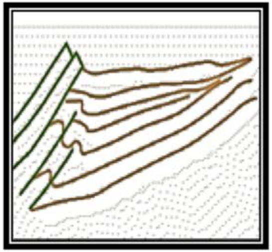
Hypothesis 2

- Tectonic setting is interpreted as a first-order control on fracture complexity
- Increasingly complex tectonic and burial histories elevate stresses and create tectonic fractures that promote increasingly complicated interactions between induced hydraulic fractures and intrinsic rock fractures
- Promotes natural discontinuities

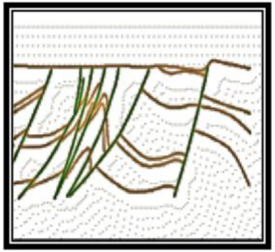
Basis of Hypothesis - Drilling



Passive Margin
Gulf Coast
Haynesville, Bossier



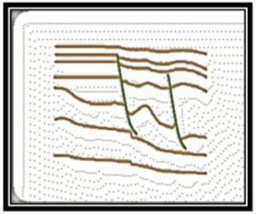
Foreland
Cretaceous Sandstone
Montney, Horn River



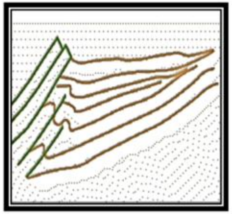
Strike Slip/Thrust

- **Drilling Effectiveness:**
  - **Wellbore Stability, Steering (porpoising)**
- **Predictability:**
  - **Stress Estimation, Compartmentalization**

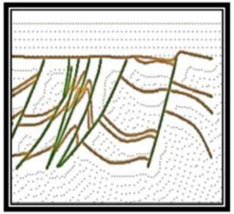
Basis of Hypothesis - Effective Stimulation



Passive Margin
Gulf Coast
Haynesville, Bossier



Foreland
Cretaceous Sandstone
Montney, Horn River



Strike Slip/Thrust

- Ease of Initiation and Execution
- Repeatability
- Interaction with Natural Features
- Lateral Spread of Stimulation
- Connectivity and Effective Aperture
- Relative Permeability

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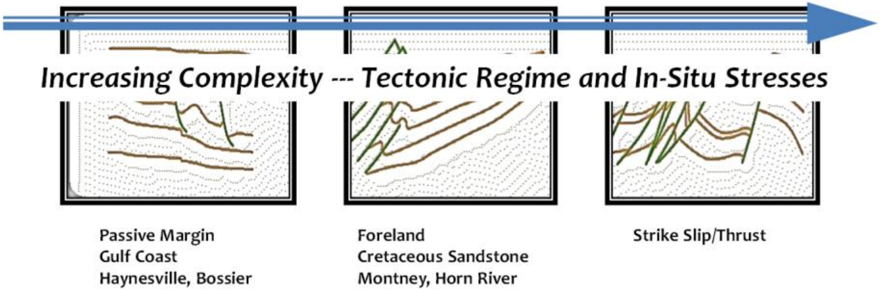
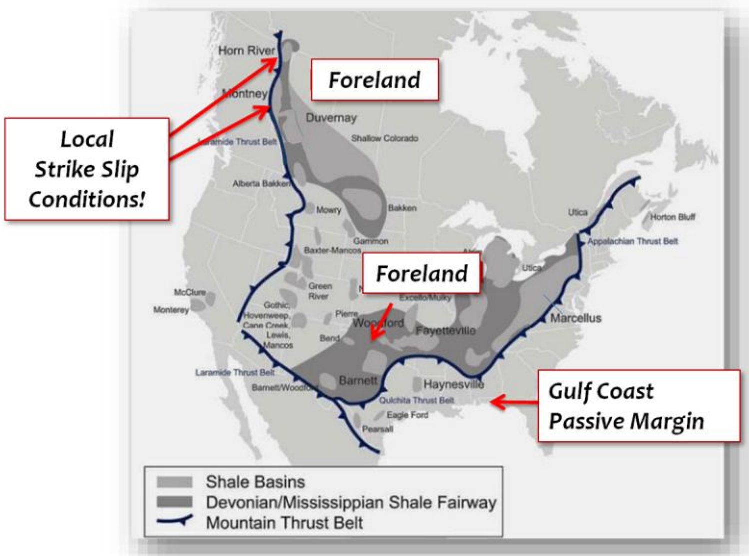
Basis of Hypothesis ....

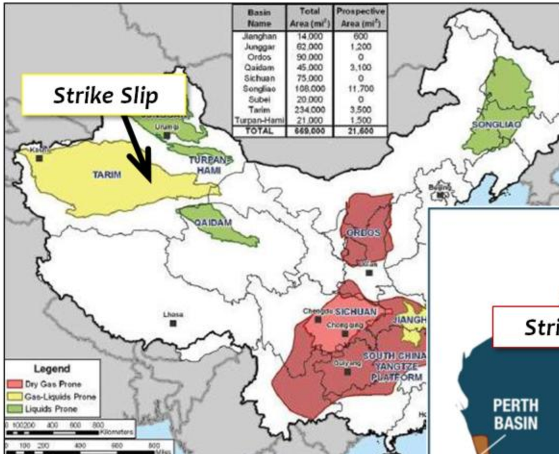


- **Geohazards:**
  - **Casing Deformation and Induced Seismicity**
- **Time and Associated Costs**
  - **Well Construction and Stimulation**

Tectonic Setting of North American Shale Plays

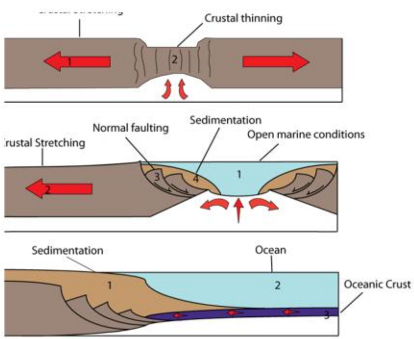


Tectonic Setting of International Shale Plays

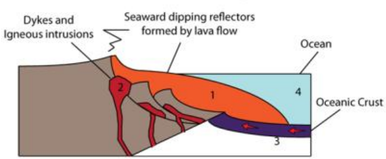


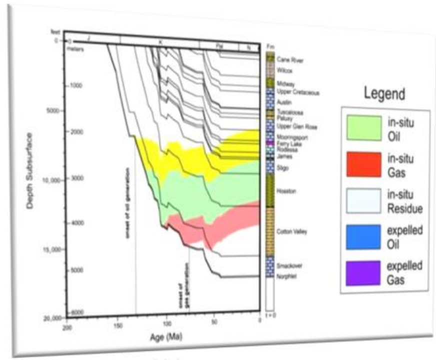
Basin Name	Total Area (mi²)	Prospective Area (mi²)
Jianghan	14,000	600
Junggar	62,000	1,200
Ordos	90,000	0
Qaidam	45,000	3,100
Sichuan	75,000	0
Songliao	108,000	11,700
Subei	20,000	0
Tarim	234,000	3,500
Turpan-Hami	21,000	1,500
TOTAL	669,000	21,600

Burial History – Passive Margin



Volcanic Passive margin

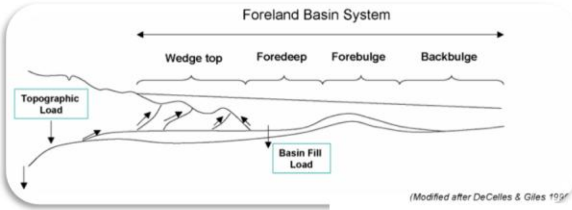




Smackover Formation where present day depths are maximum burial depths, Barnaby 2006

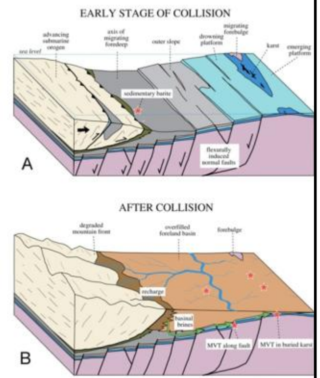
WHAT ARE STIMULATION IMPLICATIONS?
-Low Complexity – Monodirectional?

More Complex Burial History – Foreland Basin



DeCelles and Giles, 1996

- Elongate, relatively unstructured asymmetric sediment-filled troughs
- Bounded on deeper side by a mountain belt
- Buried sediments in proximity to mountains locally contain folds and faults (normal, strike-slip and thrust)
- Rocks may exhibit increased tectonic fracture complexity and remnant higher stress remaining from the active tectonics that formed mountains.



From Economic Geology

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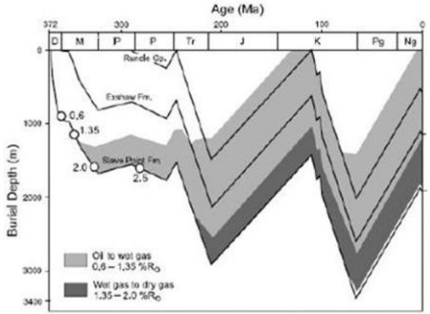
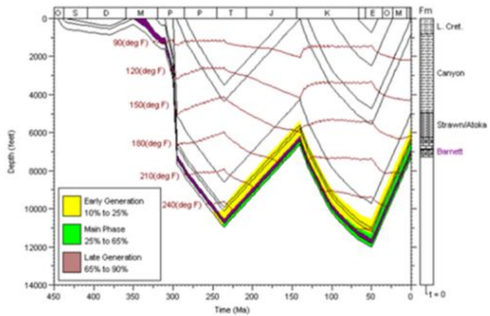
Presenter's notes: A foreland basin is a structural basin that develops adjacent and parallel to a mountain belt. Foreland basins form because the immense mass created by crustal thickening associated with the evolution of a mountain belt causes the lithosphere to bend, by a process known as lithospheric flexure. The width and depth of the foreland basin is determined by the flexural rigidity of the underlying lithosphere and the characteristics of the mountain belt. The foreland basin receives sediment that is eroded off the adjacent mountain belt, filling with thick sedimentary successions that thin away from the mountain belt. Foreland basins represent an end-member basin type, the other being rift basins. Space for sediments, accommodation space, is provided by loading and down-flexure to form foreland basins, in contrast to rift basins, where accommodation space is generated by lithospheric extension.

More Complex Burial History – Foreland Basin



Horn River Equivalent: Slave Point Formation immediately south of Horn River basin (Lonnee and Machel, 2006)

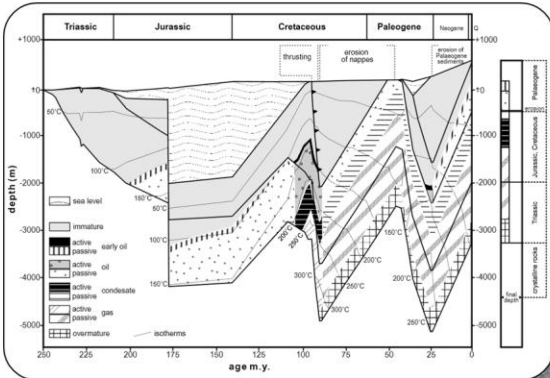


Barnett *(Jarvie et al., 2004)*

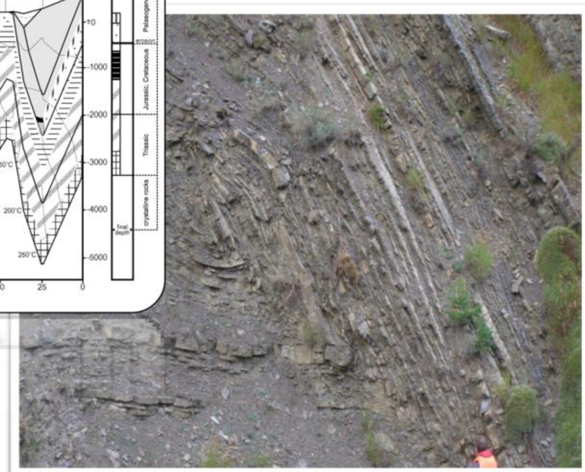
WHAT ARE STIMULATION IMPLICATIONS?

-Existing and maybe infilled fractures

Even More Complex Burial History – Some Strike Slip/Thrust Settings



Central Carpathian Paleogene Basin (Sotak et al., 2001)

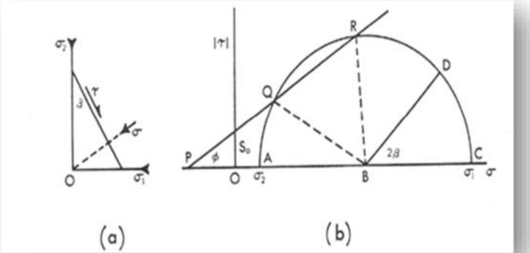


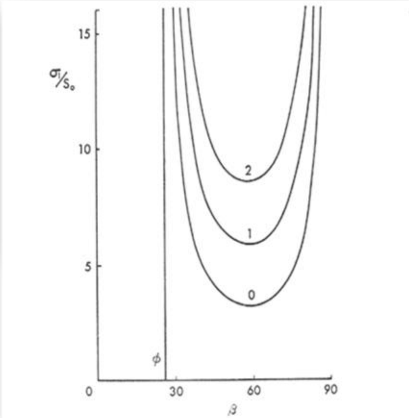
WHAT ARE STIMULATION IMPLICATIONS?

-Substantial Complexity and Shearing

Ineffective Conductivity

Preferred Angles

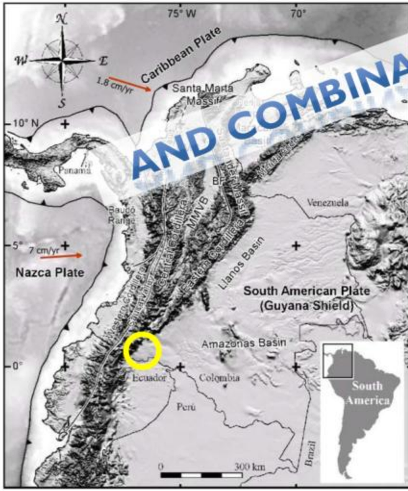


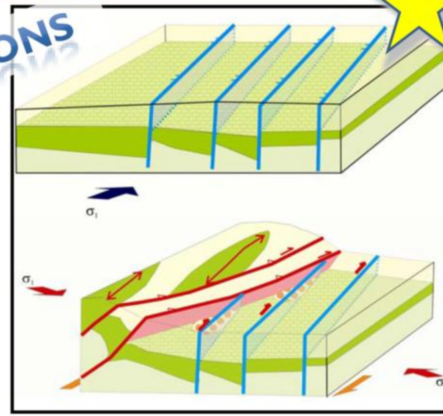


- Cohesion – How to Measure/Infer
- Angle of Friction - How to Measure/Infer
- Shear strength - How to Measure/Infer
- Orientation - Window
- Roughness – How to Measure?
- Stress Field – Three-Dimensional
- Bedding-Plane Parting

$$2\beta_1 = \pi + \phi - \sin^{-1}\{[(\sigma_m + S_0 \cot\phi)/\tau_m] \sin\phi\},$$
$$2\beta_2 = \phi + \sin^{-1}\{[(\sigma_m + S_0 \cot\phi)/\tau_m] \sin\phi\}.$$

Putumayo Basin, Columbia





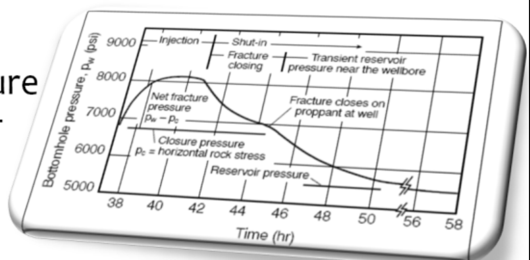
Evolution and inversion of pre-Eocene extensional faulting (top) and post-Eocene transpressional faulting (bottom showing maximum stress fields

Rossello, E.A., Salvay, R.O., Nevistic, V.A., and Araque, L. Microtentonic Evaluation of the Vileta Formation Carbonate Cores (Putumayo Basin, Columbia): Its Potential As Fractured Reservoir

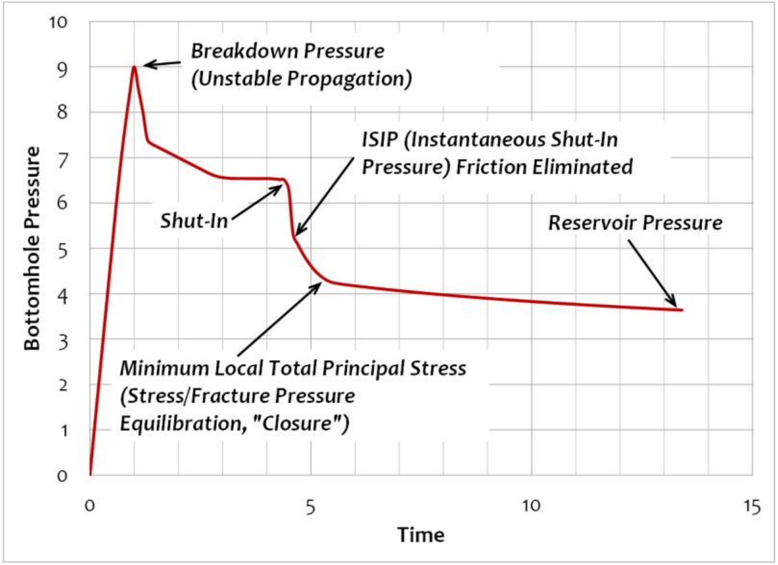
Bottomhole Fracturing Pressure Signatures

1. Minimum Local Normal Stress PLUS
2. Pressure Drop near the Wellbore (perforations and tortuosity) PLUS
3. Frictional Pressure Drop Along the Fracture PLUS
4. Resistance to Propagation – Rate Independent – Preserved Immediately after Shut-In – Reflection of the Energy Dissipated During Fracturing
5. Single Fracture, Interaction with Fabric

NFP - difference between instantaneous shut-in pressure (ISIP) and closure pressure – interpreted as indicator of far-field complexity

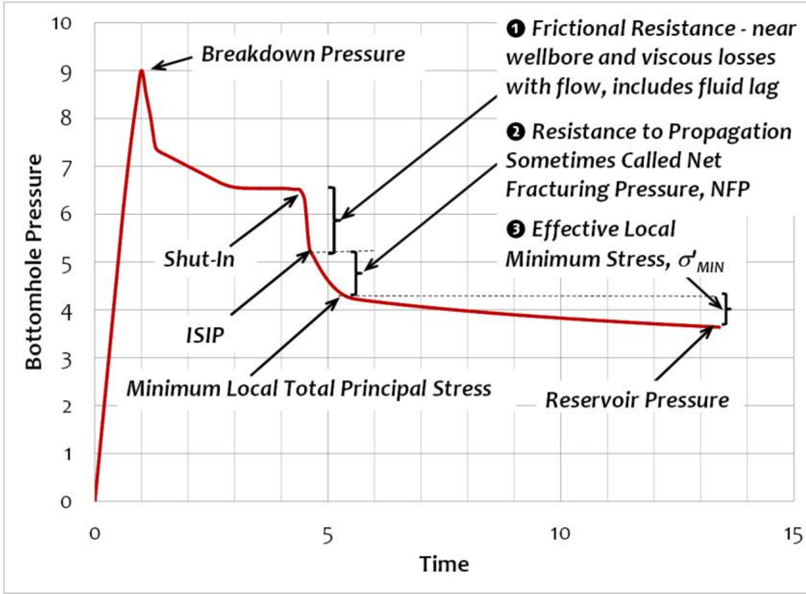


Diagnosis



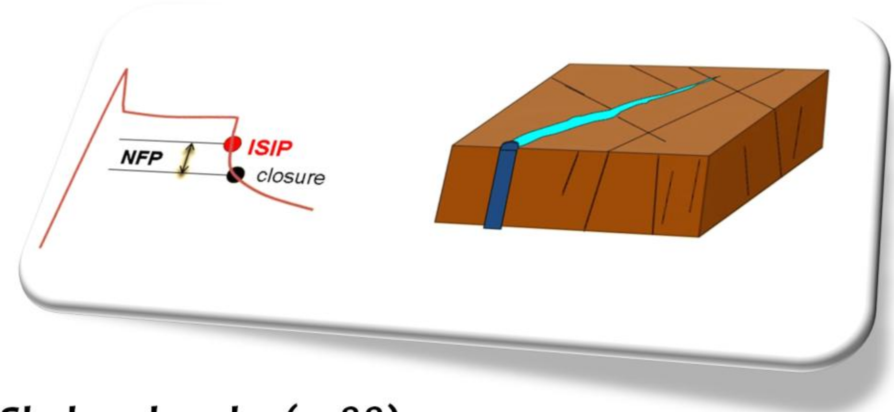
Bottomhole Pressure
Time
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
Breakdown Pressure
(Unstable Propagation)
ISIP (Instantaneous Shut-In
Pressure) Friction Eliminated
Shut-In
Reservoir Pressure
Minimum Local Total Principal Stress
(Stress/Fracture Pressure
Equilibration, "Closure")

Diagnosis



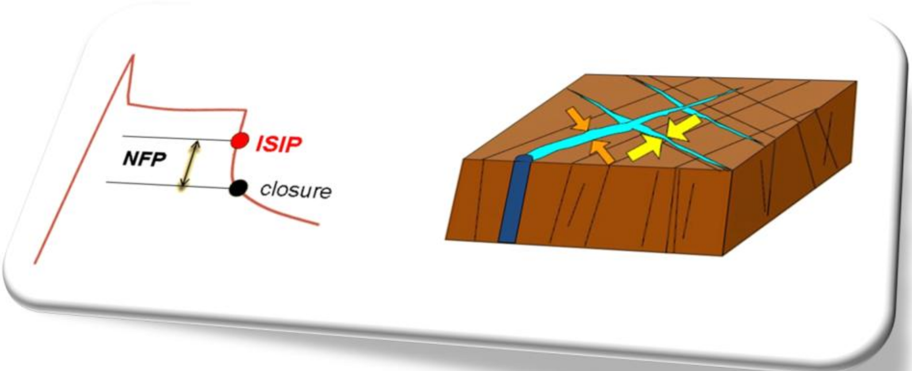
Bottomhole Pressure
Time
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
Breakdown Pressure
Shut-In
ISIP
Minimum Local Total Principal Stress
Reservoir Pressure
❶ Frictional Resistance - near wellbore and viscous losses with flow, includes fluid lag
❷ Resistance to Propagation Sometimes Called Net Fracturing Pressure, NFP
❸ Effective Local Minimum Stress, σ'_{MIN}

Speculation 1
Resistance to Propagation



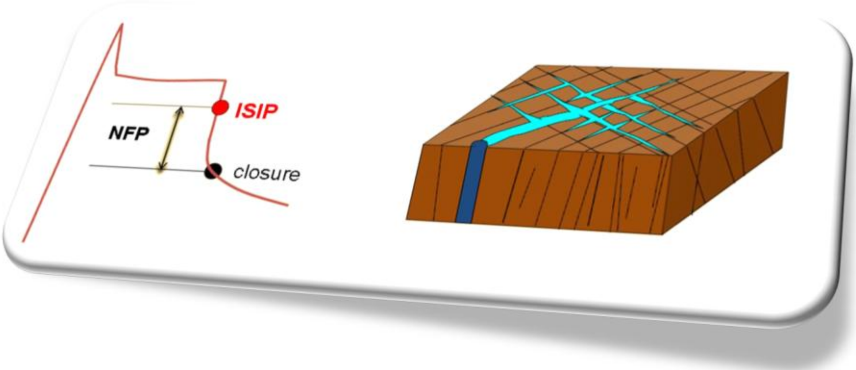
Shylapobersky (1988)

Slightly More Complexity

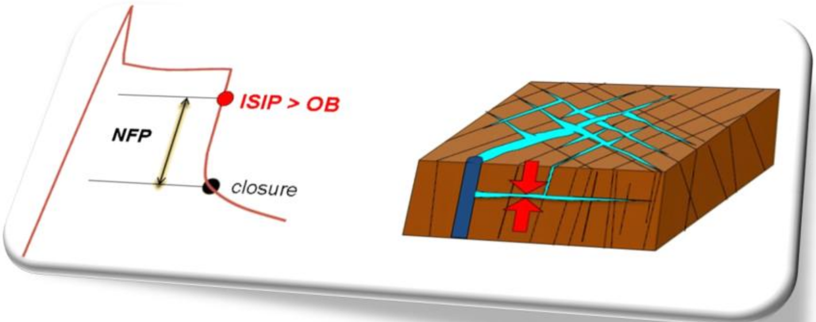


Process Zone Stress

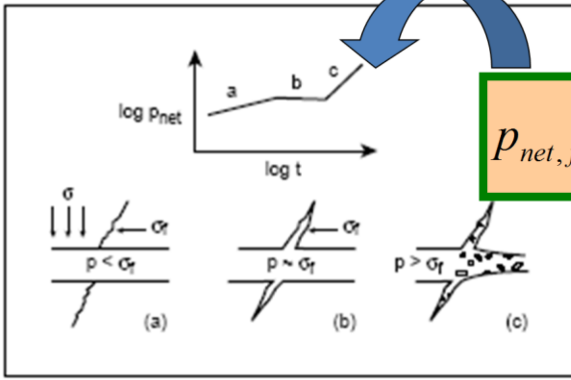
More Complexity



Horizontal Components



What We Don’t Always Consider



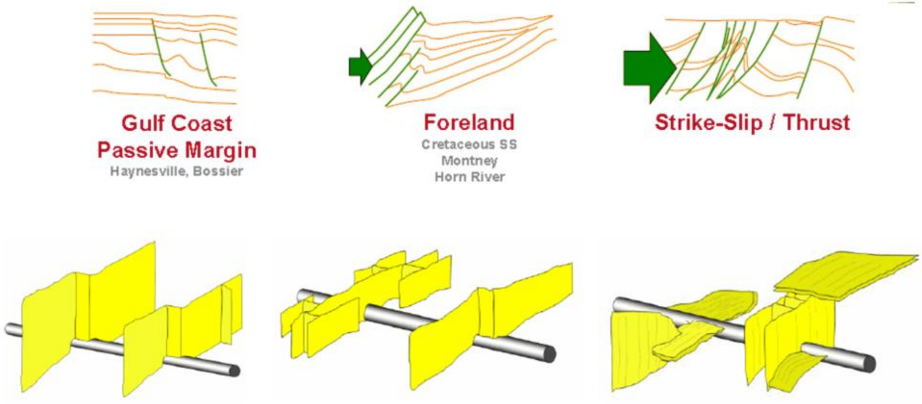
$$p_{net,fo} = \frac{\sigma_V \, or - \sigma_{HMIN}}{1-2\nu}$$

INTERFACES

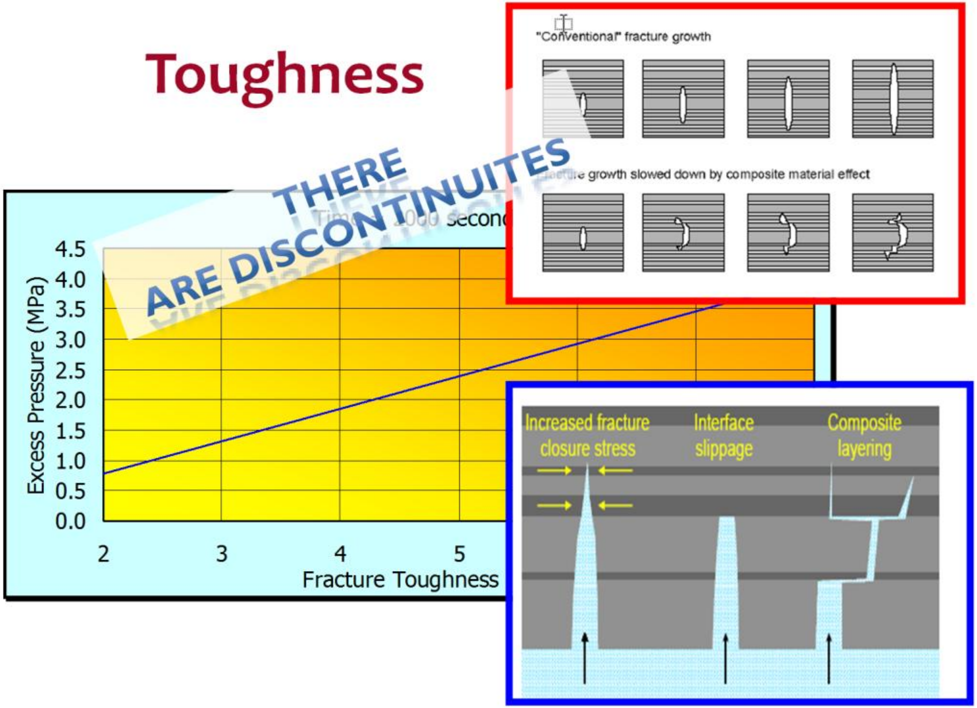
- ❖ Vertical Stress
- ❖ Shear Before Opening

$$k = k_o \left\{ C \ln\left[\frac{p_f - \sigma_{HMIN}}{p_f - \overline{p}} \right] \right\}$$

Near-Wellbore and Far-Field

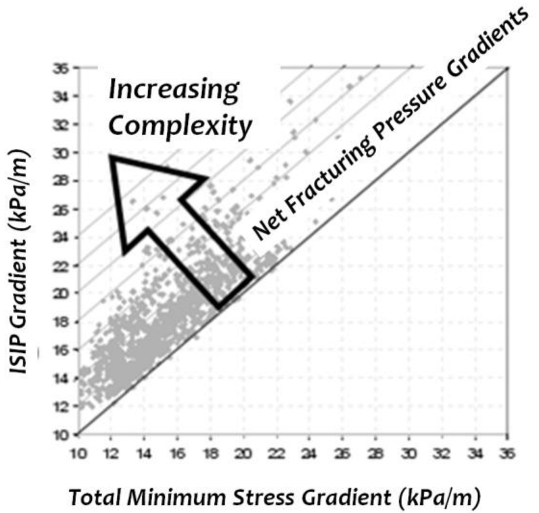


Toughness



THERE
ARE DISCONTINUITES
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Excess Pressure (MPa)
2
3
4
5
Fracture Toughness
"Conventional" fracture growth
growth slowed down by composite material effect
Increased fracture closure stress
Interface slippage
Composite layering

Hypothesis

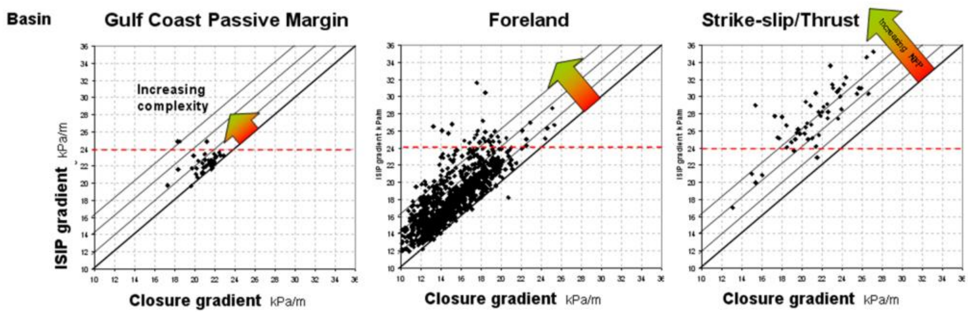


Increasing
Complexity
Net Fracturing Pressure Gradients
ISIP Gradient (kPa/m)
Total Minimum Stress Gradient (kPa/m)
10
12
14
16
18
20
22
24
26
28
30
32
34
36

Hypothesis

Increasing Net Fracture Pressure Gradient

Increasing Complexity --- Tectonic Regime and In-Situ Stresses

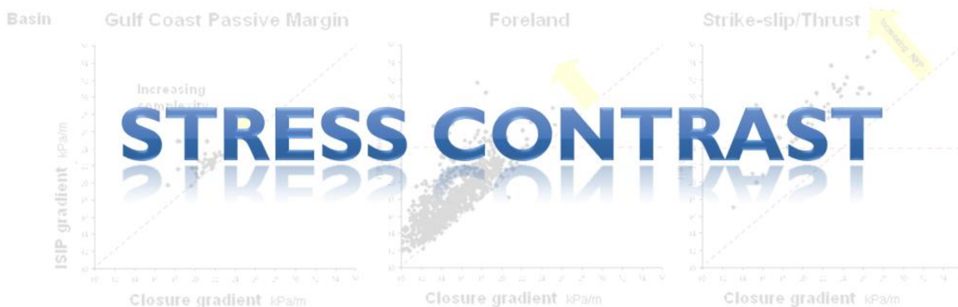


After Potocki, 2012, SPE 162814

More To It ....

Increasing Net Fracture Pressure Gradient

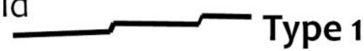
Increasing Complexity --- Tectonic Regime and In-Situ Stresses



STRESS CONTRAST

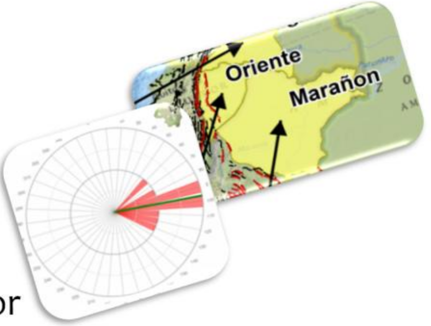
Infer Complexity of Created Fracture Regime

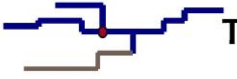
- Basin by Basin Compilation of σ_{HMAX} Stress Direction
- Local Variations
- Broad Areal Variations (flanks, etc. …)
- **Type 1 Stress Distribution**
- Tightly Clustered
- Strike-Slip Faulting
- $\sigma_{HMAX} >> \sigma_{HMIN}$????
- What are the implications for hydraulic fracturing?
- Anticipate narrow but long field of influence
- Poor Inter-strand Connectivity



Infer Complexity of Created Fracture Regime

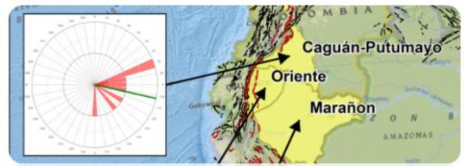
- Basin by Basin Compilation of σ_{HMAX} Stress Direction
- Local Variations
- Broad Areal Variations (flanks, etc. …)
- **Type 2 Stress Distribution**
- Widely Varied, Conjugate
- Strike-Slip Faulting
- σ_{HMAX} ~> σ_{HMIN} ????
- What are the implications for hydraulic fracturing?
- Anticipate intermediate field of influence and reasonable interconnectivity

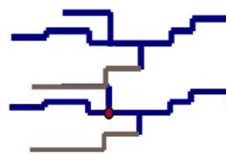




Infer Complexity of Created Fracture Regime

- Basin by Basin Compilation of σ_{HMAX} Stress Direction
- Local Variations
- Broad Areal Variations (flanks, etc. …)
- **Type 3 Stress Distribution**
- Orthogonal
- Strike-Slip Faulting
- $\sigma_{HMAX} \approx \sigma_{HMIN}$????
- What are the implications for hydraulic fracturing?
- Anticipate symmetric field of influence and excellent interconnectivity



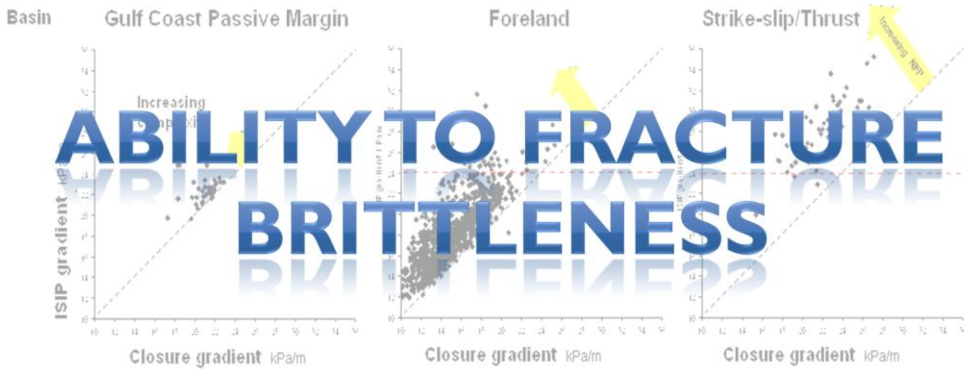


Type 3

More To It ….

Increasing Net Fracture Pressure Gradient

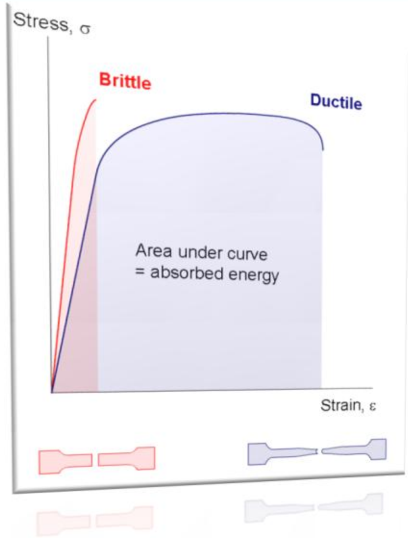
Increasing Complexity --- Tectonic Regime and In-Situ Stresses



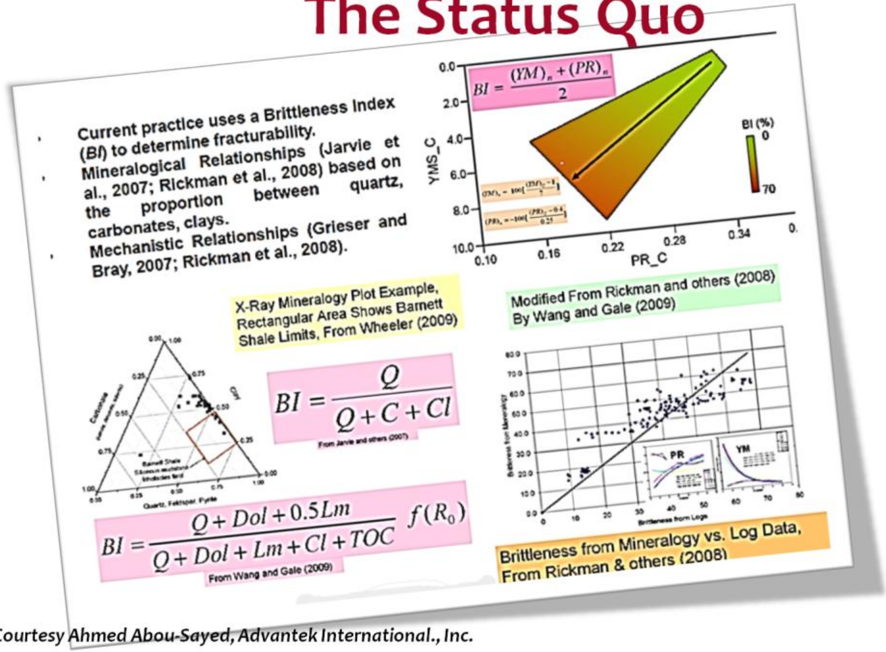
ABILITY TO FRACTURE
BRITTLENESS

I. Brittle Versus Ductile Behavior

- We casually use terms such as brittleness and fracability
- Is this more than just bad grammar and semantics?
- Compounded by:
  - Basing predictions strictly on compositional characteristics
  - Using elastic properties such as Young's modulus and Poisson's ratio
  - Without regard to how fracturing is occurring and associated rate of release of stored energy

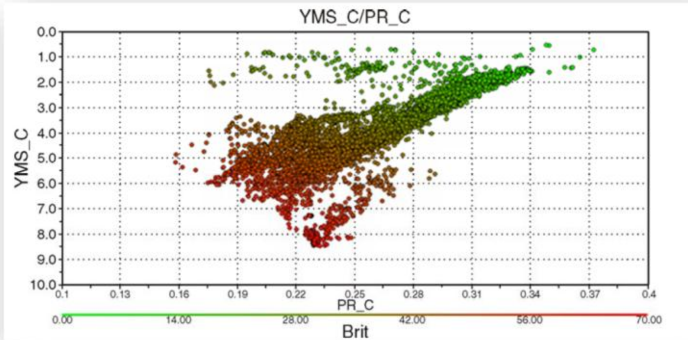


The Status Quo



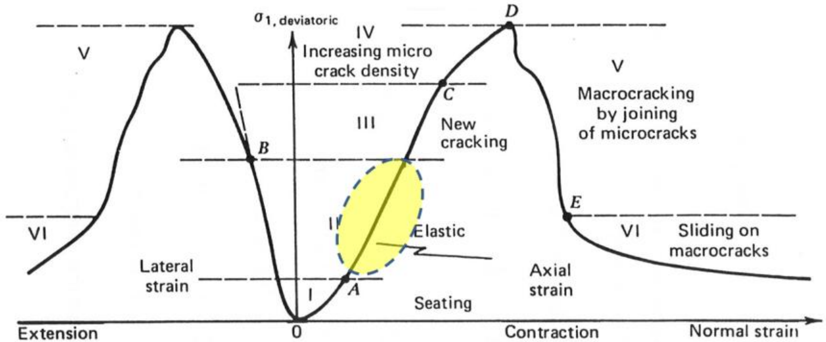
Courtesy Ahmed Abou-Sayed, Advantek International., Inc.

Rickman et al., 2008



$$BRIT = 0.5\left\{\left(\frac{E-1}{8-1}\right)\times 100 + \left(\frac{\nu - 0.4}{0.15-0.40}\right)\times 100\right\}$$

--- Stress and Strain ---

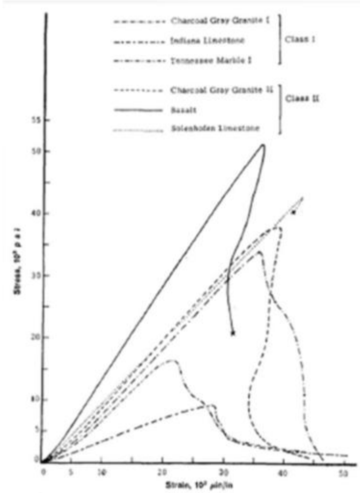


$$\varepsilon_r = \frac{\Delta r}{r_0}$$

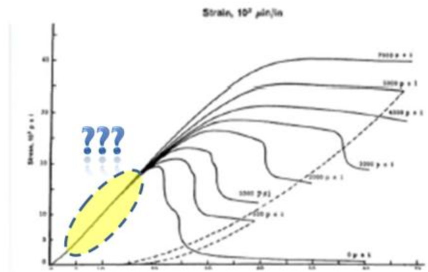
$$\varepsilon_a = \frac{\Delta \ell}{\ell_0}$$

Elastic Definition – Unique?

Stiff Testing Machines

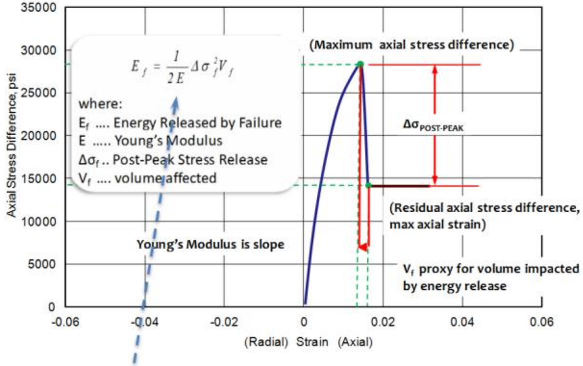


Confining Pressure

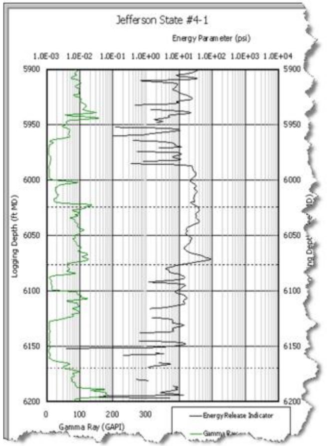


After Wawersik and Fairhurst (1970)
Young's Modulus Similar for High Modulus Rock

What Should/Could Be Done?



See Tang and Kaiser (1998)



See Bereskin et al. (2009)
See Bereskin and McLennan (2008)

Fracture Growth Models/Types
Brittleness

Can We Predict It?

Multiple regression analysis – RGU-1 core only
Energy released (E_f) versus 6 geologic variables: grain size, bioturbation, degree of lamination, HCl reaction (proxy for calcite content), Poisson's ratio, bulk density (g/cm³)

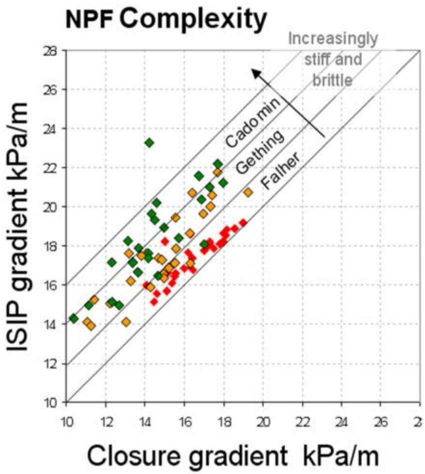
Multiple R = 0.84 (correlation coefficient)
R^2 = 0.71 (coefficient of determination or "goodness of fit")

Suggests the total combined geologic variability accounts for approximately 70% of the variability in E_f.

							Clay (%)
							22.5
							36.3
							24.3
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	59.6
CS020R	15260	5.47	5.92	4.19	15.80	66.70	17.5
CS024R	9910	6.73	11.43	1.71	51.40	1.90	46.7
CS045R	19175	0.52	1.31	0.13	58.40	5.00	36.6

After Birgenheier

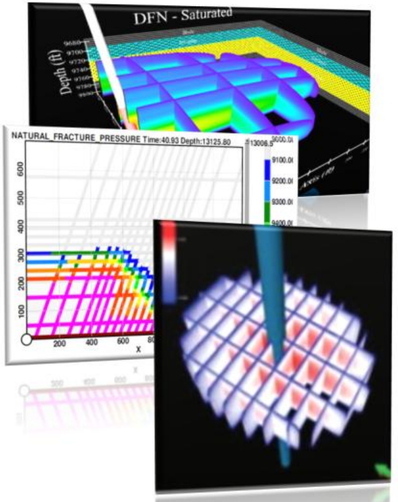
Still Missing ….



- Pore Pressure
- Tectonic Fracturing
- Uplift History
- ….

Not Just Academic….

- What are reservoir characterization procedures to most reliably and cost-effectively delineate where to drill and complete? [**prospects commercial sooner**]
- What are the situation-appropriate stimulation and completion technologies? [**efficient, cost-effective**]
- How can environmental measures be implemented most economically? [**assurance**]
- **WHAT CAN THE INDUSTRY DO DIFFERENTLY?**

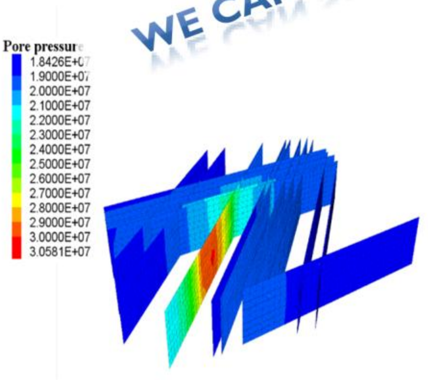


Schlumberger offers Mangrove

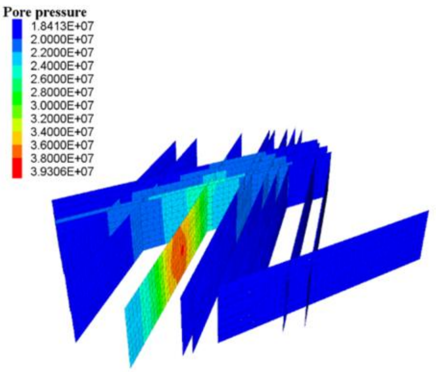
Newer Methods for Simulation

WE CAN SIMULATE

25 BPM



75 BPM

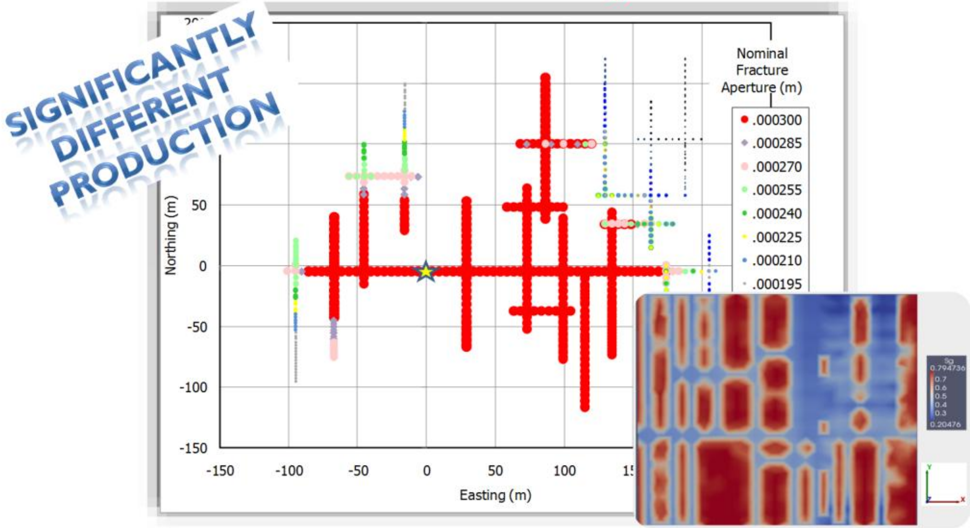


Morphology Nominally the Same – Treating Pressures Vary, Is Stress Field Dependent (Anisotropy in Stresses)

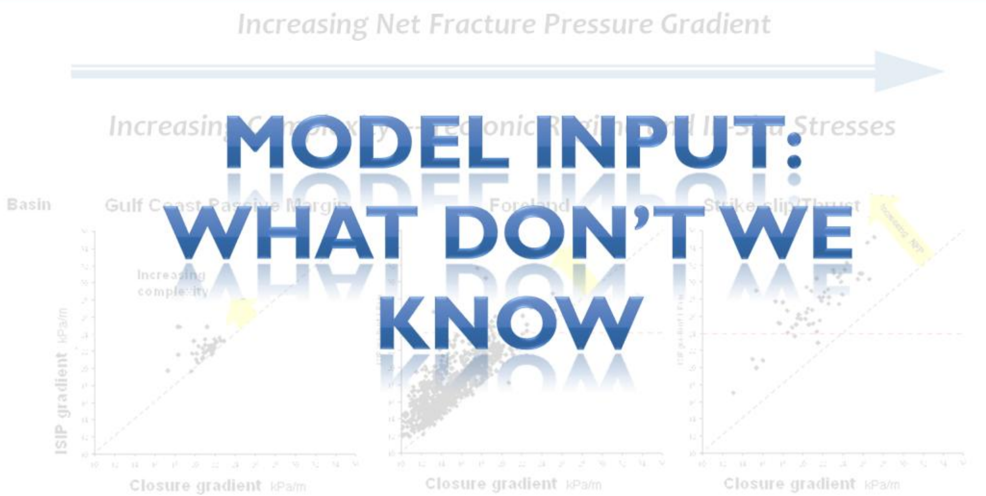
Production Simulation

100 days,

Absolute Matrix Permeability 0.001 md



More To It ....



MODEL INPUT: WHAT DON'T WE KNOW

Properties of Fractures Measured
Triaxial Shear Test