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ARMA 13-254

Comparisons of Plane Propagation from Dilating Casing and Conventional Perforations when Stimulating the Milk River Formation

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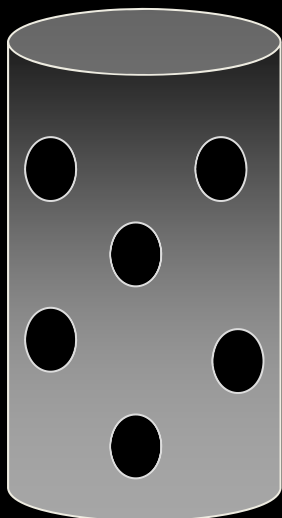
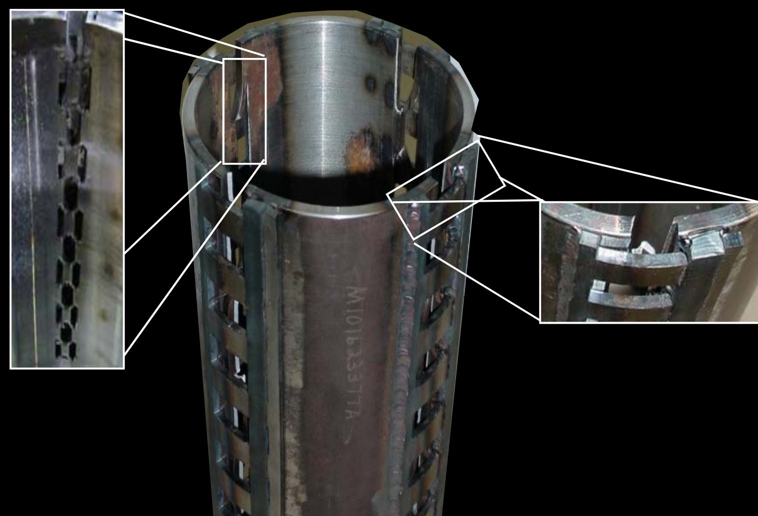
Offset Well Stimulation Comparison

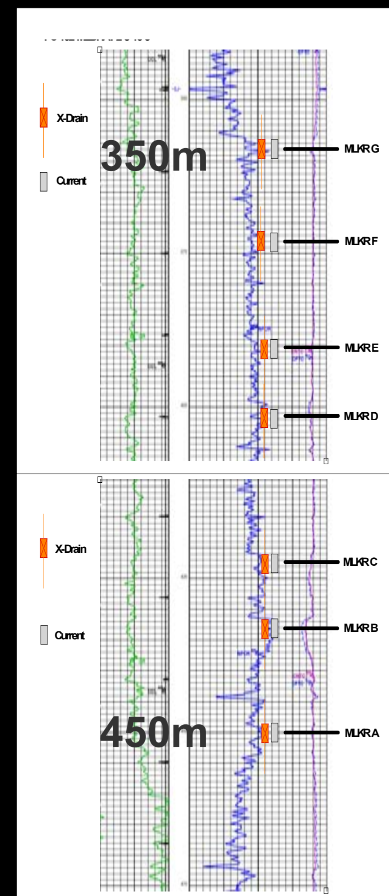
Perforations



Dilating Casing



Milk River

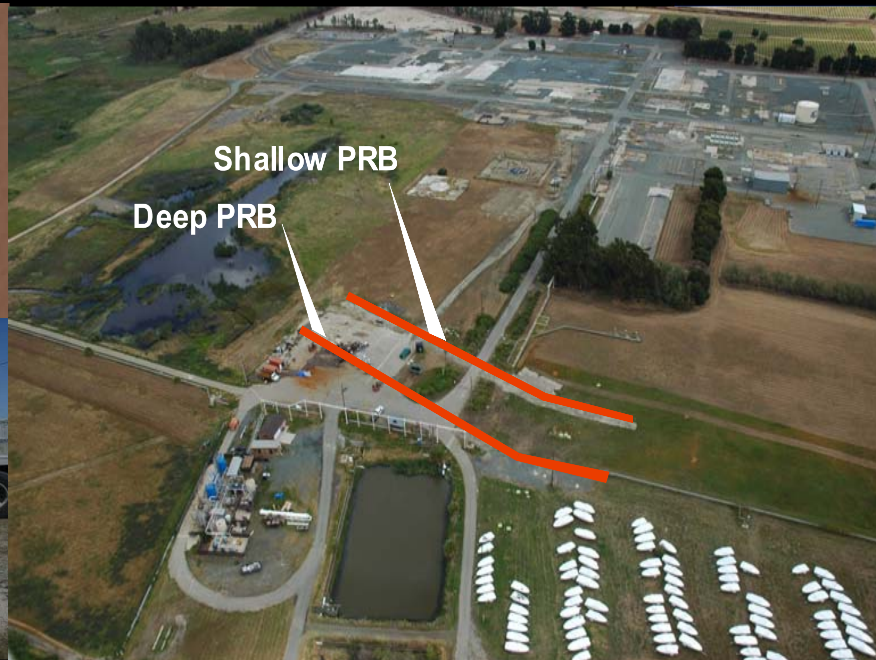


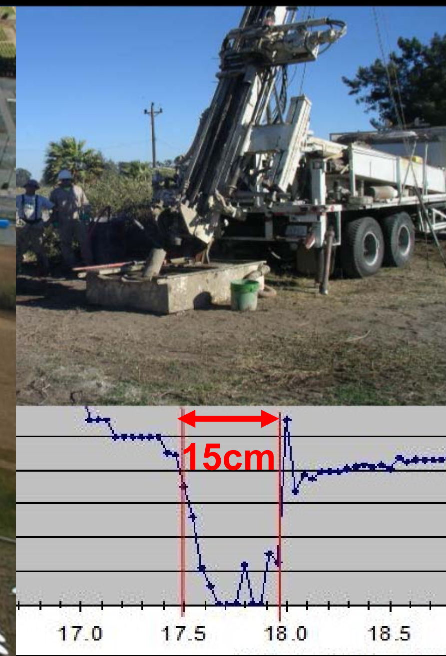
MlkR G

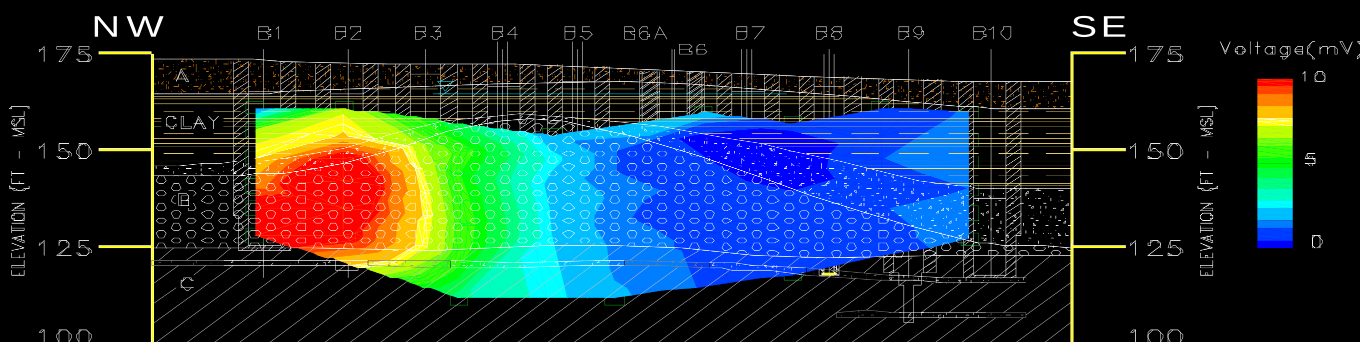
MlkR A

Azimuth Controlled Fracturing

Azimuth Controlled Fracturing







Real Time Active Resistivity Image

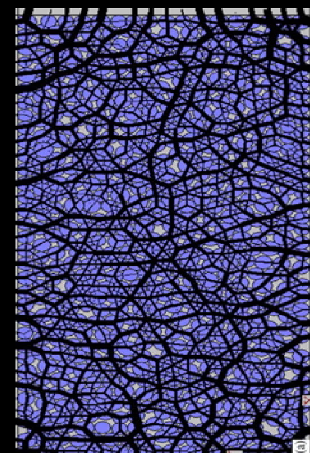
Unconsolidated Formations

Non-Brittle Weak Formations

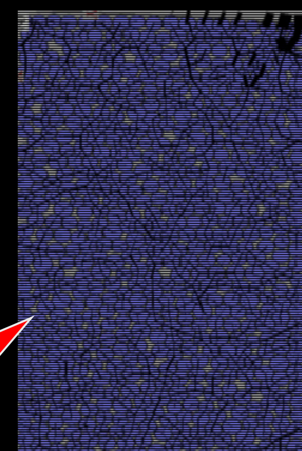
Weakly Cemented Formations

- Minimal Cementation, Soft & Weak
- Stress State
  - Force Chains Fragile
    - Easily Destroyed
    - Minor Vibration or Shearing
    - Grain Contact Dissolution
    - Over-Pressurization
  - Minimal Horizontal Stress Contrast
    - Horizontal Stress Contrast can not be maintained over geological time
- Constitutive Behavior
  - Ductile Frictional Behavior
  - Anelastic
  - Skempton's B parameter

Isotropic Compression Force Chains Shown



Force Chains Destroyed

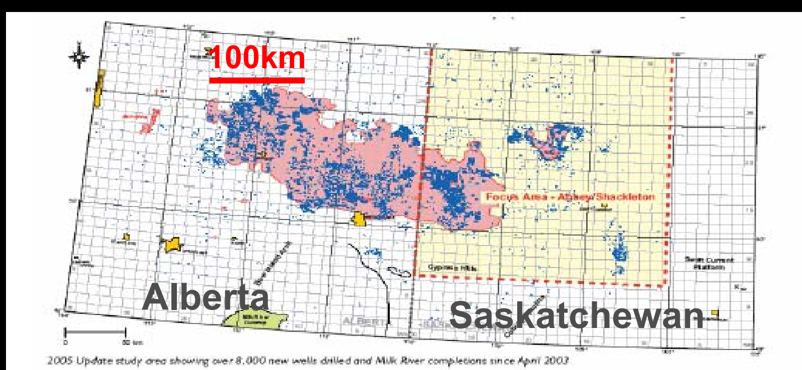


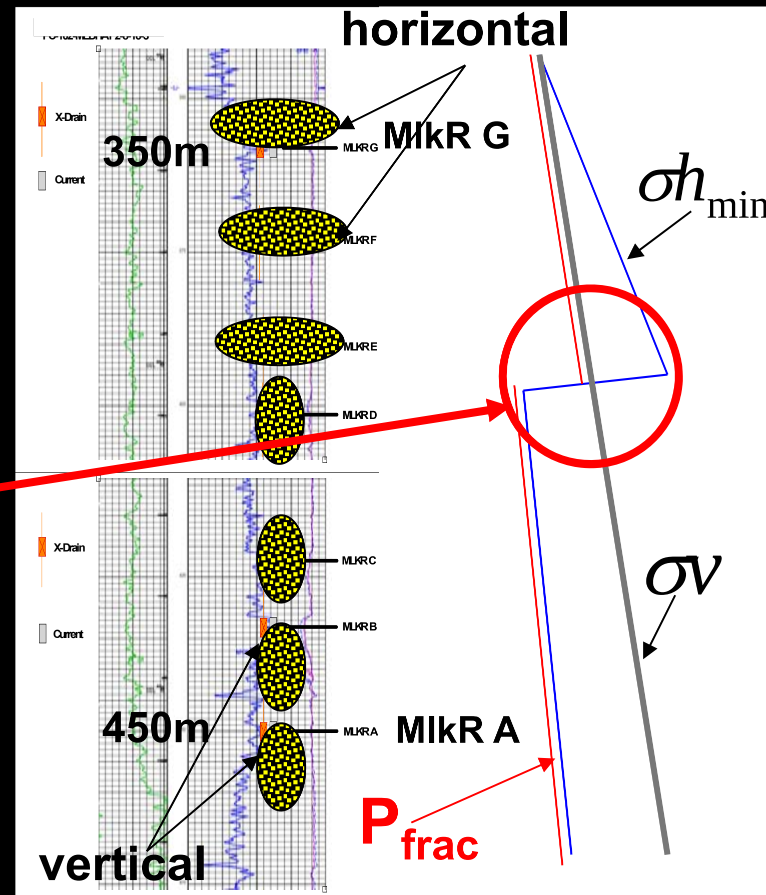
Minor Shear Strain Destroys Force Chains

Milk River Tight Gas Reservoir

Non-Brittle Weak Formation

- E~3GPa c'~2.5MPa ϕ~35° UCS*~10MPa
- 40,000 wells conventionally stimulated
- CO_2 fluid 20/40 sand 10tons/horizon
- Surface & Downhole Tiltmeter Arrays
- Injection Pressures ↑~40% at <400m depth
- Vertical 'Fracs' >400m Horiz 'Fracs' <400m
- Stress Crossover at 400m



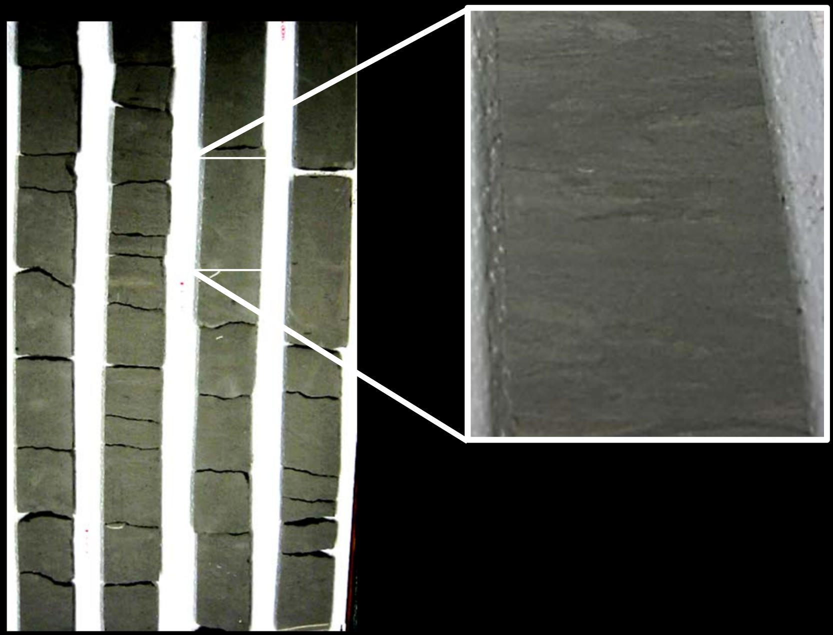


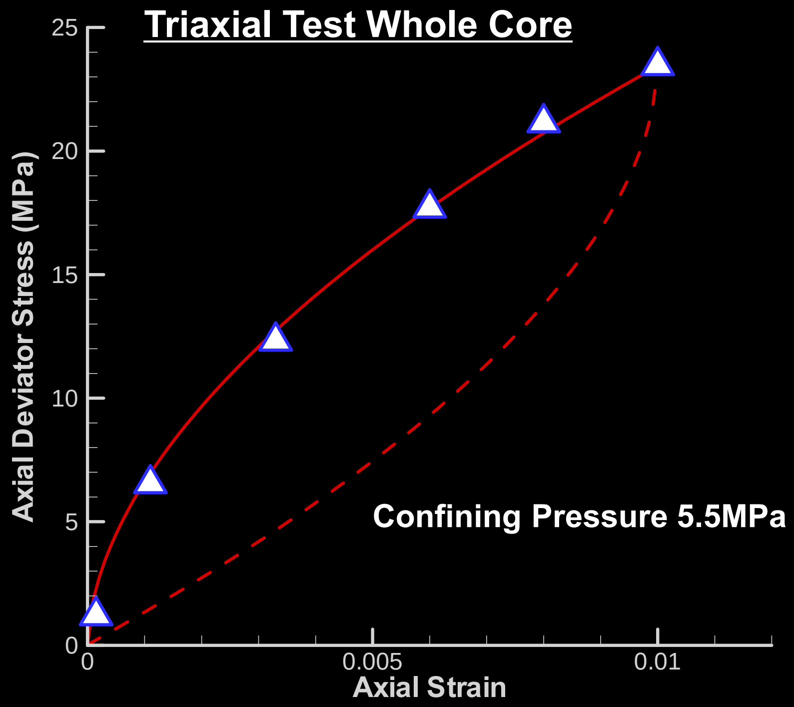
Note: UCS*=2c'tan(45+ ϕ/2)

Milk River Reservoir Core Data

Continuous Cores of Reservoir

- Weak mudstone shallow low energy deposition
- Thin sand lenses upward coarse grading
- Clear shoreline anisotropy
- Anelastic behavior from triaxial tests

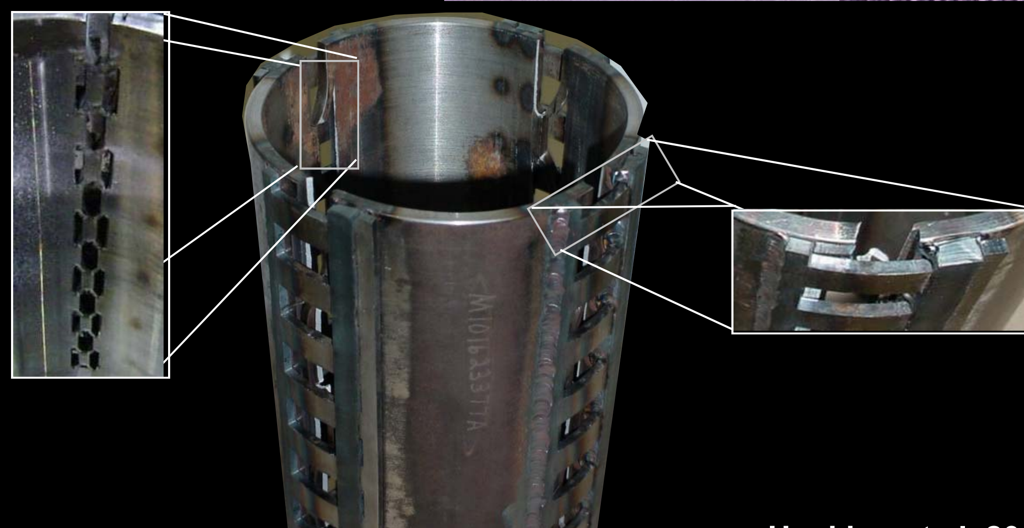




Milk River Tight Gas Reservoir

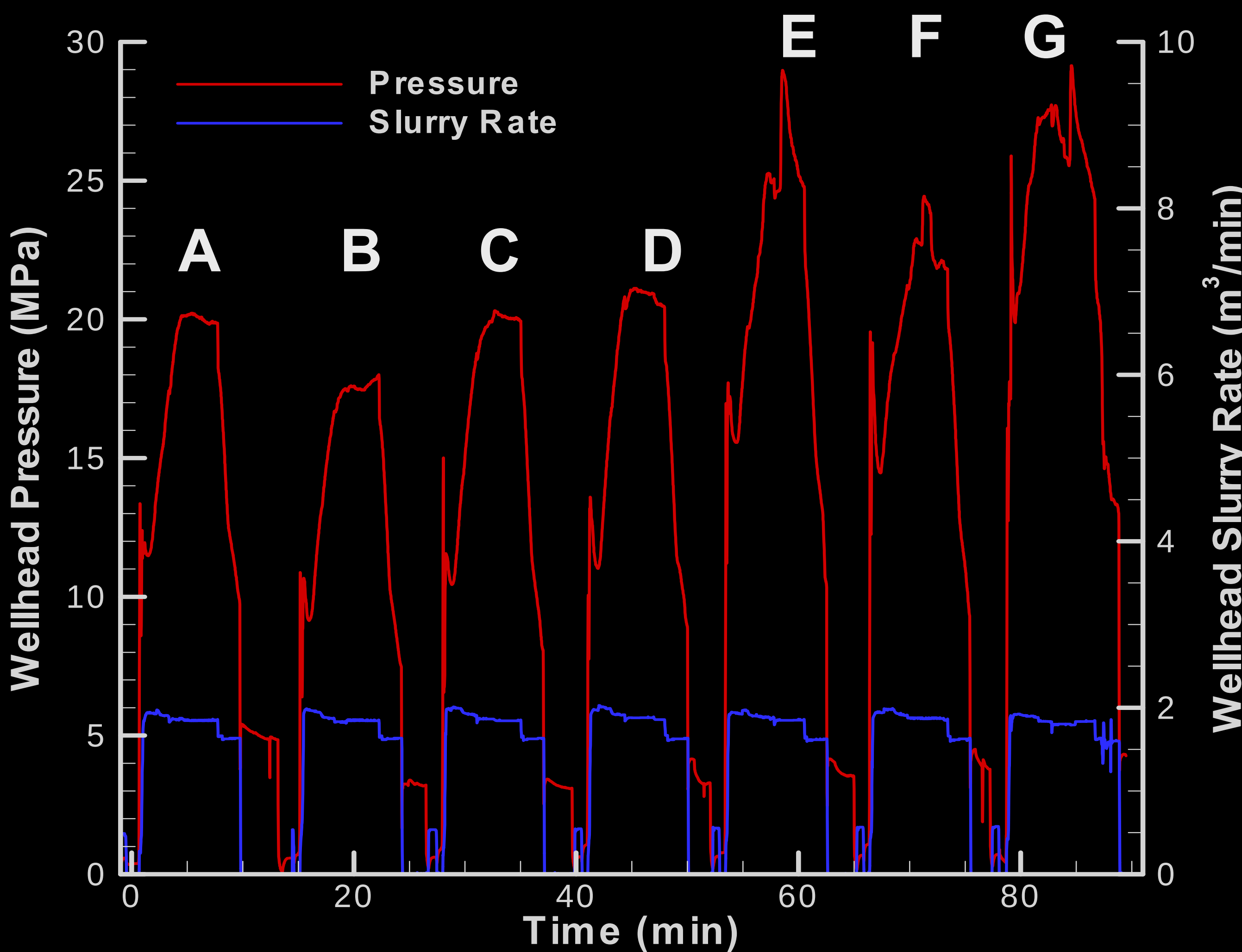
Stimulation Split Dilating Casing

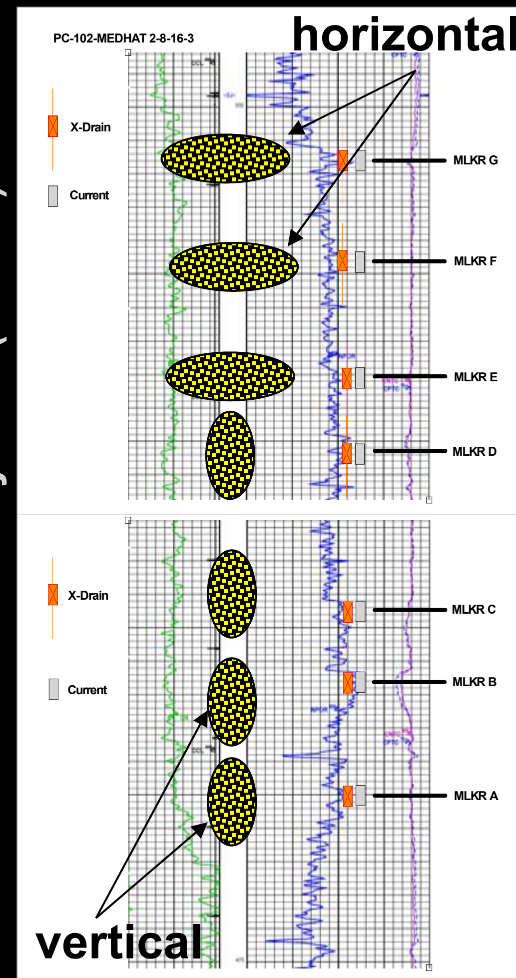
- Cemented by Inner String
- Mechanically Split & Expanded
- 10% Radial Strain
- Locked in Open Position
- Multiple Wings intersect Formation
  Shoreline Anisotropy



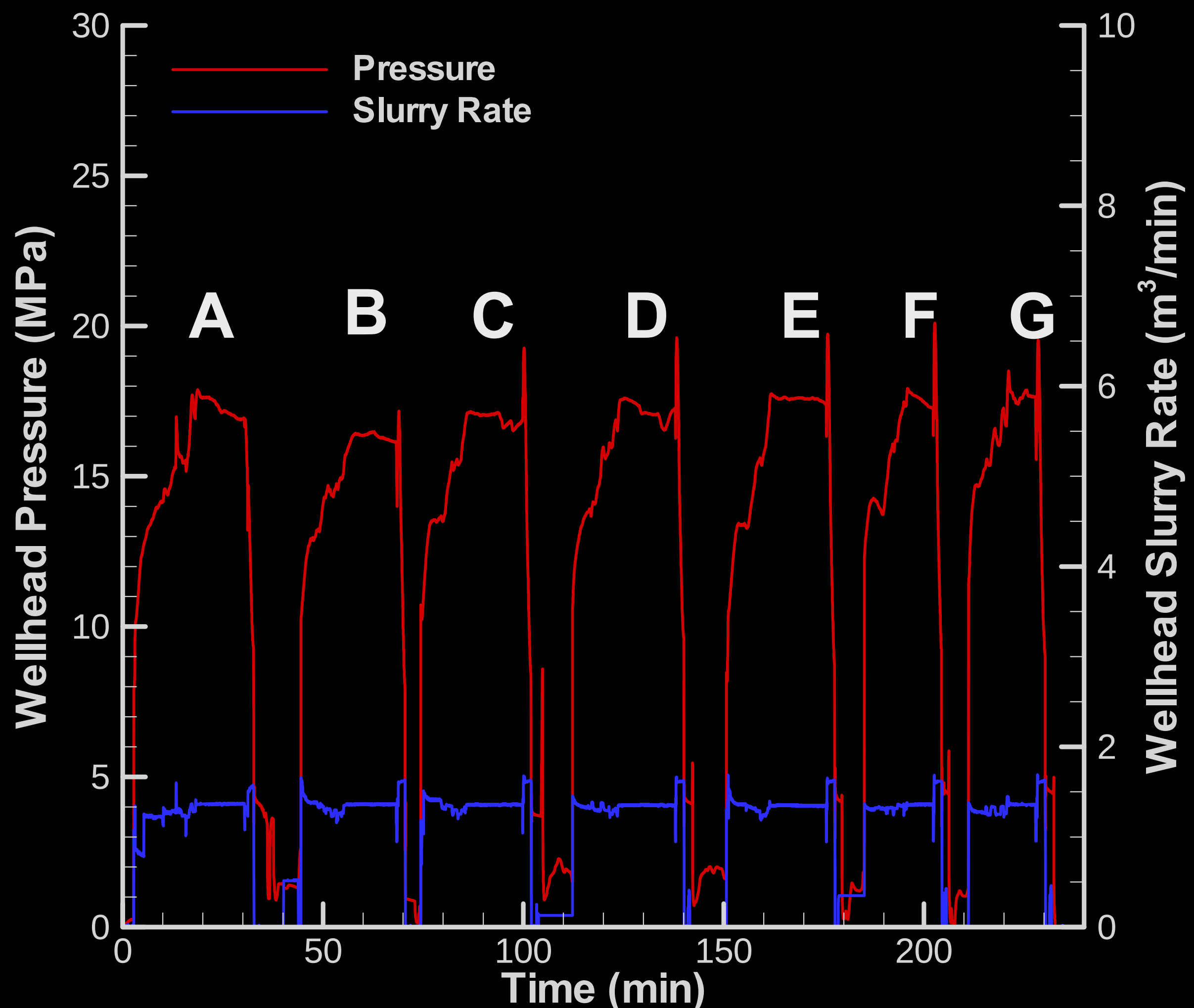
Hocking et al. 2011

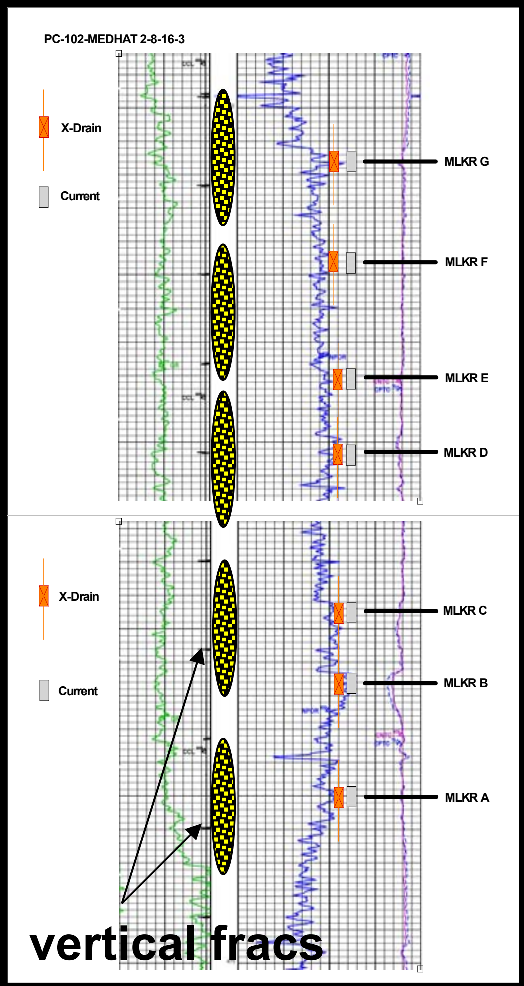
Conventional Stimulations





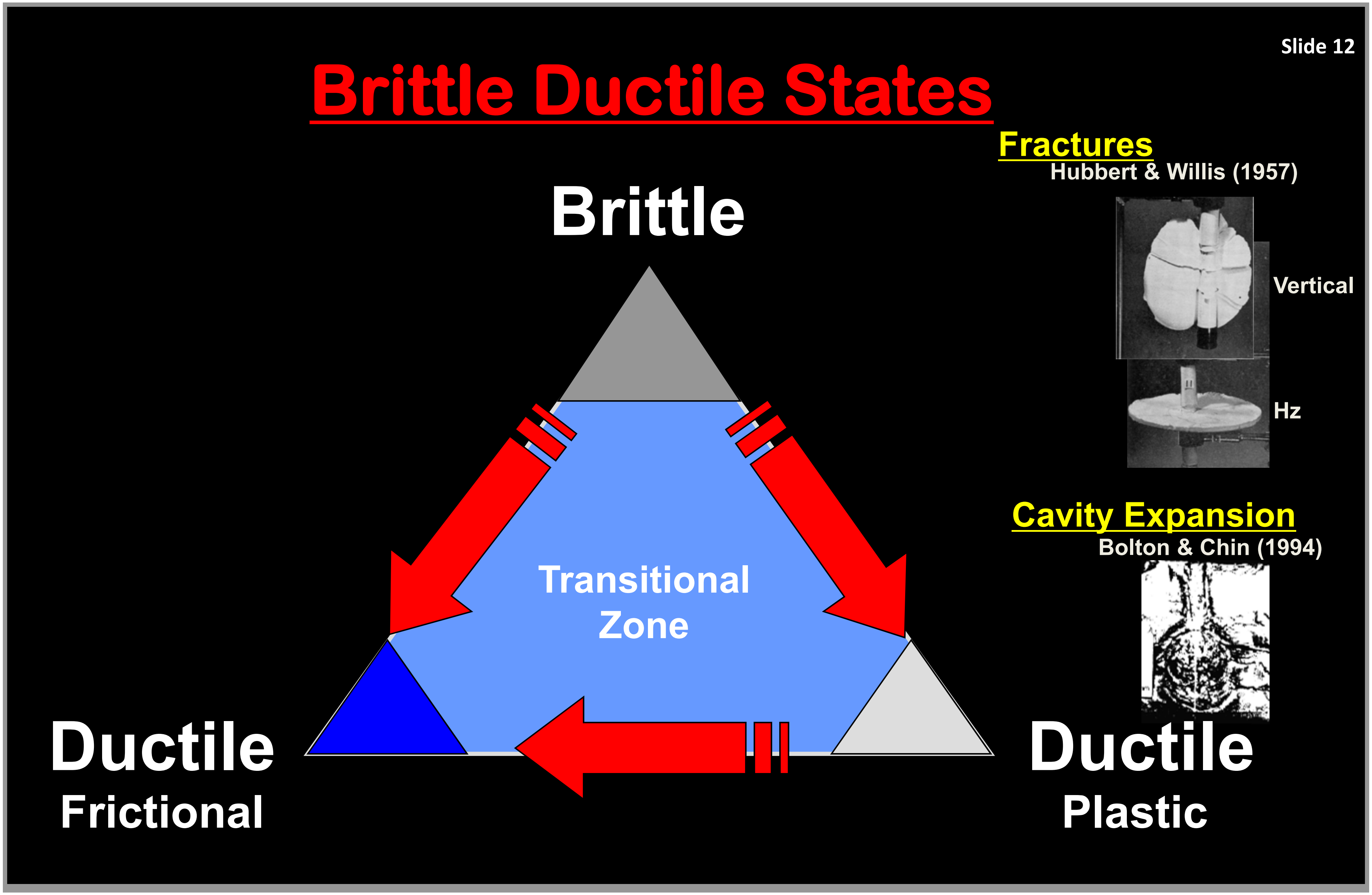
Split Dilating Casing Stimulations



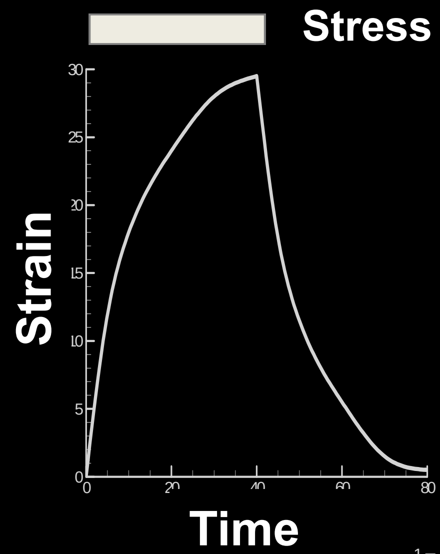


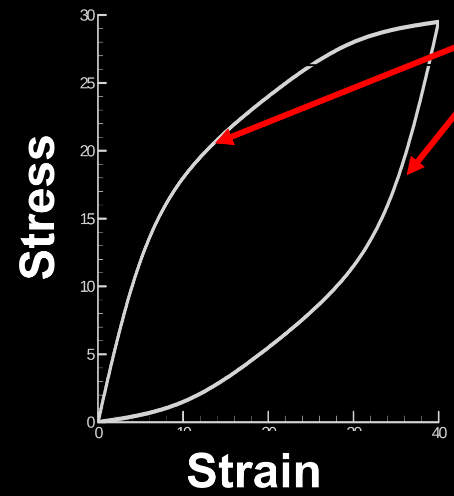
Lessons Learnt

- **Completion Method Controls the Outcome**
  - How do you interpret stimulation and shut-in pressure records?
  - Mapping injected geometries only tells you of the outcome
  - Stimulation thru' perfs or open-hole do not excite least energy dissipating mechanism
  - Frac initiation is essential
- **Why? Non-Brittle Weak Formations**
  - Anelasticity
  - Skempton's B Parameter


Slide 12
Brittle Ductile States
Fractures
Hubbert & Willis (1957)
Vertical
Hz
Cavity Expansion
Bolton & Chin (1994)
Brittle
Transitional Zone
Ductile
Frictional
Ductile
Plastic

Anelasticity

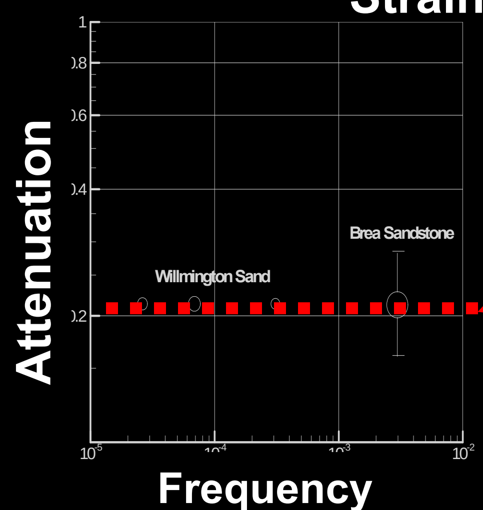




Hysteresis strain lags stress lost energy

Loss Factor $\eta = \frac{E''}{E'} = \tan\phi$

$$\eta = \phi = \tan\phi = \frac{\delta}{\pi} = \frac{\psi}{2\pi} = Q^{-1}$$



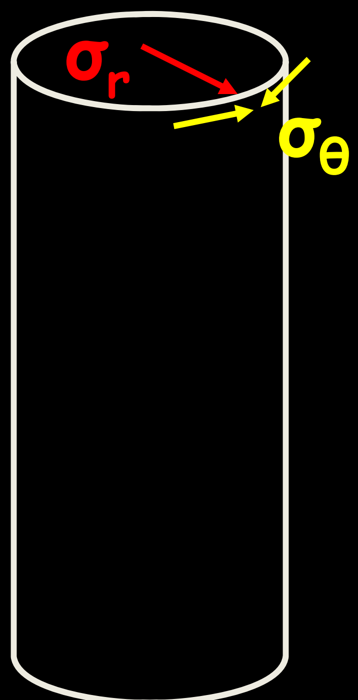
Dry Sand/Weak Sandstone

Q=5 Quality Factor

Milk River Formation

Q=3.5 at 5.5MPa confining pressure

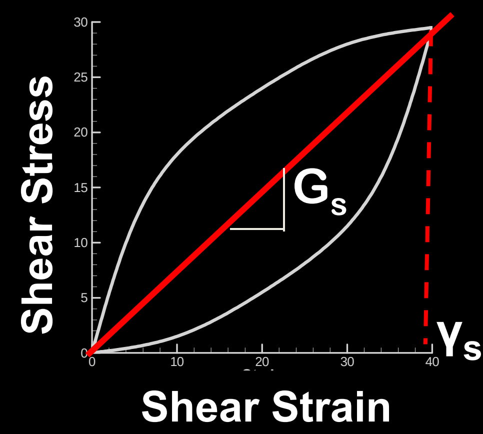
Anelasticity - Cylindrical Cavity



Field Stress p_0
compression +ve

Linear Elastic

$$\sigma_r = p_0 + \Delta p$$
$$\sigma_\theta = p_0 - \Delta p$$



$$\tau = \alpha \gamma^{\beta}$$
$$\alpha = G_s \gamma_s^{1-\beta}$$

Bolton & Whittle (1999)

Non-Linear Elastic

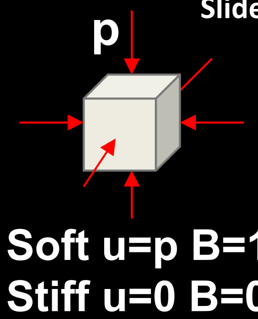
$$\sigma_r = p_0 + \frac{\alpha}{\beta}\gamma^{\beta}$$
$$\sigma_\theta = p_0 - \alpha\left(2 - \frac{1}{\beta}\right)\gamma^{\beta}$$

β=0.5	Q=3	η=0.3
β=0.65	Q=5	η=0.2
β=0.8	Q=10	η=0.1

Inclusion Tip and Mobility

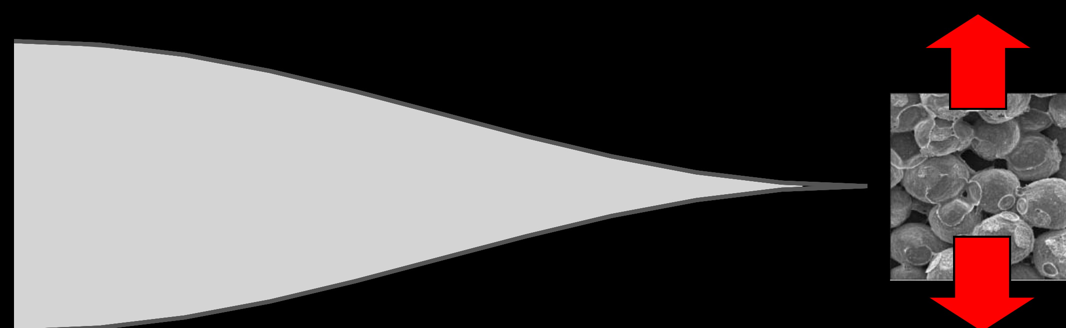
Skempton's B parameter

- >0.75 at low p'
- >0.5 at high p' at significant depth

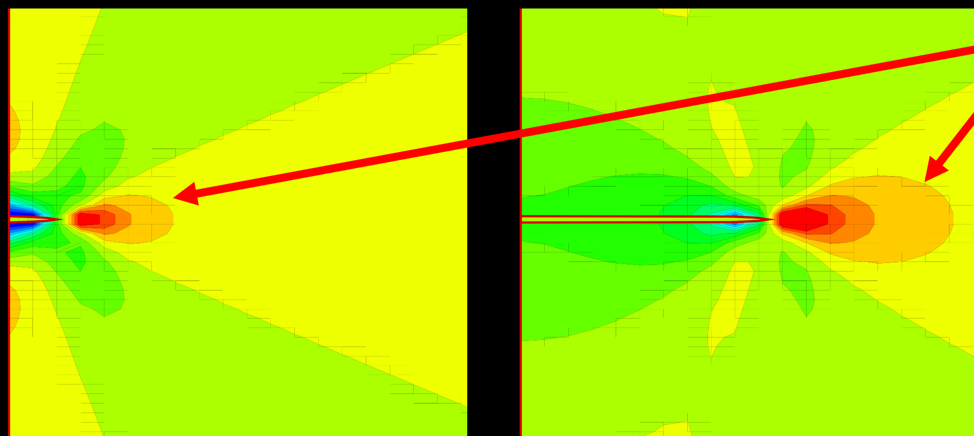


Inclusion Tip Mobility & Geometry

- negative pore pressure in front of tip
- inclusion clamped by apparent cohesion
- inclusion sucked into the unloaded zone
- remains on azimuth due to anelasticity

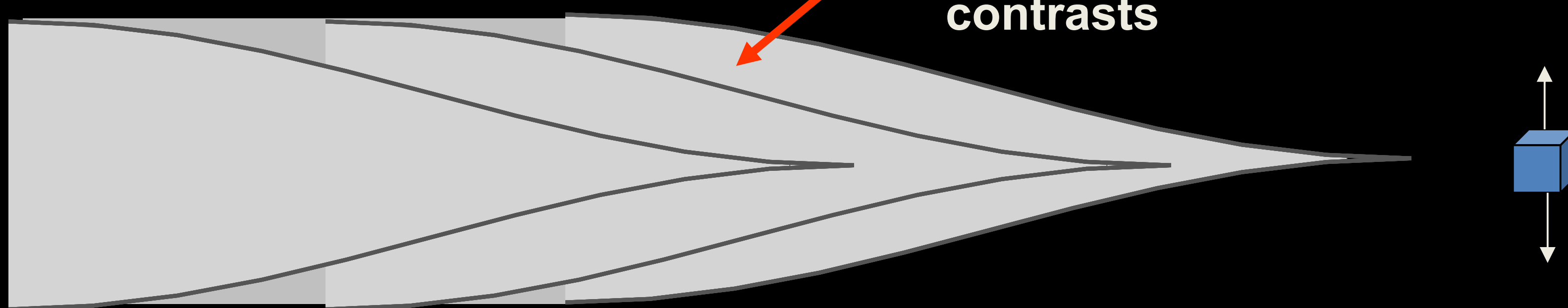


Inclusion on Azimuth - Anelasticity



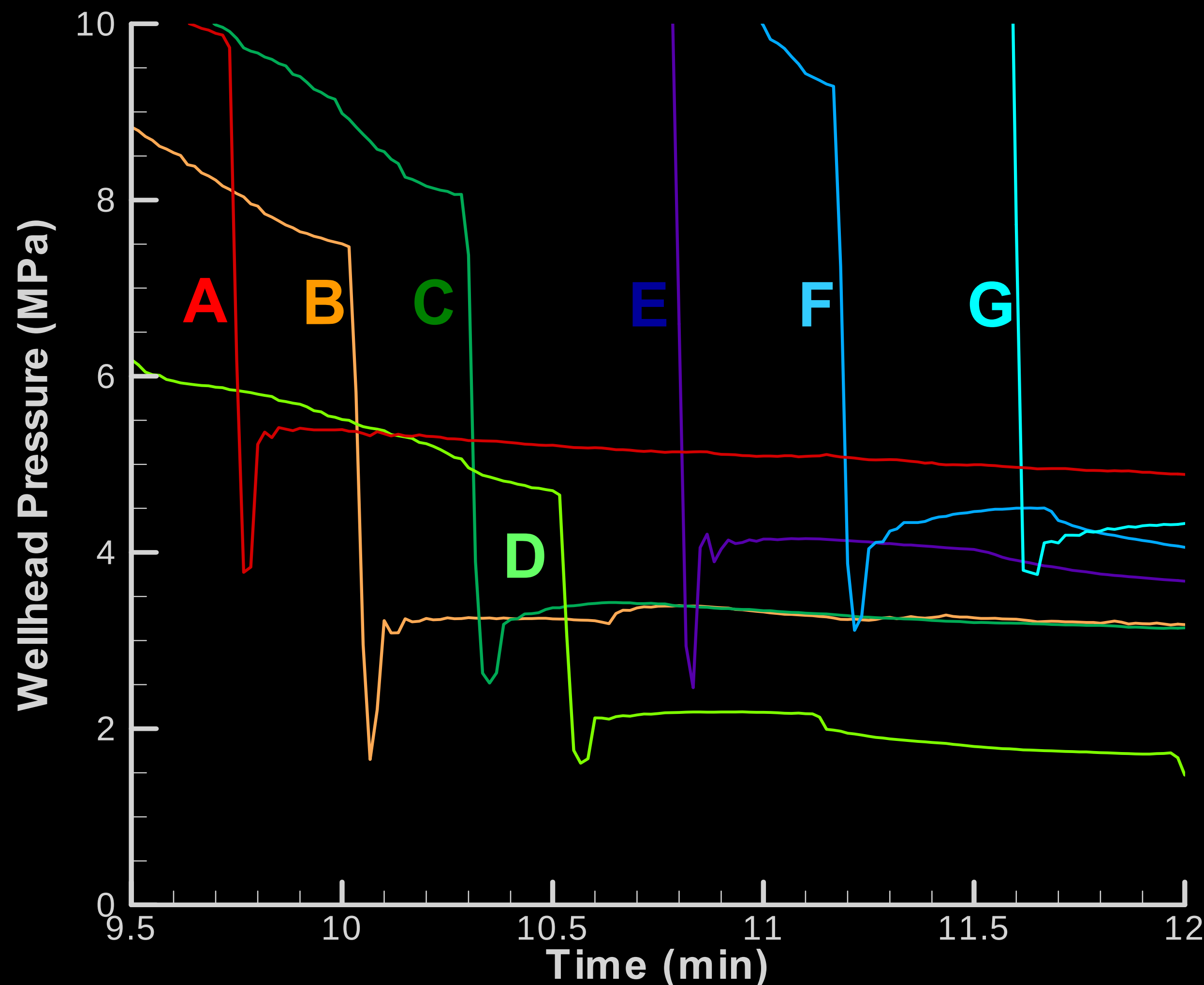
Process zone grows with inclusion length due to anelasticity resulting in a more robust propagating inclusion remaining on azimuth

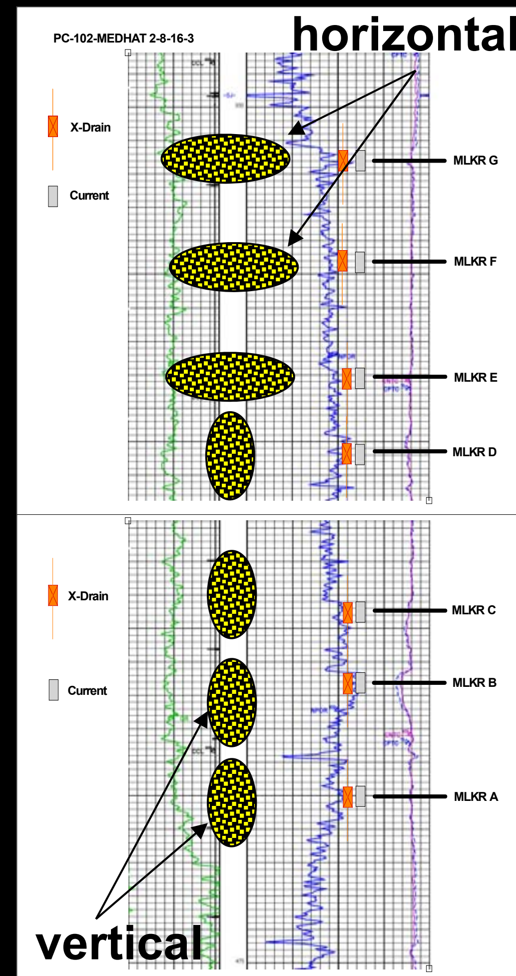
Propagating inclusion remains on azimuth even with modest stress contrasts



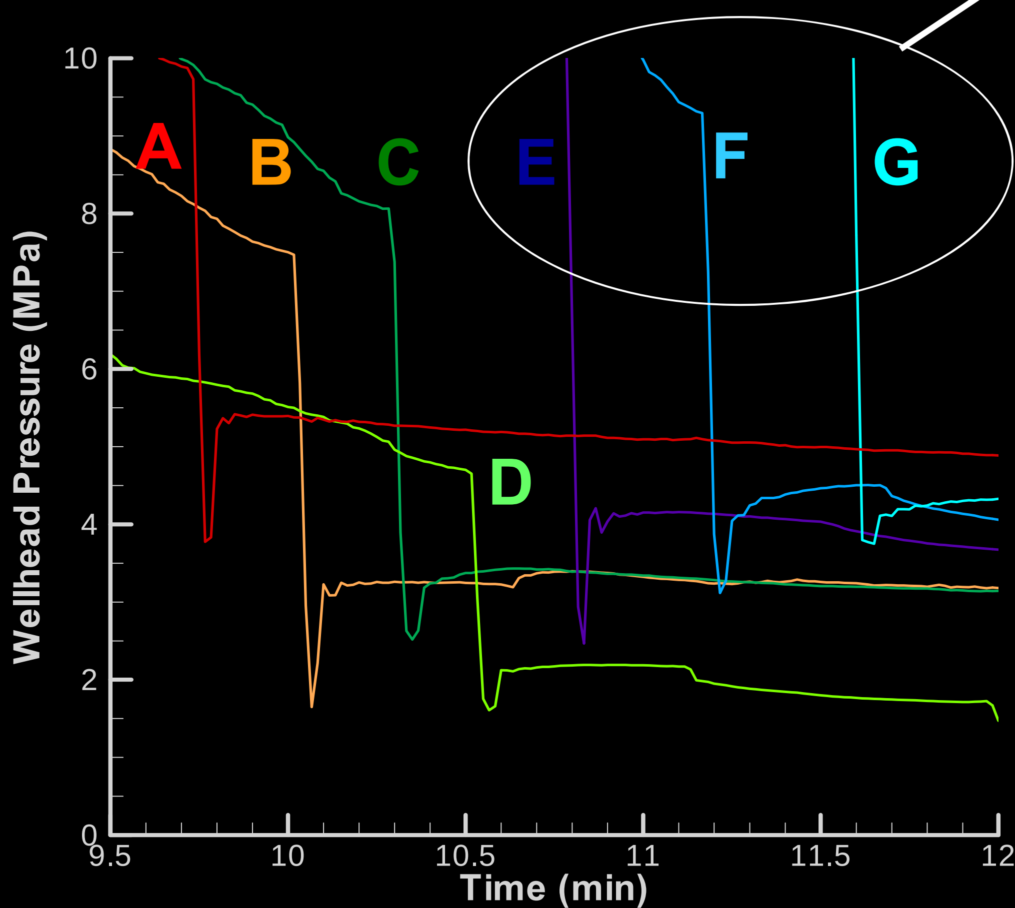
Anelasticity, Skempton’s B parameter – no mention of plasticity

Conventional Stimulations





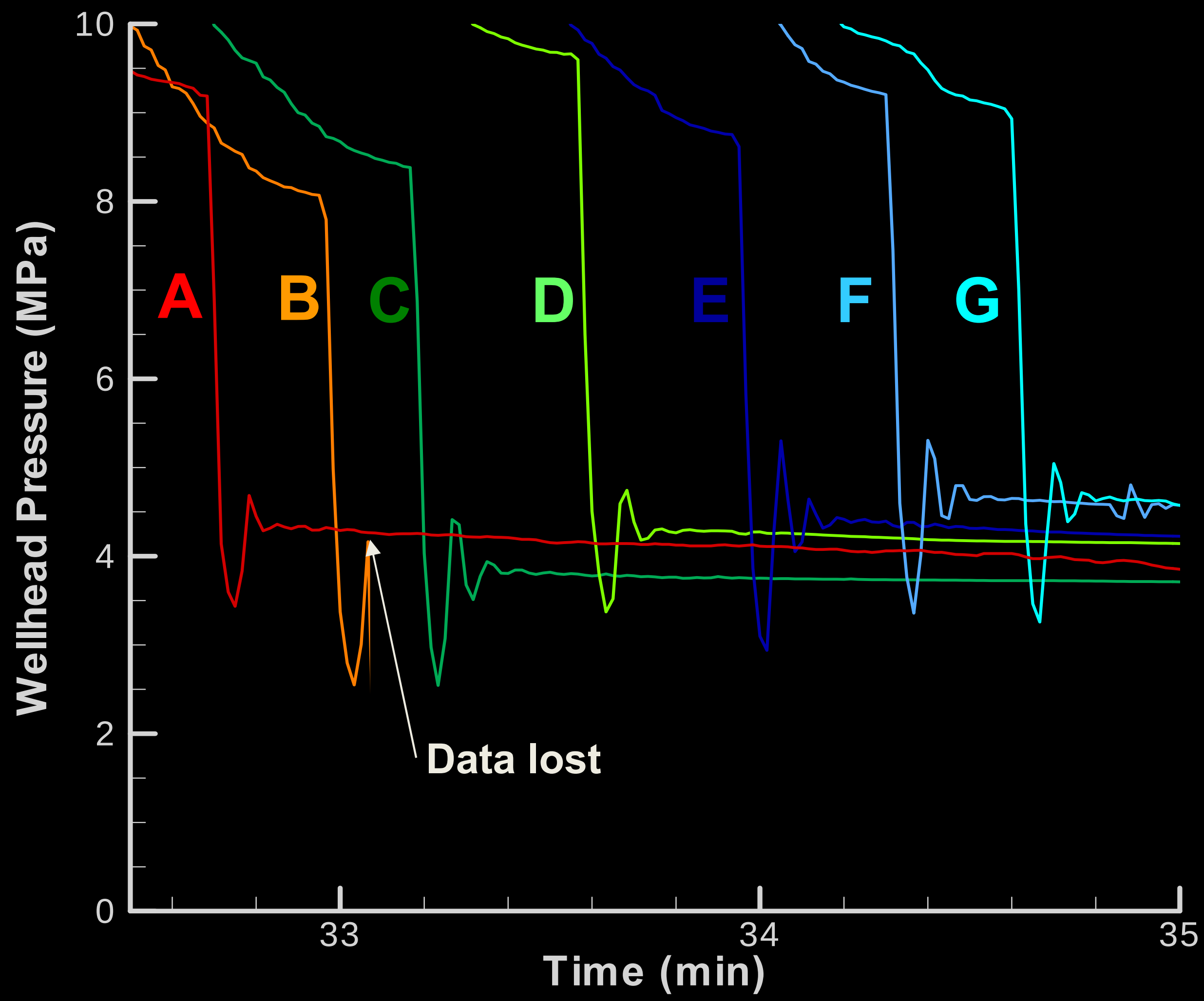
Conventional Stimulations

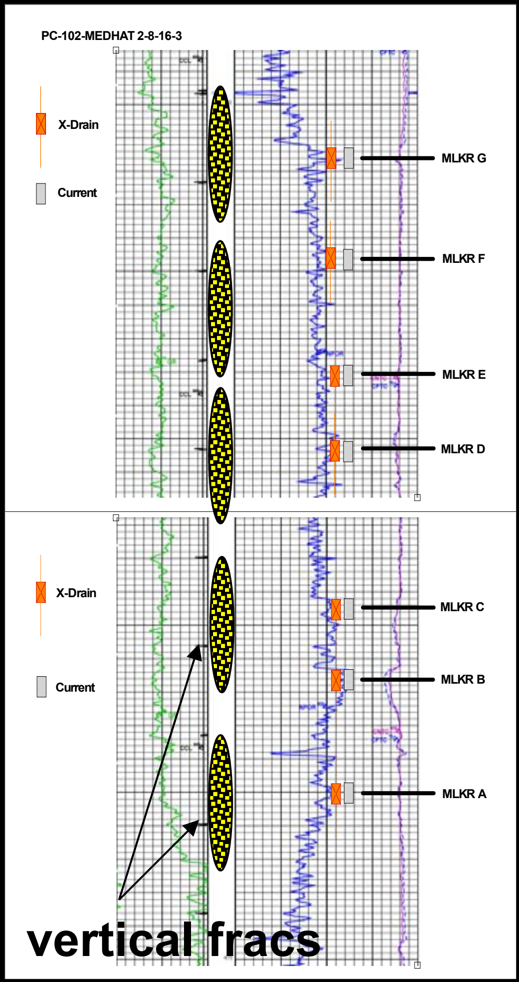


Short Stubby Horizontal Fracs

Short Bulbous Vertical 'Fracs'

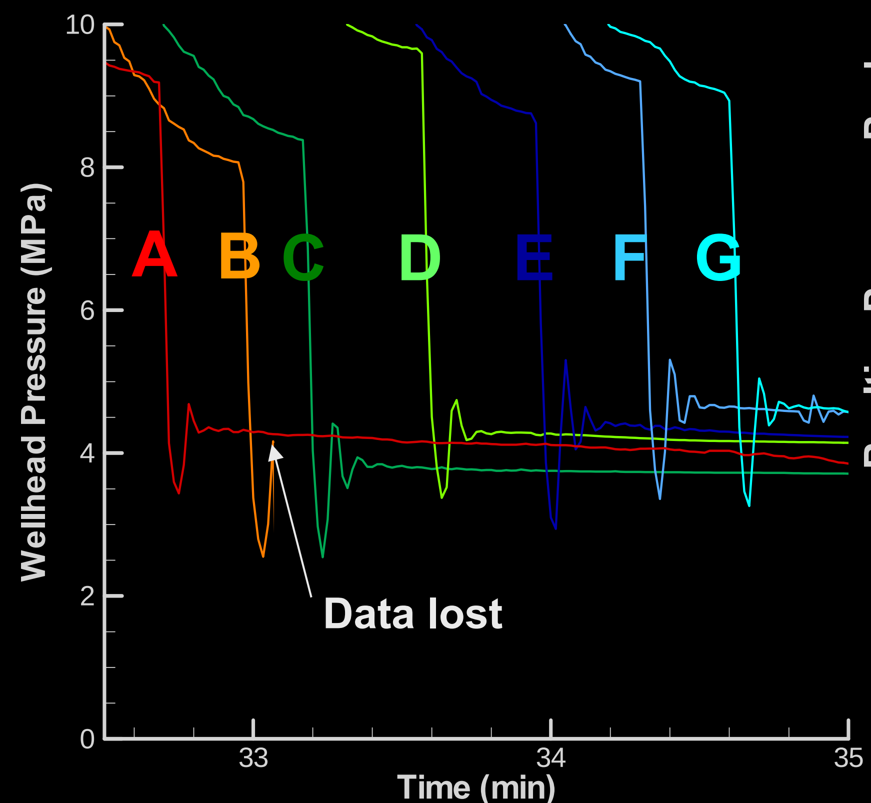
Split Dilating Casing Stimulations

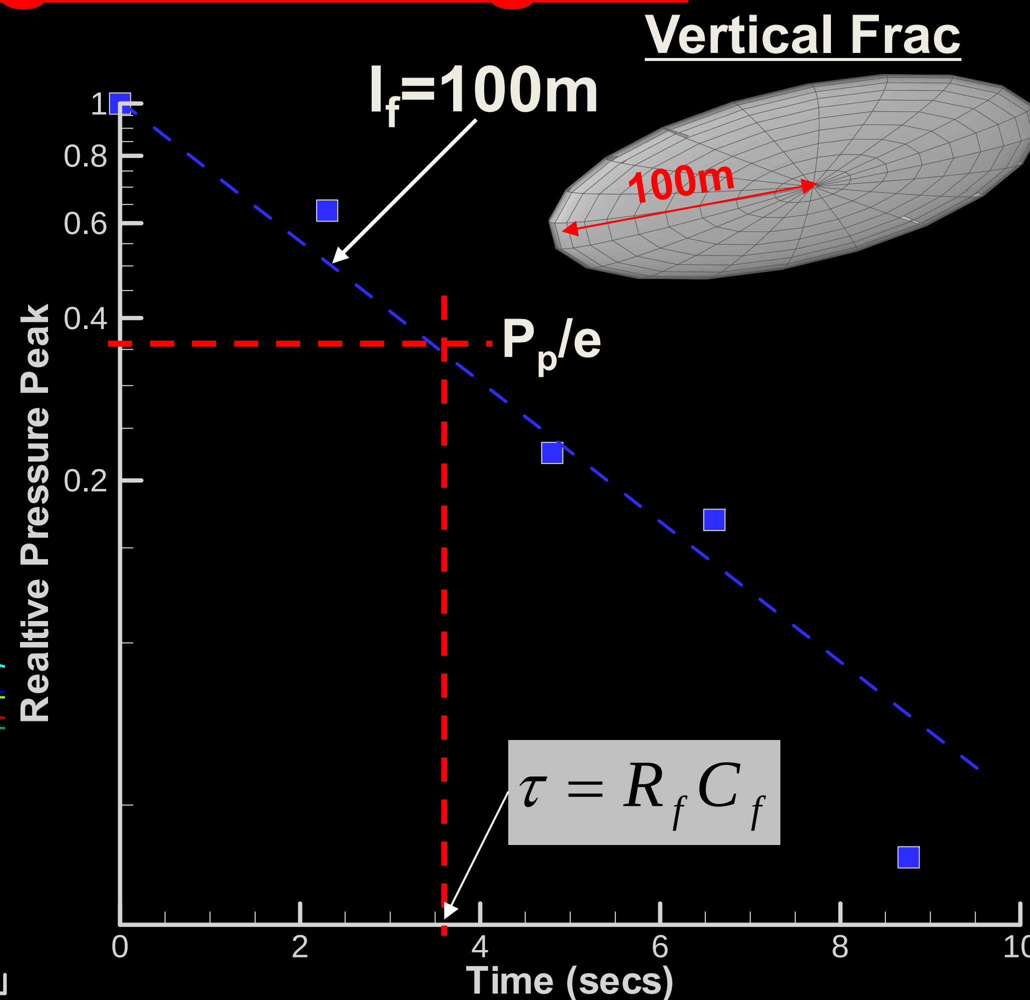




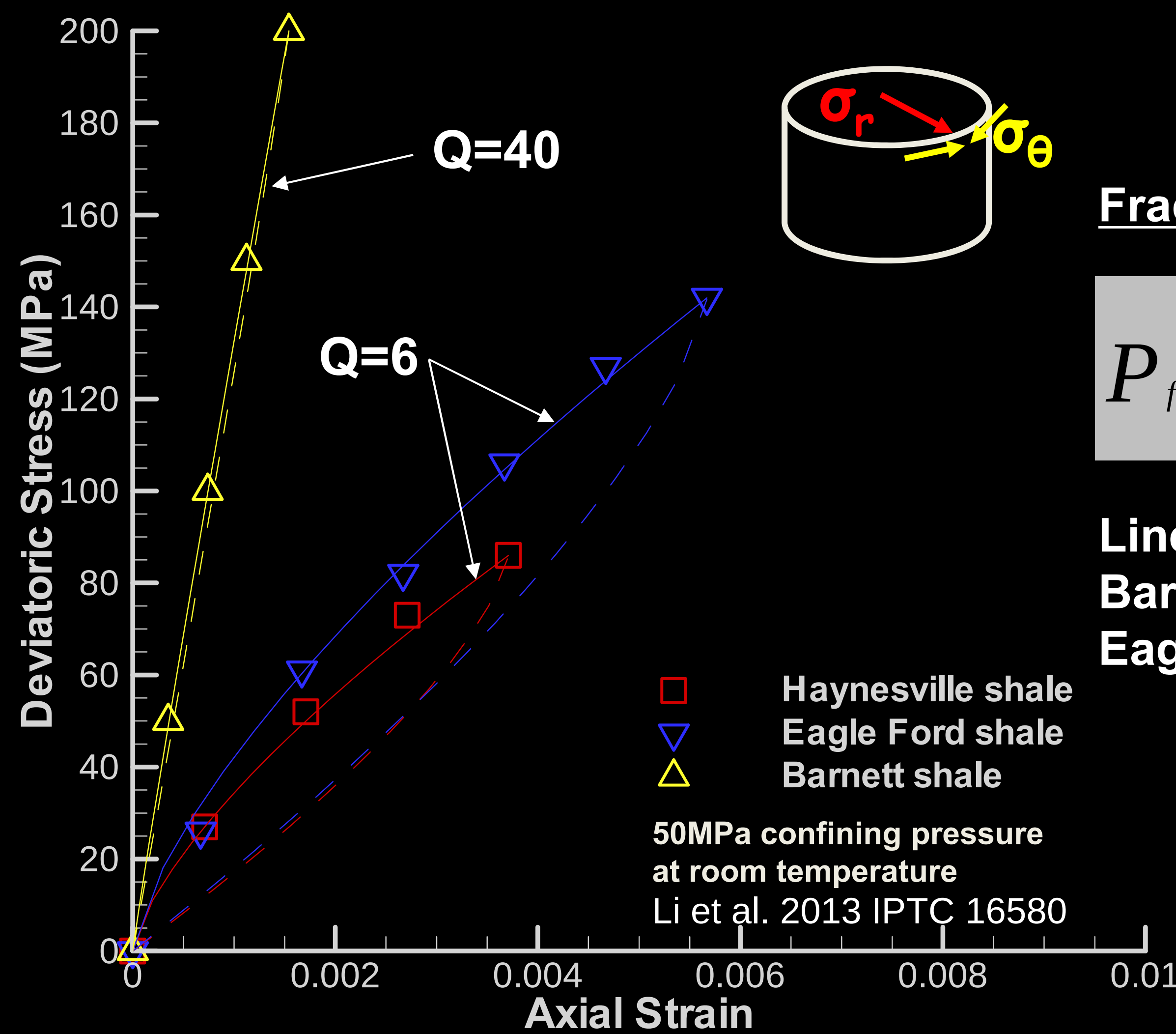
Split Casing Frac Lengths

$$R_f C_f = \frac{32\mu(1-\upsilon)h_f l_f}{a_s G b_f^3}$$





Strong Shale Source Rocks



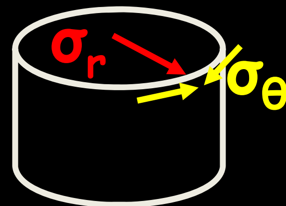
Frac Fluid Pressure Efficiency

$$P_{frac}eff = \frac{\Delta\sigma_\theta}{\Delta\sigma_r} = \frac{Q-3}{Q+1}$$

Linear Elastic P_{frac}eff=100%
Barnett P_{frac}eff=90%
Eagle Ford P_{frac}eff=40%

Strong Shale Source Rocks

Brittleness Index:



- Young's Modulus
- Poisson's Ratio
- Mineralogy

Current Frac Target:

Highly Brittle low TOC

- Ability to frac
- Presumed complex frac pattern

High TOC less Brittle

- Frac initiation may be required
- Production data needed
- Potential proppant embedment

Frac Fluid Pressure Efficiency

$$P_{frac}eff = \frac{\Delta\sigma_\theta}{\Delta\sigma_r} = \frac{Q-3}{Q+1}$$

Linear Elastic P_{frac}eff=100%
Q=6 P_{frac}eff=40%
Q=3 P_{frac}eff=0%

Conclusions

- **Stimulation completion dictates the outcome**
  - Mini-Frac thru' perfs or open-hole suspect in non-brittle weak formations
  - Stimulation thru' perfs will not excite least energy dissipating mechanism in non-brittle weak formations
  - Essential to initiate frac in non-brittle formations
  - Need to re-assess earlier stimulation data & experience
- **Anelasticity defines need for frac initiation**
  - Frac fluid pressure efficiency α Q
  - Frac fluid pressure alone may not initiate a frac in anelastic formations, whether strong or weak
  - Brittleness Index to include anelasticity or lack of
  - Quantify production data in high TOC less brittle shale zones

Acknowledgement: Authors thank Halliburton for permission to publish this paper.