

Petroleum Geomechanics

The Importance of Anelasticity

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Presentation Overview

Anelasticity

- Linear elastic vs anelastic
- Superposition with explicit path dependence
- Analytical solutions
- Better behavior & mechanistic insight

Applications

- Drilling, mud weight, frac gradient, wellbore stability.
- Sonic log & formation evaluation
- Mechanical earth model
- Initiation, breakdown & propagation of hydraulic fractures and interaction with natural fractures
- Stress shadow effects – Zipper fracs

Conclusions

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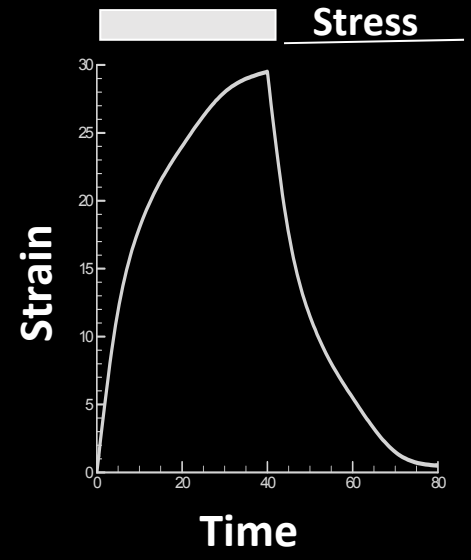
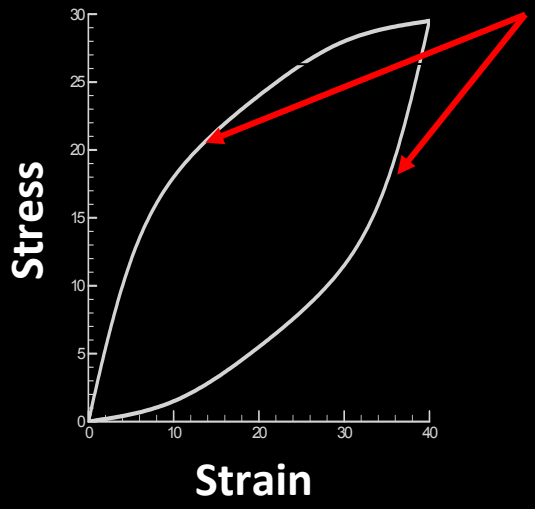
Anelasticity



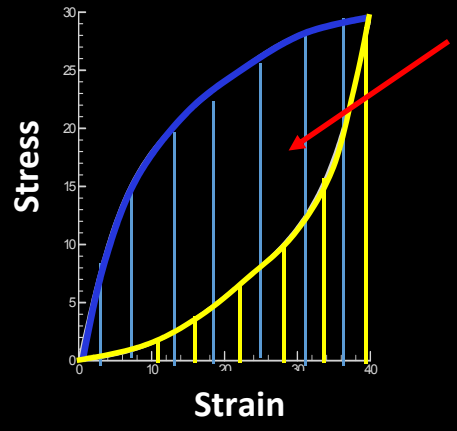
Loss Factor $\eta = \frac{E''}{E'} = \tan\phi$

For small losses

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



Hysteresis strain lags stress lost energy



Q – Quality Factor

Q=3 33% energy loss over load/unload cycle

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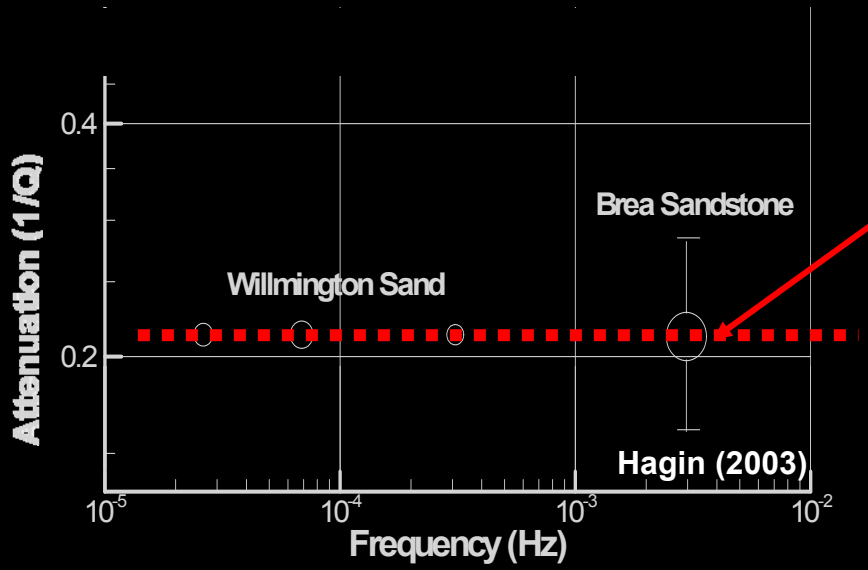
Anelasticity

Anelasticity Q Factor

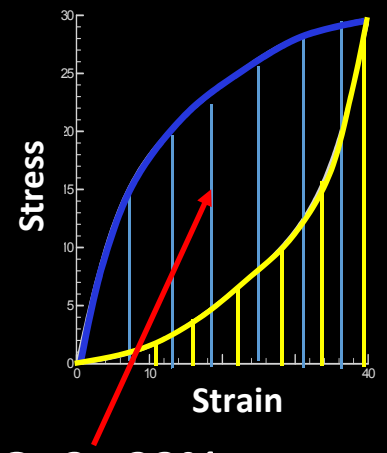
- Energy lost over load/unload cycle divided by total energy

Acoustic/Seismic Attenuation Q_a Factor

- Energy lost per radian divided by average energy, for $Q_a>20$, $Q=Q_a$, at low Q_a, $Q\approx0.6Q_a$



Q – Quality Factor



Q=3 33% energy lost over load/unload cycle

Dry Sands/Weak Sandstones

$Q_a\approx5$ i.e. $Q\approx3$ Quality Factor, being a 33% energy loss over load/unload cycle

Fluids, porosity, permeability, fractures all affect Q_a, as does the mineral composition.

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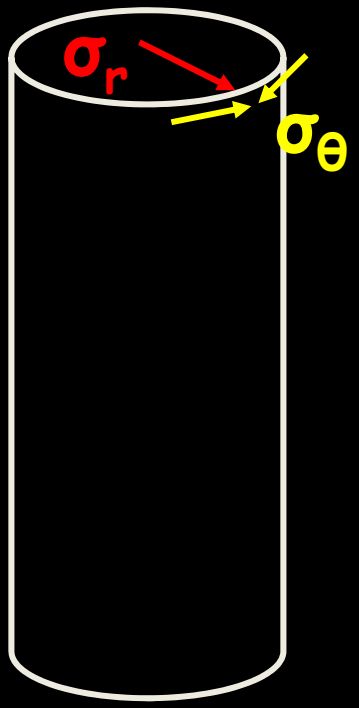
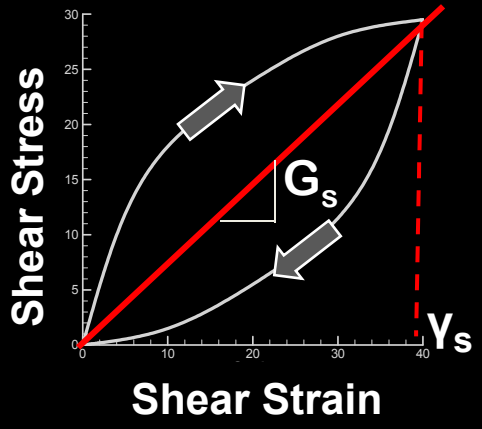
Anelasticity – Borehole

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

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

$$\beta = \frac{Q-1}{Q+1}$$

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

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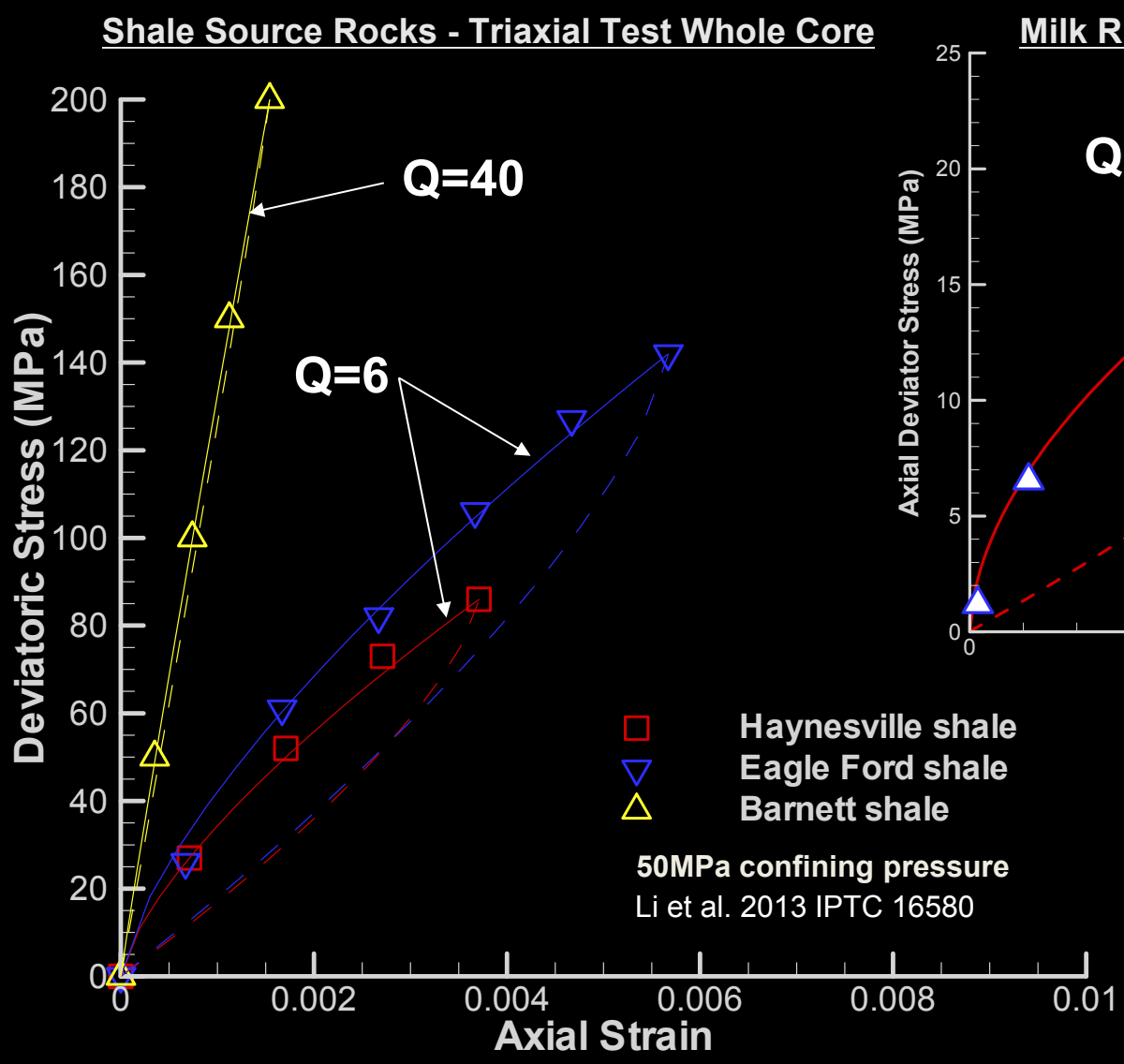
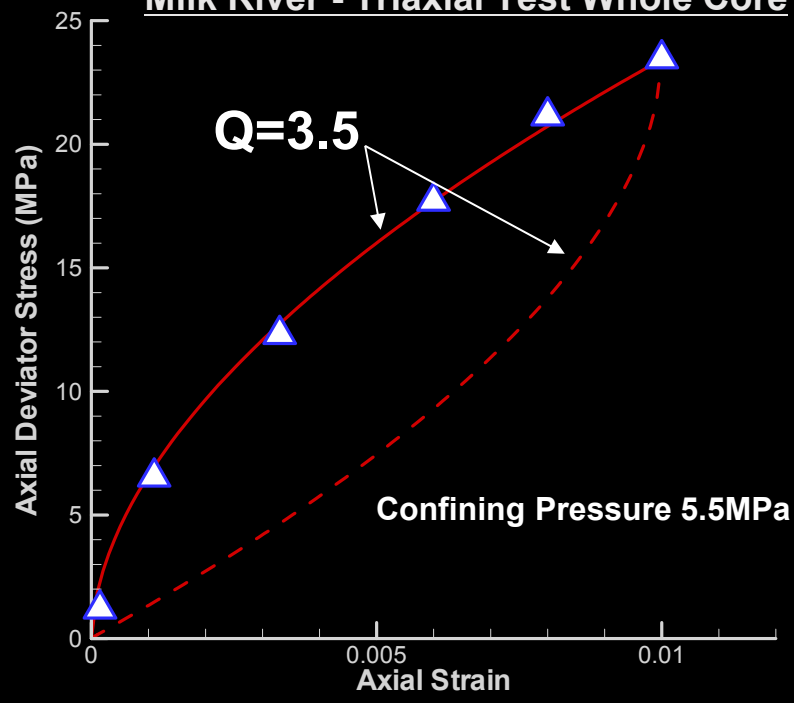
Anelasticity – Q Factors





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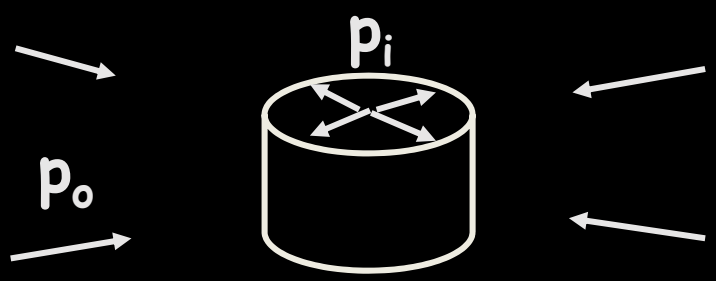
Anelasticity – Analytic Solutions



Analytic Anelastic Solutions

- Viscoelastic with minimal time constant
- Superposition path dependent

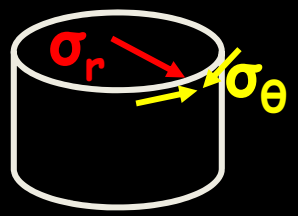
Pressurized Borehole

Airy Stress Function:

$$\varphi = \frac{p_i}{2(1-\beta)}\left(\frac{a}{r}\right)^{2\beta} r^2$$

Pressurized Borehole

Stress at infinity p_o:



$$\sigma_r = p_o + (p_i - p_o)\left(\frac{a}{r}\right)^{2\beta}$$

$$\sigma_\theta = p_o + (p_i - p_o)(1-2\beta)\left(\frac{a}{r}\right)^{2\beta}$$

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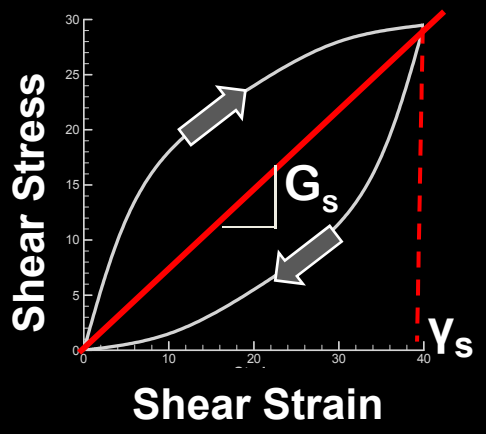
Anelasticity – Linear vs Anelastic

Linear Elastic

- Analytical solutions available
- Superposition path independent
- Q<20 invalid model, large errors

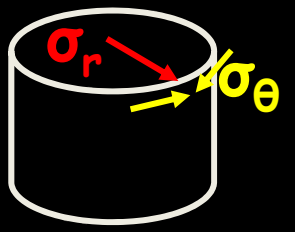


Anelastic

- Elastic but not linear, simple model
- Superposition path dependent
- Superior behavior & mechanistic insight

Analytic Anelastic Solutions

- Circular, elliptical & crack
- General stress state at infinity
- Pressurized



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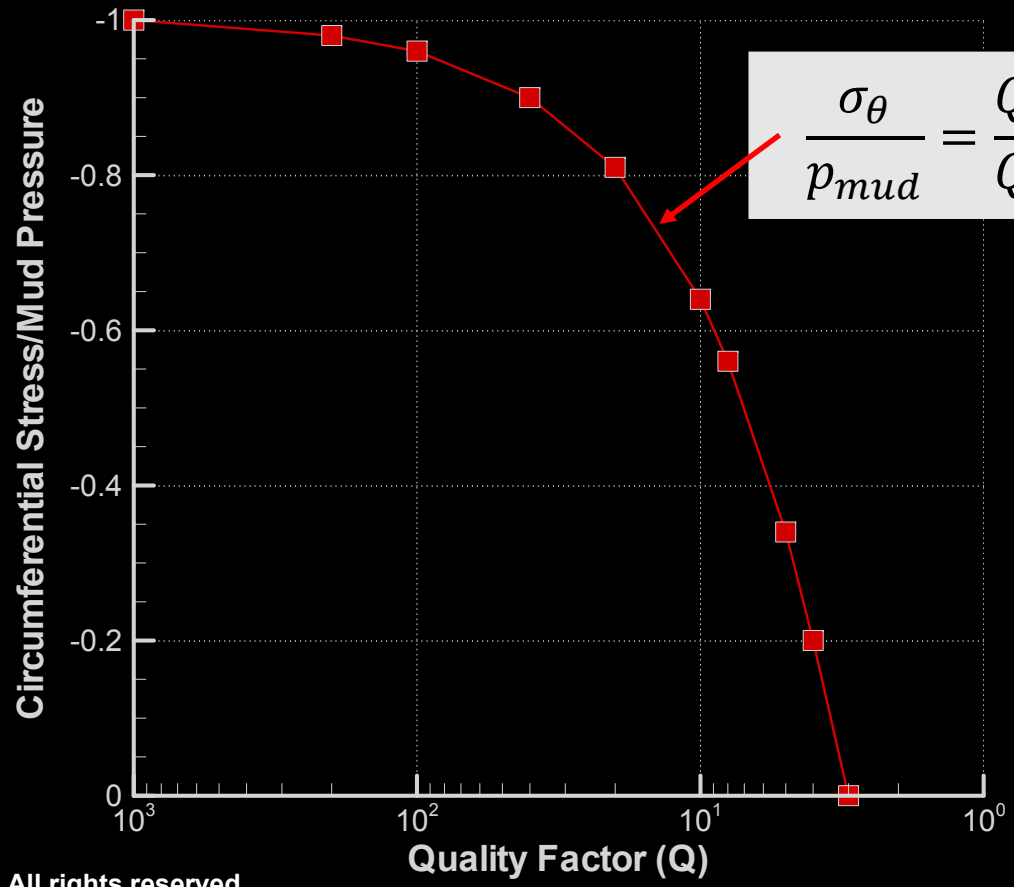
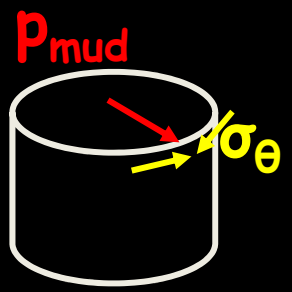
Anelasticity – Drilling Mud

Drilling Mud Impact vs Q

- Non-penetrating fluid
- Mud pressure on borehole circumferential stress



$$\frac{\sigma_\theta}{p_{mud}} = \frac{Q-3}{Q+1}$$



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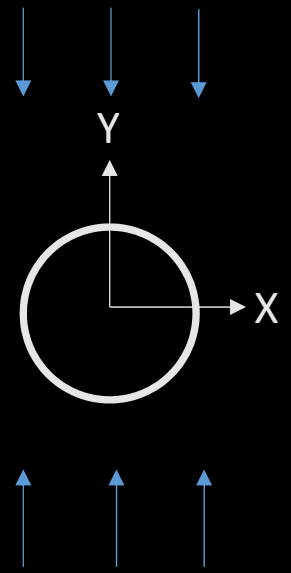
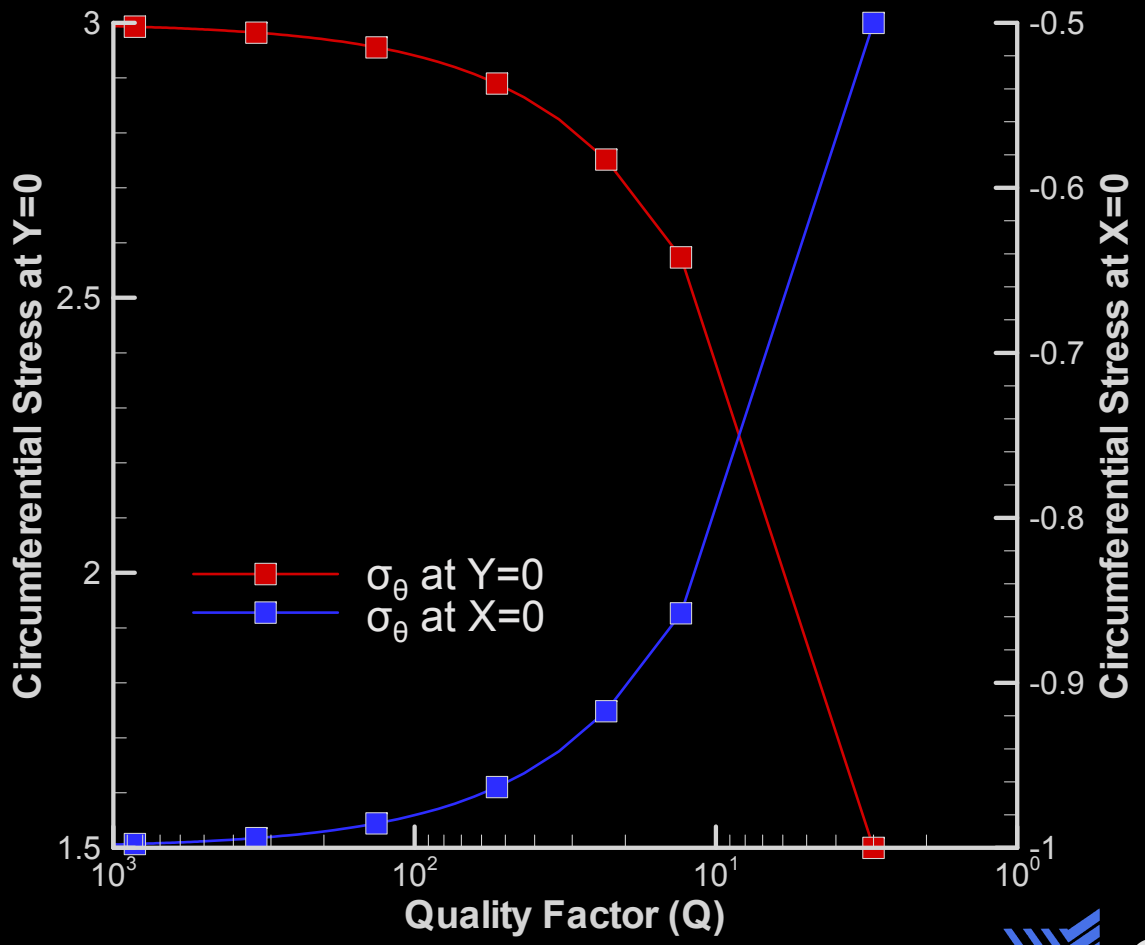
Anelasticity - Borehole

Unixial Stress at Infinity – No Pressurization





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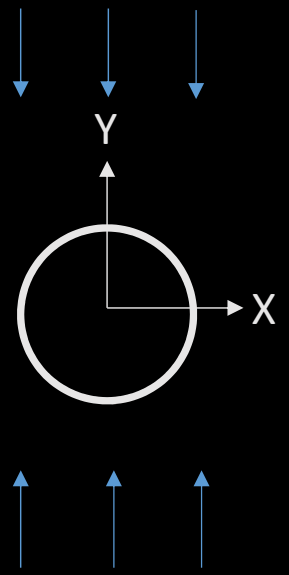
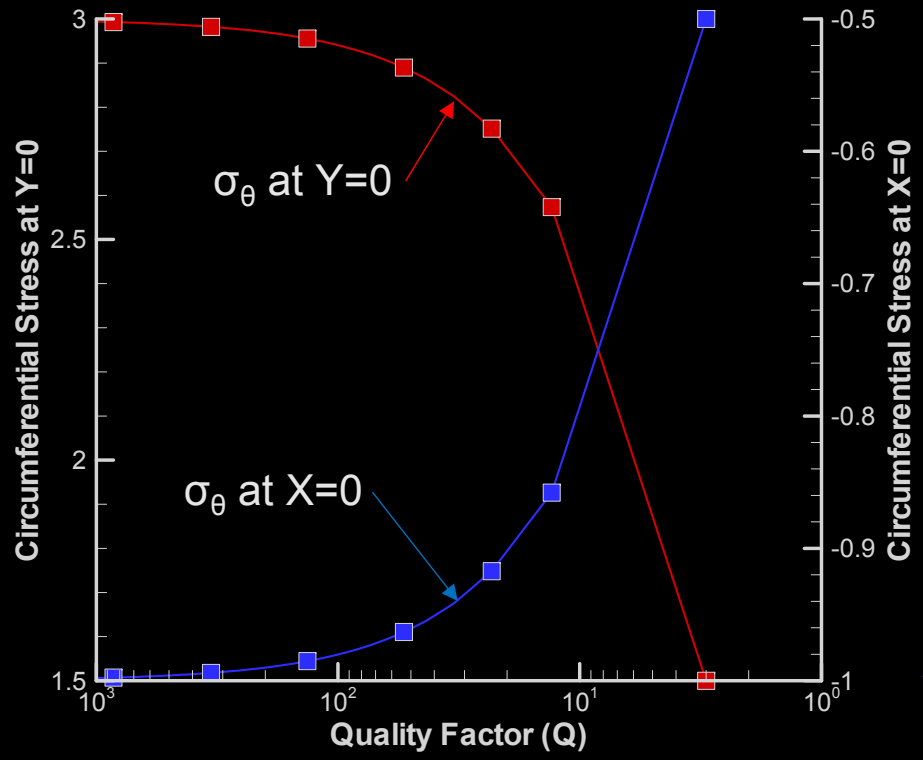
Anelasticity - Borehole

Mechanical Earth Model

- Linear elastic
  - large errors in $\sigma_{h\ max}$
  - misinterpret of sonic logs
- Anelastic model essential for Q<20





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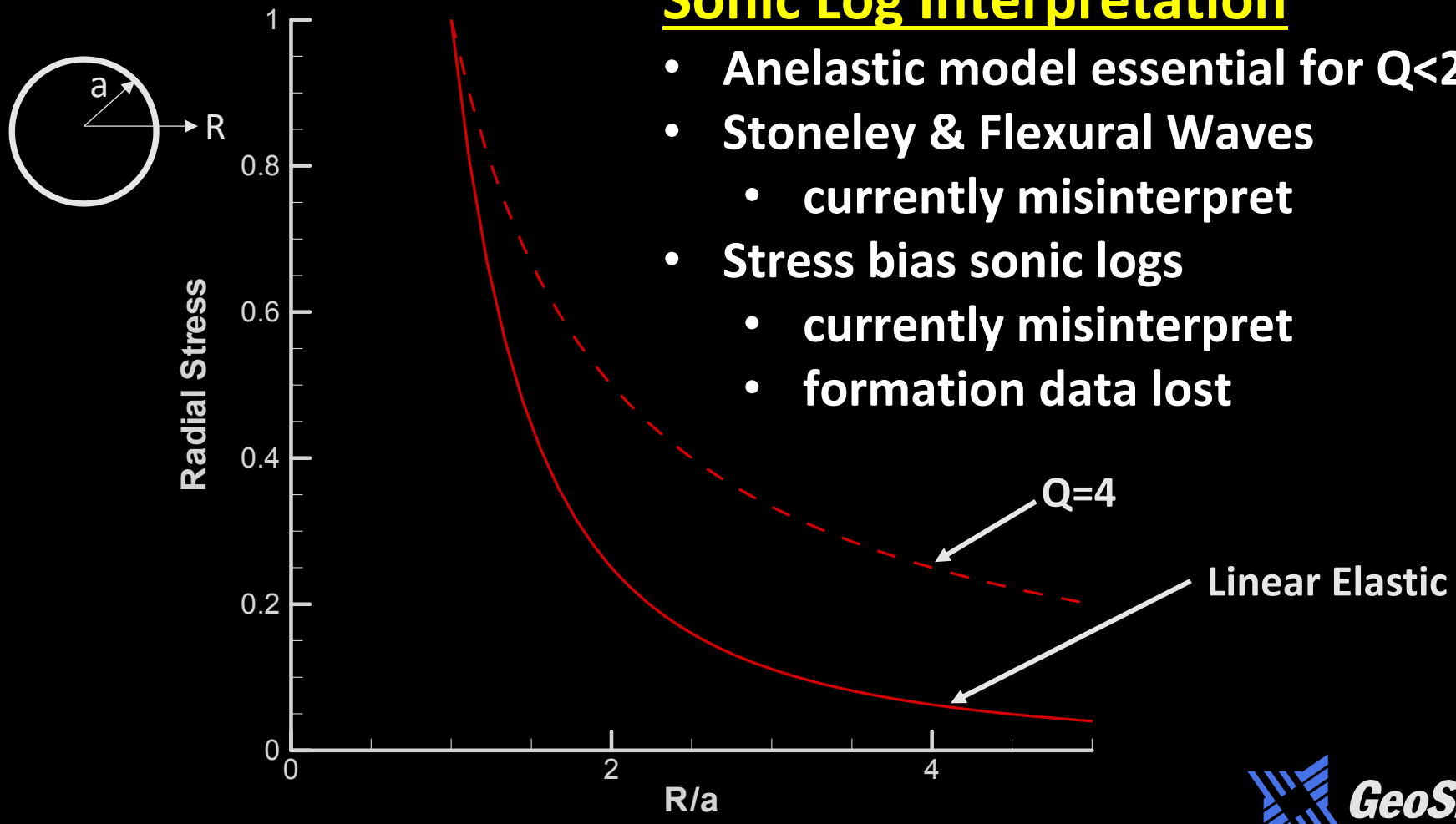
Anelasticity - Borehole

Pressurized Borehole – Zone of Influence



Sonic Log Interpretation

- Anelastic model essential for Q<20
- Stoneley & Flexural Waves
  - currently misinterpret
- Stress bias sonic logs
  - currently misinterpret
  - formation data lost

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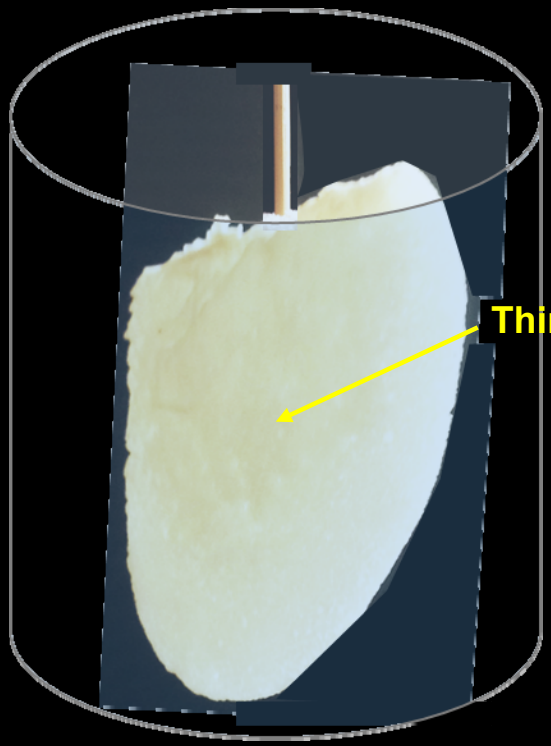
Hydraulic Fracturing – Gelatin

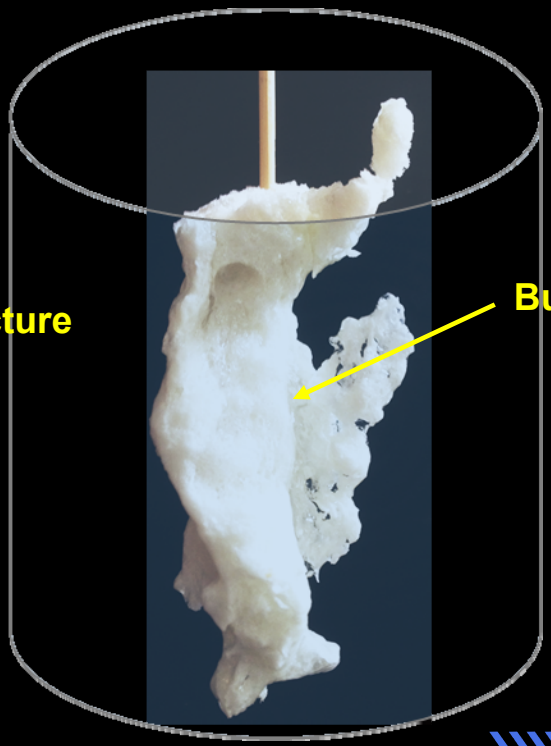
Ballistic Gelatin

- Foam injected through vertical tube
- Same gelatin but at different temperatures

Cold Gelatin Q=6



Warm Gelatin Q=3



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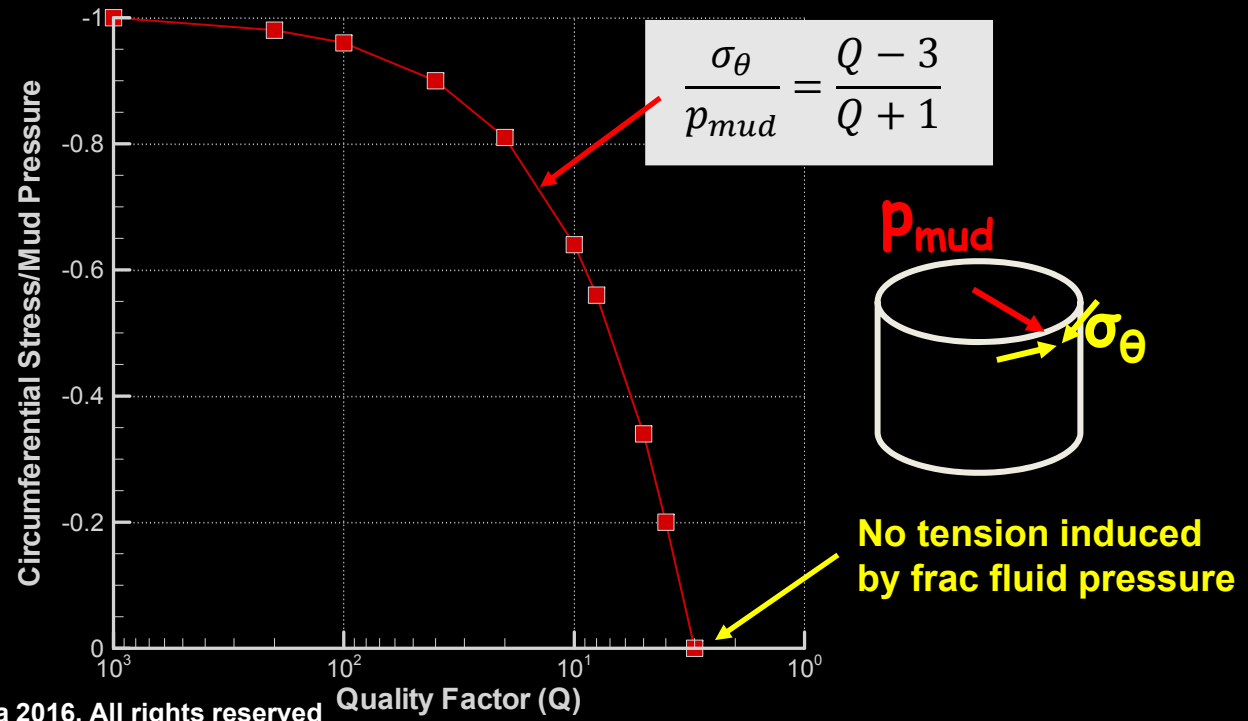
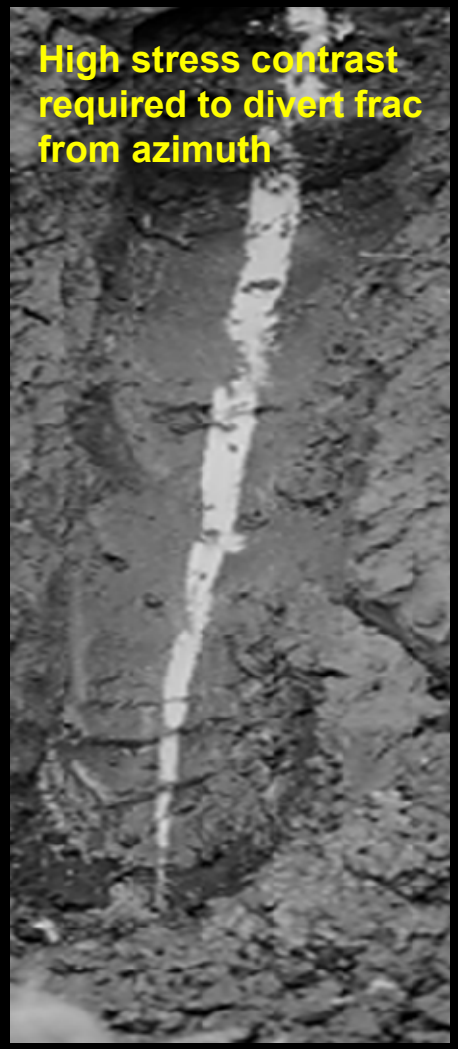
Anelasticity – Frac Initiation

Low Q Factor Formations – Frac Initiation

- Hydraulic fracturing fluid can't induce tension
- Need to initiate tension to generate frac
  - Slotting, shape charge, sleeve frac, etc.
- Frac propagation plane more azimuth stable





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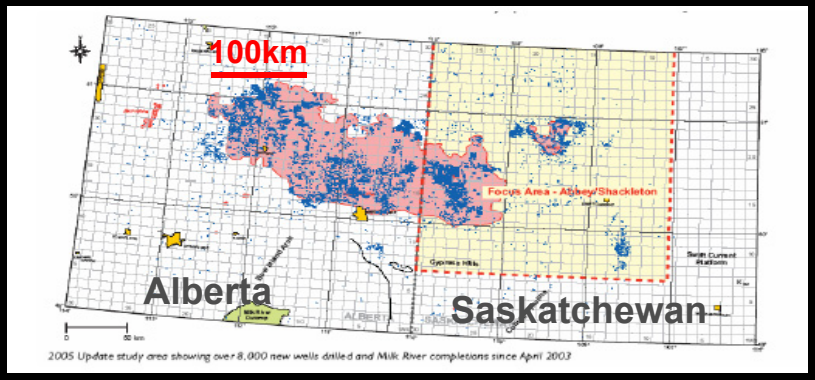
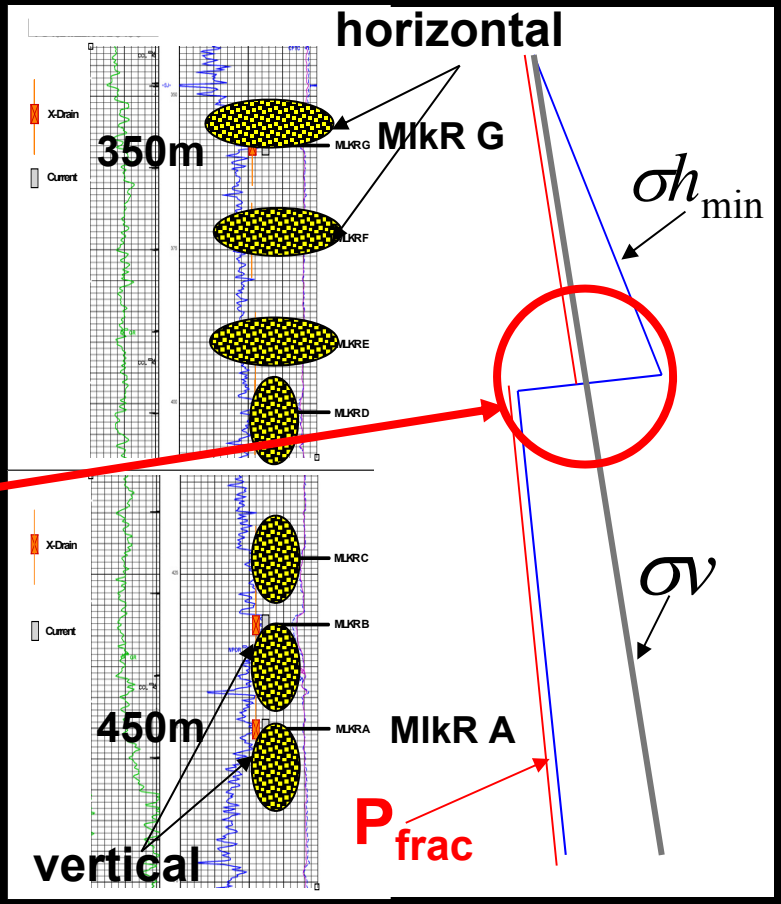
Milk River Tight Gas Reservoir

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)

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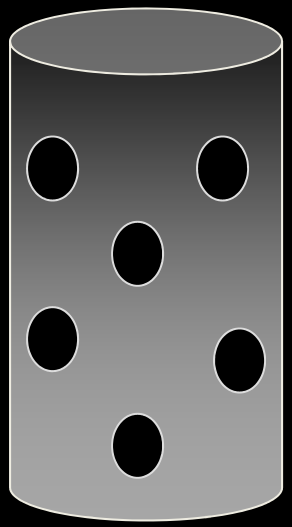
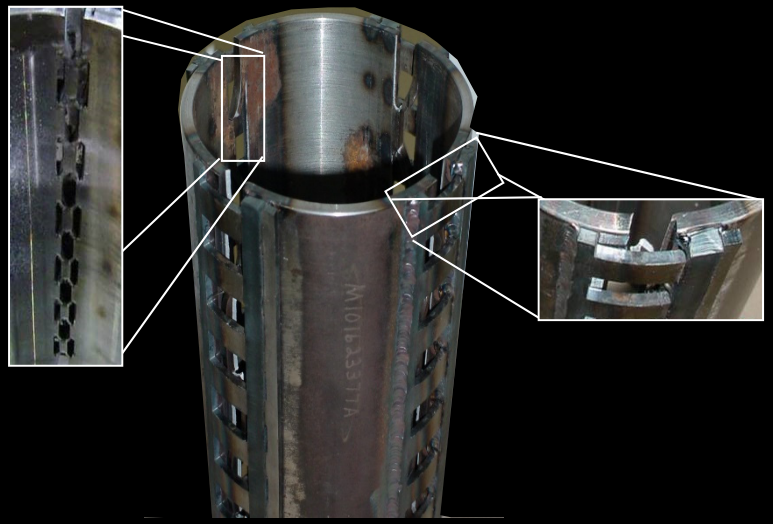
Offset Well Stimulation Comparison

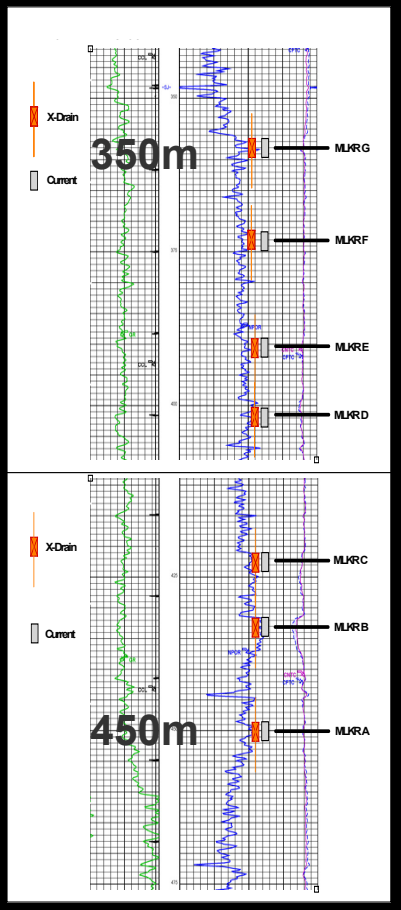
Perforations



Dilating Casing



Milk River



MlkR G

MlkR A

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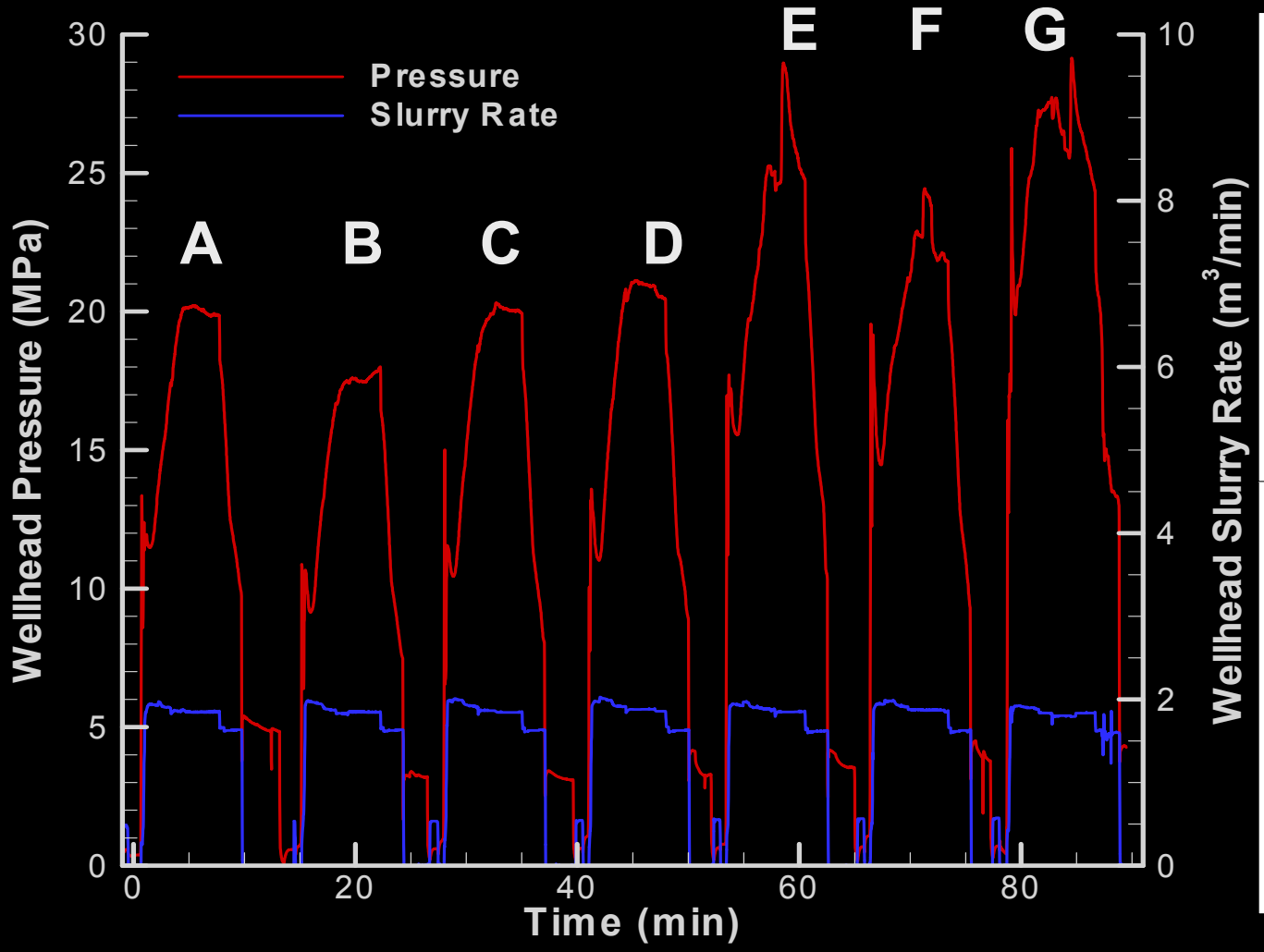
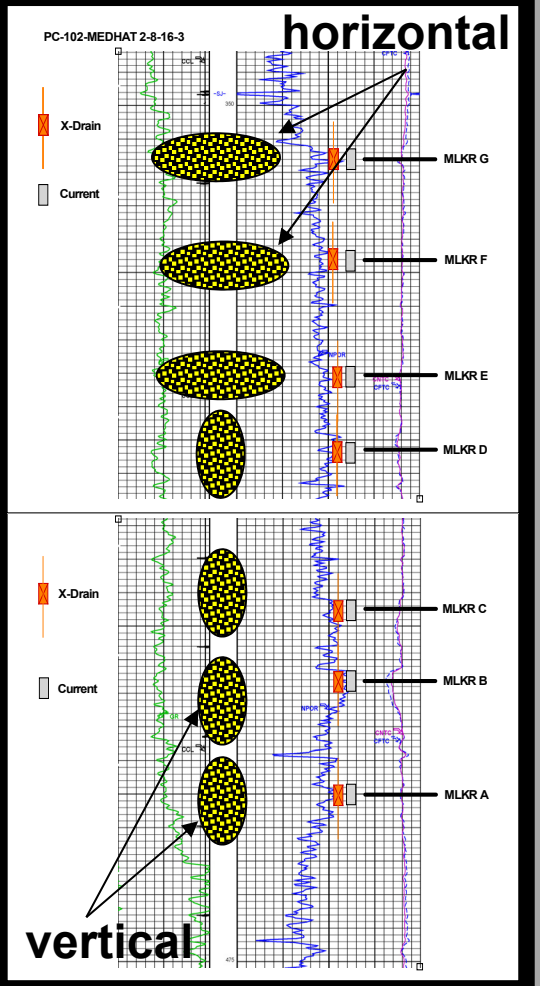
Conventional Stimulations





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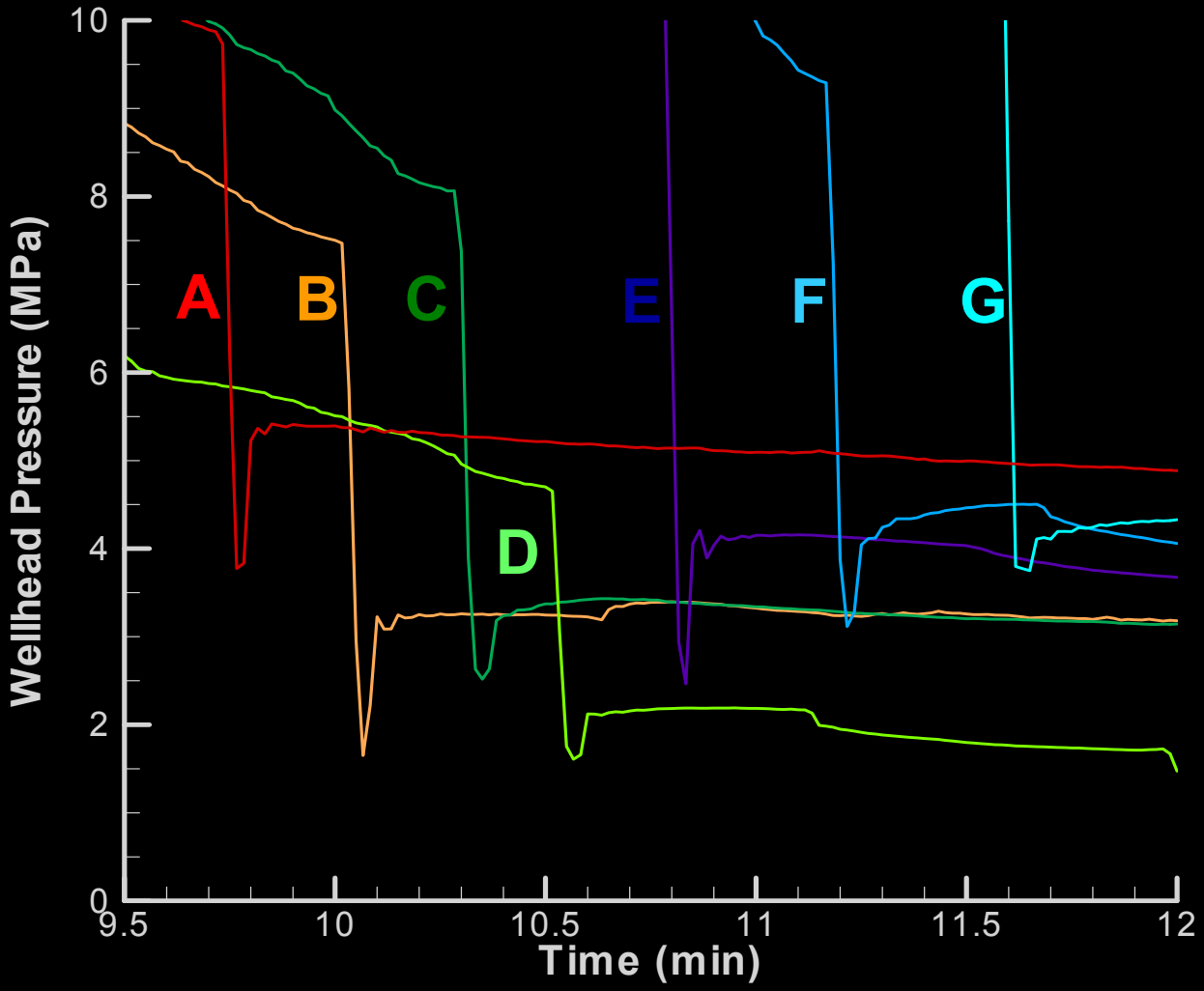
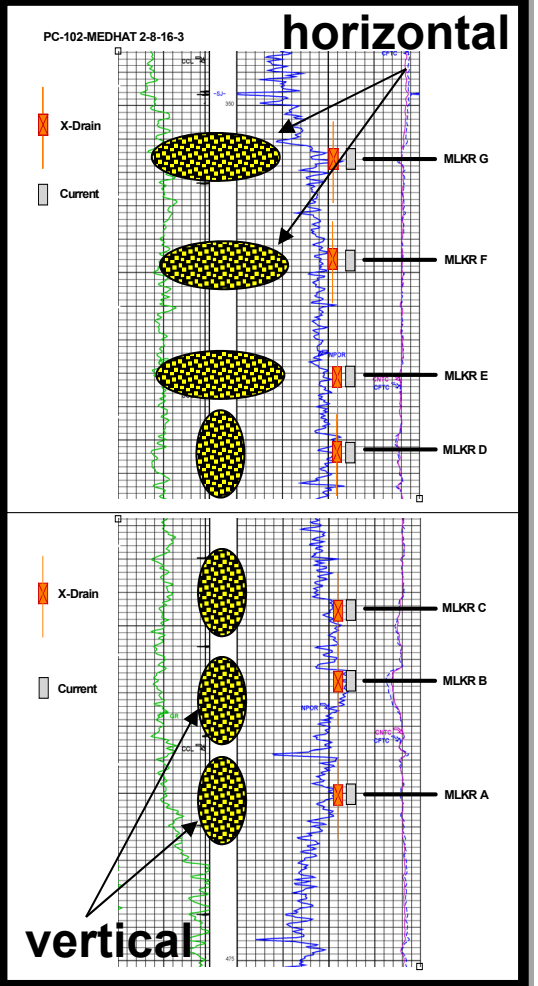
Conventional Stimulations





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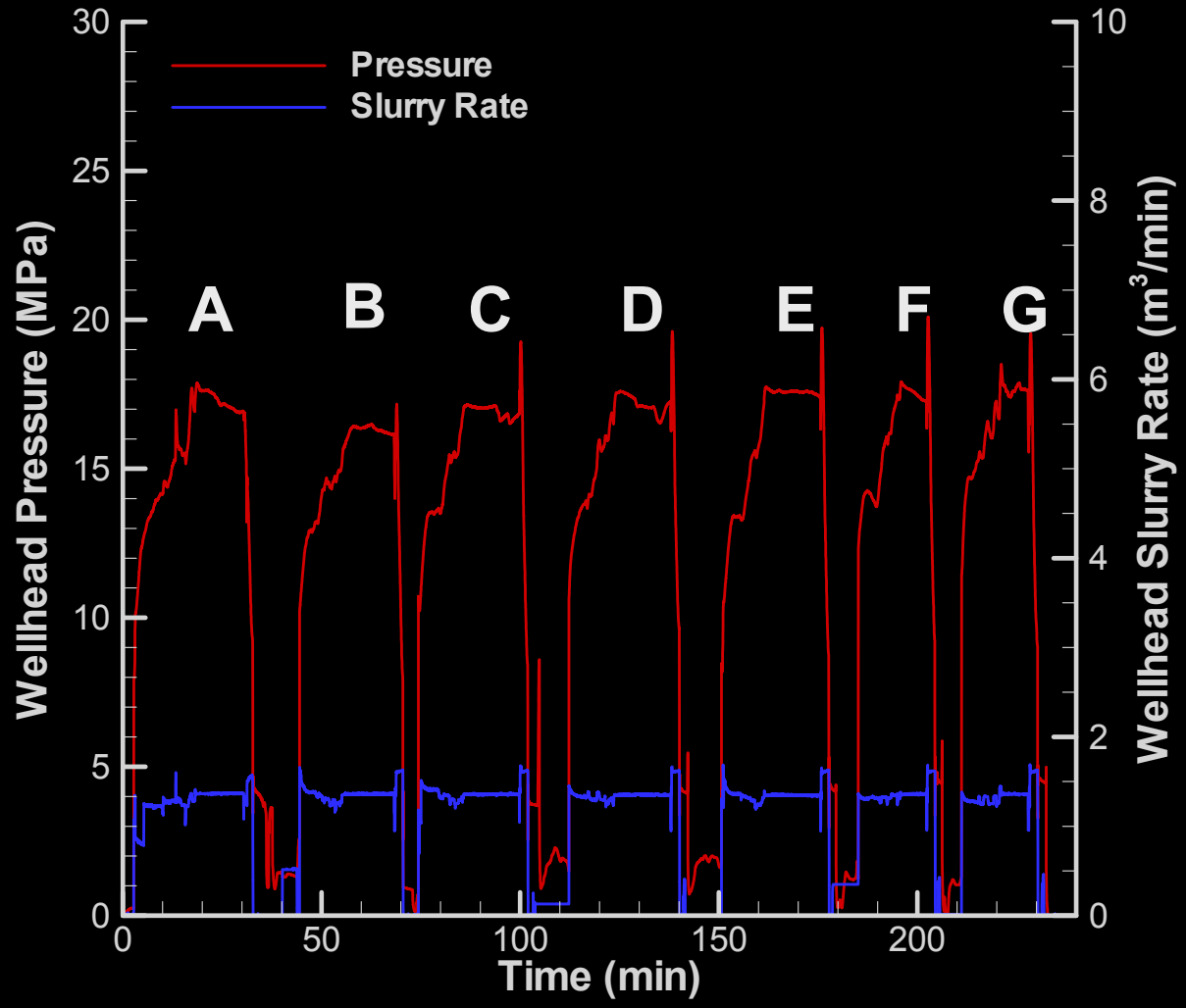
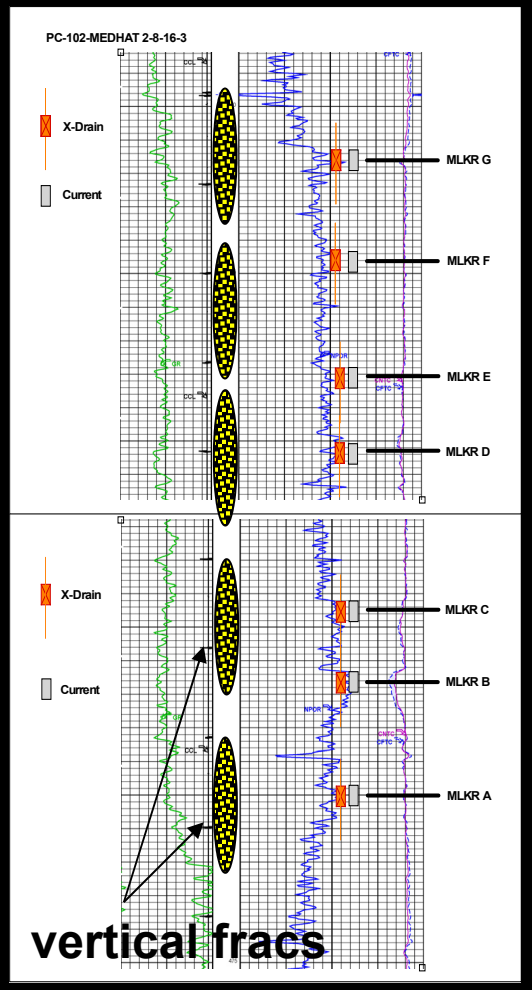
Split Dilating Casing Stimulations





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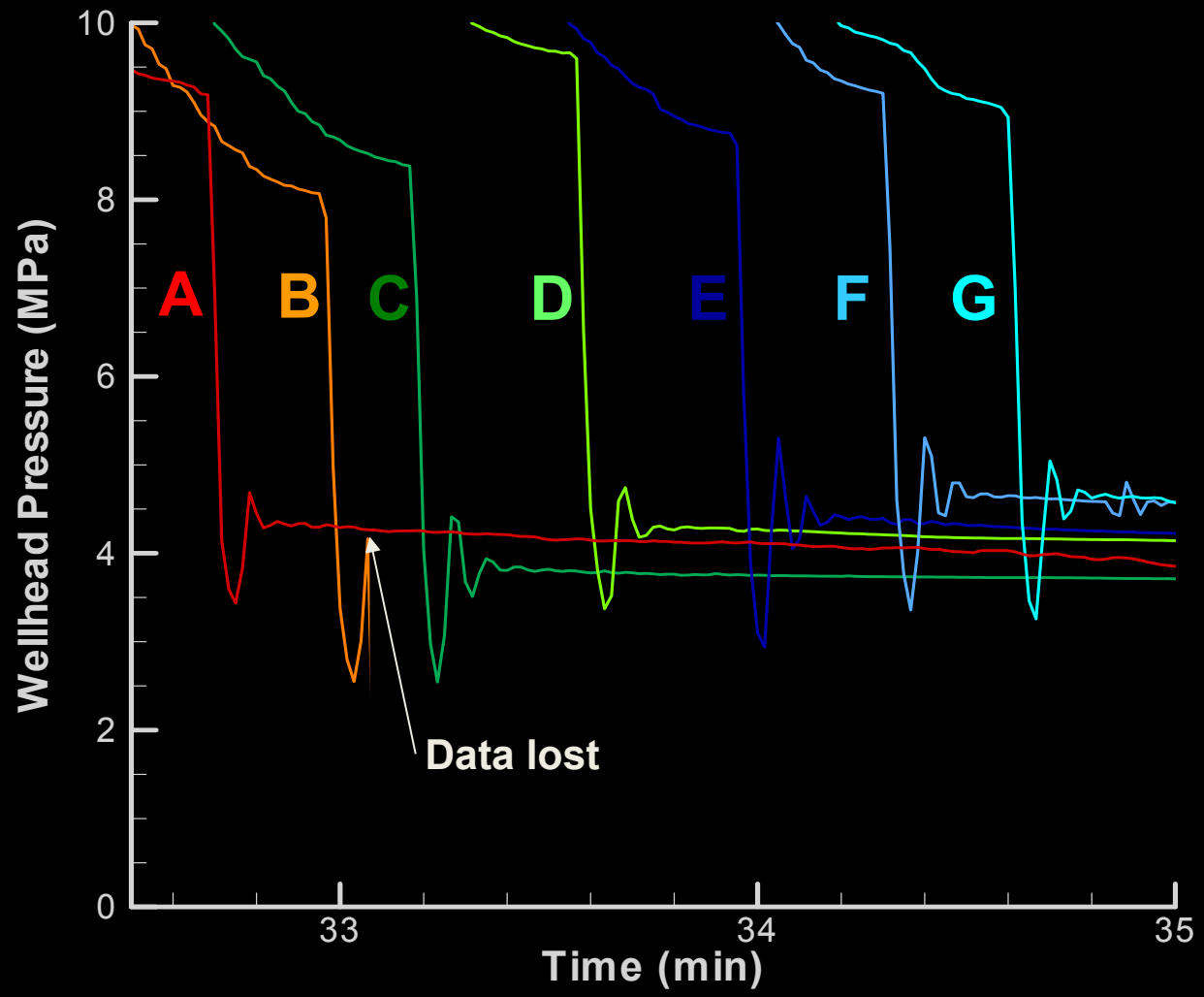
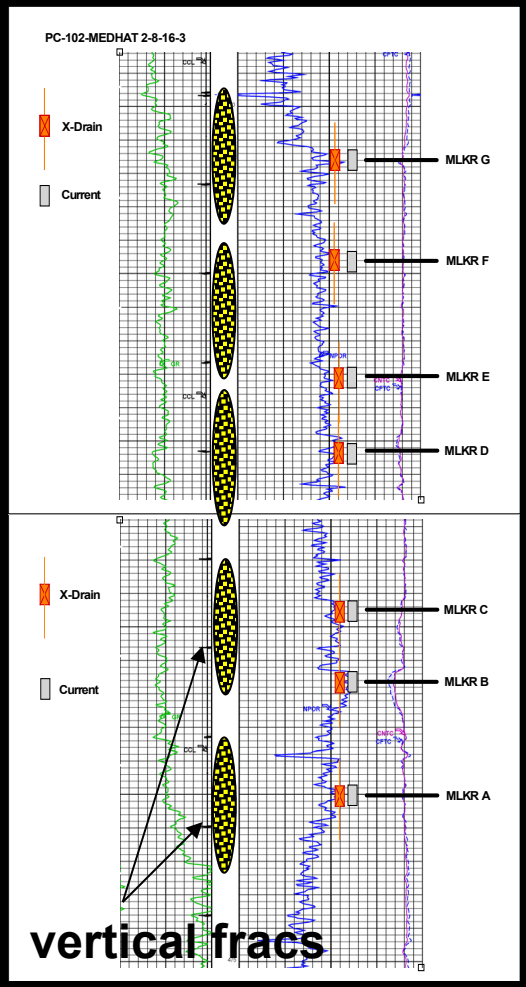
Split Dilating Casing Stimulations





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Anelasticity – Frac Initiation

Low Q Factor Formations

- Hydraulic fracturing thru' perfs
  - fluid can't induce tension – no frac
  - vertical bulbous cavity expansions
  - horizontal fracs with σ_v not minimum
- Need to initiate tension to generate frac
  - Slotting, shape charge, sleeve frac, etc.

Short Bulbous Cavities

Experience – no Prod Enhancement

- Milk River tight gas reservoir
- Lower Stevens turbidites - light oil
- Turbidites with higher clay content
  - edge of fan or diagenesis

Short Stubby Hz Fracs

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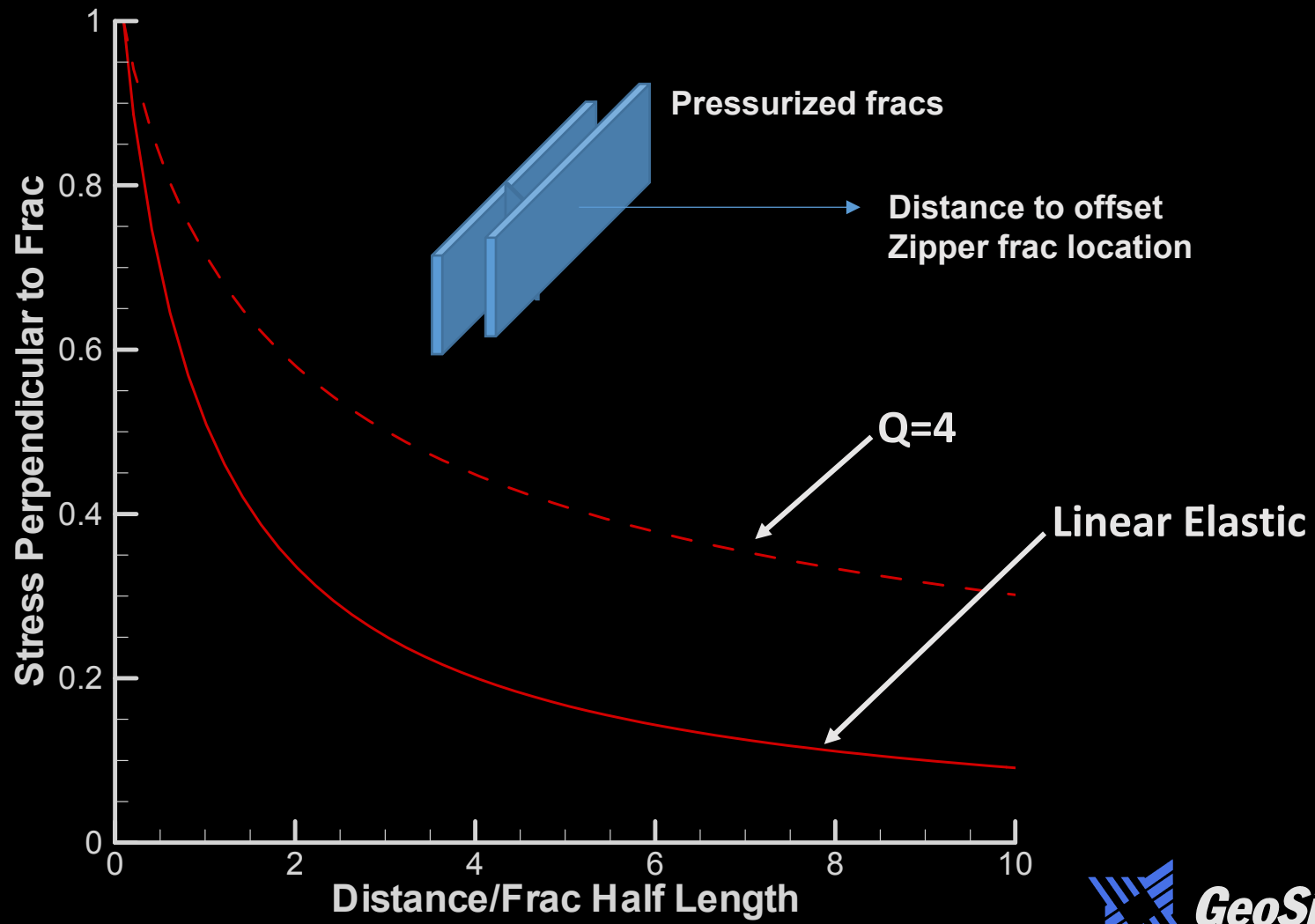
Anelasticity – Zipper Fracs

Pressurized Fracs – Stress Shadow Effects



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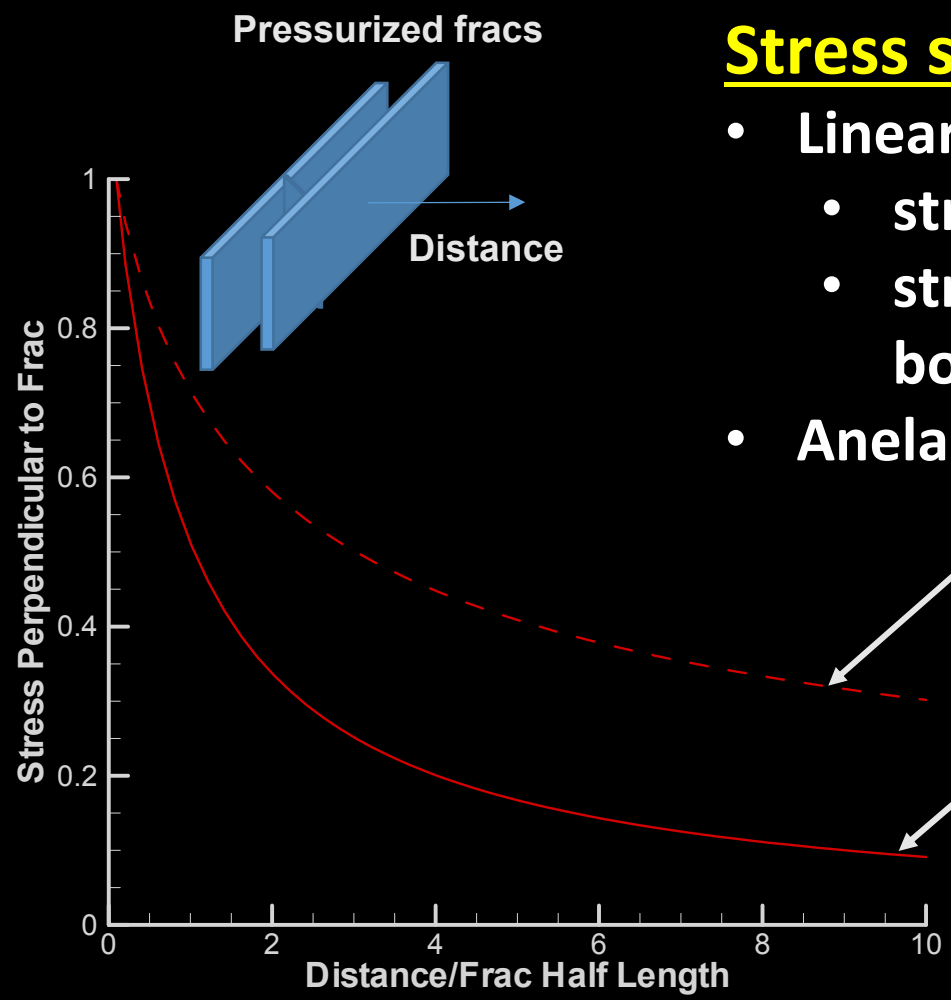
Anelasticity – Zipper Fracs

Pressurized Fracs – Stress Shadow Effects



Stress shadow effects

- Linear elastic
  - stress regime incorrect
  - stress shadow underestimated both in magnitude & extent
- Anelastic model essential for Q<20

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Conclusions

Linear Elastic

- Q<20 invalid model with large errors

Anelasticity

- Elastic but not linear, simple model
- Analytic solutions available
- Superposition path dependent
- Superior behavior & mechanistic insight

Application

- Most shale source & clay rich reservoir plays
  - Drilling, sonic logs, MEM, formation evaluation
  - Frac initiation & propagation
  - Stress shadow effects

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