SPE HeavyOil CONFERENCE Canada
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SPE165433

Vertical Single-Well SAGD with Multiple Producers

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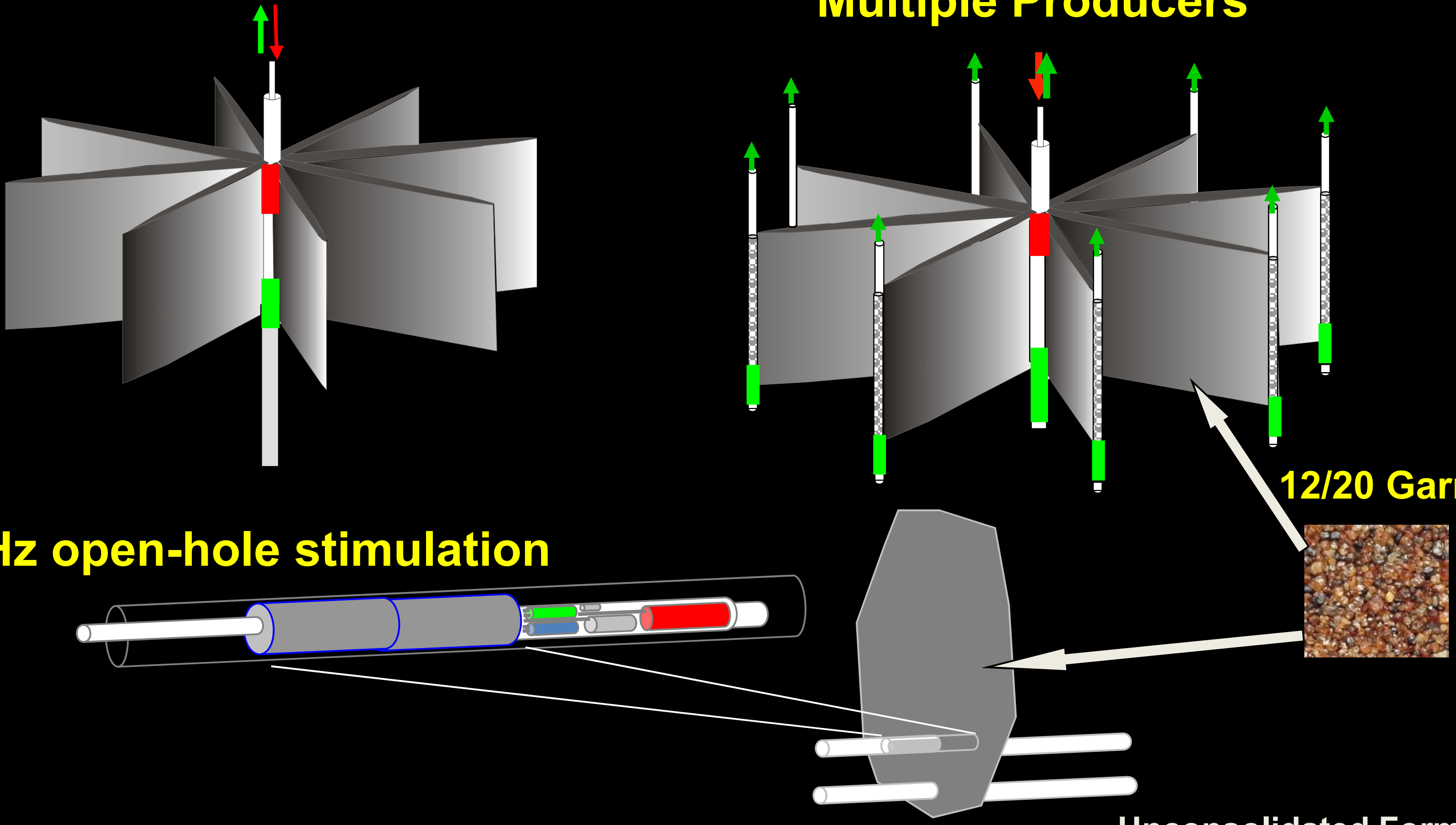
Frac Enhanced SAGD



Single-Well SAGD

Single-Well SAGD with Multiple Producers

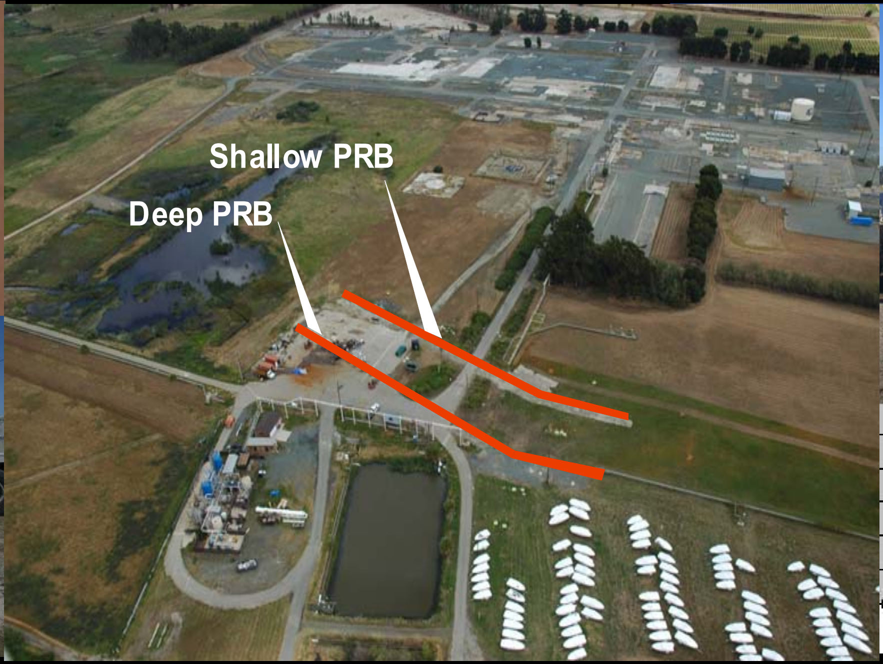
Hz open-hole stimulation

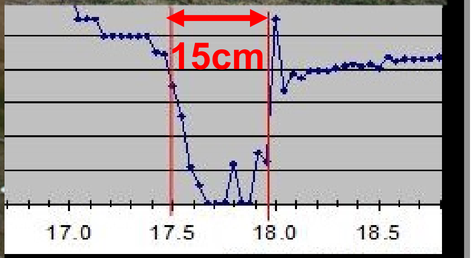
12/20 Garnet

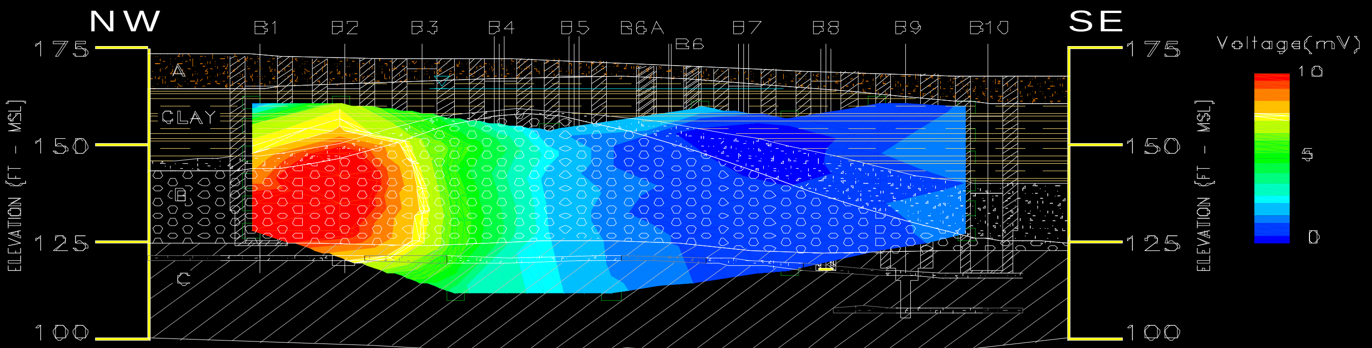
Unconsolidated Formations

Azimuth Controlled Fracturing

Azimuth Controlled Fracturing







Real Time Active Resistivity Image

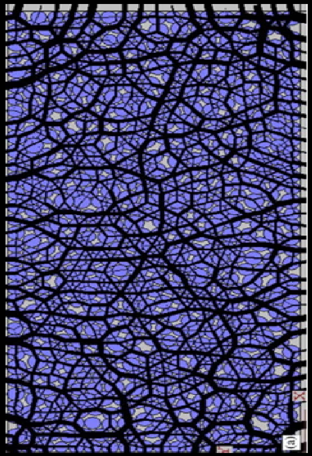
Unconsolidated Formations

Non-Brittle Weak Formations

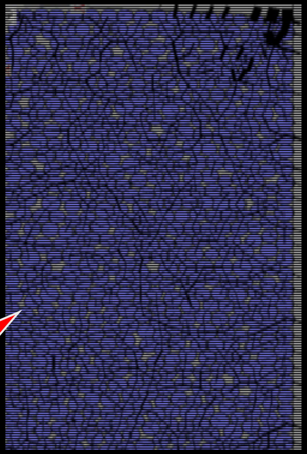
Weakly Cemented Formations

- 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



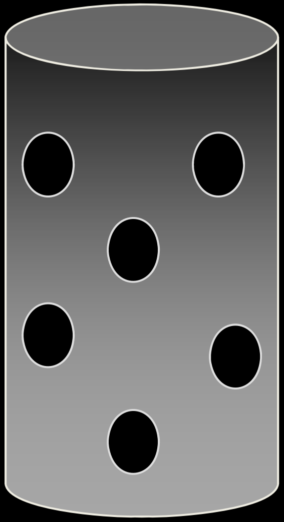
Force Chains Destroyed



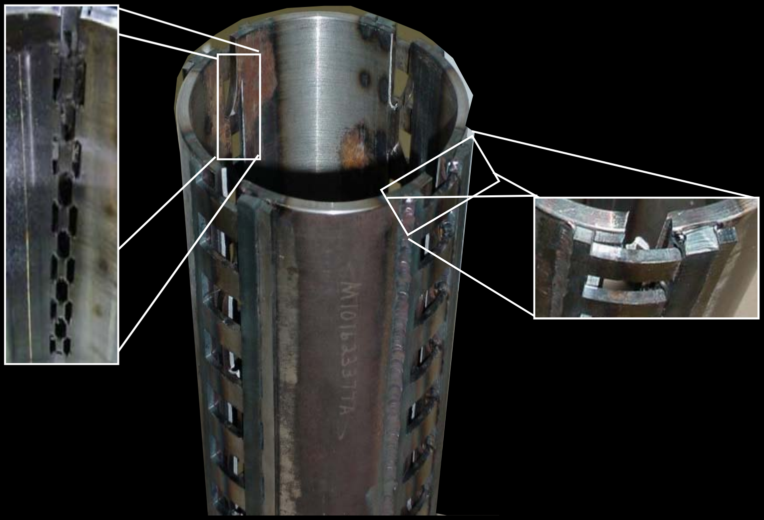
Minor Shear Strain Destroys Force Chains

Offset Well Stimulation Comparison

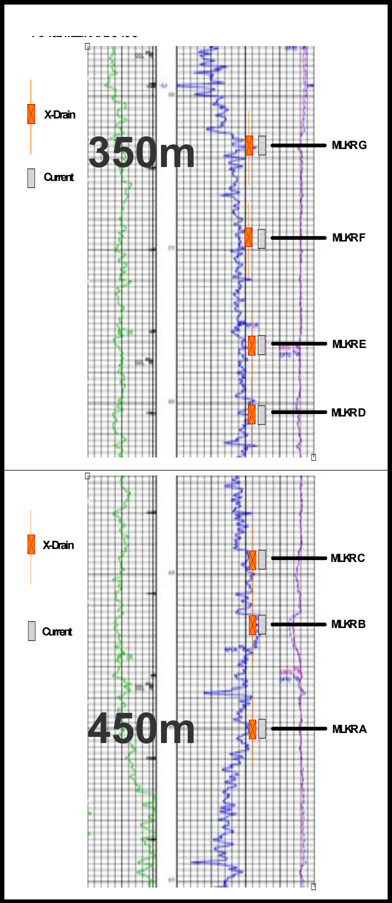
Perforations



Dilating Casing



Milk River



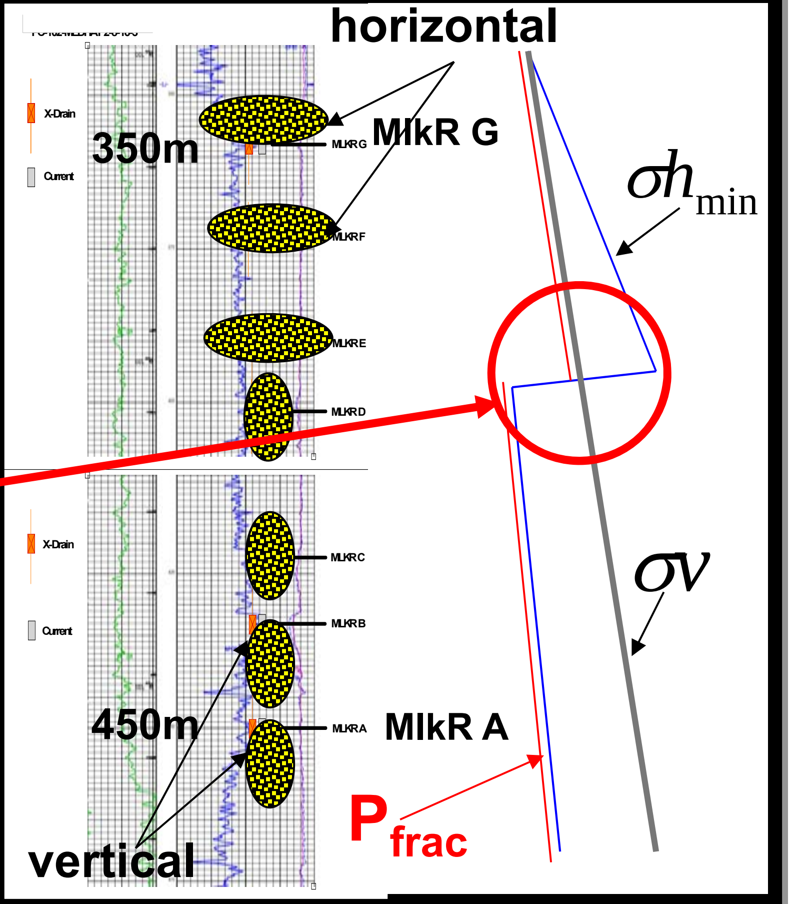
MlkR G

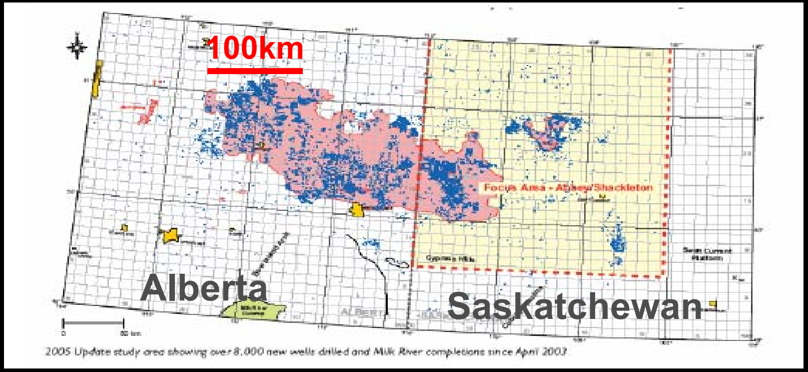
MlkR A

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





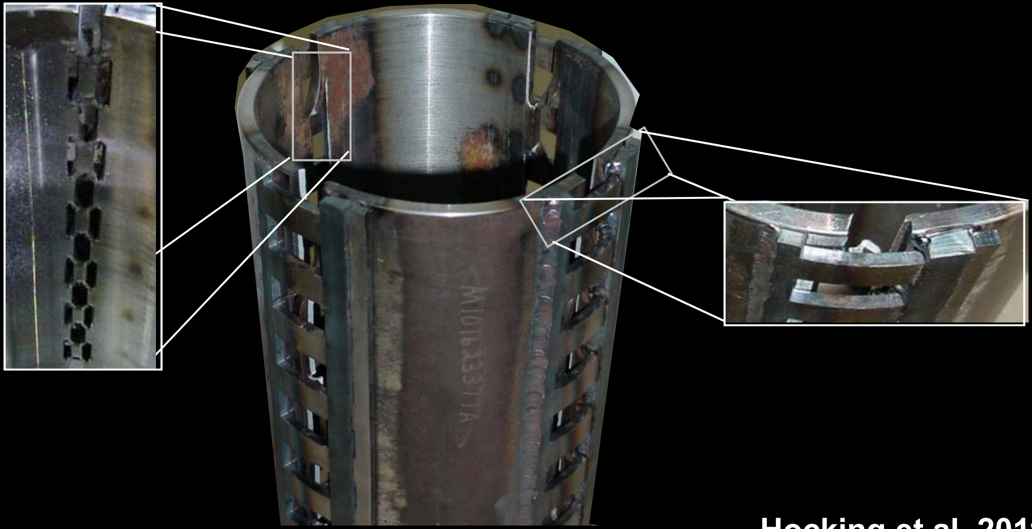
2005 Update study area showing over 8,000 new wells drilled and Milk River completions since April 2003

Note: UCS*=2c'tan(45+ ϕ/2)

Milk River Tight Gas Reservoir

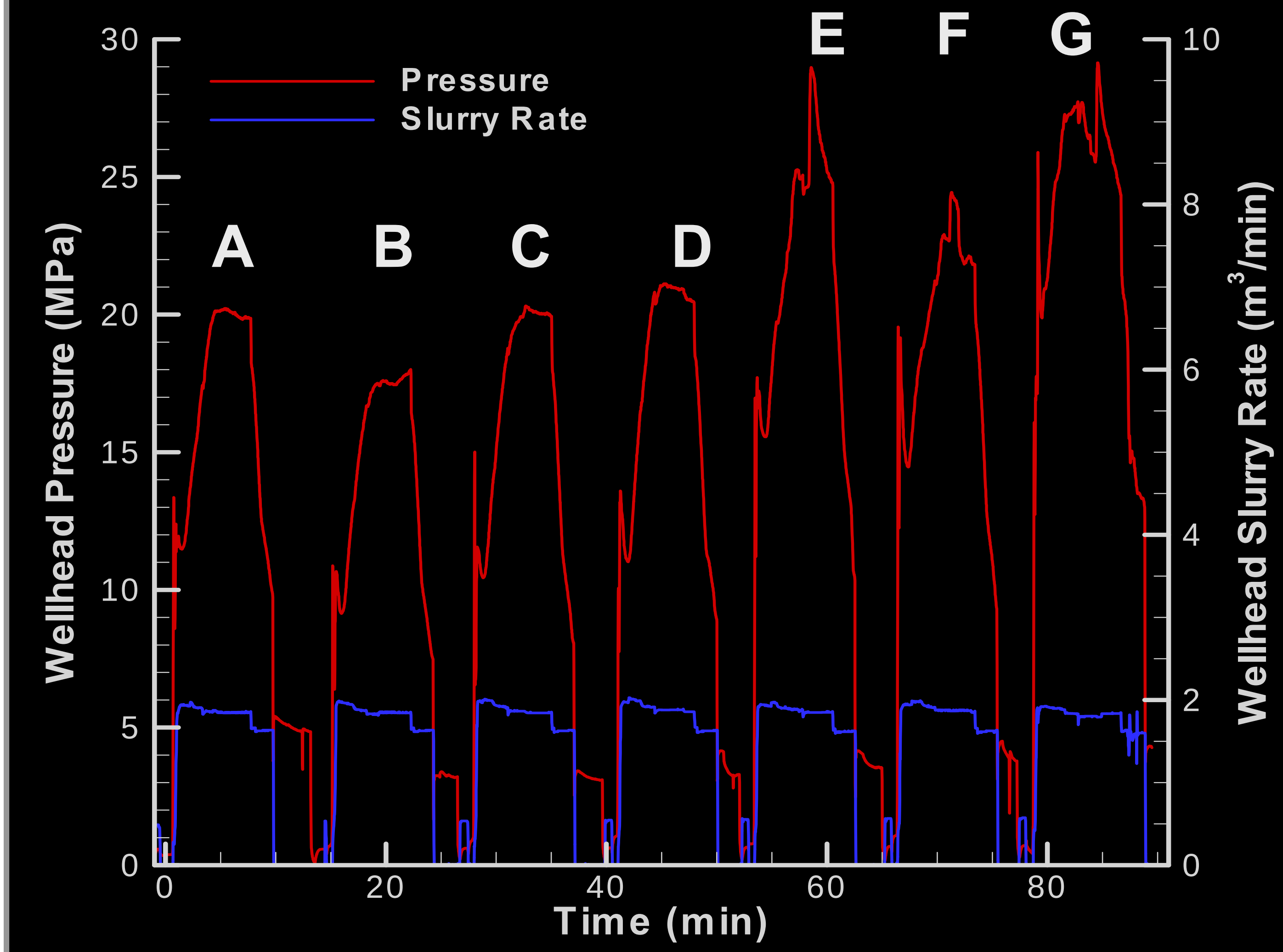
Stimulation Split Dilating Casing

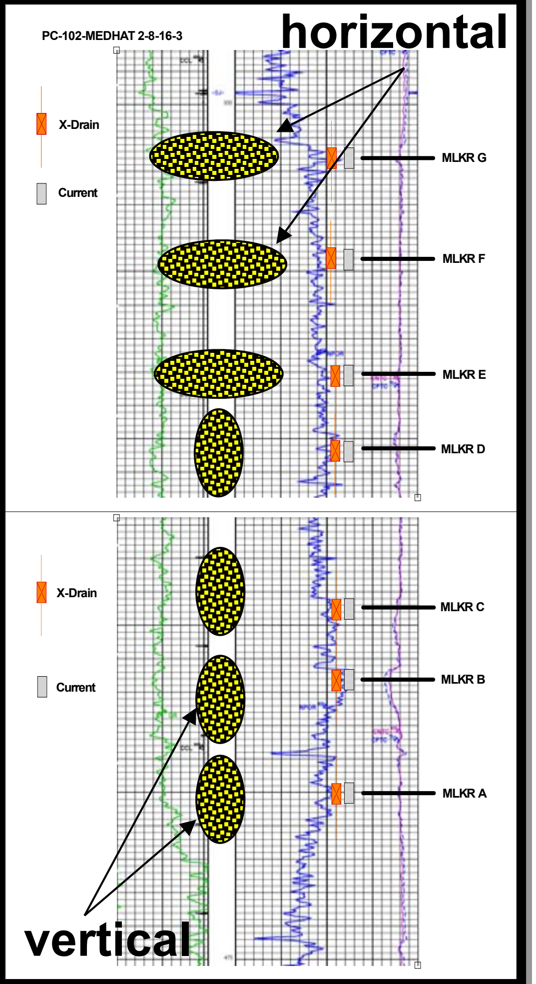
- Cemented by Inner String
- Mechanically Split & Expanded
- 10% Radial Strain
- Locked in Open Position
- Multiple Wings intersect Formation Shoreline Anisotropy



Hocking et al. 2011

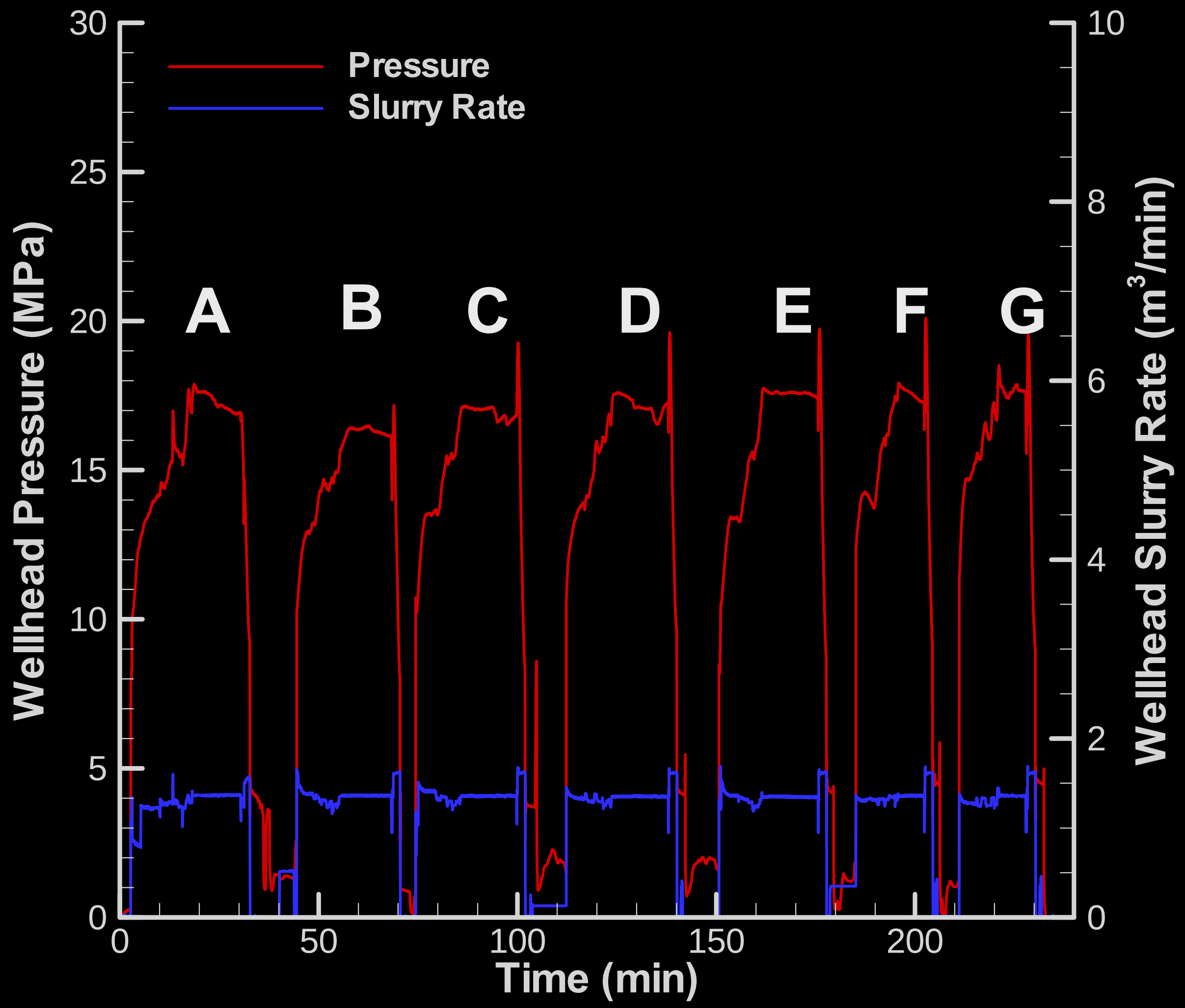
Conventional Stimulations

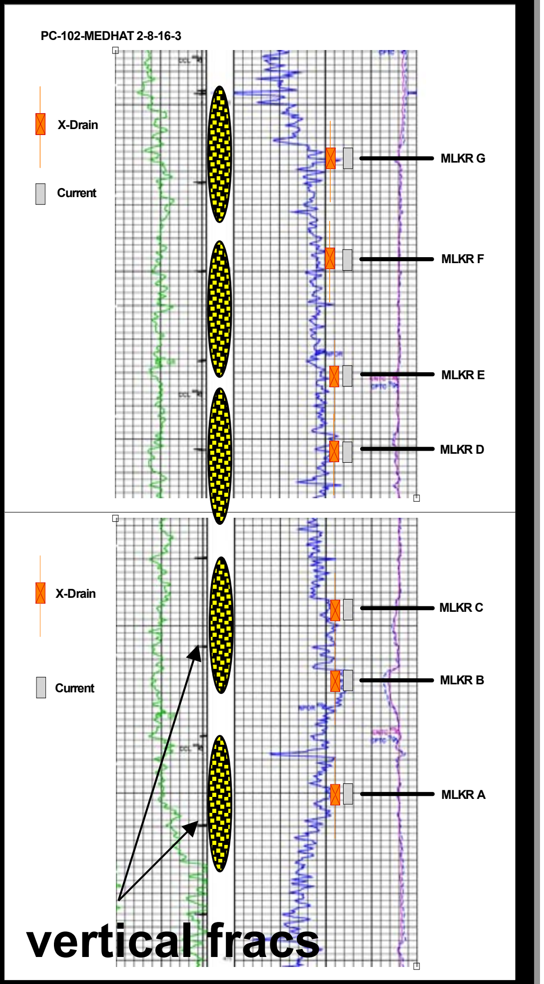




Hocking et al. 2013

Split Dilating Casing Stimulations



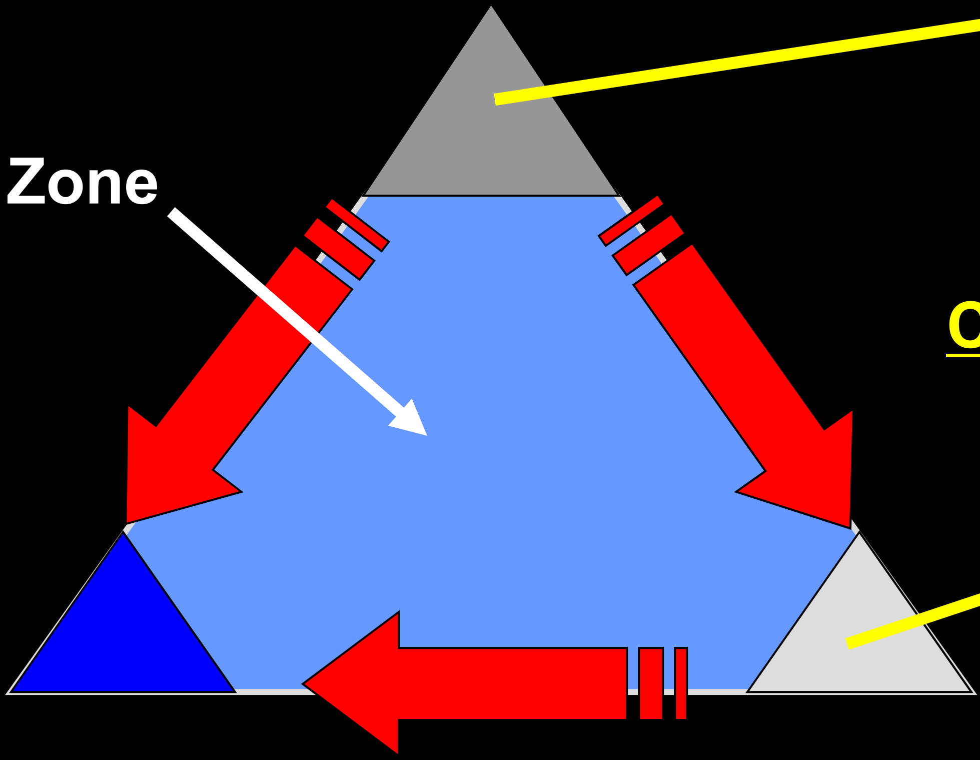


Hocking et al. 2013

Lessons Learnt

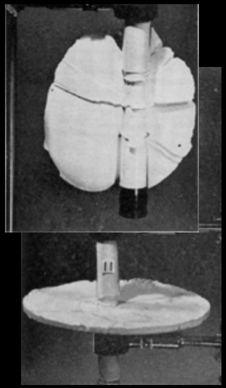
- Completion Method Controls the Outcome
  - How do you interpret stimulation and shut-in pressure records?
  - Mapping injected geometries only tells you of the outcome
  - Stimulation thru' perfs or open-hole do not excite least energy dissipating mechanism
  - Frac initiation is essential
- Why? Non-Brittle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

Brittle Ductile States



Fractures

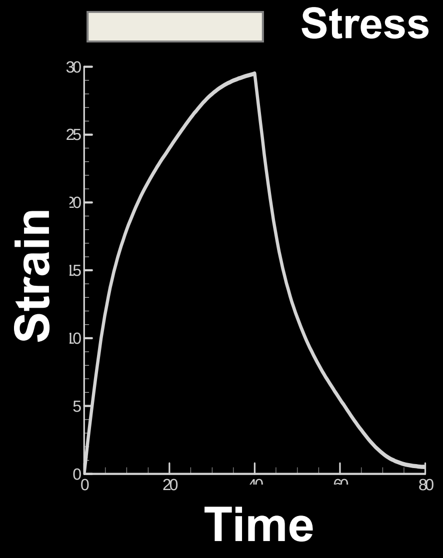
Hubbert & Willis (1957)

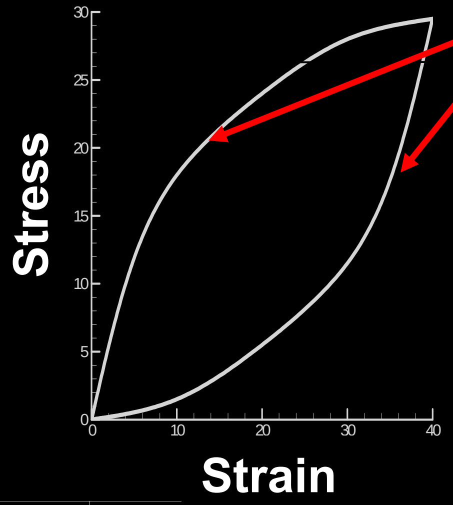


Cavity Expansion

Bolton & Chin (1994)

Anelasticity

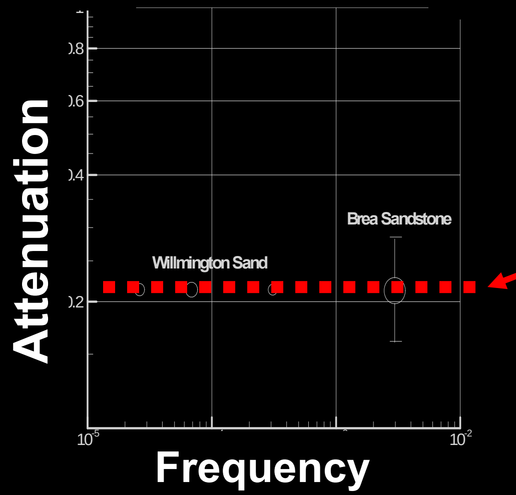




Hysteresis strain lags stress lost energy

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

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

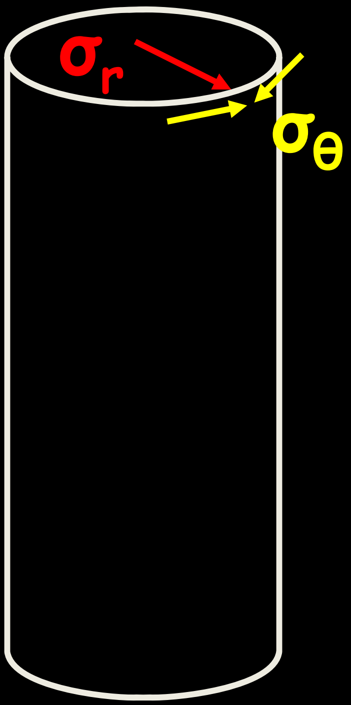


Dry Sand/Weak Sandstone

Q=5 Quality Factor

Anelasticity - Cylindrical Cavity

Field Stress p_0
compression +ve



Linear Elastic

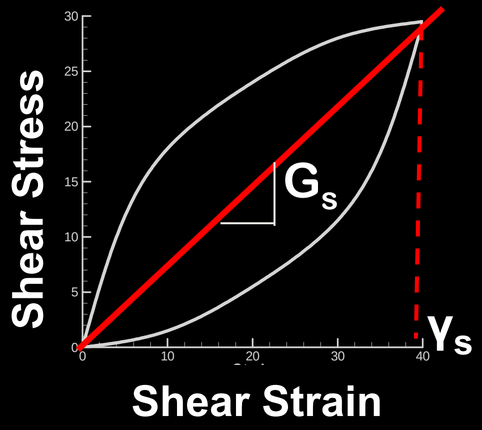
$$\sigma_r = p_0 + \Delta p$$

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

Non-Linear Elastic

$$\sigma_r = p_0 + \frac{\alpha}{\beta}\gamma^\beta$$

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



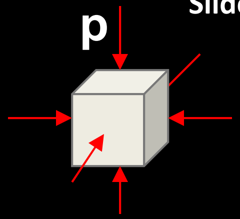
$$\tau = \alpha\gamma^\beta$$

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

Bolton & Whittle (1999)

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



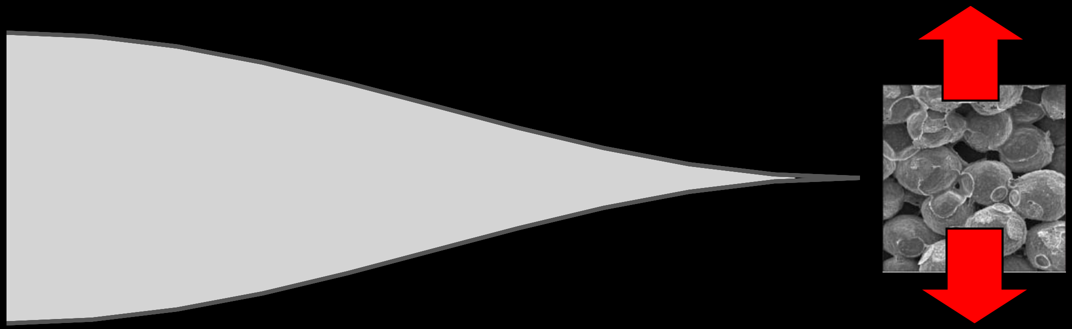
Soft u=p B=1
Stiff u=0 B=0

Skempton's B parameter

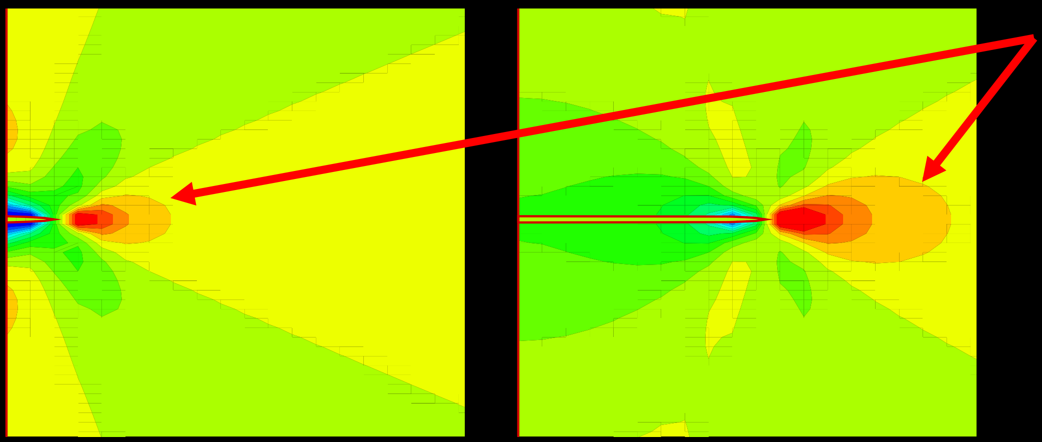
- >0.75 at low p'
- >0.5 at high p' at significant depth

Inclusion Tip Mobility & Geometry

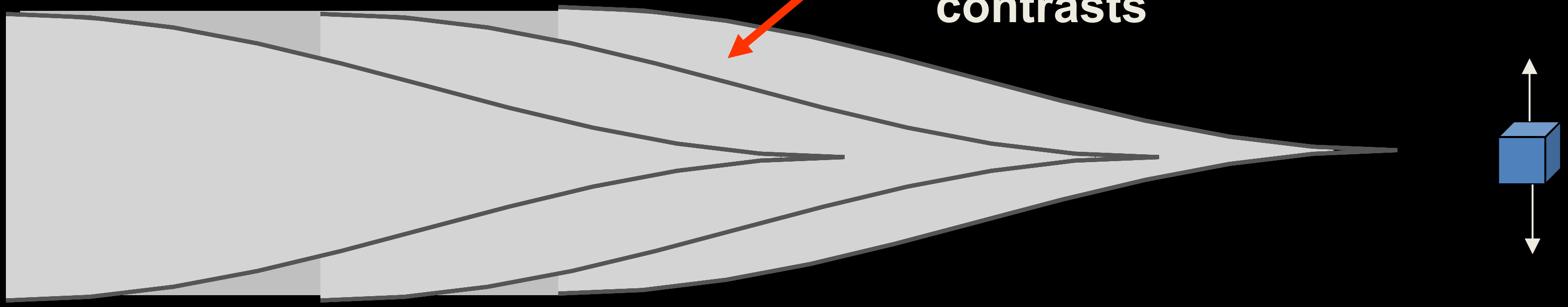
- negative pore pressure in front of tip
- inclusion clamped by apparent cohesion
- inclusion sucked into the unloaded zone
- remains on azimuth due to anelasticity



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

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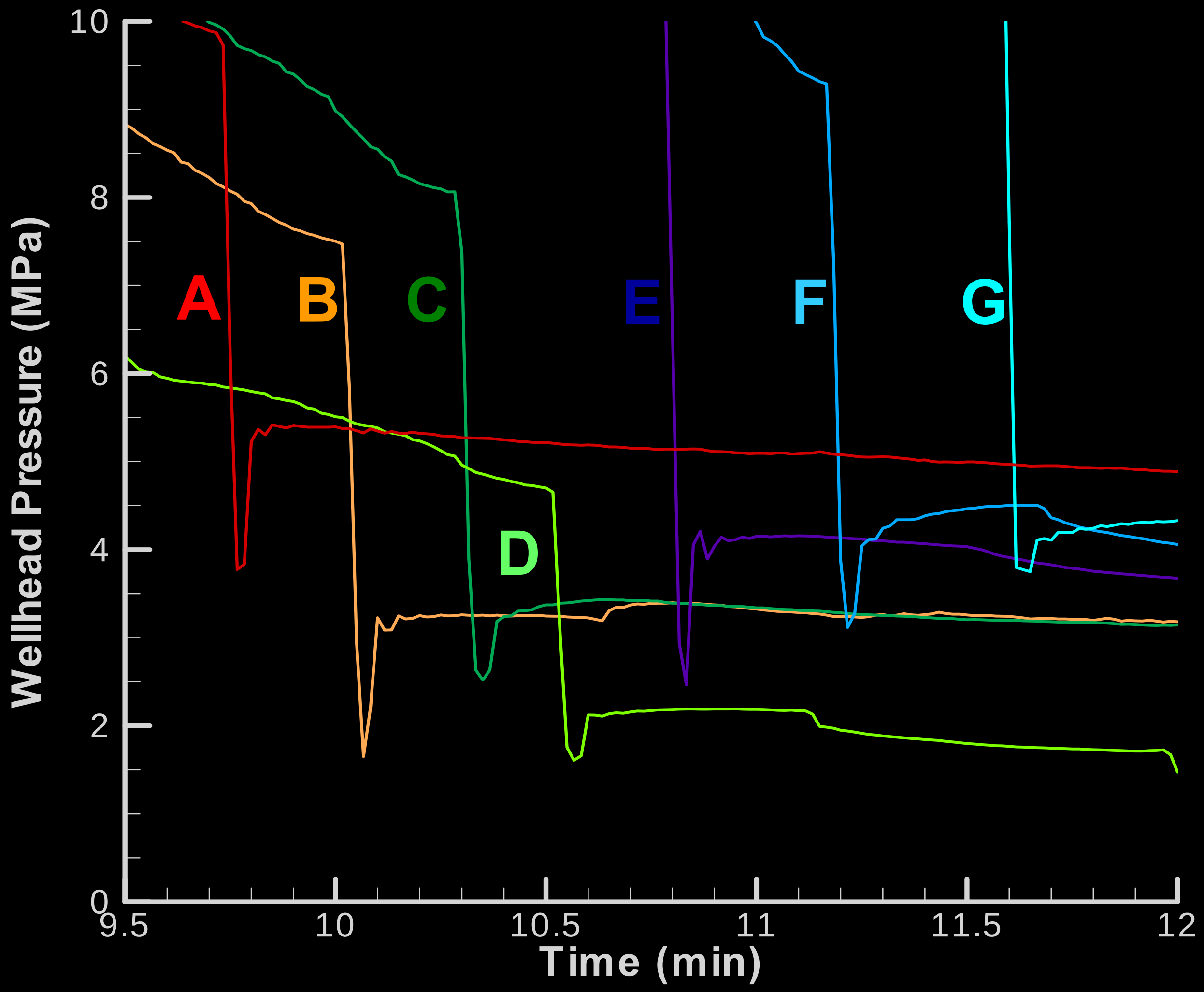
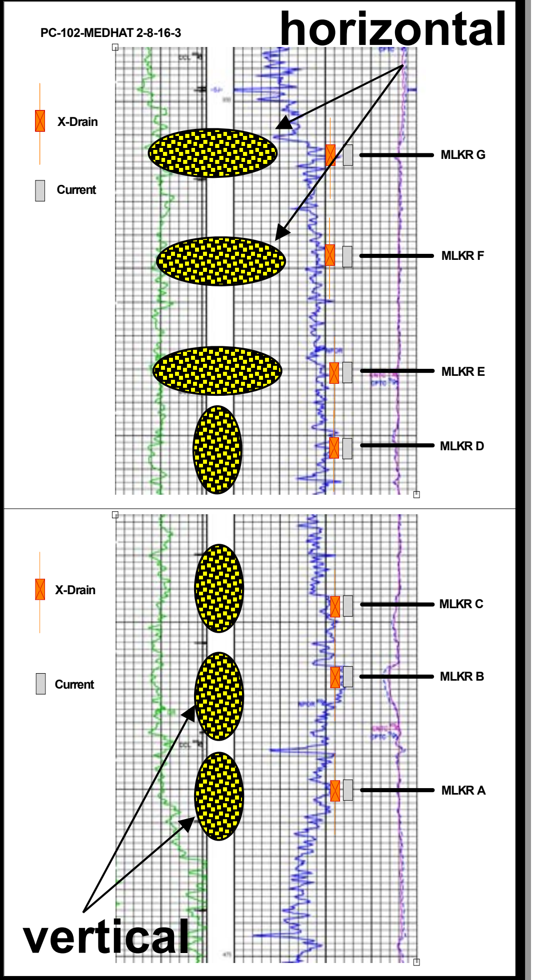
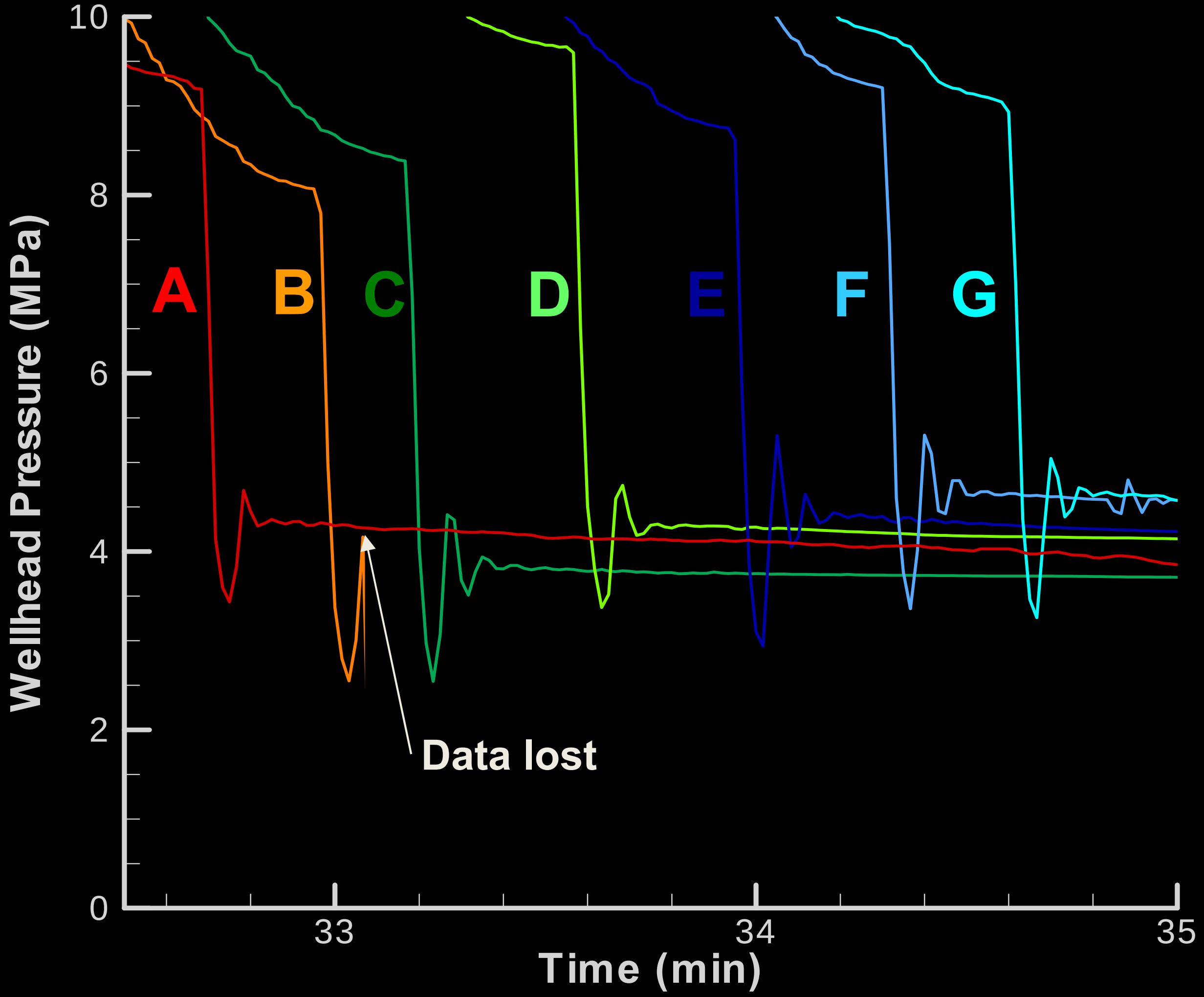
Conventional Stimulations

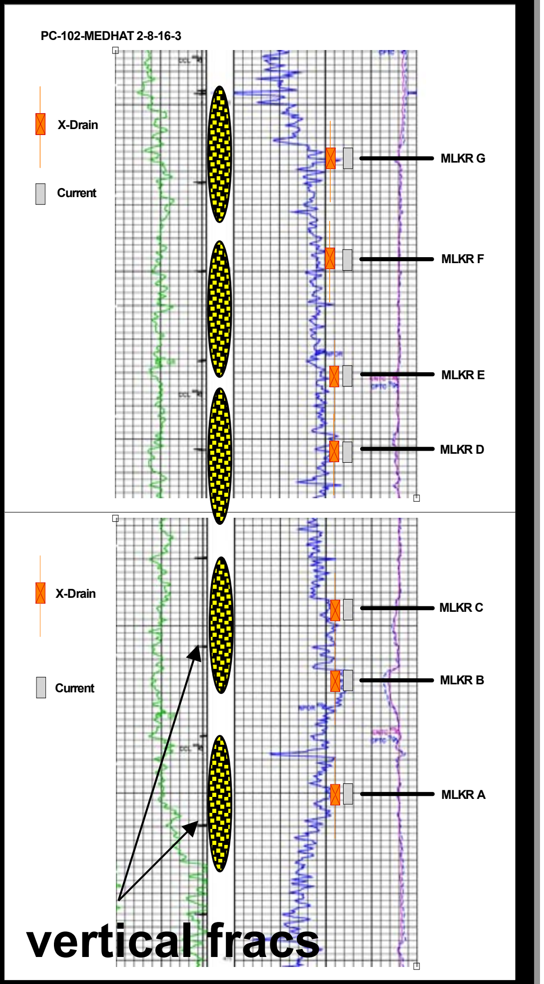




Hocking et al. 2013

Split Dilating Casing Stimulations

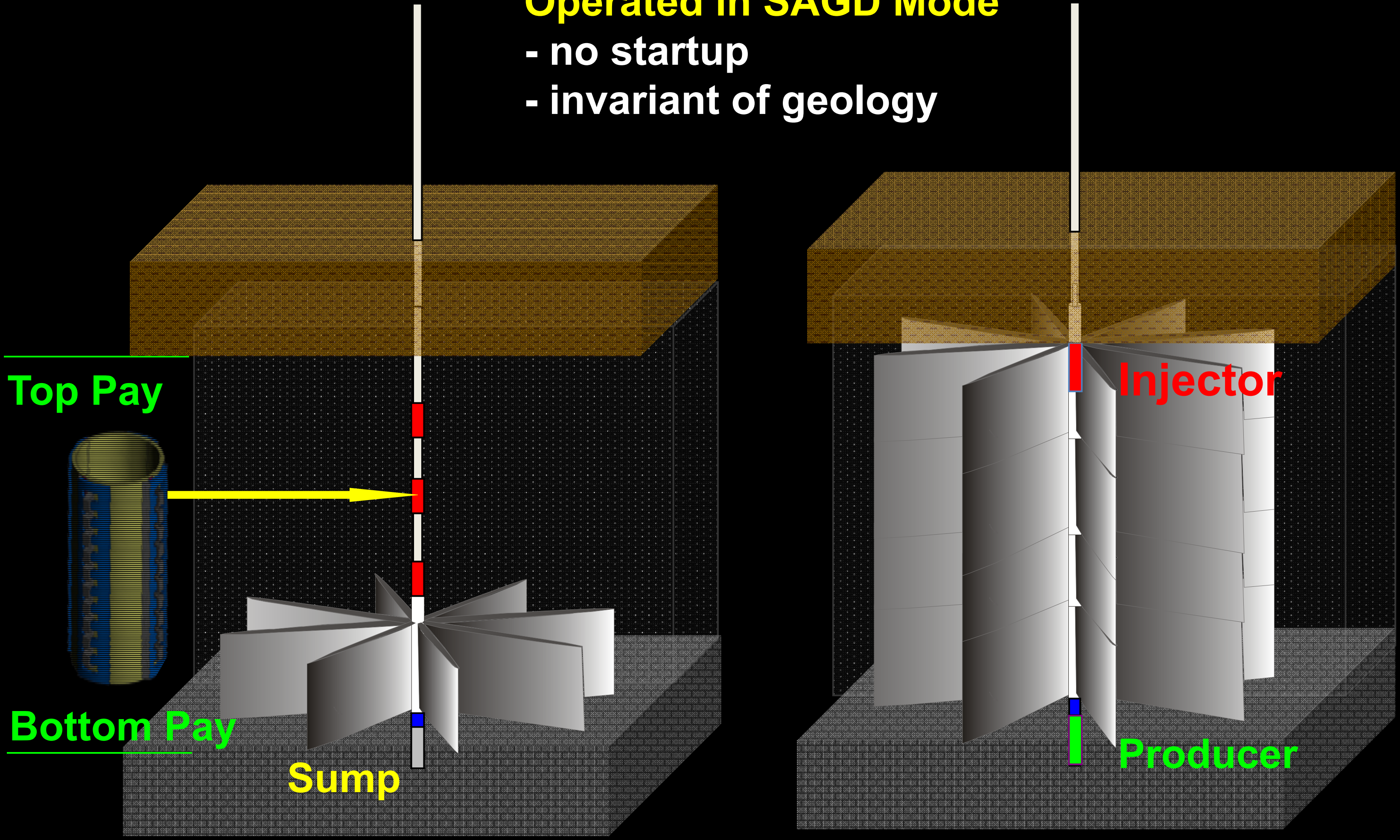




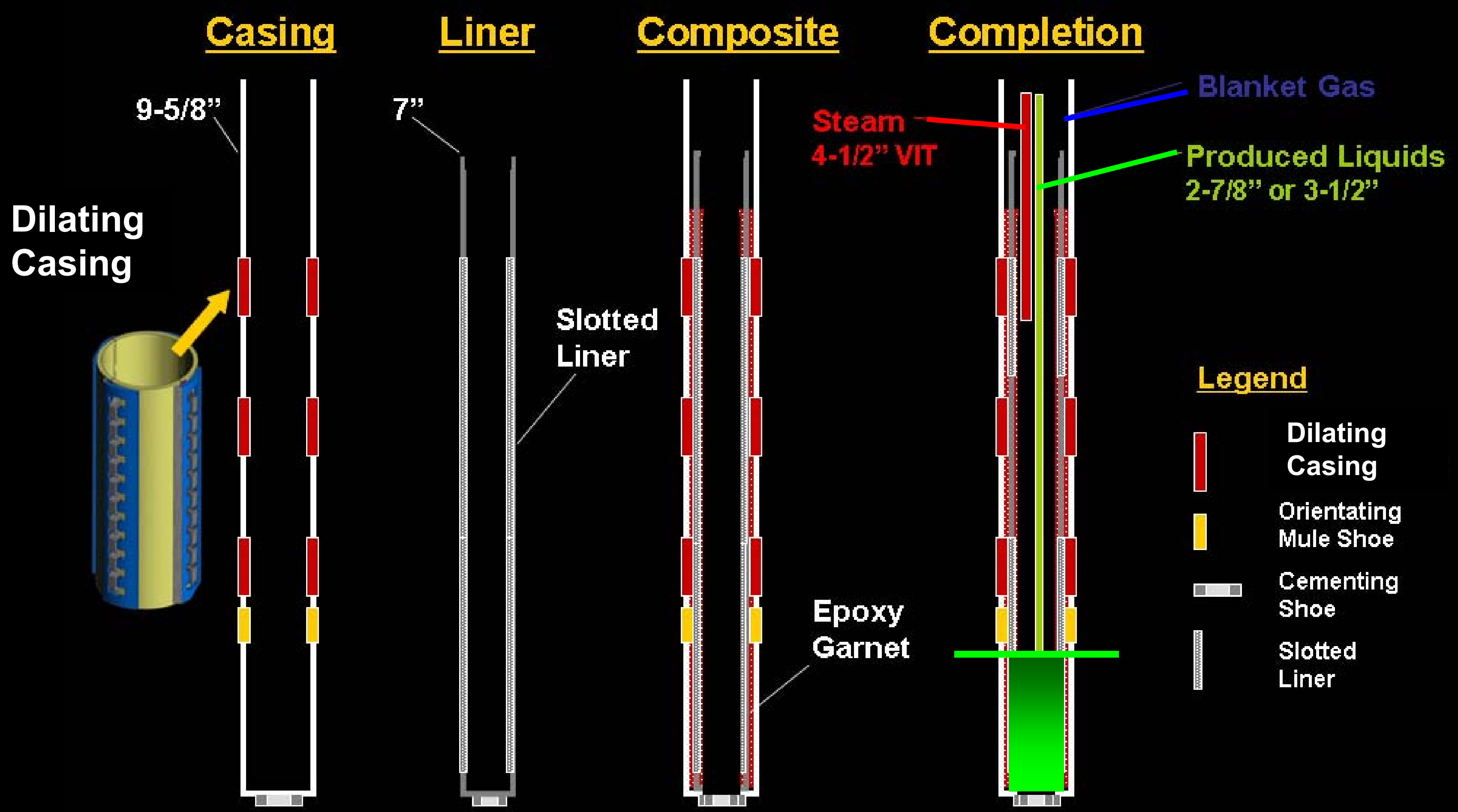
Hocking et al. 2013

Well Construction Sequence

Operated in SAGD Mode
- no startup
- invariant of geology



Single-Well SAGD Completion



Casing

Liner

Composite

Completion

9-5/8”

7”

Dilating Casing

Slotted Liner

Epoxy Garnet

Steam 4-1/2” VIT

Blanket Gas

Produced Liquids 2-7/8” or 3-1/2”

Legend

🟥 Dilating Casing

🟨 Orientating Mule Shoe

▭ Cementing Shoe

▯ Slotted Liner

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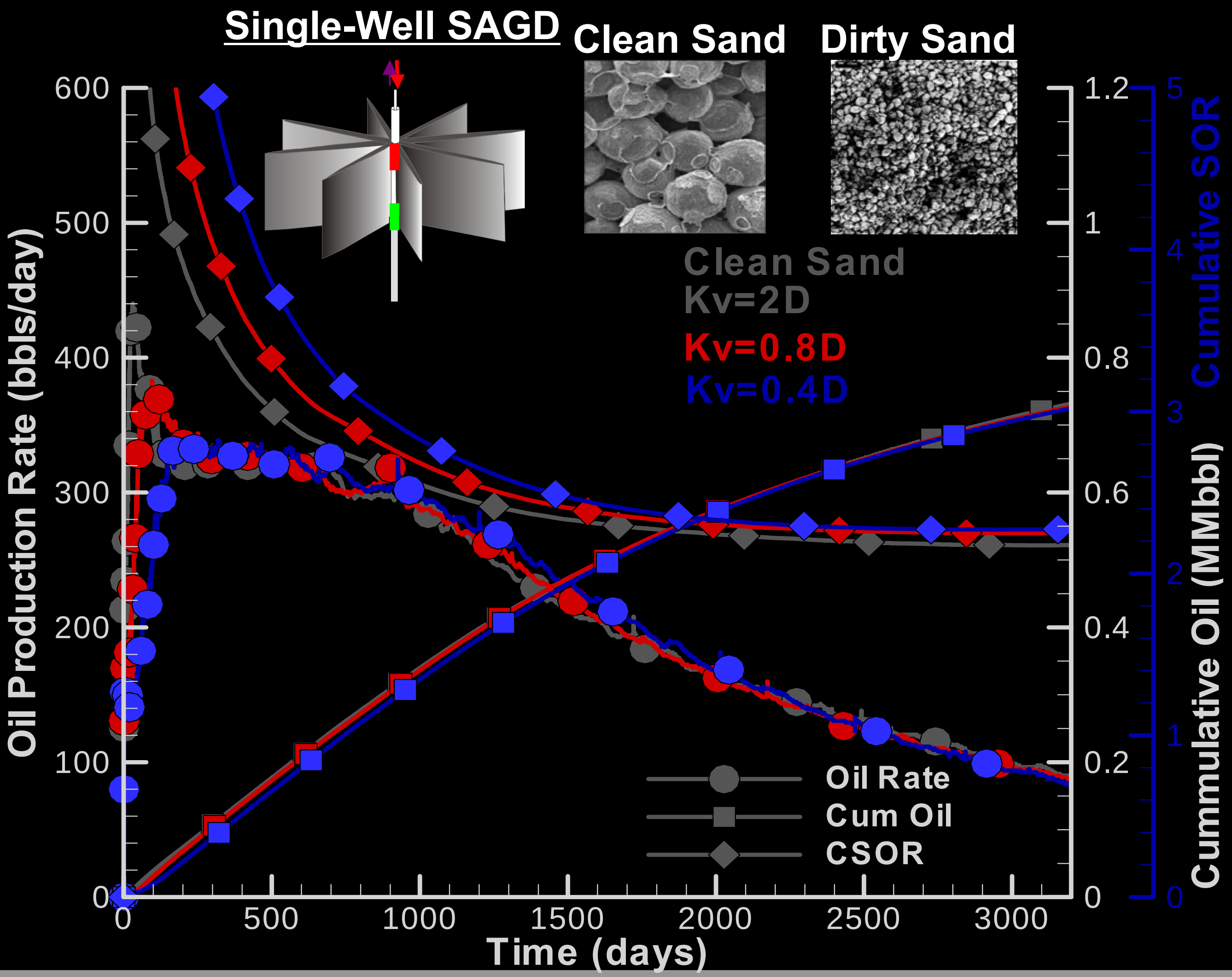
Single-Well SAGD vs Vert Perm



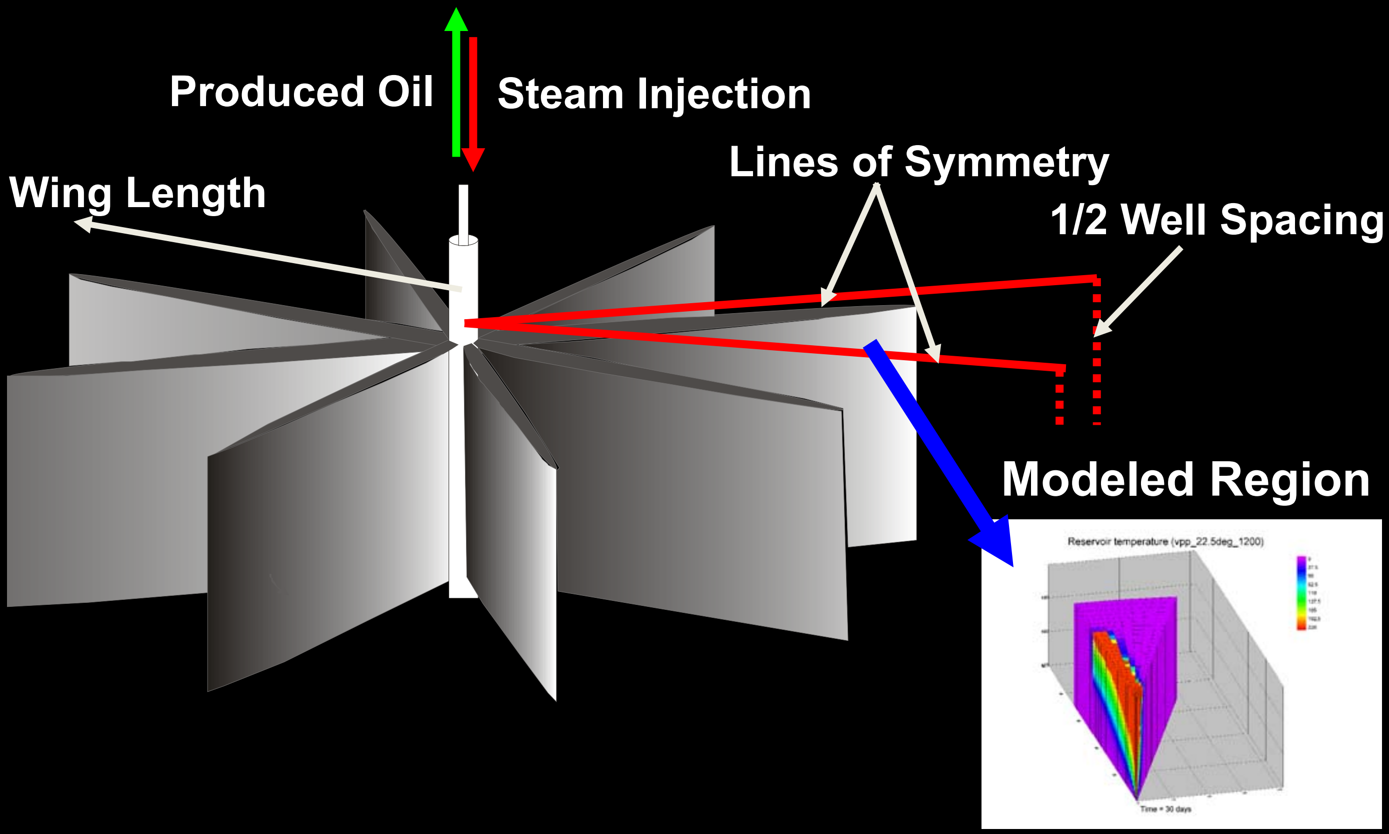
SAGD

$$q \propto \sqrt{k_v}$$

$$t \propto \frac{1}{\sqrt{k_v}}$$

Athabasca Bitumen
Sp=1,750kPa

Reservoir Idealization



Produced Oil

Steam Injection

Wing Length

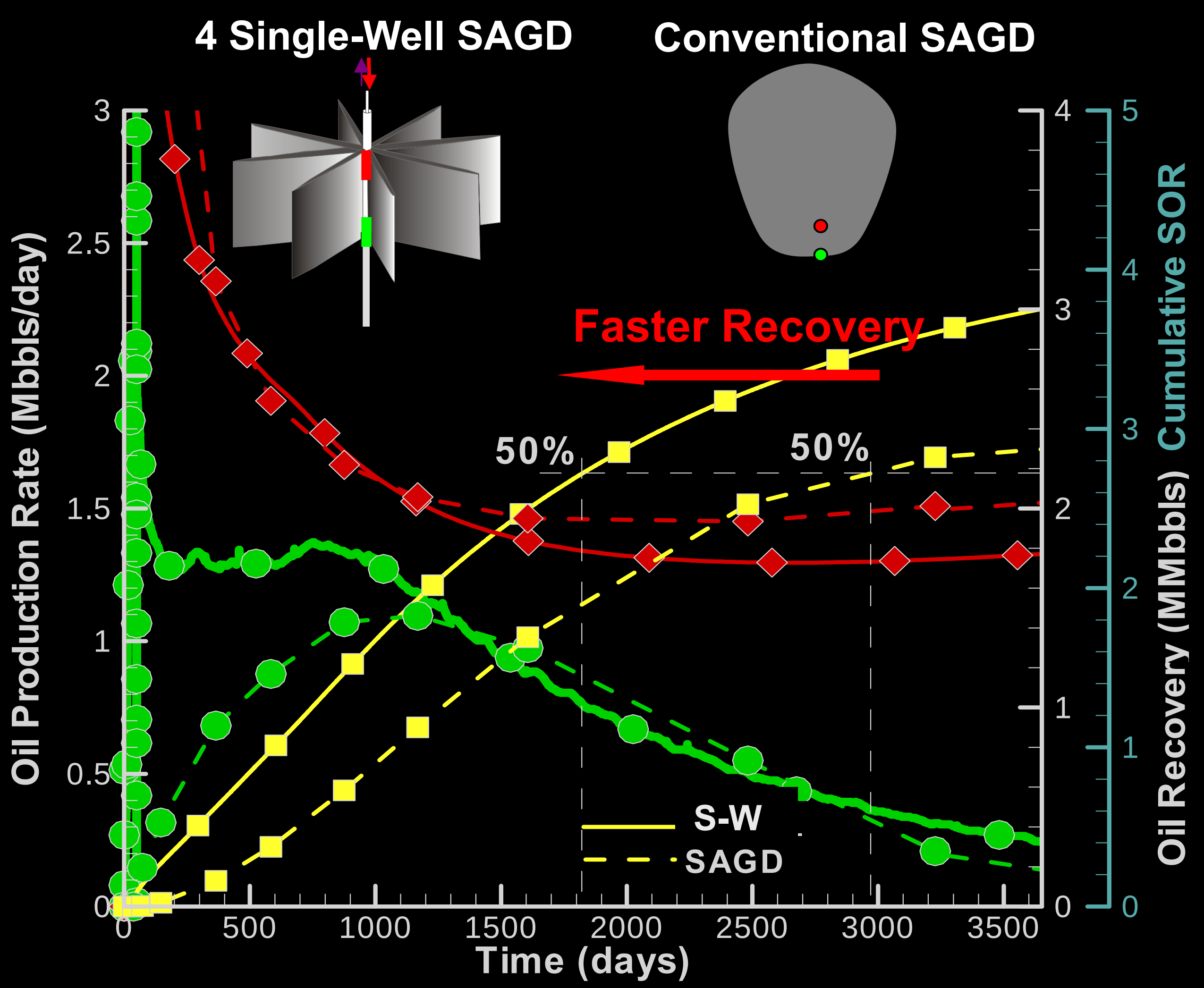
Lines of Symmetry

1/2 Well Spacing

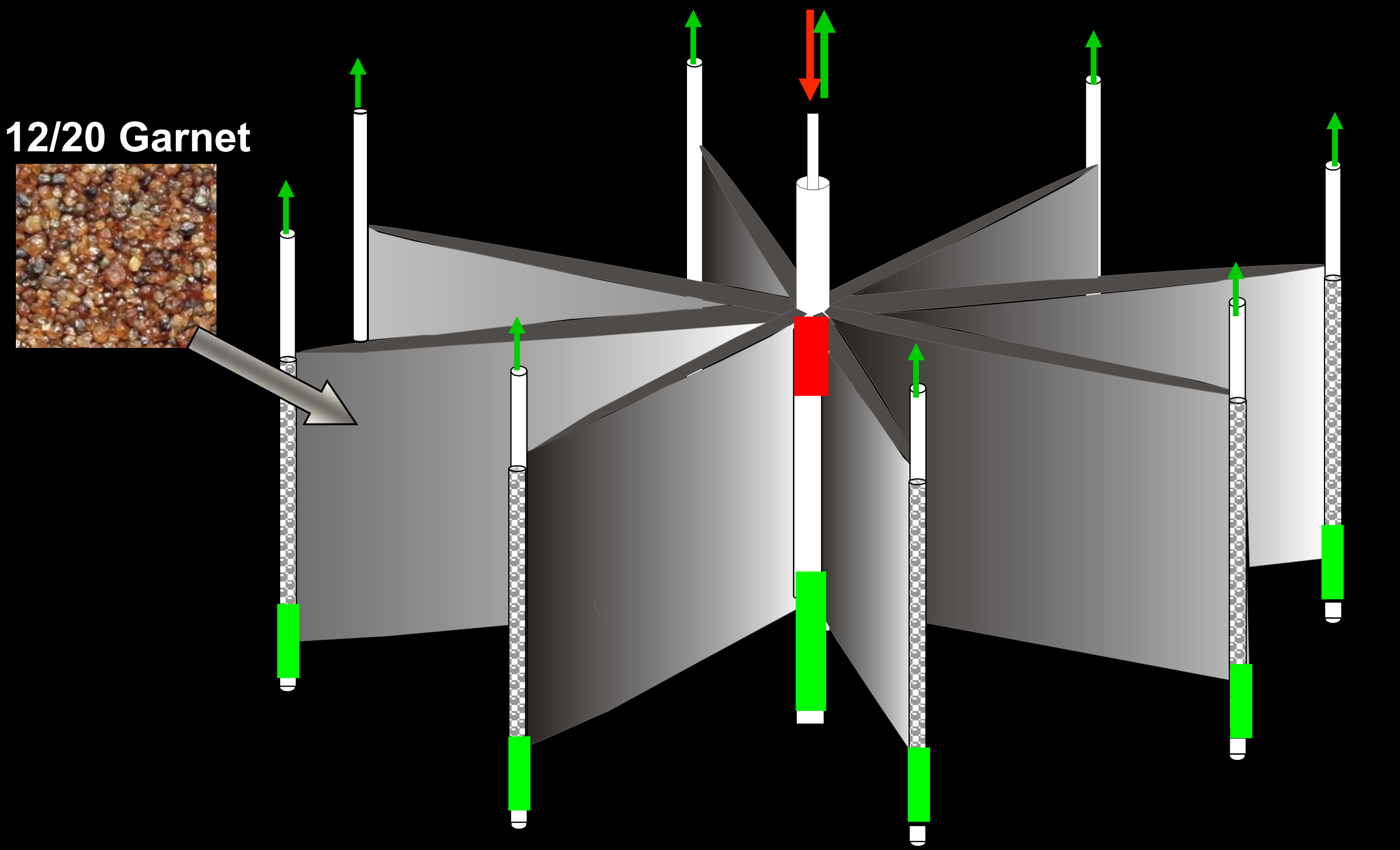
Modeled Region

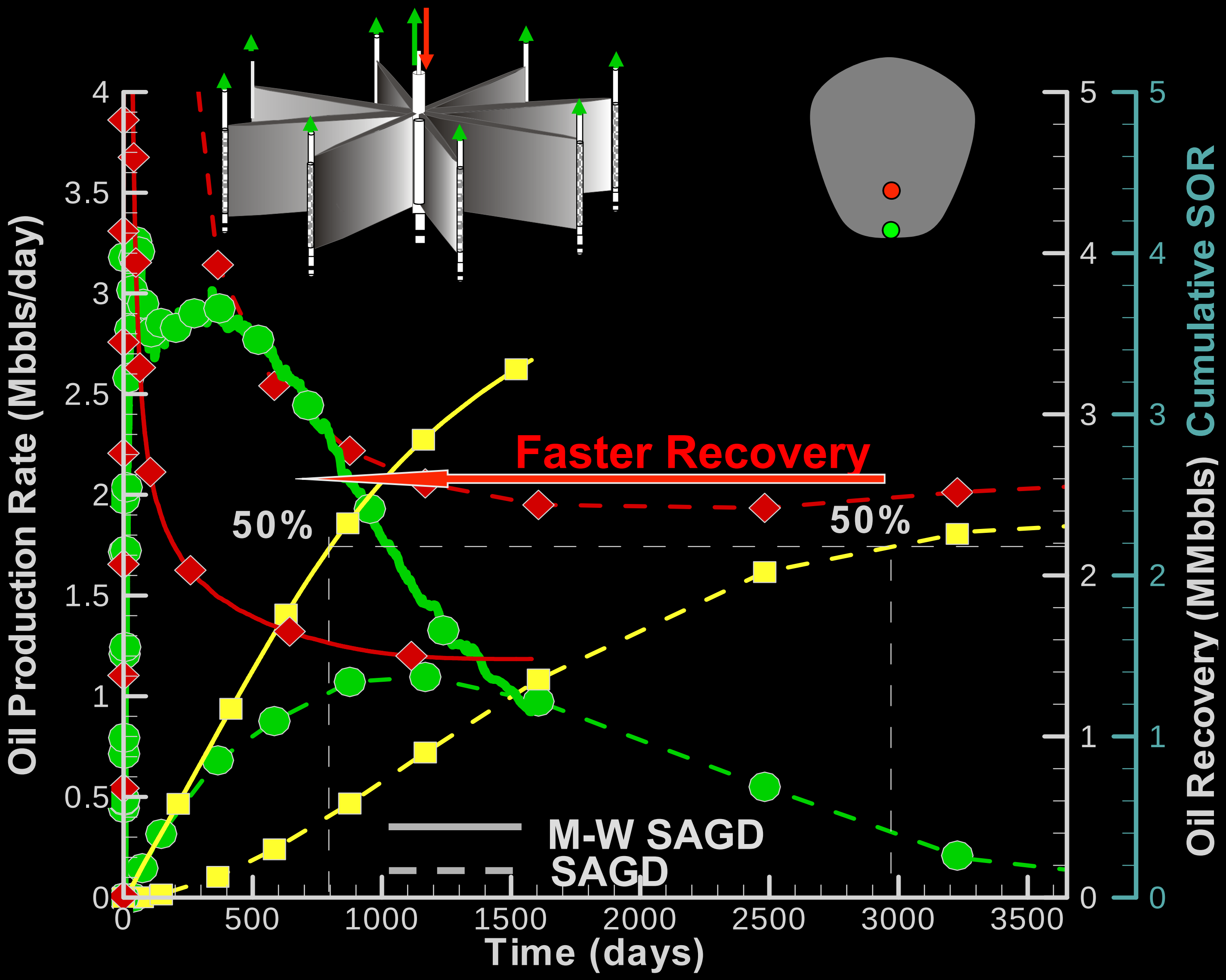
High confidence in reservoir simulations due to minimal dependence on vertical perm

Single-Well SAGD vs Conv SAGD



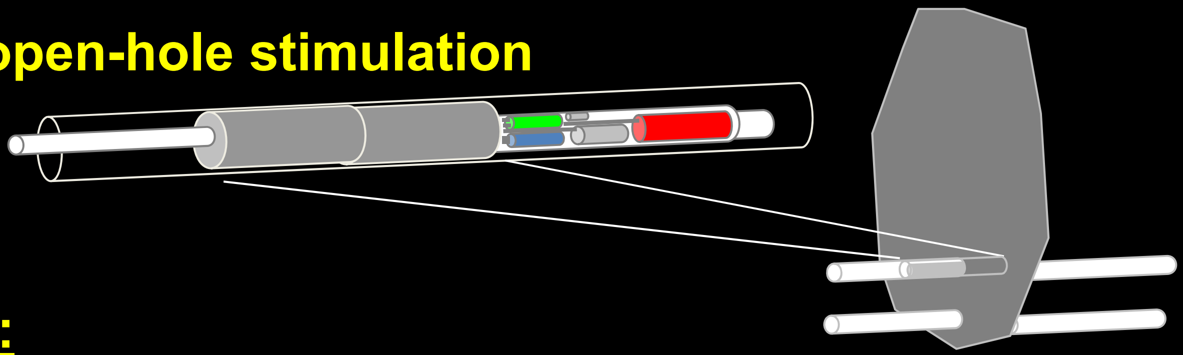
Vertical Single-Well SAGD with Multiple Producers




Faster Recovery
50%
50%
M-W SAGD
SAGD
Oil Production Rate (Mbbls/day)
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (days)
0
500
1000
1500
2000
2500
3000
3500
Oil Recovery (MMbbls)
Cumulative SOR
0
1
2
3
4
5

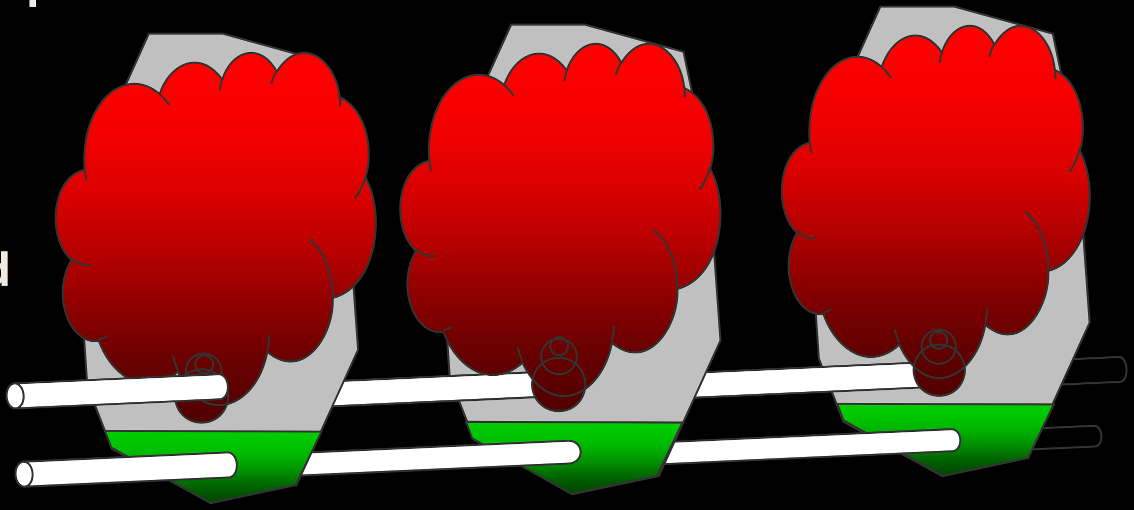
Frac Enhanced Conventional SAGD

Hz open-hole stimulation

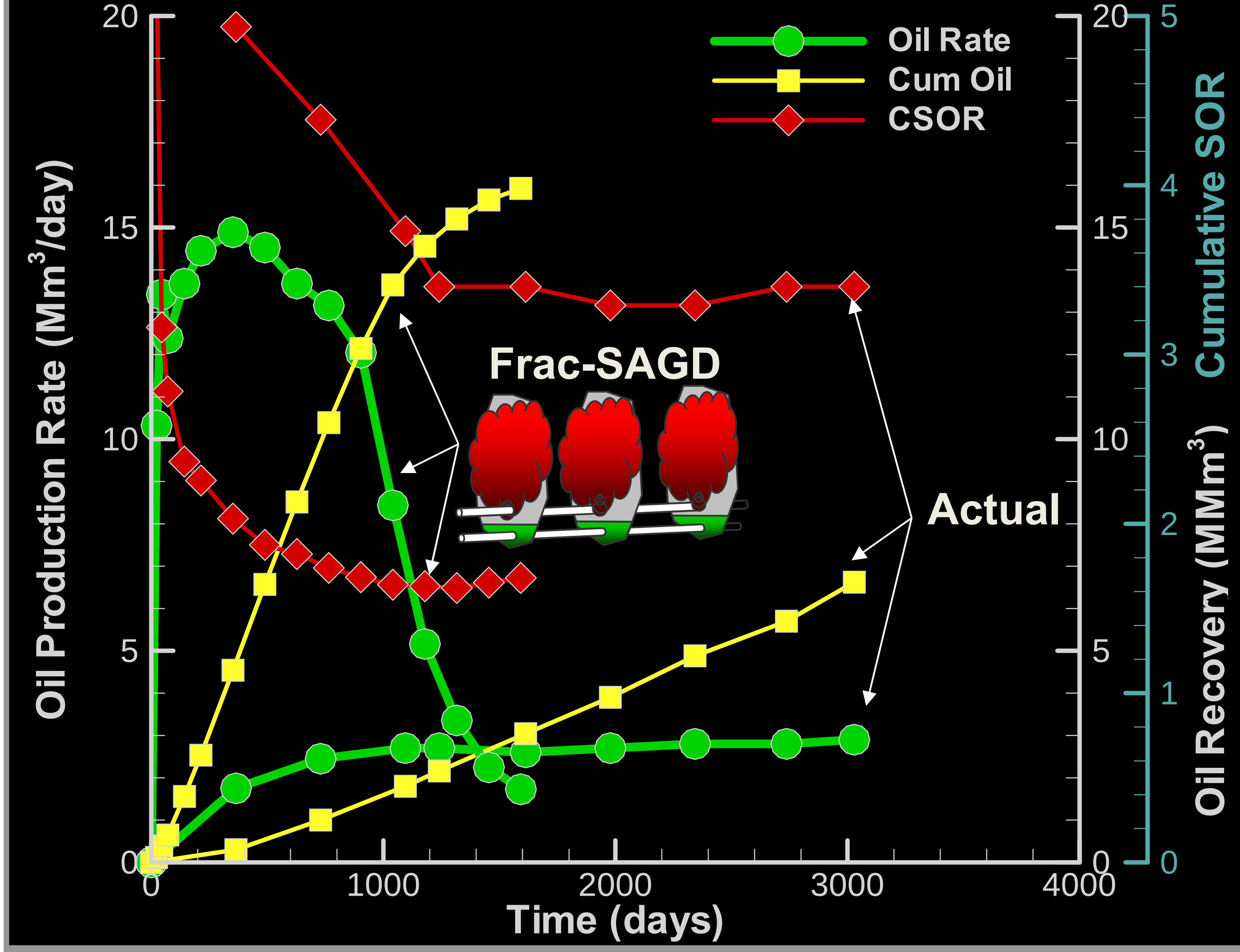


Benefits:

- Simpler & more reliable to operate
- SAGD mode at startup
- Engineer around geology
- Quick re-startup
- Operate at low pressure
- Flow conformance assured



Frac Enhanced SAGD @ Firebag



Benefits:

- Lower CSOR
- Faster Recovery
- 6x NPV$_{10}$

Quantified:

- Cost
  $16 vs $32 /bbl
- Capacity
  380k vs 180k bpd
- Carbon Footprint
  <50% carbon/bbl
- Net Income
  up by 4x Δ$3.4B/yr*

*Bitumen $50/bbl

52m pay, 1,850kPa, ϕ=0.3, So=0.79

Conclusions

- Stimulation completion dictates the outcome
  - Mini-Frac thru' perfs or open-hole suspect in non-brittle weak formations
  - Essential to initiate frac in non-brittle formations
  - Need to re-assess earlier stimulation data & experience
- Process not depth limited, strength limited
- Frac SAGD performance ~invariant of geology
- Frac enhance best geology first, not poorest
  - Highest ROI, best sustainable and environmental practice
- As built issues
  - Permeability of planes needs to be high
  - Demonstrate azimuth control of planes from Hz wells
  - Steaming trials required to quantify performance