Why Permeability and Geomechanics Drive the Completion And Stimulation Success In Multiple Fractured Horizontal Wells?

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Presentation Outline

• Why It Matters? The Keys To Success!
• Historical Perspective: Horizontal Wells
• Horizontal Well Characterization & Objectives
  – What We Want To Do?
• The Geomechanics Of Horizontal Wells
  – What We Can Do?
  – Complexity?
• Basis of Water Frac Designs – Ductility
• Permeability
• Summary
Why It Matters

• Where Do I Land the Horizontal Well?
• How Do I Complete The Well?
• Where Do I Complete The Well?
• How Many Completions Do I Need?
• How Do I Fracture Stimulate The Well?
• What Fracturing Fluid Do I Use?
• What Pump Rate Should I Use?
Why It Matters

• Where Do I Land the Horizontal Well?
• How Do I Complete The Well?
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*Geomechanics And Permeability Are The Keys To Success
Horizontals: A Historical Perspective

**Horizontal Drilling Boom**
1998 Only 40 Horizontal Capable Rigs In U.S.
2008 28% Of U.S. Rigs Horizontal Capable
2011 57% Of U.S. Wells Are Drilled Horizontal

- **First**
- **Russia**
- **Thermal Cold Lake**
- **Austin Chalk**
- **North Sea**
- **1st Barnett**
- **East Texas**
- **Coning, Empire Abo**

Year:
- 1930
- 1940
- 1950
- 1960
- 1970
- 1980
- 1990
- 2000
- 2010
- 2020

SPE Horizontal Well Papers
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Well Characterization & Objectives

Metrics Used To Determine The Optimum Distance Between Fractures/Compleions

The IP And Annualized Rate Metrics Are Based On The Distance Between Fractures When Interference Occurs At 30 Days Or 365 Days, Respectively.
Well Characterization & Objectives

Effect Of Lateral Length On Completion Optimization

The Longer The Lateral The More Completions To Be Optimal
Well Characterization & Objectives

Effect Of Fracture Length On Completion Optimization

The Longer The Fractures The More Completions To Be Optimal
Well Characterization & Objectives

Unconventional → Tight → Conventional

Distance Between Fractures, Feet

Reservoir Permeability, md

Control ← Limited Control ← No Control

Cased & Cemented ← External Packers ← Open Hole
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We Have Known Of The Effects Of Well Deviation, $\beta$, For A Long Time!

Slide Keys:
- Up to $\beta = 30^\circ$, No Real Effect on Pressures!
- Limited Proppant Was Placed In The High $\beta$ Well!
- The Increased ISIP Is An Indication of Fracture Complexity “Tortuosity”!
Geomechanics of Horizontal Wells

Slide Keys:
• The Further The Azimuth, \( \alpha \), And Perforations Were From \( \sigma_{H_{\text{max}}} \):
  • The Greater The \( \Delta p \) Losted,
  • The Poorer The Productivity

BP-Prudhoe Bay
Circa 1992, J. P. Martins
Geomechanics of Horizontal Wells

\( \sigma_v = 10,000 \) psi, \( \sigma_{H\text{max}} = 7,500 \) psi, \( \sigma_{H\text{min}} = 6,000 \) psi

\[ \beta = 90^\circ \]

\[ \alpha = 0^\circ, \ BD = 4,000 \) psi \]
\[ \alpha = 30^\circ, \ BD = 4,154 \) psi \]
\[ \alpha = 60^\circ, \ BD = 5,574 \) psi \]
\[ \alpha = 90^\circ, \ BD = 8,500 \) psi \]
Geomechanical Implications

Slide Keys:
When The Distance Between The Fractures Is > 2 Times The Fracture Height Minimal Effect On Fracture Width & Flow Resistance!

Two Interfering Fractures w/ Contained Fracture Geometry
Geomechanical Implications

**Description**
- Inter-perforation Distance (ft)
- Height/Interwell Distance Ratio
- Transverse Horizontal Treating Pressure
- Transverse Horizontal Fracture Width

**Flow Resistance Multiplier**

**Fracture Width Multiplier**

Vertical Well Treating Pressure Is 6,000 psi
Fracture Height is 500 feet
Single Fracture Width is 0.25 inches

**Case 1** | **Case 2** | **Case 3** | **Case 4**
---|---|---|---
1000 | 500 | 250 | 100
2.00 | 1.00 | 0.50 | 0.20

| Flow Resistance | 5700 | 6600 | 9000 | 12000 |
|---|---|---|---|
| Fracture Height Multiplier | 0.188 | 0.125 | 0.063 | 0.025 |

| Flow Resistance Multiplier | 0.95 | 1.10 | 1.50 | 2.00 |
| Fracture Width Multiplier | 0.75 | 0.50 | 0.25 | 0.10 |

Did we actually breakdown the perforations?
Were we able to place proppant?

**Remember That The Bridging Criteria is Wf = 3 x Proppant Diameter**

- 20/40 Ottawa Sand Avg Diameter Is 0.023 inches: 0.069
- 40/70 Ottawa Sand Avg Diameter Is 0.011 inches: 0.033
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Geomechanical Implications

The Object Of The Completion(s) & Fracture Stimulation(s) Is To Effectively Contact As Much Reservoir As Possible:

– Micro-Seismic Data Used To Assess Contacted Volume Or Stimulated Reservoir Volume

Where:

\[ SRV = L \times H \times W \] of Micro-Seismic Event Map

Often \[ 2(x_f) \times H_f \times L_L \]
Geomechanical Implications

Stimulated Reservoir Volume

Bigger the Frac Volume the Greater
The Stimulated Reservoir Volume &
The Greater the Hydrocarbon Recovery

Fisher 2002
Geomechanical Implications

But Does Complexity Or Stimulated Reservoir Volume Add Up To Hydrocarbon Recovery

Study Showed That SRV Not Very Effective, Neither Was Induced Fracture For That Matter

Additional Simulations Show That SRV May Not Be Critical Or Is It? What About Over The Long Term?
If SRV Important How Do You Get More?

**Geomechanical Implications**

Study showed that higher fluid viscosity slightly increased the tensile failure area.

Study showed that low fluid viscosity dramatically increased the shear failure.
Geomechanical Implications

If SRV Important How Do You Get More?

Study showed that higher treatment rate increased the tensile failure area.

Results less clear for shear failure.
Geomechanical Implications

If SRV Important How Do You Get More?
– How About Simultaneous Fracturing?

Fracture Stimulations Are Pumped In Two Parallel Horizontal Wellbores Simultaneously To Create Greater Stimulated Reservoir Volume
Geomechanical Implications

Woodford Case History Of Bashing

Probability Of Gas & Water Impact Due To Bashing Over 70% If Offset Within 1,000’ & Well More Than A Year Old

Kelkar
Geomechanical Implications

What Is The Likely Fissure Direction In The Current Stress State Whereby:
- The Natural Fissures Are Open,
- The Fissures Are Conductive, And
- Potentially Contributory To Well Performance

Such A Natural Fissure Is Deemed Critically Stressed

Critically Stressed Fracture Orientations
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Basis of Fracture Design

Perfect Transport

Imperfect Transport

Slick Water

Hybrid

Lower Permeability

Higher Permeability

Increasing Viscosity

Increasing Complexity

Increasing Prop Vol.

Ductile

XL Gel

Foam

Linear

Brittle

Increasing BPM
Schematic of a Water-Frac

Un-propped Crack Tests Integrate The Lab Results With The Field & Explains The Effect Of Poor Proppant Coverage!
Water Frac Guidelines
Must Depend on Un-Propped $k_{fw}$

$$F_{CD-Vert} = \frac{(k_f w)_{Unpropped}}{k H_{F-Unpropped}}$$

As Long As $F_{CD-Vert} > 2$
The Propped Fracture Height Doesn’t Matter!

For $(k_f w)_{Un-propped} = 1$ mdft
$H_{F-Un-propped} < 50$ feet
Why Un-Propped Crack Testing?

With Un-Propped $k_w$ a Shale Reservoir Can Support Hundreds Of Feet Of Un-Propped Fracture!

This Is Why Water-Fracs Should Only Be Applied To Tight Unconventional Reservoirs & Proppant Is Always Needed!
Water-Frac’s Must Depend On Un-Propped Fracture Conductivity

Area 4, 5, & 7 Represents Woodlawn & Blocker Fields Where Taylor (CV) Sand Is 100+ Feet Thick!
Mineralogy & Ductility

Proppant And Fluid Selection & Quantity:

Mineralogy

Clay Constituents Less Than 40%
Minimal Swelling Clays (Smectite)
Young’s Modulus & Brittleness

Proppant And Fluid Selection & Quantity:

Young’s Modulus

$\text{Young’s Modulus} > 3.5 \times 10^6 \text{ psi}$

Fits Clastic Modulus Correlation
Un-Propped Crack Test & Ductility

Proppant And Fluid Selection & Quantity:

Un-Propped Crack Conductivity

Maintains Un-Propped Conductivity
Fits Within Acceptable Range

Best Shale Plays
Marginal Shale Plays

Normalized Stress
Normalized k
Basis of Fracture Design

- Increasing Viscosity
  - Brittle
- Increasing Prop Vol.
  - Perfect Transport
  - Imperfect Transport
- Increasing BPM
  - XL Gel
  - Foam
  - Linear
  - Hybrid
  - Slick Water
- Lower Permeability
  - Higher Permeability
  - Ductile
Water Frac Design Example

Barnett Design:

- Young’s Modulus $4 \times 10^6$ psi
  - 25 BPM Need 35 lbs
  - 50 BPM Need 40 lbs
  - 100 BPM Need 45 lbs

Minimal Required Proppant, lbs

Fluid Viscosity, 1 cP
Frac Height, 300’
40/70 Ottawa Sand

Static Young’s Modulus, $x \times 10^6$ psi
Water Frac Design Example

Barnett Design:

- Young’s Modulus $4 \times 10^6$ psi
  - 0.25 PPG Need 250 mgals
  - 0.50 PPG Need 110 mgals
  - 1.00 PPG Need 60 mgals

Minimum Fluid Requirement
Does Not Consider Dilation!
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Post Fracture Decline Analysis Example

Logistical & Material Sourcing Issues Required An Extended Shut Down: So We Monitored Pressure Decline!

Stage 6
Stage 4
Stage 2
Stage 5
Stage 3
Stage 1
Post Fracture Decline Analysis Example

Used The Shut Down To Make Real Time Completion & Stimulation Decisions!
Post Fracture Decline Analysis Example

Type Curve Analysis Analysis Of Post Fracture Pressure Decline!

Type Curve Analysis Indicates A Permeability Of 0.018 md!
Keys to Horizontal Success

• Understand The Keys For Success
  – Ductility (Mineralogy, Rock & Geomechanics)
  – Permeability

• Completion(s) & Stimulation(s)
  – Fracture Length & Lateral Length

• Execute, Execute, Execute