What Is The Goal Of Multi-Well Completions?

Because of the low (ultra-low) permeability in many of the Unconventional plays, operators are investigating all manner of mechanisms to improve well productivity at the same or lower costs. Multi-well completions, like Zipper Fracs, are viewed as another mechanism to achieve this goal. Key issues:

- An important goal of many completion operations in Unconventionals is to increase ‘complexity’ – wherein a complex fracture pattern is stimulated (rock failure) within the reservoir formation (providing a large, enhanced drainage volume) as opposed to vertical, bi-planar hydraulic fractures.

- In a multi-well completion scheme, the intent is that the operational timing of hydraulic fractures, well placement, and placement of the hydraulic fractures themselves will further increase the size and/or permeability of the enhanced drainage area from a single well alone.

- Note that some operators report using multi-well completions solely for operational efficiency (mostly pad operations) rather than production improvement.
Multi-Well Completion Concepts

In multi-well completions, the operational timing of injections, the well spacing, and the injection locations (stages) are used in an attempt to increase the overall ‘complexity’ generated and increase production.

Geomechanics 101

Every geomechanics evaluation consists of four primary components and these components must be understood in order to evaluate a given geomechanical response:

1. Stress and stress changes – a stress increase tends to lead to rock failure.

2. Formation pressure – a pressure increase tends to reduce the effective stress, which tends to increase rock failure.

3. Mechanical properties – changes in stress and pressure are resisted by the properties (e.g., strength) of the rock.

4. Geometry – the orientation of a structure or feature (e.g., natural fracture) within the stress and pressure fields.
Critical Fundamental Concepts

The effects from multi-well configurations must build upon critical, fundamental, geomechanics concepts:

- Hydraulic fractures induce the Stress Shadow effect – which increases the total normal stress on ALL natural fractures around it.
- The Stress Shadow effect can be offset by increasing natural fracture pressure.
- HF tip shear is a key driver for (common?) shale formations with closed/cemented or partially cemented weakness planes or natural fractures in order to open them for a fluid pressure change.

*The punchline: In order to understand (and design) Zipper Fracs, we must understand the changes in stress and pressure on the rock mass, natural fractures, and weakness planes from hydraulic fractures.*

Hydraulic Fracturing Scenarios in Unconventionals

- **Highly Fractured Rock Mass**
  - Limited or no HF is created.
  - Characterize NF sets for differences.
  - Optimize Operational Parameters.

- **Cemented Natural Fractures: Weak or Partially Open**
  - Interaction of HF with NFs & discontinuities is critical.
  - Design: How to fail and open the NFs to create flow area.
  - Characterization of NF sets and stress and pressure is key.

- **No Natural Fractures or Fractures with Strong Cementation**
  - Treat as conventional HF.
  - Economics of multiple stages.
  - Optimization of length/area in pay.

*The key starting point for hydraulic fracture design in Unconventionals is to understand the rock mass...which may vary within the play or even along the wellbore...*
Hydraulic Fracturing Scenarios in Unconventionals

KEY: These do NOT stimulate the same – whether in a single well or multi-well configuration!

The reason the rock mass is the key starting point for hydraulic fracture design is that these different rock mass types do not stimulate the same!

Natural Fracture Mechanical Behavior

Natural fracture and weak plane mechanical behavior is commonly tested in a direct shear test. A total normal stress is applied, with a given pressure in the natural fracture, and a shear stress is applied until the natural fracture or weakness plane slips.

Effective stress=$\sigma'$
Total stress=$\sigma_N$
Pore pressure=$p_o$

$\sigma' = \sigma_N - p_o$
Natural Fracture Mechanical Behavior

As the normal stress acting on natural fractures and weak planes increases, the required shear stress to cause slippage (and generate microseismicity) significantly increases.

Slippage (and generated microseismicity) is a coupled function of the stress change due to stress shadows and the pressure increase in the natural fractures due to pressure diffusion from the main hydraulic fracture.
Stress Change Due to Increasing Pressure in Natural Fractures

A key (the key?) to understanding natural fracture and weakness plane shear (‘complexity’) is the influence of pressure on reducing the effective normal stress.

Stress Changes From A Bi-Planar, Vertical Hydraulic Fracture

The Stress Shadow is generically, the change in the total stress field due to a hydraulic fracture.

Note: The white region behind the HF is simply off the color scale (>0.4 MPa).
**Single Stage Stress Shadow**

The Stress Shadow occurs in 3D, but it is not piston-like; rather, the Stress Shadow mimics the width of the created hydraulic fracture and, as width is often greatest at the wellbore, so, too, is the Stress Shadow.

Warmer colors represent a greater stress increase.

---

**Shmin \( \sim f(\text{height}) \) – Single Stage**

The Stress Shadow affects all three Principal Stresses and is a function of net pressure/propped width, HF height (for a PKN geometry) and distance.
**SHmax \sim f(\text{height}) – Single Stage**

The Stress Shadow affects all three Principal Stresses. The change in SHmax is related to Poisson’s ratio and Biot’s coefficient. Note the smaller affected area of SHmax.

**Sv \sim f(\text{height}) – Single Stage**

The Stress Shadow affects all three Principal Stresses. The change in Sv is related to Poisson’s ratio and Biot’s coefficient. Note the smaller affected area of Sv.
**Stress Before Hydraulic Fracturing**

Before the HF is pumped, the stress field in this example indicates that vertical natural fractures or weakness planes at ~20° to Shmin are just ready to slip...

**Stress Change Due To Hydr. Fracture-Induced Stress Shadow**

Near the HF, the stress field moves away from the failure surface and natural fractures and weakness planes are more stable...
Stress Change Due To Hydr. Fracture-Induced Stress Shadow

Away from the HF, the stress field also moves away from the failure surface stabilizing natural fractures and weakness planes stable...

Two Frac Stress Shadows

Note: The white region behind the HF is simply off the color scale (>0.4 MPa)
\( \Delta \text{Shmin} – \text{Dual Frac, } Sp=56\text{m} \)

Shmin Wellbore Stress Profile: 56m Stage Spacing
Change in Shmin measured at the wellbore as f(frac height)

- 56m_40
- 56m_60
- 56m_80

Frac Height

HF Position

Distance Along Wellbore (m)

\( \Delta \text{Shmin} – \text{Dual Frac, } Sp=70\text{m} \)

Shmin Wellbore Stress Profile: 70m Stage Spacing
Change in Shmin measured at the wellbore as f(frac height)

- 70m_40
- 70m_60
- 70m_80

Frac Height

HF Position

Distance Along Wellbore (m)
**Shmin – Dual Frac, Sp=154m**

Shmin Wellbore Stress Profile: 154m Stage Spacing
Change in Shmin measured at the wellbore as f(frac height)

The profiles show that the additive effect of Stress Shadows is a function of the hydraulic fracture height and the stage spacing. As height increases and stage spacing decreases, the Stress Shadow gets larger.

**Dynamic Stress Shadows**

Single Hydraulic Fracture  
Dual Hydraulic Fractures

Reduction Compression Region Around HF Tip

Note the region of combined Stress Shadow

Planview at injection point
**Stress Shadows Along the Wellbore**

Multi-stage fracturing causes a rise in interfrac stress, which stabilizes natural fractures!

Change in Shmin along the wellbore (comparable to a change in ISIP).

---

**ΔShmin: 18 Stage Irregular Spacing**

Consider the effect that this variable change in the stress field might have on microseismicity generation and interpretation!
Influence of DFN Orientation on Stress Shadow

Depending upon the orientation of the underlying natural fracture pattern and the developed pressure distribution, the stress shadow can be very complicated.

Stress Shadows: Tip Shear Stresses

Shear stresses (both horizontal and vertical) are generated at the HF tip; these stresses are the primary cause of tip-related microseismic events.

Note: The white region behind the HF is simply off the color scale (>0.4 MPa)
**Stress Shadows: Tip Shear Stresses**

Change in Syx (MPa)

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<th>Vertical shear stress</th>
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</table>

Note: The white region behind the HF is simply off the color scale (>0.4 MPa)

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**Shear Stress at a Hydraulic Fracture Tip**

Horizontal plane crossing fracture origin at z = 0

The region in red exhibits an increase in horizontal shear stress, while the green region is largely unchanged. The blue region represents areas where the shear stress is reduced. The reduction behind the HF tip is caused by the Stress Shadow.

Shear stresses at the tip may play a critical role in opening closed/cemented natural fractures so that they can accept fluid.

Note the rotation in principal stresses immediately at the HF tip.
**Dual Hydr. Fractures: Horizontal Shear Stress Development**

The Stress Shadow from the first hydraulic fracture greatly reduces the horizontal tip shear from the second hydraulic fracture.

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</tr>
<tr>
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<td>1.000E+04</td>
</tr>
</tbody>
</table>

2nd HF is half propagated

2nd HF is fully propagated

Note: The white region behind the HF is simply off the color scale (>0.4 MPa)

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**Dual Hydr. Fractures: Vertical Shear Stress Development**

Whereas the horizontal tip shear was suppressed, the vertical shear combines.

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</tbody>
</table>

250m

Note: The white region behind the HF is simply off the color scale (>0.4 MPa)
Static Zipper Frac Stress Shadows: Stg#1-Shmin

A four stage Zipper frac is shown. The first frac has been pumped.

Shmin has increased both towards the Toe (left) and the Heel (right).

Static Zipper Frac Stress Shadows: Stg#1-ΔShmin

A four stage Zipper frac is shown. The first frac has been pumped.

Around the hydraulic fracture, the stress field has increased in magnitude.
Static Zipper Frac Stress Shadows: Stg#1-Max Shear

A four stage Zipper frac is shown. The first frac has been pumped. Max Shear is the maximum shear stress within the region. There is no higher shear stress. As shown, Max Shear decreases significantly (~5MPa) around a hydraulic fracture.

Static Zipper Frac Stress Shadows: Stg#2-ΔShmin

A four stage Zipper frac is shown. The second frac has been pumped. ΔShmin has increased both towards the Toe (left) and the Heel (right) of both wells. ΔShmin is higher in the overlap region of the fractures, but there is little effect of the combined fractures.
Static Zipper Frac Stress Shadows: Stg#2-Max Shear

A four stage Zipper frac is shown. The second frac has been pumped.

With regard to the Max Shear, there is a combining effect of two wells – as shown, the reduced Max Shear region is now significantly larger.

Static Zipper Frac Stress Shadows: Stg#4-ΔShmin

A four stage Zipper frac is shown. The fourth frac has been pumped.

ΔShmin has increased both towards the Toe (left) and the Heel (right) of both wells. ΔShmin is higher in the overlap region of the fractures, but there is little effect of the combined wells.
A four stage Zipper frac is shown. The fourth frac has been pumped.

With the exception of minor, very near fracture effects, the Max Shear stress is significantly reduced throughout the region of the two wells.

When Hydraulic Fractures Interact

There are two basic forms of HF interaction: overlapping tips (A) or direct communication (B).

The basic behavior of these needs to be considered before considering the impact on natural fractures or weakness planes in a multi-well completion (e.g., Zipper Fracs).
Tip Movement for Overlapping HFs

Overlapping Hydraulic Fracture Wing Growth

As the tips overlap, their movement is impeded and the HFs grow outwards.

Through ~375 time units, both HFs are essentially bi-wing of equal length. After ~375 time, the outer tips stop propagating and only the inner tips propagate. However, at ~525 time units, the inner tips stop propagating entirely and only the outer tip propagate.

Dynamic Zipper Frac Stress Shadows: Well#1, Stage#1

Shmin (29 to 34 MPa)  Sxy Shear (0 to 5 MPa)

Planview of injection point

HF Trace
Summary of Dynamic Stress Shadows

- The first frac stage on Well#1 shows clear bi-wing grow, a significant, symmetric Stress Shadow, and significant, deep shear stress from the hydraulic fracture tips.

- The first frac stage on Well#2 is bi-wing, but the inner wing is slightly longer than the outer wing. Further, for the same fluid injection, the hydraulic fracture is ~27% longer.

- The stress shadow effect (Shmin) from the first frac stage on Well#2 (HF#2) is now a bit more complicated and asymmetric. The shear stresses are markedly different: 1) the overall area of shear stress from the inner tips is significantly reduced; and 2) the magnitude of the shear stress near the tip of the Well#1 HF has increased notably.

Summary of Dynamic Stress Shadows

- The second frac stage on Well#1 (HF#3) shows a longer inner wing than on the first Well#1 frac stage (for the same injection volume); however, the outer wing length is significantly increased (the second HF on Well#1 is ~74% longer than the first HF stage).

- The shear stress from the inner tip of the second stage on Well#1 is almost completely gone; however, there is significant shear stress from the outer tip – likely because it has extended so far beyond the limits of the first frac stage on Well #1.
Dynamic Zipper Frac Stress Shadows: Propped vs. Pressurized Shear Behavior

Pressurized - Sxy Shear (0 to 5 MPa)  Propped - Sxy Shear (0 to 5 MPa)

The shear stresses and Stress Shadow effects can be markedly different when stages are allowed to close vs. remain pressurized during subsequent HF stages.

Quantify Zipper Frac Hydr. Fracture Tip Shear Stresses

Using 2D simulations and multiple natural fracture networks, the shear stresses from a Zipper Frac configuration are evaluated by comparing the area (volume) of sheared rock mass.
Model Schematics

Using two different fracture networks (180° and 145°), Xf1 from the left well was set at 125m. Xf2 was grown from the right well at various lengths and at positions 20, 35, and 45m offset from Xf1.

Nat. Fracture Shear $f(\text{Friction Angle})$

A critical key to designing Zipper Fracs must be understanding the frictional properties of the underlying natural fractures and weakness planes. As the friction angle decreases, the sheared area (volume) increases. For the simulations, the blue natural fractures are in a shear condition (and could generate microseismicity).
**Shear Region vs. Friction Angle**

**Image Description:**

- **A 15° Friction Case:**
  - Area: 5740m²
  - The shaded regions represent the sheared natural fractures as X1 propagates to its 125m length. The underlying blue sheared natural fractures represent the tip shear for a given length of hydr. fracture X1. As friction angle increases, the sheared region decreases.

- **B 25° Friction Case:**
  - Area: 2220m²

**Importance of Natural Fracture Network Orientation:**

The area (and by default the volume) of formation sheared (5740m²) for the 15° FA for the ‘180°’ model was similar to the 25° case of the ‘145°’ DFN (5250m²)
Shear Region Overlap in Multi-Well Configuration – 15° Friction

When sheared regions overlap, it is assumed that this a neutral or negative effect on production. Consequently, a Zipper Frac design should limit overlap.

Shear Region Overlap in Multi-Well Configuration – 25° Friction

When the friction angle is greater, less overlap occurs for a given separation distance. Again, this means that the shear strength of the natural fractures and weakness planes needs to be considered in Zipper Frac design.
Possible Multi-Well NF Shear

Question: In overlapping regions, do we simply re-shear the same fractures (neutral or negative) or increase the sheared volume?

Multi-Well Shear, 25° FA: f(Length)

‘145°’ Model / 20m Separation / 50m HF#2

20m Separation/50m HF#2
Sheared nat. fractures (blue) and open nat. fracture (red) when Xf1 (left) is 125m and Xf2 (right) is 50m.

20m Separation/50m HF#2
Sheared nat. fractures (blue) not covered by the shaded regions (shear from independent wells) are ‘extra’ due to Zipper Fracs.
Multi-Well Shear, 25° FA: \( f(\text{Length}) \)

**‘145°’ Model / 20m Separation / 75m HF#2**

- **20m Separation/75m HF#2**
  - Sheared nat. fractures (blue) and open nat. fracture (red) when \( xF1 \) (left) is 125m and \( xF2 \) (right) is 75m.

**20m Separation/75m HF#2**

- Sheared nat. fractures (blue) not covered by the shaded regions (shear from independent wells) are 'extra' due to Zipper Fracs.

---

Multi-Well Shear, 25° FA: \( f(\text{Length}) \)

**‘145°’ Model / 20m Separation / 100m HF#2**

- **20m Separation/100m HF#2**
  - At \( xF2 = 100 \text{m} \), sheared natural fractures are eliminated and only tensile opening occurs.

**20m Separation/100m HF#2**

- Open (mode 1) NFs
**Multi-Well Shear, 25° FA: f(Length)**

‘145° Model / 20m Separation / 125m HF#2

20m Separation/125m HF#2
Sheared nat. fractures (blue) and open nat. fracture (red) when Xf1 (left) is 125m and Xf2 (right) is 75m.

---

**Multi-Well Shear, 25° FA: f(Separation)**

‘145° Model / 75m HF#2

20m Sep 45deg DFN
Sheared nat. fractures (blue) and open nat. fracture (red) when Xf1 (left) is 125m and Xf2 (right) is 75m for separation distances of 20m, 35m, and 45m.

NF Friction Angle=25deg
Multi-Well Shear, 25° FA: \( f(\text{Separation}) \)

‘145°’ Model / 125m HF#2

20m Sep 45deg DFN
Sheared nat. fractures (blue) and open nat. fracture (red) when Xf1 (left) is 125m and Xf2 (right) is 125m for separation distances of 20m, 35m, and 45m.

NF Friction Angle=25deg

Distance (meters x 10)
Distance (meters x 10)
Distance (meters x 10)

Multi-Well Shear, 35° FA: \( f(\text{Separation}) \)

‘145°’ Model / 75m HF#2

A 45deg DFN
Sheared nat. fractures (blue) and open nat. fracture (red) when Xf1 (left) is 125m and Xf2 (right) is 75m for separation distances of 20m, 35m, and 45m.

NF Friction Angle=35deg

Distance (meters x 10)
Distance (meters x 10)
Distance (meters x 10)
Multi-Well Shear, 35° FA: \( f(\text{Separation}) \)

\[ '145^\circ' \text{ Model} / 125m \text{ HF}\#2 \]

Sheared nat. fractures (blue) and open nat. fracture (red) when Xf1 (left) is 125m and Xf2 (right) is 125m for separation distances of 20m, 35m, and 45m.

\[ \text{NF Friction Angle}=35\text{deg} \]

Multi-Well Shear, 25° FA: \( f(\text{Separation}) \)

\[ '180^\circ' \text{ Model} / 75m \text{ HF}\#2 \]

Sheared nat. fractures (blue) and open nat. fracture (red) when Xf1 (left) is 125m and Xf2 (right) is 75m for separation distances of 20m, 35m, and 45m.
**Multi-Well Shear, 25° FA: \( f(\text{Separation}) \)**

*‘180°’ Model / 125m HF#2*

- 20m Sep
  - Sheared nat. fractures (blue) and open nat. fracture (red) when Xf1 (left) is 125m and Xf2 (right) is 125m for separation distances of 20m, 35m, and 45m.

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**Results: Shear From Zipper Fracs**

- **Sheared Length w/Dual Fracs**
  - ‘145°’ Results
  - ‘180°’ Results

**KEYS:**
- Shear is a function of separation distance, NF orientation, and FA;
- Maximum shear at 50 to 25m tip-to-tip distance;

**KEYS:**
- Minimum shear generally at 100m (tips aligned); and
- For 35m separation & ‘145°’ case, 35° FA was greater shear.
Influence of Stress Field

KEYS:
- More isotropic stress greatly reduced shear;
- More isotropic required more overlap to maximize shear;
- Maximum shear occurred at 45m separation; and
- Maximum shear occurred at 100m XF2 (tips aligned)

Zipper Fracs with Pressure Diffusion

In order to investigate the role of pressure change and Zipper Fracs, the simulations were re-run accounting for significant pressure diffusion in association with hydraulic fracture propagation. The picture left shows an example of the magnitude of the pressure change.
**Sheared Length: Zipper Fracs w/PP**

**KEYS:**
- For the 180° model, the amount of sheared area did not significantly change; however,
- The maximum benefit of a Zipper Frac occurred when hydraulic fractures overlapped.

**Sheared Length-Dual Fracs w/PP**

**KEYS:**
- For the 145° model, the amount of sheared area also did not significantly change; however,
- The greater benefit of a Zipper Frac occurred when hydraulic fractures overlapped.
Key Learnings

1. Natural fracture orientation significantly influences the amount and location of natural fracture shear, and multi-well completion optimization must account for this.

2. Natural fracture friction controls the depth and amount of natural fracture shear, and multi-well completion optimization requires the evaluation and consideration of friction properties.

3. The optimum hydraulic fracture separation distance for multi-well completions must also account for the in-situ stress ratio.

Key Learnings

4. For multi-well completion schemes, the design length of the second hydraulic fracture (Xf2) should be kept less than the point of overlap with the first hydraulic fracture (Xf1) and be optimized in conjunction with the hydraulic fracture separation distance.

5. Overall, the study results suggest that there is the potential for only modest improvements in stimulation complexity from the modified zipper-frac completion schemes while the potential for well-to-well communication (and possible screenout conditions) increases..
Summary

The four key elements of the potential improvement in production from multi-well completions (Zipper Fracs) are: Stress Shadows, Tip Shear, Natural Fracture Pressure Changes, and the underlying Fracture Network Connectivity.

– Stress shadows stabilize natural fractures, reducing their ability to shear.
– Tip shear controls the opening of closed or partially closed natural fractures and weakness planes to accept pressure.
– Fracture network connectivity affects the depth of pressure diffusion from a hydraulic fracture.
– Increasing natural fracture pressure decreases the effective normal stresses increasing the ability to shear natural fractures.

Critical Zipper Frac Design Issues

Some Critical Optimization Issues:

• Correctly predicting the horizontal overlap of HFs;
• Correctly predicting HF spacing (from separate wells) at the location of overlap;
• Maximizing tip shear stresses (relative to the HF spacing);
• Knowing the underlying natural fracture (weakness plane) pattern;
• Knowing natural fracture connectivity/aperture;
• Understanding in-situ natural fracture pressure changes during the HF; and
• Knowing the in-situ stress ratio
References


