Rockfield
Think. Explore. Solve

Hydraulic Fracturing

Stress Shadow Impact of Fracture Growth and Geometry

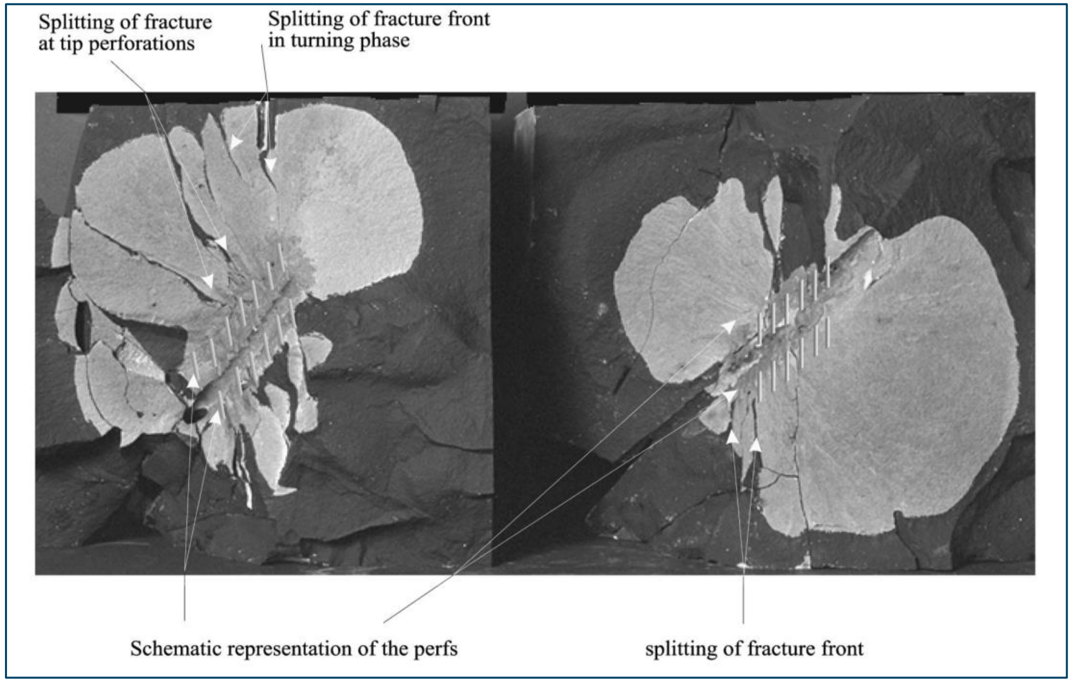
Narrated by: Adam Bere

rockfieldglobal.com

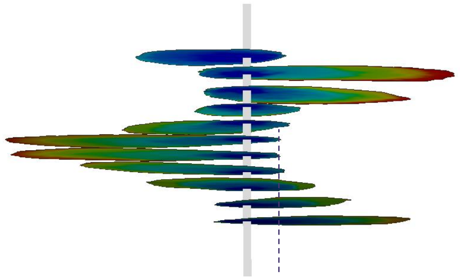
Contents

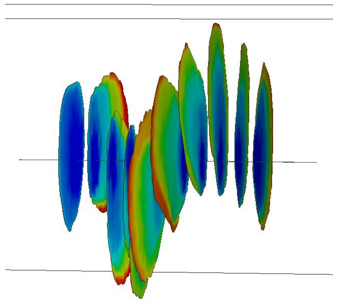
Induced hydraulic fractures may follow complex paths associated by aspects such as:

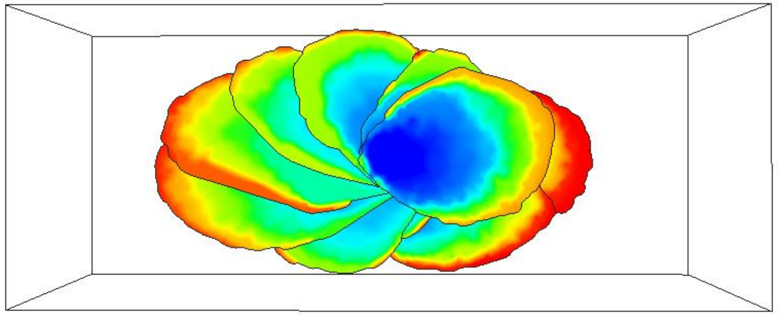
- **Stress shadowing**, interactions, branching, choking, curving and swarms



Impact of perfs on HF geometry and Ketterji & Pater (1999)

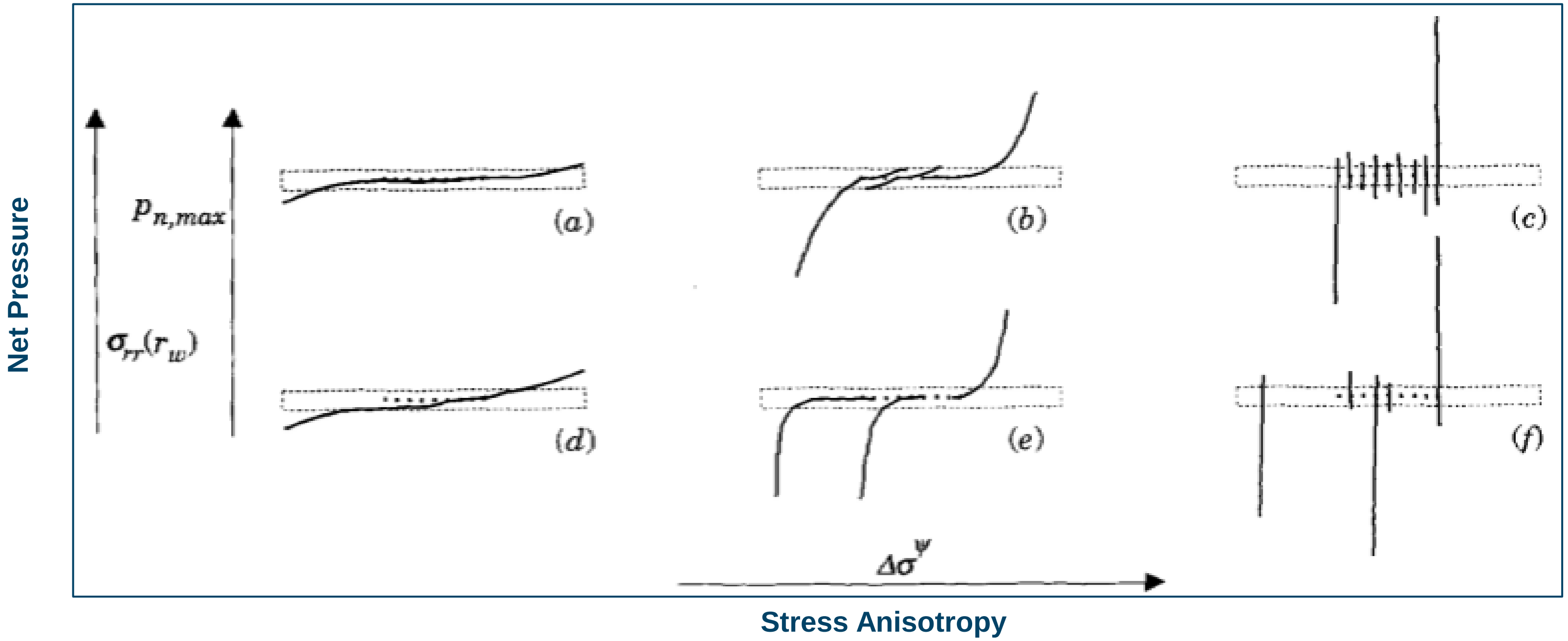






Considering lab scale fracture propagation:

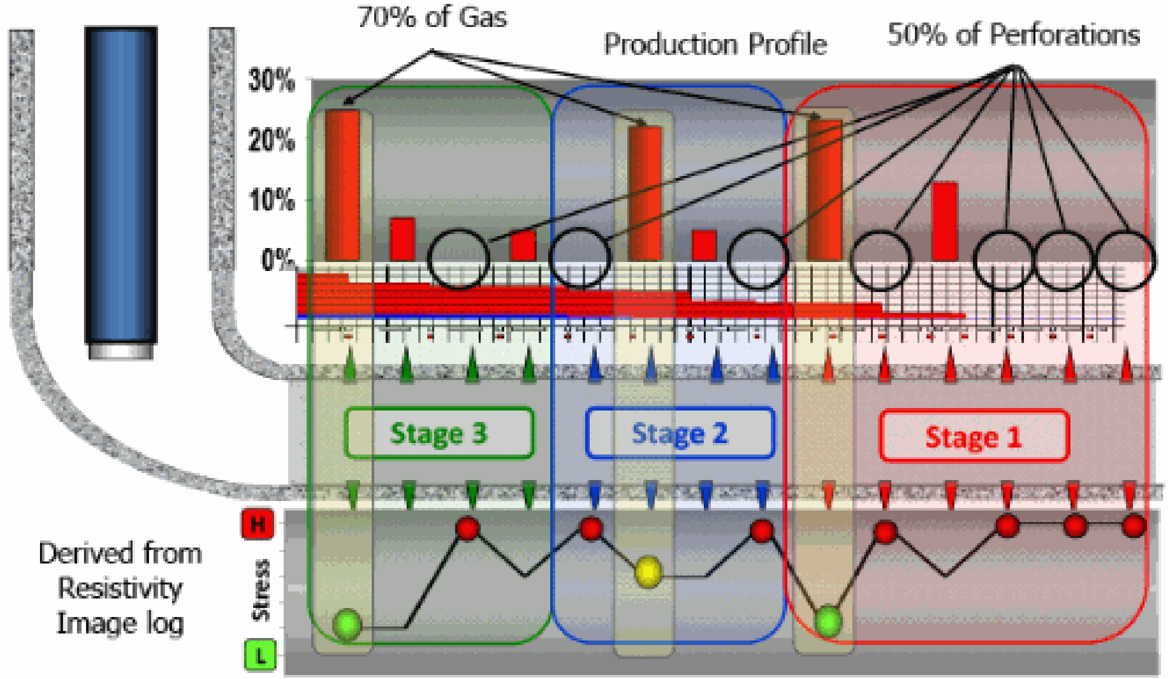
- Observations suggest not all clusters generate equal sized fractures
- Fracture propagation can be asymmetric from the well
- Stress shadowing could contribute to competition for fracture propagation from multi-clusters



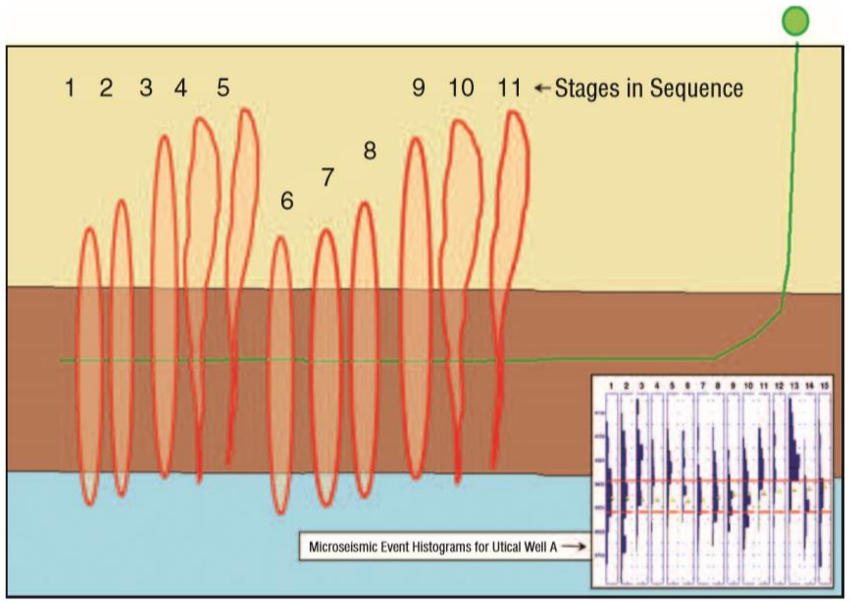
Weijers (1995)

Considering field scale fracture propagation:

- Observations suggest not all clusters contribute to overall production
- Stress shadowing could contribute to competition for fracture propagation from multi-clusters/stages/wells



Rahim (2017)

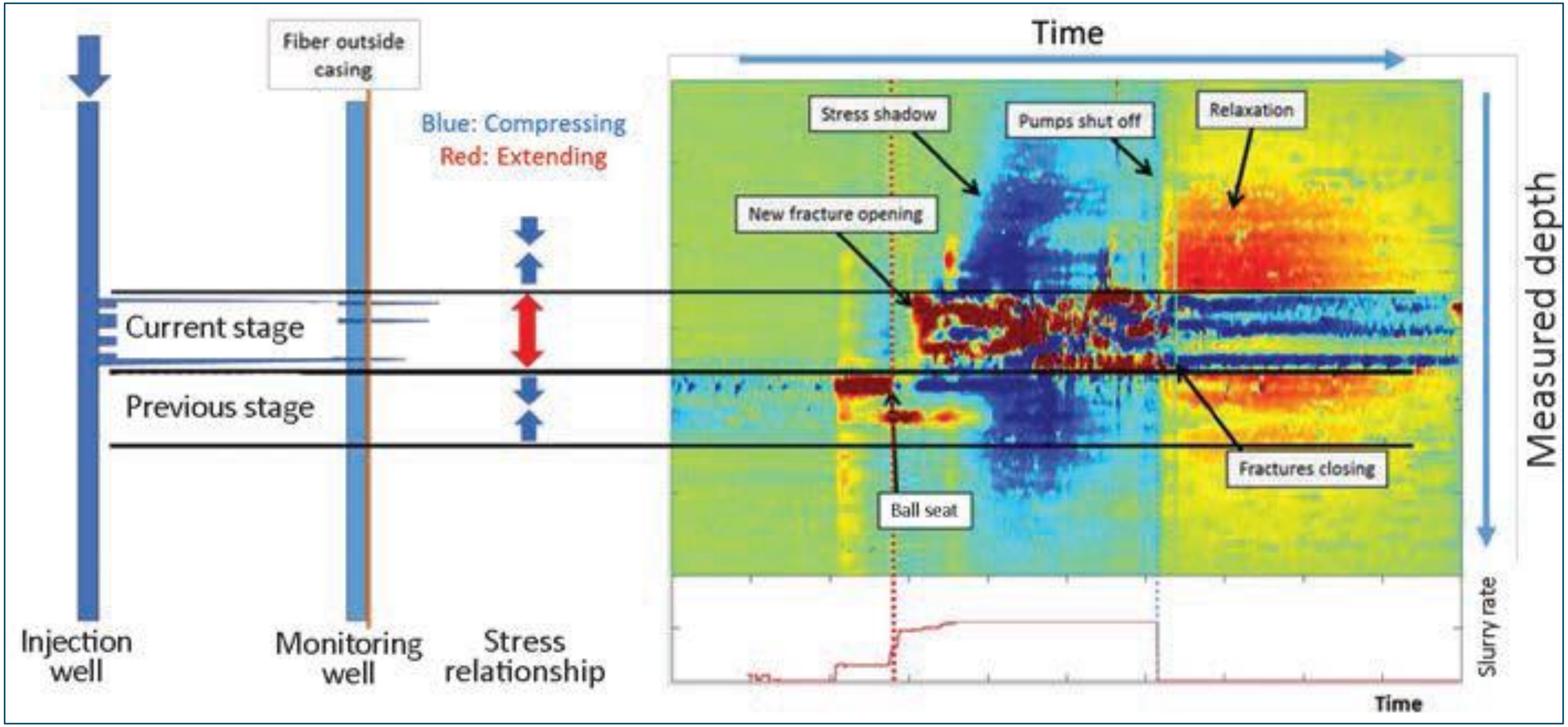


Dohmen et al. (2015) – Multi Stage Observations

Background, Motivation & Observations

Fracture Complexity – Field Scale

- Field observations demonstrate the significant extent of stress shadows

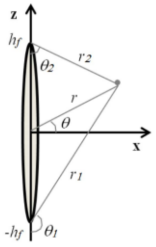


Jin and Roy (2017): Single Stage & Multi-Cluster

Analytical Assumptions for Stress Shadows

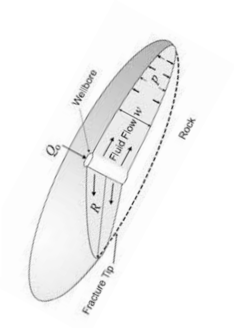
- Analytical solutions developed for stress distribution in the vicinity of dilated fractures form the basis of industry stress shadowing calculations e.g. semi infinite fracture and penny shaped fracture
- These solutions provide approximations for delta stress increase in the vicinity of pressurized fractures and are typically utilised by modelling software

$$\Delta\sigma_{xx} = p_{net}\left[1 - \frac{x^3}{\left(x^2 + h_f^2\right)^{3/2}}\right]$$

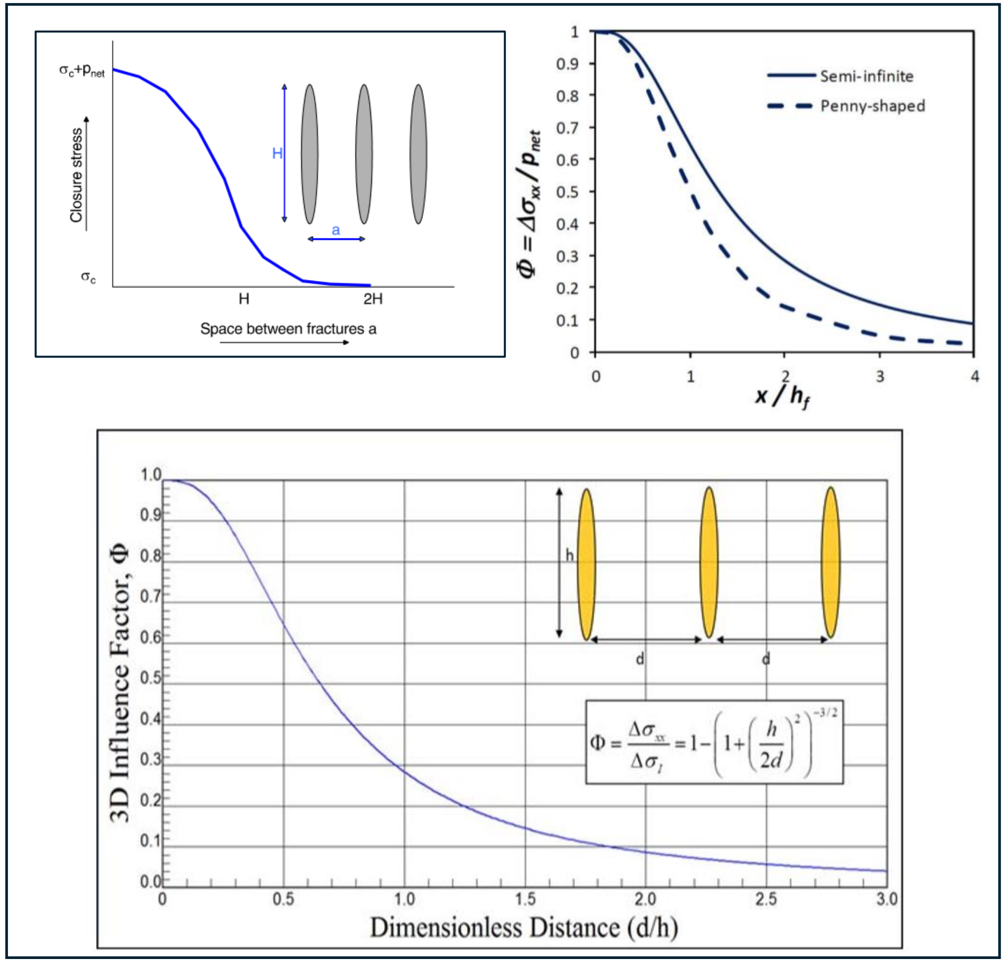


Semi-infinite fracture

$$\Delta\sigma_{xx} = \frac{2p_{net}}{\pi}\left[\frac{x}{h_f}\frac{\left(x^2 - h_f^2\right)^2}{\left(x^2 + h_f^2\right)^2} - \tan^{-1}\left(\frac{h_f}{x}\right)\right]$$



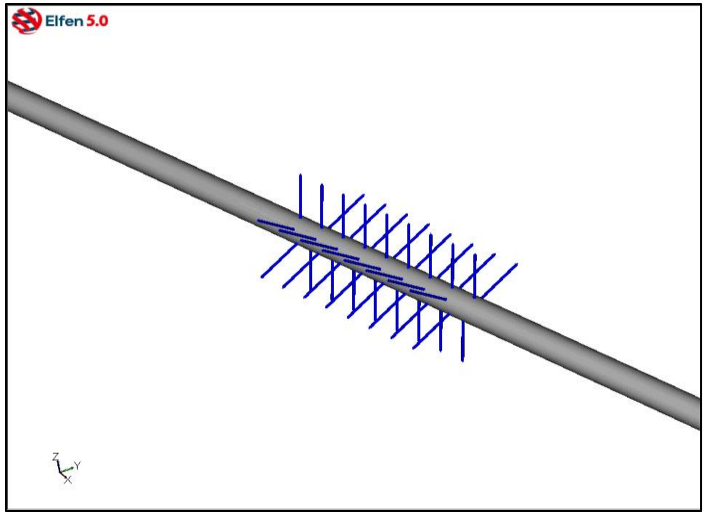
Penny shaped fracture



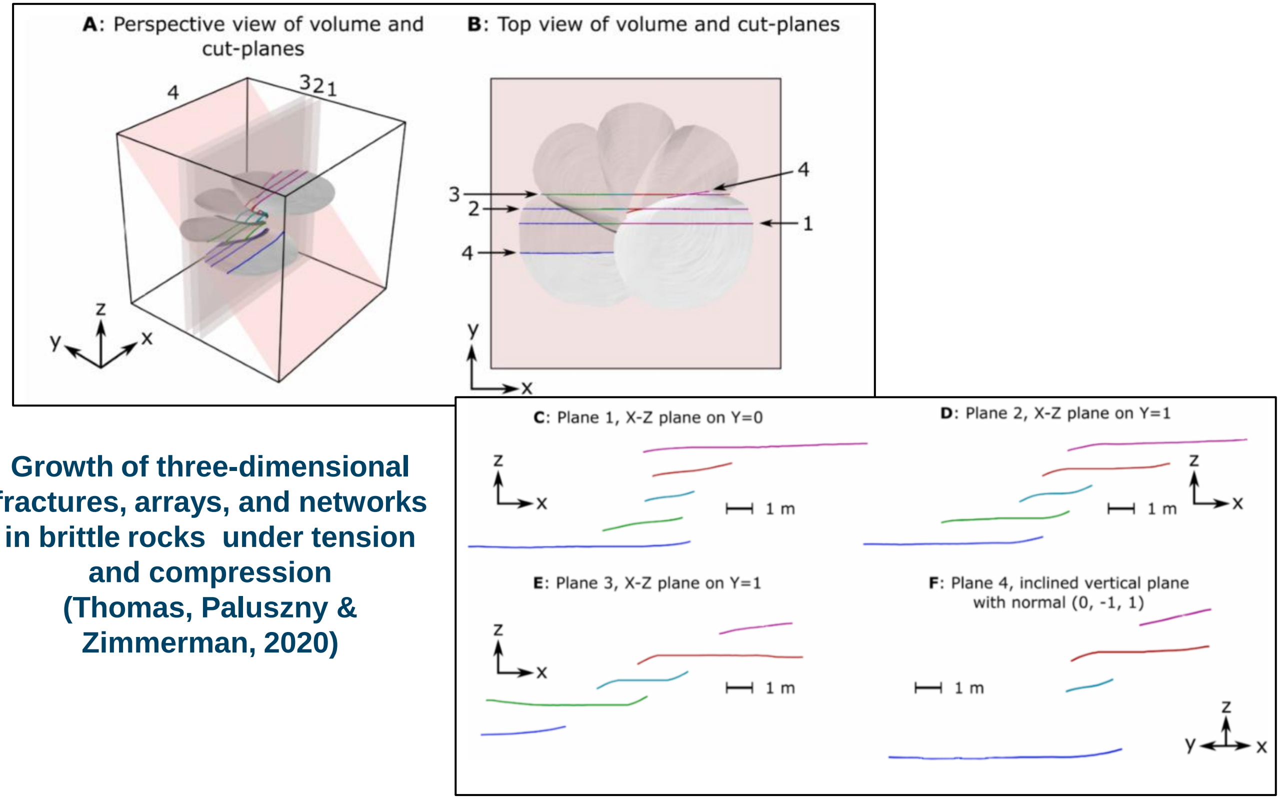
Background, Motivation & Observations

Fracture Complexity – Analytical/Modelling Approaches

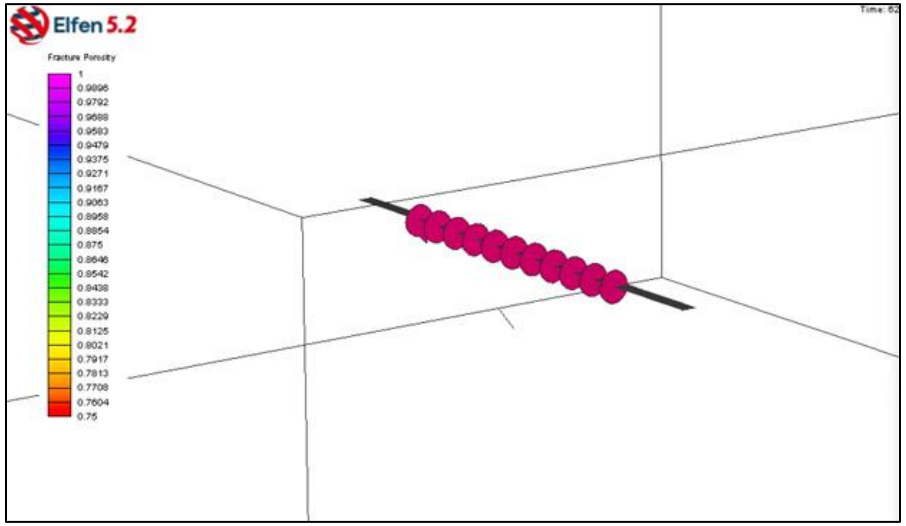
- Without imposing analytical approximations/constraints, physics-based numerical modelling can capture the influences of stress shadowing during fracture propagation and dynamic modification of the stress field giving rise to alternative fracture geometries



Multi-Perforations (Stress Shadows @ Wellbore Scale)



Growth of three-dimensional fractures, arrays, and networks in brittle rocks under tension and compression (Thomas, Paluszny & Zimmerman, 2020)

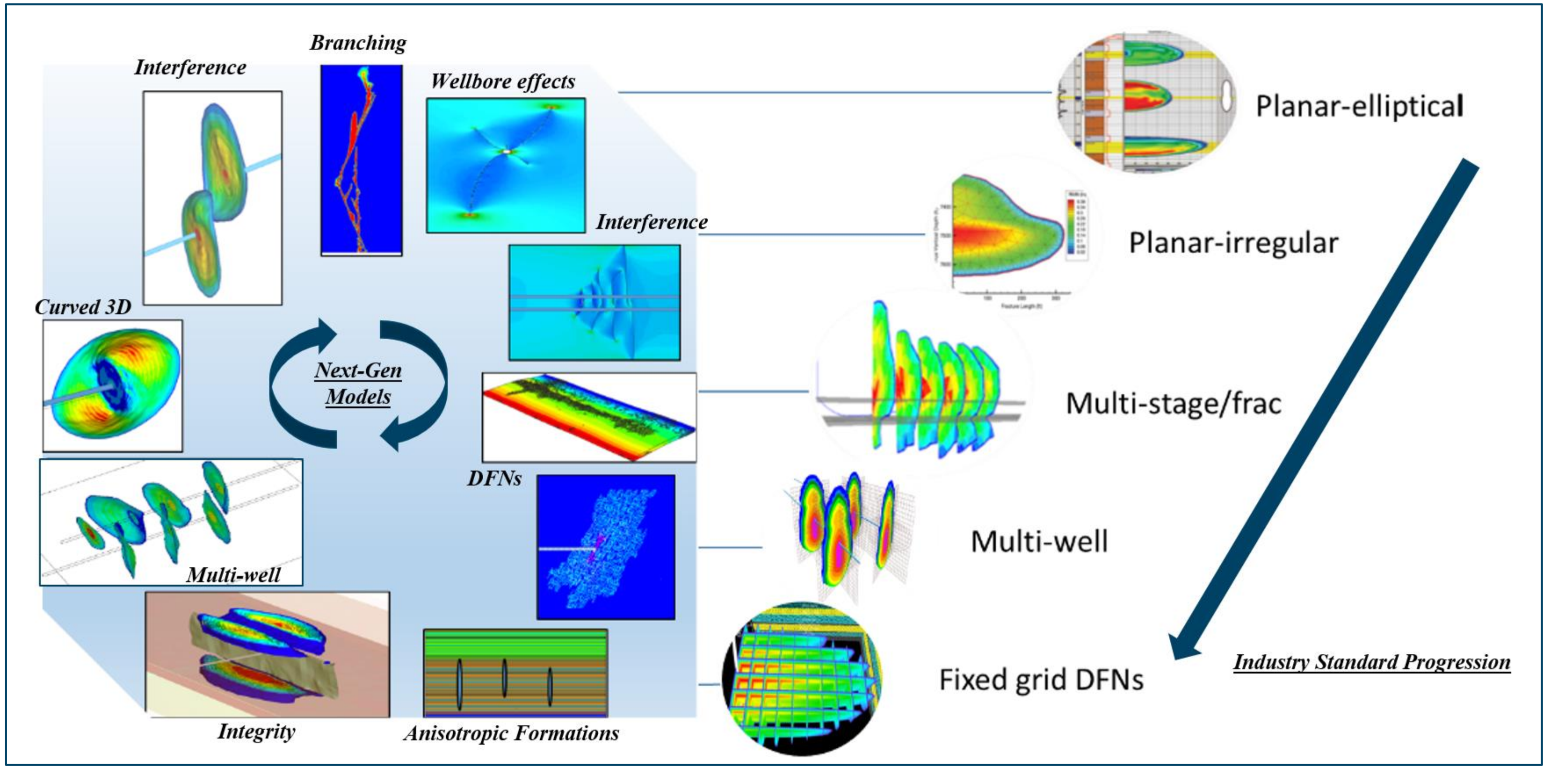


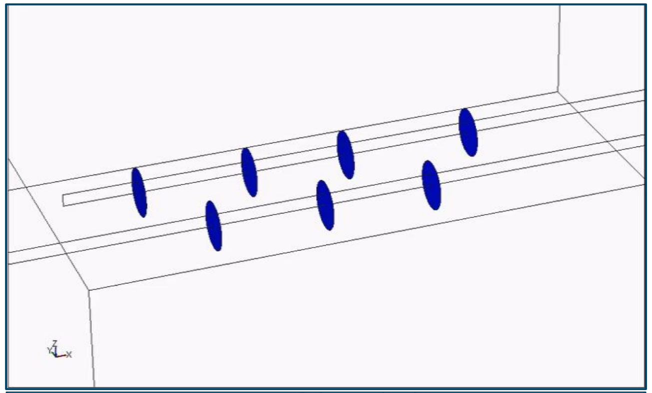
Multi-Clusters (Stress Shadows @ Reservoir Scale)

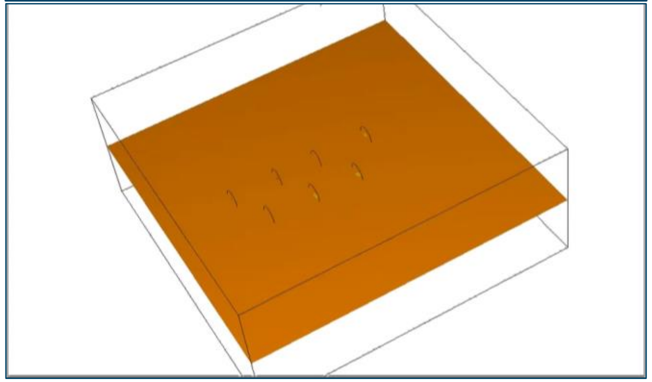
Agenda

- Background, Motivation & Observations
- Hydraulic Fracture Modeling in Challenging Rocks (State of the Art)
- Single Fracture Stress Shadowing
- 3-Cluster Stress Shadowing
- Multi-Cluster Stress Shadowing – Fracture Patterns and Implications
- Conclusions & Further Work

- **Finite Element full-physics based models include:**
  - DFNs
  - Anisotropy
  - Mixed mode failure
  - Layering and laminations
  - 3D curved fracture paths
  - Multi-wells / stages







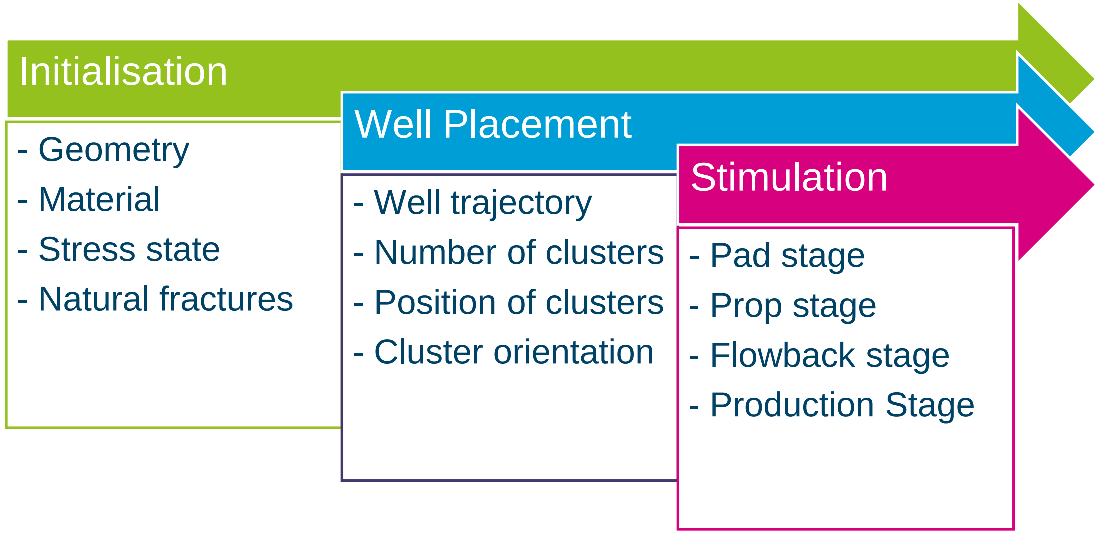
Agenda

- Background, Motivation & Observations
- Hydraulic Fracture Modeling in Challenging Rocks (State of the Art)
- **Single Fracture Stress Shadowing**
- 3-Cluster Stress Shadowing
- Multi-Cluster Stress Shadowing – Fracture Patterns and Implications
- Conclusions & Further Work

To demonstrate the effects of stress shadowing we explore the fundamentals associated with a single fracture propagating in 3D

Elfen tgr **considers the stress intensity at all locations around each fracture and accounts for:**

- in-situ and evolving stresses
- formation elasticity/yield parameters
- fracture fluid flow/pressure



Single Fracture Stress Shadowing

Model Set-up

Elfen tgr

Initialisation

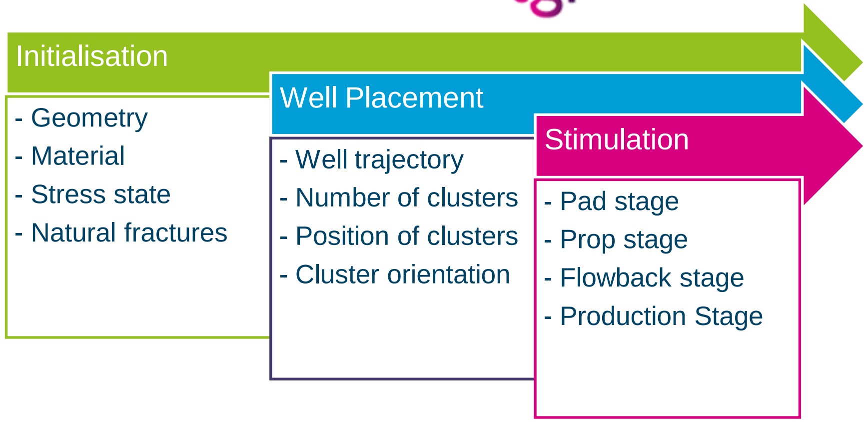
- <u>Model type:</u>
  - 3D, fixed boundaries
- <u>Dimensions (L,W,D):</u>
  - 250 m x 250 m x 100 m
- <u>Material:</u>
  - Homogeneous *(Minor Spatial Heterogeneity)*
  - Young's Modulus: 32 GPa
  - Poisson's Ratio: 0.2
  - Tensile Strength: 7 MPa
  - Facture Energy: 30 Nm
- <u>In-situ stress state:</u>
  - Stresses (Total):
    - 50 MPa (vertical)
    - 40, 42 MPa & 0° Azi (horiz)
  - Pore Pressure: 30 MPa

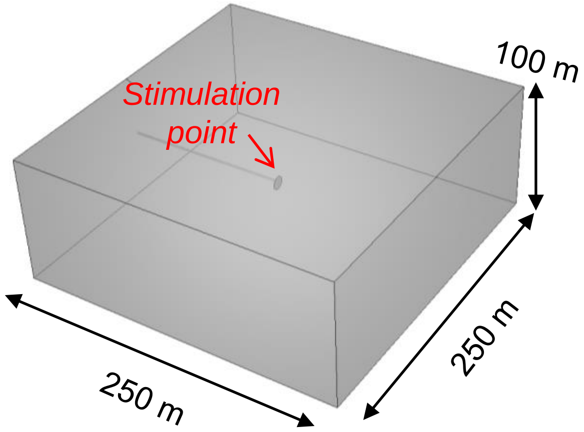
Well Placement

- <u>Number of clusters:</u>
  - 1
- <u>Cluster depths:</u>
  - 2000 m

Stimulation

- <u>Injection fluid:</u>
  - Slick-water (1cP)
- <u>Stimulation schedule:</u>
  - 1250bbl @ 15bbl/min
- <u>Leakoff type:</u>
  - Constant Leak-off model (30-40%)

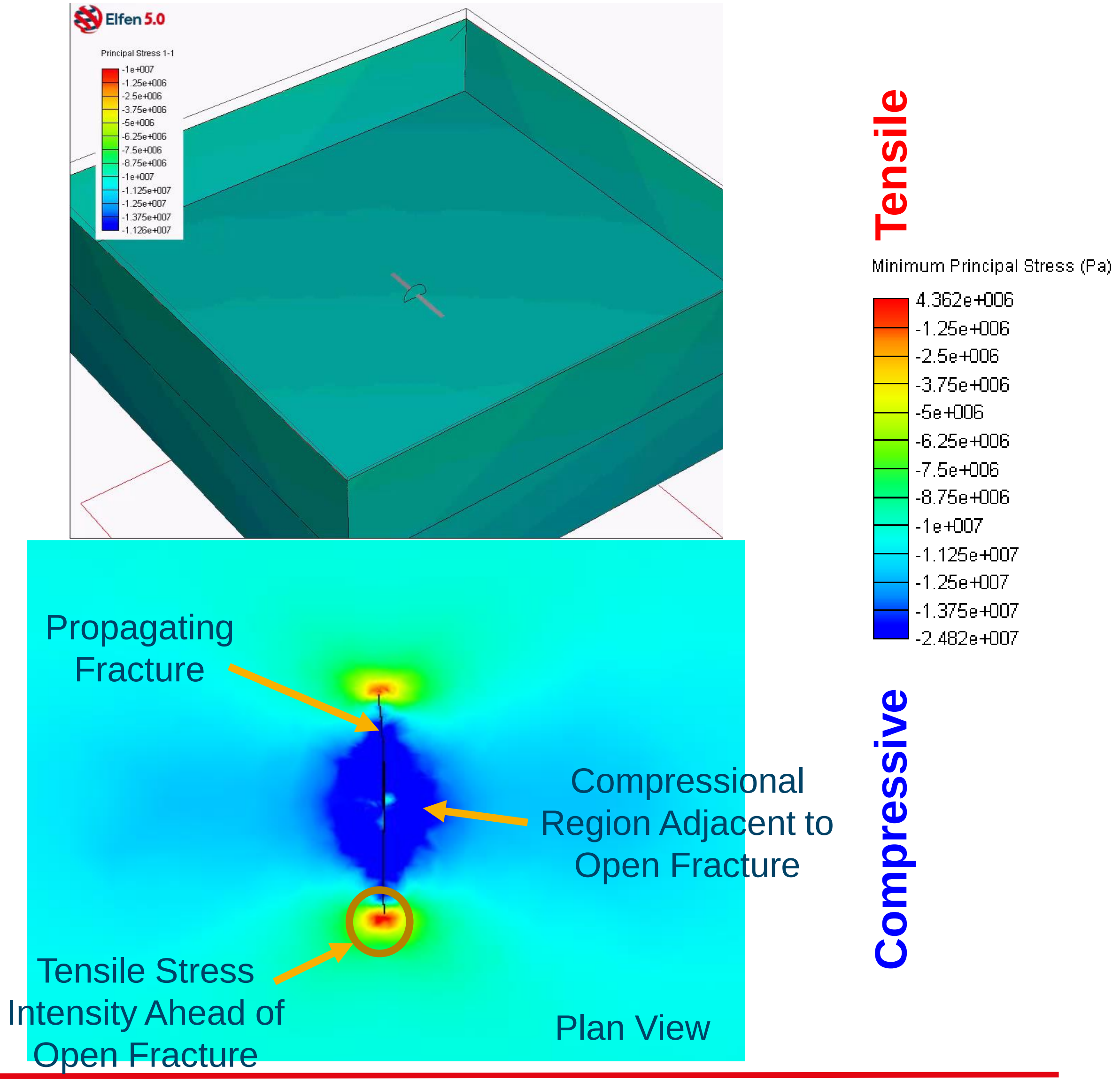




Single Fracture Stress Shadowing

Methodology

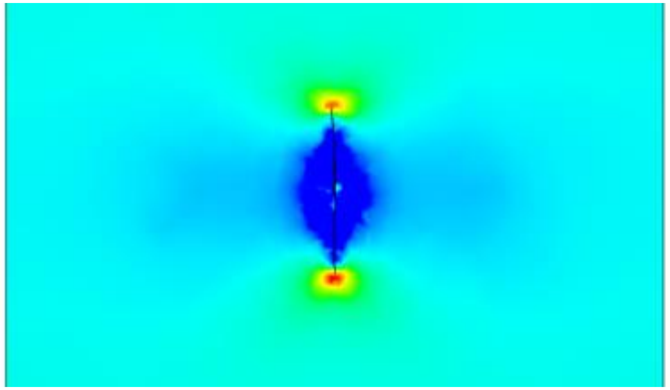
- **Fracture Insertion Criteria**
  - To propagate a fracture the injection pressure must generate a tensile **stress intensity** which exceeds the sum of:
    - *Current* minimum total principal stress
    - Formation tensile stress
  - The injection fluid also imposes significant **compressional stresses** adjacent to the open fracture
  - The fracture tip stress intensity and compressional stresses create stress shadows around the fracture



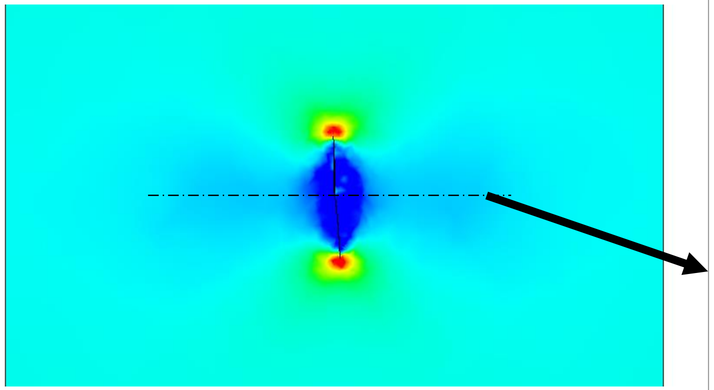
Single Fracture Stress Shadowing

Key Parameters Contributing to Stress Shadows

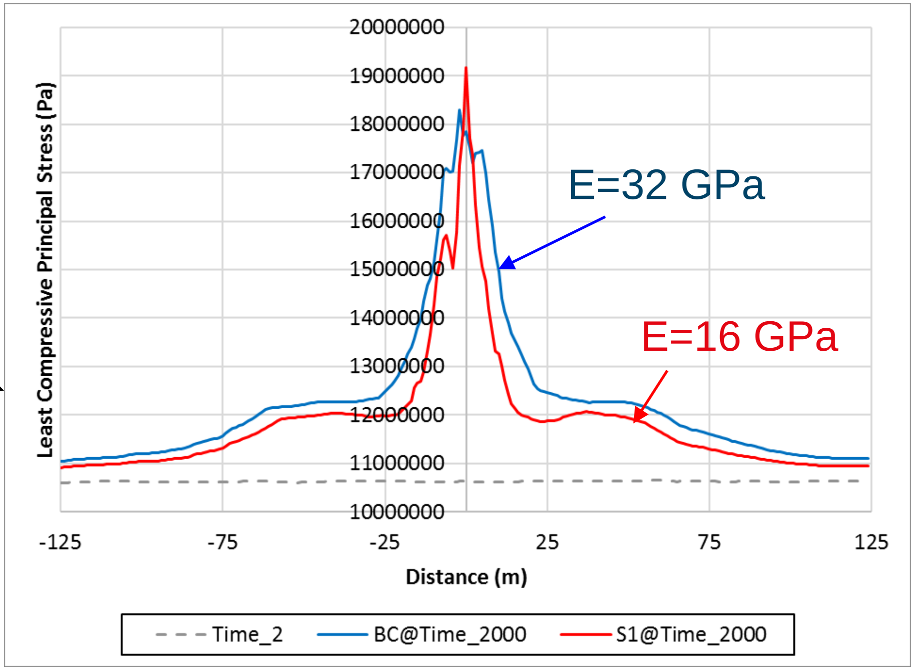
- **Influence of Elastic Modulus**

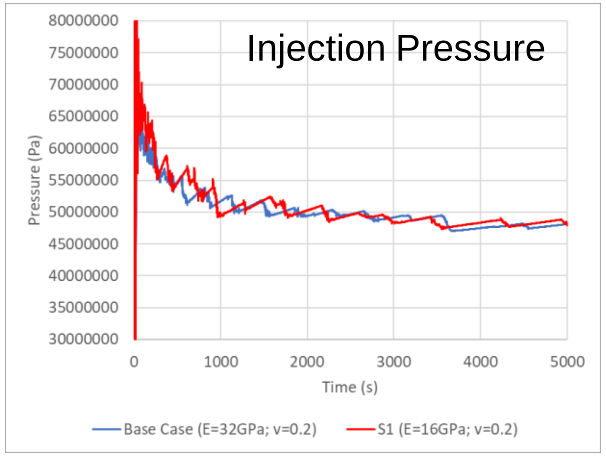


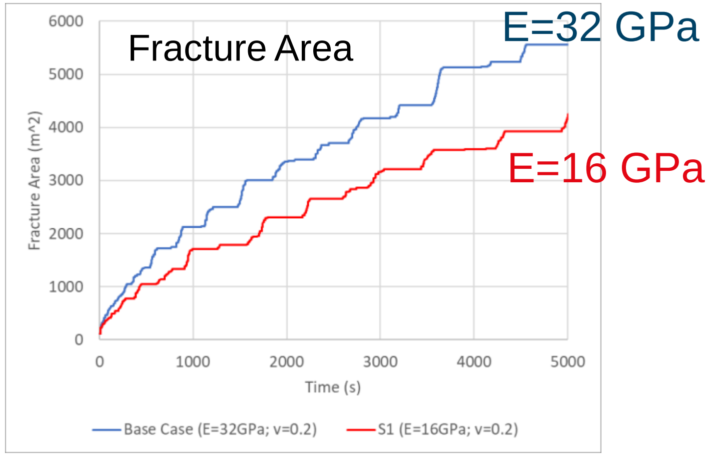
E=32 GPa (4.64e6 psi)



E=16 GPa (2.32e6 psi)

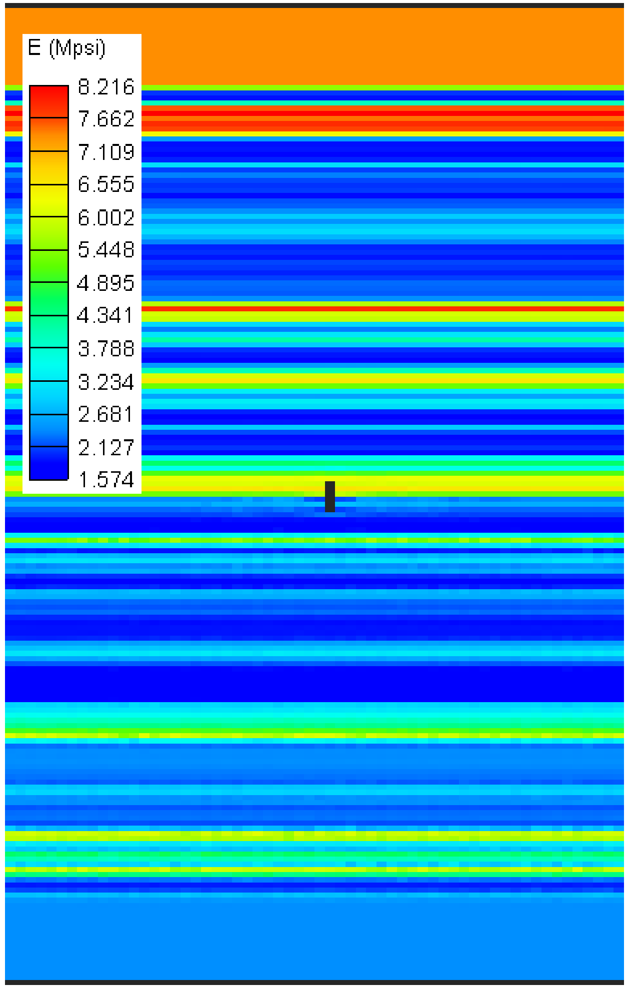


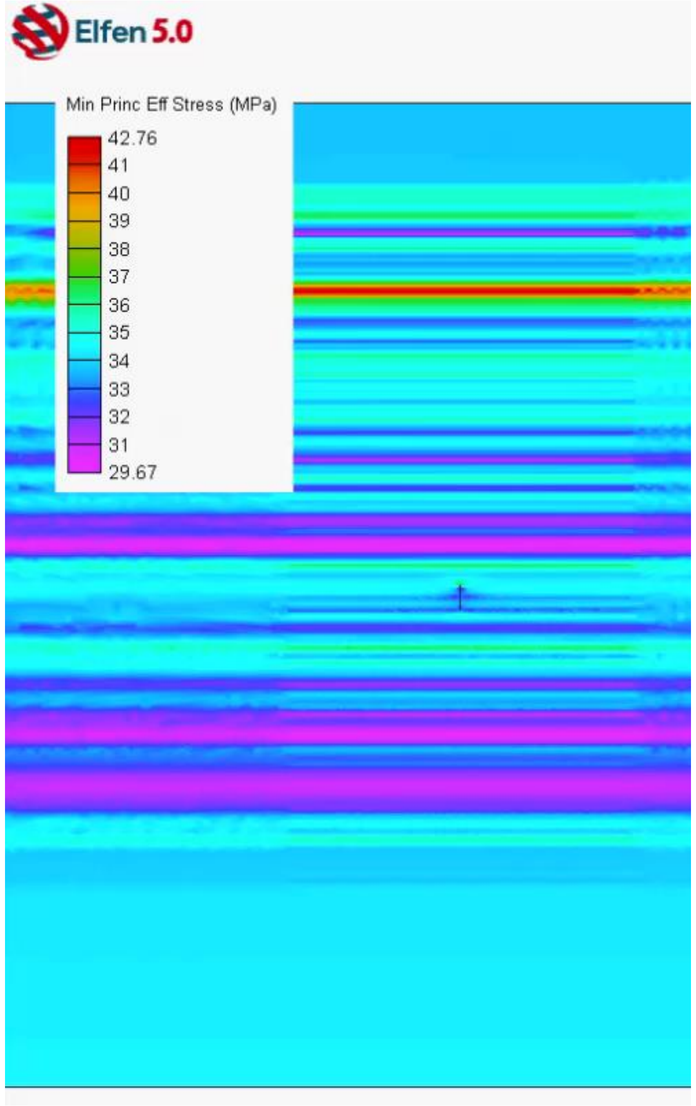




- **Stiffer formations induce larger stress shadows**
- **Stiffer formations attract larger stress intensity at fracture tip and hence → larger fracture area and smaller aperture**

- **Elastic heterogeneity**





Agenda

- Background, Motivation & Observations
- Hydraulic Fracture Modeling in Challenging Rocks (State of the Art)
- Single Fracture Stress Shadowing
- 3-Cluster Stress Shadowing
- Multi-Cluster Stress Shadowing – Fracture Patterns and Implications
- Conclusions & Further Work

3-Cluster Stress Shadowing

- In order to ensure fracture propagation from *all* clusters in a stage, completion design utilises perforations to induce Limited Entry Perforation Pressure Drop
- Limited Entry Perforation pressure drop model uses the flow rates at the stimulation points, i.e. q_i, each perforation could have a different pressure drop depending on the stimulation point flow rate

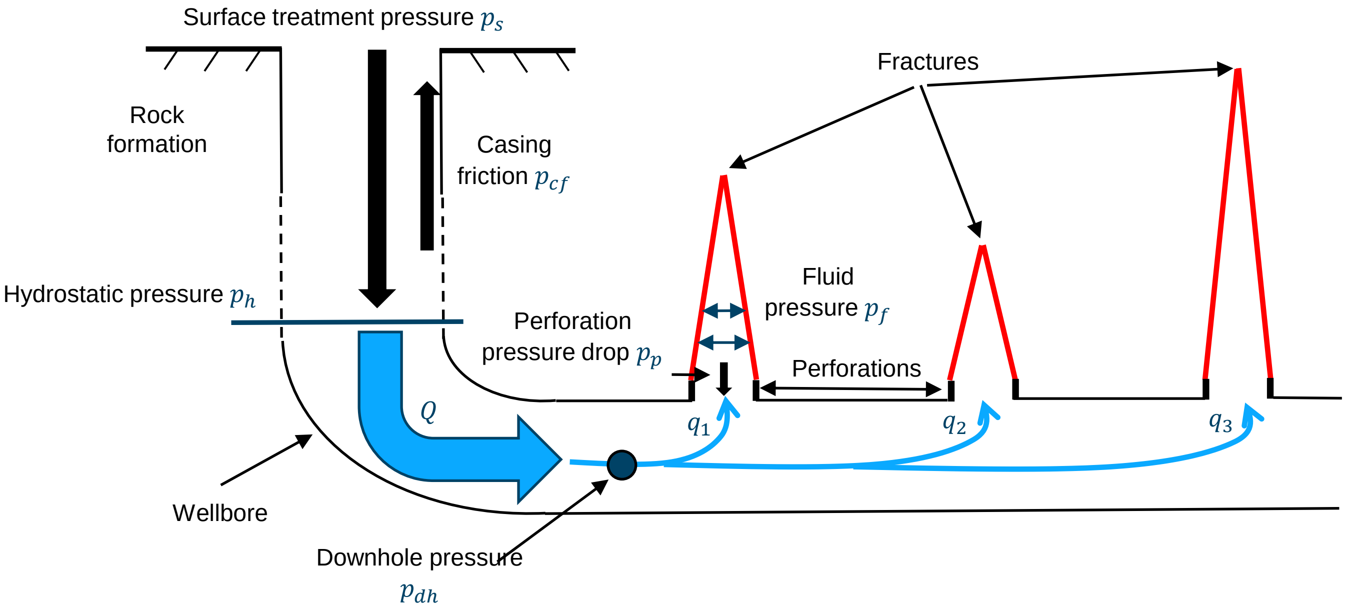


Illustration of pressure losses perforations

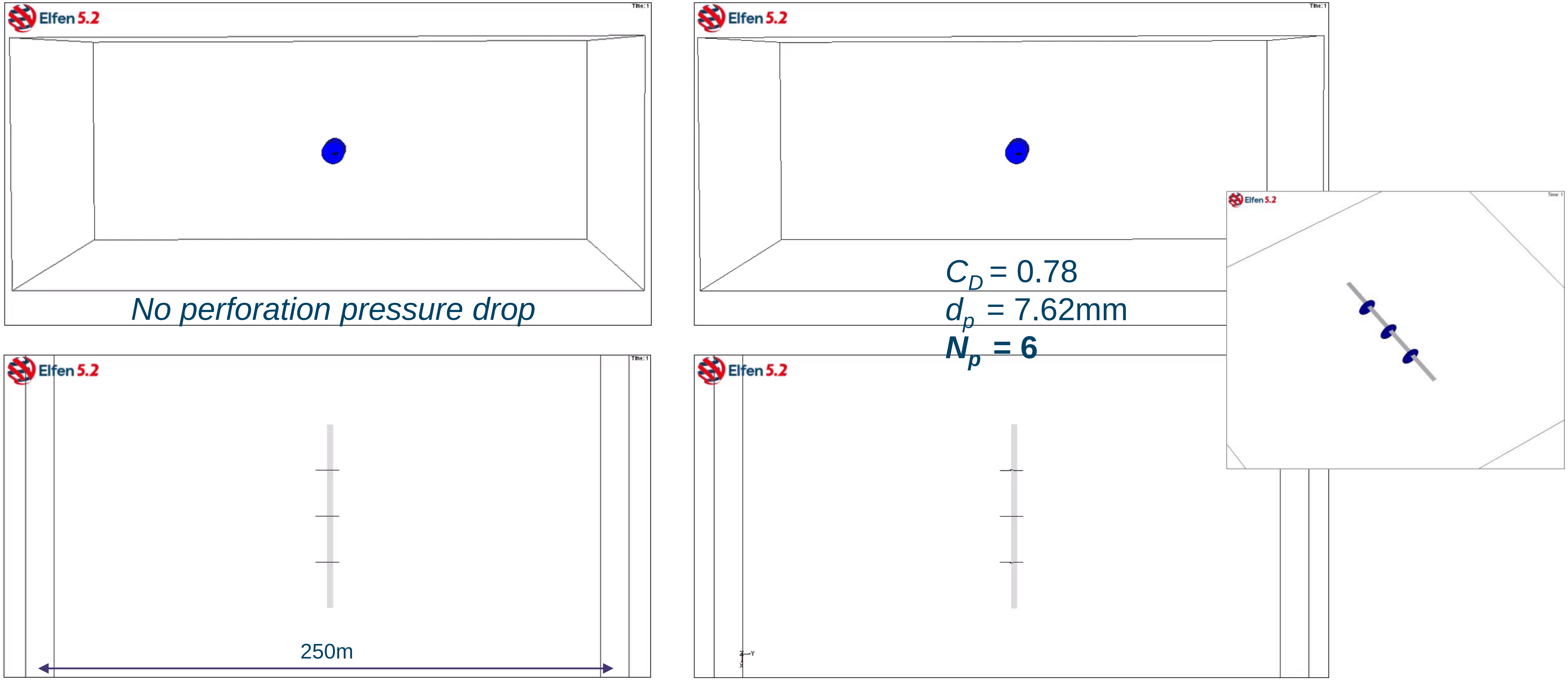
- Generally the Bernoulli equation is adopted by the petroleum industry to estimate the perforation pressure drop:

$$\Delta p_p = \frac{8\rho_f}{\pi^2 C_D^2 d_p^4}\left(\frac{q_i}{N_p}\right)^2$$

N_p - Number of perforation
d_p - Perforation diameter
C_D - Discharge coefficient
ρ_f - Fluid density

3-Cluster Stress Shadowing

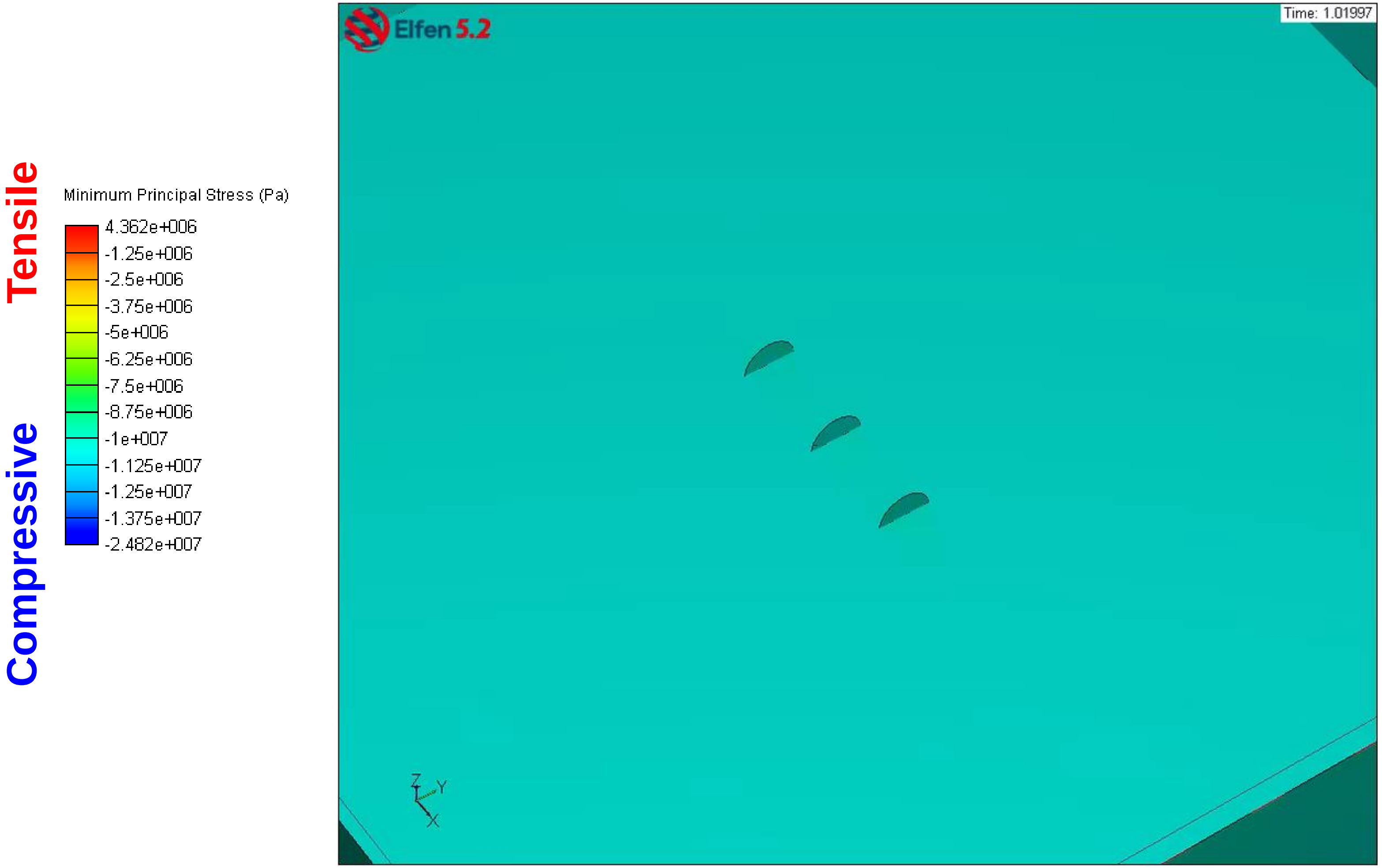
Perforation Pressure Drop Modelling- Demonstration



Multi-Cluster Fracture Propagation – 3750bbls Slick-water @ 45bbls/min

3-Cluster Stress Shadowing

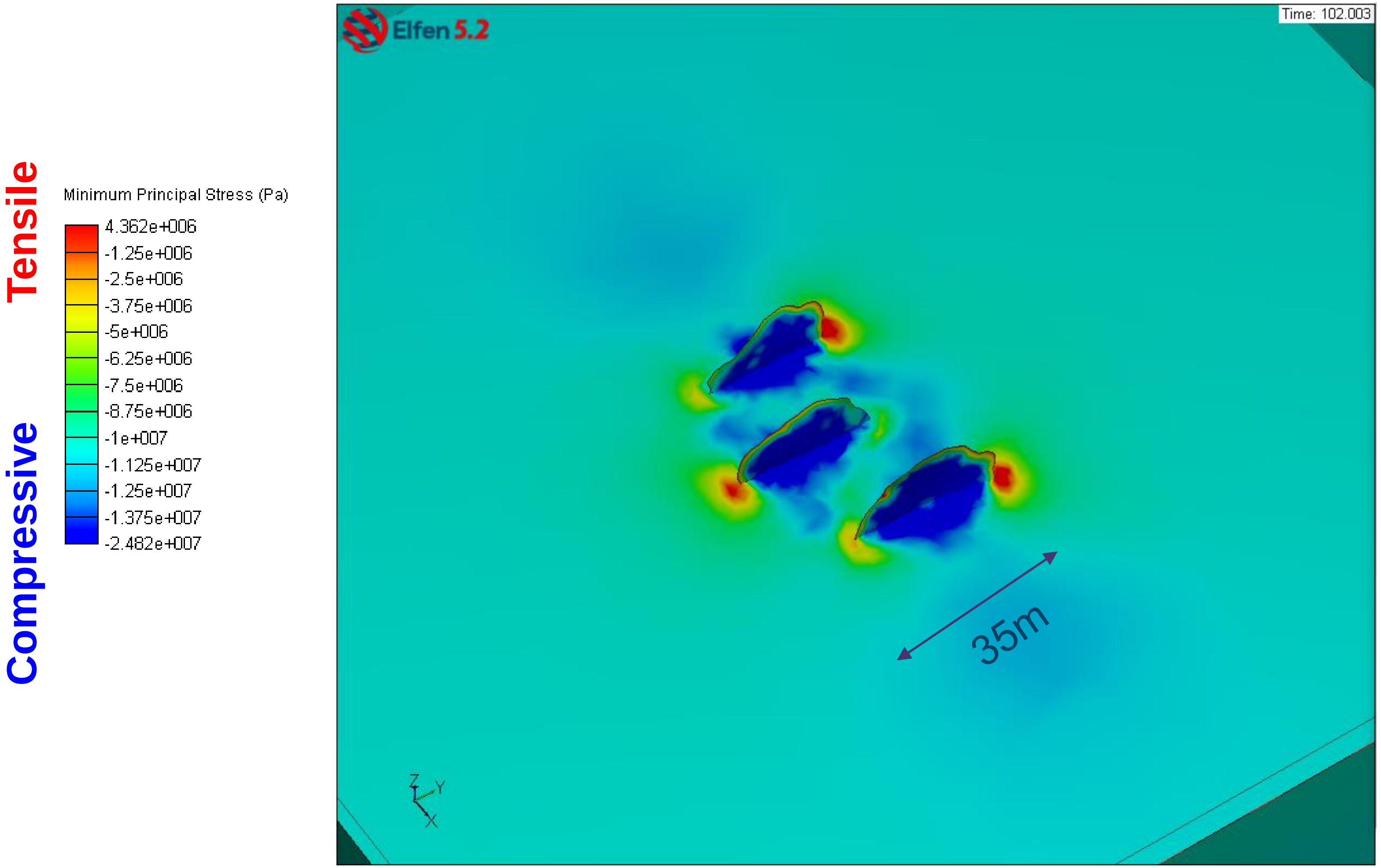
Minimum Stress Evolution & Fracture Propagation



- Significant impact of stress shadowing in the fracture propagation
- All fractures propagate asymmetrically
- Similar size of all three propagating fractures
- Stress shadow extent increases as the fracture grow

3-Cluster Stress Shadowing

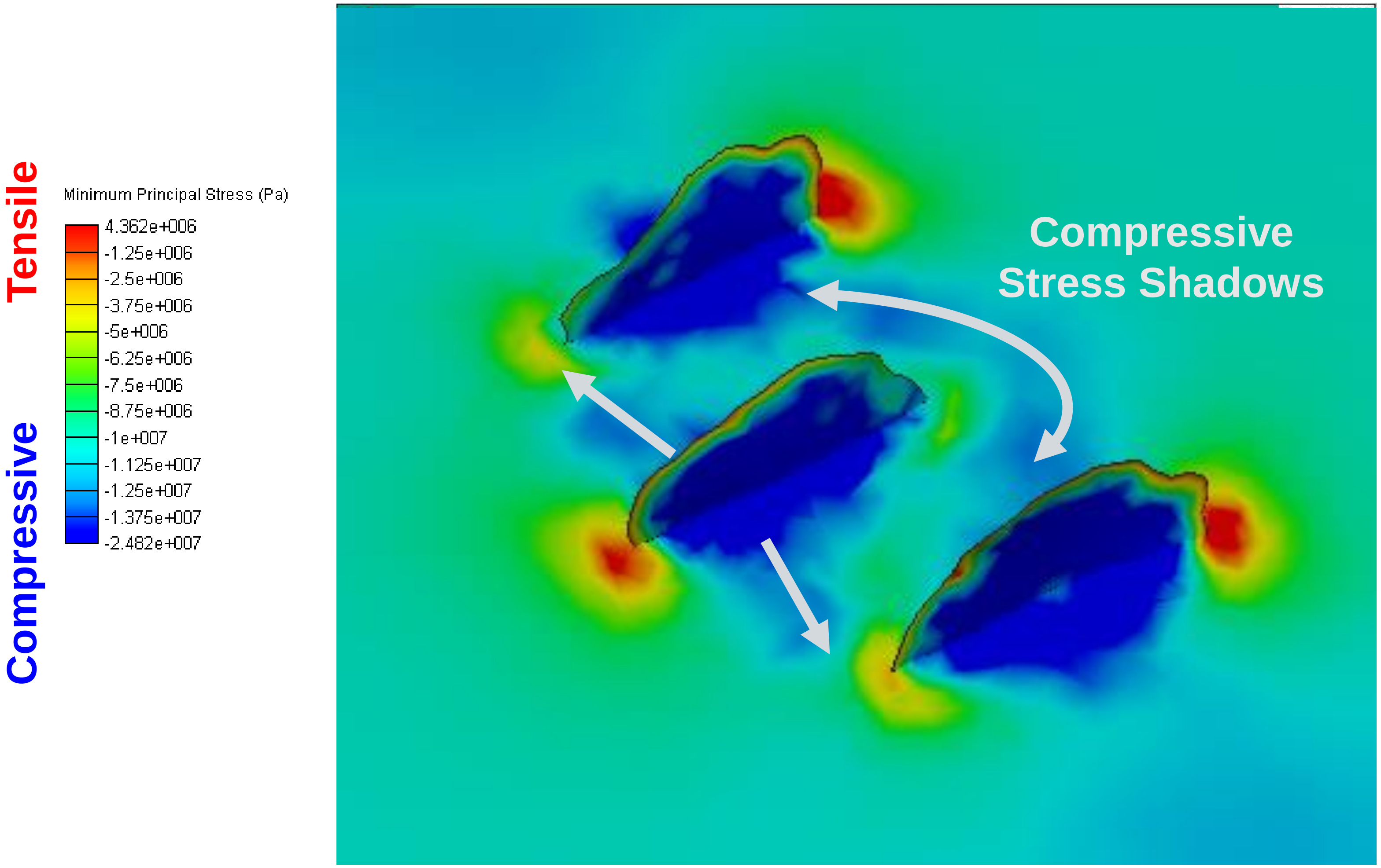
Minimum Stress Evolution & Fracture Propagation



- Stress shadow effects are seen in the early propagation of the fractures (100s)

3-Cluster Stress Shadowing

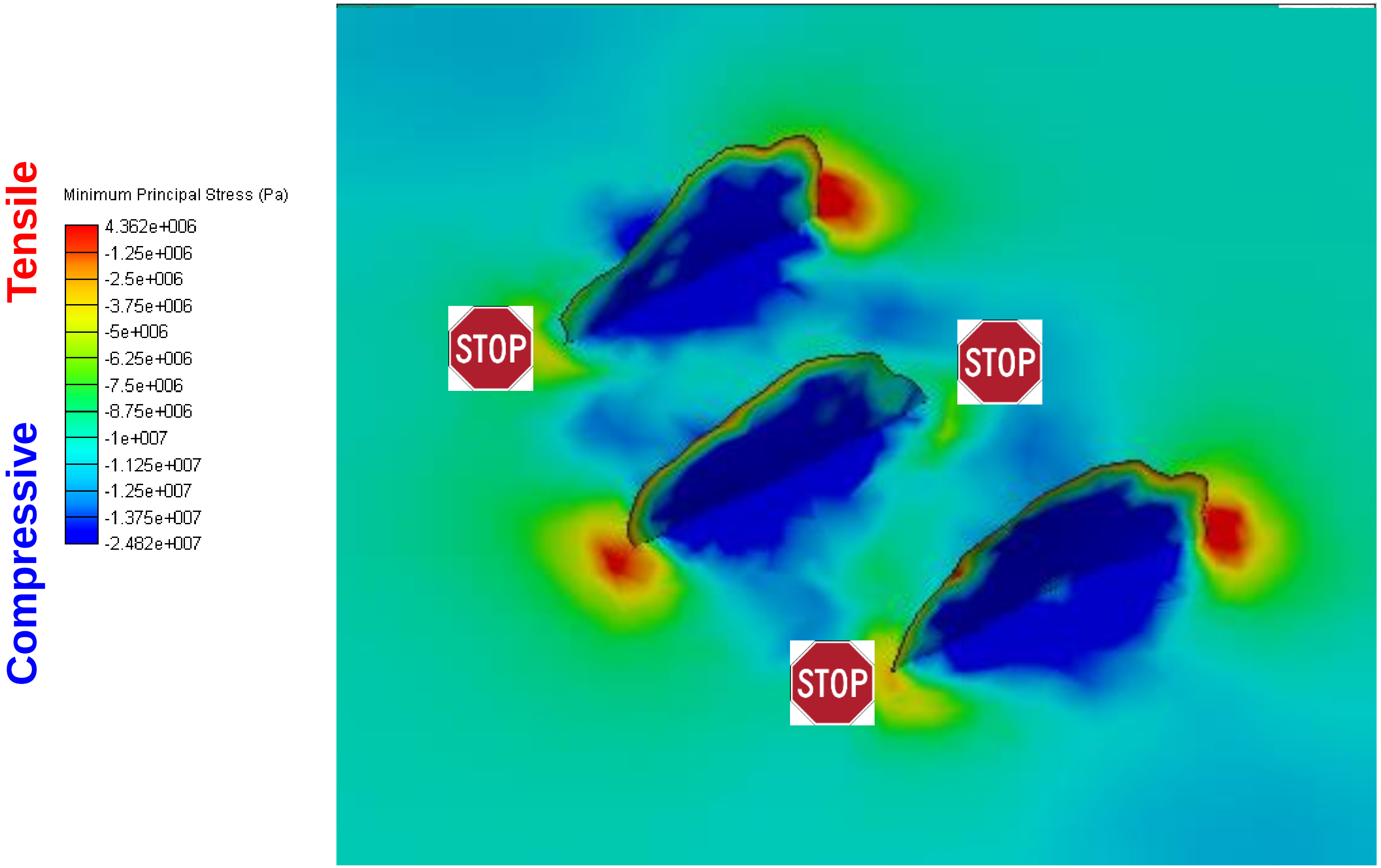
Minimum Stress Evolution & Fracture Propagation



- Stress shadowing is propagating from all fractures
- Stress shadows from multiple fractures may coalesce

3-Cluster Stress Shadowing

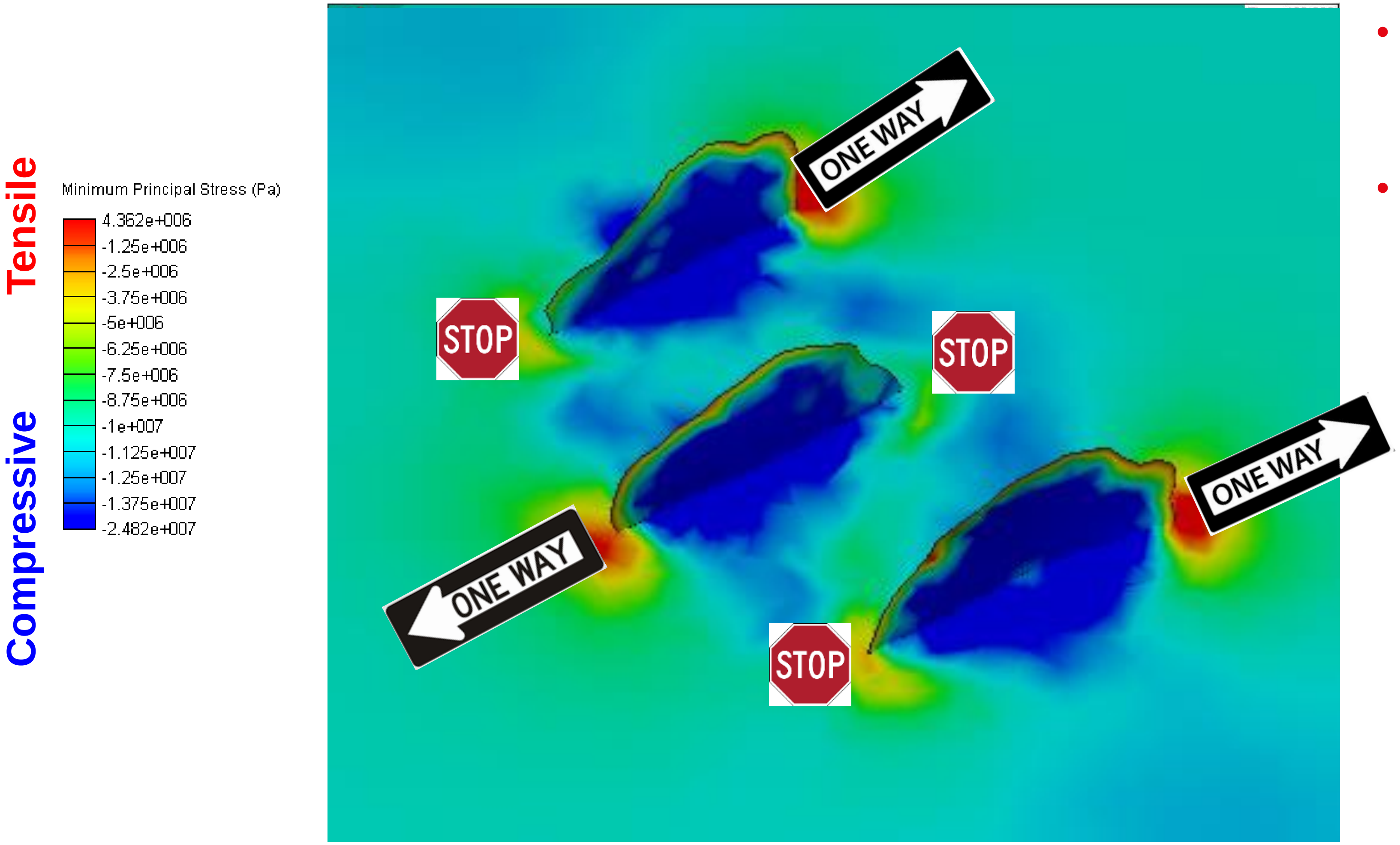
Minimum Stress Evolution & Fracture Propagation



- Stress shadowing which *increases* the in-situ minimum principal stress will place a greater demand for further fracture propagation
- *Note: in order for a fracture to propagate, the fracture tip stress must exceed the **current** minimum principal stress*

3-Cluster Stress Shadowing

Minimum Stress Evolution & Fracture Propagation



- Fractures will propagate in the ‘path of least resistance’
- Due to stress shadowing increasing the demand for fracture propagating in certain directions, the fractures will inevitably propagate towards areas of **no/minimal** compressive stress shadowing

Agenda

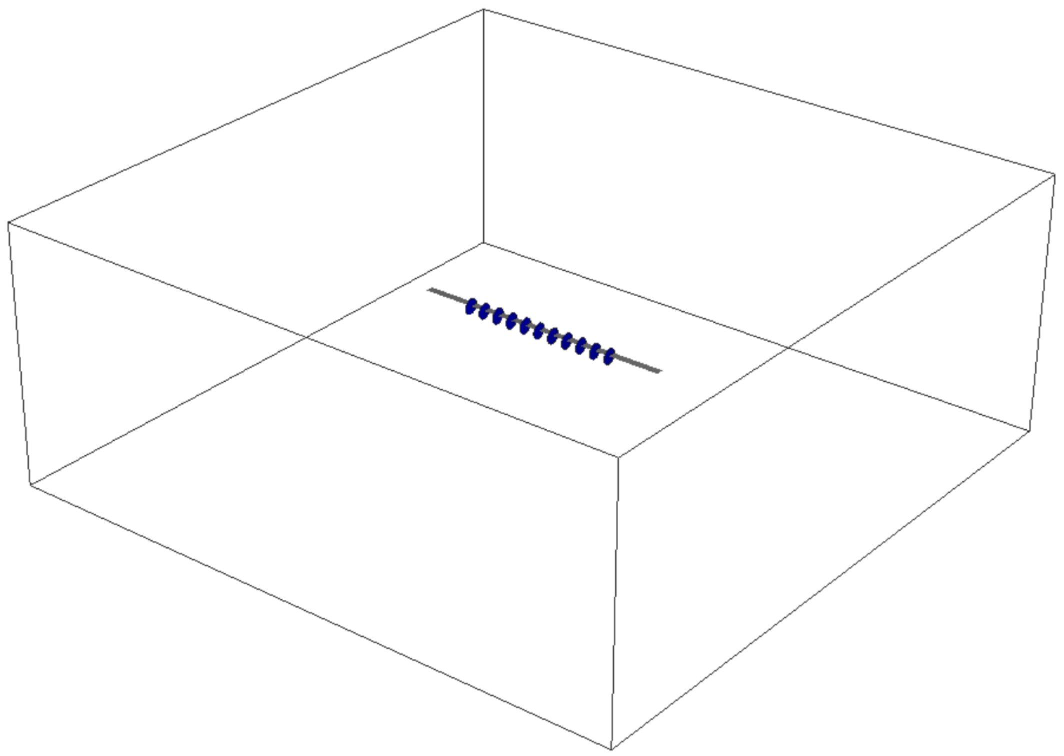
- Background, Motivation & Observations
- Hydraulic Fracture Modeling in Challenging Rocks (State of the Art)
- Single Fracture Stress Shadowing
- 3-Cluster Stress Shadowing
- Multi-Cluster Stress Shadowing – Fracture Patterns and Implications
- Conclusions & Further Work

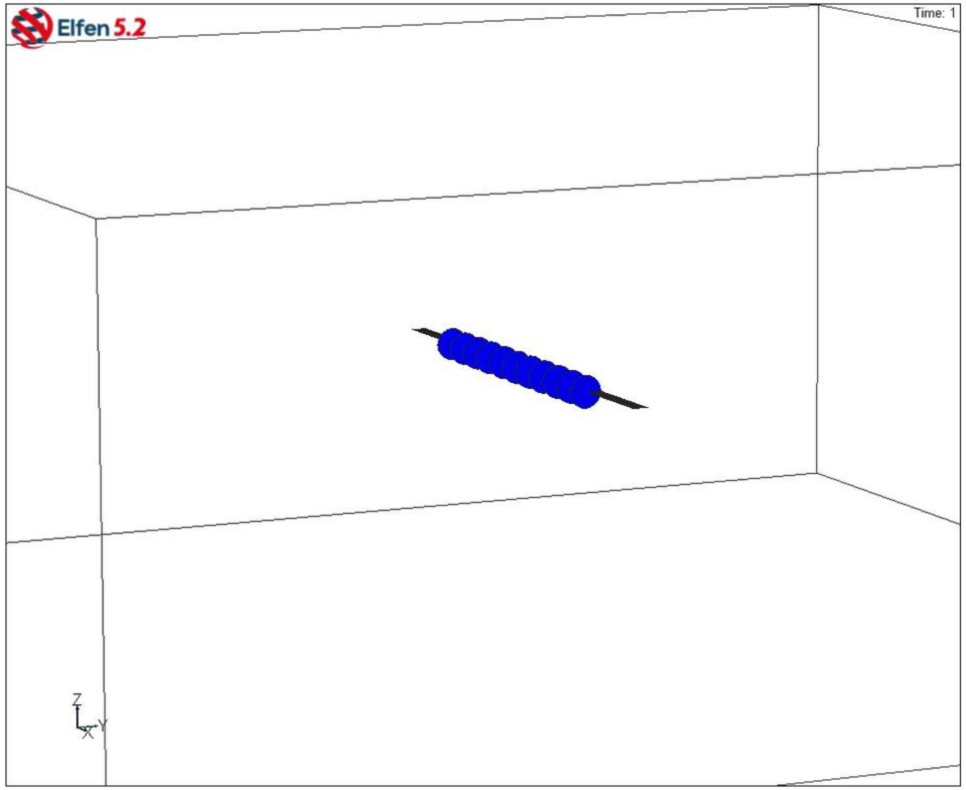
Multi-Cluster Stress Shadowing

Model Configuration and Results

Model Configuration

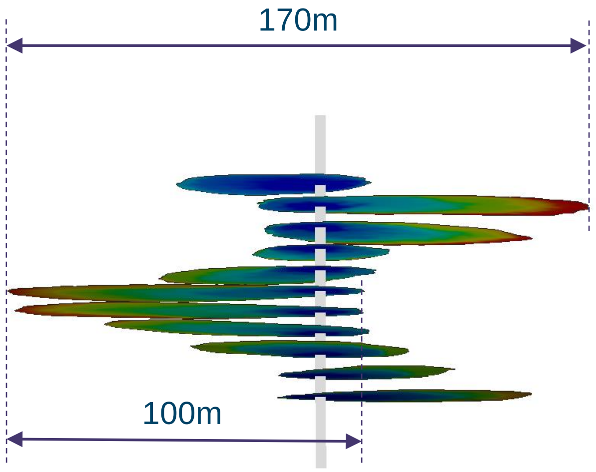
- 11 clusters @ 6m spacing
- 5650 bbls Slick-water @ 80bbls/min
- 250m x 250m x 100m deep

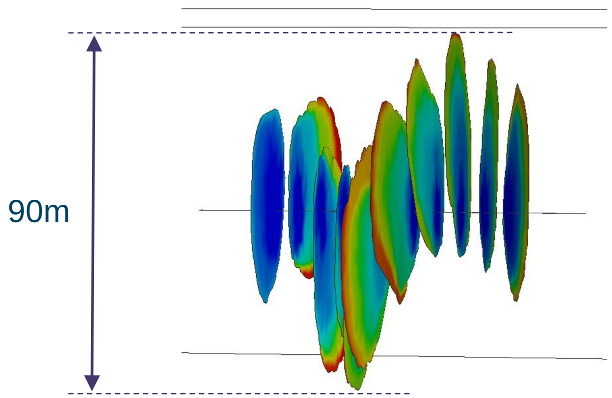


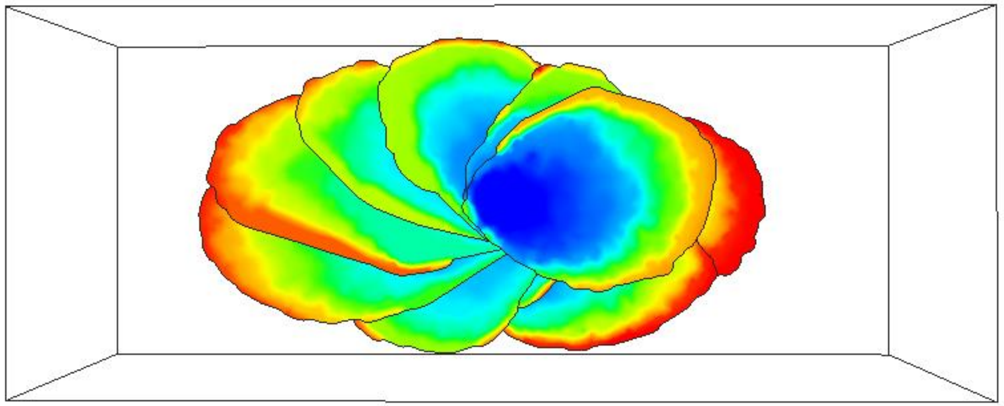


Observations

- Significant asymmetry of fractures in all directions
- A helical pattern of fractures emerges
- Single fracture extent is 100m, although the total lateral extents of the fractures is 170m
- Height growth of fractures is 90m



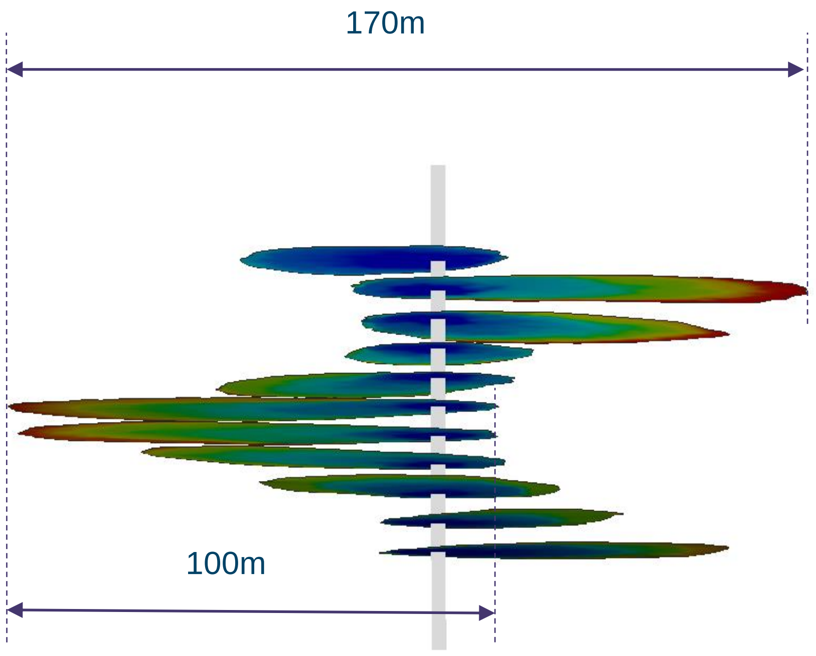




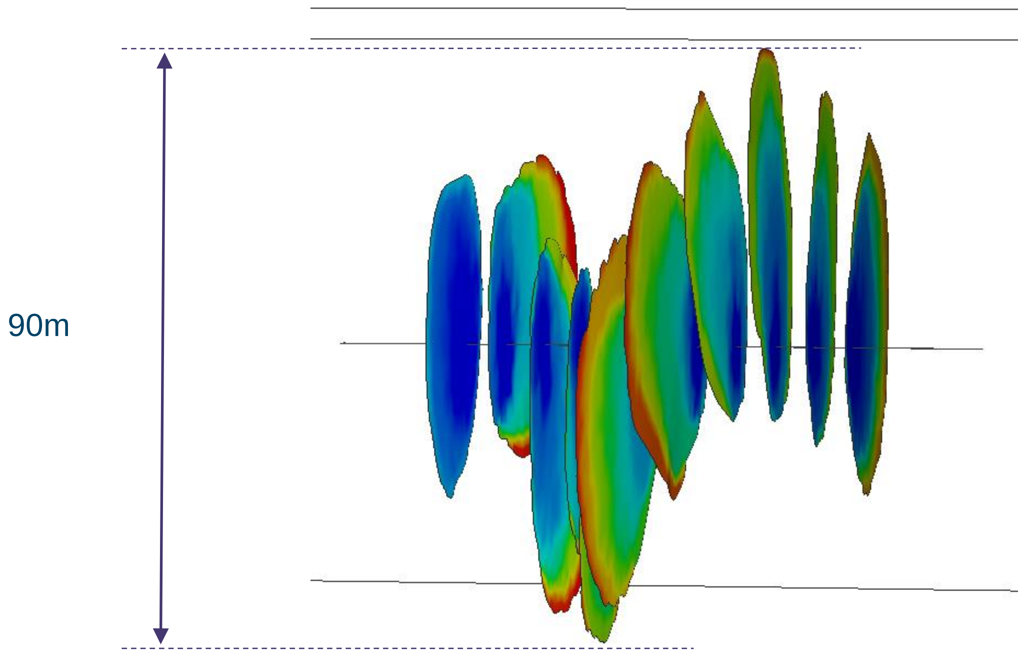
Agenda

- Background, Motivation & Observations
- Hydraulic Fracture Modeling in Challenging Rocks (State of the Art)
- Single Fracture Stress Shadowing
- 3-Cluster Stress Shadowing
- Multi-Cluster Stress Shadowing – Fracture Patterns and Implications
- Conclusions & Further Work

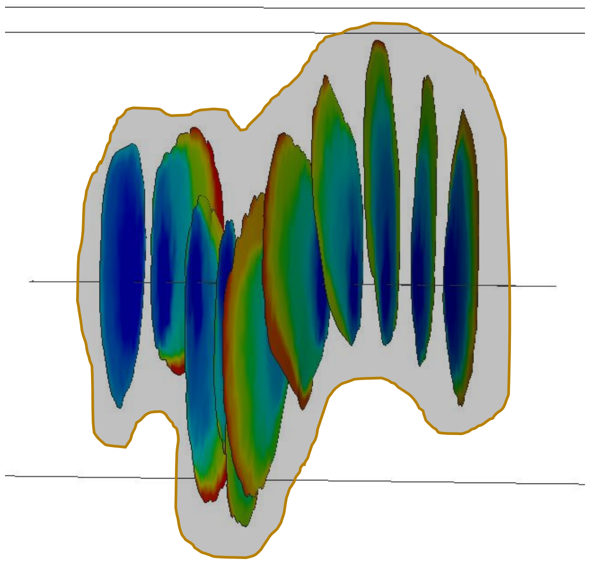
- **Implications to:**
  - Frac-hits - what is considered a fracture half length?

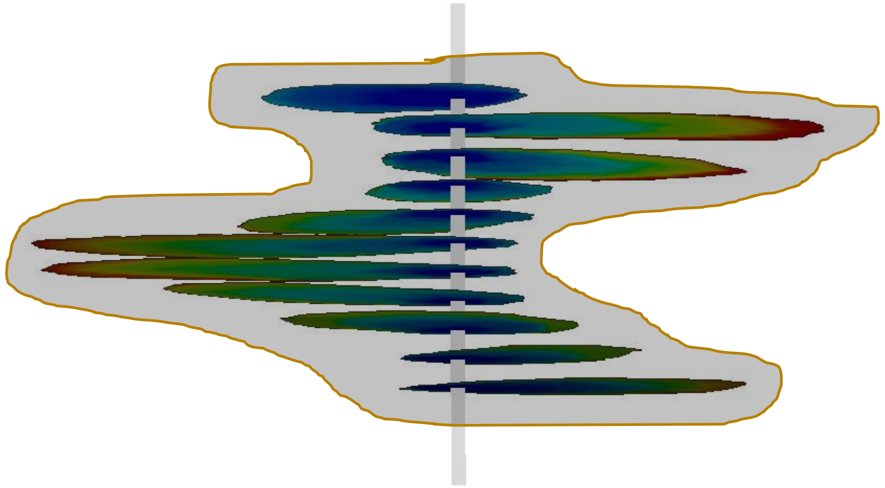


- **Implications to:**
  - Frac-hits - what is considered a fracture half length?
  - Fracture height growth – growing out of zone

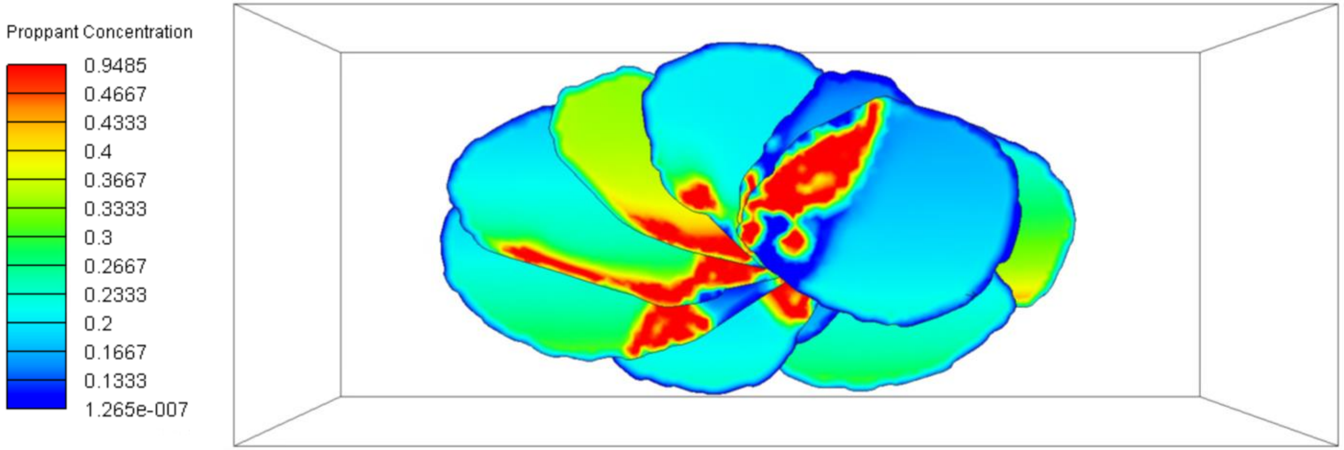


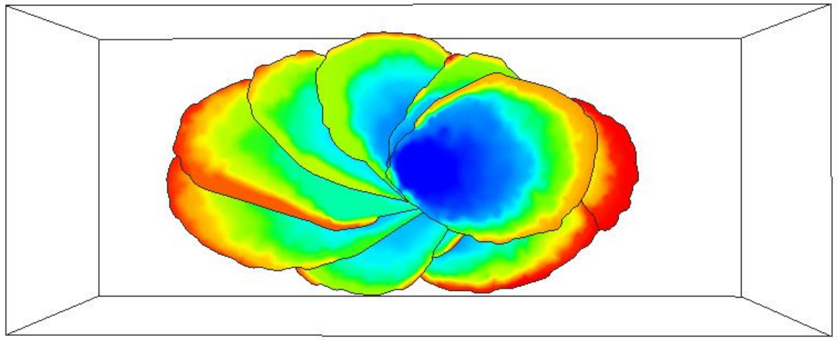
- **Implications to:**
  - Frac-hits - what is considered a fracture half length?
  - Fracture height growth – growing out of zone
  - SRV – does the fracture geometry affectively leave undrained sections of the reservoir?





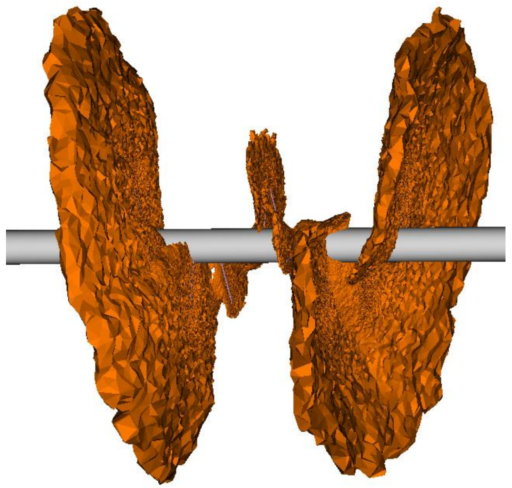
- **Implications to:**
  - Frac-hits - what is considered a fracture half length?
  - Fracture height growth – growing out of zone
  - SRV – does the fracture geometry affectively leave undrained sections of the reservoir?
  - Proppant Placement – timing of fracture growth vs proppant injection

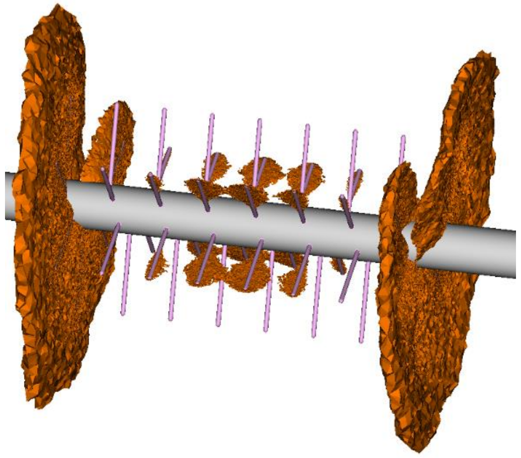




Fracture Insertion Time (Red – most recent)

- **Further applications:**
  - Input for completion design
  - Cluster/stage spacing
  - Well spacing
  - Near wellbore fracture stress shadowing
  - Injection fluid (viscosity effects)
  - Proppant placement
  - 3D heterogeneity





Thank you for your time and attention

Rockfield
Think. Explore. Solve

Rockfield
ETHOS
Prince of Wales Dock
King’s Road
Swansea
SA1 8AS

Tel: +44 (0)1792 455577
Email: enquiries@rockfieldglobal.com

rockfieldglobal.com