

# **Hydraulic Fracture Propagation in Fractured Media\***

**Marc Thiercelin<sup>1</sup>, Dmitry Chuprakov<sup>2</sup>, Eduard Siebrits<sup>2</sup>, Robert Jeffrey<sup>3</sup> and Xi Zhang<sup>3</sup>**

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<sup>1</sup>RTC UG, Schlumberger, Addison, TX. ([thiercelin1@slb.com](mailto:thiercelin1@slb.com))

<sup>2</sup>SMR, Schlumberger, Moscow, Russian Federation.

<sup>3</sup>CSIRO Petroleum Resources, Clayton, VIC, Australia.

## **Abstract**

Hydraulic fracture is commonly used to stimulate the gas production of low permeability formations such as tight gas sandstones, coal-bed methane or gas shales. It is also observed naturally especially in low permeability formations, when overpressure were generated due to specific diagenesis mechanisms which happened once the rock was deposited. However, these formations being brittle in nature are often fractured and discontinuous. Understanding the propagation of hydraulic fractures through natural interfaces or discontinuities is therefore an important topic to predict or interpret the fracturing of these complex media. One main issue is whether the induced fracture will cross a discontinuity, be arrested by it or reinitiates at a location not aligned with its initial direction. If an offset exists between the direction of the initial hydraulic fracture and the newly reinitiated hydraulic fracture, it is important to understand what parameters are controlling it.

The paper uses the state of the art in the modeling of the hydraulic fracture propagation in fractured media. When the hydraulic fracture does not cross directly a natural fracture and starts to follow the path of the natural fracture, the model checks whether the maximum tensile stress at any location along the natural fracture is high enough to initiate a new hydraulic fracture branch. The influence of various parameters on the presence or not of the offset and on its value is presented. These parameters include the rock strength, the inclination of the natural fracture with respect to the principal stress direction, its friction angle, the values of the far-field state of stress, the fluid injection rate and fluid viscosity.

The paper shows that tensile stress, if it occurs, occurs at the tip of the fluid pressurized zone which propagates in the natural fracture once the hydraulic fracture has intersected it. However, the value of this tensile stress depends on the position of this tip and may either increase with the length of the pressurized zone or decrease, depending on the input parameters. This behavior will control whether or not and where the hydraulic fracture might reinitiated from the natural fracture. All the parameters mentioned above control this behavior and their influences are presented. This includes the tensile strength of the rock which may vary along the natural fracture due to the presence of defects.

### **Selected References**

Jeffrey, R.G., C.R. Weber, W. Vlahovic, and J.R. Enever, 1994, Hydraulic fracturing experiments in the Great Northern coal seam: SPE paper No. 28779, Web accessed 27 August 2010,

<http://www.onepetro.org/mslib/app/Preview.do?paperNumber=00028779&societyCode=SPE>

Renshaw, C.E. and D.D. Pollard, 1995, An experimentally verified criterion for propagation across unbounded frictional interfaces in brittle, linear elastic materials: International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, v. 32/3, p. 237-249.

Van As, A. and R.G. Jeffrey, 2002, Hydraulic fracture growth in naturally fractured rock; mine through mapping and analysis: Proceedings of NARMS-TAC, Toronto, p. 1461-1469.

Zhang, X. and R.G. Jeffrey, 2006, The role of friction and secondary flaws on deflection and reinitiation of hydraulic fractures at orthogonal pre-existing fractures: Geophysical Journal International, v. 166/3, p. 1454-1465.

Zhang, S. and Q. Tu, 2005, Analysis of water and sediment regulation based on sediment transport capacity and rule of hydraulic channel shape: Hydrology, v. 25/6, p. 33-36.

# HYDRAULIC FRACTURE PROPAGATION IN FRACTURED MEDIA

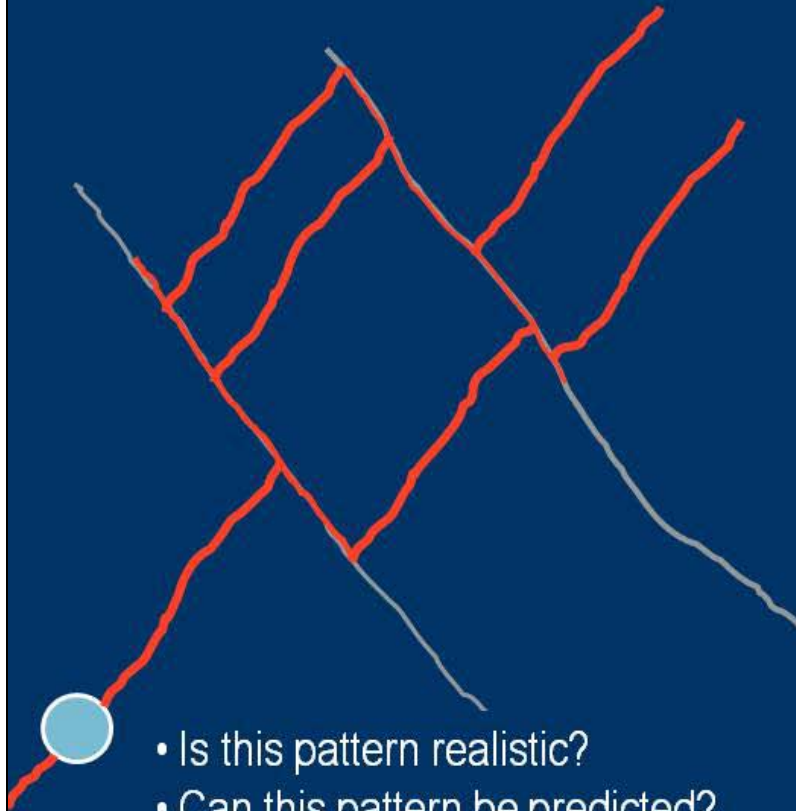
M. Thiercelin, Schlumberger Regional Technology Center, Dallas;  
D. A. Chuprakov, Schlumberger Moscow Research;  
E. Siebrits, TerraTek, a Schlumberger Company;  
R.G. Jeffrey and X. Zhang, CSIRO Earth Science and Resource  
Engineering

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New Orleans, Louisiana

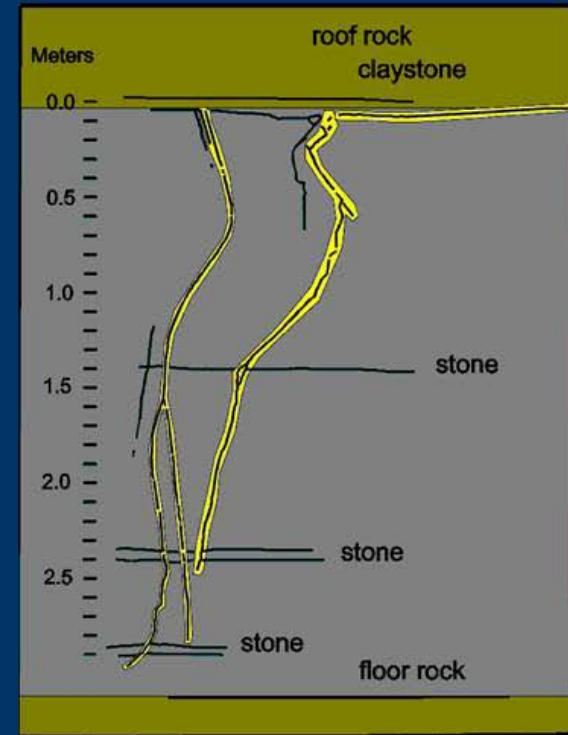
11 – 14 April 2010



# Stimulation of Fractured Formations



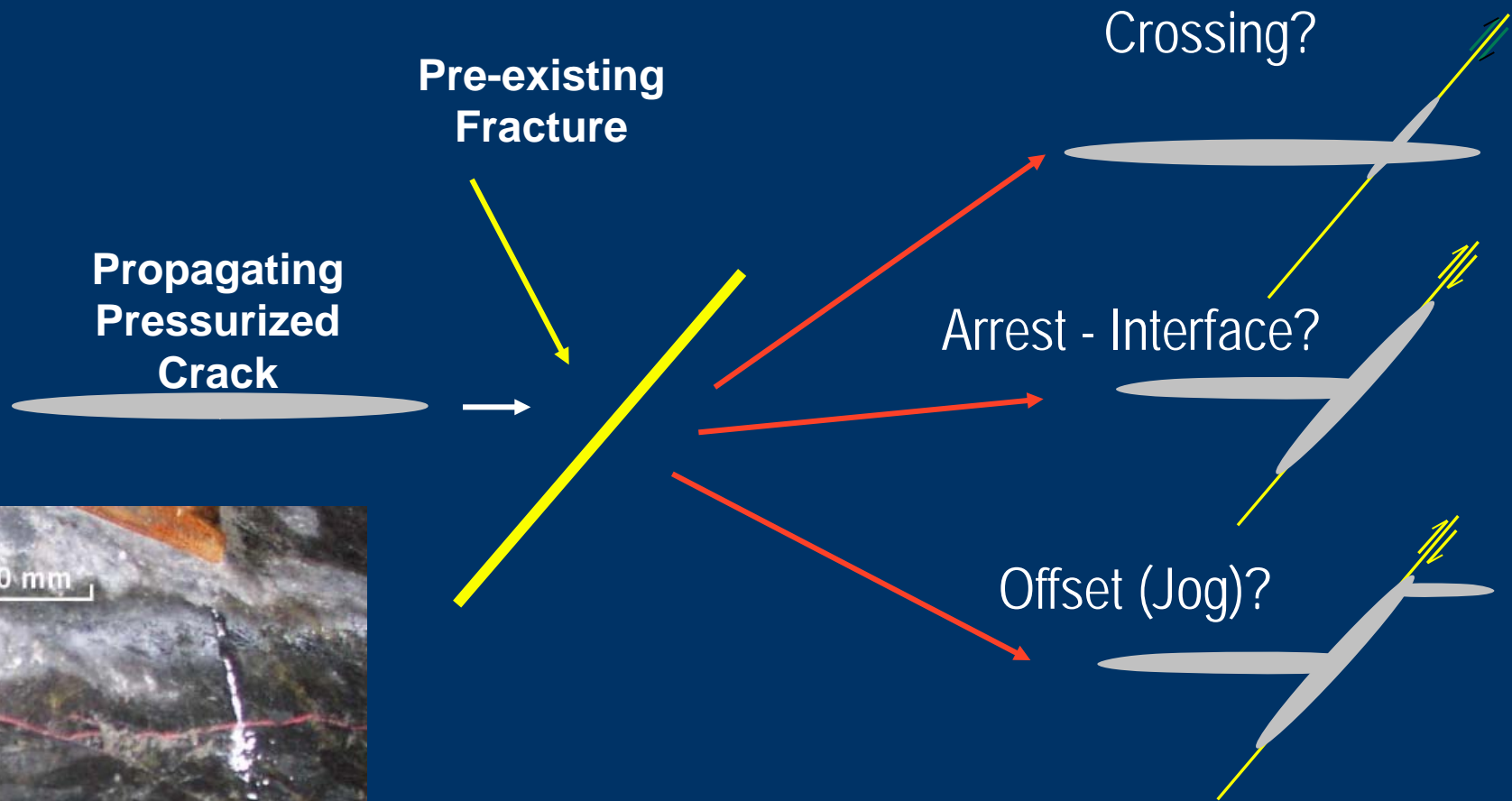
- Is this pattern realistic?
- Can this pattern be predicted?
- What is the expected hydraulic pressure?



Jeffrey *et al.*, 1994

Notes by Presenter: The slide on the right above is from a site where the fracture entered and followed a pre-existing sheared zone/fault which was aligned with the S1 direction. Some of the complexity at this site – the parallel fractures that extended for a considerable distance as parallel fractures – was likely to have resulted from the shear zone being there.

# Fracture Propagation Criteria Through Discontinuities



# Fracture Propagation Model: Governing Equations

## Elastic deformation

$$\sigma_n(\mathbf{x}, t) - \sigma_1(\mathbf{x}) = \sum_{r=1}^N \int_0^{\ell_r} [G_{11}(\mathbf{x}, s, \alpha, \beta)w(s) + G_{12}(\mathbf{x}, s, \alpha, \beta)v(s)]ds$$

$$\tau_s(\mathbf{x}, t) - \tau_1(\mathbf{x}) = \sum_{r=1}^N \int_0^{\ell_r} [G_{21}(\mathbf{x}, s, \alpha, \beta)w(s) + G_{22}(\mathbf{x}, s, \alpha, \beta)v(s)]ds$$

Displacement discontinuity

## Fluid flow in open fracture

$$\frac{\partial(w + \varpi)}{\partial t} = \frac{\partial}{\partial s} \left[ \frac{(w + \varpi)^3}{\mu'} \frac{\partial P_f}{\partial s} \right]$$

## Contact and Friction Coulomb's frictional law

$$|\tau_s| = \lambda(\sigma_n - p_f)$$

## Fluid front movement

$$\dot{\ell}_f = \frac{q(\ell_f)}{w(\ell_f) + \varpi(\ell_f)}$$

$$q = -\frac{(w + \varpi)^3}{12\mu} \frac{\partial p_f}{\partial x}$$

$$\tau_s \cdot \Delta v \leq 0$$

If the fluid pressure is larger than the local confinement, local hydraulic opening occurs.

# Auxiliary Conditions

1. At injection point  $q(0) = Q_0$

At crack tip  $w(l) = v(l) = 0$

2. Crack growth criterion

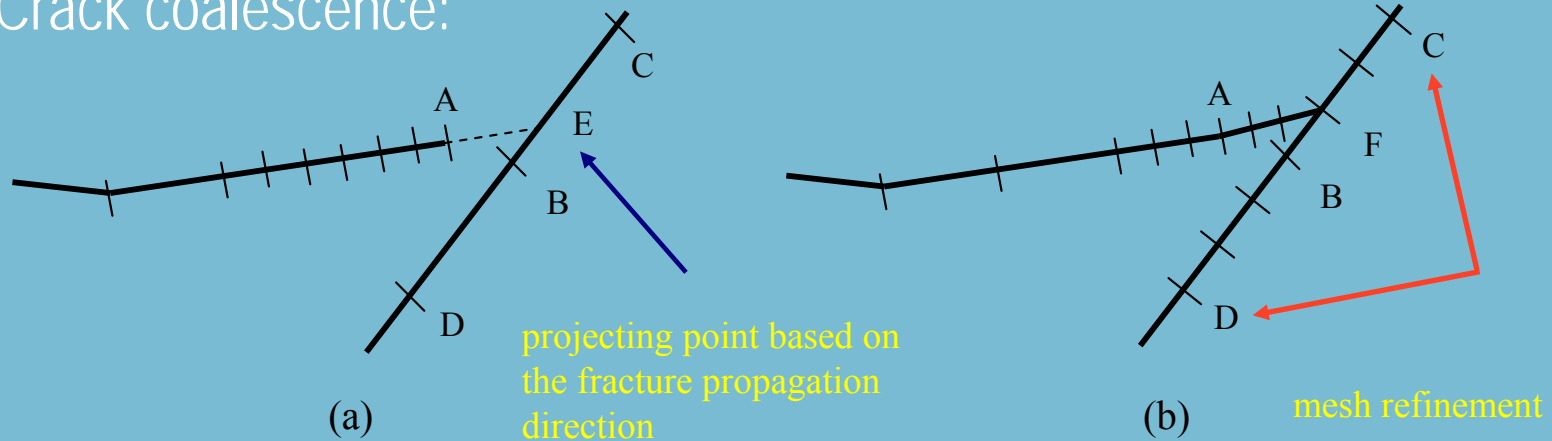
$$\cos \frac{\Theta}{2} \left( K_I \cos^2 \frac{\Theta}{2} - \frac{3}{2} K_{II} \sin \Theta \right) = K_{IC}$$

Crack propagation direction

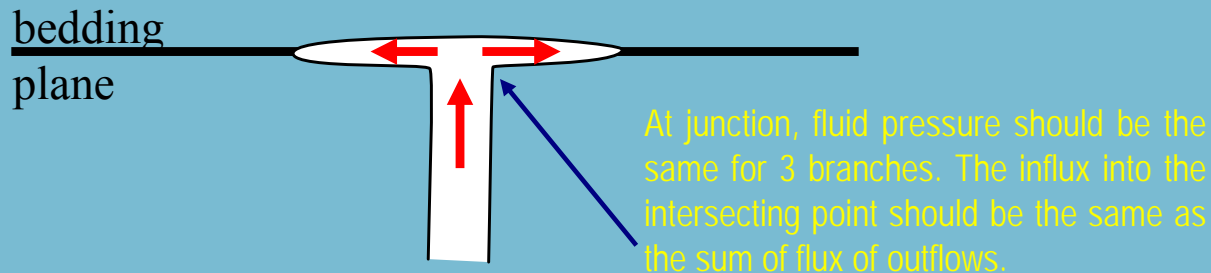
$$K_I \sin \Theta + K_{II} (3 \cos \Theta - 1) = 0$$

# Fracture Coalescence and Fluid Diversion

Crack coalescence:



Fluid diversion:

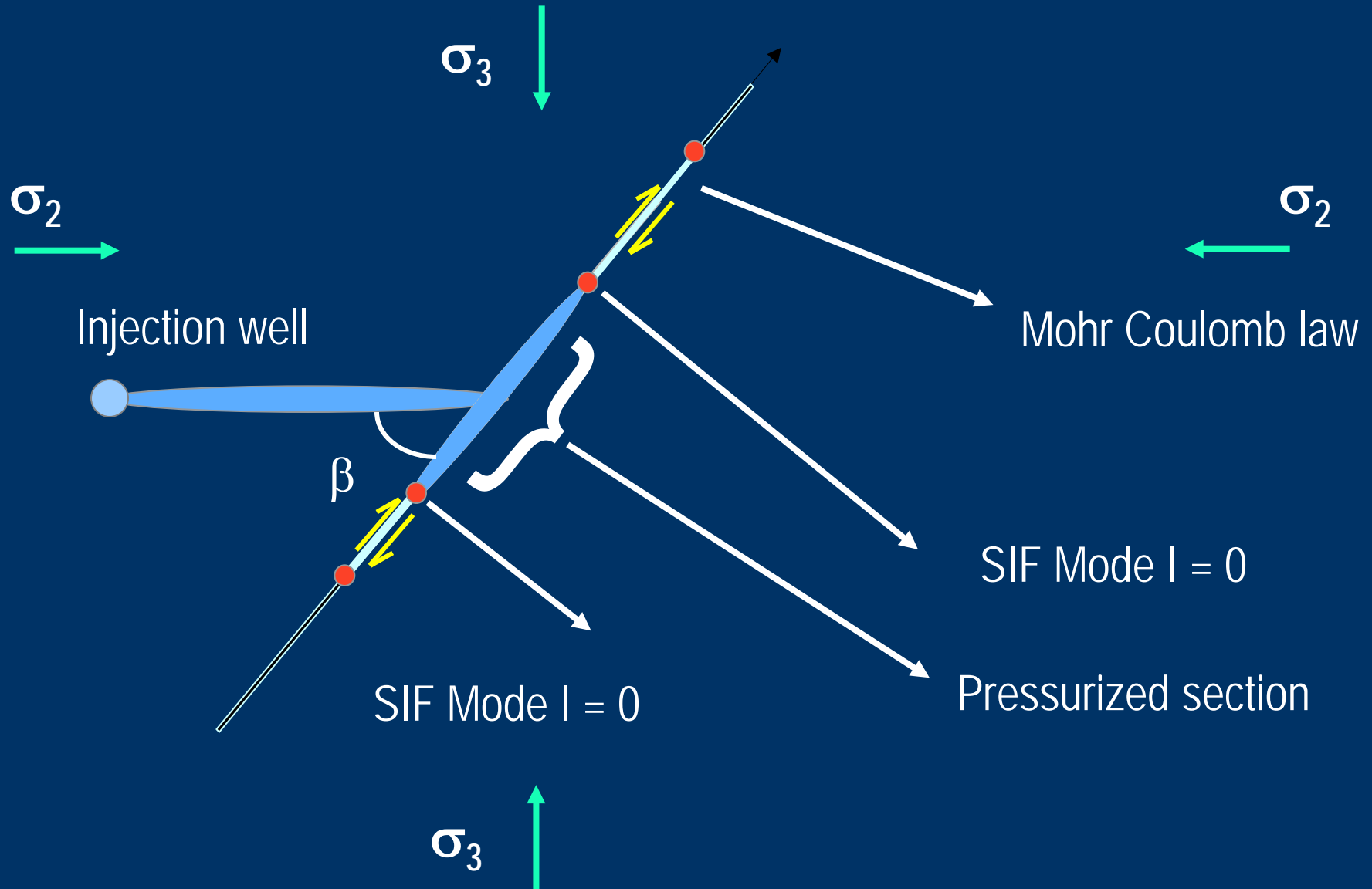


Zhang and Jeffrey, 2006

# Numerical Method (Zhang *et al.*, 2005; Zhang and Jeffrey, 2006)

- 2D plane strain boundary element model, using fixed grid, adaptive mesh.
- Explicit time step, and an implicit method to solve the coupling problem involving fluid flow, rock deformation and slip along natural fractures.
- Iteration method for contact mode at each contact.
- At all intersections including the borehole, fluid and pressure continuity enforced.

# Check of max tensile stress along the discontinuity



# Examples

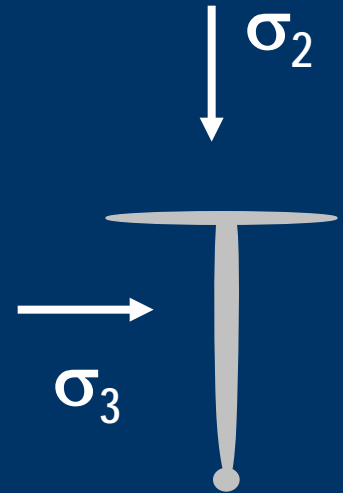
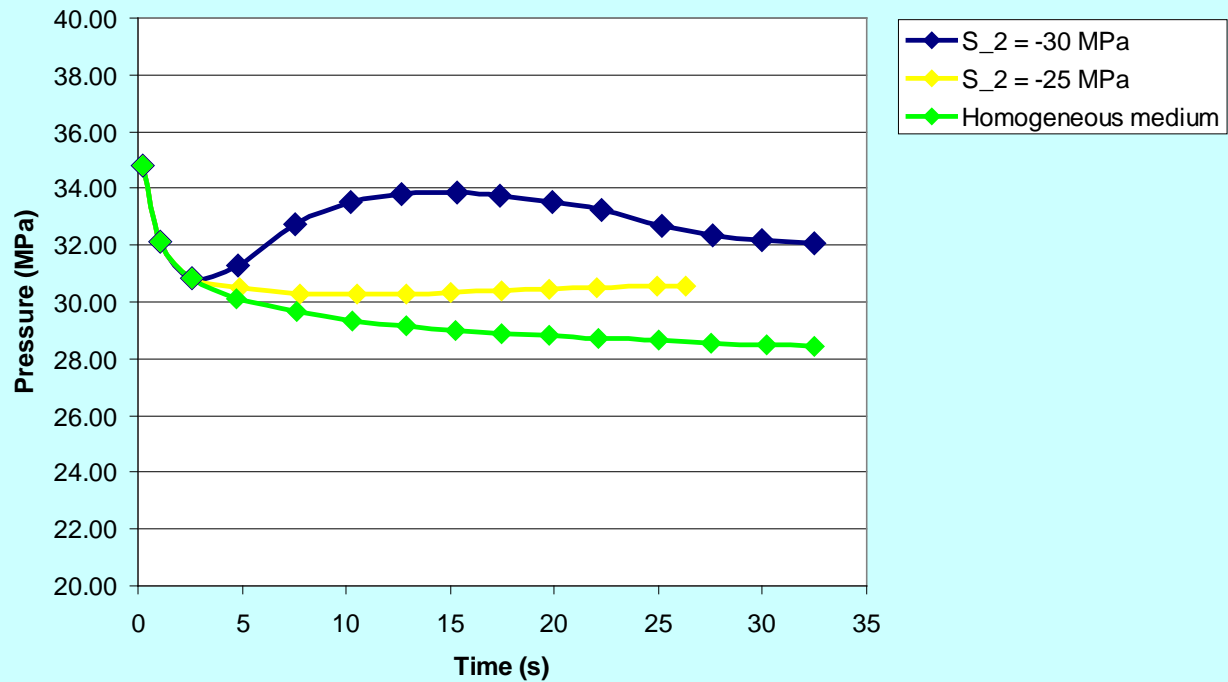
$$E = 30 \text{ GPa}; \quad \nu = 0.3$$

$$K_{Ic} = 1 \text{ MPa}\sqrt{\text{m}}; \quad K_{IIc} = 10 \text{ MPa}\sqrt{\text{m}}$$

$$\mu = 0.002 \text{ Pa.s}$$

- Tensile stress criterion checked at 0.0125 m from the discontinuity
- Injection well at 1 m from the interface
- Discontinuity is (-0.5 m, +1 m), the intersection occurs at (0, 0)
- The discontinuity has a very low permeability, unless open
- If no re-initiation is observed after a fracture propagation of 1 m along the discontinuity, calculations are stopped
- Other parameters are varied

# Pressure Response at the Wellbore

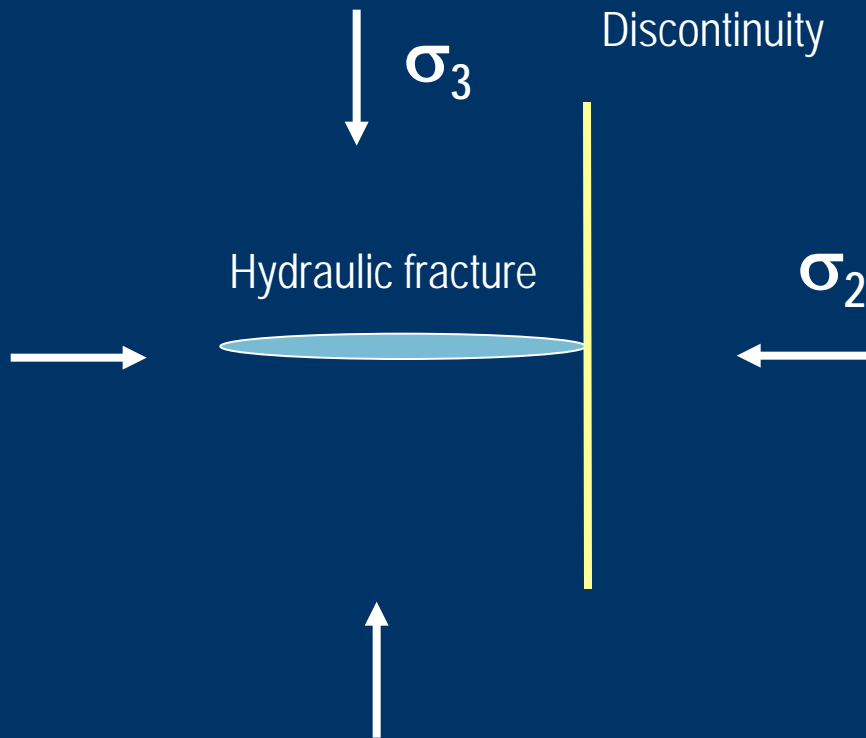


$$\sigma_3 = -25 \text{ MPa}$$

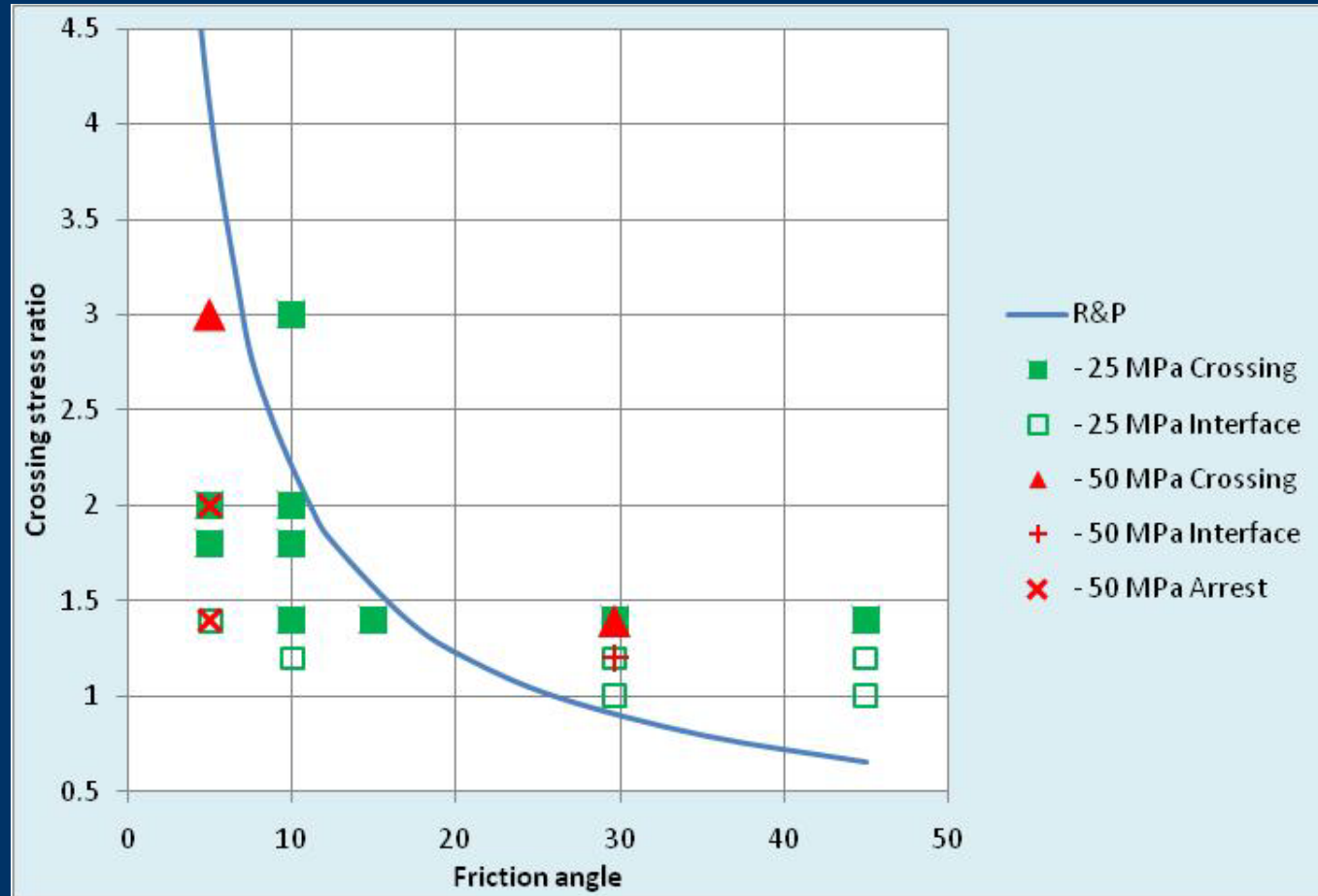
# Crossing Criterion: Renshaw and Pollard, 1995

$$\frac{-\sigma_2}{T - \sigma_3} > \frac{0.35 + \frac{0.35}{\lambda}}{1.06}$$

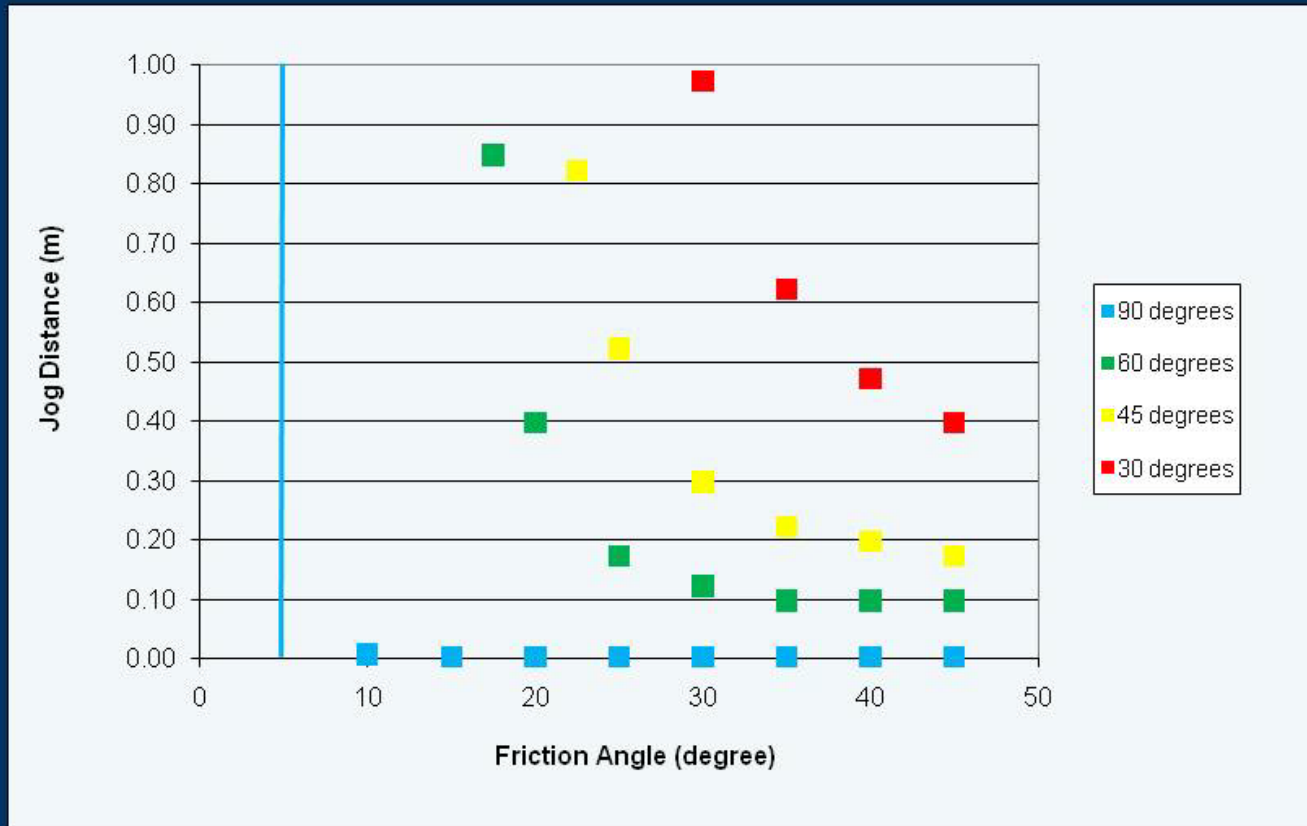
$T$  = rock tensile strength  
 $\lambda$  = coefficient of friction



# Crossing Criterion: Numerical Experiment



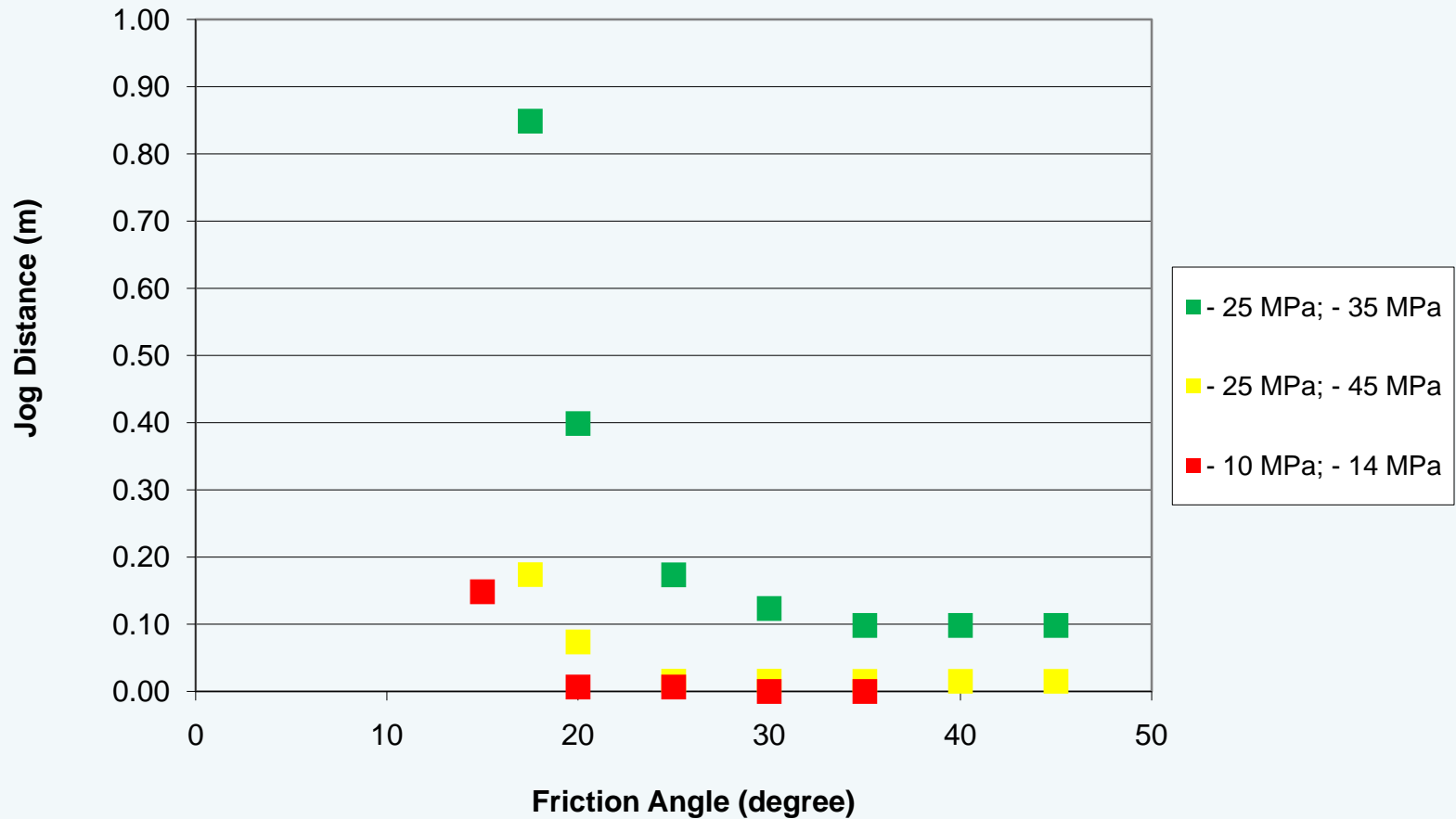
# Influence of Fault Inclination



$\sigma_3 = -25 \text{ MPa}$ ,  $\sigma_2 = -35 \text{ MPa}$ ;  $T = 0.1 \text{ MPa}$ ;  
 $Q = 0.001 \text{ m}^2/\text{s}$

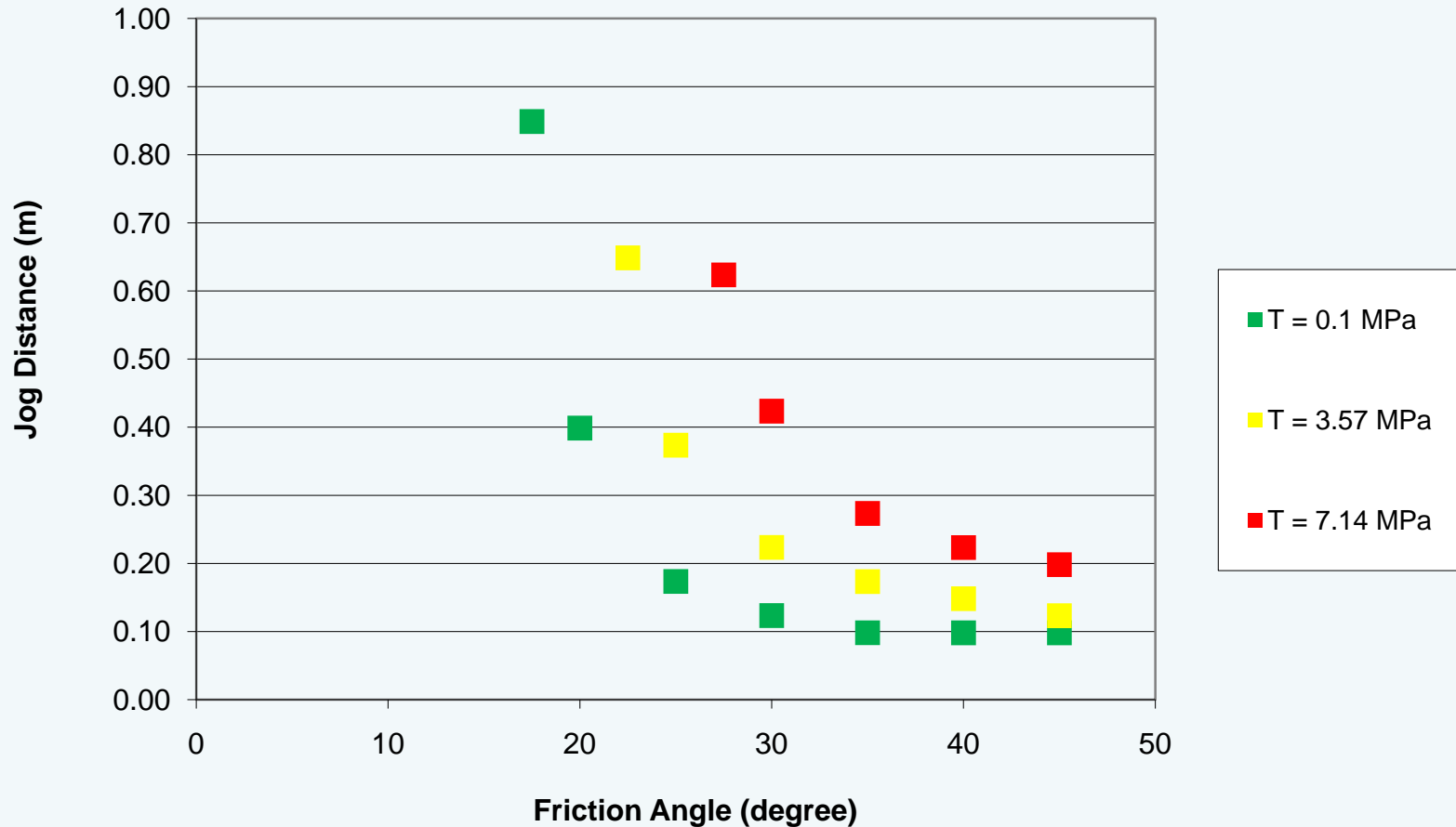
Notes by Presenter: The blue line is when the fracture does not cross the interface (orthogonal case).

# Influence of Stress Ratio



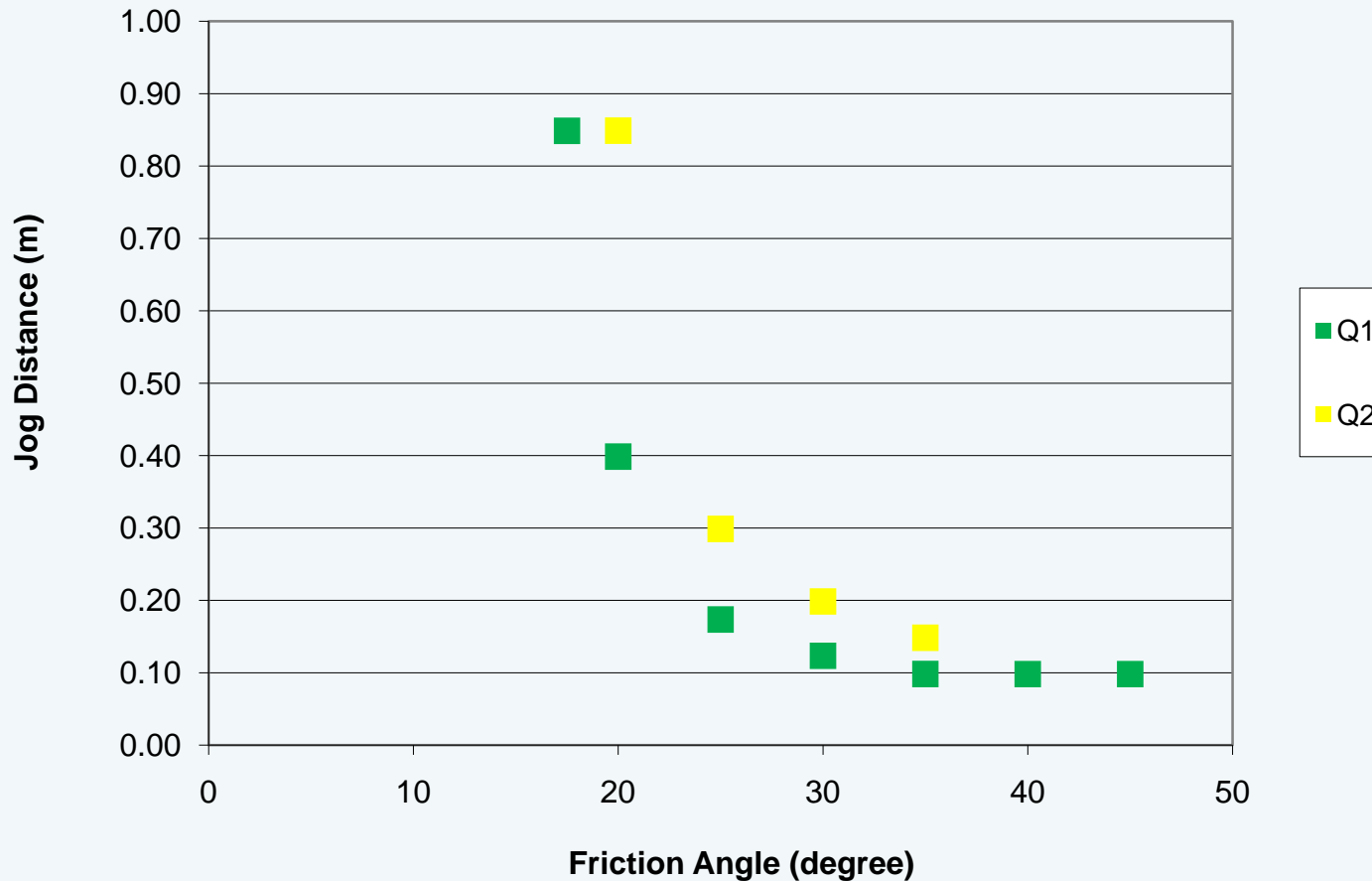
$T = 0.1 \text{ MPa}; \beta = 60^\circ,$   
 $Q = 0.001 \text{ m}^2/\text{s}$

# Influence of Tensile Strength



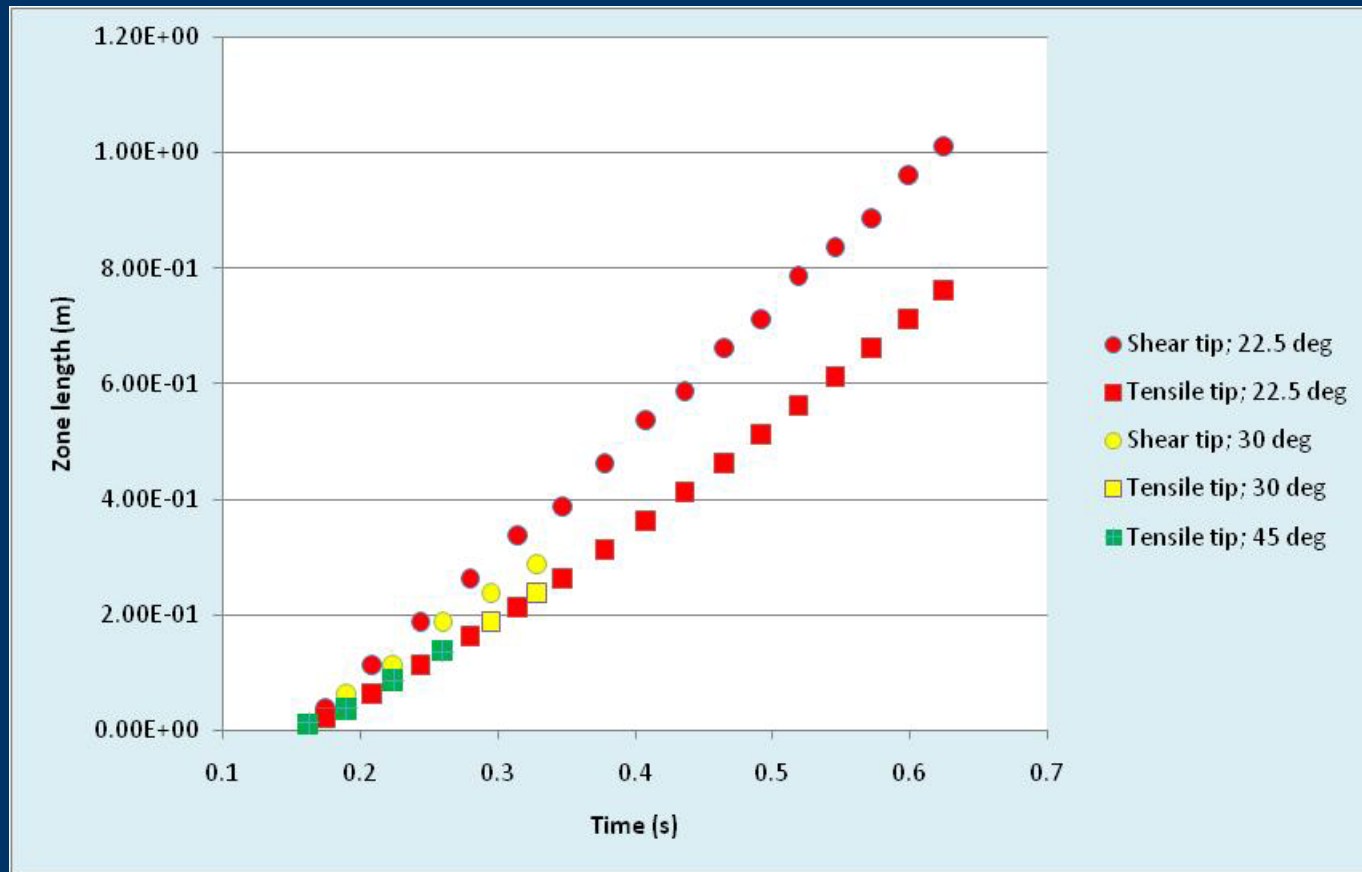
$$\sigma_3 = -25 \text{ MPa}, \sigma_2 = -35 \text{ MPa}; \beta = 60^\circ,$$
$$Q = 0.001 \text{ m}^2/\text{s}$$

# Influence of Injection Rate



$\sigma_3 = -25 \text{ MPa}$ ,  $\sigma_2 = -35 \text{ MPa}$ ;  $T = 0.1 \text{ MPa}$ ;  $\beta = 60^\circ$ ,  
 $Q1 = 0.001 \text{ m}^2/\text{s}$ ,  $Q2 = 0.0001 \text{ m}^2/\text{s}$

# Hydraulic Fracture Lengths Along Discontinuity, as Function of Friction Angle and Time



$\sigma_3 = -25 \text{ MPa}$ ,  $\sigma_2 = -35 \text{ MPa}$ ;  $T = 0.1 \text{ MPa}$ ;  $\beta = 45^\circ$ ,  
 $Q = 0.001 \text{ m}^2/\text{s}$

Notes by Presenter (for previous slide):

At high friction angle, only a tensile fracture propagates. At high friction angles, the behavior is independent of the friction angle. Consequently, the offset is small and its value is independent of the friction angle. At lower friction angle, a shear zone develops ahead of the tensile fracture. This zone is a function of the friction angle.

Note that the tensile fracture length is the same for the three cases. This assumption is that the shear zone remains of very low permeability. The re-initiation crack starts at the tip of the tensile section.

# Conclusions

- Fracture behavior at an intersection with a discontinuity is controlled by various parameters, including the discontinuity properties, in-situ stress field, and hydraulic fracturing pressure
- An opening zone and a shear zone might develop along the discontinuities, characterized by direct controlling parameters for the type of intersection, including the presence and size of an offset
- The friction angle plays a role only when it is low enough for a shear zone to develop ahead of the tensile zone
- The tensile strength of the rock is a significant parameter; fracture re-initiation from the discontinuity will most likely start from a weak point