Introduction to Reservoir Geomechanics

UFPE

1 Introduction
Definitions and some challenges of reservoir geomechanics.
Modeling of coupled phenomena.

2 Constitutive Laws: Behavior of Rocks
Fundamentals of Pore-Mechanics.

3 Constitutive Laws: Behavior of Fractures
Geomechanics of Fractured Media.

4 Reservoir Geomechanics
Elements of a geomechanical model and applications.

5 Unconventional Reservoirs
Naturally fractured reservoirs, hydraulic fracture, proppant and fracture closure model, validation (microseismicity).

6 Advanced Topics
Injection of reactive fluids and rock integrity.

OUTLINE

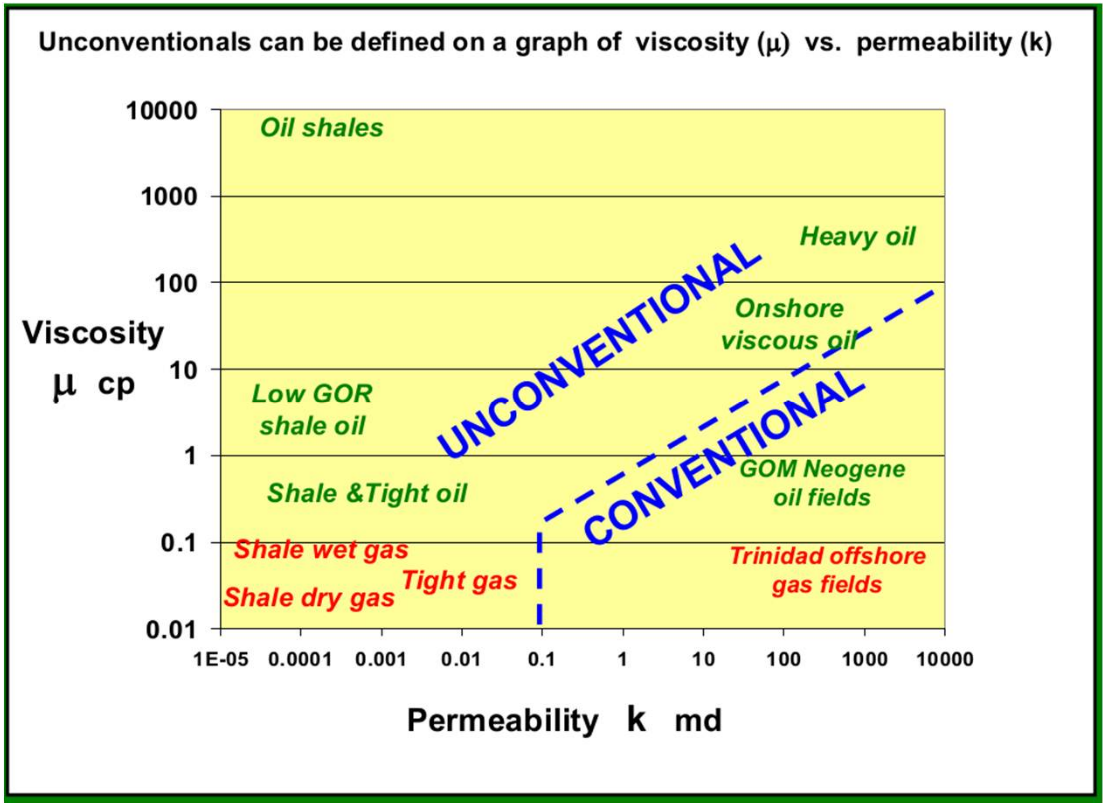
- Introduction: Unconventional Reservoir
- Natural Fractures Network
- Hydraulic Fracturing Modeling
- Proppant and Fracture Closure Model
- HF Validation: Microseismicity
- Final Remarks

OUTLINE

- **Introduction: Unconventional Reservoir**
- Natural Fractures Network
- Hydraulic Fracturing Modeling
- Proppant and Fracture Closure Model
- HF Validation: Microseismicity
- Final Remarks

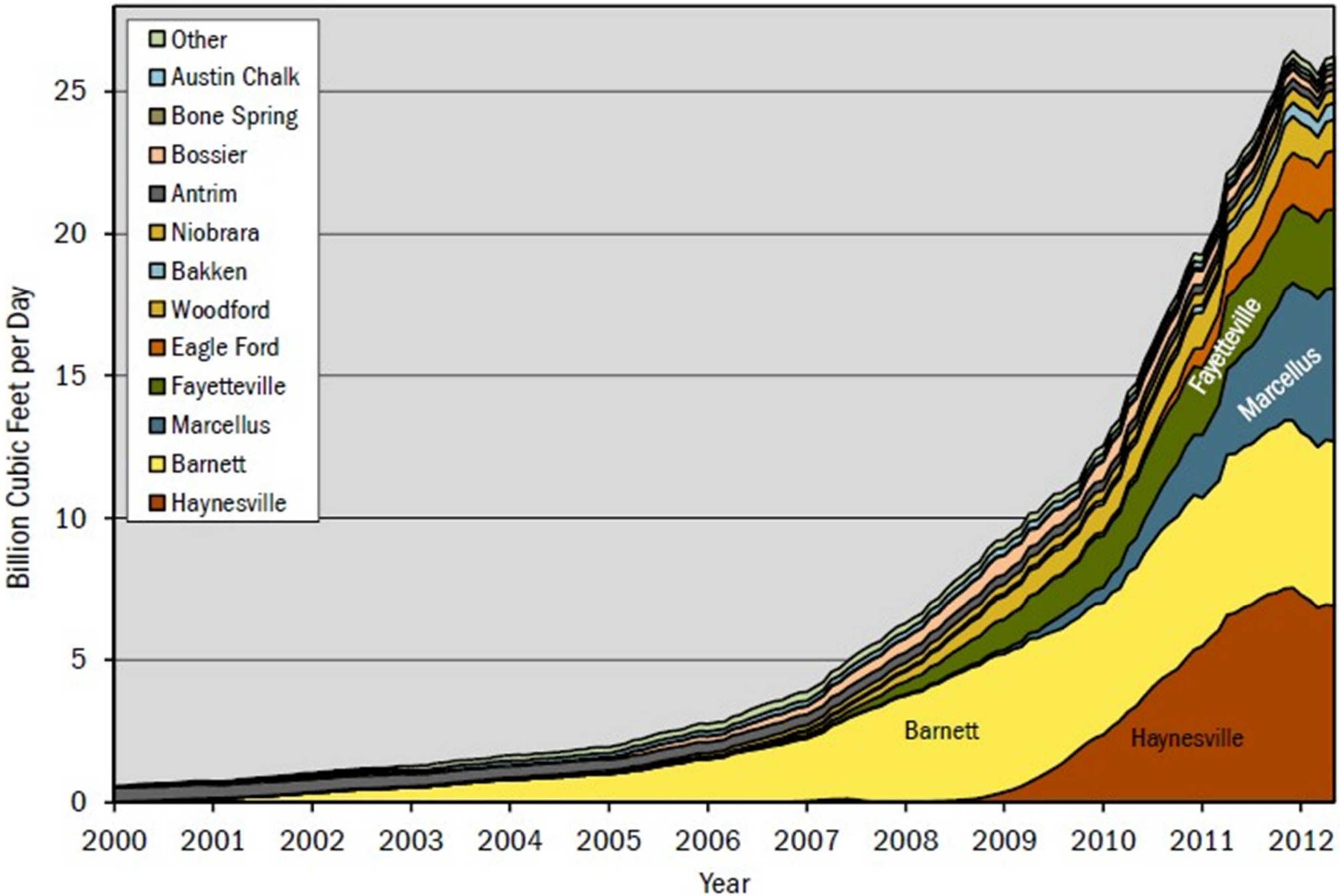
Unconventional Reservoirs

Permeability threshold (< 0.1 md) (< 10^{-16} m^2) Meckel and Thomasson (2008)



Cander (2012)

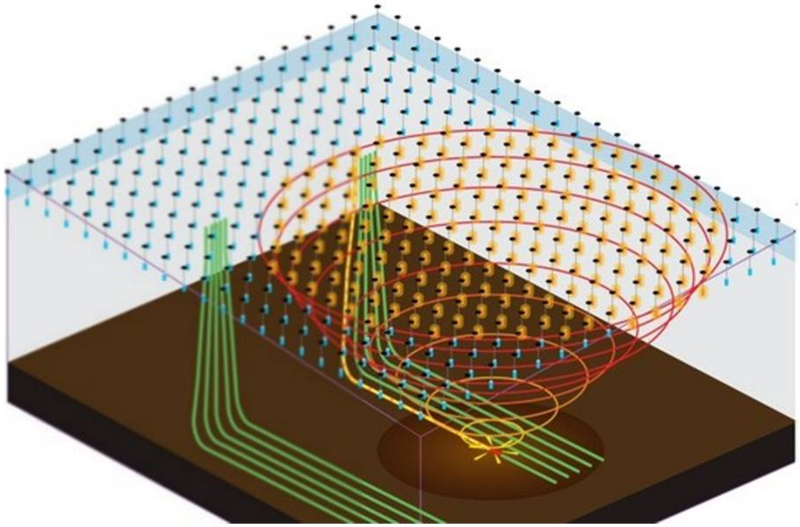
Unconventional Reservoirs



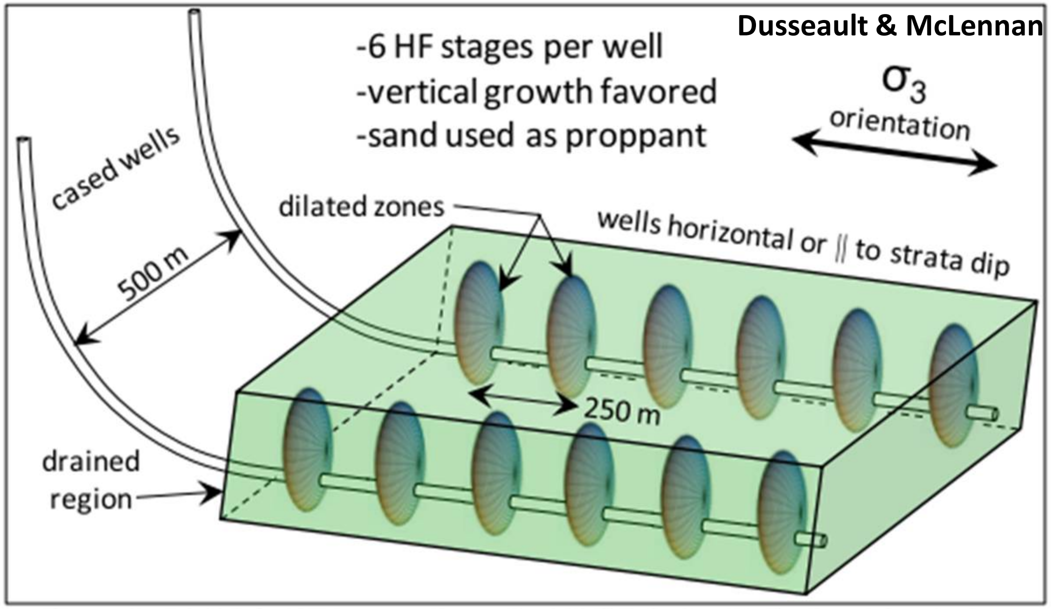
Massive Multi-Stage Hydraulic Fracturing
The Technology

The well is placed close to the base of the reservoir because fractures tend to rise as they are formed by high pressure fluid injection.

Hydraulic fracturing "rise" occurs when the fracturing fluid pressure gradient is less than the local σ_{hmin} gradient.

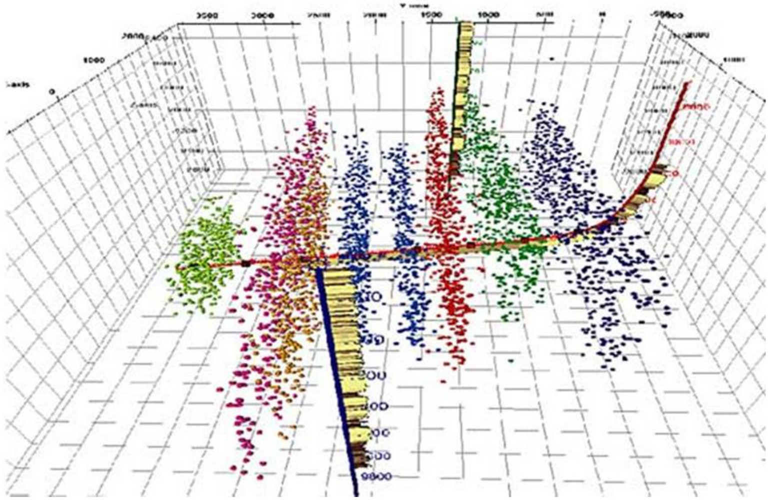


Dusseault & McLennan



Multiple HF Stages along the Well Axis for Shale Gas Stimulation

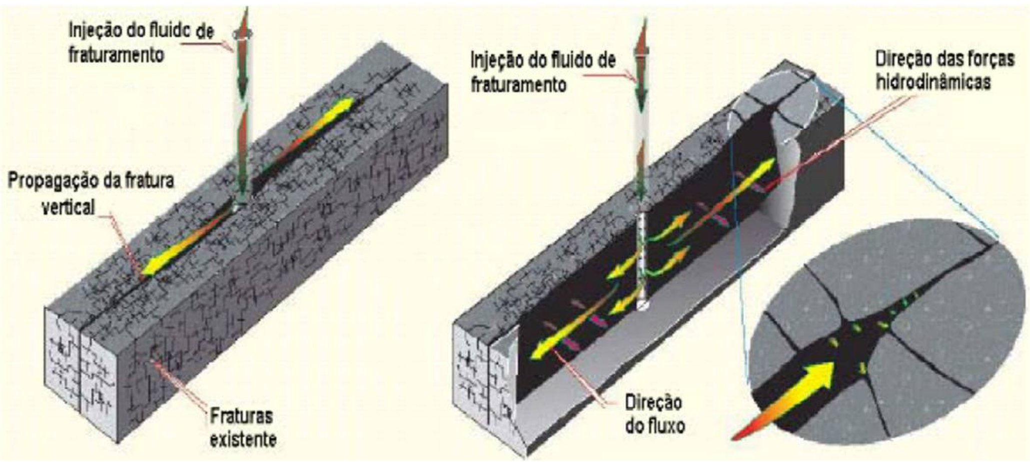
(Canadian National Energy Board
www.neb-one.gc.ca)



Microseismic Imaging of a Multi-stage Frac

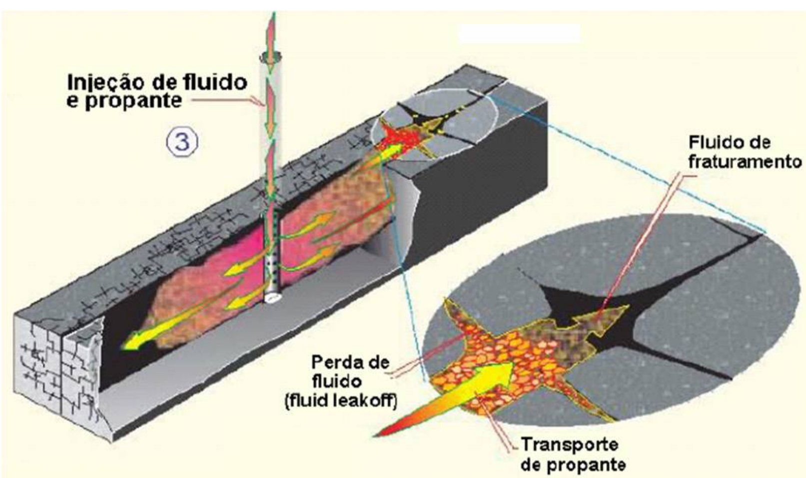
Consideration of Natural Fractures

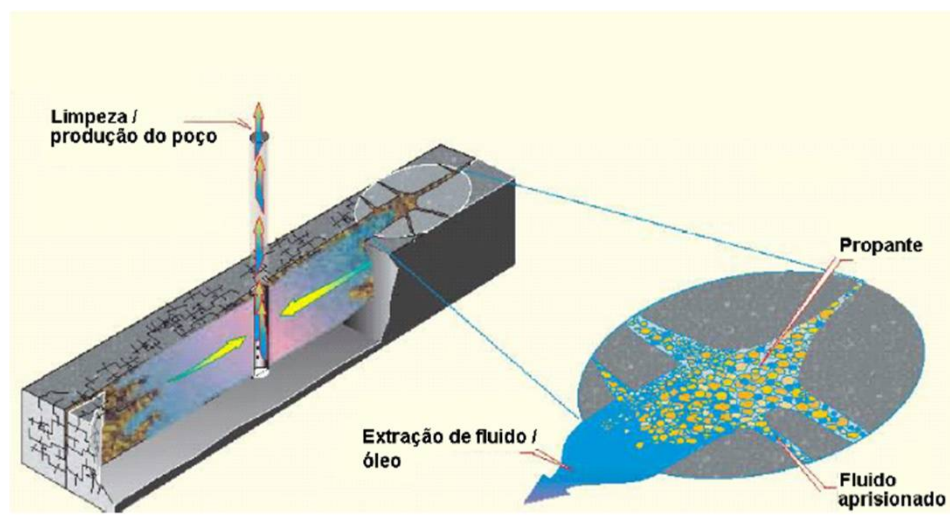
Objective of the proppant: to hold the fracture open and provide a highly conductive path for fluid to flow



The fracturing of a well creates a complex network of cracks in the shale formation. This is achieved by pumping water, sand and a small amount of additives down the wellbore under high pressure.

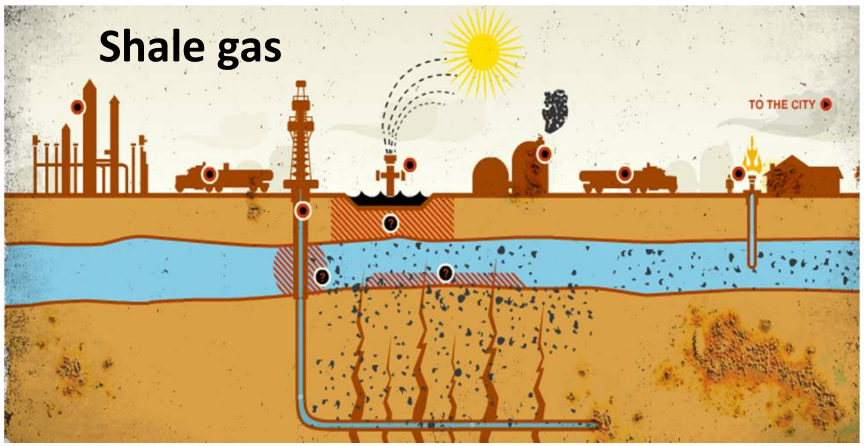
After these cracks are created the sand will remain in the formation propping open the shale to create a pathway for the gas to enter the wellbore and flow up the well.





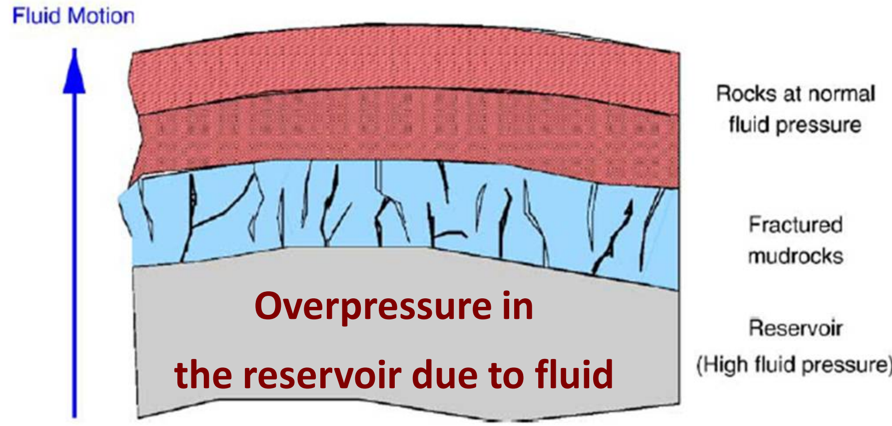
Integrity of sealing rocks in reservoir-seal systems subjected to fluid injection

(Source: The Old Speak Journal, 2011)



Contamination of an aquifer caused by hydraulic fracturing

(Rouainia et. al , 2005)



Overpressure in the reservoir due to fluid injection (water, CO_2,...)

OUTLINE

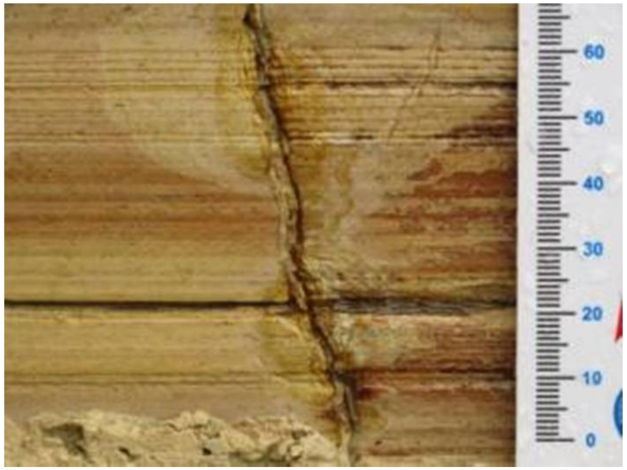
UFPE

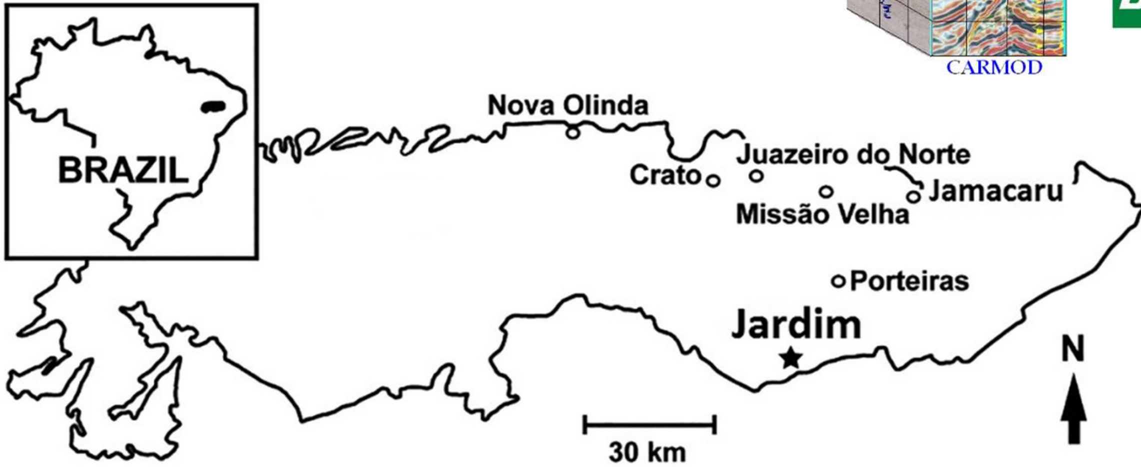
- ☐ Introduction: Unconventional Reservoir
- ☐ **Natural Fractures Network**
- ☐ Hydraulic Fracturing Modeling
- ☐ Proppant and Fracture Closure Model
- ☐ HF Validation: Microseismicity
- ☐ Final Remarks

Carbonate Reservoirs and Natural Fractures

Crato Formation - Araripe Basin (Tight Carbonate Analogue)

Fractures at different scales

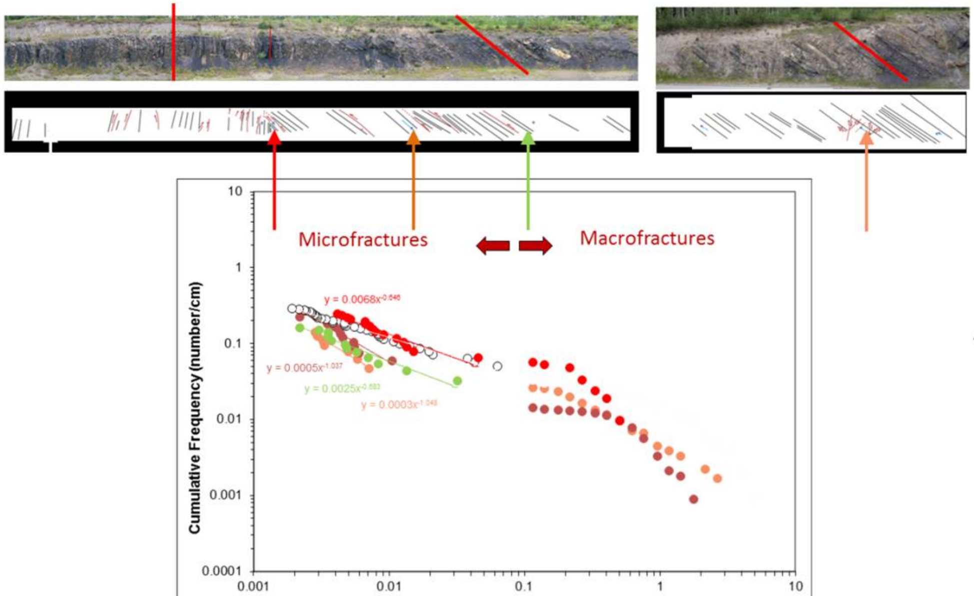




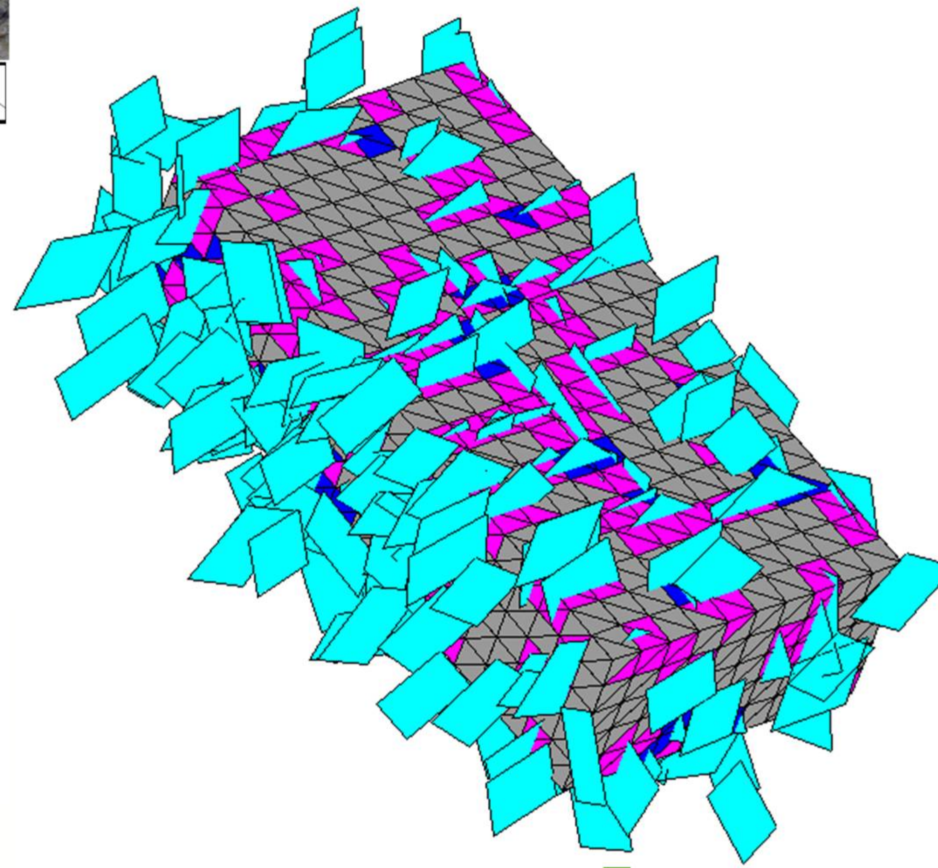
CARMOD

Fracture Network Modeling

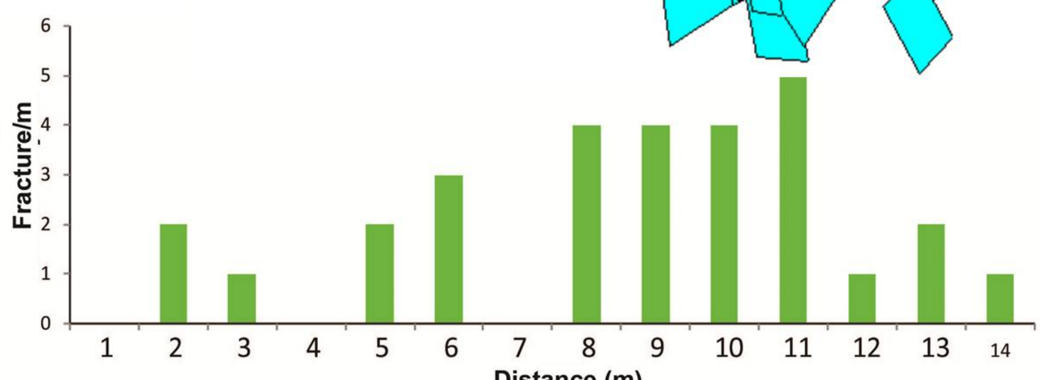
Araripe Basin (Tight Carbonate Analogue)



Ukar et al, (2012)



- Fracture Sets
- Azimuth
- Strike and Dip
- Fracture Intensity



Natural Fracture Network

Some important questions about the characterization of rock fabric (Dusseault, 2013):

➔ **What is the natural fracture fabric at depth?**

Spacing, persistence, cohesion, roughness…
Mineralization, conductivity

➔ **Are natural fractures open or closed?**

➔ **What is their orientation with respect to the principal stresses?**

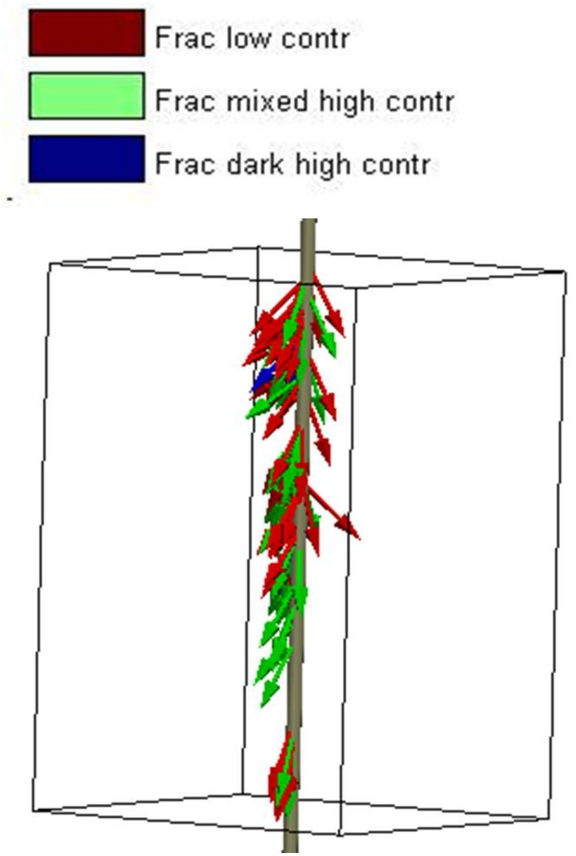
These are extremely challenging questions to answer with reasonable precision.

Outcrops are unreliable (weathering, different [σ])

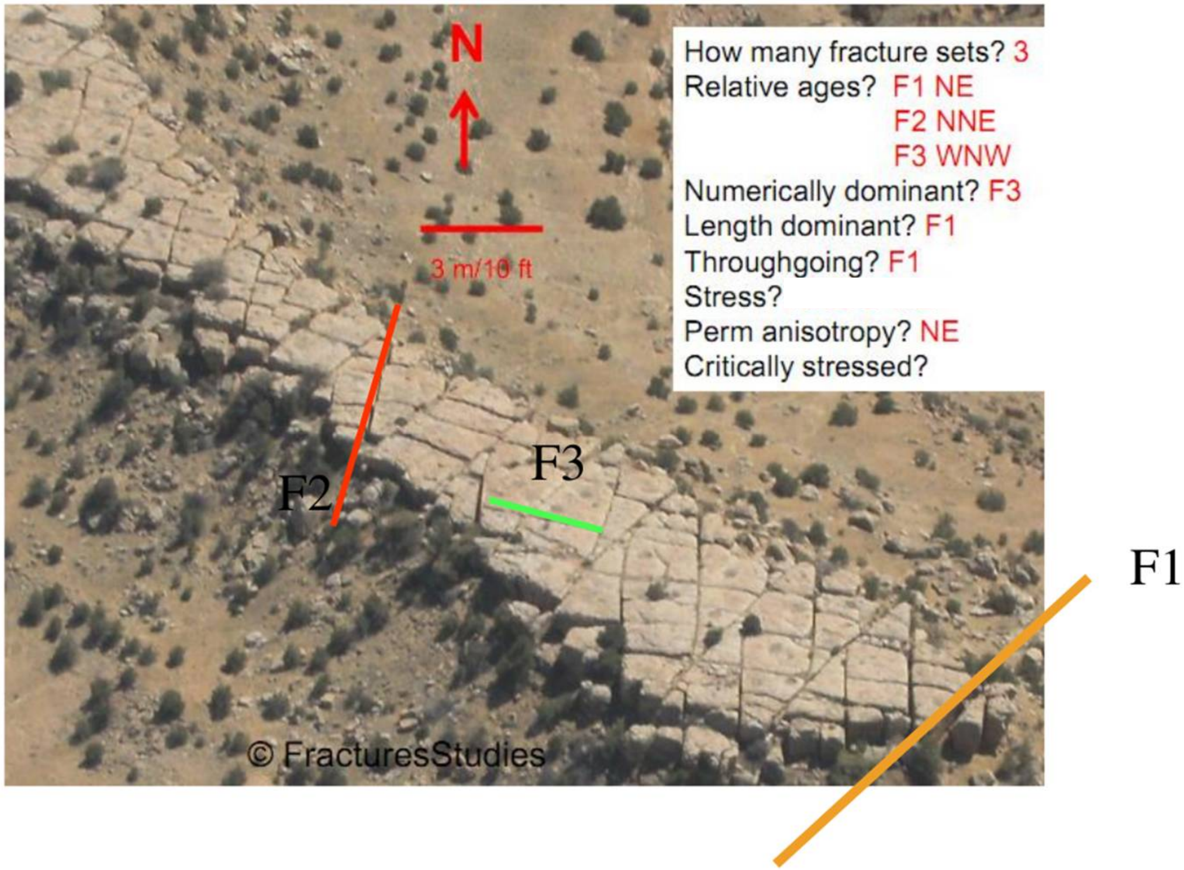
Full core is rarely collected in sufficient quantities

Geophysical methods (backscatter and reflections in borehole seismics) are in development, but what about 3 km deep?

Natural Fracture Network



Well



Outcrop

Stress Field and Fractures

Drivers:

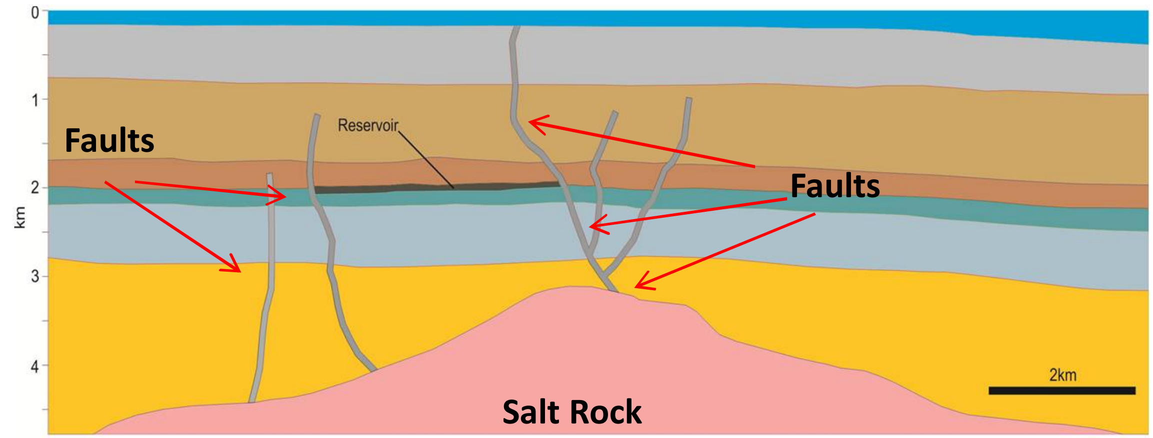
Faults

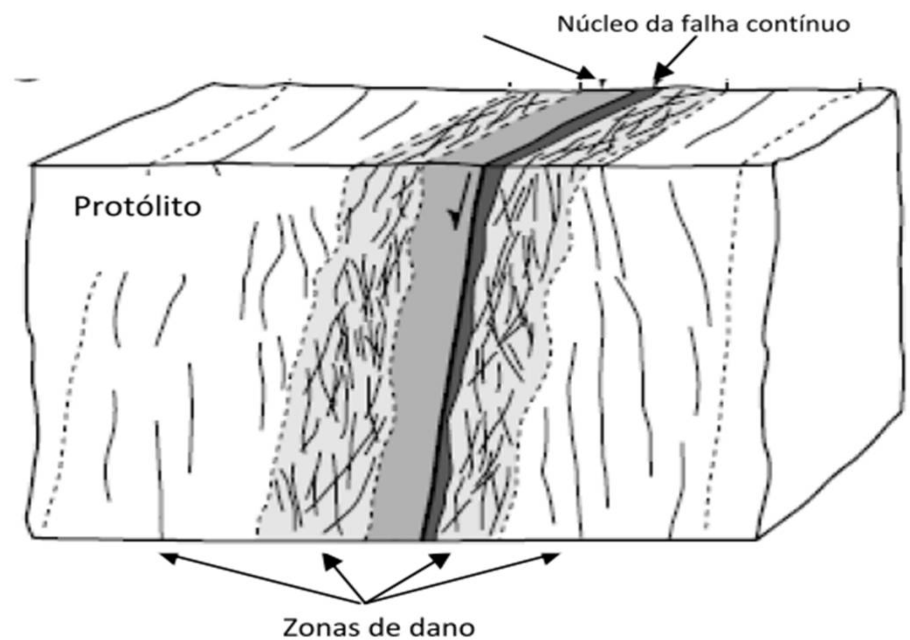
Folds

Lithology

Porosity

Bed Thickness





Stress Field and Fractures

Drivers:

Faults

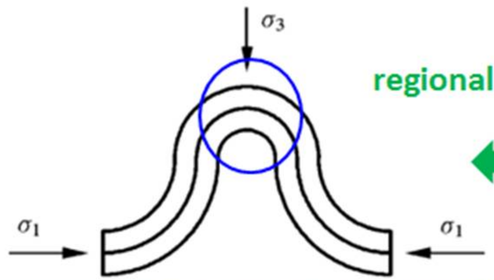
<u>Folds</u>

Lithology

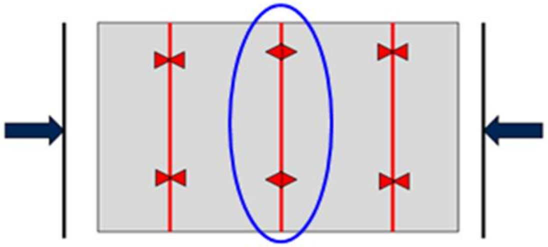
Porosity

Bed Thickness

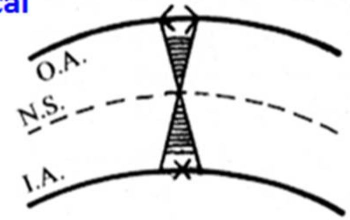
Local and regional stress fields:



regional



local



Colombian Andes, Tona, Santander

Stress Field and Fractures

Drivers:

Faults

Folds

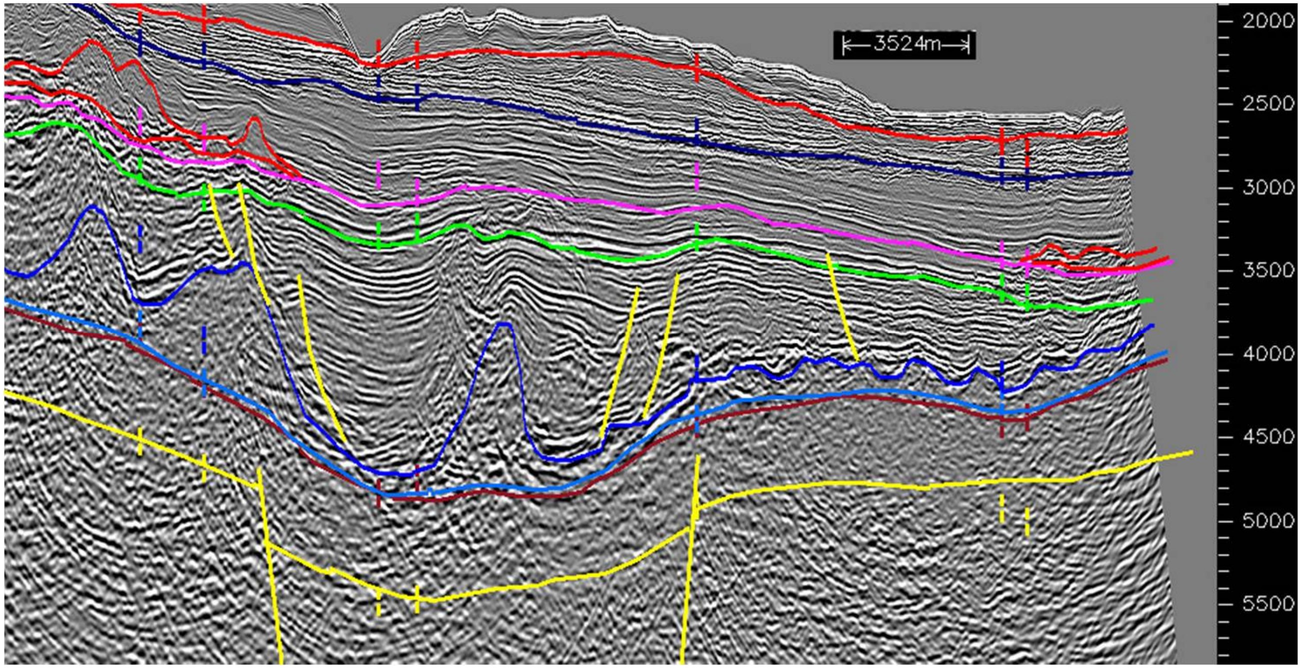
Lithology

-

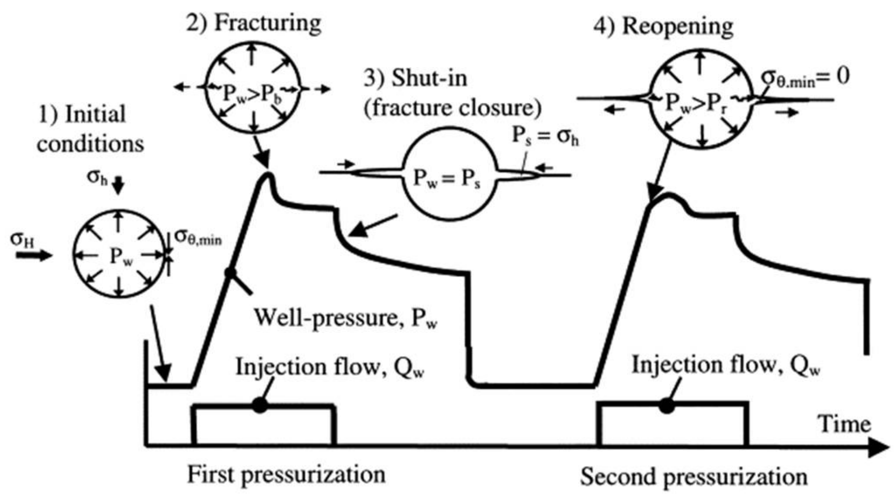
Porosity

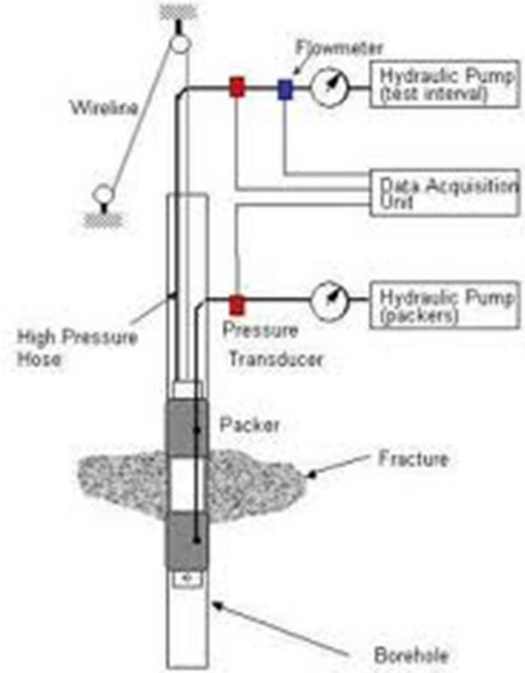
-

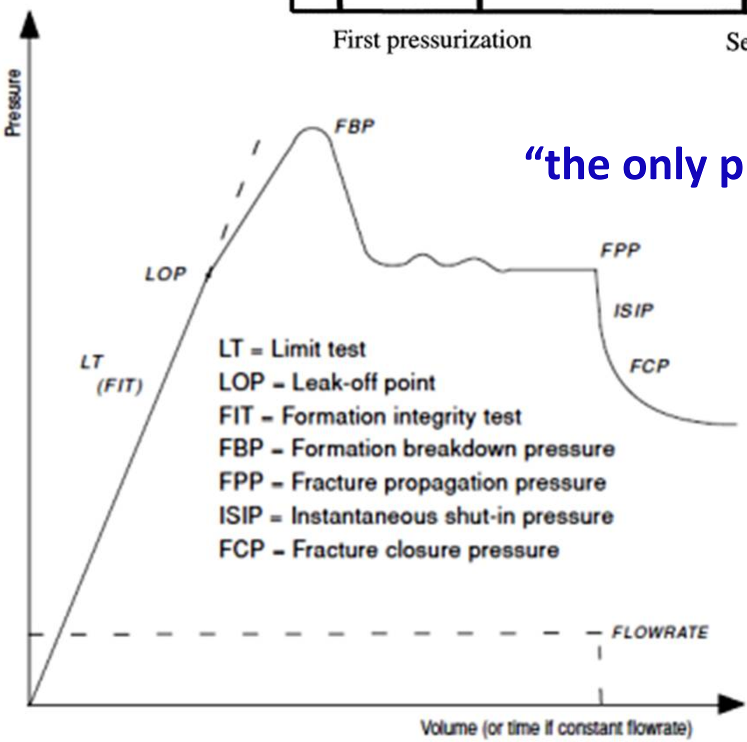
Bed Thickness



Leak-off test: obtainig the minimum principal stress (Smin)







"the only practical and reliable"

LOP (leak-off point)

FBP (fracture breakdown pressure)

FPP (fracture propagation pressure)

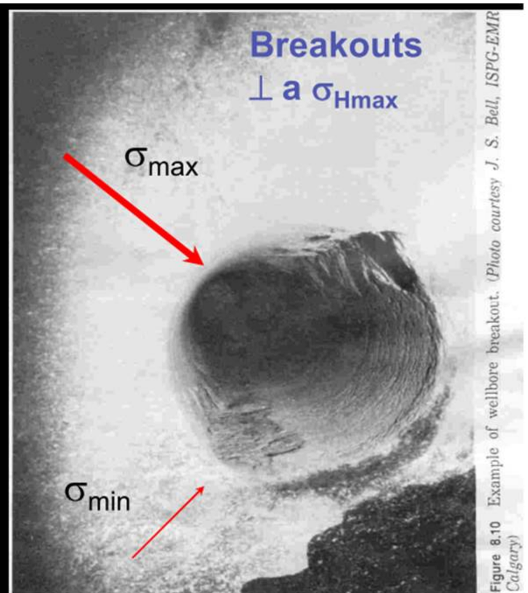
ISIP (instantaneous shut-in pressure)

FCP (fracture closure pressure)

BREAKOUTS

- Este método baseia-se no mapeamento por perfil de imagem ou caliper de regiões do poço onde ocorrem rupturas por cisalhamento da parede.
- A direção dos *breakouts* é ortogonal à direção da maior tensão horizontal.

L. C. Pereira (MSc, 2007)



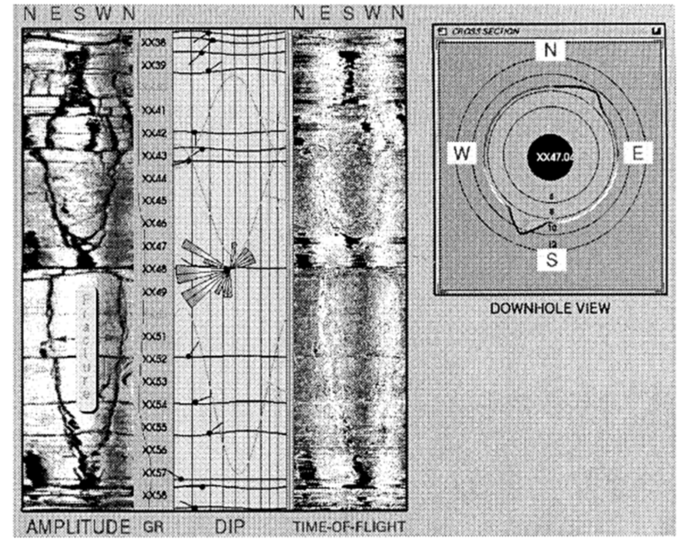


Fig. 5. Ultrasonic imaging log showing natural fractures with a cross-section showing borehole breakout in a NE–SW direction.

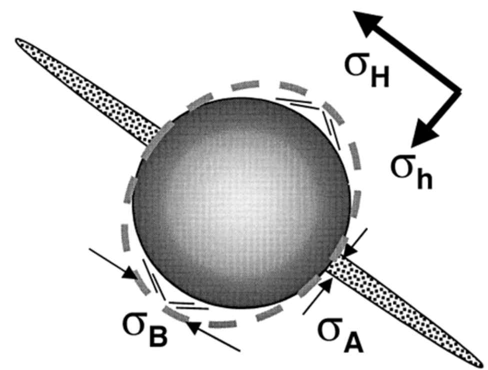


Fig. 4. Directions of borehole breakout and fractures in relation to the orientation of the horizontal stress field.

A **breakout** is the evidence of **wall yield** (the formation strength at the borehole wall is exceeded). A breakout **is not considered to be a borehole failure** since the borehole remains useful. Borehole breakout can be **measured** using four- or six-arm **caliper tools**. The preferred tool, however, is the **ultrasonic imaging tool**, which makes up to 200-caliper measurements at every depth level.

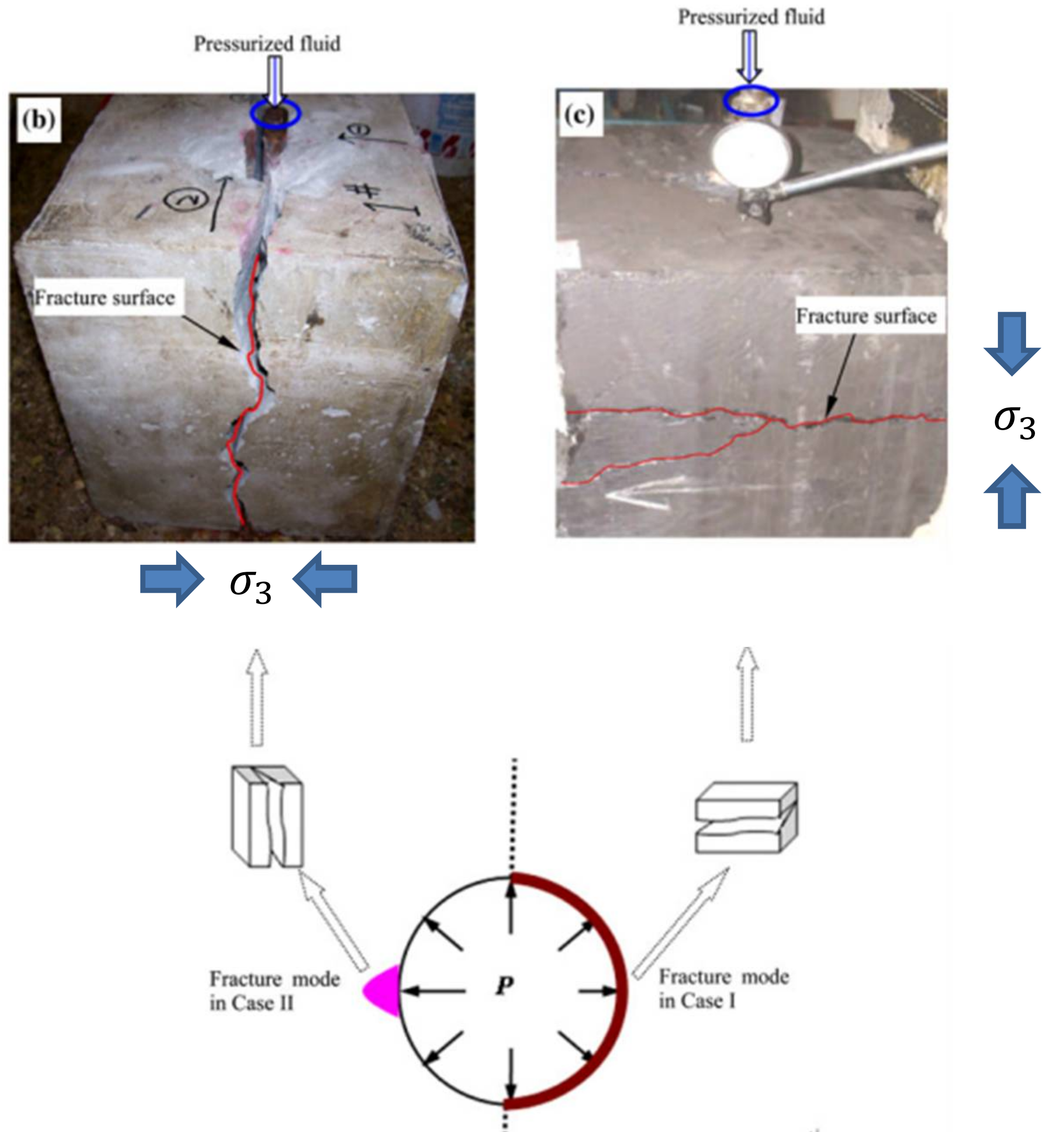
M.Y. Soliman*, Paul Boonen Journal of Petroleum Science and Engineering 25 (2000) 187–204

OUTLINE

- Introduction: Unconventional Reservoir
- Natural Fractures Network
- **Hydraulic Fracturing Modeling**
- Proppant and Fracture Closure Model
- HF Validation: Microseismicity
- Final Remarks

HYDRAULIC FRACTURING

fracture parallel to wellbore | **fracture perpendicular to wellbore**

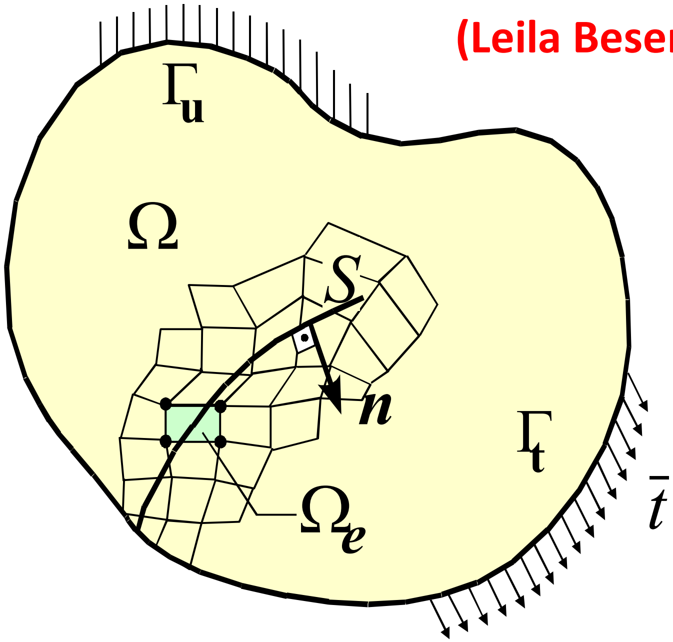


(Deng et al. 2004 ; Meng et al. 2010)

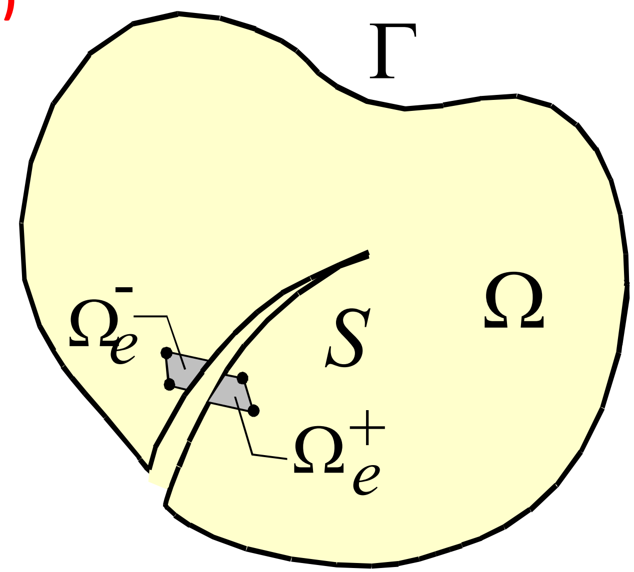
Finite Elements with embedded discontinuities

- The discontinuity path is placed inside the elements irrespective of the size and specific orientation.

(Leila Beserra, PhD)



Discontinuity tracing in a domain



Finite Element divided by discontinuity

Oliver et al. (1999), Oliver (2000)

FLUID FLOW IN DISCONTINUITIES

Darcy Flow in domain	$\mathbf{q}_\Omega = -\mathbf{K}_\Omega \cdot \nabla P$
Darcy Flow in discontinuity	$q_S = -K_S \mathbf{t} \cdot \nabla P$
Continuity	$\mathbf{n} \cdot (\mathbf{q}_\Omega - \mathbf{q}_S) = 0$

$$\mathbf{q}_\Omega = \left(-\mathbf{K}_\Omega - \gamma_S \mathbf{t} \otimes \mathbf{t} K_S\right) \nabla \overline{P}$$

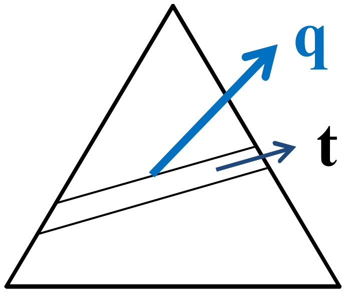
Equivalent Permeability Tensor

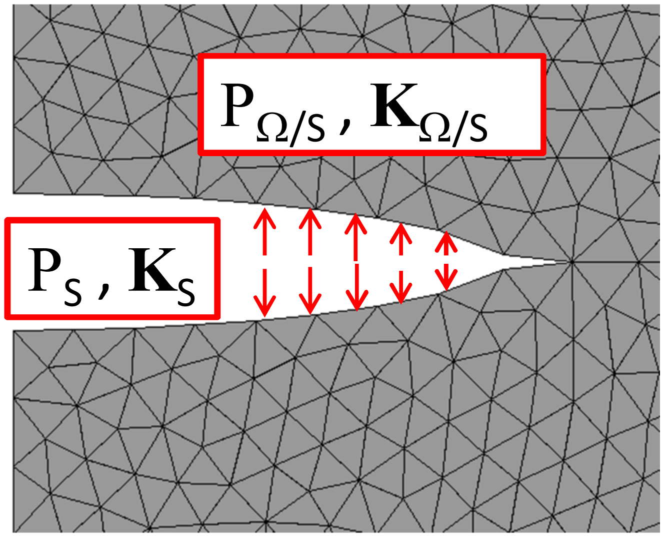
Permeability Evolution Law

$$K_S = \frac{[[u_n]]^2}{12}$$

Normal jump Aperture

The fluid flow law for the discontinuity portion considers only the flow in its direction





HYDRO MECHANICAL COUPLING

Traction Continuity (total stress):

$$\mathbf{n}\cdot(\boldsymbol{\sigma}_{\Omega/S}-\boldsymbol{\sigma}_S)=\mathbf{0}$$

Effective stress:

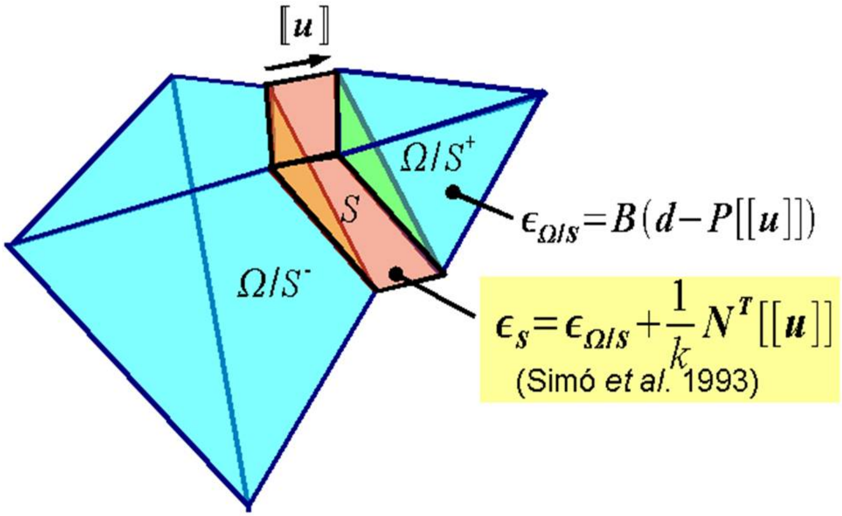
$$\boldsymbol{\sigma}'=\boldsymbol{\sigma}-\alpha P_f\mathbf{I}$$

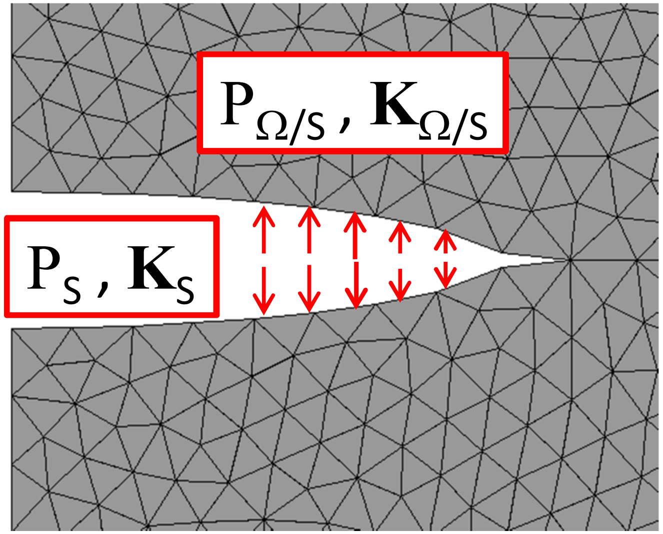
Traction Continuity (effective stress):

$$\mathbf{n}\cdot(\boldsymbol{\sigma}'_{\Omega}-\alpha P_{\Omega/S}\mathbf{I}-\boldsymbol{\sigma}'_S+\alpha P_S\mathbf{I})=\mathbf{0}$$

Constitutive Relation

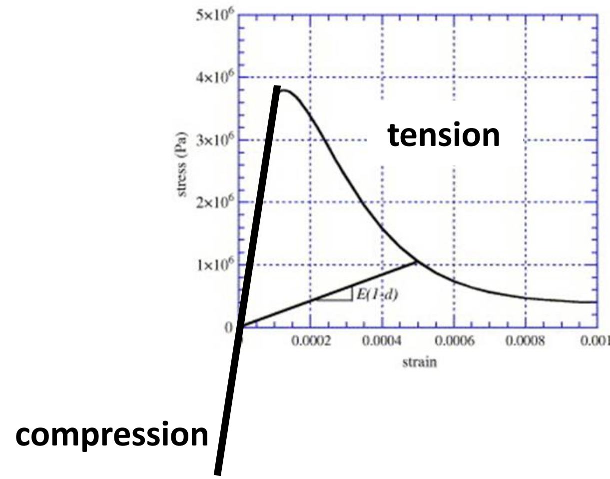
$$\begin{cases}\boldsymbol{\sigma}'_{\Omega/S}=\mathbf{D}^e:\boldsymbol{\varepsilon}_{\Omega/S}\\ \boldsymbol{\sigma}'_S=(1-d)\mathbf{D}^e:\boldsymbol{\varepsilon}_S\end{cases}$$



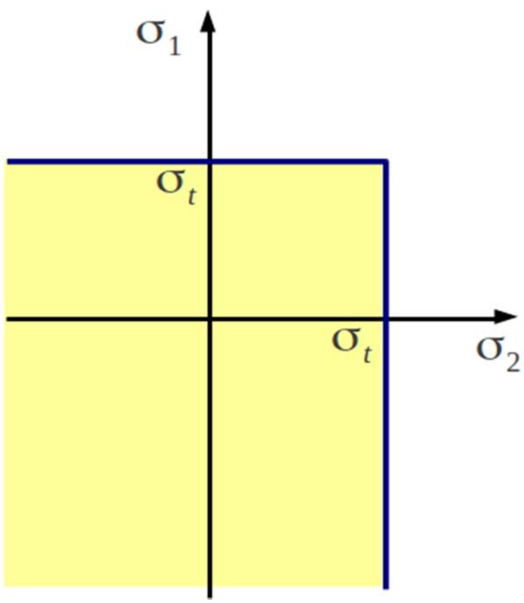


TENSILE DAMAGE MODEL

$$\begin{cases} \boldsymbol{\sigma} = (1-d)\overline{\boldsymbol{\sigma}} & \text{if } tr(\overline{\boldsymbol{\sigma}}) \geq 0 \\ \boldsymbol{\sigma} = \overline{\boldsymbol{\sigma}} & \text{if } tr(\overline{\boldsymbol{\sigma}}) < 0 \end{cases}$$



$\bar{\boldsymbol{\sigma}} = \mathbf{C} : \boldsymbol{\epsilon}$ Effective stresses (elastic)

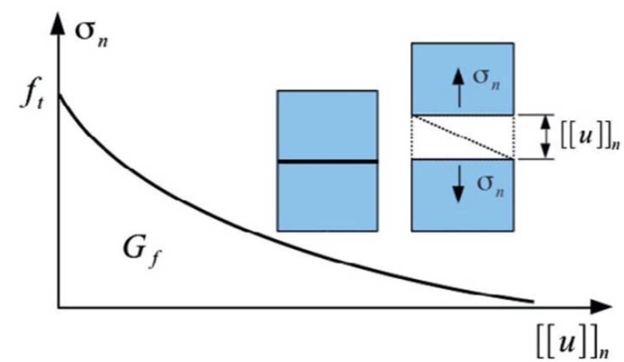


Damage criterion

$$\phi = \sigma_1 - q(r) \leq 0$$

⇓

First principal stress

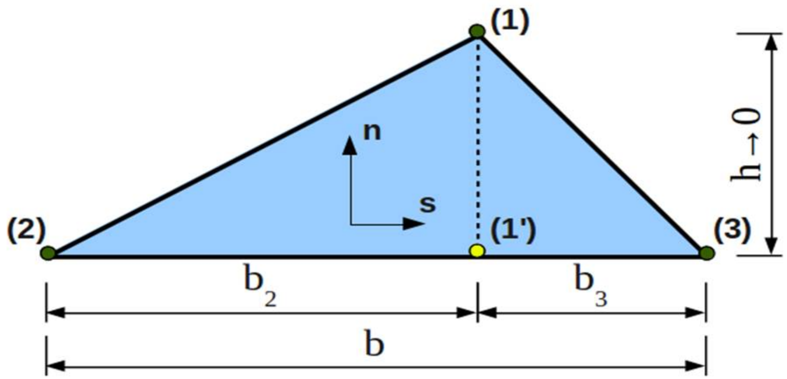


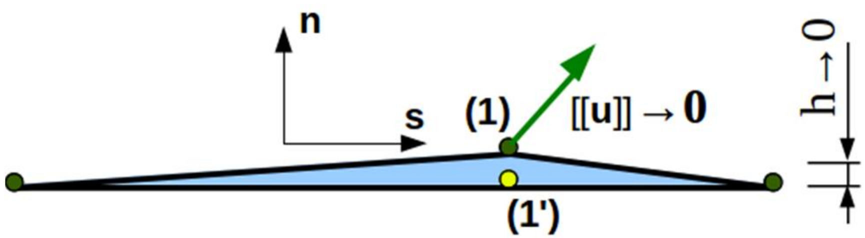
Softening law (fracture energy)

Interface Finite Elements Formulation

Triangular element / strong discontinuity kinematics (Marcela Seixas, PhD)

Finite element with high aspect ratio





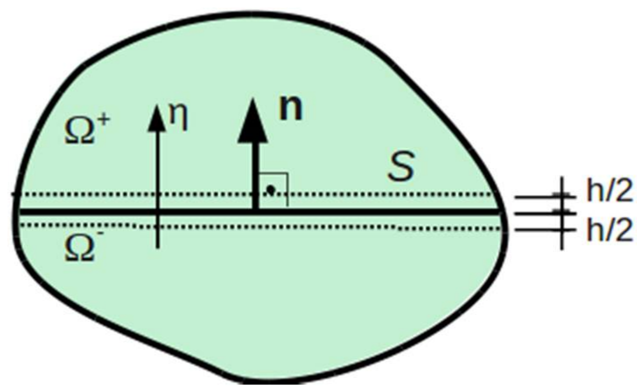
$$\epsilon = \tilde{\epsilon} + \underbrace{\frac{1}{h}(\mathbf{n}\otimes[[\mathbf{u}]])^s}_{\hat{\epsilon}}$$

Weak/strong discontinuity kinematics

Same kinematics !!!

MANZOLI *et al*, 2012

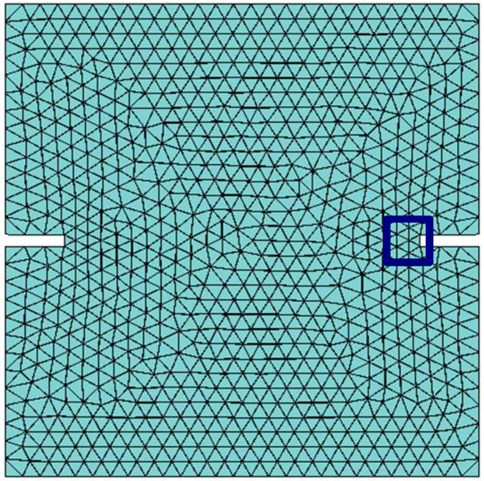
Computers and Structures 94–95 (2012) 70–82



$$\epsilon = \bar{\epsilon} + \frac{\mu_s(\eta)}{h}([[\mathbf{u}]]\otimes\mathbf{n})^s$$

Fracturing of rocks with Interface Finite Elements Technique

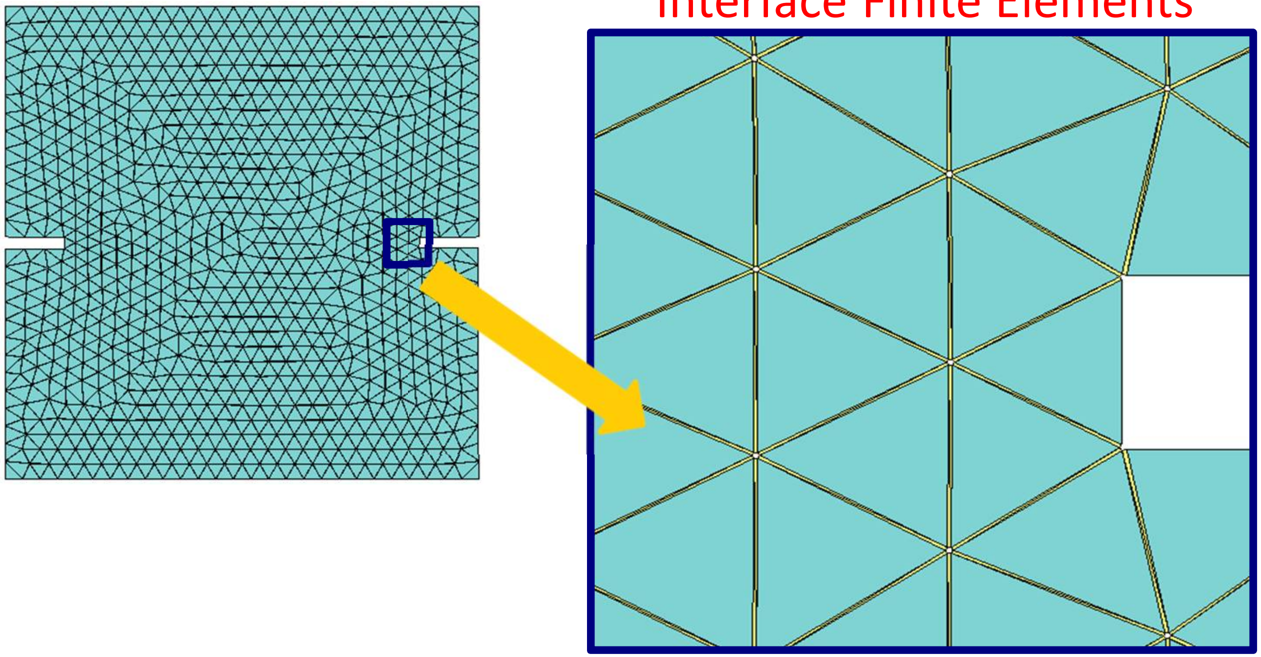
Initial Finite Element mesh



Fracturing of rocks with Interface Finite Elements Technique

Initial Finite Element mesh

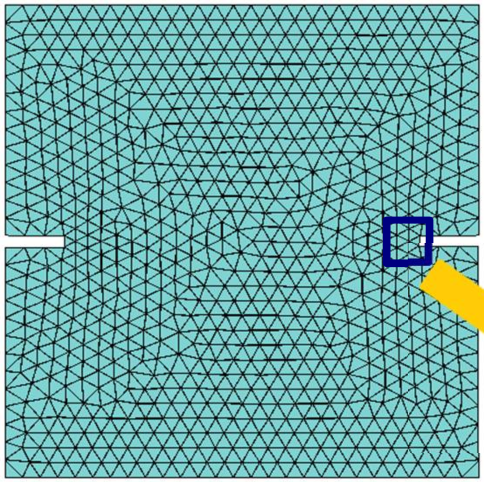
Interface Finite Elements



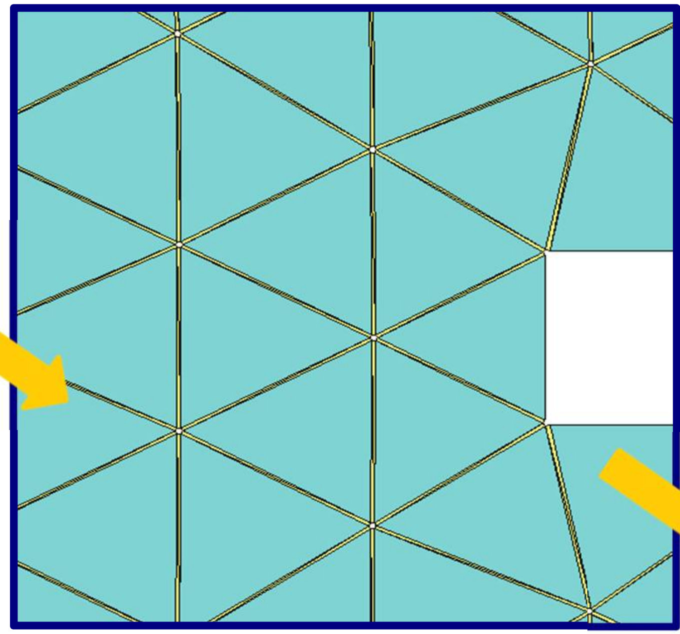
Interface finite elements are inserted throughout the mesh or in the most requested area of the mesh. Depending on the boundary conditions of the problem and stress states resulting, the elements will be opening by a preferential path, forming a fracture and relaxing the stress in other candidate elements at the same time.

Fracturing of rocks with Interface Finite Elements Technique

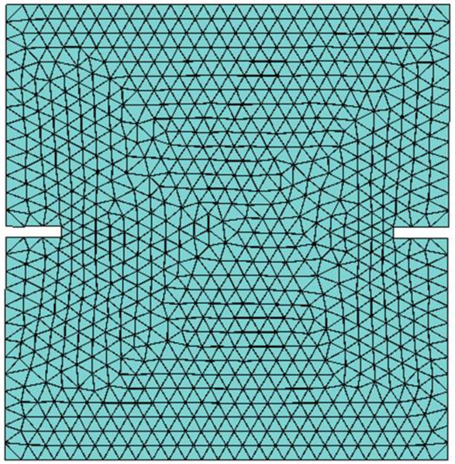
Initial Finite Element mesh



Interface Finite Elements

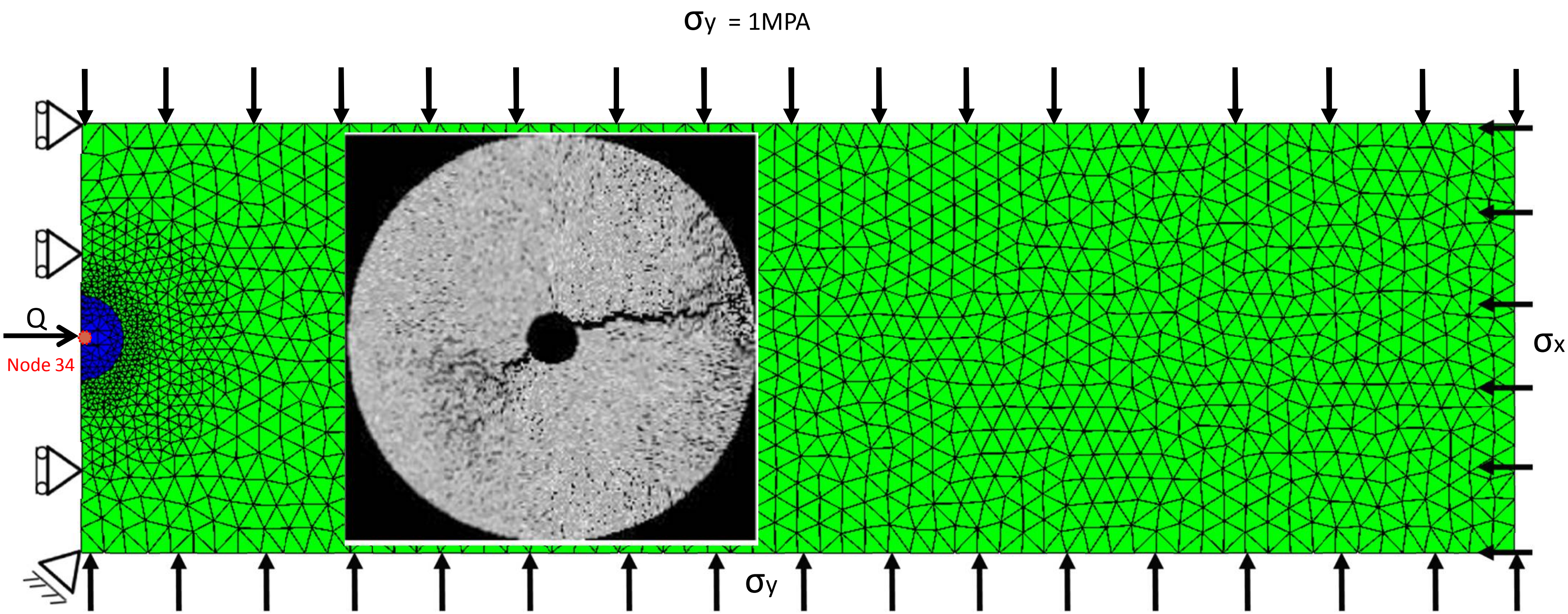


Fractures formation



Leak-off test

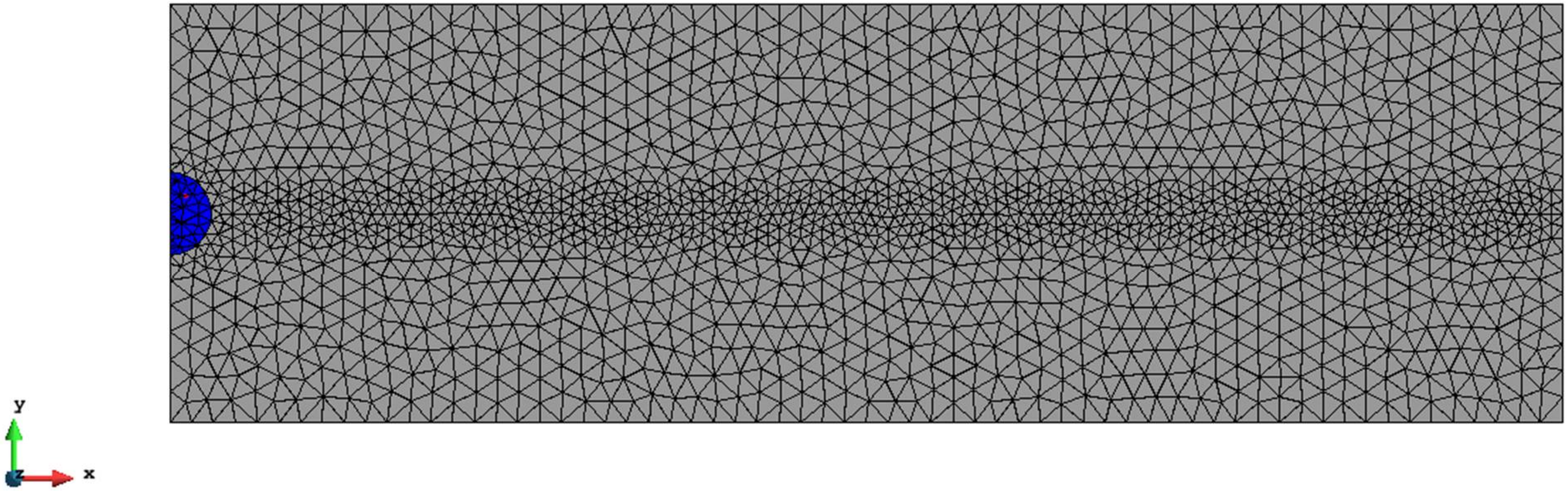
CASE 2: 2D situation

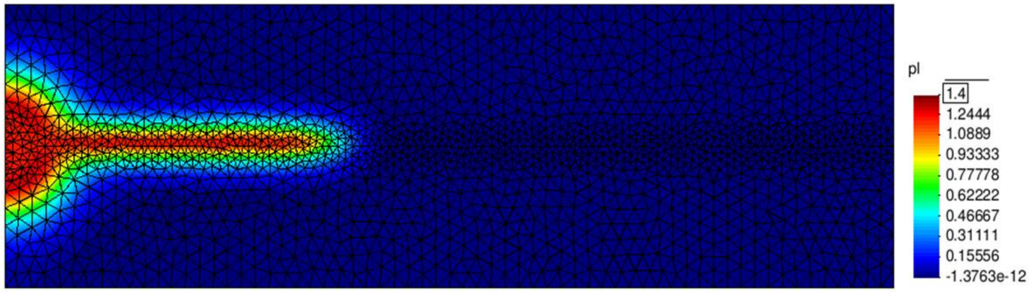


$Q=6x10^{-5}kg/s$
$\sigma v=1MPa$
$\sigma x=2MPa$

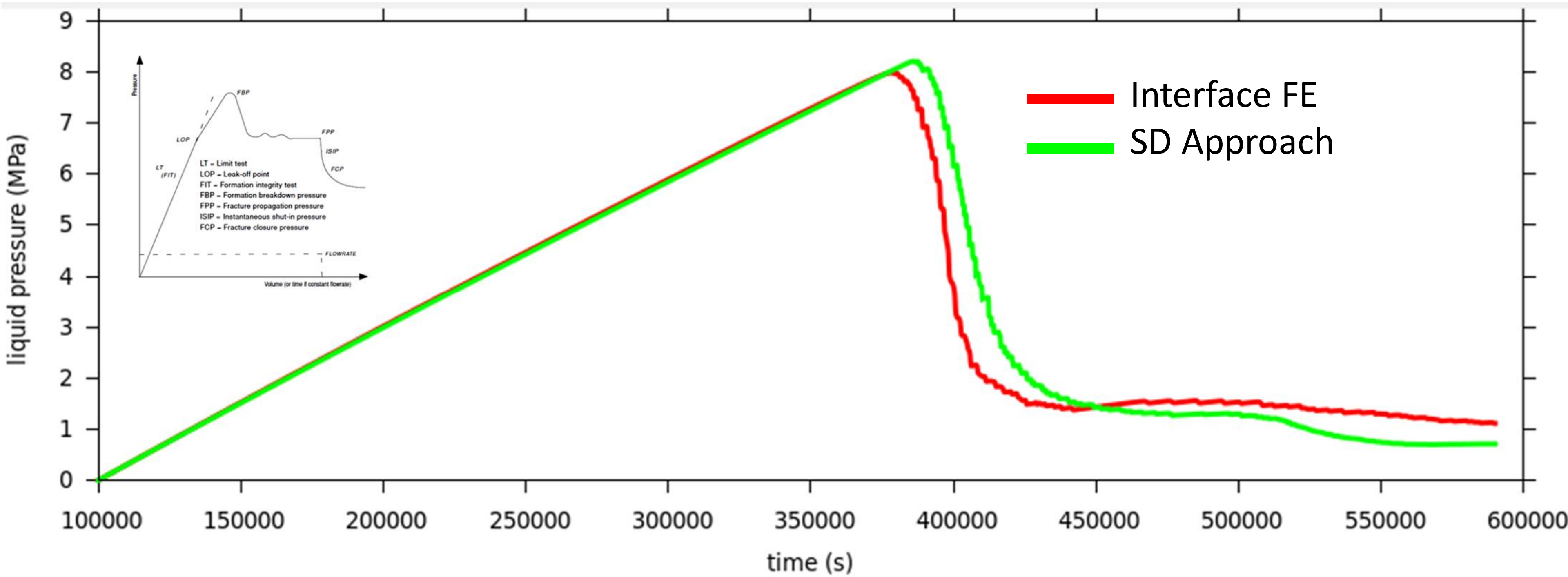
tensile strength of material :
$(\sigma y)=5$ MPa

Leak-off test





Strong Discontinuity Approach and Interface Finite Element

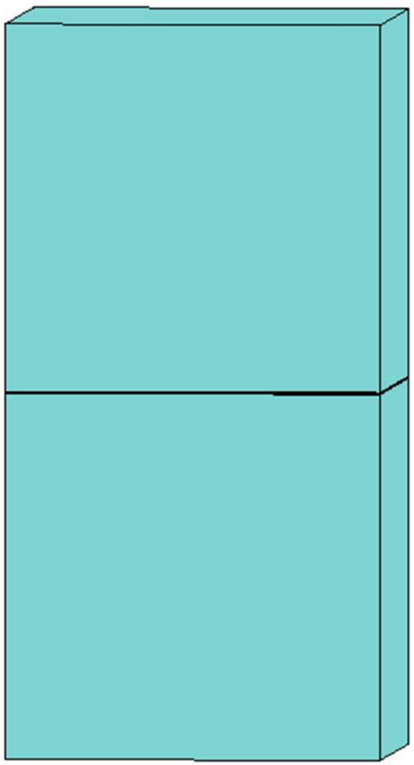


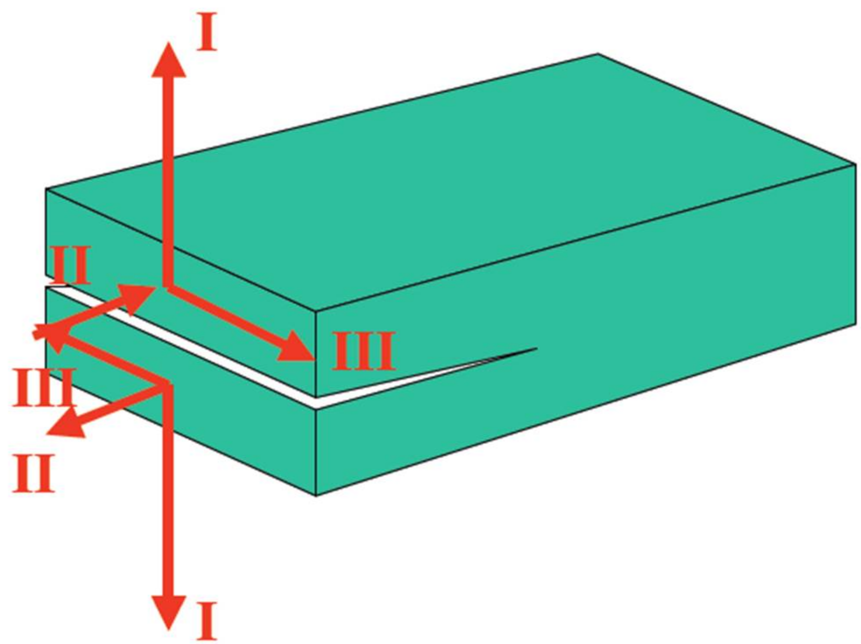
	Strong Discontinuity Approach	Interface Finite Element
Nodes	1595	10256
Elements	2993	20162
CPU time (s)	1210.51	6289.43

Geomechanics of Fracturated Reservoirs

Much more complex behavior of fractures...

Improvement of constitutive of interface elements

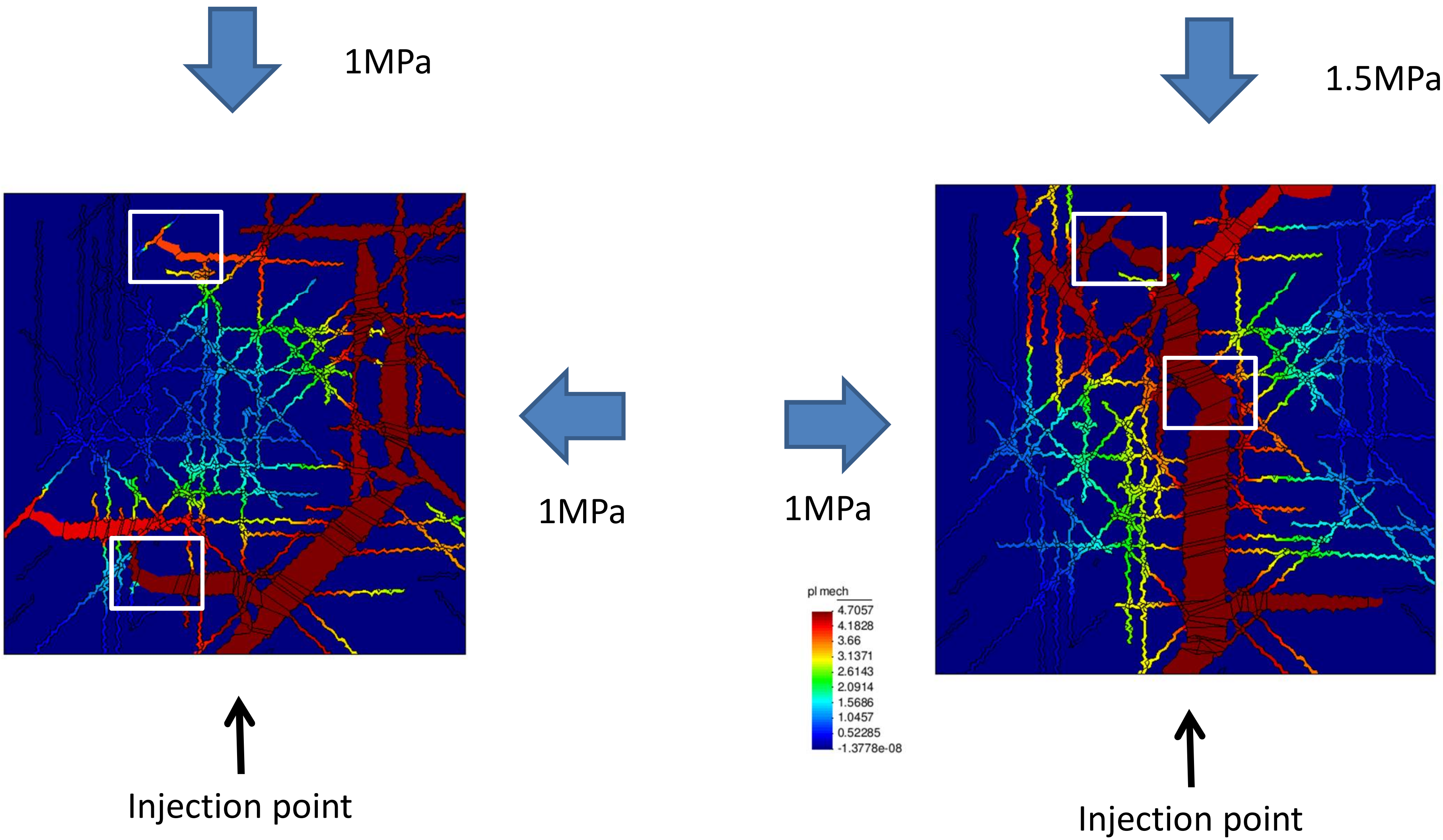




Up to now: isotropic tensile damage model (mode I)

Improvements: shear modes (II and III) and inelastic effects due to dilatancy and compression

Fracture Propagation



OUTLINE

- Introduction: Unconventional Reservoir
- Natural Fractures Network
- Hydraulic Fracturing Modeling
- **Proppant and Fracture Closure Model**
- HF Validation: Microseismicity
- Final Remarks

Proppant Migration and Agglomeration

Physical modeling

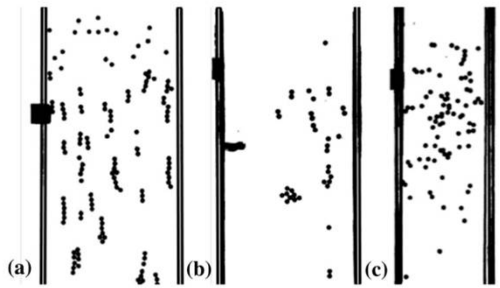


Fig. 1 Experimental results of particle settling in 1.25 % aqueous polyox solution (**a**), SI (**b**) and STP (**c**) (Joseph et al. 1994)

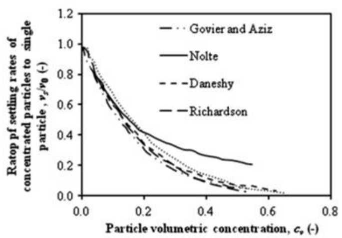


Fig. 2 Correlations for the effects of solid concentration on settling velocity

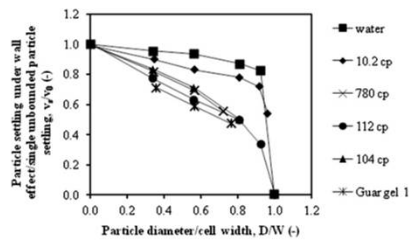


Fig. 3 Wall effect on particle settling (Liu and Sharma 2005)

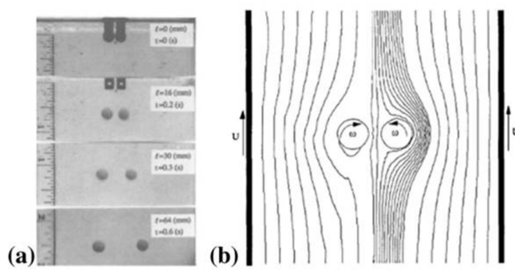
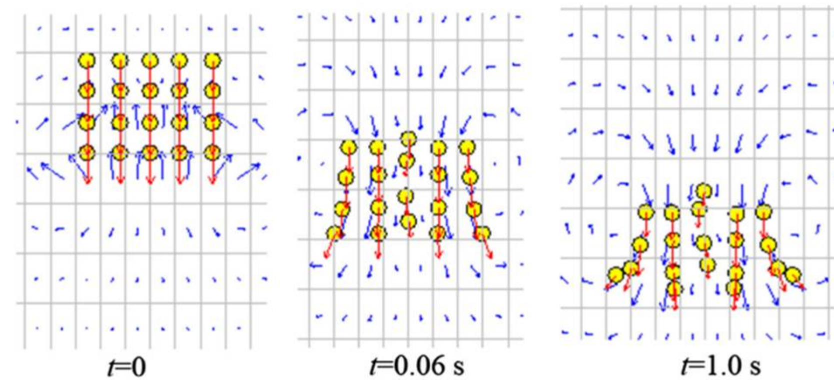


Fig. 4 Falling of two spheres in Newtonian fluid: **a** experimental results, **b** simulation results (Joseph et al. 1994)

Numerical modeling

Tomac and Gutierrez (2015)

Fig. 8 A set of particles settling in Newtonian fluid ($\mu = 0.01$ Pa s)



Discrete element method coupled with computational fluid dynamics (DEM–CFD) (Itasca 2004)

$$\rho_f \frac{\partial e\vec{v}}{\partial t} + \rho_f \vec{v} \rho \nabla (e\vec{v}) = -e\nabla p + \mu \nabla^2 (e\vec{v}) + \vec{f}_b,$$

$$\frac{\partial e}{\partial t} + \nabla (e\vec{v}) = 0,$$

$$e = 1 - \frac{V_p}{V}$$

$$\vec{f}_b = \beta \vec{U},$$

$$\vec{U} = \bar{\vec{u}} - \vec{v},$$

average relative or slip velocity between the particles and the fluid

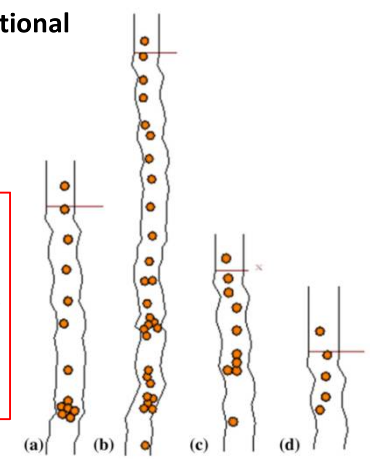
$$r_{ij} = r_i + r_j - d_{ij}$$

if $r_{ij} > 2r_c = r_{cr}$,

$$F_c = m\ddot{a} = -6\pi\mu a^2 \frac{v_{ij}}{x_{ij}} = -l_c \frac{v_{ij}}{(r_{ij} - 2r_c)}$$

if $r_{ij} \leq 2r_c = r_{cr}$ and

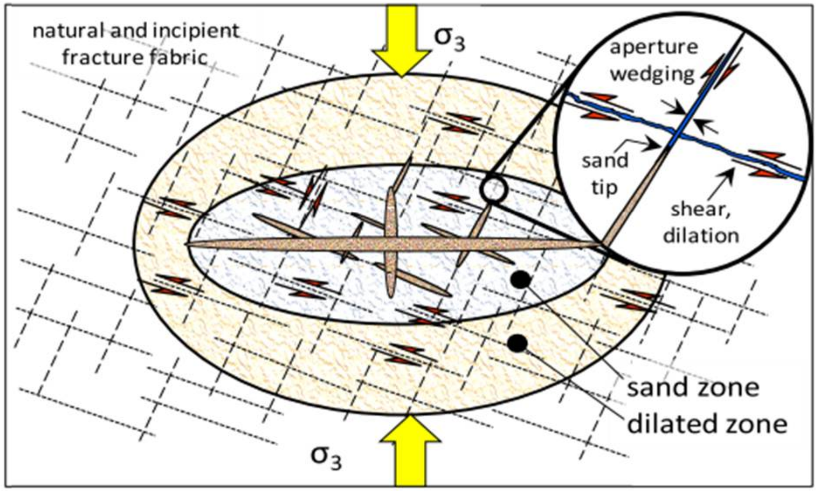
$$F_c = m\ddot{a} = k(2r_c - r_{ij}) + cv_{ij},$$

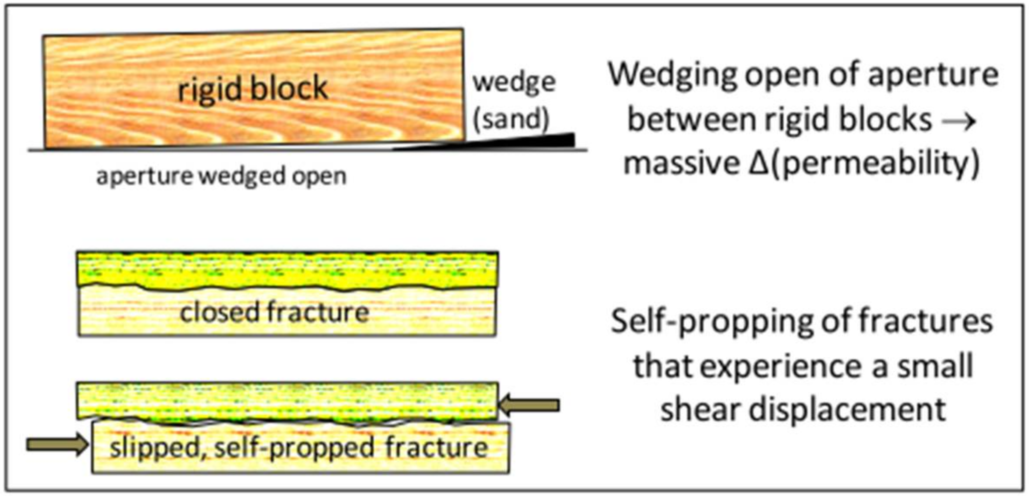


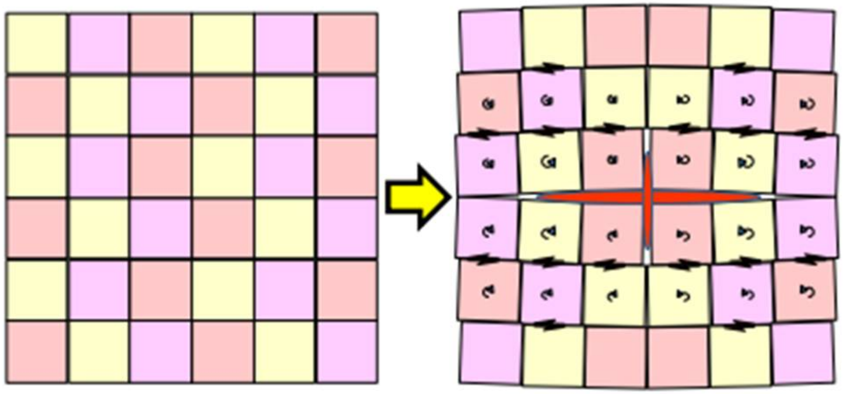
Massive Multi-Stage Hydraulic Fracturing
The Technology

Wedging of Aperture and Self-Propping Behavior of Shear-Displaced Fractures

Dusseault & McLennan



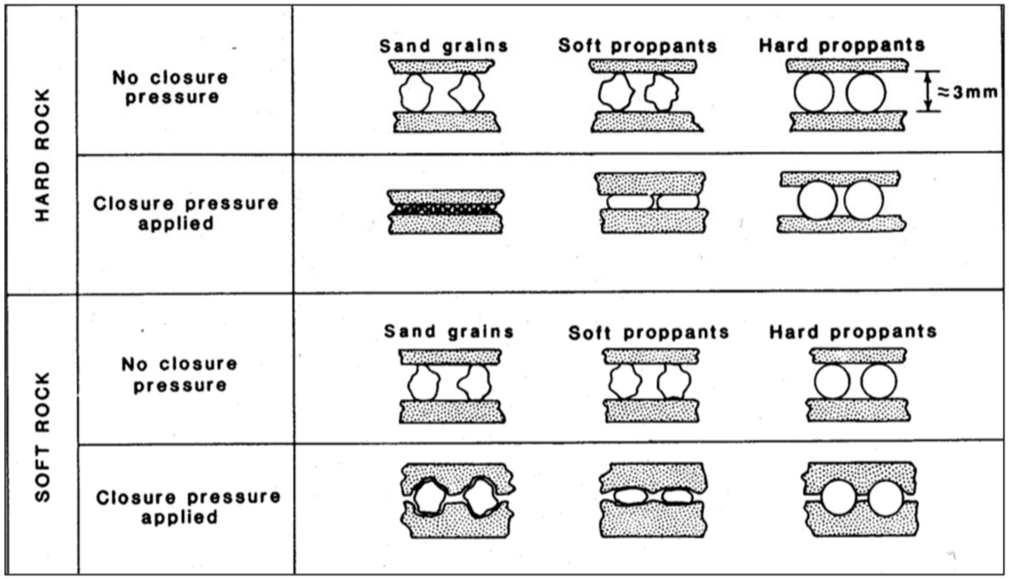


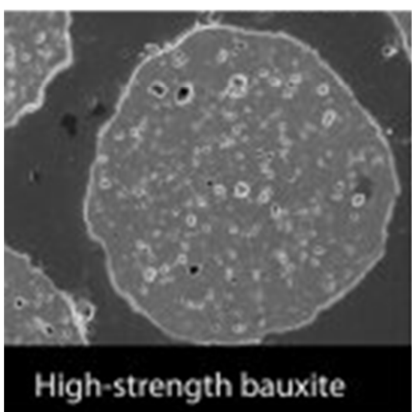


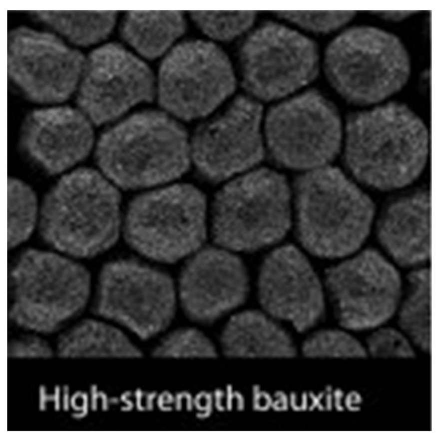
"sand-zone" surrounded by a <u>much larger</u> "dilated zone", where natural fractures have been opened permanently by wedging and block rotation, or propped by shear displacements.

Proppant Behavior During Production

<u>Response of propping agents to fracture closure pressure</u>

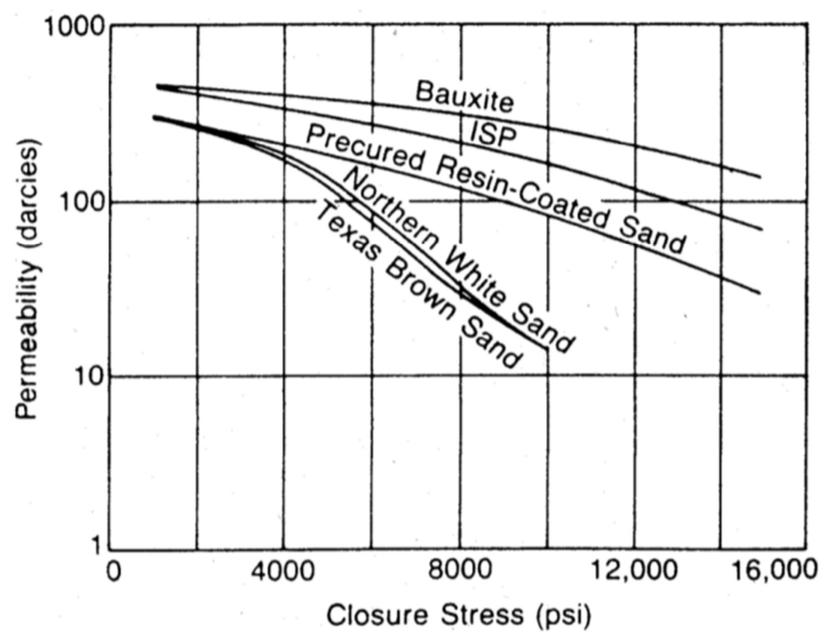



High-strength bauxite


High-strength bauxite

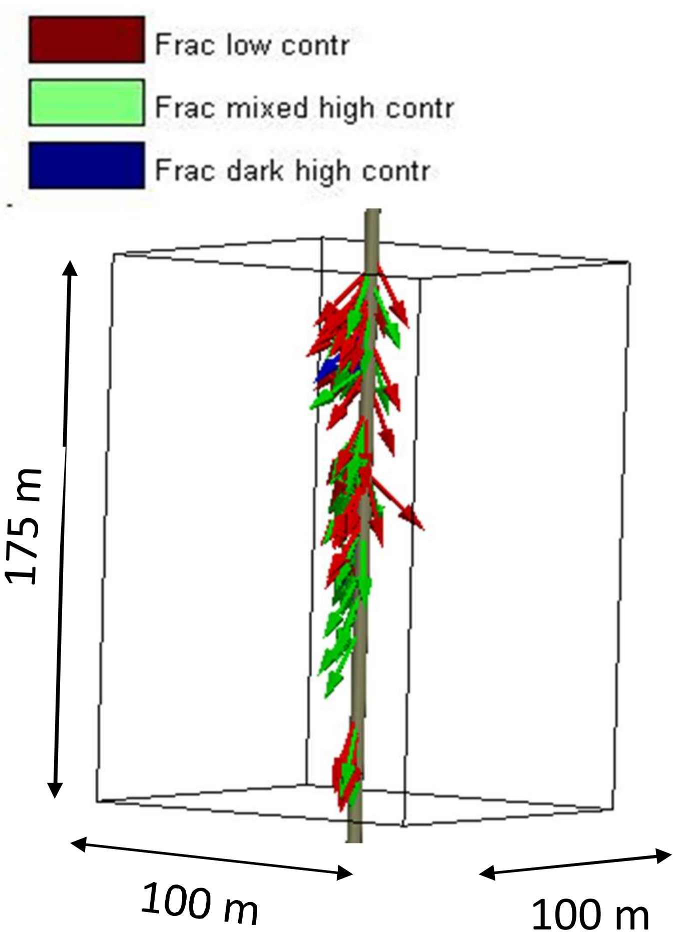
Types of Proppants

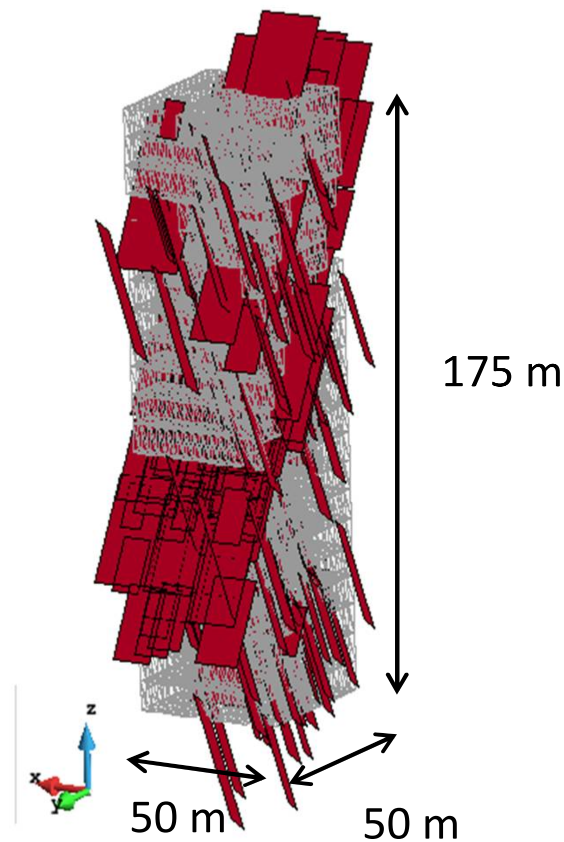
1. Sand, Sp. Gr. = 2.65, – low cost
2. Resin-coated sand, 2.55 – improves proppant strength
3. Intermediate Strength Proppants (ISP), 2.77-3.3, - fused ceramics
4. High Strength Proppants (Bauxite), >3.4 - expensive



Fracture Network Modeling

Colombian naturally fractured, low porosity sandstone reservoir





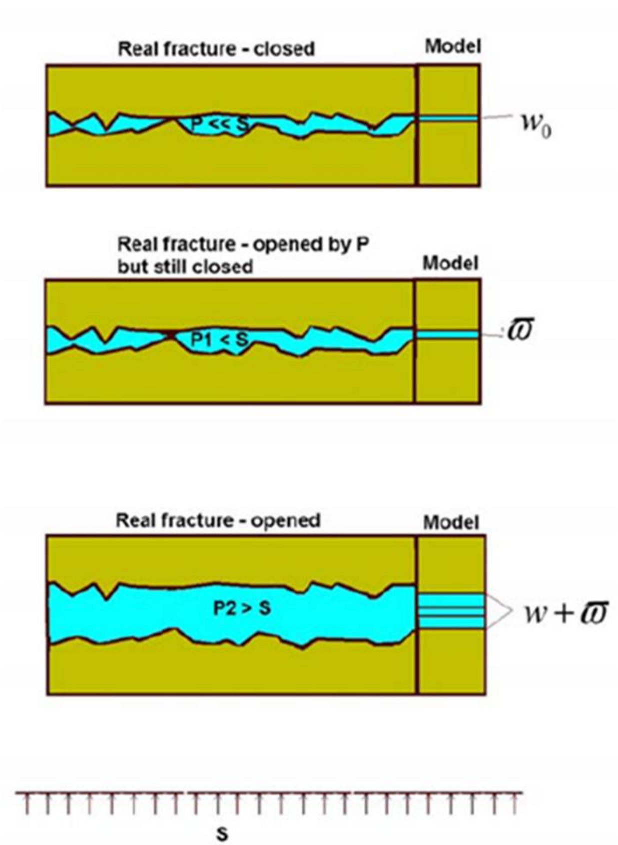
Normal Closure Modeling
Barton & Bandis

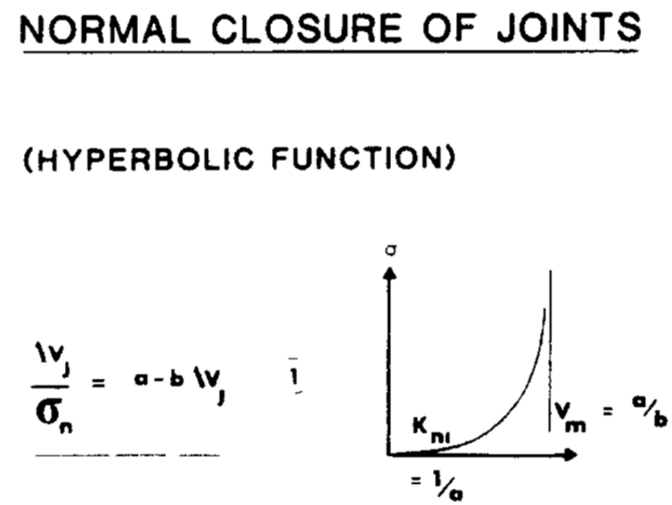
Net deformation of the joints

$$\Delta V_j = \Delta V_t - \Delta V_r$$

Total deformation across the jointed samples (ΔV_t)

Deformation across the intact samples (ΔV_r)



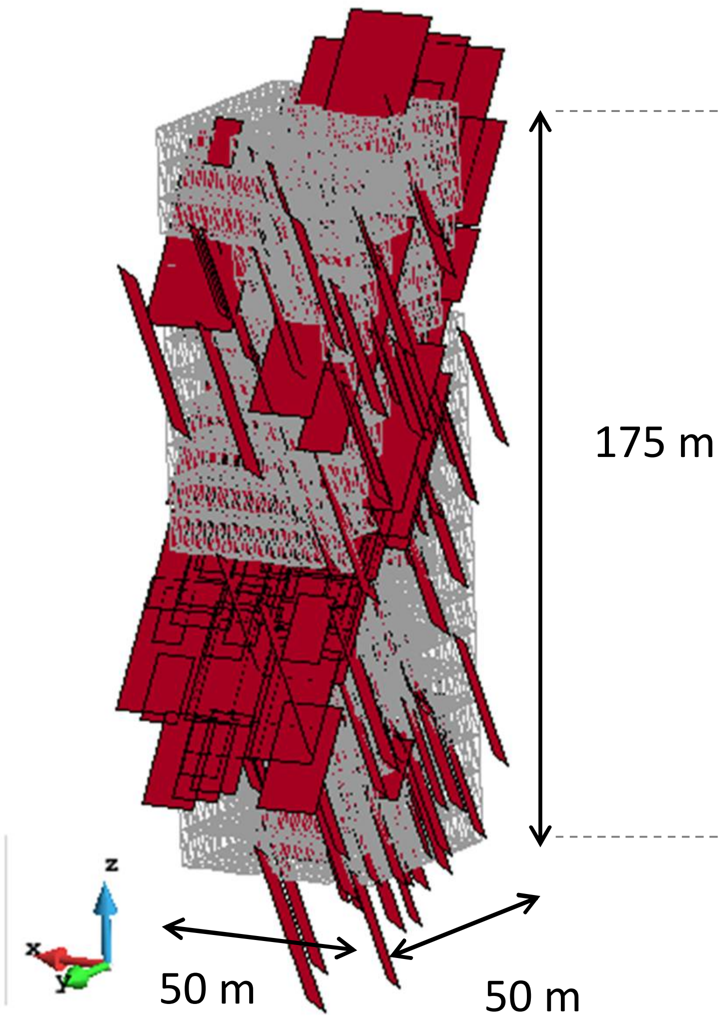


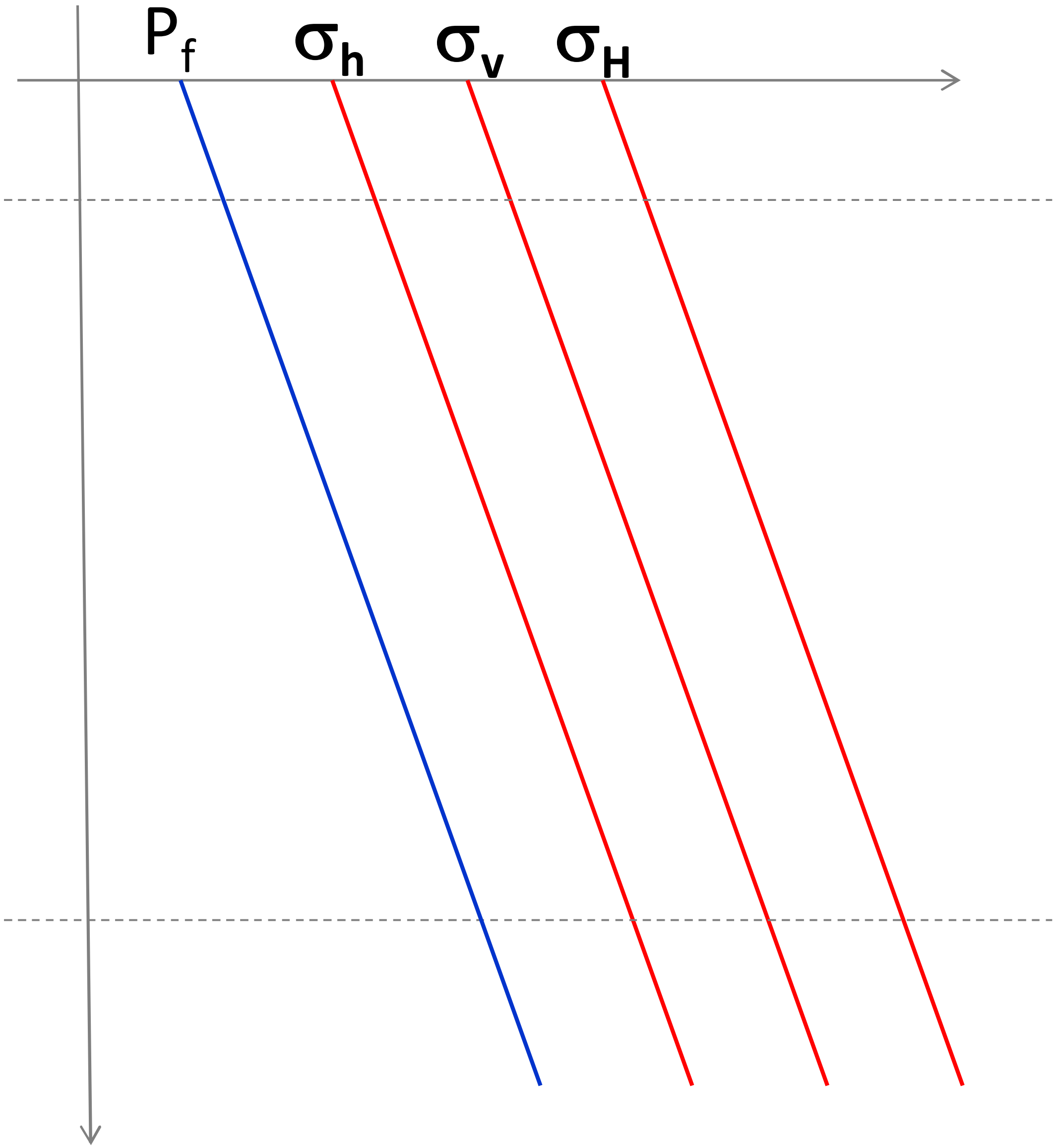
Closure $$j = \frac{\sigma_n V_m}{\sigma_n - K_{ni} V_m}$$

Hydraulic Closure $$e = e^0 + j$$

Fracture Permeability $$k_f = \frac{e^2}{12}$$

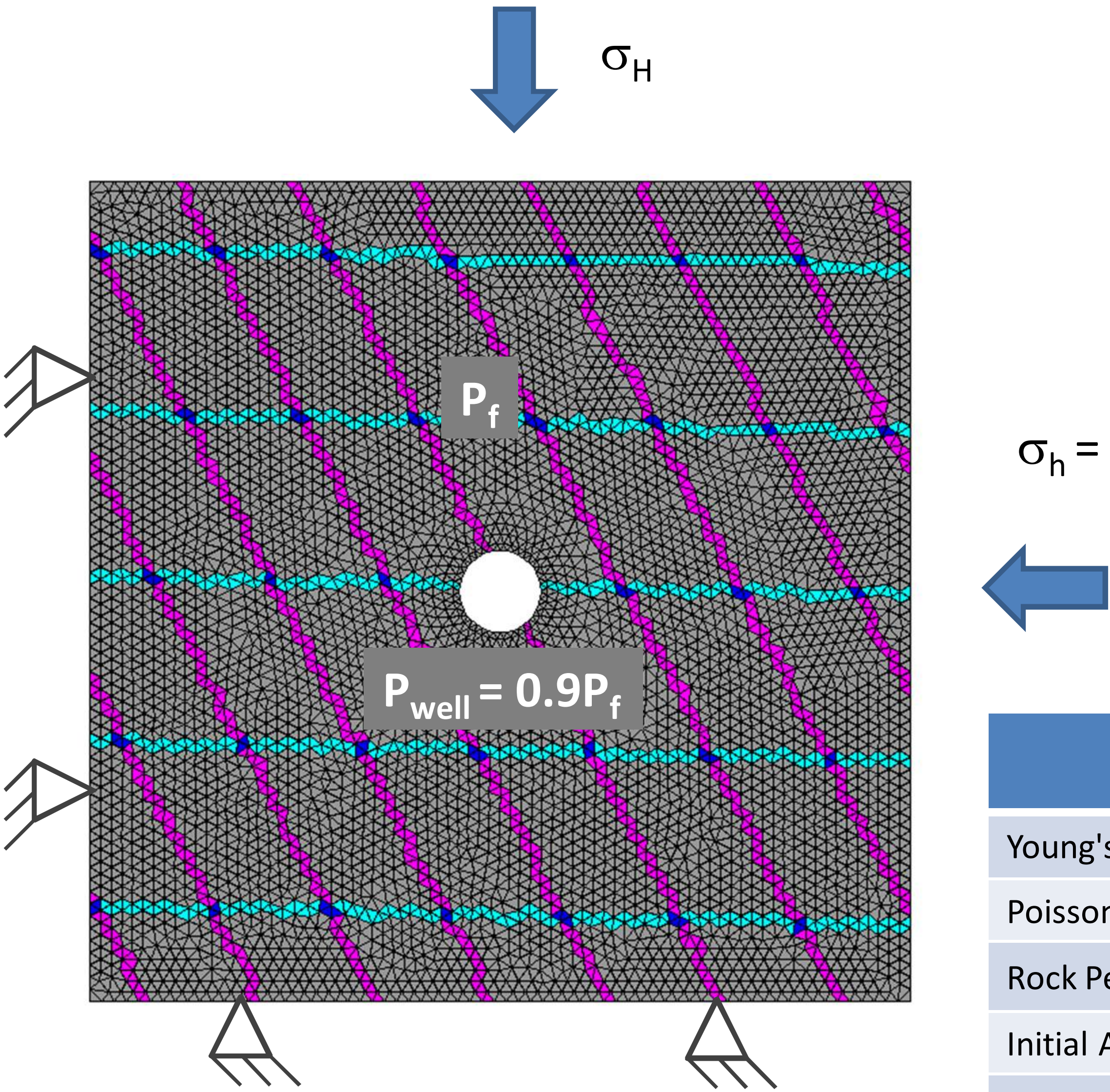
In Situ Stress State





Fracture Closure Problem
Boundary and Initial Conditions and Material Properties

$\sigma_V \sim 100\text{MPa}$

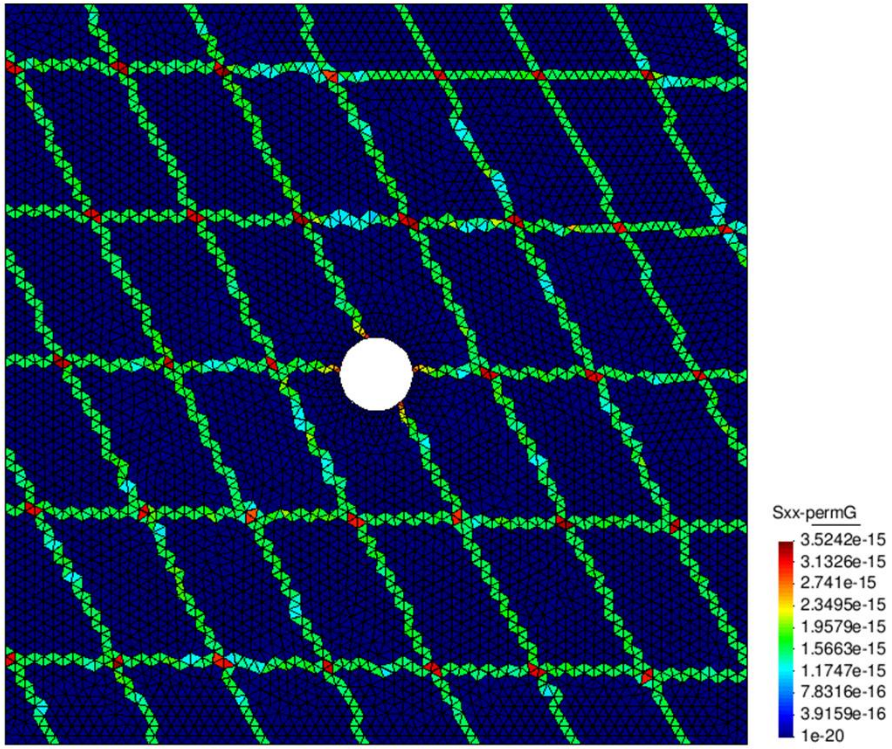


$\sigma_h = 0.62\ \sigma_H$

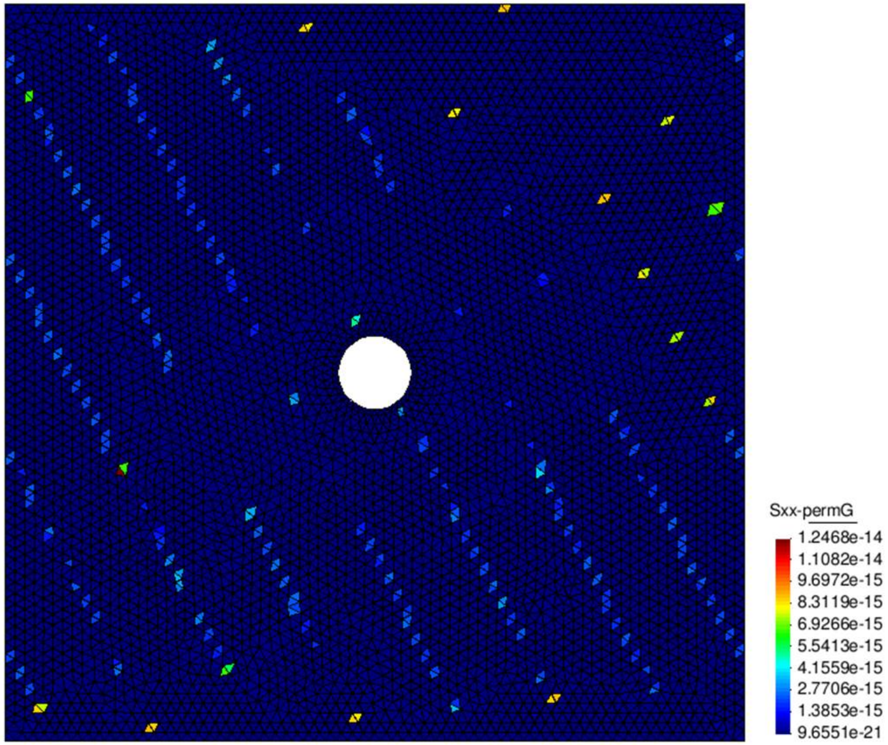
Properties	
Young's modulus	10 Gpa
Poisson	0.30
Rock Permeability	10^{-20} m²
Initial Aperture of Fractures	10^{-5}m
Barton & Bandis modulus (K_{ni})	100

Permeability Field

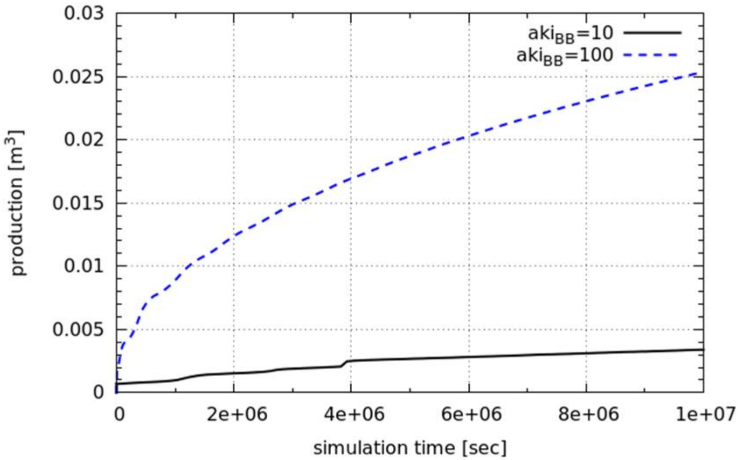
Initial



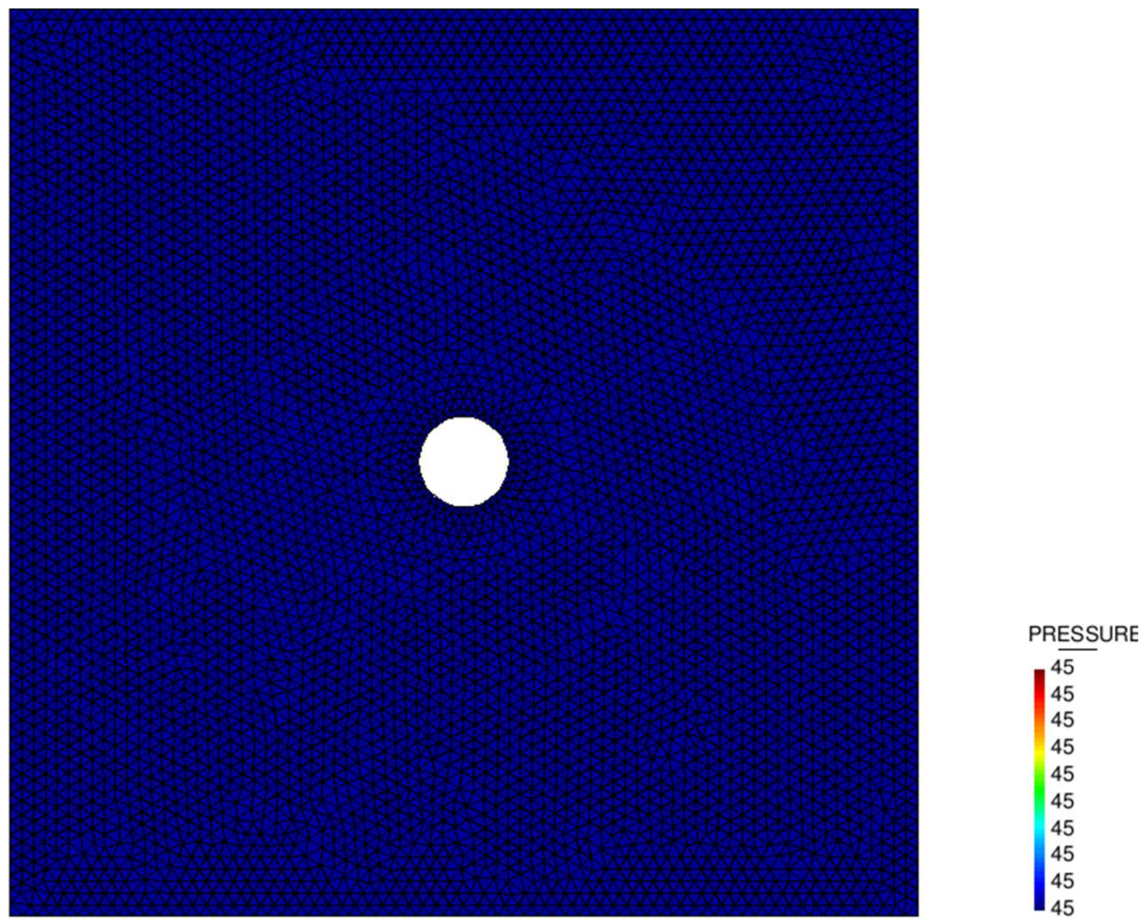
Final



FLUID PRESSURE PROPAGATION



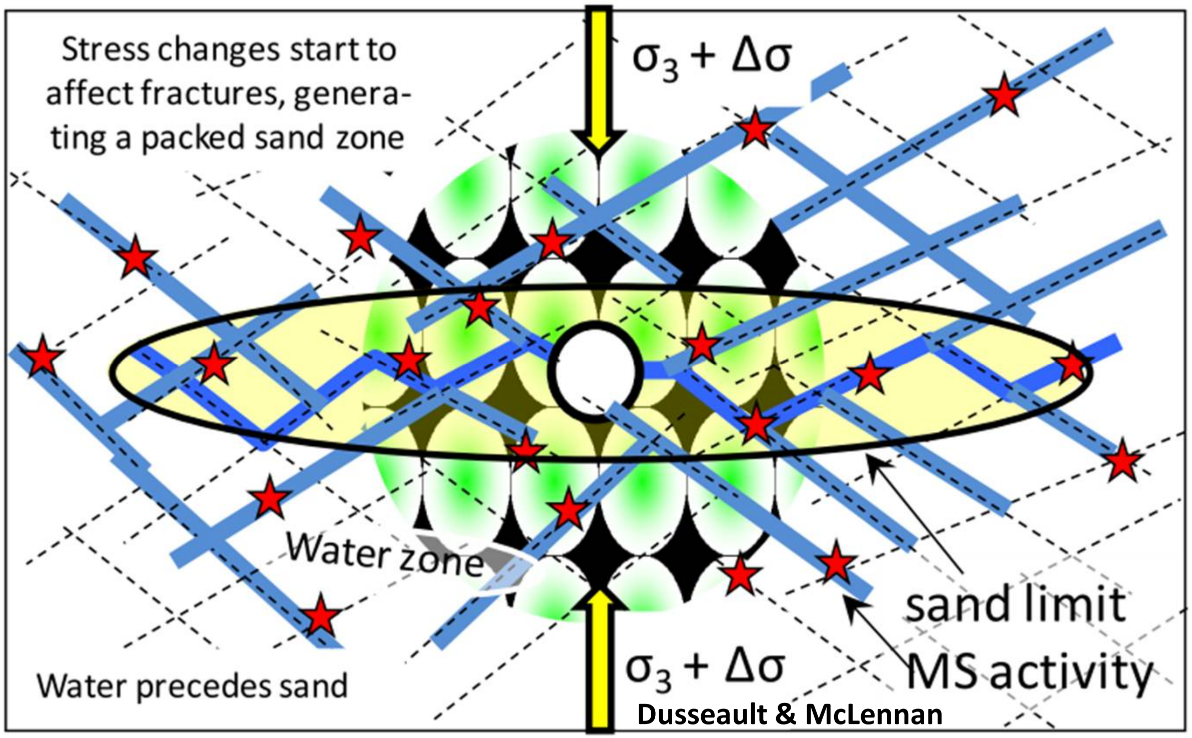
$$j = \frac{\sigma_n V_m}{\sigma_n - K_{ni} V_m}$$



OUTLINE

- ☐ Introduction: Unconventional Reservoir
- ☐ Natural Fractures Network
- ☐ Hydraulic Fracturing Modeling
- ☐ Proppant and Fracture Closure Model
- ☐ **HF Validation: Microseismicity**
- ☐ Final Remarks

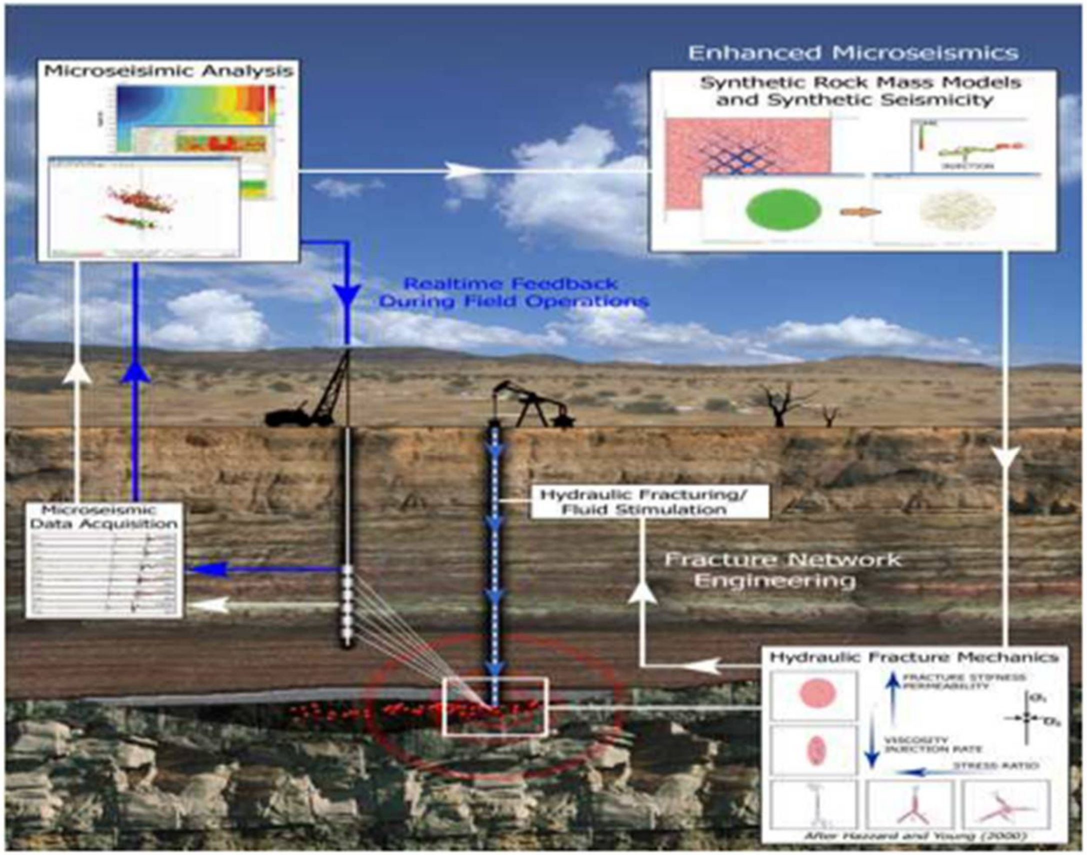
Massive Multi-Stage Hydraulic Fracturing



Stimulated Zone generated by MMSHF

- **Pore pressures travel far beyond the propped zone**
- **Changes of stress**
- **MS activity**

Massive Multi-Stage Hydraulic Fracturing Monitoring



Fracture Network Engineering applied to hydraulic fracturing.

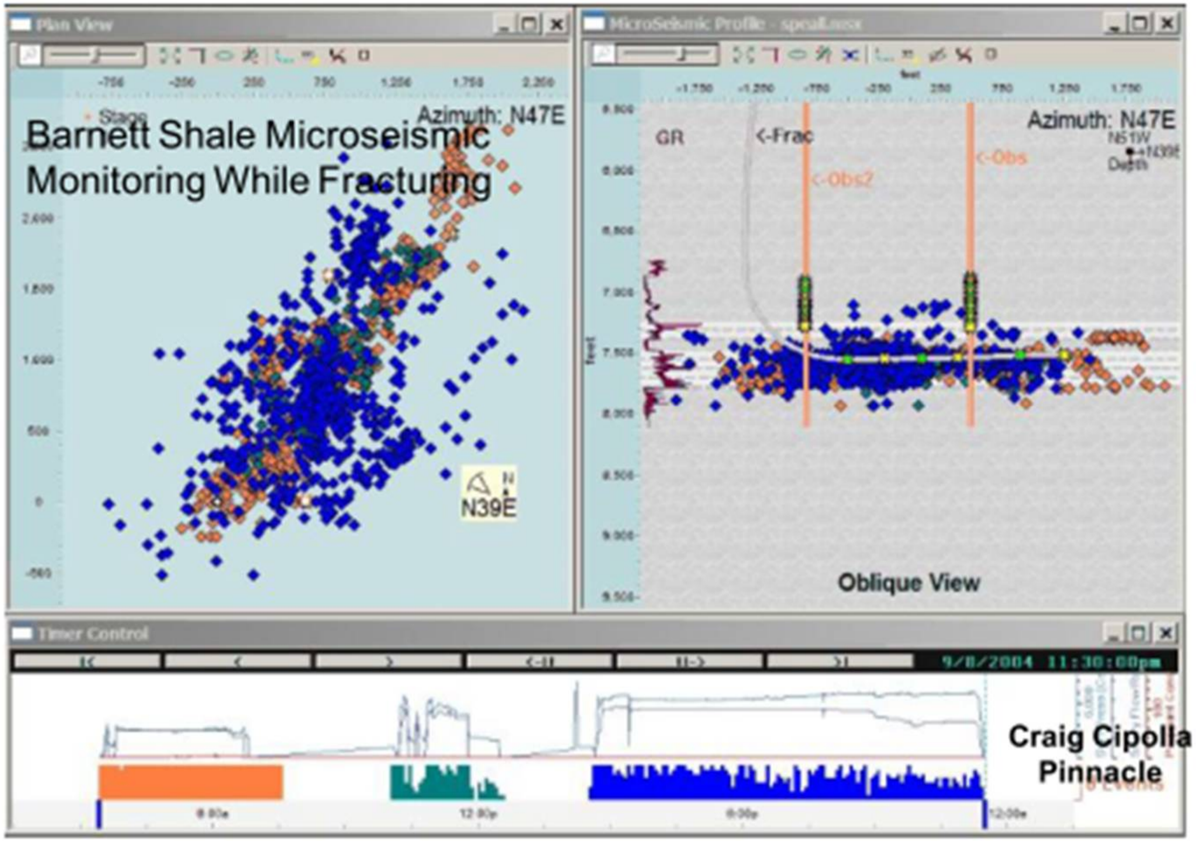
Nagel et al., 2011

SPE 140480

Microseismic monitoring:

Shows the spatial distribution and magnitude of seismicity associated with bedding plane slip as well as slip of natural and incipient fractures

Effective monitoring of hydraulic fracturing stimulations is critical to their optimization, and the evaluation of field microseismic data is now commonly used in many of the active shale



Unconnected natural fractures can be reactivated during HF process

Over estimation of
Stimulated Reservoir Volume (SRV).
Geomechanical modeling can
help in the interpretation of the MS data

Massive Multi-Stage Hydraulic Fracturing Mathematical Modeling

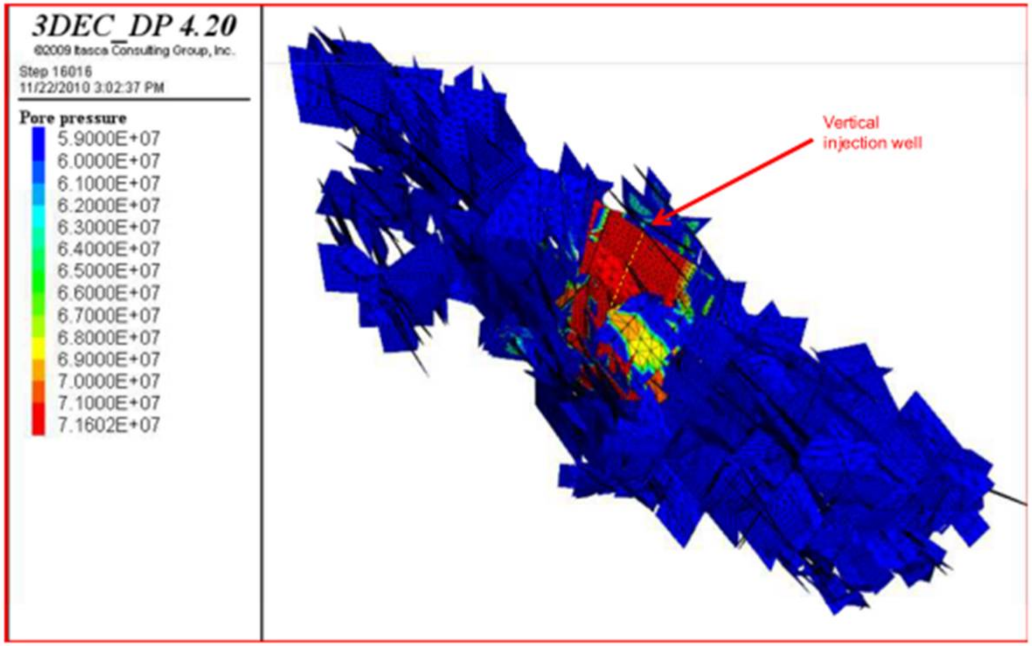
UFPE

SPE 140480

Simulating Hydraulic Fracturing in Real Fractured Rock - Overcoming the Limits of Pseudo3D Models

Neal Nagel, Ivan Gil, and Marisela Sanchez-Nagel, SPE, Itasca Houston, Inc., Branko Damjanac, Itasca Consulting Group, Inc.

SPE International



Pore pressure distribution

Three-Dimensional DEM Simulation of Hydraulic Injection into a Fractured Medium

Discrete element models (DEM), in which both matrix block behavior and fracture behavior are explicitly modeled, offer one option for the specific modeling of hydraulic fracture creation and growth in naturally fractured formation without, for example, the assumption of bi-planar fracture growth.

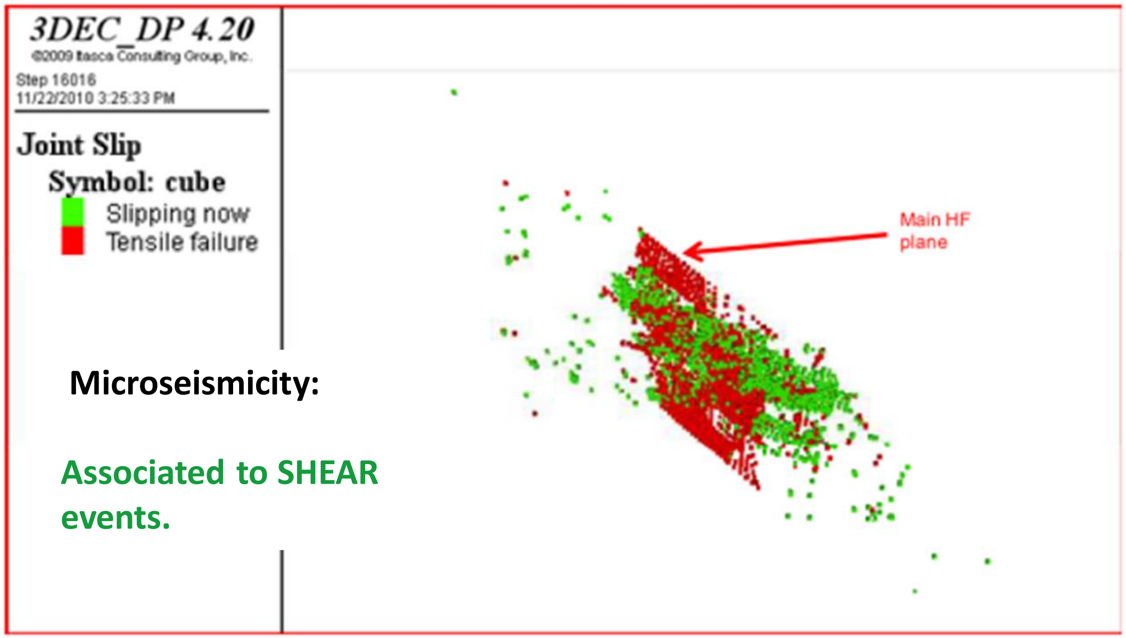
Massive Multi-Stage Hydraulic Fracturing Mathematical Modeling

UFPE

SPE 140480

Simulating Hydraulic Fracturing in Real Fractured Rock - Overcoming the Limits of Pseudo3D Models

Neal Nagel, Ivan Gil, and Marisela Sanchez-Nagel, SPE, Itasca Houston, Inc., Branko Damjanac, Itasca Consulting Group, Inc.



Three-Dimensional DEM Simulation of Hydraulic Injection into a Fractured Medium

<u>Shear and tensile failure were Identified.</u>

<u>Numerically computed shear events were associated with microseismicity</u>

Discrete element models (DEM), in which both matrix block behavior and fracture behavior are explicitly modeled, offer one option for the specific modeling of hydraulic fracture creation and growth in naturally fractured formation without, for example, the assumption of bi-planar fracture growth.

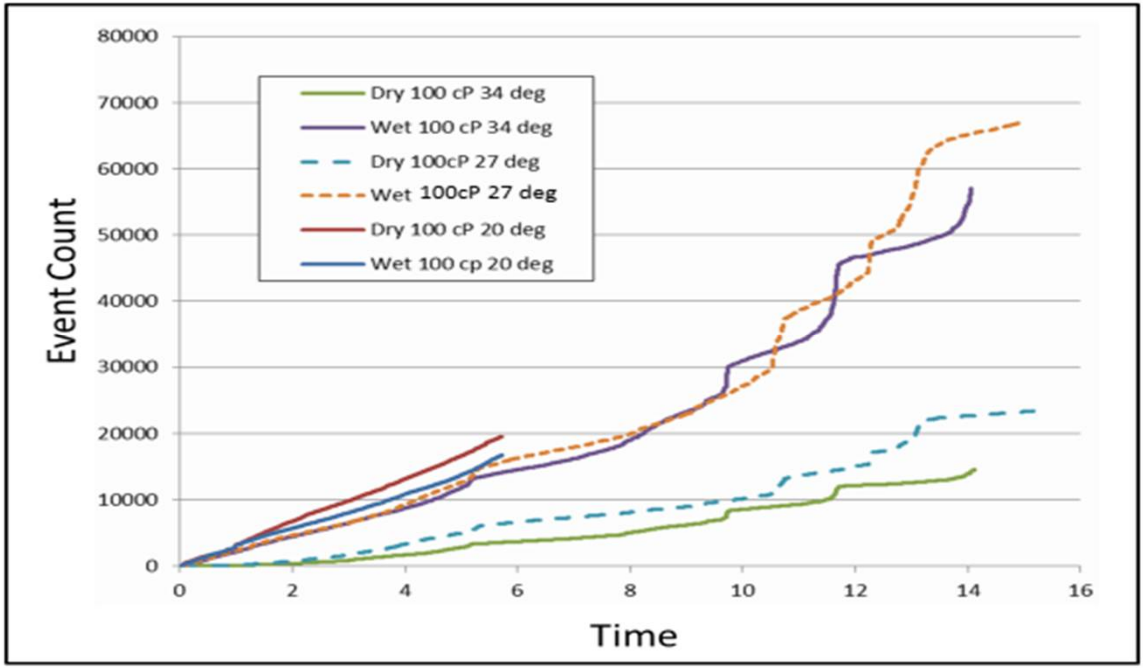
Massive Multi-Stage Hydraulic Fracturing Mathematical Modeling

UFPE

SPE 140480

Simulating Hydraulic Fracturing in Real Fractured Rock - Overcoming the Limits of Pseudo3D Models

Neal Nagel, Ivan Gil, and Marisela Sanchez-Nagel, SPE, Itasca Houston, Inc., Branko Damjanac, Itasca Consulting Group, Inc.



Cumulative event count versus time for the variable friction angles.

The lower the friction angle, the more dry events were recorded, with a significant jump between the 27 degree and 20 degree cases.

- Rock failure - the cause of microseismicity - is a result of changes in the in-situ effective stresses relative to a given rock strength.

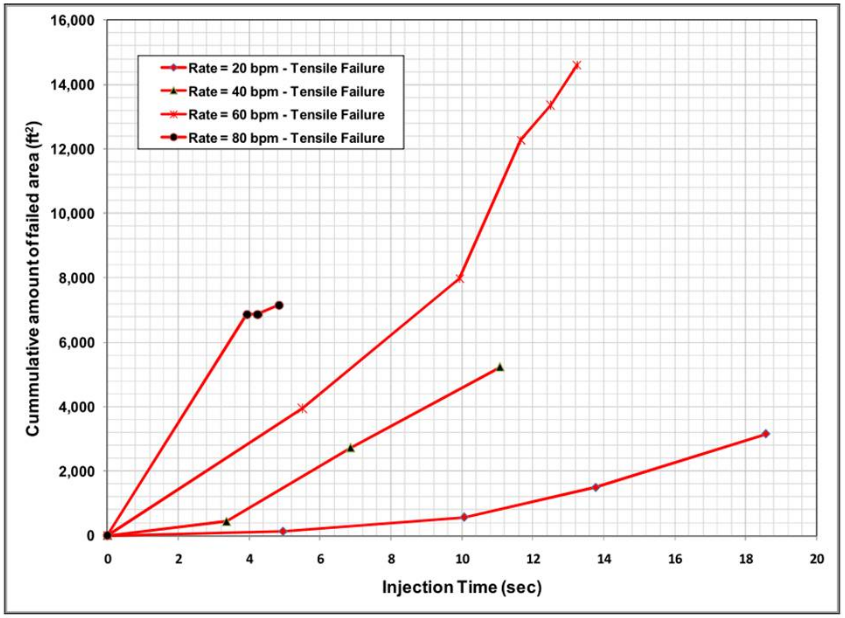
- Effective stress - which is the stress acting on the rock matrix - may change either through a change in pore pressure (leading to 'wet' microseismicity) or through a change in the total stress (leading to 'dry' microseismicity).

- Dry microseismicity may occur beyond the pressure field and be hydraulically disconnected from the wellbore.

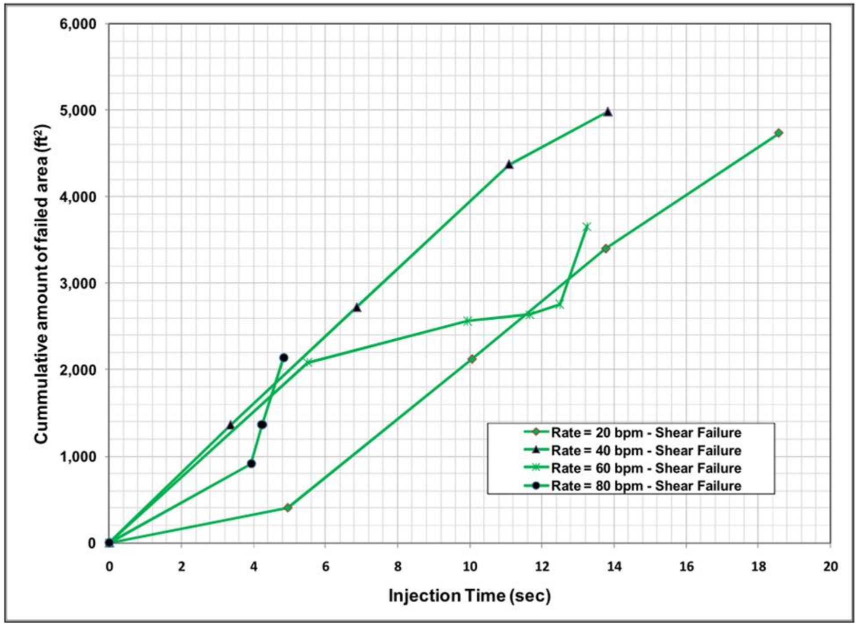
Massive Multi-Stage Hydraulic Fracturing Mathematical Modeling

UFPE

Changes in injection rate showed a clear effect on the amount of tensile failure being triggered as a result of injection. Increases in injection rate greatly increased the amount of tensile failure within the model. These results were somewhat expected as higher injection rates, translate into higher injection pressures and more energy available for rock failure near the injection well. Furthermore, the results suggested that lower injection rates favored the creation of shear failure. Despite the short time scale of these simulations, this behavior suggests the very interesting possibility of using injection rate as a parameter to actively control the amount and type of failure to be generated during a fracturing job.



Effect of injection rate on tensile failure generation.



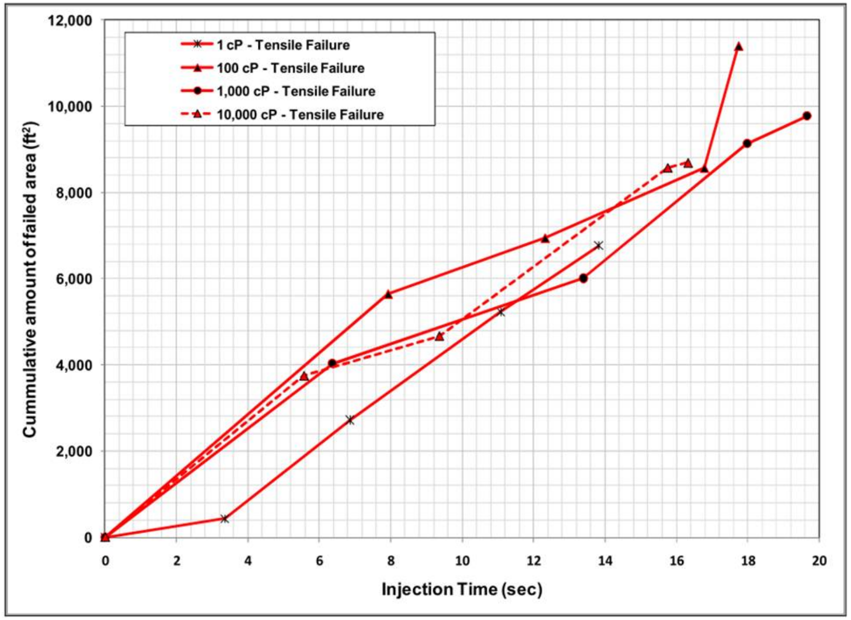
Effect of injection rate on shear failure generation.

Nagel et al., 2011 SPE 140480

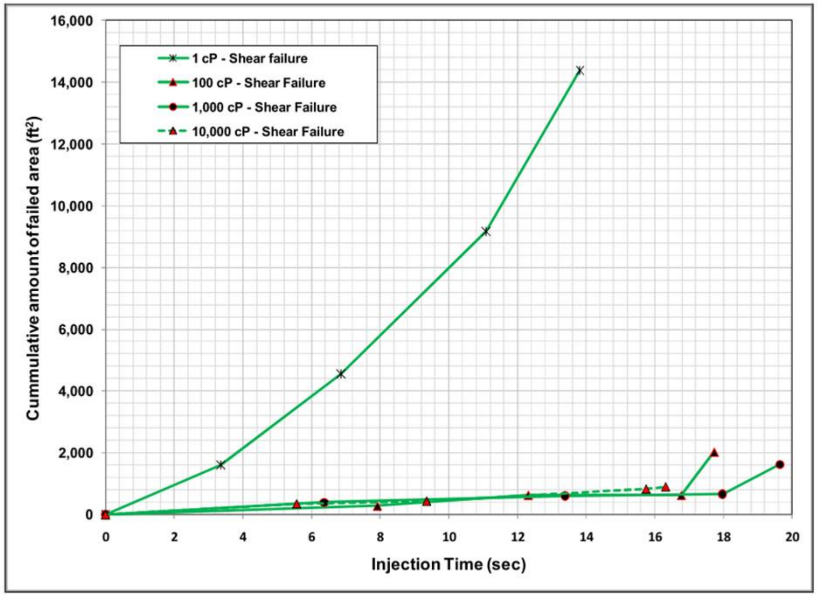
Massive Multi-Stage Hydraulic Fracturing Mathematical Modeling

UFPE

The amount of shear failure generated as a result of fluid injection showed a very distinct response to changes in fluid viscosity. In the case where low viscosity fluid ($\mu = 1$ cP) was injected, the amount of area failing in shear was dramatically higher than in the cases with higher viscosity fluids ($\mu > 100$ cP). Moreover, such difference appears to increase even more with time. When the ratio of shear to tensile areas was plotted as a function of time, a similar picture emerged: the ratio of shear to tensile area being generated for the case with low viscosity was about an order of magnitude higher than in the cases with high viscosity fluids. Once again, and despite the short scale of the simulation run here, this results suggest that fluid viscosity has the potential to change the way a reservoir reacts (and fails) when subjected to fluid injection.



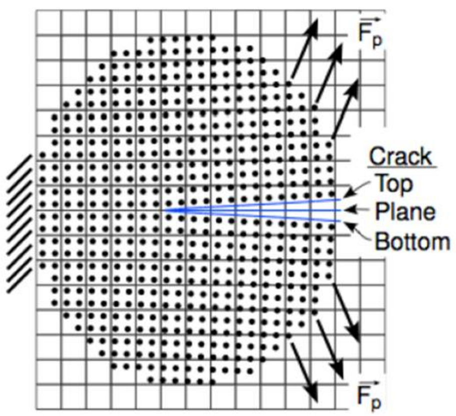
Effect of injected fluid viscosity on tensile failure generation.



Effect of injected fluid viscosity on shear failure generation.

Nagel et al., 2011 **SPE 140480**

Massive Multi-Stage Hydraulic Fracturing Validation



(2015)

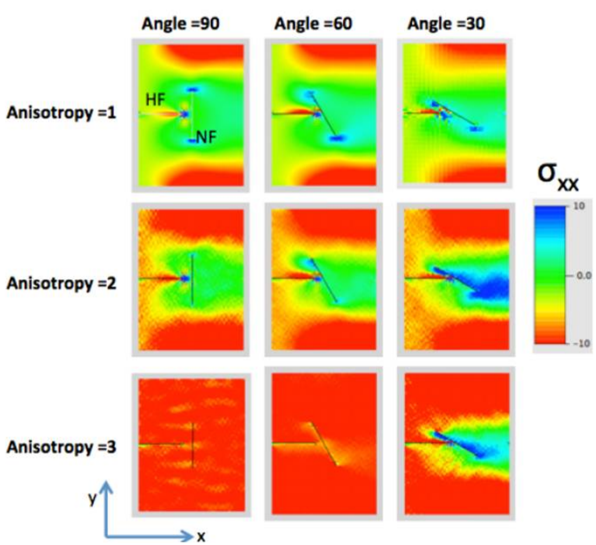
UNCONVENTIONAL RESOURCES TECHNOLOGY CONFERENCE FUELED BY SPE • AAPG • SEG

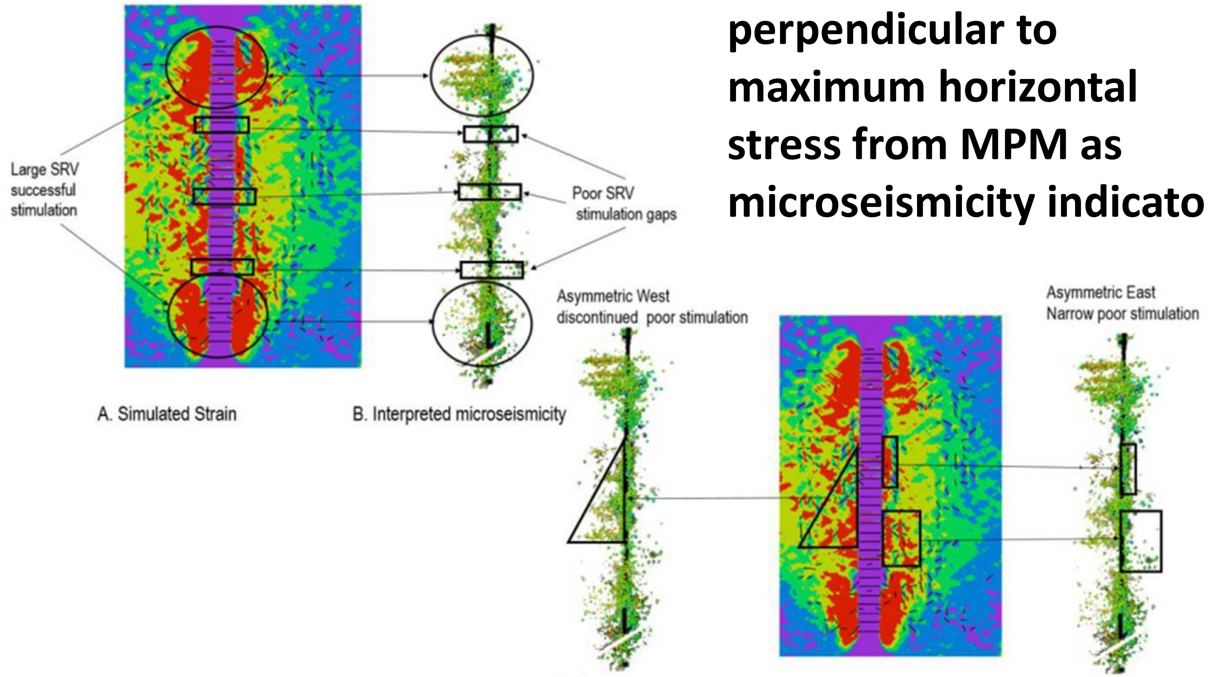
URTeC 2173459

Using Geomechanical Modeling to Quantify the Impact of Natural Fractures on Well Performance and Microseismicity: Application to the Wolfcamp, Permian Basin

A. Ouenes*, N. Umholtz, FracGeo, Y. Aimene, Oregon State University

Material Point Method (MPM)





Validation using strain perpendicular to maximum horizontal stress from MPM as microseismicity indicator.

OUTLINE

- Introduction: Unconventional Reservoir
- Natural Fractures Network
- Hydraulic Fracturing Modeling
- Proppant and Fracture Closure Model
- HF Validation: Microseismicity
- **Final Remarks**

FINAL REMARKS

- ➔ Strong coupling between fluid flow and deformations (Coupled HM Problem).
- ➔ A strong impact of the natural fractures and initial stress state (with many uncertainties about both).
- ➔ Natural fracture network must be represented into the numerical model.
- ➔ Packing of proppant into fractures, with the liquid propagating far beyond the sand zone.
- ➔ Models for proppant migration and fracture closure with proppant are needed.
- ➔ Evaluation of field microseismic data is now commonly used to monitor hydraulic fracturing stimulations (validation of the geomechanical model).
- ➔ Validation of MMHF (Massive Multi-Stage Hydraulic Fracturing) at field scale is still a challenge.