# Simultaneous initiation and propagation of multiple hydraulic fractures from a horizontal well

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CFMR – Oct. 16, 2014

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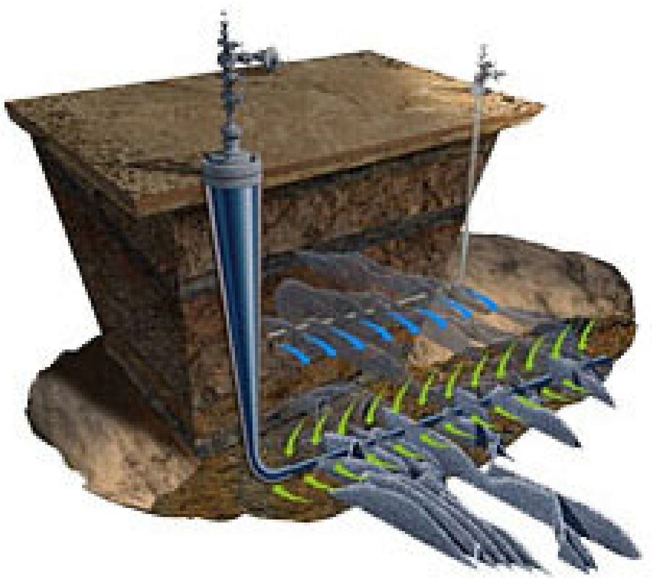
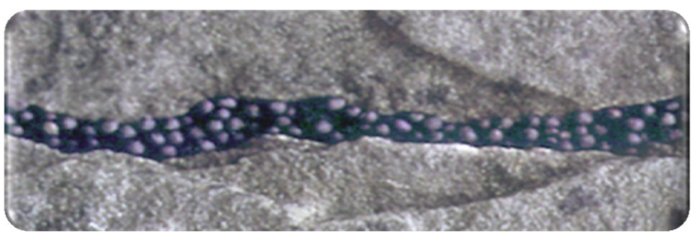


*Producing nanoD reservoirs through a series of high conductivity channels.*



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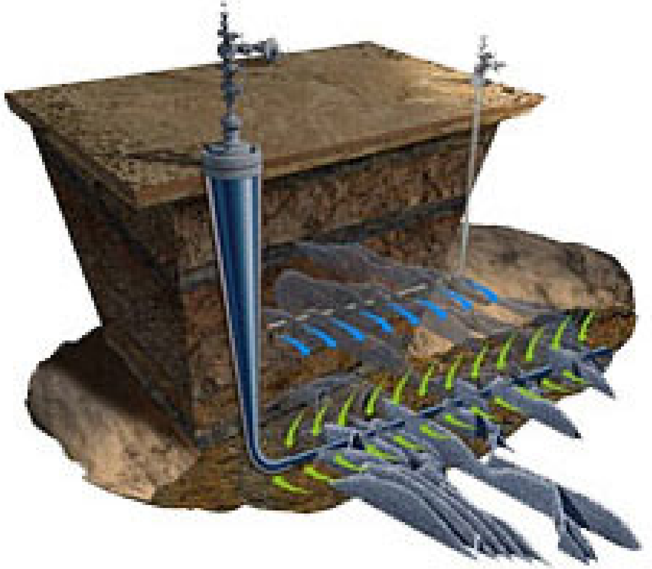
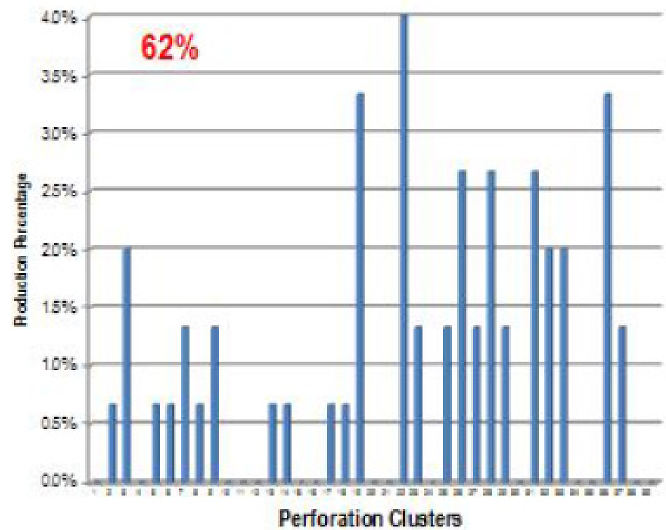
# Poor production distribution between fractures



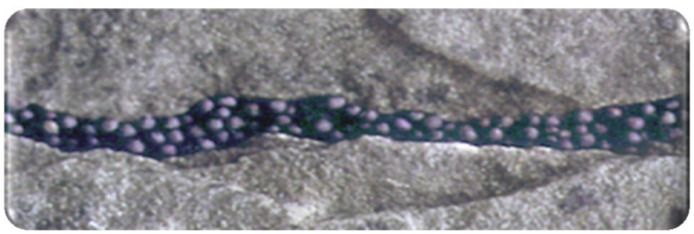
**~30-40% of fractures**
**are found not producing at all!**

Miller et al. 2011 (across US basins), Slocombe et al. 2013 (Eagleford Consortium), Noble Underground Lab. 2014 (Niobrara) etc.




Slocombe et al. SPE 166242

*Producing nanoD reservoirs through*
*a series of high conductivity channels.*

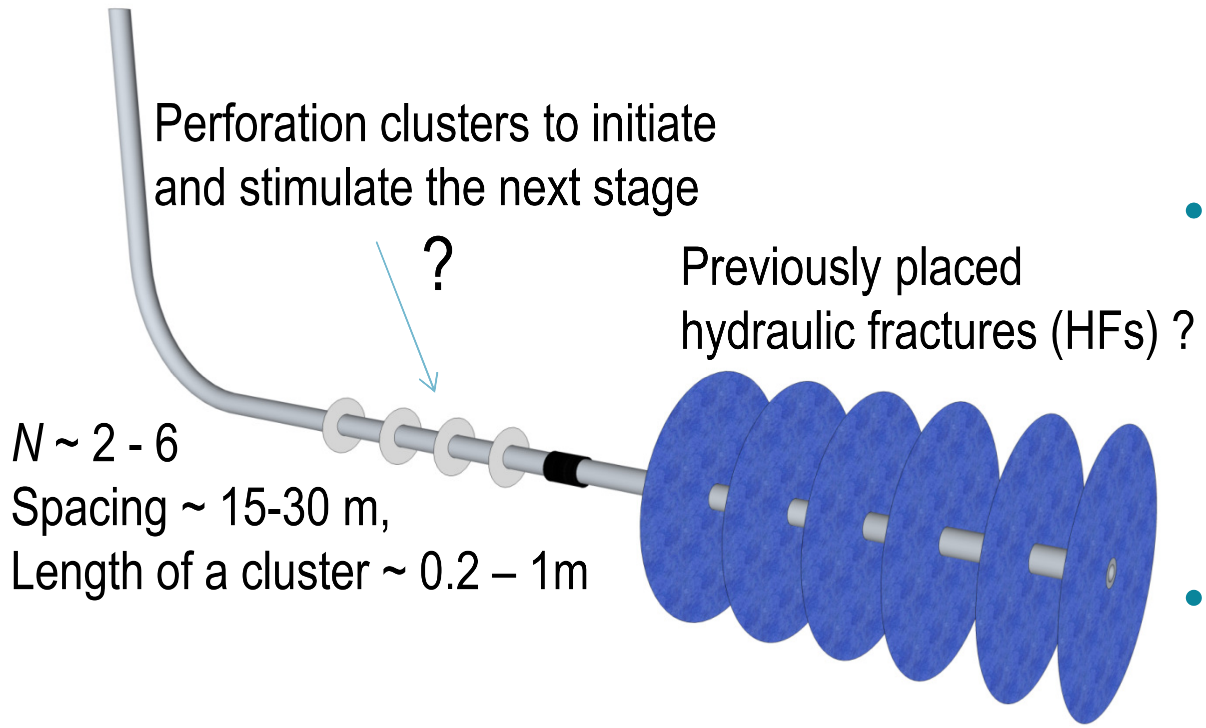


Is it just all about heterogeneities in reservoir quality?
Are there any inefficiencies intrinsic to the completion technique?

# “Plug & perf” multistage fracturing

## *a trade off between completion efficiency & rig time*

Propagate *N* hydraulic fractures (HFs) simultaneously




## During one stage:

- Pump bridge plug & perforation guns
  - Perforate N clusters
  - Retrieve guns
- Pump fracture treatment
  - Pad (i.e. clear fluid)
  - Add proppant

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# Why radial ?

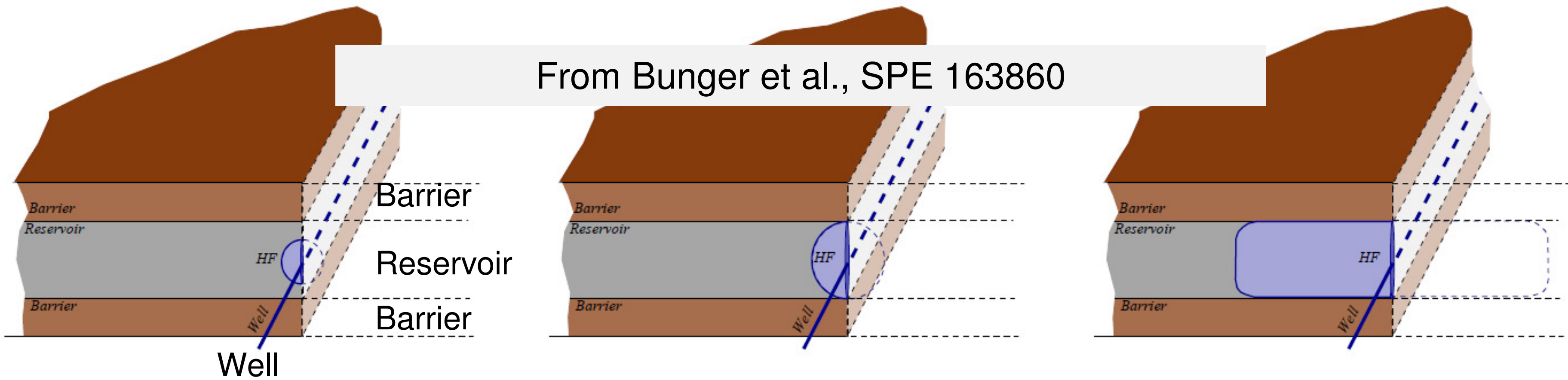


**Fig. 1**: Sketch of growth progression from radial to PKN geometry for a height constrained hydraulic fracture growing transverse to a horizontal well.

It is the most likely early stage geometry.

We're going to look at the flux at the end of the radial stage:

- flux at the end of the fluid pad, when proppant starts to enter
- Proxy for how much proppant will enter the fracture

E.g. if I design for 20 BPM and only 10 BPM enters the fracture, I only get half the proppant in that fracture…

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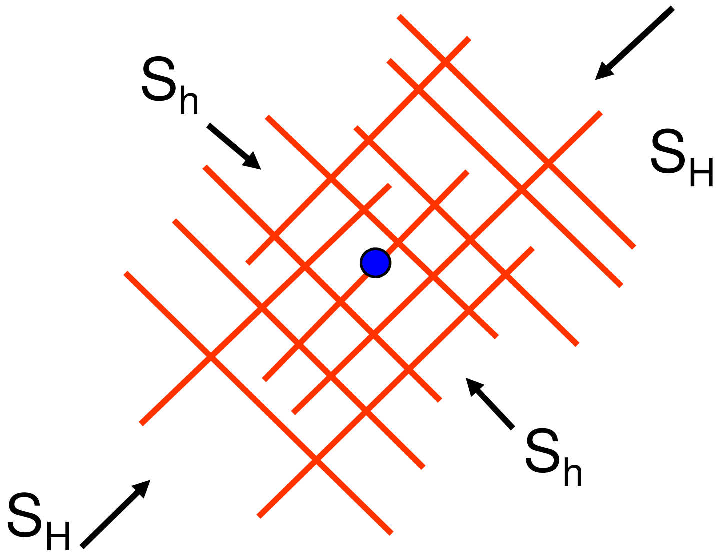
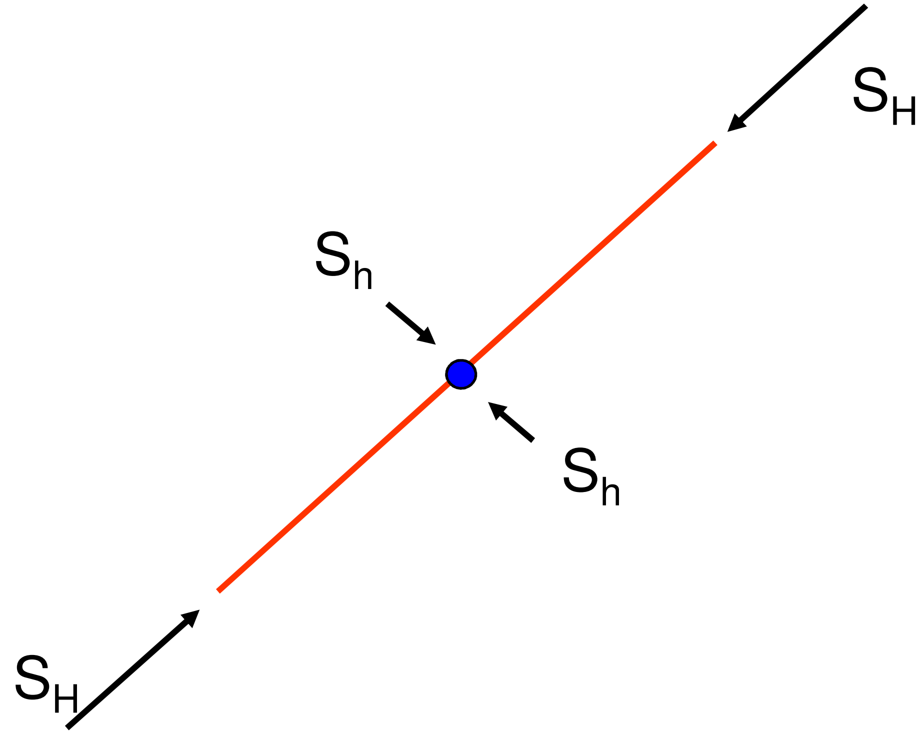
# Why Planar ?




- Low horizontal differential stress
- Wide fracture fairway

**e.g. Barnett shale $S_h \sim S_H$**




- Some horizontal differential stress (>2MPa)
- Planar fracture

**Most of the other play $S_h < S_H$**

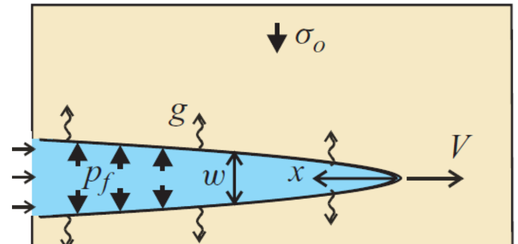
The stresses ultimately dictates the complexity of the created fracture(s)

# Hydraulic fracture mechanics – in a nutshell

Fracture surface creation

Fluid flow

Solid deformation




[Garagash et al., 2011]

- Mass balance: injected fluid = storage + leakoff
- Energy balance:

$$P_{\text{Input}} = \underbrace{\dot{U}_{\text{strain ener.}}}_{\textit{stored in the rock}} + \overbrace{Q_o \sigma_o}^{\textit{In-situ stress}} + \overbrace{\underbrace{D_{\text{Viscous}}}_{\text{Frac.+WB+Perf}} + D_{\text{Frac.}}}^{\textit{Dissipations}}$$

Very different propagation regimes depending on the dominant mechanisms (e.g. Viscosity vs Toughness)

[e.g. Detournay, 2004; Garagash 2000, 2009]

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# A non-local, highly non-linear, time-dependent, moving boundary problem

- Elasticity

$$p(x,y) - \sigma_o(x,y) = \int_{\Omega_c} G(x,y;\xi,\eta)w(\xi,\eta)\ \mathrm{d}\xi\ \mathrm{d}\eta$$

- Fluid continuity

$$\frac{\partial w}{\partial t} + \nabla \cdot \mathbf{q} + g_L = Q_{in}(t)\delta(x,y)$$

- Poiseuille's law

$$\mathbf{q} = -\frac{w^3}{\mu'}\nabla p \qquad (\mu' = 12\mu)$$

- Leak-off

$$g_L = 2C_l/\sqrt{t - t_o(x,y)}$$

- Boundary conditions

$$w = 0,\ q_n = 0 \text{ on } \Gamma_c$$

- Fracture Propagation (mode I)

inner lefm asymptote $\hat{x} \ll \ell_{mk}$

$$w = \frac{K'}{E'}\hat{x}^{1/2}$$

$$(K' = 4\sqrt{2/\pi}K_{Ic})$$

outer viscosity asymptote $\hat{x} \ll \ell_{mk}$

$$w = \left(\frac{V\mu'}{E'}\right)^{1/3}\hat{x}^{2/3}$$

$$\ell_{mk} = K'^6/(E'^4\mu'^2V^2)$$

Assumption of zero fluid lag valid for

$$\frac{K'\sigma_o^{1/2}}{E'V^{1/2}\mu'^{1/2}} > 1$$

[Garagash & Detournay, 2000]

[Desroches et al. 1993; Garagash et al.,2000, 2011; Bunger & Detournay 2008]

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# Hydraulic fracture initiation

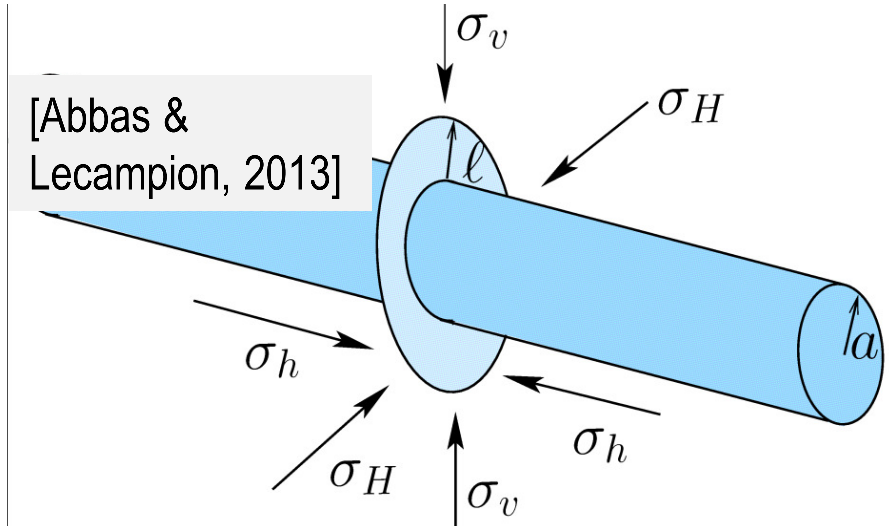
- Initiation from a pre-existing notch using linear elastic fracture mechanics
  [see e.g. Lecampion, 2012; Sarris & Papanastasiou 2012 for cohesive zone models]
- Effect of wellbore storage during pressurization

$$Q_o - \sum_{I=1,N} Q_I = (c_f V_b)\frac{\partial p}{\partial t}$$

- Perforation friction at the wellbore-fracture connection:

$$\Delta p_I = f_p \times Q_I^2$$

- Influence of rate & fluid viscosity on initiation and maximum pressures
  [e.g. Haimson & Fairhust, 1969; Zhao, 1995; Garagash 1998, Lhomme 2005 etc.]




[Abbas & Lecampion, 2013]

Simulator [Lecampion & Desroches, 2014]

- Implicit scheme – strong full coupling
- Displacement Discontinuity Method
- Finite Volume scheme
- Implicit level set using HF asymptotics
- Multiple hydraulic fractures
- Coupled with wellbore dynamics

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# Single Hydraulic Fracture Initiation

*theory vs experiments*

- Cement Properties

$E' = 24.1$ GPa, $K_{Ic} = 0.5$ MPa.m$^{1/2}$

$C_l = 6\ 10^{-5}$ m.s$^{1/2,}$ $L_o = 0.8$ mm

- Test Parameters

$\mu = 130$ Pa.s, $Q_o = 0.2$ cc/min

$\sigma_o = 10$ MPa

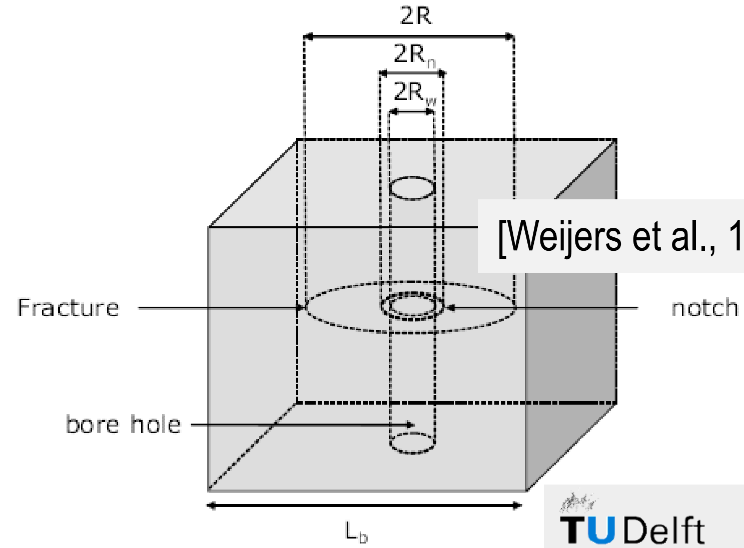
Borehole friction (disp. transducer)

0.45 MPa at designed rate

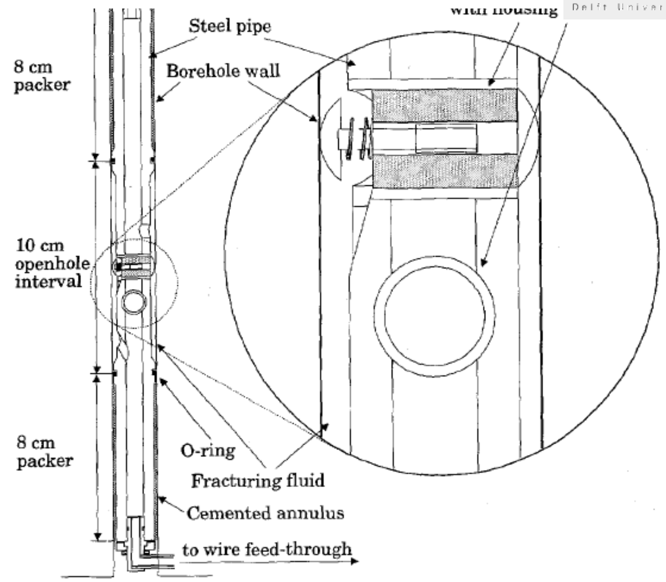
- Measurements

Pressure, wellbore width

Acoustic transmission for fracture footprint




[Weijers et al., 1995]




SPE 28561

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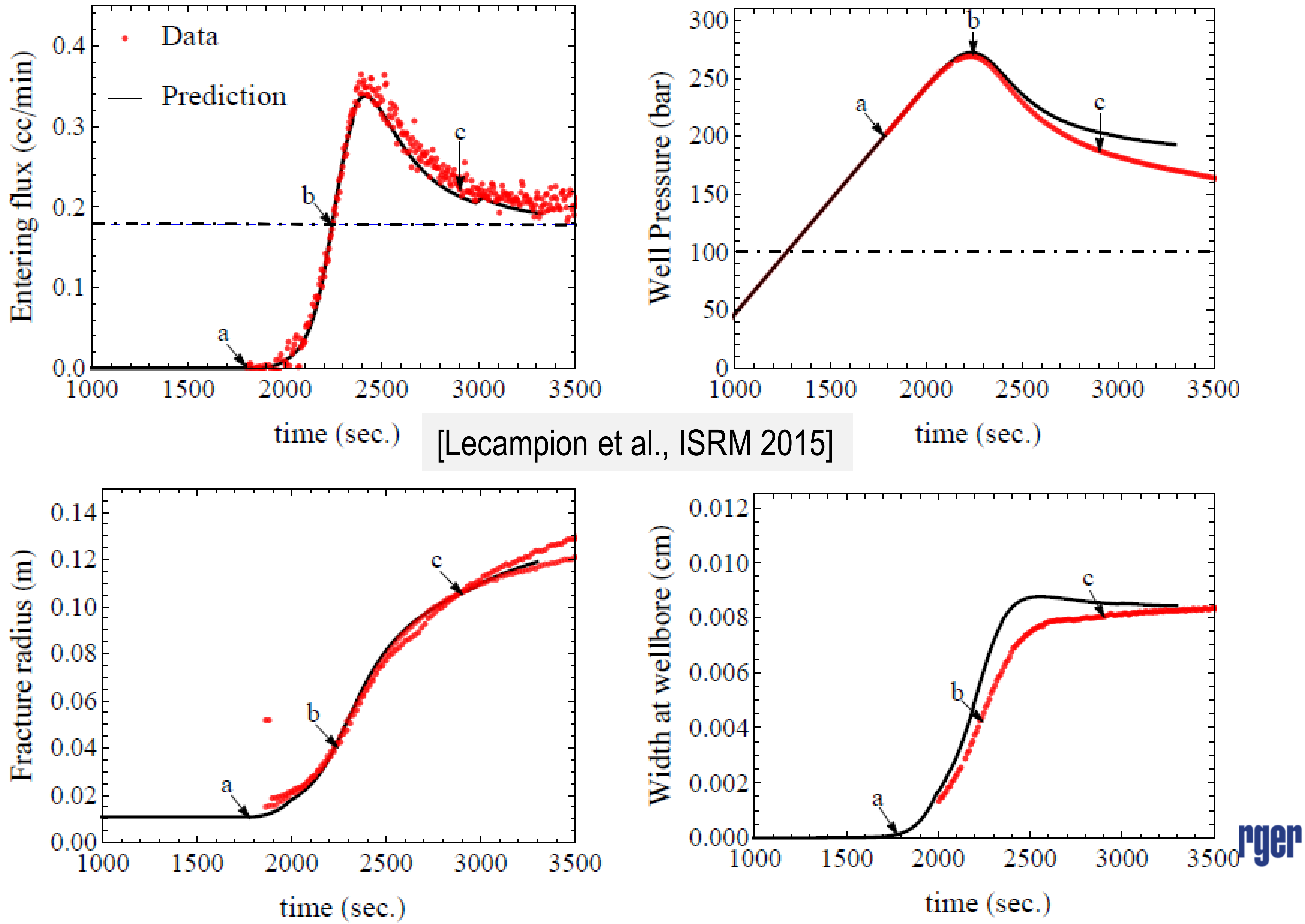
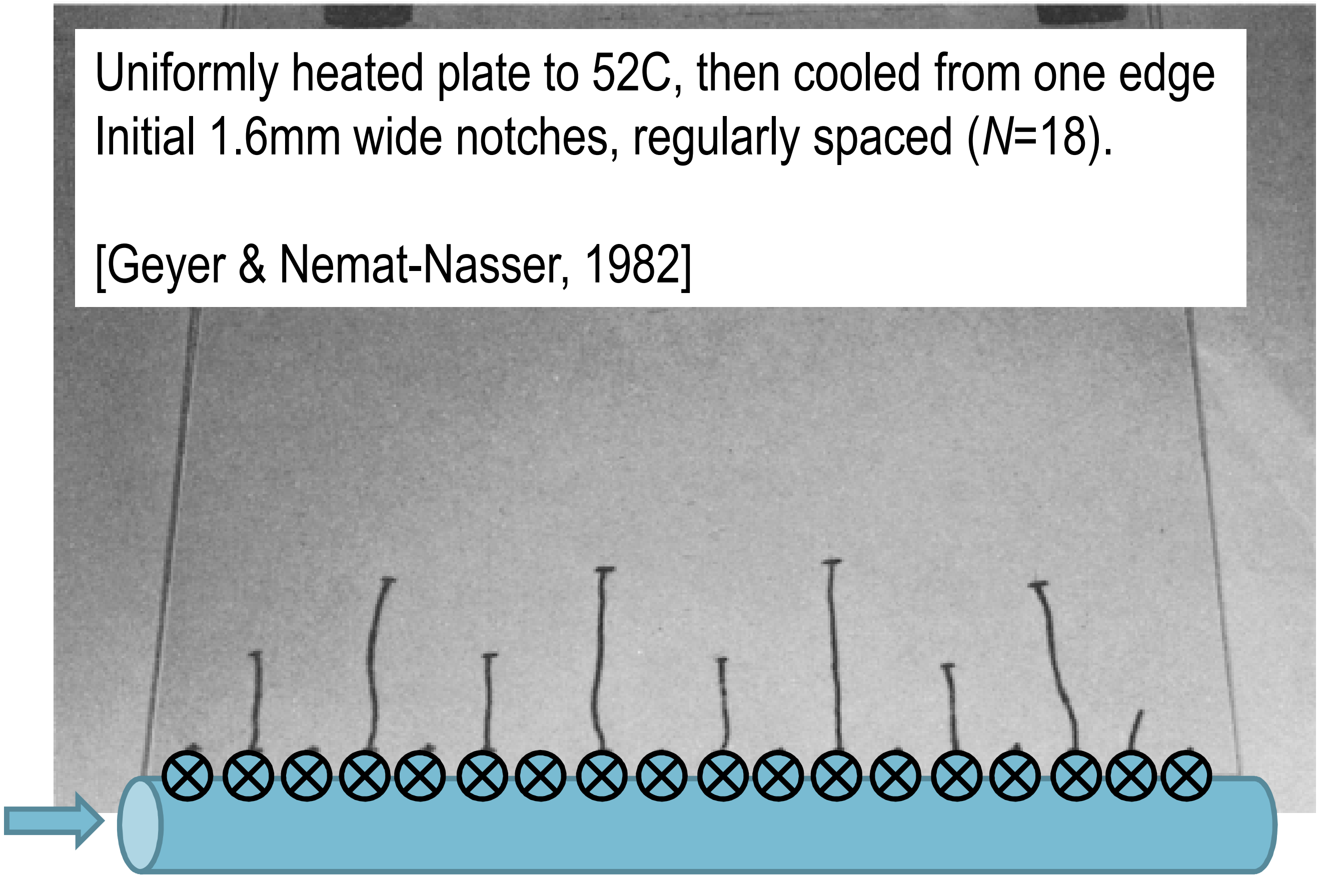
# *Theory vs experiments* – TU Delft cov12c experiment




[Lecampion et al., ISRM 2015]

# Multiple HFs growth – “Stress shadow” vs “limited entry”

**Growth of parallel (dry) cracks in glass**

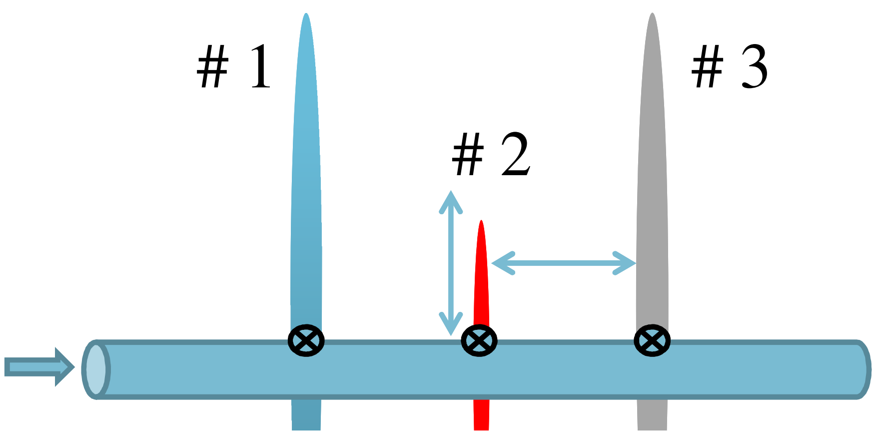



- Viscous forces may dampen the effect of stress interference
- Perforations at each fracture entrance (Bernouilli-like nozzles) will surely modify the system dynamics (limited entry). $\Delta p_I = f_p \times Q_I^2$

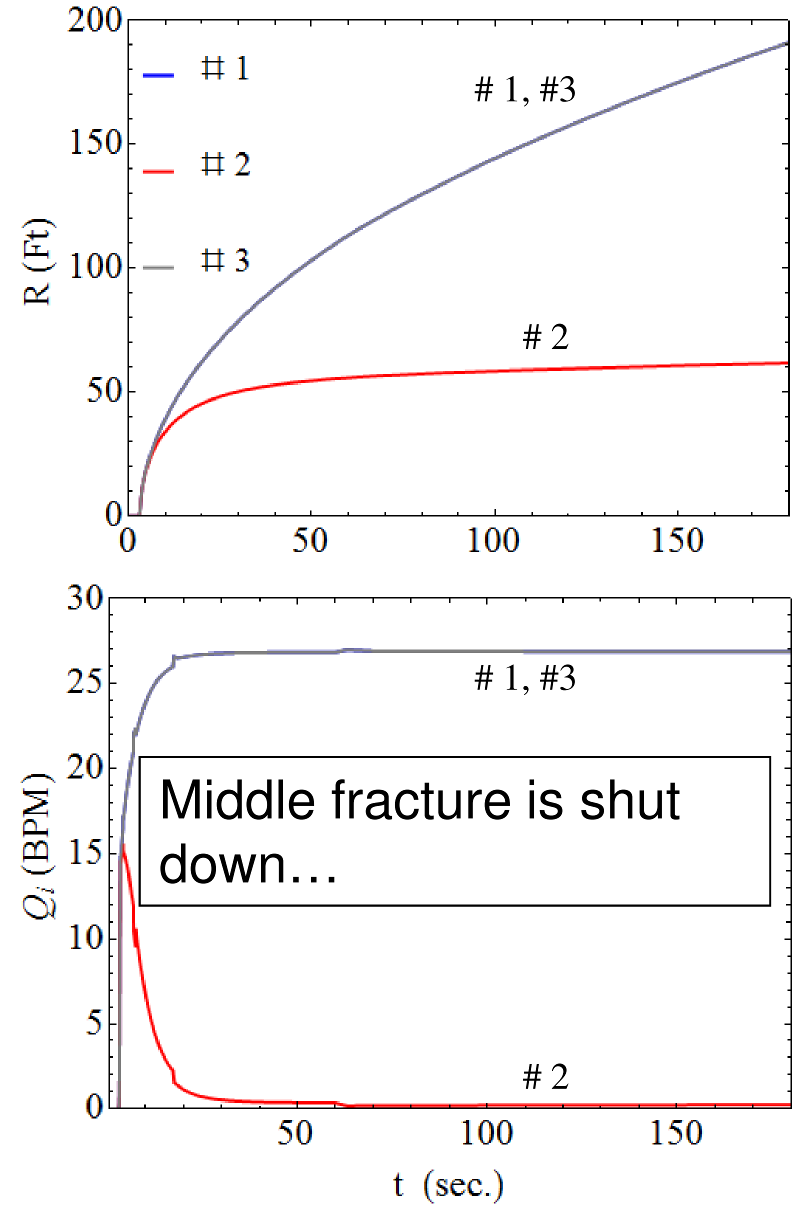
# "Stress Shadow" versus "Limited Entry"

Example of 3 fractures 50ft apart
**without perforation friction**

$$\Delta p_I = 0$$



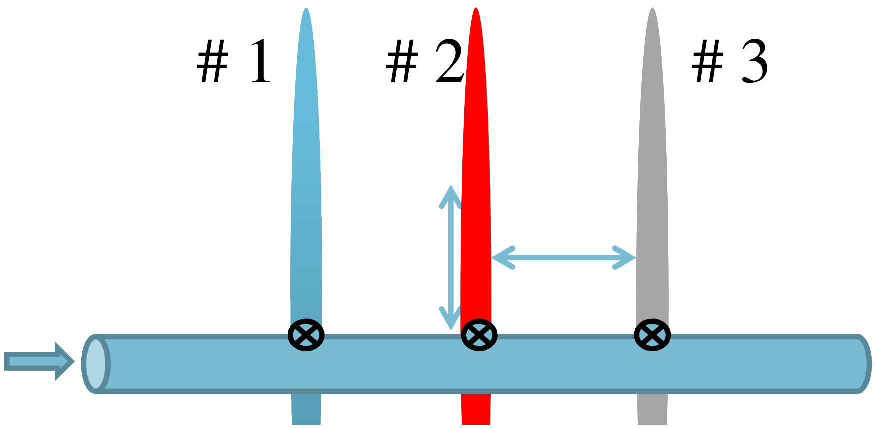

Kicks in when Spacing ≈ Height or Length



# "Stress Shadow" versus "Limited Entry"

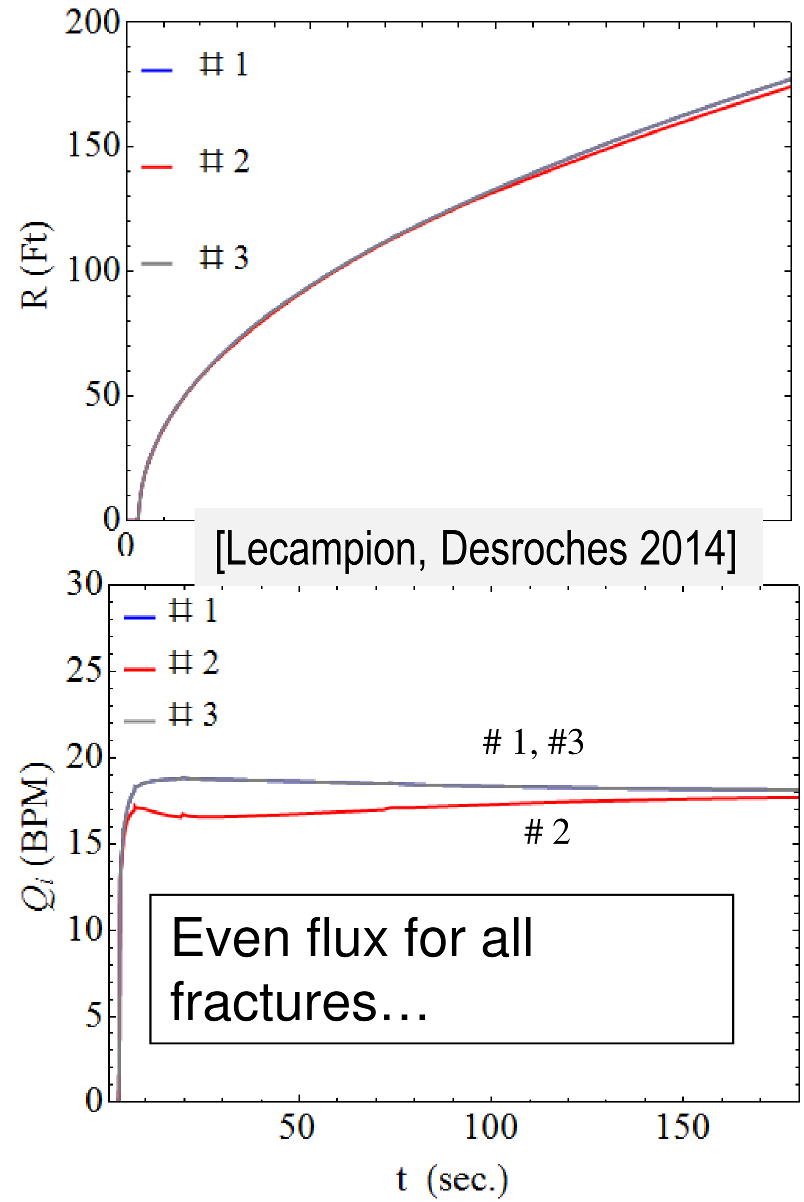
Example of 3 fractures 50ft apart
**with 200 psi perforation friction**

$\Delta p_I = 200 PSI$ at designed rate




Kicks in when Spacing ≈ Height or Length

$$\Gamma = \frac{\sigma_{Int}}{\Delta p_I}$$




[Lecampion, Desroches 2014]

# A ‘typical’ horizontal well: local variations of in-situ stresses

| $E$ | $\nu$ | $E' = \frac{E}{1-\nu^2}$ | $K_{Ic}$ |
|---|---|---|---|
| GPa (kPSI) | [-] | GPa (kPSI) | $MPa.\sqrt{m}$ ($PSI.\sqrt{Inch}$) |
| 25 (3625) | 0.2 | 26.04 (3777) | 1.2 (1092) |

- 7000ft TVD
- *N* = 4 fractures
- Spacing 50 ft
- Injection Rate 18BPM * 4 = 72 BPM
- Perforations:
  - ½” diameter
  - C=0.6 (discharge coef.)

In-situ stress heterogeneities on the different fractures

– 0.71 PSI/ft – 0.77 PSI/ft
– 0.74 PSI/ft – 0.8 PSI/ft

– 34 MPa – 37 MPa
– 35.6 MPa – 38 MPa

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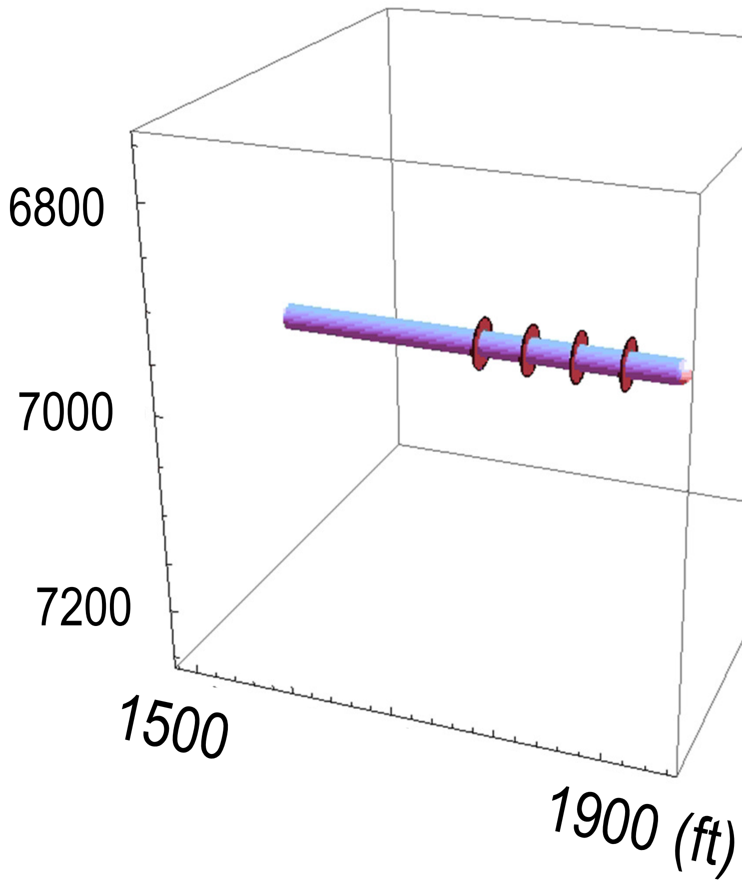
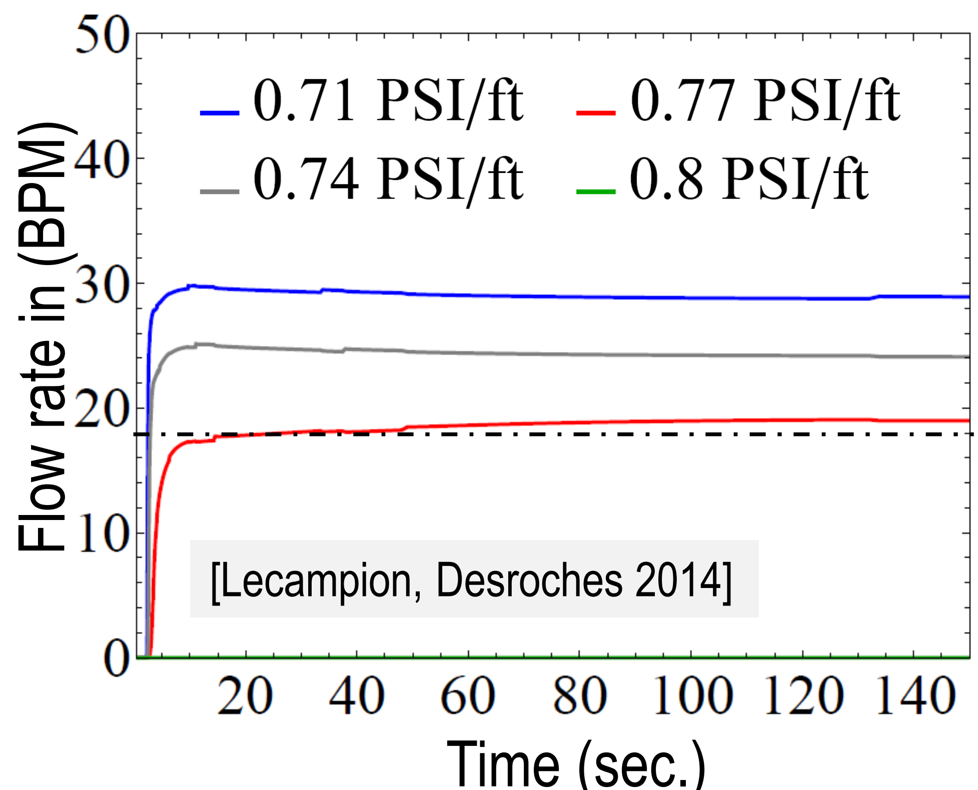
# What if you don't know the stress variation along the lateral?

<u>Uniform</u> perforation friction – **250psi pressure drop**

*a stage with 4 fractures with different in-situ stress (everything else uniform)*




4th fracture does NOT initiate!

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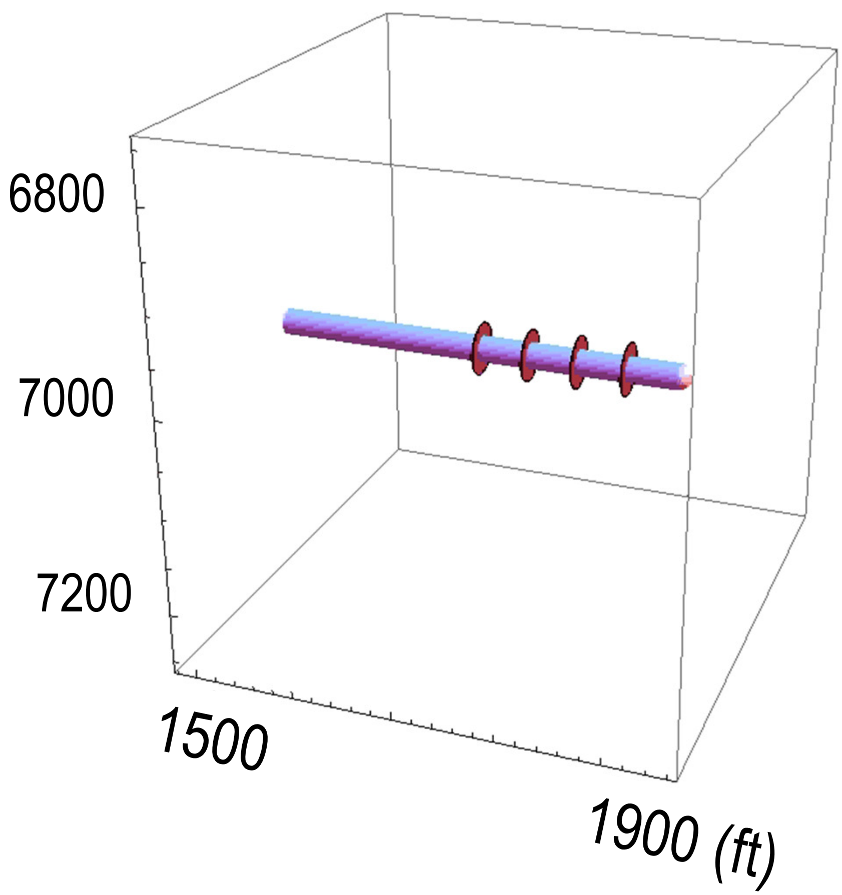
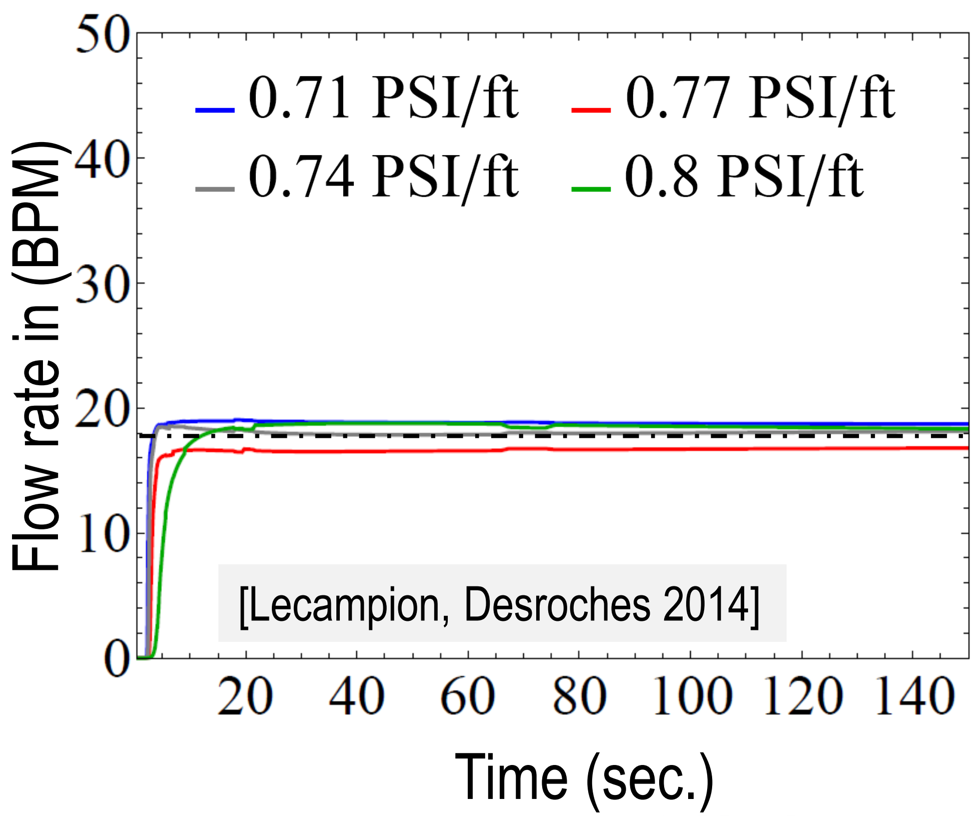
# Designing out the effect of stress heterogeneities?

<u>Engineered</u> perfs friction – choking down clusters with lower stress

*a stage with 4 fractures with different in-situ stress* *(everything else uniform)*

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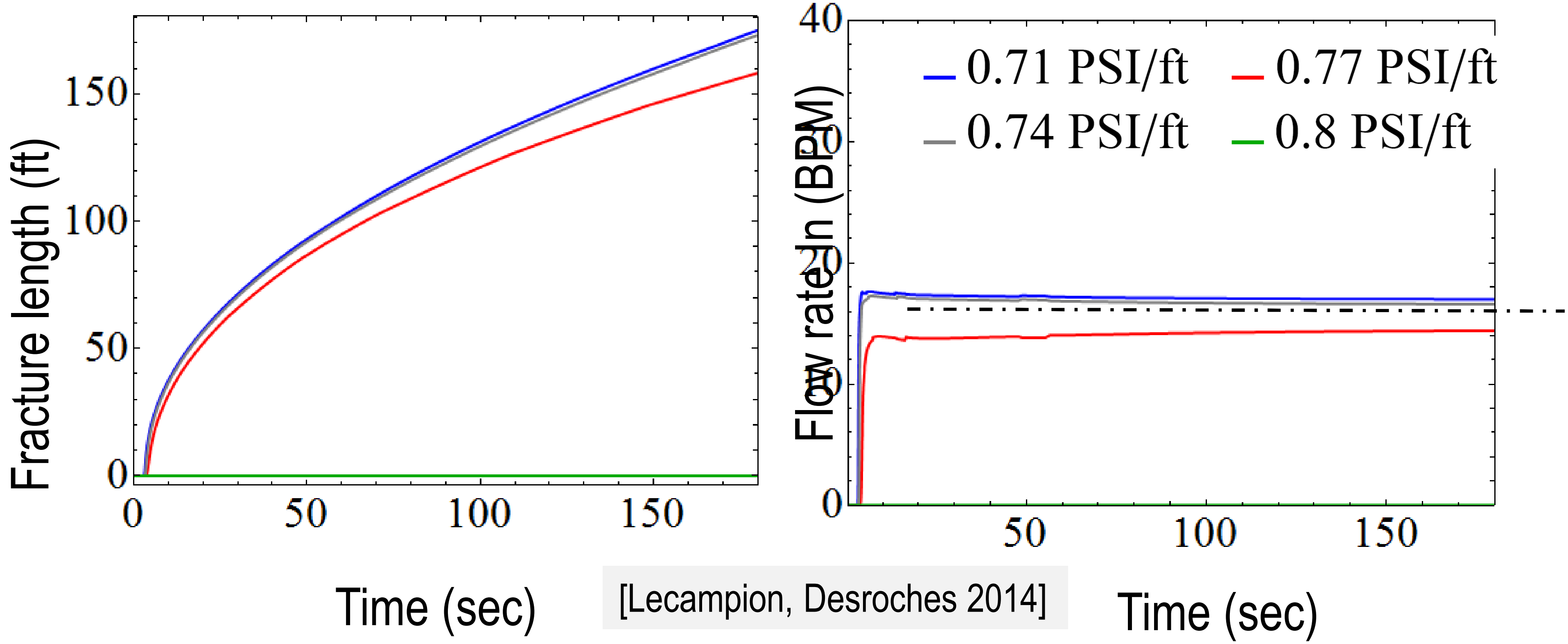
# This is not robust !

e.g. what if the surface rate is lower ? (Surface rate = 2/3 designed)

*a stage with 4 fractures with different in-situ stress (everything else uniform)*




[Lecampion, Desroches 2014]

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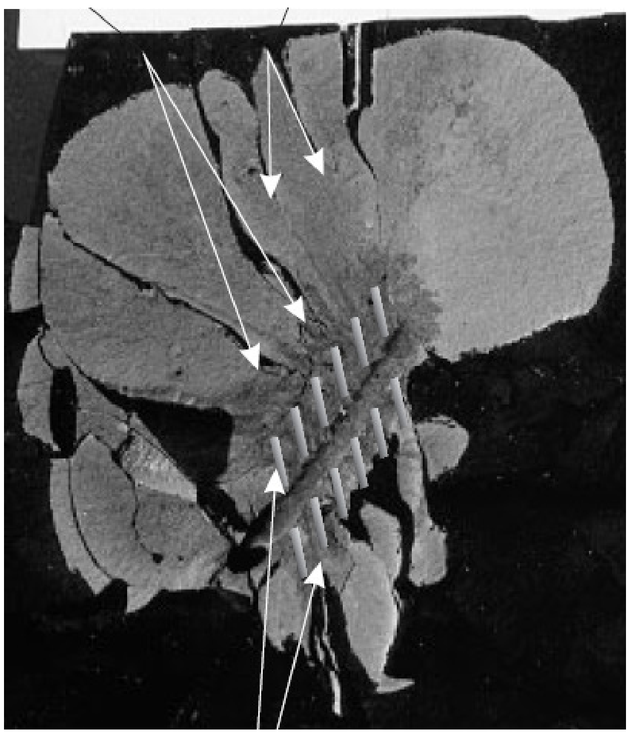
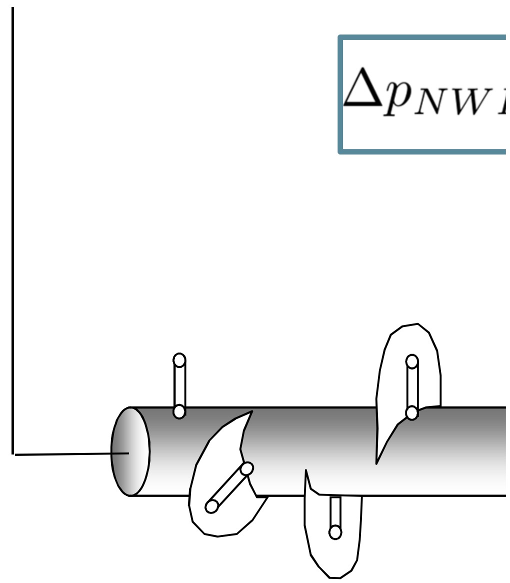
4th fracture does NOT initiate!

# It is even worse in practice: near wellbore fracture tortuosity



[Van der Ketterij et al., 1997 ]




i) Initiation of multiple fractures from the # perforations

ii) link-up to form a single fracture in the "far-field"

→ an extra near-wellbore pressure drop and an extra near-wellbore closure stress.

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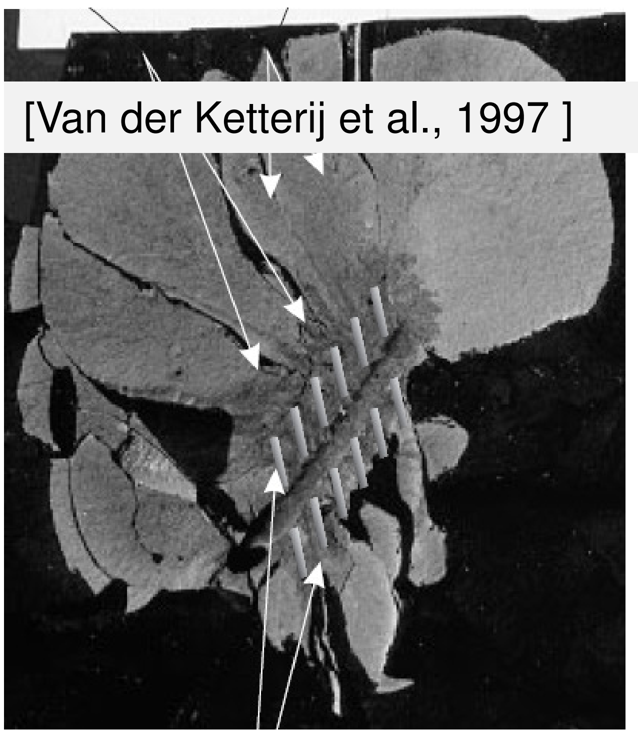
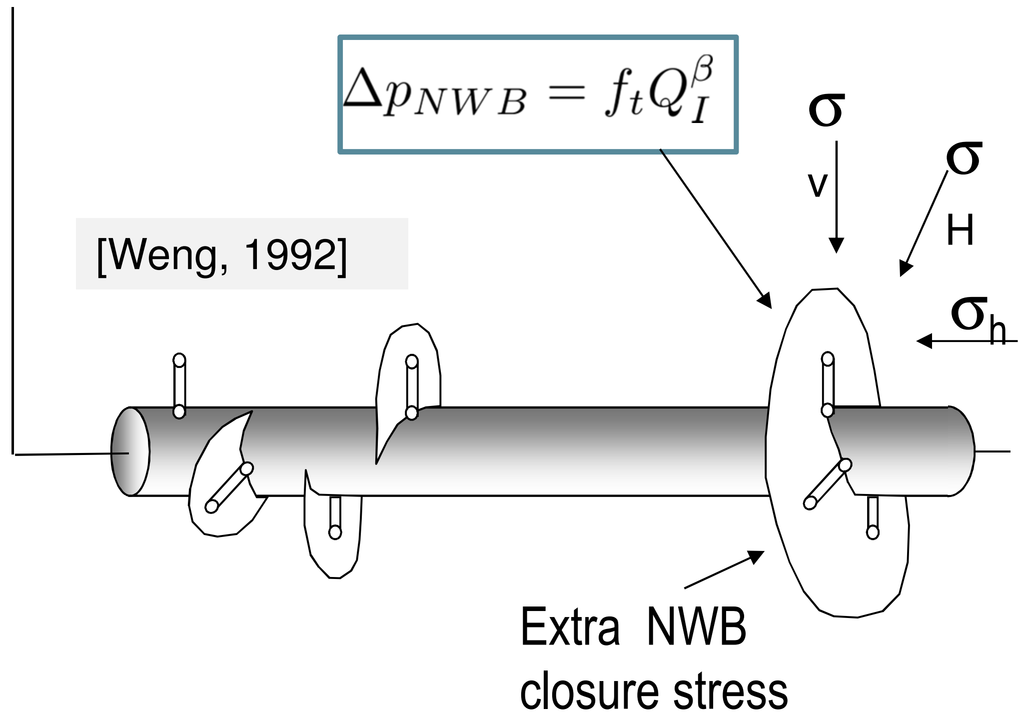
# It is even worse in practice: near wellbore fracture tortuosity




i) Initiation of multiple fractures from the # perforations

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# Single entry fracturing – Field experiment

One fracture at a time (single entry fracturing)

Robustness in the amount of proppant placed

Competition between growing fractures is not a problem anymore

Completion technology: Coil Tubing activated sleeves

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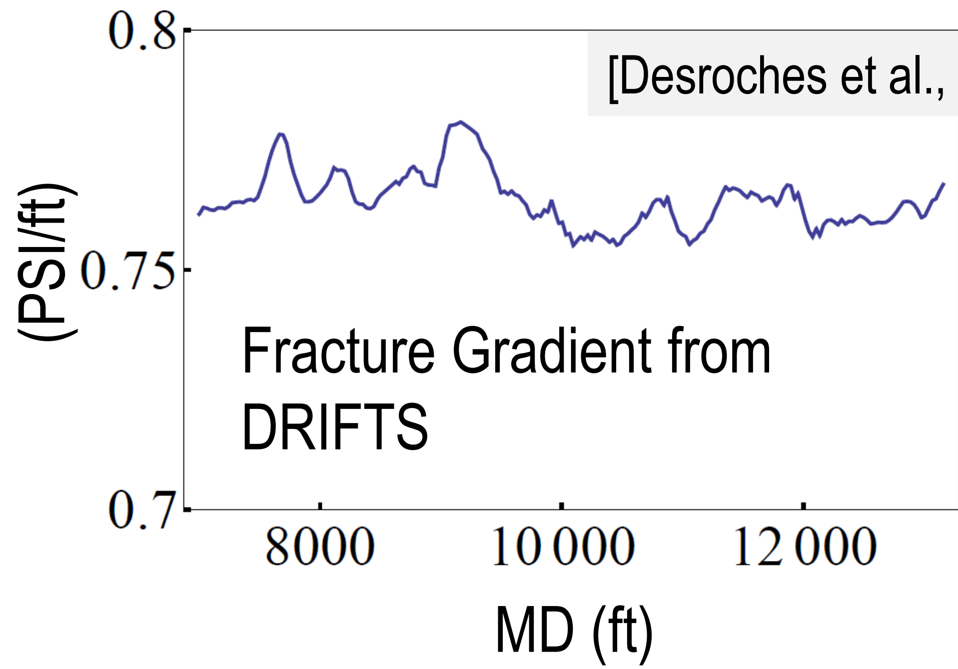
# Rowell-Chandler – single entry field experiment *Eagle Ford Shale*

Goal: Place 92 fractures, 65ft apart

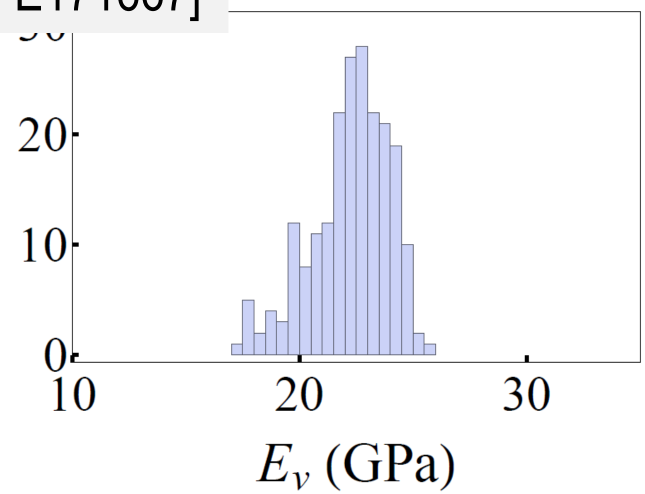
Same treatment throughout

14 diagnostic stages (step-downs ...)

Well drilled in the direction of $S_h$




[Desroches et al., 2014 SPE171667]




Very homogeneous formation…

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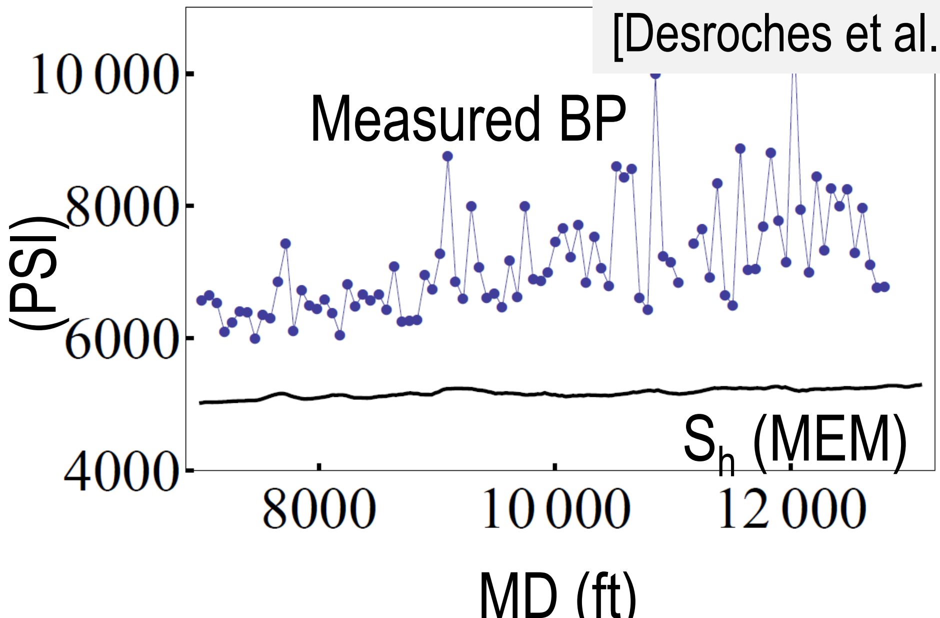
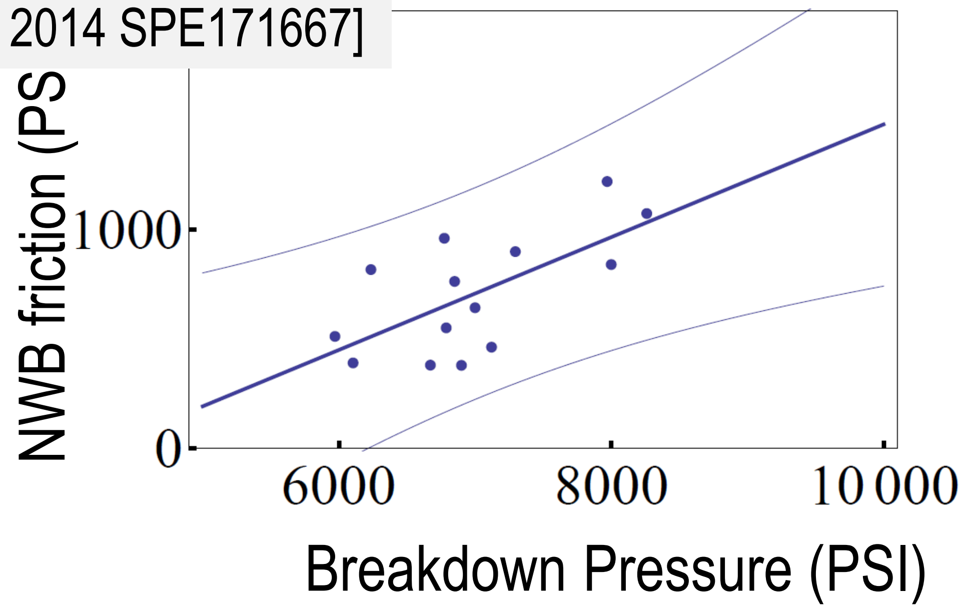
# Can we ignore Near Wellbore effects in Modeling?

Large variation in measured Breakdown pressure (BP)

From step-down tests, correlation between BP & NWB friction
(the strongest of all, better than BP vs TVD)




[Desroches et al., 2014 SPE171667]

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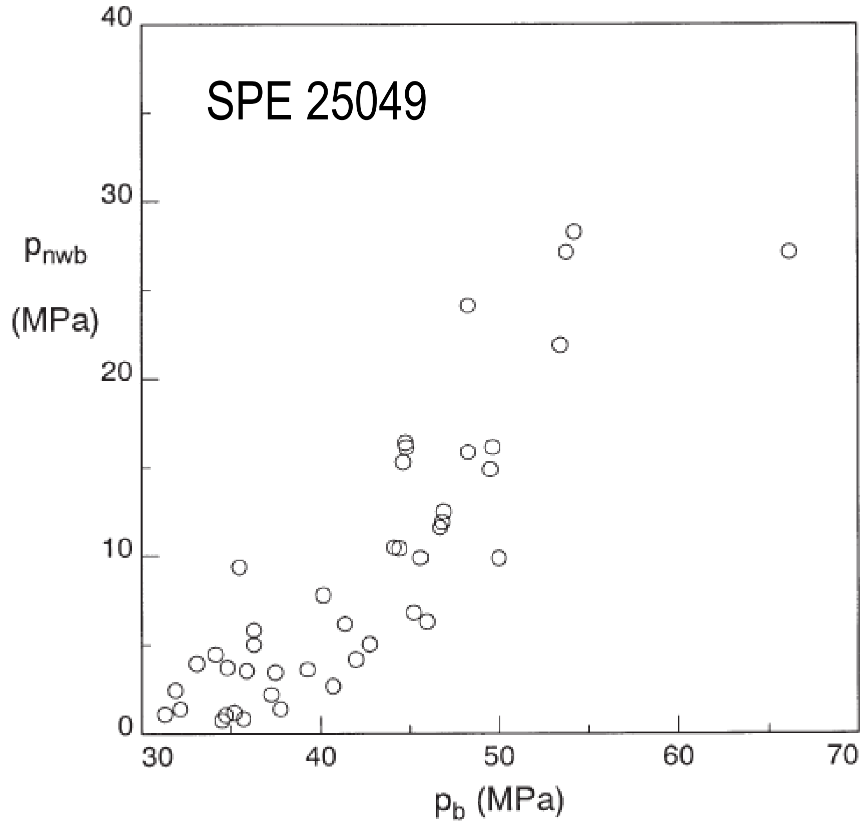
# Other observations

## Dan Field in the North Sea

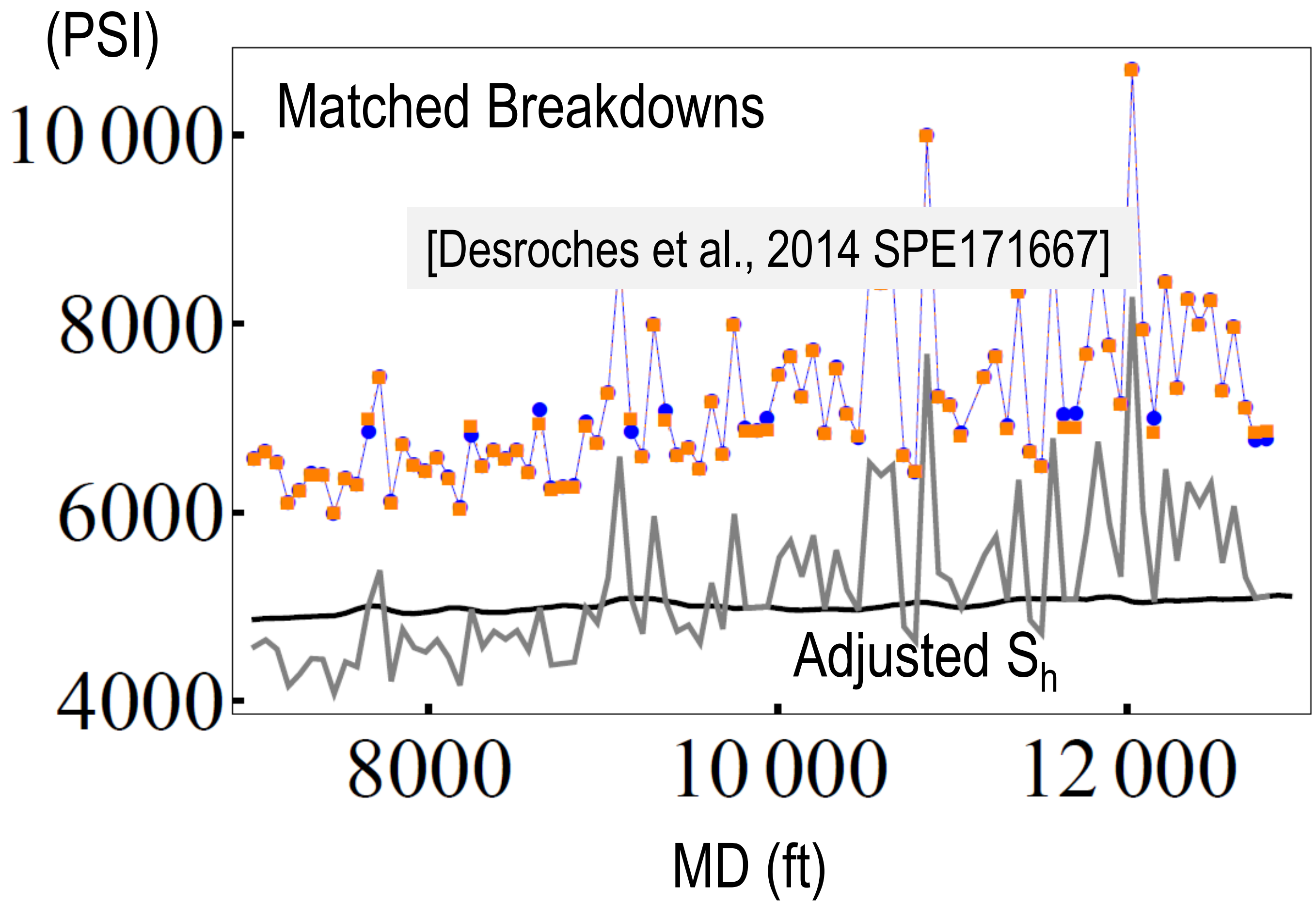
- Horizontal wells development in the early 90s
- Cemented liner with perforation clusters
- Linear correlation between near-wellbore friction (from steps-down test) and breakdown pressure



# Rowell-Chandler – single entry field experiment
## *Eagle Ford Shale – Model Calibration*

Calibration of the near-wellbore stress to match measured breakdown pressure

All the remaining parameters from characterization & treatment data

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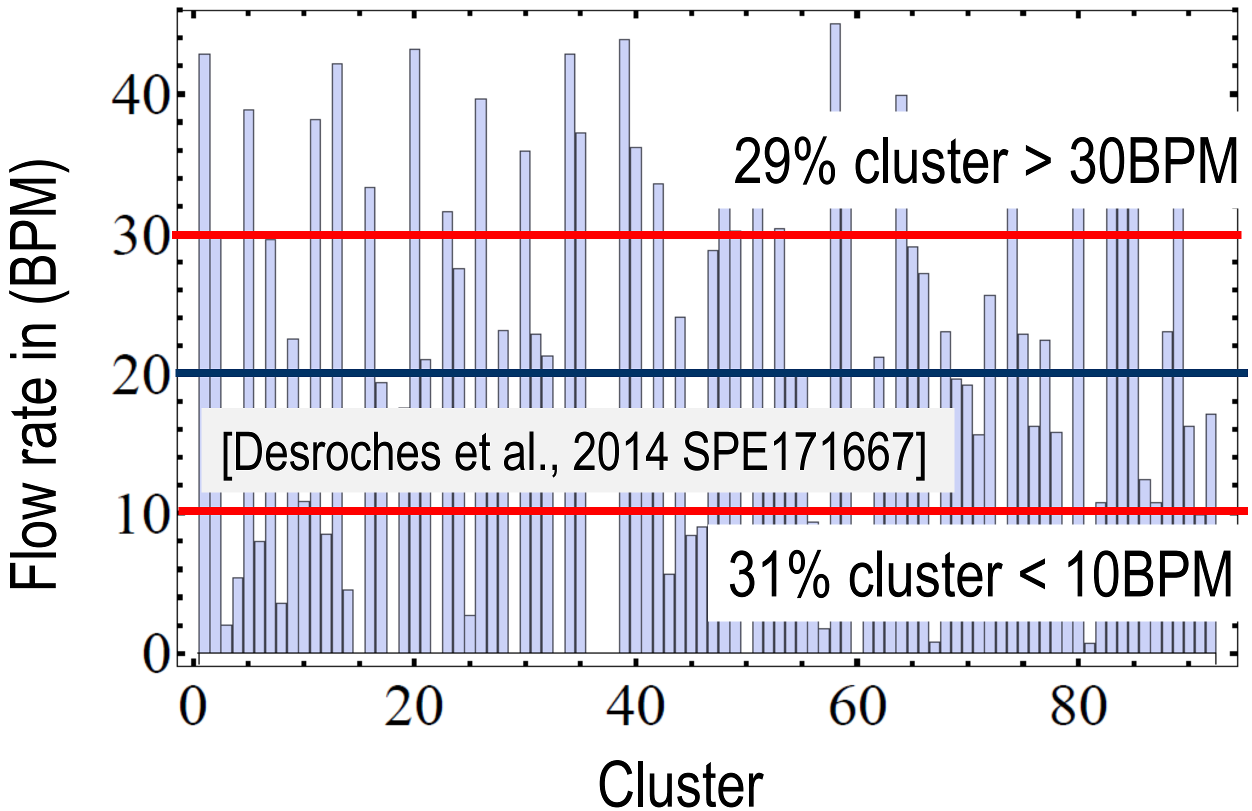
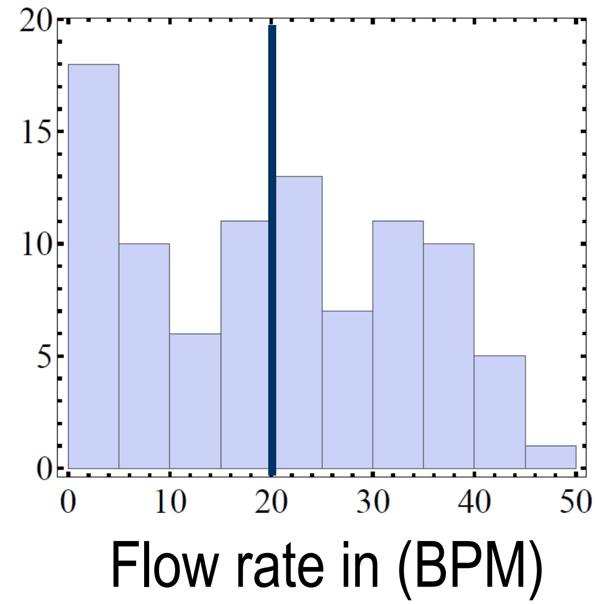
# What if we had done a “plug & perf” – 4 clusters?




*Only 26% clusters within 5 BPM of the designed rate!*

Proppant transport is extremely poor with slickwater for rate below 15BPM (settling even in the pipe).

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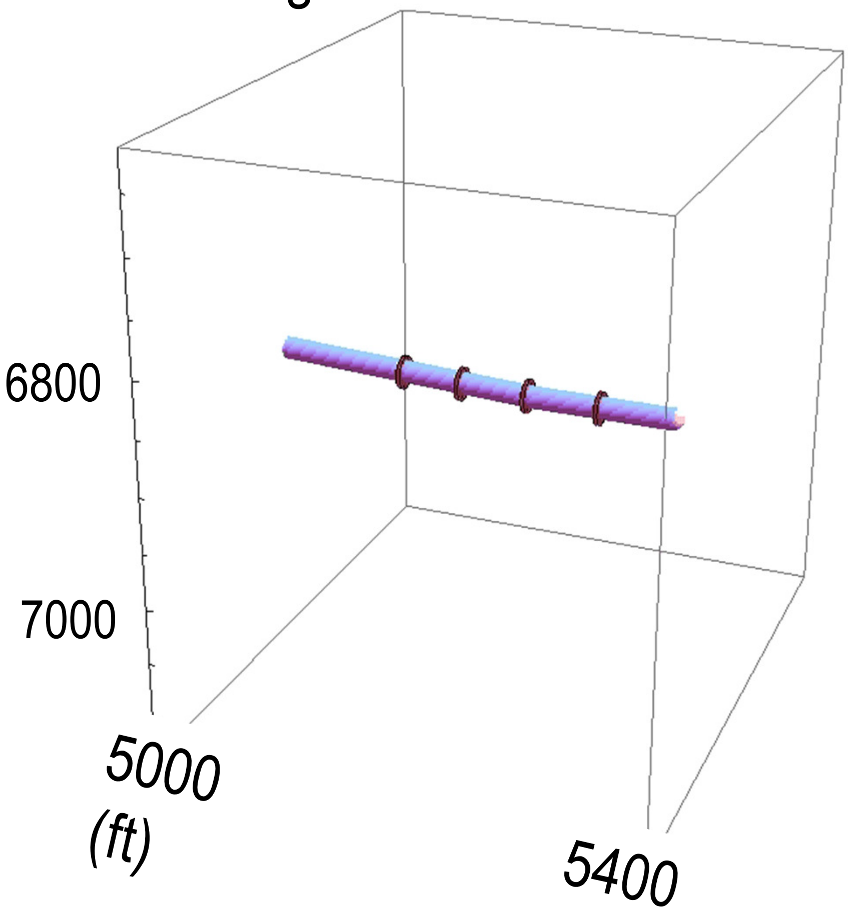
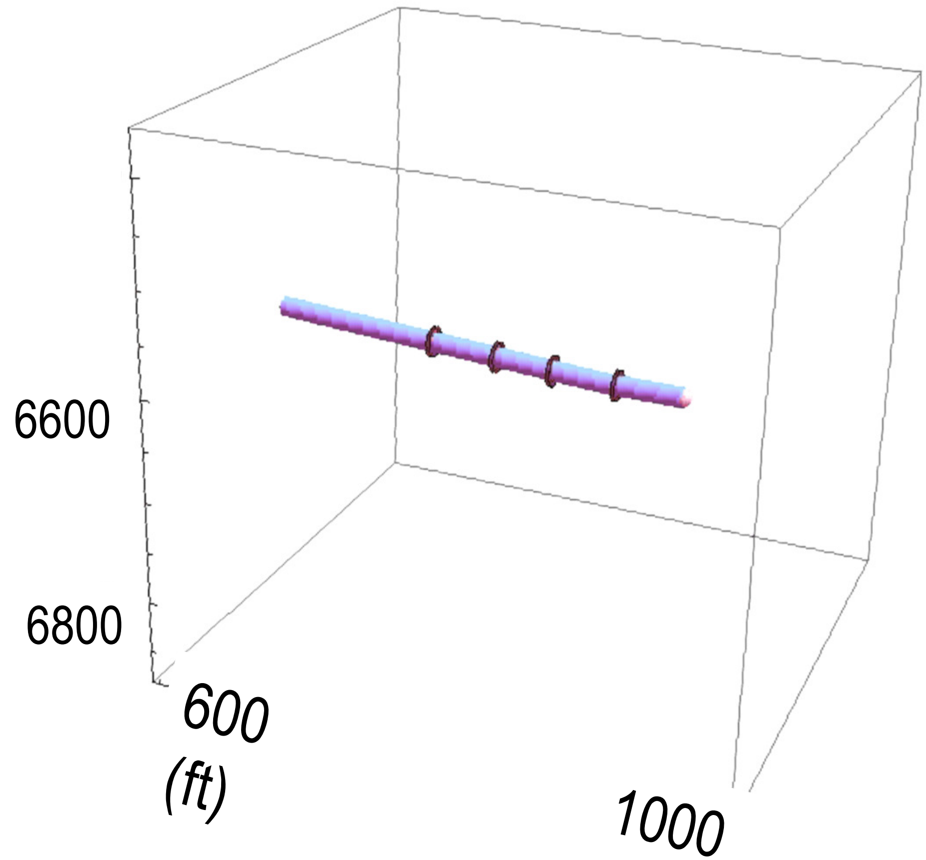
# What if we had done a plug & perf – 4 clusters?

Stage 4 – Clusters 14-17




Stage 22 – Clusters 85-88



# Summary

- Hydraulic fracturing theory is predictive (for simple fracture geometry).
- First simulator combining initiation & propagation of multiple radial hydraulic fractures
- Simultaneous fracture placement is inherently not robust
  - Combination of initiation & propagation
  - Engineered perforation friction design can counterbalance stress interference
    - But it is not very robust in the presence of typical heterogeneities
  - A large heterogeneity in near-wellbore tortuosity exists
    - We can't predict it
    - In a multi-cluster setting, it strongly affects fluid intake of the fractures (and proppant distribution, and production)
    - Fracture optimization is thus not straightforward: no fracture follows the design…
- Single-entry is a simple tool to:
  - diagnose that issue
  - optimize the pumping schedule for a single fracture
  - make informed decisions on how to proceed further

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