The Importance of coupling wellbore hydraulic & simultaneous fractures propagation in multistage design

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Poor production distribution between fractures

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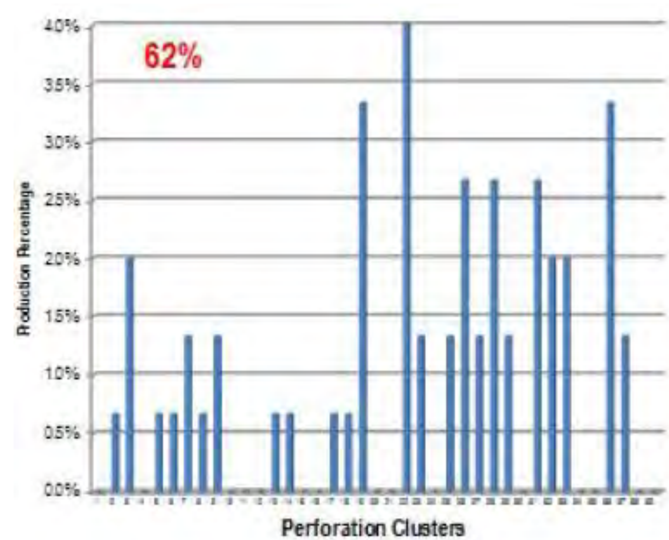
Unconventionals:
Producing nanoD reservoirs through a series of high conductivity channels.

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

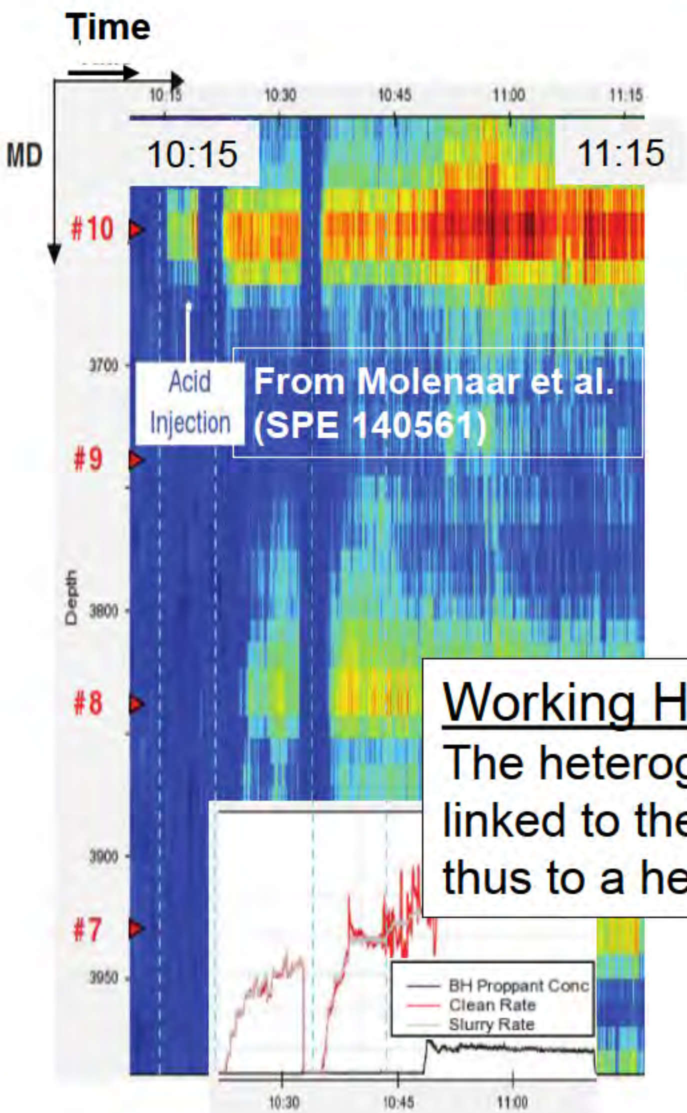
- Miller et al. 2011 (across US basins), Slocombe et al. 2013 (Eagleford Consortium), Noble Underground Lab. 2014 (Niobrara), Lim et al. (2015) etc.



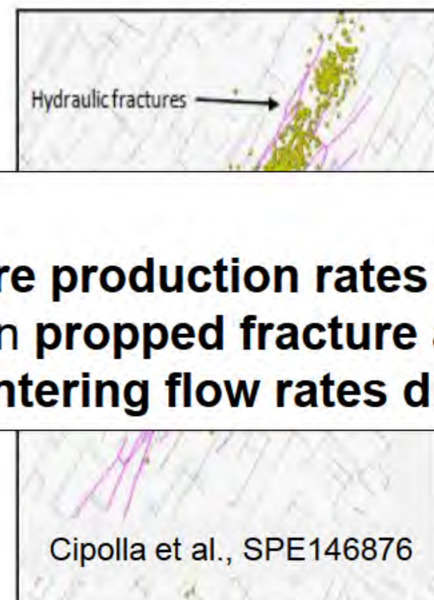
Slocombe et al. SPE 166242

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

Treatment Observations (during one stage)



- DTS/DTA
  - Variation in flow rate entering the different clusters during treatment (cooling)
  - Variation of producing rates between clusters during clean-up (warm up)
- Microseismic
  - Different fractures length in a stage

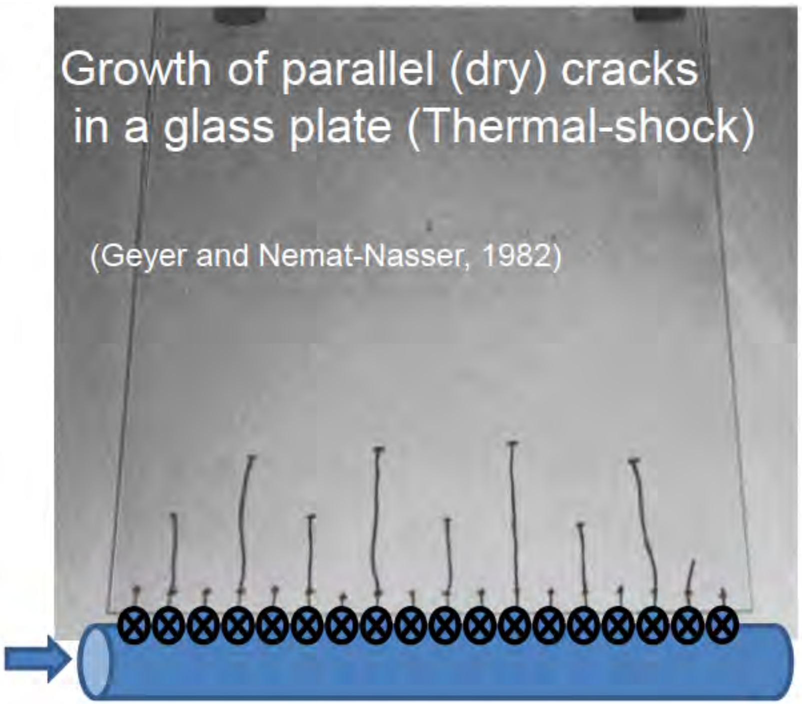


Cipolla et al., SPE146876

Working Hypothesis:

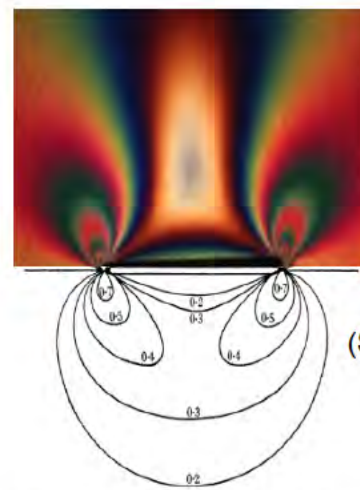
The heterogeneity in **fracture production rates** is strongly linked to the heterogeneity in **propped fracture areas**, thus to a heterogeneity of **entering flow rates during a stage**.

Multiple fracture propagation: Is it stable?



Interaction kicks in when
Spacing ≈ Height or Length

Stress perturbation
around a crack



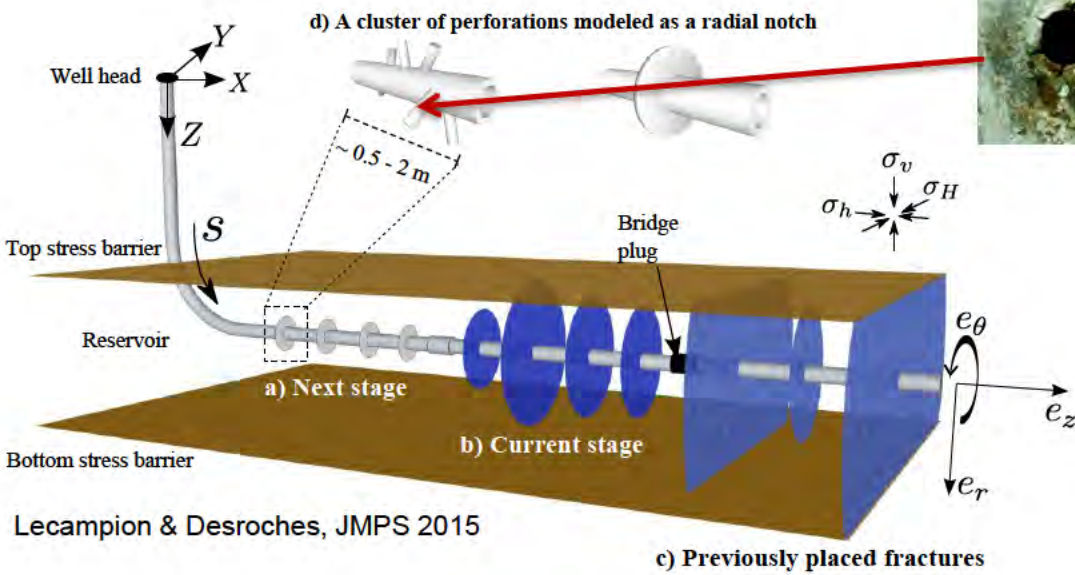
(Sneddon, 1946)

Fracture shielding occurs due to stress interactions.

Hydraulic fractures **are not** dry cracks / constant pressure: viscosity plays an important role

(Bunger et al. SPE 163860, Lecampion & Desroches JMPS 2015, Detournay ANRFM 2016, Lecampion et al. JGR 2017).

Fluid partitioning during a stage is key



Lecampion & Desroches, JMPS 2015

Entry friction

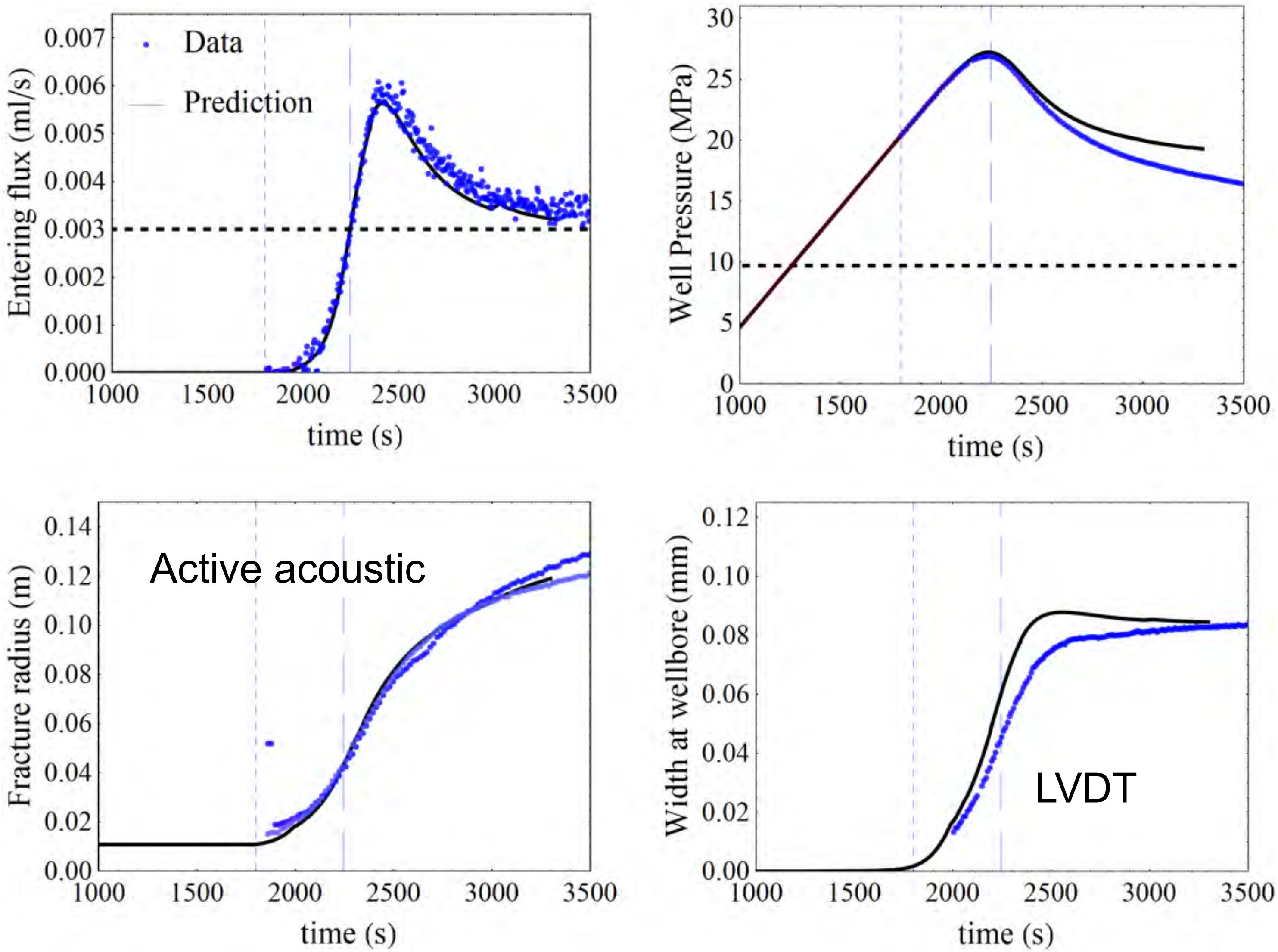
$$\Delta p_i(\mathbf{Q}) = f_{p,i} Q_i^2$$

[e.g. Reservoir Stimulation book 2000]

- One control the surface pump rate not the rate entering each of the fractures. This fluid partitioning is unknown & evolves with time.
- Competition between the following:
  - Stress interactions between fractures (aka stress shadow)
  - Well/Fracture entry pressure drop (entry friction)
  - Length of the stages (N clusters and spacing) & associated pressure drop in the well.
- One needs to couple
  - Hydraulic fracture propagation solver
  - Wellbore flow solver

Single Hydraulic Fracture Initiation

theory vs experiments



Lecampion et al., JGR 2017

Experiment in cement with silicone oil
(TU Delft 1998)

Fluid flow in the well

Cross-sectional averaging, neglect small transient effects (e.g. water hammer type)

Mass balance

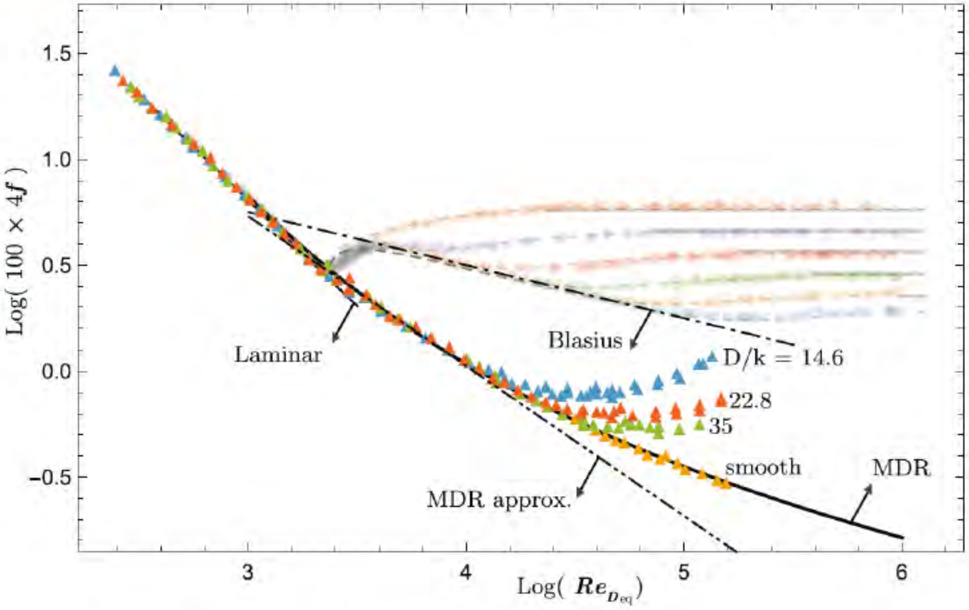
$$\frac{\partial \rho A}{\partial t} + \frac{\partial \rho A V}{\partial s} = \delta(s)\rho Q_o - \sum_{I=1}^{N} \delta(s - s_I)\rho Q_I$$

Momentum balance

$$\frac{\partial p}{\partial s} = -\frac{2\pi a}{A}\tau_w + \rho g \sin\alpha(s)$$

Local steady-state wall shear-stress

$$\tau_w = \rho \frac{f(Re, \varepsilon)}{4} \frac{V\,|V|}{2}$$



Haaland (1983) correlation in the turbulent regime
Vick (1975) correlation at maximum drag reduction

Zero flux at the bridge plug location

$$V(s = L, t) = 0$$

Classic 1D Finite Volume scheme

Solving for fluid partitioning – *very stiff*

- Within a full implicit scheme (Backward Euler)

- Wellbore / Fracture(s) coupling

$$\Delta p_i(\mathbf{Q}) = p_{w,i}(\mathbf{Q}) - p_{f,i}(\mathbf{Q}) = f_{p,i} Q_i^2 + f_{t,i} Q_i^{\beta_i}$$

  Quasi-Newton iterations

  - For each *trial* values of entry flow rates in different fractures

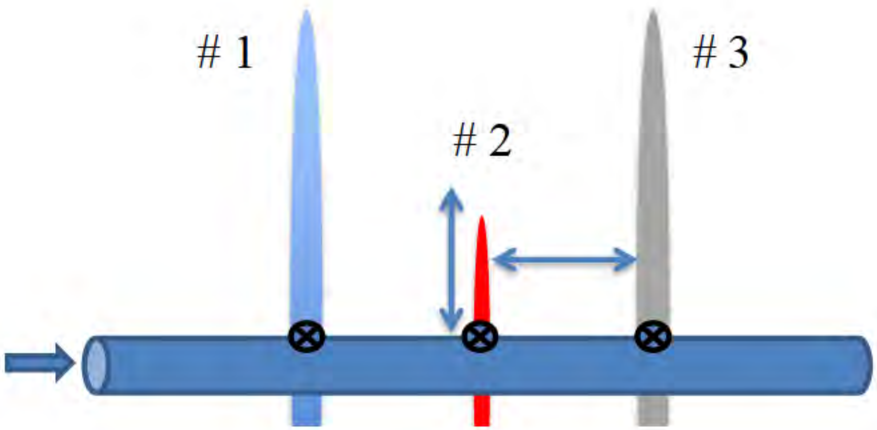
    - Solve for wellbore flow (given **Q**) to find cluster outlet pressure(s) $p_{w,i}(\mathbf{Q})$
    - Solve hydraulic fractures propagation step (given **Q**)

      to estimate HF inlet pressure(s) $p_{f,i}(\mathbf{Q})$
    - Compute residuals $\mathcal{R}_i(\mathbf{Q}) = p_{w,i}(\mathbf{Q}) - p_{f,i}(\mathbf{Q}) - (f_{p,i} Q_i^2 + f_{t,i} Q_i^{\beta_i})$
    - Compute Jacobian $\dfrac{\partial \mathcal{R}_i}{\partial Q_j}$ (using finite difference approx.)
    - Compute increments of **Q**

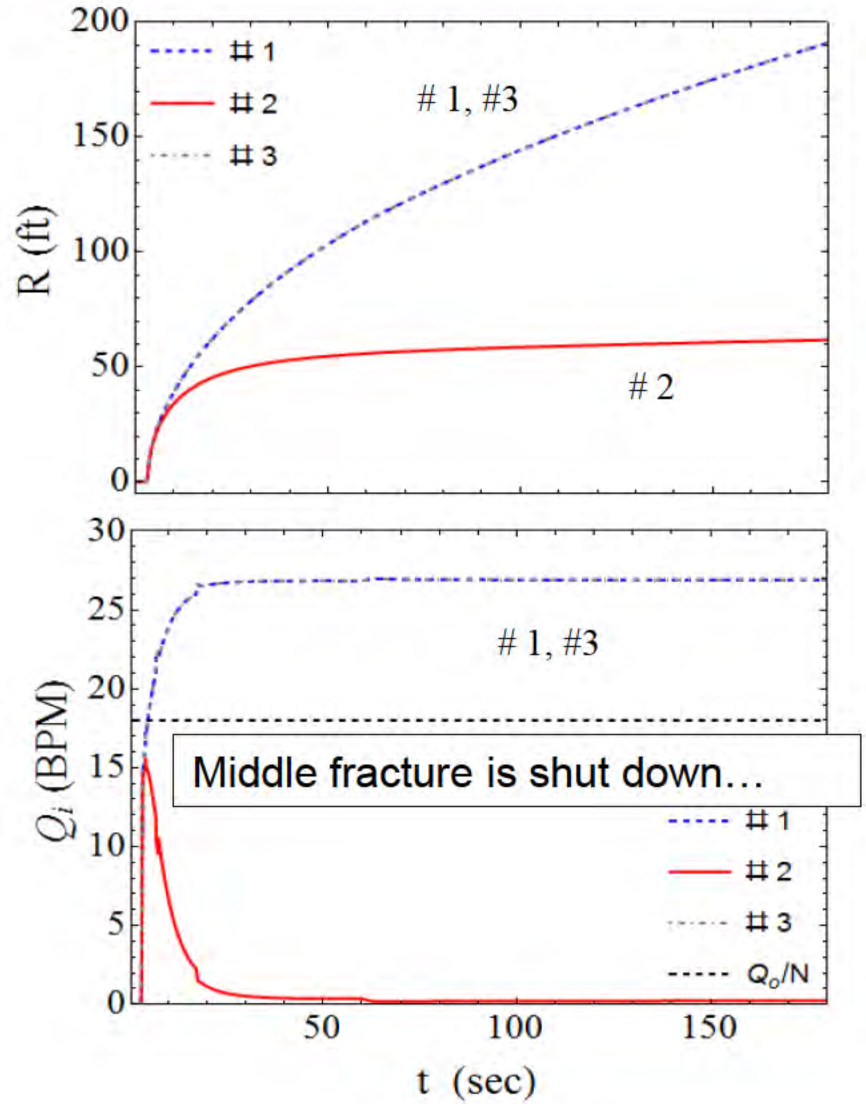
  - Iterate until convergence
    (on residuals & subsequent estimates of **Q**)

A simple case – 3 fractures – no entry friction

Example of 3 fractures 80 ft apart
without perforation friction

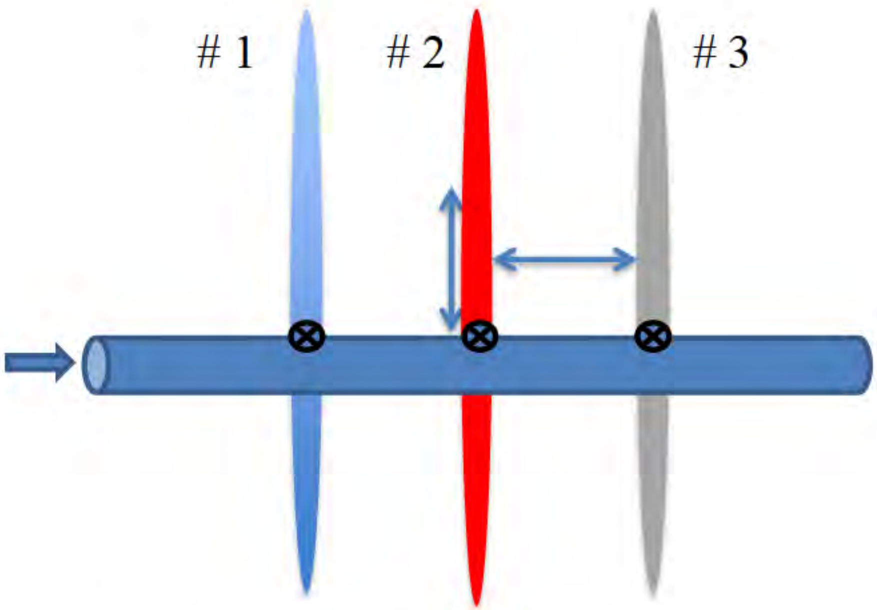


“Kicks in” when Spacing ≈ Height or Length



A simple case – 3 fractures – entry friction

Example of 3 fractures 80 ft apart
with 200 psi perforation friction



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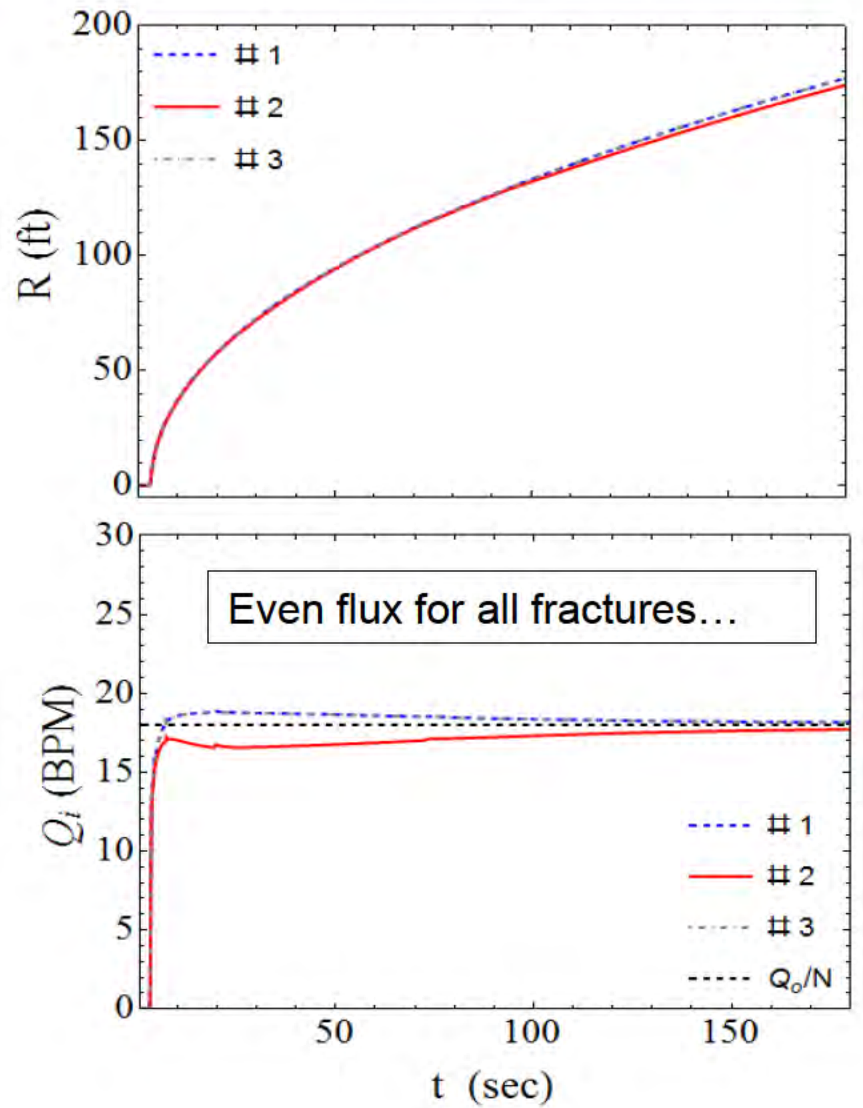
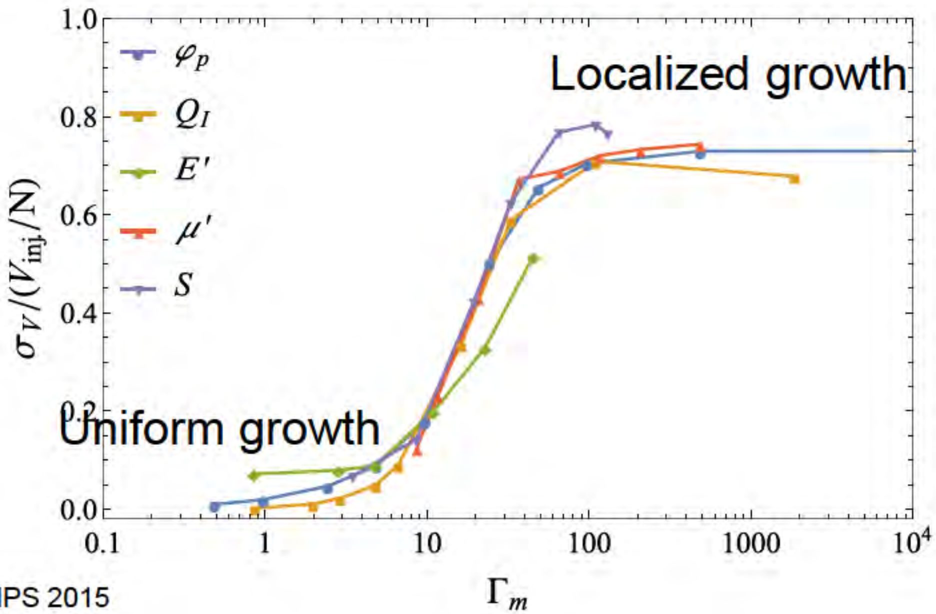


Uniform vs localized growth

- Uniform growth is promoted when $\Delta p^{\text{entry}} \gg \sigma^{\text{Int}}$
- Introducing $\Gamma = \sigma^{\text{Int}} / \Delta p^{\text{entry}}$, we can estimate its order of magnitude from system parameters (when *R*~*S*) for a given regime of propagation

$$\Gamma_m = \frac{\sigma^{\text{Int}}}{\varphi_p \times (Q_o/N)^2} = \frac{E'^{3/4} \mu'^{1/4}}{\varphi_p \, S^{3/4} \, (Q_o/N)^{7/4}}$$

- Series of simulations (3 fractures array), looking at the standard deviation of fracture volume scaled by the volume of a single fracture



Lecampion & Desroches, JMPS 2015

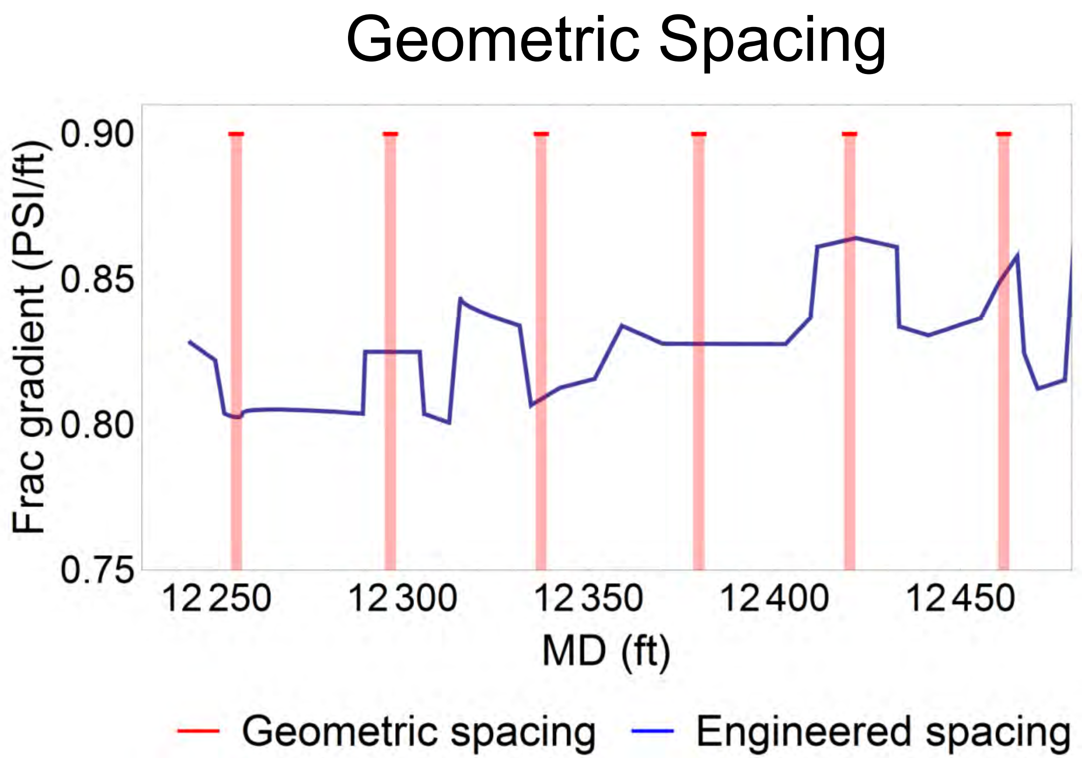
Remark #1 - Stress shadow

- The effect of stress shadow between fractures
  can be counterbalanced by typical perforation friction.
  (i.e. when perforation pressure drops are larger than the interaction stress)

- Perforation erosion decreases entry friction,
  which may result in stress shadow kicking in.

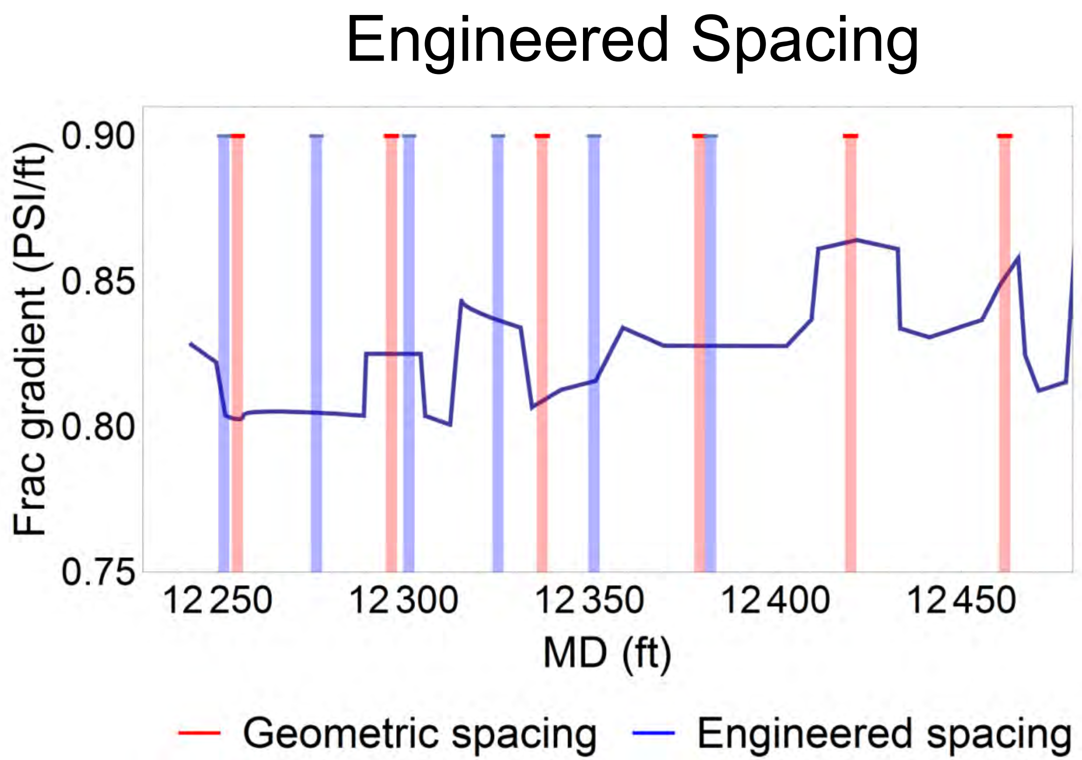
- Something else than stress shadow?
  Is formation heterogeneity the cause for production heterogeneity?

How do we handle heterogeneity in practice ?



Eagle Ford example (taken from Slocombe et al., SPE 166242)

How do we handle heterogeneity in practice ?



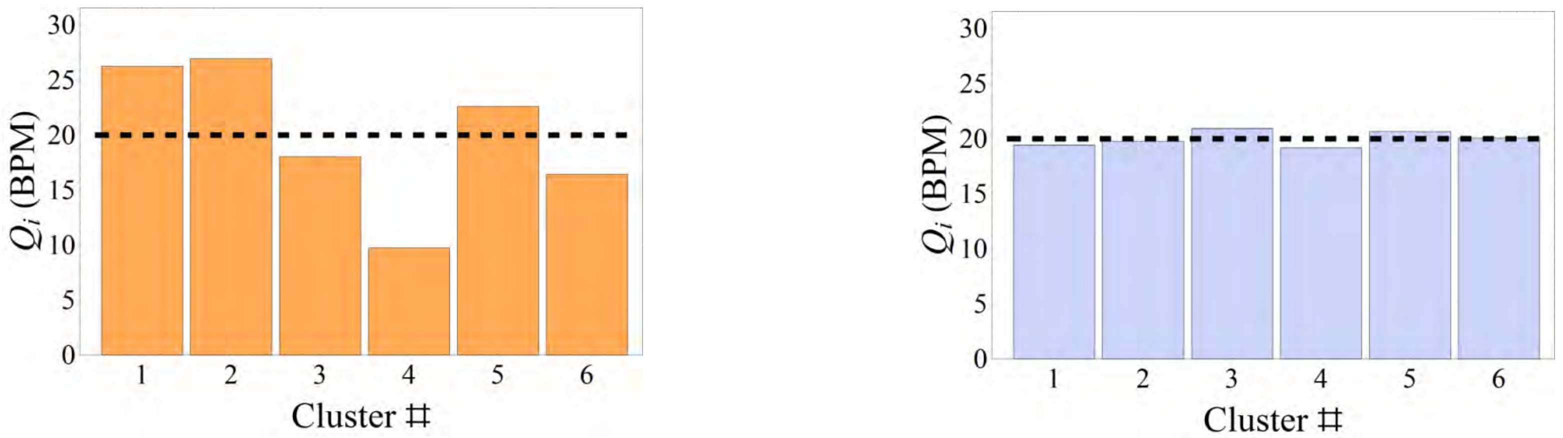
Minimizing stress variation between clusters in a stage (while limiting by-pass pay)

How do we handle heterogeneity in practice ?

Limited Entry Design

Uniform — $N_{perf} = 8$

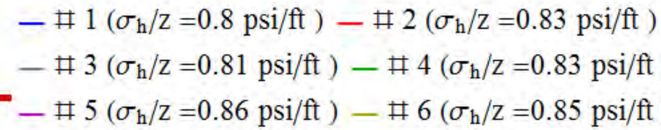
Engineered — $N_{perf} = [6, 6, 8, 9, 7, 8]$



Choking down clusters in front of lower stress to balance entering fluxes (taking Sh as the fracturing pressure)

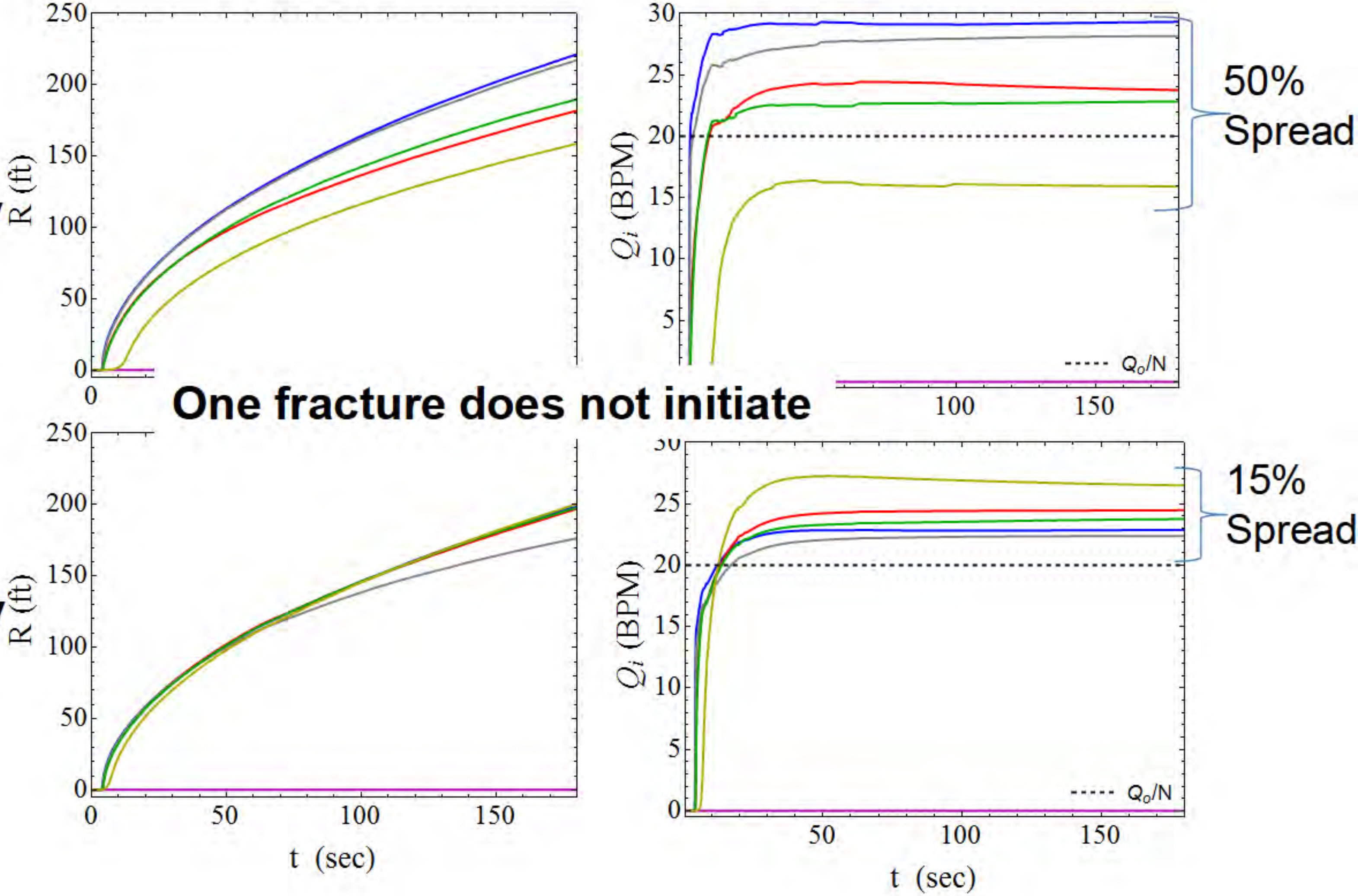
(Lagrone & Rasmussen, 1963)

Geometric Spacing

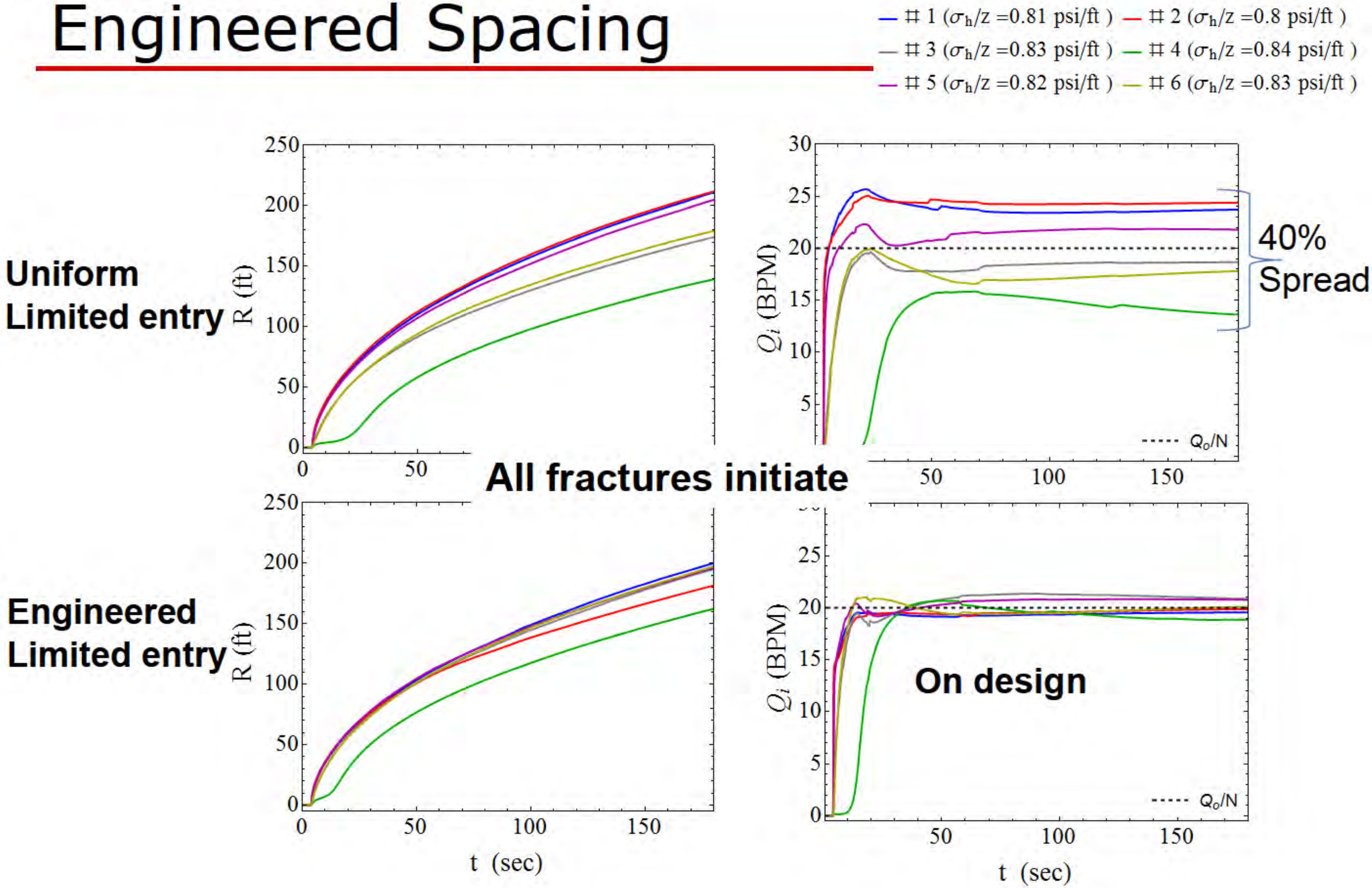


Uniform Limited entry

Engineered Limited entry



Engineered Spacing



Remark #2 - Stress Heterogeneity

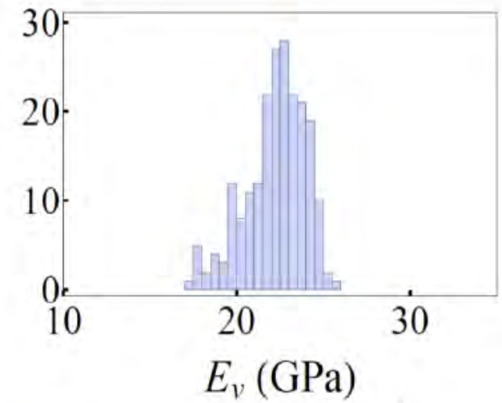
- Stress heterogeneity can be managed
  - 100% balancing of the entering fluxes and all fractures propagating is achievable *but it is not very robust*
    (slight changes in entry friction directly impact fluid partitioning)
    see e.g. Lecampion & Desroches RMRE 2015
  - 80% entering flux balancing should be achievable
  - Heterogeneity needs to be properly quantified
- However production performance seems worse from field observations ☹

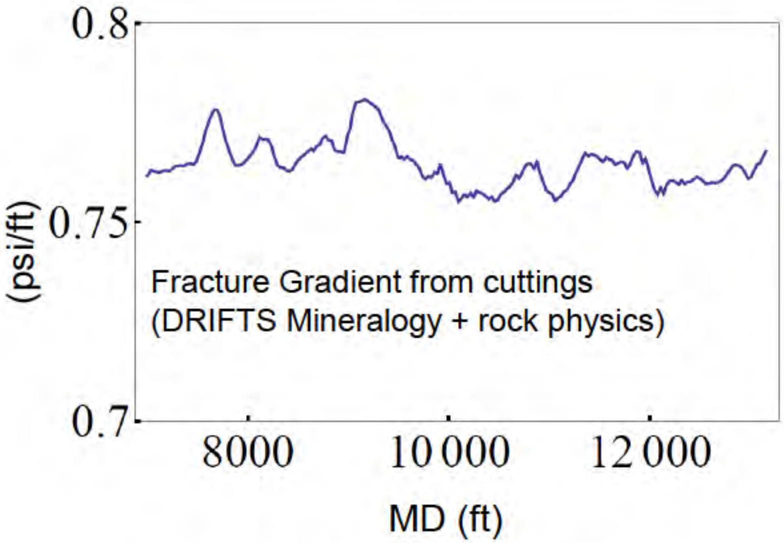
➢ Let's have a look at a field experiment without much stress heterogeneity

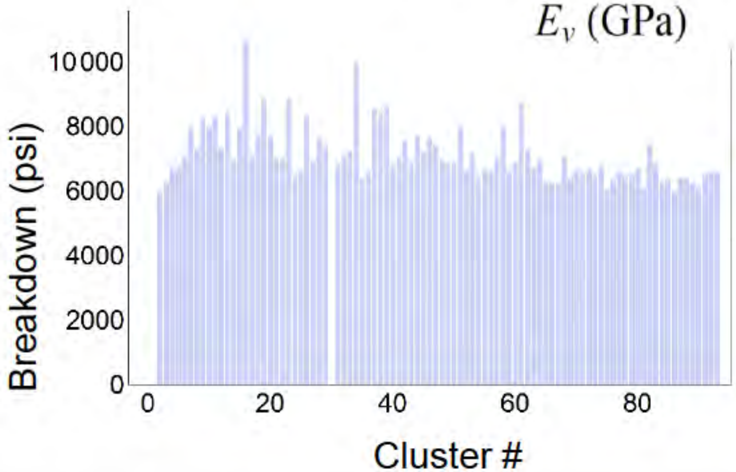
Field Case – Single Entry Experiment

Eagle Ford Shale

- Horizontal well, 6000ft lateral drilled in the direction of S_h
- From cuttings analysis: mineralogy, elastic properties, stress index
  → fairly homogeneous along the lateral length
- 93 single entry clusters
  Bottomhole pressure gauges on each stage
- 14 diagnostics stages with step downs







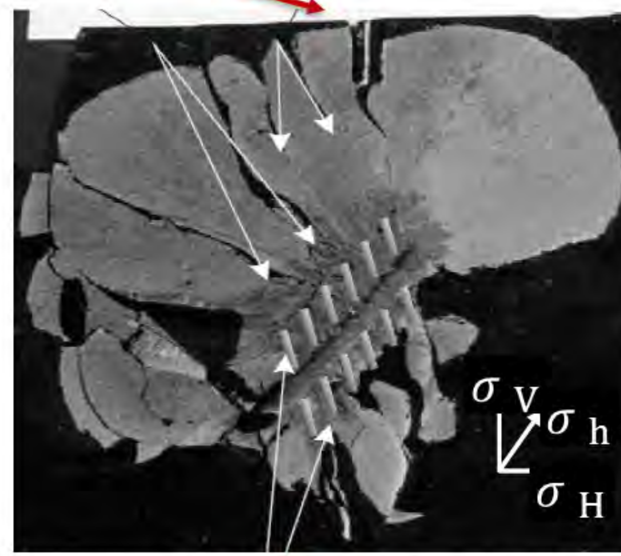
Details in SPE 171667

Very different breakdown pressures

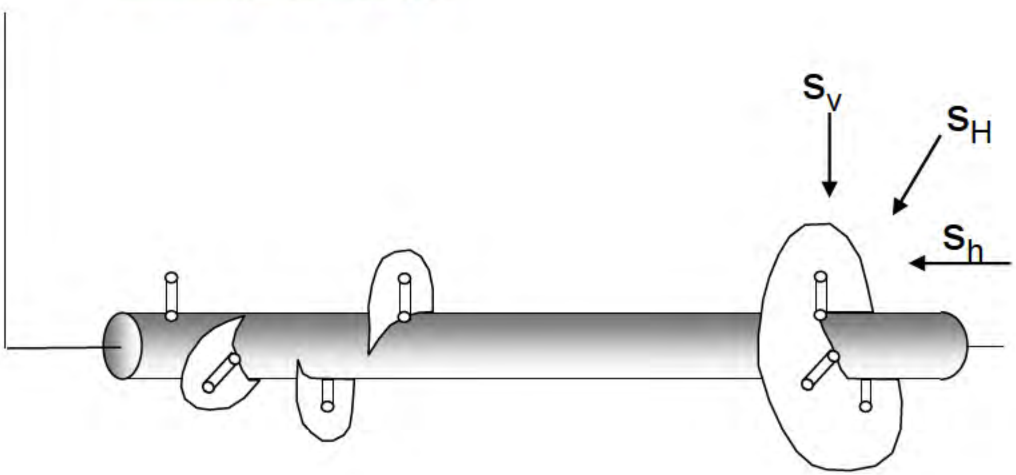
WB-HF coupling & fluid partitioning

- WB-HF coupling via entry friction: perf + near-wellbore

$$\Delta p_i(\mathbf{Q}) = p_{w,i}(\mathbf{Q}) - p_{f,i}(\mathbf{Q}) = f_{p,i}Q_i^2 + f_{t,i}Q_i^{\beta_i}$$



(Taken from Van der Ketterij *et al.*, SPE 38149)

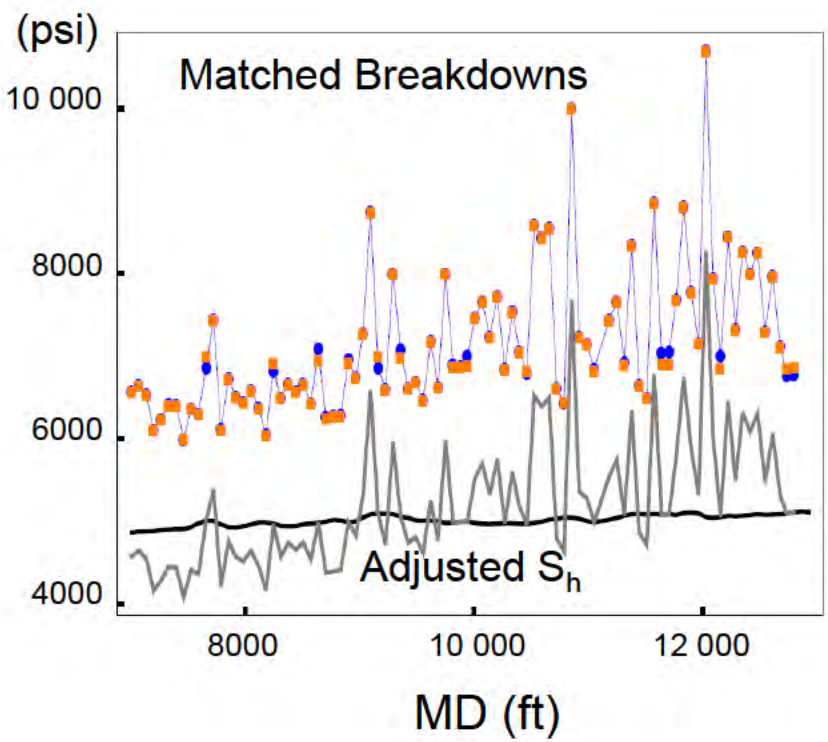


Very sensitive to local heterogeneities (stresses, rock fabric, cementing..)

Eagle Ford Shale – Model Calibration

- For each treatment, determine from bottom-hole pressure record
  - ΔP_{NWB} (from correlation with breakdown)
  - ΔS_h (local re-orientation)

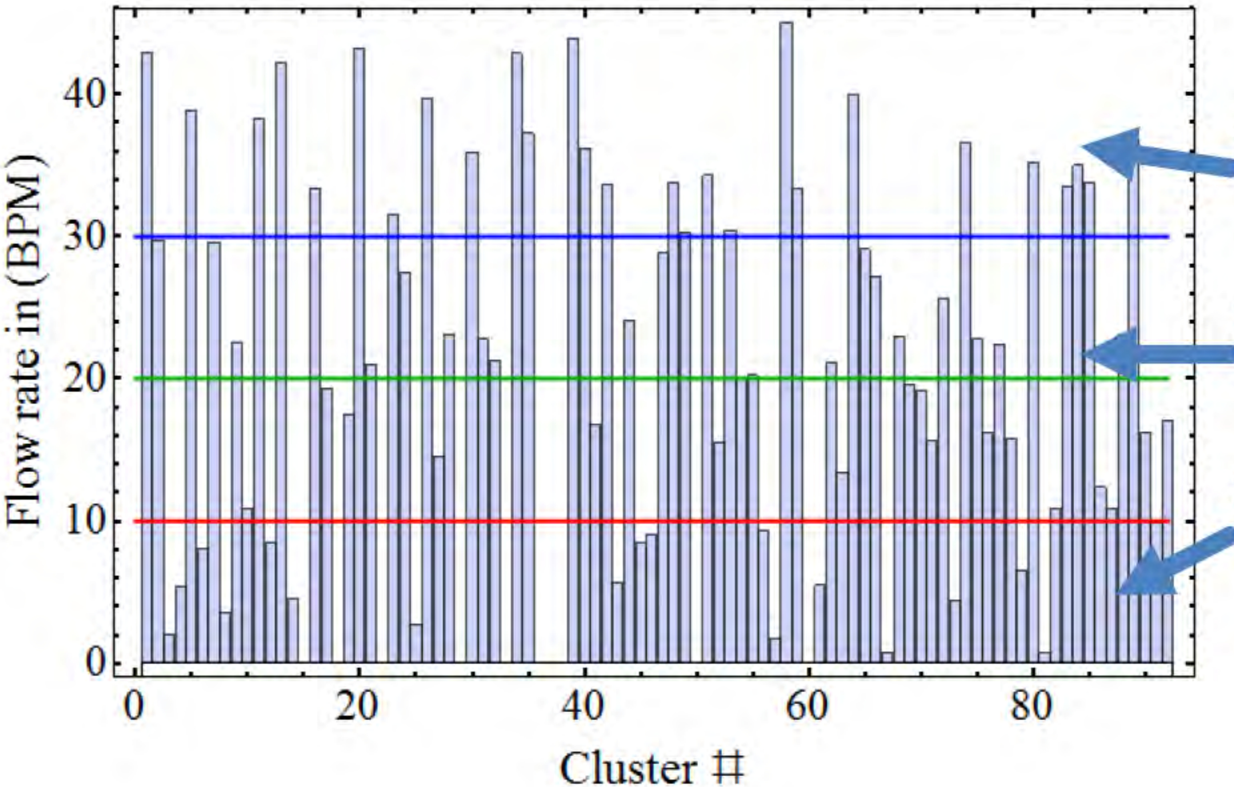
- All the remaining parameters from the characterization & treatment data



What if the well had been stimulated with N (>1) clusters per stage ?

Playing scenarios

Reconstructing the entire well with 4 cluster stages



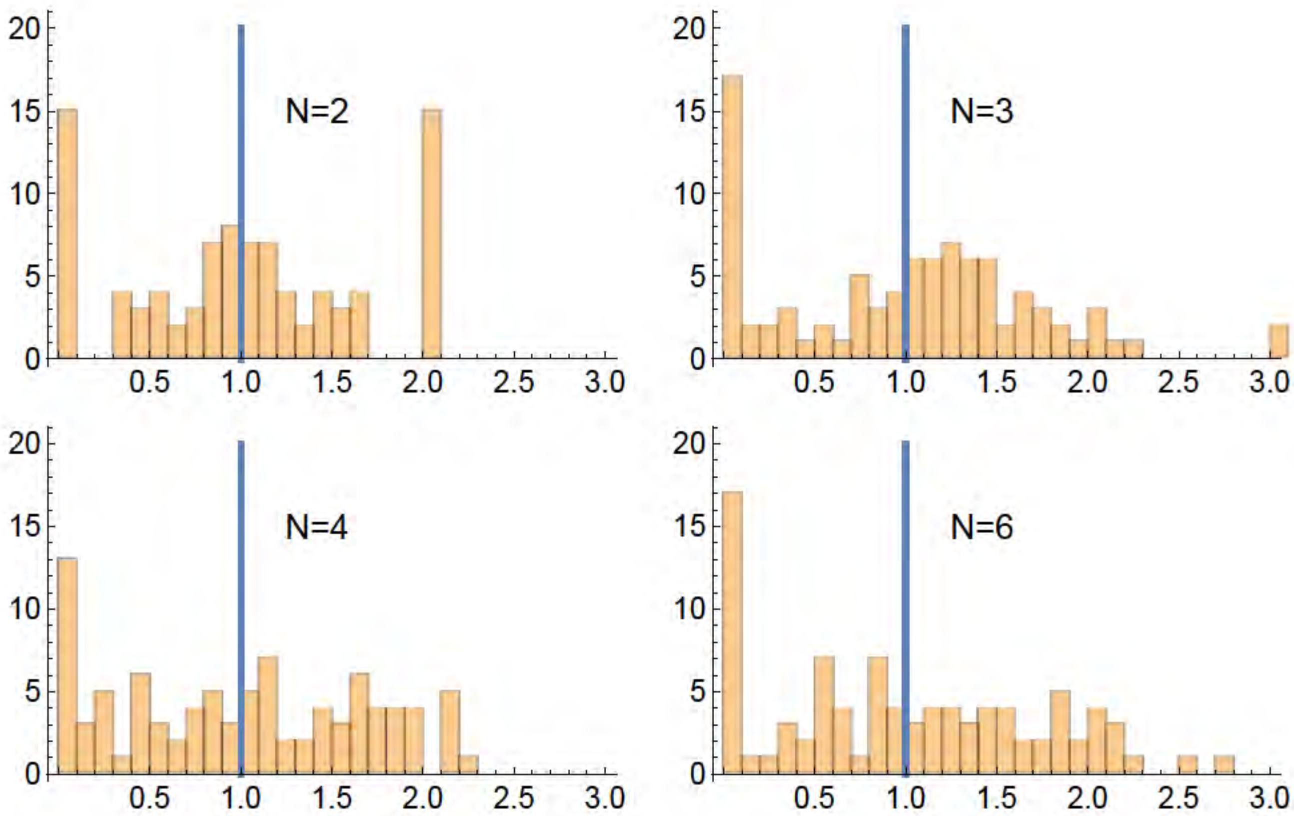
30% > 30 BPM
(most sand)

25 % between 15 and 25 BPM
(design)

30% < 10 BPM
(proppant settling?)

Playing scenarios

Histograms of fluid intake in each clusters as a function of number of clusters per stage



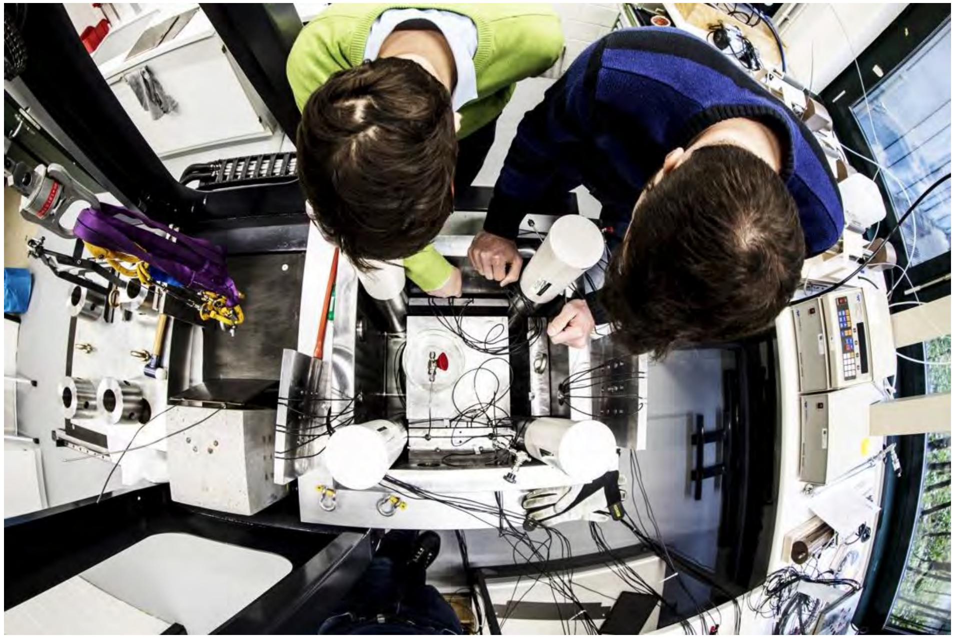
Conclusions

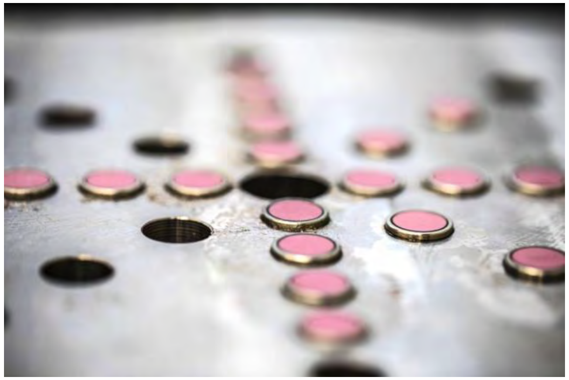
- Fluid partitioning between fractures within a stage is unknown a-priori
  - Part of the solution
  - very stiff non-linearity between wellbore flow, hydraulic fracture growth and entry friction
- Stress interactions between fractures (and stages) can be completely counteract by entry friction
  - A word of caution… as long as $S_H > S_h$ + 1MPa (100psi)
- Entry friction: perf + near-wellbore fracture re-orientation
  - Vary from cluster to cluster,
  - Huge effect on fluid partitioning & final well completion
- Inefficiencies intrinsic to the simultaneous propagation of hydraulic fractures from a well

Can we do something about it ?

- In practice – *currently the options are*
  - Live with the inefficiencies and optimize the ‘supply’ chain
  - Spend a test well & do single entry HF treatment to:
    - Sample the heterogeneities of the entry friction (Near-wellbore fracture geometry) via rate step down tests
    - Perform MC HF multistage simulations with proper well/HF coupling to choose the optimum stage length & number of clusters (in a probabilistic sense)
  - Fluid diverters – far-from achieving full efficiency (just allow larger stages in terms of clusters)
- Gaps in our understanding to be filled in order to go a step further are
  - 3D HF growth in the near-wellbore
    - Nasty fracture mechanics problem (mixed mode I+IIII front splitting etc.) very sensitive to local heterogeneities difficult to characterized
  - Effect of rock anisotropy/laminations on HF growth both at:
    - Large scale (sensitivity to layering, preferred growth direction, induced flow roughness etc.)
    - Near-wellbore scale – initiation from perforations etc.

- 3 principal stresses
- Pore-pressure
- 25cm*25cm*25cm sample
- Any materials
- Extensive acoustic monitoring
  - 64 piezos
    (32 sources / 32 receivers)
  - 16 piezos for passive AE





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Questions ?

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