Hydraulic fracturing & Seismicity

a hydraulic fracture mechanics perspective

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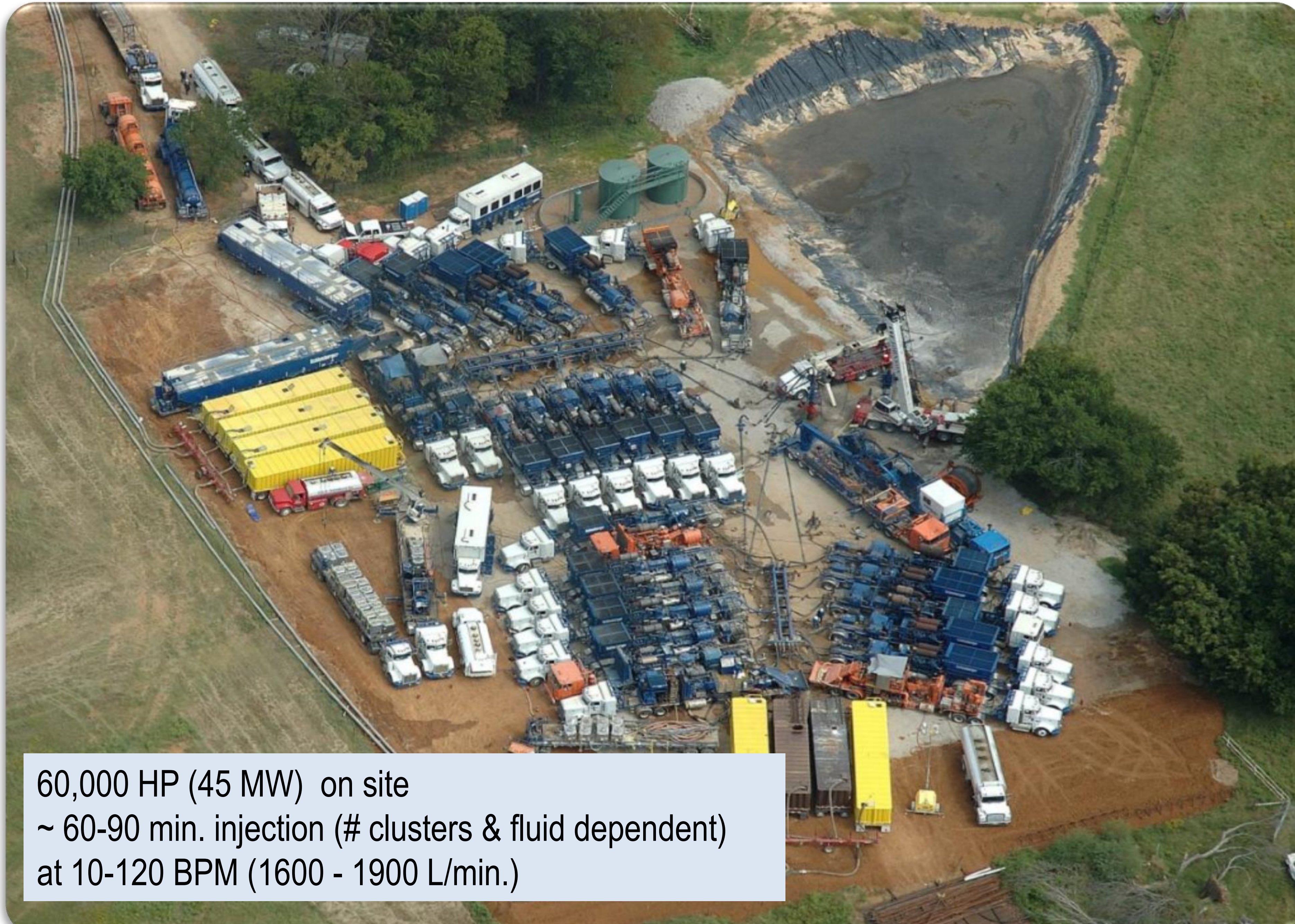
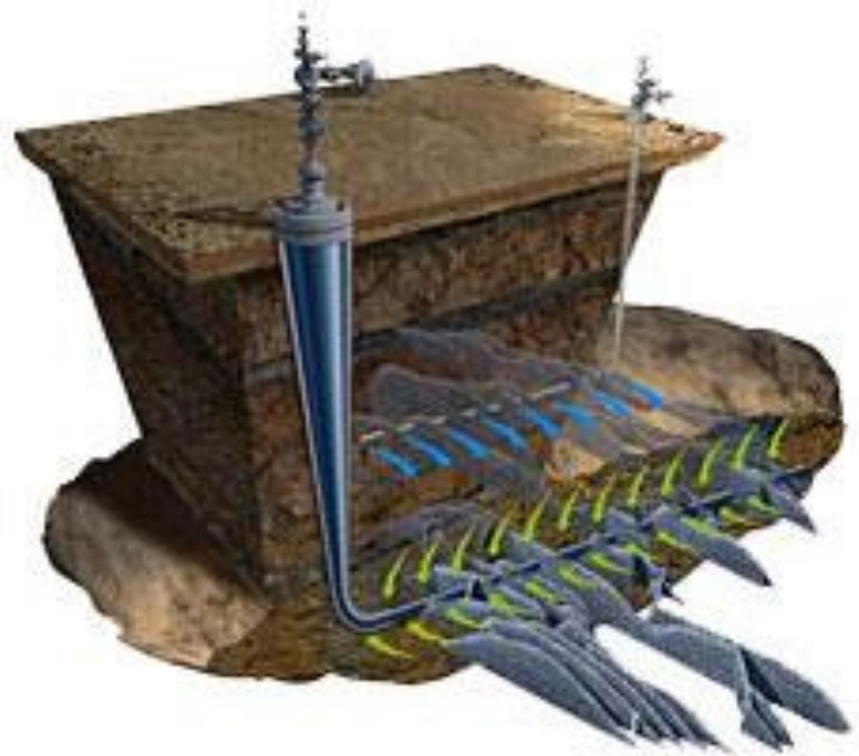


60,000 HP (45 MW) on site
~ 60-90 min. injection (# clusters & fluid dependent)
at 10-120 BPM (1600 - 1900 L/min.)

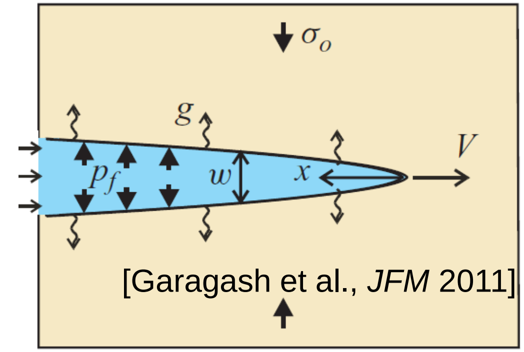
The Hydraulic Fracturing Process

- **Main stages:**
  - Break formation down with a fluid “pad”
  - Create fracture geometry and aperture with fracturing fluid
  - Inject slurry with proppant
  - Flush, shut-in
  - Clean up
- **Physics :**
  - Fracture propagation
  - Fluid flow
  - Proppant transport
  - Wellbore hydraulics
- **Basics:**
  - Vertical fractures (in most basins)
  - Vertical containment due to
    - Stress contrasts
    - Bedding, laminations, permeability etc.



Hydraulic Fracture Mechanics in a Nutshell

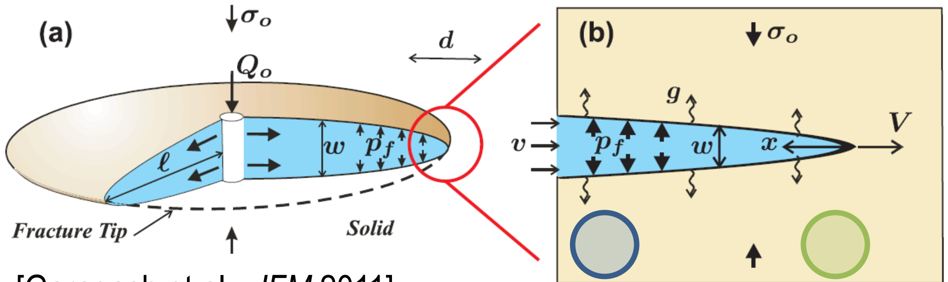
- Solid deformation
- Fracture surface creation
- Fluid flow / slurry flow
- Mass balance:
  injected fluid = storage + leak-off
- Energy balance:



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

- Very different propagation regimes depending on the dominant mechanisms (e.g., Viscosity / Toughness, Leak-Off / Storage)
[e.g. Detournay, 2004, 2016; Garagash 2000, 2009]
- Largest energy spent: viscous flow (WB mostly) + $Q_o\sigma_o$

HF tip asymptotes – zero lag – with leak-off

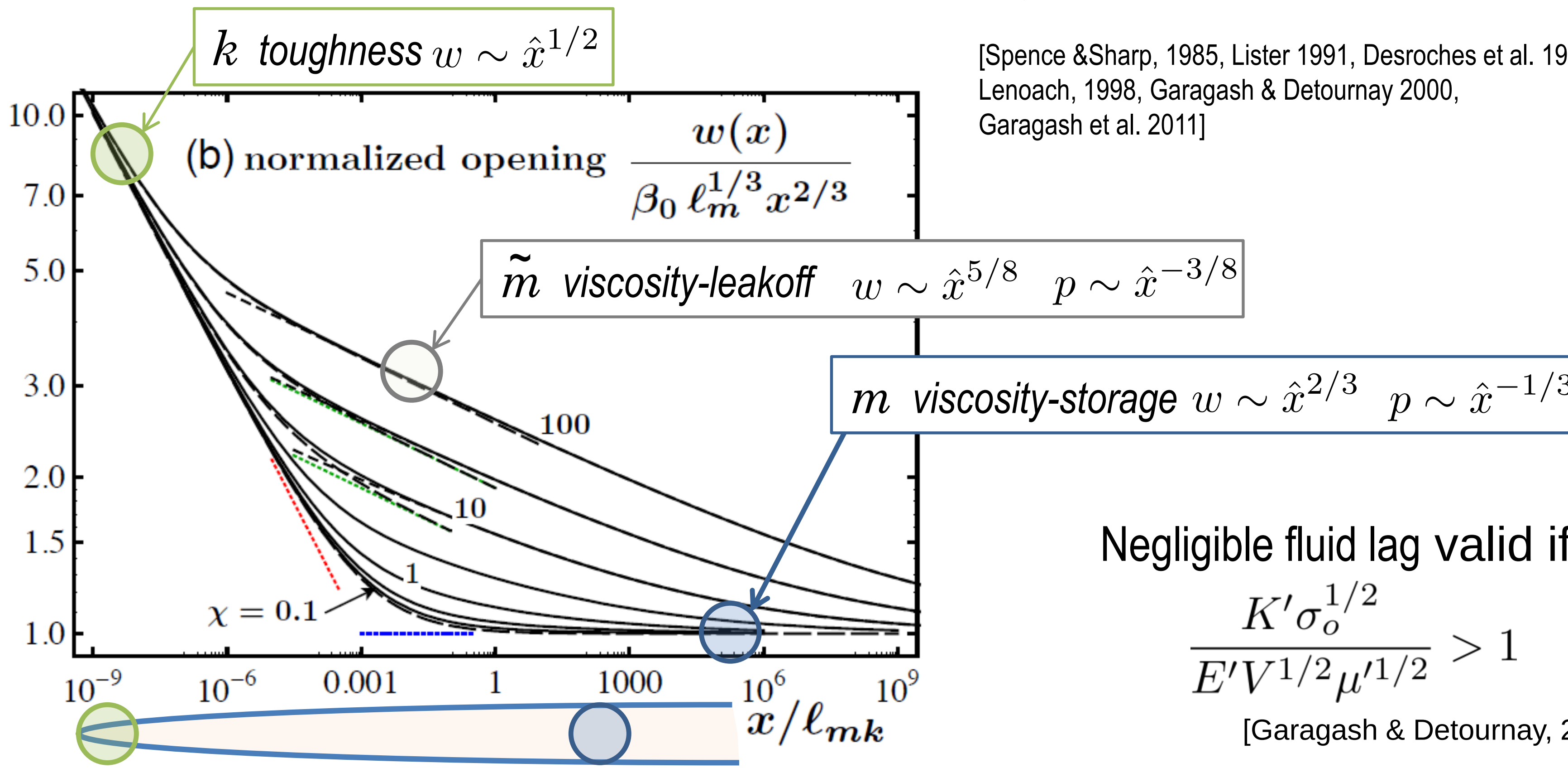


[Garagash et al., *JFM* 2011]

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

$$\chi = \frac{C' E'}{V^{1/2} K'}$$

[Spence &Sharp, 1985, Lister 1991, Desroches et al. 1994, Lenoach, 1998, Garagash & Detournay 2000, Garagash et al. 2011]

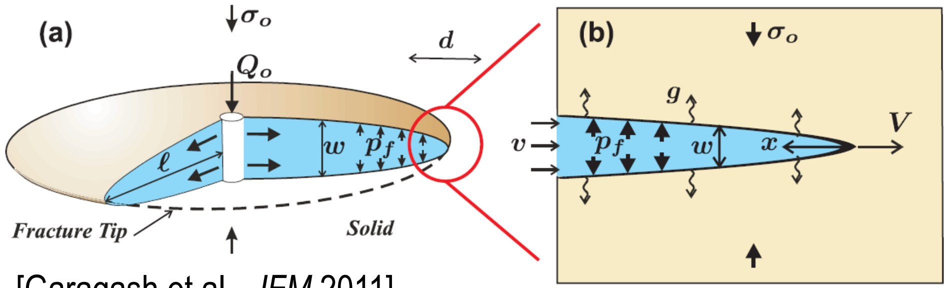


Negligible fluid lag valid if

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

[Garagash & Detournay, 2000]

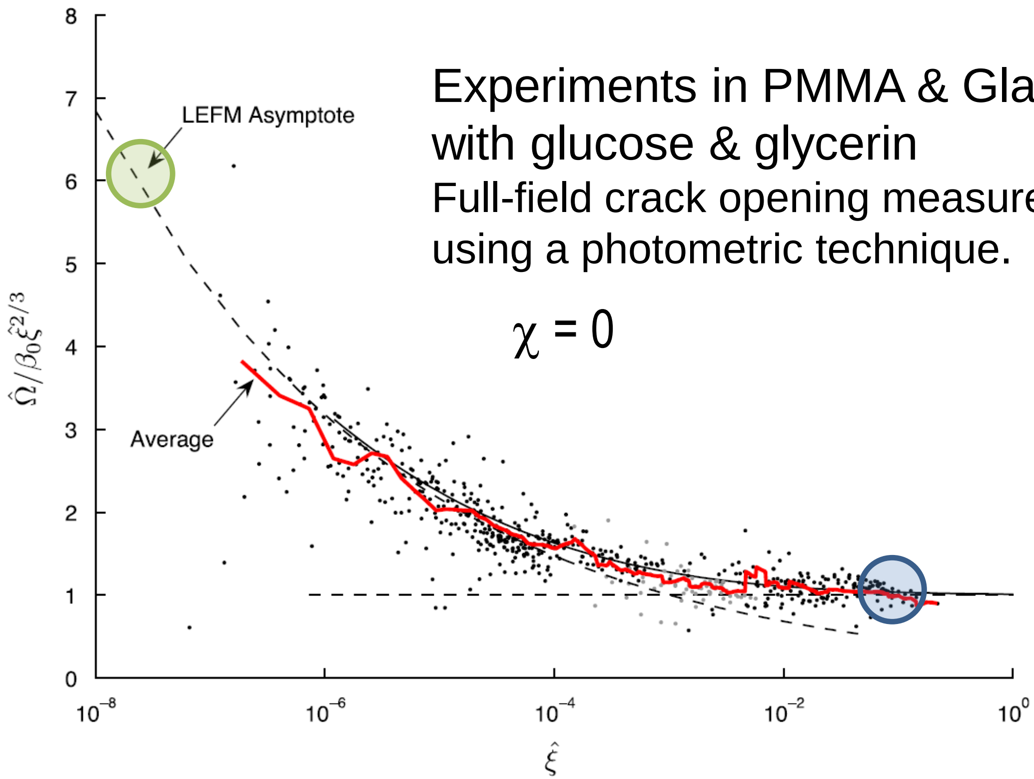
HF tip asymptotes – vs experiments



[Garagash et al., *JFM* 2011]

$$\chi = \frac{C'E'}{V^{1/2}K'}$$

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



Experiments in PMMA & Glass with glucose & glycerin

Full-field crack opening measured using a photometric technique.

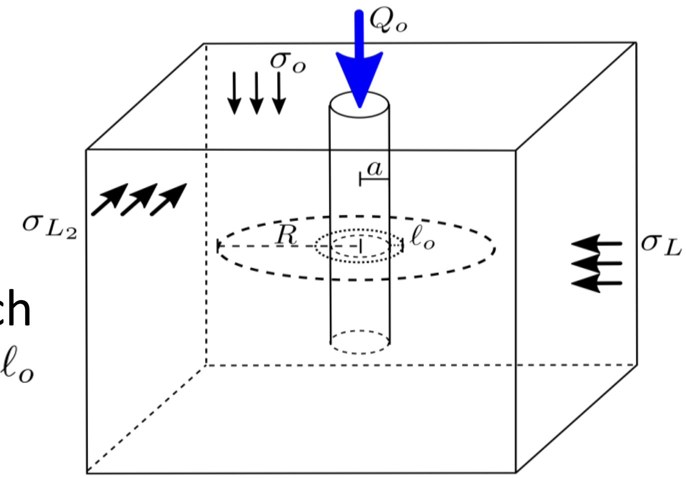
$\chi = 0$

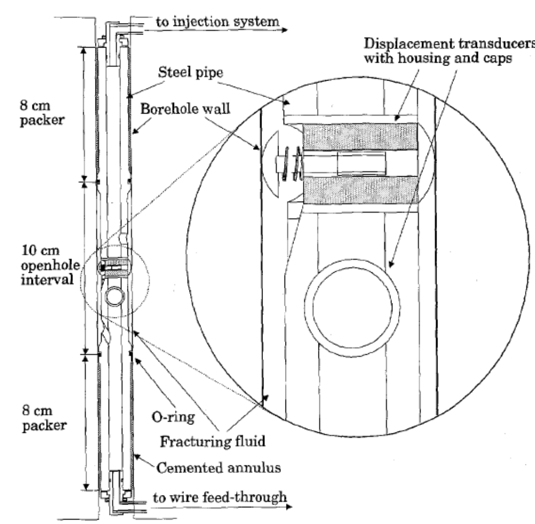
[Bunger & Detournay, JMPS, 2008]

Radial HF - theory vs experiments

- Material Properties
  - Via material testing
- Notch length
  - via casting
- Test Parameters
  - Injection rate, viscosity, system compliance
- Measurements
  - Wellbore Pressure
  - Width: Lvdt (crack mouth), optics (Beer's law)
  - Fracture footprint: Acoustic Transmission, Acoustic Emission

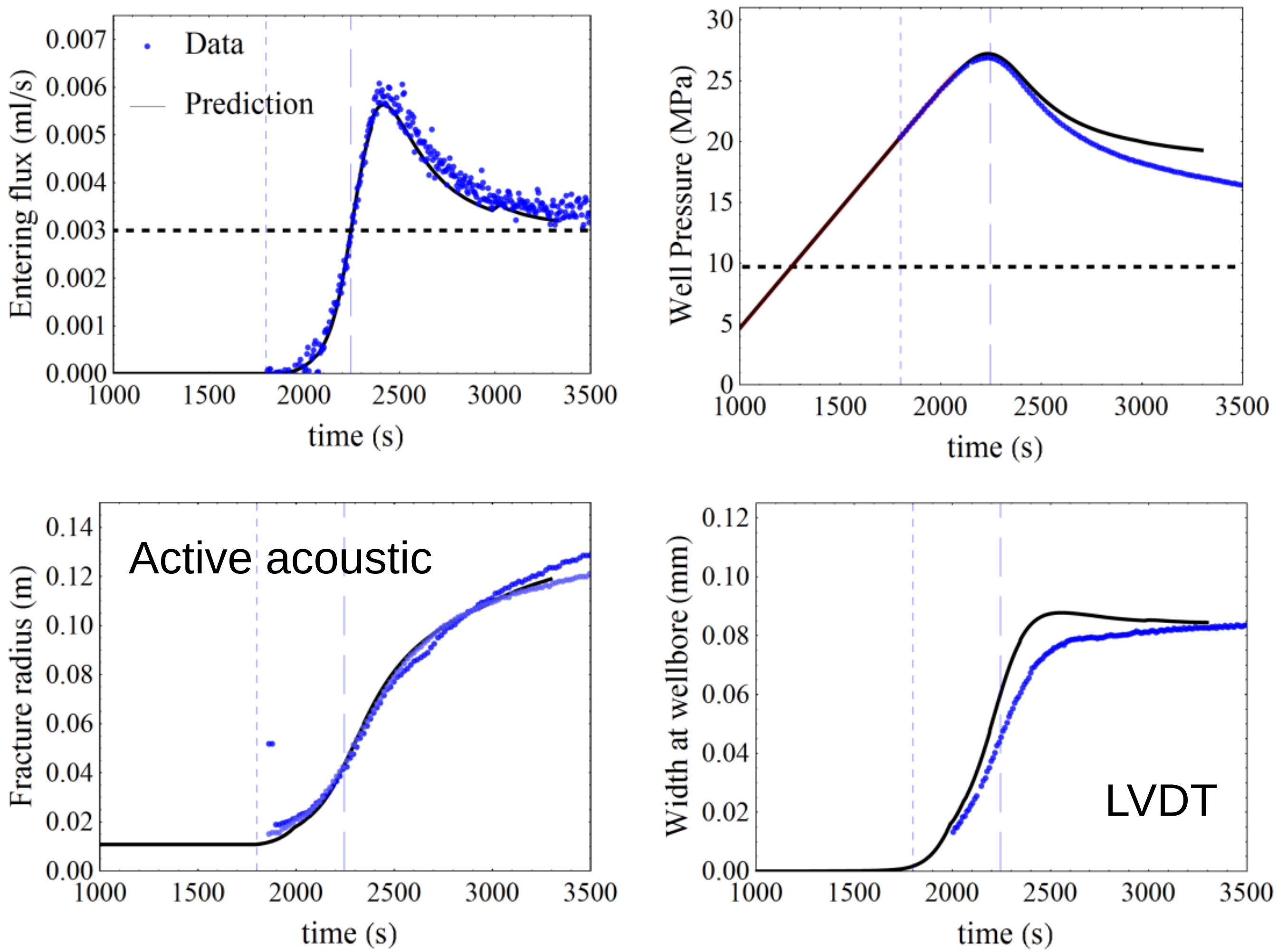
Initial notch
$R(t=0)=\ell_o$





[Weijers et al., 1995]

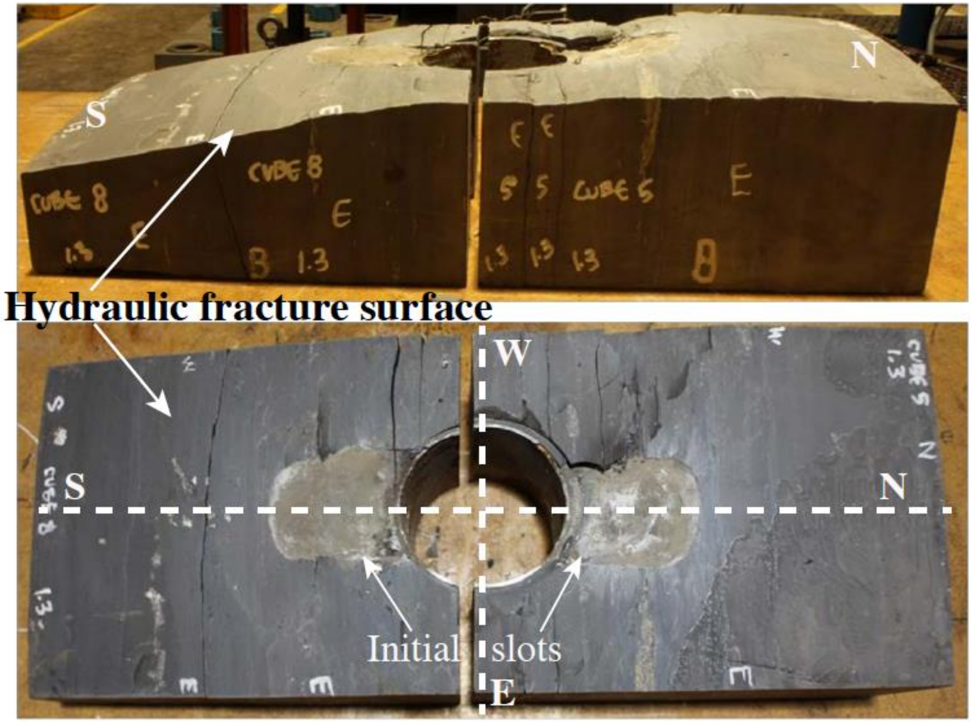
Cement – cov12c

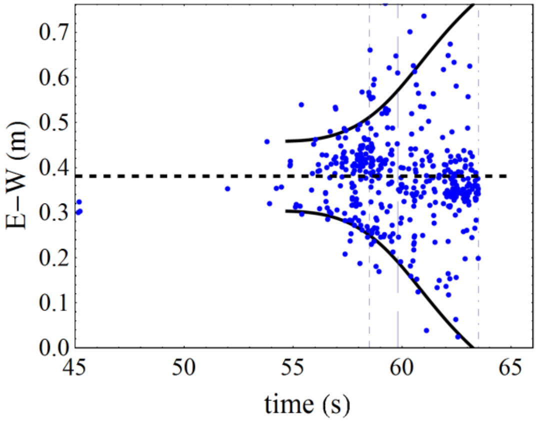


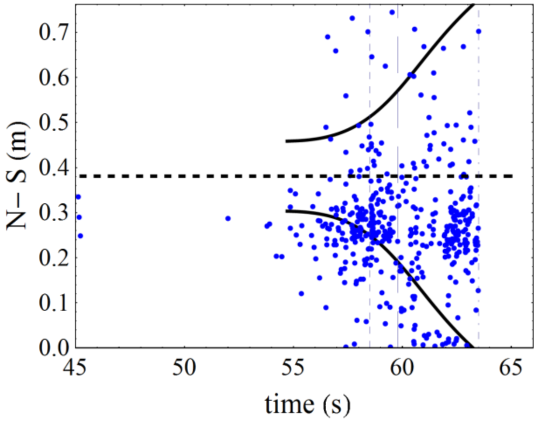
[Lecampion et al. 2017]

Niobrara shale

- 2 slots not a radial notch
- Asymmetric propagation
  - N/S vs E-W
- Radial model captures initiation & growth

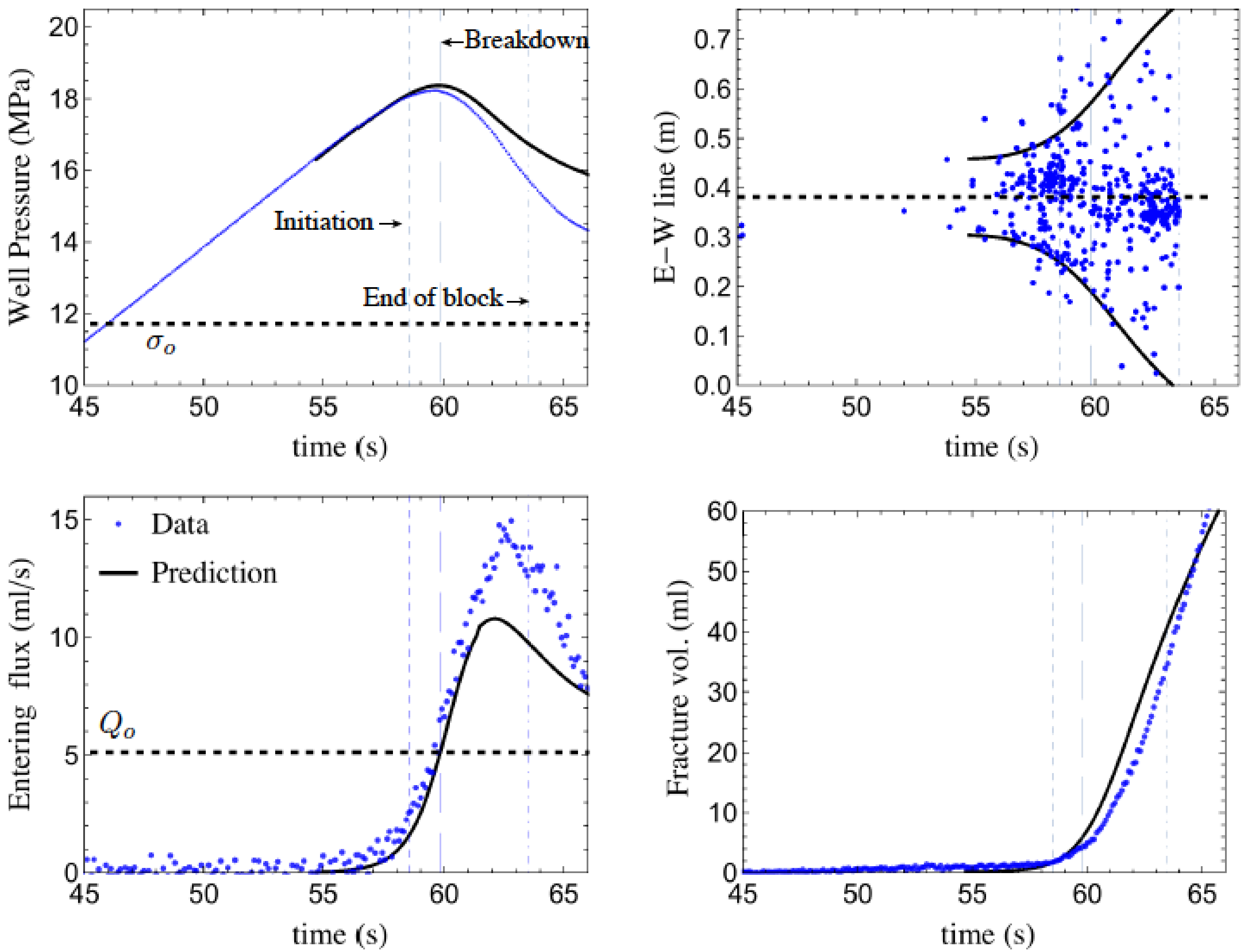






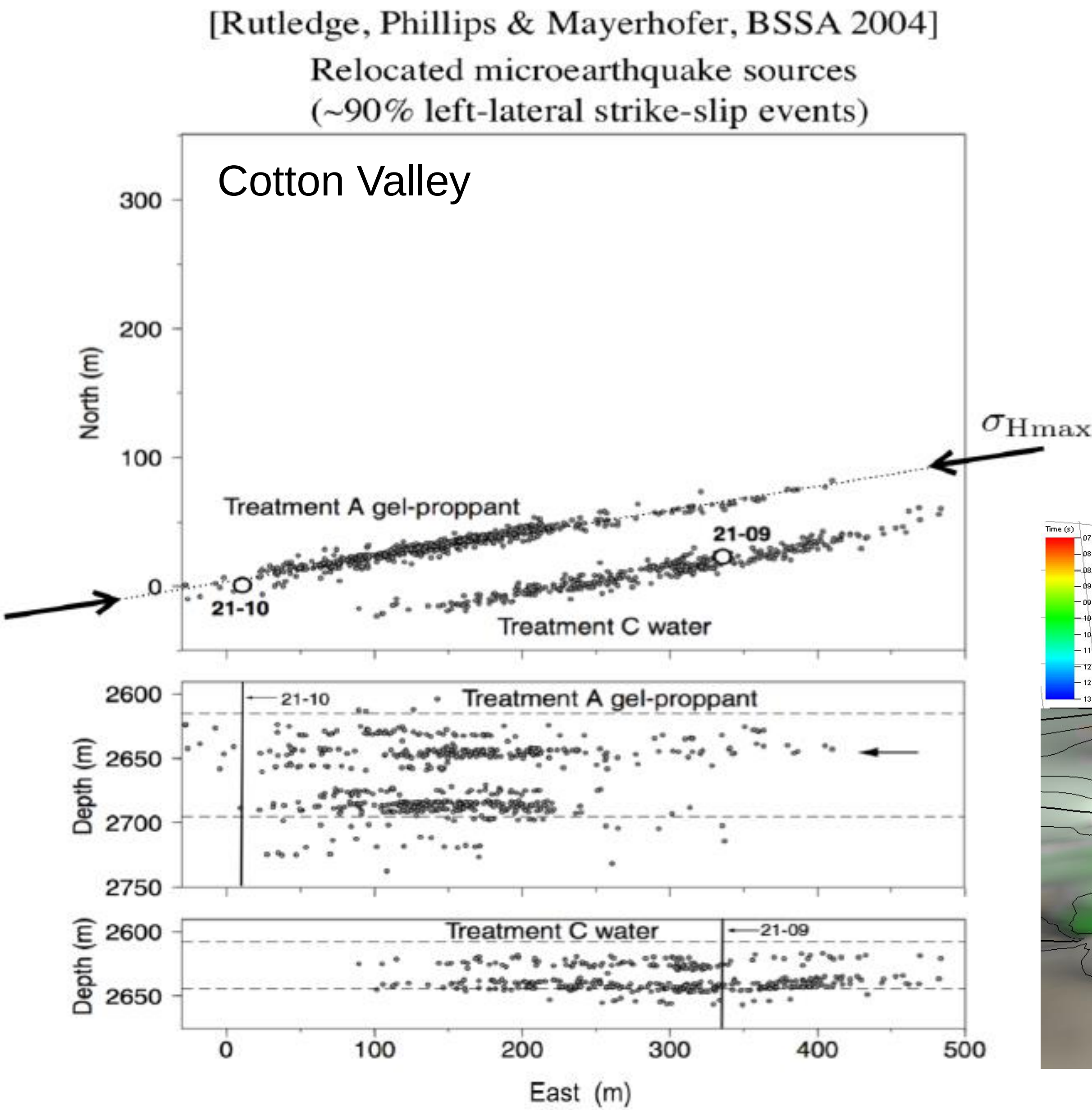
[Lecampion et al. 2015]

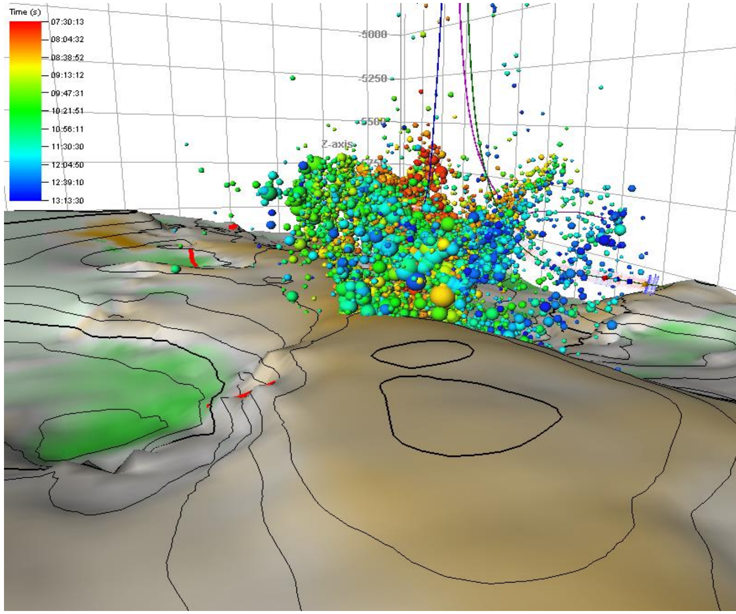
Niobrara shale



[Lecampion et al. 2015]

Micro-Seismicity as a monitoring tool





Mostly small events

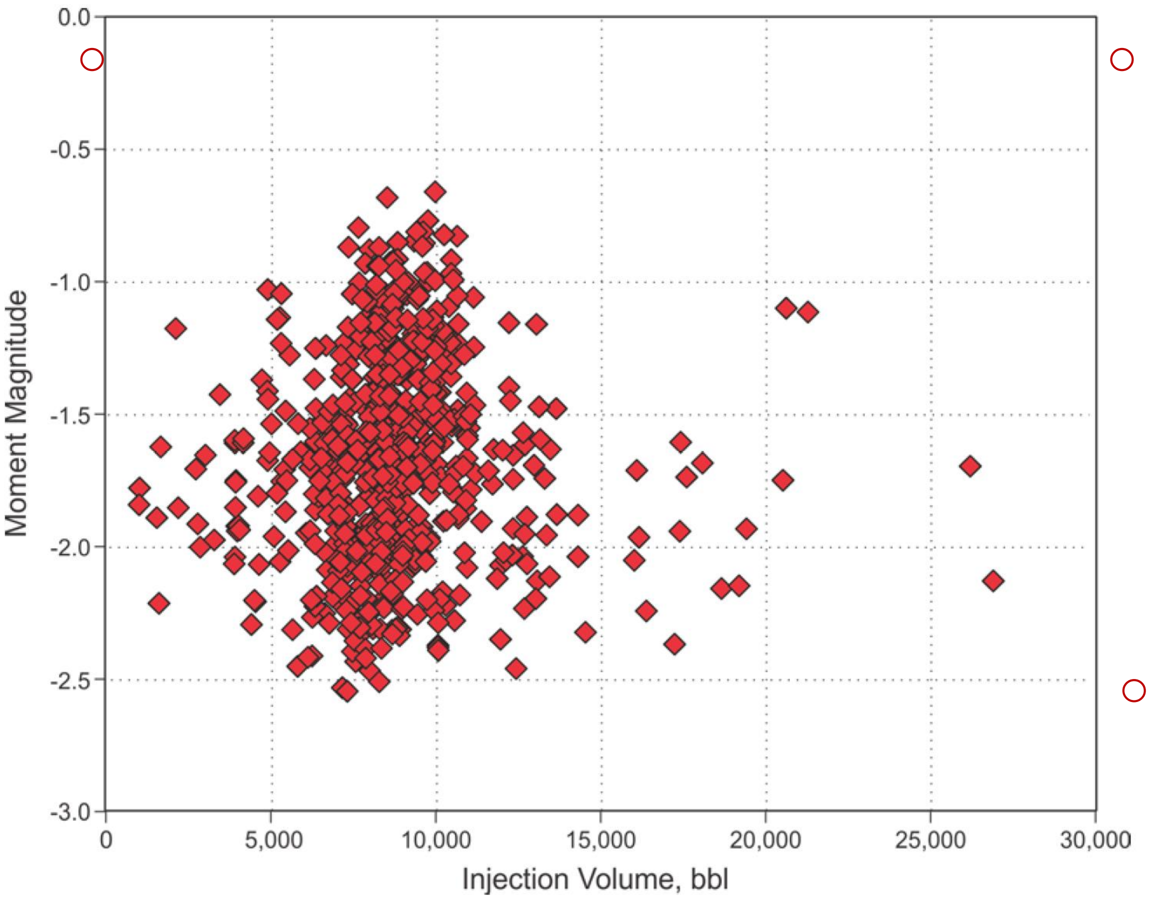


Fig. 10—Moment magnitude versus injected volume for Marcellus shale projects.

[Warpinski et al, 2012]
SPE 151597

- MS events during HF
  - M_w -3. up to 0-1
  - Less than 0.01% to the total energy input !

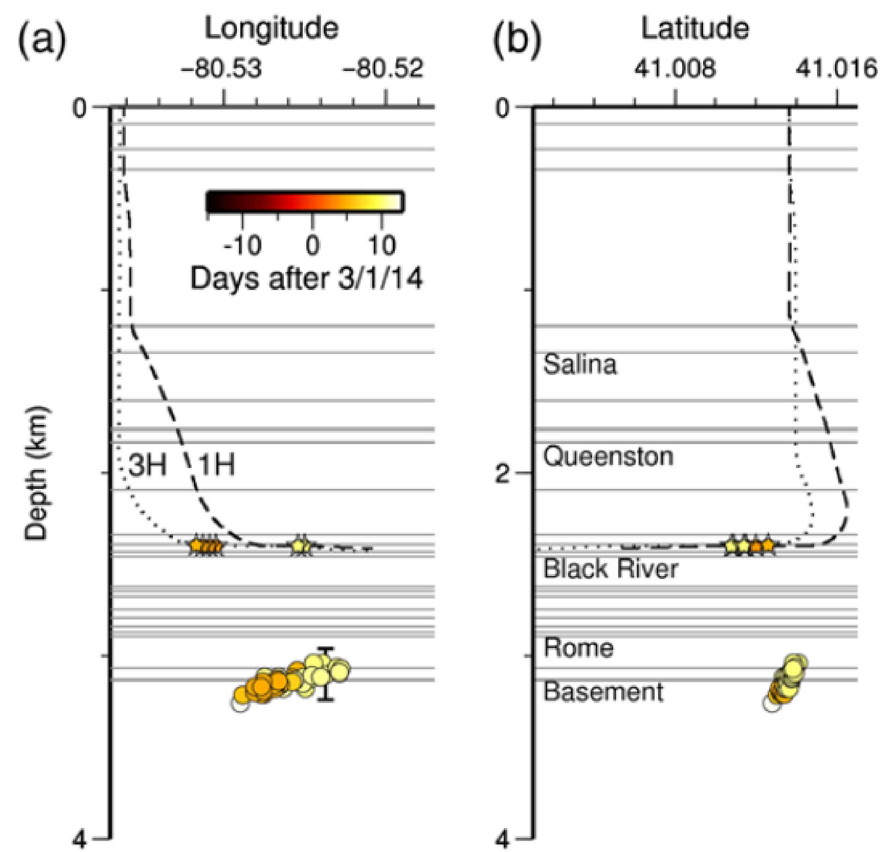
[Cipolla et al, 2012] SPE152165
[Warpinski et al, 2012] SPE 151597
etc.

- Note
  - Events also after shut-in
  - Combination of stress perturbation & pore-pressure diffusion

[Shapiro, 2015]

Examples of 'Large' events associated with HF

- Blackpool, UK 2011 (M_L~2.7)
  Bowland shale
  - Strike-slip stress regime
  - Reverse fault
  - Distance to injection zone:
    360m below, 400m east
    [e.g. Clarke et al., 2014]
- Ohio, Poland Township (M_L~3)
  Utica shale
  - Strike-slip stress regime
  - Distance to injection zone:
    ~ 600m deeper
    [Skoumal et al., 2015]
- Fox Creek 2013-15 (M_w ~ 3.9)
  Duvernay Shale
  - Strike-slip stress regime
  - Distance to injection zone:
    >1km horizontally,~ 200-700m deeper
    [Schultz et al. 2015, Bao & Eaton, 2016]

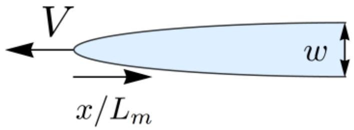


[Taken from Skoumal et al., 2015]

Stresses perturbation due to a growing HF

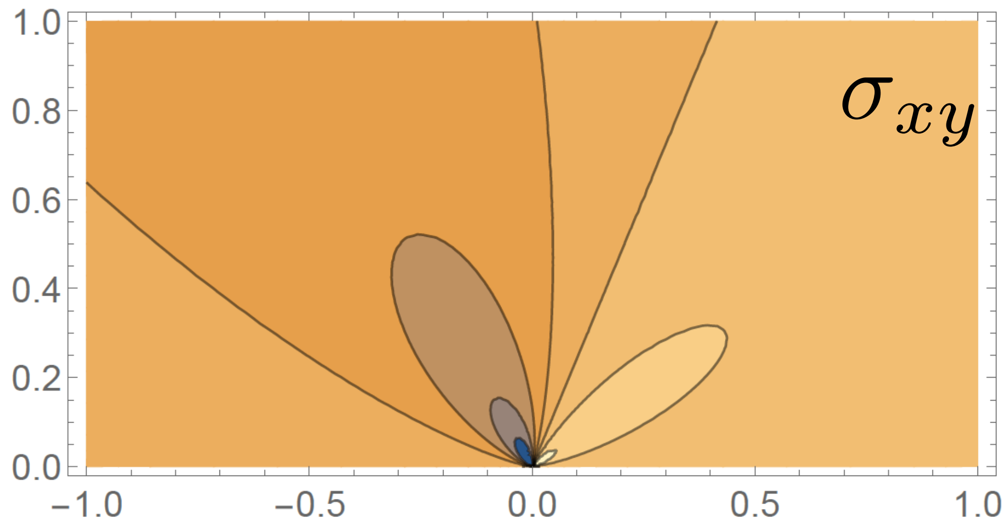
- Near tip – viscosity dominated asymptote

[Desroches et al. 1994]



$$\sigma_{ij} \propto \frac{4E'}{27 \times 3^{1/3}} \left(\frac{r}{L_m} \right)^{-1/3}$$

$$L_m = \frac{V\mu}{E'}$$



Example

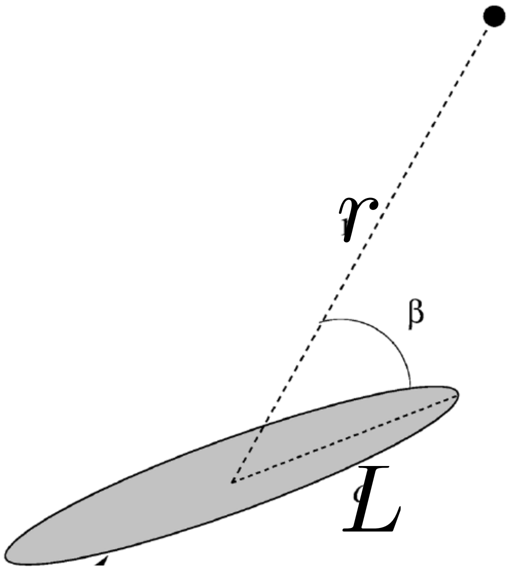
$$\mu = 5\text{cP},\, V = 2\text{m/s},$$

$$E' = 25\text{GPa}, L_m \approx 10^{-12}\text{m}$$

$$\sigma_{ij} \propto 256\text{kPa at 1 meter}$$

$$\sigma_{ij} \propto 111\text{kPa at 10 meters}$$

Stresses perturbation due to a growing HF



- Far-field asymptote
  Stress perturbation decays as

$$\sigma_{ij} \approx \frac{E'}{4\pi} \times \frac{V_{frac}}{r^3} \Sigma_{ij} \text{ when } r > L$$

- Example:

$$V_{frac} = 70\text{m}^3,\ E' = 25\text{GPa},\ r = 300\text{m}$$

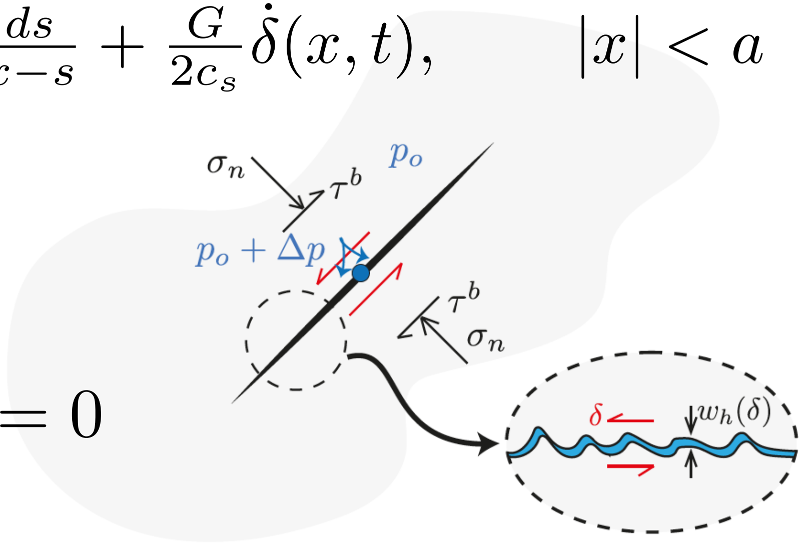
$$\sigma_{ij} \propto 6\text{kPa}$$

Pressurization of a fault

- Shear crack

$$\tau(x,t) = \tau^b - \frac{G}{2\pi\cdot(1-\nu)} \int_{a_-(t)}^{a_+(t)} \frac{\partial\delta(s,t)}{\partial s} \frac{ds}{x-s} + \frac{G}{2c_s}\dot{\delta}(x,t), \qquad |x| < a$$

$$\tau(x,t) \leq f(\delta)(\sigma_n - p(x,t))$$

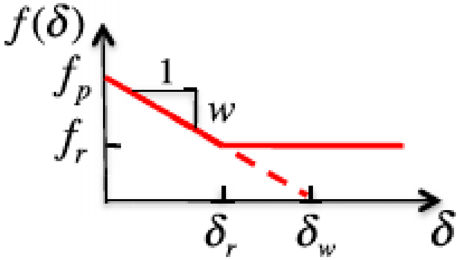


- Fluid flow along the fault

$$w_h c_f \frac{\partial p}{\partial t} + \frac{\partial w_h}{\partial t} - \frac{\partial}{\partial x}\left(\frac{w_h k_f}{12\mu}\frac{\partial p}{\partial x}\right) = 0$$

- Ultimately stable vs unstable

$$\tau^b < f_r(\sigma_n - p_o)$$
$$\tau^b > f_r(\sigma_n - p_o)$$



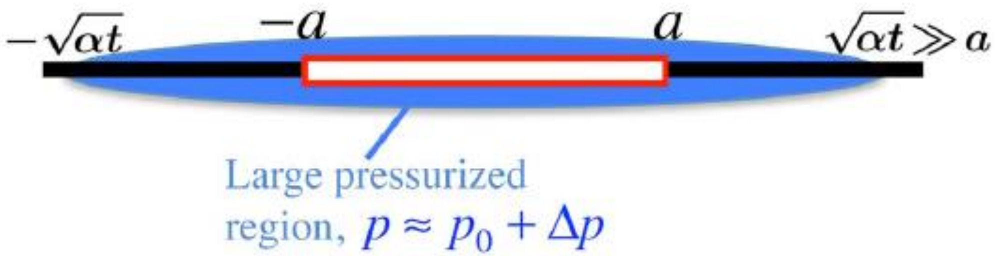
- Marginally pressurized fault can exhibit dynamic nucleation and arrest

[Garagash & Germanovitch, 2012]
[Viesca & Rice, 2012]
etc.

Pressurization of a fault

(a) $\tau_p - \tau^b \simeq f_p \Delta p$

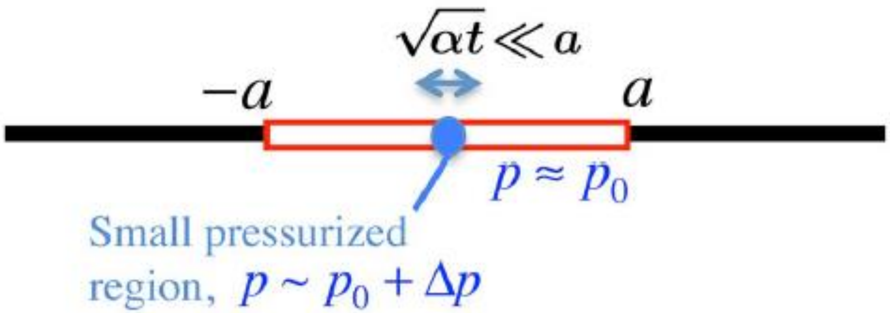
Marginally pressurized



$$a_c = 0.579 \frac{G}{\tau_b} \delta_w$$

(b) $\tau_p - \tau^b \ll f_p \Delta p$

Critically stressed

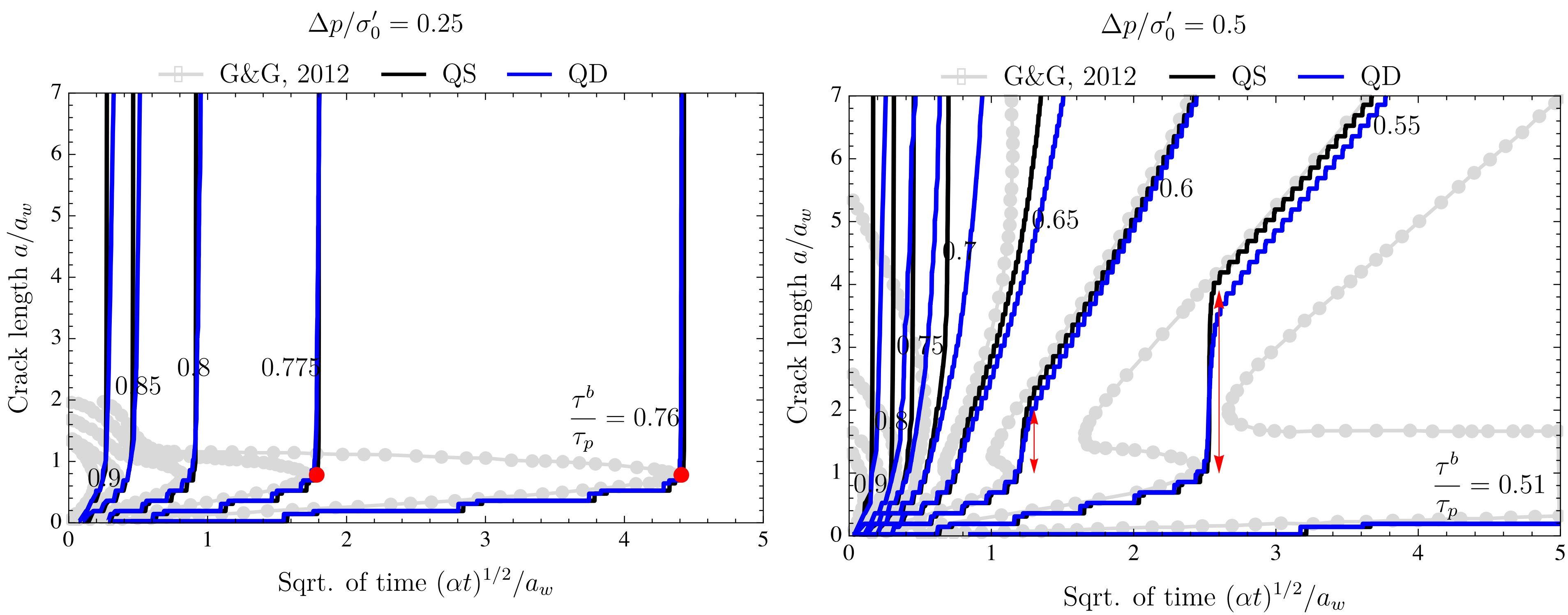


$$a_c = 0.579 \frac{G}{f_p(\sigma_n - p_o)} \delta_w$$

[Garagash & Germanovitch, 2012]
[Uenishi & Rice, 2003]

Numerical examples – No dilatancy case

Benchmarking with semi-analytical results from Gargarash & Germanovitch



P1-15
F. Ciardo

$$a_w = \frac{G}{\tau_p(1-\nu)}\delta_w \qquad \alpha = \frac{k_f}{c_f\, 12\mu}$$

$$f_r/f_p = 0.6$$

Conclusions

- Hydraulic fracture mechanics is predictive at least for simple fracture geometry (pure mode I)
- Micro-seismic events are related to stresses perturbations around the growing HF ('undrained like response')
- "Large" events occurring during hydraulic fracturing are due to the nucleation of dynamic slip on a pre-existing fault
  - Due to pore fluid pressurization into the fault
  - (less likely to be stress changes induced by the HF)
- Dynamic nucleation appears to occur below the injection interval (basement)… variation of in-situ stress & frictional properties ?
- In view of EGS applications, models must account for both quasi-static slip and dynamic nucleation
- Development of fully coupled model for mixed mode fluid driven fractures (& EQ nucleation) requires careful benchmarking with both semi-analytical solutions & lab experiments