GEOMECHANICS FOR GEOPHYSICISTS

Hydraulic Fracturing

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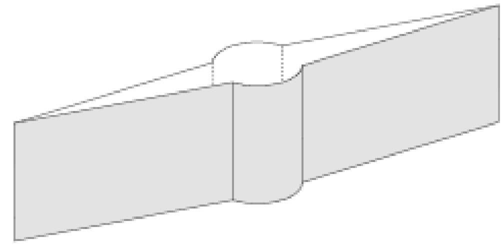
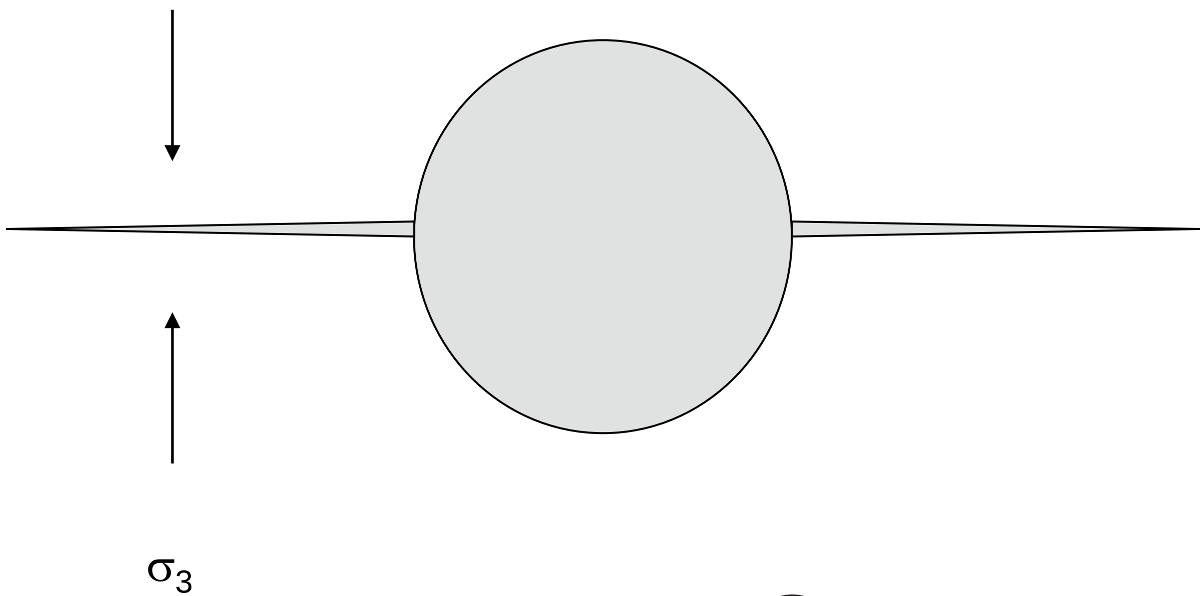


Hydraulic Fracturing



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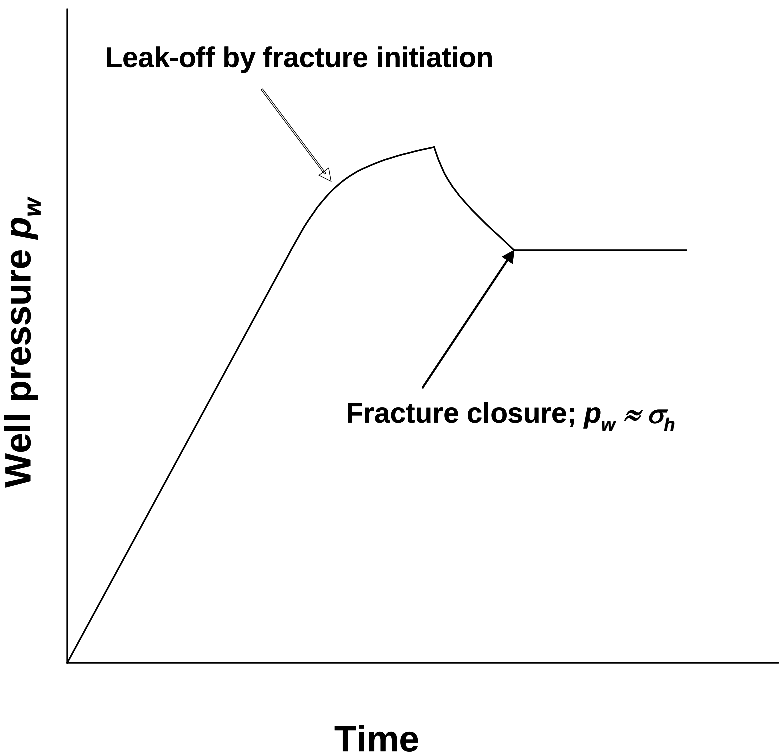
Hydraulic Fracturing

- First done in Hugoton gas field, Kansas, USA (1947)
- Since then ~ 1 mill. wells fractured
- Applications:
  - Well stimulation (low permeability formations)
    - Tight gas sands; Gas Shale
  - ”Frac & pack”:
    - Reduced sanding potential (reduced pressure drop near well); Skin removal (high permeability formations)
  - Fracturing during water injection
    - To overcome plugging problems around injector
    - Thermally induced fracturing
  - Waste storage
  - Stress determination & Well design
    - Tests to assess mud weight window for stable drilling

- Hydraulic fracturing may also take place
  - By accident during drilling → lost circulation / mud loss
  - Naturally (e.g. migration of hydrocarbons from source to reservoir rocks)

Hydraulic Fracturing



Fracturing by increasing well pressure in a closed interval of the well

Fracture initiation pressure is given by:

$$\sigma_\theta' = -T_0$$

Impermeable borehole wall (upper limit; fast pressurization):

$$p_w^{frac} = 3\sigma_h - \sigma_H - p_{f0} + T_0$$

VERTICAL WELL

Permeable borehole wall (pore pressure equilibrium has been established; lower limit, slow pressurization):

$$p_{w,frac} = \frac{3\sigma_h - \sigma_H + T_0 - \alpha \frac{1-2\nu}{1-\nu} p_{f0}}{2 - \alpha \frac{1-2\nu}{1-\nu}}$$

Always applicable to rocks with > µDarcy permeability?

Fracture closure:

$$p_w^{close} = \sigma_3 \qquad (usually = \sigma_h)$$

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Hydraulic Fracturing

- **Fractures open up perpendicular to the minimum principal Earth stress**
- **Fractures are usually thin and wide in extension (energetically favourable)**

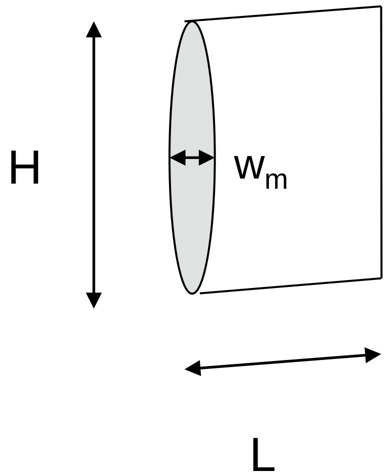
$$W \propto \left[(\sigma_3 + T_0) + \left(\frac{\eta Q}{d^2} \right) \right] Ad$$

Δp

- **High viscosity (η) or high injection rate (Q)→ thick & short cracks (d is thickness)**
- **If stresses are equal :**
  - Fractures prefer to grow in soft & weak formations
  - Fractures prefer to grow in low permeability formations (less fluid leakage to surrounding rocks)
- **But: Often lower horizontal stresses in sand than shale, so fractures may still prefer sands...**
- **Fractures prefer to grow upwards (towards reduced stress environment)**

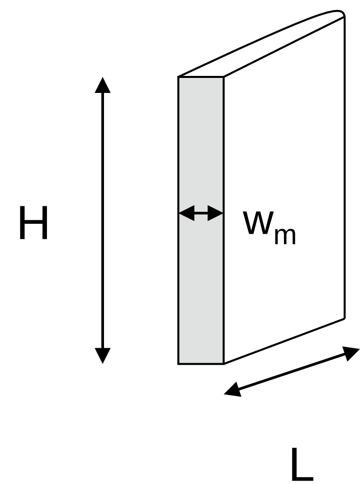
Simple fracture models

- PKN (Perkins-Kern-Nordquist)



$$w_m = \frac{\pi}{E'} L(p_0 - \sigma_3) \qquad \frac{L}{H} >> 1$$

- KGD (Kristianovitch-Geertsma-de Klerk)



$$E' = \frac{E_{fr}}{1 - \nu_{fr}^2}$$

$$w_m = \frac{4}{E'} L(p_0 - \sigma_3) \qquad \frac{L}{H} \leq 1$$

Both models assume constant fracture height H and zero pressure at fracture tip

Fracture geometry

- Assuming constant injection rate (Q=V/t) & no leak-off:

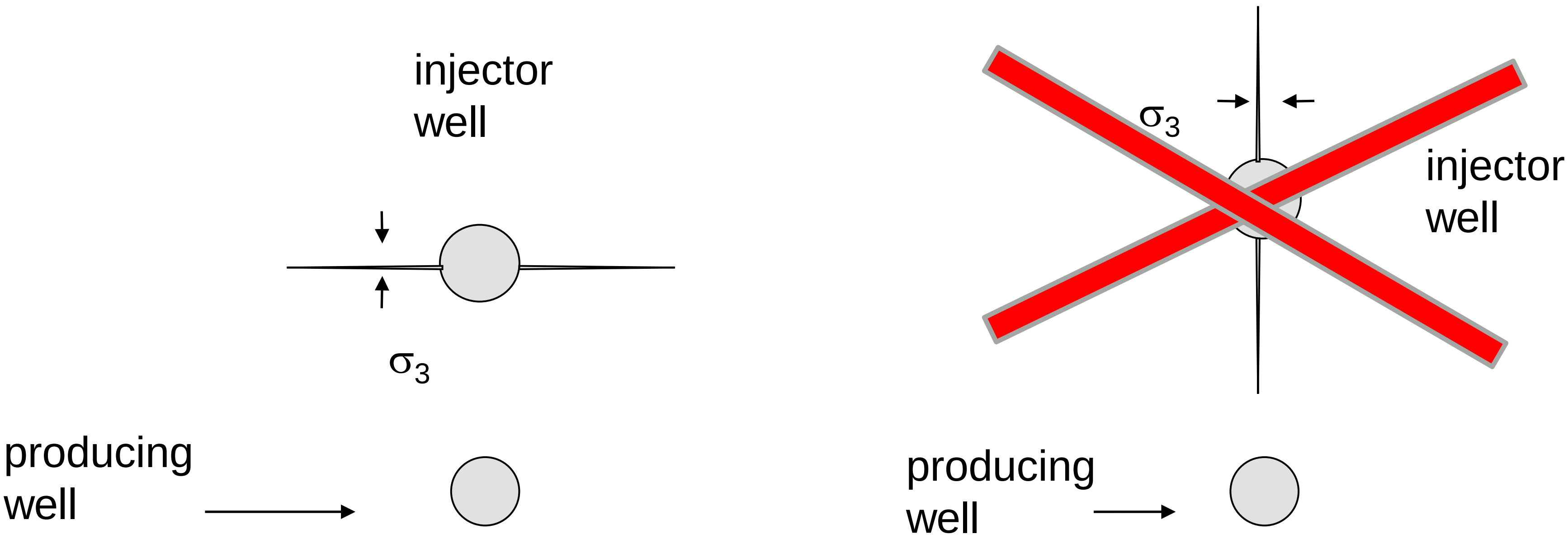
  – PKN: $$L \propto \left\{ \frac{Q^3 E'}{\eta H^4} \right\}^{\frac{1}{5}} t^{\frac{4}{5}}; \quad \overline{w} \propto \left\{ \frac{\eta Q L}{E'} \right\}^{\frac{1}{4}} = \left\{ \frac{\eta Q^2 t}{E' H} \right\}^{\frac{1}{5}}$$ $$\frac{L}{H} >> 1$$

  – KDG: $$L \propto \left\{ \frac{Q^3 E'}{\eta H^3} \right\}^{\frac{1}{6}} t^{\frac{2}{3}}; \quad \overline{w} \propto \left\{ \frac{\eta Q L^2}{E' H} \right\}^{\frac{1}{4}} = \left\{ \frac{\eta Q^3 t^2}{E' H^3} \right\}^{\frac{1}{6}}$$ $$\frac{L}{H} \leq 1$$

Linearly elastic fracture mechanics models are too simple – quantitative predictions are difficult....

Hydraulic Fracturing

- **For all applications: Knowledge of the *in situ* principal stress directions is essential!**



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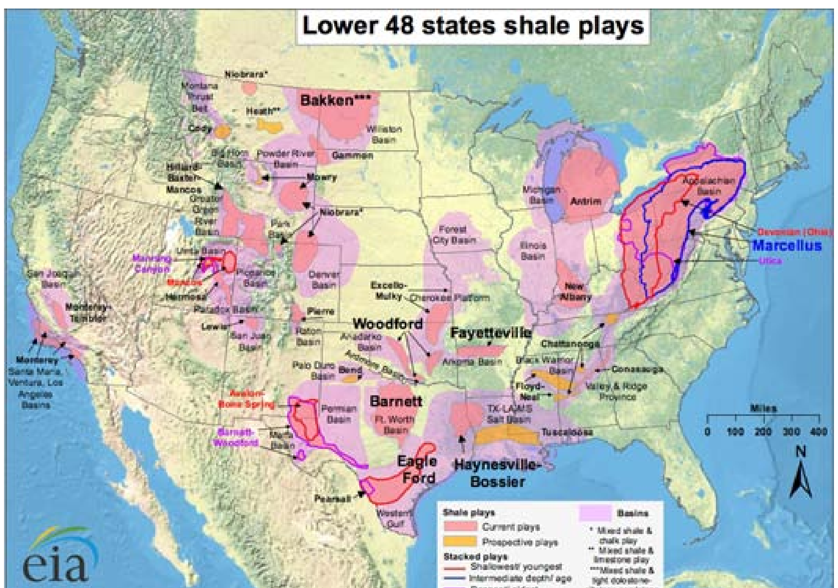
Fracturing for stimulation

- Fractures should be long and narrow
- Minimized leakoff to surrounding formations during fracture propagation
- Fracture is filled with proppants (glass beads, sand) to stay open for fluid flow
  - > 10^3 m^3 fluid & 10^6 kg proppants
- In chalk, acid is used to etch the fracture surfaces and make it stay open

A ”new” application area: Gas Shales

- The 1st producing US natural gas well was drilled in shale in New York in 1821
- During the last 10 years, US development of gas shale has increased steadily; in 2009 amounting to an equivalent of 30 % of US crude oil production
- Recoverable resources have ben estimated to cover ~ 100 years of US gas consumption

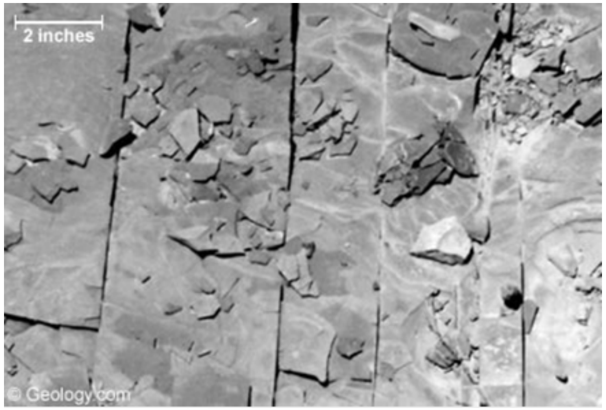


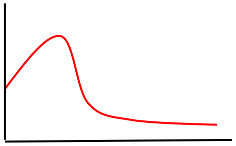
Zoback et al., WWI 2010

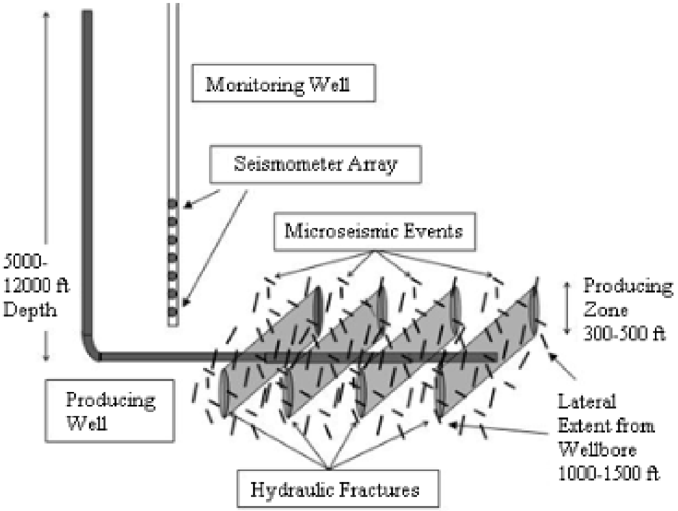
Europe: Several prospects are evaluated, Poland about to start production

Gas Shales

- Shale gas is produced directly from the source rock (not necessarily shale in geological terms! – clay contents may be 10 – 40 %)
- Shales have low permeability (towards nanoDarcy)
- Shale gas reservoirs are often naturally fractured
- Natural gas is in fractures, in pores and adsorbed to organic matter
- The key to success has been combined use of horizontal wells & multi-stage hydraulic fracturing
- But: Recovery peaks early (after ~ 1 year) and shows a rapid decline (over ~ 10 years)







Zoback et al., WWI 2010

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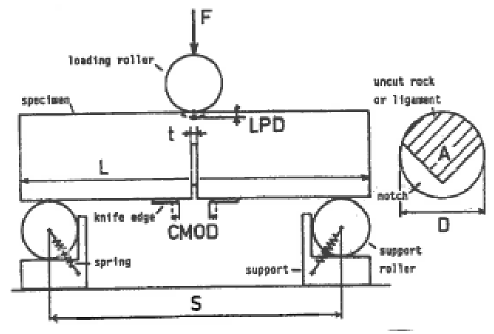
”Frac-ability”?

- Key parameters for fracture initiation & propagation:
  - ”Fracture toughness”: The critical value of the stress intensity factor that makes a fracture unstable (Griffith-theory) (W_s is the specific surface energy characteristic of a created new surface; not directly measurable):

$$K_{IC} = \sqrt{\frac{2W_s E'}{\pi}}$$



  - Brittleness”: Not very well defined – but introduced as a conceptual index parameter for selecting fracturing sites

What is Brittleness?

A material is brittle if, when subjected to stress, it breaks without significant deformation (strain). Brittle materials absorb relatively little energy prior to fracture, even those of high strength. Breaking is often accompanied by a snapping sound.

WIKIPEDIA
The Free Encyclopedia

- Intuitive concept – but is it scientific?
- In rock mechanics: Hucka & Das (1974): 6 different definitions / brittleness index parameters
- + another 10 or so….

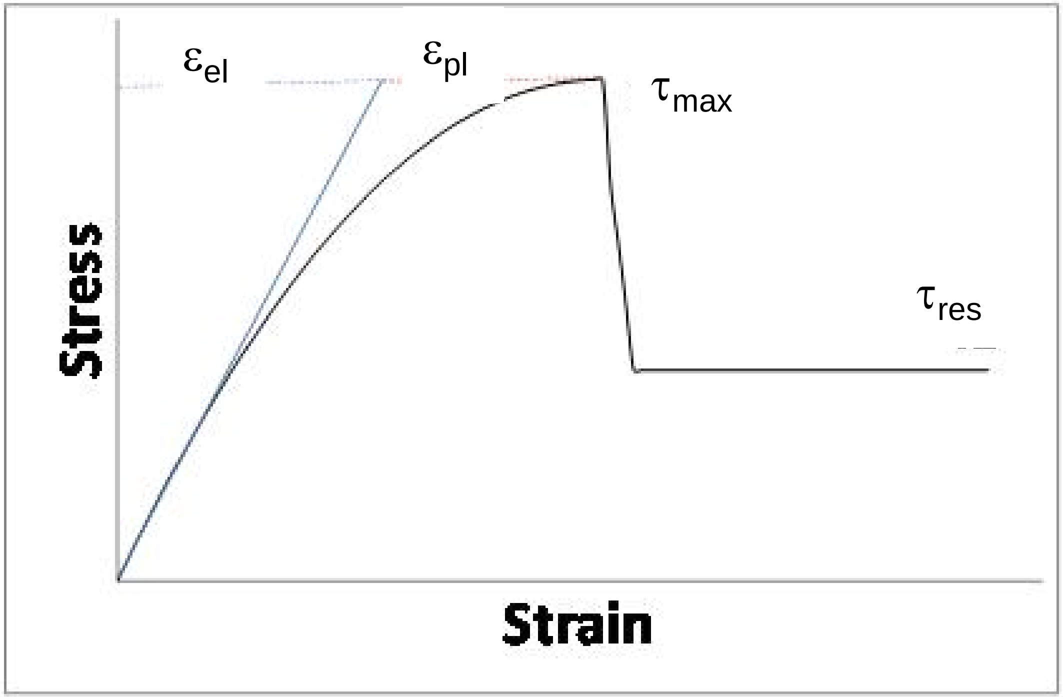
Brittleness

$$B_1 = \frac{\varepsilon_{el}}{\varepsilon_{tot}}$$

$$B_2 = \frac{W_{el}}{W_{tot}}$$

$$B_5 = \frac{\tau_{\max} - \tau_{res}}{\tau_{\max}}$$

$$B_6 = \left| \frac{\varepsilon_f^p - \varepsilon_c^p}{\varepsilon_c^p} \right|$$



- B_1, B_2, B_5 (Hucka & Das, 1974) & B_6 (Hajiabdolmajid & Kaiser, 2003) can be estimated from a single core test
- Post-failure behavior depends on test machine, strain rate control etc
- Note: B_6 is a strain dependent parameter

Brittleness

$$B_3 = \frac{C_0 - T_0}{C_0 + T_0}$$

$$B_4 = \sin\varphi$$

C_0: Unconfined strength
T_0: Tensile strength
φ: Friction angle

- B_3 & B_4 require multiple core tests

$$B_7 = OCR^b$$

$$OCR = \frac{\sigma'_{\mathrm{v,max}}}{\sigma'_{\mathrm{v}}}$$

$$\sigma'_{\mathrm{v,max}}[MPa] = 8.6C_0[MPa]^{0.55}$$

$$C_0[MPa] = 0.77\mathrm{v}_P[km/s]^{2.93}$$

$$B_8 = \frac{1}{2}\left(\frac{E_{dyn}\left[Mpsi\right](0.8-\phi)-1}{8-1} + \frac{\nu_{dyn} - 0.4}{0.15-0.4}\right)\cdot 100$$

- B_7 (Ingram & Urai, 1999; with Nygaard *et al*., 2006; and Horsrud, 2001) & B_8 (Rickman *et al*., 2008) may be estimated from field data

Gas Shales

- Evironmental aspects:
  - Hydrofrac fluid effects on water quality?
    - Use of enormous amounts of water in dry places…
  - Gas leakage from reservoir to surface?
  - Impact on residents and land use –”footprints”
  - On the other hand: Natural gas is ”green” compared to use of coal and oil…
    - Development of shale gas reduces the need for large scale CO_2 storage

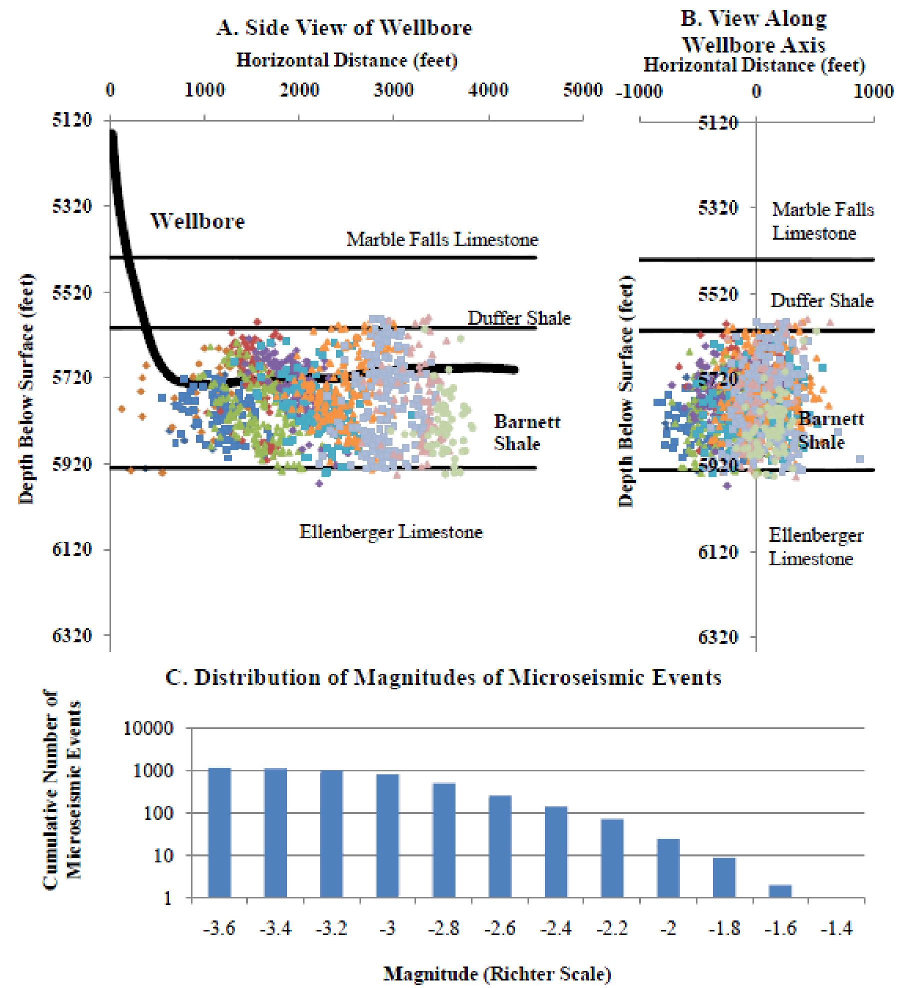
Zoback, 2011

Gas Shales

- **Where do fractures go?**
  - µseismic events: Magnitude -2 corresponds to 0.1 mm slip on a 1 m fault
  - No evidence (based on 2000 frac jobs in Barnett shale) that fractures have grown out of the reservoir sections
  - Leakage: Mainly along wells, i.e. a cement problem

Zoback et al., 2010

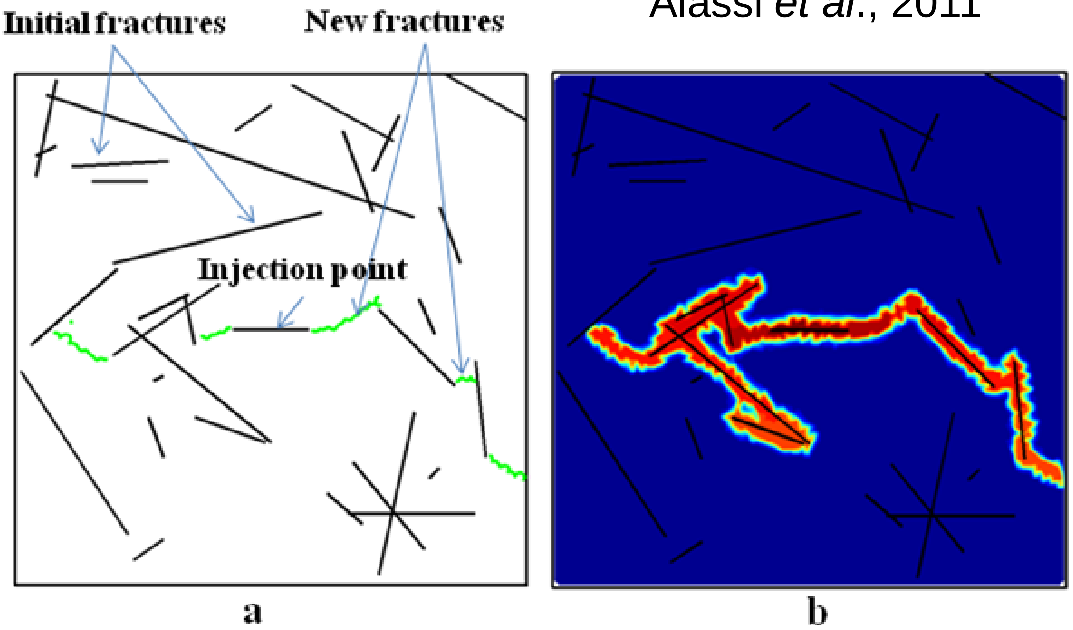
Figure 4. Microseismic Diagrams of Typical Hydraulic Fracturing Job in the Barnett Shale



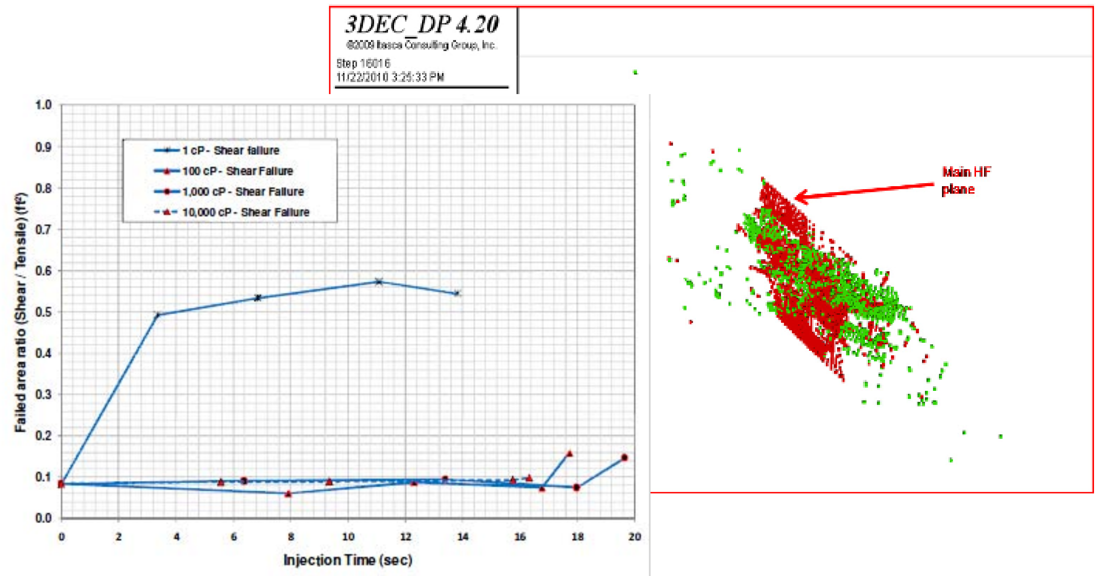
Each dot in Figure 4A and B represents a microseismic event induced during hydraulic fracturing of an actual well in the Barnett Shale, with each color representing a distinct fracturing stage. Figure 4C displays the distribution of these microseismic events by magnitude. Figures are not to scale.
Source: Data courtesy of the Stanford Department of Geophysics

Gas Shales

Alassi *et al*., 2011



- **Where do fractures go?**
  - Computer modelling using a modified Discrete Element code (by SINTEF) permits simulation of fracture initiation and growth in a naturally fractured rock
  - Evidence from DEM study by Itasca that low viscosity injection at moderate rate generates more shear failures associated with natural fractures, which tend to enhance recovery more than opening of tensile hydrofracs



Gil *et al*., 2011

Thermal Fracturing

- **Thermal stresses reduce the tangential stress at the borehole wall by**

$$\Delta\sigma_\theta = \alpha_T \frac{E_{fr}}{1-\nu_{fr}}(T_w - T_f)$$

α_T is the thermal expansion coefficient of the rock (~10^{-5} $^\circ C^{-1}$), T_w is the well temperature, and T_f the formation temperature

- **Cold water injection therefore leads to strongly reduced fracture pressures (~0.2 MPa/ $^\circ$C)**
- **Most injection wells are fractured**
- **Fractures improve performance of injectors**

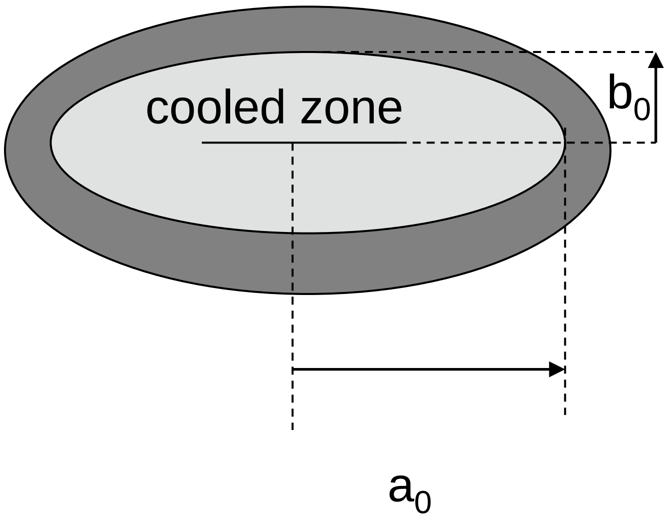
Thermal Fracturing

- Perkins & Gonzales (1985):
  - Change in minimum horizontal stress

$$\Delta\sigma_y = \frac{\alpha_T E_{fr} \Delta T}{1-\nu_{fr}} \frac{(b_0/a_0)}{1+(b_0/a_0)}$$

  - Change in maximum horizontal stress

$$\Delta\sigma_x = \frac{\alpha_T E_{fr} \Delta T}{1-\nu_{fr}} \frac{1}{1+(b_0/a_0)}$$



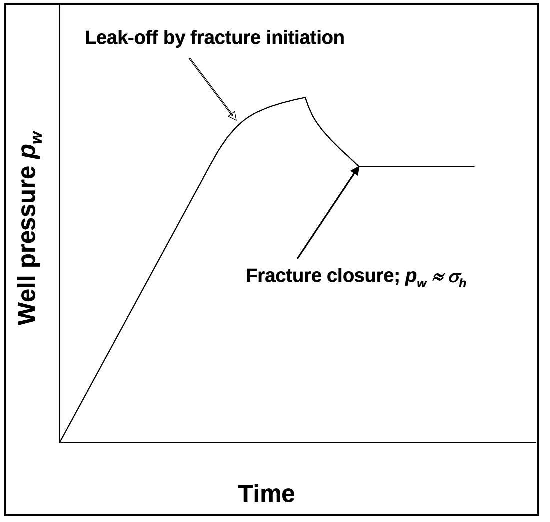
Principal stress directions may swap…

Fracturing for waste disposal

- Injection of solid / fluid / gas waste:
  - drill cuttings, produced sand → ground into a slurry with sub-mm particles and injected as fracturing fluid
  - produced water, CO_2
  - poisonous chemicals, radioactive waste
- Site requirements: Depleted reservoirs or shale (tight) zones
  - No communication to surface, nearby aquifers, or oil & gas wells
- Fractures should be
  - short & thick
  - max leak-off
  - preferentially horizontal

Stress determination

- FIT (Formation Integrity Test):
  - Well pressure is increased in drilling phase to see how large mud weight can be used: Useless for stress determination
- LOT (Leak-Off Test):
  - Pumping until leak-off point; not very reliable
- XLOT (Extended Leak-Off Test):
  - Pumping past fracture initiation with monitoring of pressure during flowback; reliable measure of σ_3 (usually σ_h)
- MiniFrac:
  - Done in order to design a fracturing job
  - Use of high viscosity fluid to generate a fracture with limited extent
  - Often repeated pump cycle, permits estimation of tensile strength



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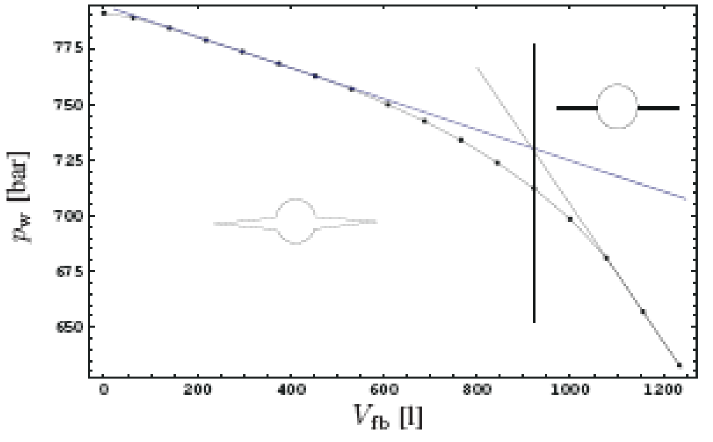
Pump-in - flow-back



Well pressure *vs.* flowback volume after Raaen *et al.* (2001)