Well stimulation in the hydrocarbon industry – Lessons for geothermal applications

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TNO | Knowledge for business

Introduction

Well Stimulation

Economic justification

Expected increased productivity / injectivity ⇔ Treatment cost

Key input: Reservoir

- Permeability
- Natural fracture network
- Soluble / non-soluble damage

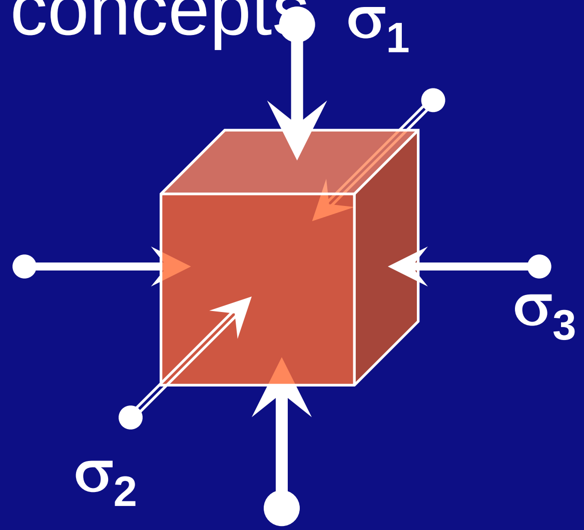
Low-permeability reservoirs: Hydraulic fracturing

Soluble damage: Acidizing

Introduction (cntn'd)

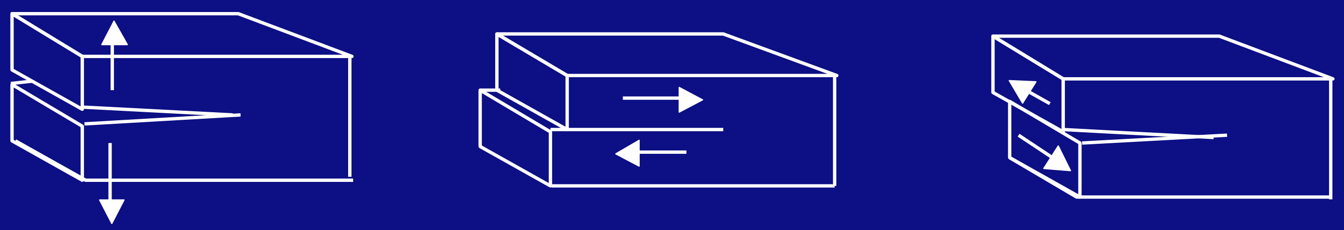
- Matrix acidizing
  - Dissolve "skin" with acid (HCl, HF, EDTA)
  - Not working with all kinds of damage
- Hydraulic fracturing
  - Increase inflow area / break through damage
  - Pump fluid with high pressure – break the formation
  - Pump "proppant" in open fracture
    - Keep frac open after shutin
    - High-permeability path from reservoir to well
- Water fracturing
  - Connect well to considerable reservoir volume
  - Low-perm naturally fractured reservoir
- Acid fracturing
  - Low-perm dolomite / limestone

Hydraulic fracturing – Basic concepts



- Stress: maximum stress vertical; minimum and medium stresses horizontal

- Modes of fracturing



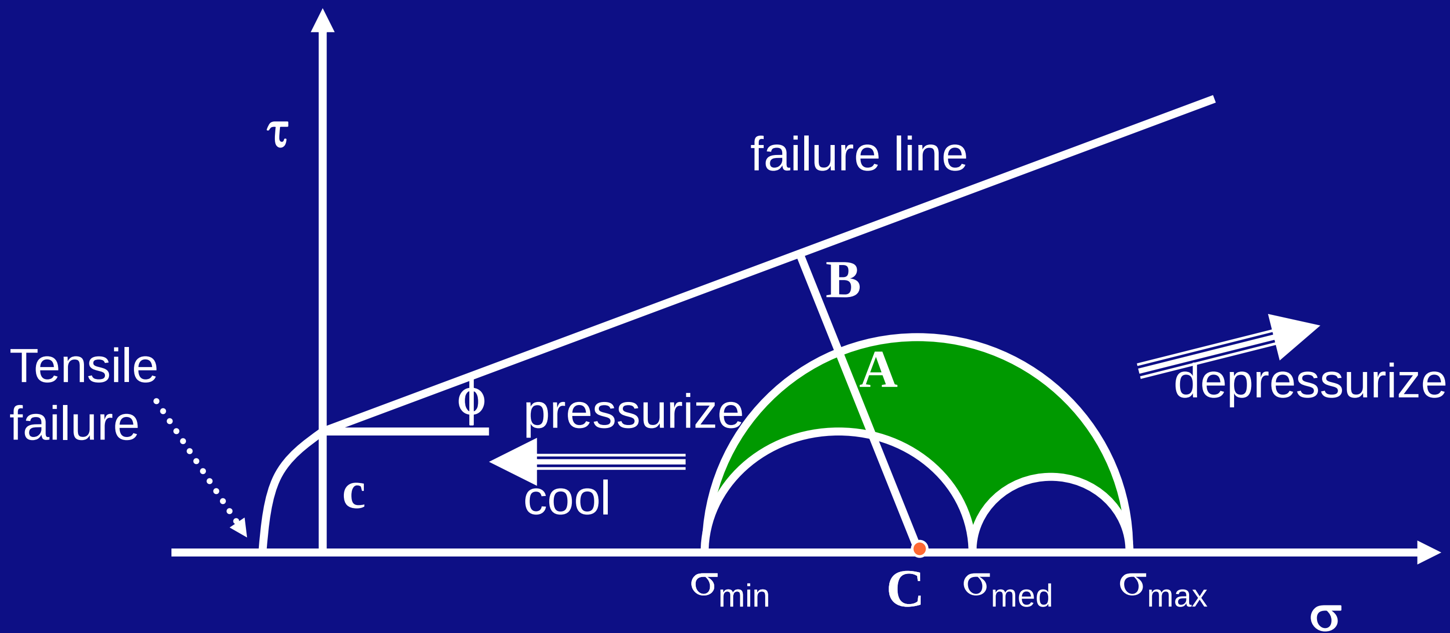
Mode I: Opening Mode II: Sliding Mode III: Tearing

- Hydraulic fracturing: Tensile (mode I) – Vertical fracture has least resistance

Mohr-Coulomb failure criterion

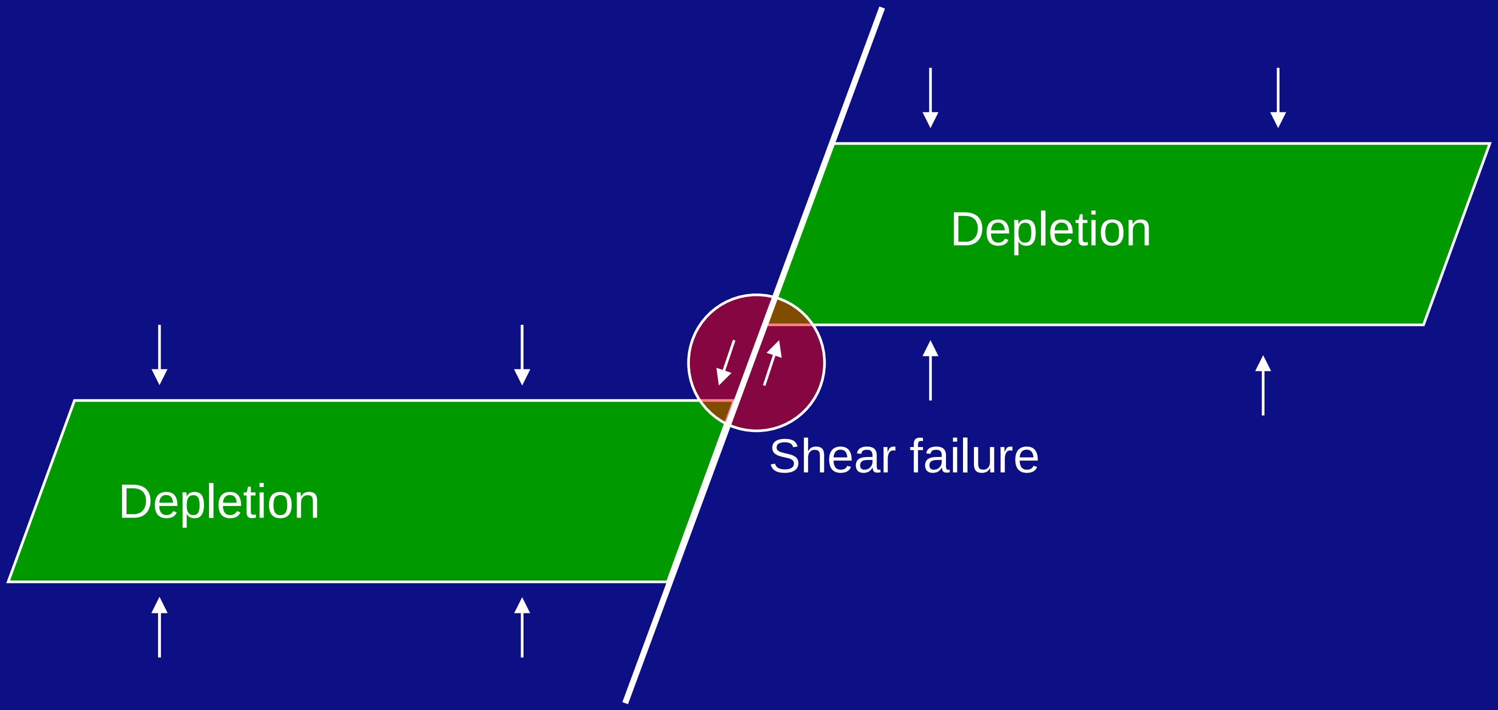
- Shear failure line (Mode II): $\tau = c + \sigma \sin \phi$
- Tensile failure (Mode I): at horizontal axis

- Horizontal axis: Net stress (total stress – pressure)



Example: Failure due to depressurization

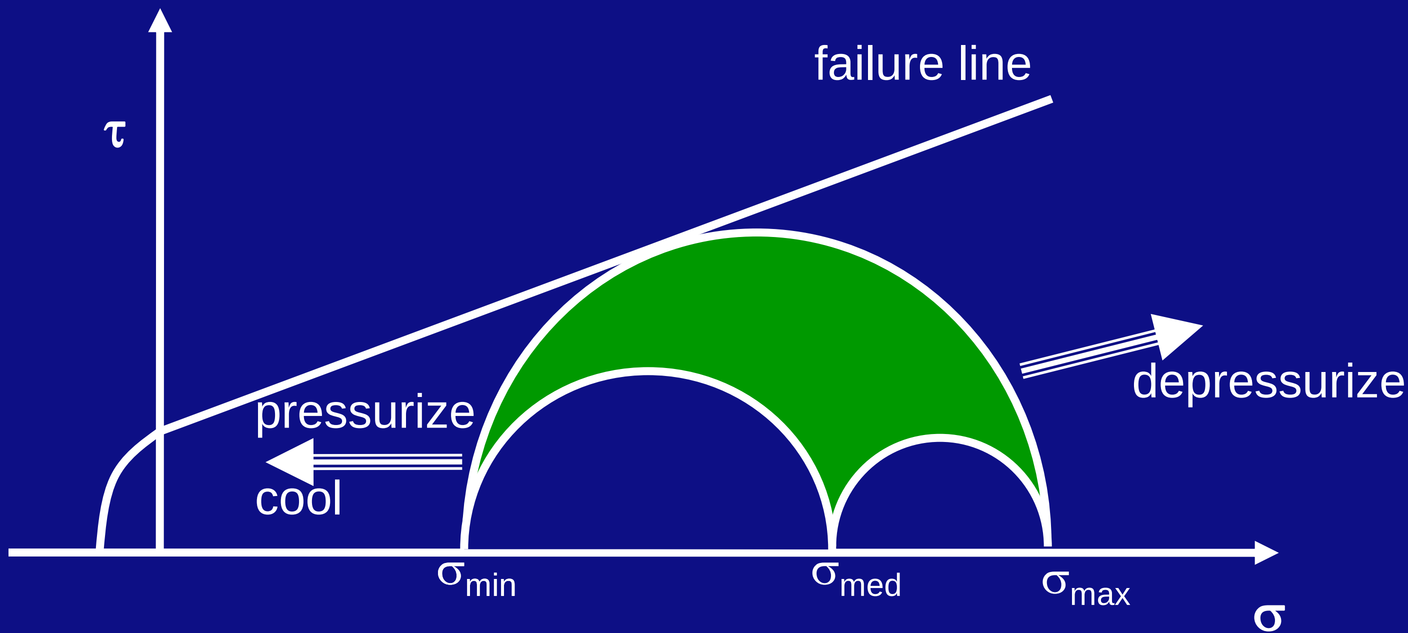
- Shear failure due to depressurization may happen in complex areas
- Reactivation of fault



Critically stressed formation

- Common in tectonically active regions
- Difference between depleted hydrocarbon reservoirs and pressurized geothermal reservoirs: no help of earlier depletion

- Use depleted hydrocarbon fields!



Hydraulic fracturing – Basics

Couple Conservation Laws and Constitutive Equations

- Conservation of Mass
- Conservation of Energy
  - Fracture propagation criterion
- Conservation of Momentum
  - Not relevant

- Incompressibility
- Stresses and strains
  - Hooke’s law
  - Stress intensity factor
- Flux laws
  - Darcy
  - Temperature
- Coupled processes
  - Thermal fracturing

$$K_I = f(w, A)$$

$$w = \frac{V_{fracture}}{A_{fracture}} \propto \frac{L(p - \sigma_3)}{E}$$

$$\frac{dV}{dt} = Q_{inj} - Q_{leakoff}$$

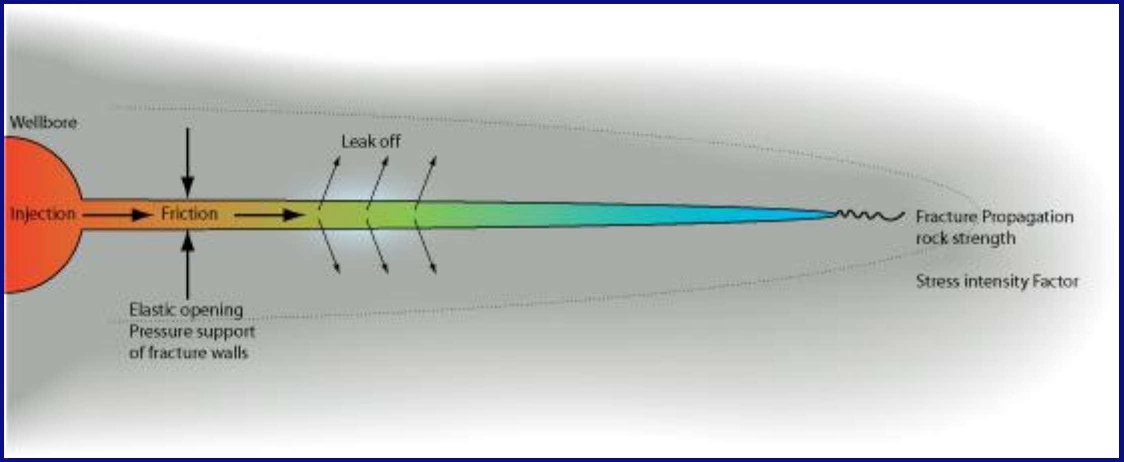
$$Q_{leakoff} = \int_{fracture} v_{leakoff} dA$$

$$v_{leakoff} = \frac{k}{\mu} \frac{p_{frac} - p_{res}}{d_{penetrated}}$$

$$d_{penetrated} = \int_0^t v_{leakoff} dt'$$

Hydraulic fracturing – Visualization of the process

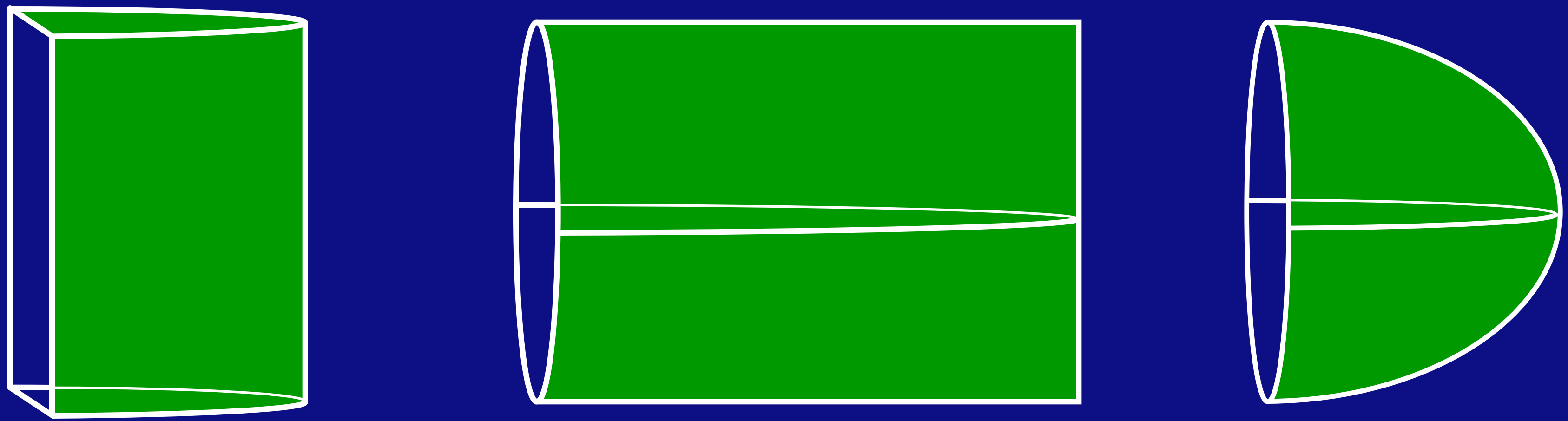
- Processes in hydraulic fracturing; top view



Hydraulic fracturing – Modeling

2D models

- Geertsma – de Klerk / Khristianovic
- Perkins – Kern – Nordgren
- Radial model

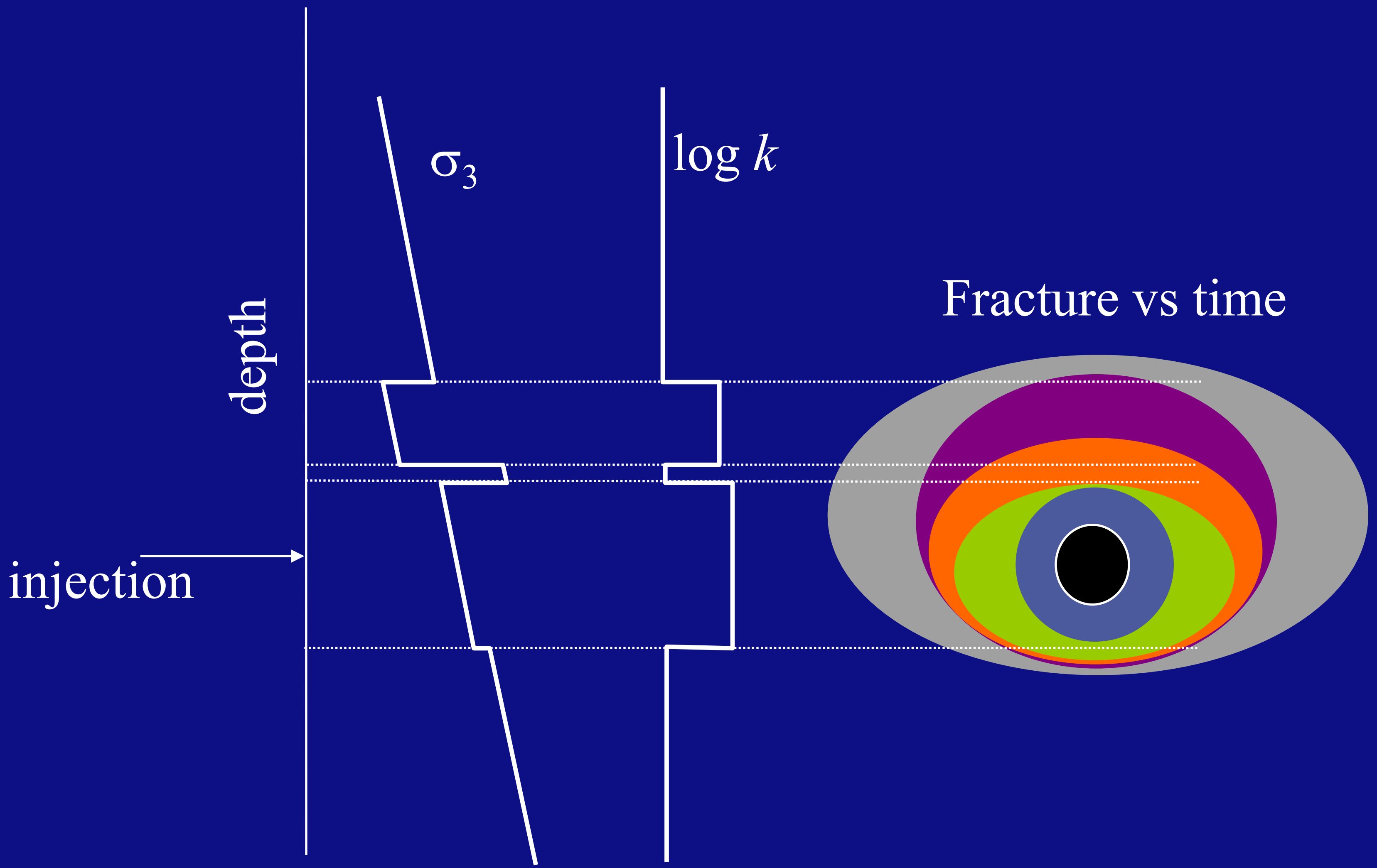


Hydraulic fracturing – Modeling (cntn'd)

3D models

- Profile of the minimum in-situ stress
- Elasticity profile
- 3D pore pressure field / leak-off

- Influence of pore pressure increase and temperature decrease on stress (poro-elasticity and thermo-elasticity)
- Plugging of the fracture interior



depth
σ_3
log k
injection
Fracture vs time

Data Collection

Static data
- Geology
- Regional stresses
- Natural fractures
- Reserves
- Elasticity

Dynamic data
- Well tests (permeability)
- Production history
- Microfracs / minifracs

Treatment data
- Pressures
- Rates
- Passive seismic
- Tiltmeter mapping

Post-treatment
- Well test results
- Productivity

Build a knowledge base!
cf Drilling

Design considerations

- The goal of hydraulic fracturing is economic
- Expected production
  - Analytic expressions (Prats)
  - Semi-analytic calculations
  - Reservoir simulation
- Connection with Geology
  - Flow barriers
  - Permeability
  - Heterogeneity
  - Natural fractures
- Dimensionless fracture conductivity $C_{fD} = \frac{k_f \cdot w}{k \cdot L}$

  Optimum value:
  - High k: maximize width and proppant permeability
  - Low k: maximize length
  - Proppant placement

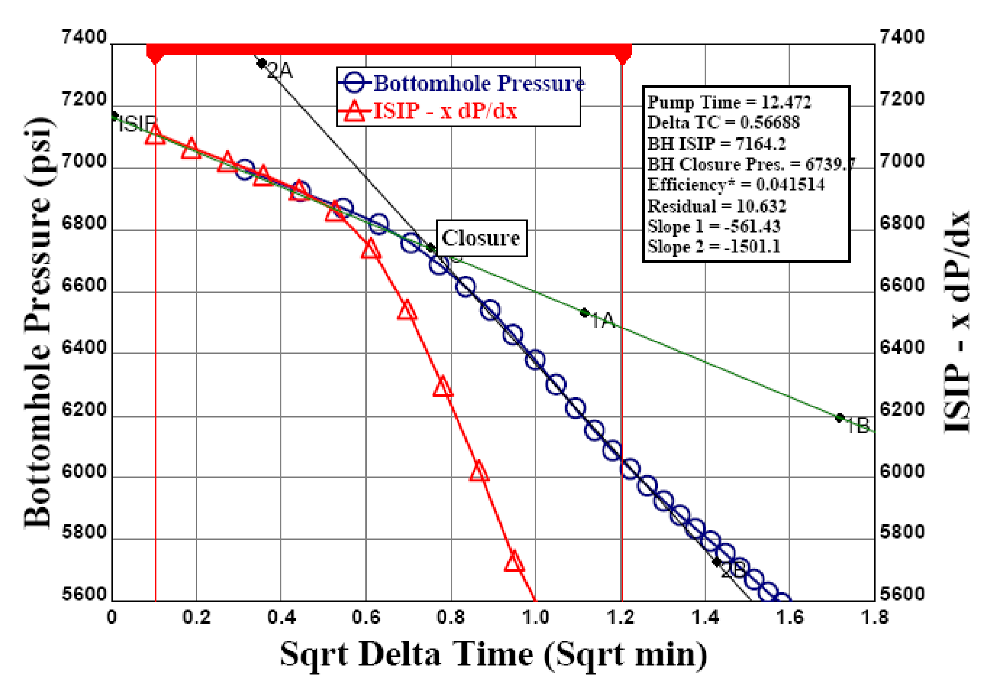
Design considerations

More input for design:

- In-situ stresses
- Fracturing pressures
- Leakoff behaviour

} Minifrac test

- Effects of layering:
  - Containing capacity
  - Connection
- Natural fractures
- Poro-elasticity
- Thermo-elasticity



Monitoring

Build up a knowledge base:

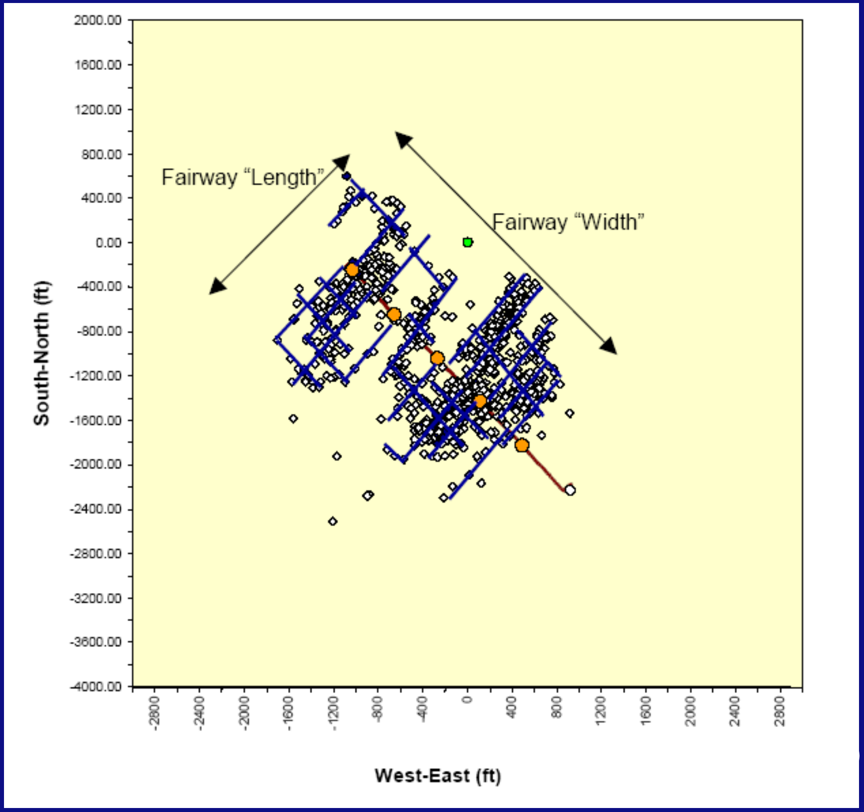
- Treatment performance
- Productivity monitoring

Treatment performance monitoring

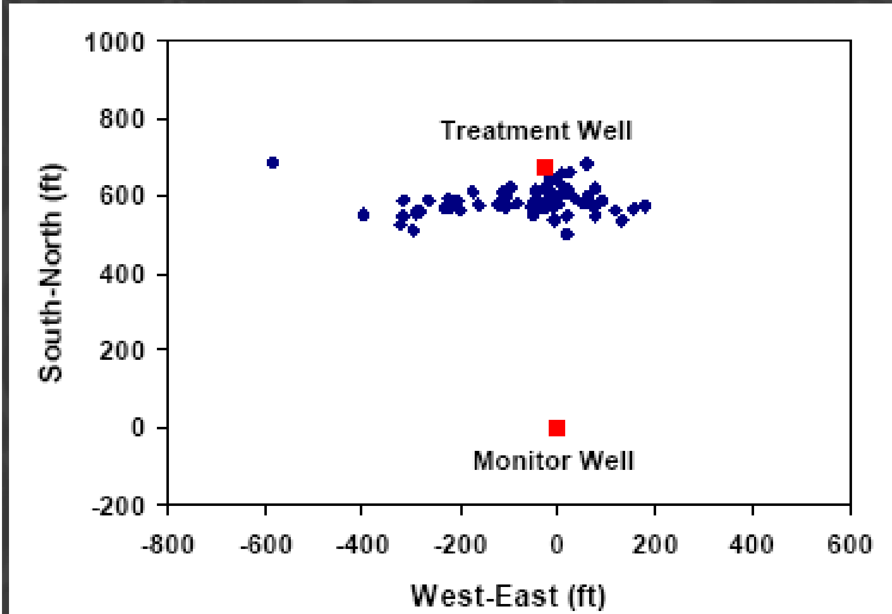
Monitoring

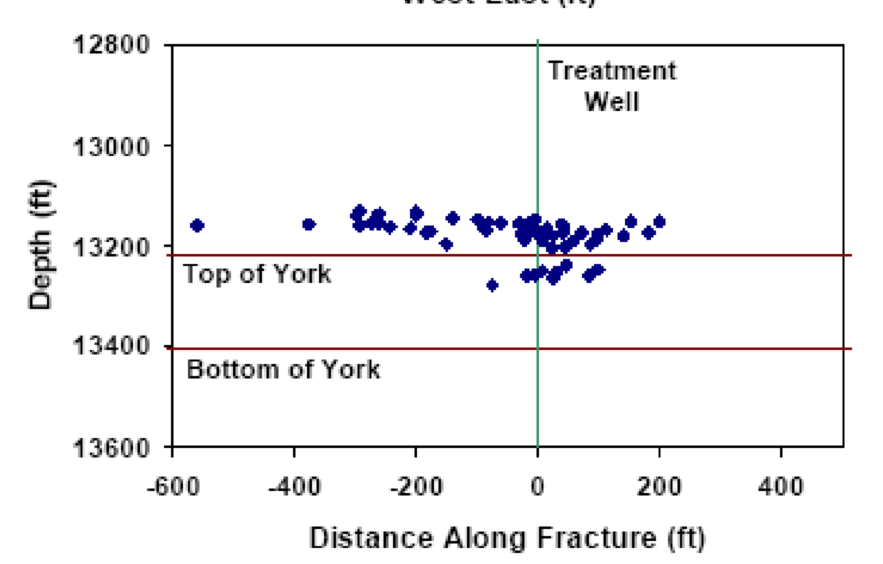
Build up a knowledge base:
- Treatment performance
- Productivity monitoring

Treatment performance monitoring
- Rates & Pressure traces (e.g. Tip-Screen-Out)
- Use fracture simulator
- Tiltmeters
  - Surface
  - Offset well
- Microseismic mapping two downhole receivers

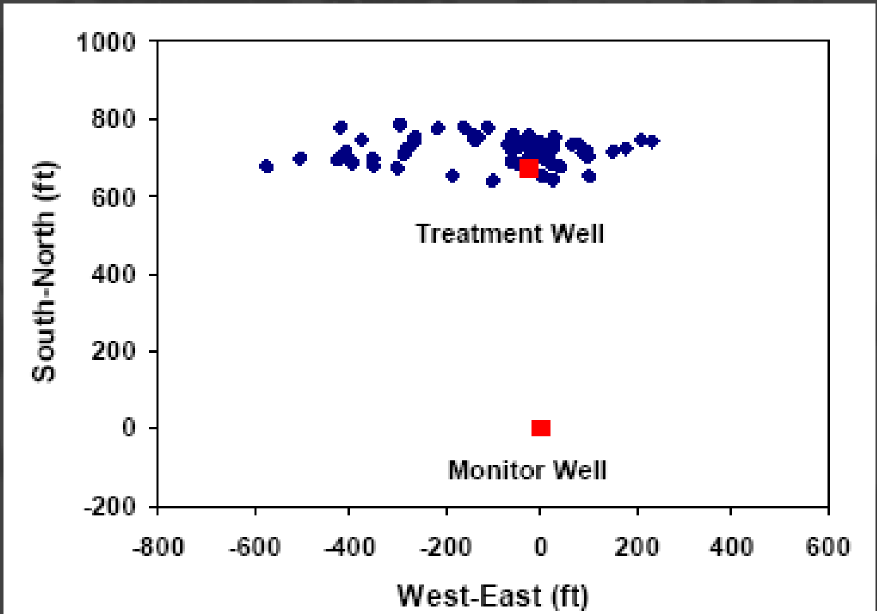


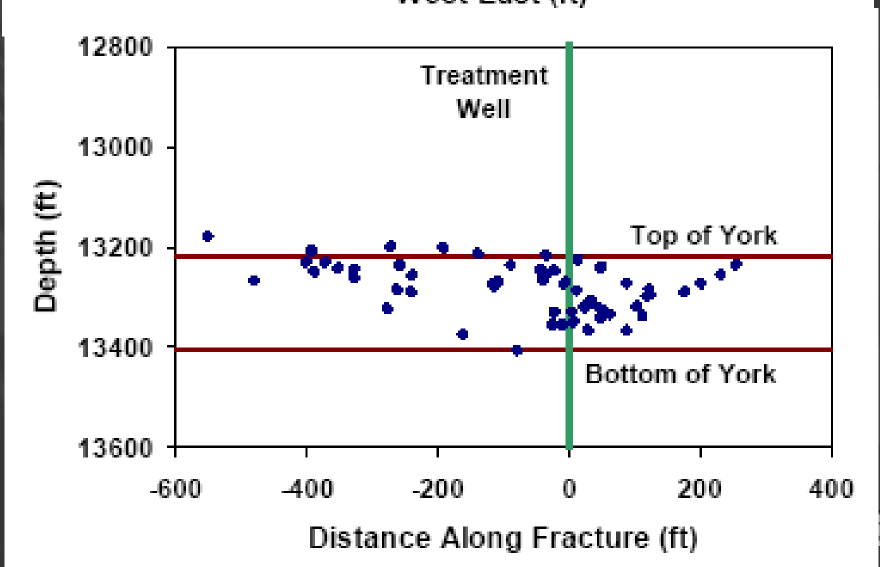
Microseismic locations using 3-layer velocity structure from dipole sonic log





Microseismic locations using 3-layer velocity structure from perforation timing





Monitoring

Build up a knowledge base:

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Productivity monitoring

Monitoring

Build up a knowledge base:

- Treatment performance
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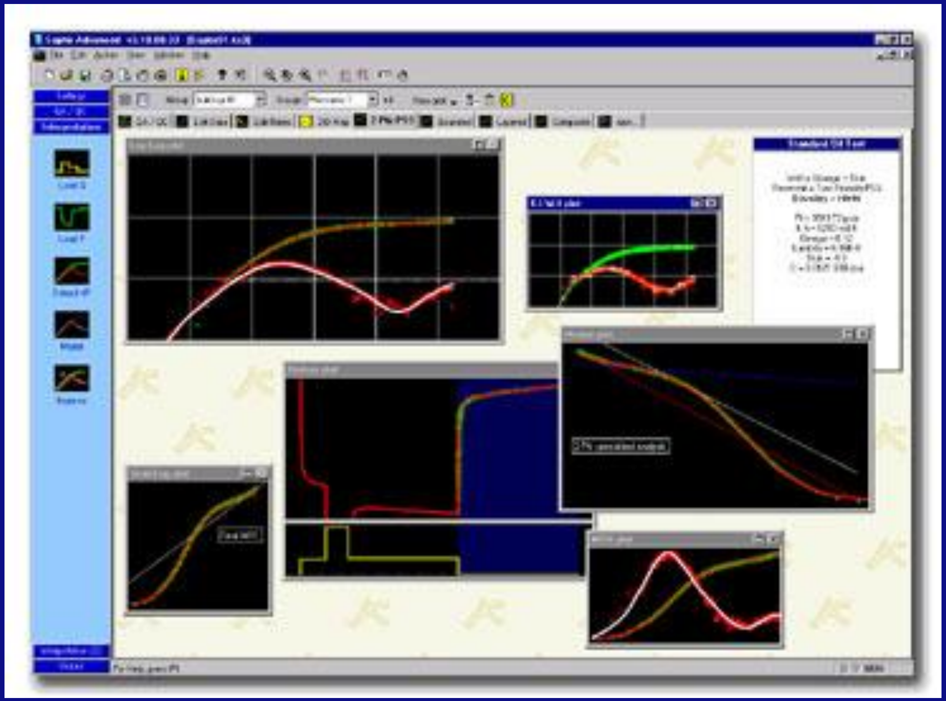
Productivity monitoring

- Well testing:
  Effective fracture size



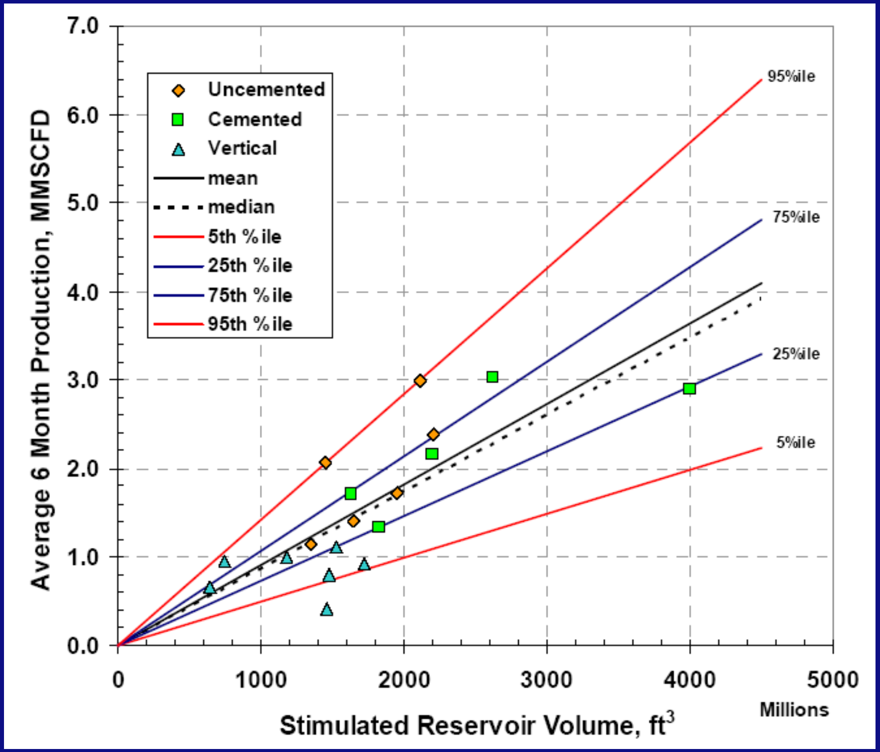
Monitoring

Build up a knowledge base:

- Treatment performance
- Productivity monitoring

Productivity monitoring

- Well testing:
  Effective fracture size
- Productivity evaluation
  e.g. Stimulated Volume
  Analysis

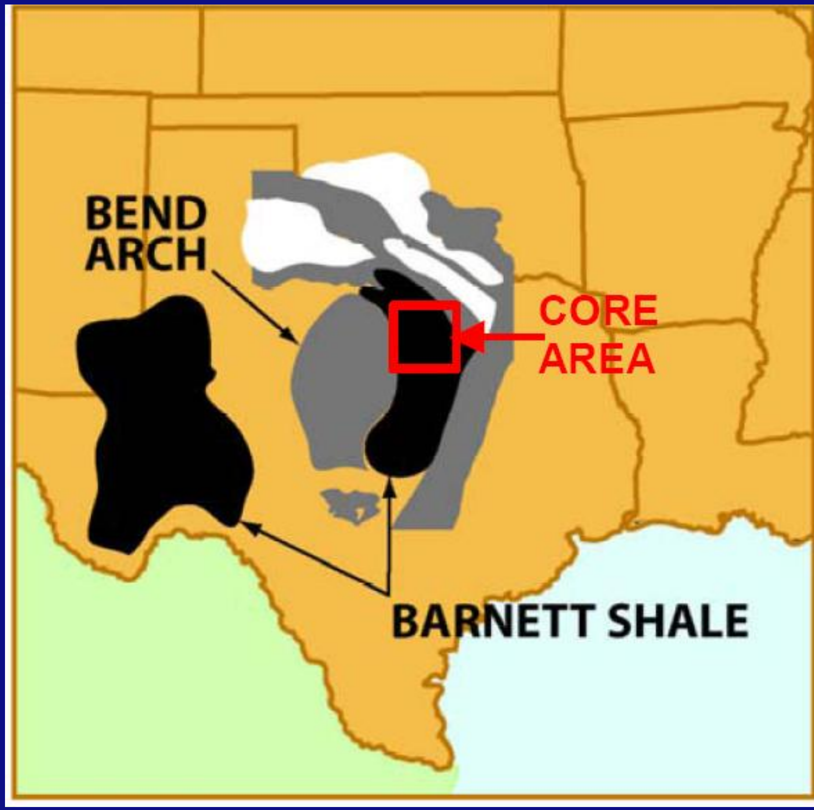


Hydraulic fracturing – Barnett Shale

- Very low permeability
- Naturally fractured

Similarities with Geothermal Systems
- Goal: interconnected fracture network
- Waterfracturing
- Monitoring is key

Translation problems
- Continuous stimulation by injection
- Effect of temperature
- No depletion



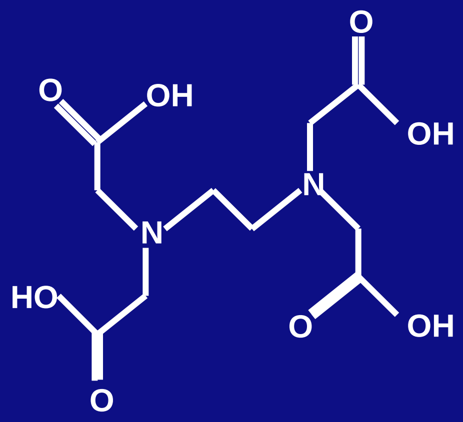
Acidizing

- Appropriate for dissolution of damage or “skin”
- What is the source of the skin?
  - Pseudoskin: limited entry, off-centred wells; perforation density/phasing/penetration
  - Turbulence or non-laminar flow
  - Real skin
- Chemical reaction
  - Diffusion (mass transfer) limited
  - Surface reaction rate limited

- Real skin: origin
  - Drilling mud invasion
  - Drilling fluid filtrate
  - Cementing damage
  - Perforation damage
  - Gravel packs
  - Completion fluids, workovers
  - Produced fines
  - Shear failure
  - Failing stimulation
  - Dirty injection water
  - Polymer flooding

Acidizing: Types of skin

- Emulsions
  Mixing water & oil – treat with surfactant
- Wettability change
  e.g. due to oil-based drilling mud – treat with solvent (remove hydrocarbons) and water-wetting surfactant
- Water block
  Increase in water saturation near the well – treat with surfactant
- Organic deposits
  Paraffins, asphaltenes – treat with solvent
- Silts & Clays
  Due to fines migration – treat with HF
- Scales
  - Carbonate – treat with HCl
  - Sulfate – treat with EDTA
  - Chloride scales – weak acid / HCl
  - Silica scales – treat with HF
  - Hydroxide scales – treat with HCl



Acidizing: Chemistry and Physics

Chemical reaction

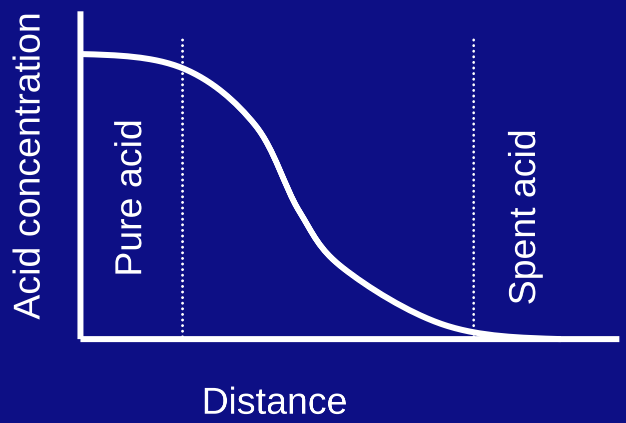
- High activation energy: reaction rate limited $q_s = k_j A C^m$
  $C_{interface} = C_{bulk}$
- Low activation energy barrier: Reaction rate limited by number of contacts (mass transfer). $q_d = \frac{DAC}{\delta}$
- Mixed kinetics

$$P = \frac{q_d}{q_s} = \frac{D}{k_j \delta C^{m-1}}$$

- Effect of temperature

Acidizing Physics

- Surface-reaction-limited
  Reaction independent of velocity



- Mass-transfer-limited: Controlled by molecular diffusion

$$\frac{\partial C}{\partial t} + u \nabla C = D \nabla^2 C$$

Wormholing

Acid fracturing

- Fracture the formation
- Etch conducting channels
- Coupling of
  - Flow behaviour
  - Leakoff
  - Viscosity changes
  - Reaction kinetics
  - Fracture mechanics
  - Temperature development

“Lessons”

- What is the goal?
  - Contact area
  - Bypass damage
  - Connect to natural fractures
  - Dissolve skin
  - Contact area in limestone / dolomite
- What is the cost?
  - Treatment cost
  - “Social cost”
- What is the cure?
  - Conventional fracturing
  - Tip-screen-out fracturing
  - Water fracturing
  - Acidizing
  - Acid fracturing
- What is the benefit?
  - Productivity
  - Injectivity
  - Reserves
  - …
  - Reservoir!

“Lessons”

- Design
  - Reservoir Permeability
  - Fracture conductivity
  - Geology
  - Rock mechanics
  - Seismic risks
  - Minifrac tests
  - Design software
  - Skin source
  - Skin type
  - Acid reaction kinetics
  - Risk of induced seismicity

- Monitoring
  - Rates
  - Pressures
  - Temperature
  - Tiltmeter mapping
  - Microseismics
  - Productivity

Build up a knowledge base