EGS Technology: hydraulic fraccing: oil and gas and shale gas best practive

Content

- rationale
- Borehole Stress and failure
- What applications for hydraulic fracturing (general)
- How does it work (theory and operational)
- Models vs reality
- Fracture aperture and permeability
- What did we learn from gas shales

Useful books

- E. Fjaer et al

  Petroleum Related Rock Mechanics

  2nd edition

- J. Jaeger, N.G. Cook & R. Zimmermann

  Fundamentals of Rock Mechanics

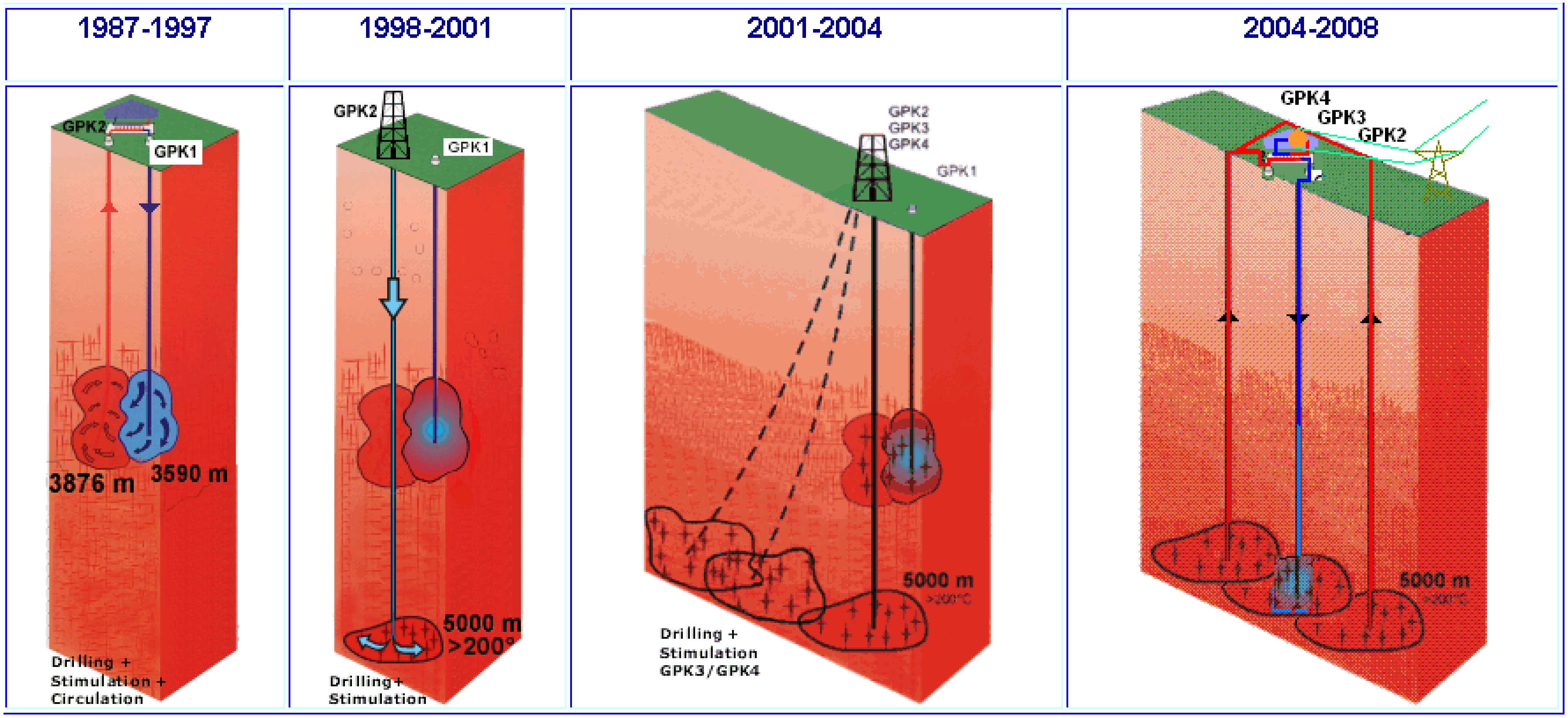
- George E. King
- Thirty Years of Gas Shale Fracturing: What Have We Learned?
- SPE 133456

- Kevin Fisher
- SPE YP presentation : Hydraulic Fracturing: Modeling vs. Reality

WHY HYDRAULIC FRACTURING IN GEOTHERMAL?

Enhanced Geothermal Systems

- EU research project > 20 years
- 3 wells > 5 Km deep
- Comprehensive Fracturing programe
- 3MW$_{el}$ Power via ORC plant



(www.soultz.net)

WHY HYDRAULIC FRACTURING IN GEOTHERMAL?

Doublet performance

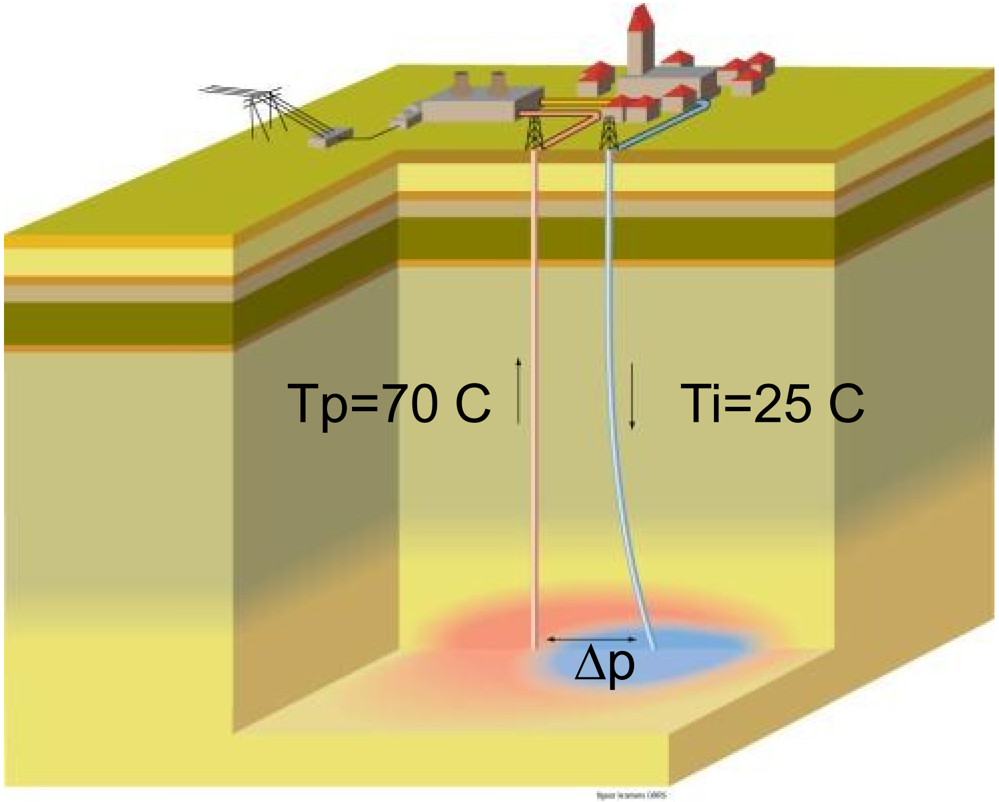
$E\,[\mathrm{MWth}] = Q*\Delta T * C_P$

Flow-rate Q

Permeability X thickness

$$Q = \Delta p \frac{2\pi k H}{\mu\left(\ln\left(\frac{L}{r_w}\right)+S\right)}$$

Viscosity distance

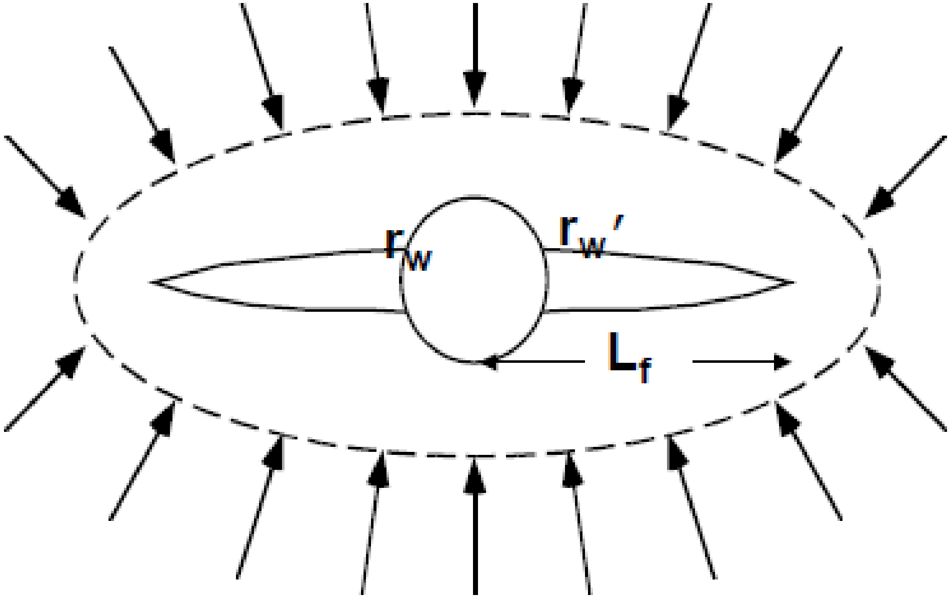


Δp generated by pumps
Which consume electricity

Δp is restricted by safety measures

Δp at surface does not linearly lead to Higher flow rates (friction in tubes)

Hydraulic fracturing can be considered as reducing skin



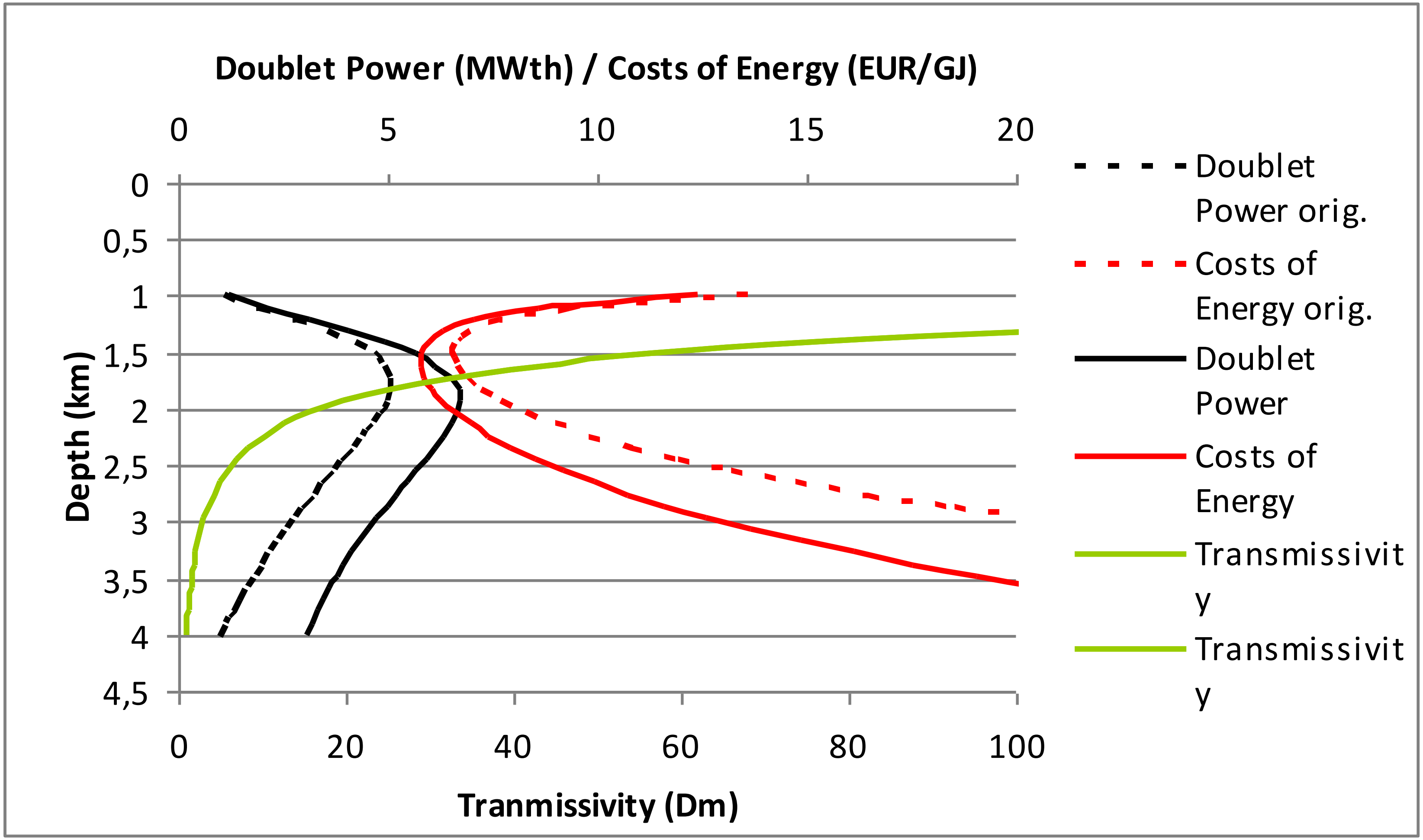
$$r'_w = r_w e^{-s} = \frac{L_f}{2}$$

Lf = 50m
Rw = 0.15m
S = - ln(0.5*Lf/rw) = -5

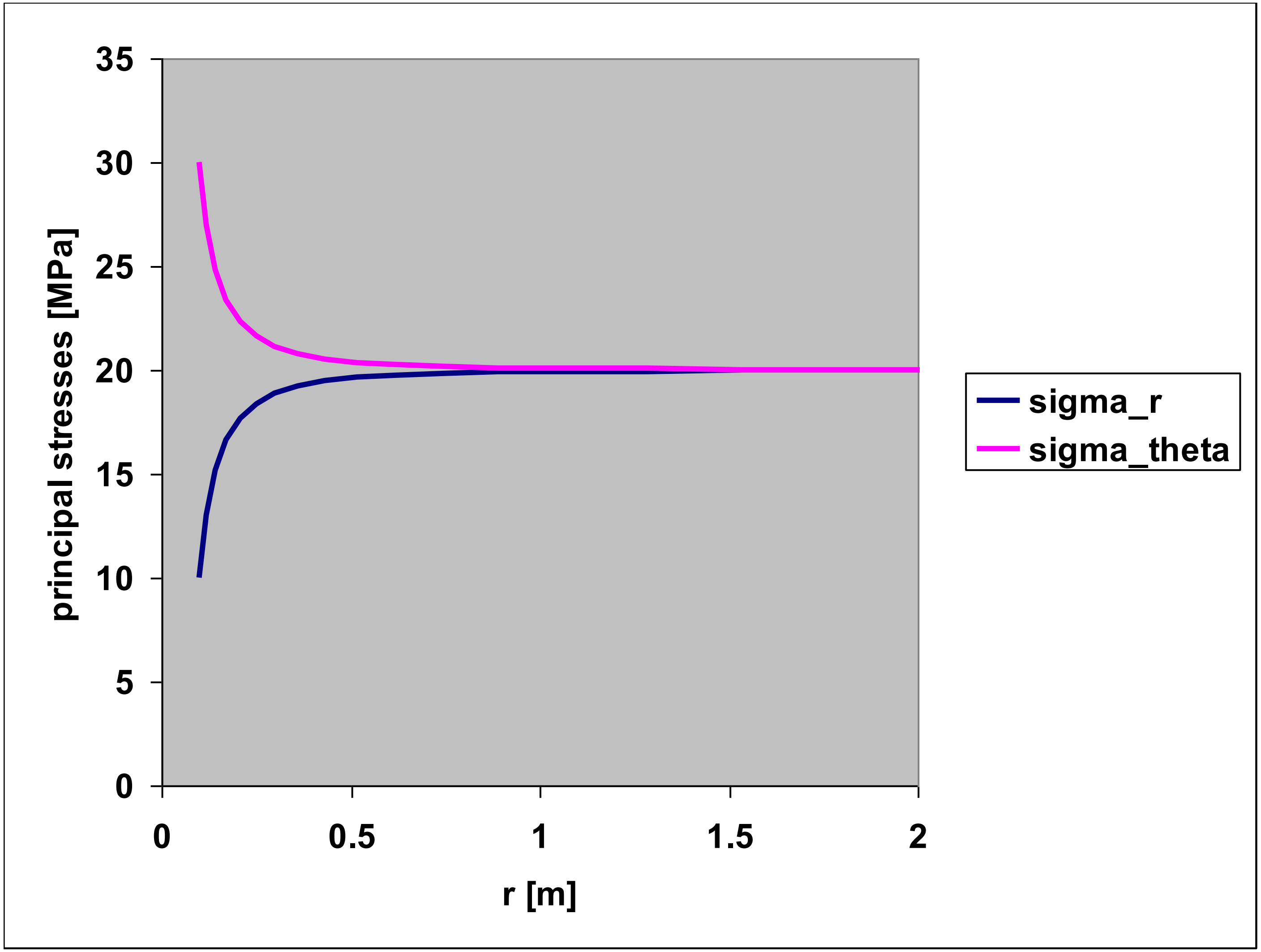
$$Q = \Delta p \frac{2\pi kH}{\mu\left(\ln\left(\frac{L}{r_w}\right)+S\right)}$$

L=1500m →
Improvement Q factor 2

Effect of hydraulic fraccing



Stresses around a borehole

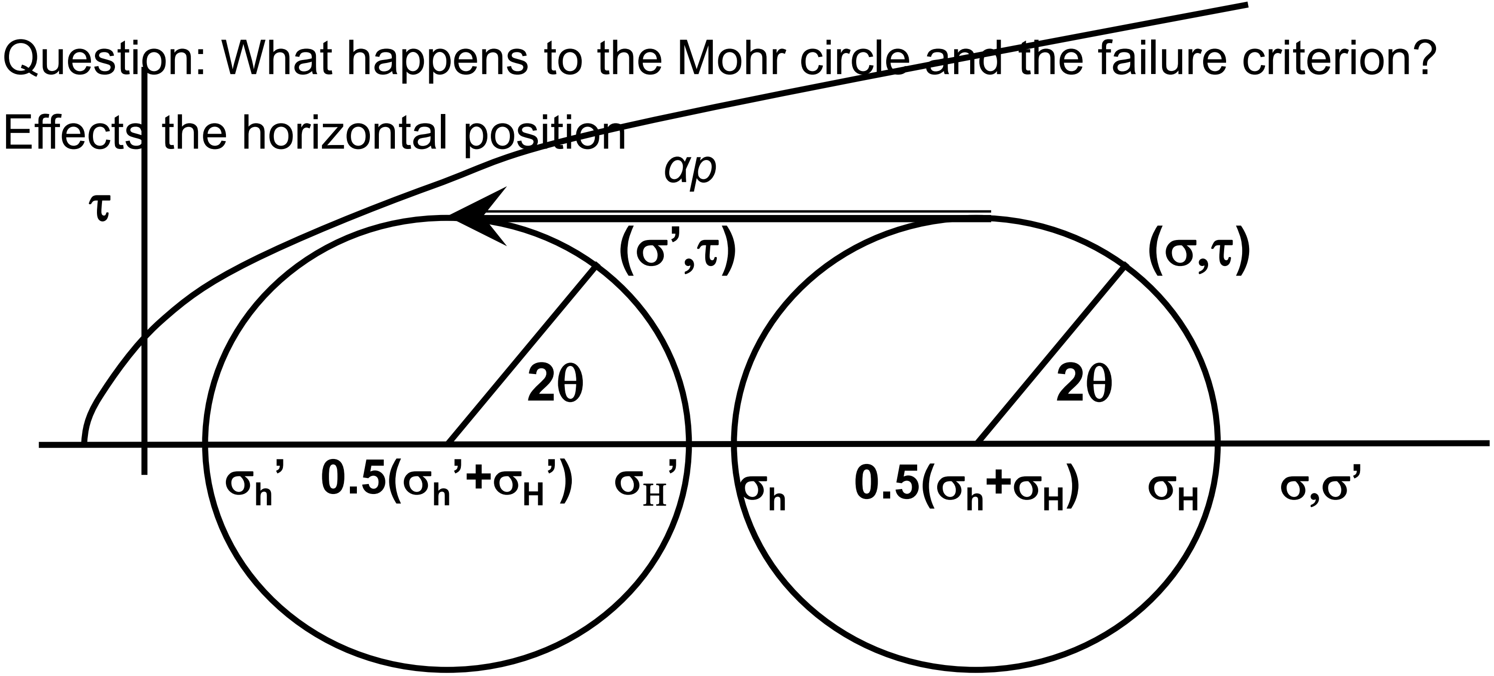


Effect of Fluid Pressure – Net Stress

- The sand grains in the rock “feel” the net stress:

$$\boldsymbol{\sigma}' = \boldsymbol{\sigma} - \alpha p \mathbf{I}$$

- Question: What happens to the Mohr circle and the failure criterion?
- Effects the horizontal position



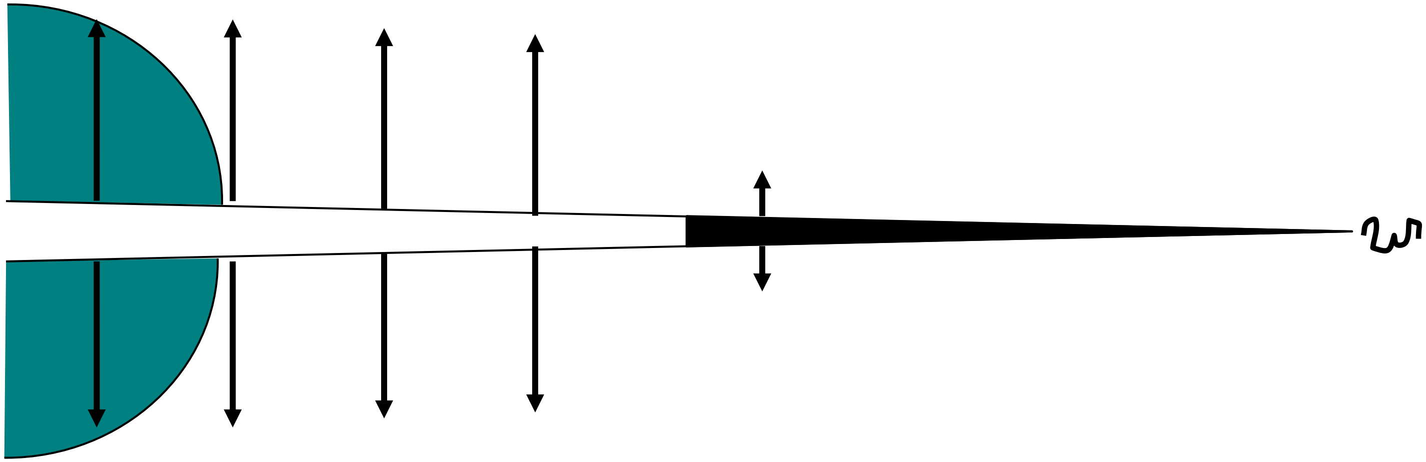
Hydraulic fracturing – Applications

- Frac & Pack
  - Weak, permeable formations
  - Bypass skin
  - Sand control
- Massive Hydraulic Fracturing
- (EGS, aquifers)
  - Low-permeability reservoir
  - Usually first minifrac test
    - Fracture pressure
    - Containment
    - Leakoff behavior
- Stimulating naturally fractured reservoir
  - Activate fracture network
  - E.g. unconventional shale gas
- Water injection
  - Maintain injectivity
  - Thermal fracturing
- Leakoff tests, Extended leakoff tests
  - Fracture gradient
  - Mininum in-situ stress
- Waste disposal
  - Drill cuttings
  - Produced water

Hydraulic fracturing – Types of applications

Tip-Screen-Out fracturing / Frac & Pack

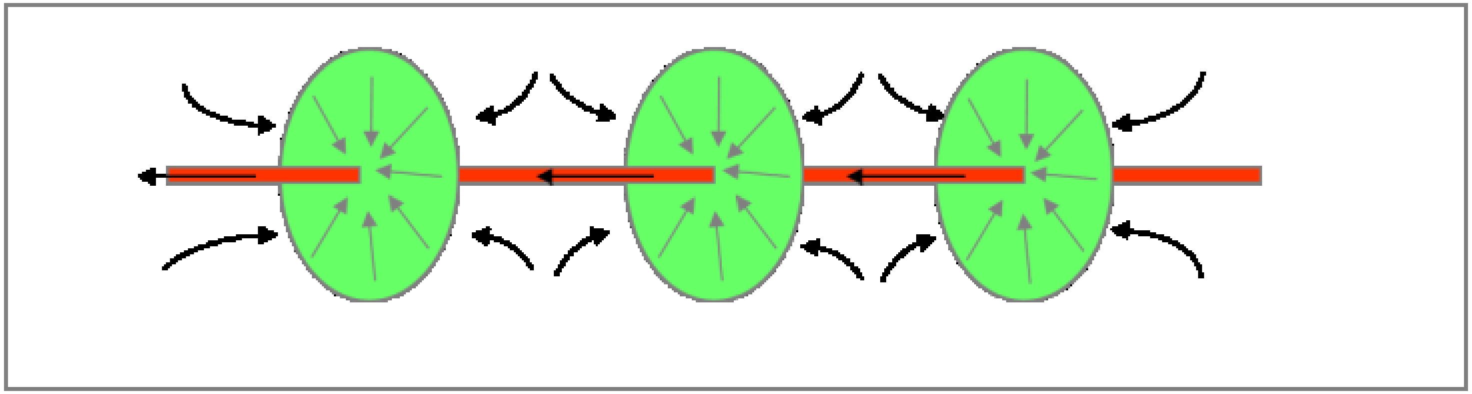
- Goal: Bypass damage
- Typically in higher-permeability reservoir
- Short fracture
- Tip-Screen-Out to increase fracture width



Hydraulic fracturing – Types of application

Massive hydraulic fracturing

- Large treatments
- Low-permeability reservoir
- Create additional contact area
- Multiple fractures in a horizontal well



Hydraulic Fracturing

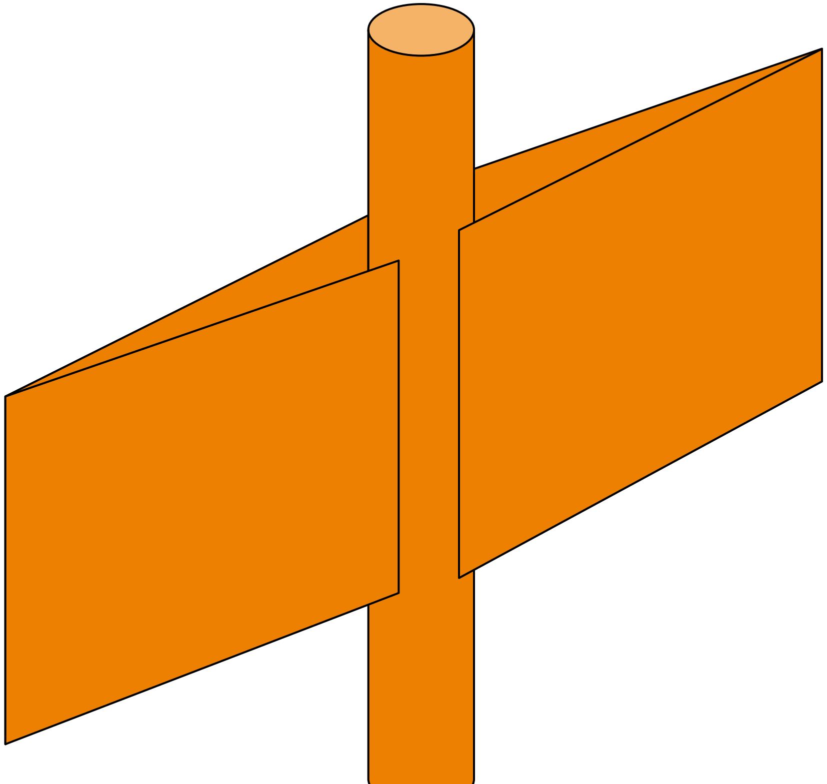
Today:

Some geomechanical notions –
much literature on fracture
operations & design

Fracturing of gas shales

What is it?

- Breaking the rock by applying fluid pressure
- Tensile failure
- For porous and for non-porous material:
  To propagate a fracture:
  $\sigma - p_f < -S_0$
  or $p_f > \sigma + S_0$



Physical process

Hydraulic fraccing

p_f>closure stress(σ_c ==σ_h)

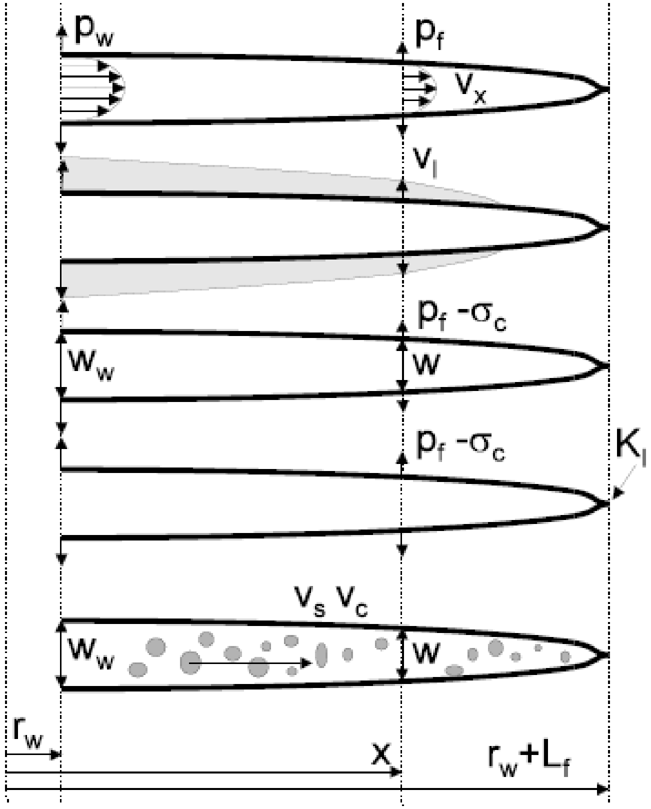
Viscous fluid flow

Fluid leakoff

Elastic deformation

Fracture propagation

Proppant transport

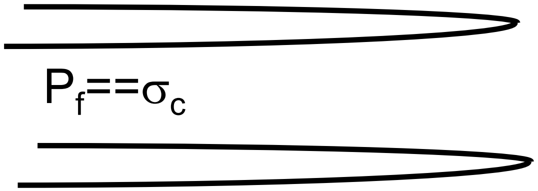


Shut-in

Elastic closure

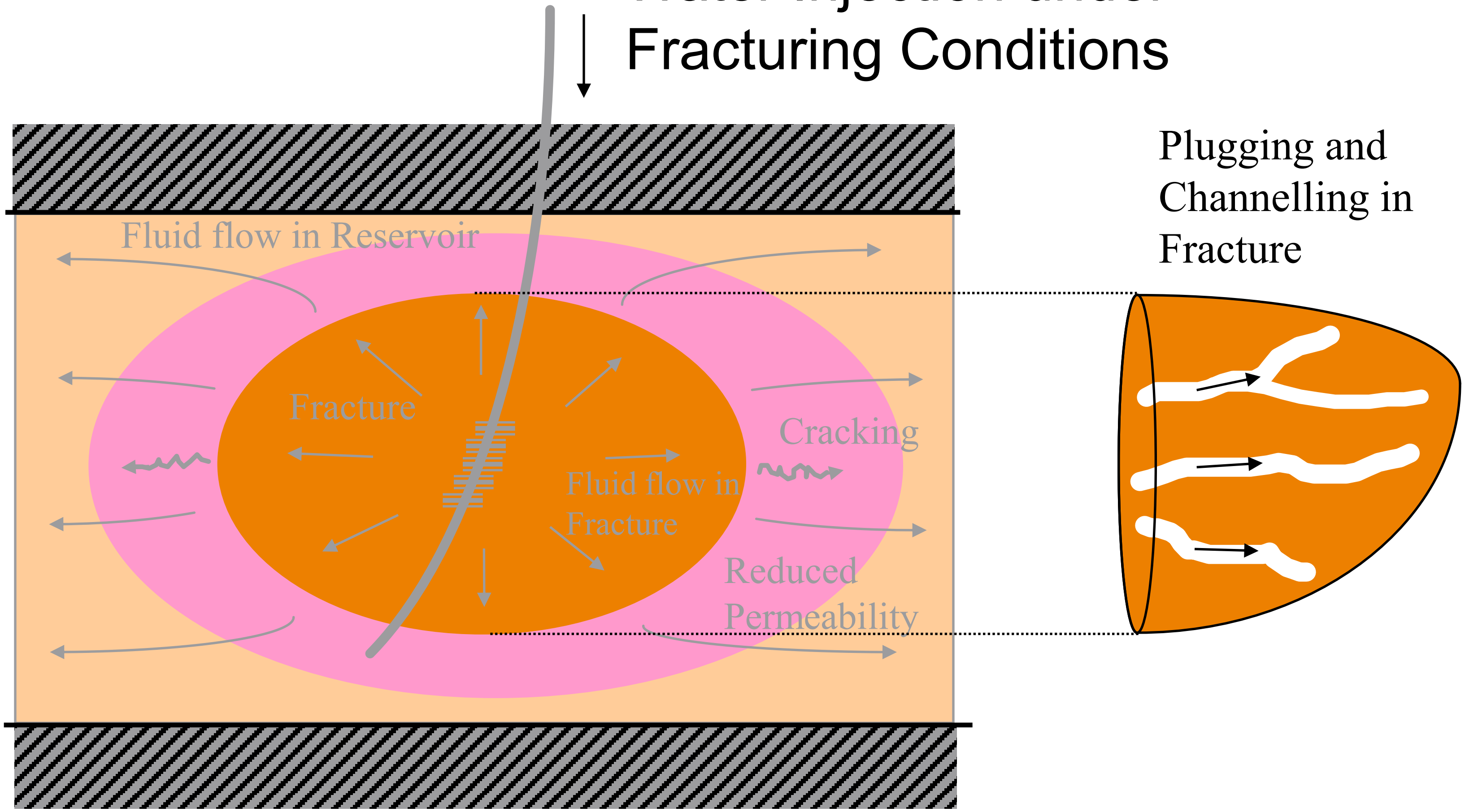
P_f==σ_c

Leakoff



Hydraulic fracturing

Water Injection under Fracturing Conditions



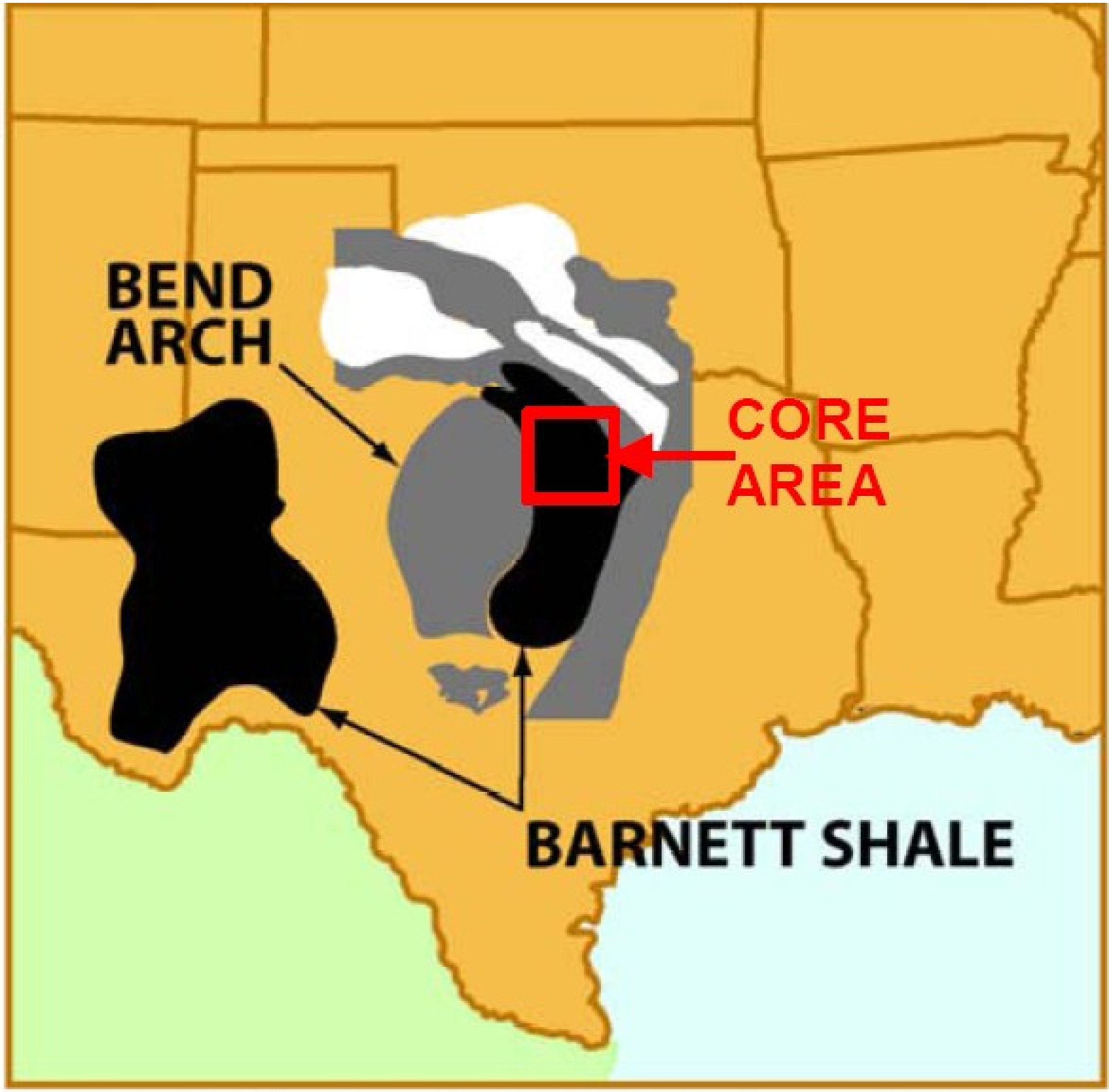
Plugging and Channelling in Fracture

Hydraulic fracturing – gas shale learning base

Barnett shale

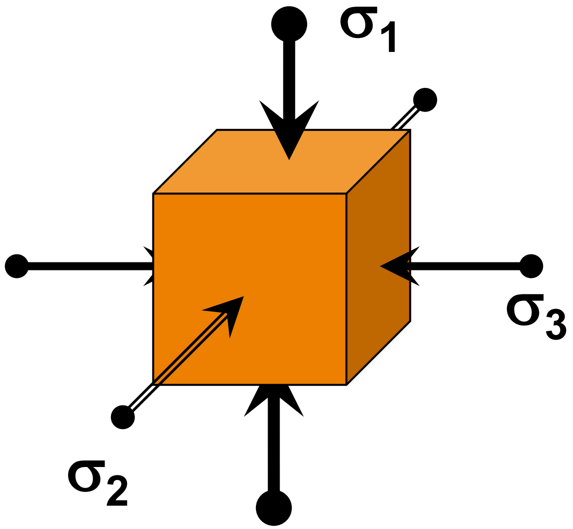
- Very low permeability
- Naturally fractured

- Goal: interconnected fracture network
- Waterfracturing
- Monitoring



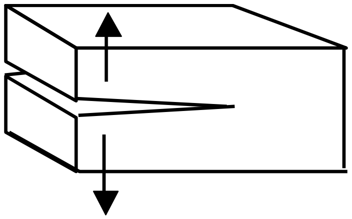
Hydraulic fracturing – Basic concepts

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

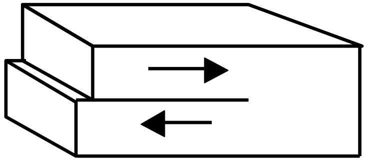


- Modes of fracturing

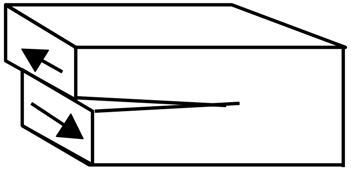
- Hydraulic fracturing: Tensile (mode I) – Vertical fracture has least resistance



Mode I: Opening



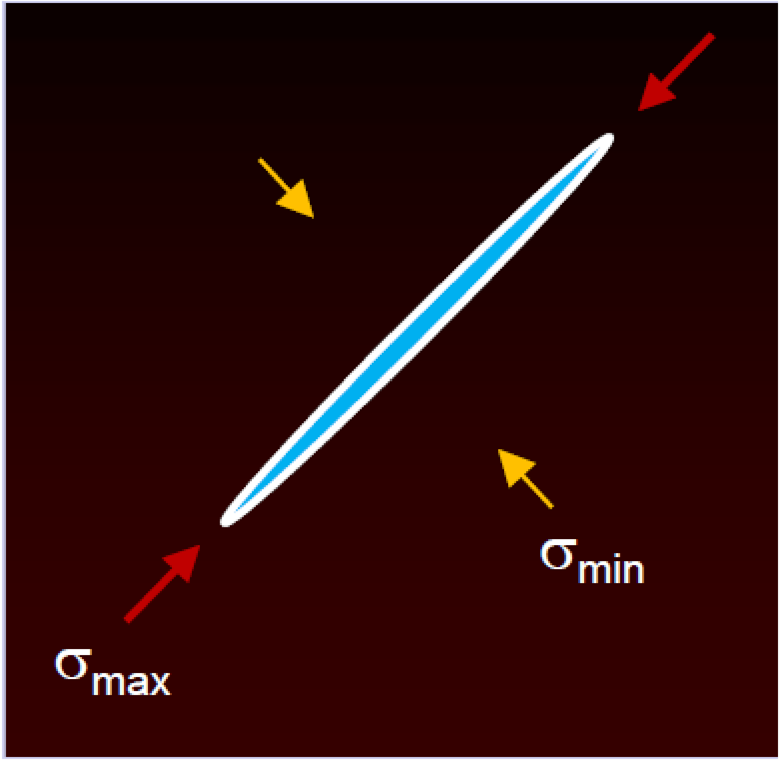
Mode II: Sliding



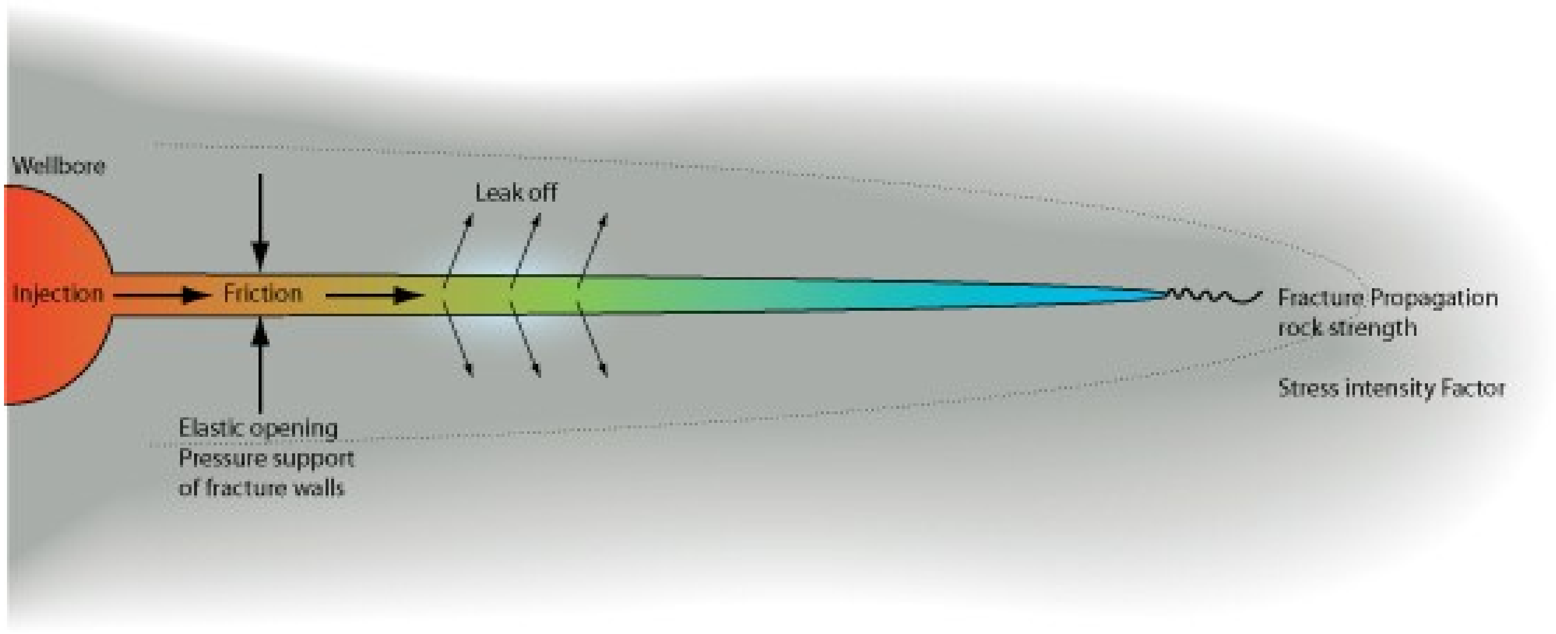
Mode III: Tearing

Hydraulic Fracturing

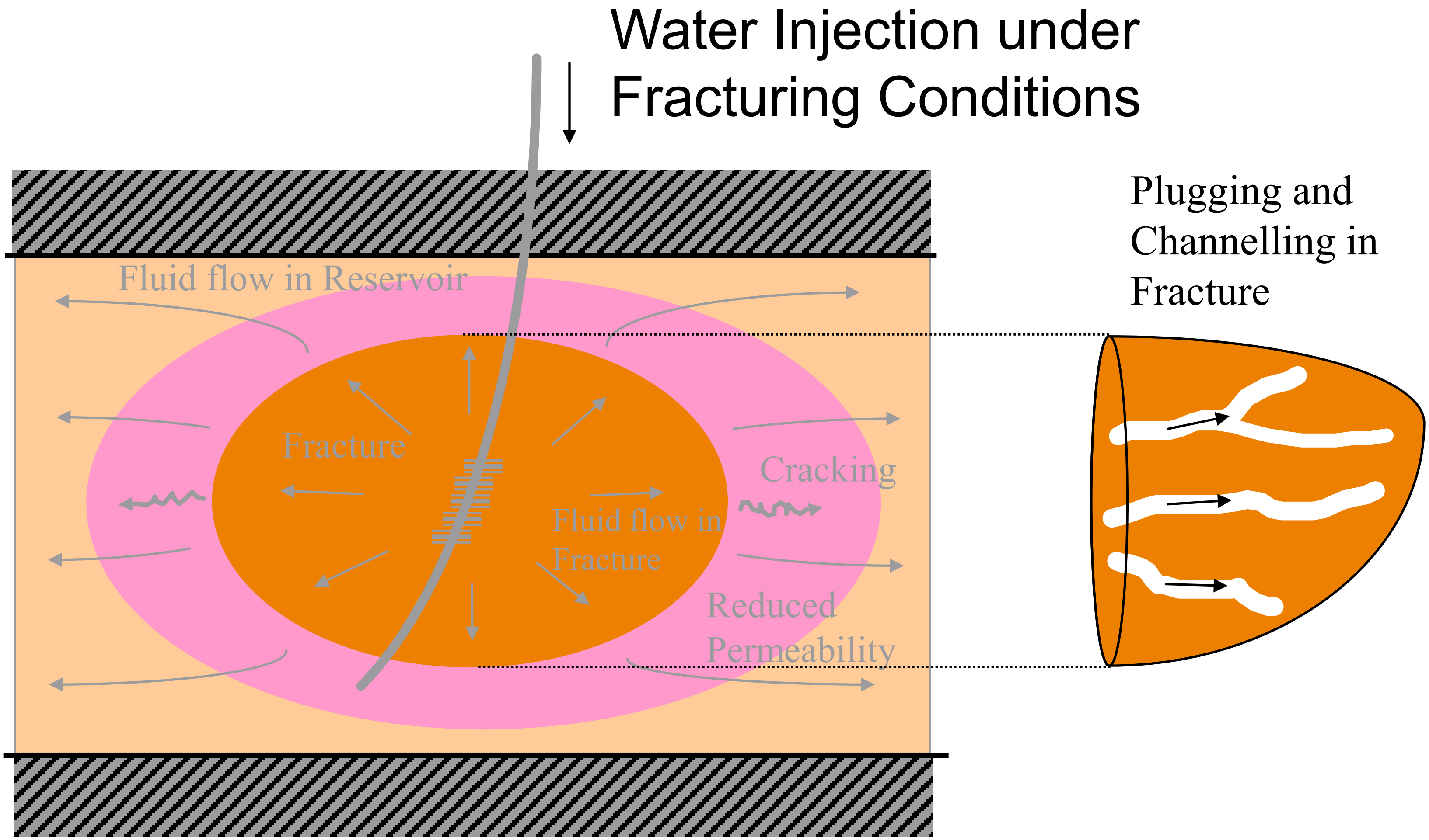
- Tensile failure, NOT shear failure
- Orientation of the fracture: that direction where $p_f > \sigma + T_0$ first, i.e. σ is minimal (T_0: tensile strength)
- The normal stress on the fracture wall “tries” to close the fracture
- Therefore the orientation is
    - Perpendicular to the minimum in-situ stress direction
    - Parallel to the medium and the maximum in-situ stress direction
    - Vertical
    - Sometimes horizontal for very shallow fractures



Hydraulic Fracturing – Coupled Processes



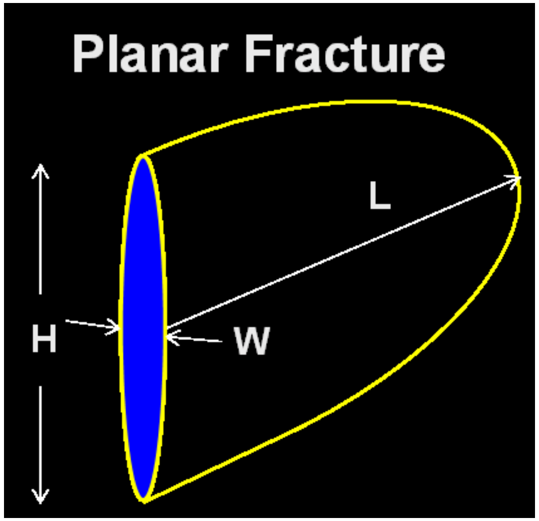
Hydraulic fracturing

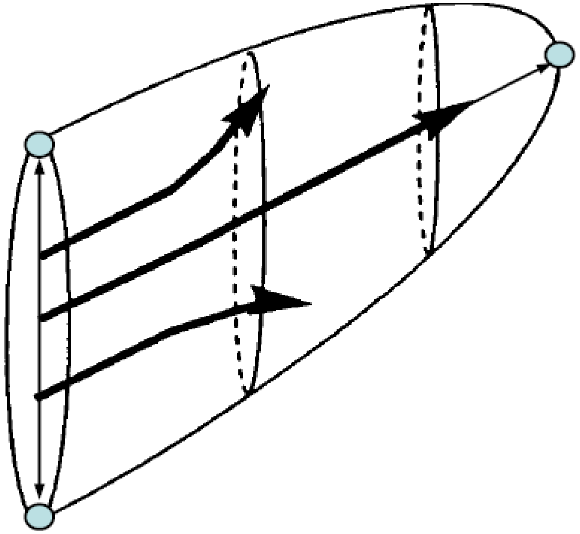


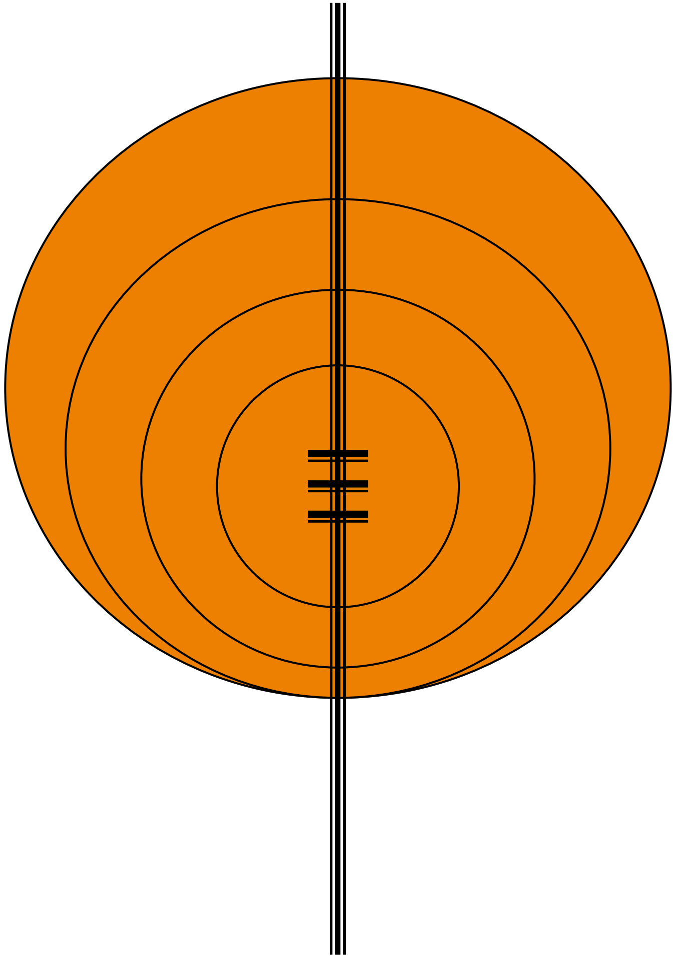
Hydraulic Fracturing

- Fracture growth
- Starting from perforation
- Breakdown pressure: Not easy to model – wellbore stability criterion does not work
- Determine propagation pressure with minifrac test
- Equal resistance in all directions within the fracture plane ⇨ Circular crack (penny-shaped)
- Gravity: σ_h increases faster with depth than p_f ⇨ tendency for upwards growth

Hydraulic Fracturing – growth and confinement

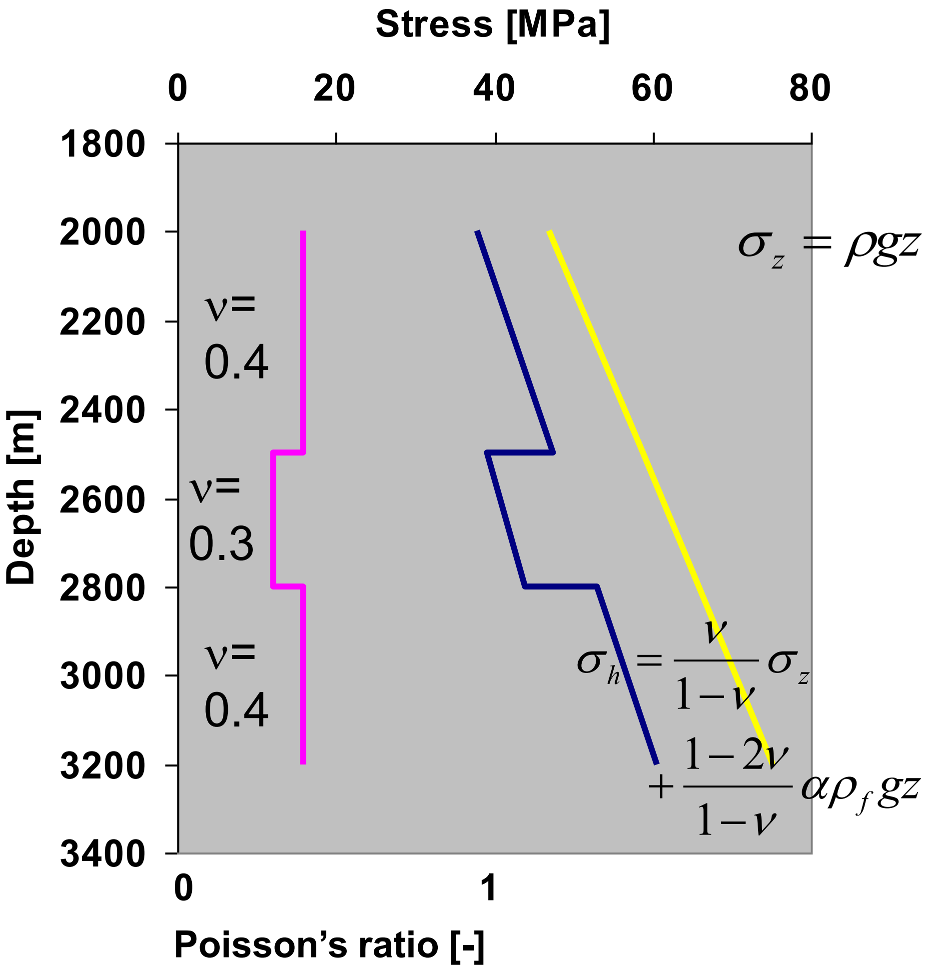






Hydraulic Fracturing

- Lithography induces contrasts in minimum in-situ stress
- Lithgraphic density: 2200 kg / m^3
- Fluid density: 1000 kg / m^3



$$\sigma_z = \rho g z$$

$$\sigma_h = \frac{\nu}{1-\nu}\sigma_z + \frac{1-2\nu}{1-\nu}\alpha\rho_f g z$$

Hydraulic fracturing – Concept

- K_I: Stress intensity – measure of singular stress behaviour beyond the tip
- Length increases when $K_I > K_{Ic}$
- Volume balance
- Elastic opening
- Leakoff correlation

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

$$K_I \approx K_{Ic}$$

$$w = \frac{V_{fracture}}{A_{fracture}}$$

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

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

$$v_{leakoff} = \left(p_{frac} - p_{res}\right) \cdot d_{penetrated}$$

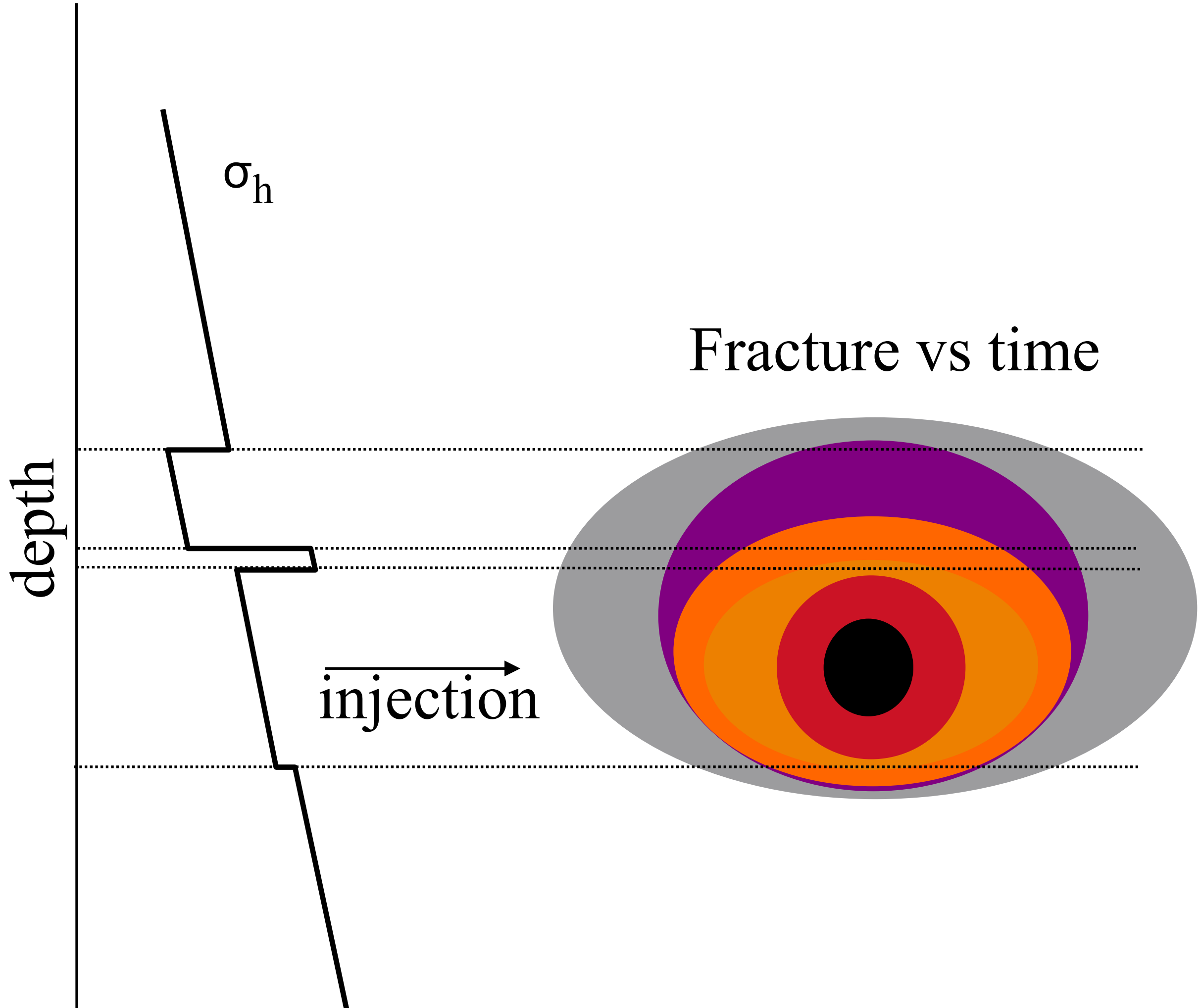
$$p_{frac} - \sigma_3 \propto \frac{w}{L} E$$

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

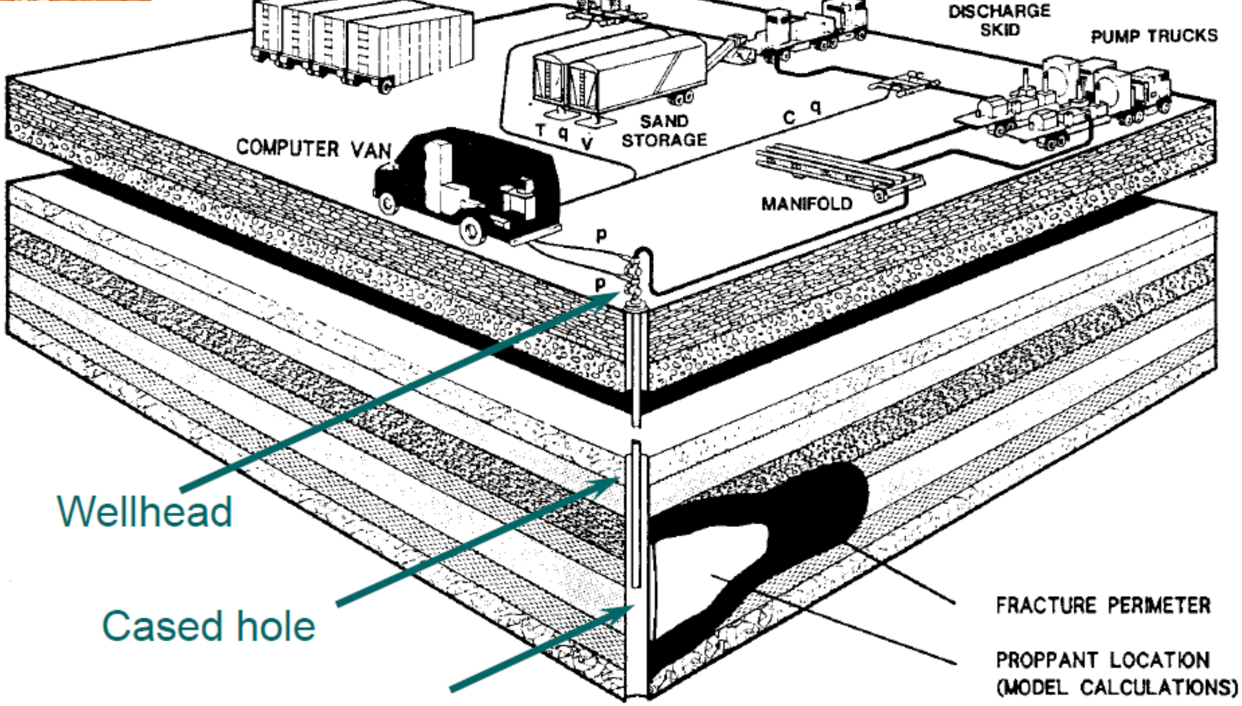
Hydraulic Fracturing – Effect of layering, confinement

Layering

- Elasticity
- Stress
- Permeability
- Porosity



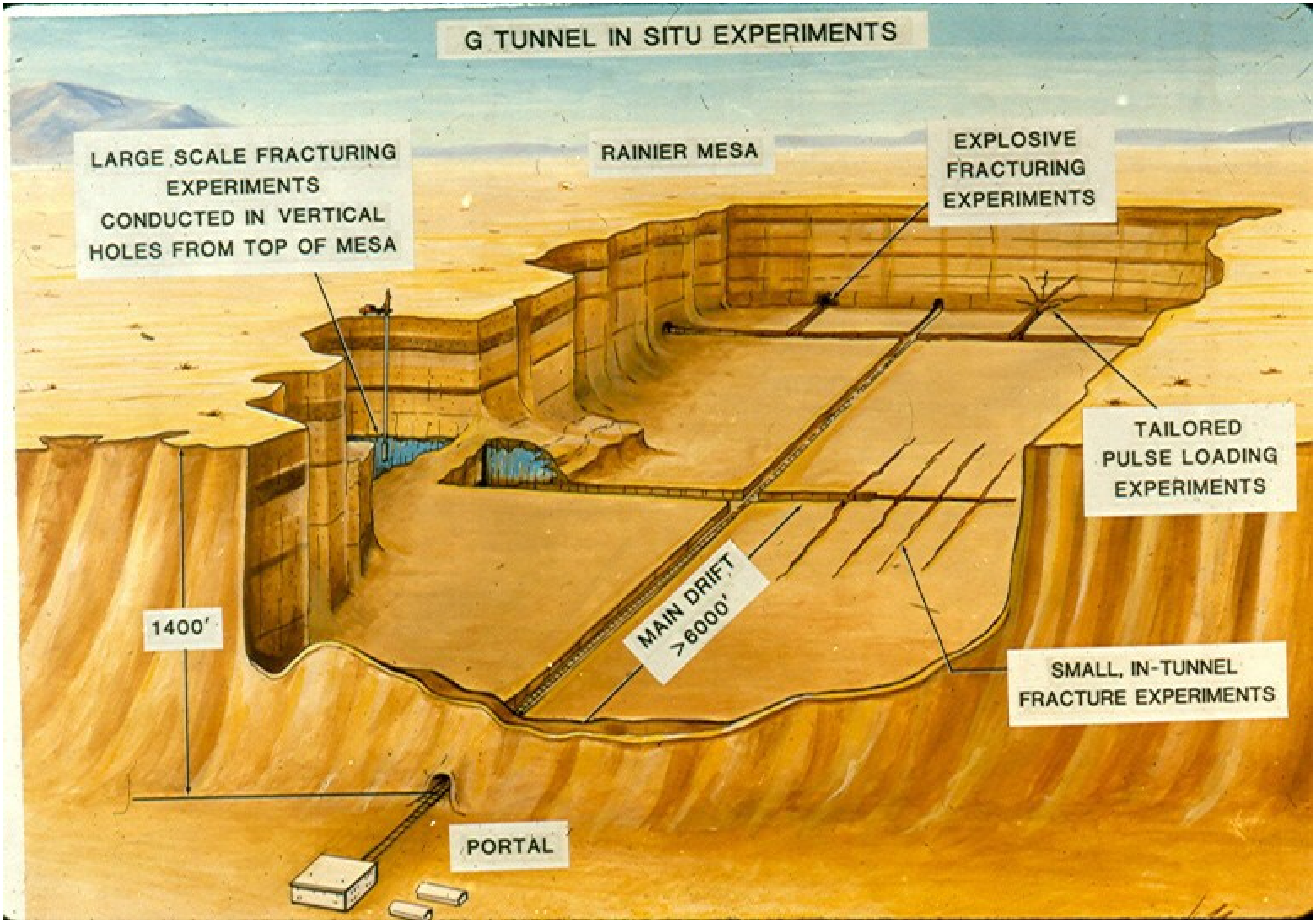
Hydraulic fracturing operations (pinnacle)



How BIG are hydraulic frac jobs

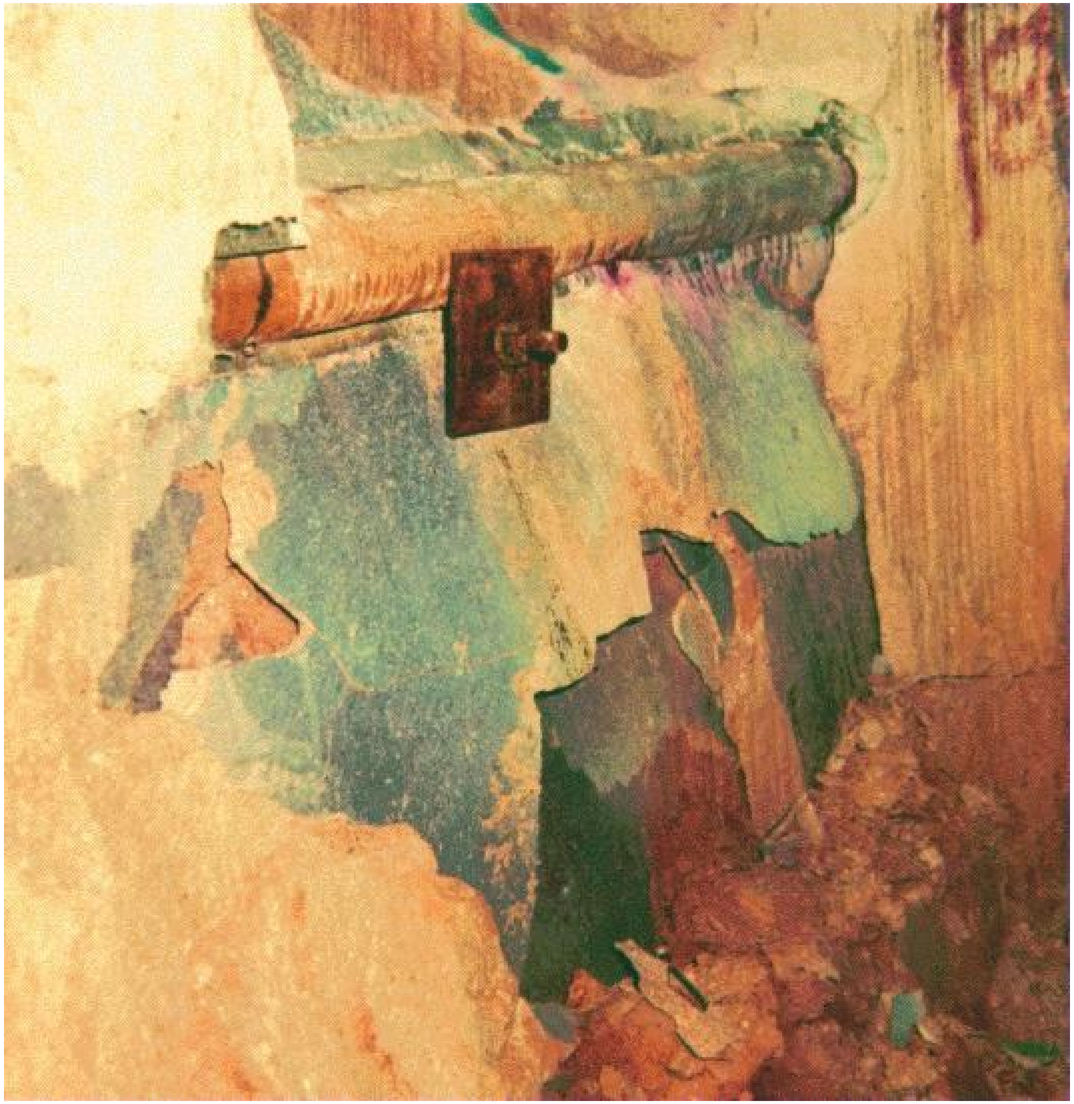
- Fracture treatment volumes can be over 10,000 m3
- Pump rates can be 100 l/s or more
- Proppant placed up to 1 mln kg
- Fracture length ranges from 3 to 1500 m
- Treatments cost ranges from $5,000 to $5,000,000 USD

Experiments (Fisher, 2010)

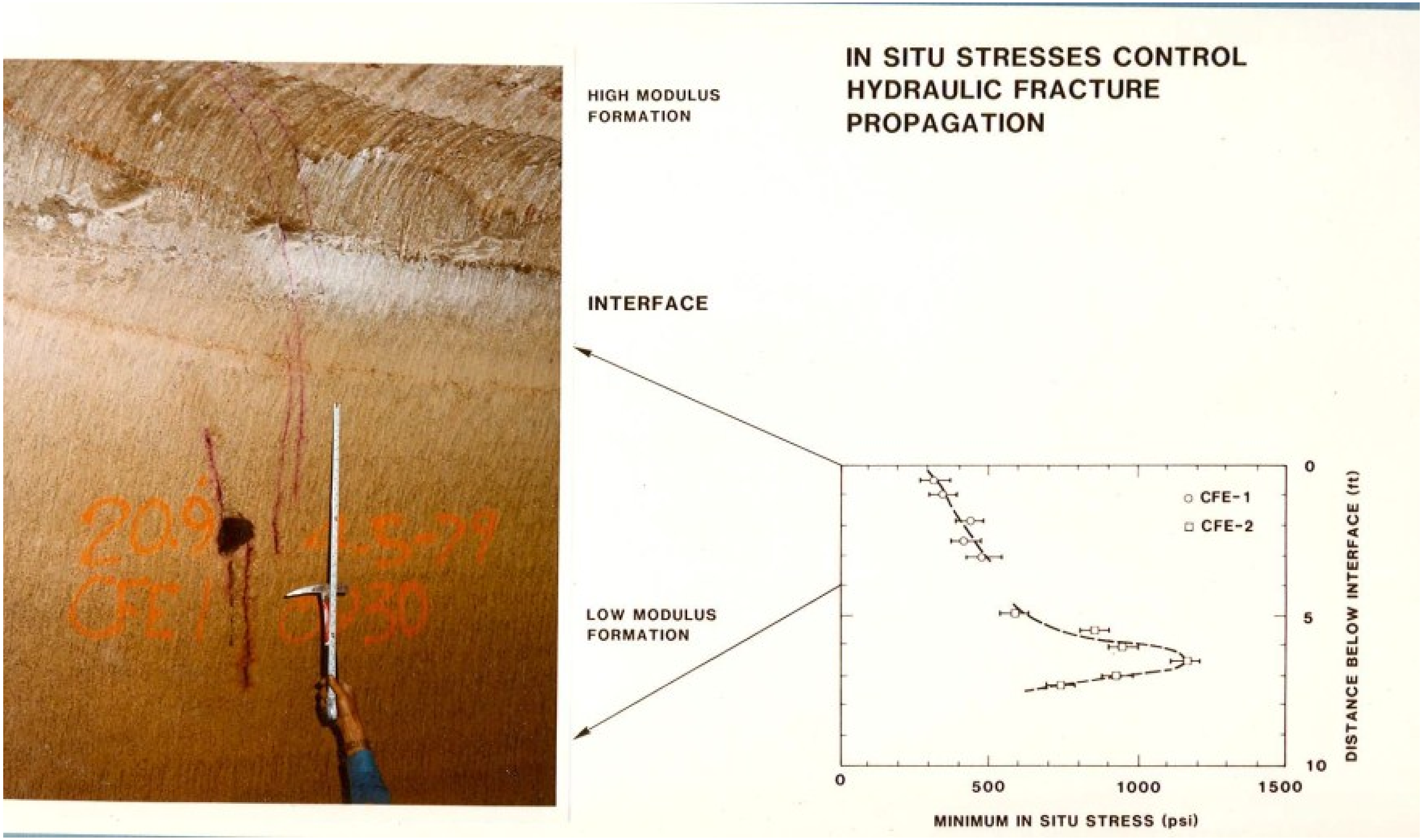


Experiments (Fisher, 2010)

- Horizontal well
- Planar fracture surface (vertical)

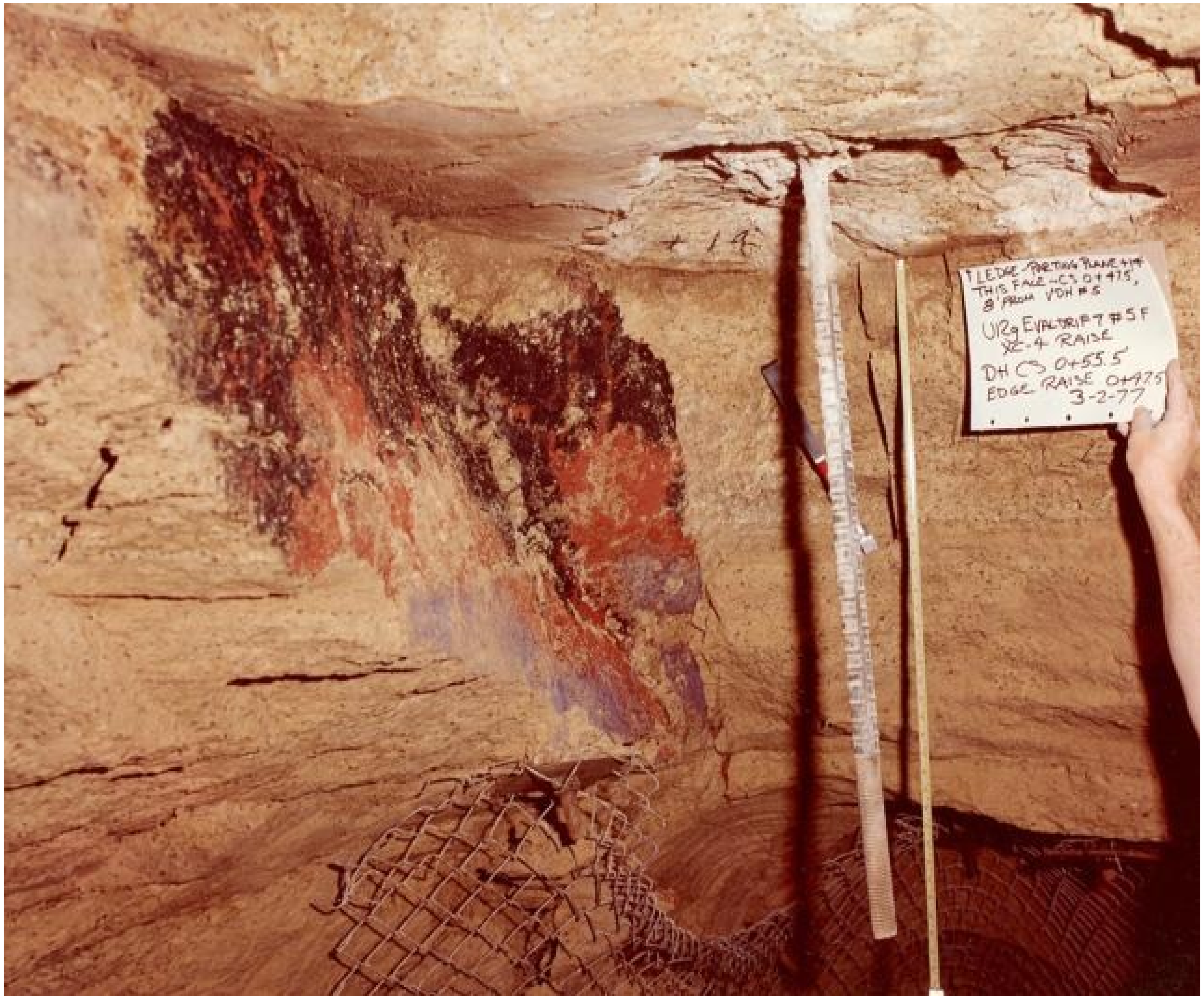


Stress CONTROLS fracture propagation over modulus

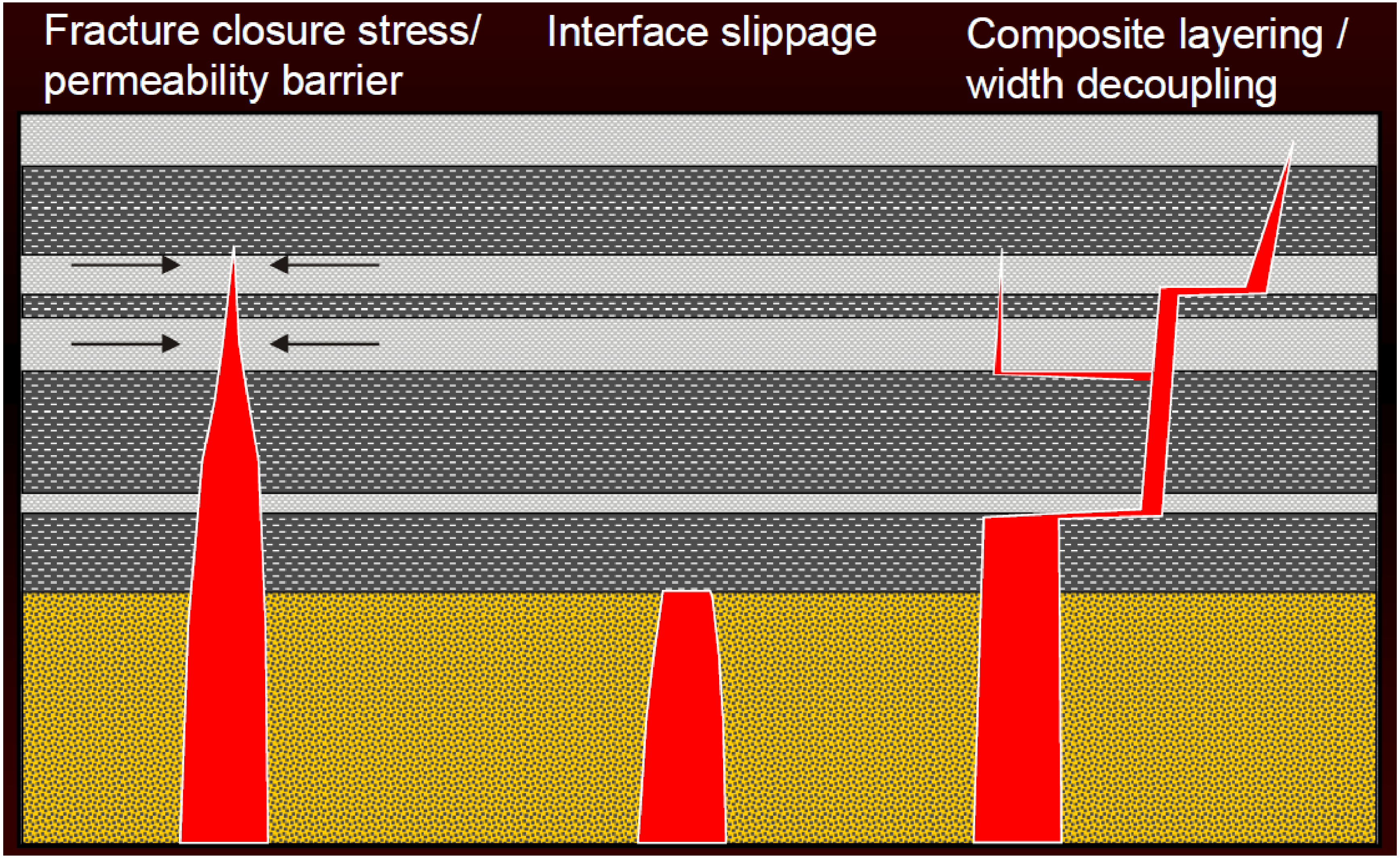


IN SITU STRESSES CONTROL HYDRAULIC FRACTURE PROPAGATION

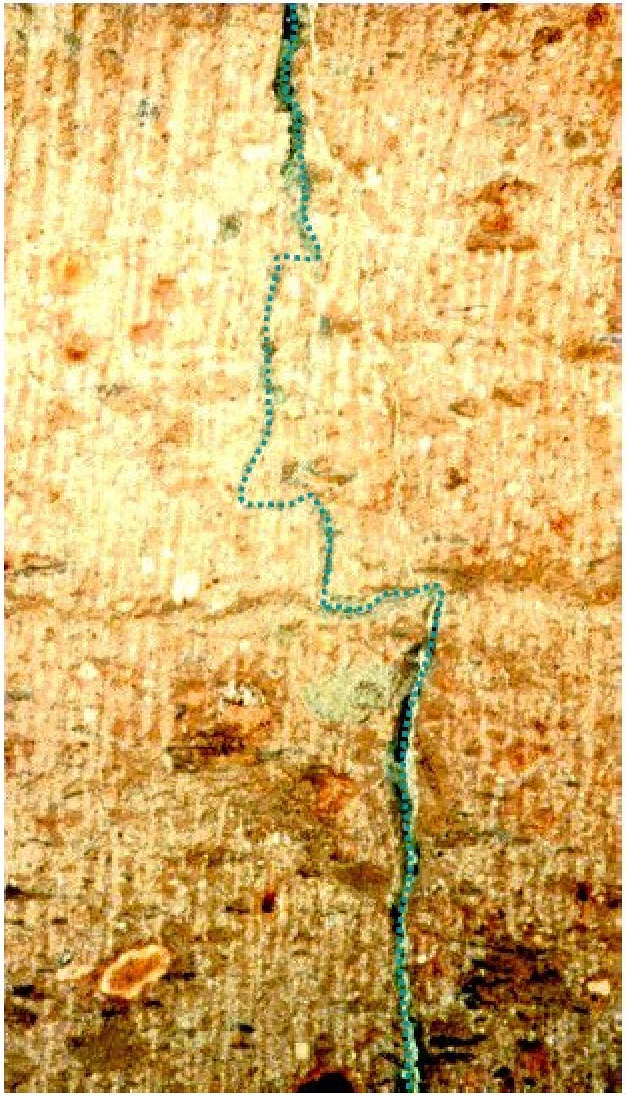
Stratigraphic layering (and overpressure) cause fractures to be abruptly blunted



Confinement mechanism related to high poison ratio (low critical stress + maybe very weak → decoupling



Fracture Complexity Due To Joints



NEVADA TEST SITE
HYDRAULIC FRACTURE
MINEBACK

Multiple fracs:

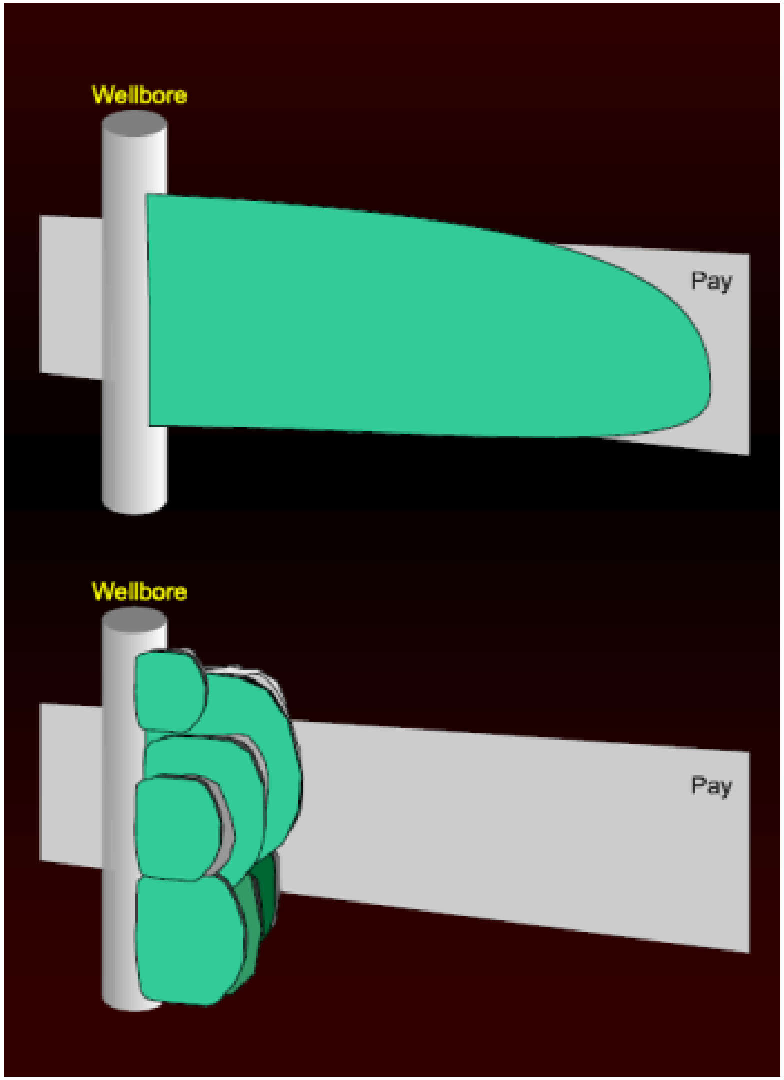
- Store excess volume
  - Reduced length

- Additional leakoff
  - Additional fracture faces
  - May change significantly with time

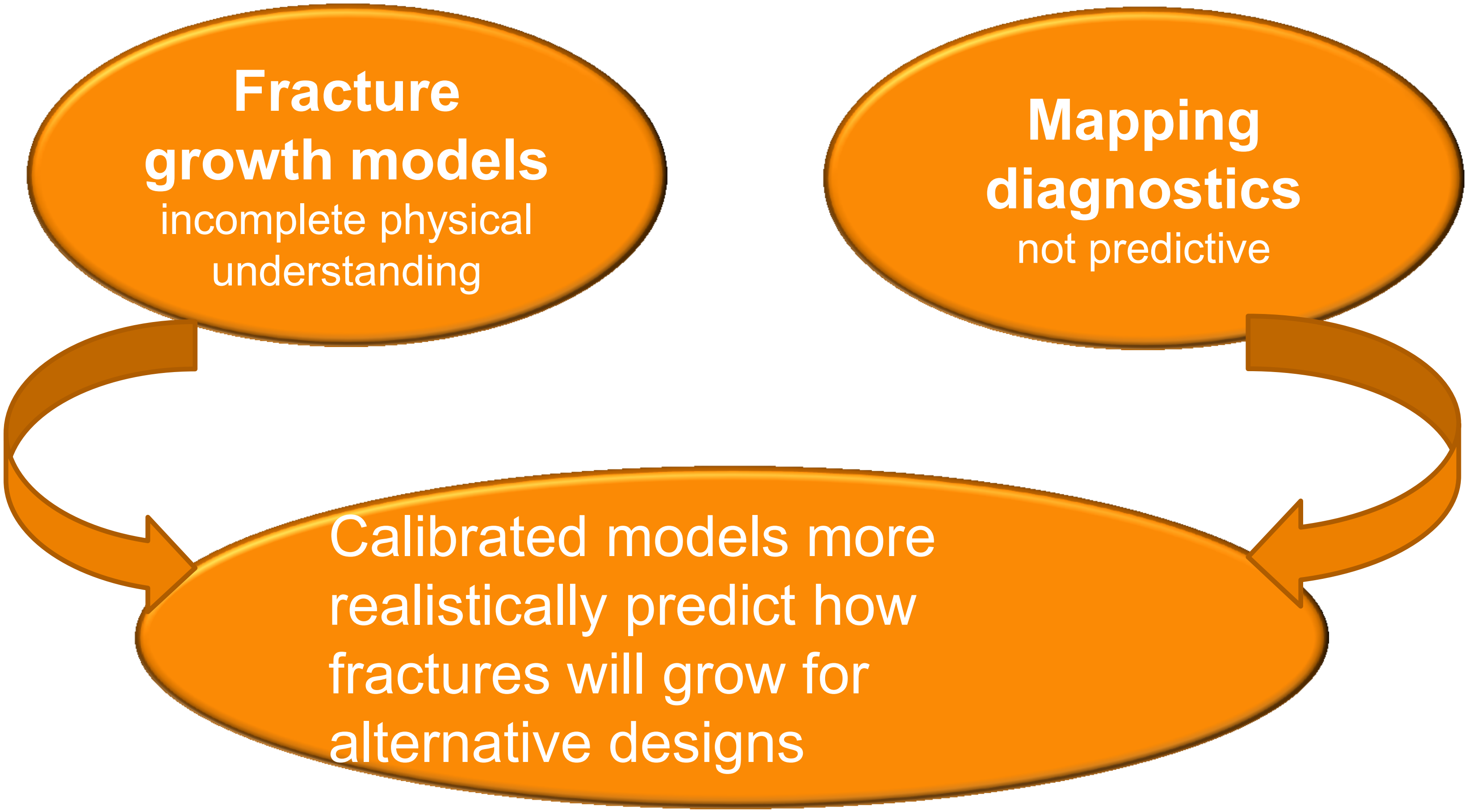
- Higher pressure drop
  - Additional fracture faces

- Tip generated effects
  - additional stress with shear dilatency

- different prop settling/transport



Modelling versus measuring

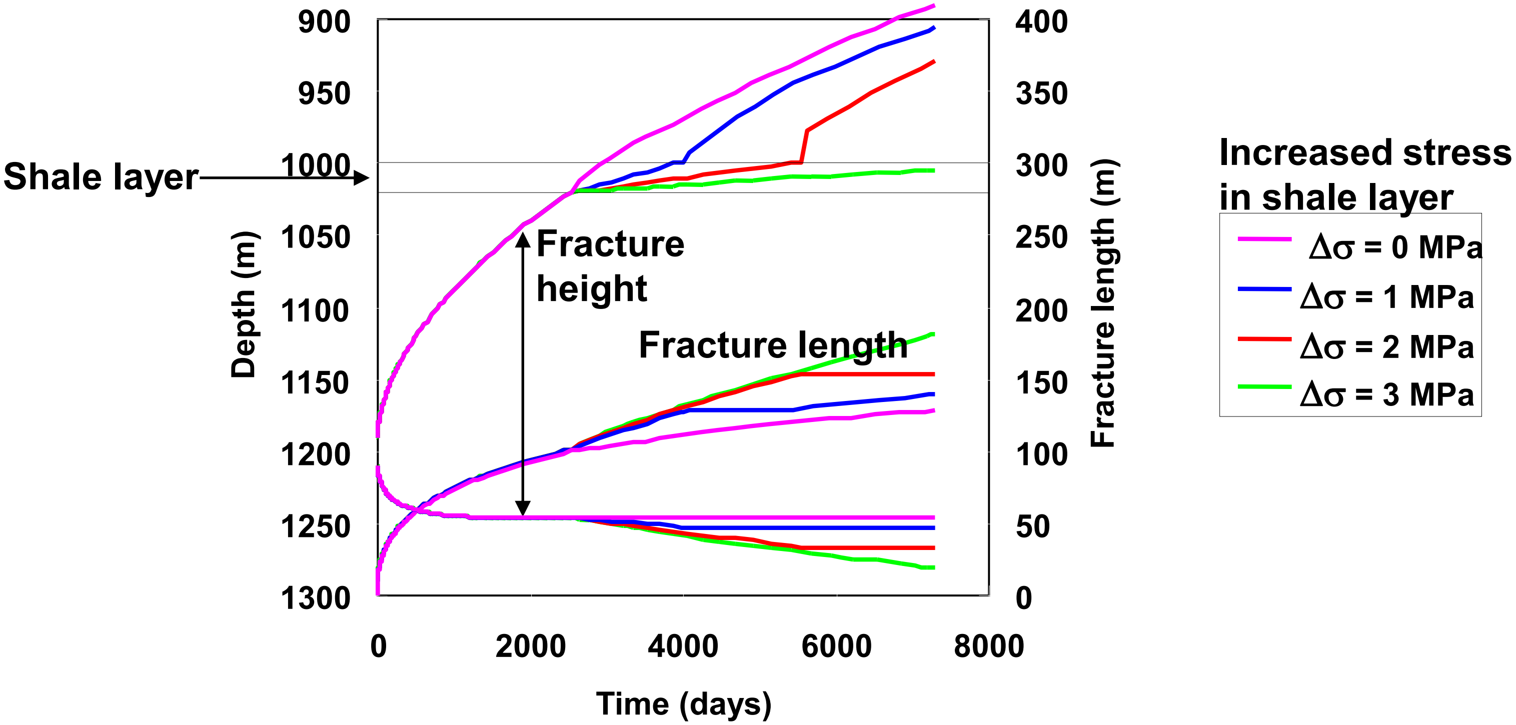


Fracture growth models
incomplete physical understanding

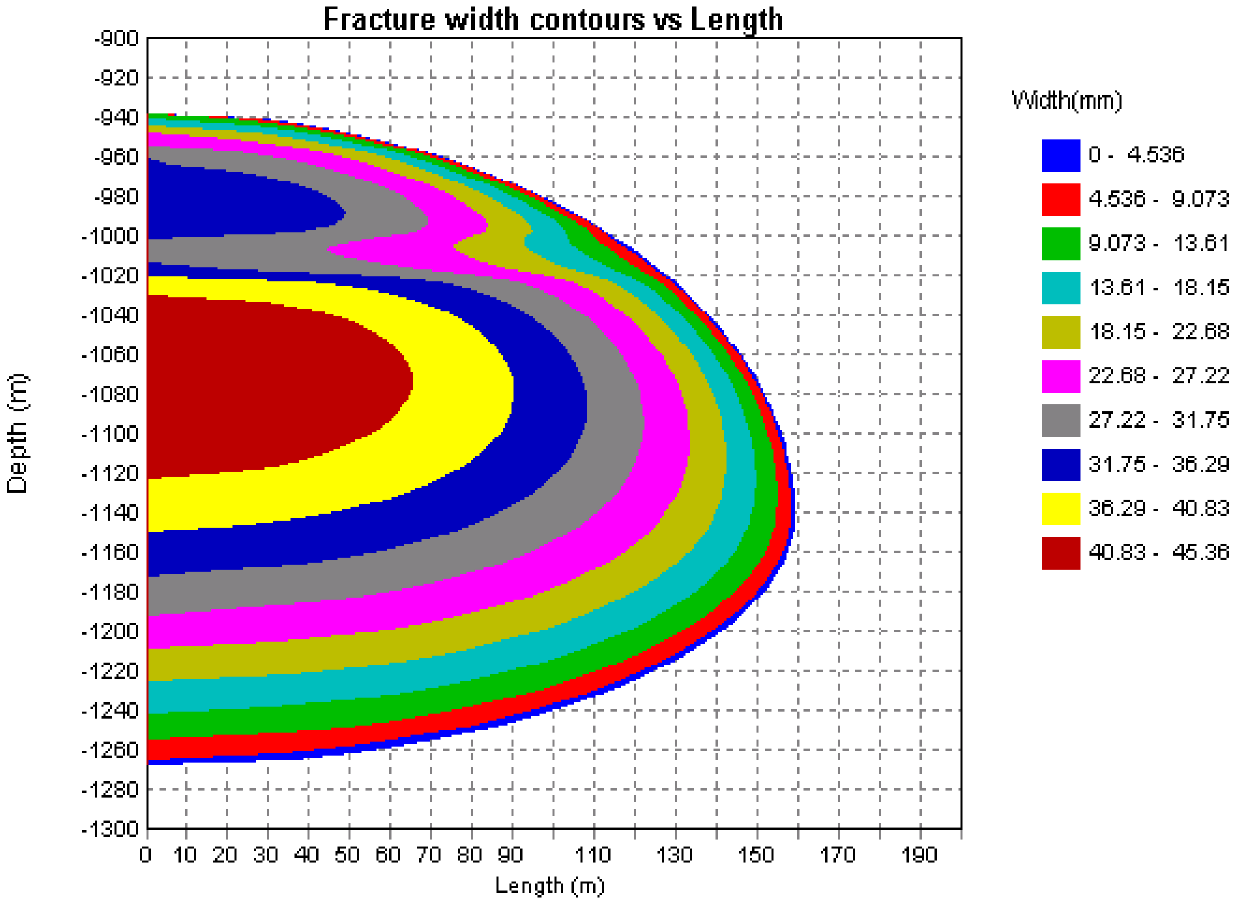
Mapping diagnostics
not predictive

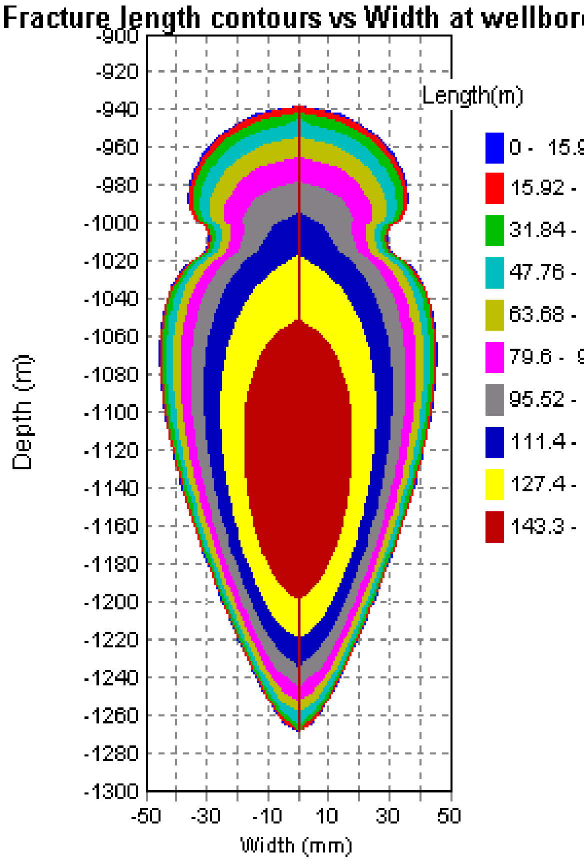
Calibrated models more realistically predict how fractures will grow for alternative designs

An example of a model:Effect of Stress Gradient and Stress Contrast



Width and length contours (Δσ = 2 MPa)





What can we measure/ESTIMATE

- Lithology (logs)
    - Gamma Ray (GR)
    - dynamic modulus (E) and
    - poision ratio (v)
- Micro-seismicity (shear failure only)
- Stress (special measurements MRX)
- Pressure
- Tilt meters

Preferably do a mini-frac test

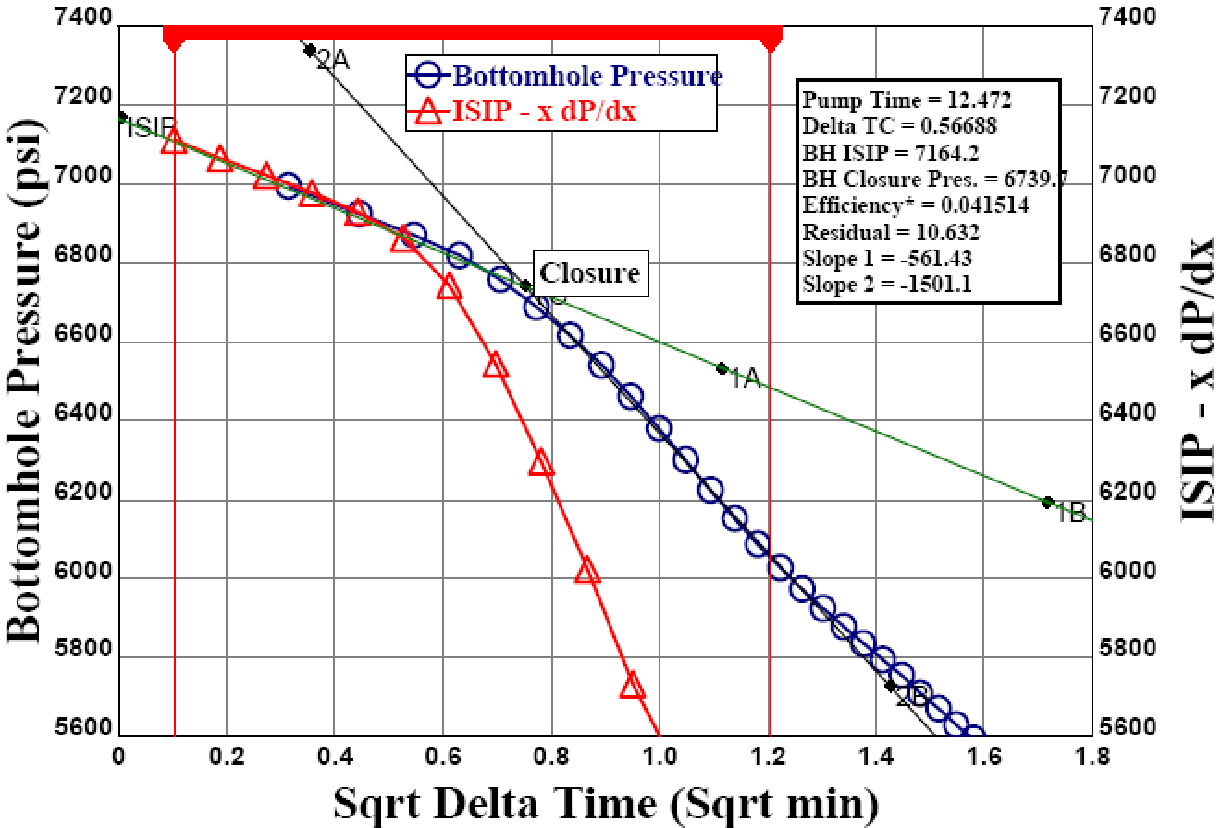
More input for design:

- In-situ stresses
- Fracturing pressures
- Leakoff behaviour

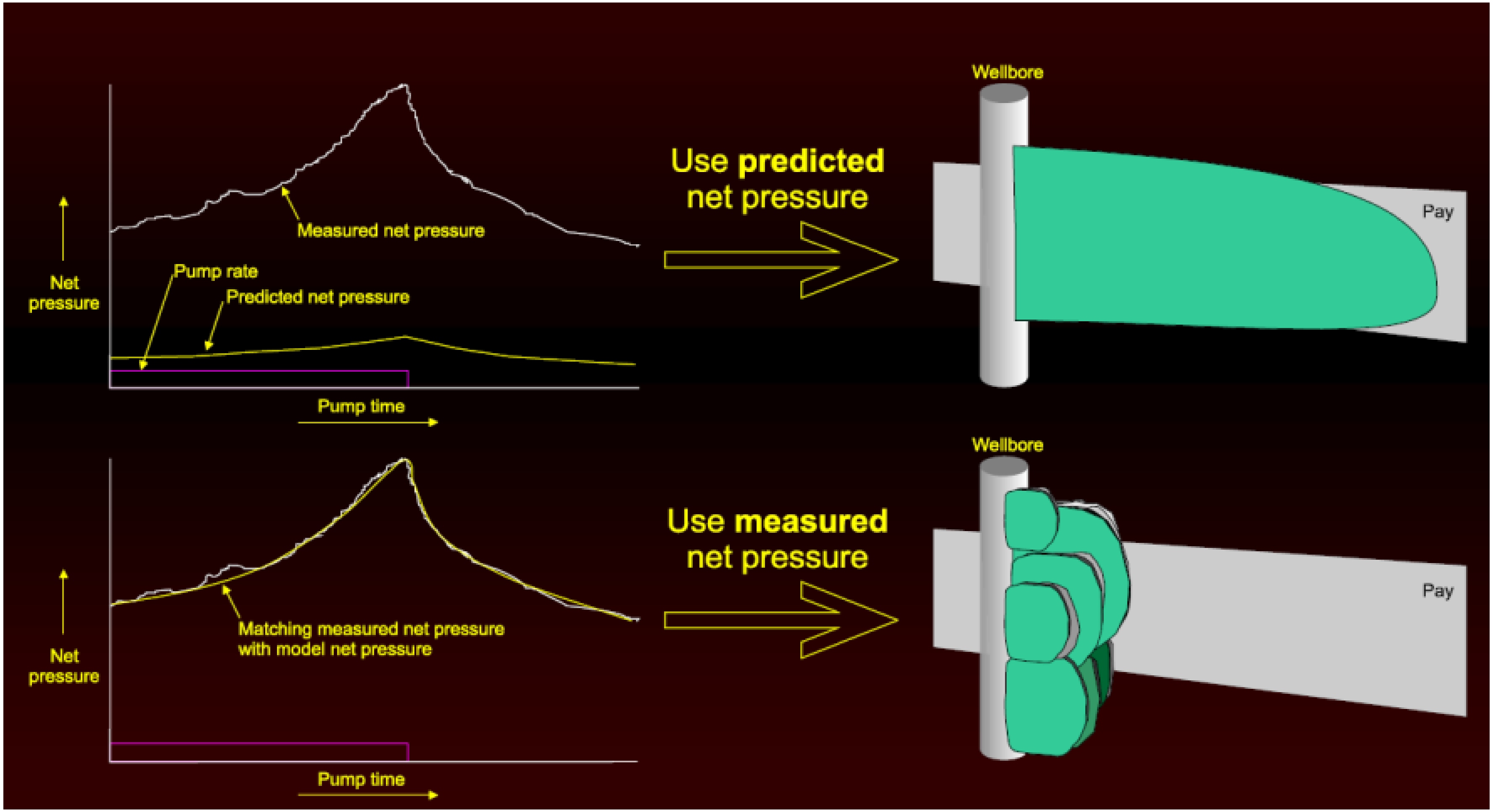
} Minifrac test

- ISIP = initial shut –in
- Pressure

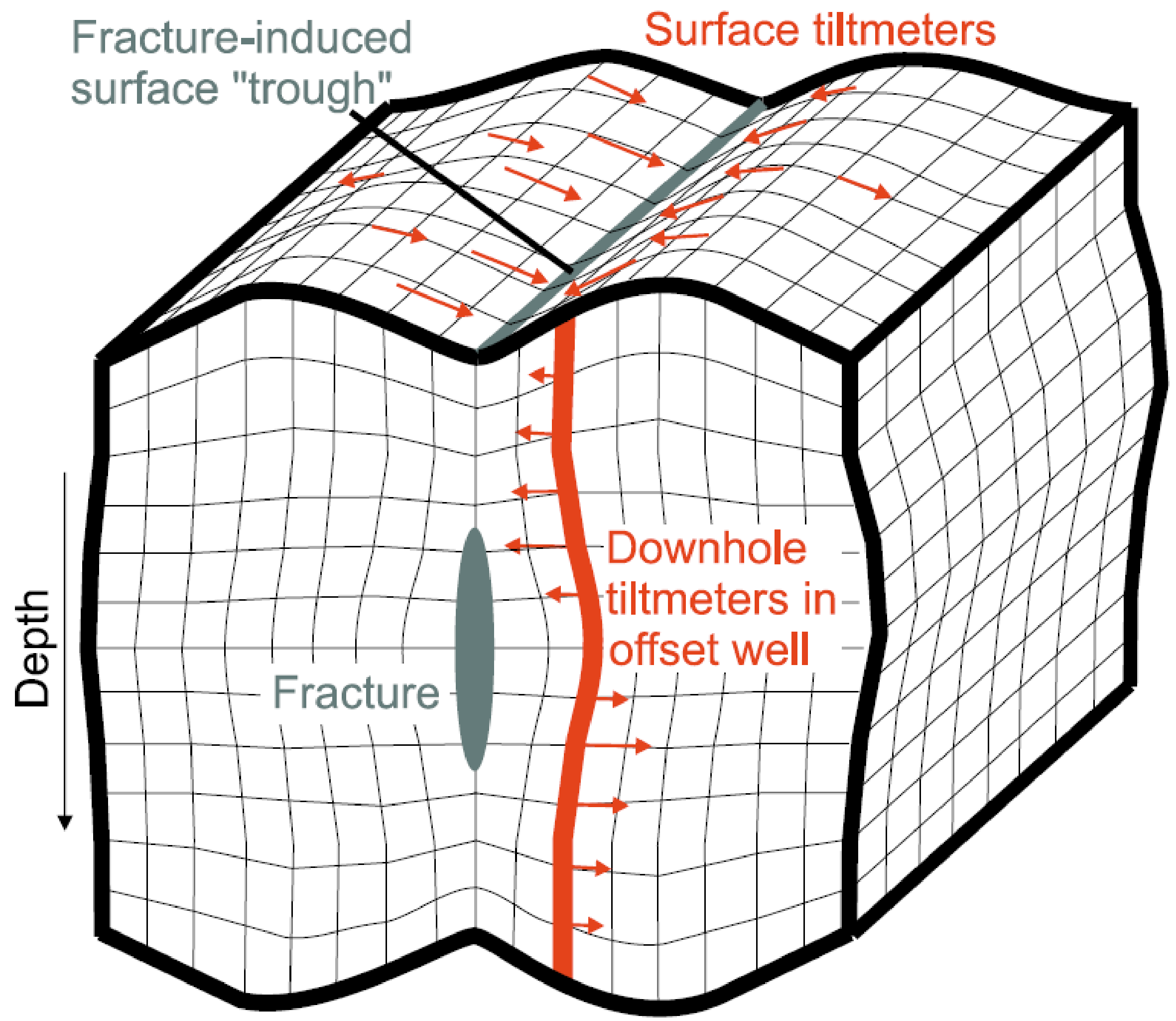
- Shut-in time



Use pressure to constrain fracs



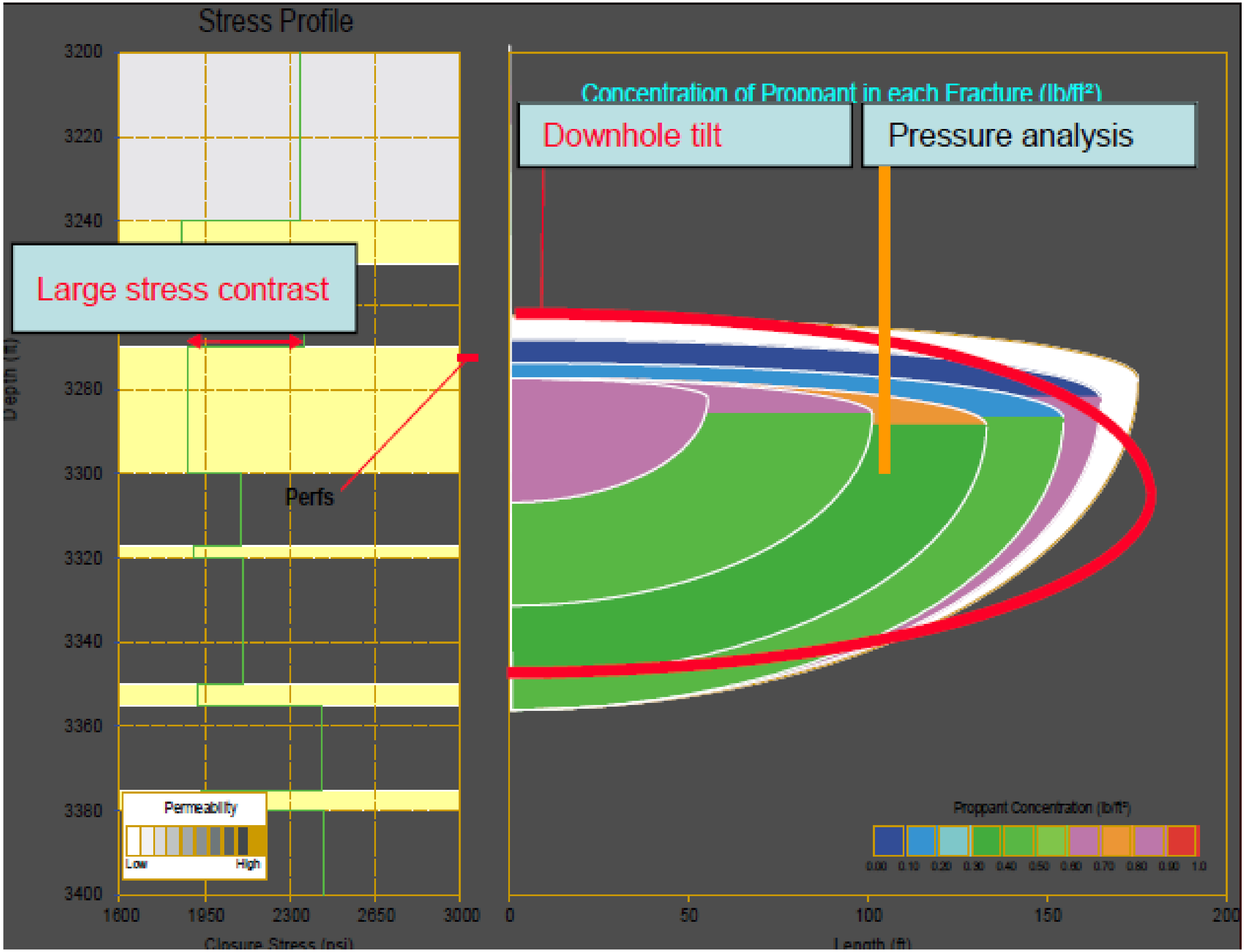
Stress changes during fracturing



Displacement field in the earth around a vertically oriented hydraulic fracture, showing induced surface and downhole tilt vector directions.

Siebrits, 2000

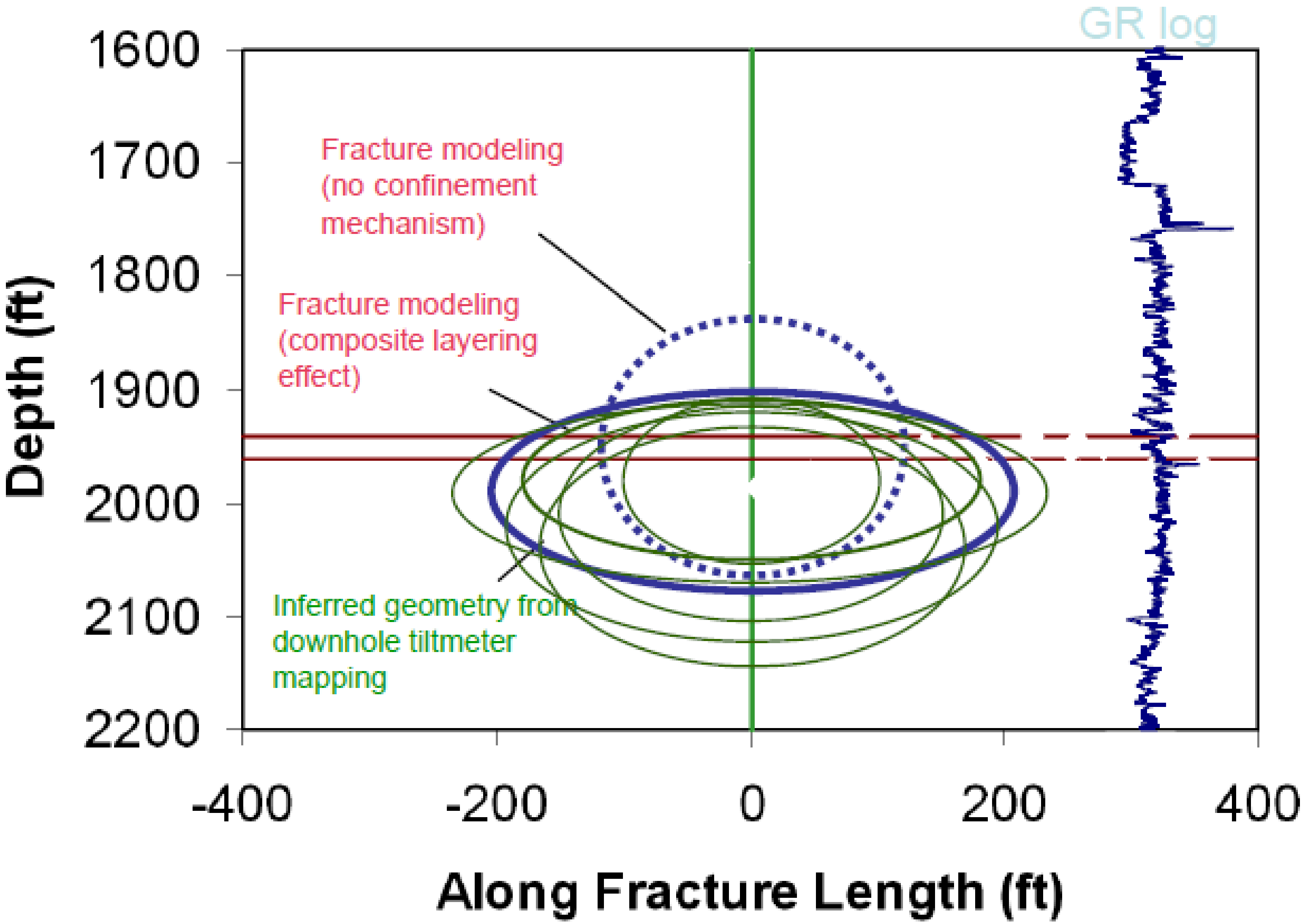
Sometimes model predictions and measurements agree well


Large stress contrast

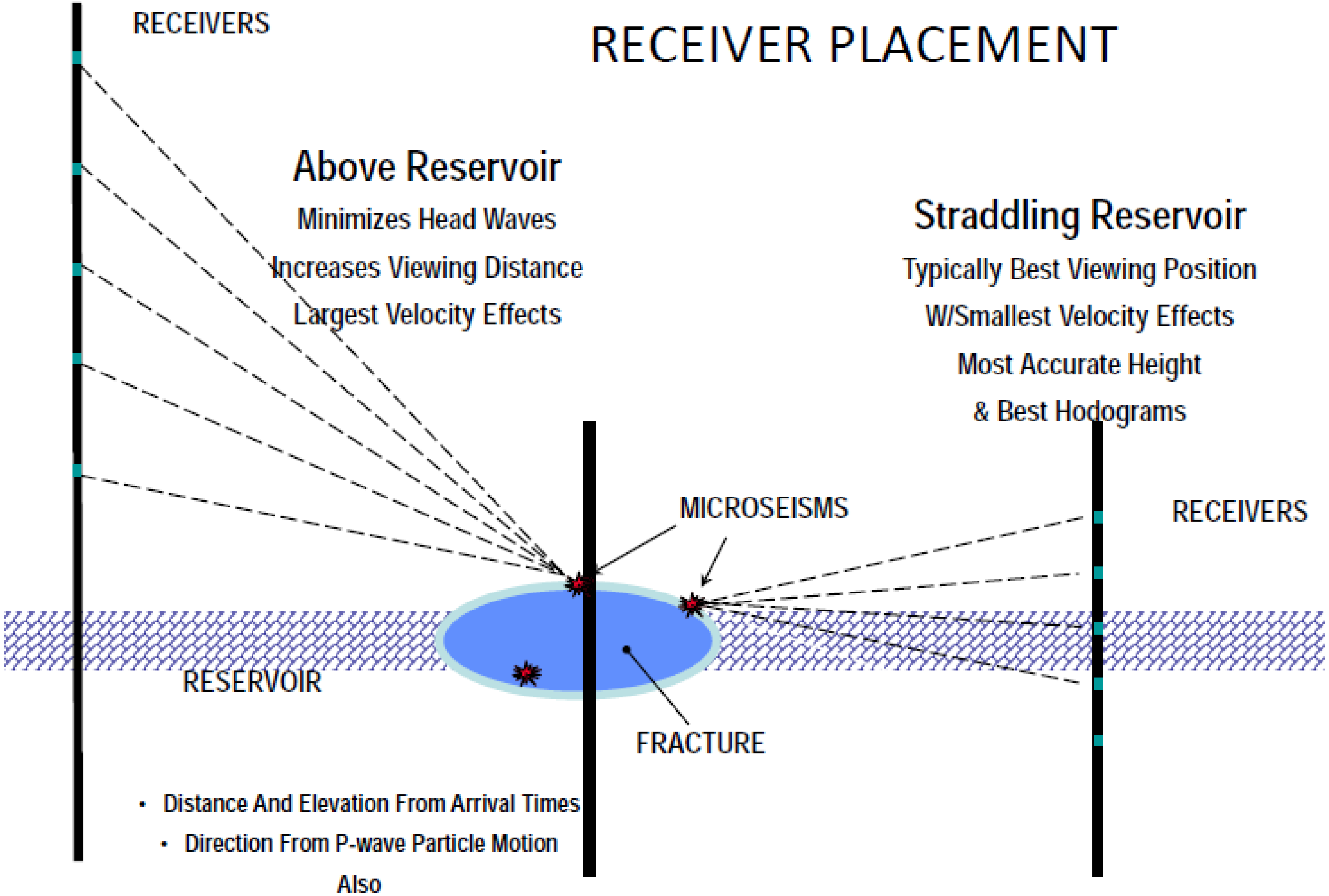
Downhole tilt

Pressure analysis

But in other cases not



MICROSEISMICITY



RECEIVER PLACEMENT

Above Reservoir

Minimizes Head Waves

Increases Viewing Distance

Largest Velocity Effects

Straddling Reservoir

Typically Best Viewing Position

W/Smallest Velocity Effects

Most Accurate Height

& Best Hodograms

- Distance And Elevation From Arrival Times
- Direction From P-wave Particle Motion

Also

- Microseisms: Small Amplitude, High Frequency
- Receiver Distance = Typical Interwell Spacing

Requires: High Quality Receivers

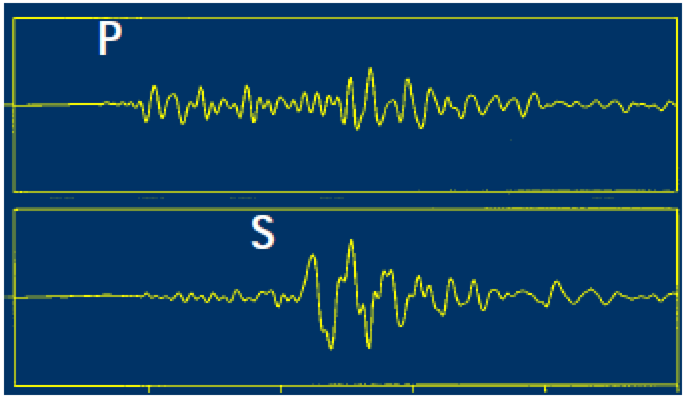
MICROSEISMICITY

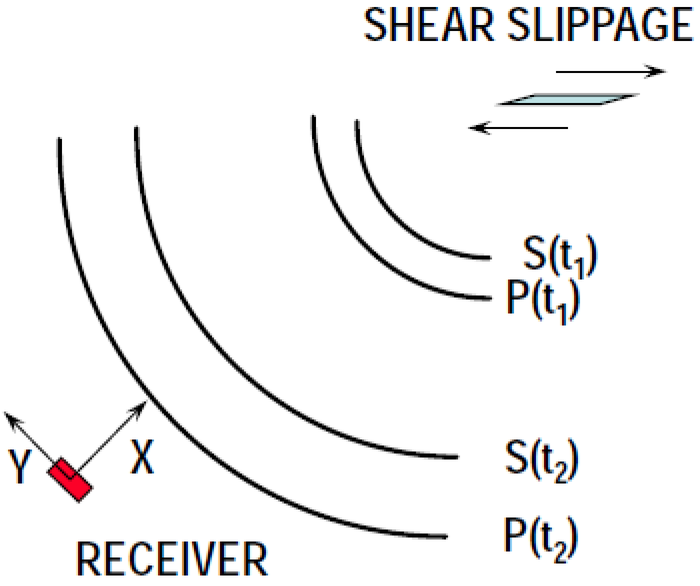
Determining Distance and Elevation

- Slippage Emits Both P & S Waves (Compressional & Shear)
- Velocities Are Different

  P Wave > S Wave

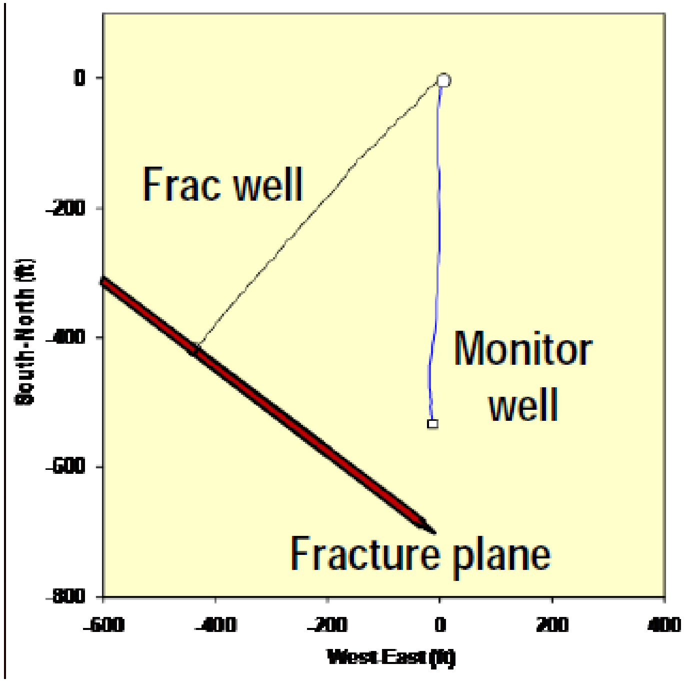
  Detected At Tri-Axial Receiver

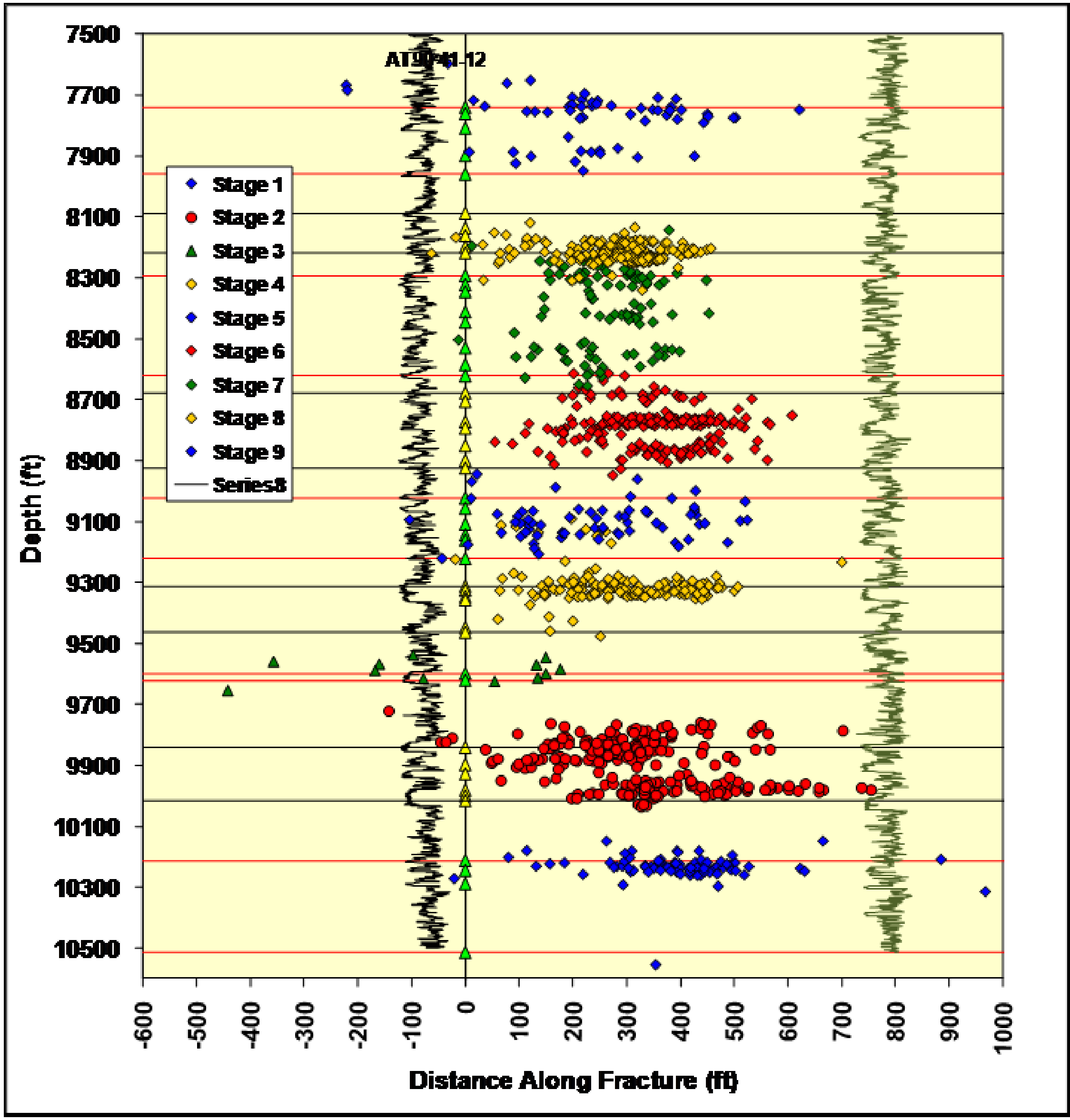




Microseismic monitoring

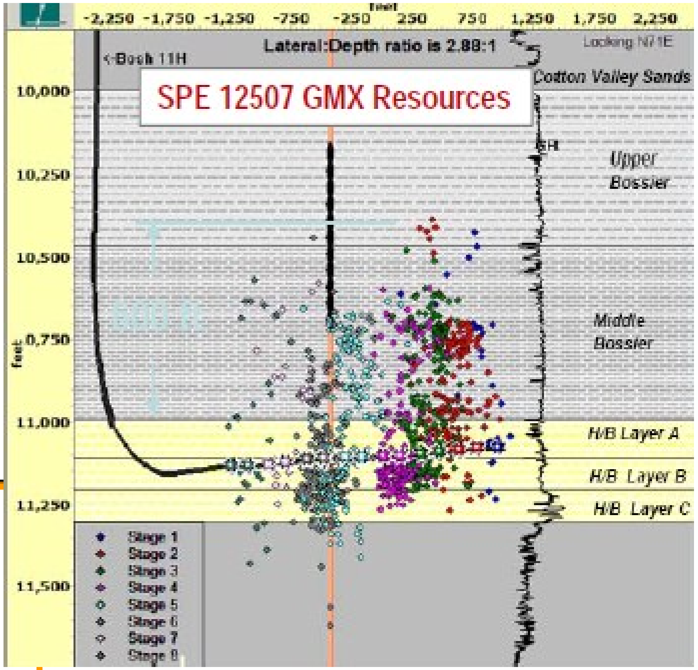
- Numerous cases where fracture grows at or close to microseismic observation well
- Height can be accurately assessed
- Usually observe fractures following lithology

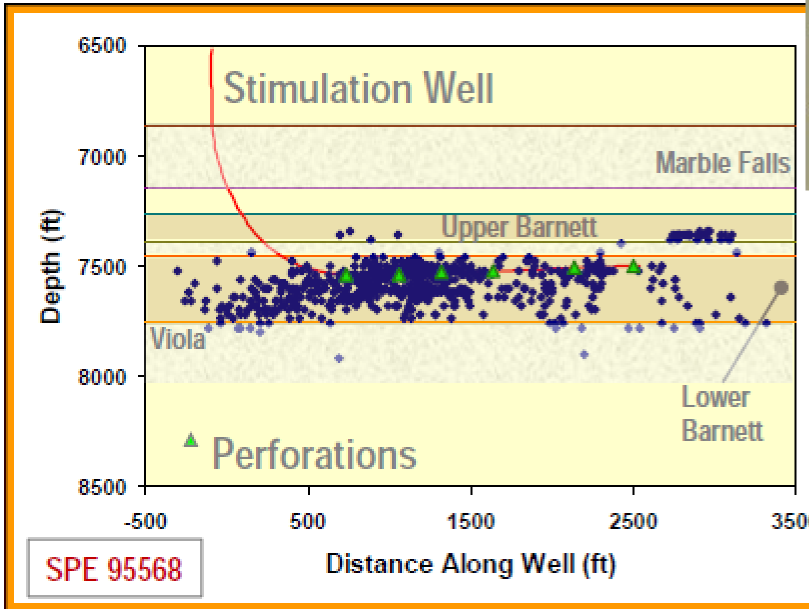




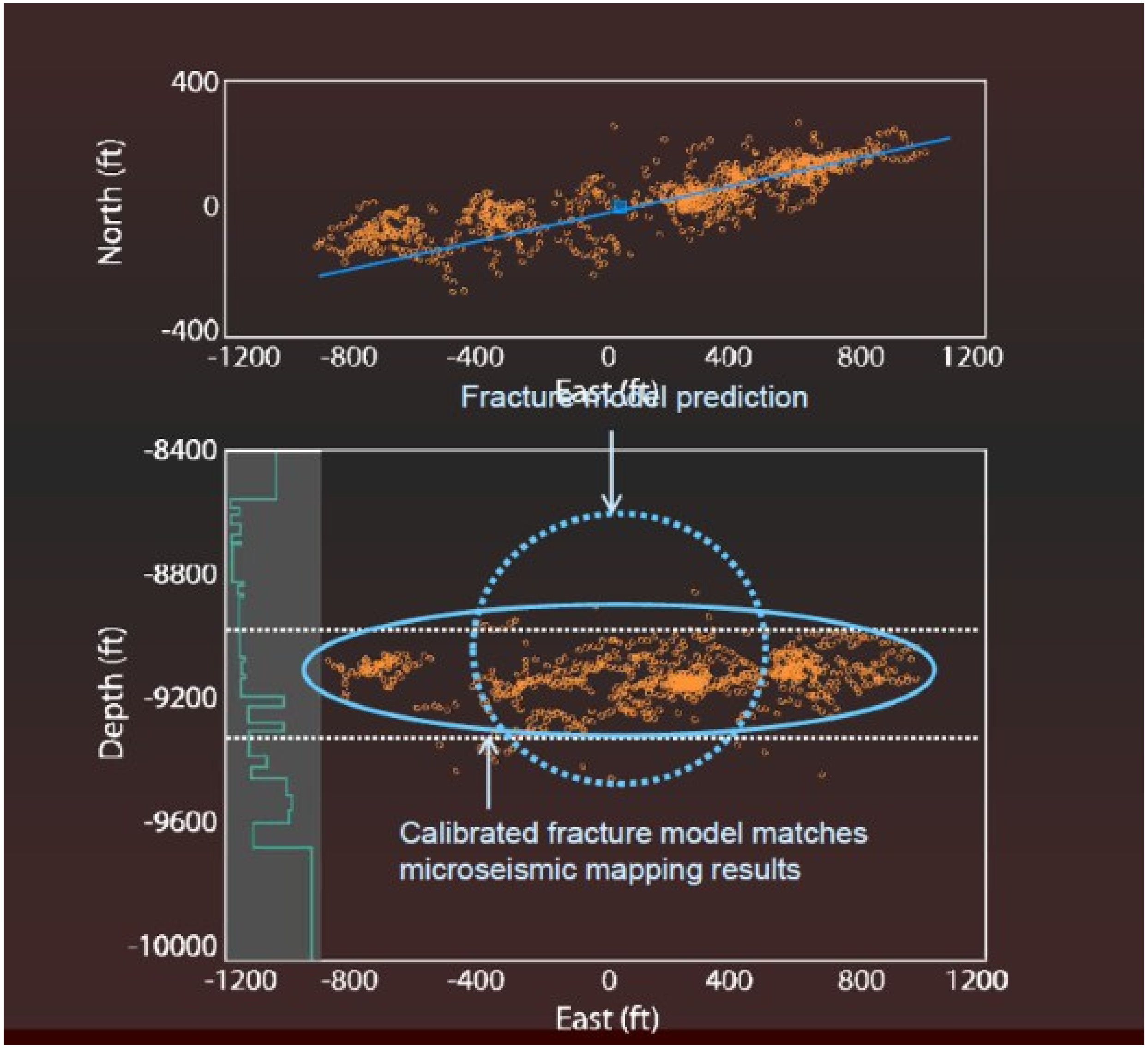
Fracture containment AS a conseqence of strength of surrounding layers

- Variable containment in shales
- Containment (e.g., Barnett)
- Bounded by carbonates
- Upward growth
- Continuous shale
- Faulting effects


SPE 12507 GMX Resources


SPE 95568

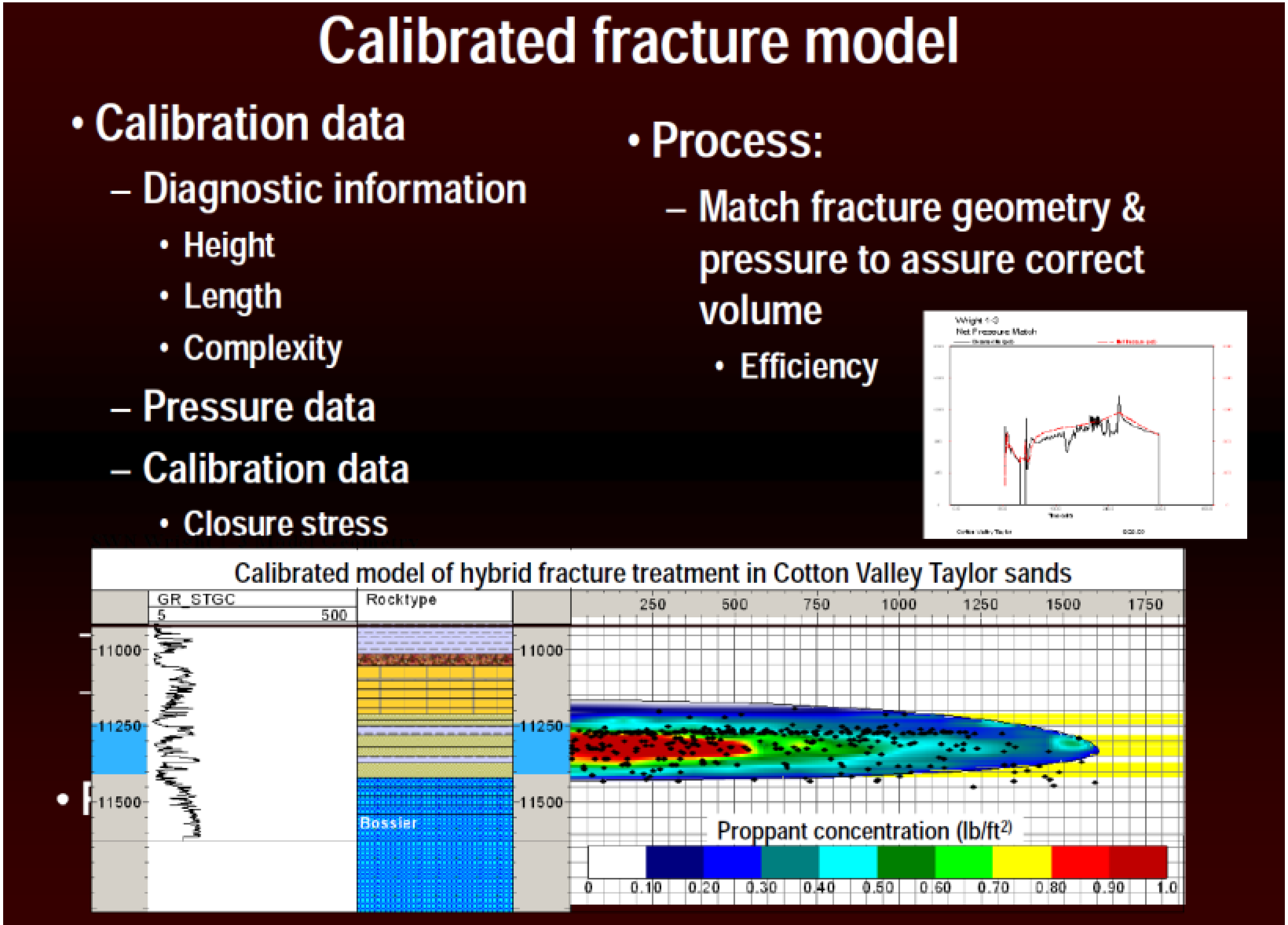
Microseismic data and model calibration-cotton valley sst



Fracture model prediction

Calibrated fracture model matches microseismic mapping results

Cotton valley sst

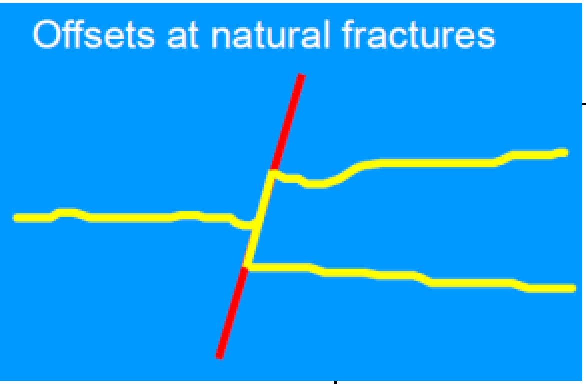


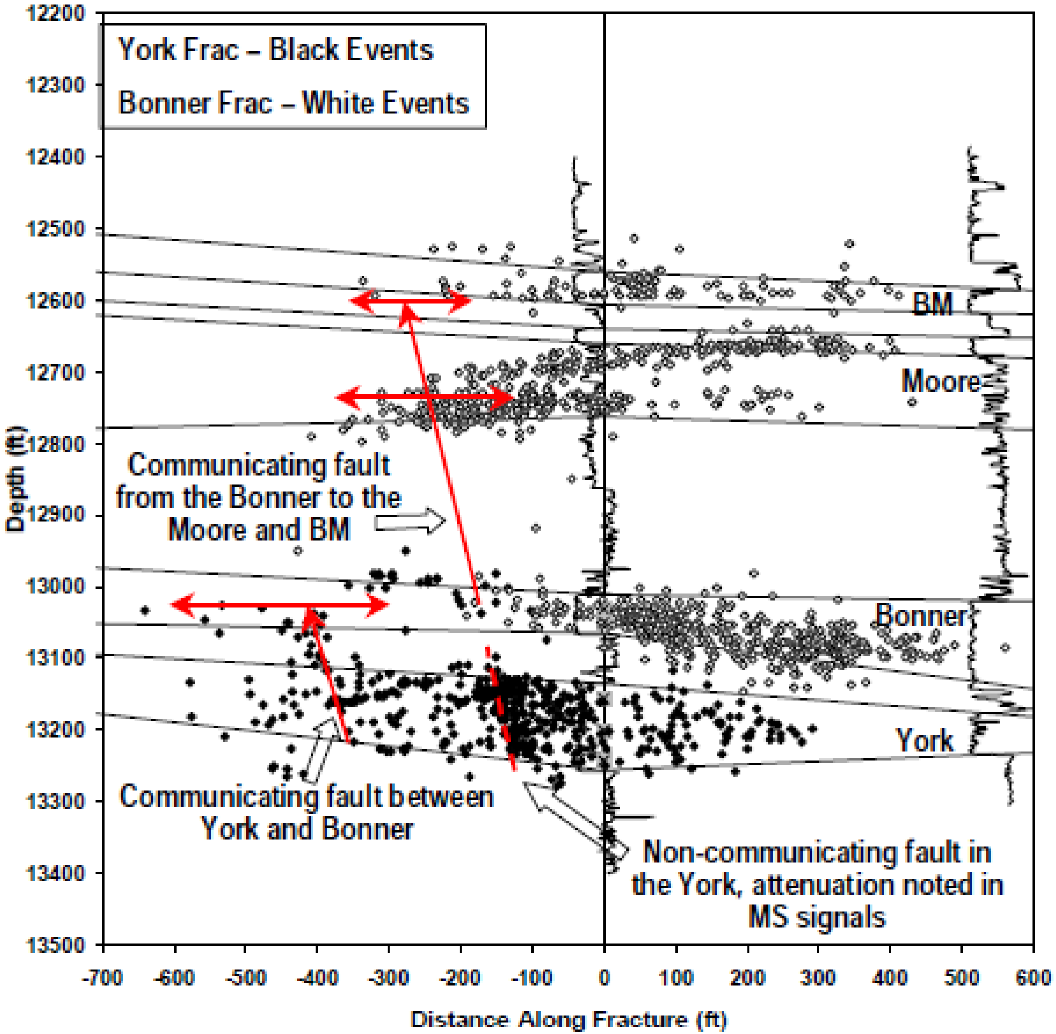
Calibrated fracture model

- Calibration data
  - Diagnostic information
    - Height
    - Length
    - Complexity
  - Pressure data
  - Calibration data
    - Closure stress
- Process:
  - Match fracture geometry & pressure to assure correct volume
    - Efficiency

Calibrated model of hybrid fracture treatment in Cotton Valley Taylor sands

Offset due to natural fractures and faults





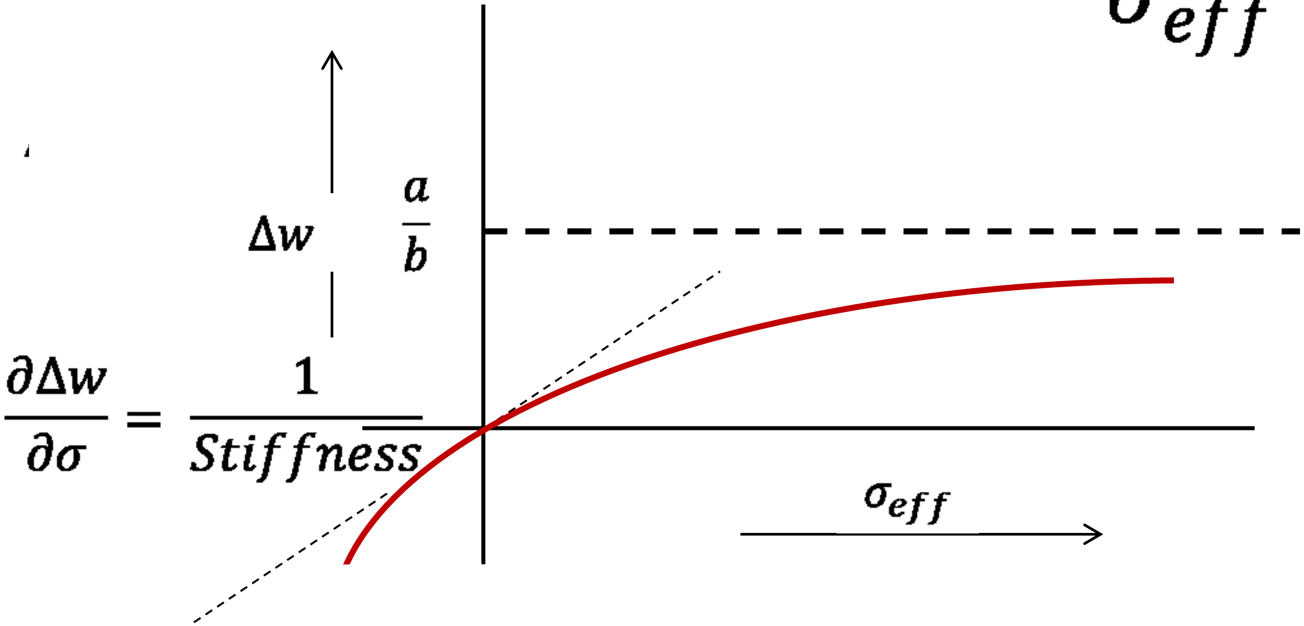
microseismicity shows shear fractures

- how about shear fracture mechanisms, aperture and permeability?

Tensile failure – elastic

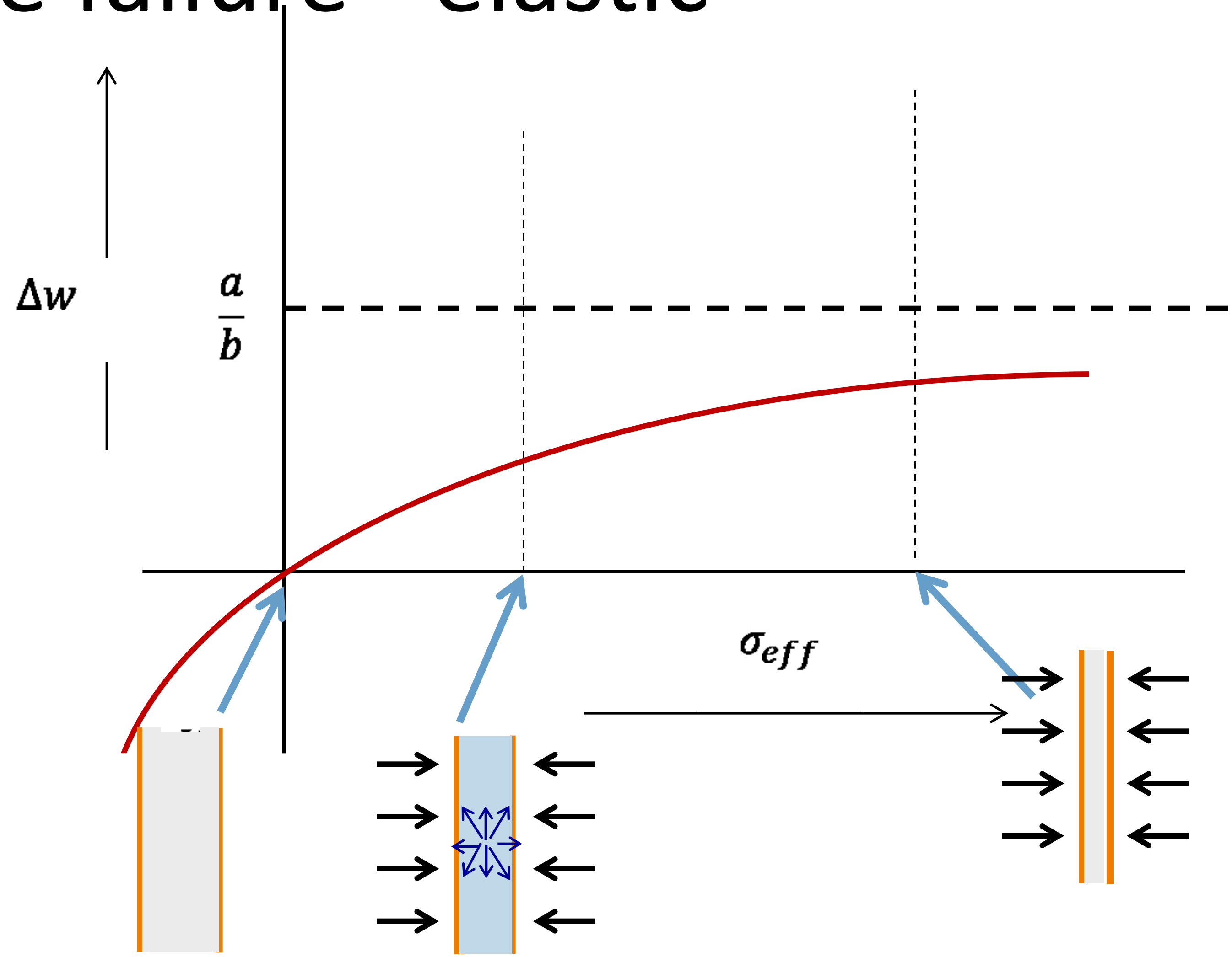
(S.C Bandis, 1983):

$$\Delta w = \frac{a}{(b + \frac{1}{\sigma_{eff}})}$$

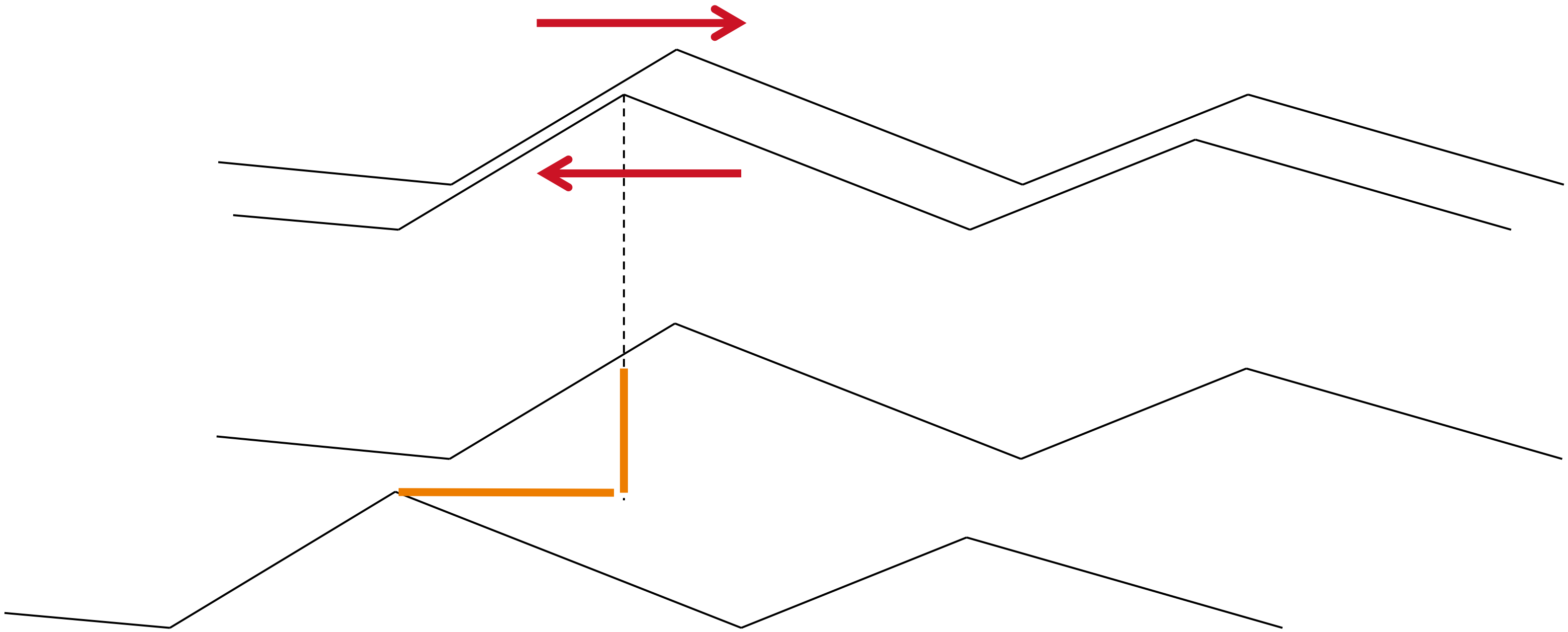


$$\frac{\partial \Delta w}{\partial \sigma} = \frac{1}{Stiffness}$$

Tensile failure - elastic



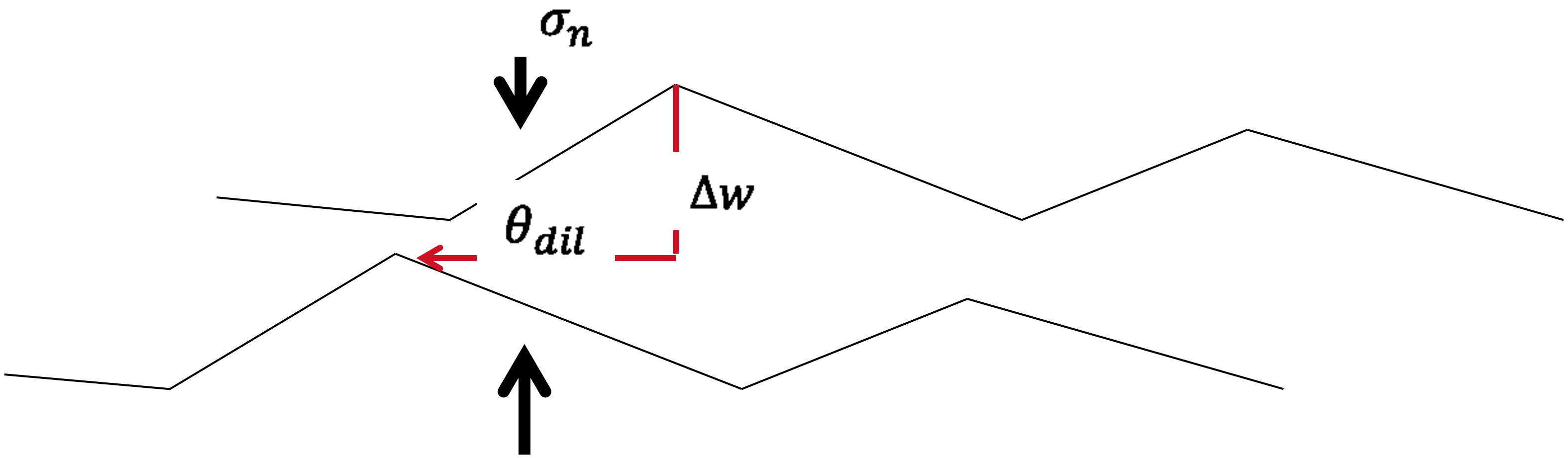
Shear failure
(shift along fracture plane):



Shear failure

$$\Delta w = \frac{\tau_{eff} - \tau_0}{K_f} \tan(\theta_{dil}),$$

(T. Kohl et al, 2007)



permeability

- Cubic law:

$$K' = c\frac{W^2}{12} \cdot \frac{W}{L}$$

W:= Fracture aperture

L := Spacing between fractures

Hydraulic Fracturing in Shale Gas - Observations

- No two shales alike. They vary aerially, vertically & along wellbore.
- Shale “fabric” differences, in-situ stresses and geologic variances often require stimulation changes.
- First need - Identify critical data set
- Second need – never stop learning about the shale.

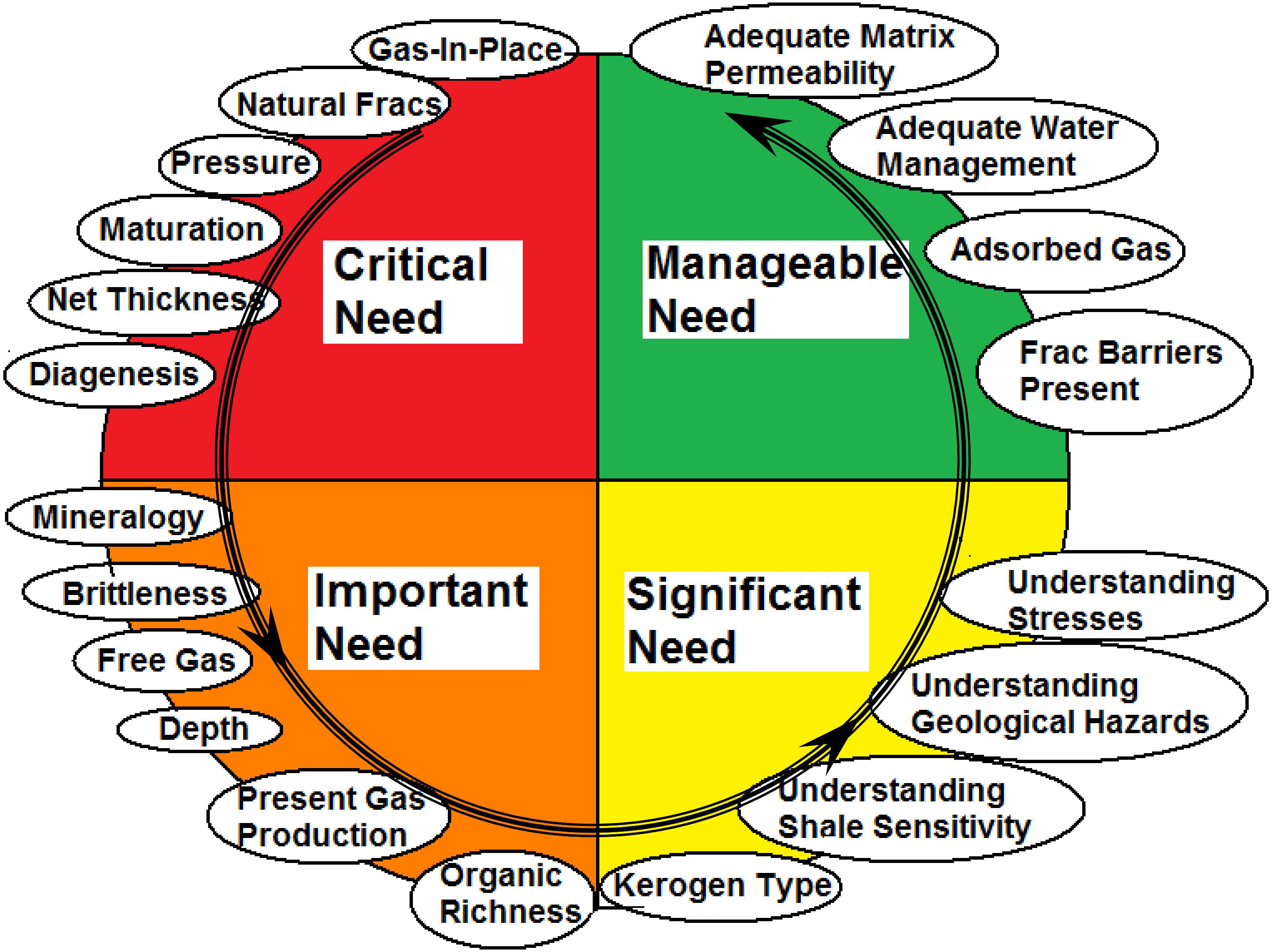
Shale Technology

Enabling

- Slick Water Fracs & Hybrid Fracs
- Horizontal Wells
- Multi-stage Fracs
- Simultaneous Fracturing

Optimizing

- Critical Data Set
- Frac Complexity
- Special Materials
- Flowback
- Water Management
- Production



Critical Need

Gas-In-Place
Natural Fracs
Pressure
Maturation
Net Thickness
Diagenesis

Manageable Need

Adequate Matrix Permeability
Adequate Water Management
Adsorbed Gas
Frac Barriers Present

Important Need

Mineralogy
Brittleness
Free Gas
Depth
Present Gas Production
Organic Richness

Significant Need

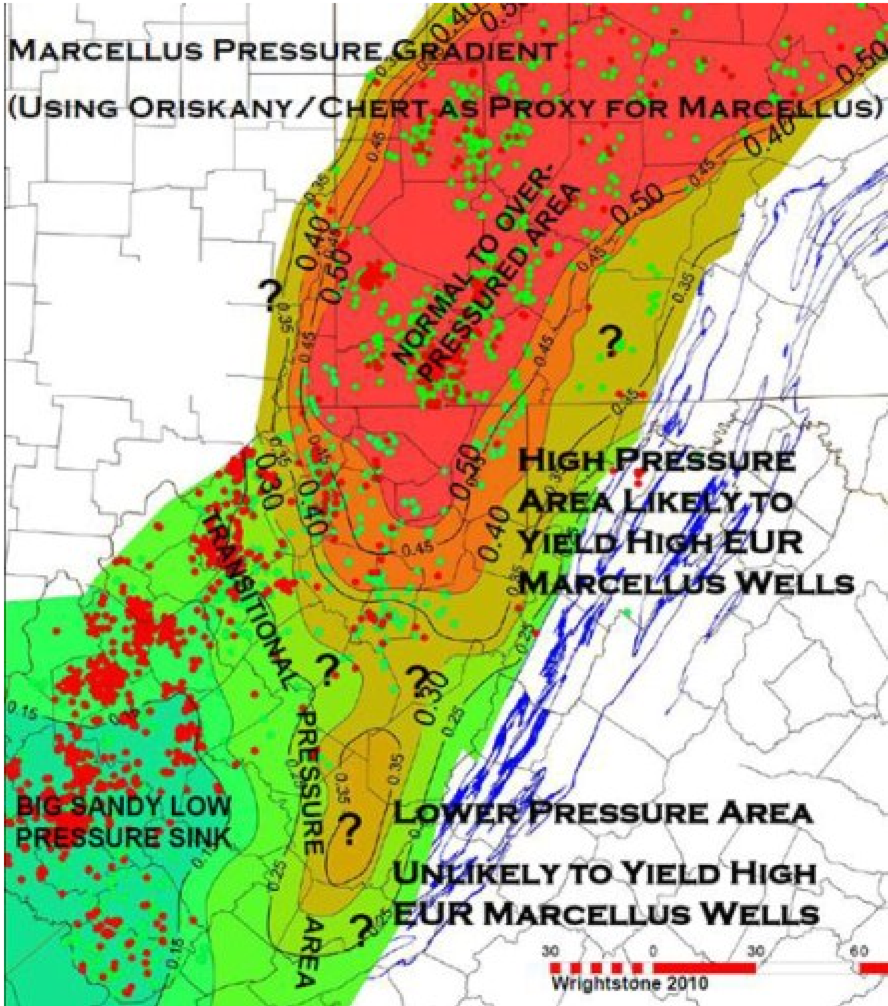
Kerogen Type
Understanding Shale Sensitivity
Understanding Geological Hazards
Understanding Stresses

Find the Sweet Spot

Mapping a “sweet spot” in a shale play reduces the risk of economic failure.

Critical Variables?

- Pore Pressure
- Gas in Place
- Maturation
- Depth of Burial
- Natural Fractures
- Shale Thickness
- Pore or Reservoir Pressure
- Structures?
- Production



Critical Factors vs. Critical Data Set

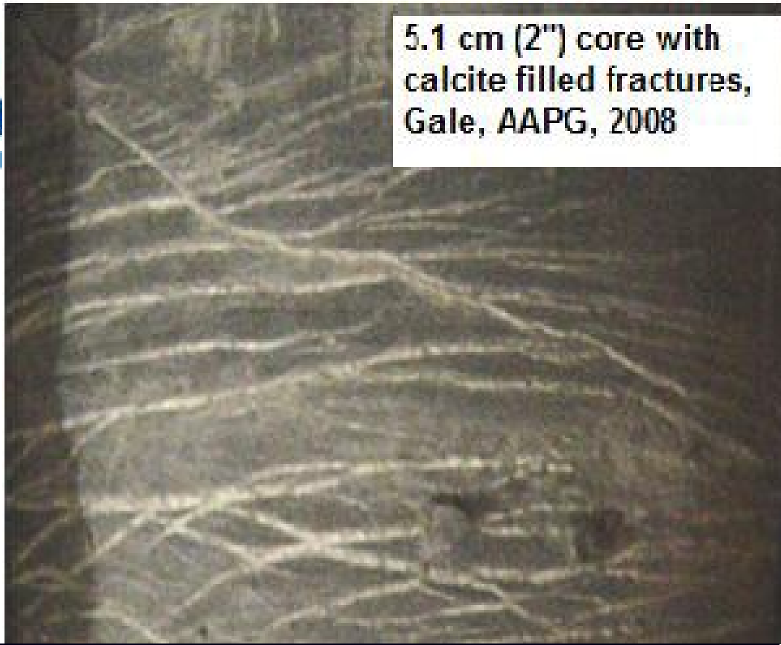
Factors describe the shale to be evaluated – not the whole play.

Data sets include:

- How to get the most accurate & representative data for the specific shale.
- Knowledge of what operations are needed to optimize production.
- “Must have data” includes environmental concerns and resolutions

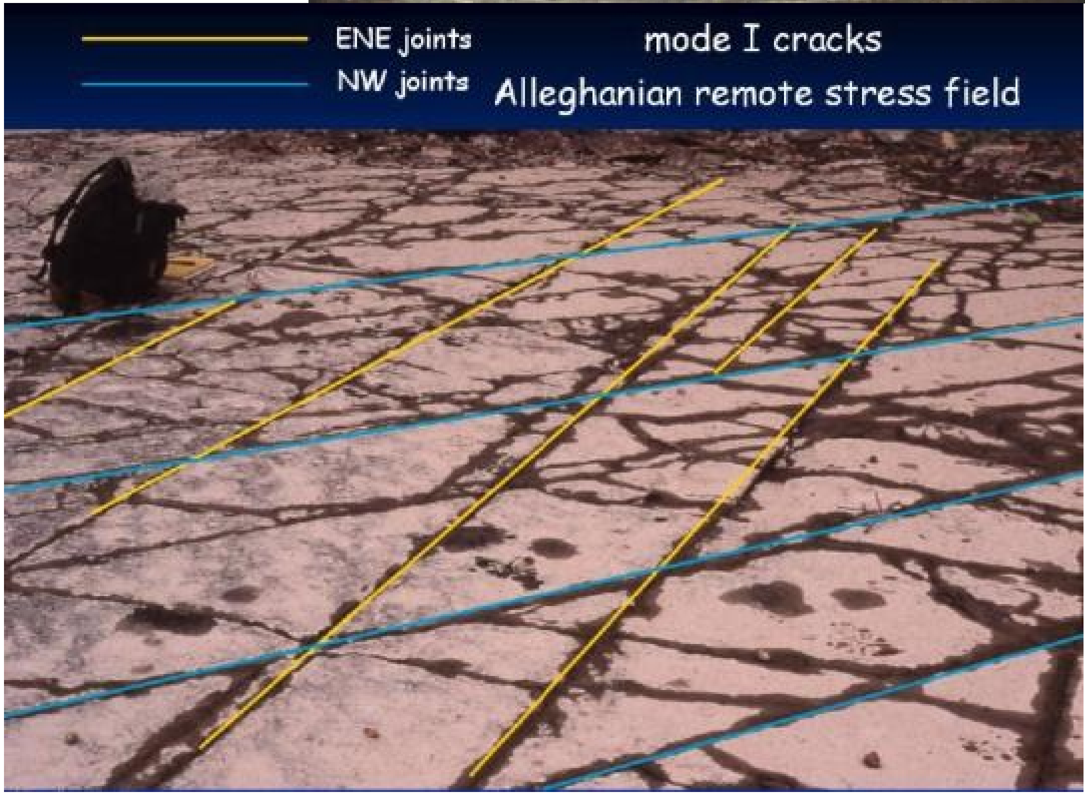
Natural pathways.

- Open at 50 to 60% of rock frac pressure.
- Open by low viscosity fluid invasion.
- Difficult to prop.
- Dominate Permeability

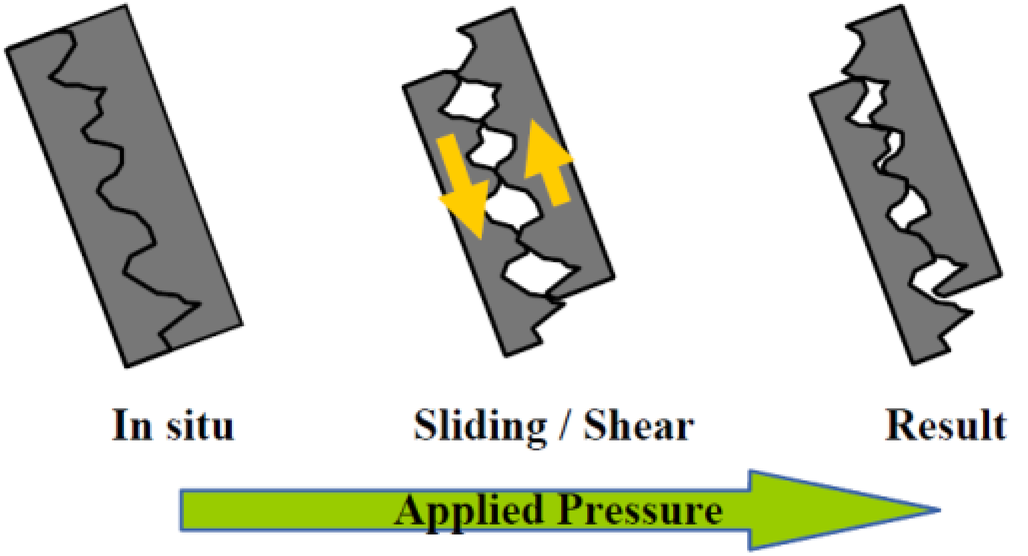


5.1 cm (2") core with calcite filled fractures, Gale, AAPG, 2008

Natural fracture systems

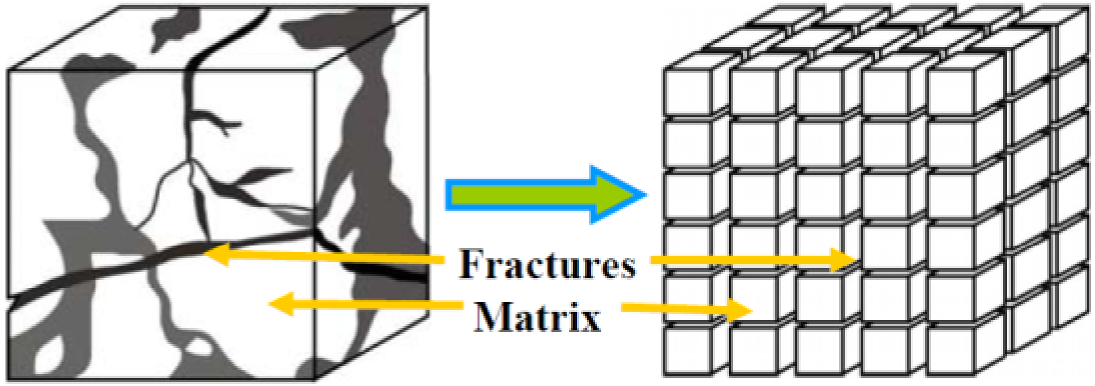


- Coupling between geomechanics (friction; fault reactivation) and flow behaviour (dual porosity system)



Shear Dilation Mechanism

Chipperfield, et.al., 2007



Reservoir Model Description; after Warren and Root (1963)
Taken from Chipperfield, 2007

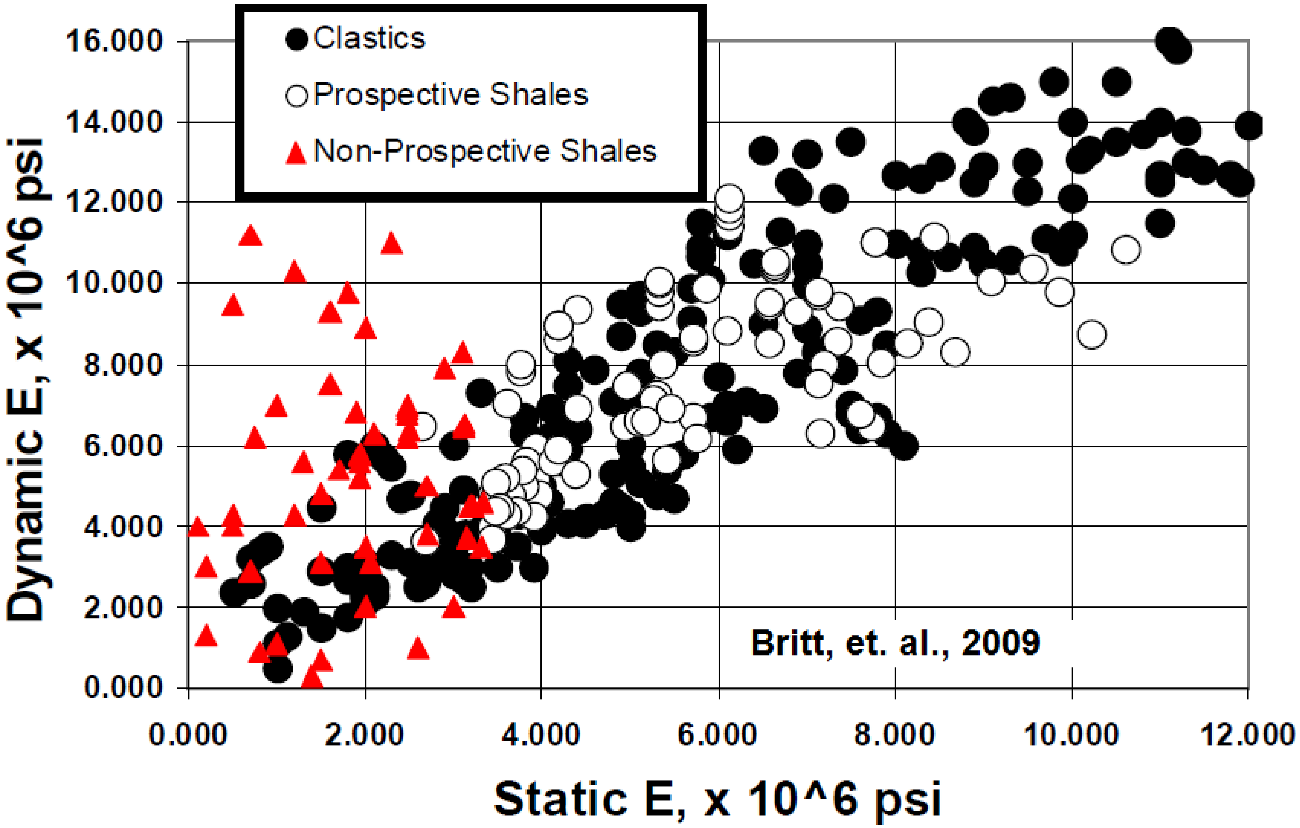
Effect of elastic / plastic behaviour

- Brittle shales are more easily fractured
- Soft material: Healing of fractures

Dynamic E=sonic

Static E=mechanical experiment

Dynamic to Static Young's Modulus Correlation



Design

The goal: Maximize frac contact with shale.

- Wellbore orientation (for transverse induced fractures)
- Wellbore length
- Toe up or down?

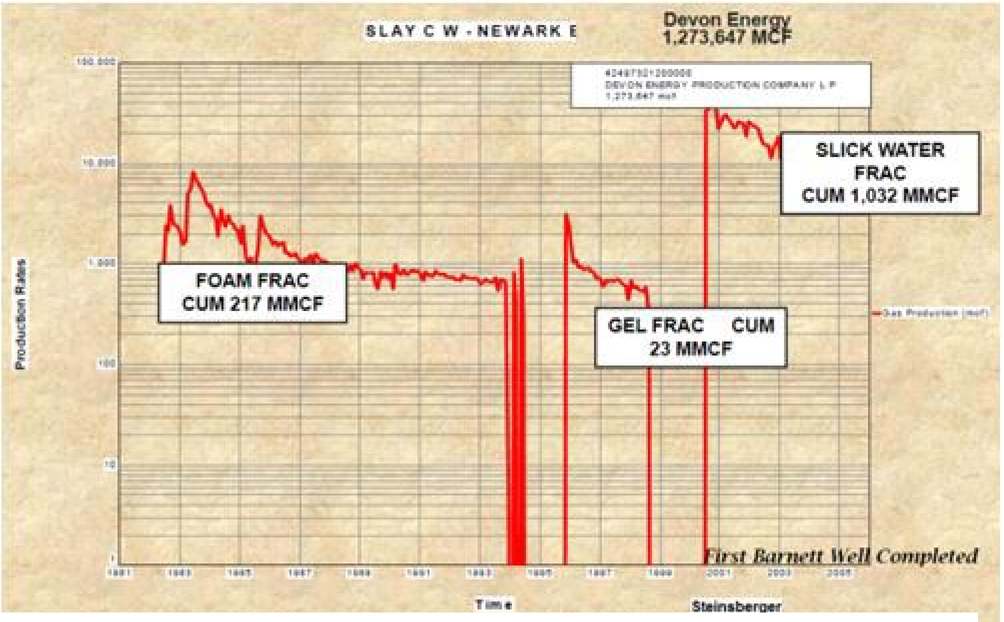
Number of Frac Stages

- How to place: by average distance or gas shows?
- Spacing, number, holes? Interference?
- Hydraulic diversion?

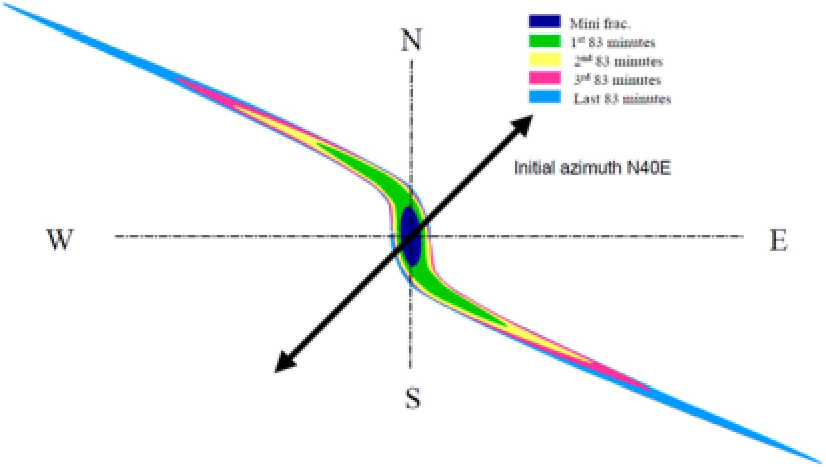
Re-Fracturing

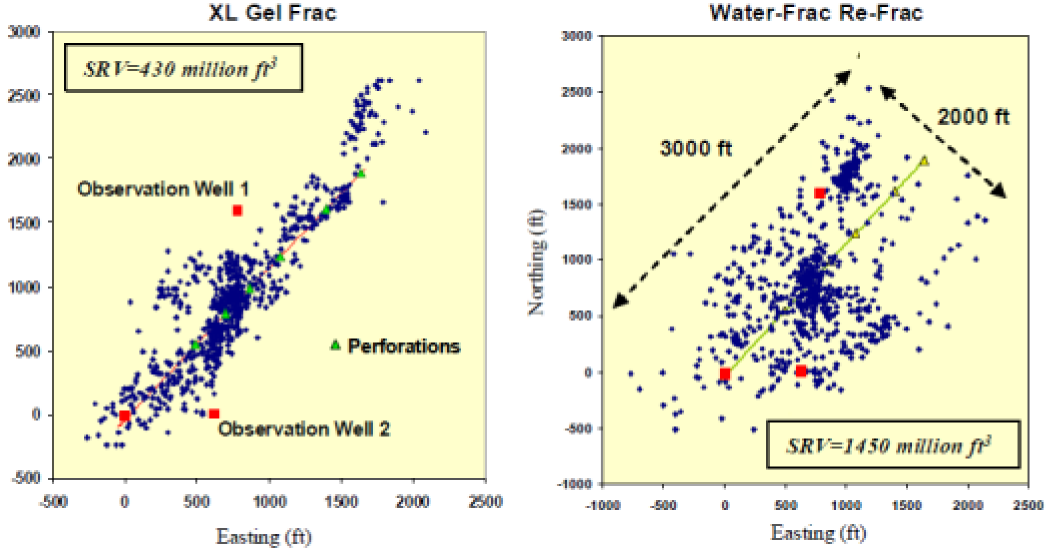
They Work – But Why?

- Old fractures with gel
  - Slick water fracturing connects to larger part of reservoir
- Change of stress orientation



Surface tilt meter record of an oblique reorientation of the frac direction during a refrac of an underperforming well in the Barnett Shale. Mitchell Energy. Wolhart, 2002. Original figure from Siebrits, 2000



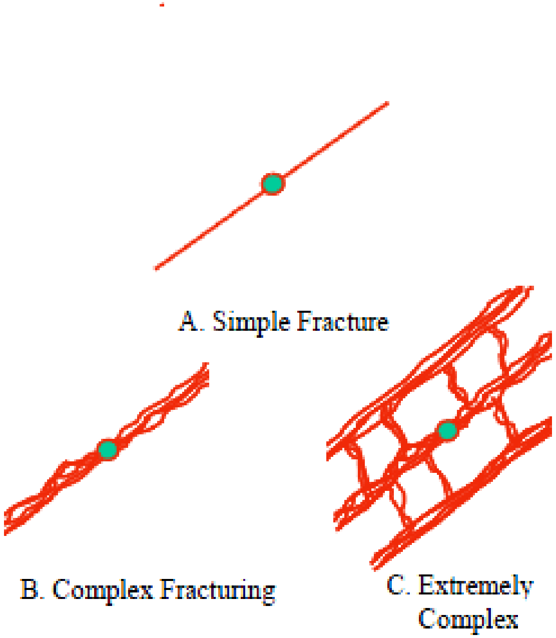


Comparison of XL Gel frac and Water-Frac Re-frac, horizontal Barnett well

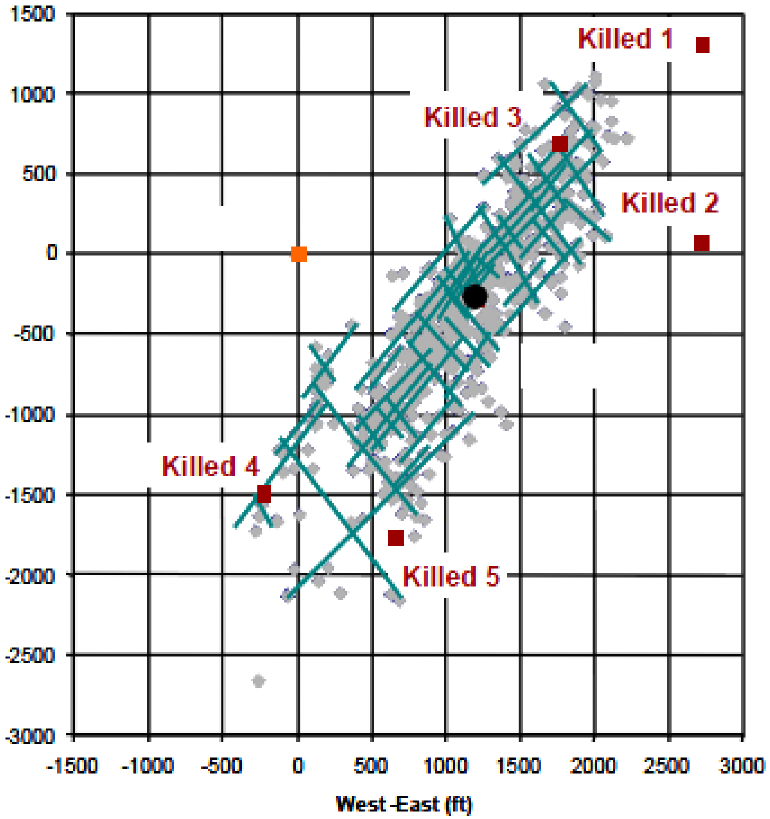
Source: Cipolla, et. al., SPE 124843 modified from Warpinski, et. al., SPE 95568.

Fracture Network Complexity

- Complexity develops if natural fracture system is connected to induced fracture and opened
- Observed with microseismic monitoring



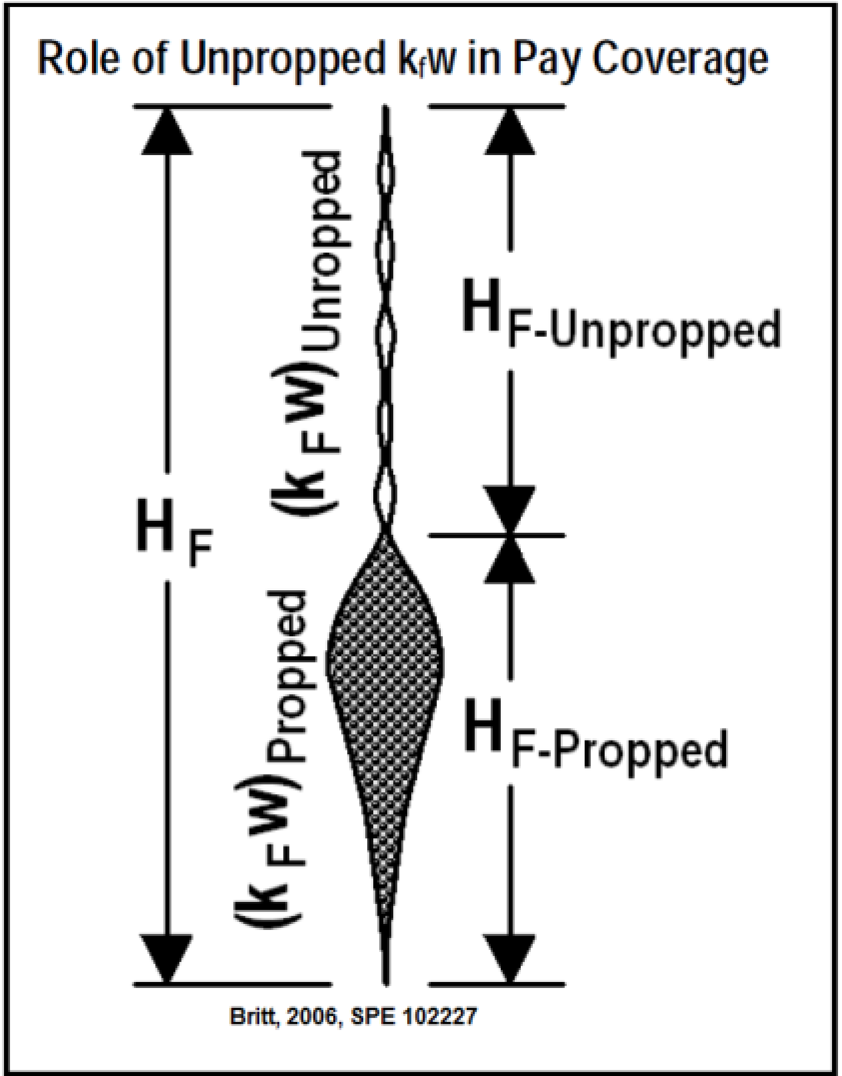
Examples of increasing fracture complexity from simple to extremely complex



Fisher, 2004 Example of fracture treatment map in vertical well core area of Barnett.

Proppant placement

- Proppant settles due to low water viscosity
- Unpropped fracture part still contributes to flow through propped part
- Distinction between brittle material (fractures stay) and ductile material (fractures heal)



Britt, 2006, SPE 102227

GAS SHALE: meaningful parameters

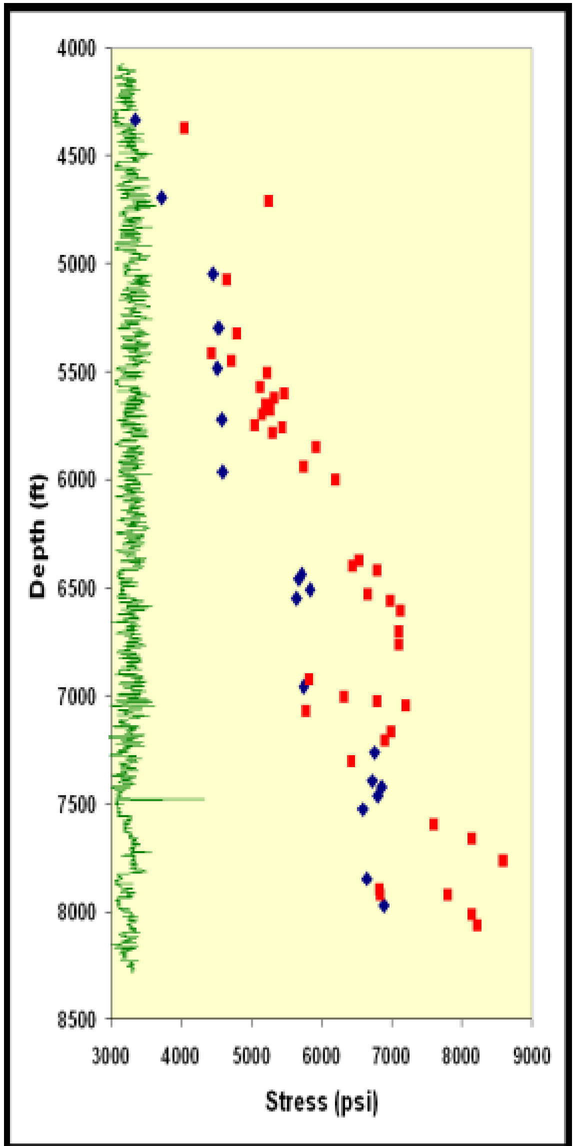
- **Young’s modulus** (We alreadry looked at this and concluded it was important)
- Static (lab) versus dynamic (log)
- Roughly factor of 2 difference

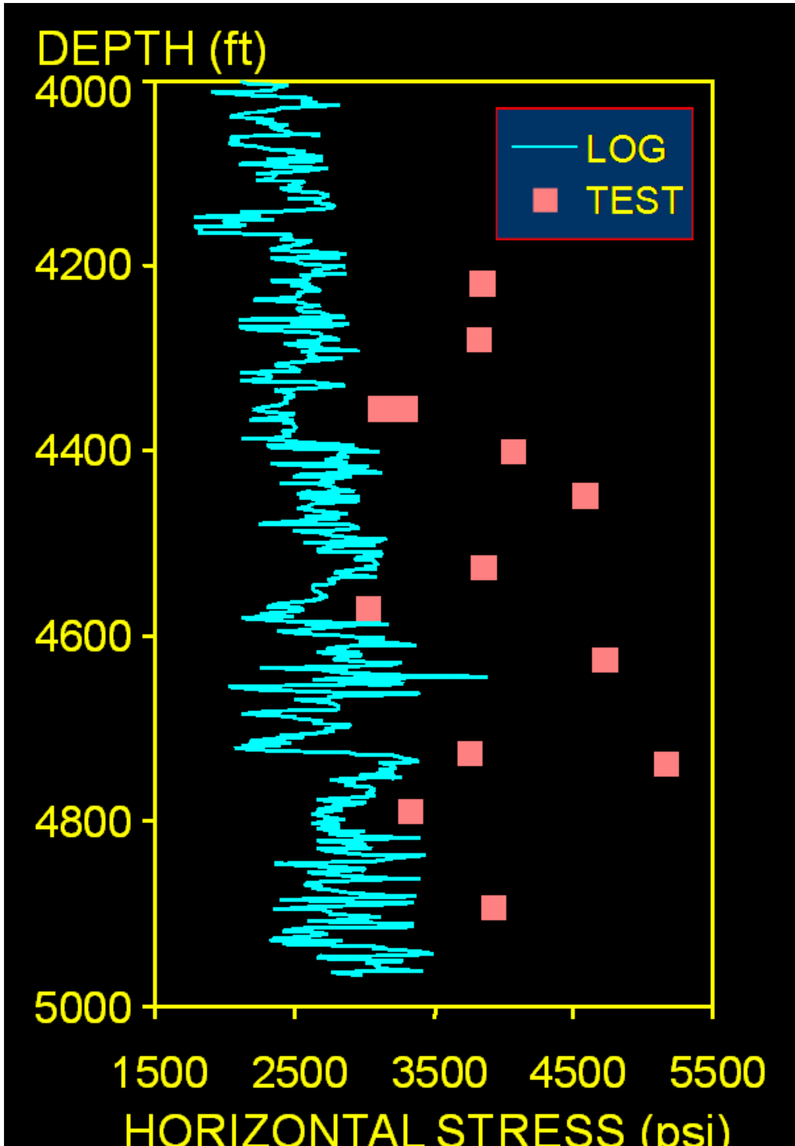
- **Poisson’s ratio**
- Minimal significance to modeled growth (but importnant thriugh stress

- **In Situ Stress**
- Important for growth

MWX stress measurements and lithology LOG

- 63 microfracstress measurements
- Sandstones in blue
- Shale lithologies in red
- Abundant variability in shale stresses with no apparent difference in lithologies

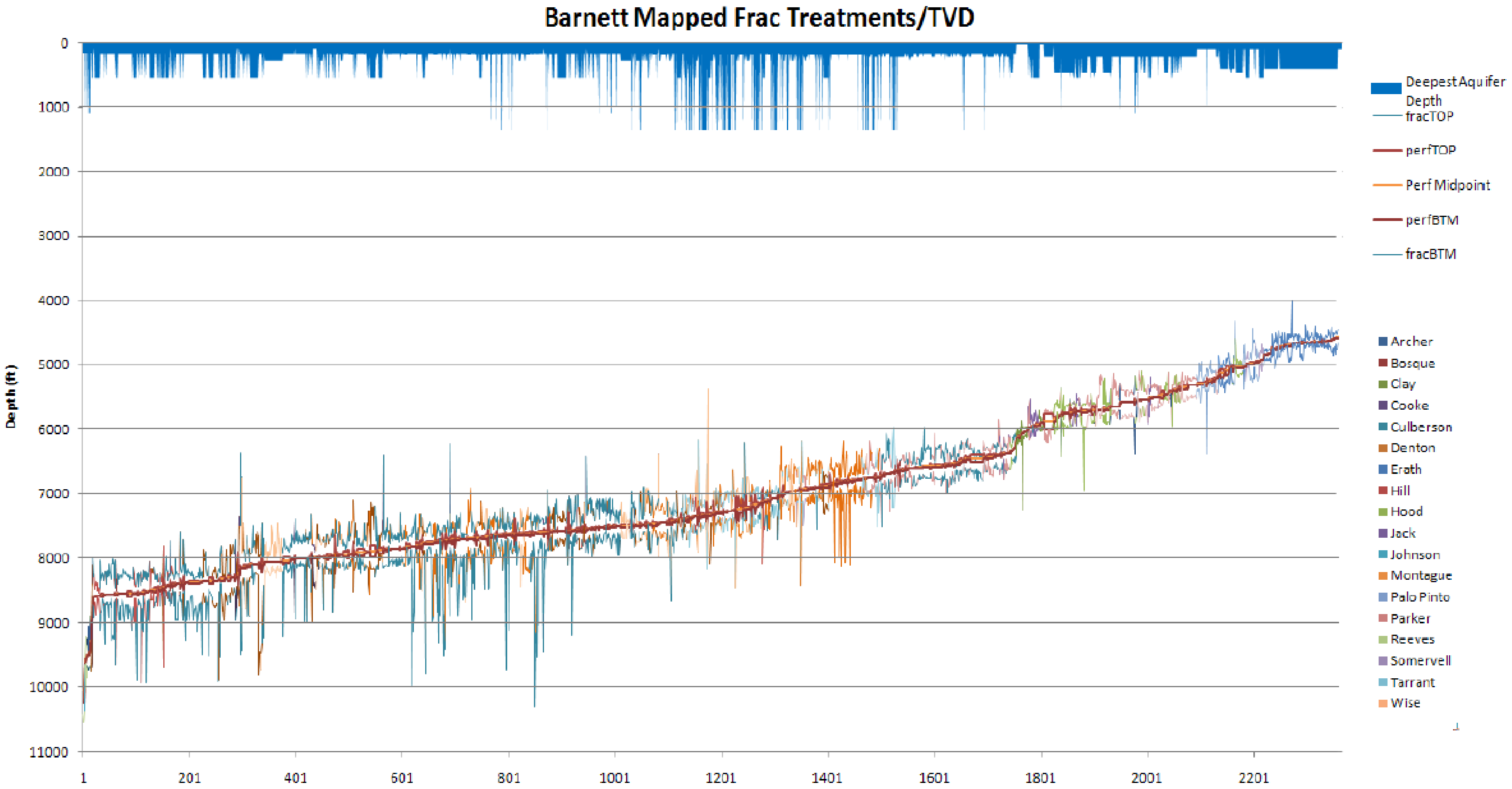




Water Management

- Cleanup water produced back early
- Use produced water for later fracture treatments
- Economic and Ecologic advantages

Interference concerns with groundwater?
Not so likely due to excellent vertical confinement



Hydraulic Fracturing – Other Issues

- Treatment Design
  - Required Productivity
  - “Tip Screen Out” design
- Minifrac analysis
  - In-situ stress
  - Leakoff behaviour
  - Fracture containment
- Fracture characterization
  - P & Q recording
  - Tiltmeters
  - Induced seismicity
- Proppant properties
  - Productivity calculation
  - Sand control
  - Strength
- Frac fluid properties
  - Leakoff control
  - Proppant placement
  - Cleanup
- Unconventional fracturing
  - Naturally fractured low perm (Barnett shales)