Rock Failure, Stimulated Volume & Permeability Enhancement in Gas Shale HF

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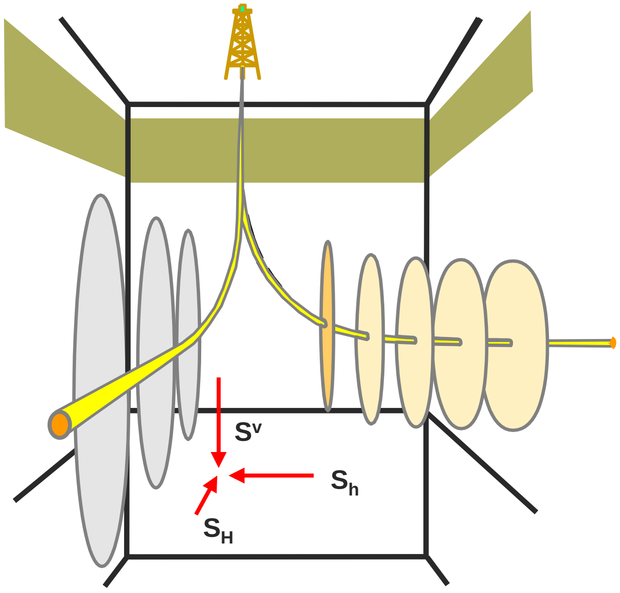
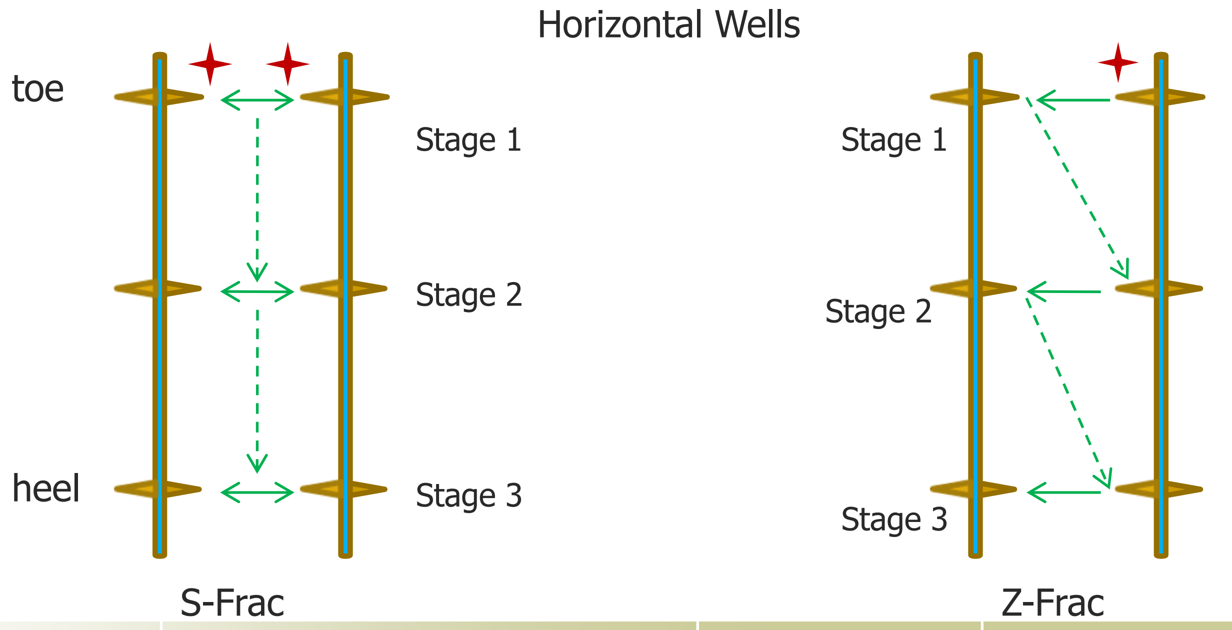
HF, Multiple Fractures

- Multiple horizontal are drilled to increase more contact area between the well and the reservoir
- Wells are stimulated in multiple stages (1-10 per well, depending on need)
- Total frac lengths 1000-1500 ft



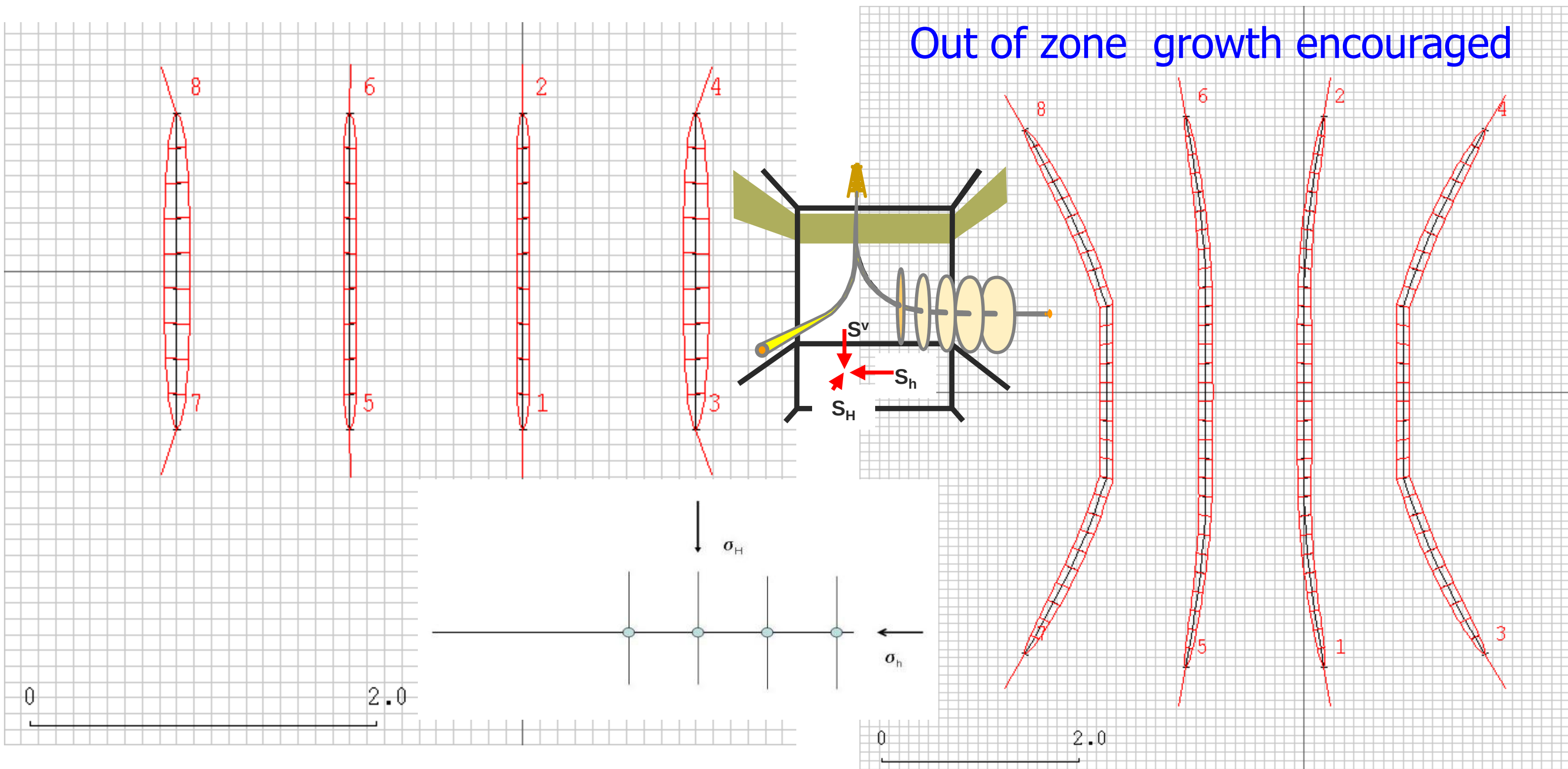
Multiple Well Stimulation

- In a typical stage, water and sand were pumped at a rate of 50-70 bbls/min
- Large volumes of pumped water per stage (100000-1,000,000 gal)



Mechanical Fracture Interaction

- HFs propagate perpendicular to the least principal in-situ stress unless:



In Addition to Stress, Fracture Growth is Controlled by

- Discontinuities
- Frac fluid density
- Permeability

- Local fracture growth controlled by rock fabric
- Global fracture growth controlled by total stress

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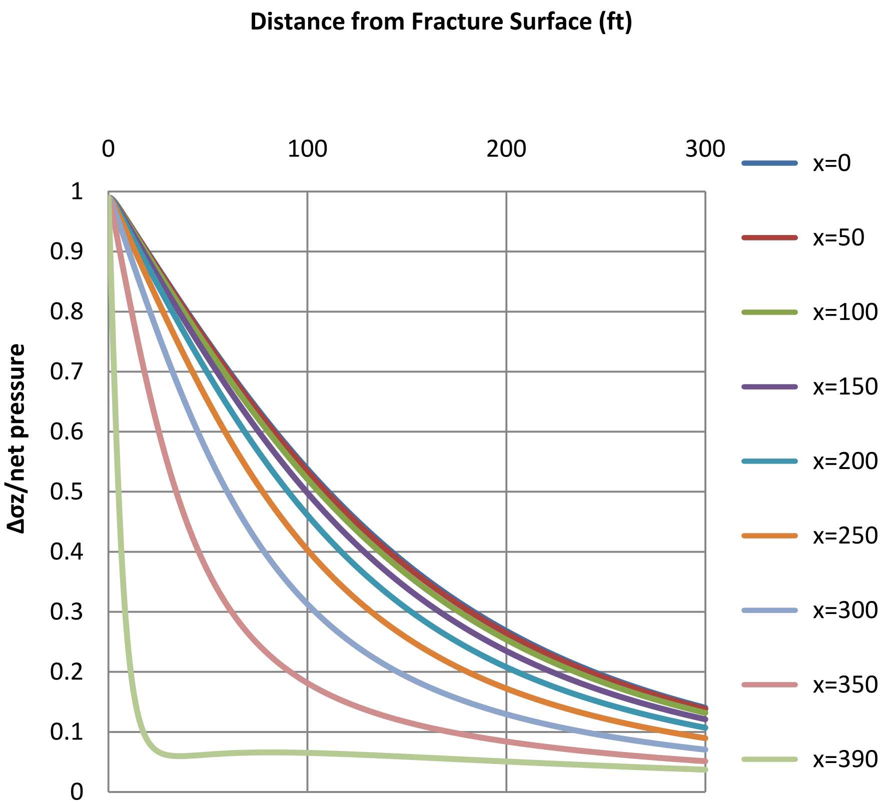
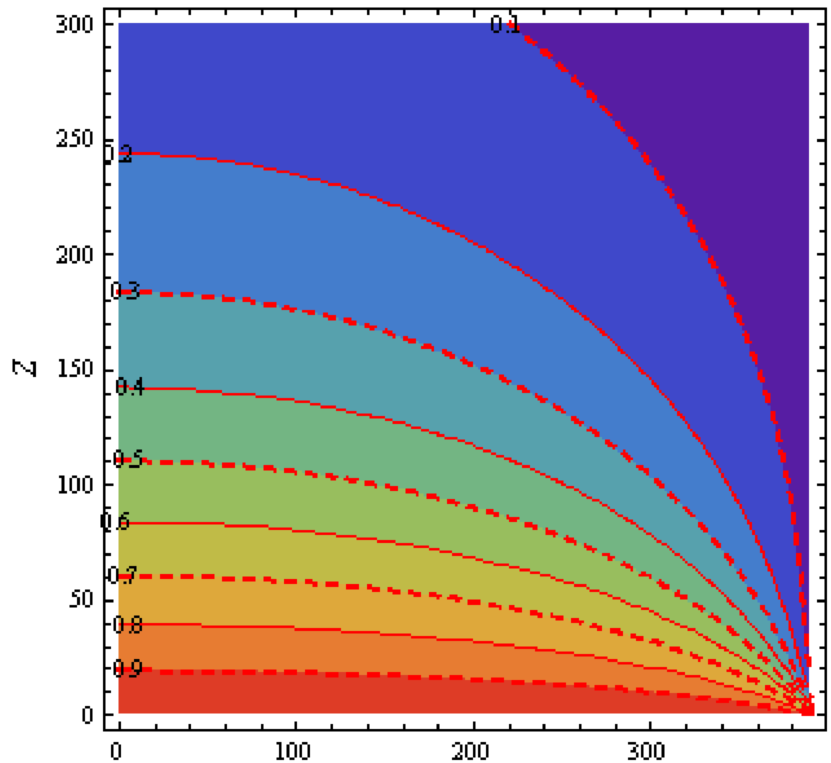
H-Fracturing Perturbs Pore Pressure & Stress in Rock





Analytical model for induced stress perpendicular to penny HF (stress shadow)-used for FRV

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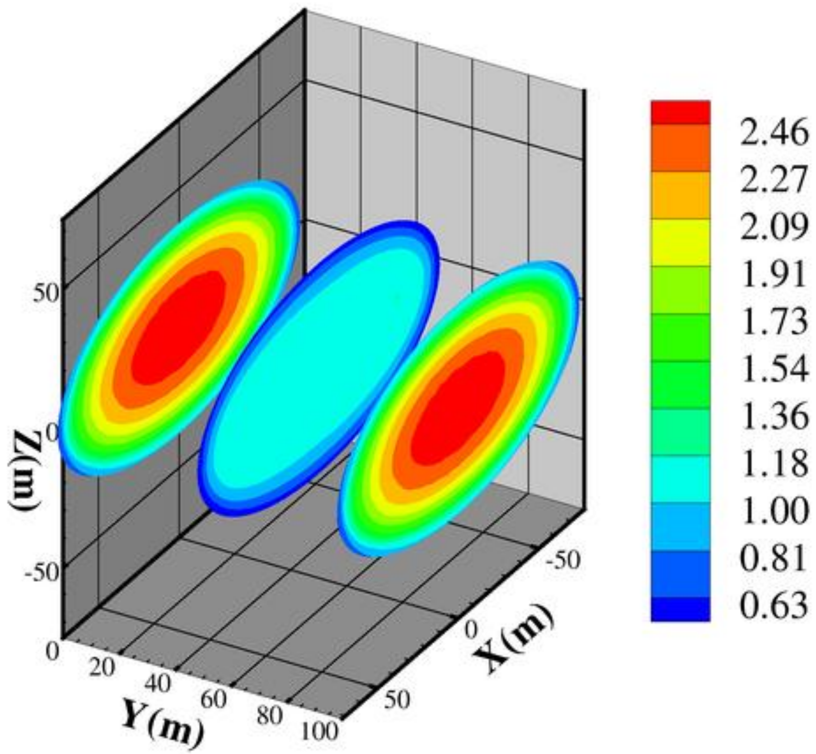
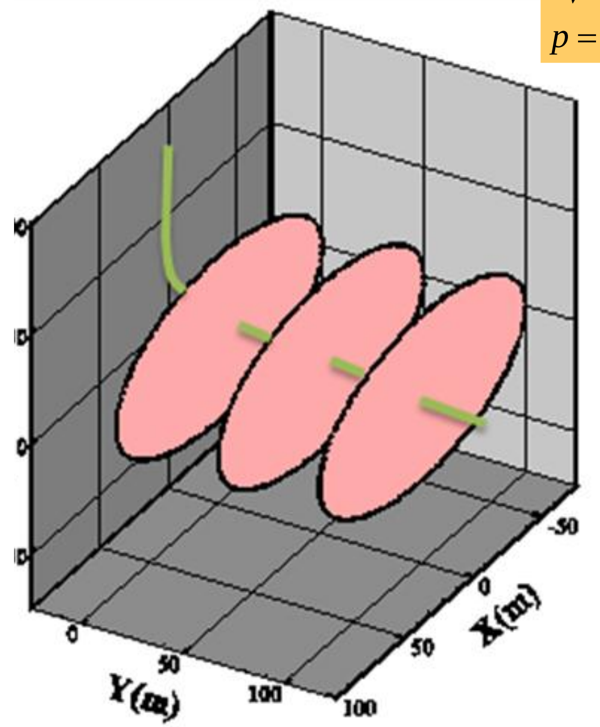
Stress, and Failure Analysis for Multiple HF-Numerical (BEM) in Barnett Shale

$\sigma_H = 43$
$\sigma_h = 39 \quad \text{MPa}$
$\sigma_V = 56$
$p = 28$

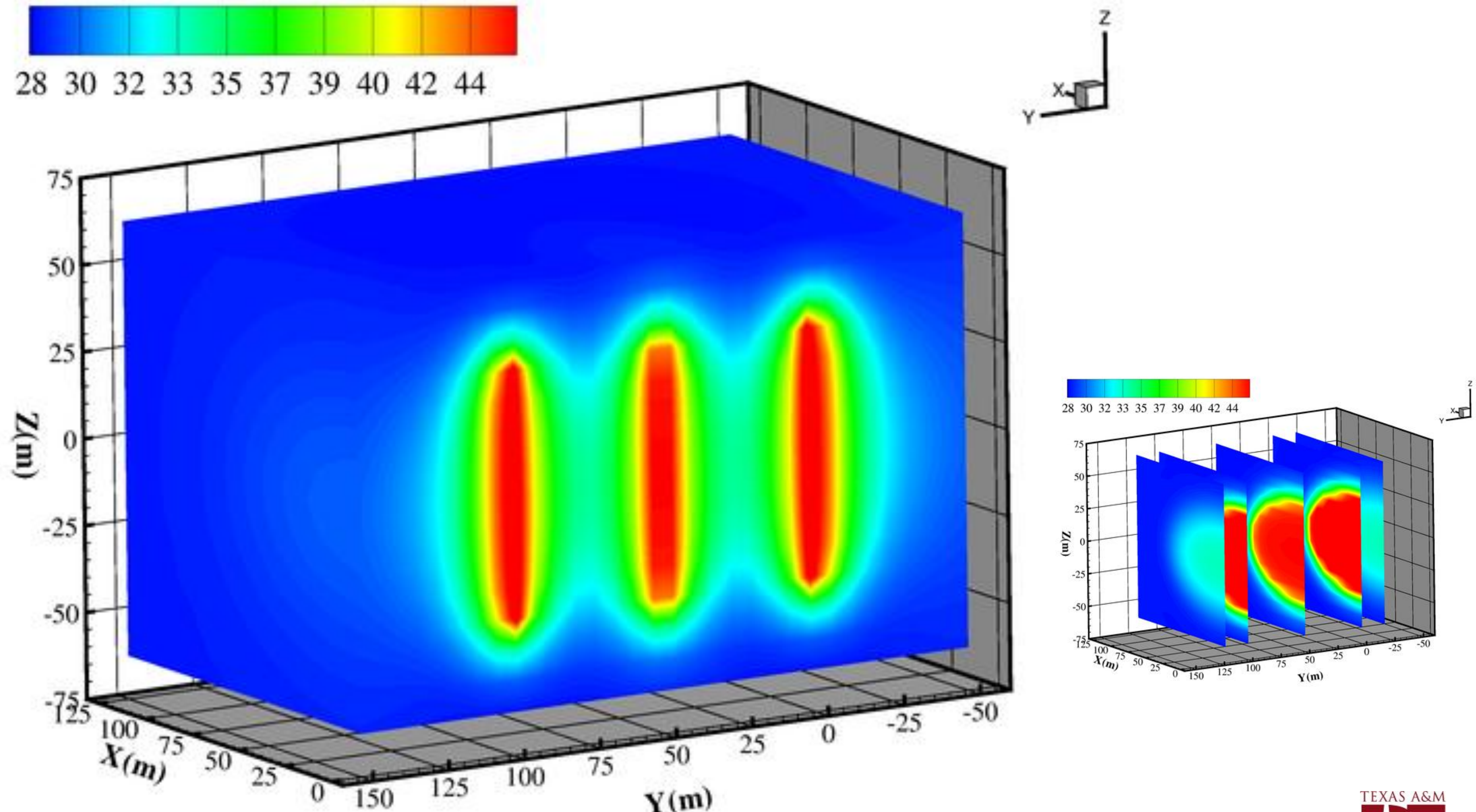
3 elliptical transverse fractures of 150 m length each (50 m spacing)





Fracture aperture distribution (in cm) after 3 hours of pumping.

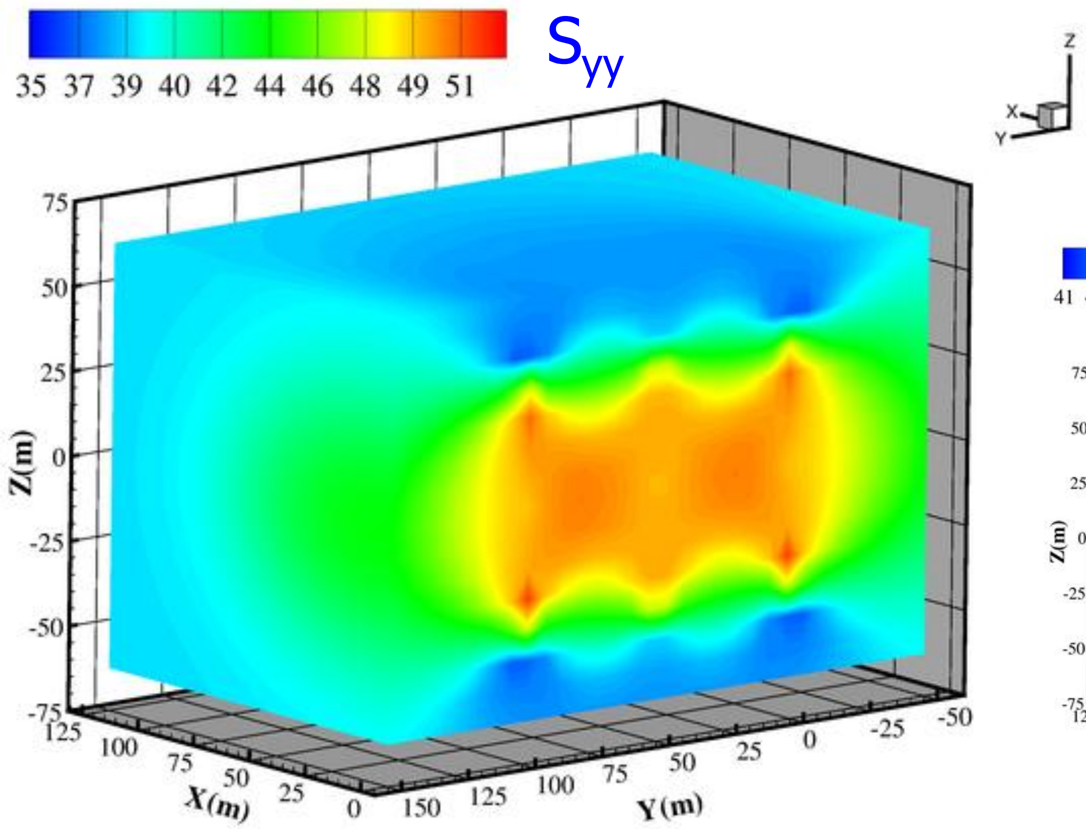
Pore Pressure Distribution



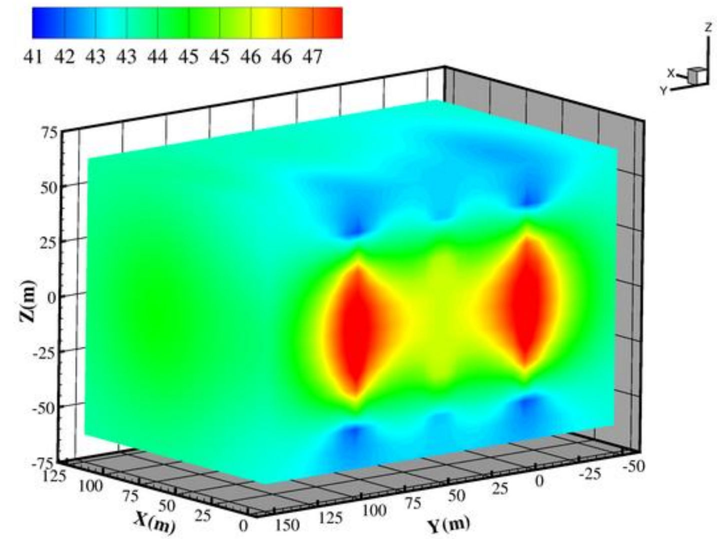
Distribution of pore pressures (MPa) in the formation after 3 hrs of injection

In-Situ Stress (S_{yy}) Increases

$$\sigma_H = 43$$
$$\sigma_h = 39 \quad \text{MPa}$$
$$\sigma_V = 56$$
$$p = 28$$

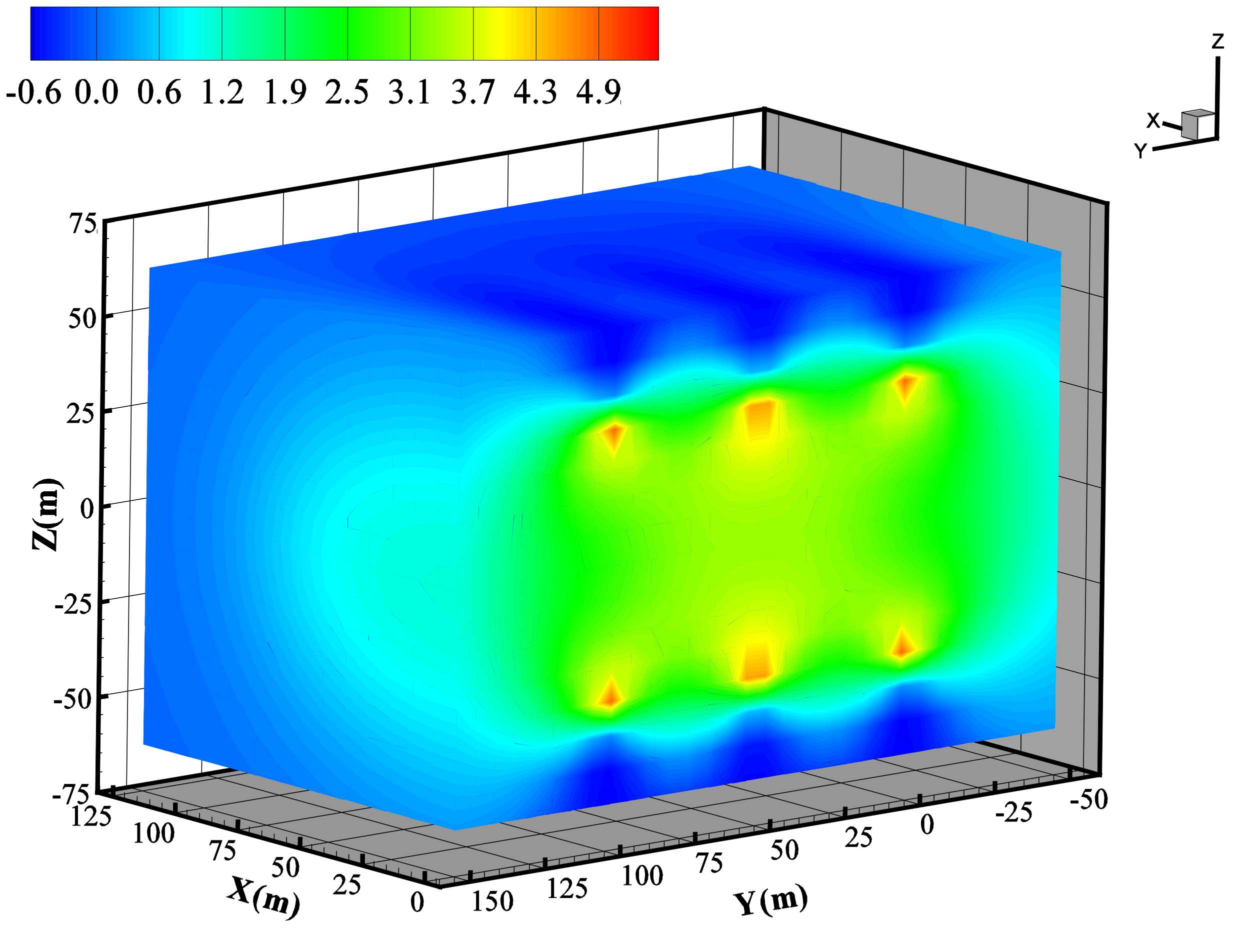


S_{yy}

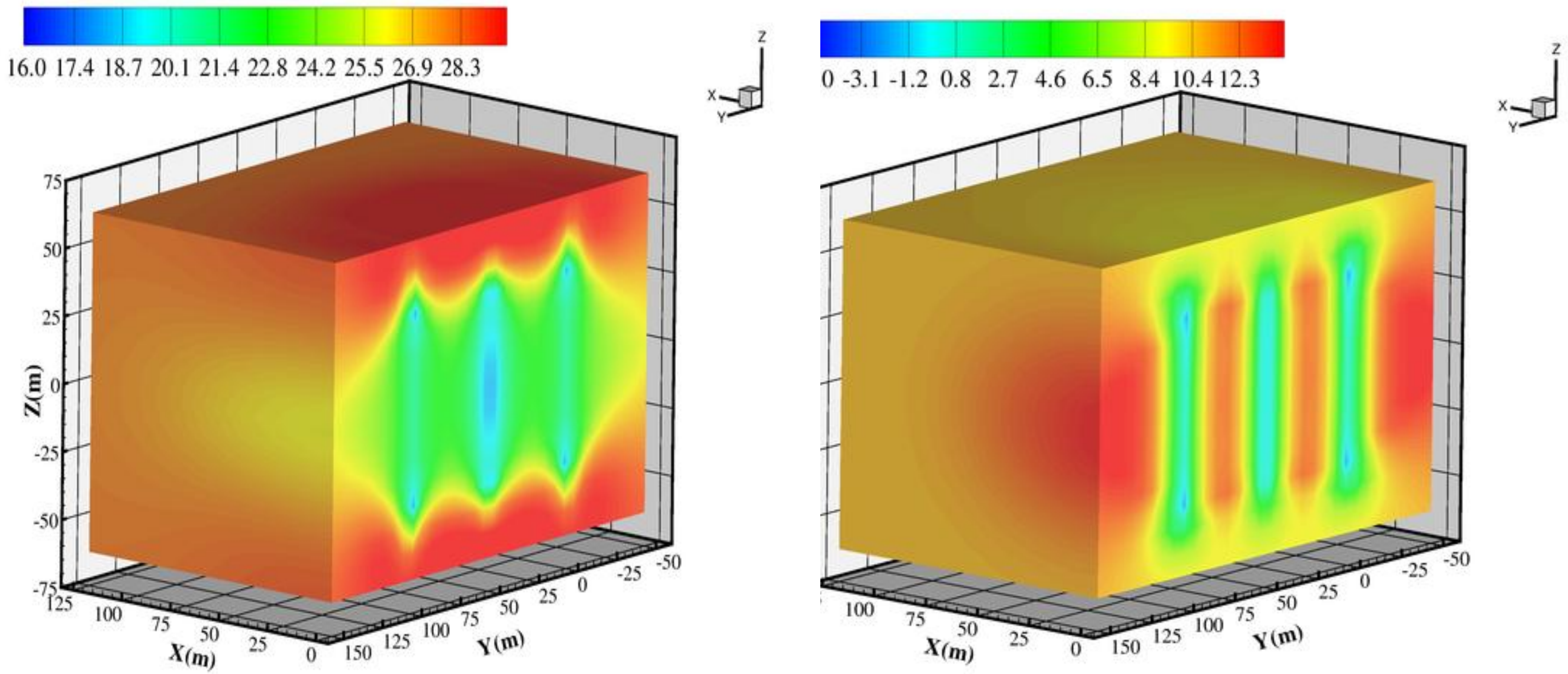


S_{xx} ; previously Max.

Poroelastic stress component for (S_{yy})



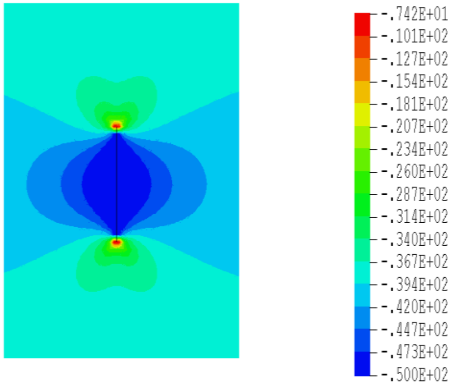
Effective Stress is Reduced, Promoting Rock Failure

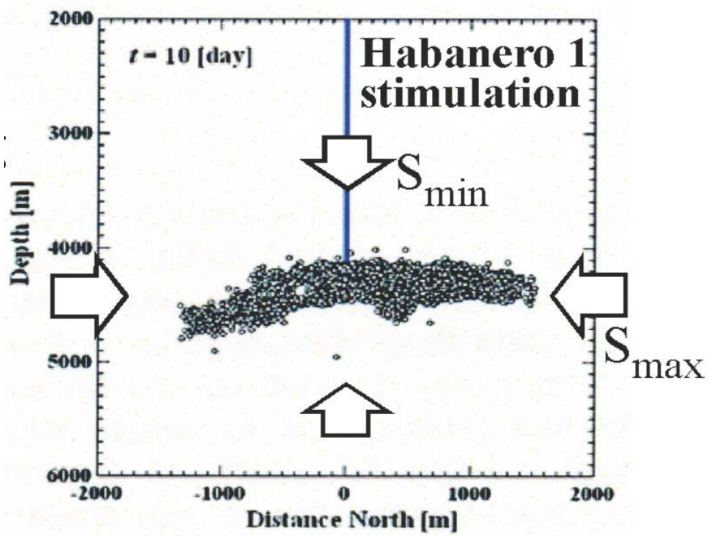


Distribution of the maximum and minimum (iii) principal effective stresses in the reservoir (MPa).

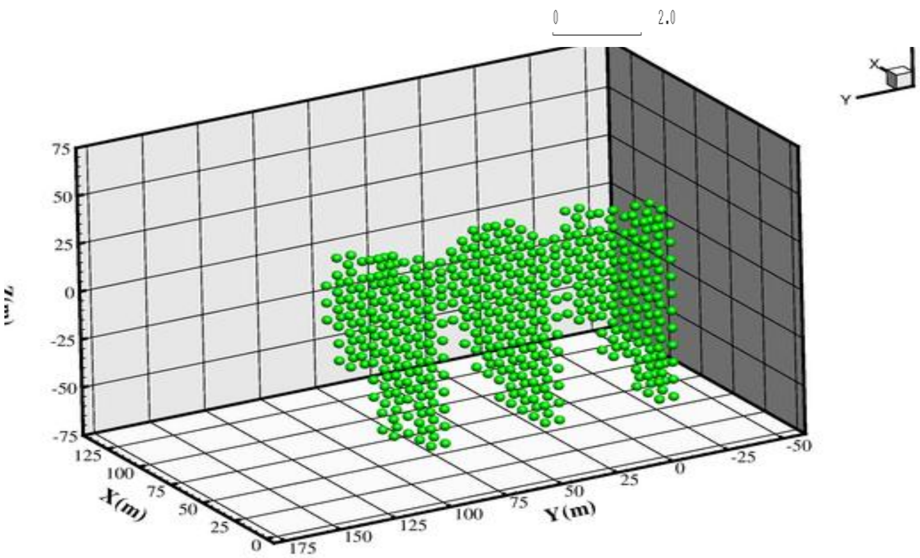
Shear/Tensile Failure

- Failure is caused by high stresses near the tip of the fractures, & by increased pore pressure elsewhere



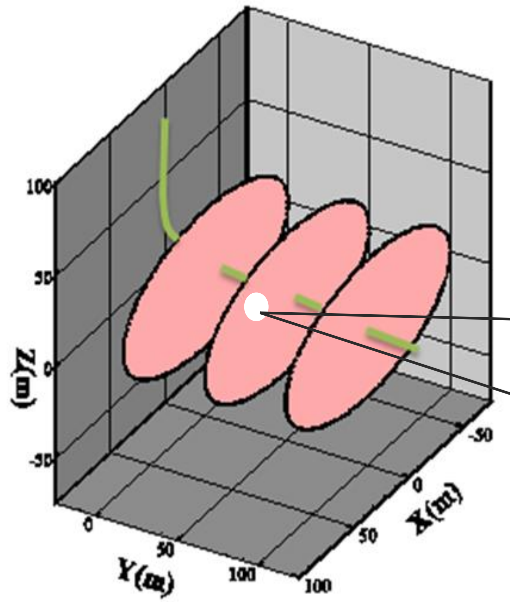


Ito et al., 2006

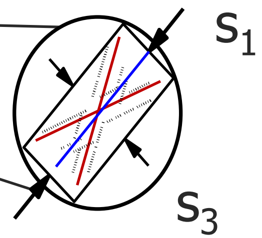


Estimating Stimulated Volume: Use MEQ

- MEQs are believed to be caused by pore pressure induced shear slip around HF
- Accepting this, the SRV (volume of "failed" rock) is assessed using the areal extent of the MEQ cloud



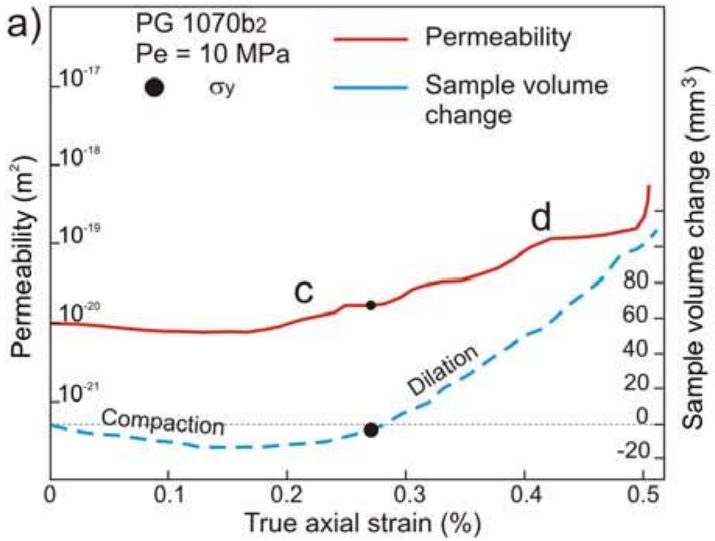
This is based on the assumption that energy release is exclusively related to fluid penetration, which may not always hold true

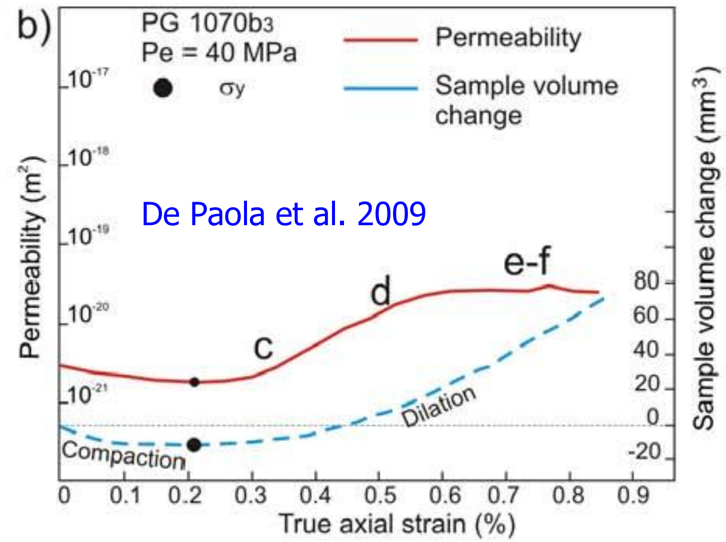


Issues

- It is assumed Mode I fracture propagation dominates, but MEQ monitoring shows shear dominates
  - Event location problems
- Need to incorporate Mode II (slip and shear dilation) into models
- History matching without considering the above mechanisms can be inadequate
- Feedback between failed rock and HF?

Rock Failure Enhances Permeability (Brittle, Ductile)





De Paola et al. 2009

Prediction of Enhanced Permeability

- The usual methodology for predicting the permeability in the failed region is a trial and error procedure:

  (i) Guess a value for permeability

  (ii) Predict the failed rock volume (FRV) using the stress analysis for a selected net fracture pressure

  (iii) Vary perm until the FRV matches the extent shown by induced seismicity for the given net fracturing pressures

Issues

- This method is based on the equivalent permeability for the failed rock, details of fracture network not considered
- Rock heterogeneity and time dependent behavior of rock and fractures not considered –Symmetric Frac envisioned
- It is assumed that the MEQ’s are related to local pore pressure perturbations
- **Aseismic deformation with significant slip and perm enhancement**

Remarks

- The interaction of the multiple hydraulic fracture stimulation on dynamics of fluid flow on a larger scale is not clearly understood
- The large volume of failed rock tends to redistribute the stresses in the nearby region and can modify the nearby rock permeability
- In this context, the presence of faults (active and inactive) need be considered
- HF/Fault interaction become important
- Others….

Rock Failure and Permeability Enhancement in Tight Gas Hydraulic Fracturing

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The statements made during the workshop do not represent the views or opinions of EPA. The claims made by participants have not been verified or endorsed by EPA.

Introduction

Generally, a tight gas reservoir is defined by its low permeability, however, it has been suggested (Holditch, 2007) to define a tight gas reservoir as one that "cannot be produced at economic flow rates or recover economic volumes of natural gas unless a special technique is used to stimulate production." Large hydraulic fracture treatments, often from a horizontal wellbore or multilaterals must be used to increase the recovery efficiency in the reservoir. Fracture conductivities of 10 mD/ft or higher appear to be necessary for economic gas production.

Shale gas reservoirs have heterogeneous geological and geomechanical characteristics that pose challenges to accurate prediction of their response to hydraulic fracturing. Experience in shale gas formations shows that stimulation often results in formation of a complex fracture structure, rather than the planar fracture aligned with the maximum principal stress. The fracture complexity arises from intact rock and rock mass textural characteristic and the in-situ stress and their interaction with applied loads. Open and mineralized joints and interfaces, and contact between rock units play an important role in fracture network complexity which affects the rock mass permeability and its evolution with time. Currently, the mechanisms that generate these fracture systems are not completely understood, and can generally be attributed to lack of in-situ stress contrast, rock brittleness, shear reactivation of mineralized fractures, and textural heterogeneity.

Stimulated Volume and Permeability Enhancement

The idea of stimulation by hydraulic fracturing is to create a large volume of fractured rock with enhanced permeability. Many tight gas reservoirs are characterized by high deviatoric stresses and hard, naturally fractured rock. Stimulation treatments in such reservoirs may result from slip on pre-existing critically stressed fracture systems and or creation of new fractures. It is generally believed that fracturing is caused by both shear and tensile failure. Shear slippage is induced by altered stresses near the tip of the fractures as well as by increased pore pressure in response to leakoff through the fracture "walls". In view of this, it has been suggested that increased viscosity promotes tensile failure and can lower complexity (Cipolla *et al.* 2008). Accordingly, water fracs are used where shear failure is anticipated to dominate (Chipperfield, S.T., Wong, J.R., Warner, D.S. *et al*. 2007). According to Cramer (2008), water is used as a base fluid in most unconventional reservoir treatments.

To determine intact rock failure and joint slippage, a failure criterion is employed. There are many failure criteria for the sliding of jointed rock masses but often the Mohr-Coulomb failure criterion is used. By combining a stress analysis with a criterion, one can assess the effects of increasing pore pressure on rock by generating a structural permeability diagram. This map that shows the ΔP required to reactivate joints of different orientations (e.g., Nygren and Ghassemi, 2005; Nelson *et al*. 2007) during fracture stimulation treatments at high treating pressures. One such map is shown in Figure 3 for the New Albany Shale.

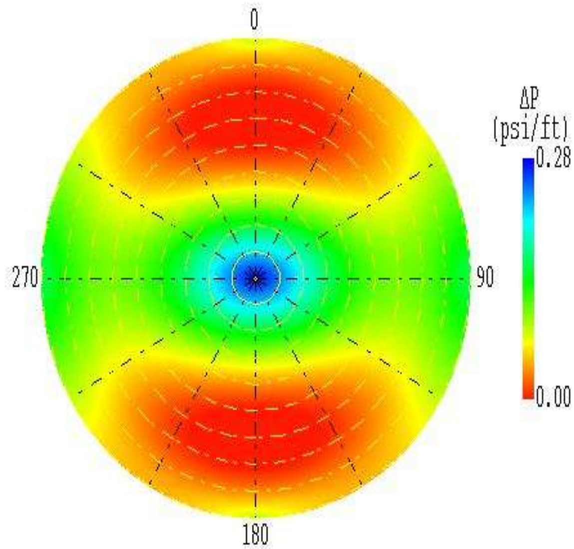

Figure 3. Structural Permeability Diagram for New Albany Shale (μ=0.6).

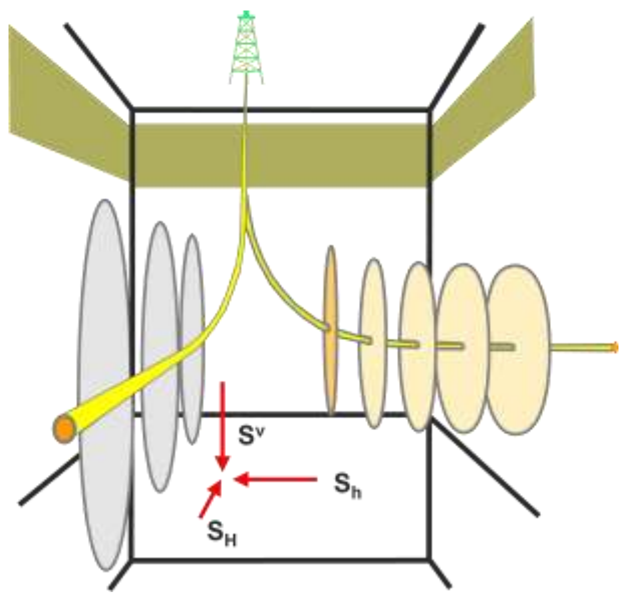

Figure 4. Fracture orientation in horizontal wells.

Most field implementation of stimulation involves creation of multiple hydraulic fractures and stimulation of the neighboring rock volume by compression and pore pressure increase.

Normally hydraulic fracturing is performed in horizontally-drilled wells. The geometry and propagation direction of a hydraulic fracture will mostly depend on the drilling direction of horizontal well and the in situ conditions as shown in Figure 4.

It is generally accepted that hydraulic fractures propagate perpendicular to the least principal stress. In shallower environments where the least principal stress is vertical, a fracture will grow horizontally. At some depth where the increase in overburden causes the least principal stress to be horizontal, the predominant fracture growth geometry will be vertical. Variations in stresses between different lithology in vertical sequences of rocks can cause fracture growth in a contained manner and generate length, or allow it grow vertically upwards or downwards. In addition to the in-situ stress, fracture growth will depend on many factors such as natural fractures, bed laminations, and other characteristics of a reservoir including the formation pore pressure in the reservoir. The pore pressure will affect the effective in situ stresses, and can further affect the post-fracturing deformation of rock and its natural fractures which will, in turn, influence the path of the hydraulic fracture (Koshelev and Ghassemi, 2001).

Fracture interaction

Multiple stage hydraulic fracturing is popular in the stimulations of tight gas reservoirs.

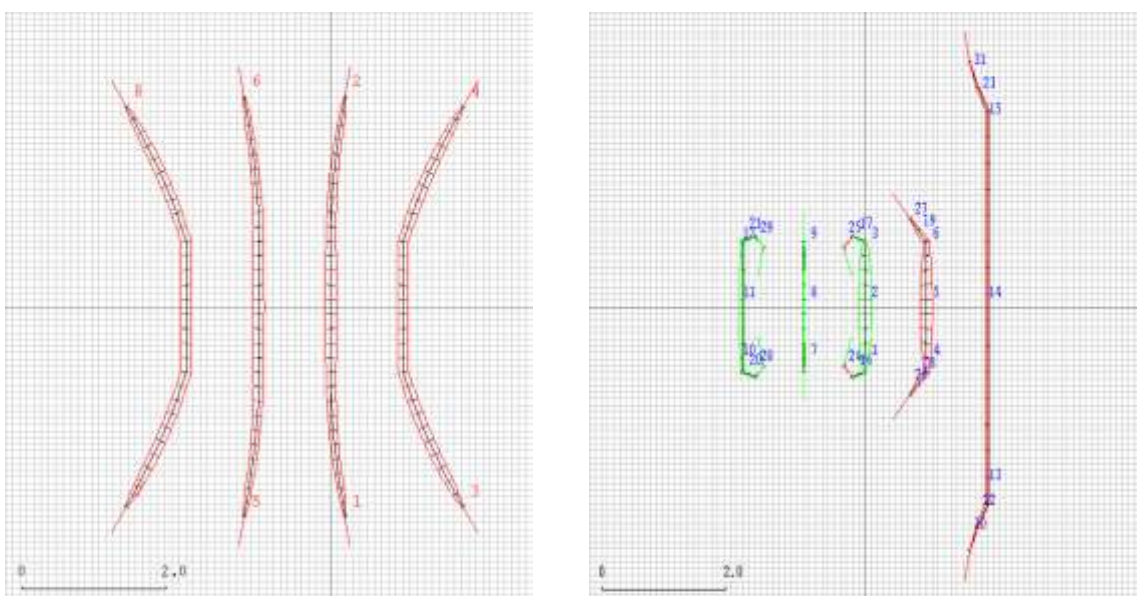

Figure 5. Interaction of multiple fractures in a horizontal well. Green represents closed fractures. Note the fractures turning away from each other to follow the path of least resistance.

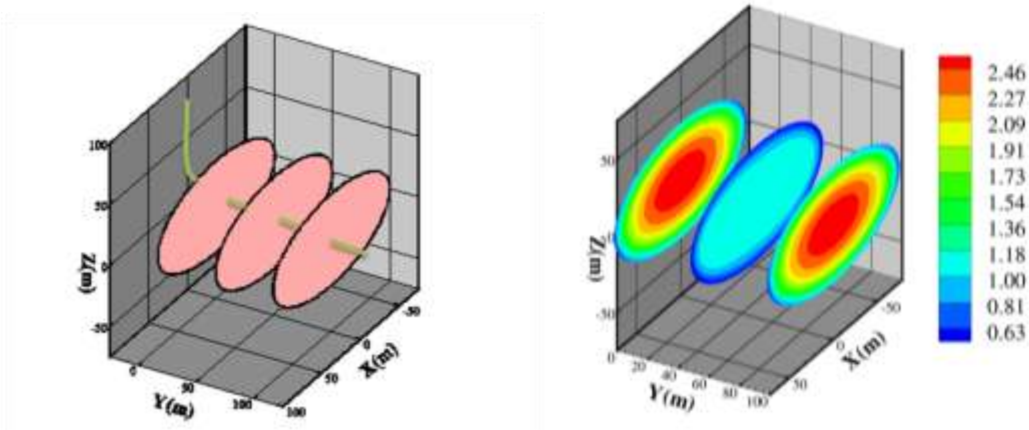

Figure 6. Fracture aperture distribution (in cm) after 3 hours of pumping in Barnett shale.

Estimating Stimulated Volume

It is believed that microseismic events (Figure 8) are mainly created as a result of shear slippages around the hydraulic fractures (Albright and Pearson (1982); Warpinski *et al*. (2001); Rutledge *et al*. (2003)). Shear slippage is induced by altered stresses near the tip of the fractures as well as shear slippages related to leakoff induced pore pressure changes.

Accepting that failure of the formation around a hydraulic fracture is caused by pore-pressure and stress perturbations, the stimulated reservoir volume (volume of "failed" rock in the reservoir) can be assessed using the areal extent of the micro-seismic cloud (Plamer *et al*. 2005; Jun and Ghassemi, 2005). However, it should be this procedure for evaluation of stimulated volume and fracture surface area is based on the assumption that energy release is exclusively related to fluid penetration, which may not always hold true. The micro-seismic record may also be used to detect hydraulic connection with the outside zone.

Prediction of enhanced permeability

The methodology of predicting the permeability in the failed region around a fracture is based on a trial and error procedure: (i) use the pressure profile at shut-in, and guesses a value for permeability, K; (ii) for a selected net fracture pressure, predict the failed rock volume (FRV) using the stress analysis; (iii) vary K until the FRV matches the particular trend-line of the stimulated reservoir volume from induced seismicity at the given net fracturing pressures. This method is based on the equivalent permeability for the failed rock and does not consider the time dependent behavior of rock and the fractures that are created. Furthermore, it is assumed that the MEQ's are related to local pore pressure perturbations.

The interaction of the multiple hydraulic fracture stimulation on the larger scale flow regime is not clearly understood. The large stimulated volume that is generated tends to redistribute the stresses within the crust and can cause changes in nearby rock permeability. In this context, the presence of faults (active and inactive) need be considered.

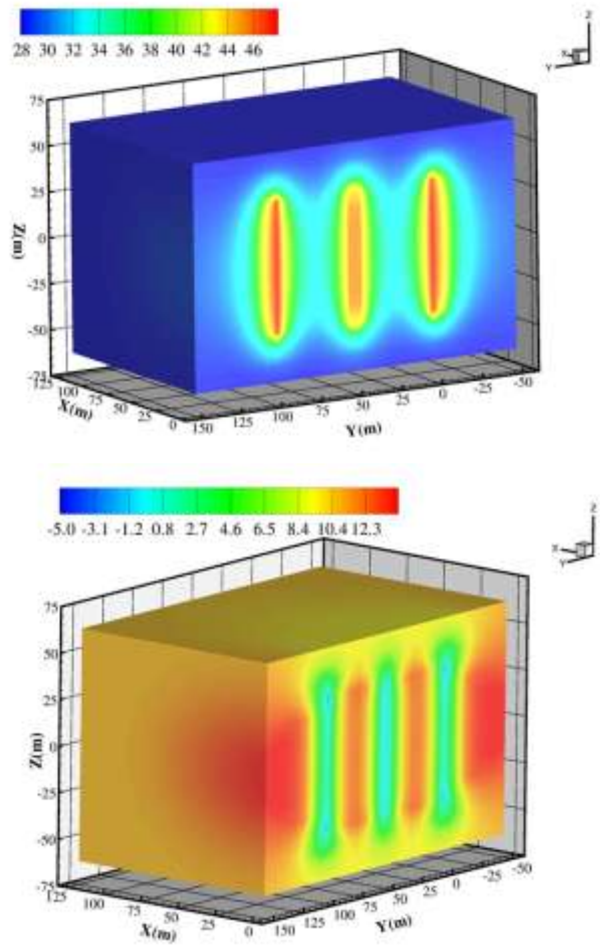

Figure 7. Distribution of pore pressures (MPa) in the formation; minimum principal effective stress (Barnett shale, 0.09 m^3/s per fracture; 3 hrs) (Rawal & Ghassemi, 2011).

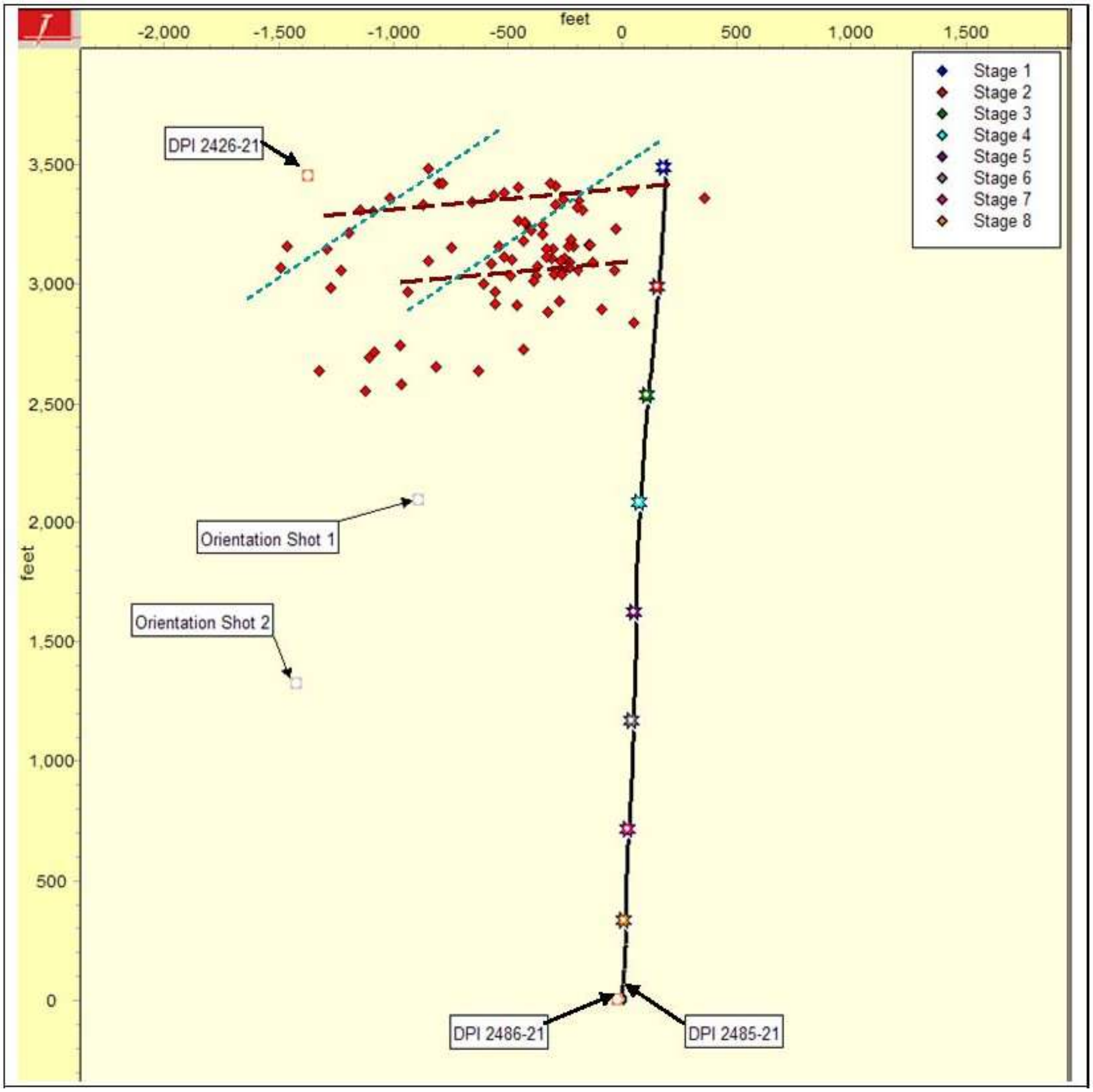

Figure 8. Microseismic map shows network growth and the potential stimulated volume in shale (GTI-NAS-Project).

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