REFRACTURING AND MULTI-FRACING HORIZONTAL WELLS: ROLE OF STRESS REORIENTATION

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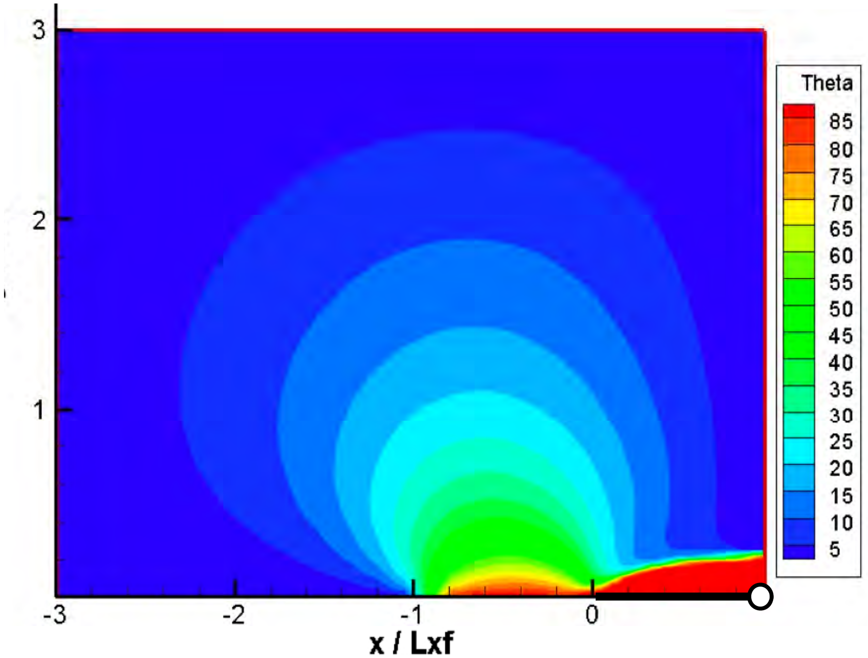
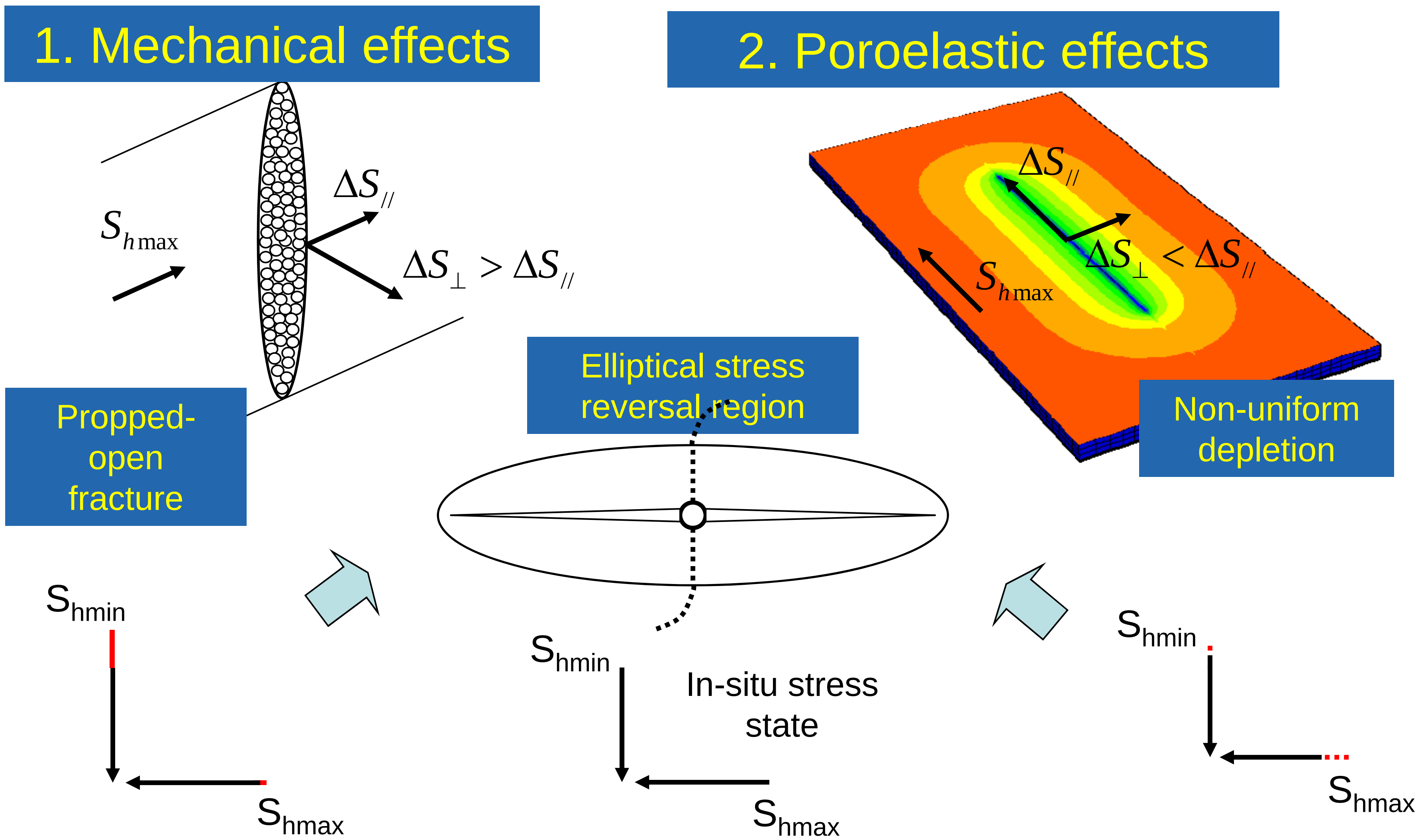


Impact of Stress Reorientation on Well / Reservoir Performance

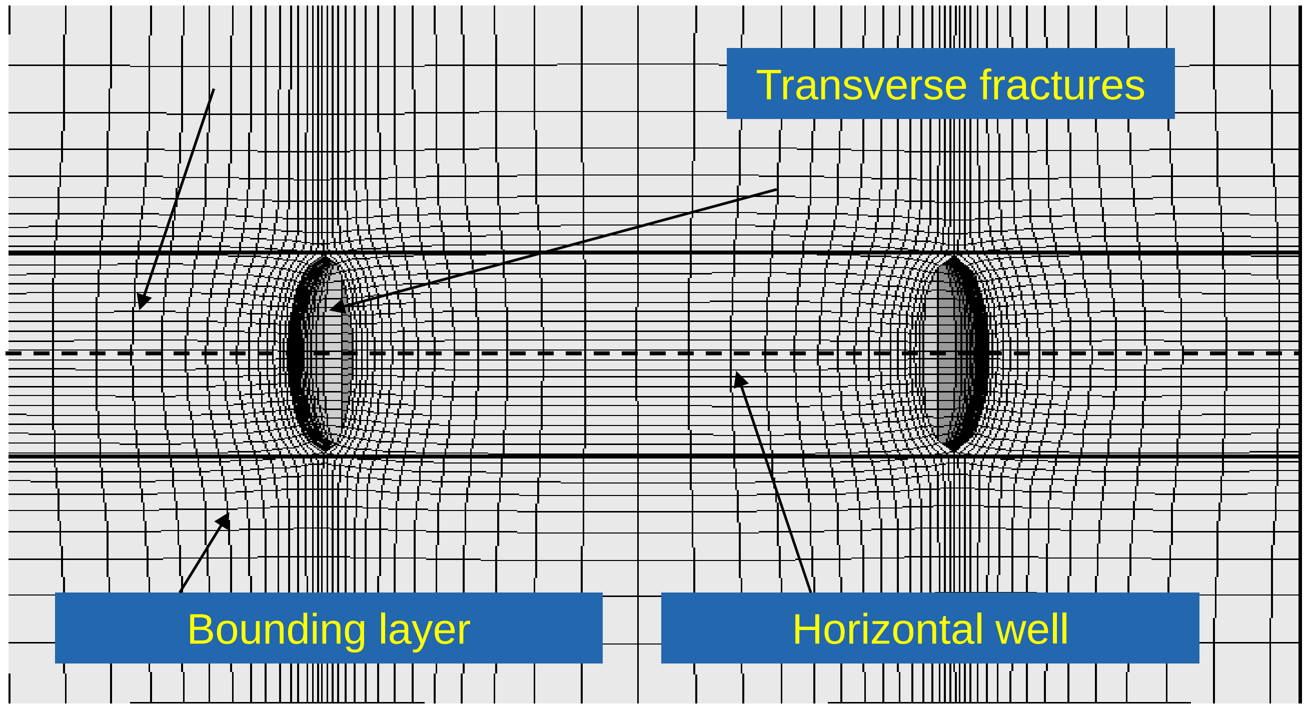
- **Multiple fracturing of horizontal wells**
- **Refracturing**
- Waterflooding
  - ✓ Reservoir sweep is impacted
  - ✓ Orientation of injection well fractures can change with time
  - ✓ Early water breakthrough is impacted
- Borehole stability
- Casing failure
- Sand production
- Reservoir compaction, subsidence
- Water, waste, drill cuttings injection

Two Contributors to Stress Reorientation



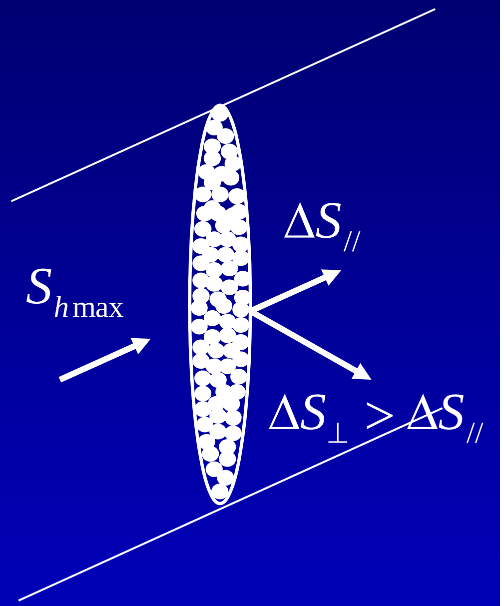
Stress Reorientation Due to Fracture Opening

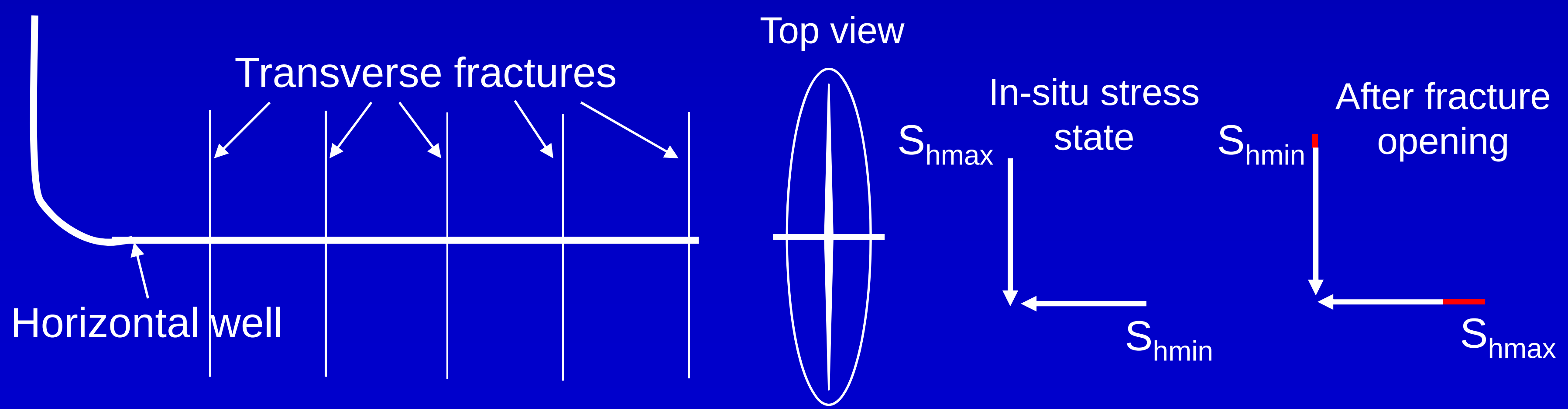
- Opening of a fracture increases the stress in the direction of fracture opening i.e. increases the minimum horizontal stress.
- Poro-elastic effects are small before production is initiated.



Stress Reorientation Limits the Number of Transverse Fractures

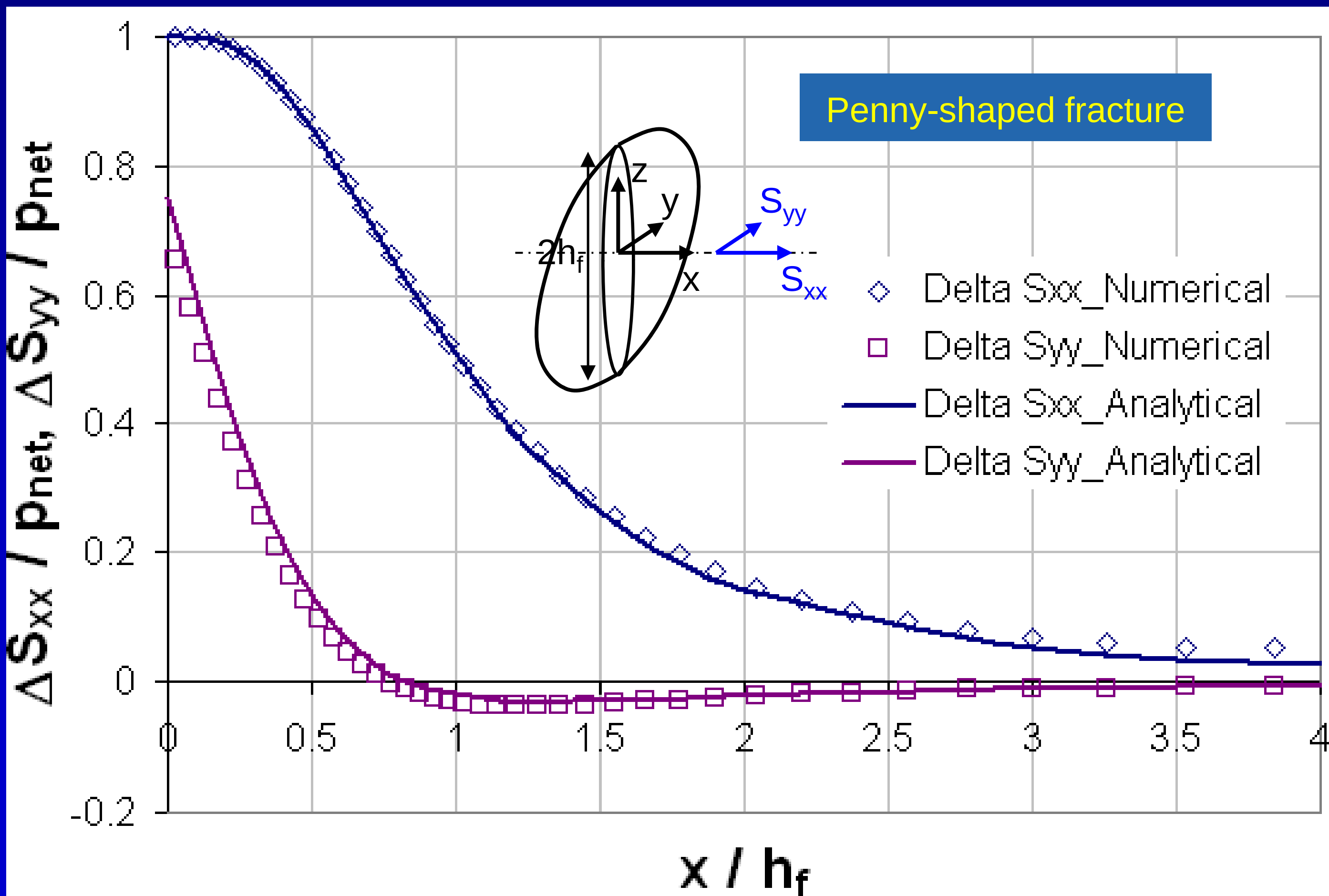
- Every fracture after the first one is affected by stress reorientation.
- Fractures tend to reorient away from previous fractures in the vertical plane.
- This can lead to TSO or longitudinal fractures.
- We have quantified this effect.





Numerical Model Agrees Well with Analytical Solution

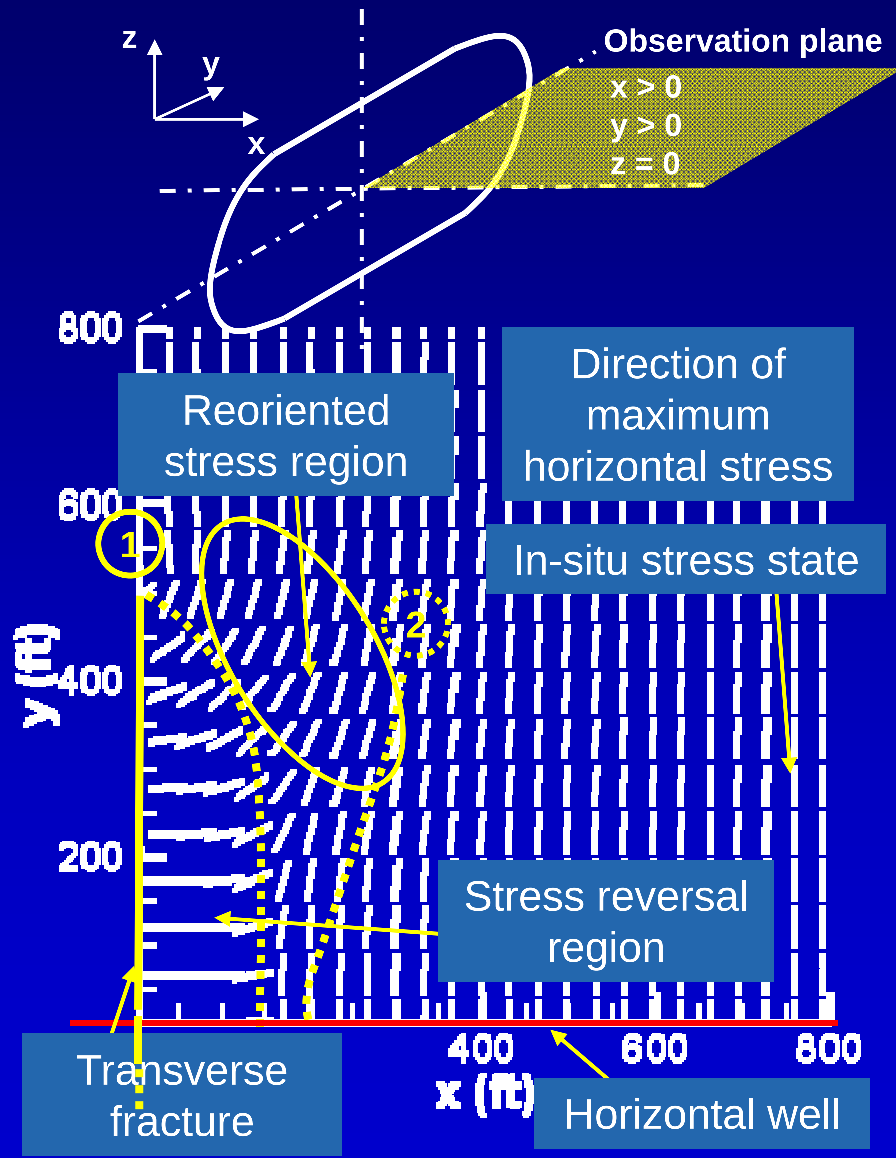
- Semi-infinite and penny-shaped fracture
  - Analytical solution from Sneddon and Elliot (1946)



Stress Reorientation in Horizontal Well Fracturing

- In the stress reversal region, risk of screen-out or longitudinal fracture.
- Second fracture propagates away if initiated too close to the first fracture.

Ref: **Nicolas P. Roussel Mukul M. Sharma, SPE 127986, "Optimizing Fracture Spacing and Sequencing in Horizontal Well Fracturing" (2010).**

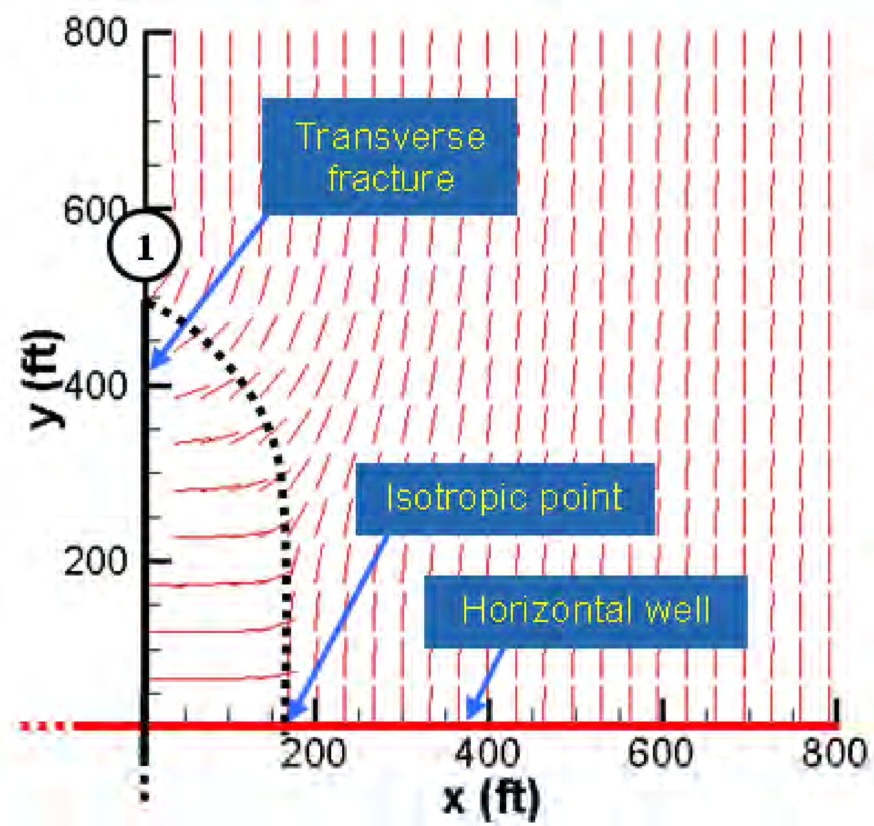


Application of the Model to a Field Case Study in the Barnett Shale

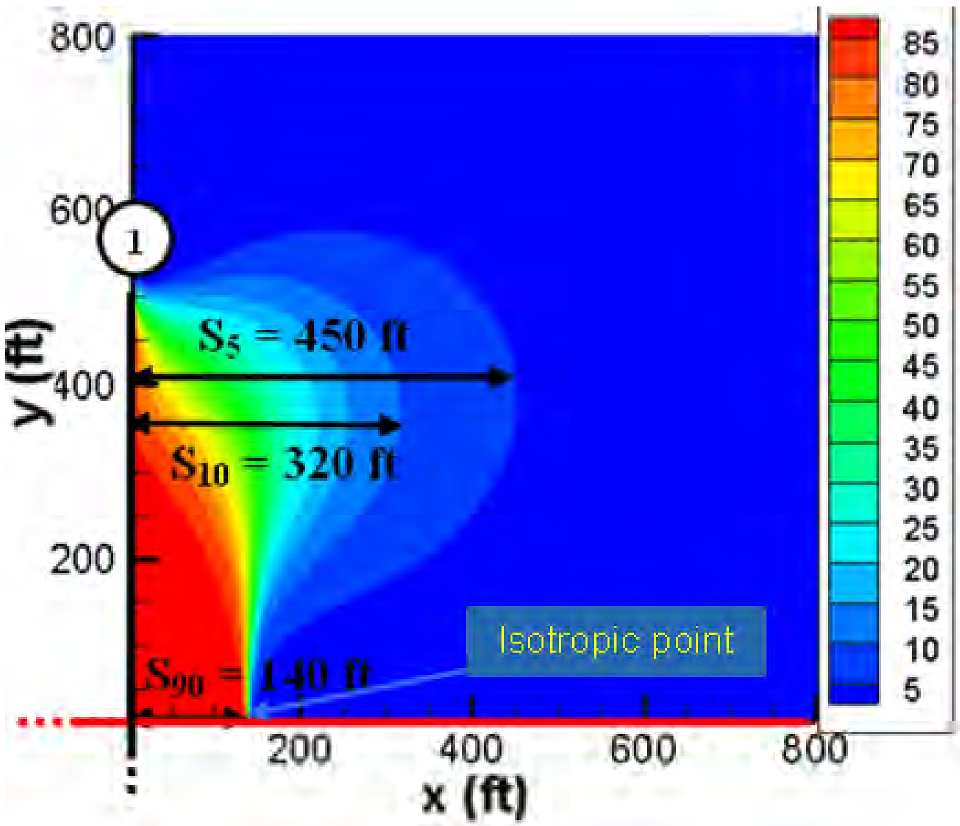
- Reservoir parameters for Barnett shale gas well (Weng *et al*., 2007)

Pay zone Young's Modulus E_p (psi)	**$7.3.10^6$**
Bounding layer Young's Modulus E_b (psi)	**$3.0.10^6$**
Poisson's Ratio	**0.2**
S_{hmax} (psi)	**6400**
S_{hmin} (psi)	**6300**
Depth (ft)	**7000**
Pay zone half-thickness h_p (ft)	**150**
Fracture half-height h_f (ft)	**150**
Fracture half-length L_f (ft)	**500**
Fracture maximum width w_0 (mm)	**4**

Stress Reorientation in Horizontal Well Fracturing



Direction of maximum horizontal stress



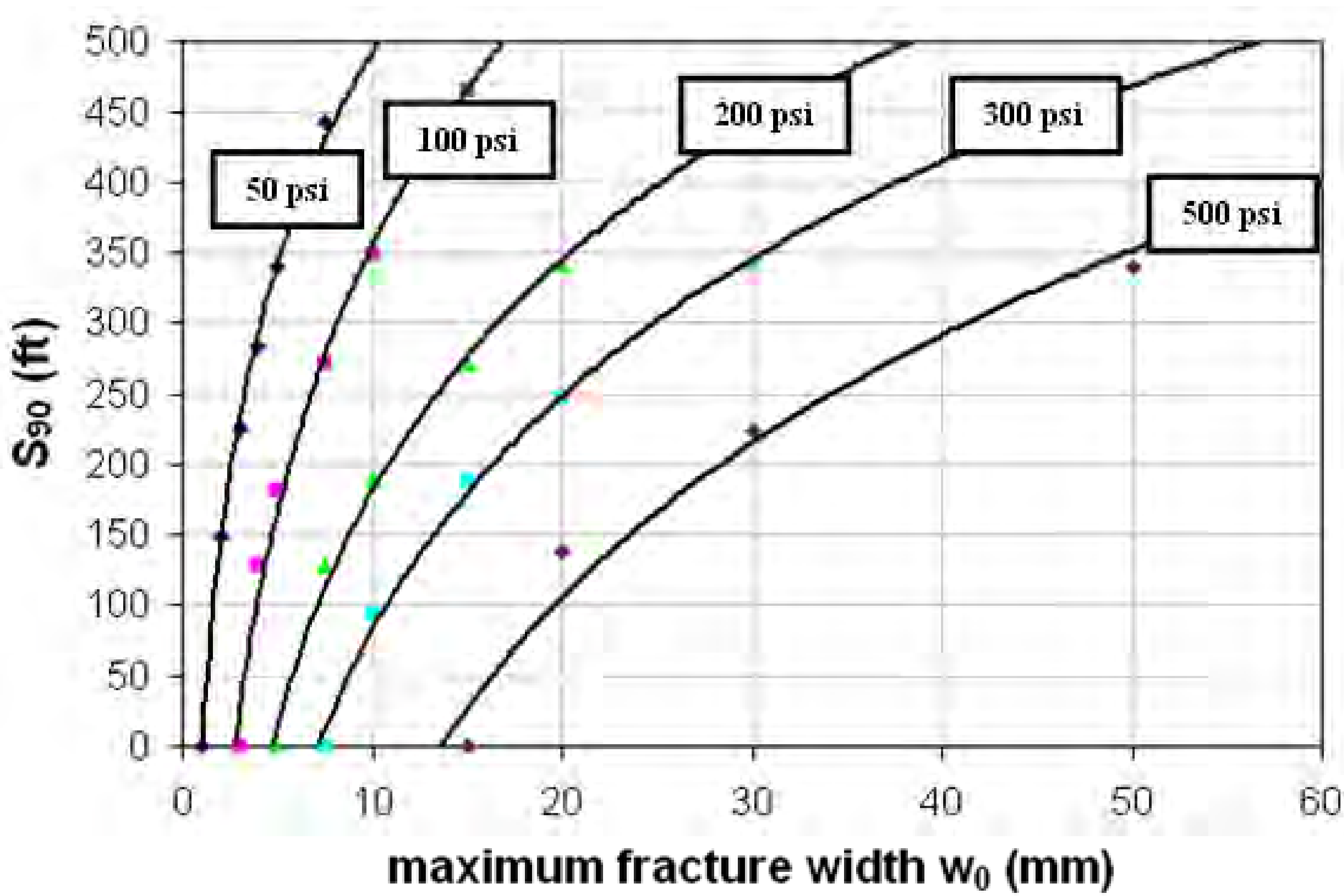
Angle of stress reorientation

Quantifying the Concept of Minimum Fracture Spacing

- If the next fracture is initiated inside the stress reversal region, there is a possibility of:
  - ✓ Longitudinal fracture
  - ✓ Risk of screen-out
- To avoid longitudinal fractures, the minimum fracture spacing, should be greater than S_{90}
- To maintain transverse fractures the fracture spacing should be greater than S_5
- For any spacing between S_{90} and S_5 fractures will deviate from the transverse plane

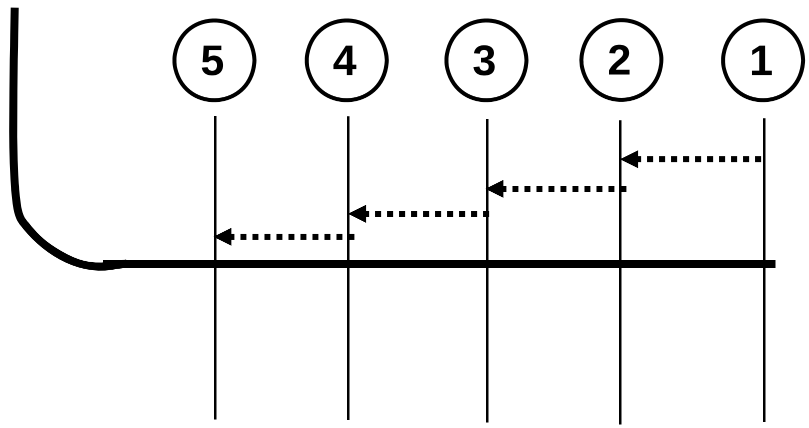
- Ref: **Nicolas P. Roussel, Mukul M. Sharma, SPE 127986,** "**Optimizing Fracture Spacing and Sequencing in Horizontal Well Fracturing" (2010).**

Effect of Fracture Width, Stress Contrast on Minimum Fracture Spacing

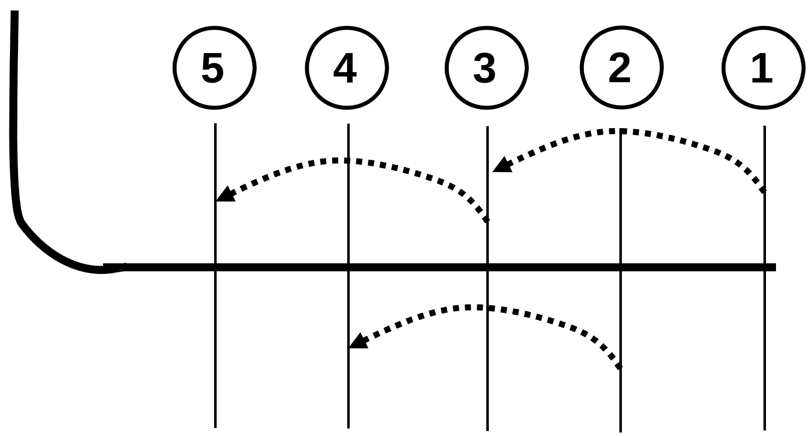


Three Fracturing Sequences

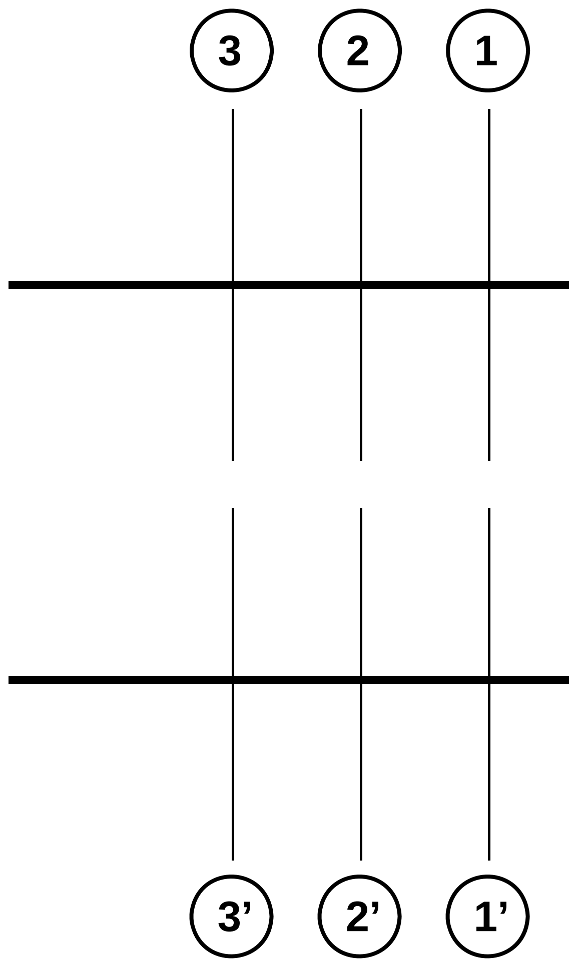
1. Consecutive fracturing



2. Alternate fracturing

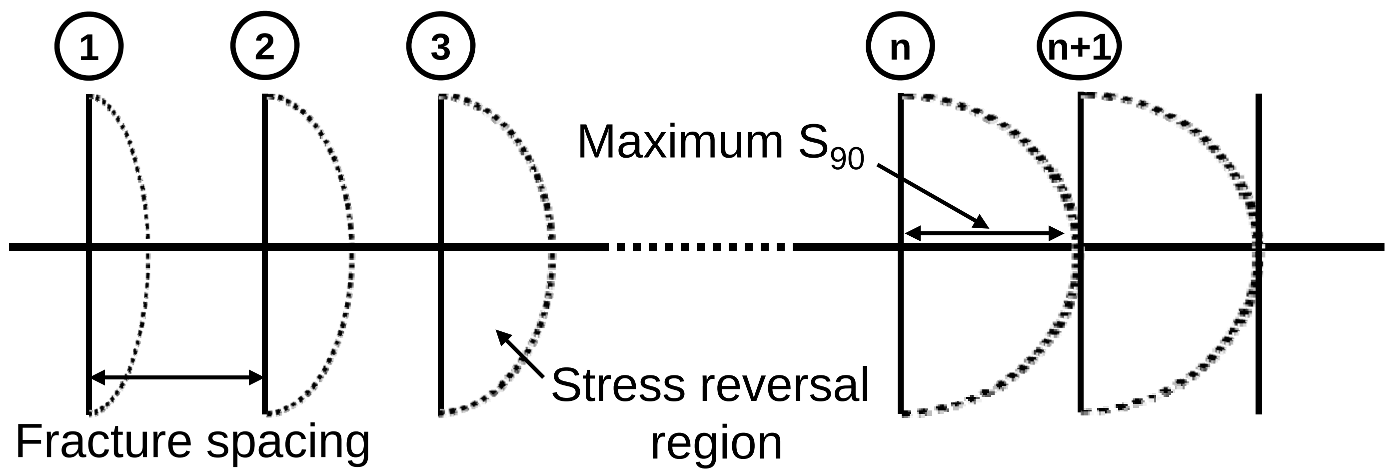


3. Zipper fracs

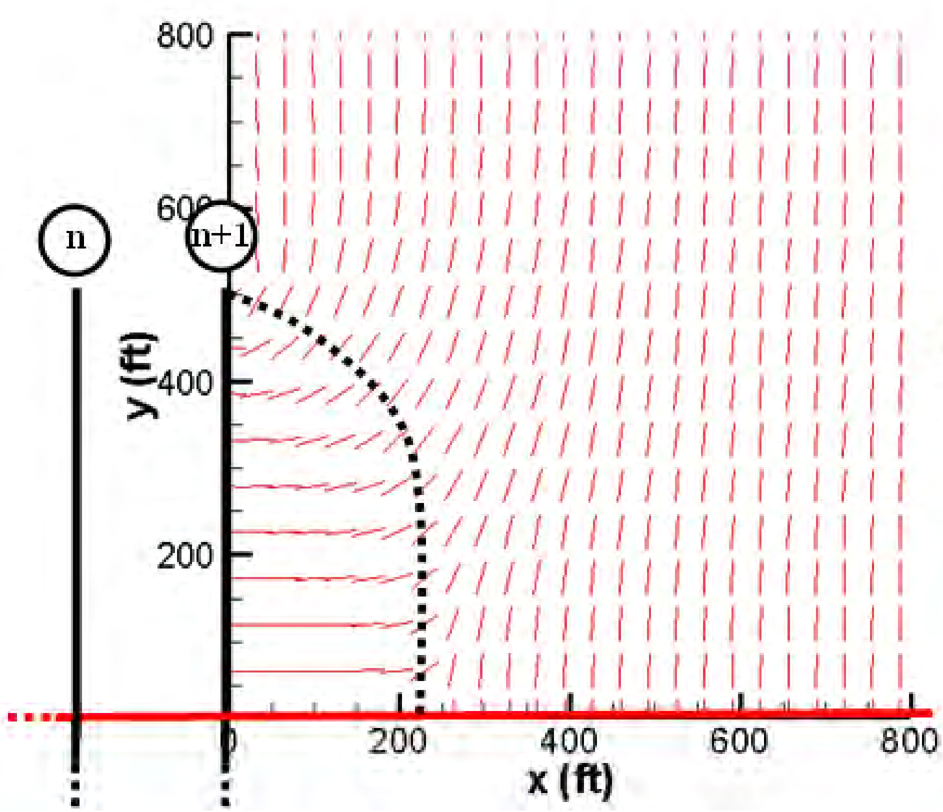


Fracture Reorientation due to Multiple Fractures

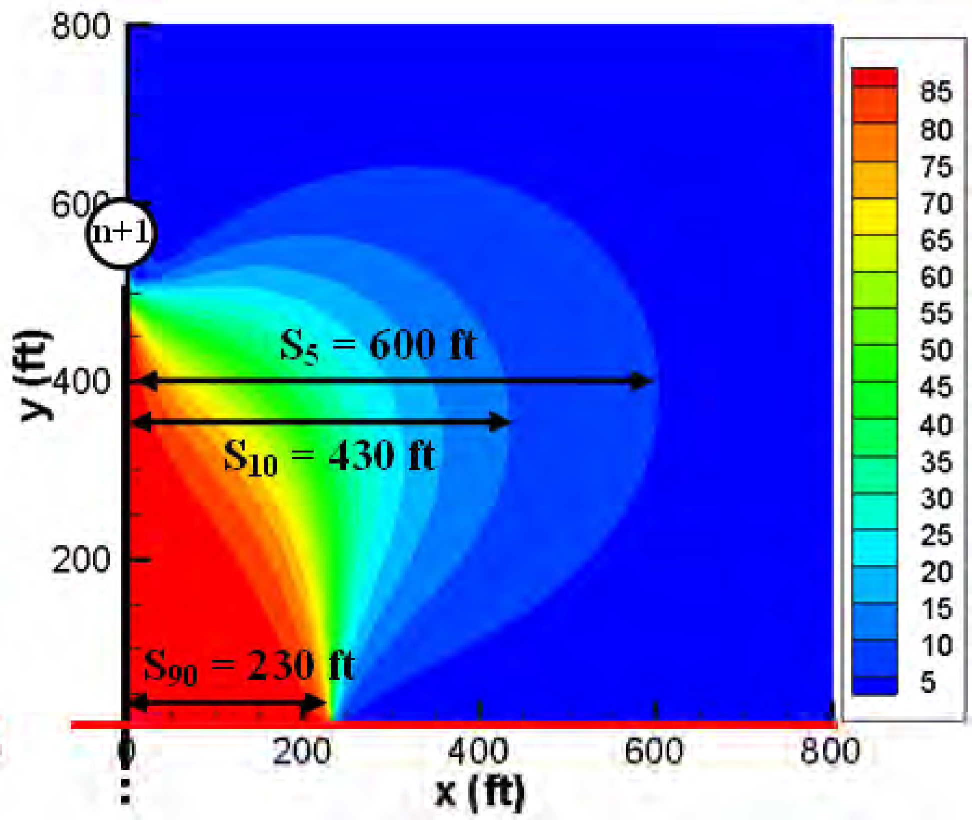
- Stress perturbations are cumulative as more fractures are added
- The stress reversal region grows with each additional fracture
- Ideally, fracture spacing should be greater than the maximum value of S_{90}



Estimating Minimum Fracture Spacing, Consecutive Multiple Fractures



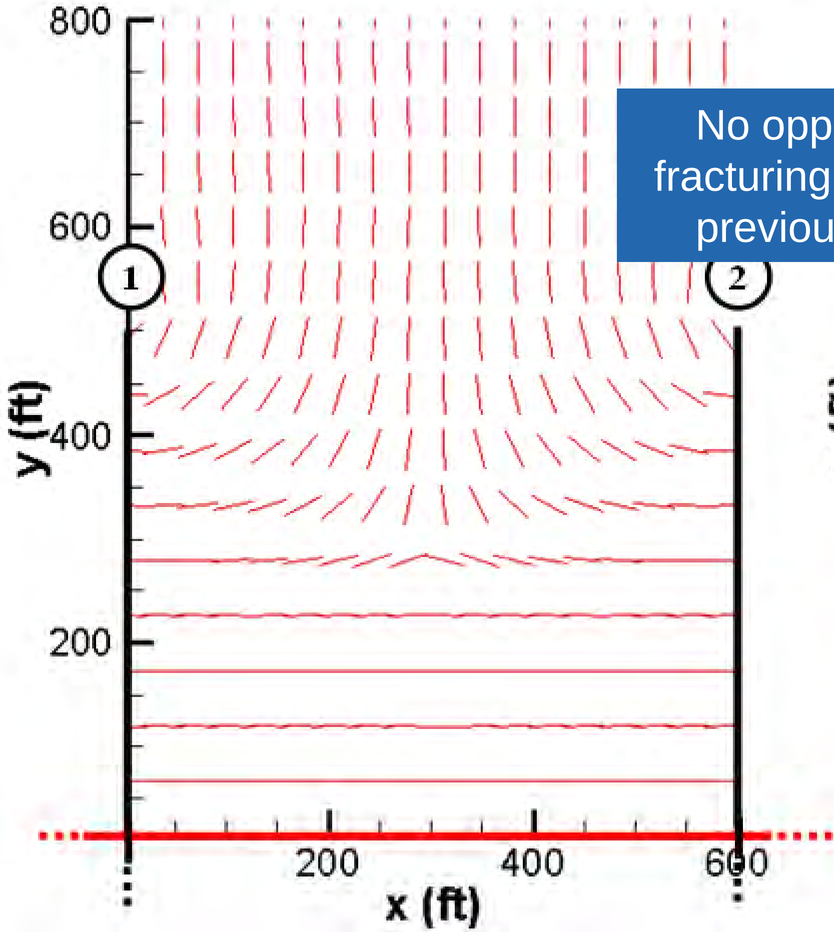
Direction of maximum horizontal stress



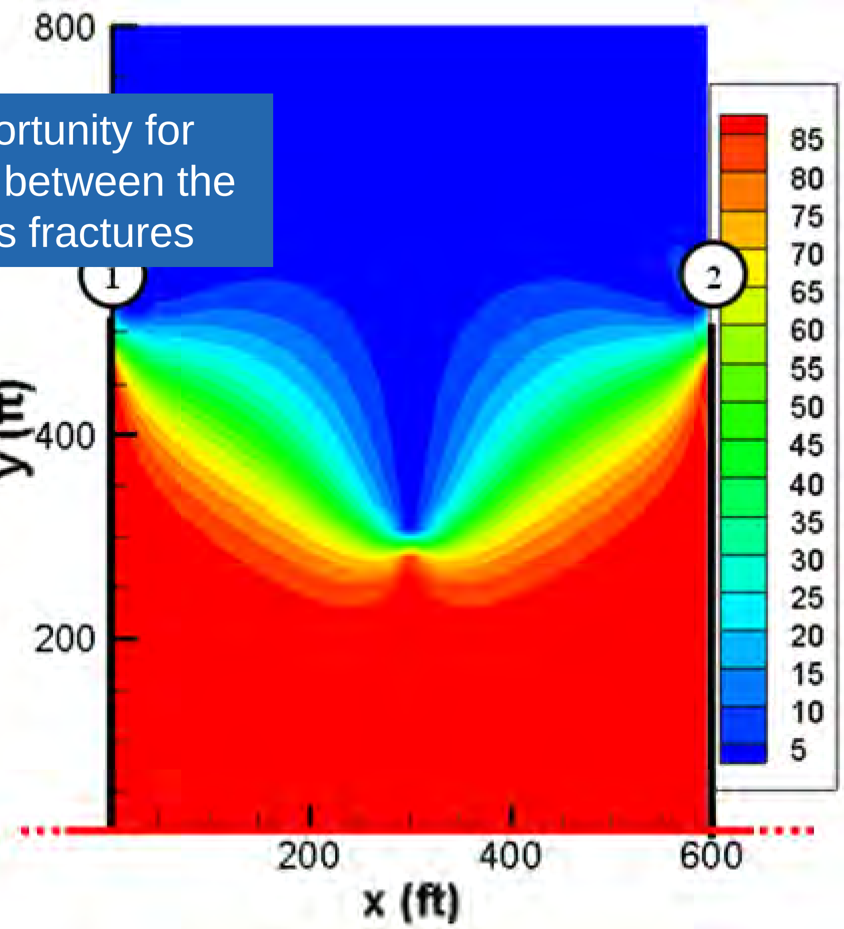
Angle of stress reorientation

Alternate Fracturing (600-ft spacing)

No opportunity for fracturing between the previous fractures

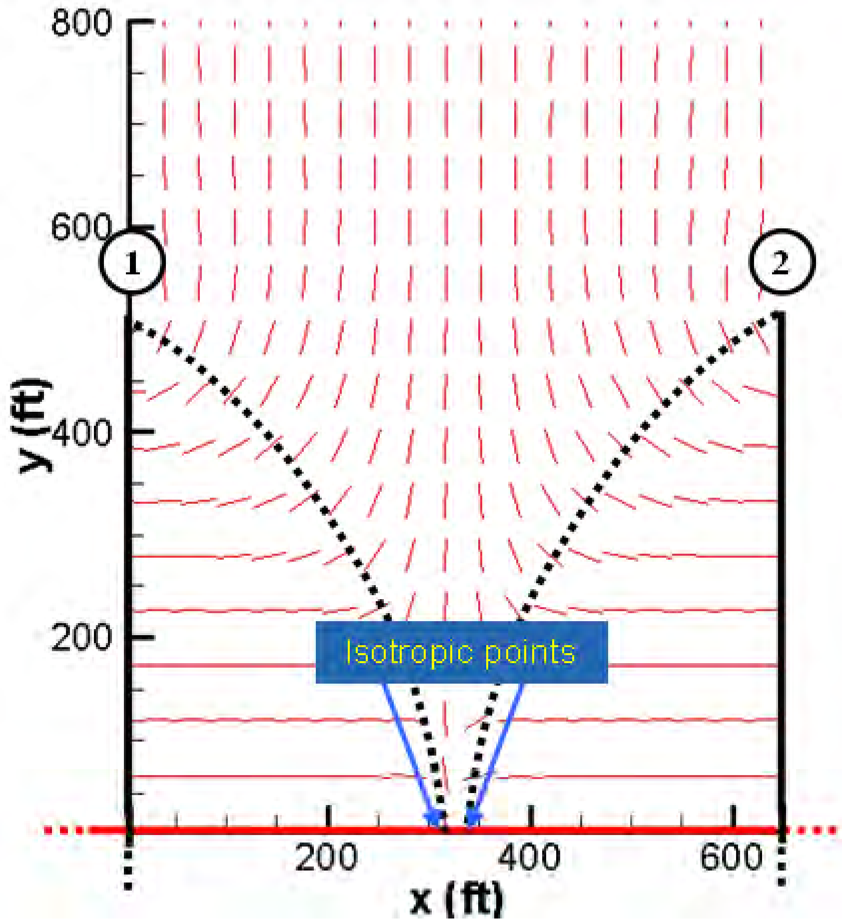


Direction of maximum horizontal stress

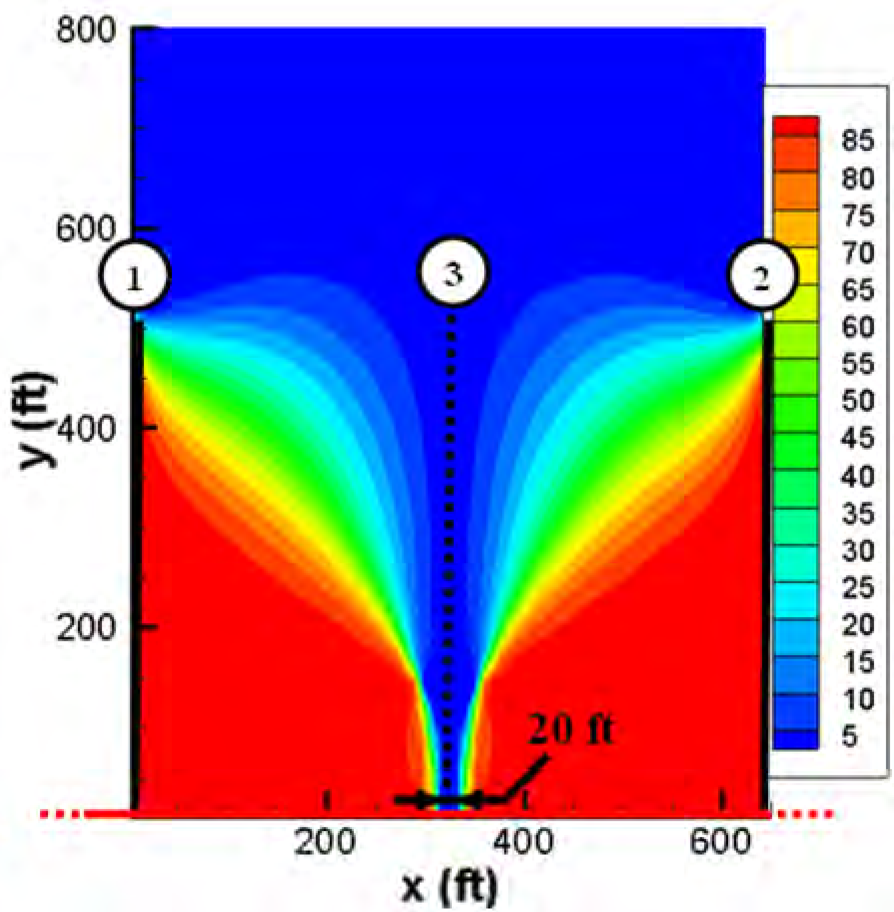


Angle of stress reorientation

Alternate Fracturing (650-ft spacing)

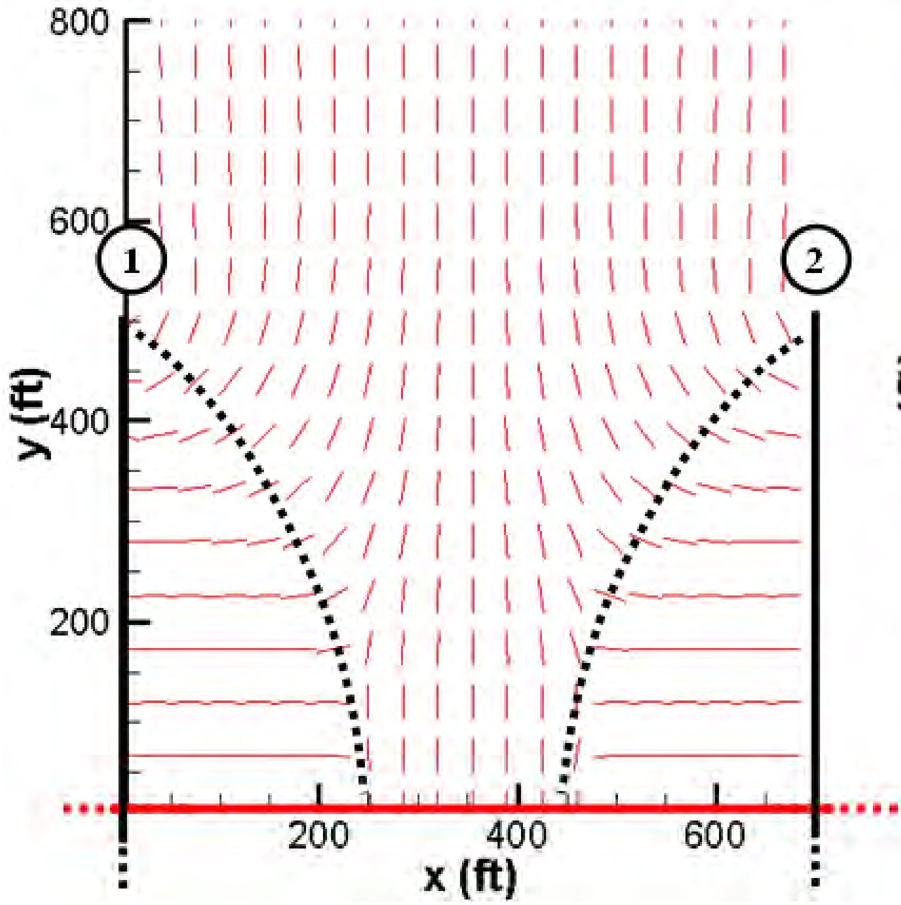


Direction of maximum horizontal stress

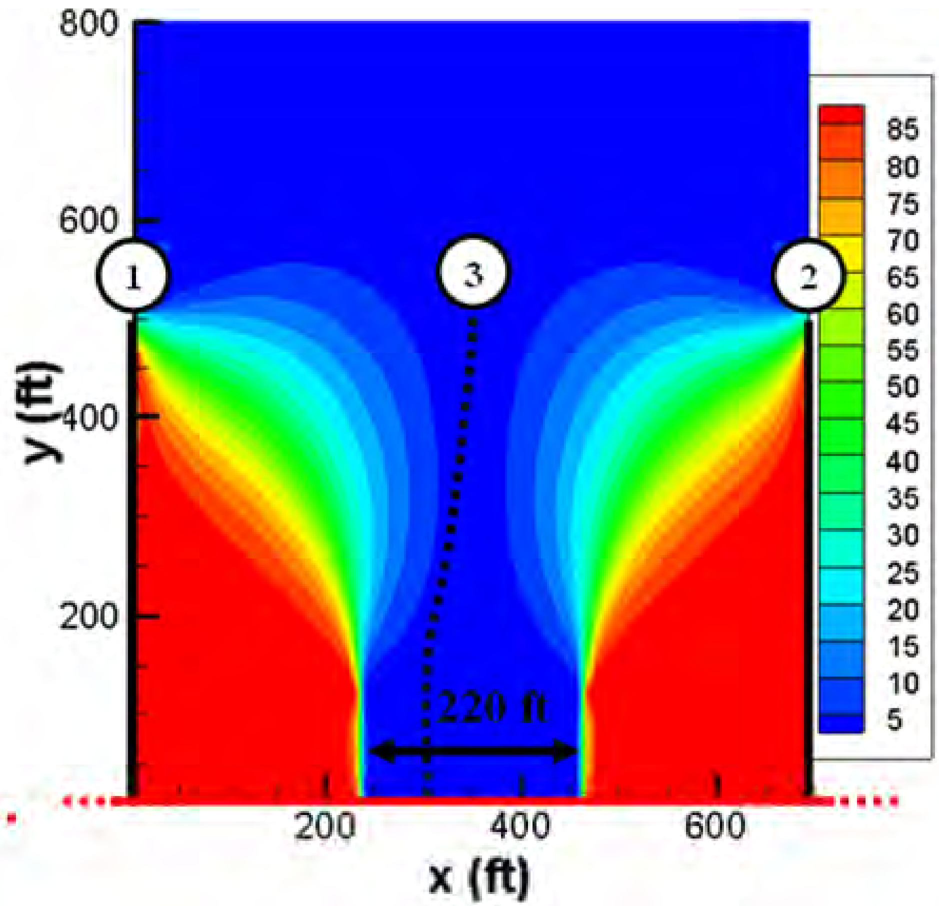


Angle of stress reorientation

Alternate Fracturing (700-ft spacing)

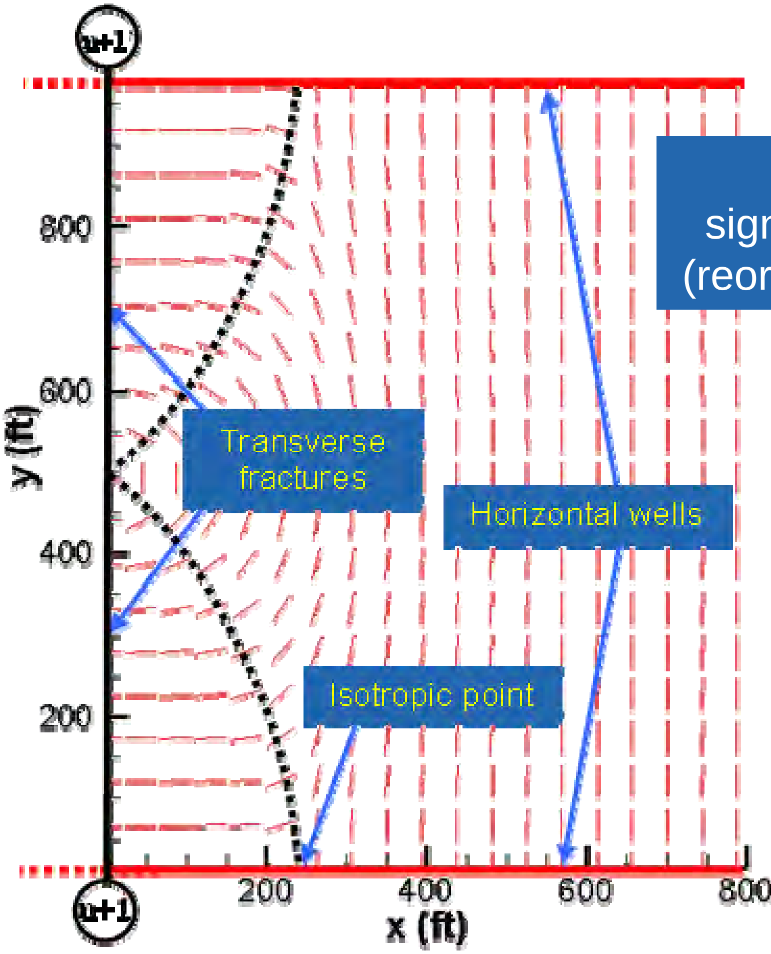


Direction of maximum horizontal stress

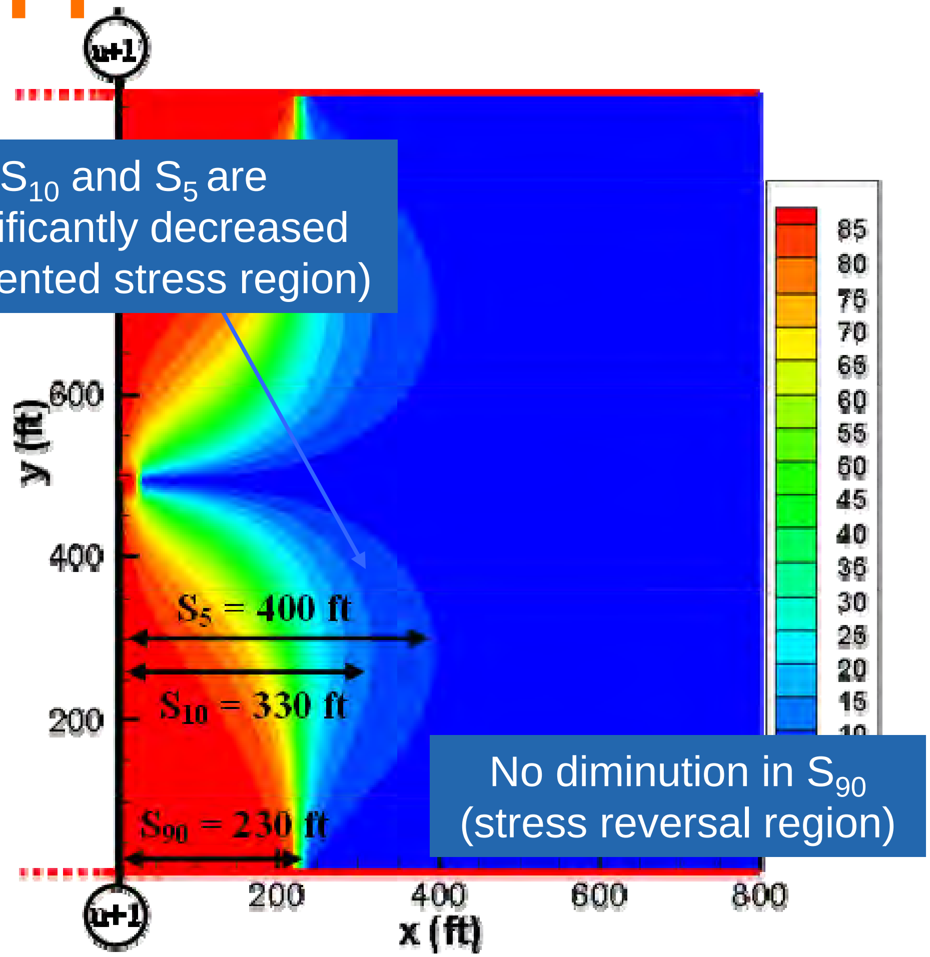


Angle of stress reorientation

Simultaneous Fracturing of Adjacent Wells: Zipper Fracs



Direction of maximum horizontal stress



Angle of stress reorientation

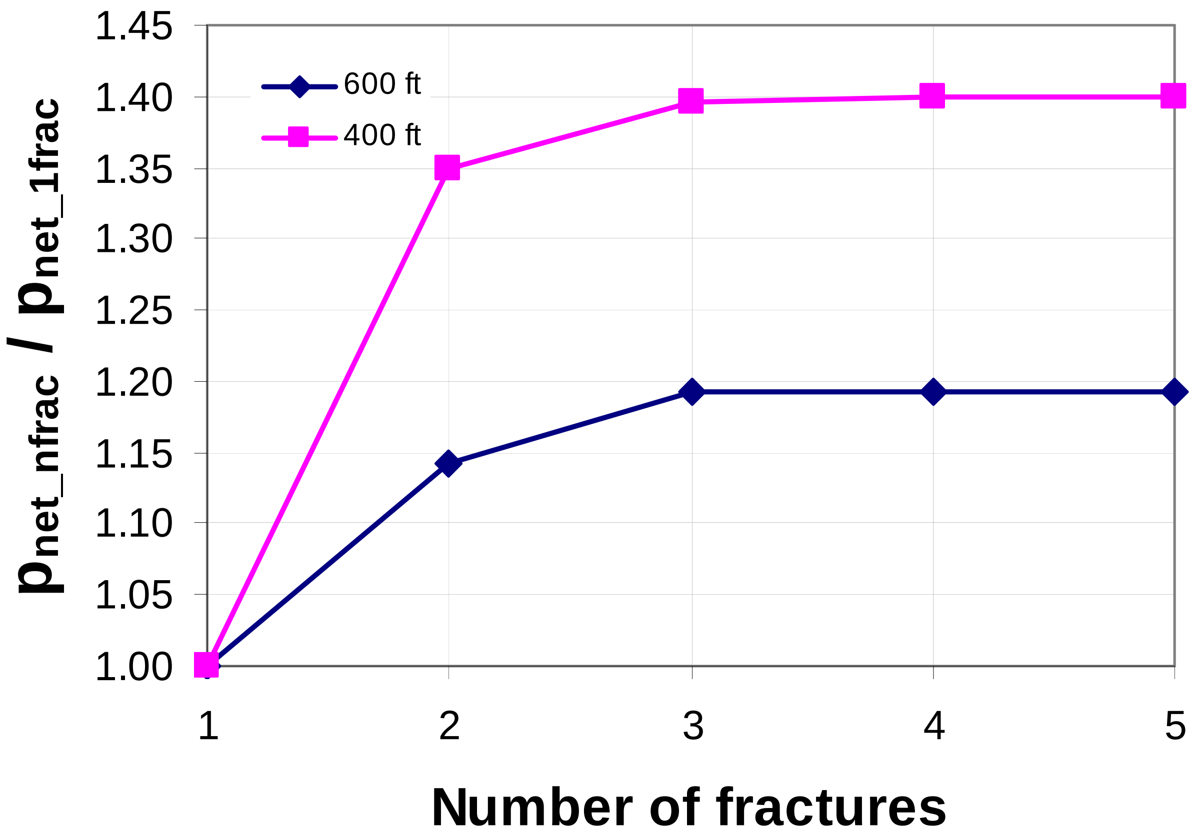
Alternate Fracturing Sequence Minimizes Fracture Spacing

- Minimum fracture spacing (S_{90}): to avoid screen-out or longitudinal fractures
- Recommended fracture spacing (S_5): to avoid fracture deviation from orthogonal path

	Consecutive fracturing (1-2-3-4-5…)	**Alternate fracturing (1-3-2-5-4…)**	**Simultaneous fracturing of adjacent wells (well spacing = 2 L_f)**
Minimum fracture spacing (ft) (= S_{90} or interval for 3rd frac>0 ft)	230	325	230
Recommended fracture spacing (ft) (= S_5 or interval for 3rd frac>100 ft)	**600**	**340**	**400**

Effect of Fracture Spacing On Net Pressures – Multiple Fracs

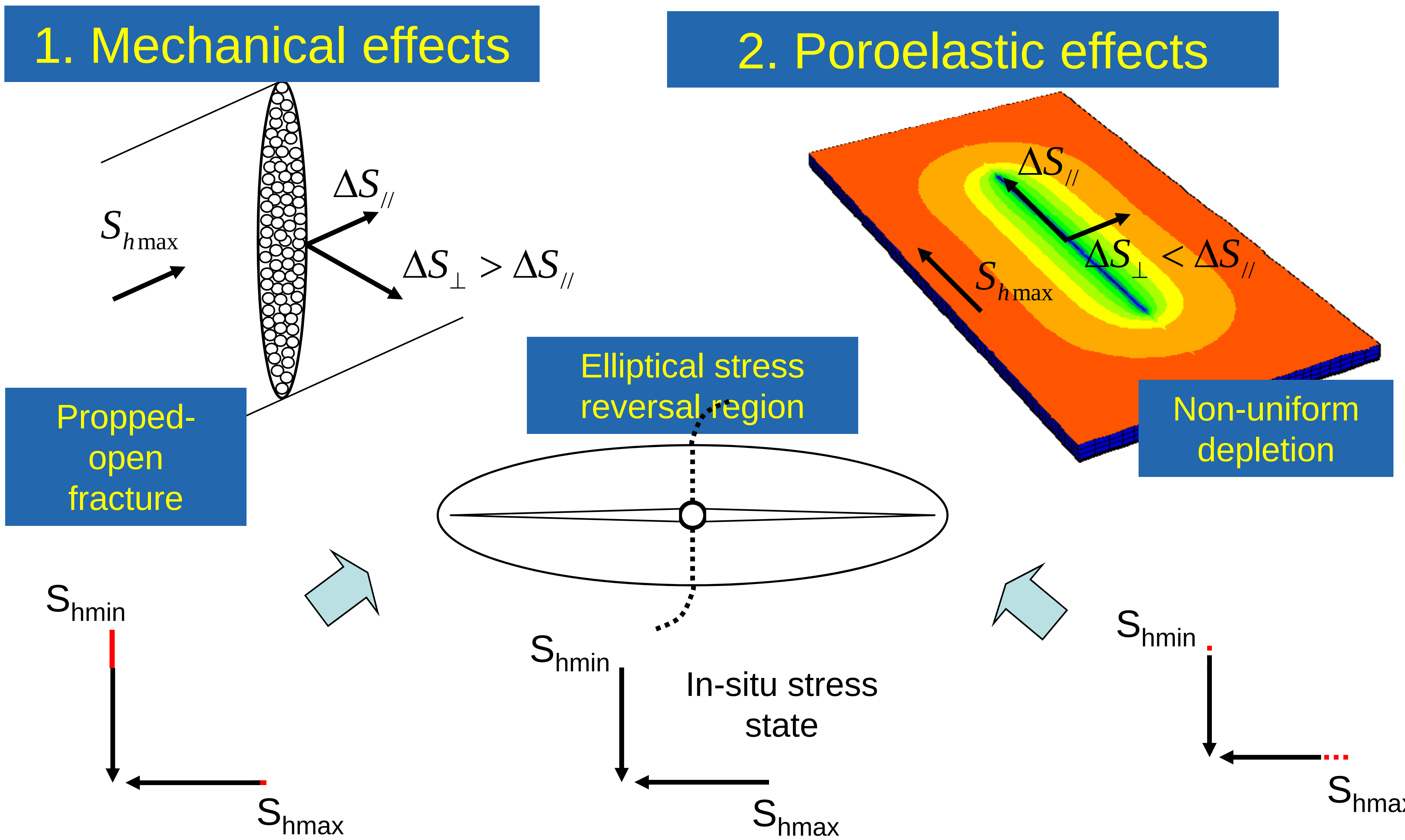
- Net pressure increase from toe to heel indicates stress interference.
- Net pressure change depends on fracture dimensions and mechanical properties



Summary

- Stress reorientation limits the spacing of multiple transverse fractures.
- Our numerical model provides estimates of the minimum and recommended fracture spacing for any given set of reservoir, fracture properties.
- The alternate fracturing technique minimizes fracture spacing.
- Significant opportunities for higher production in horizontal well completions may be possible with the alternate fracturing method.

Two Contributors to Stress Reorientation



Impact of Stress Reorientation on Well / Reservoir Performance

- **Multiple fracturing of horizontal wells**
- **Refracturing**
- Waterflooding
  - ✓ Reservoir sweep is impacted
  - ✓ Orientation of injection well fractures can change with time
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Motivation

- Beating the decline curve in unconventional gas reservoirs requires continuous drilling and fracturing.
- In a low gas price environment re-frac treatments offer a low cost alternative to drilling new wells.
- Multiple fracs in horizontal wells are becoming the norm and the placement and geometry of these is impacted by stress reorientation.
- Performance of re-fracs and multi-fracs is highly variable and must be made more reliable and predictable.

Stress Reorientation & Refracturing

- Production enhancement from refracturing operations can occur due to:
  - ✓*Extension of existing fractures.
  - ✓*Creation of new fractures
  - ✓*Connection with natural fracture system
  - ✓*Fracture extension into adjoining sands
  - ✓Improve conductivity of existing fracture

  * Stress reorientation plays a role

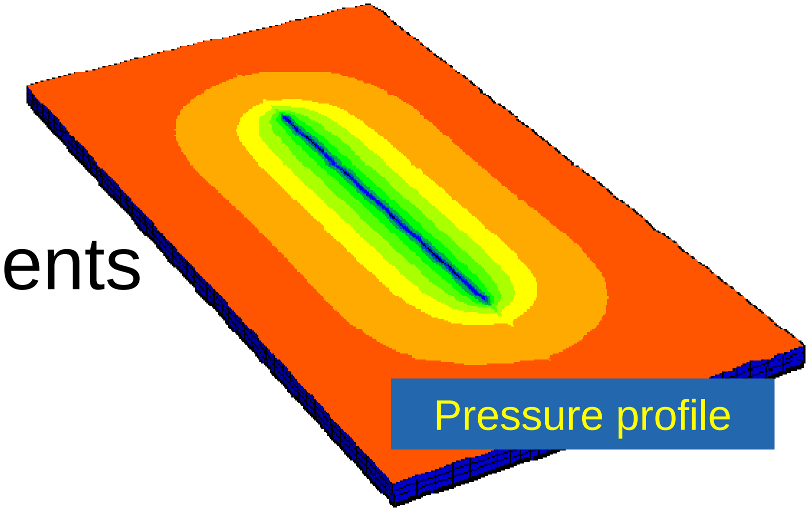
Stress reorientation plays a key role in the success of refracturing operations

Past Work

- Field measurements of stress reorientation, tiltmeter mapping, microseismic imaging
  - ✓ Maxwell *et al*. (2002), Wright *et al*. (1994, 1995, 2002), Wolhart *et al*. (2007)
- Numerical simulations of stress and fracture reorientation
  - ✓ Elbel *et al*. (1993), Olson *et al*. (2008), Roussel *et al*. (2009, 2010), Siebrits *et al*. (1998, 2000), Warpinski *et al*. (1989)
- Analytical and numerical models of stress distribution around open cracks
  - ✓ Sneddon and Elliott (1946), Soliman *et al.* (1997, 2004), Cheng (2009)

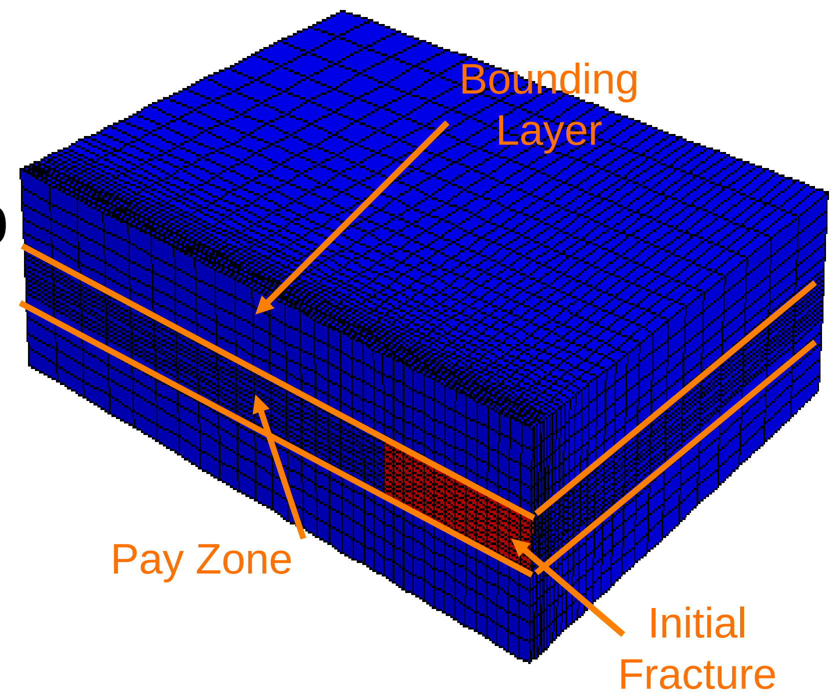
Depletion vs. Stress Reorientation

- The stresses decrease due to depletion. The impact of depletion on fracture containment is well known.
- The principal stresses may change not only in magnitude but also in direction:
  - ✓This is called stress reorientation
  - ✓It is due to pressure gradients

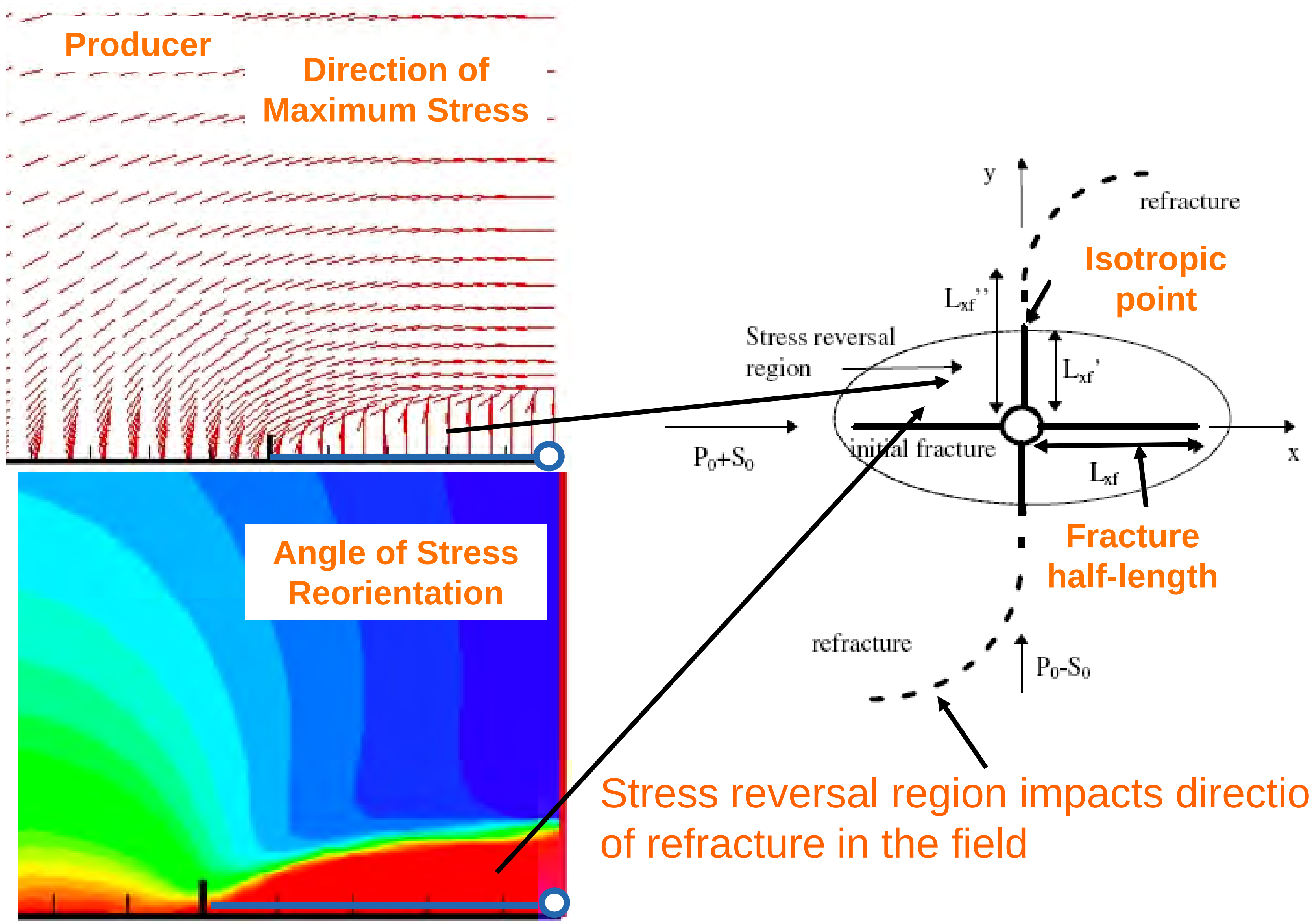


Stress Reorientation

- Model is 3D and capable of handling, heterogeneity elasto-plasticity, multiple layers and anisotropy.
- Stress reorientation due to two factors:
  - Poroelastic effects
  - Fracture opening
- Constant pressure in vertical well and initial fracture.

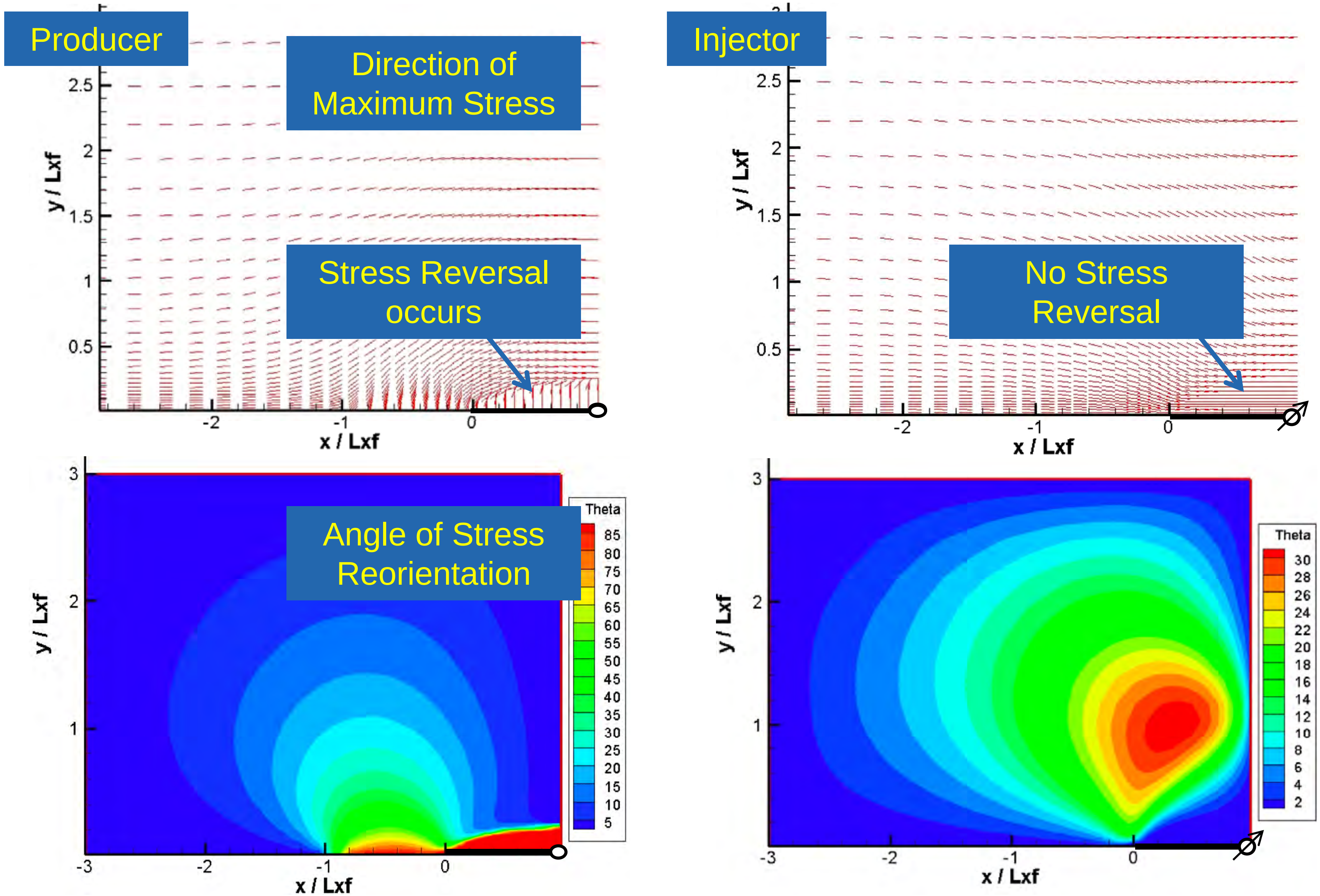


Stress Reversal Region

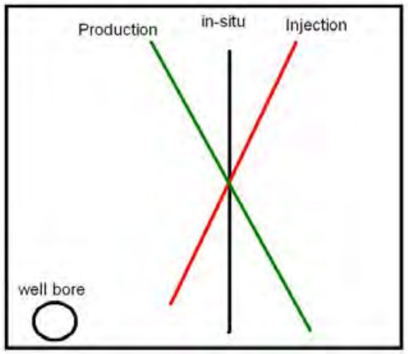


Stress reversal region impacts direction of refracture in the field

Stress Reorientation Around Producers and Injectors

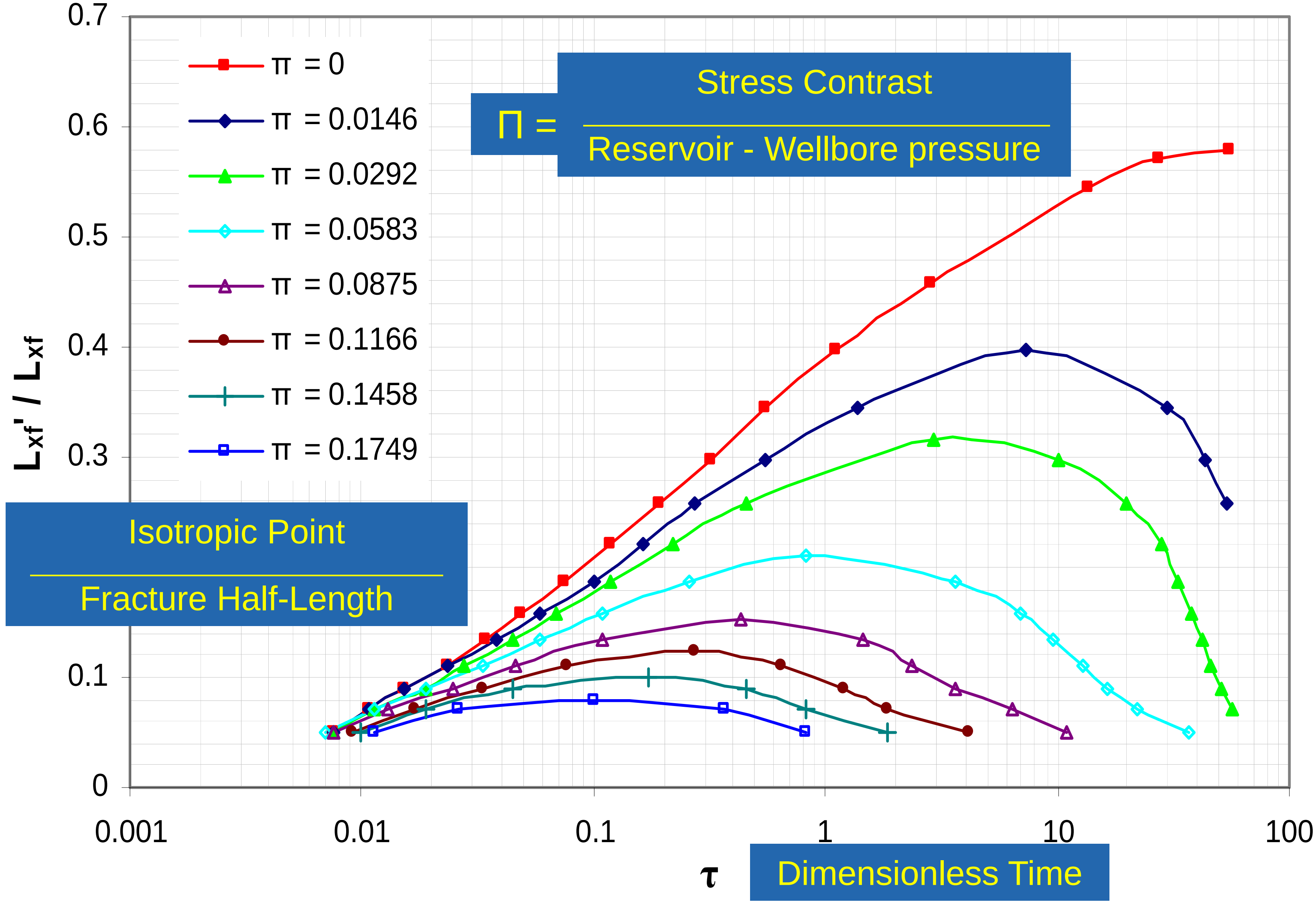


Summary of Findings

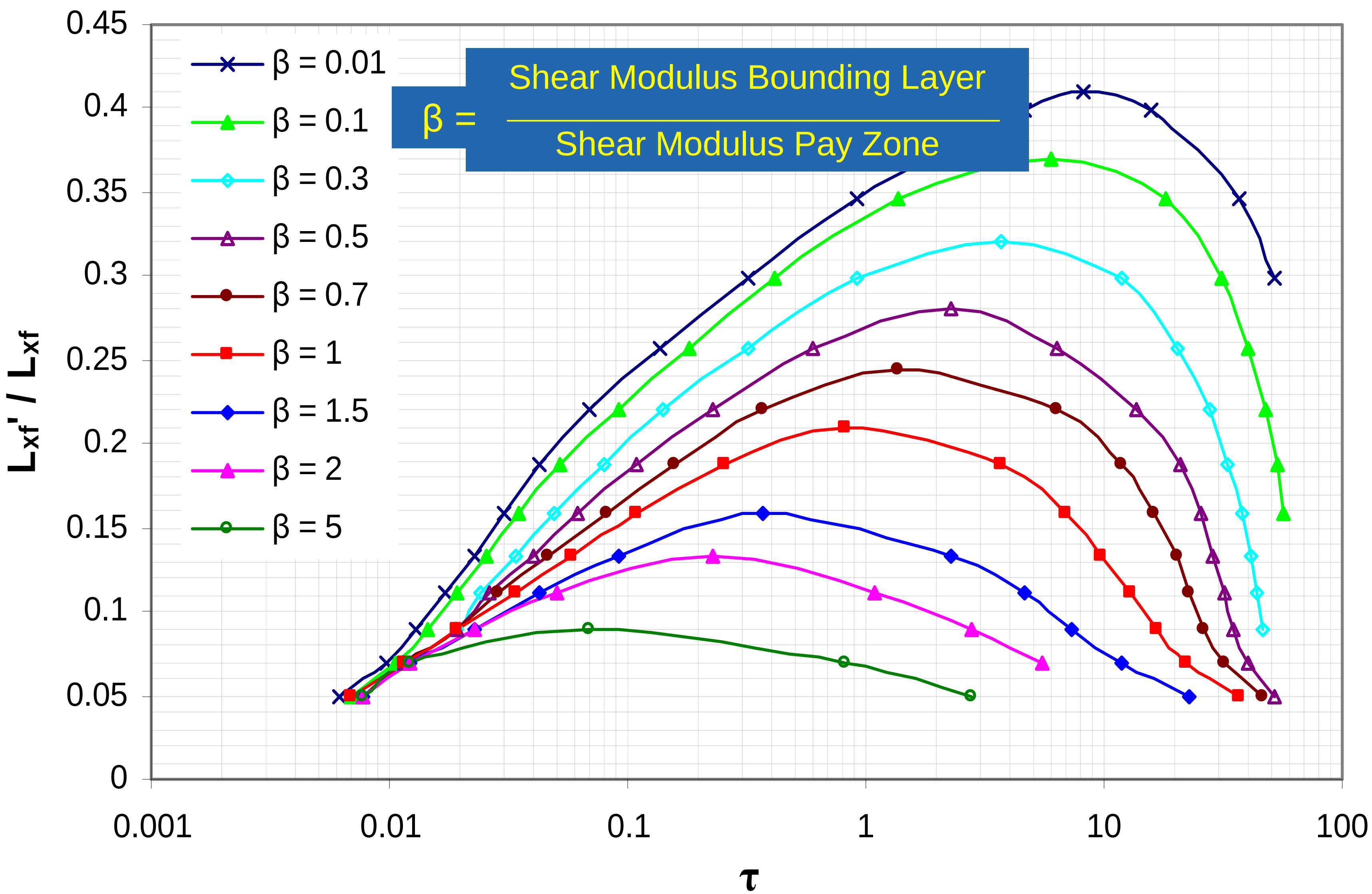


- Stress reorientation depends on:
  - ✓ Drawdown
  - ✓ Stress anisotropy
  - ✓ Moduli of sand and bounding layers
- Stress reversal does occur in fractured producers. For a given set of reservoir / well conditions, we can now compute its,
  - ✓ Spatial extent
  - ✓ Timing
- Far-field, an approaching fracture will go:
  - ✓ Away from a production well
  - ✓ Toward an injection well
  - ✓ In the immediate vicinity of a producer or injector, the opposite will be true.

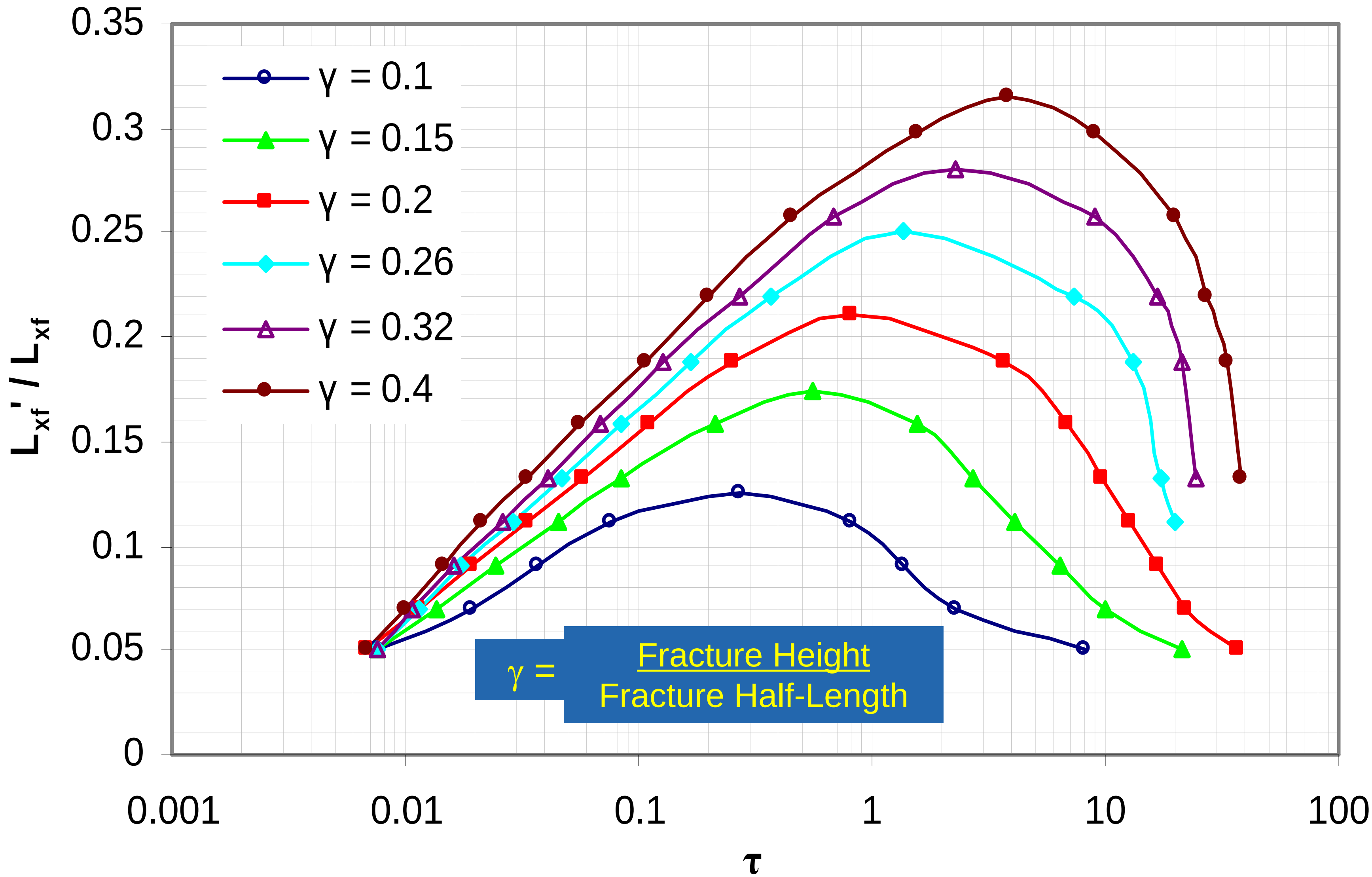
Stress Reorientation Increases with Increasing Drawdown and Decreasing Stress Contrast



Stress Reorientation Decreases with Increasing Shear Modulus of Bounding Layers



Stress Reorientation Increases with Fracture Height (β = 1)



Dimensionless Parameters

(Berchenko *et al*., 1997; Siebrits *et al*., 1998; Roussel and Sharma, 2009)

- Dimensionless Time

$$\tau = \frac{4ct}{L_{xf}^2} = 4\frac{\kappa}{S}\frac{t}{L_{xf}^2} = \frac{4kt}{\mu L_{xf}^2\left(\frac{1}{M} + \frac{\alpha(1+\nu)(1-2\nu)}{(1-\nu)E}\right)}$$

- Dimensionless Stress Deviator

$$\Pi = \frac{S_0}{\sigma_*} = \frac{S_0}{\eta p_*} = \frac{\sigma_{h\max} - \sigma_{h\min}}{\frac{\alpha(1-2\nu)}{1-\nu}\left|p_{R_i} - p_{wf}\right|}$$

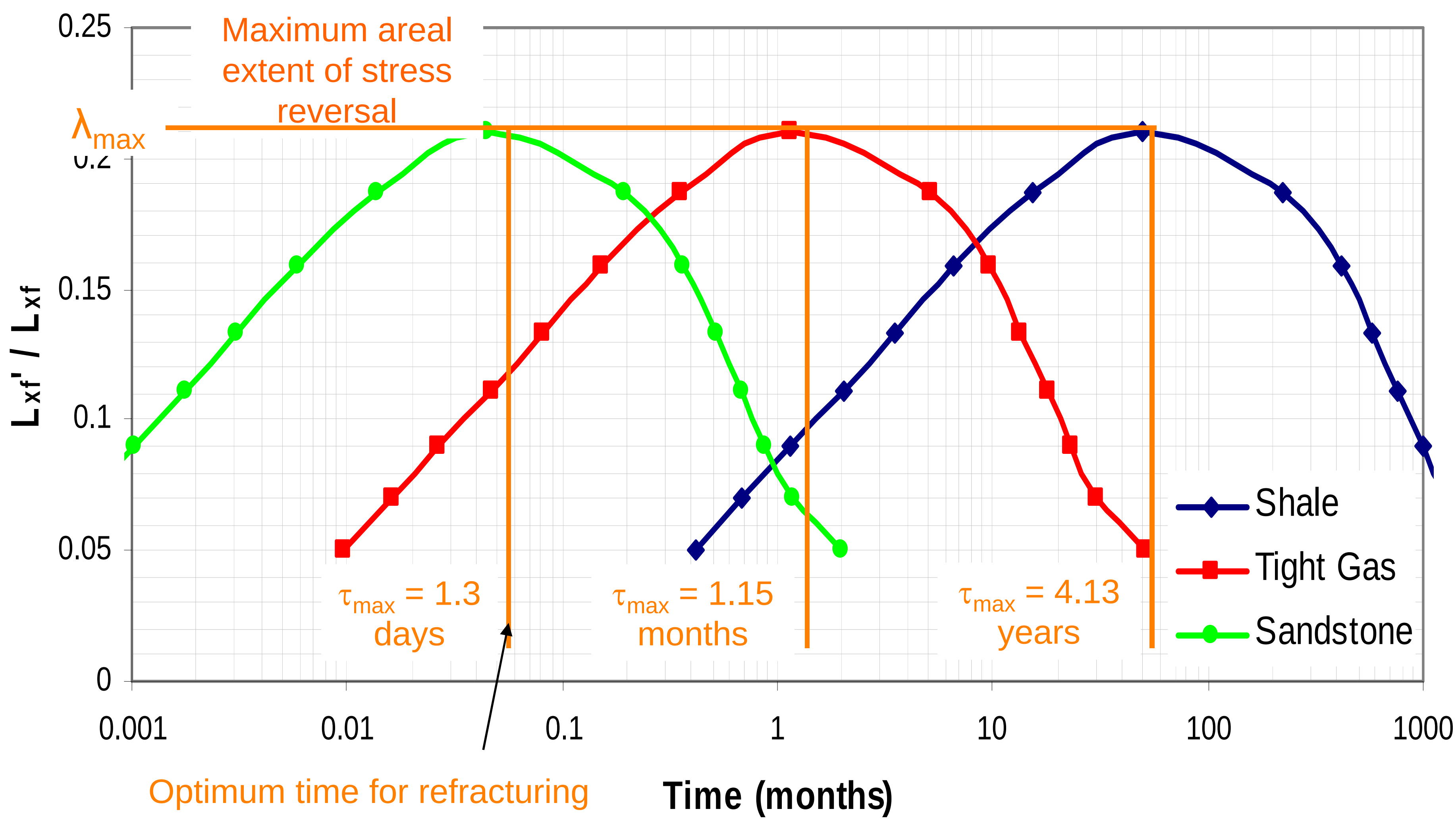
- Dimensionless Fracture Height Ratio

$$\gamma = \frac{H}{L_{xf}}$$

- Dimensionless Shear Modulus Ratio

$$\beta = \frac{G_b}{G_r}$$

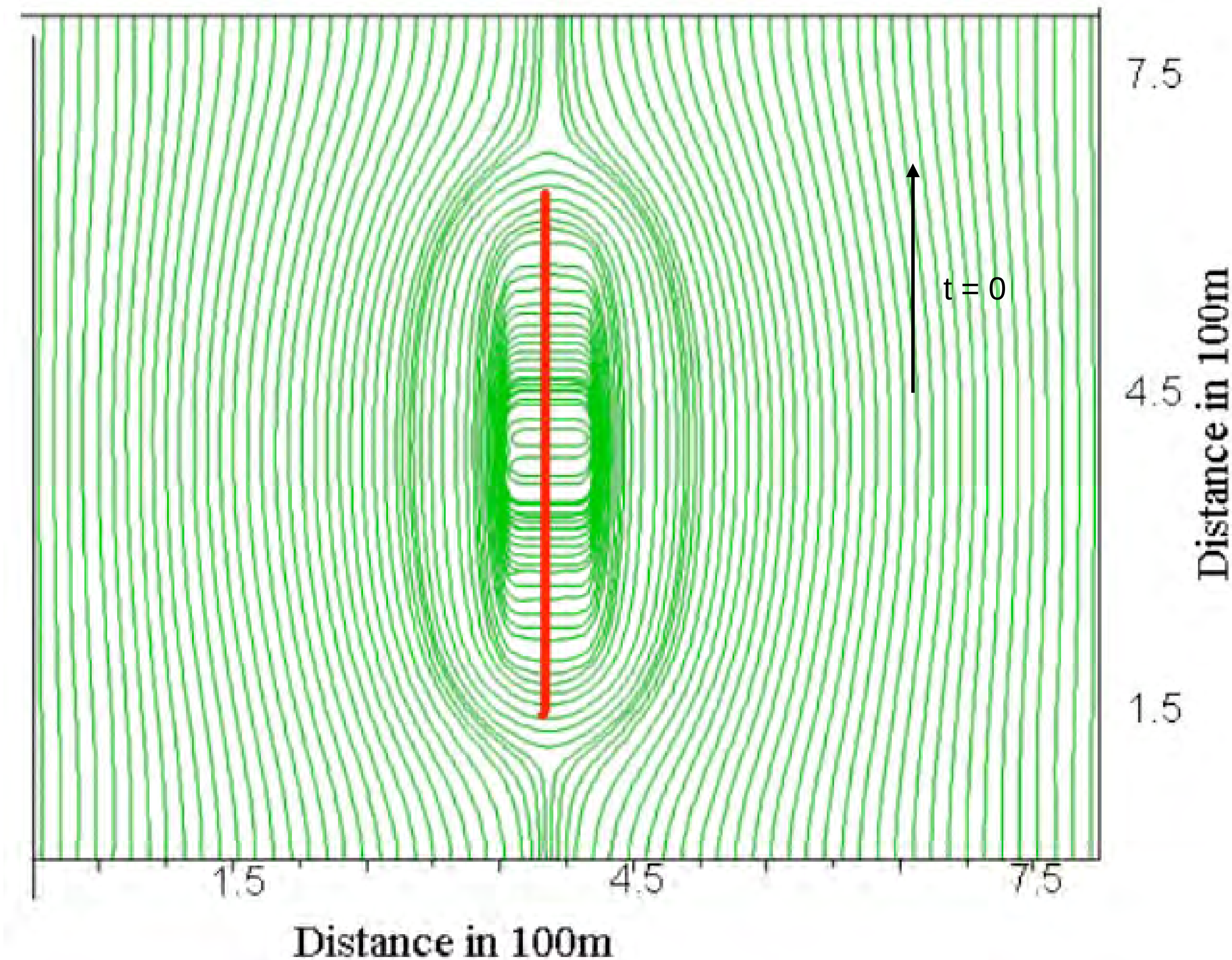
Selecting Timing and Candidate Wells for Re-fracturing



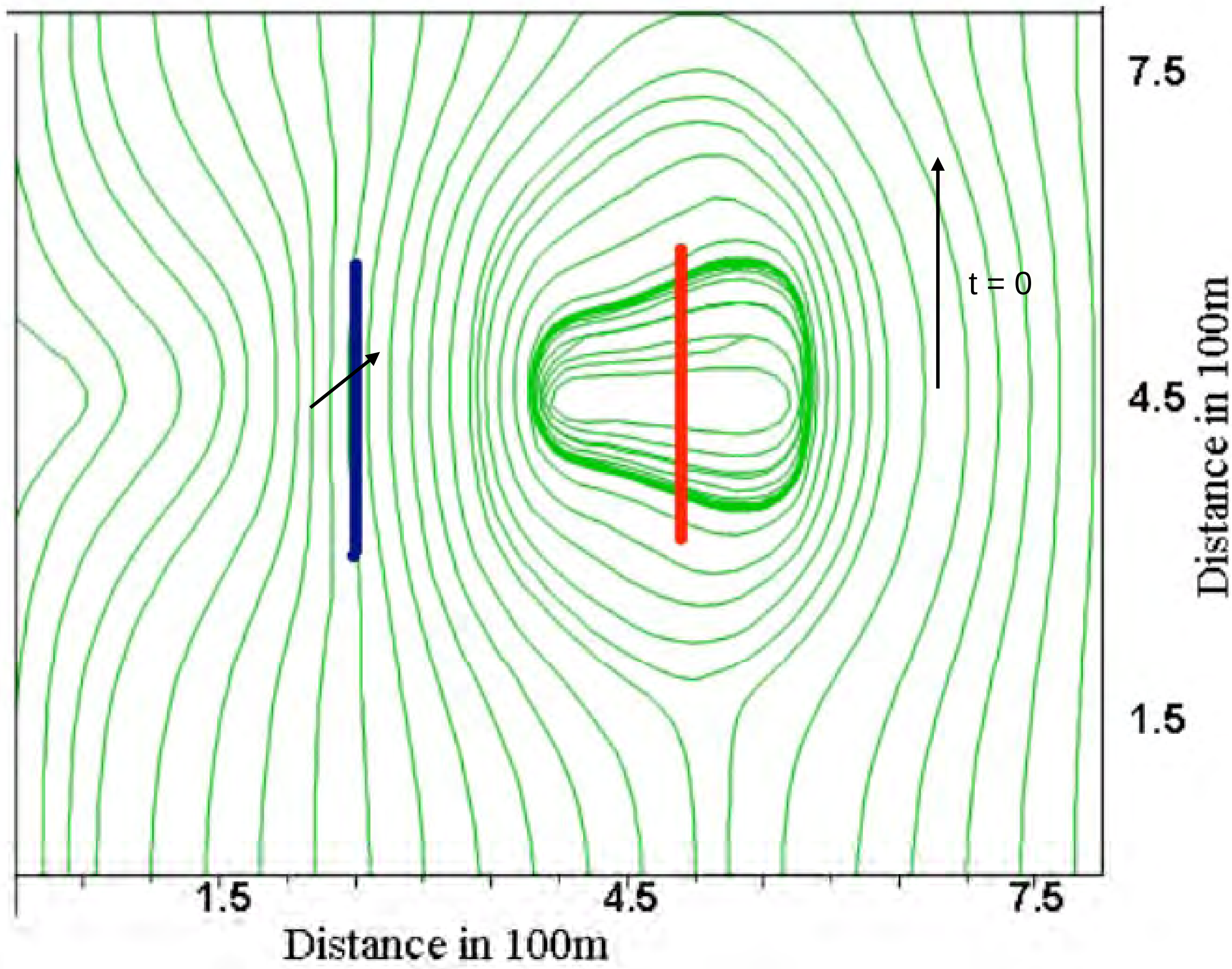
Selecting Timing and Candidate Wells for Re-fracturing

- For a given set of reservoir and well conditions we can now estimate the extent of stress reorientation. This should be one of the primary criteria for re-frac candidate well selection.
- The main results have been published.
  - ✓ *"Quantifying Transient Effects in Altered-Stress Re-fracturing of Vertical Wells",* SPE 119522, Presented at the SPE Hydraulic Fracturing Meeting, Woodlands, 2009, Nicolas P. Roussel, Mukul M. Sharma.

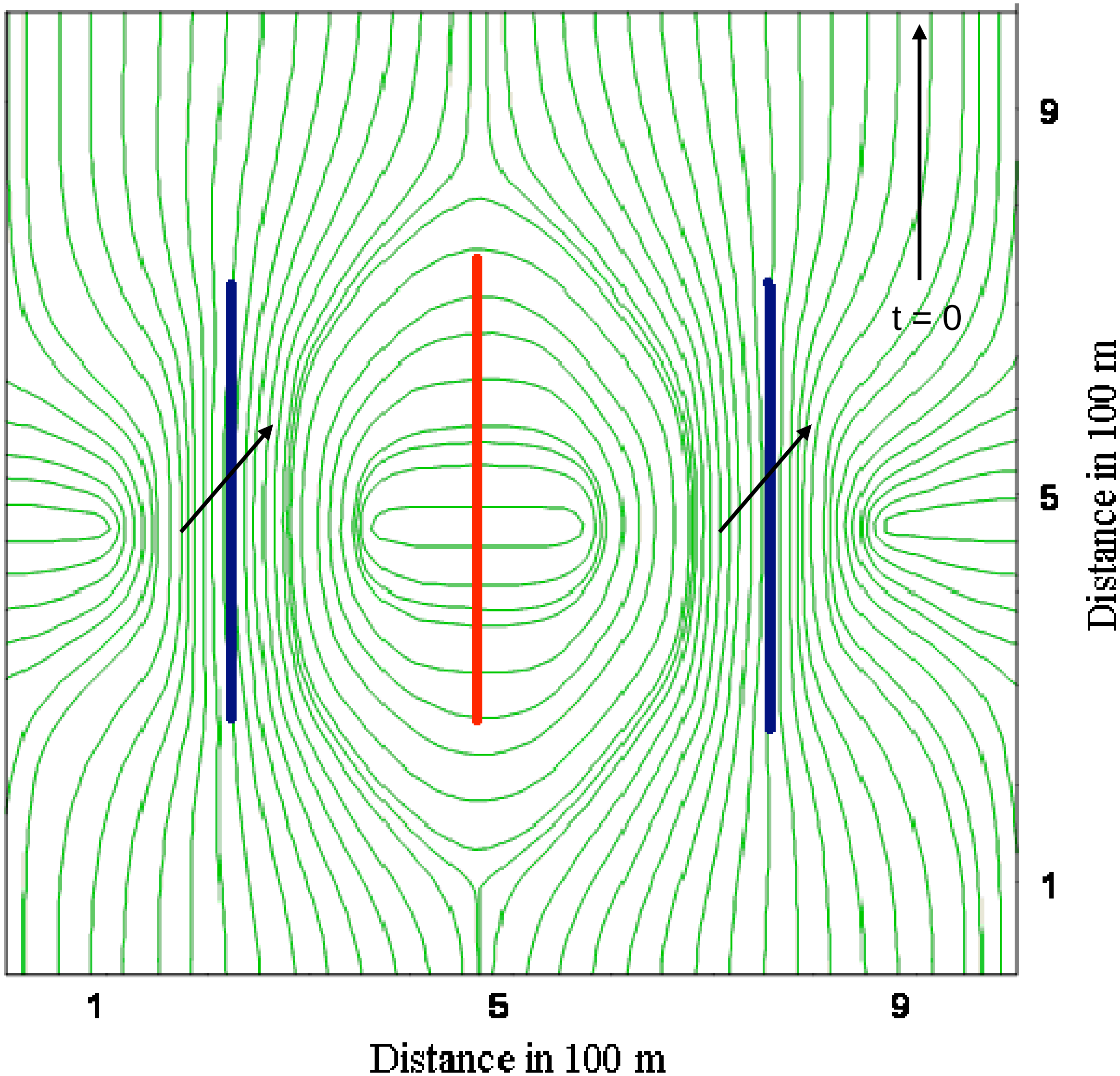
Re-fracture Designs for Deviated and Horizontal Wells



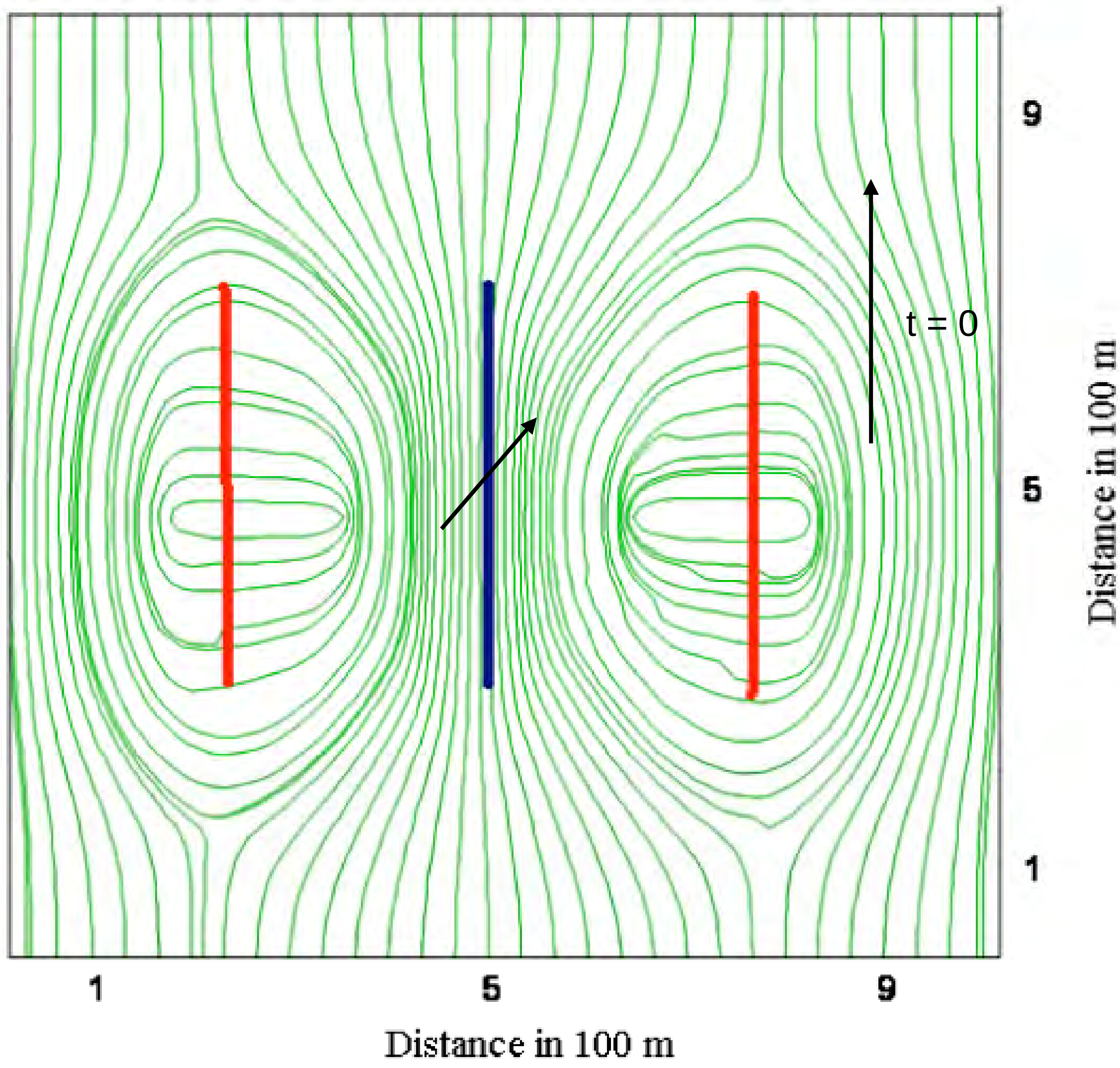
Stress Reorientation for a Production - Injection Well Pair



Stress Reorientation for 1 Production, 2 Injection Wells



Stress Reorientation for 2 Production, 1 Injection Well



Conclusions

- Stress reversal occurs in production wells but not injection wells.
- We showed the existence of an optimum time at which the areal extent of the stress reversal region is maximum.
- The magnitude (λ_{max}) and timing (τ_{max}) of the stress reversal depend on the fluid properties (τ), the stress contrast and drawdown (Π), the thickness of the reservoir (γ) and the shear modulus of the reservoir and the bounding layers (β).

Conclusions

- The effect of permeability heterogeneity and anisotropy on the magnitude and timing of maximum stress reversal can be incorporated by an appropriate definition of τ.
- Fractured production wells in unconventional reservoirs (tight gas, shale gas, heavy oil) with modest stress contrasts constitute ideal candidates for refracturing
- Dimensionless type curves are presented to estimate the optimum time-window for refracturing.

I would like to Acknowledge:

- ✓ **RPSEA for their support.**
- ✓ **Members of the Fracturing and Sand Control JIP at the University of Texas at Austin (Apache, Baker Hughes, BP, BHP, ConocoPhillips, ExxonMobil, Halliburton, Pioneer, Schlumberger, Shell) for providing support for this project.**

Thank you
Questions?

Application of the Model to Typical Gas Reservoir Types

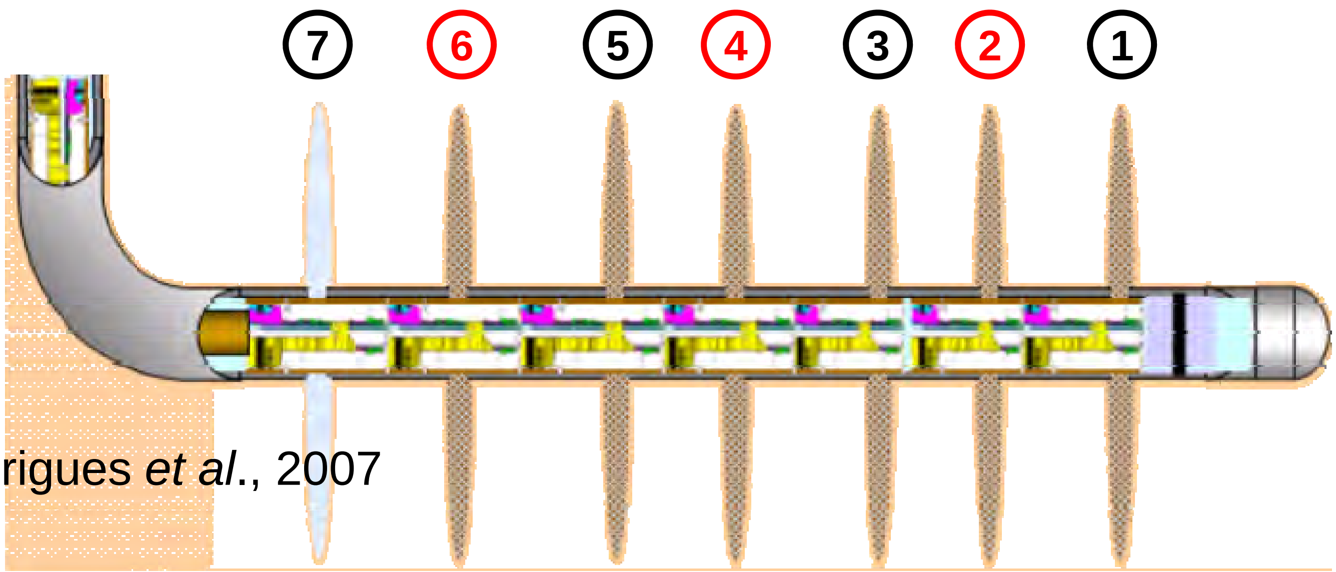
- Parameter values for sandstone gas, tight gas and shale gas

	Shale gas	Tight gas	Sandstone gas
Permeability k (md)	10^{-4}	10^{-2}	1
Young's Modulus E (psi)	$5.1.10^{6}$	$1.0.10^{6}$	$2.8.10^{6}$
Poisson's Ratio v	0.3	0.3	0.3
Porosity ϕ	0.05	0.05	0.2
Compressibility (1/psi)	2.10^{-4}	3.10^{-4}	3.10^{-4}
Viscosity μ (cp)	0.02	0.03	0.03
Fracture Length 2 L_{xf} (ft)	600	600	600

Application of Alternate Fracturing in the Field

- Hydra-jet in open-hole completions
- Modified Ball-Activated Sliding Sleeves (BASS)
- Coiled tubing and packers

Other suggestions ?



Rodrigues *et al*., 2007