HF initiation and propagation in heterogeneous rock

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2nd ARMA Hydraulic Fracturing Workshop

Outline

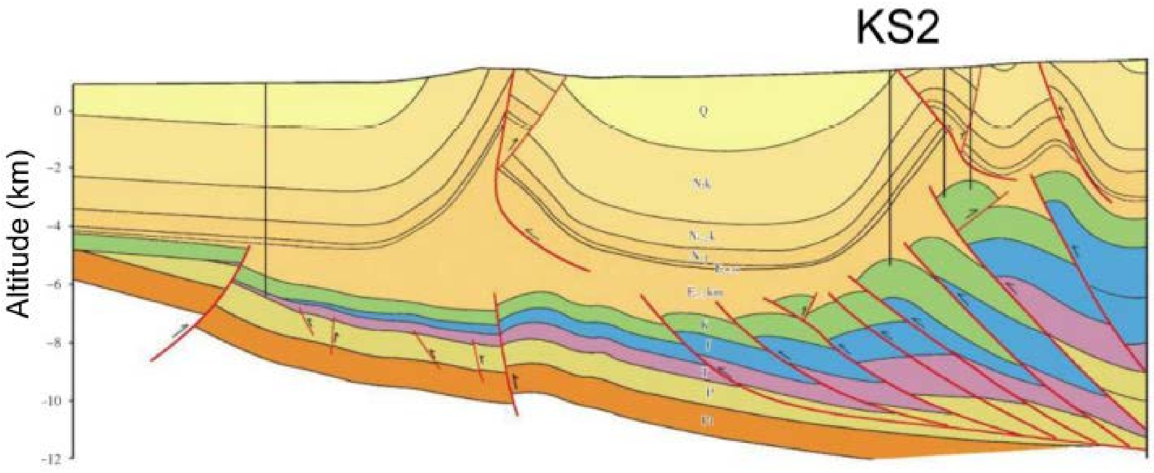
- Fracturing in KS reservoir
  - Deep, tight, HPHT, challenging drilling, etc.

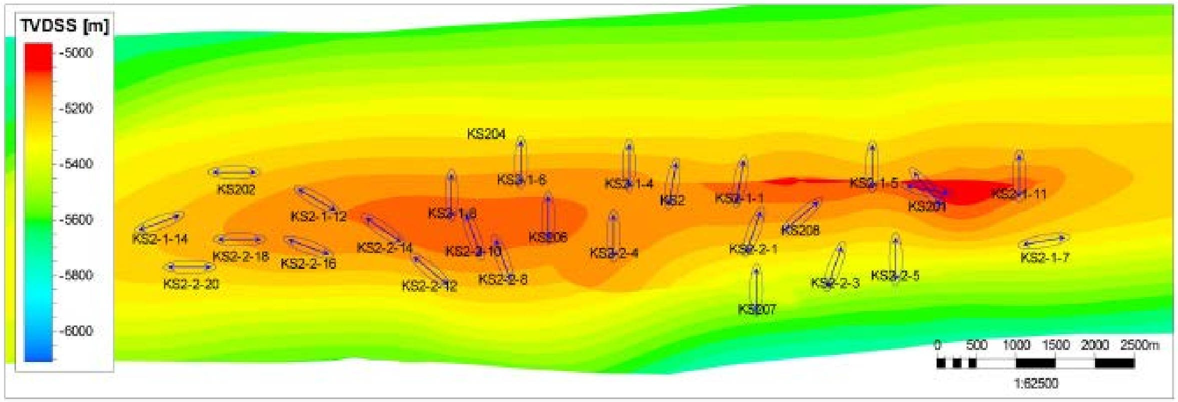
- Designing scaled laboratory tests
  - Is complete similarity possible? (answer: no)
  - A tractable way forward…

- Test results

Motivation: Keshen SS Reservoir

- Large gas reserves
- Tight:
  - 5% porosity
  - 0.01 mD
- Deep with difficult drilling
- HPHT
- Pervasive NF, but stimulation required
- NF and stress orientation varies significantly

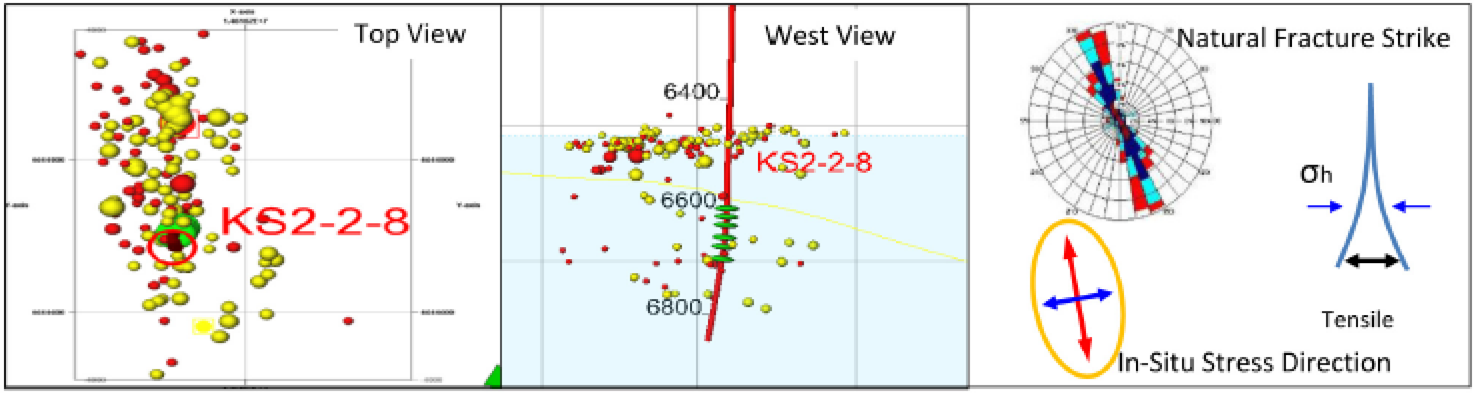




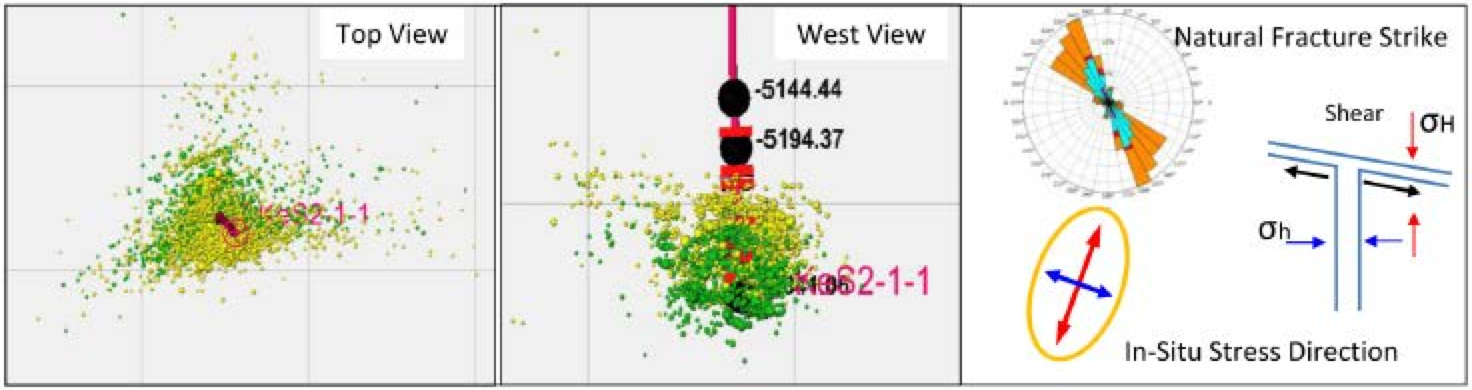
Zhang et al (2015), "A Study of the Interaction Mechanism between Hydraulic Fractures and Natural Fractures in the KS Tight Gas Reservoir," SPE-174384-MS

Motivation: Keshen SS Reservoir

KS2-2-8: events extend 250 m from well



KS2-1-1: most events are <100 m from well



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Designing scaled laboratory tests

For homogeneous, isotropic, impermeable rocks there are six parameters:

	Parameter	Units
1	E'	Pa [$M^1 L^{-1} T^{-2}$]
2	μ	Pa-s [$M^1 L^{-1} T^{-1}$]
3	Q_o	m³/s [$L^{-3} T^{-1}$]
4	t	s [T^{-1}]
5	K_{Ic}	Pa-$\sqrt{\mathrm{m}}$ [$M^1 L^{-0.5} T^{-2}$]
6	σ_3	Pa [$M^1 L^{-1} T^{-2}$]

Buckingham-Pi theorem:

- There are n=6 dimensional parameters
- There are m=3 independent dimensions
- Problem should be reducible to n-m=3 independent dimensionless parameters

Designing scaled laboratory tests

- if fluid lag is neglected then σ_3 can be eliminated by posing problem in terms of net pressure
- μ and Q_o only appear as a product in governing equations, so they can be combined
- Now we have 4-3=1 independent dimensionless parameter (dimensionless toughness)

$$\Pi_1 = K'_{Ic}\left[\frac{t^2}{\mu^5 Q_o^3 E'^{13}}\right]^{\frac{1}{18}}$$

	Parameter	Units
1	E'	Pa [$M^1L^{-1}T^{-2}$]
~~2~~	~~μ~~	~~Pa-s [$M^1L^{-1}T^{-1}$]~~
3	$\boxed{Q_o\mu}$	$\boxed{\text{Pa-m}^3\ [M^1L^2T^{-2}]}$
4	t	s [T^{-1}]
5	K_{Ic}	Pa-$\sqrt{\text{m}}$ [$M^1L^{-0.5}T^{-2}$]
~~6~~	~~σ_3~~	~~Pa [$M^1L^{-1}T^{-2}$]~~

- In principle, full similarity can be attained by choosing μQ_o

Savitski & Detournay (2002), “Propagation of a penny-shaped fluid-driven fracture in an impermeable rock: asymptotic solutions,” Int. J. of Solids and Structures, 39, pg. 6311-6337

What about stress?

For toughness similarity with the same rock:

$$\Pi_1 = K'_{Ic}\left[\frac{t_f^2}{\mu_f^5 Q_{fo}^3 E'^{13}}\right]^{\frac{1}{18}} \quad \rightarrow \frac{\mu_l}{\mu_f} = \frac{t_l}{t_f}\frac{V_{fo}^{3/5}}{V_{lo}^{3/5}} \approx 1 \times 10^3$$

For stress similarity this then requires:

$$\Pi_2 = \sigma_f\left[\frac{t_f}{E'^2\mu'_f}\right]^{1/3} \quad \rightarrow \frac{\sigma_l}{\sigma_f} = \left[\frac{t_f\mu'_l}{t_l\mu'_f}\right]^{1/3} \sim 37$$

Conclusion: if the magnitude of stress is important, then complete similarity is infeasible if using same material. This is common in other domains (Froude number in free-surface flows)

Scaling the HF/NF problem

- A NF with general orientation now results in 15 independent parameters
- 15-3=12 dimensionless parameters
- Complete similarity is nearly hopeless when using real rock
- Focus on most important mechanisms

	Parameter	Symbol	SI Unit	Dimensions
1	Plane strain modulus	E'	Pascal	$M^1L^{-1}T^{-2}$
2	Viscosity-Rate	μQ_o	Pa-m^3	$M^1L^2T^{-2}$
3	Rock fracture toughness	K_{IC}	Pascal-$\sqrt{m}$	$M^1L^{-0.5}T^{-2}$
4	Minimum horizontal stress	σ_h	Pascal	$M^1L^{-1}T^{-2}$
5	Maximum horizontal stress	σ_H	Pascal	$M^1L^{-1}T^{-2}$
6	Vertical principal stress	σ_V	Pascal	$M^1L^{-1}T^{-2}$
7	Pore pressure	P_p	Pascal	$M^1L^{-1}T^{-2}$
8	Natural fracture Biot coefficient	α	Dimensionless	$M^0L^0T^0$
9	Natural fracture azimuth	β	Dimensionless	$M^0L^0T^0$
10	Natural fracture dip	ϕ	Dimensionless	$M^0L^0T^0$
11	Interface mode-I fracture toughness	K_{IC}^{NF}	Pascal-$\sqrt{m}$	$M^1L^{-0.5}T^{-2}$
12	Interface mode-II fracture toughness	K_{IIC}^{NF}	Pascal-$\sqrt{m}$	$M^1L^{-0.5}T^{-2}$
13	Interface friction coefficient	λ	Dimensionless	$M^0L^0T^0$
14	Interface hydraulic conductivity	k_{NF}	Cubic meter	$M^0L^3T^0$
15	Time	t	Second	$M^0L^0T^1$

Simplified NF/HF parameter set

Some have used a normalized stress contrast of $\frac{\sigma_H - \sigma_h}{\sigma_h}$

This neglects importance of net pressure

Define a net normal stress on a NF: $\sigma_{net} = \sigma_{N,NF} - \sigma_h$

$$\Pi_2 = \frac{\sigma_{net}}{P_{net}}$$

For large stress anisotropy, or small P_{net}:

$\Pi_2 \gg 1$ opening of fracture not possible

For small stress anisotropy, or large P_{net}:

$\Pi_2 \ll 1$ fracture is likely to open and follow NF

Simplified NF/HF parameter set

Define the critical shear stress, normalize by P_{net}:

$$\tau_c = \lambda \sigma'_{N,NF} \qquad \rightarrow \Pi_3 = \frac{\tau_c}{P_{net}}$$

Is a function of σ_V, σ_H, σ_h, λ, strike and dip of NF, P_p, and Biot coefficient.

For “small” values of Π_3 shearing of NF is likely

For “large” values of Π_3 shearing of NF is unlikely

Meaning of “small” and “large” needs to be determine experimentally

Simplified NF/HF parameter set

For hydraulically open NF, conductivity is important

$$\Pi_4 = \frac{k_{NF}}{w^3}$$

aperture

For a viscosity-dominated model this equates to

$$\Pi_4 = k_{NF}\left[\frac{E'^2}{\mu'^2 t Q_o^3}\right]^{1/9}$$

Means that NF should have much lower conductivity in lab than in field!

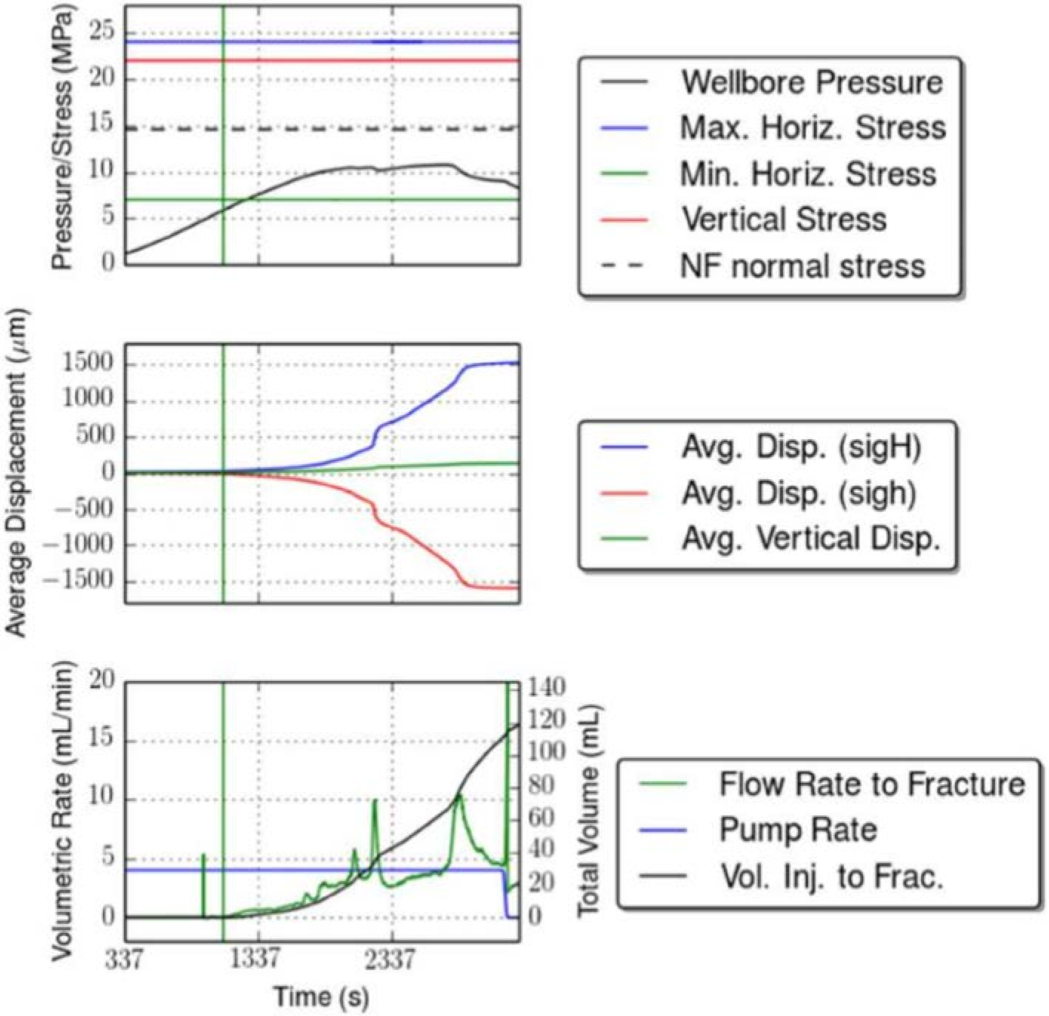
Block test design

Dimensionless parameter	KS2-1-1	Recommended medium-block test
Natural fracture azimuth (β)	40°	40°
NF dip (ϕ)	75°	75°
Dimensionless toughness (Π_1)	0.5	1.75
Dimensionless natural fracture closure stress (Π_2)	1.5	1.55
Dimensionless natural fracture shear resistance (Π_3)	2.4	1.86
Dimensionless natural fracture conductivity (Π_4)	9.6×10^{-13}	9×10^{-8}

Yang, Burghardt et al (2016), “Experimental Study of Hydraulic Fracture/Natural Fracture Interaction on a Tight Sandstone Formation,” URTec: 2460449

Zhang et al (2015), “A Study of the Interaction Mechanism between Hydraulic Fractures and Natural Fractures in the KS Tight Gas Reservoir,” SPE-174384-MS

Test results



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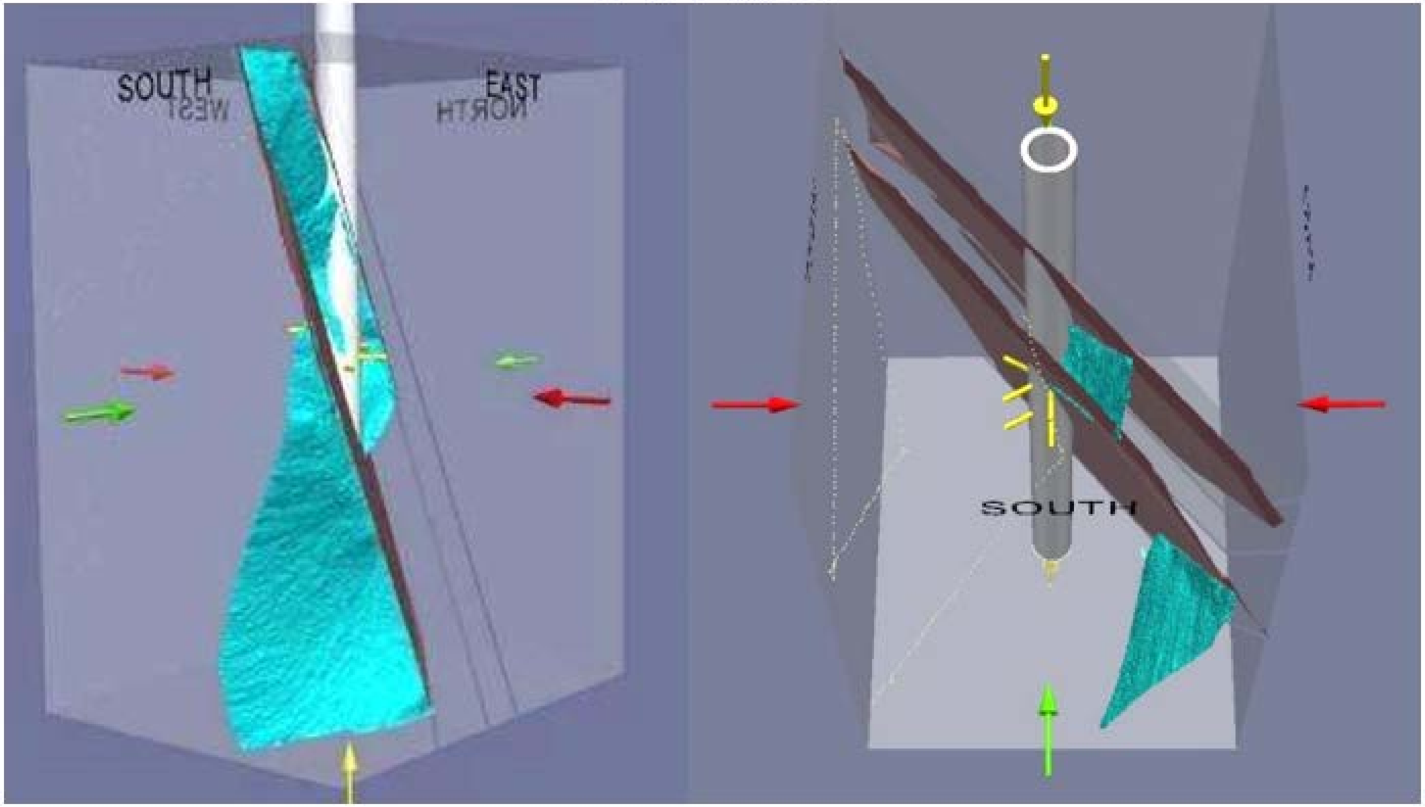
Test results

TEST MB-5



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