Using scaling laws and hydraulic fracturing simulations to design and interpret block test experiments for future field extrapolation

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Outline

1. **Review of few key lab experiments**
2. **Scaling for point- and borehole-wellbore**
3. **Impact of completion design on multi-stage fracturing:**
    - Design strategy
    - Experimental setup
    - Multi-cluster single stage experimental design and observations
    - Multi-perforation single-cluster experimental design and observations
4. **Observations and discussions**

Based on:

- **2017 ARMA Hydraulic Fracturing Workshop "On the role of laboratory experiments to validate hydraulic fracturing simulators"**
- **ARMA-2017-0404 on "2D Experimental and Numerical Results for Hydraulic Fractures Interacting With Orthogonal and Inclined Discontinuities"**
- **ARMA 21-1309 on "Understanding the Impact of Completion Designs on Multi-Stage Fracturing via Block Test Experiments"**

ARMA

On the role of laboratory experiments to validate hydraulic fracturing simulators

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(2) University of Pittsburgh, Pittsburgh, USA

2017 ARMA Hydraulic Fracturing Workshop

ARMA 17-404

2D Experimental and Numerical Results for Hydraulic Fractures Interacting With Orthogonal and Inclined Discontinuities

Kear, J., Kasperczyk, D. and Zhang X.
CSIRO Clayton, Victoria, Australia
Jeffrey, R. G.
SCT Operations Pty Ltd
Chuprakov, D.
Schlumberger Moscow Research, Moscow, Russian Federation
Prioul, R.
Schlumberger-Doll Research, Cambridge, Massachusetts, USA

ARMA 21-1309

Understanding the impact of completion designs on multi-stage fracturing via block test experiments

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Review of (some) key lab experiments over last 20 y

Increasing fracture and material complexity

More parameters to control and measure

- The importance of scaling hydraulic fracture experiments: lab ↔ field [1]
- Planar and non-planar fractures and artificial materials (PMMA, Glass, Cement):
  - Validation of tip asymptotics for fluid-driven cracks [CSIRO exp. + UMN] [2]
  - Hydraulic fracture height growth through stress contrasts [CSIRO exp. + SLB] [3,4]
  - Radial fracture initiation and propagation from a borehole [Delft + CSIRO exp. + SLB] [5]
  - Saucer-shaped (axi-symmetric) hydraulic fractures [CSIRO exp. + UMN] [6]
- Network of "planar" fractures and real rock materials (Sandstone, Limestone, Shale)
  - HF interacting with frictional discontinuities [Sandia, Delft, CSIRO, TerraTek exp.] [7,8]
  - HF interacting with discontinuities and laminated medium [TerraTek exp. + SLB] [9]
- 3D fractures in various materials (artificial and rock)
  - 3D fracture initiation and propagation [CSIRO and Delft]

[1] **Bunger, Jeffrey, and Detournay**, 2005. Application of Scaling Laws to Laboratory-Scale Hydraulic Fractures, 40th US Rock Mechanics Symposium, Alaska

[2] **Bunger and Detournay,** 2008. Experimental Validation of the Tip Asymptotics for a Fluid-Driven Fracture, Journal of the Mechanics and Physics of Solids, vol.56, no.11, pp. 3101-3115

[3] **Wu, Bunger, Jeffrey and Siebrits**, 2008. A comparison of numerical and experimental results of hydraulic fracture growth into a zone of lower confining stress, ARMA-08-267

[4] **Jeffrey and Bunger**, 2009. A detailed comparison of experimental and numerical data on hydraulic fracture height growth through stress contrasts. Soc. Pet. Eng. J., 14(3):413–422, 2009

[5] **Lecampion, Desroches, Jeffrey, Bunger**, 2016. Experiments versus theory for the initiation and propagation of radial hydraulic fractures in low permeability materials, JGR

[6] **Bunger, Gordeliy, and Detournay**, 2013. Comparison between laboratory experiments and coupled simulations of saucer-shaped hydraulic fractures in homogeneous brittle-elastic solids, J.Mech. Phys. Solids, 61(7):1636–1654

[7] **Chuprakov, Melchaeva and Prioul,** 2014, Injection-sensitive mechanics of hydraulic fracture interaction with discontinuities, Rock Mechanics Rock Engineering, 47 (5), 1625-1640.

[8] **Kear, Kasperczyk, Zhang, Jeffrey, Chuprakov, and Prioul**, 2017. 2D Experimental and Numerical Results for Hydraulic Fractures Interacting With Orthogonal and Inclined Discontinuities, ARMA 2017, San Francisco

[9] **Burghart, Desroches, Lecampion, Stanchits, Surdi, Whitney, Houston**, 2015, Laboratory study of the effect of well orientation, completion design, and rock fabric on near-wellbore hydraulic fracture geometry in shales, ISRM13

Review of (some) key lab experiments over last 20 y

Increasing fracture and material complexity

- The importance of scaling hydraulic fracture experiments: lab ↔ field [1]
- Planar and non-planar fractures and artificial materials (PMMA, Glass, Cement):

What we learned:
- ✓ Excellent match experiments-models
- ✓ Hydraulic fracturing mechanics theory works
- ✓ If material homogeneous and geometry of fracture known and simple

- Network of "planar" fractures and real rock materials (Sandstone, Limestone, Shale)
  - ✓ Experiments and models matches partially or in some cases only
  - ✓ Many parameters can't be measured and models are too simple
- 3D fractures in various materials (artificial and rock)
  - ✓ No successful comparison experiment-model for 3D non-planar fractures

More parameters to control and measure

[1] **Bunger, Jeffrey, and Detournay**, 2005. Application of Scaling Laws to Laboratory-Scale Hydraulic Fractures, 40th US Rock Mechanics Symposium, Alaska

[2] **Bunger and Detournay,** 2008. Experimental Validation of the Tip Asymptotics for a Fluid-Driven Fracture, Journal of the Mechanics and Physics of Solids, vol.56, no.11, pp. 3101-3115

[3] **Wu, Bunger, Jeffrey and Siebrits**, 2008. A comparison of numerical and experimental results of hydraulic fracture growth into a zone of lower confining stress, ARMA-08-267

[4] **Jeffrey and Bunger**, 2009. A detailed comparison of experimental and numerical data on hydraulic fracture height growth through stress contrasts. Soc. Pet. Eng. J., 14(3):413–422, 2009

[5] **Lecampion, Desroches, Jeffrey, Bunger**, 2016. Experiments versus theory for the initiation and propagation of radial hydraulic fractures in low permeability materials, JGR

[6] **Bunger, Gordeliy, and Detournay**, 2013. Comparison between laboratory experiments and coupled simulations of saucer-shaped hydraulic fractures in homogeneous brittle-elastic solids, J.Mech. Phys. Solids, 61(7):1636–1654

[7] **Chuprakov, Melchaeva and Prioul,** 2014, Injection-sensitive mechanics of hydraulic fracture interaction with discontinuities, Rock Mechanics Rock Engineering, 47 (5), 1625-1640.

[8] **Kear, Kasperczyk, Zhang, Jeffrey, Chuprakov, and Prioul**, 2017. 2D Experimental and Numerical Results for Hydraulic Fractures Interacting With Orthogonal and Inclined Discontinuities, ARMA 2017, San Francisco

[9] **Burghart, Desroches, Lecampion, Stanchits, Surdi, Whitney, Houston**, 2015, Laboratory study of the effect of well orientation, completion design, and rock fabric on near-wellbore hydraulic fracture geometry in shales, ISRM13

Application of Scaling Laws to Laboratory-Scale Hydraulic Fractures and validation of tip-asymptotics and HF regimes

- Energy dissipation during fluid-driven fractures (multi-scale tip asymptotics):
  - Breaking material bond ahead of tip → Toughness-dominated regime (K) → LEFM
  - Flow of viscous fluid → Viscosity-dominated regime (M, Desroches et al, 1994)

$w \sim s^{1/2}$

$w \sim s^{2/3}$

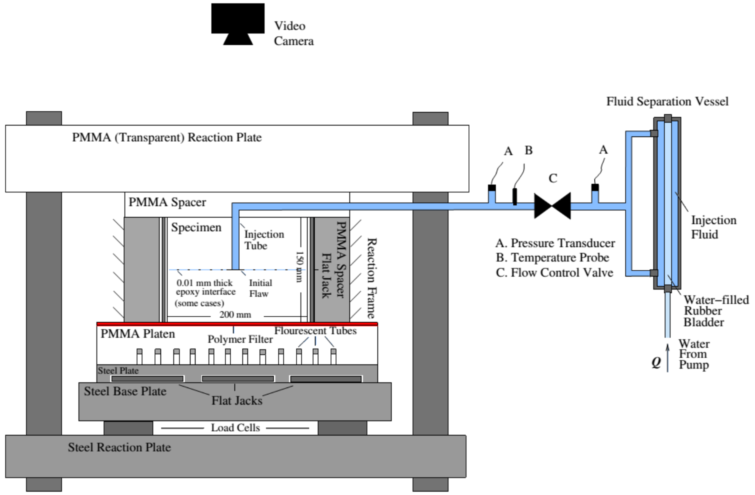
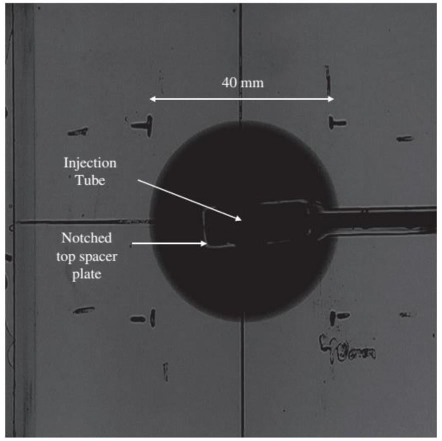
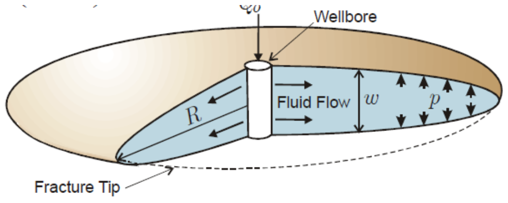
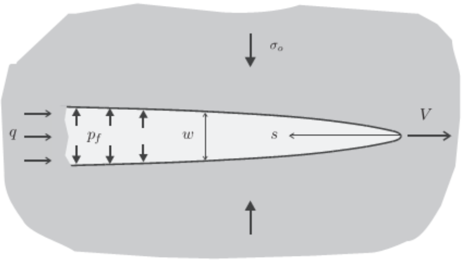


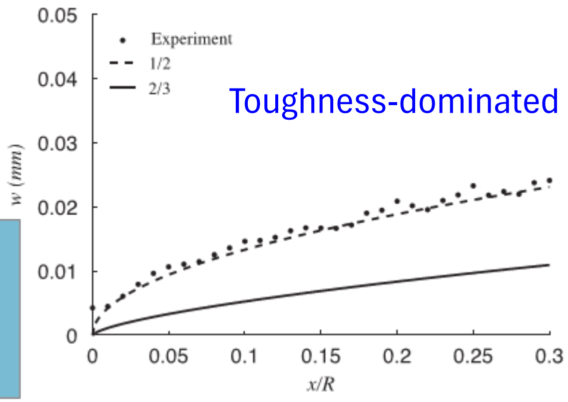
Fig. 3. Cross-sectional diagram of the setup for the laboratory experiments.

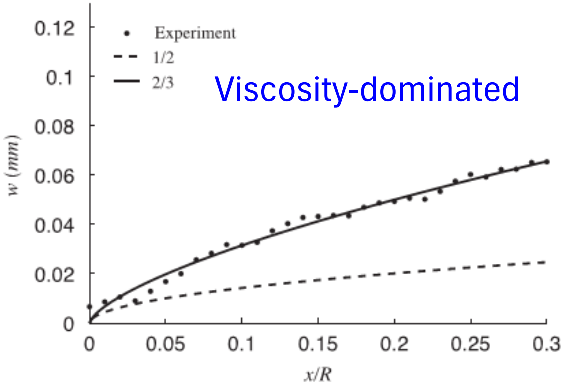






- Experiments in PMMA (8 exp) & Glass (3 exp) with glucose & glycerin
- Full-field crack opening measured using a photometric technique
- Known parameters: K_{IC}, E’, m, Q_0, s_0



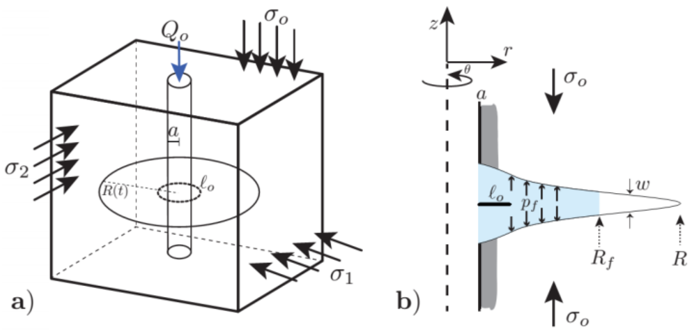


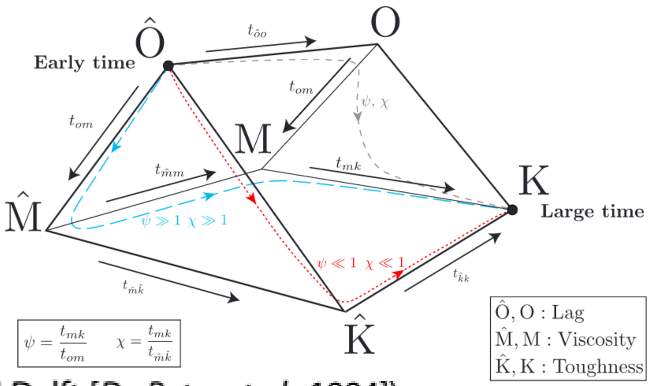
✓ HF mechanics theory works!
✓ Regime important to scale lab exp
✓ Other regimes: leakoff, lag…

Bunger, Jeffrey, and Detournay, 2005. Application of Scaling Laws to Laboratory-Scale Hydraulic Fractures, 40th US Rock Mechanics Symposium, Alaska

Bunger and Detournay, 2008. Experimental Validation of the Tip Asymptotics for a Fluid-Driven Fracture, Journal of the Mechanics and Physics of Solids, vol.56, no.11, pp. 3101-3115

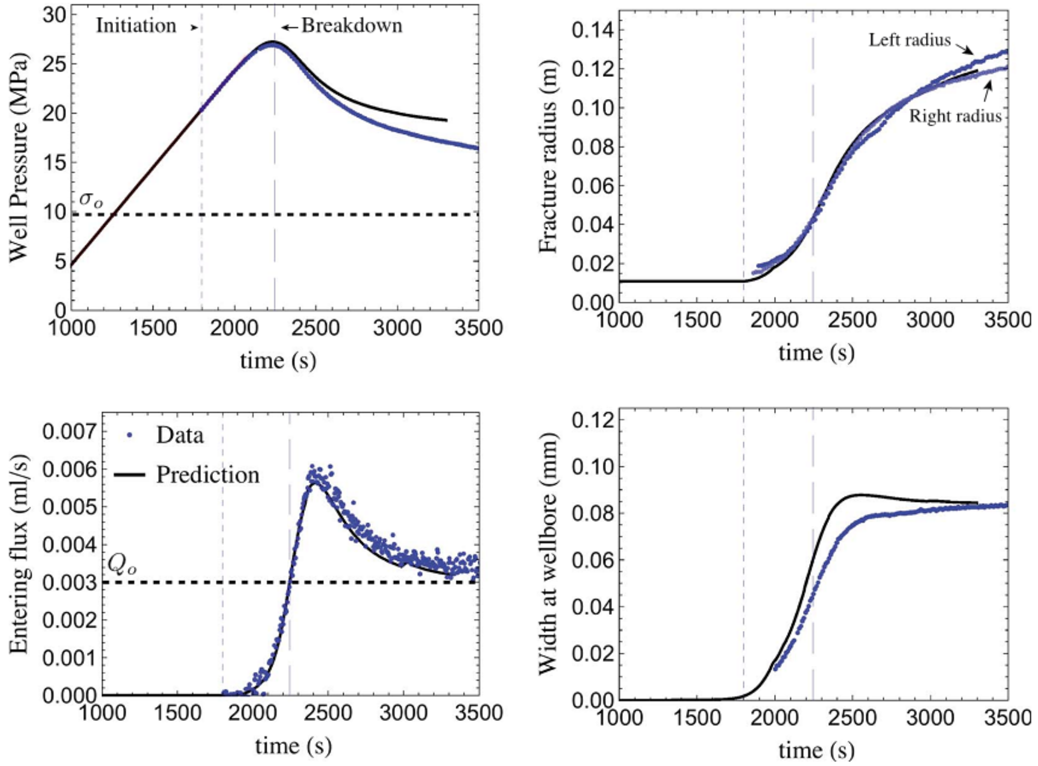
Radial fracture initiation & propagation from borehole





- Early time: Ô-M̂-K̂ face
  - Near-wellbore injection transient
  - Fluid lag/compressibility dominated
- Late time: O-M-K face
  - Constant injection rate propagation
  - Toughness dominated

COV21c experiment (performed at TU Delft [*De Pater et al.*, 1994])



- ✓ Initiation pressure ≤ max pressure (aka breakdown):
  - Due to compressibility and viscosity/rate effects (observed Weijers, 1995, Zhao, 1995…)
- ✓ Breakdown pressure (a misnomer): related to injection transient
- ✓ HF mechanics works for simple geometry!
- ✓ We see again how important the fluid part is to understand the mechanics of HF

Lecampion, Desroches, Jeffrey, Bunger, 2016. Experiments versus theory for the initiation and propagation of radial hydraulic fractures in low permeability materials, JGR

Dimensionless Parameters and Characteristic Timescales

- **Radial fracture from a point source – most likely early-stage geometry (Bunger *et al.*, 2005)**
  - Viscosity $M = \left(\frac{t_m}{t}\right)^{2/5}, \quad t_m = \left(\frac{\mu'^5 Q_o^3 E'^{13}}{K'^{18}}\right)^{1/2}$
  - Stress/Lag $S = \left(\frac{t}{t_o}\right)^{1/5}, \quad t_o = \frac{K'^6}{\sigma_o^5 E' Q_o}$
  - Leak-off $C = \left(\frac{t}{t_c}\right)^{3/10}, \quad t_c = \left(\frac{K'^4 Q_o}{C'^5 E'^4}\right)^{2/3}$
  - Characteristic time for fracture radius to reach R_{max}: $t_{\max} = \frac{R_{\max}^{5/2} K'}{Q_o E'}$

In the tight fields:

M – large: viscosity dominated

S – large: no lag, small $t_o \sim 10^{-4}$ s

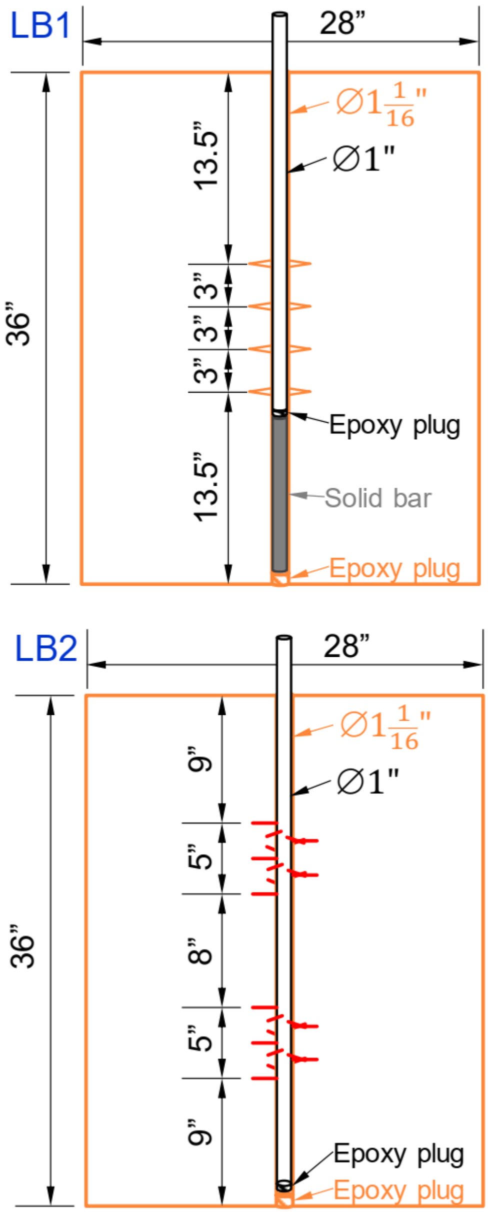
C – small: little leak-off, Large $t_c \sim 10^6$ s

- **Borehole source with compliance U (Lecampion *et al.*, 2017)**
  - Transient flow $t_{\text{lag}} = \frac{E'^2 \mu'}{\sigma_o^3}, \quad t_U = \frac{E'^{5/2} U^{1/2} \mu'}{K'^3}$

$$\psi = t_m / t_{\text{lag}}, \quad \chi = t_m / t_U$$

How to study impact of completion design on multi-stage fracturing in the lab for field purposes?

- **Initiation and propagation of multiple hydraulic fractures from perforation clusters in a single stage**
  - Simultaneous growth, cluster efficiency
  - Complex network vs. localized growth
  - Near-wellbore tortuosity
  - Effect of stage geometry, fluid rate, and viscosity
  - Effect of perforations
  - Interaction with bedding planes, joints, and natural fractures
- **Large Block hydraulic fracturing tests to study fracture patterns**
  - Far-field fracture geometry for multi-cluster one stage – LB1
  - Near-wellbore complexity from individual perforations in a single cluster – LB2



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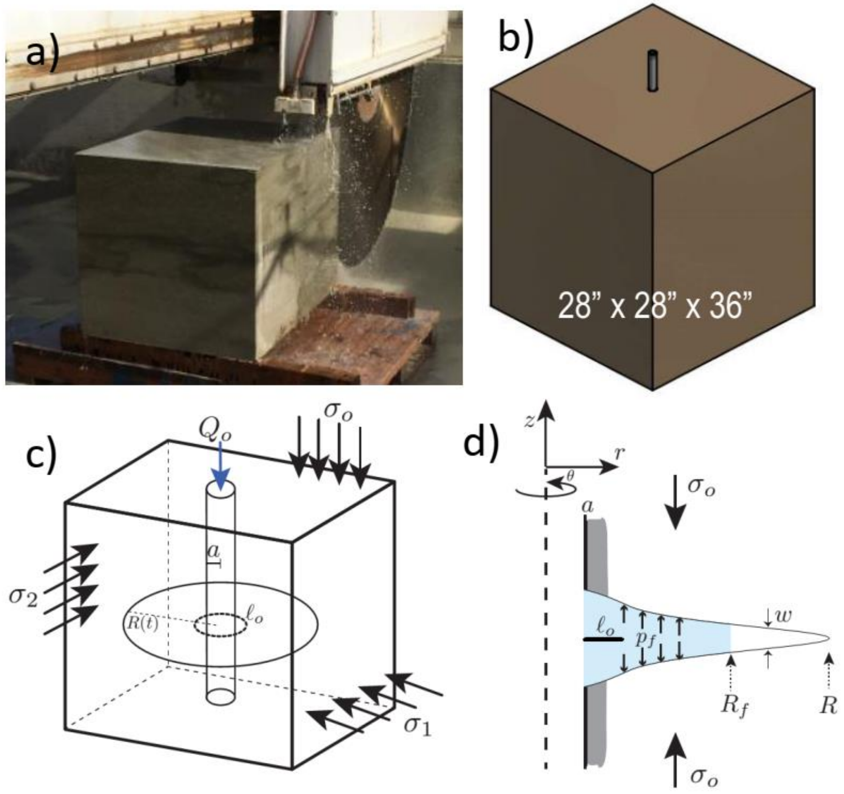
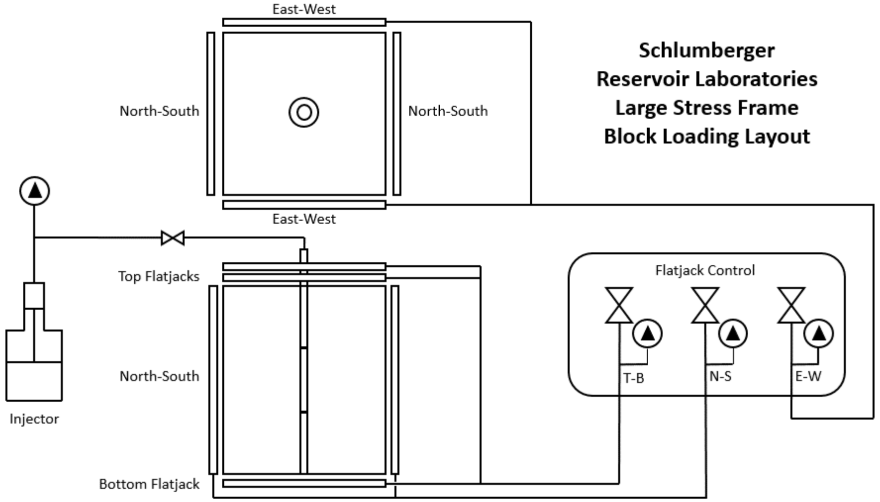
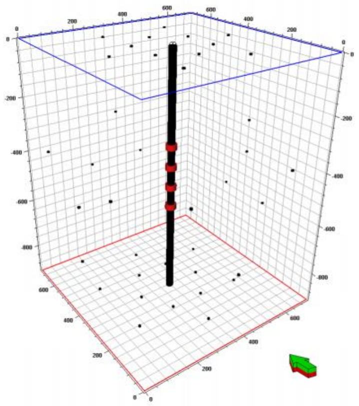
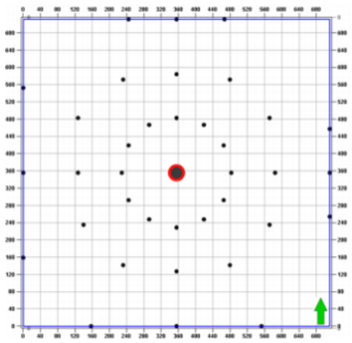
Experimental setup









	Field Scale	LB1	LB2
E_H(GPa)	30	17.55	23.2
ν_H	0.22	0.24	0.22
K_{Ic} $(MPa.m^{1/2})$	1.5-2.21	2.21	1.87
Porosity (%)		9.16	10.94
Permeability (mD)		0.1	0.443

- Polyaxial stress frame (sample 28 × 28 × 36")
- Three independent stresses applied by flatjacks, $\sigma_3' \le \sigma_2' \le \sigma_1' \le 40$ Mpa
- Wellbore fluid injection: viscosity $\mu = 1 - 2.5\times10^6$ cp, rate $Q = 1 - 3{,}000$ mL/min, pressure $p \le 70$ Mpa
- Acoustic emission monitoring (38 sensors)

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Design of field-to-lab parameters using scaling analyis

- **Balance between various physics – HF propagation regime:**
  - Lab experiment must reproduce propagation regime in the field using proper scaling of the parameters and test conditions need to be as close all possible to field conditions

- **Scaling of stress conditions**

$$(\sigma'_H/\sigma'_V)_{lab} = (\sigma'_H/\sigma'_V)_{field} \qquad (\sigma'_h/\sigma'_V)_{lab} = (\sigma'_h/\sigma'_V)_{field}$$

$$R = (\sigma_H - \sigma_h)/(\sigma_V - \sigma_h) = 0.32$$

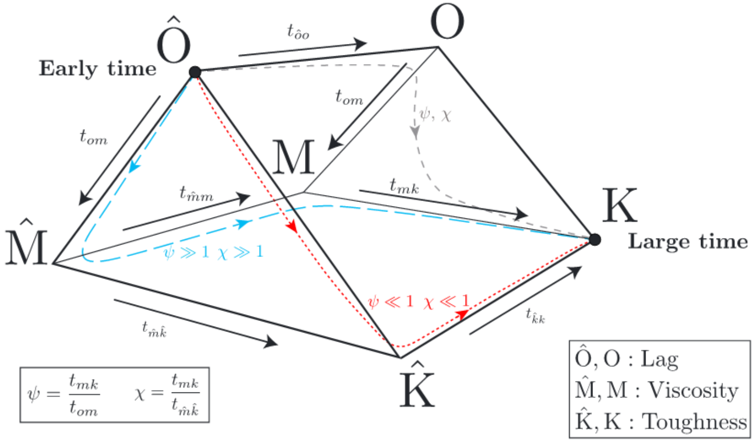
	Field Scale				Lab Scale			
σ_V	68	MPa	9863	psi	34	MPa	4931	psi
σ_H	51	MPa	7397	psi	19.55	MPa	2835	psi
σ_h	43	MPa	6237	psi	12.75	MPa	1849	psi
P_p	28	MPa	4061	psi	0	MPa	0	psi
σ'_V	40	MPa	5801	psi	34	MPa	4931	psi
σ'_H	23	MPa	3336	psi	19.55	MPa	2835	psi
σ'_h	15	MPa	2176	psi	12.75	MPa	1849	psi
R	0.32	-	0.32	-	0.32	-	0.32	-

- **Scaling of viscosity and injection rate - point-source:**
  - Matching dimensionless viscosity, M, between field and lab at characteristic "field" and "lab" propagation times (t_{field} and t_{lab}) leads to the viscosity-rate relation (lab viscosity ~1,000 times greater than field):

$$\mu_l Q_l = \mu_f Q_f \left(\frac{E'_f}{E'_l}\right)^3 \left(\frac{K_l}{K_f}\right)^4 \left(\frac{R_{l\,max}}{R_{f\,max}}\right) \qquad t_{max} = \frac{R_{max}^{5/2} K'}{Q_o E'}$$

- Scaling of viscosity and injection rate: borehole-source

$$\psi \gg 1 \qquad \chi \gg 1$$



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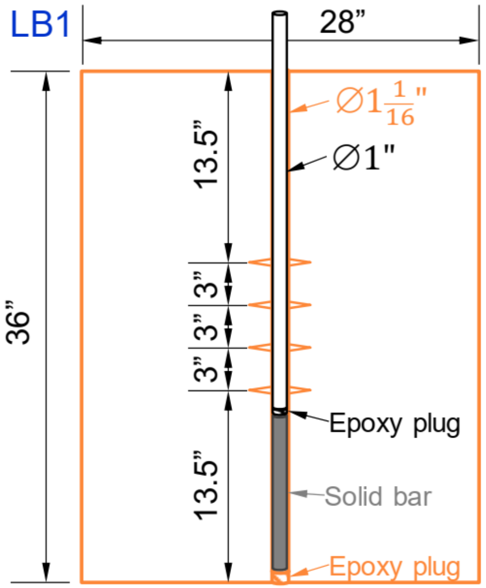
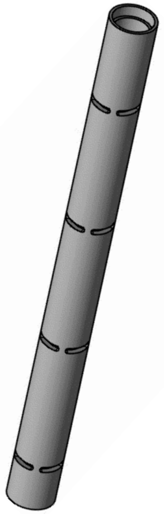
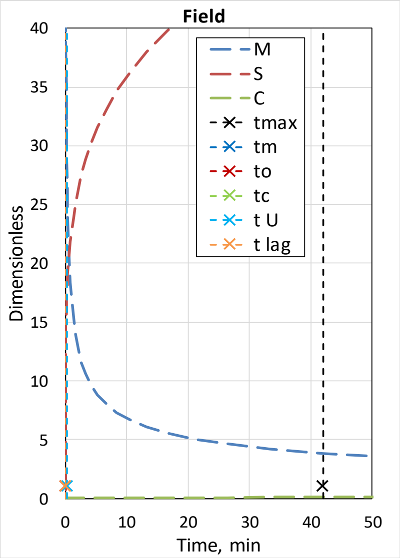
LB-1 – multi-stage cluster

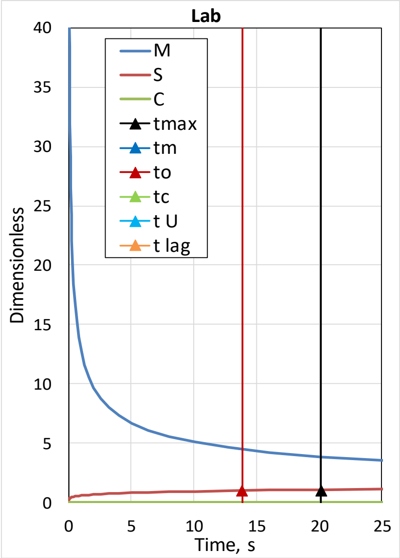


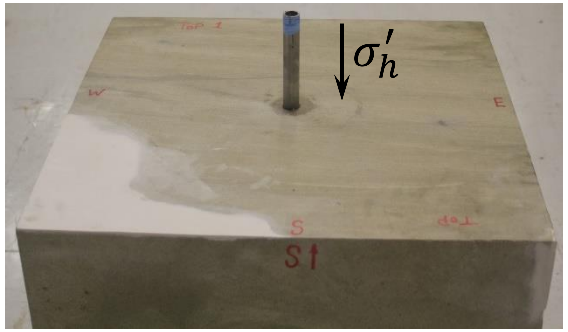


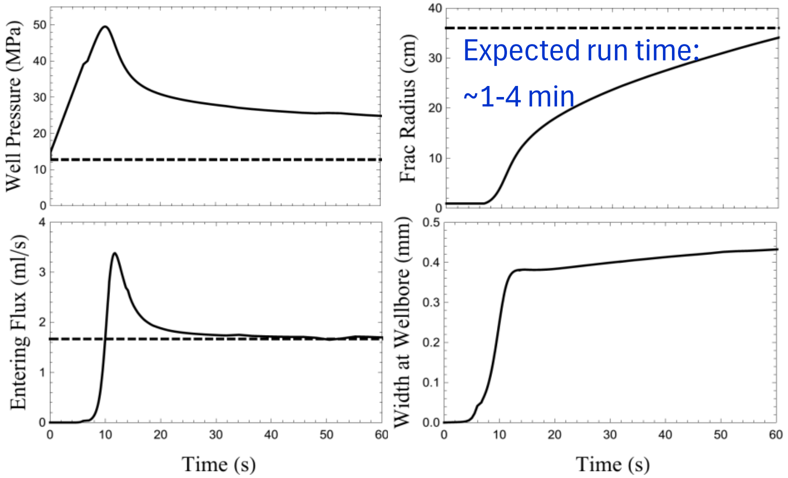
	Field scale		Lab scale LB1	
Propagation characteristics				
R_{max}	233 $\sim$ 765	m ft	35.56 14	cm in
t_{max}	2, 517 $\sim$ 42	s min	20 1/3	s min
Fluid & Pumping				
Q	3 19	m^3/min bbl/min	85 5.3×10^{-4}	mL/min bbl/min
μ	25	cp	30, 768	cp
U	1.67	m^3/GPa	0.41	mL/MPa
C_l	2.45×10^{-6}	$m/\sqrt{s}$	2.45×10^{-7}	$m/\sqrt{s}$
Characteristic dimensions				
Radius a	7.62	cm	1.35	cm
Notch l_o	30.48	cm	1.9	cm

	Field scale	Lab scale LB1	Unit
ψ	8.2×10^5	9.4	-
χ	3, 689	18.3	-









- Dimensionless viscosity M can be match between field and lab but S difficult to match

$$\psi \gg 1 \qquad \chi \gg 1$$

- Q and μ needs to be chosen based on M matching and observation time
- HF simulation for one cluster very useful to give an indication of initiation/breakdown pressure, entering fluxes, width and observation time

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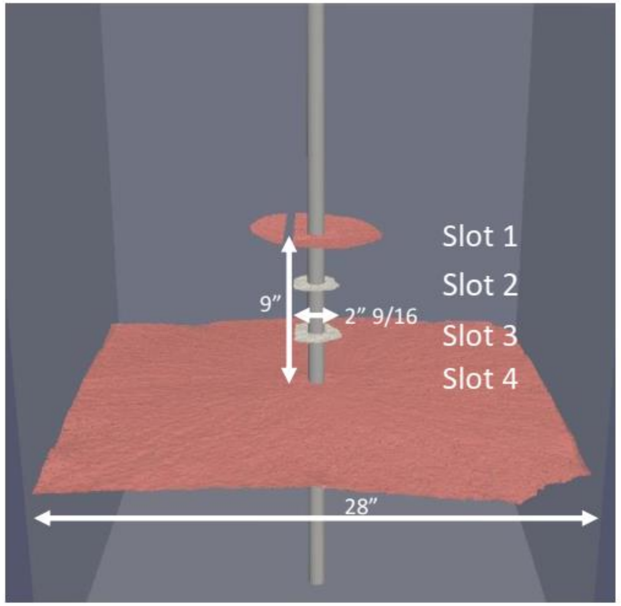
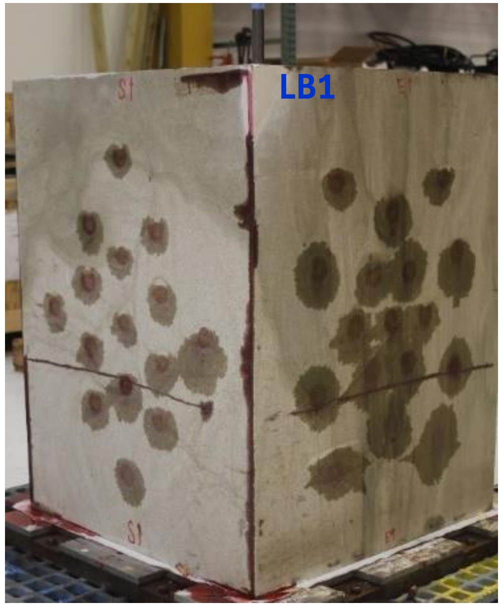
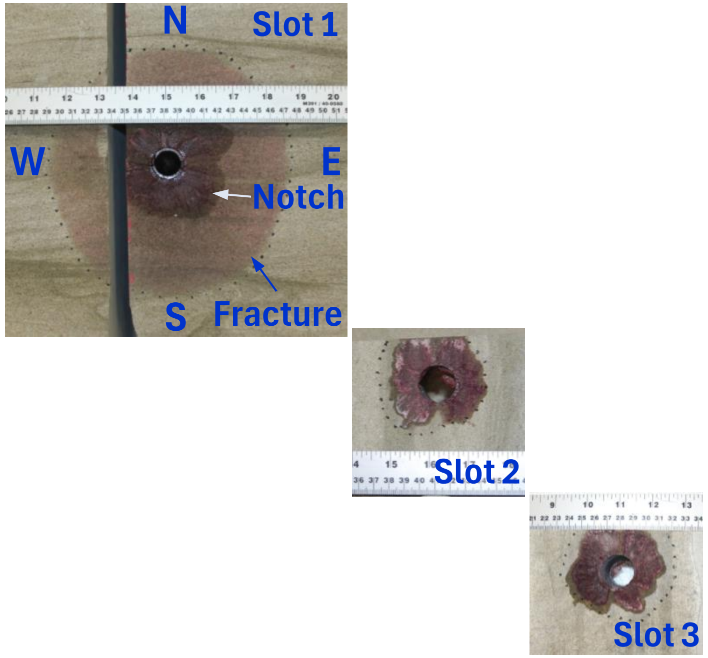
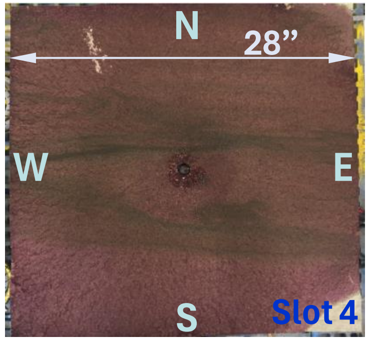
LB-1 – Test Results

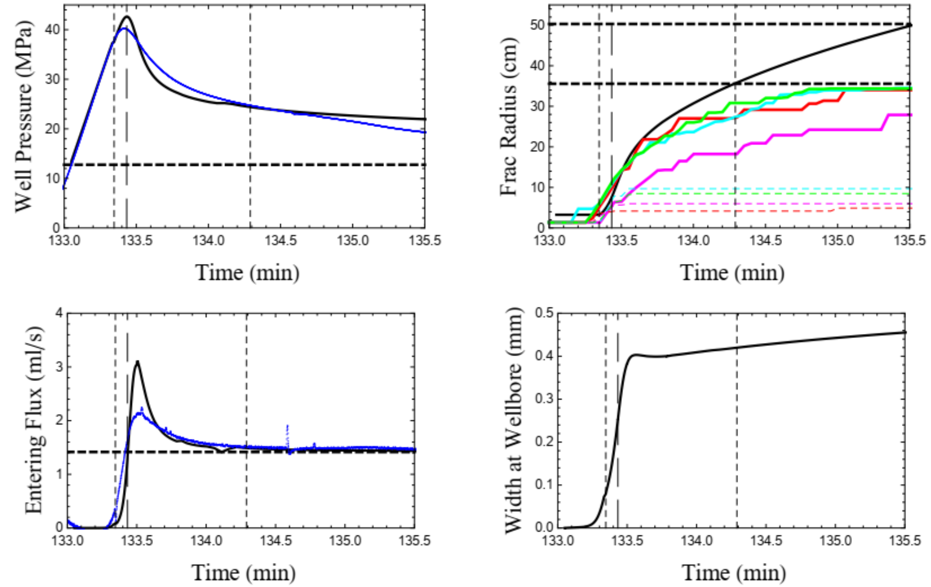








- Slot 1 frac ~ 4" radius
- Slots 2 & 3, fracs did not initiate
- Slot 4 frac ~ entire cross-section



	Test	Model
Frac Initiation p_i, MPa	30.05	37.61
Breakdown p_b, MPa	40.23	42.64
Time: Init – Edge, s	87	55

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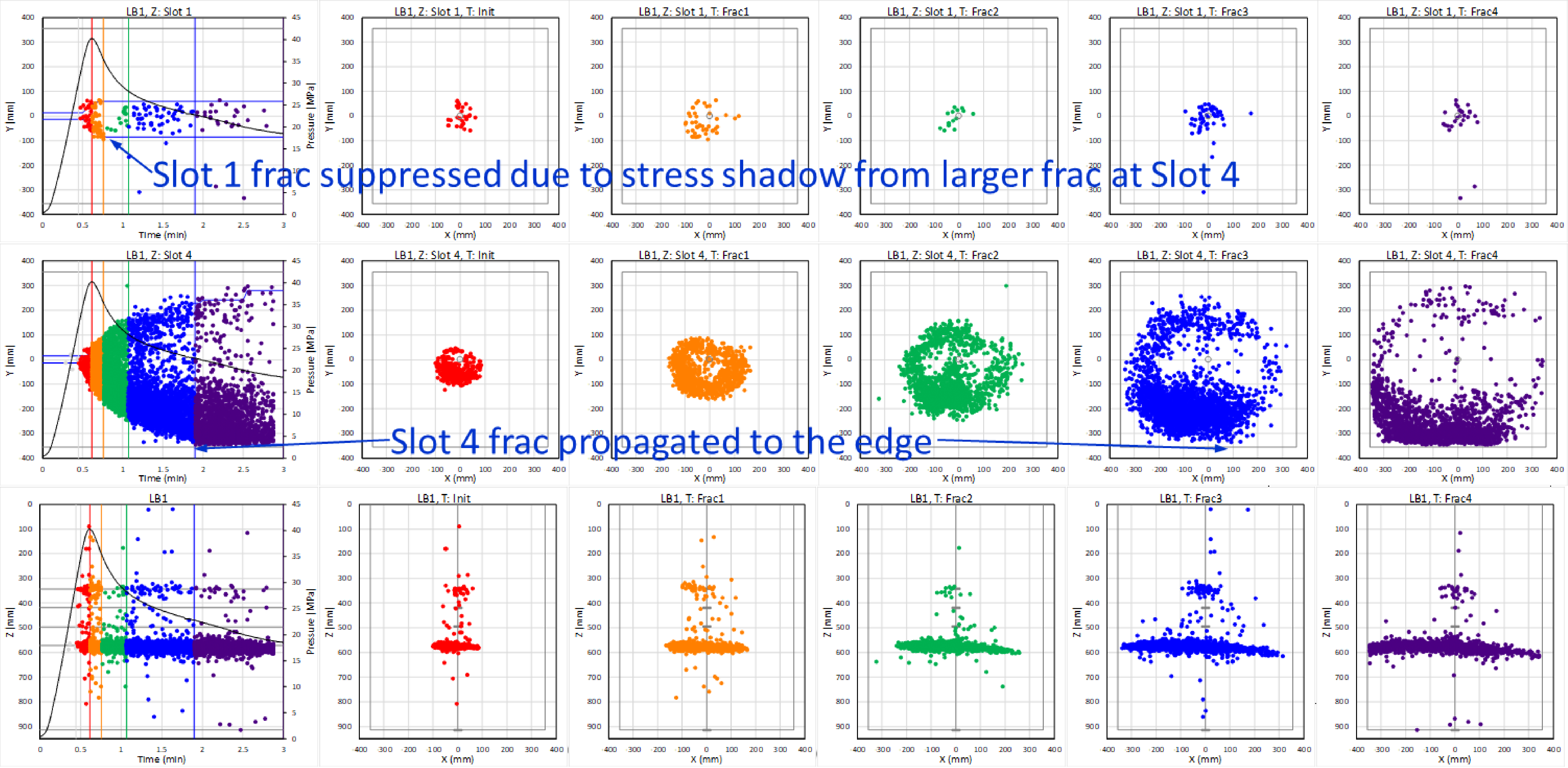
LB-1 – Acoustic Emissions



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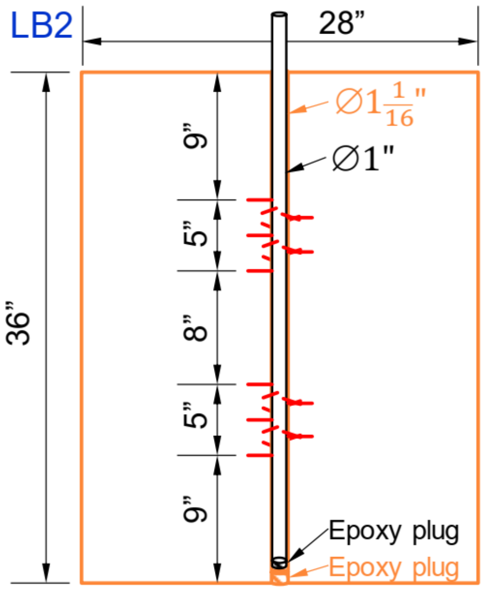
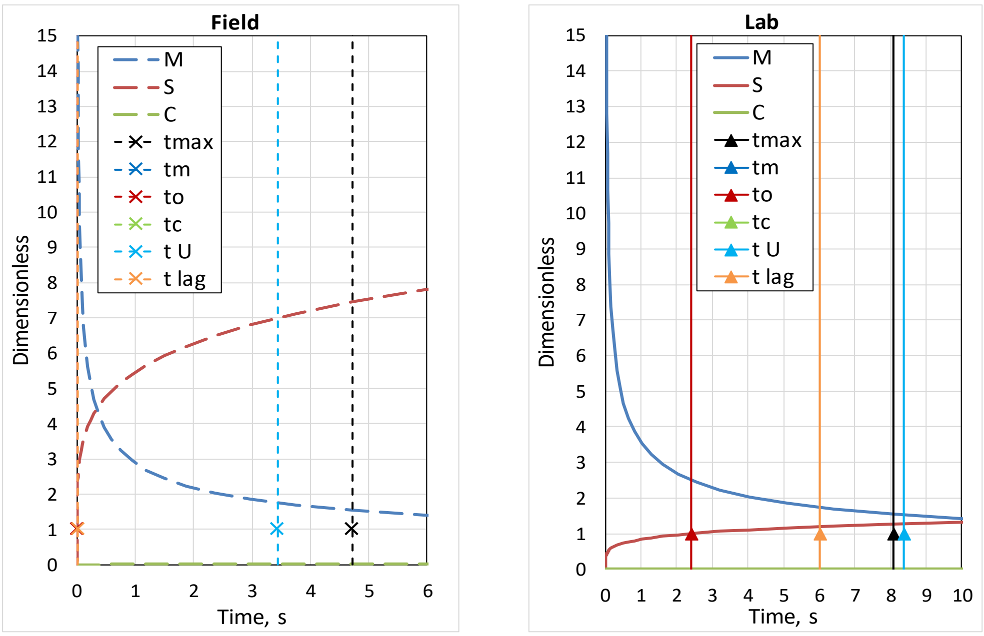
LB-2 – Individual perforations in a single cluster – 2 stages



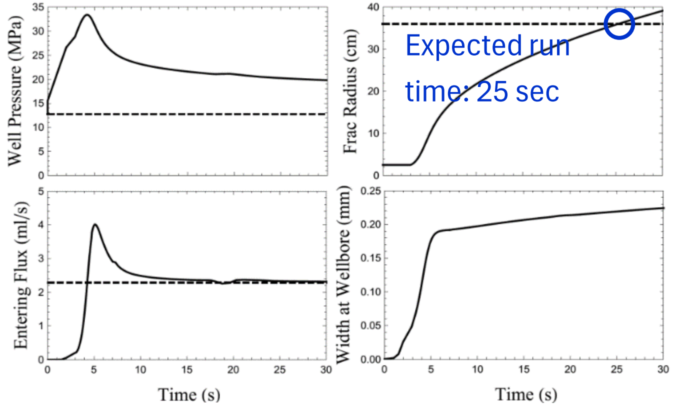
	Field scale		Lab scale LB2	
Propagation characteristics				
R_{max}	12.27 ~ 40	m ft	35.56 14	cm in
t^{top}_{max} t^{bot}_{max}	4.7 9.4	s s	8 16	s s
Fluid & Pumping				
Q^{top} Q^{bot}	1.5 0.75	m^3/min m^3/min	137 69	mL/min mL/min
μ^{top} μ^{bot}	5 5	cp cp	1,758 1,745	cp cp
U	13	m^3/GPa	0.41	mL/MPa
C_l	2.45×10^{-6}	$m/\sqrt{s}$	2.45×10^{-7}	$m/\sqrt{s}$
Characteristic dimensions				
Radius a	7.62	cm	1.35	cm
Perf depth l_p	30.48	cm	2.54	cm

	Field scale		Lab scale LB2	
Q	1.5 m^3/min	0.75 m^3/min	137 mL/min	69 mL/min
ψ	796	281	4	1.4
χ	4.1	1.45	4.1	1.45

LB2 Top Stage Design



- 2 stages with different injection rates
- 13 Perforations (60° phased) per stage, sand-jetted through holes in casing
- Packer system to isolate stages



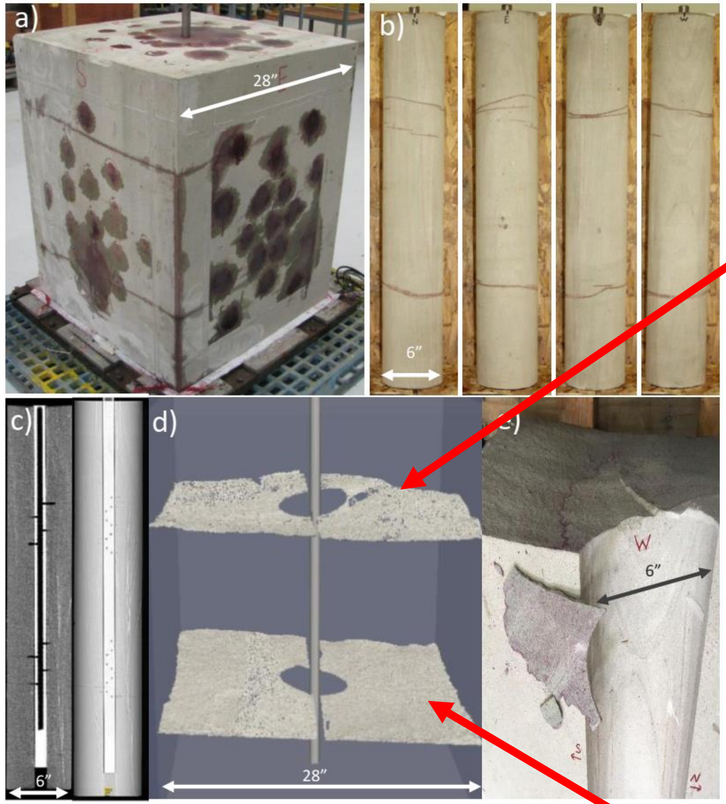
- Dimensionless viscosity M can be match

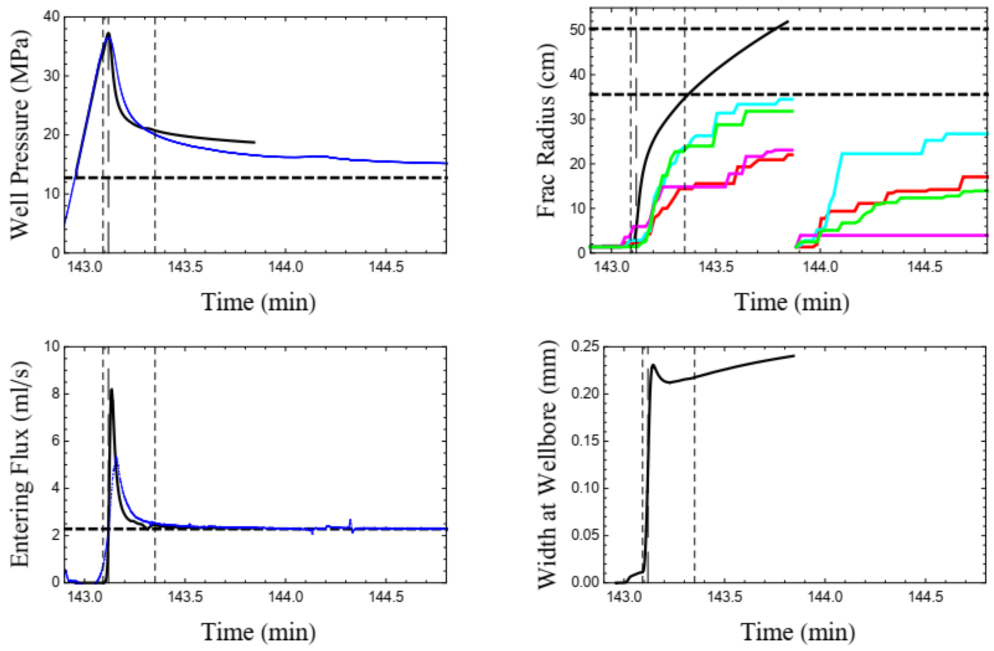
$$\chi_f^{top} = \chi_l^{top} = 4.1 \qquad \psi > 1$$
$$\chi_f^{bot} = \chi_l^{bot} = 1.45$$

- Initiation/breakdown pressure, entering fluxes, width and observation time much more difficult to estimate prior to experiment with single radial fracture simulator given completion design

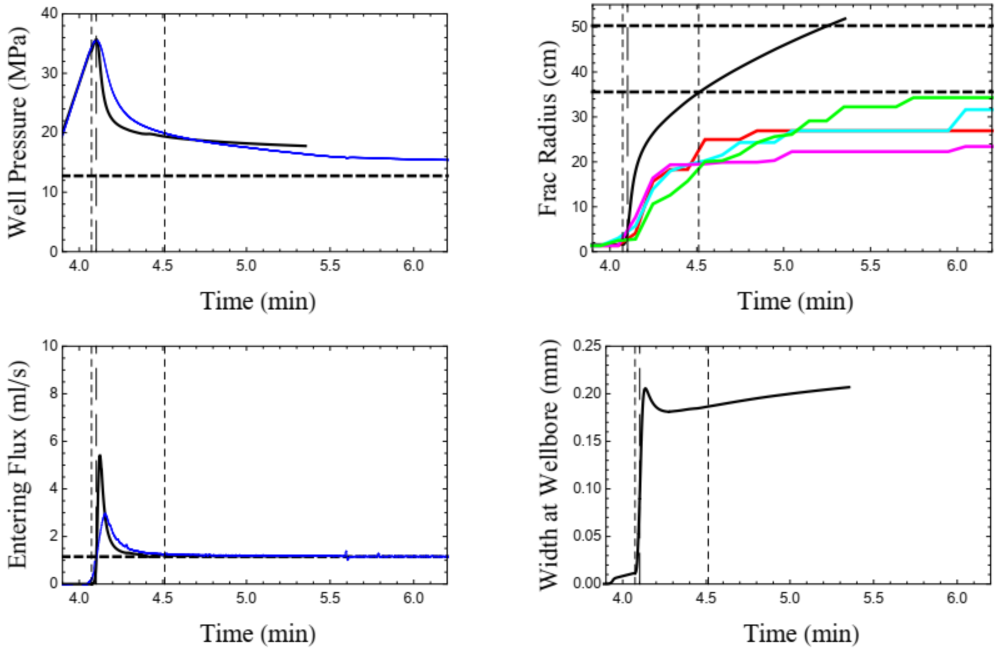
Madyarov, Prioul et al., 2021, Understanding the Impact of Completion Designs on Multi-Stage Fracturing via Block Test Experiments, ARMA 21-1309

LB-2 – Test Results





LB2 Top	Test	Model
Frac Initiation p_i, MPa	29.12	33.77
Breakdown p_b, MPa	36.46	37.26
Time: Init – Edge, s	31	16.5

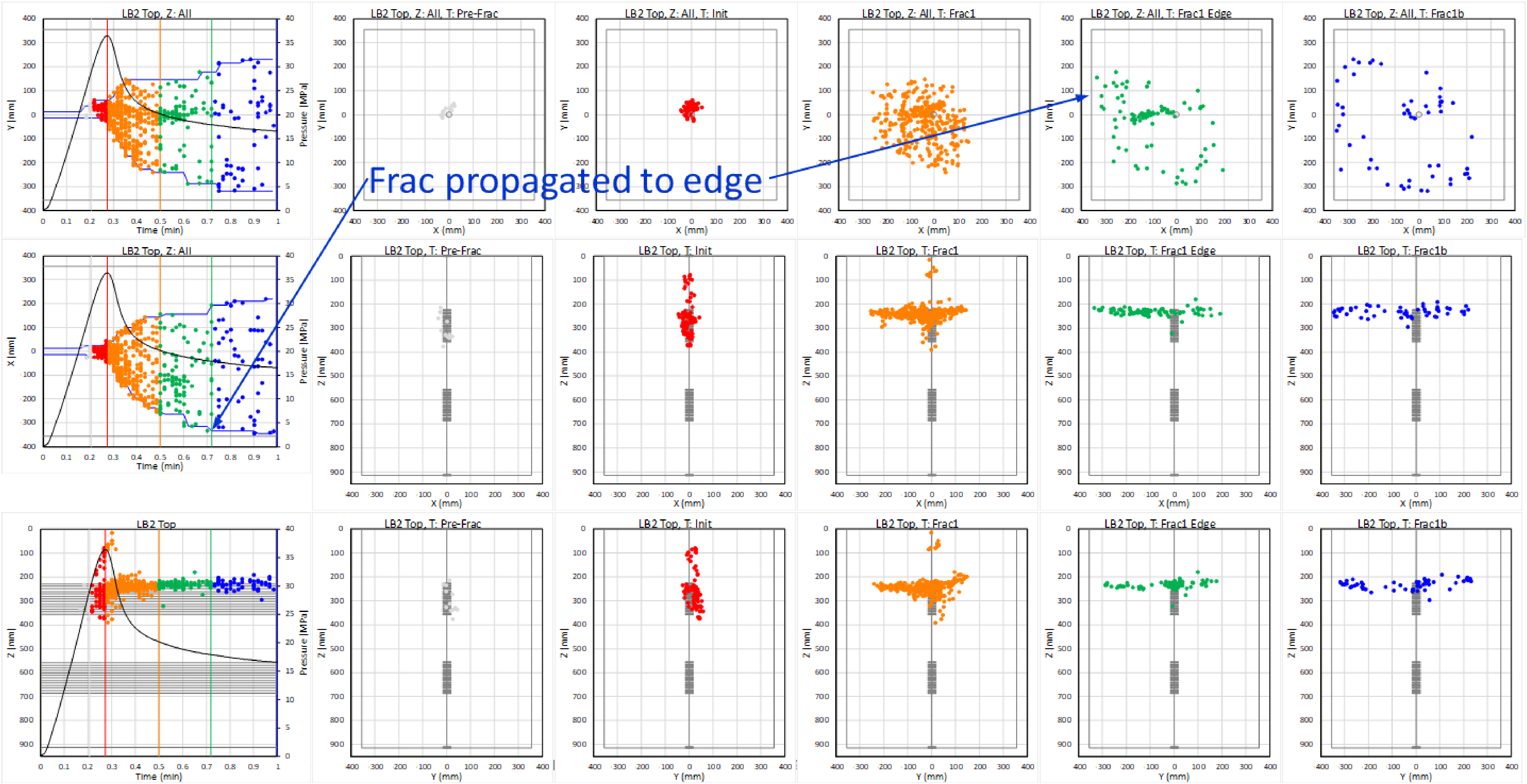


LB2 Bottom	Test	Model
Frac Initiation p_i, MPa	31.8	33.76
Breakdown p_b, MPa	35.48	35.68
Time: Init – Edge, s	90	27.6

- One fracture reached block faces at each stage
- "Petal" fractures at individual perforations join into a twisted frac
- Fractures merge at Top stage

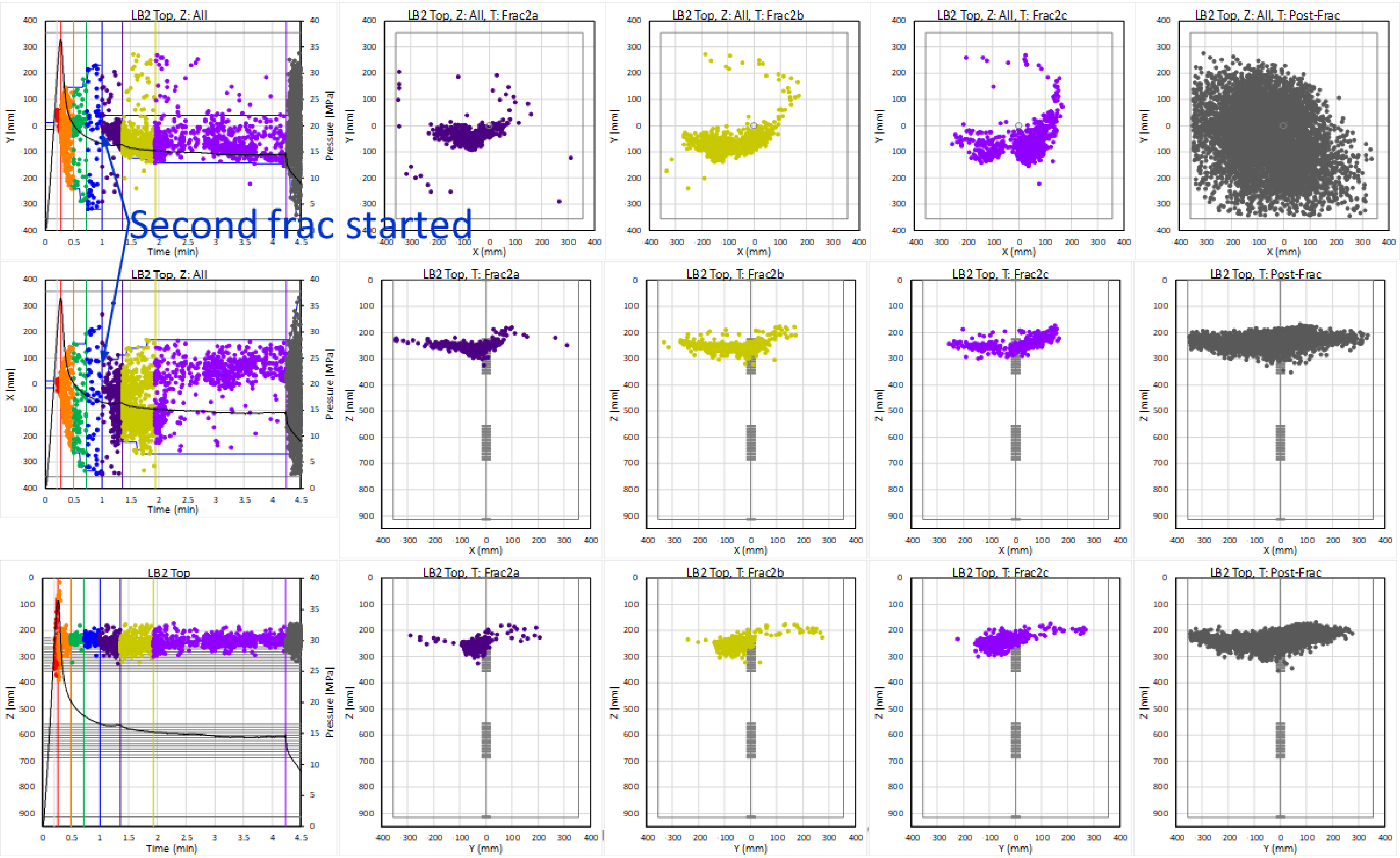
Madyarov, Prioul et al., 2021, Understanding the Impact of Completion Designs on Multi-Stage Fracturing via Block Test Experiments, ARMA 21-1309

LB-2 Top – Acoustic Emissions: First Fracture

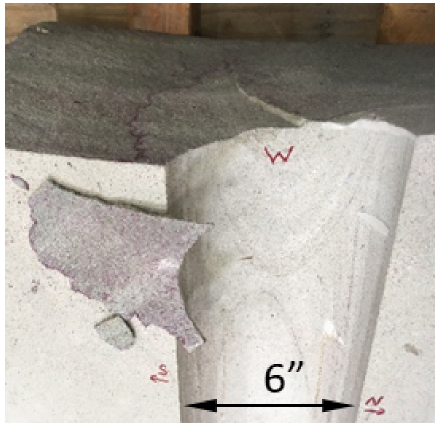


Madyarov, Prioul et al., 2021, Understanding the Impact of Completion Designs on Multi-Stage Fracturing via Block Test Experiments, ARMA 21-1309

LB-2 Top – Acoustic Emissions: Second fracture

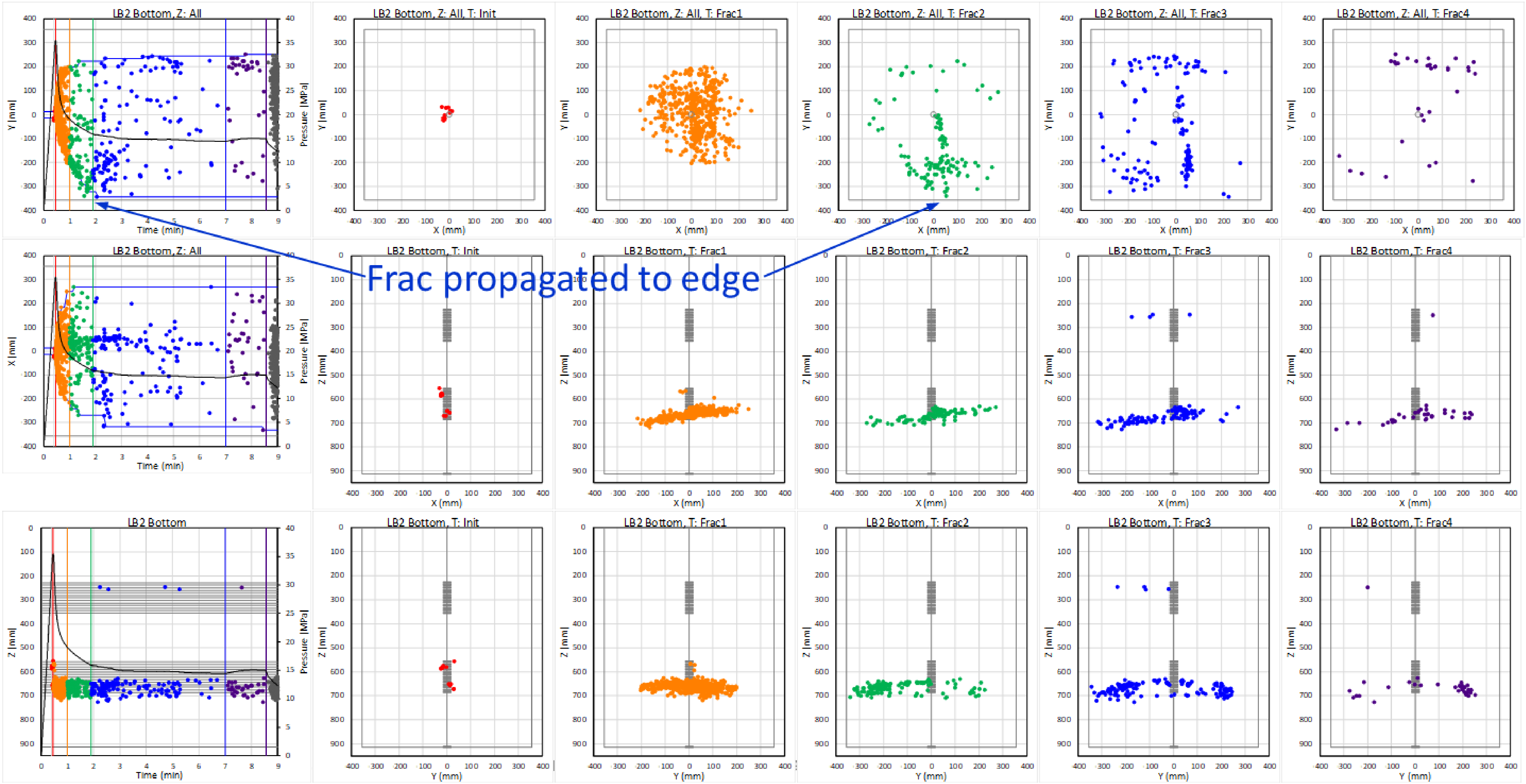


Top Stage



Madyarov, Prioul et al., 2021, Understanding the Impact of Completion Designs on Multi-Stage Fracturing via Block Test Experiments, ARMA 21-1309

LB-2 Bottom – Acoustic Emissions



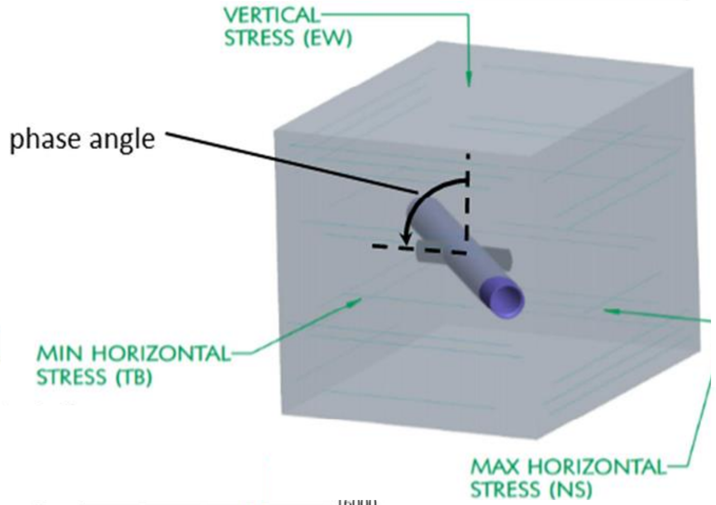
Madyarov, Prioul et al., 2021, Understanding the Impact of Completion Designs on Multi-Stage Fracturing via Block Test Experiments, ARMA 21-1309

Observations on LB-1 and LB-2 block experiments

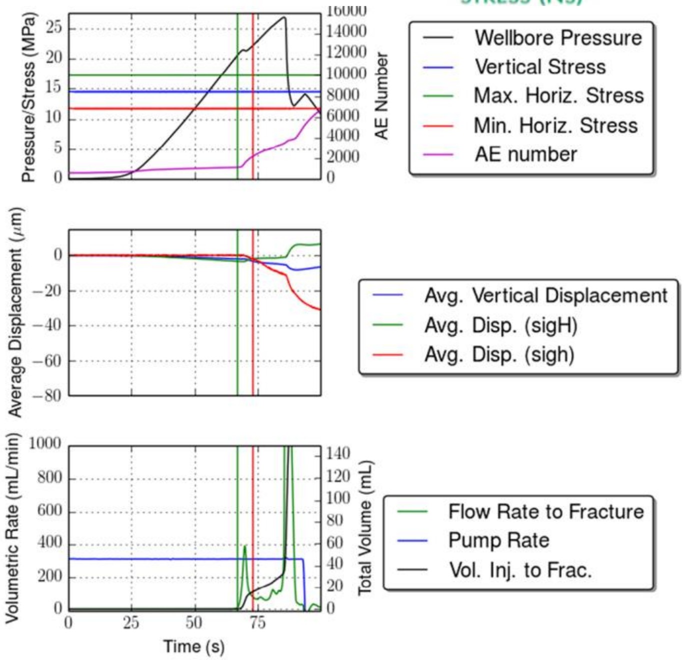
1. **LB1 – far field design: one stage with 4 slots**
   - Cluster efficiency: only two clusters activated but one fracture dominated, maybe due to stress shadow or unbalanced fluid partitioning into one fracture (?)
2. **LB2 – near-wellbore design: two single-cluster stages with different injection rate**
   - Complex initiation, increasing with injection rate (counter-intuitive)
   - Near-wellbore complexity limited to 2-3 perf lengths
   - Top stage: primary fracture with near-wellbore tortuosity, then second fracture once first one reached the end of the block
3. **Observations on design:**
   - Field-to-lab scaling to match viscosity dominated conditions easy to do with scaling relationship but not easy to match all M, S, and C parameters at the same time
   - Borehole-source parameters more difficult to match but possible
   - HF simulator for single radial fracture very useful to define rate and viscosity and assess observation time, initiation and breakdown pressure
   - Acoustic emissions most useful for interpretation of time-evolving geometry
   - Difficult to control “limited entry friction” akin to field conditions

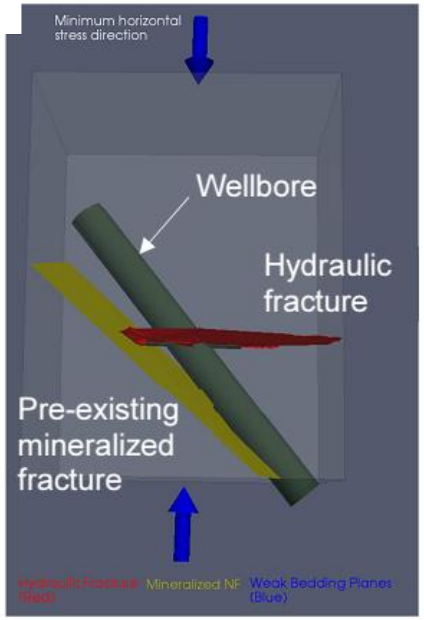
HF interacting with many discontinuities/laminations

Niobrara shales

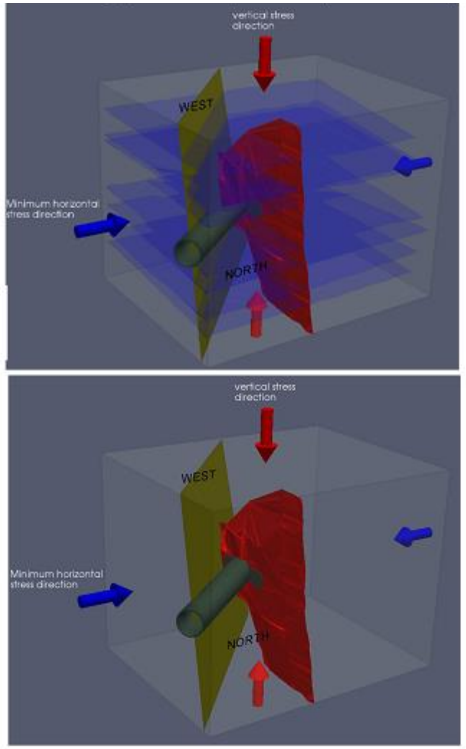


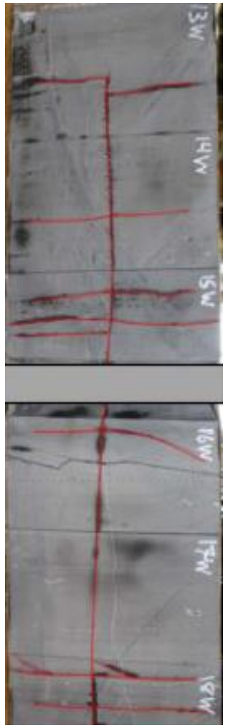
Parameter	Typical field treatment	Laboratory
Wellbore diameter (mm)	133	89
Pumping rate (m^3/s)	0.01325	5.1×10^{-6}
Fluid viscosity (Pa-s)	0.01	0.1
Plane strain modulus (GPa)	28.7	28.7
Toughness (Pa-$\sqrt{m}$)	1.5×10^6	1.5×10^6
Wellbore storage compressibility (m^3/Pa)	2.3×10^{-8}	8.9×10^{-12}





Top view

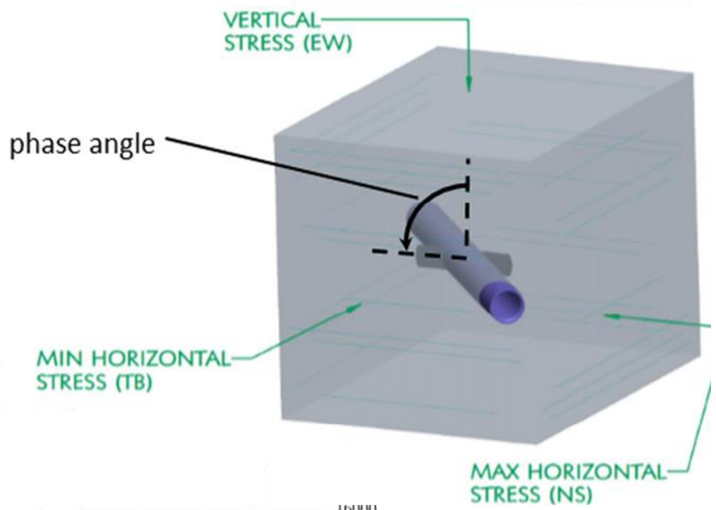




Burghart, Desroches, Lecampion, Stanchits, Surdi, Whitney, Houston, 2015, Laboratory study of the effect of well orientation, completion design, and rock fabric on near-wellbore hydraulic fracture geometry in shales, ISRM13

HF interacting with many discontinuities/laminations

Niobrara shales



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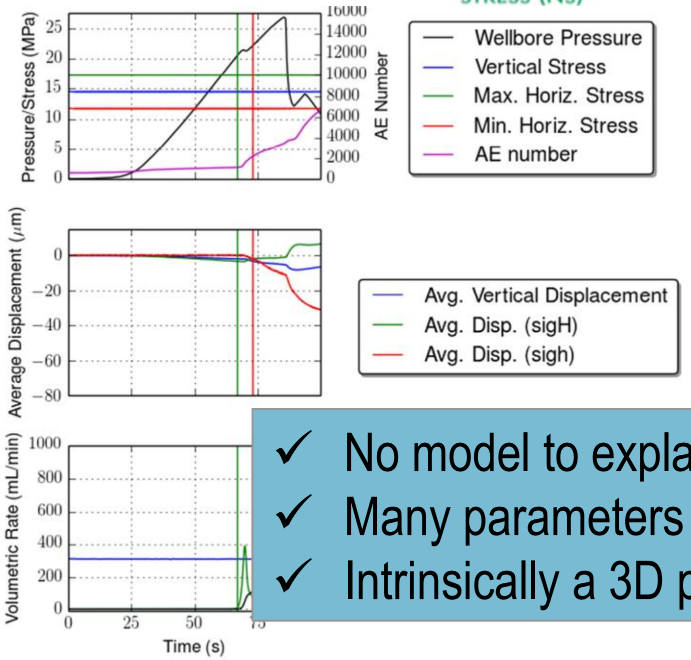
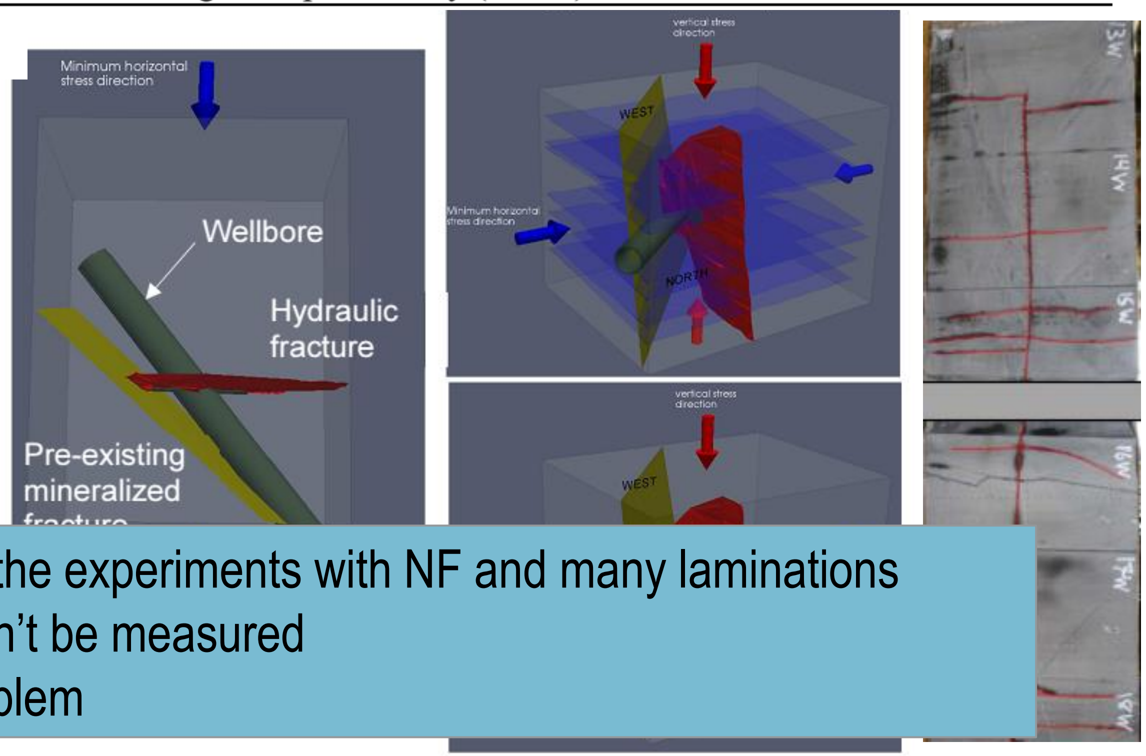


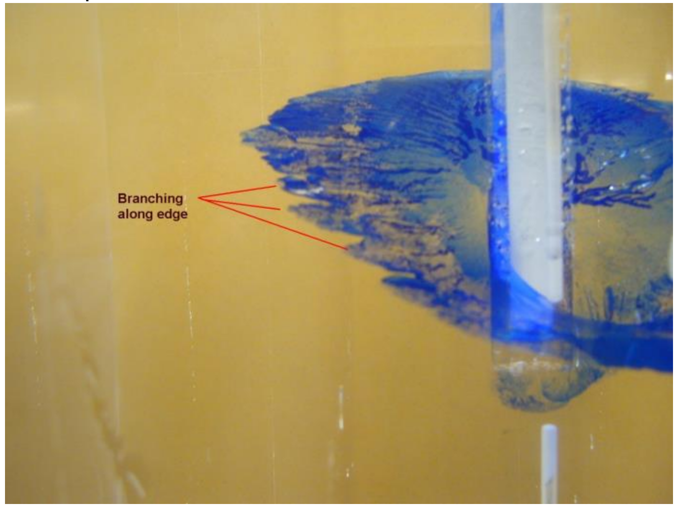


- ✓ No model to explain the experiments with NF and many laminations
- ✓ Many parameters can't be measured
- ✓ Intrinsically a 3D problem

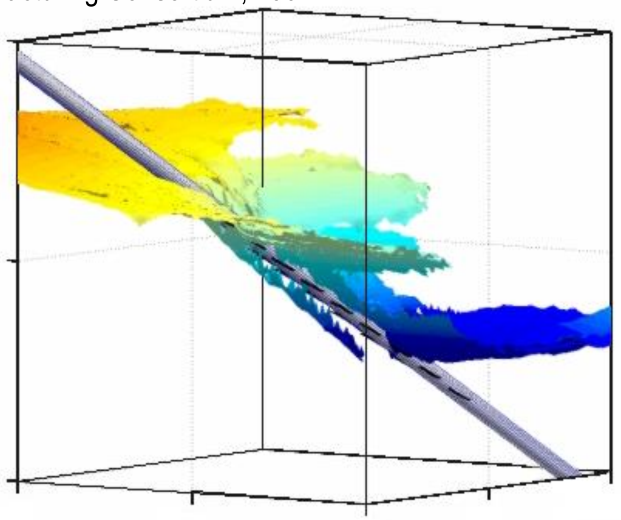
Burghart, Desroches, Lecampion, Stanchits, Surdi, Whitney, Houston, 2015, Laboratory study of the effect of well orientation, completion design, and rock fabric on near-wellbore hydraulic fracture geometry in shales, ISRM13

3D hydraulic fracture initiation and propagation

CSIRO experiment



Delft Fracturing Consortium, 1997



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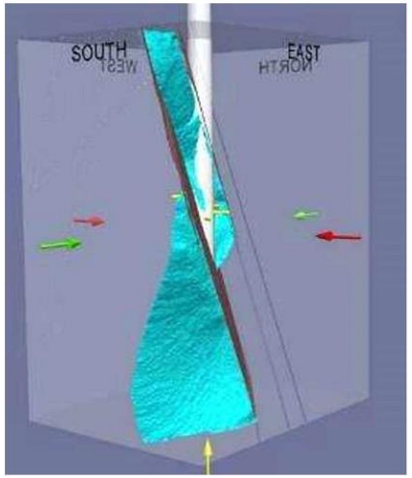

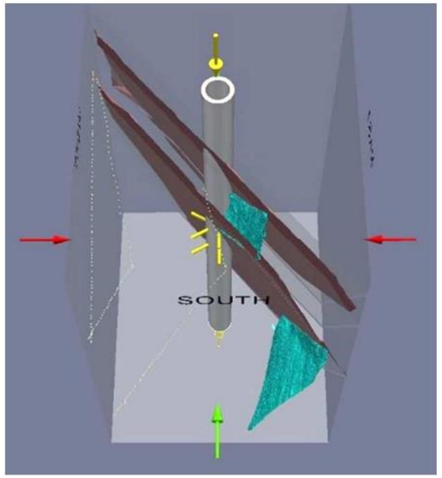

✓ No successful comparison experiment-model for 3D non-planar fractures (mode I, II, III)?

Discussion points

- Tremendous lab experiment progresses over the last 20 years: Hydraulic fracturing mechanics theory works!
- Excellent match experiments-models if material homogeneous and geometry of fracture known and simple
- Scaling laws and simple HF simulator essential to design lab experiments to match field conditions for “viscosity” regime
- Hard to match all the far-field and near-wellbore dimensionless quantities: trade-off necessary on focused goals

What’s missing:

- We do a good job from Field-to-Lab, less obvious to translate learnings from Lab-to-Field? Seems easier with fluid experiments (proppant, fibers), not so when rock and fracturing involved
- Limited-entry conditions difficult to reproduce in the lab: what is a simple criteria to achieve conditions akin to the field?
- We need new “simple” dimensionless quantities for more complex cases
- Increasing fracture and material complexity means increasing number of parameters: necessary evil or a dead-end? Is there another way?
- How do we address the heterogeneity and multiscale nature of HF in the lab with real rocks? Linking the lab and field scales?
- What are the key missing experiments to validate numerical simulators?