CONDUCTIVITY OF COMPLEX FRACTURING IN UNCONVENTIONAL SHALE RESERVOIRS

Project Number (11122-07)

PIs: Ding Zhu and Dan Hill
Texas A&M University
Petroleum Engineering Department

U.S. Department of Energy
National Energy Technology Laboratory
Mastering the Subsurface Through Technology, Innovation and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting
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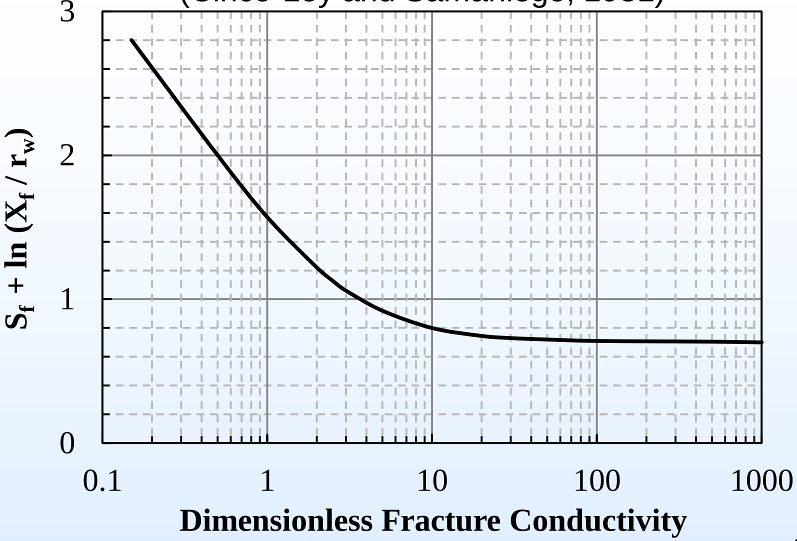
Benefit to the Program

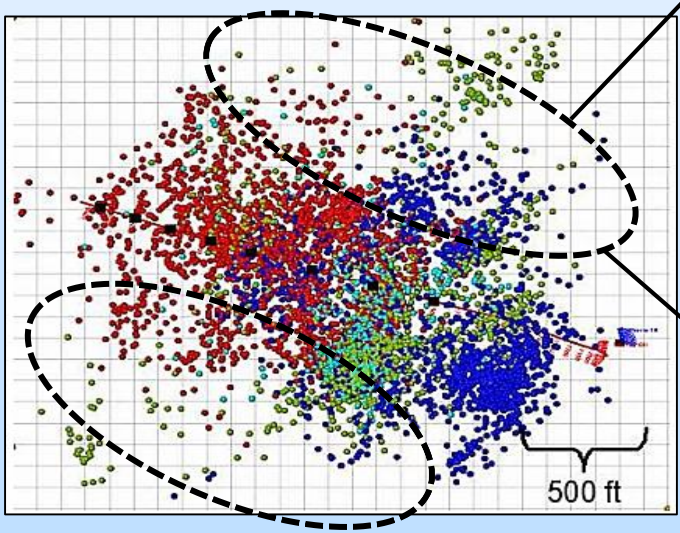
- A better physics-based understanding of fracture conductivity behavior in shale formations, which leads to:
  - an improved fracture treatment design
  - a more effective and economical hydraulic fracturing
  - an improved fractured well performance
  - a reduced environmental impact by reducing water and other materials used in fracturing activities
- A systematic experimental study of fracture conductivity in shale oil and gas formations, including:
  - Barnett shale
  - Fayetteville shale
  - Marcellus shale
  - Eagle Ford shale
- Addresses the concerns of conductivity measurement procedures and mimics the field conditions for more accurate evaluation of conductivity

Importance of Fracture Conductivity in Shale

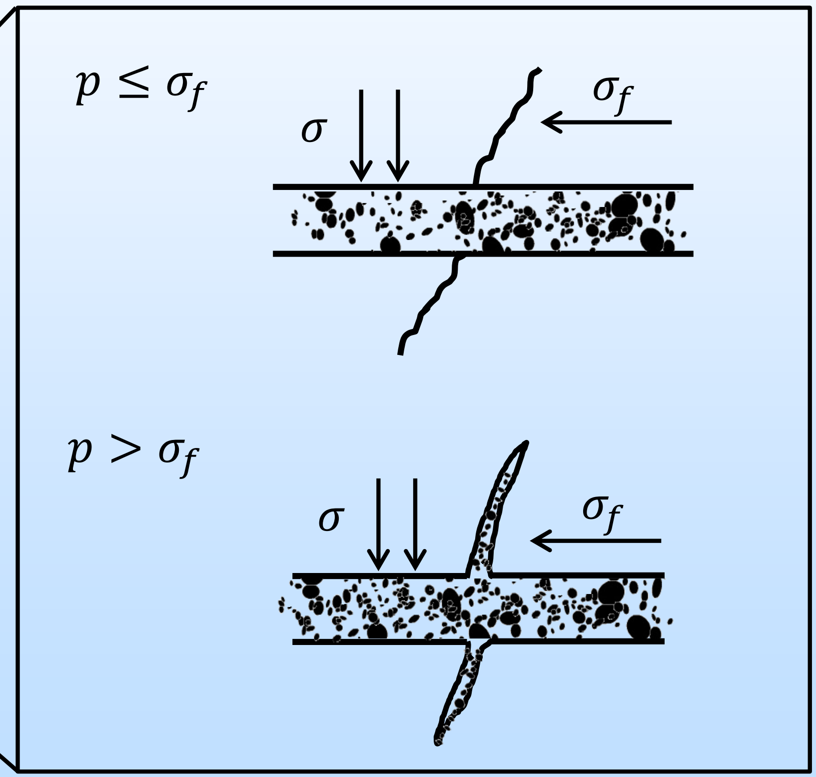
(Cinco-Ley and Samaniego, 1981)



$$C_{fD} = \frac{k_f w_f}{k_m x_f} = \frac{5}{0.0001 \times 1000} = 50$$



(Daniels et al., 2007; Cramer, 2014)



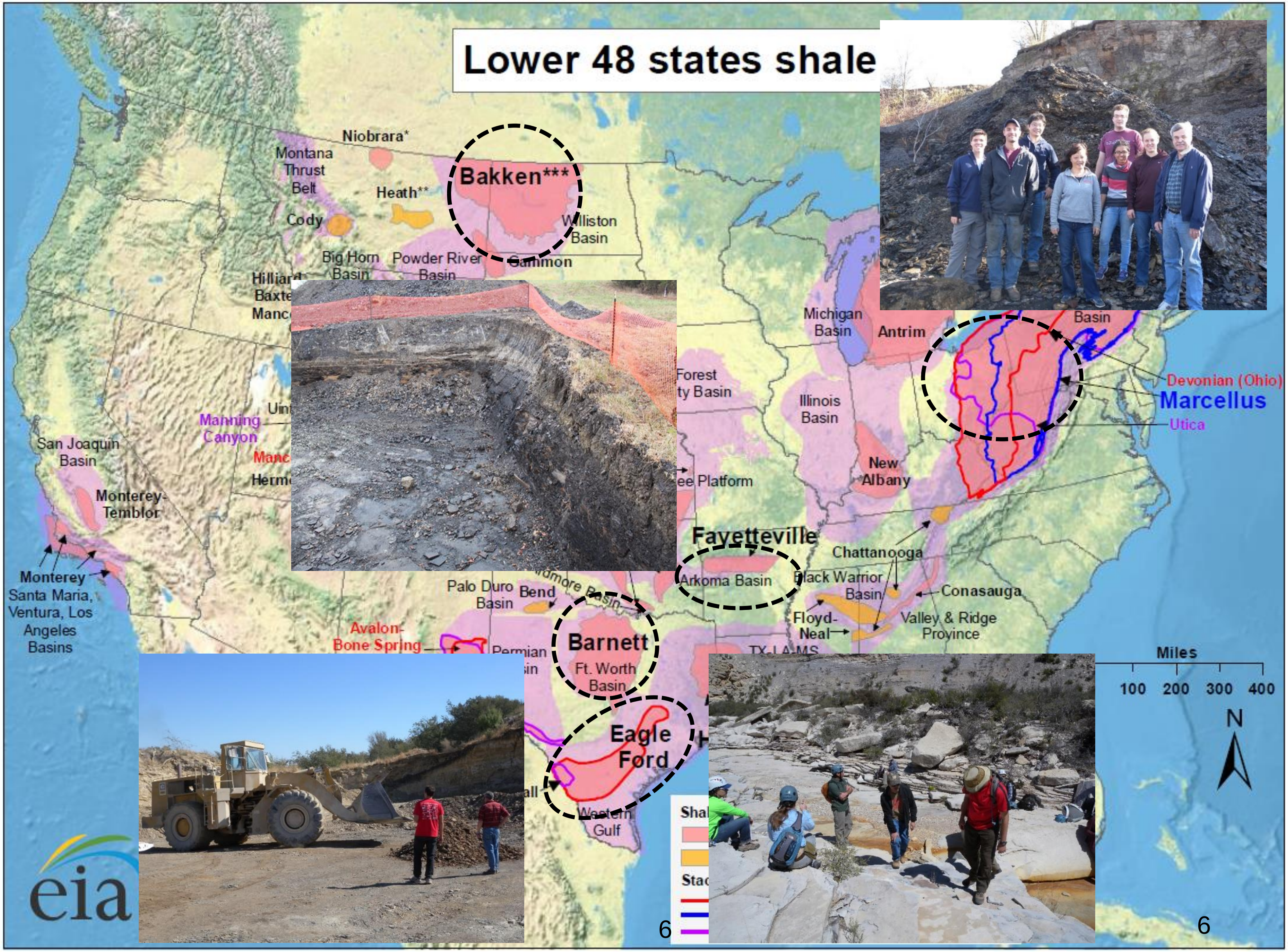
Reservoir Conditions and Frac Design

Properties	Barnett shale	Fayetteville shale	Eagle Ford shale	Marcellus shale	(Bakken shale)
True Vertical Depth (ft)	6,000 ~ 8,500	1,500 ~ 6,500	5,000 ~ 14,000	4,000 ~ 8,000	7,000 ~ 11,000
Closure stress gradient (psi/ft)	0.61 ~ 0.73	0.70 ~ 0.80	0.70 ~ 0.95	0.67 ~ 0.76	0.48 ~ 0.80
Effective closure stress (psi)	3,000 ~ 5,500	1,000 ~ 5,000	2,000 ~ 8,000	2,500 ~ 6,000	5,500 ~ 9,500
Hydrocarbon	Gas	Gas	Condensate, Oil	Gas, Condensate	Oil, Gas, NGL
Fracturing design	Water frac	Water frac	Gelled frac, Hybrid, High-way	Water frac, Foam	Water frac, Crosslinked gel, Hybrid
Proppant size (mesh)	100, 40/70, 30/50	100, 30/70	40/70, 30/50, 20/40,	100, 40/70, 30/50	100, 40/70, 30/50, 20/40, 16/20
Typical max. proppant concentration (ppga)	3.5	2	4	4	5
Average concentration (ppga)	0.6	0.6	1.2	1.2	1.7

(USGS Fact S. 2008-3021; Hexion fracline, 2009; Sunday Udoh, 2013; Zhang, 2014; Murex Petro. Corp., 2014; A. Plas Otwe, 2014)

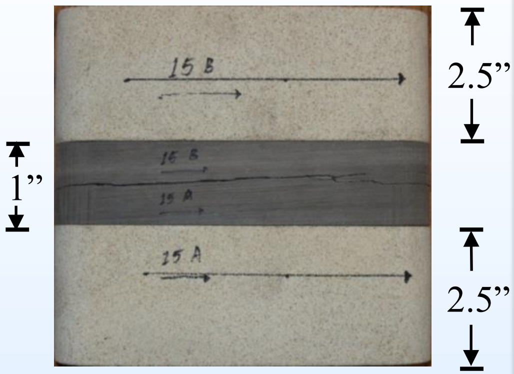
Project Overview:
Goals and Objectives

- Build shale baseline frac conductivity database
  - Rocks: Barnett, Fayetteville, Eagle Ford, Marcellus, Bakken
  - Fracture: natural fracture, induced fracture; unpropped, propped
  - Proppant: 100, 40/70, 30/70, 30/50; Predominantly ≤ 0.20 lb/ft^2
- Correlate shale frac conductivity with rock properties
  - Mineralogical: clay-rich shale, carbonate-rich, silica-rich
  - Mechanical: elastic properties of shale
  - Structural: fracture orientation and surface roughness
- Investigate the conductivity damage by water
  - Mineralogical: clay softening
  - Damage mechanisms

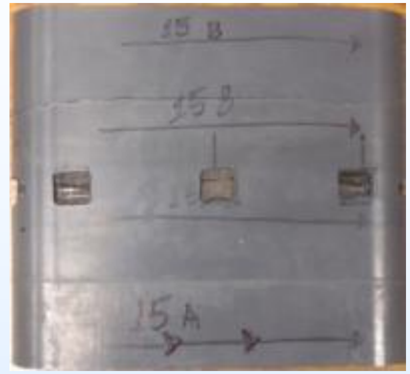

Lower 48 states shale
Niobrara*
Montana Thrust Belt
Heath**
Bakken***
Cody
Williston Basin
Big Horn Basin
Powder River Basin
Gammon
Hilliard
Baxte
Manc
Michigan Basin
Antrim
Basin
Devonian (Ohio)
Marcellus
Utica
Forest
ty Basin
Illinois Basin
Manning Canyon
Uin
San Joaquin Basin
Manc
Herm
ee Platform
New Albany
Monterey-Temblor
Fayetteville
Chattanooga
Arkoma Basin
Black Warrior Basin
Conasauga
Monterey
Santa Maria, Ventura, Los Angeles Basins
Palo Duro Basin
Bend
Floyd-Neal
Valley & Ridge Province
Avalon-Bone Spring
Permian
Barnett
Ft. Worth Basin
TX-LA-MS
Miles
100 200 300 400
N
Eagle Ford
Western Gulf
Shal
Stac
eia
6

Conductivity Experimental Procedure

1. Induce fracture

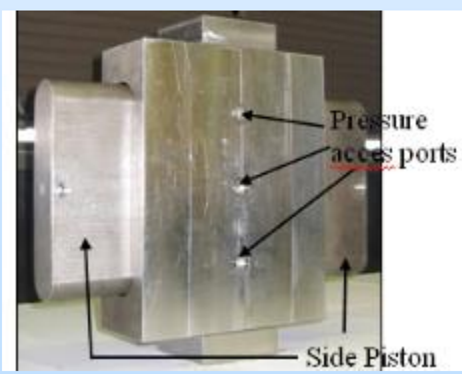


2. Coat samples

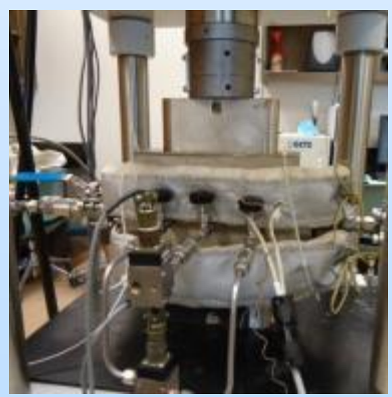


3. Place proppants

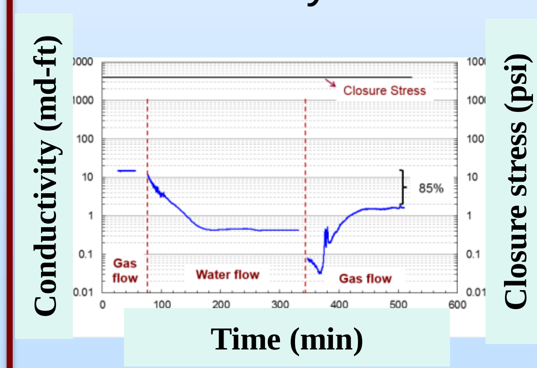
4. Mod. API cell



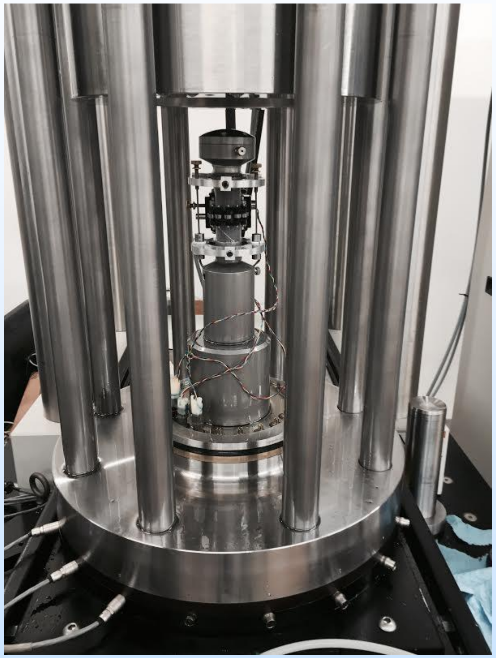
5. Measurement



6. Analysis

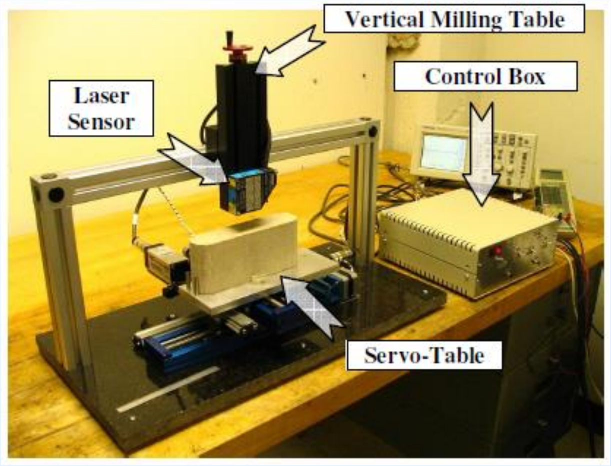


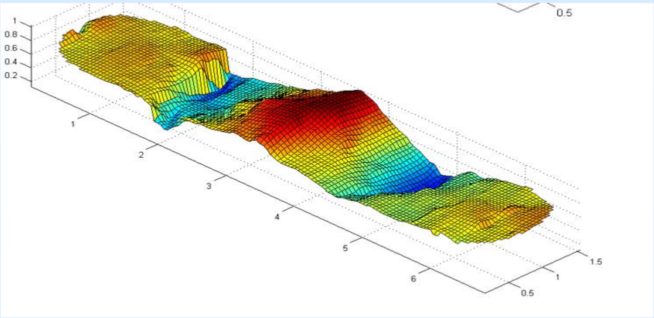
Triaxial Compression Test Setup



Triaxial test: mechanical properties (E, υ)

Brinell hardness test





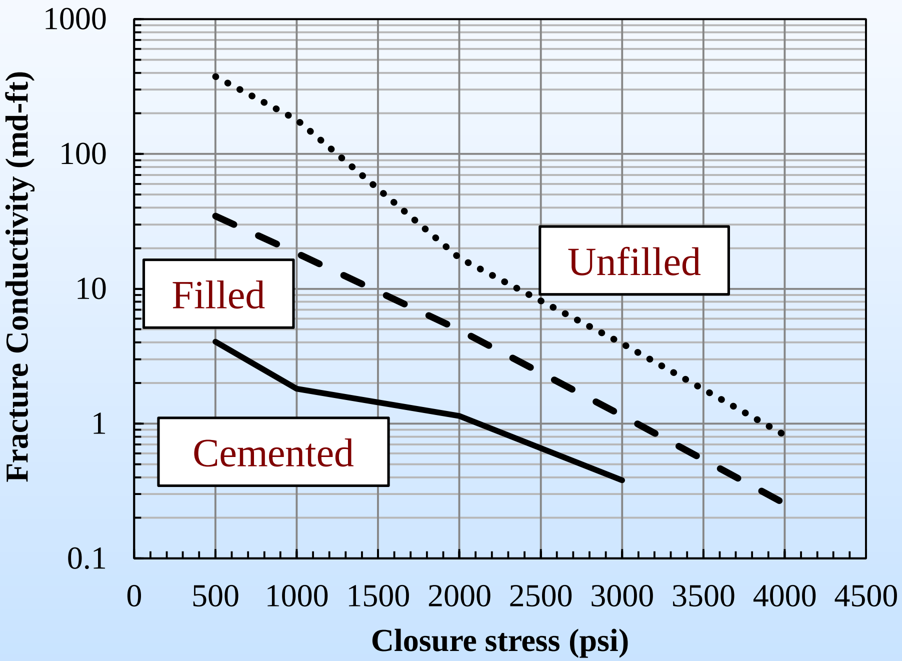
profilometer: topography

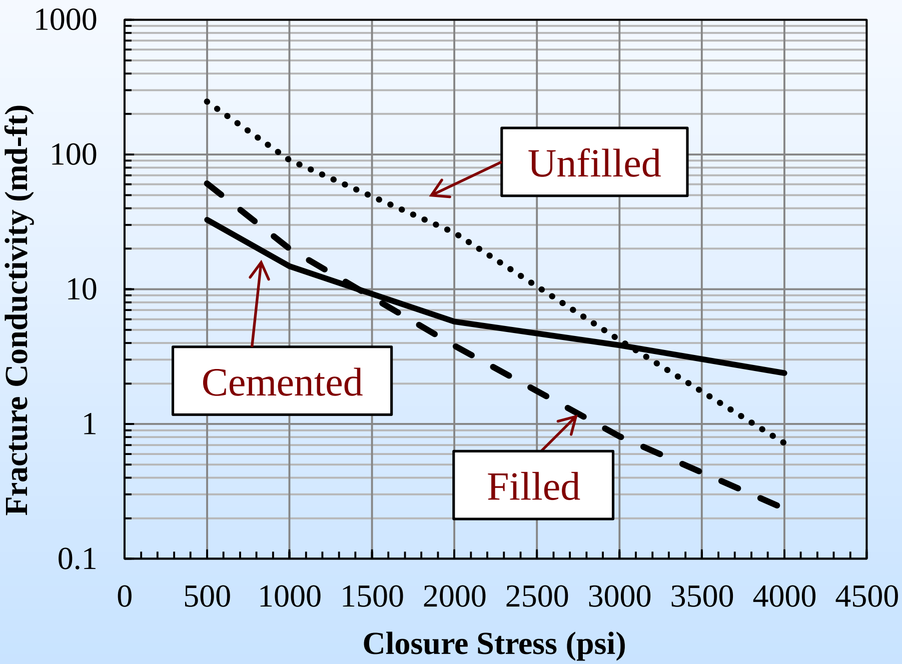
Barnett: Unpropped Natural Fracture

Cemented

Filled

Unfilled





With infill in fracture

Without infill in fracture

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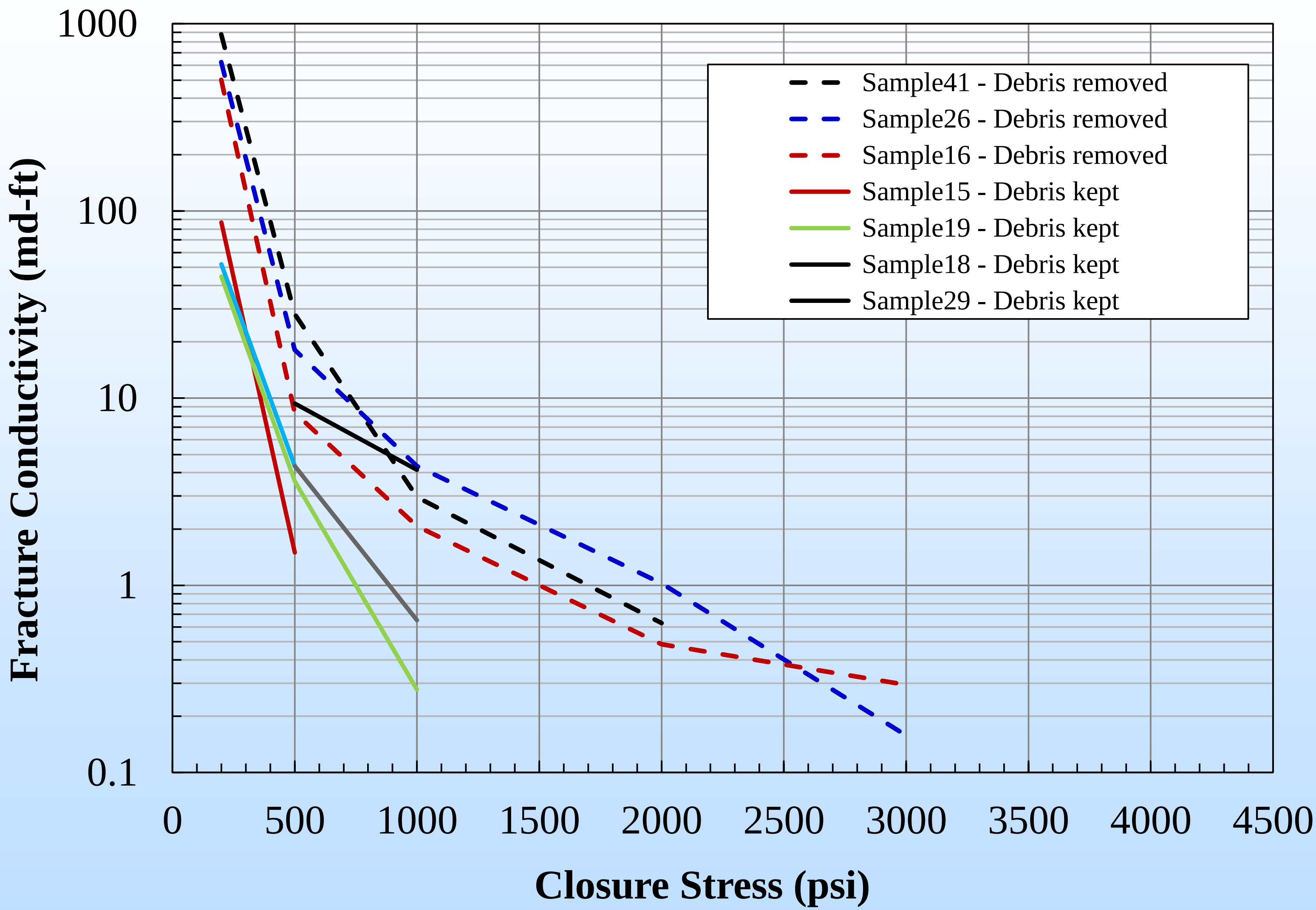
Barnett: Unpropped Aligned Fracture



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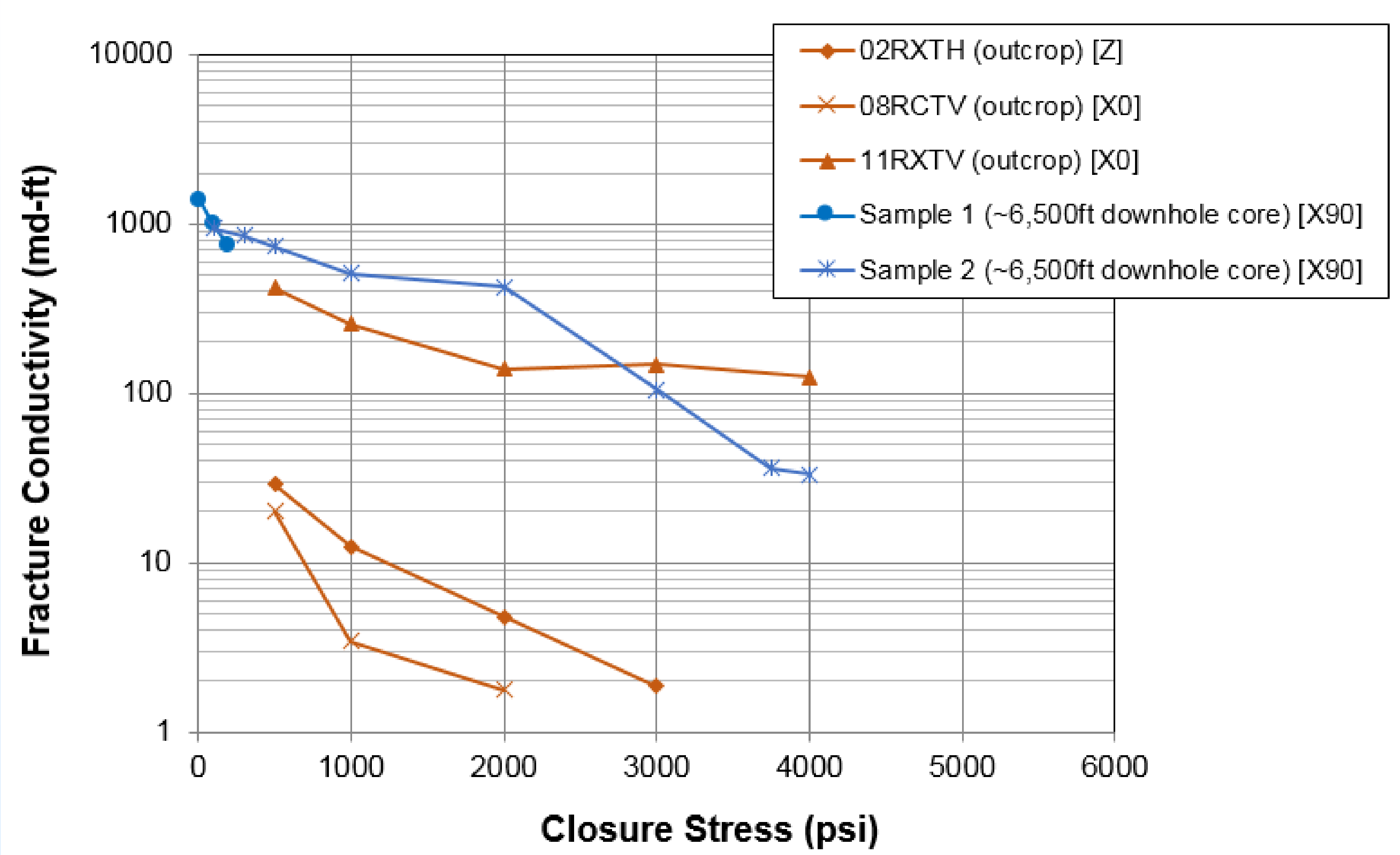
Marcellus: Downhole Core vs. Outcrop Samples



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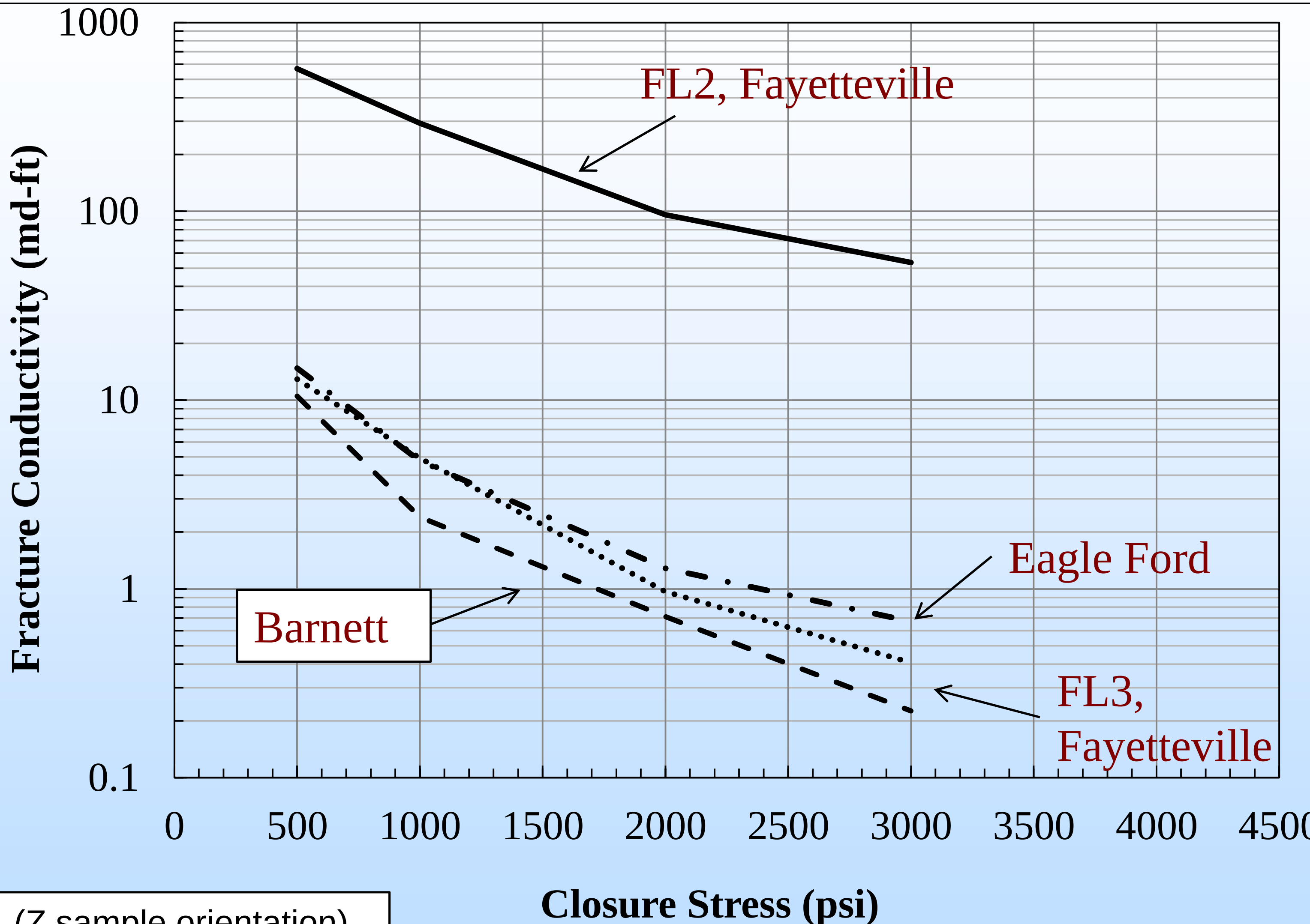
Unpropped Aligned Fracture



(Z sample orientation)

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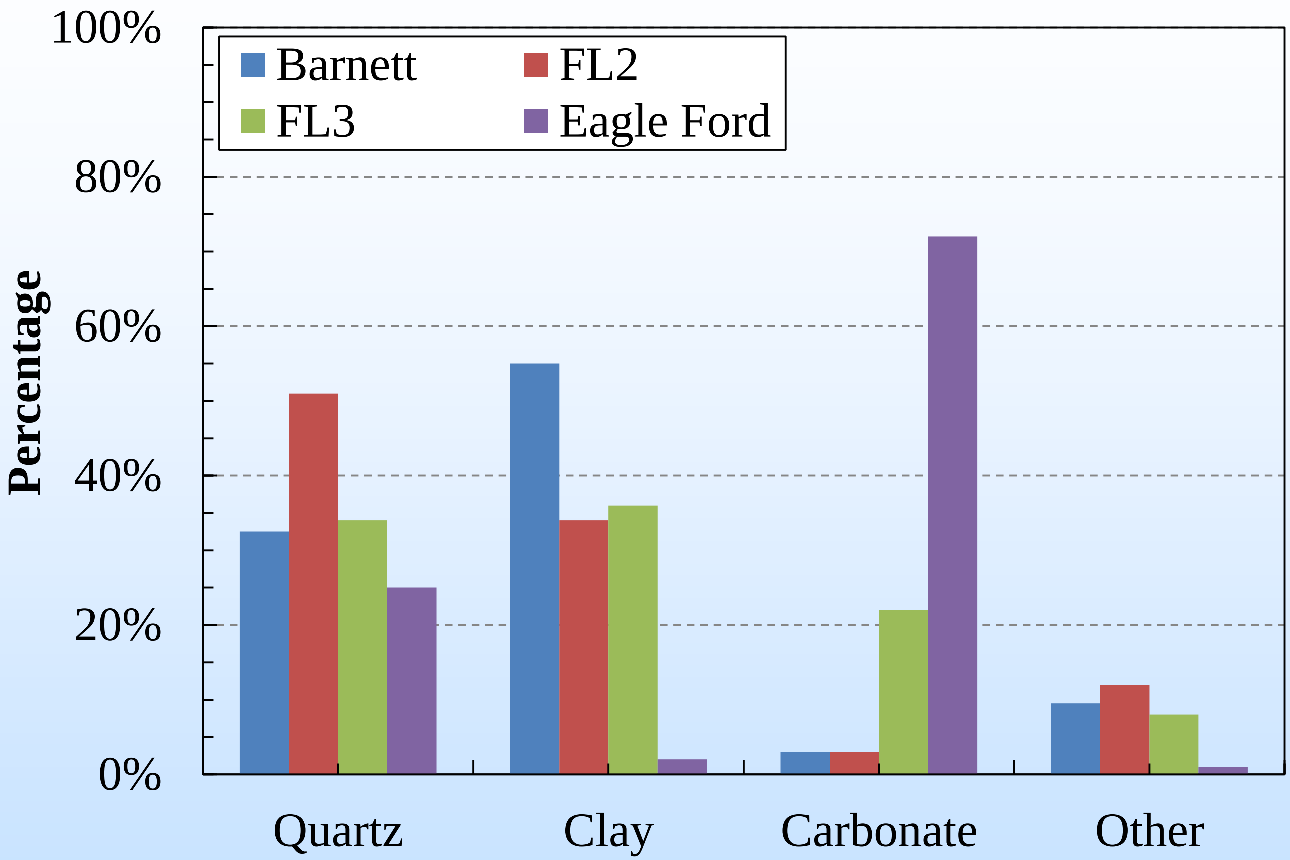
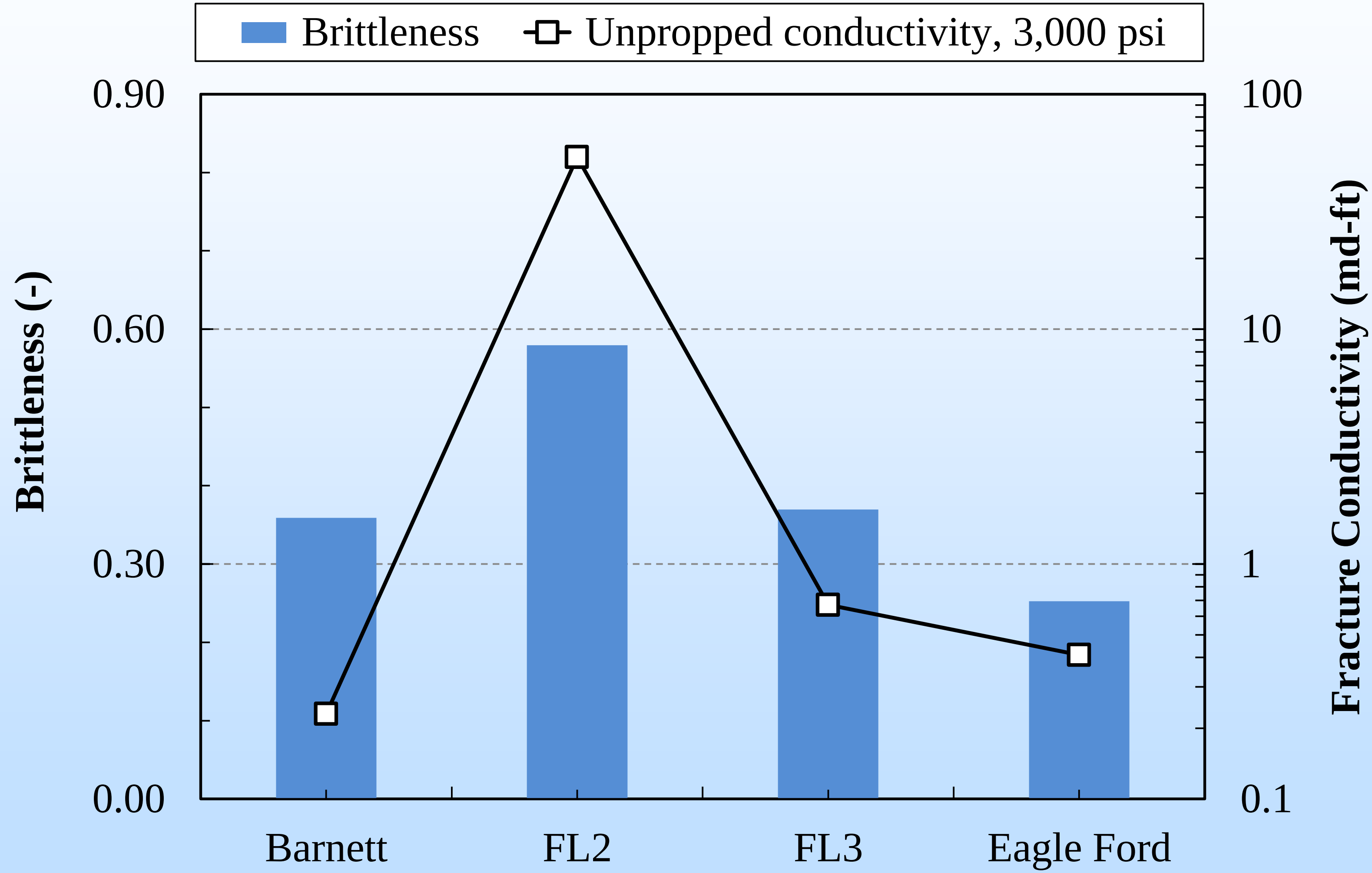
Mineralogy and Rock Brittleness



$$BI = \frac{V_{quartz} + V_{dolomite}}{V_{quartz} + V_{dolomite} + V_{limestone} + V_{clay} + V_{TOC}}$$

(Jarvie et al., 2007; Wang and Gale, 2009)

Unpropped Fracture Conductivity and Rock Brittleness



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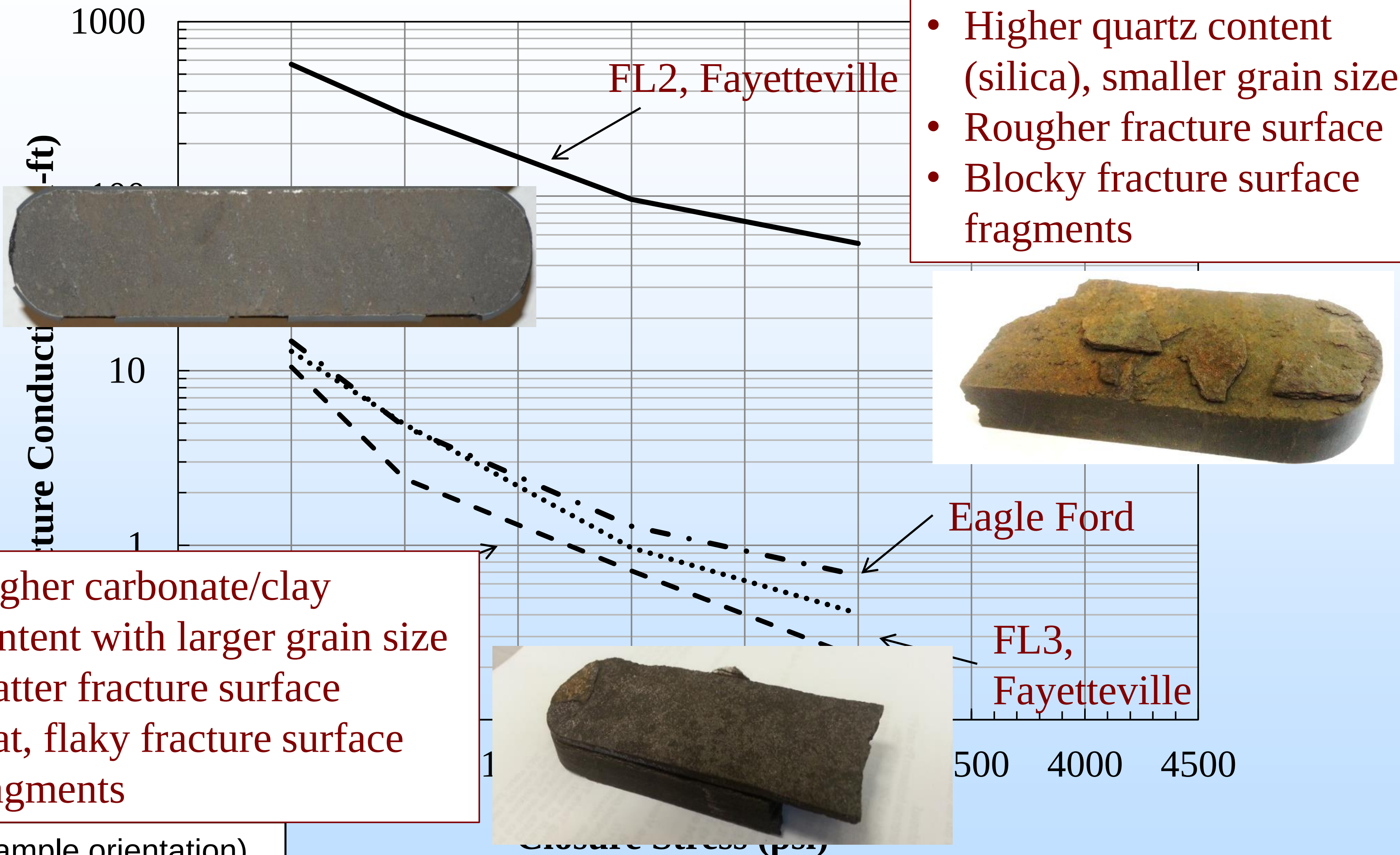
Conductivity Difference Explained

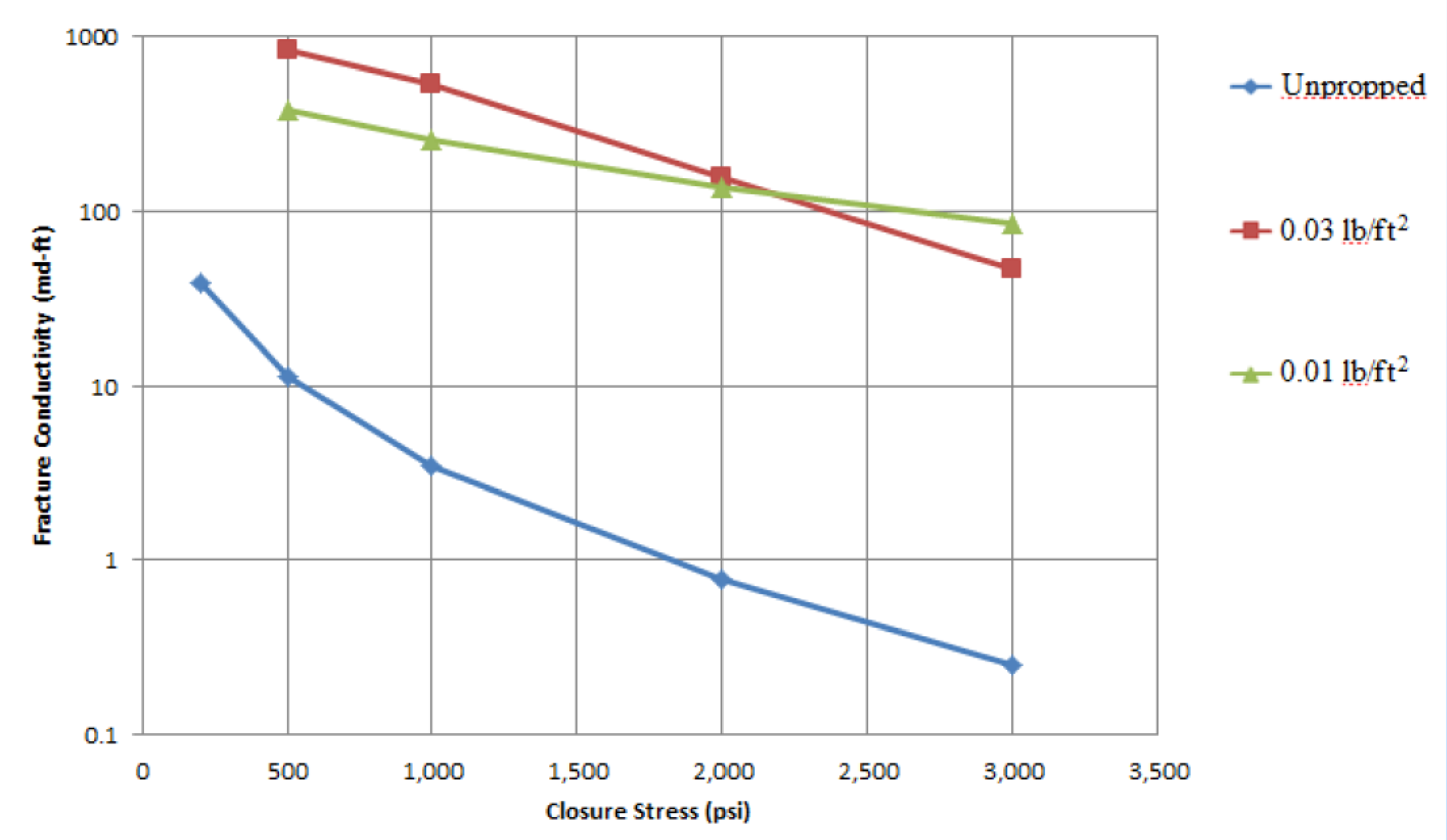


- Higher quartz content (silica), smaller grain size
- Rougher fracture surface
- Blocky fracture surface fragments

- Higher carbonate/clay content with larger grain size
- Flatter fracture surface
- Flat, flaky fracture surface fragments

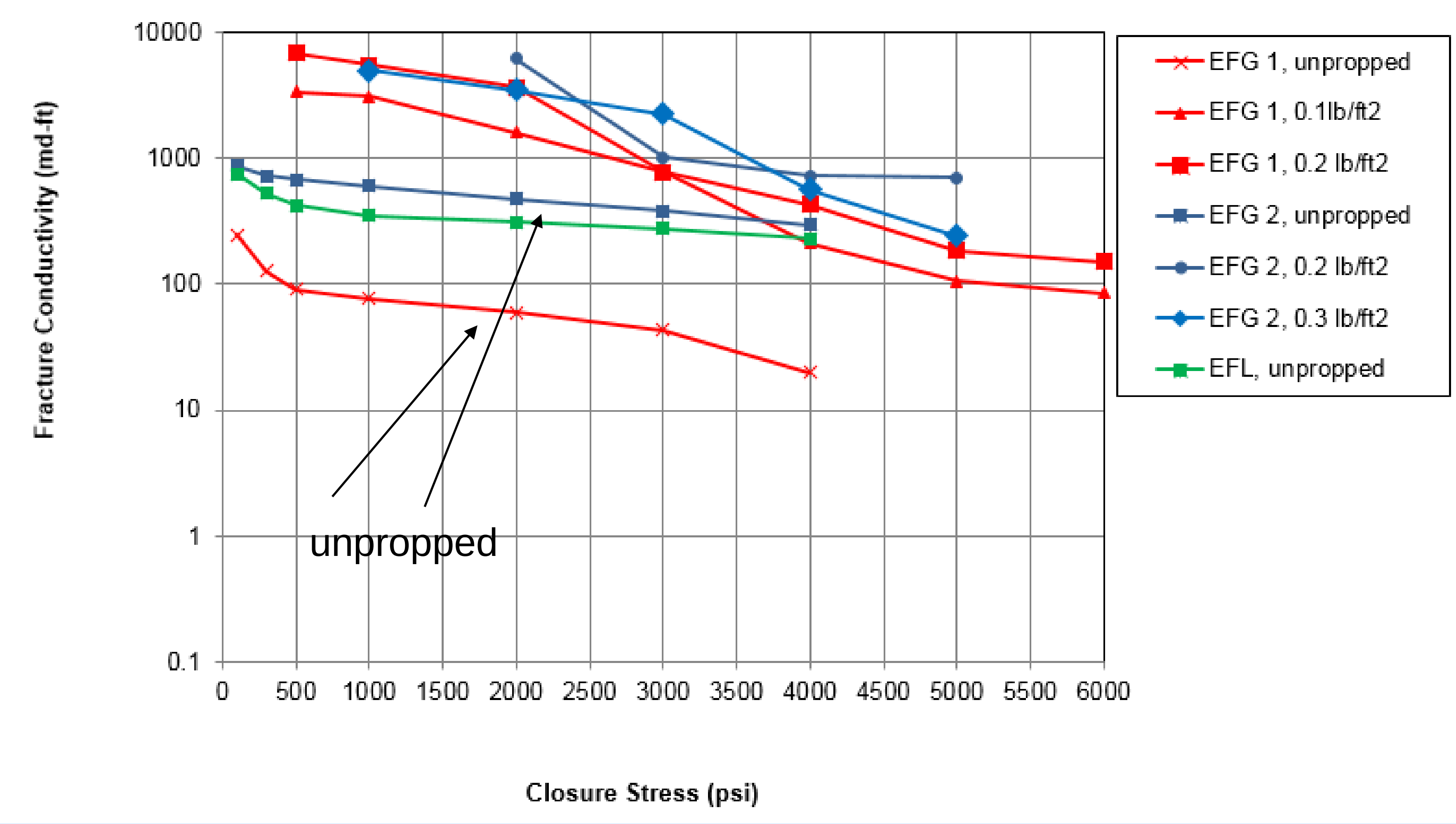
(Z sample orientation)

Unpropped vs. Propped Fracture: Fayetteville



Eagle Ford, Zone B

100 Mesh Sand



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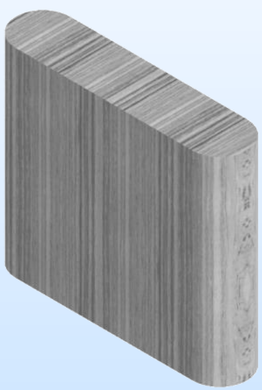
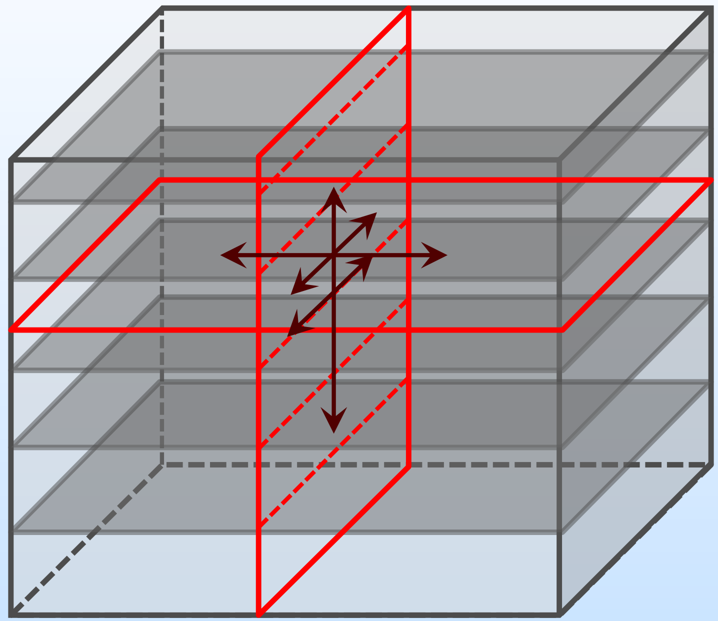
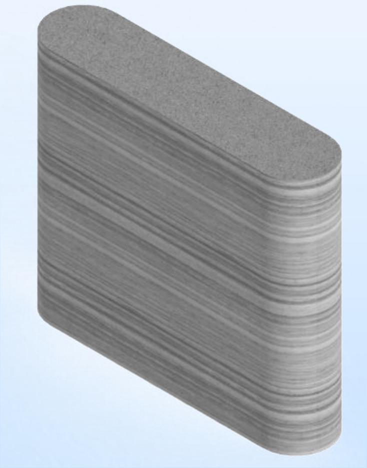
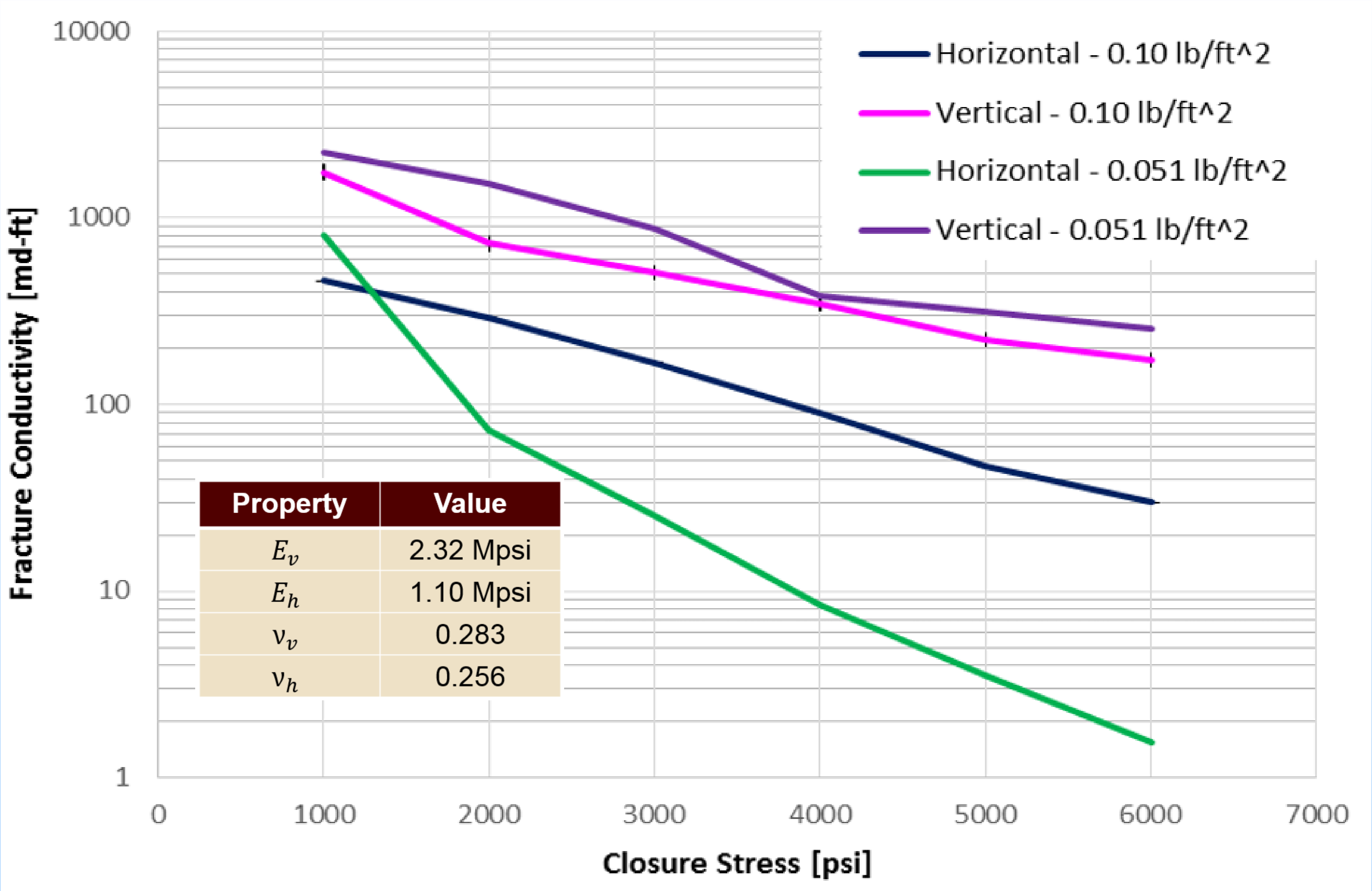
Sample Orientation







Marcellus, Elimsport: Conductivity



Property	Value
E_v	2.32 Mpsi
E_h	1.10 Mpsi
ν_v	0.283
ν_h	0.256

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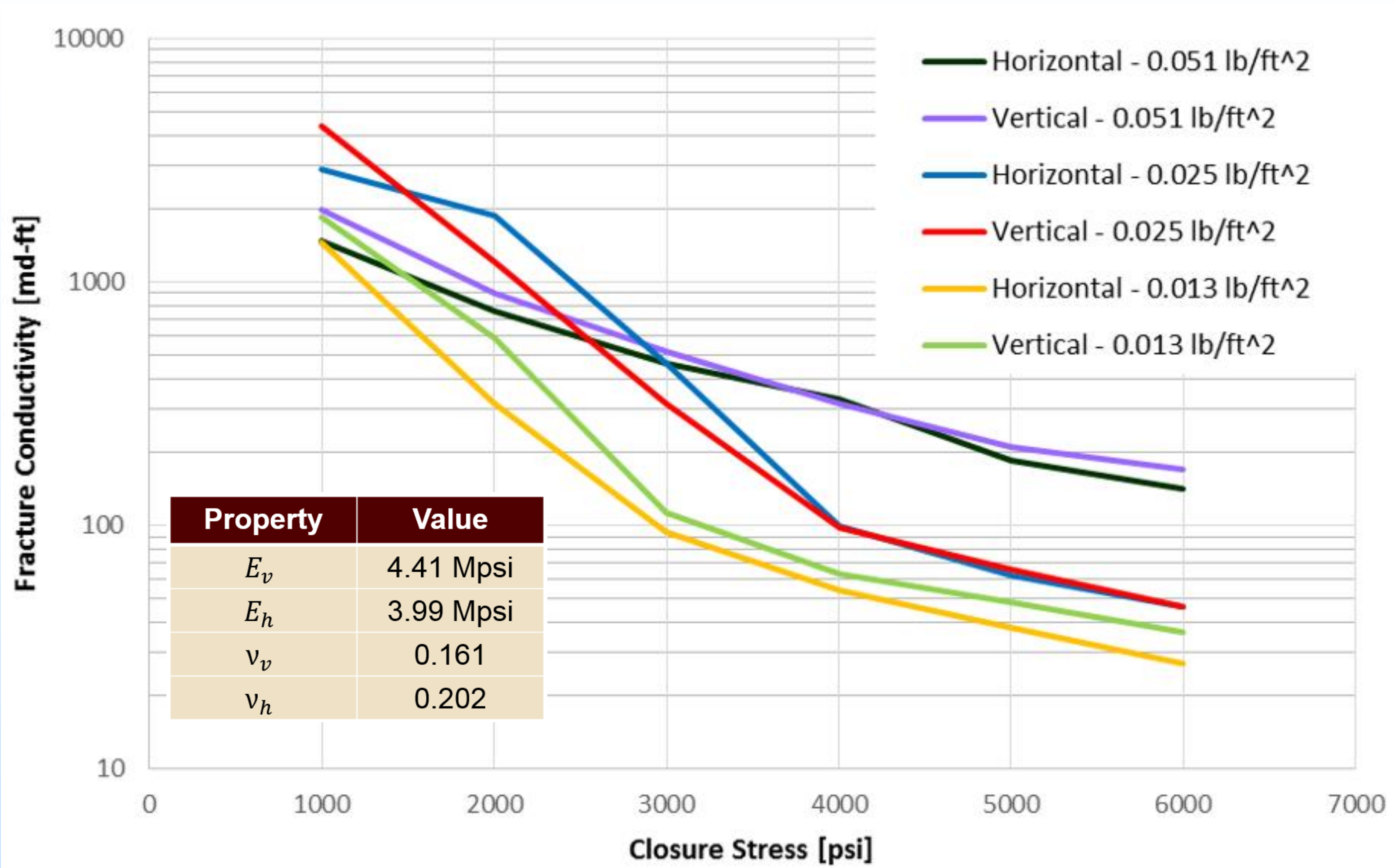
Marcellus, Allenwood: Conductivity



Property	Value
E_v	4.41 Mpsi
E_h	3.99 Mpsi
ν_v	0.161
ν_h	0.202

(Z = horizontal sample orientation)
(X0 = vertical sample orientation)

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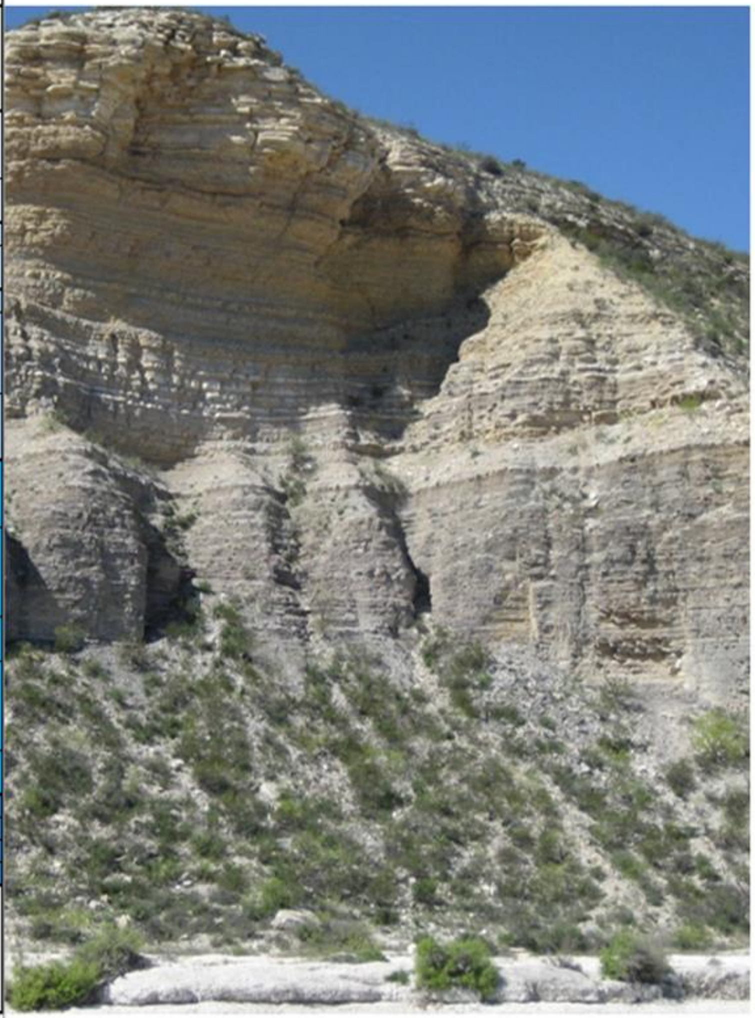
Eagle Ford Outcrop: Lozier Canyon

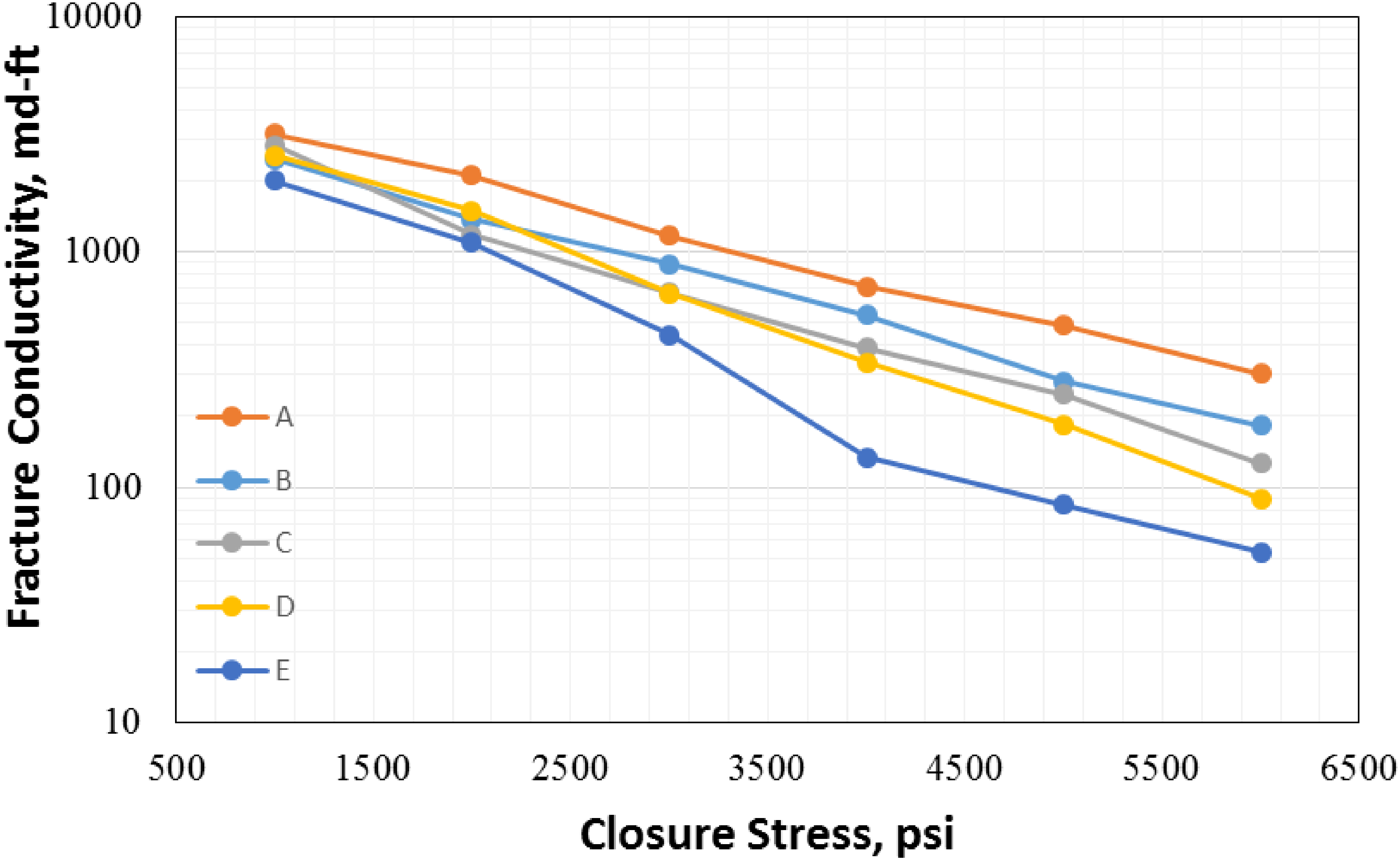
Group	Formation	Member	Unit	Sub-unit	Thickness (ft)	
Austin						
					0	
Eagle Ford	Upper Eagle Ford	Upper	E	E2		14
Eagle Ford	Upper Eagle Ford	Upper	E	E1		12
					26	
Eagle Ford	Upper Eagle Ford	Upper	D	D2		5
Eagle Ford	Upper Eagle Ford	Upper	D	D1		12
					43	
Eagle Ford	Upper Eagle Ford	Lower	C	C3		5
Eagle Ford	Upper Eagle Ford	Lower	C	C2		18
Eagle Ford	Upper Eagle Ford	Lower	C	C1		15
					81	
Eagle Ford	Lower Eagle Ford	Upper	B	B5		15
Eagle Ford	Lower Eagle Ford	Upper	B	B4		19
Eagle Ford	Lower Eagle Ford	Upper	B	B3		11
					126	
Eagle Ford	Lower Eagle Ford	Lower	B	B2		19
Eagle Ford	Lower Eagle Ford	Lower	B	B1		12
					157	
Eagle Ford	Lower Eagle Ford	Lower	A	A4		4
Eagle Ford	Lower Eagle Ford	Lower	A	A3		4
Eagle Ford	Lower Eagle Ford	Lower	A	A2		4
Eagle Ford	Lower Eagle Ford	Lower	A	A1		5
					174	
Buda						



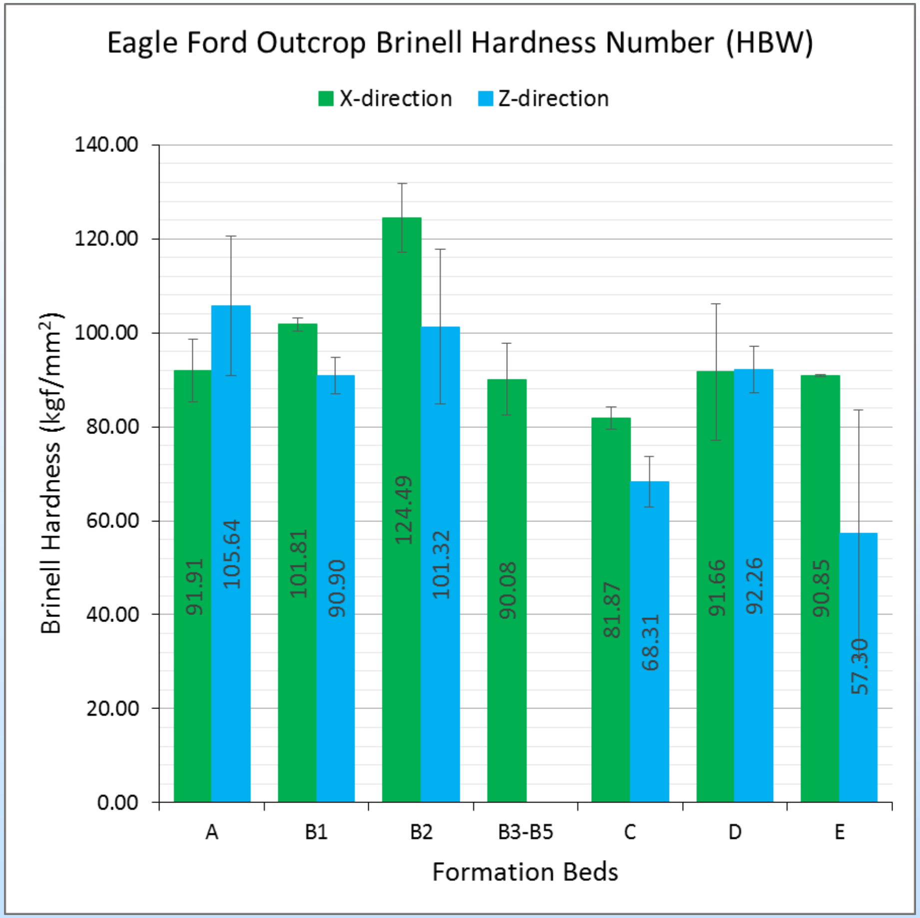
Comprehensive Study

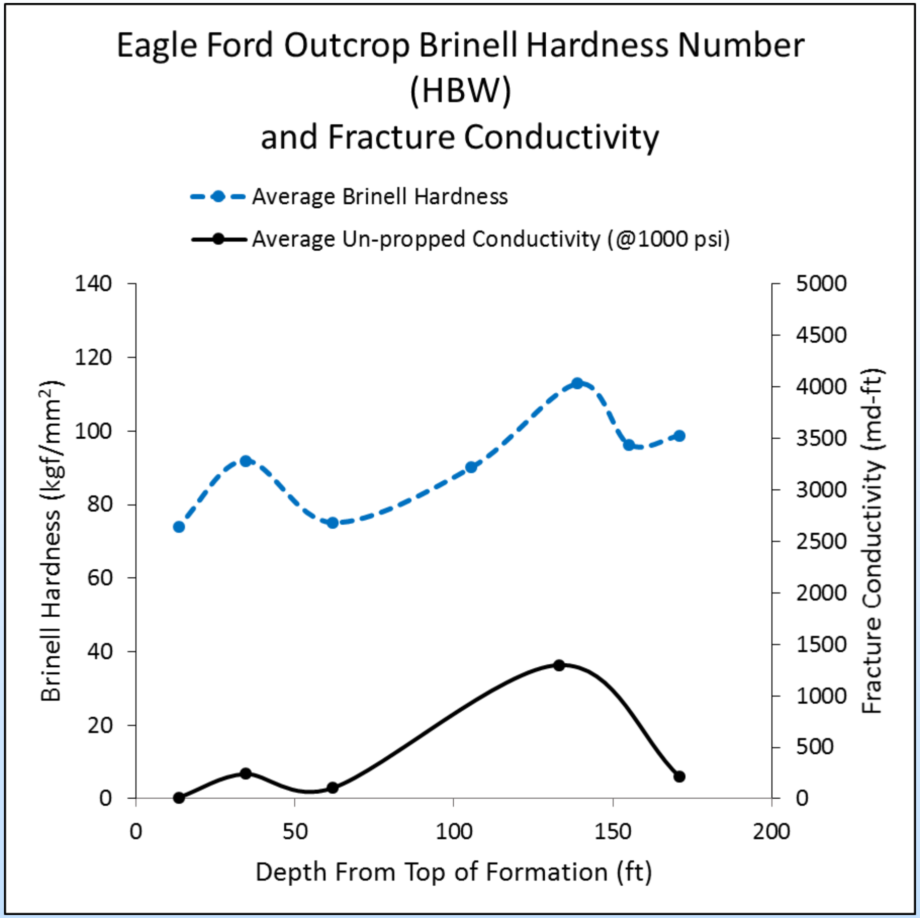
- Fracture conductivity, unpropped, propped with different size and concentration
- Mechanical property: Young’s Modulus and Poisson’s Ratio
- Surface topography
- Brinell hardness
- Brittleness
- Sample orientation

Conductivity for 100-Mesh



Brinell Hardness Number





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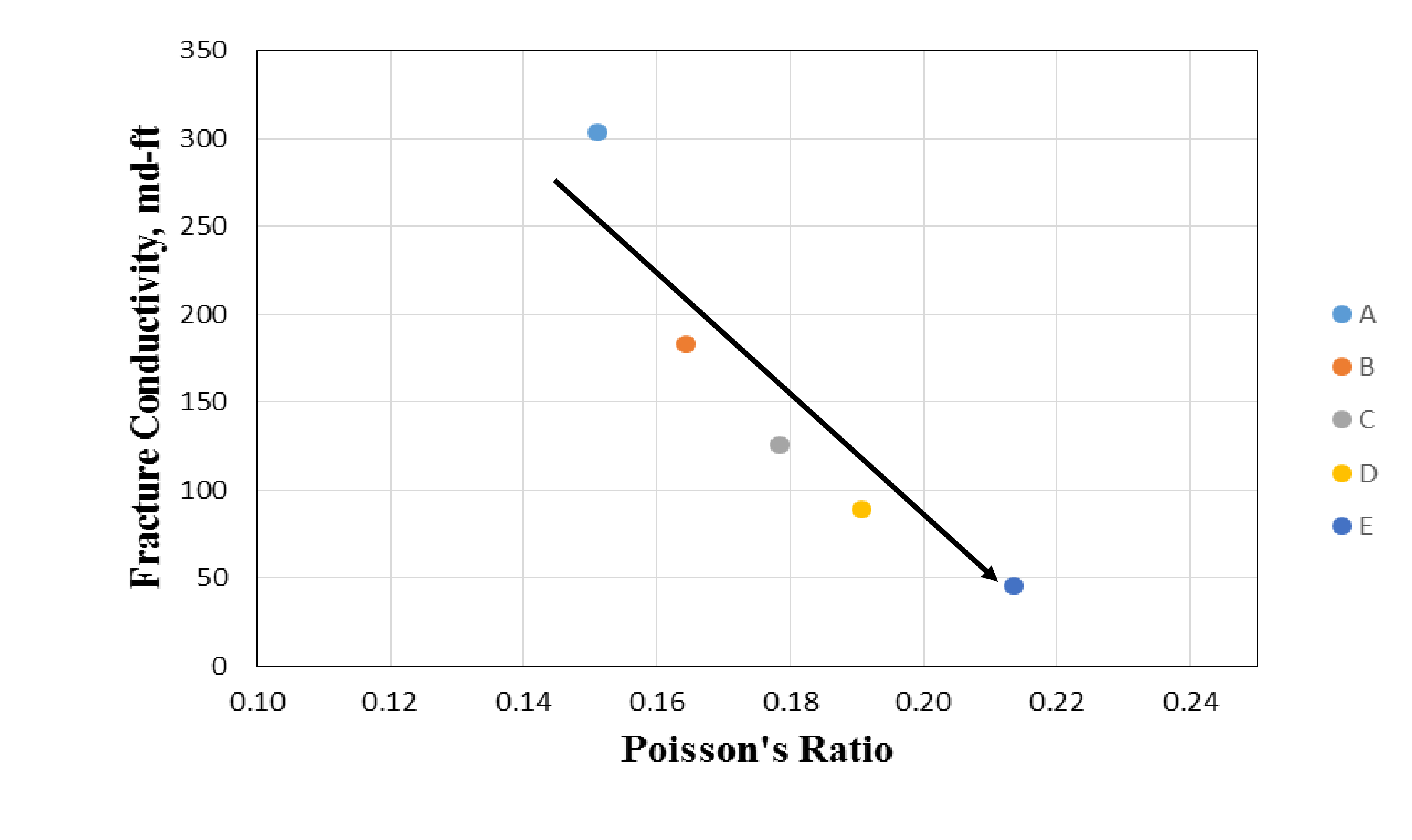
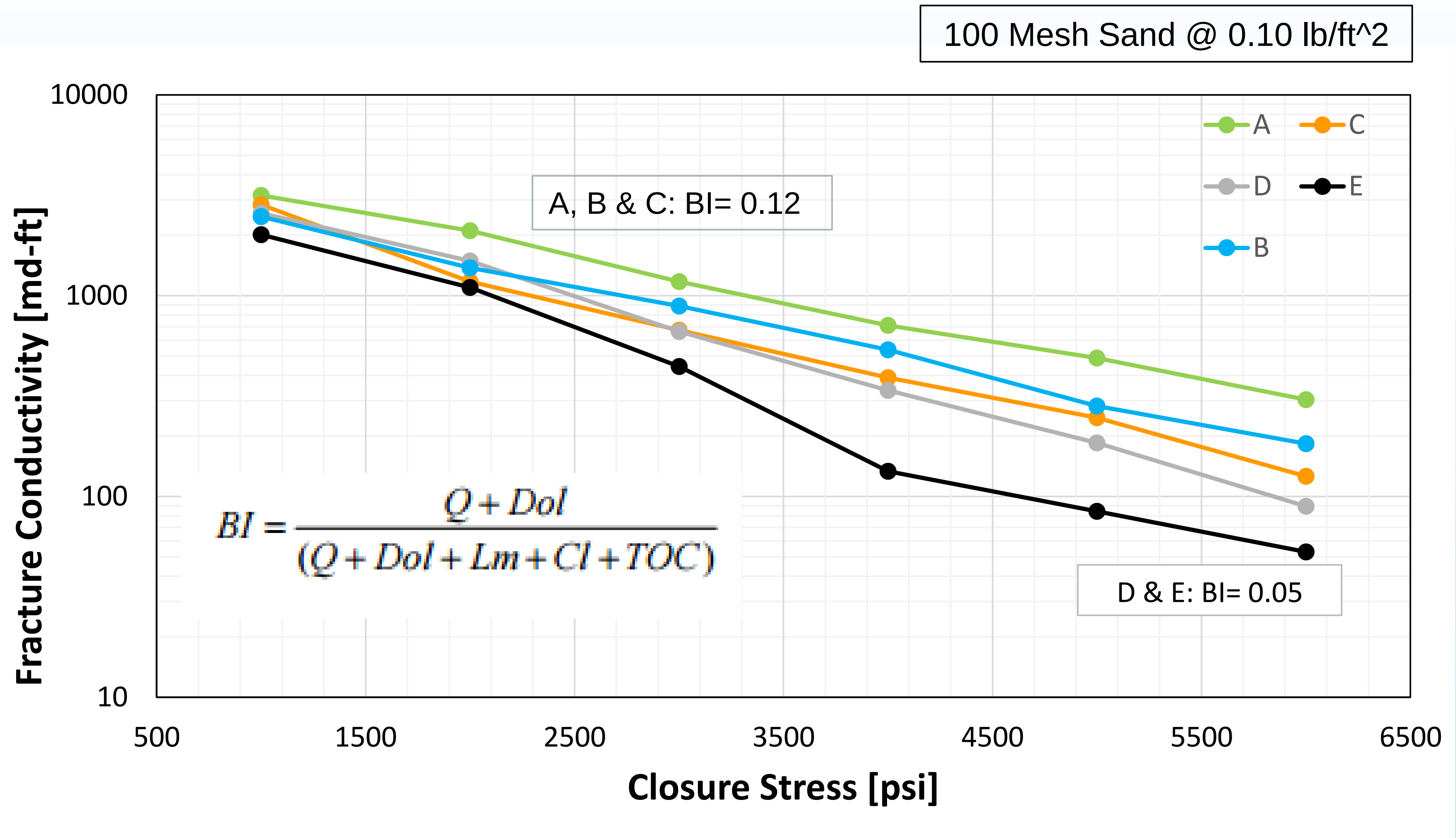
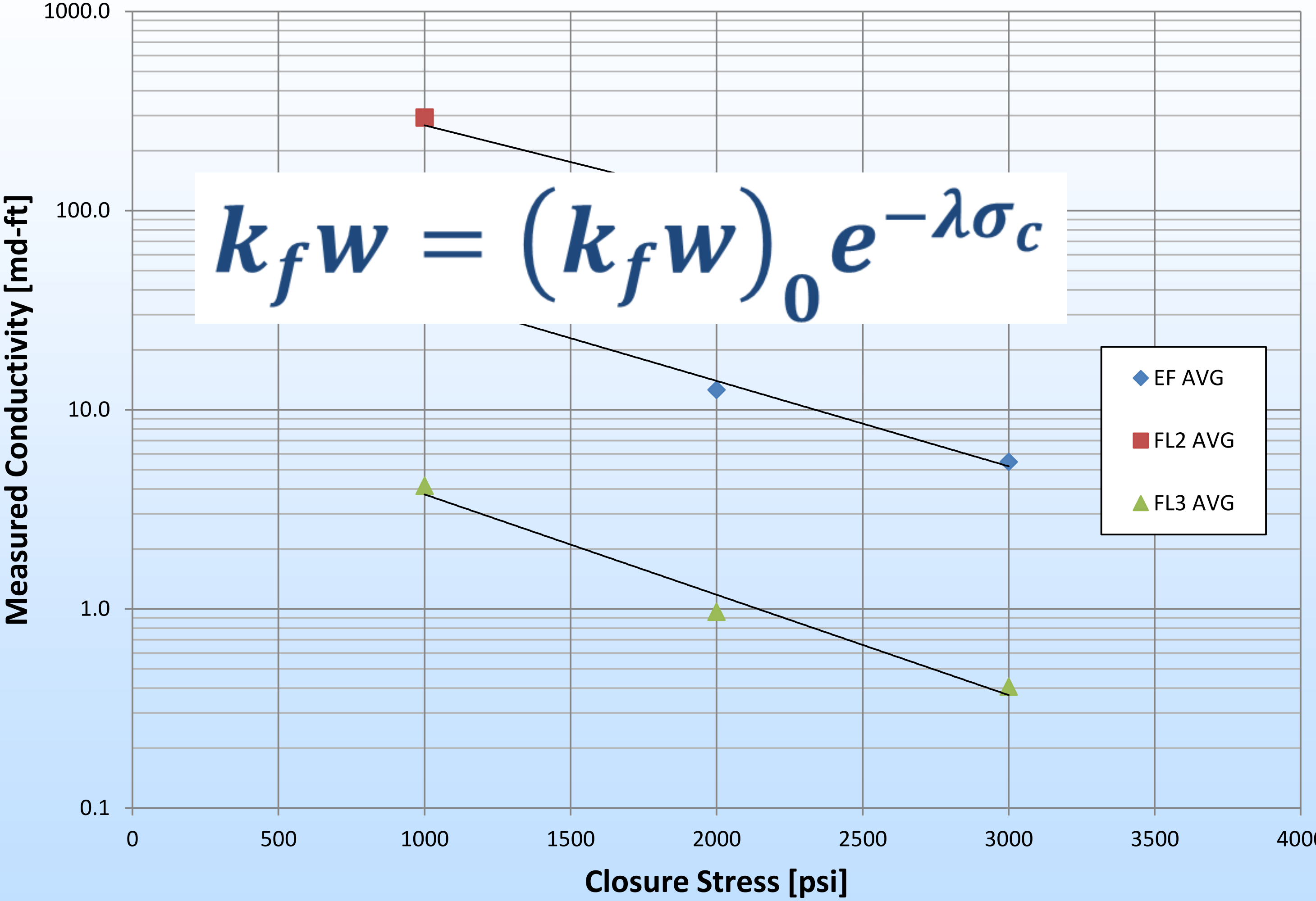
Fracture Conductivity at 6,000 psi vs Poisson's Ratio



Brittleness Effect on Conductivity

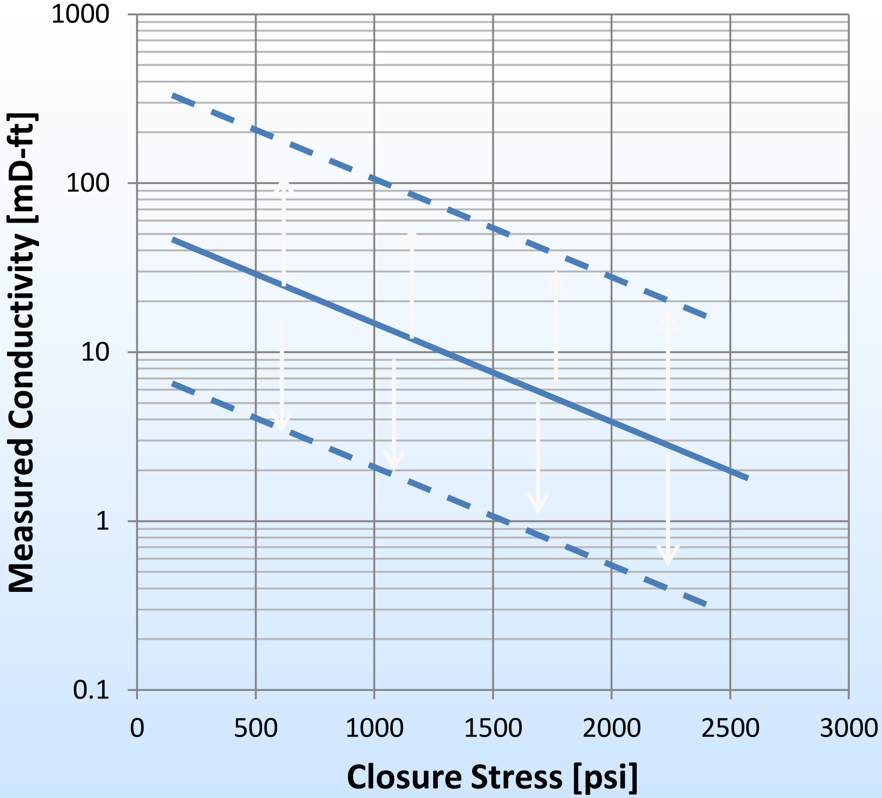


Unpropped Conductivity Correlation

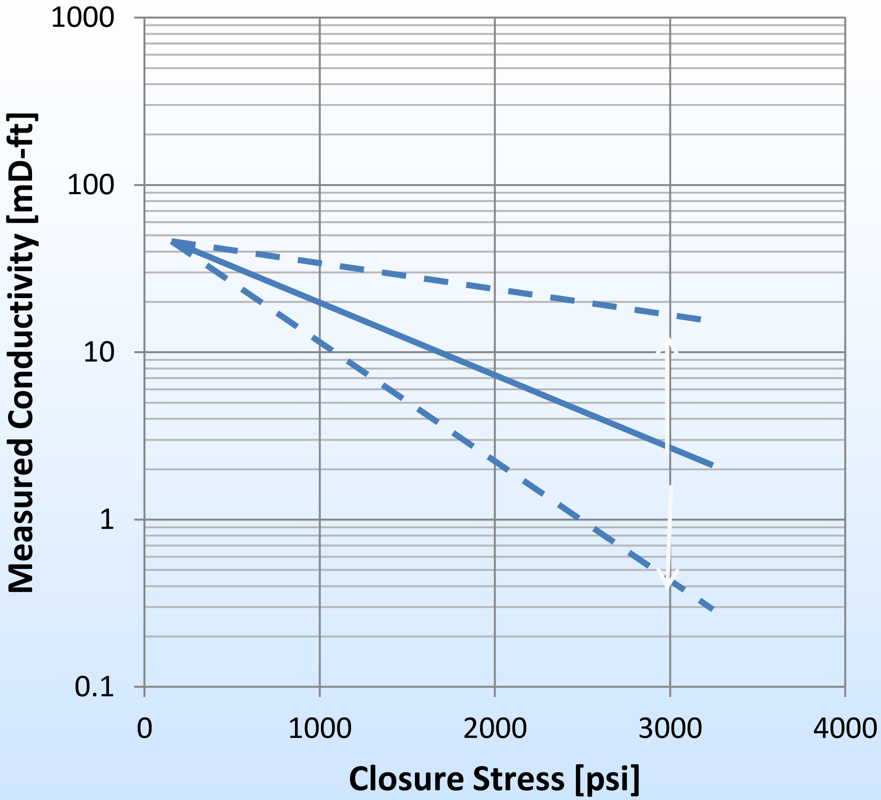


$$k_f w = \left(k_f w\right)_0 e^{-\lambda \sigma_c}$$

General Observation



Magnitude of initial conductivity is dominated by surface topography



Conductivity decline rate is controlled by mechanical properties

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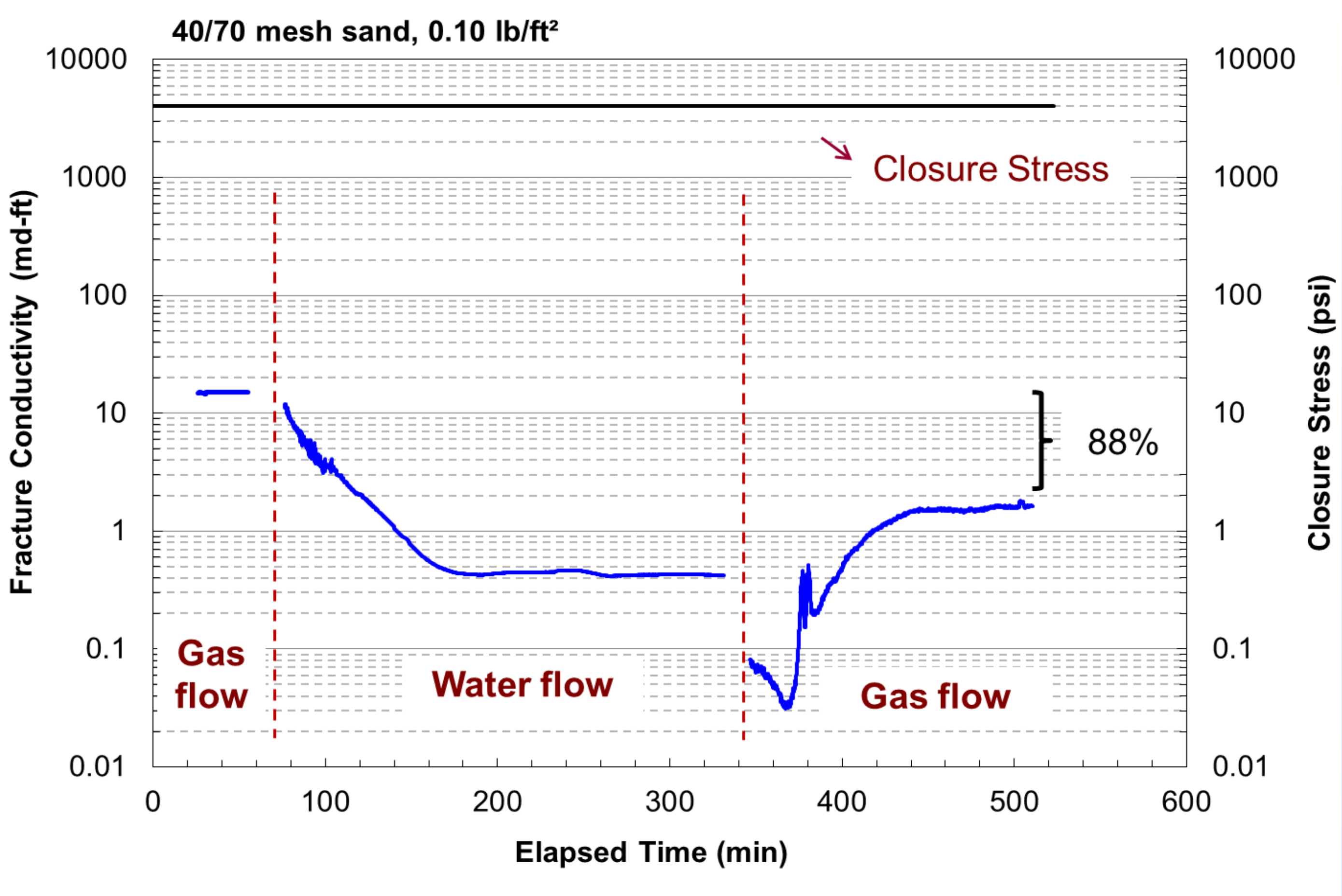
Water Damage

Water Damage to Conductivity in Shale Formation



Accomplishments to Date

- A comprehensive experimental database of fracture conductivity in shale oil and gas formations, including:
  - Barnett shale, Fayetteville shale, Marcellus shale, and Eagle Ford shale
- Unpropped and propped fracture conductivity behavior due to:
  - fracture alignment
  - closure stress
  - rock mechanical properties
  - mineralogy
  - fracture orientation
  - proppant type and concentration
- Water-induced fracture conductivity impairment

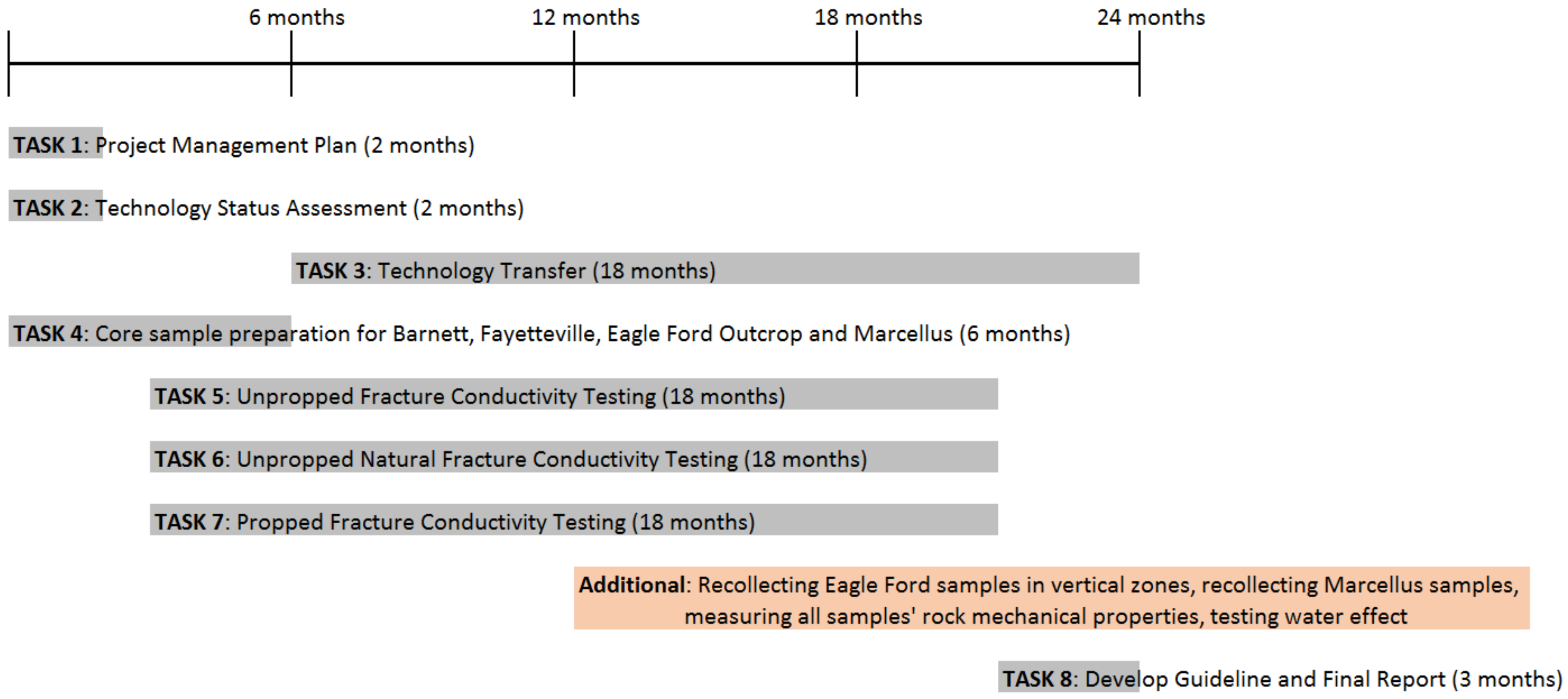
Summary

- Unpropped natural fracture conductivity is significant and important in unconventional reservoir fracturing. It is orders of magnitudes smaller than propped conductivity
- Samples obtained from downhole cores tend to have a higher unpropped conductivity due to a larger amount of debris generated and removed during the process of inducing fracture.
- Orientation of samples only has impact on tested conductivity when mechanical property is anisotropic. When it does, the conductivity can be an order of magnitude smaller
- Surface mechanical properties (Brinell Hardness) and topography (surface area) show a direct impact on fracture conductivity, specially unpropped. Higher hardness results in a higher conductivity.
- Effect of mineralogy on conductivity in terms of Brittleness showed that higher brittleness yields higher conductivity.

Organization Chart and Industrial Collaboration

- Two faculty:
  - Professor Ding Zhu
  - Professor Dan Hill
- 9 MS students with thesis
- 4 PhD students with dissertation
- Industrial support
  - Southwestern Energy
  - Pioneer
  - Hess
  - StimLab
  - Carbo Ceramics

Gantt Chart



NO COST EXTENSION (12 months)

Recollecting Eagle Ford samples in vertical zones (2 months, done)

Recollecting Marcellus samples with better integrity (1 month, done)

Measuring all samples' rock mechanical properties (12 months, done)

Testing water effect (12 months, to be completed by September, 2016)

Revisiting report (1 month, to be completed by September, 2016)

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4. Zhang, J., Hill A. D., and Zhu, D. :Experimental and Numerical Studies of Reduced Fracture Conductivity due to Proppant Embedment in Shale Reservoir, SPE paper 170775 prepared for presentation at the SPE Annual Technical Conference and Exhibition held in Amsterdam, The Netherlands, 27–29 October 2014.
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QUESTIONS?