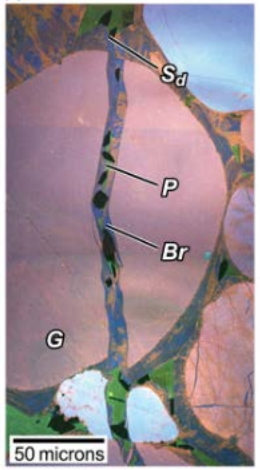
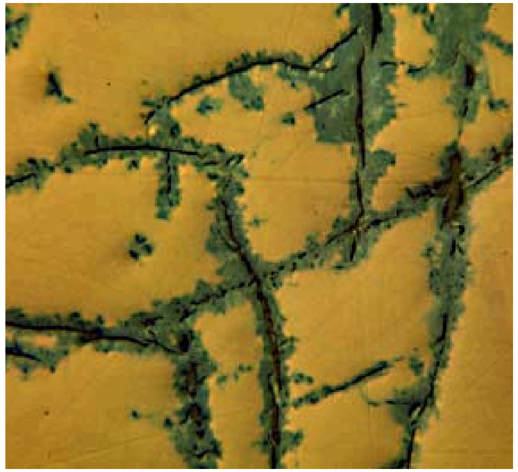
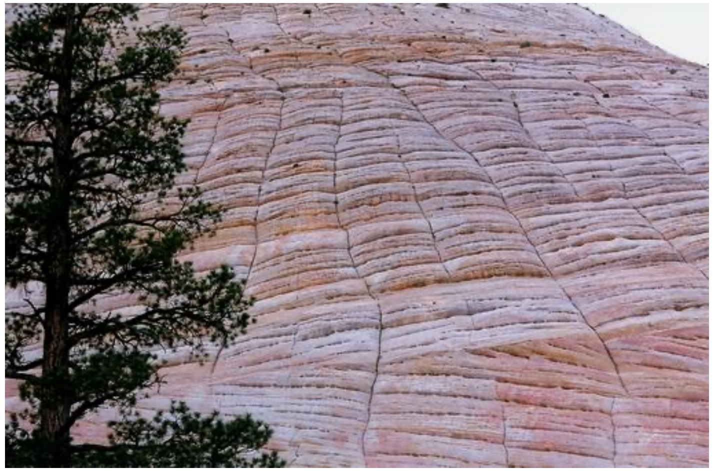
The Central Role of Geometry in Fracture Behavior

Laura J. Pyrak-Nolte
Purdue University








Sources available upon request

Topics that will be Touched on:

Advances in Fracture Characterization Methods: Highlight any recent breakthroughs or innovative approaches related to fracture characterization. This could include advancements in data collection, imaging techniques, or modeling.

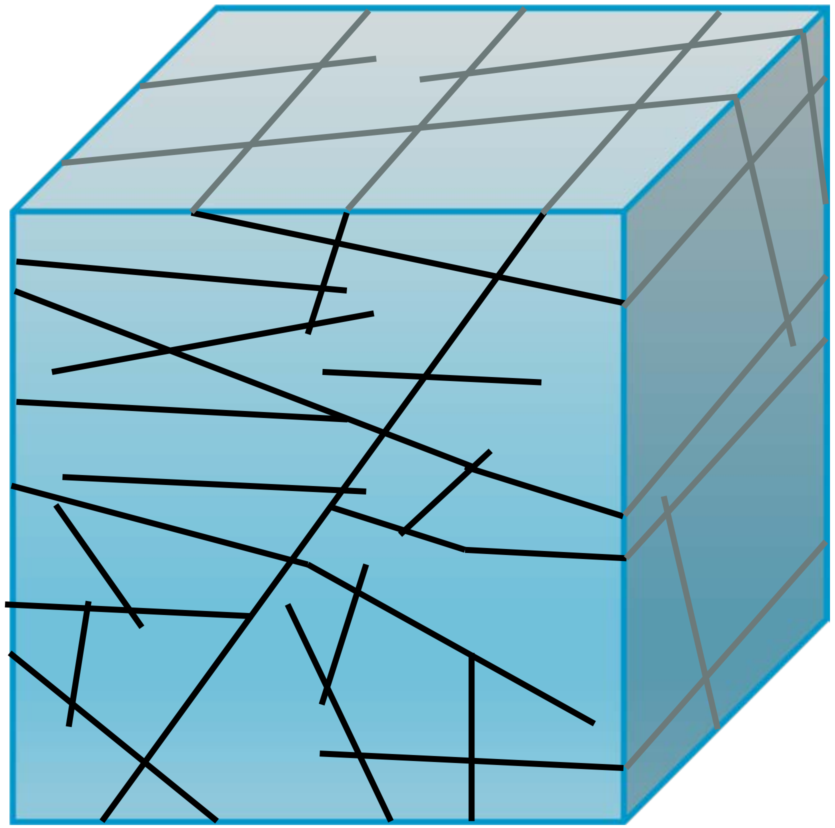
Representation of Fractures and Fracture Networks in Flow Models: Share insights into representing fractures within flow models. Consider discussing how these representations impact thermal, mechanical, and chemical processes in crystalline rocks.

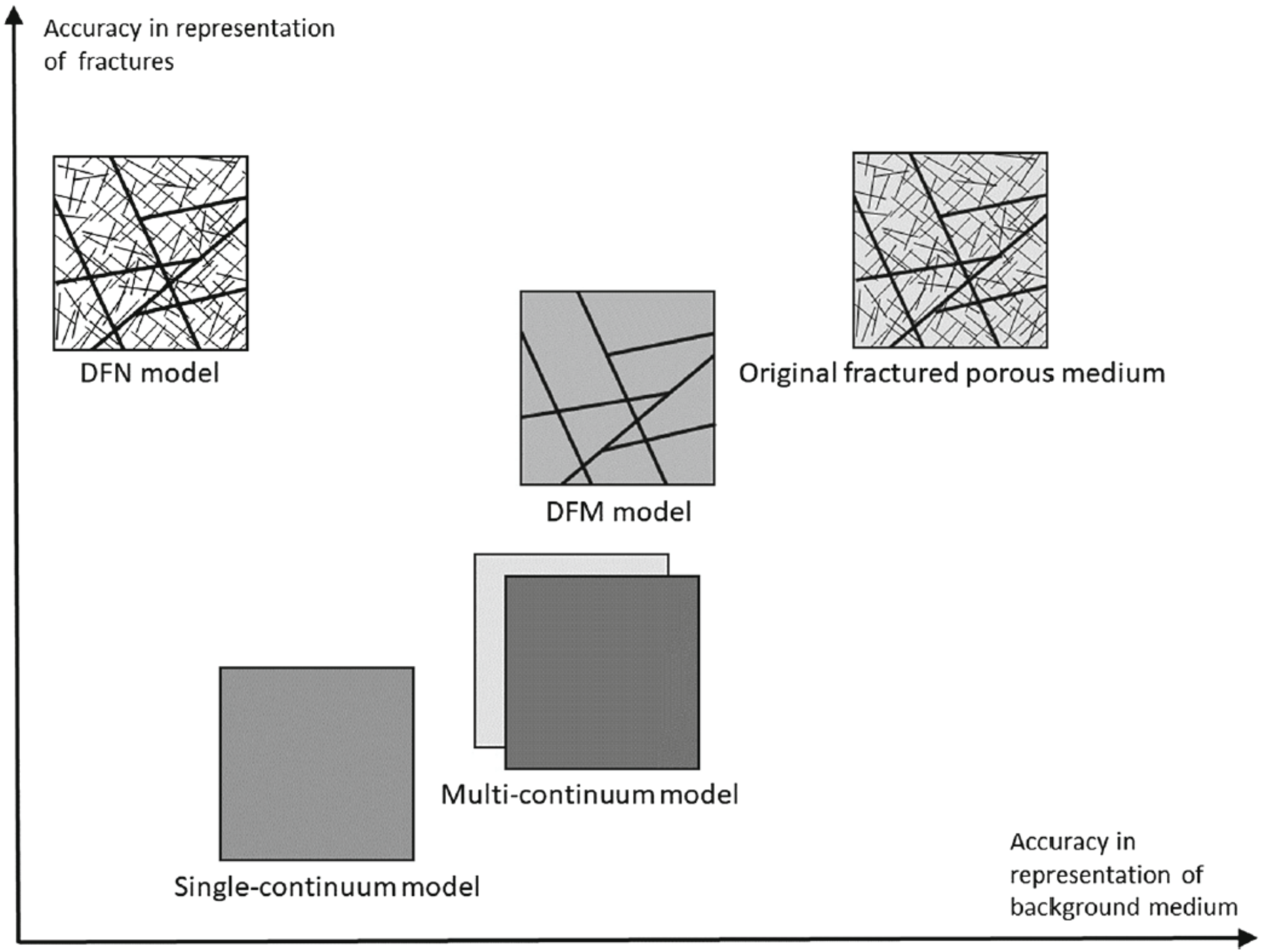
Projects Focused on Crystalline Rock Processes: If you've been involved in recent projects related to crystalline rock behavior, please provide an overview. Lessons learned from these endeavors would be valuable.

Lessons learned/insights from your research journey and future outlook: Valuable insights gained based on your research experience related to crystalline rocks. Additionally, share your vision for future research in this field.

Fracture Network Flow Models

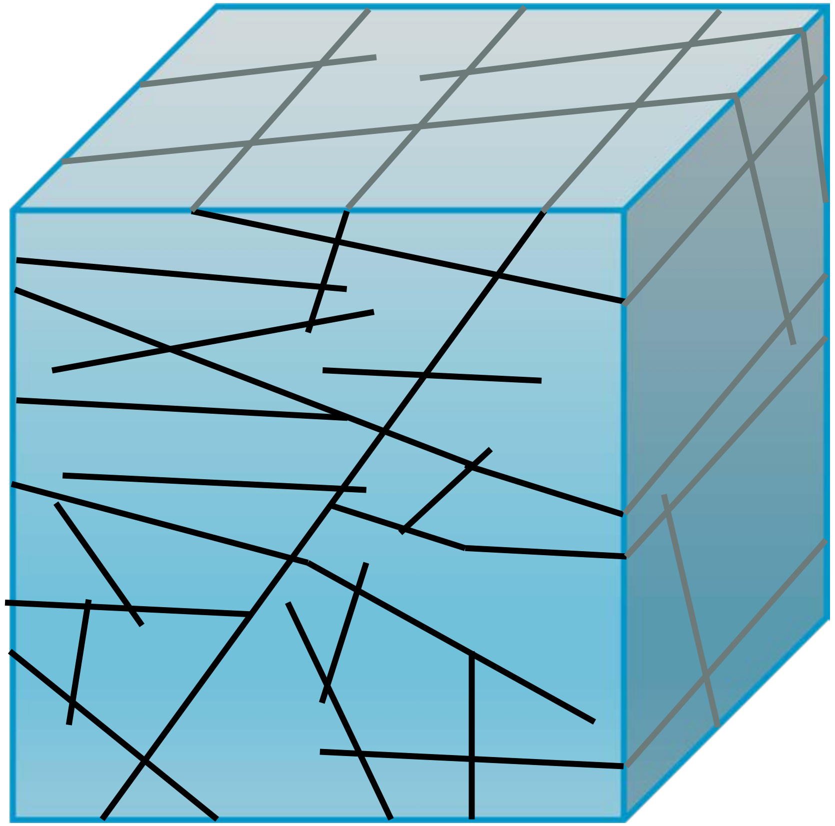
Laura J. Pyrak-Nolte | Purdue University





Berre et al., 2019

Fracture Network Models



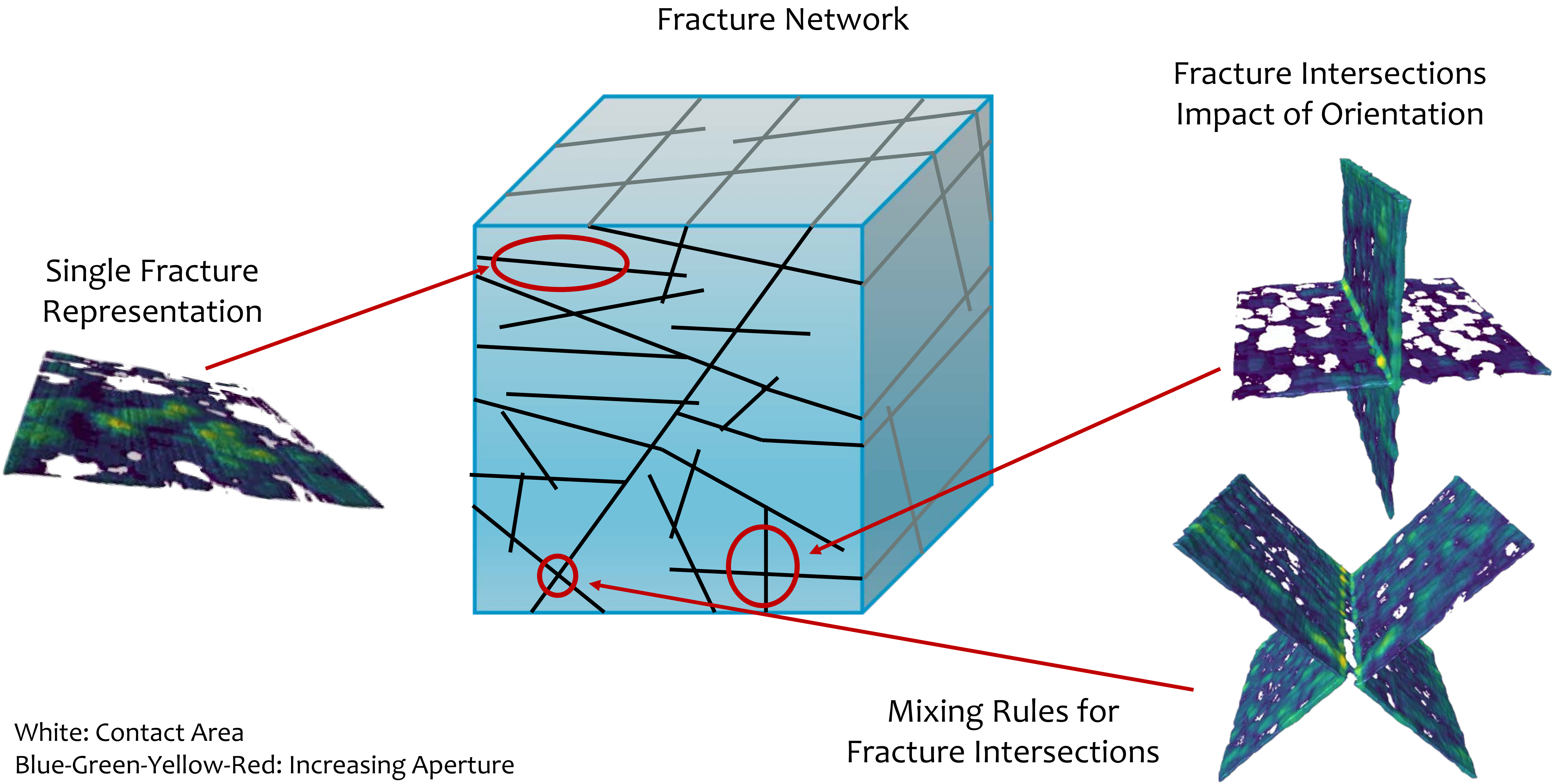
Key to Fracture Flow & Deformation Models:

Assumptions:

- fracture geometry (aperture, contact area, length, location, number, orientation, …)
- geometry evolution under stress or from other physical and chemical processes
- intersections (aperture, contact area, pinch points, …)
- fluid & material properties

Today: Insights from the Laboratory

Laura J. Pyrak-Nolte | Purdue University

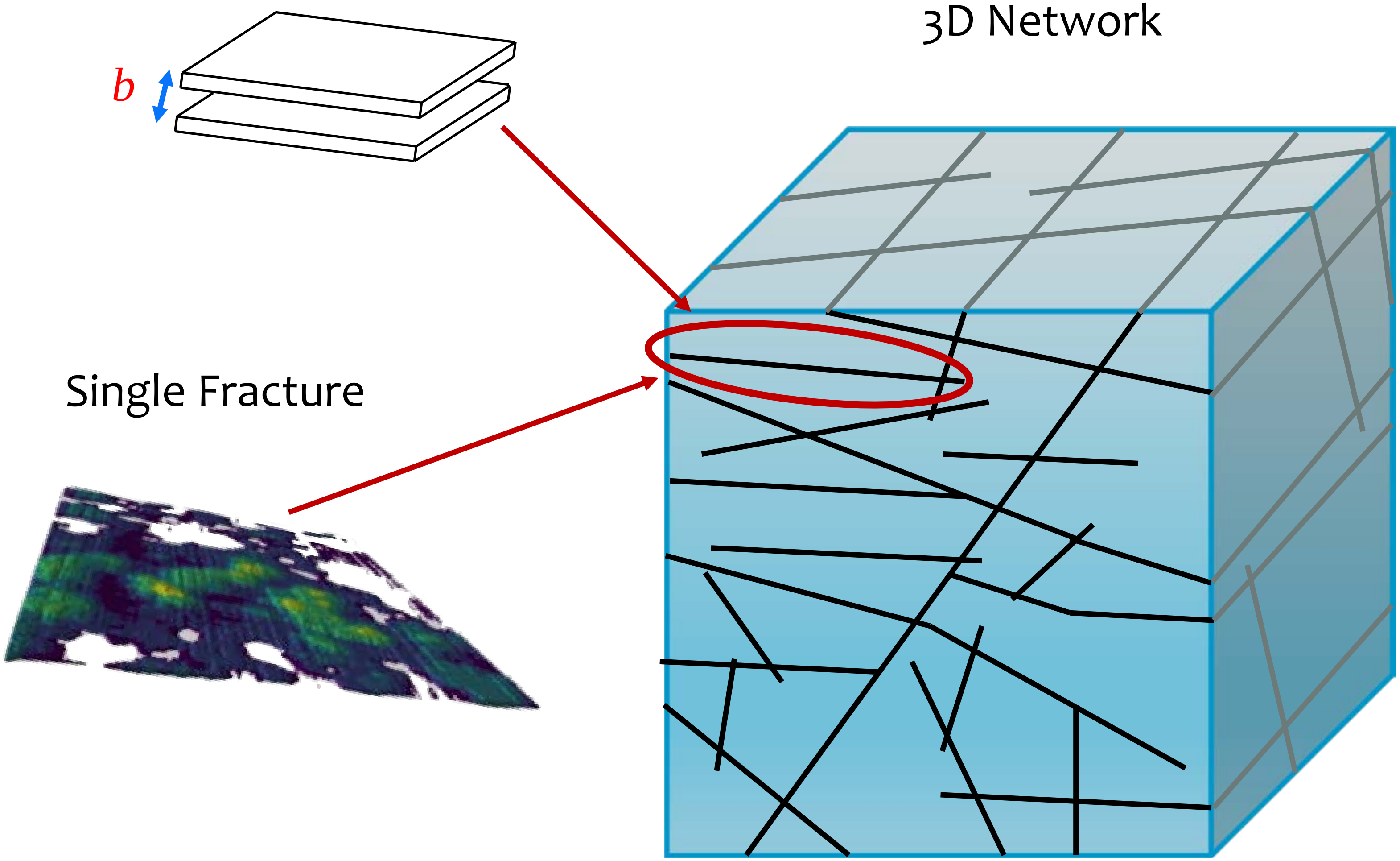


White: Contact Area
Blue-Green-Yellow-Red: Increasing Aperture

Begin with Flow in a Single Fracture

Laura J. Pyrak-Nolte | Purdue University

3D Network



Single Fracture

White: Contact Area
Blue-Green-Yellow-Red: Increasing Aperture

Cubic Law – parallel plates

$$Q = \frac{b^3 \Delta P}{12\mu L}$$

(Lomize, 1950)

b - *aperture*

ΔP – pressure drop

μ – viscosity

L – fracture length

Which aperture?

Hydraulic aperture

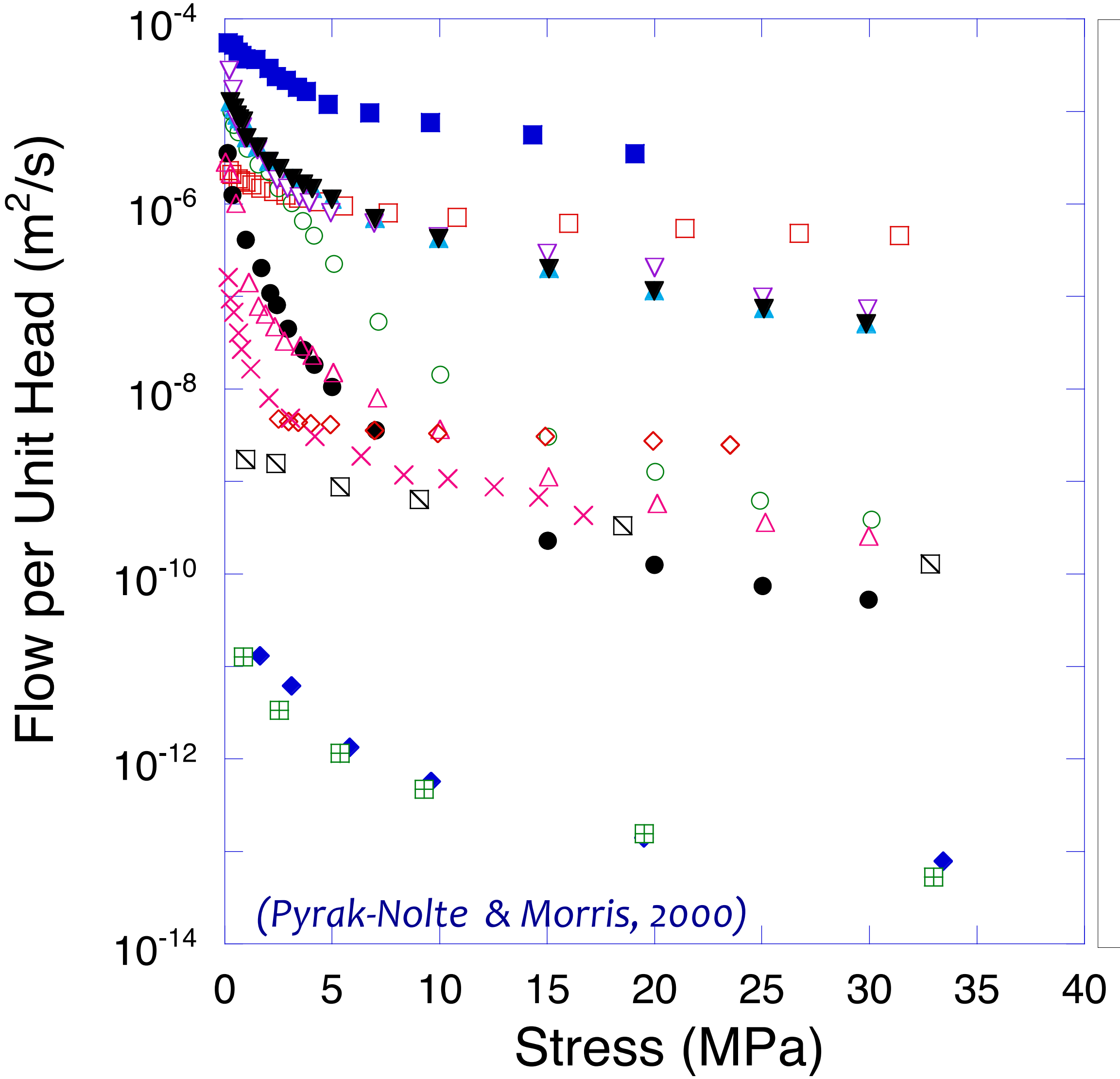
Mechanical aperture

Are either sufficient?

What about anisotropy?

Flow in a Single Fracture in Granitic Rock for different Fracture Lengths

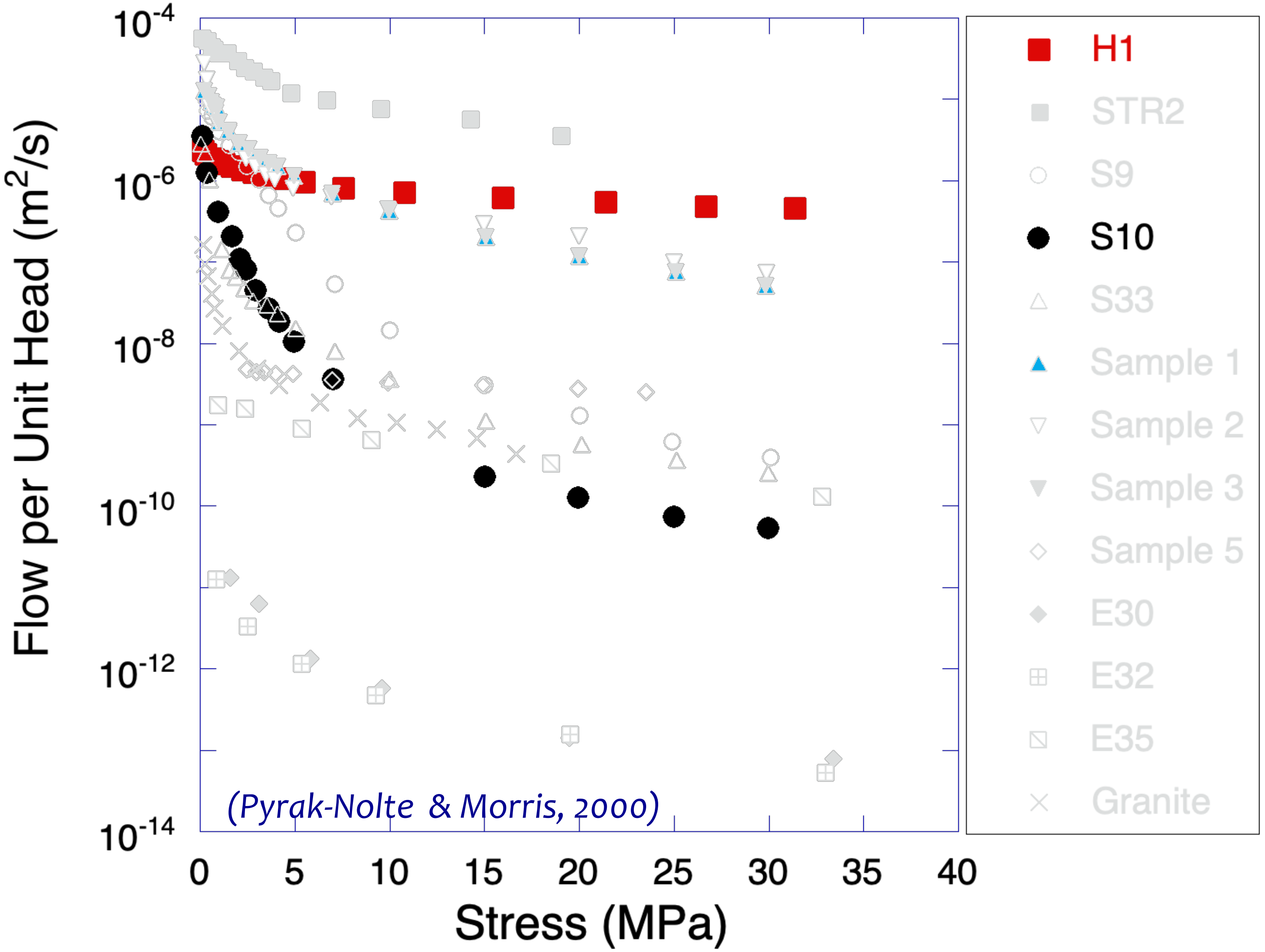
Laura J. Pyrak-Nolte | Purdue University



Sample	Fracture Length (m)	Rock Type
H1	0.159	Granite, URL, Manitoba
STR2	0.152	Stripa Granite
S9	0.15	Granitic Gneiss
S10	0.15	Granitic Gneiss
S33	0.15	Granitic Gneiss
Sample 1	0.1	Charcoal Black Granite, MN
Sample 2	0.15	Charcoal Black Granite, MN
Sample 3	0.193	Charcoal Black Granite, MN
Sample 5	0.294	Charcoal Black Granite, MN
E30	0.052	Stripa Granite
E32	0.052	Stripa Granite
E35	0.052	Stripa Granite
Granite	0.207	Granite

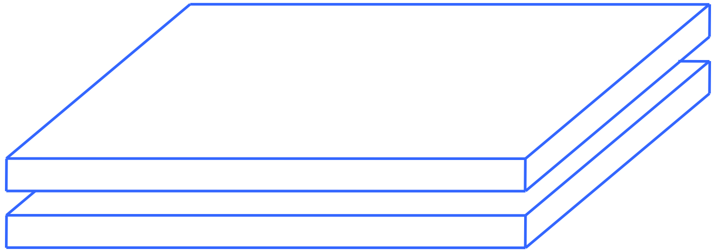
Flow in a Single Fracture in Granitic Rock for different Fracture Lengths

Laura J. Pyrak-Nolte | Purdue University

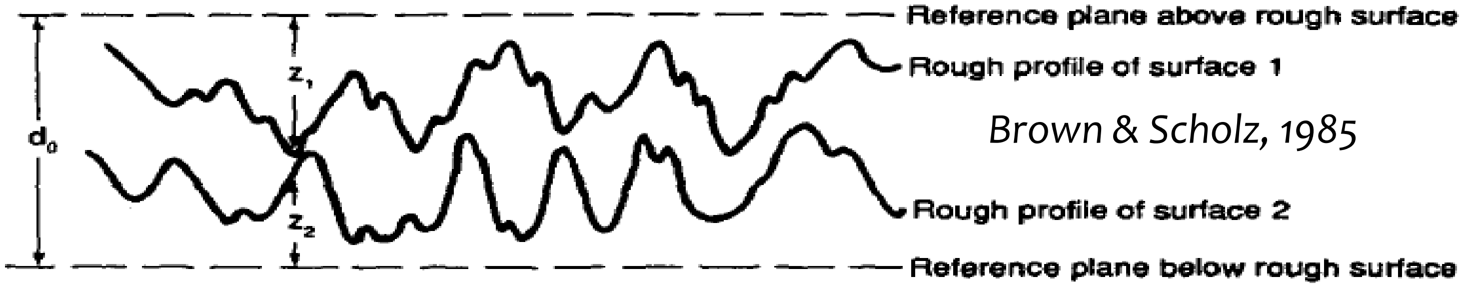


Fracture Length (m)	Rock Type
0.159	Granite, URL, Manitoba
0.152	Stripa Granite
0.15	Granitic Gneiss
0.15	Granitic Gneiss
0.15	Granitic Gneiss
0.1	Charcoal Black Granite, MN
0.15	Charcoal Black Granite, MN
0.193	Charcoal Black Granite, MN
0.294	Charcoal Black Granite, MN
0.052	Stripa Granite
0.052	Stripa Granite
0.052	Stripa Granite
0.207	Granite

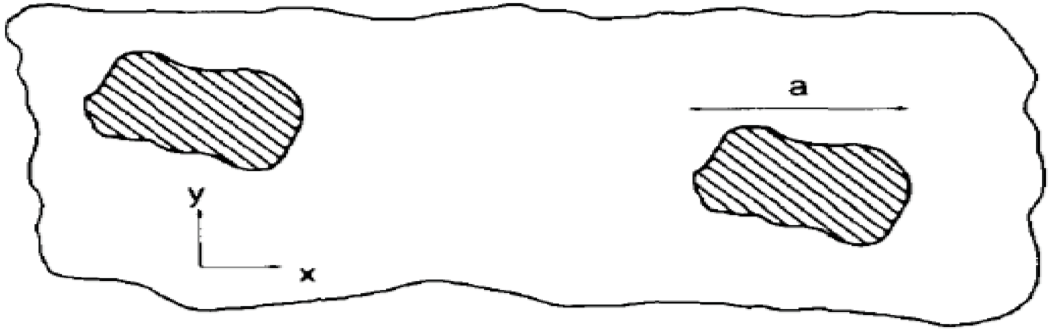
Fluid Flow: Evolution of Single Fracture Representation from Experimental Data



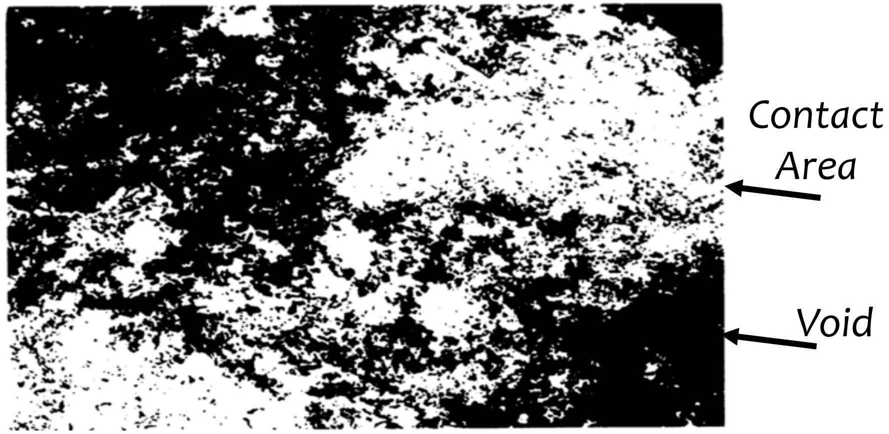
Lomize, 1951



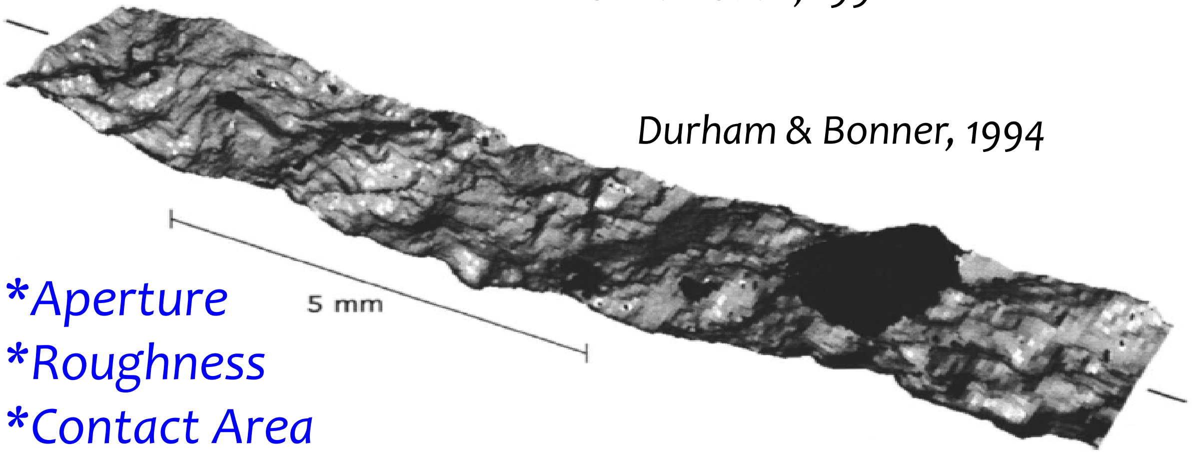
Brown & Scholz, 1985



Zimmerman et al., 1992



Pyrak-Nolte et al., 1987



Durham & Bonner, 1994

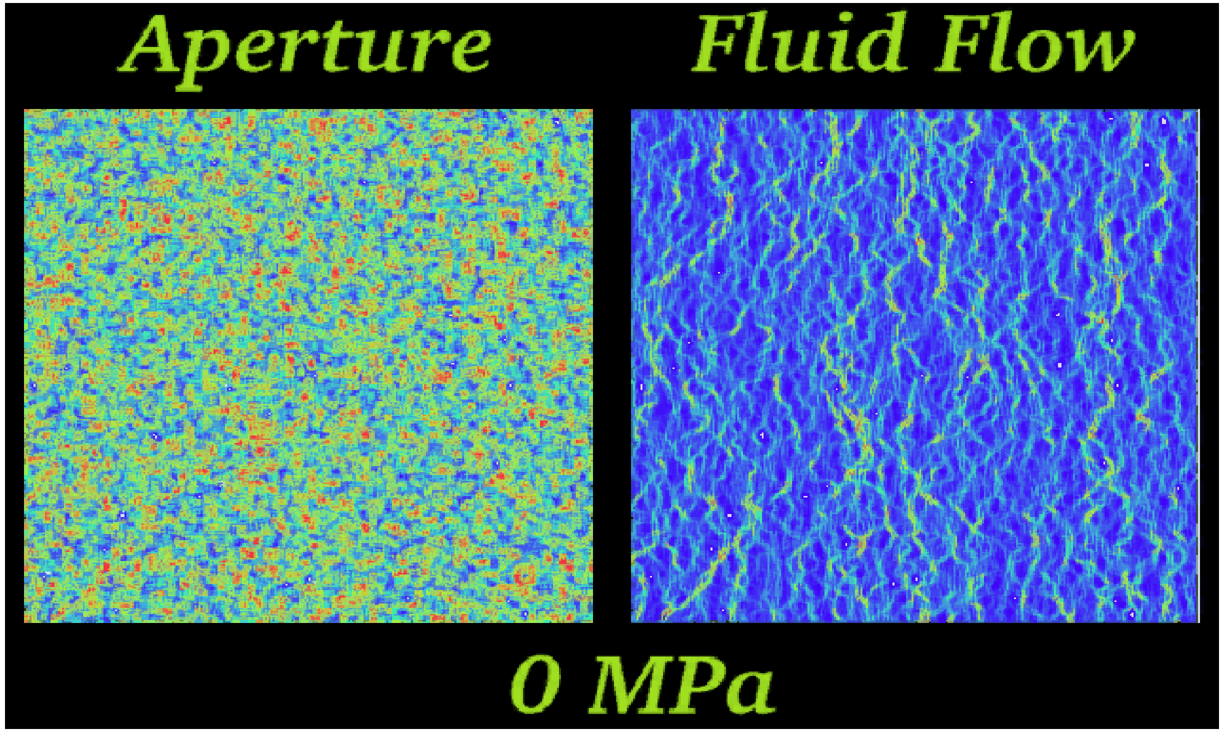
Grader et al., 2003

**Aperture*
**Roughness*
**Contact Area*

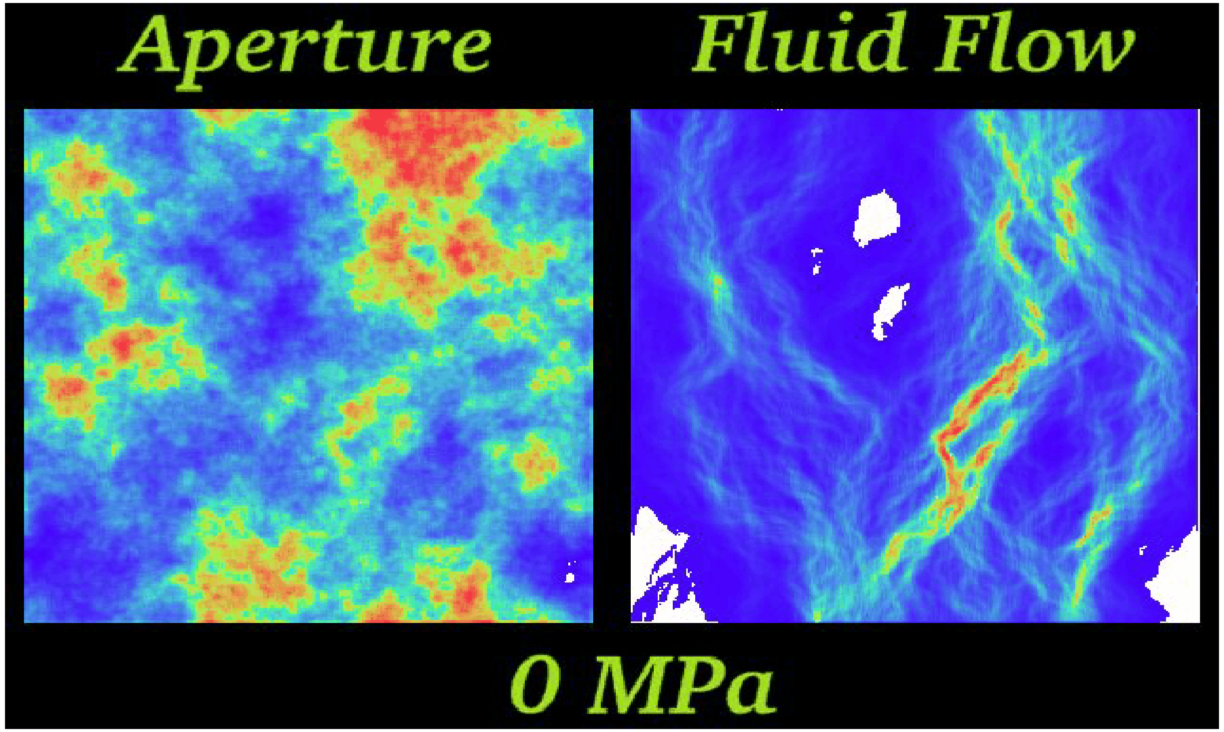
Spatial Distribution of Apertures & Contacts Matter

Laura J. Pyrak-Nolte | Purdue University

Random Distribution



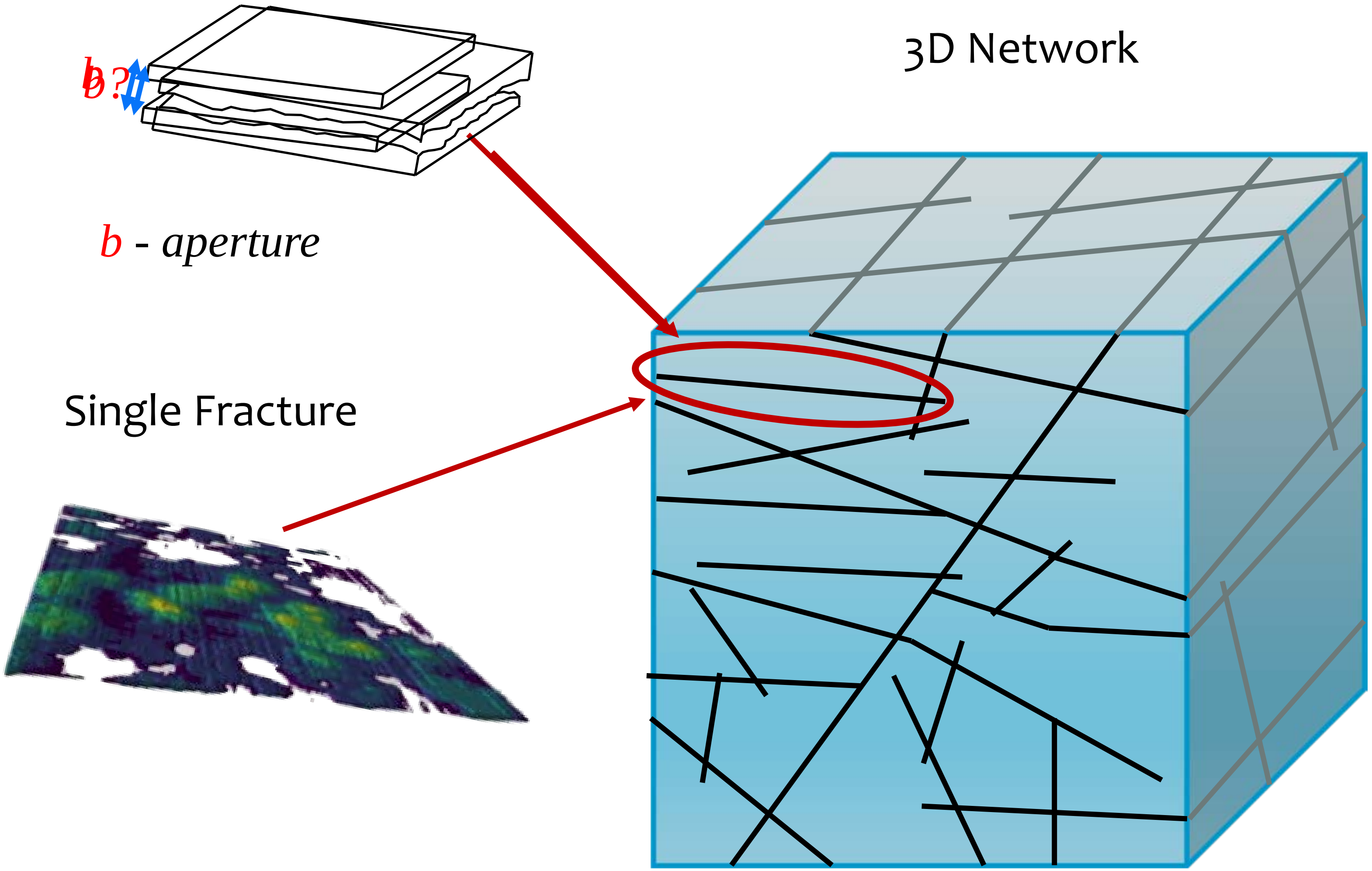
Spatially Correlated



White: Contact Area/No Flow
Blue-Green-Yellow-Red: Increasing Aperture/Increasing Flow Rate

Representation of Deformation of a Single Fracture

Laura J. Pyrak-Nolte | Purdue University



White: Contact Area
Blue-Green-Yellow-Red: Increasing Aperture

Closure law

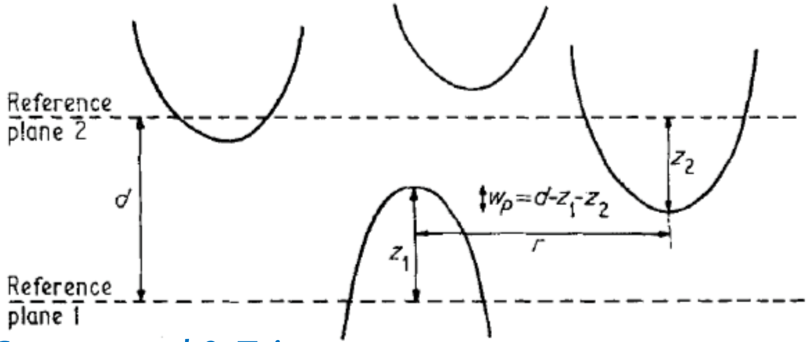
$$\sigma = C\frac{\delta_{max}}{\delta_{max} - \delta}$$

δ - *closure*
C – *modulus*
σ – *normal stress*

(Bandis & Barton, 1983)

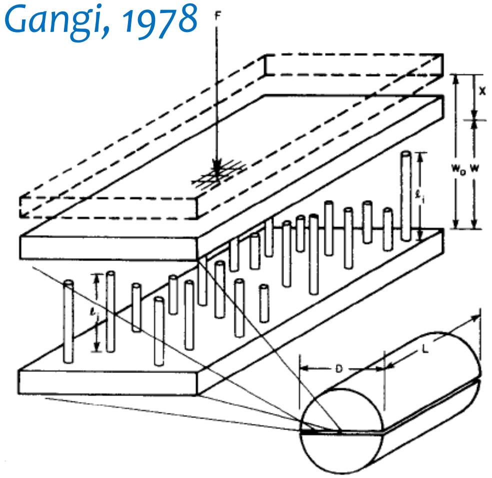
How does *δ* relate to *b*?
Is there a disconnect between Cubic law assumption & closure law?

Deformation: Evolution of Single Fracture Representation from Experimental Data

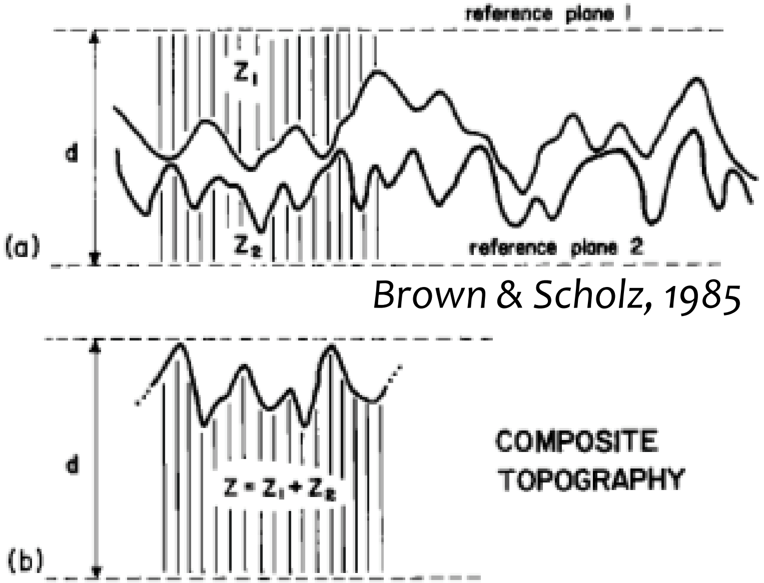


Greenwood & Tripp, 1971

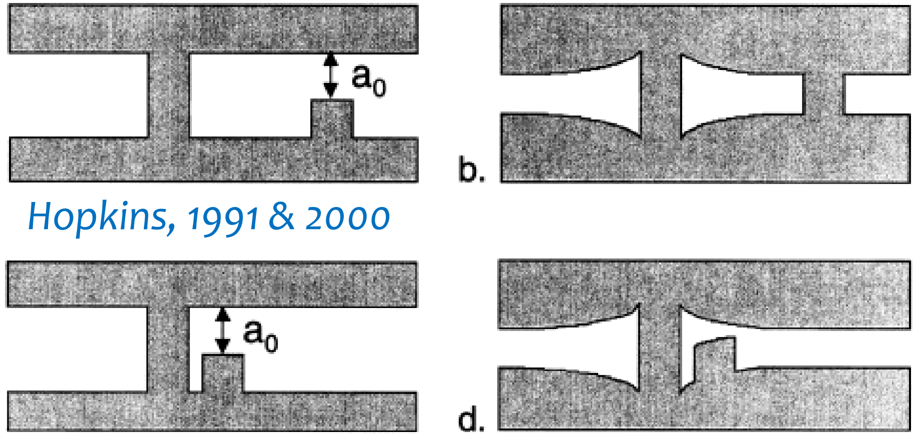
Gangi, 1978



*Roughness
*Contact Area
*Aperture

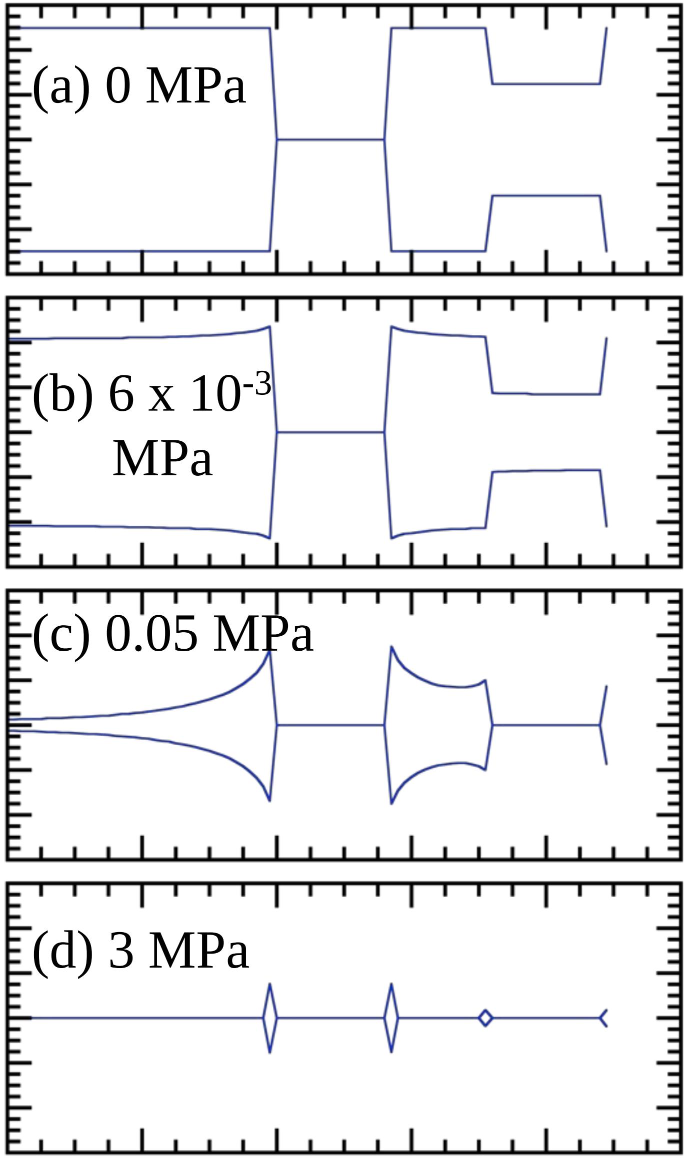


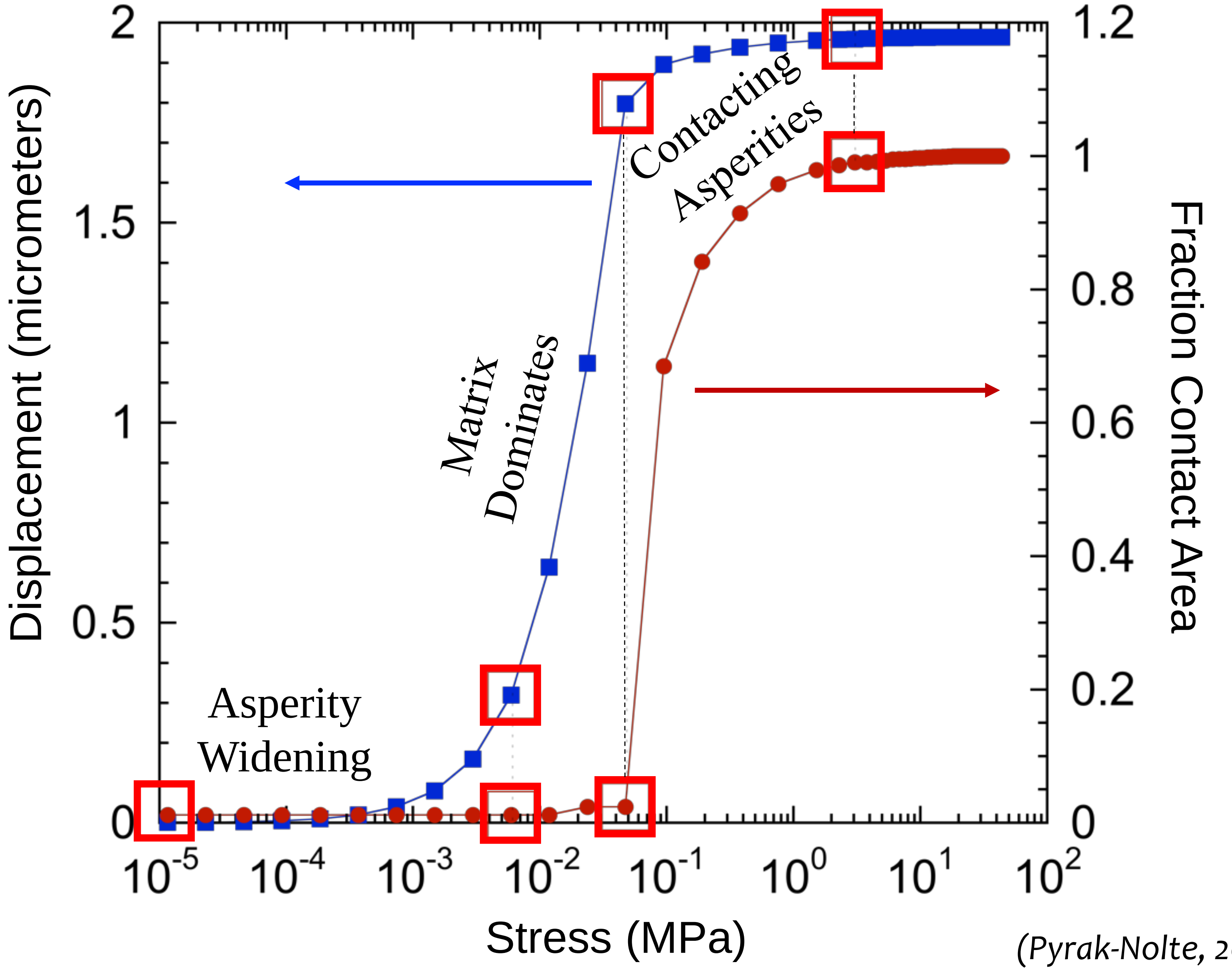
Brown & Scholz, 1985



Hopkins, 1991 & 2000

Simple Example of Hopkin's Approached to Fracture Deformation



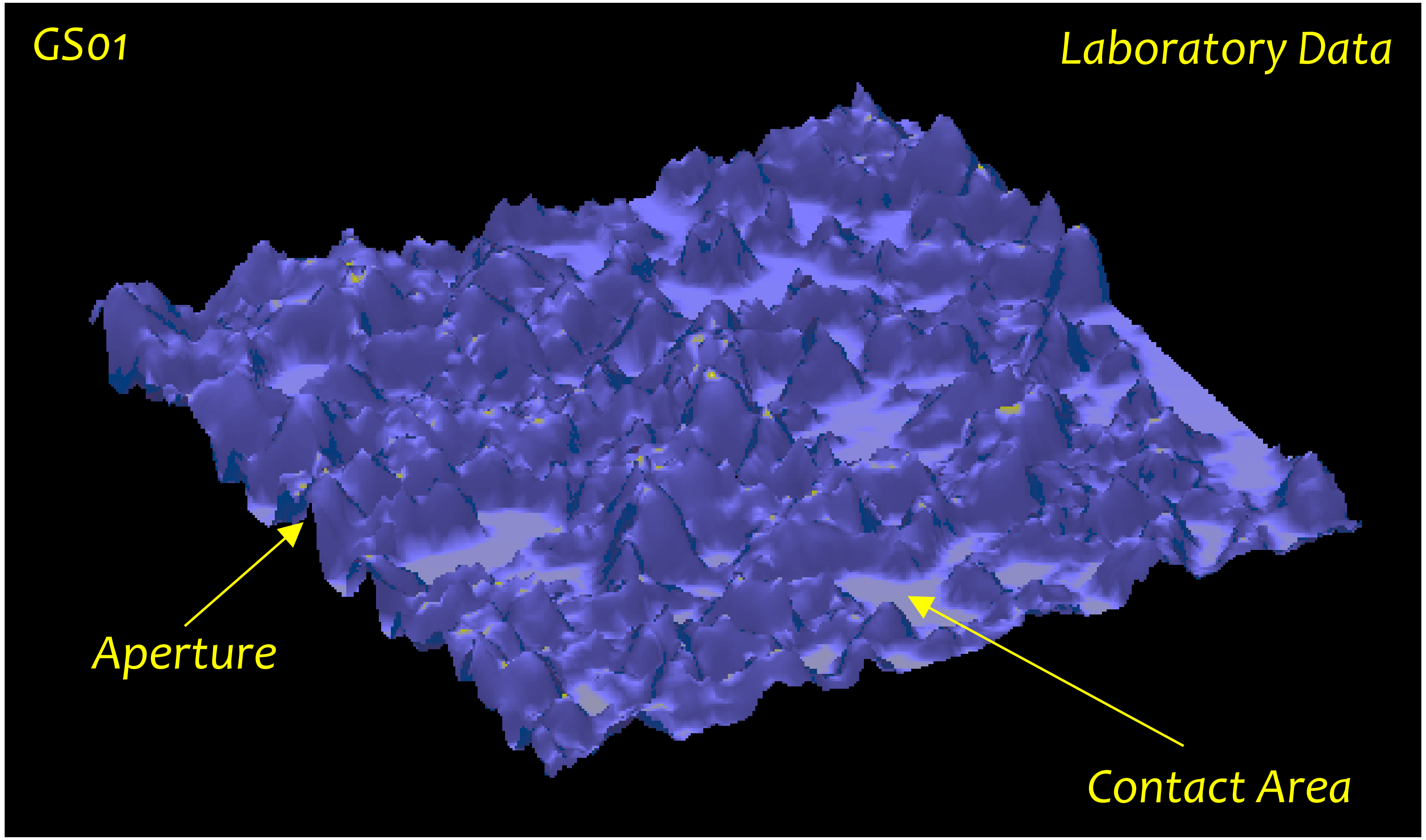


(Pyrak-Nolte, 2019)

Single Fractures: What really matters for flow & deformation?

Laura J. Pyrak-Nolte | Purdue University

- *Deformed geometry of two rough surfaces in contact: Spatial & Probability Distributions of Apertures & Contact Area*

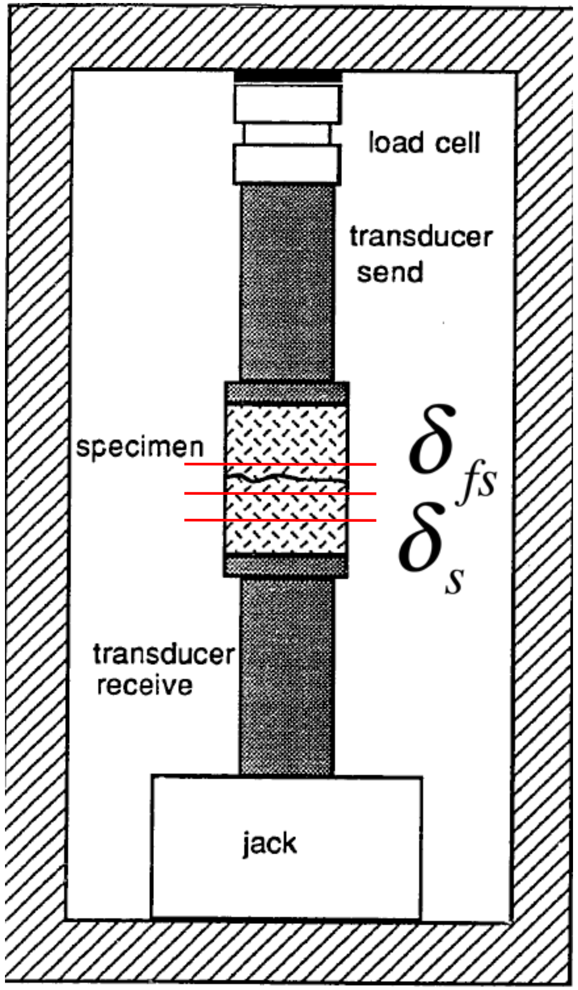


Fracture Specific Stiffness

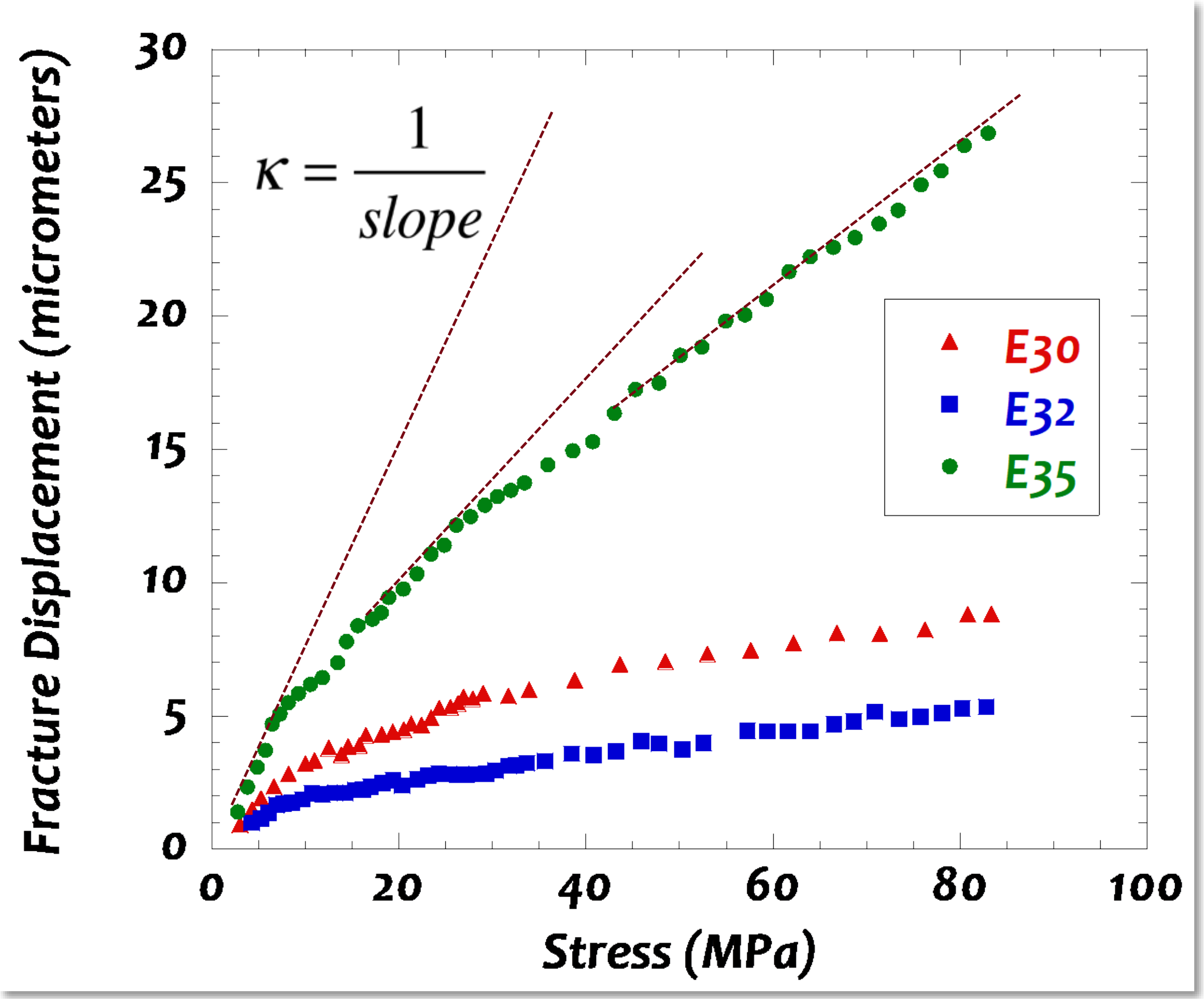
Laura J. Pyrak-Nolte | Purdue University

- *relates an increment in stress to the resulting additional increment in displacement from the fracture*

$$\kappa = \frac{\partial \sigma}{\partial \delta}$$

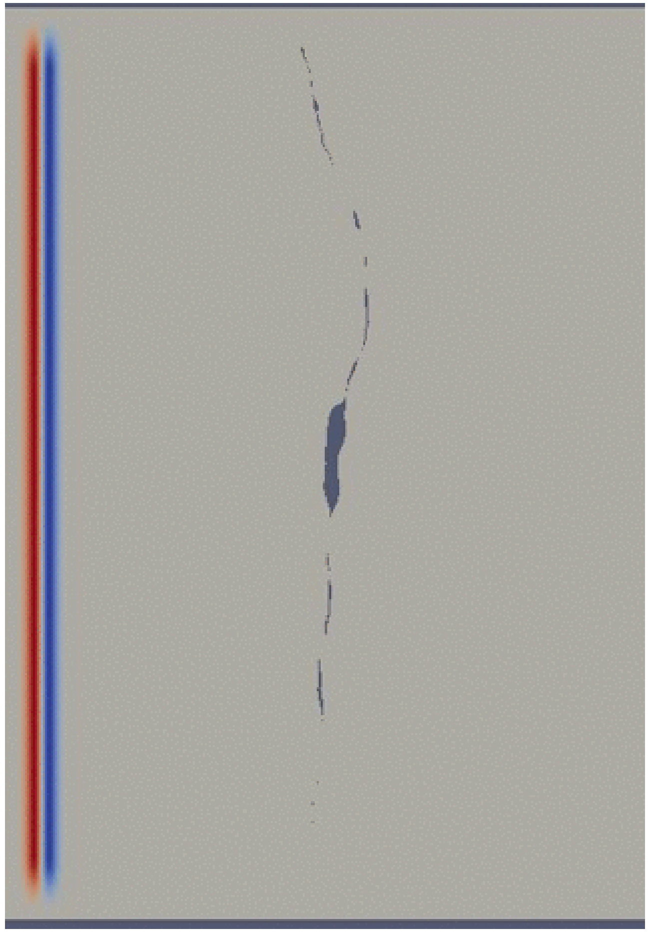


$$\delta = \delta_{fs} - \delta_s$$



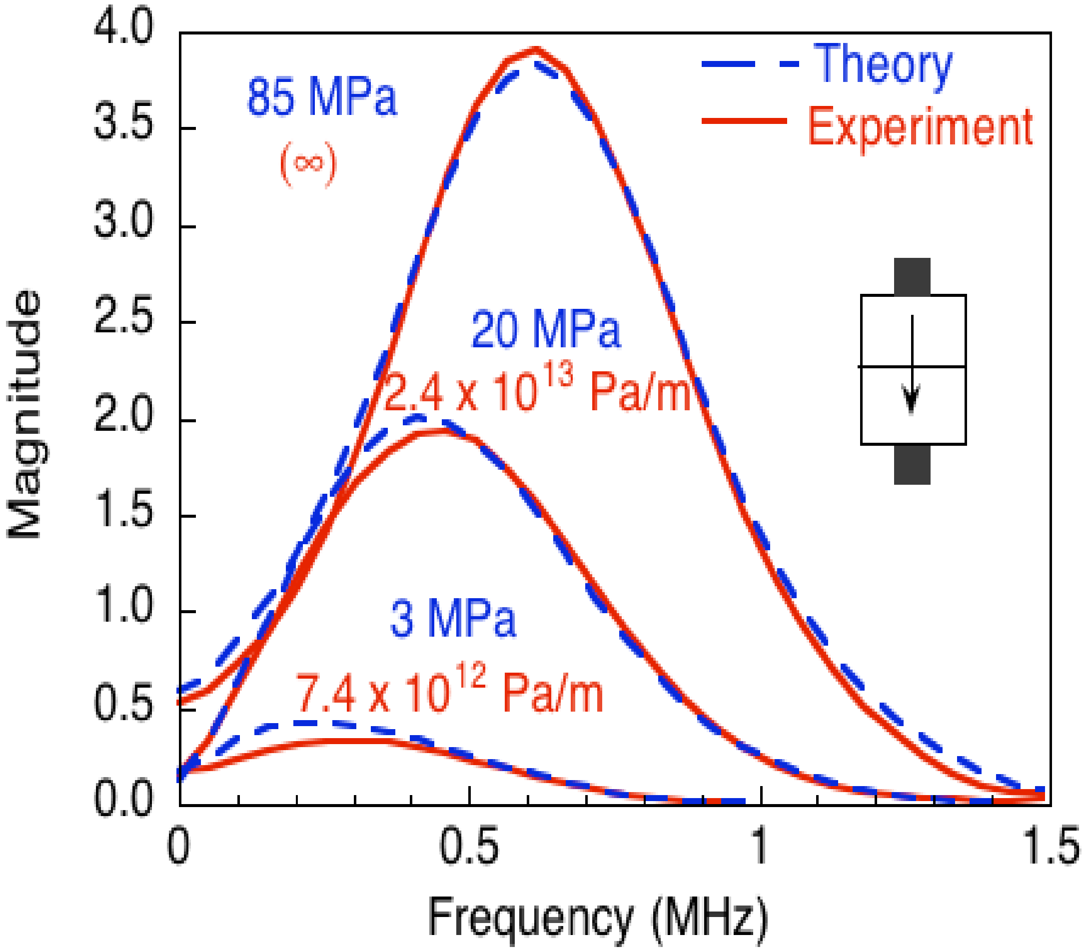
Wave Propagation across a Single Fracture: Simulations & Experiments

Discontinuous Galerkin Method



(Petrovitch, 2013; Shao et al., 2015; Ye, de Hoop, Petrovitch, Pyrak-Nolte & Wilcox, 2016)

Comparison Theory & Experiment



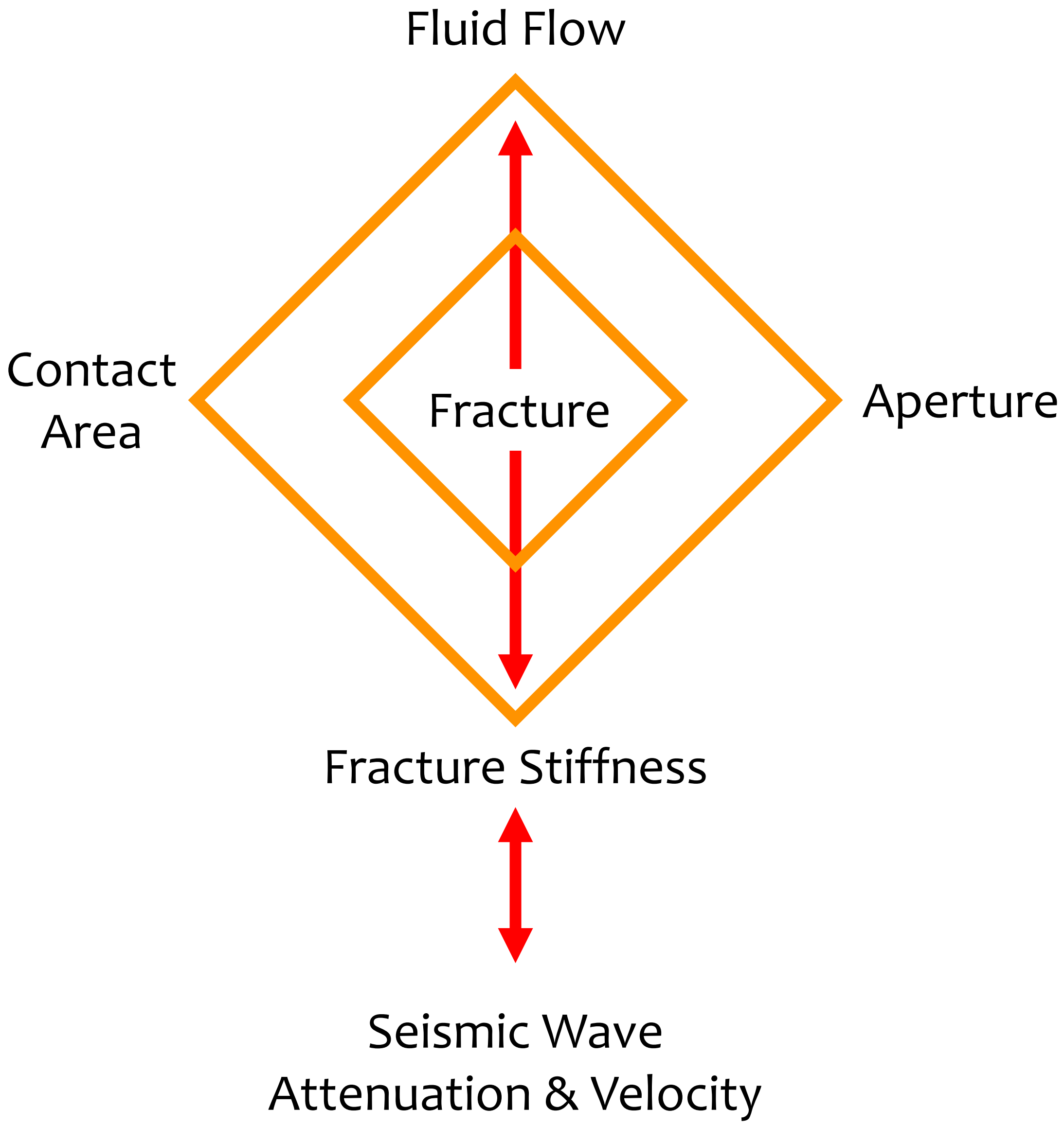
(Pyrak-Nolte, Myer & Cook, 1990)

$$T(\omega) = \frac{1}{1 + i\frac{\omega Z}{2\kappa}}$$

κ – Fracture Specific Stiffness
ω – frequency
Z – seismic impedance = velocity * density

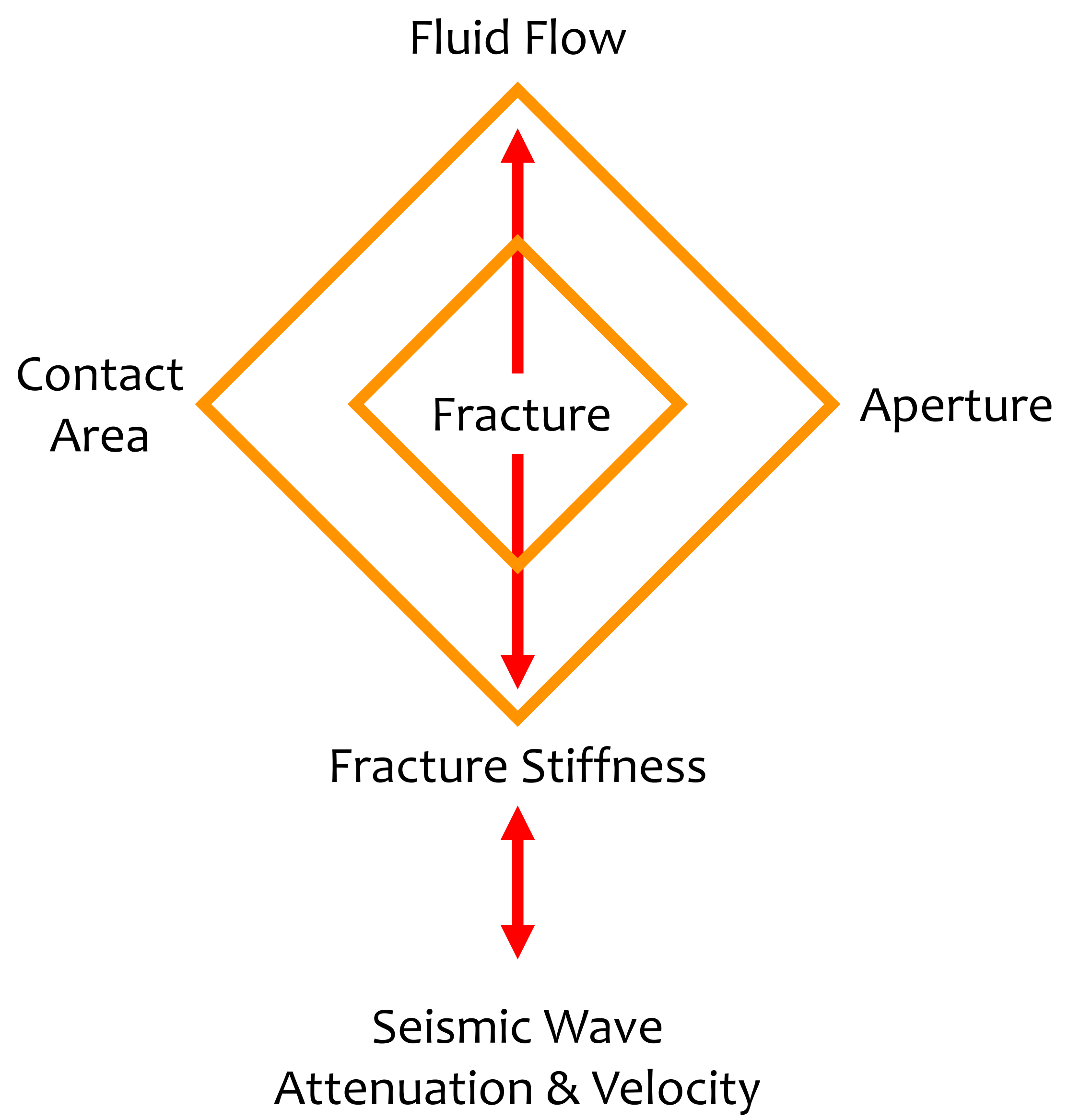
Interrelationship among Fracture Properties

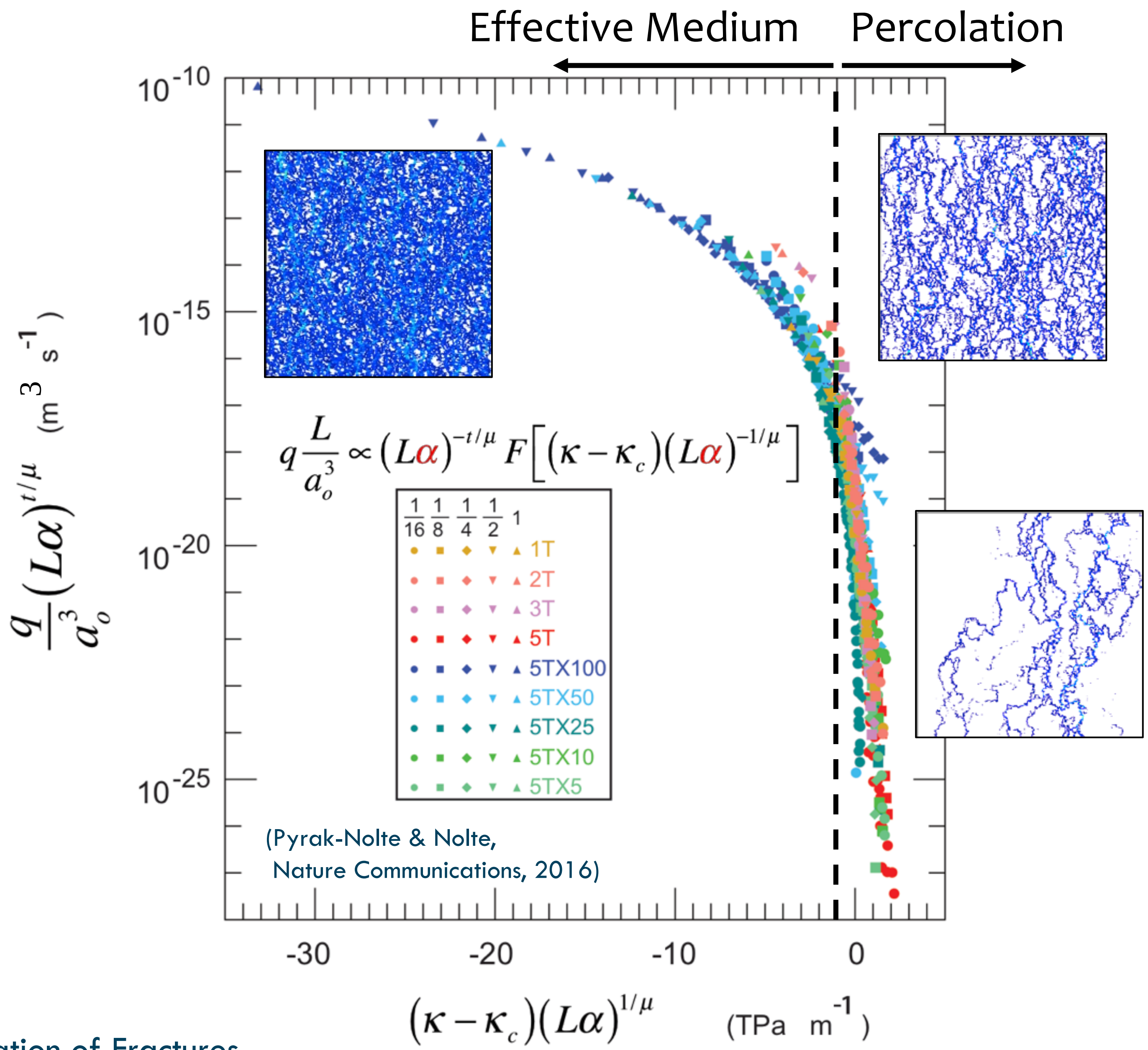
Laura J. Pyrak-Nolte | Purdue University



Scaling relationship for Flow-Stiffness

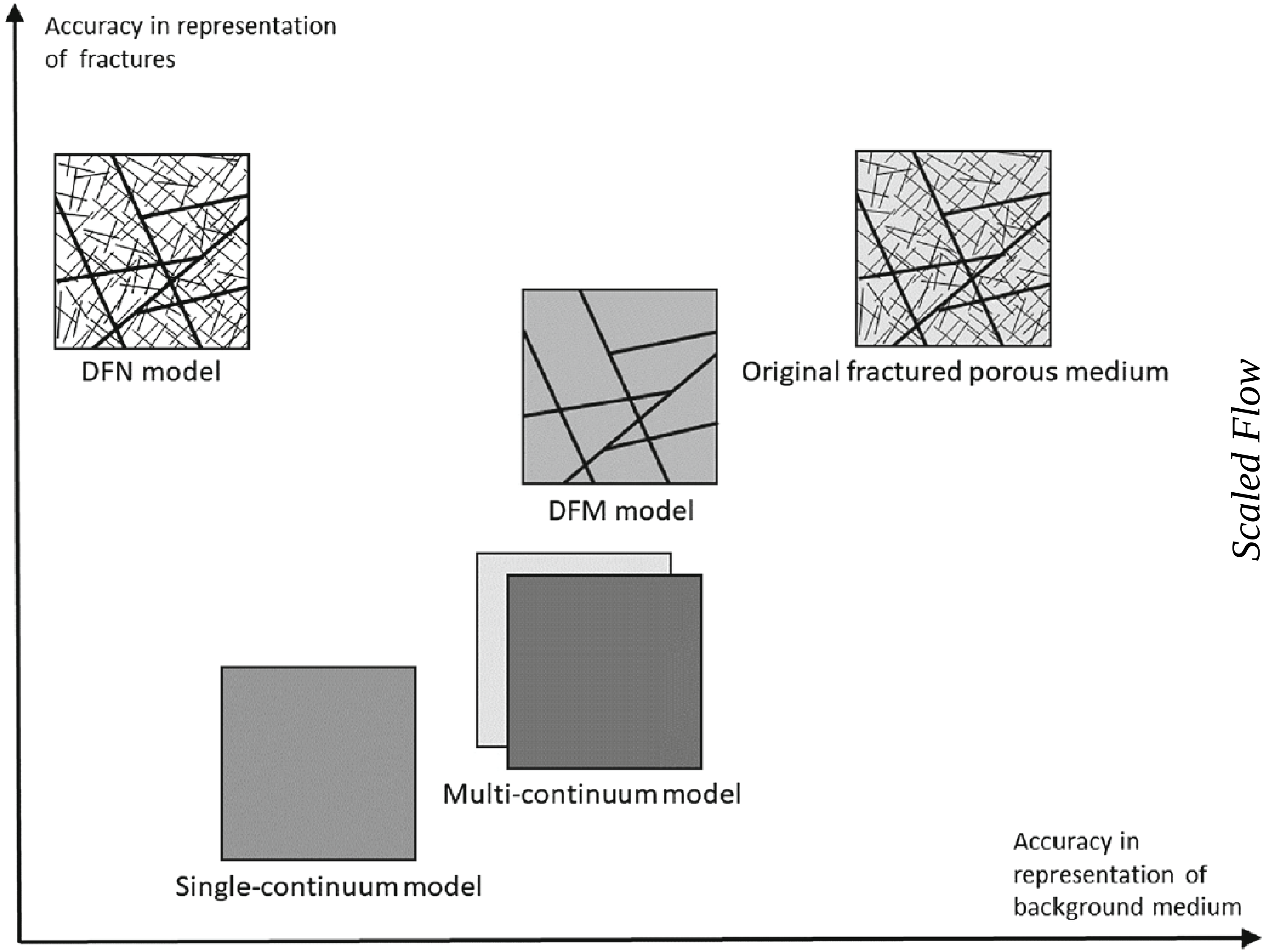
Laura J. Pyrak-Nolte | Purdue University





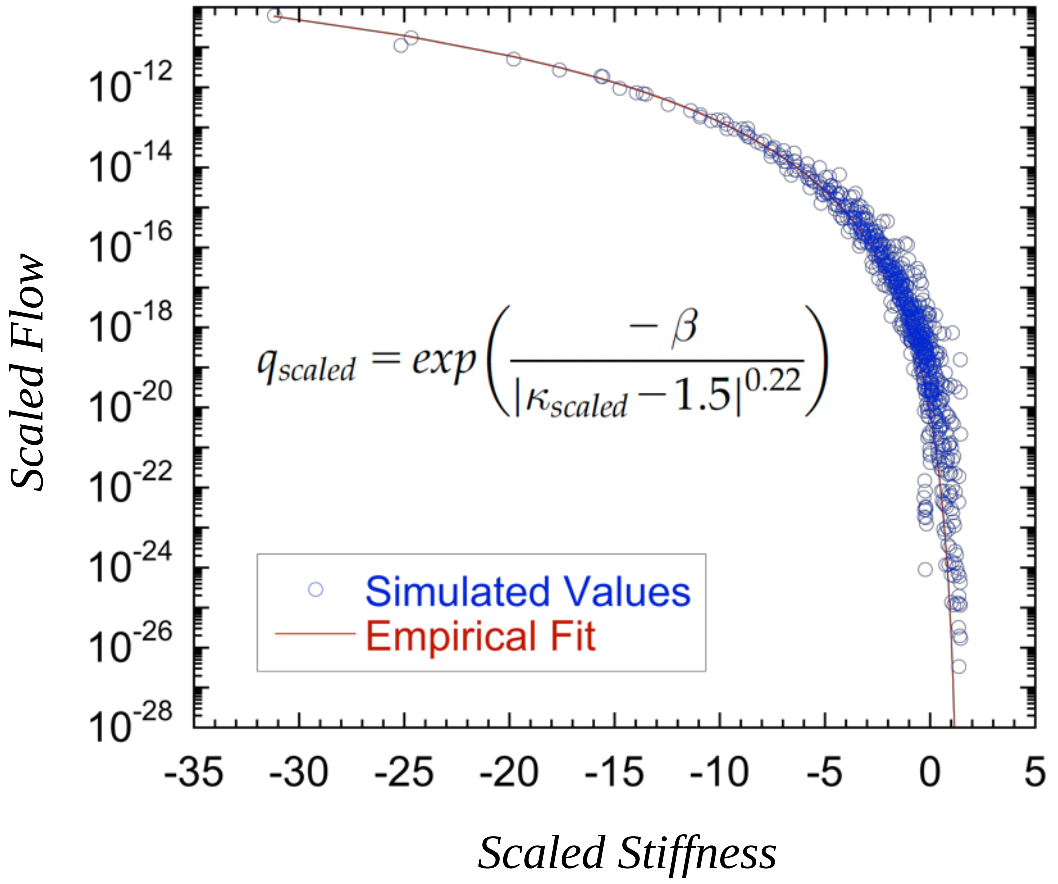
For more details: 21st ISRM Online Lecture: Geophysical Characterization of Fractures

Implement into Models of Fracture Networks



Berre et al., 2019

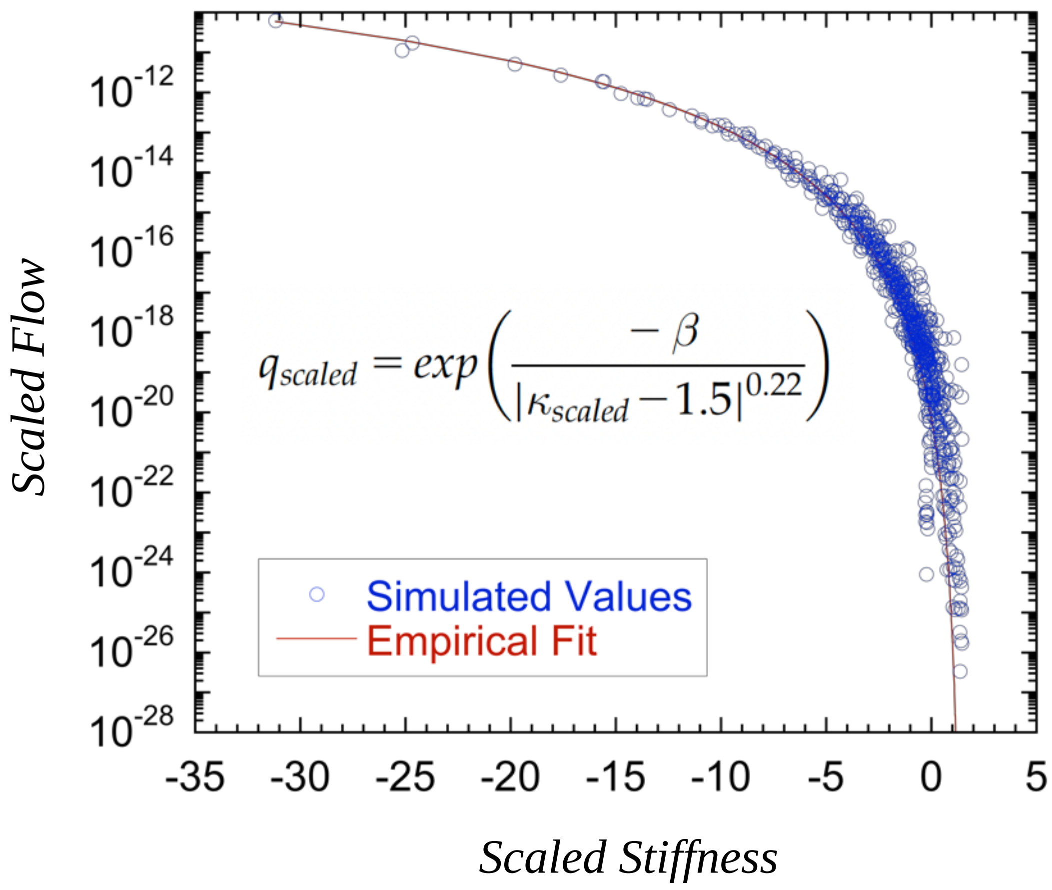
(Based on 9,300 Simulations)



(Pyrak-Nolte, 2019)

Future Directions:

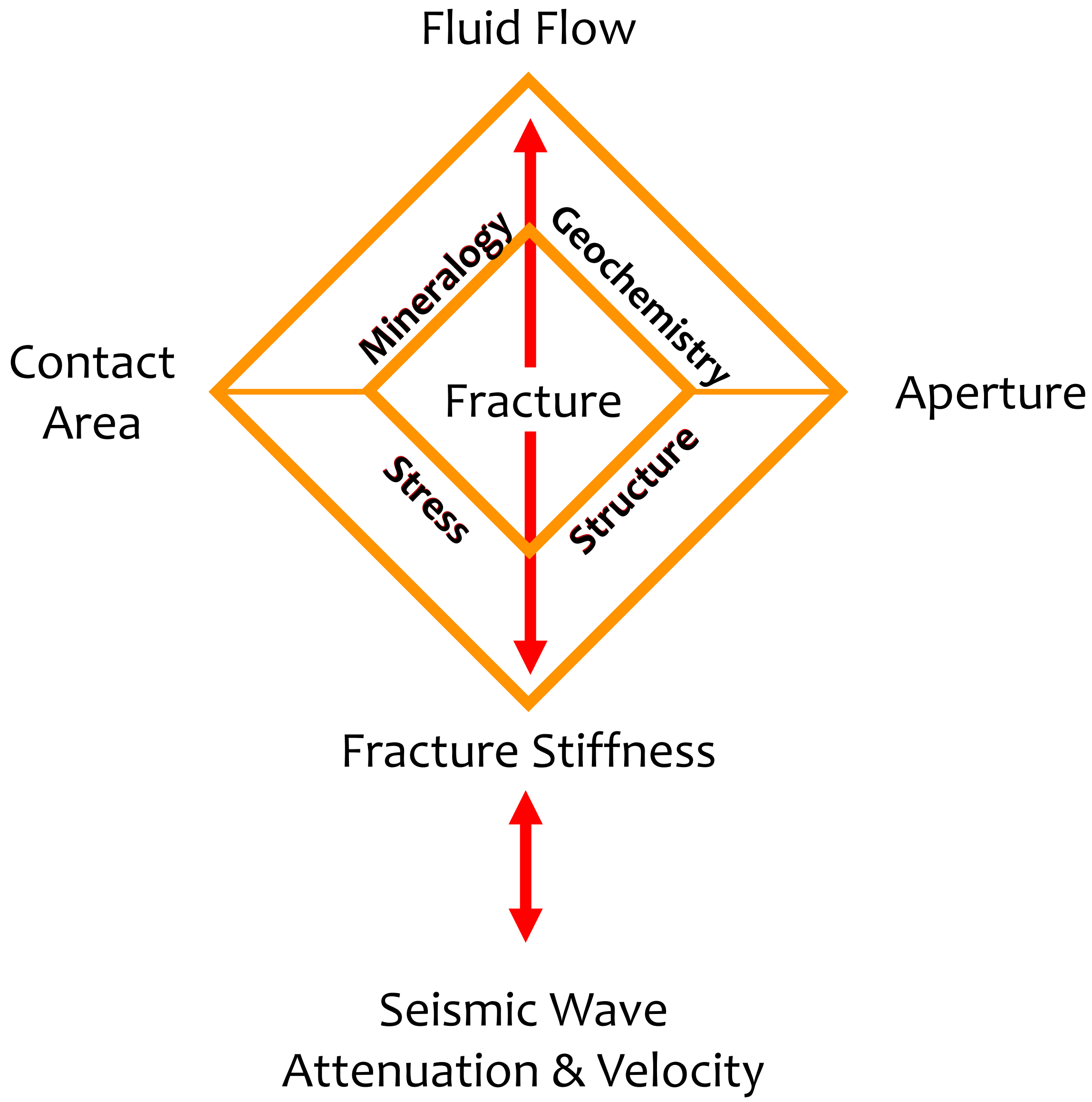
- Implement flow-stiffness relationship to more accurately capture stress dependent changes in fracture geometry or permeability.
- What is the flow-stiffness relationship for other stress conditions?
- Is there a flow-stiffness relationship for fracture networks?



(Pyrak-Nolte, 2019)

What Controls Fracture Geometry?

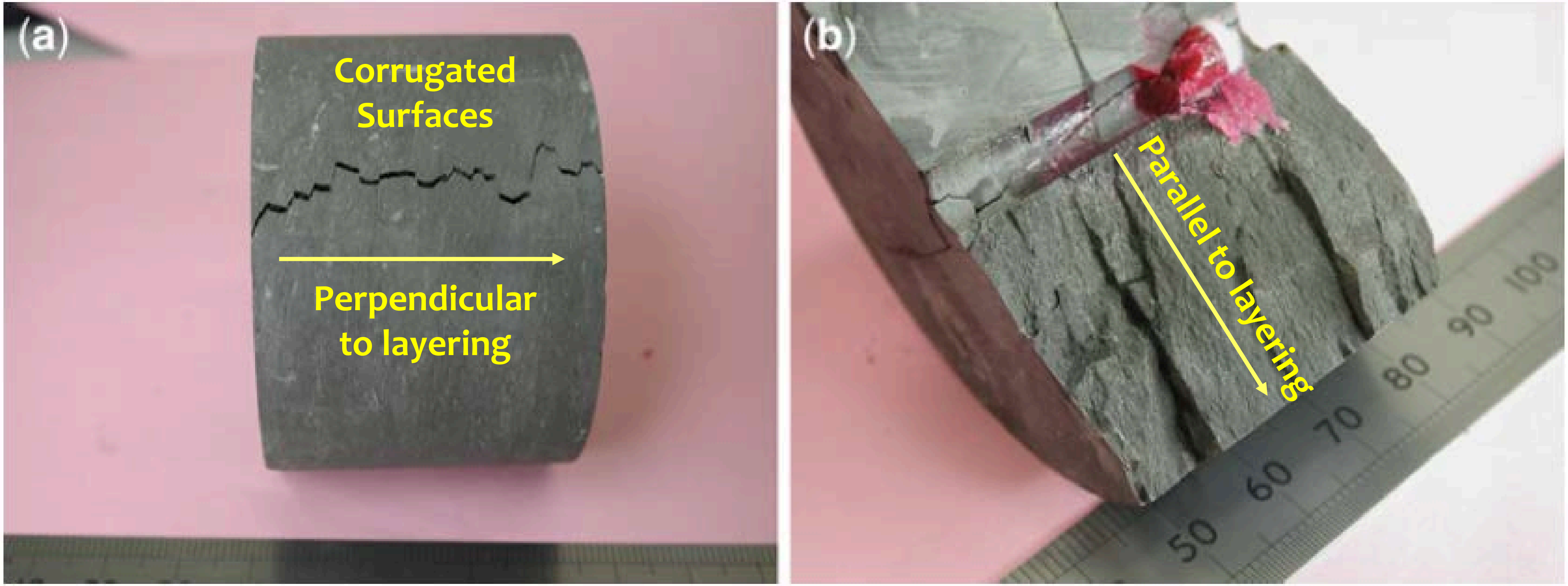
Laura J. Pyrak-Nolte | Purdue University



Sources available upon request

Can we gain insight into fracture geometry from core inspection

Hydraulically induced fracture in a carboniferous shale laboratory sample recovered from a deep (2 km) borehole in northern England.

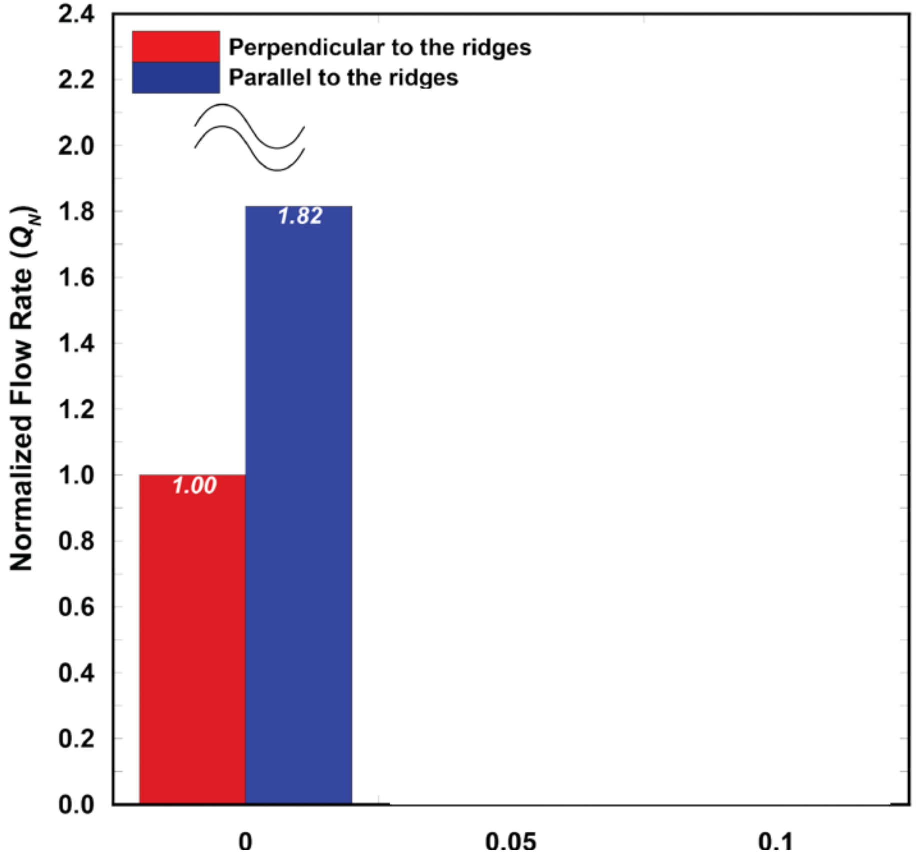


Rutter & Mecklenburgh, 2017, Geological Society, London,

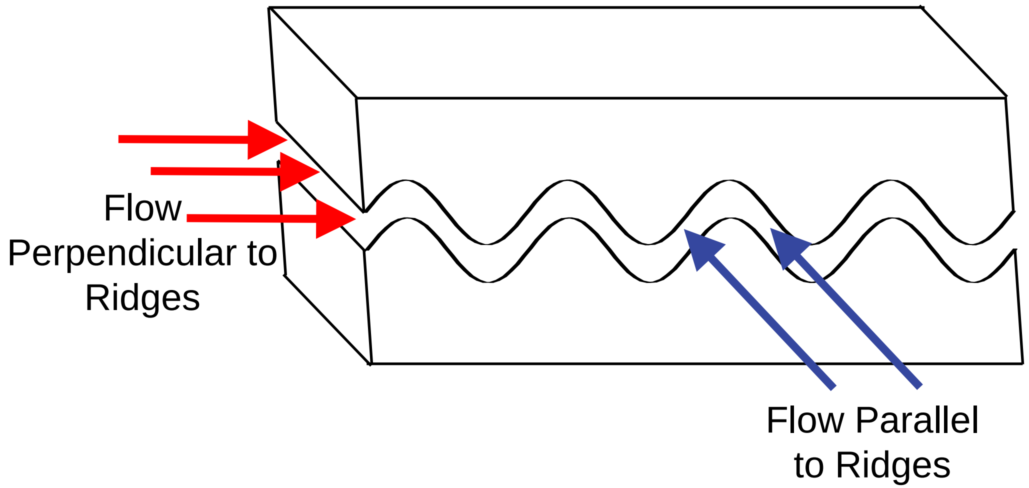
Function: Impact of Corrugated Roughness on Flow

Laura J. Pyrak-Nolte | Purdue University

From Computer Simulations of Flow with Increasing Offset from Shearing



$$\frac{\text{Shear Offset}}{\text{Wavelength of Corrugation}}$$



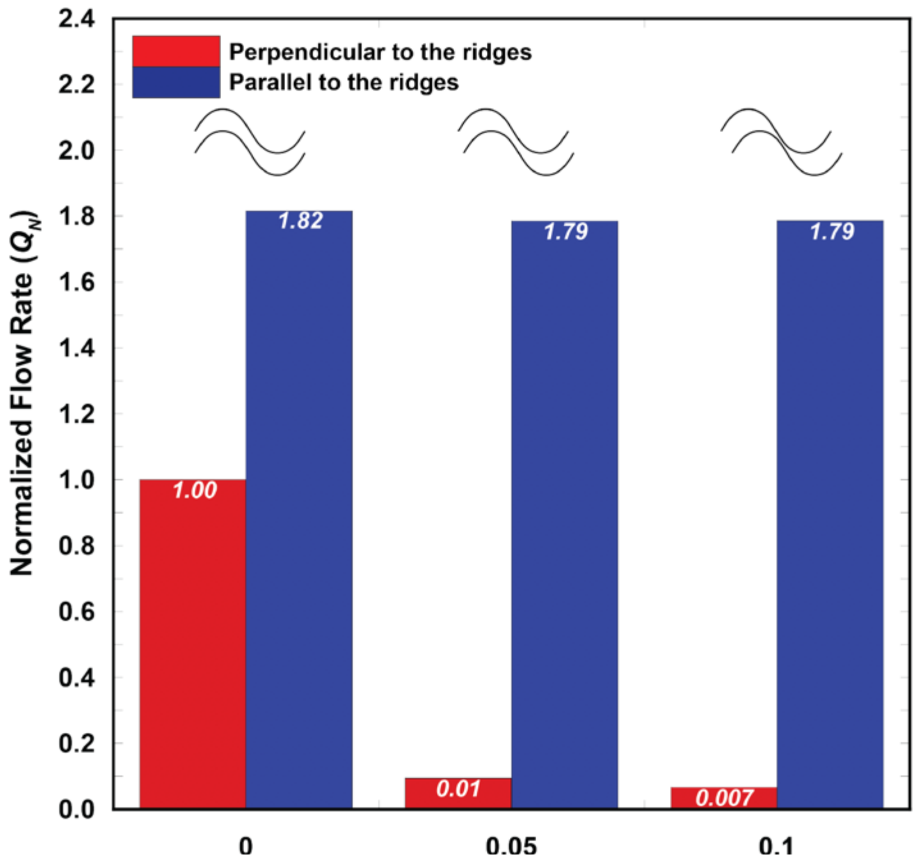
*(*Flow normalized by magnitude perpendicular to the ridges for zero shear offset)*

(Wang & Pyrak-Nolte, ARMA Letters, 2020)

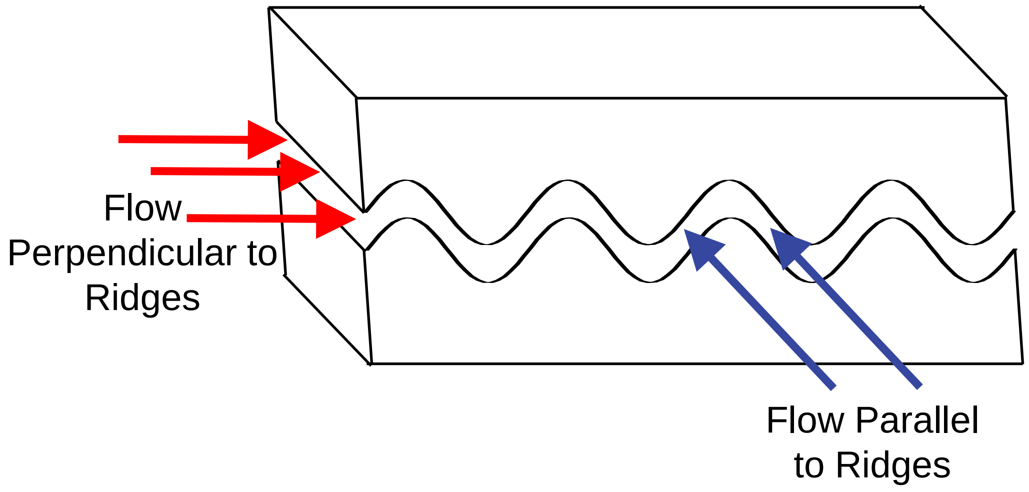
Function: Impact of Corrugated Roughness on Flow

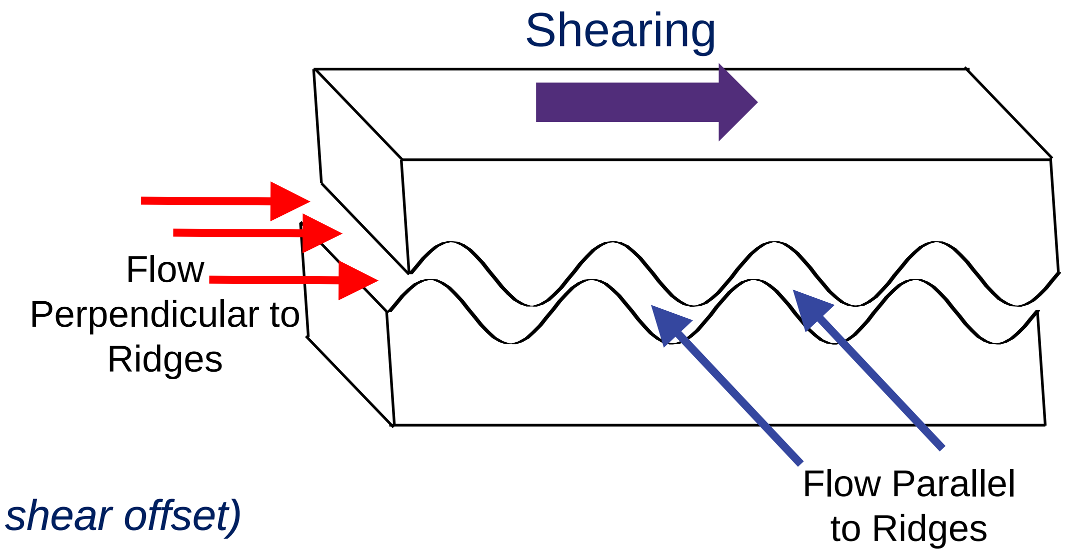
Laura J. Pyrak-Nolte | Purdue University

From Computer Simulations of Flow with Increasing Offset from Shearing



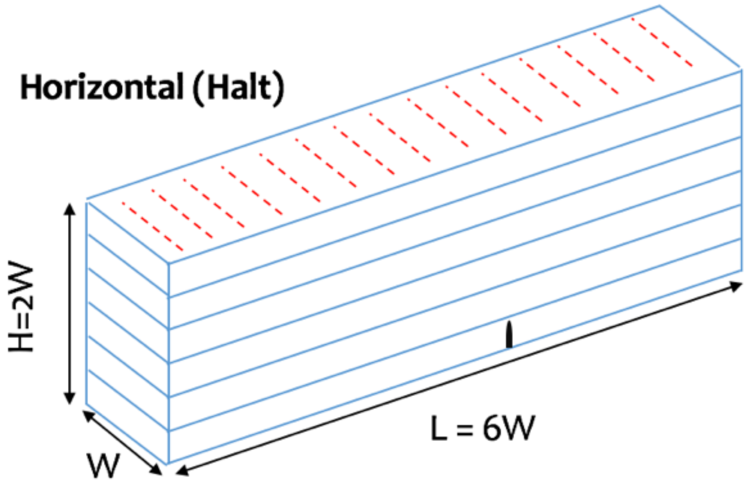
$$\frac{\text{Shear Offset}}{\text{Wavelength of Corrugation}}$$

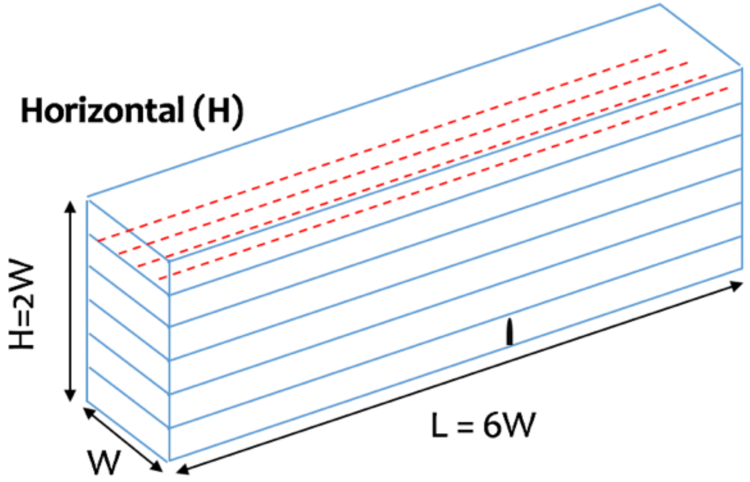


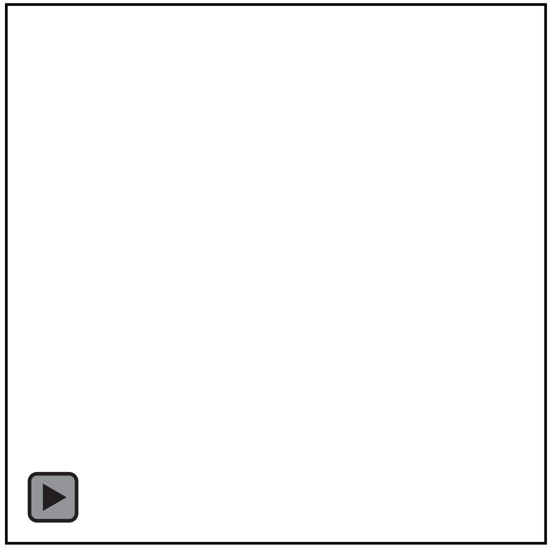


*(*Flow normalized by magnitude perpendicular to the ridges for zero shear offset)*

Induced Tensile Fractures in Layered Samples

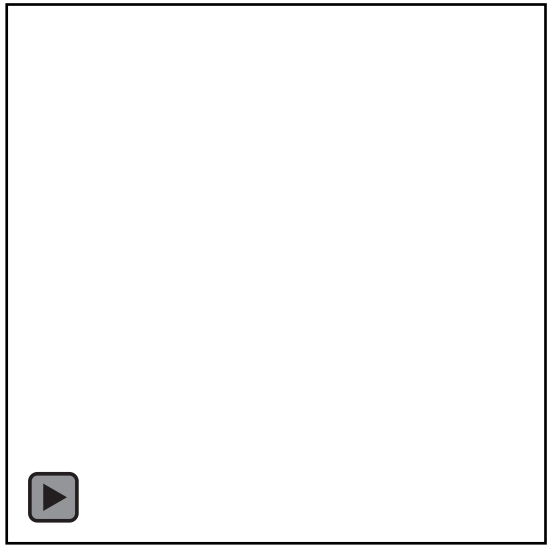






1.75 µm resolution

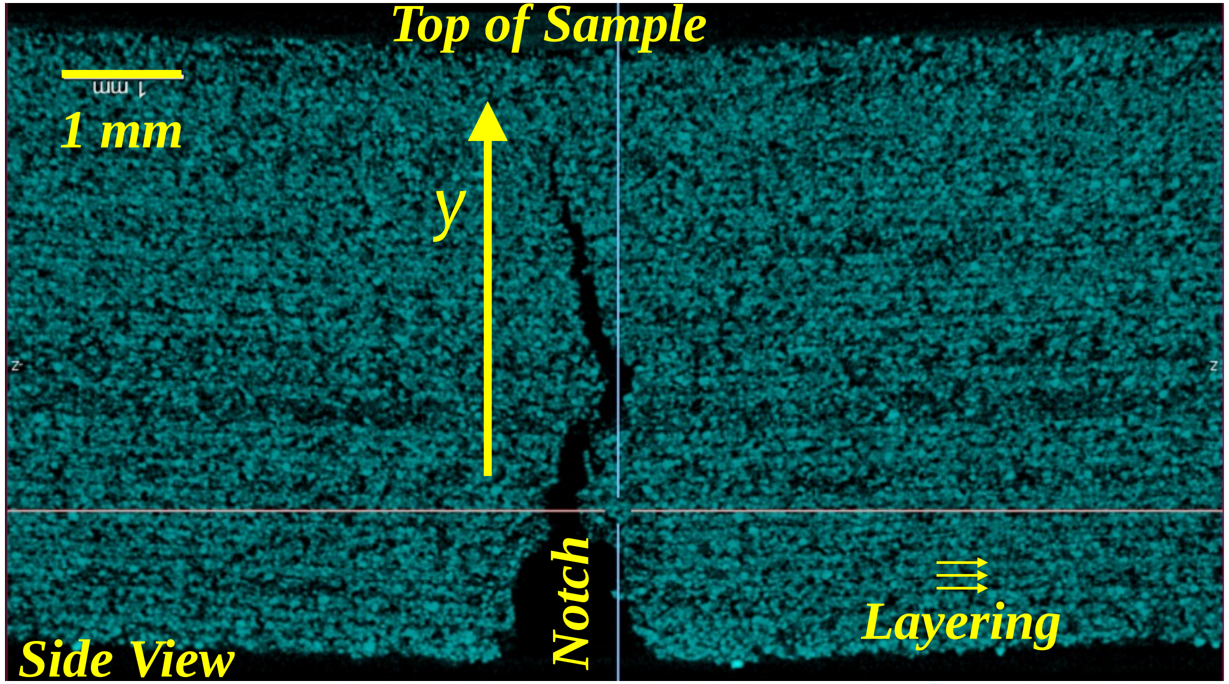
250 um

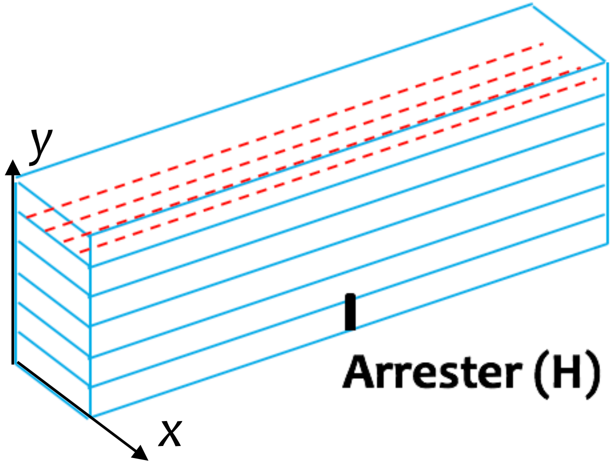


Animation of 2D X-ray radiographs taken during 3 Point Bending Test

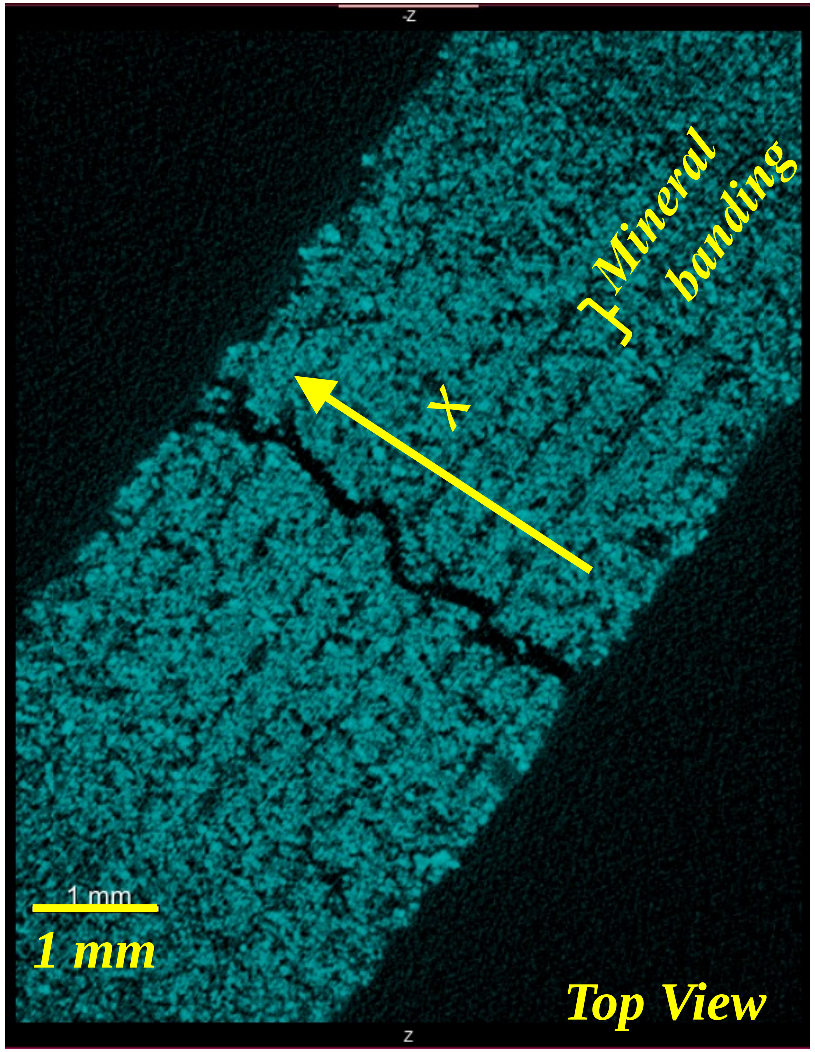
Fracture Trace from X-ray Reconstructions

Layering





Mineral Texture

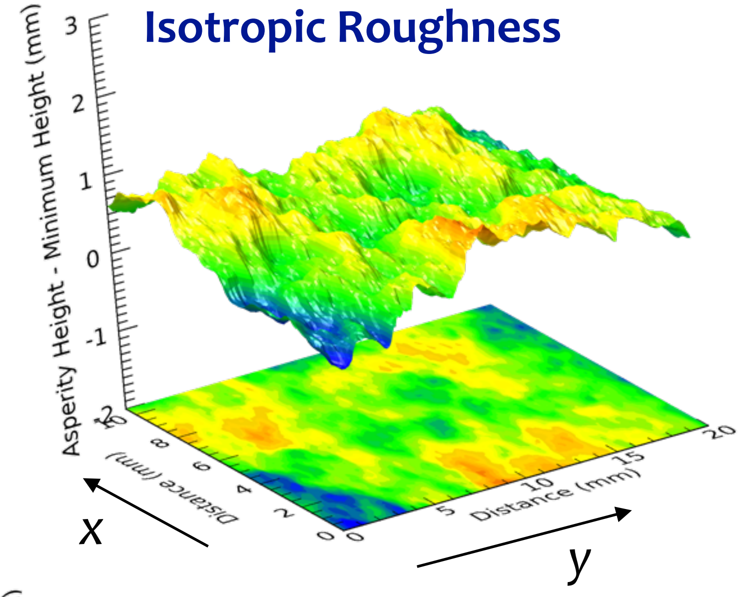


Jiang, L., Yoon, H., Bobet, A. and L. J. Pyrak-Nolte, Scientific Reports, 2020

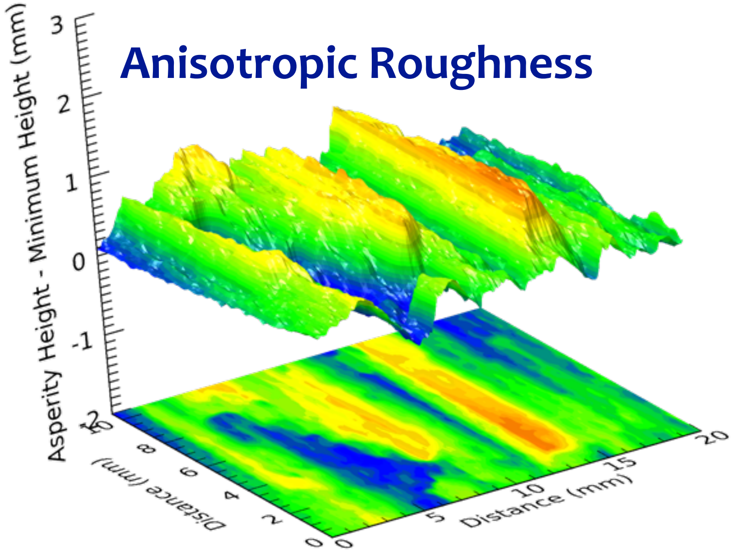
Contributions to Roughness to Permeability

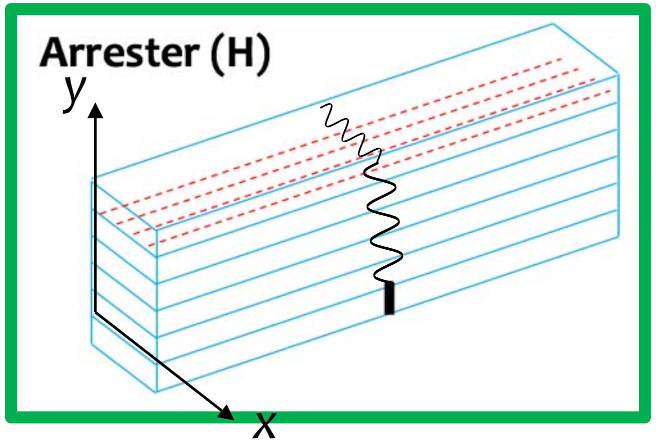
Laura J. Pyrak-Nolte | Purdue University

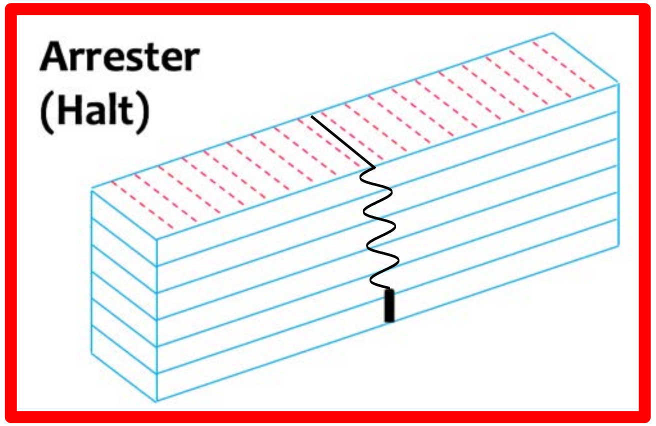
Isotropic Roughness



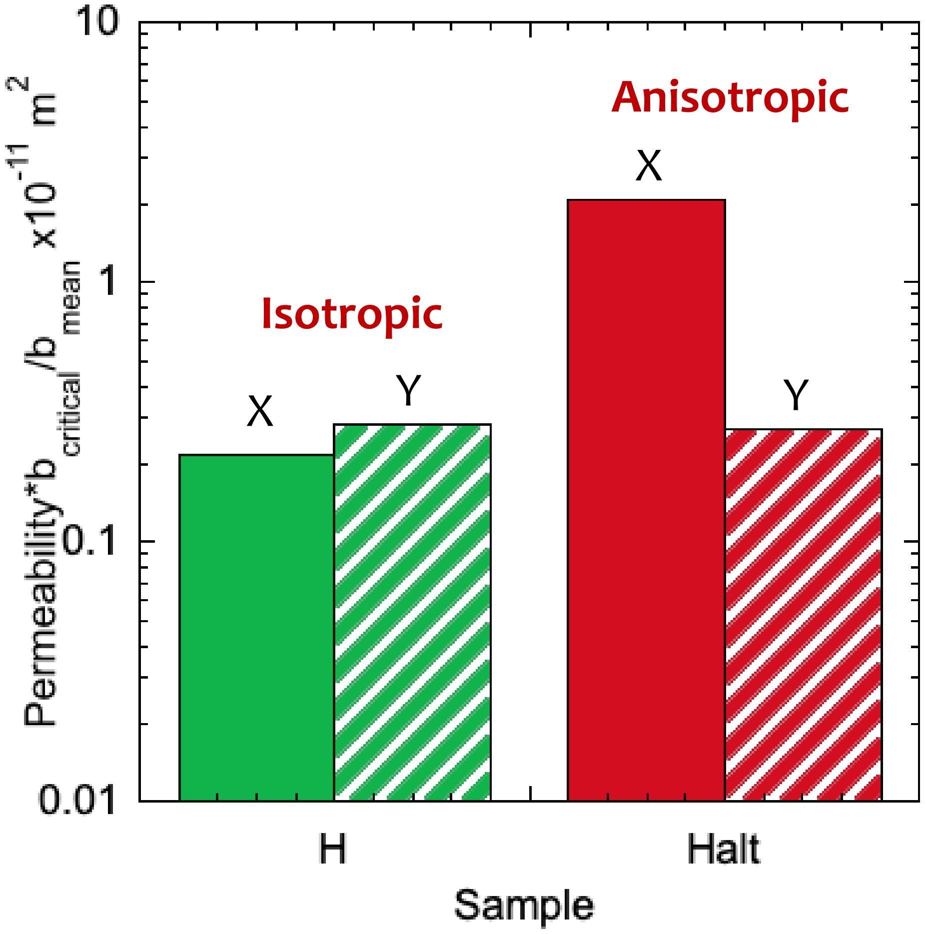
Anisotropic Roughness





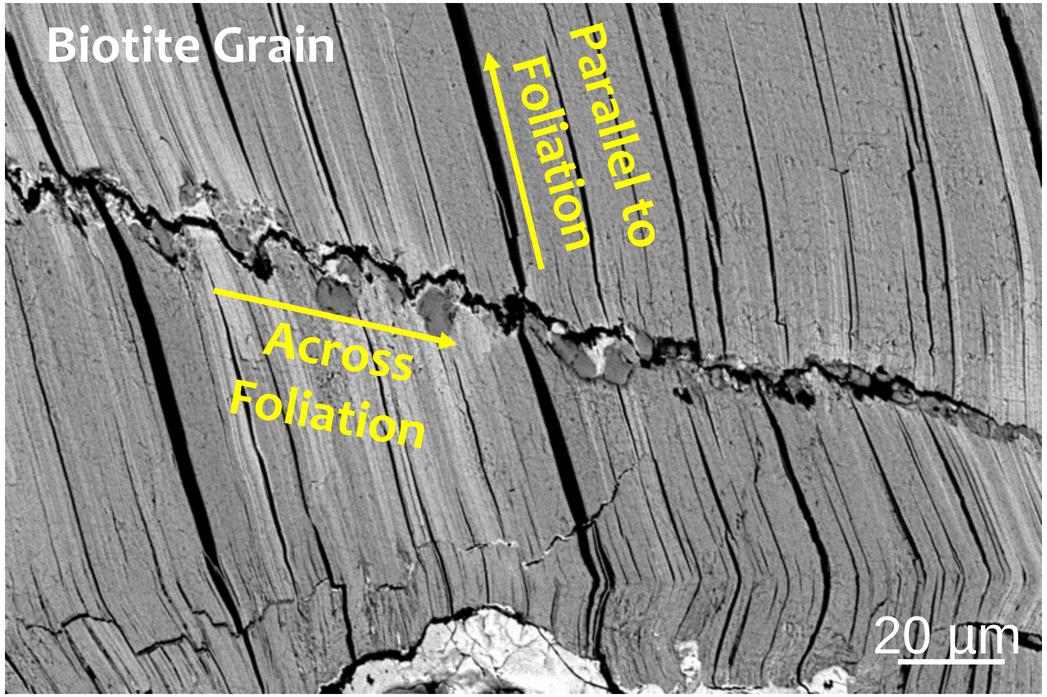


Permeability

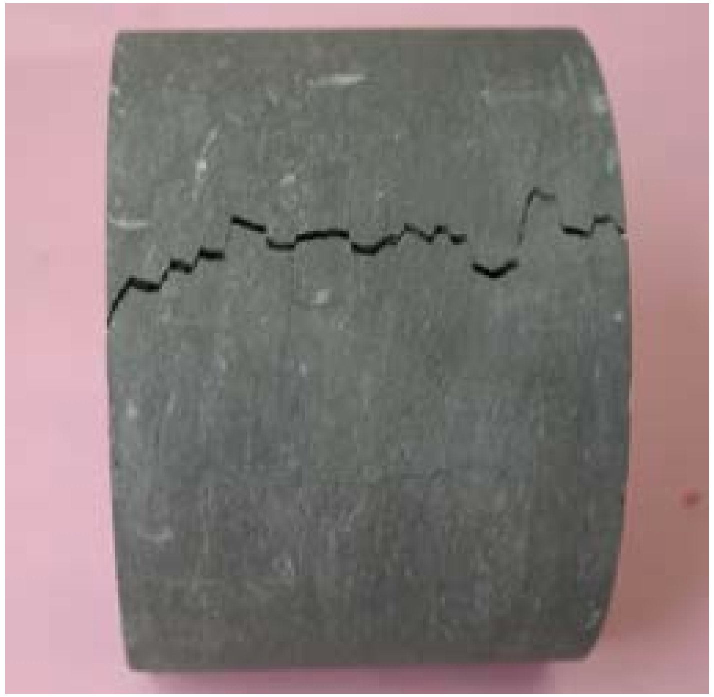


Jiang, L., Yoon, H., Bobet, A. and L. J. Pyrak-Nolte, Scientific Reports, 2020

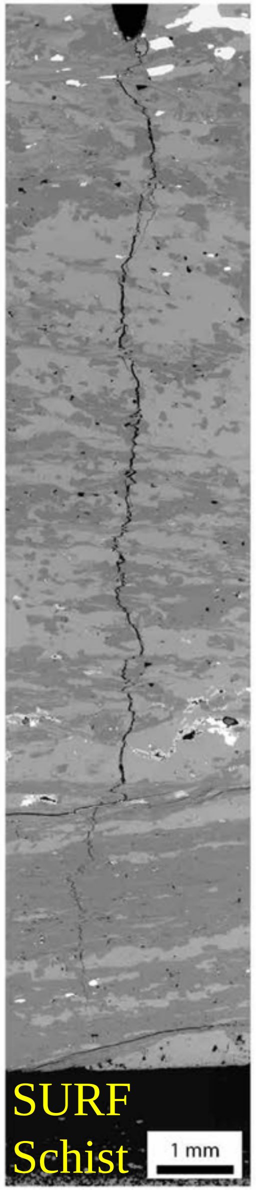
Future Directions: Implications



(Courtesy of Xin Gu, ORNL, 2022)



Rutter & Mecklenburgh, 2017, Geological Society, London,



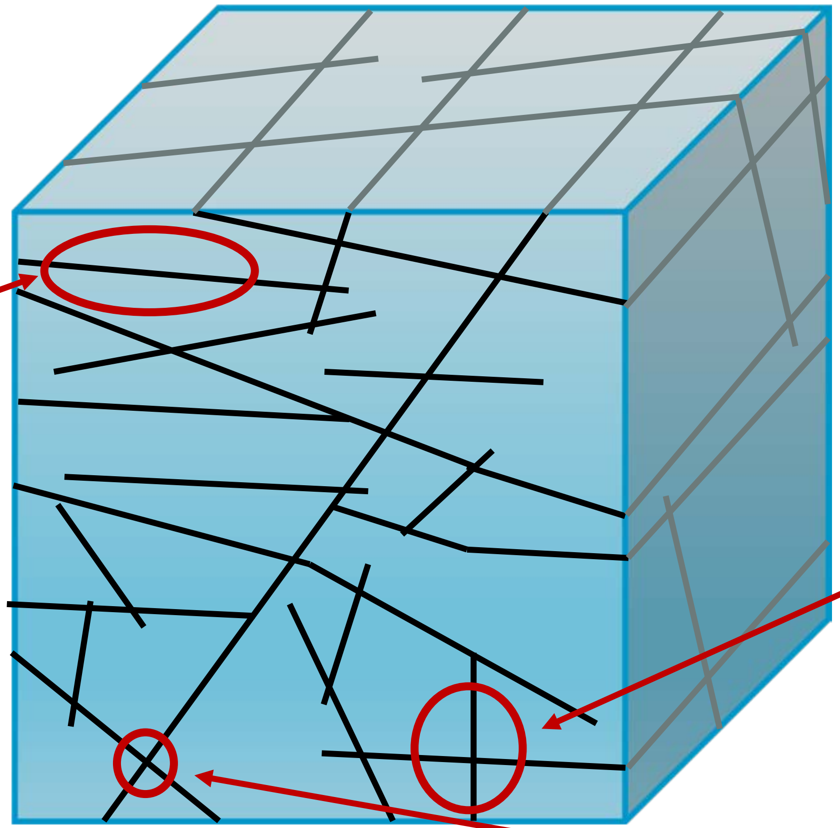
Jahnke et al., Scientific Reports, 2022

- *Site geology and the stress conditions should be considered when selecting aperture distributions for flow simulations*
- Specifically, examination of rock type, layering, oriented mineral fabric and/or structural features.

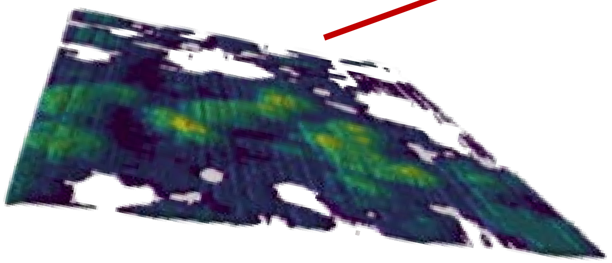
Today: Insights from the Laboratory

Laura J. Pyrak-Nolte | Purdue University

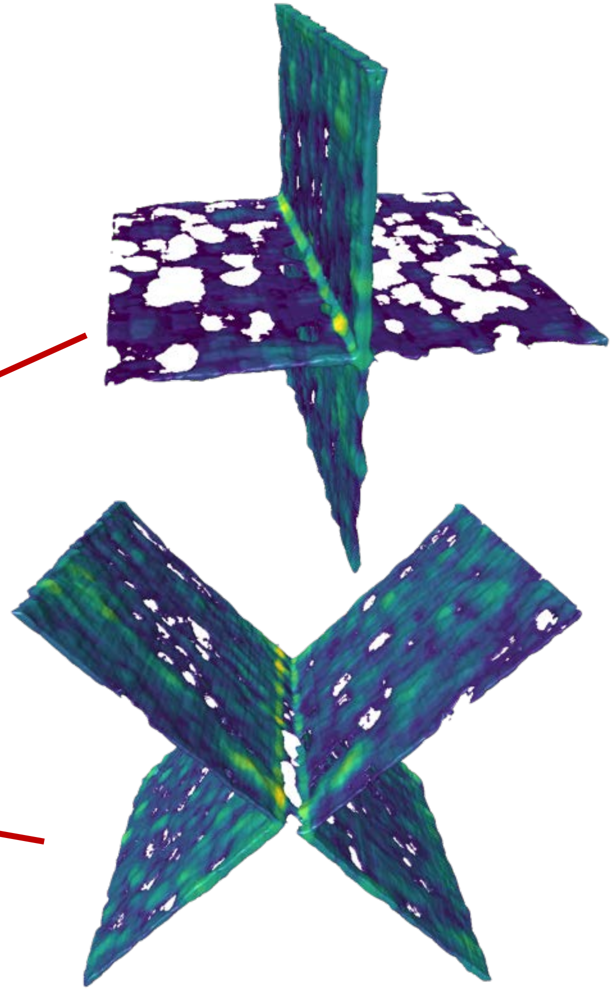
Fracture Network



Single Fracture Representation



Fracture Intersections Impact of Orientation

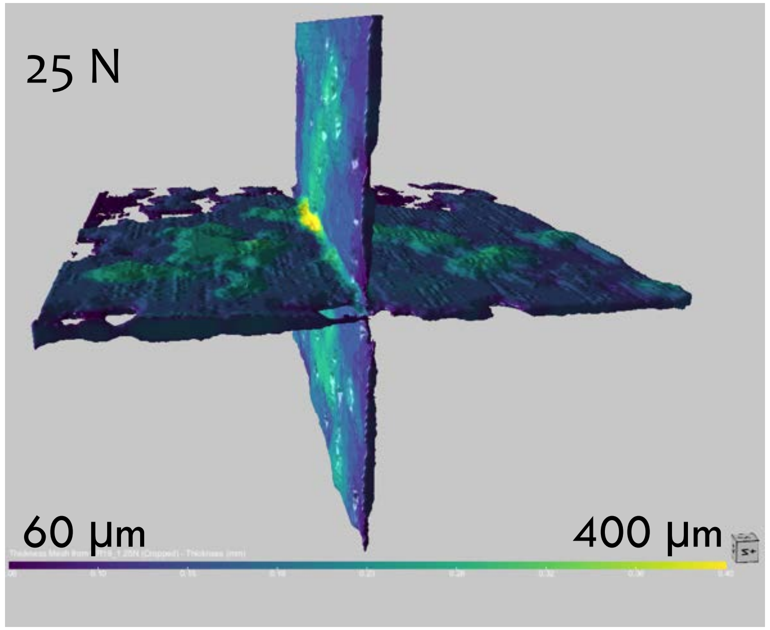


White: Contact Area
Blue-Green-Yellow-Red: Increasing Aperture

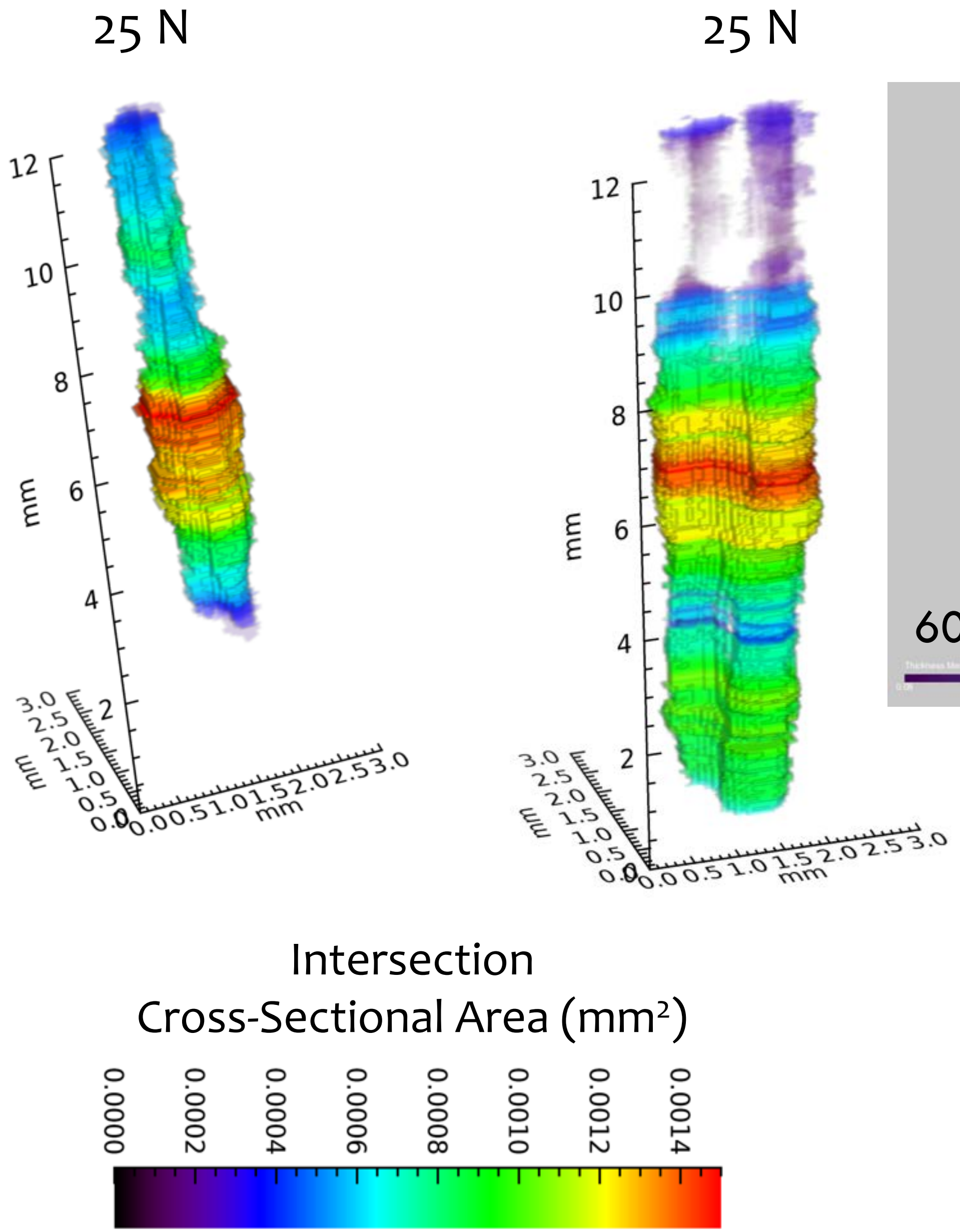
3D Xray Imaging: Effect of Stress on Intersection Geometry & Network Topology

Laura J. Pyrak-Nolte | Purdue University
NWTRB May 2024

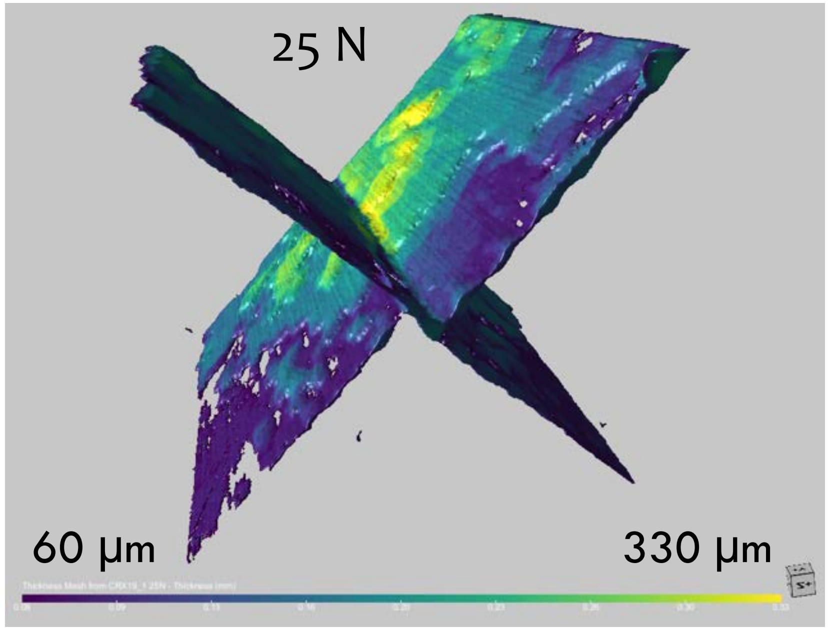
3D Thickness Map



2D Cross Section



3D Thickness Map



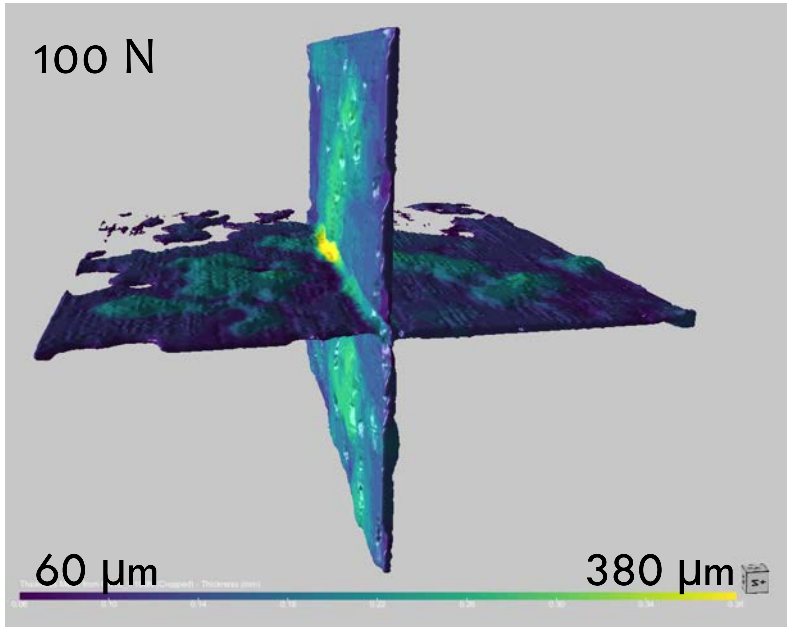
2D Cross Section

3D Xray Imaging: Effect of Stress on Intersection Geometry & Network Topology

Laura J. Pyrak-Nolte | Purdue University

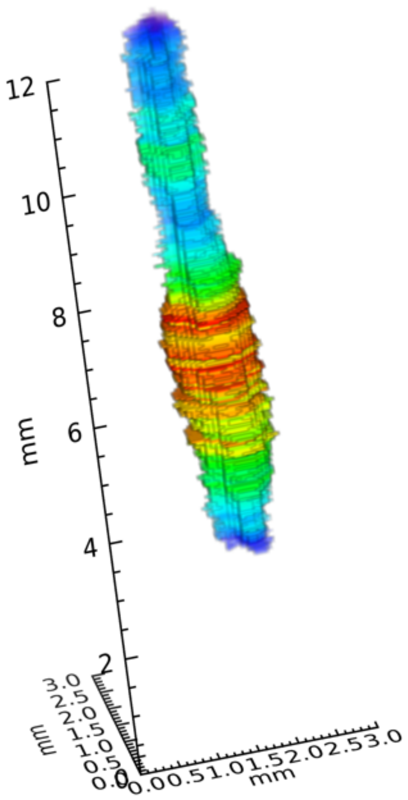
NWTRB May 2024

3D Thickness Map

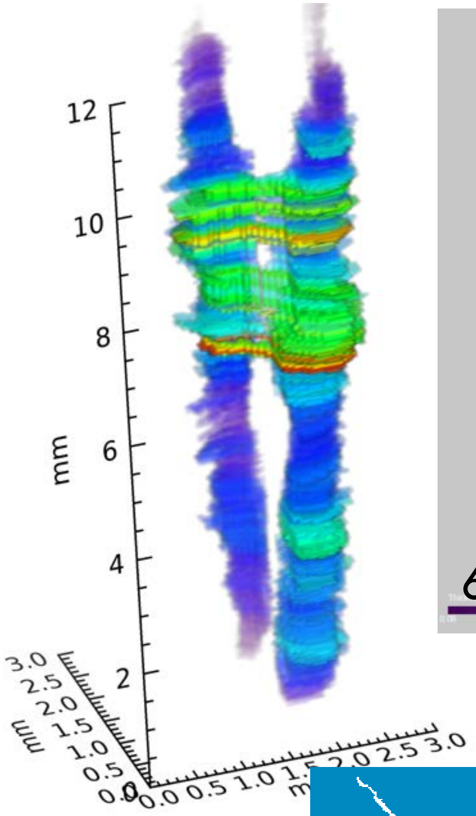


2D Cross Section

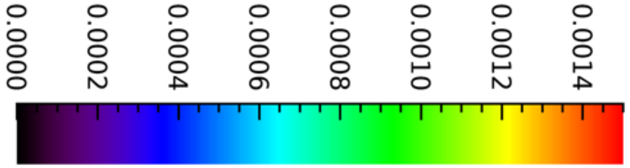
100 N



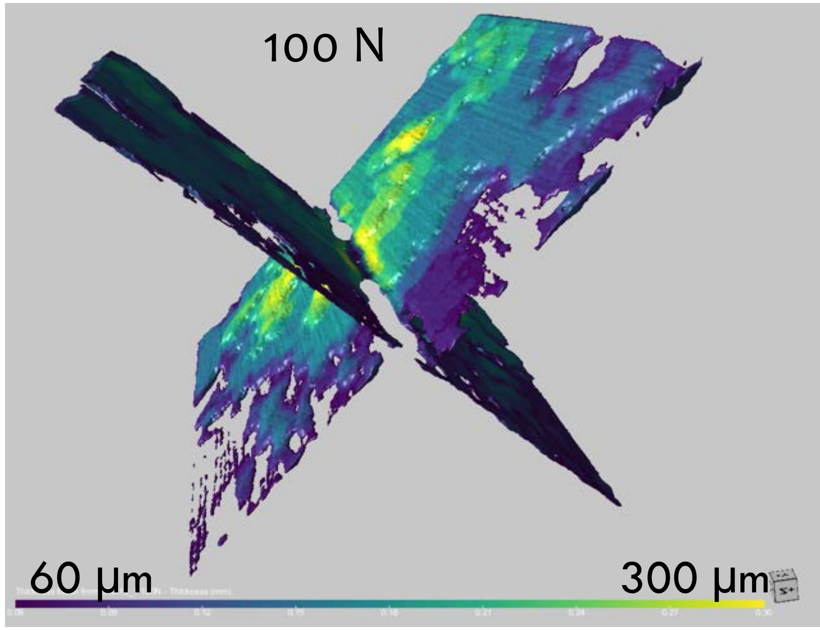
100 N



Intersection
Cross-Sectional Area (mm²)



3D Thickness Map

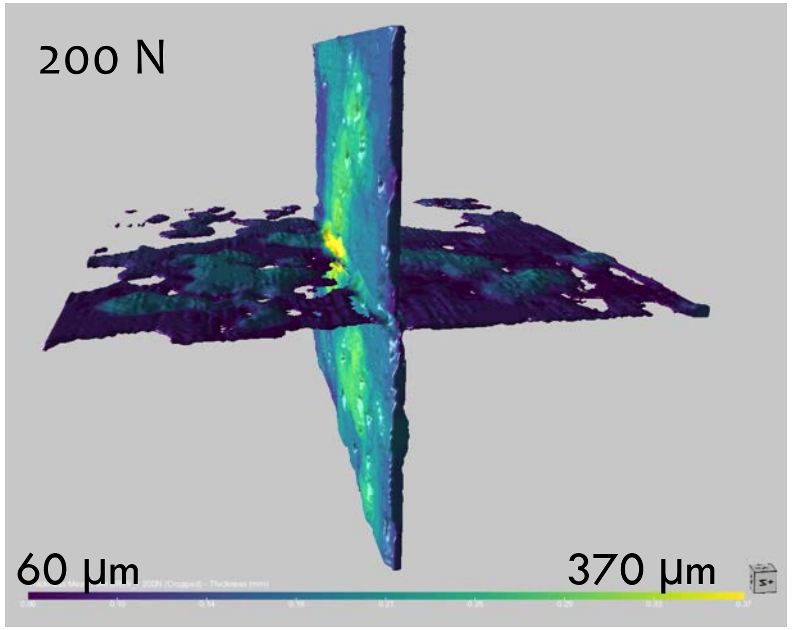


2D Cross Section

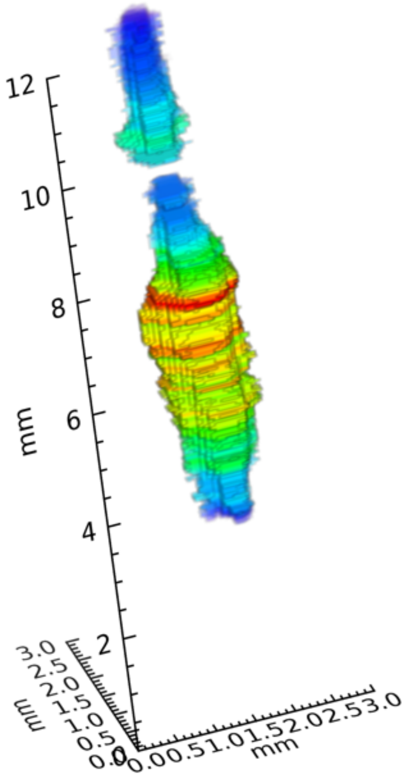
3D Xray Imaging: Effect of Stress on Intersection Geometry & Network Topology

Laura J. Pyrak-Nolte | Purdue University

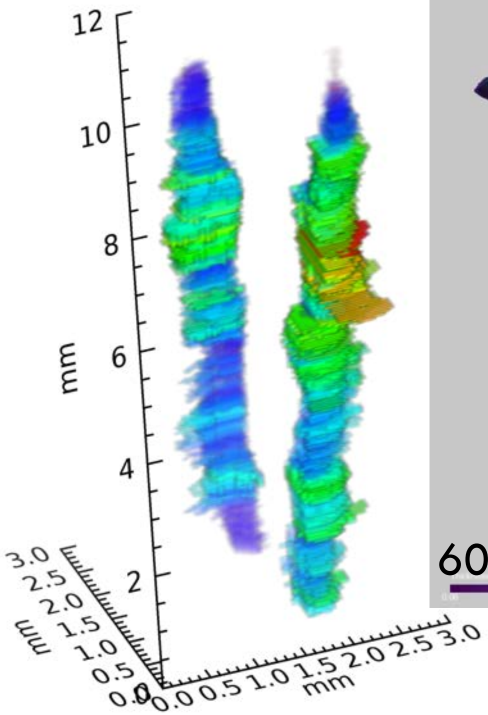
3D Thickness Map



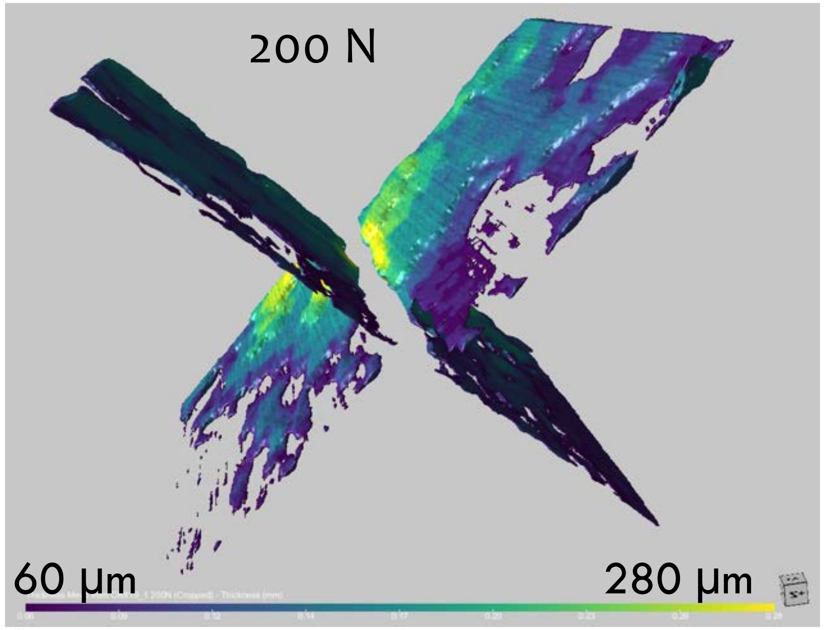
200 N



200 N

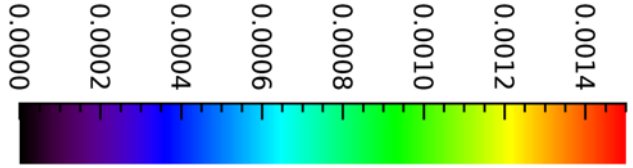


3D Thickness Map



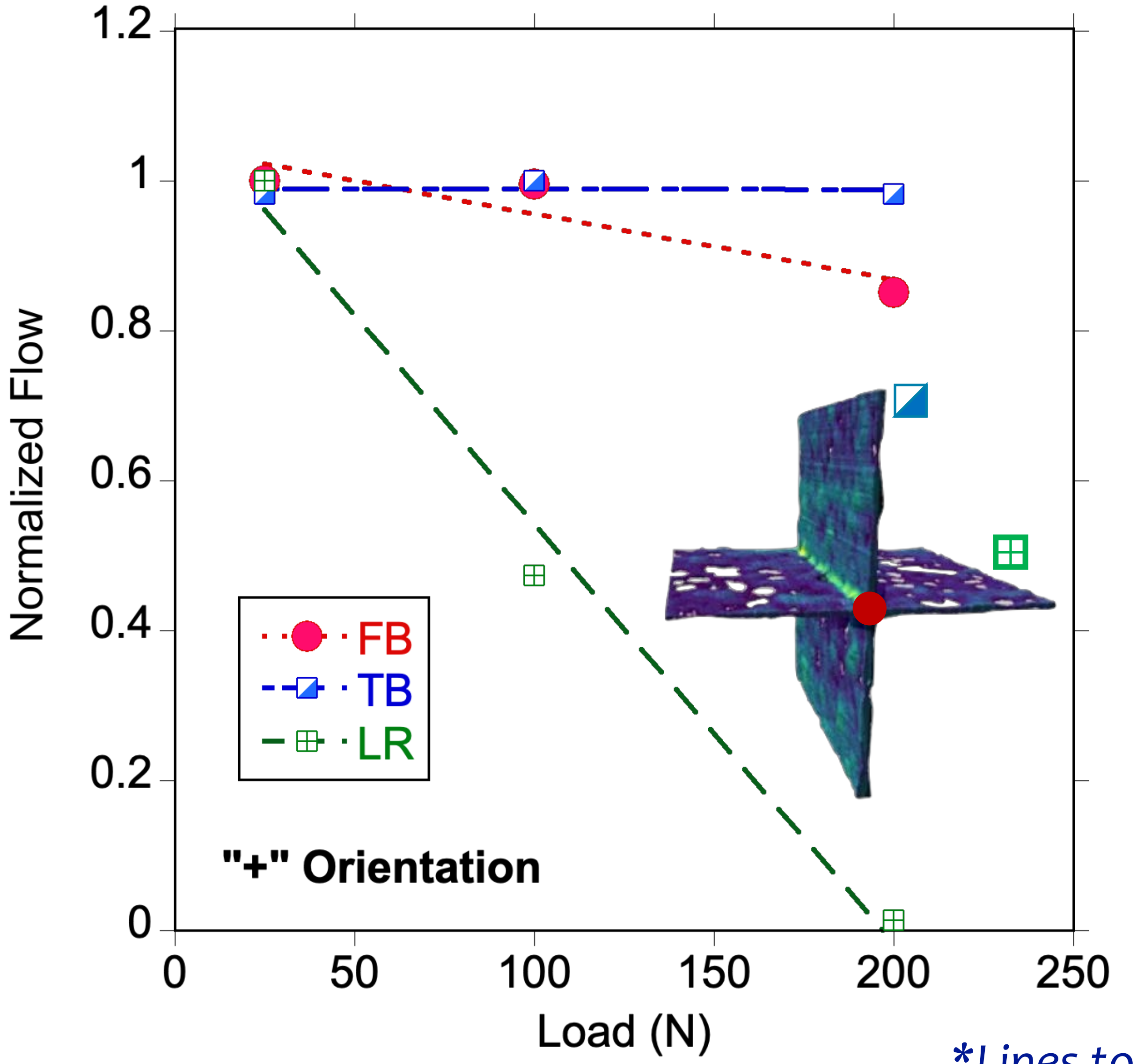
2D Cross Section

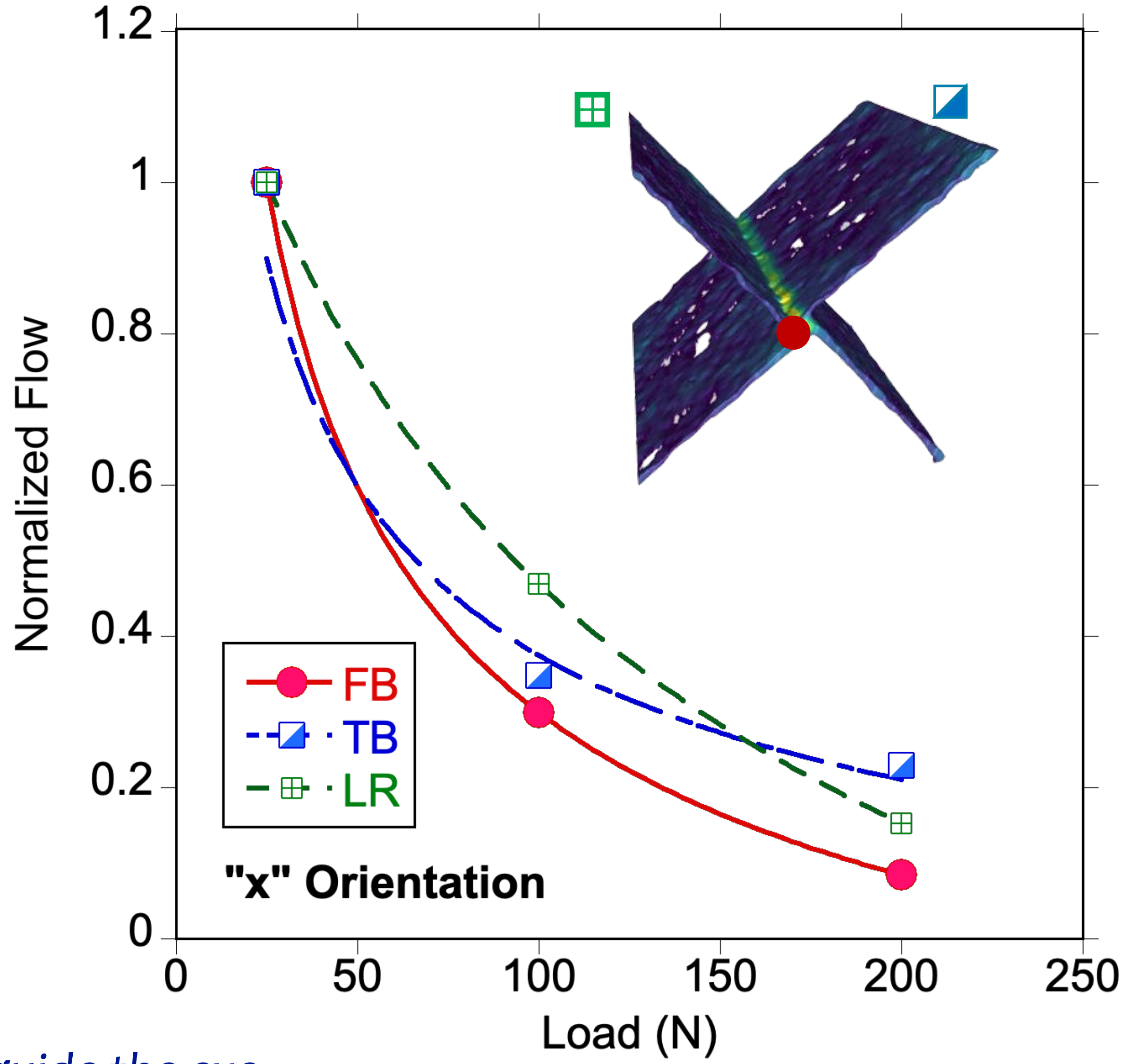
Intersection Cross-Sectional Area (mm^2)



2D Cross Section

Impact of Orientation relative to Stress on Flow





**Lines to guide the eye*

(Santos & Pyrak-Nolte, 2023; Sumners & Pyrak-Nolte, 2024)

Future Directions:

Pyrak-Nolte, Hickory Nut Park, SC 2022

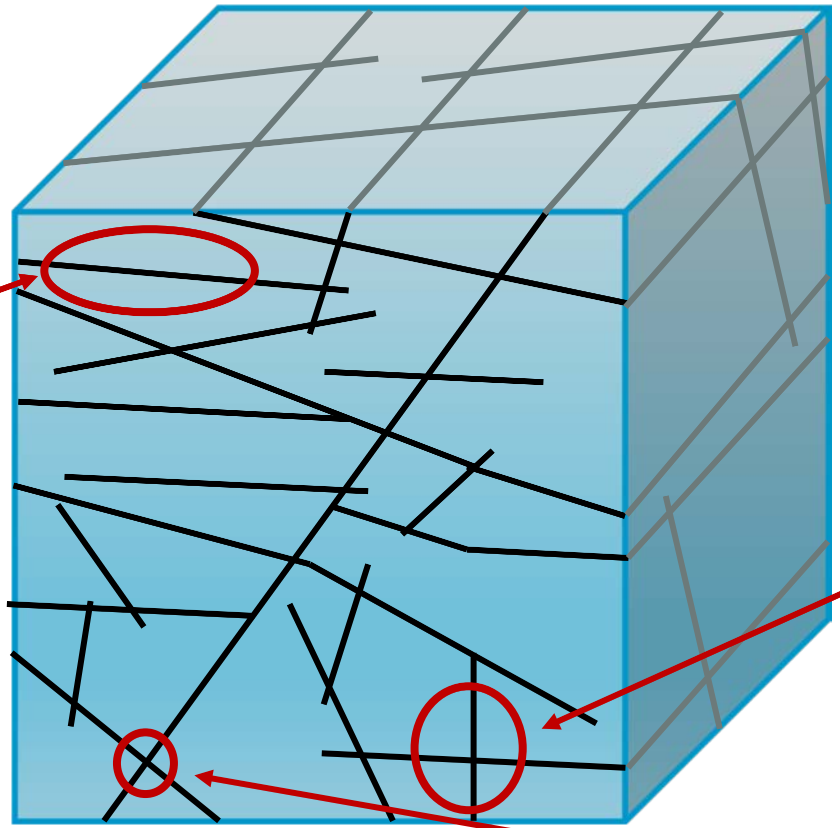
Gary Hayes, Geotripper, Joshua Tree National Park, November 5, 2011.

- Do current models adequately capture the difference in fracture deformation with orientation?
- Can the effects of fracture orientation on network connectivity be incorporated into network models?
- Develop methods to incorporate deformation and closure of intersections in flow network simulations

Today: Insights from the Laboratory

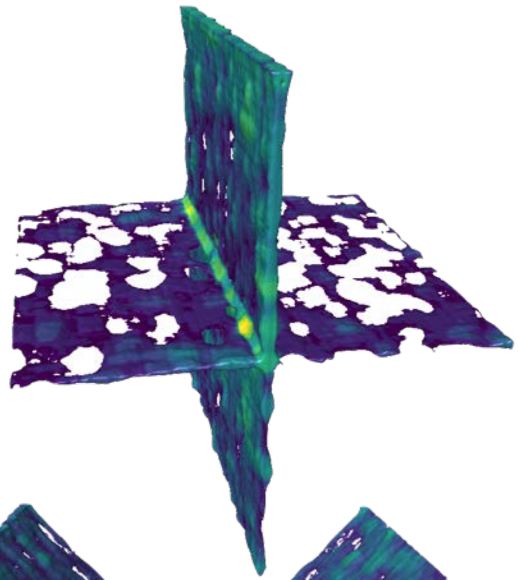
Laura J. Pyrak-Nolte | Purdue University

Fracture Network

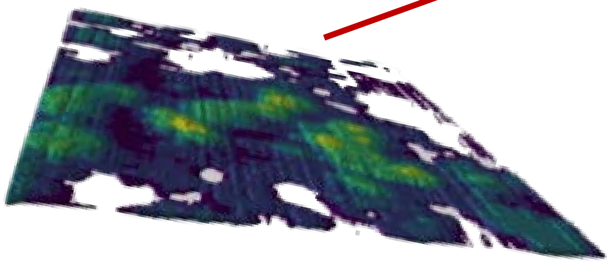


Critical Link: Fracture Intersections

Impact of Orientation



Single Fracture Representation



Mixing Rules for Fracture Intersections

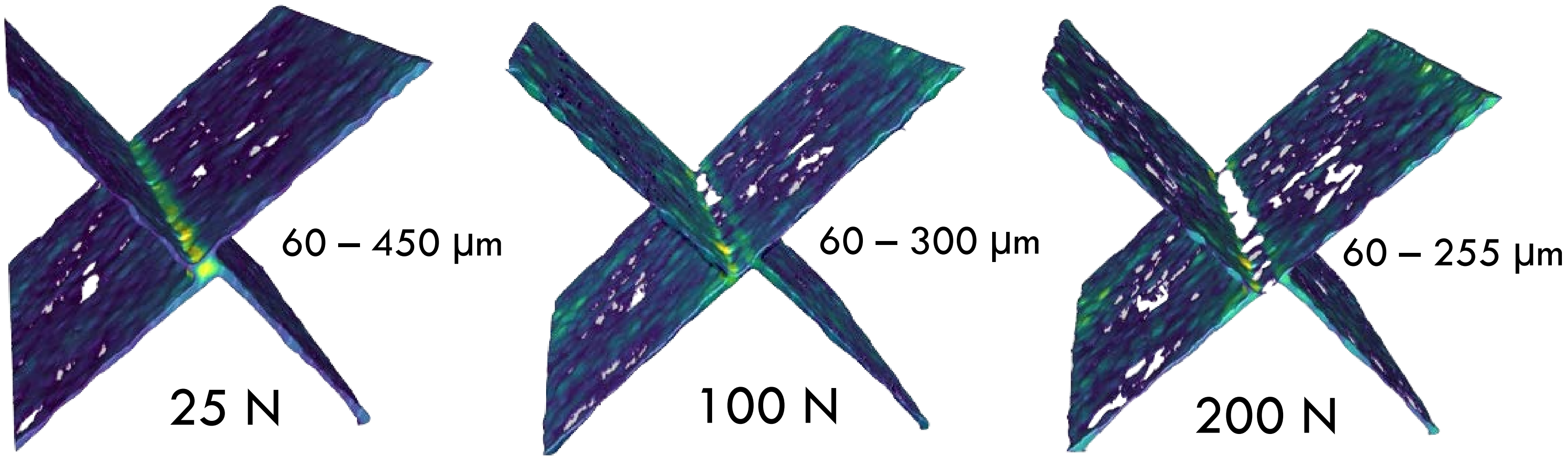
White: Contact Area

Blue-Green-Yellow-Red: Increasing Aperture

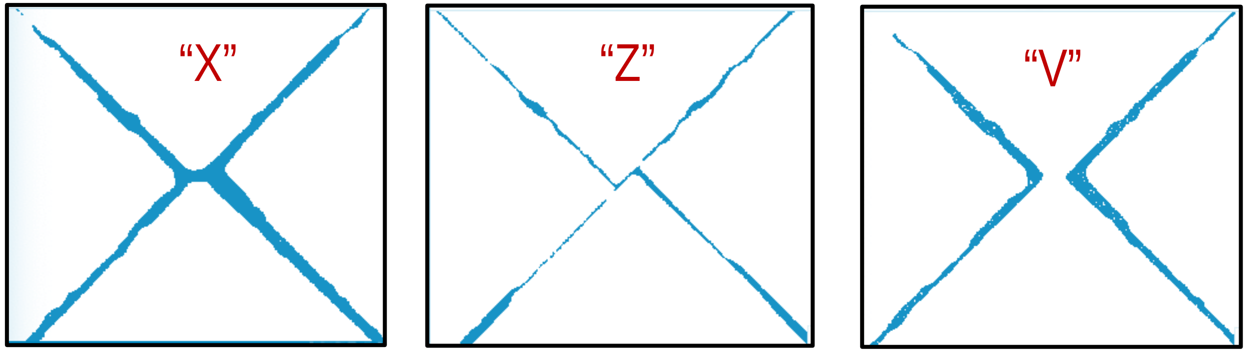
What did we learn about Intersecting Fractures under Stress

CRX_Rand_4

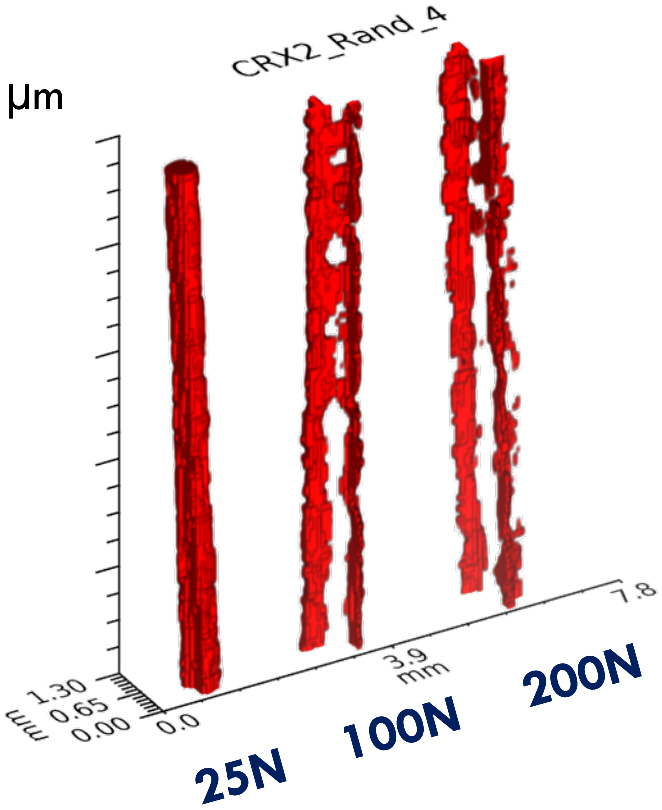
Aperture Distribution



Topology



Intersection Geometry

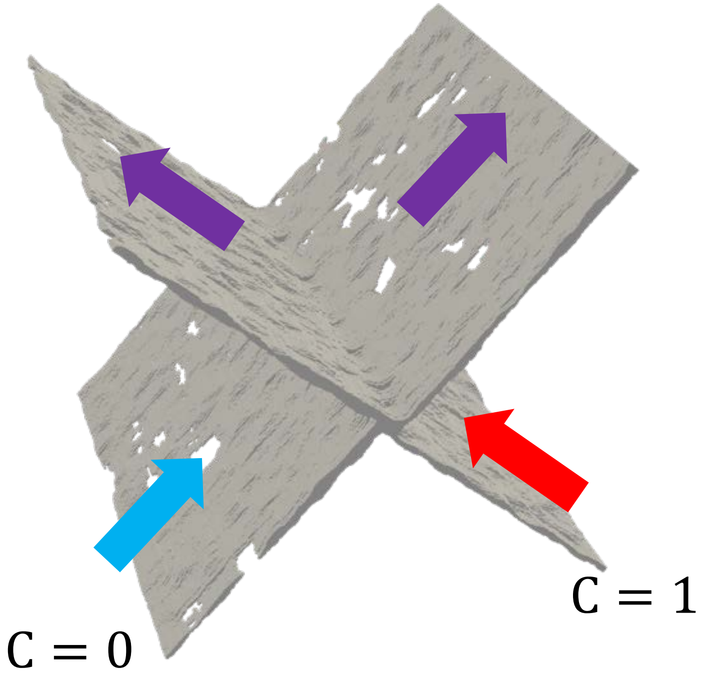


❖*Stress changes the topology of network from X to V and possibly Z*

Santo et al., 2022; Sumner et al., 2023

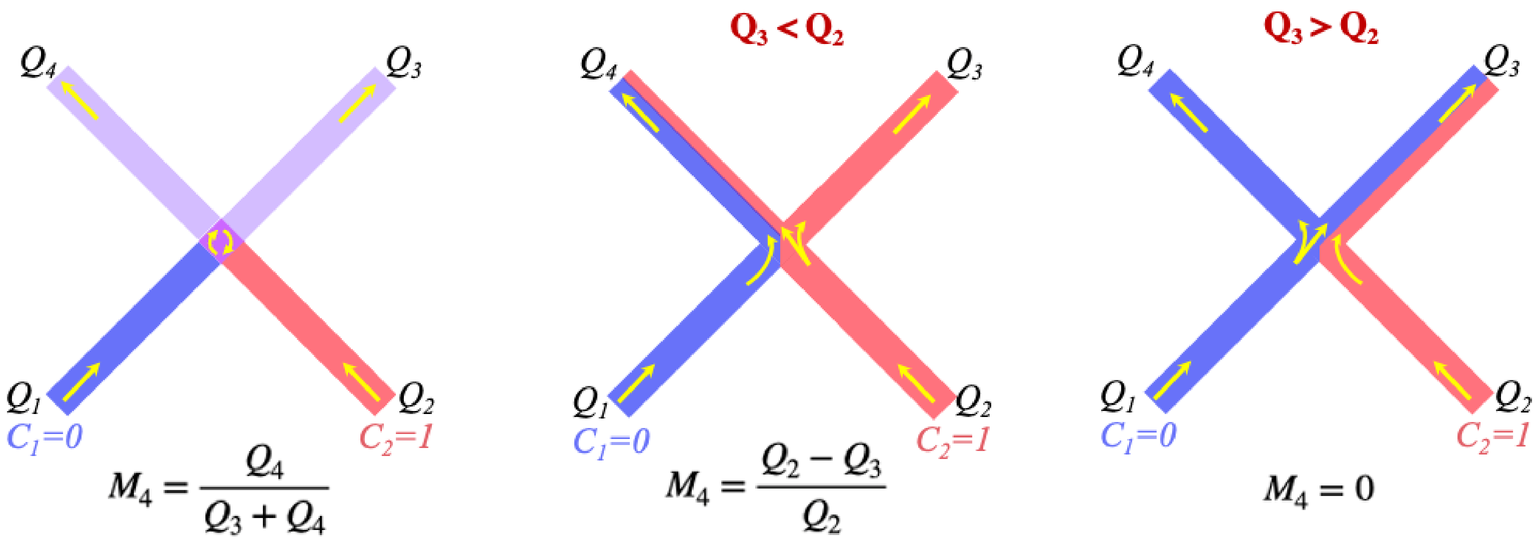
Pore-Scale Mixing Simulations on Experimentally Measured Network Geometry

Pore Scale Modeling



Simulations by Kang & Deng (U. Minnesota)

DFN Mixing Rules

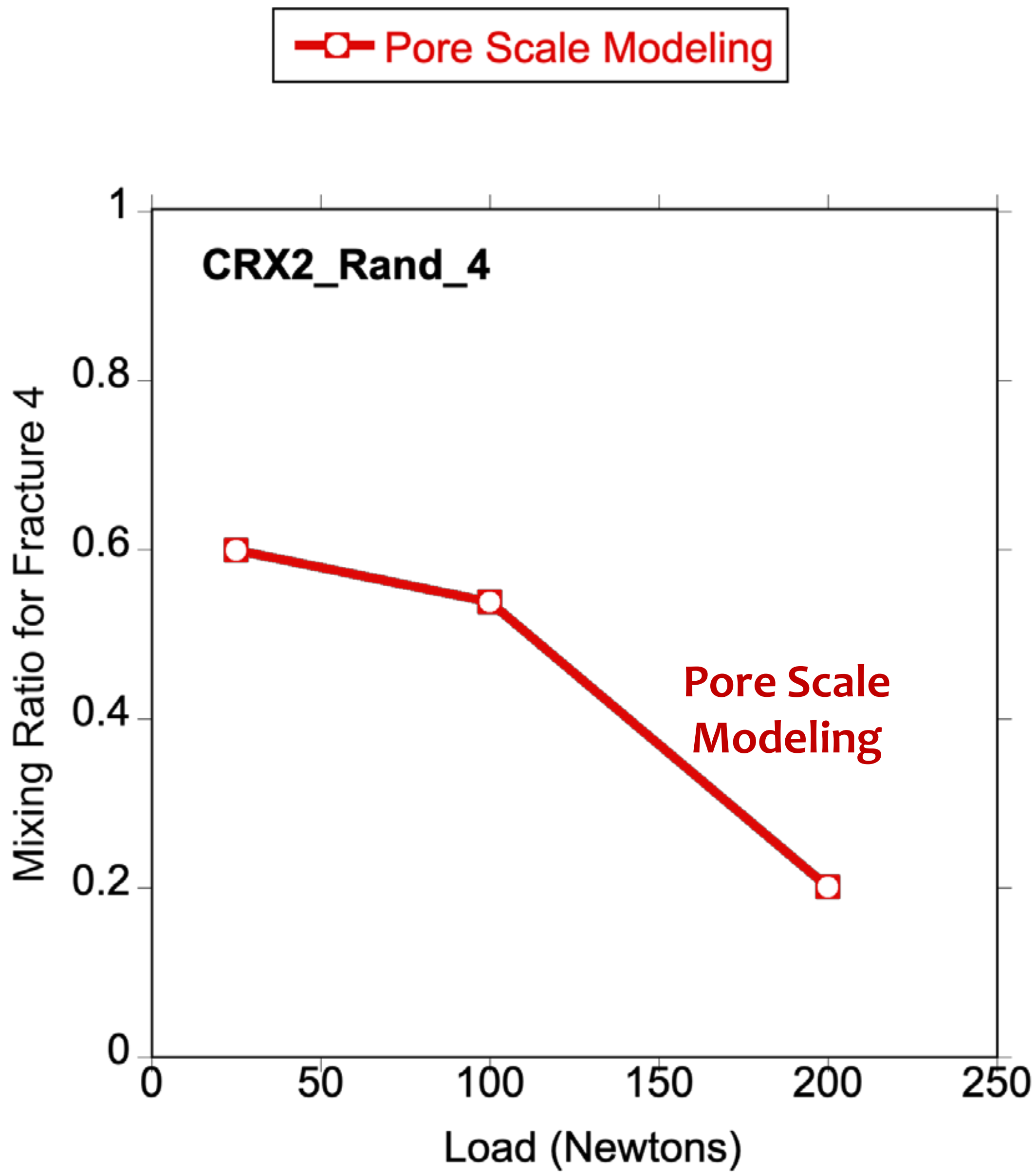


- Diffusion-dominated (Pe << 1)
- Advection-dominated (Pe large) solutes do not transition between streamlines.

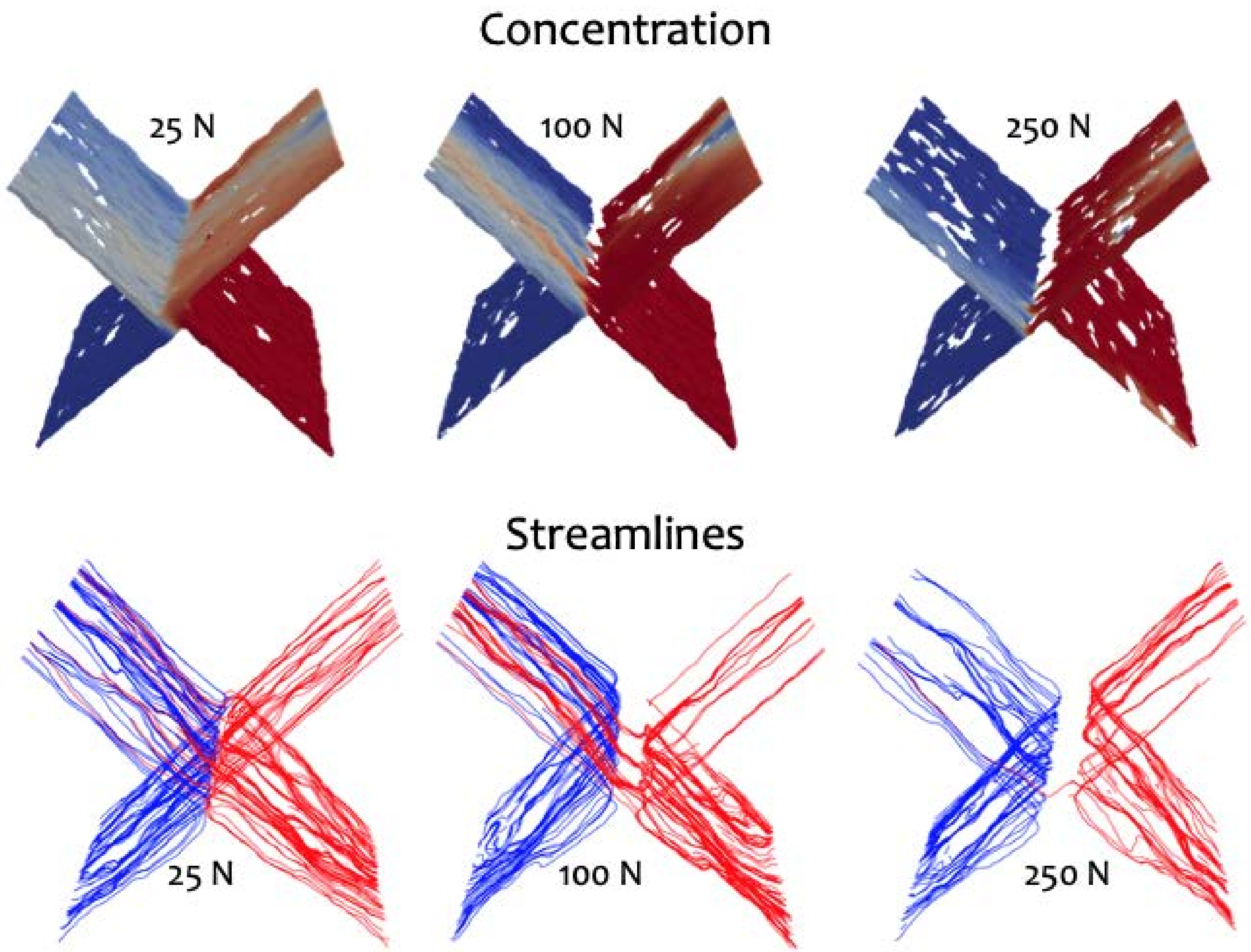
- *Pore scale modeling uses Navier-Stokes equation and the advection-diffusion equation on the laboratory measured fracture network geometry.*
- *Discrete Fracture Network (DFN) Models use "Mixing Rules" based on mean aperture or hydraulic aperture to partition mass at intersections.*

Comparison of DFN Mixing Ratios to Simulated Ratio

Laura J. Pyrak-Nolte | Purdue University



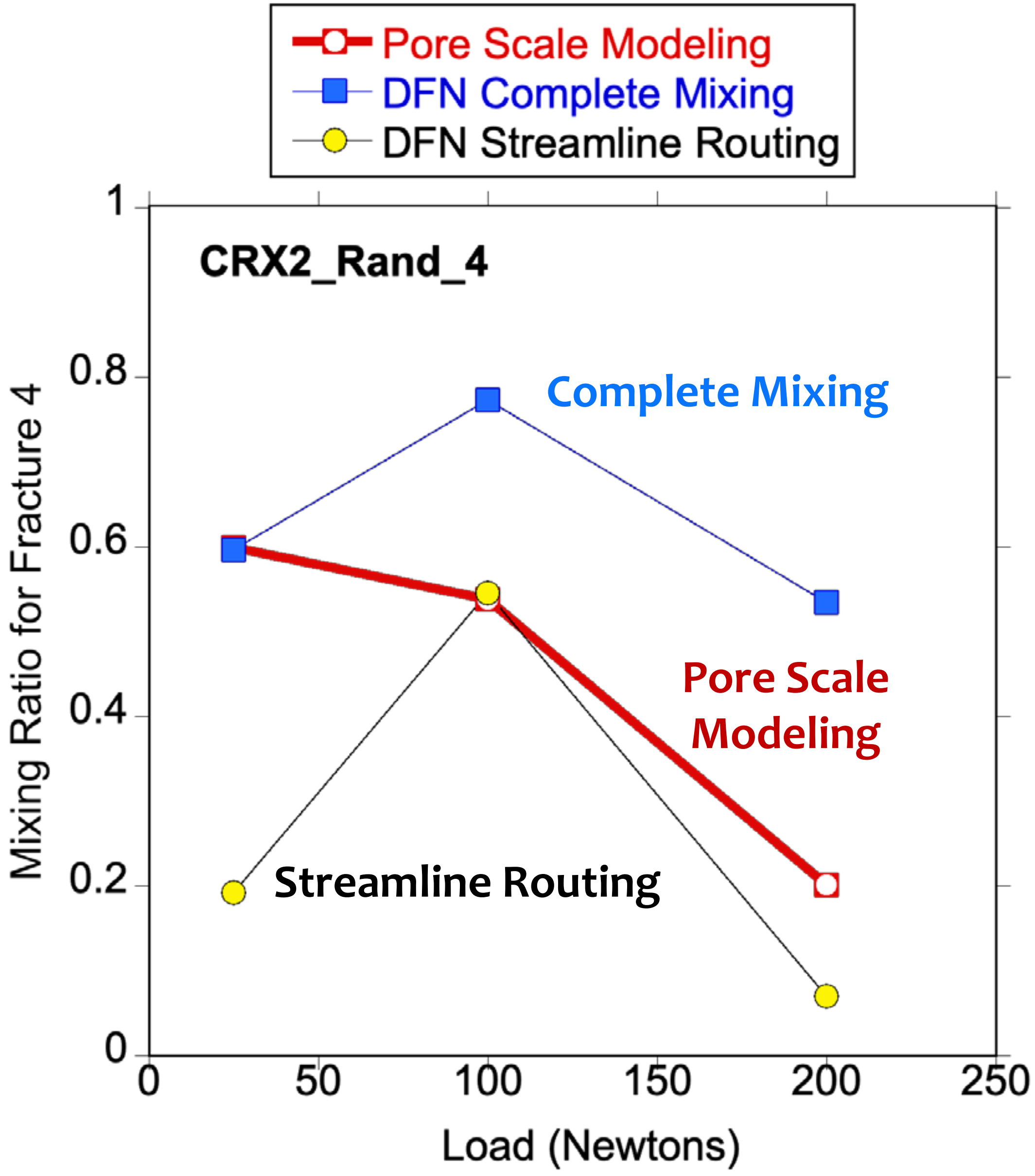
Pore Scale Simulations



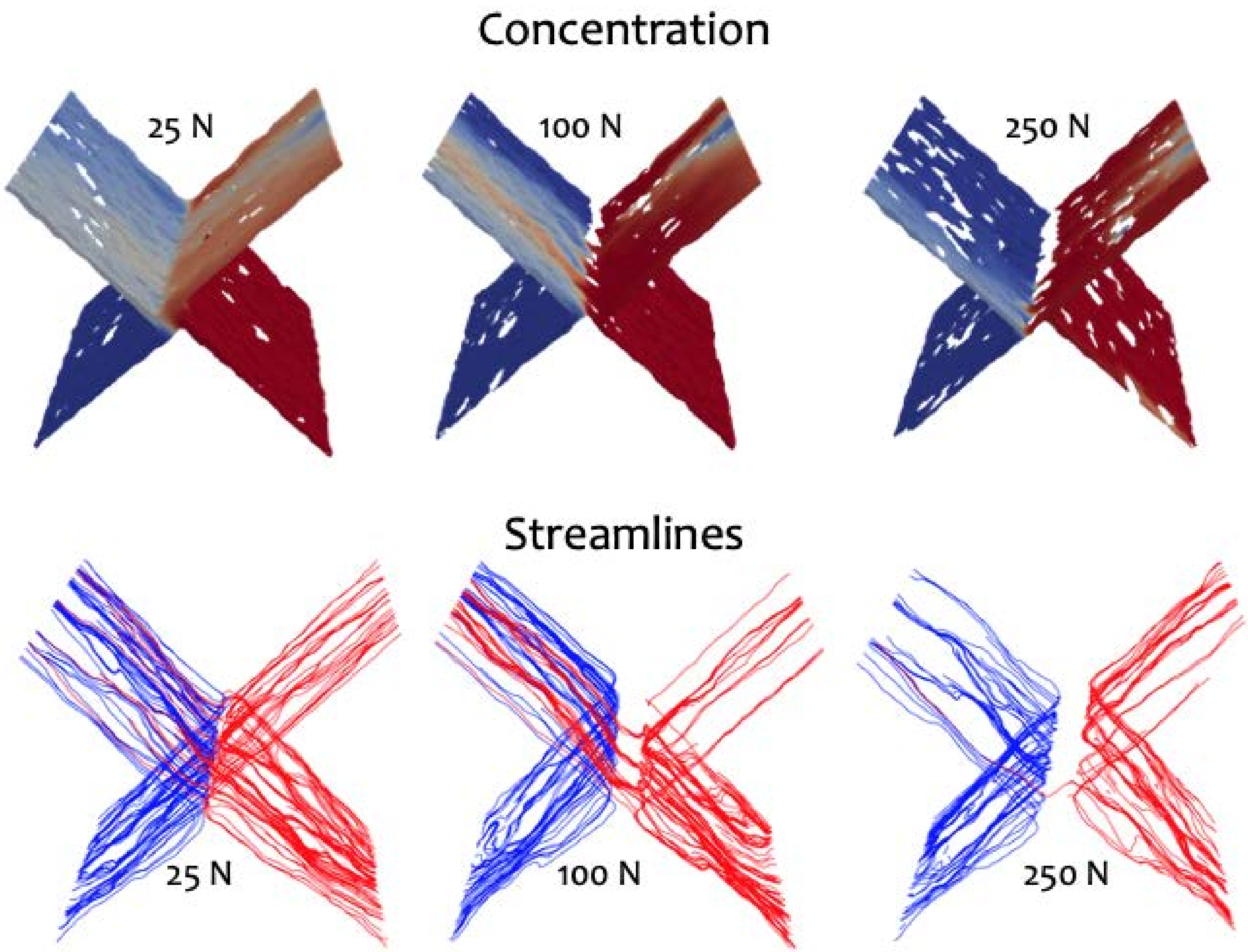
Simulations by Kang & Deng (U. Minnesota)

CRX2_Rand_4

Comparison of DFN Mixing Ratios to Simulated Ratio



Pore Scale Simulations



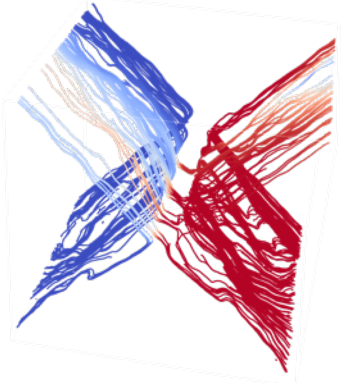
Simulations by Kang & Deng (U. Minnesota)

CRX2_Rand_4

Implications

- *Deformation of a fracture network affects connectivity and geometry of flow paths.*

- *Mixing ratios that only depend on mean aperture can lead to under- or over-prediction of mixing.*



- *Mixing ratios depend on network and intersection geometry and topology that evolve with stress.*

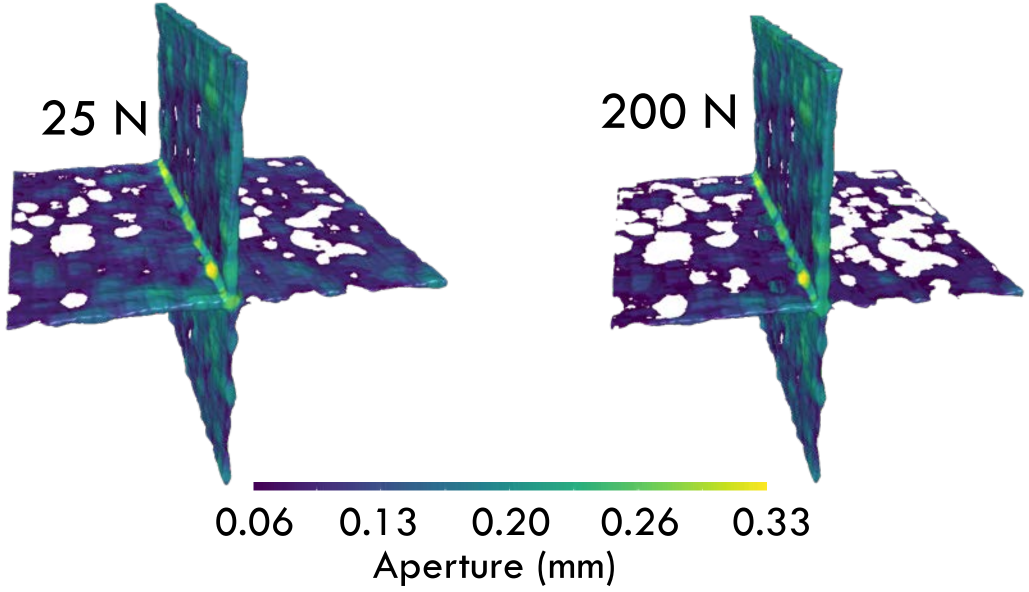
Future Direction: Development of a stress dependent mixing ratio formulation or a mixing ratio that depends on intersection geometry and how it deforms under stress or is altered by chemical processes.

Summary

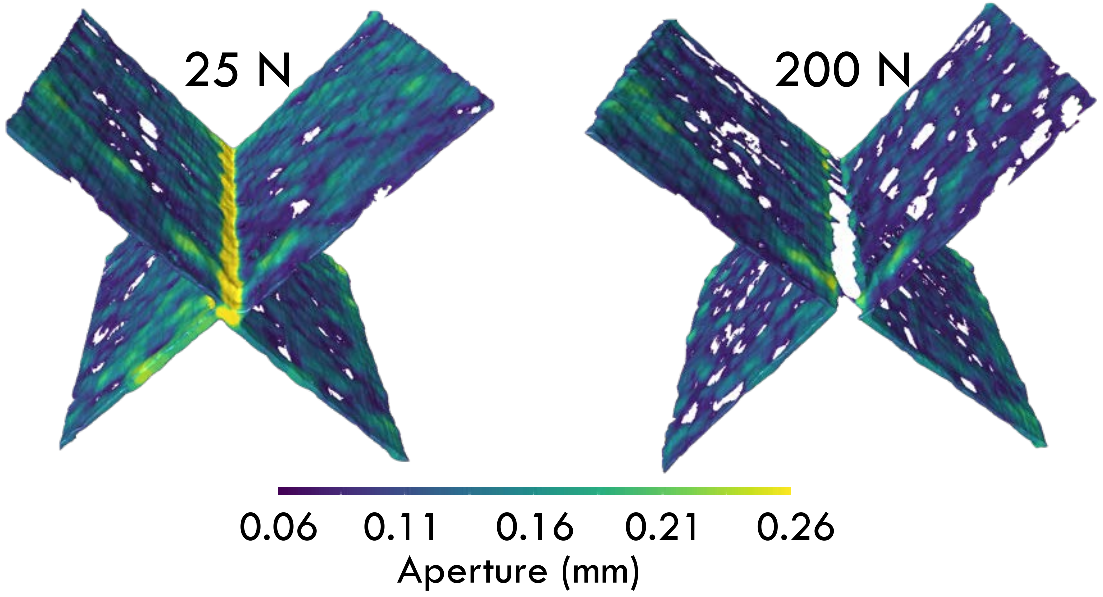
Laura J. Pyrak-Nolte | Purdue University

- ❖ *For fracture networks: The geometry matters & how this geometry is controlled by material properties & alterations from physical and chemical processes.*

CR2_Rand_4



CRX2_Rand_4



The work was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, Geosciences Research Program under Award Number (DE-SC0001048)

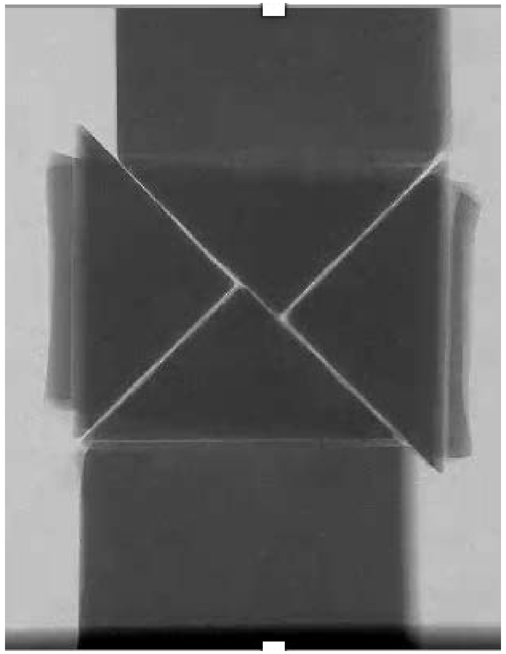
Summary

❖ *Need: Experimentalist & Modelers working together.*

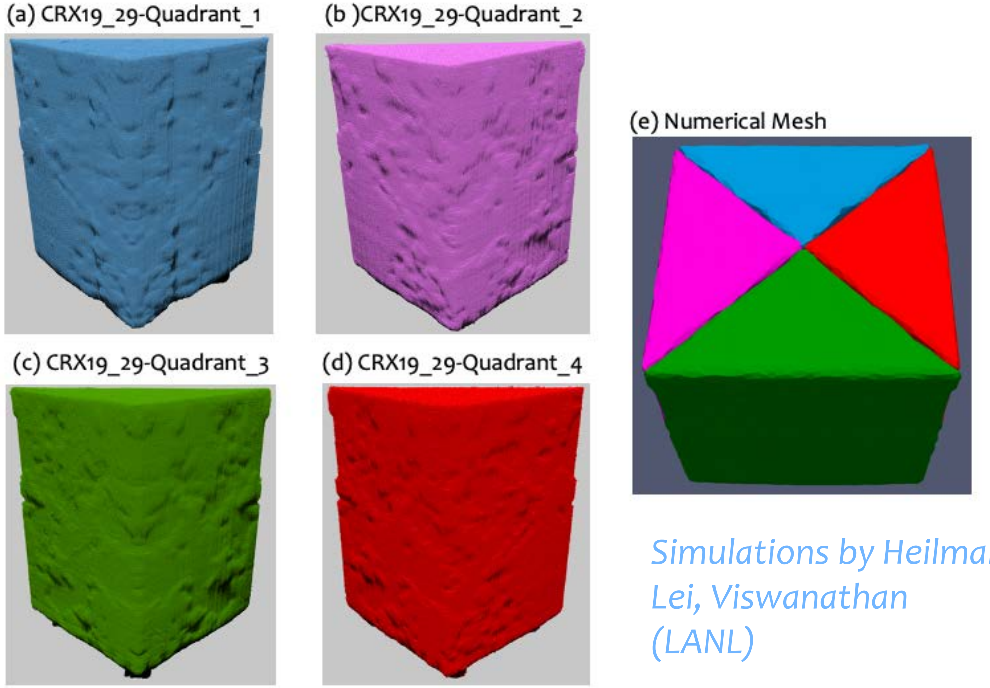
-Experimentalists can't run all permutations in the laboratory.

-Models that capture the experimentally observed behavior can be used to explore conditions found in the field or not possible in the laboratory.

X-ray Imaging Uniaxial Loading

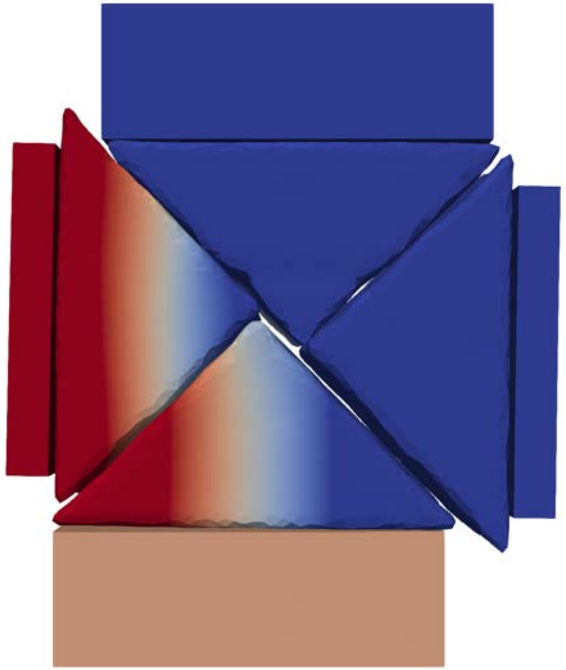


Individual Blocks from X-ray 3D Reconstructions



Simulations by Heilman, Lei, Viswanathan (LANL)

Geomechanics Simulation



The work was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, Geosciences Research Program under Award Number (DE-SC0001048)

Summary

- *For fracture networks: The geometry matters & how this geometry is controlled by material properties & alterations from physical and chemical processes.*

- *Need: Experimentalist & Modelers working together.*
  -Experimentalists can't run all permutations in the laboratory
  -Models that capture the experimentally observed behavior can be used to explore conditions found in the field or not possible in the laboratory.

- *Need: Incorporation of better representation of fracture behavior in models. Possibly need pre-modeling of individual fractures from different stress conditions to correctly update their behavior under the stress conditions produced in the simulation.*

The work was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, Geosciences Research Program under Award Number (DE-SC0001048)

Thank you

The work was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, Geosciences Research Program under Award Number (DE-SC0001048)