Modeling and Characterization of Fracture Roughness and its Impact on Heat and Mass Transport Processes

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(Sean Porse, also Chad Augustine)

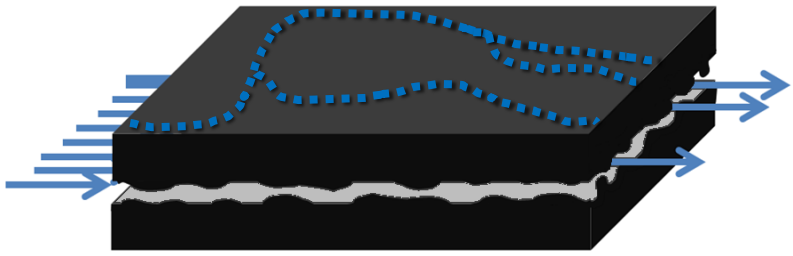
RESERVOIR CREATION

FRACTURE MANAGEMENT

- Command and Control

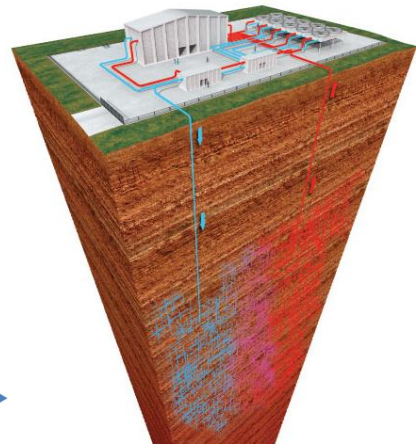
0. What kind of fractures do we want?
1. How do we create the fractures we want?
2. How do we determine what kind of fractures we've created?

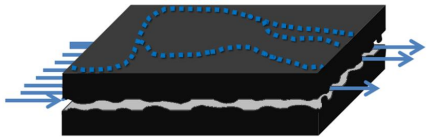
Rough Fractures



Fractures in Geothermal Reservoirs

- Renewable energy resource
- Faults/fractures are the main flow conduits
- Accurate flow models → production
- Flow channeling
  - Flow area
  - Heat conduction surface area

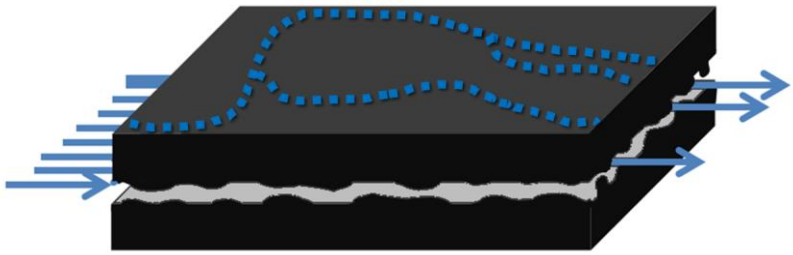




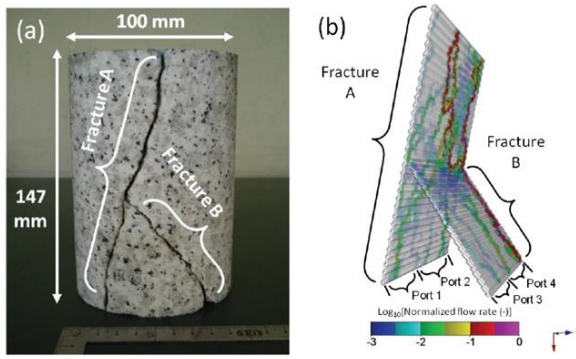
From Lawrence Livermore National Laboratory (2012)

Overall Issue

How important is the fracture roughness?
How does it affect mass and thermal energy transport?

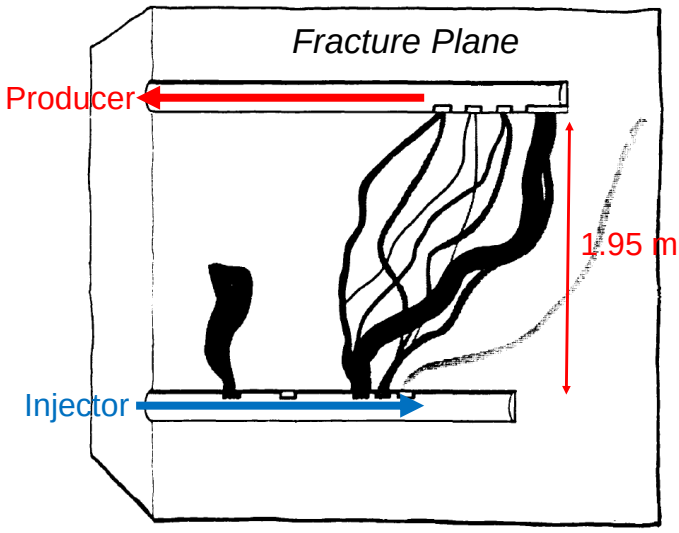


Channeling Flow in Natural Granite Fractures



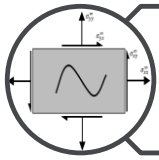
From Ishibashi et al. (2012)

Heterogeneous Tracer Flow within a Fracture



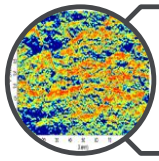
From Abelin et al. (1990)

Overall Research Problem



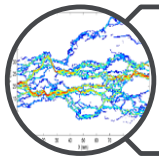
Fracture Generation

- How are rough fractures created with stress?
- Boundary element method (DDM)



Fracture Characterization

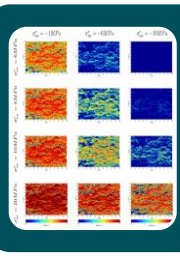
- How can we describe the spatial distribution?
- Variogram



Fracture Flow

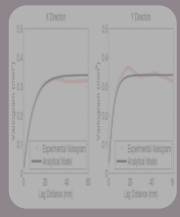
- What is the impact of roughness on flow?
- How can we predict flow behavior?
- Local cubic law, Sequential Gaussian simulation

Presentation Outline



Fracture Generation with Stress

- Numerical model (DDM)



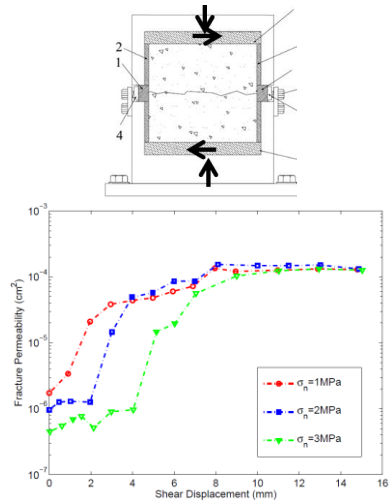
Fracture Characterization

- Stress correlation (DDM fractures)
- Length + Stress correlation (Laboratory fractures)

Motivation: Fracture Generation w/ Stress

- Fracture aperture/permeability evolution with stress application
- **Need to develop a consistent, physical model**
- Boundary element method (DDM)
- Initial fracture surfaces generated from laboratory compression tests
  - Granite sample
  - Sandstone sample

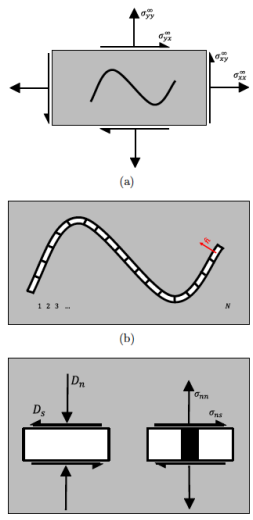
From Strickfaden (2009)



From Lee and Cho (2002)

Displacement Discontinuity Boundary Element Method (DDM) Model: Introduction

- Ritz et al. (2012)
- Discretize only on the fracture
- Models element stress interactions within the fracture trace
- Relate $[D_n, D_s]$ to $[\sigma_{nn}, \sigma_{ns}]$ using influence coefficients
- Integrated Complementarity algorithm → Eliminate interpenetration of cracks

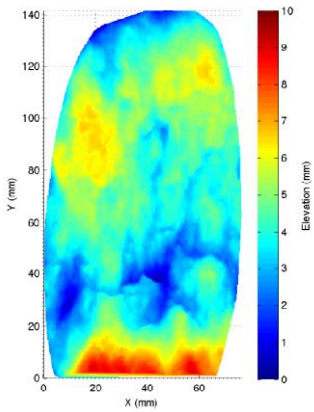


D_n : normal displacement (opening)
D_s : shear displacement (slip)
σ_{nn} : normal stress
σ_{ns} : shear stress

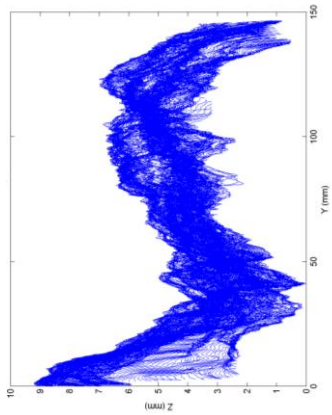
Modified from Ritz et al. (2012)

DDM Input Data

Fracture Surface Elevation

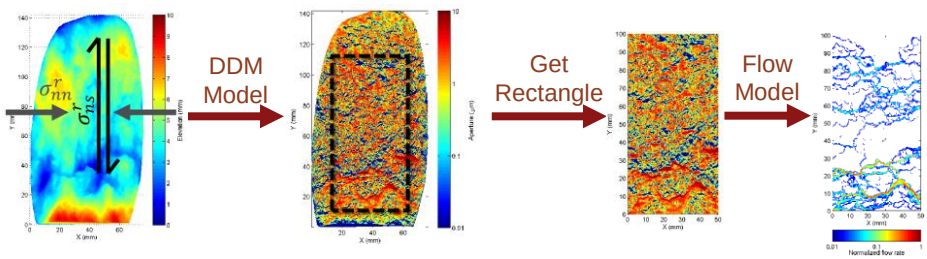


Fracture Trace



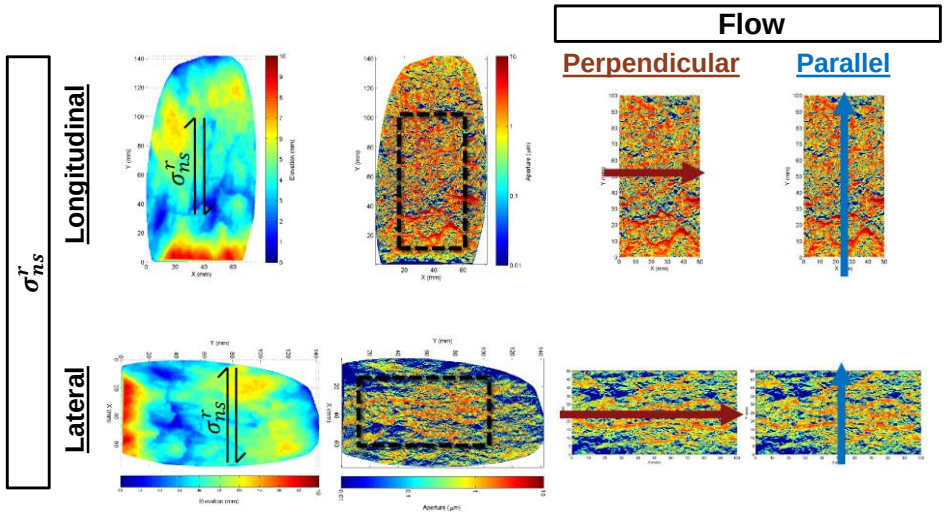
Overall Procedure after Preprocessing

Whole Fracture Plane | **Rectangular Section**

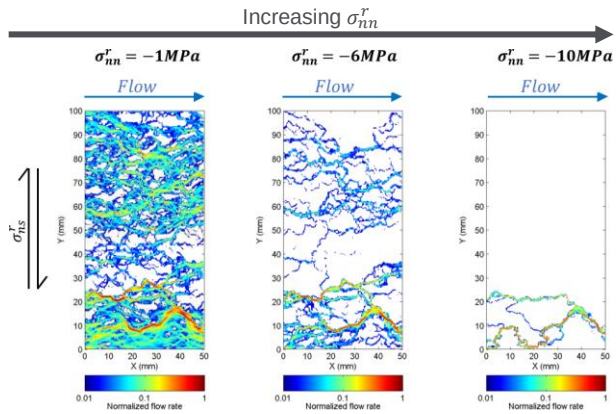


Filtered Elevation | Aperture | Aperture | Relevant Flow

DDM Run Configurations: σ_{ns}^{r} and Flow Orientation

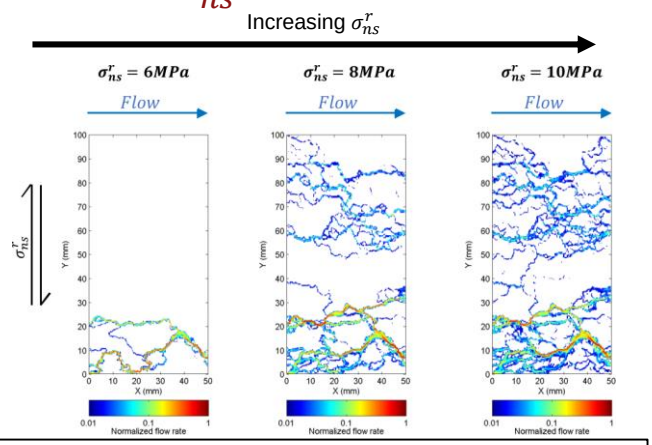


Flow Results: σ_{nn}^{r} Effect



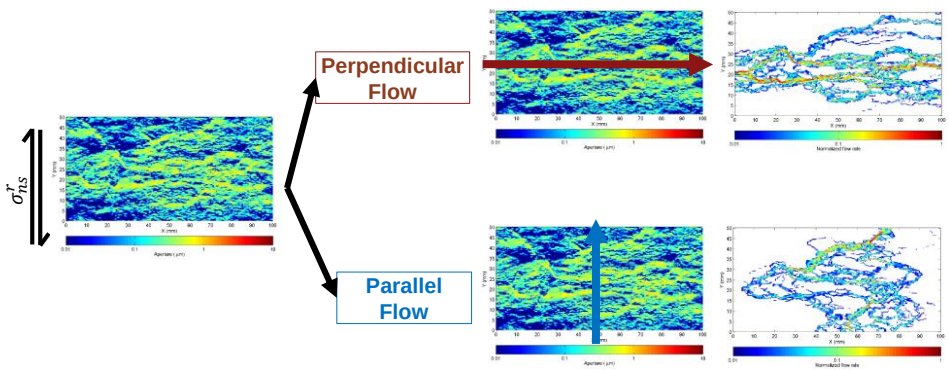
- Higher σ_{nn}^{r} → increases resistance to slip, less elements open
- Most restrictive case emphasizes dominant flow paths

Flow Results: σ_{ns}^{r} Effect



- Higher σ_{ns}^{r} → more elements slip and open
- Most restrictive case emphasizes dominant flow paths

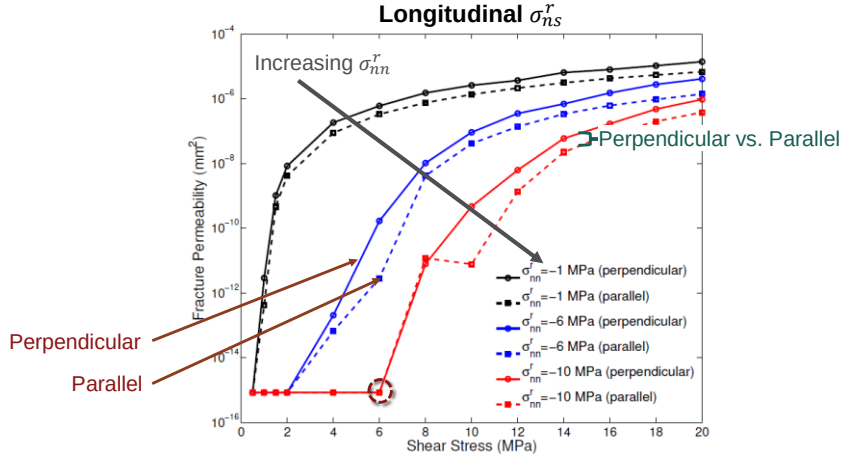
Flow Results: Flow Orientation Effect



- Higher flow perpendicular to σ_{ns}^{r}
- Perpendicular: channelized flow pattern
- Parallel: distributed flow pattern
- Flow patterns → heat transfer efficiency

Results Summary: Permeability vs. Stress

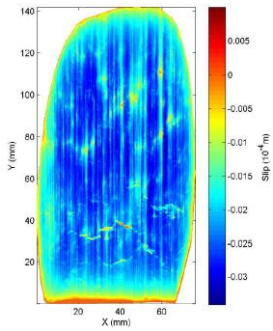
Longitudinal σ_{ns}^{r}



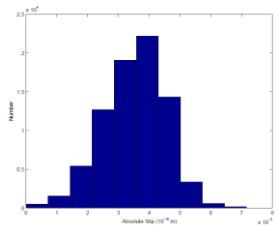
- $\uparrow Permeability$: $\downarrow \sigma_{nn}^{r}$, $\uparrow \sigma_{ns}^{r}$, flow $\perp \sigma_{ns}^{r}$
- Critical σ_{ns}^{r} $(\mu\sigma_{nn}^{r})$ before a permeability increase

Defining the Representative Fracture Slip

Fracture Slip Map



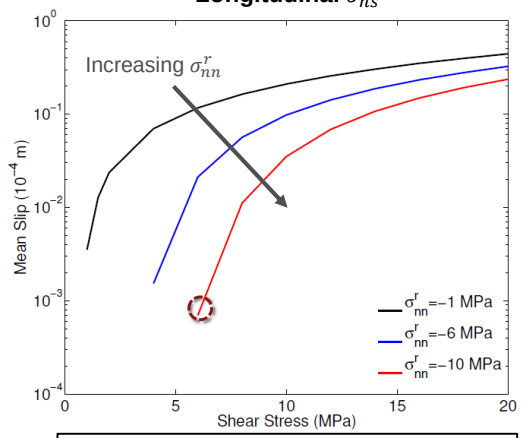
Fracture Slip Distribution



- Surface roughness → heterogeneous fracture slip distribution
- Difficult to define a single fracture slip value
- Use mean slip as a representative slip value

Results Summary: Slip vs. Stress

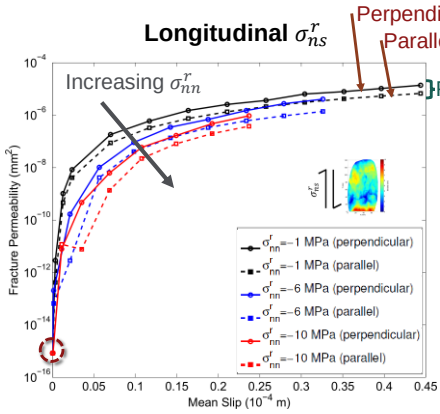
Longitudinal σ_{ns}^{r}



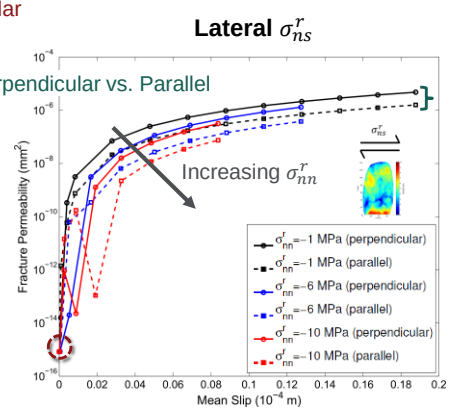
- Same trend as permeability vs. stress
- Small slip at critical σ_{ns}^{r} $(\mu\sigma_{nn}^{r})$
- Variability in slip values

Results Summary: Permeability vs. Slip

Longitudinal σ_{ns}^{r}



Lateral σ_{ns}^{r}

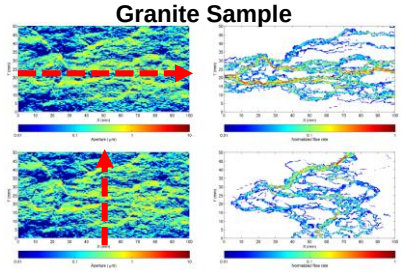


- $\uparrow Permeability$: $\downarrow \sigma_{nn}^{r}$, $\uparrow mean\ slip$, $\uparrow \sigma_{ns}^{r}$, flow $\perp \sigma_{ns}^{r}$
- At critical σ_{ns}^{r}: small slip and no permeability increase
- General trend fits experimental data and empirical models

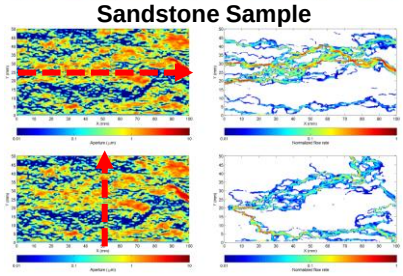
Granite vs. Sandstone DDM Results

- Main difference in input:
  - Elastic properties
  - Initial surface
- Similar Results:
  - Consistent permeability vs. normal and shear stress trends
  - Higher permeability in the perpendicular direction with respect to the shear stress
- Sandstone sample:
  - Higher permeability values
  - Smoother aperture texture

Granite Sample

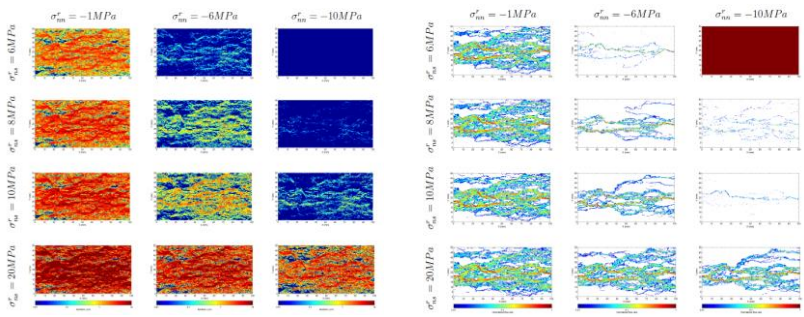


Sandstone Sample

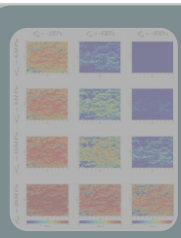


Conclusions: Fracture Generation with DDM

- DDM is a consistent physical model for generating rough fractures
- Surface roughness has a significant impact on the aperture and slip
- Permeability increases with σ_{ns}^{r} and decreases with σ_{nn}^{r}
- Permeability is higher in the flow direction perpendicular to σ_{ns}^{r}

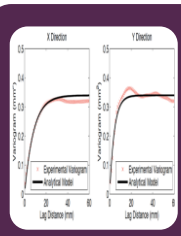


Presentation Outline



Fracture Generation with Stress

- Numerical model (DDM)

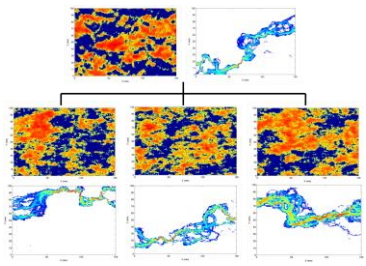


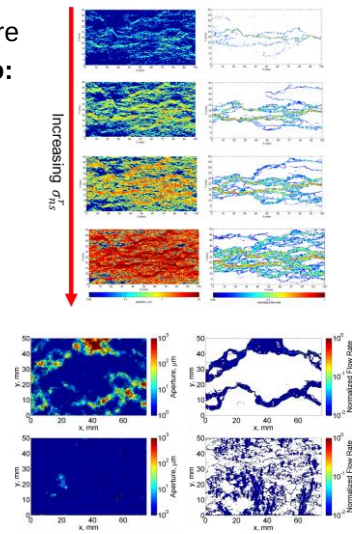
Fracture Characterization

- Stress correlation (DDM fractures)
- Length + Stress correlation (Laboratory fractures)

Motivation: Fracture Characterization

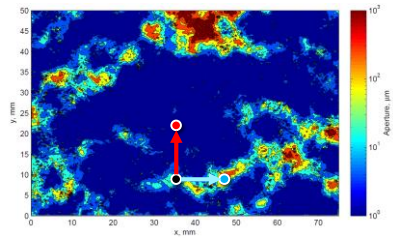
- Capture the spatial trends in aperture
- **Need parameters that correlate to:**
  - Generation mechanism?
  - Effect for flow?
- Variogram models
- Generate artificial fractures

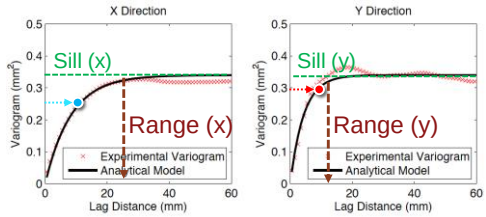




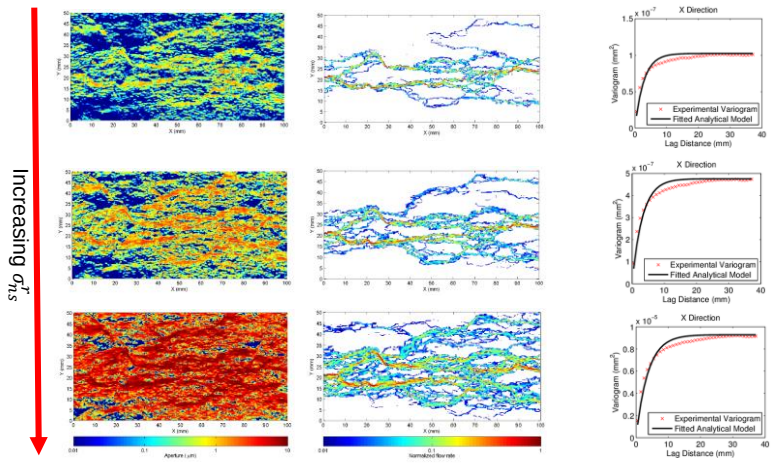
Variogram: Introduction

- Two-point correlation
- Reflects the difference of the values of 2 points separated by a lag distance in a particular direction
- Main Parameters:
  - Range : correlation length
  - Sill : variance
- Geometric Anisotropy
  - Different range
  - Spatial continuity

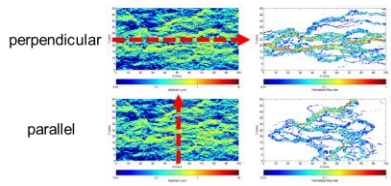


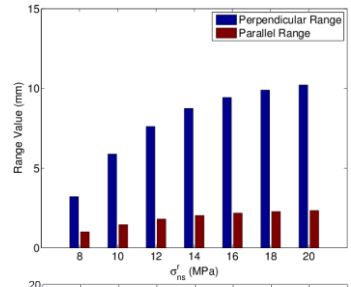


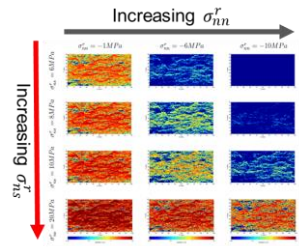
Variogram Analysis of DDM Fractures

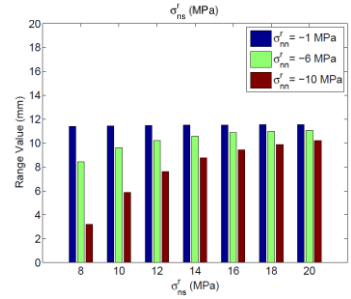


Variogram Analysis of DDM Fractures

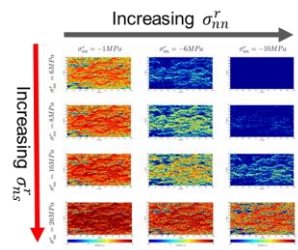


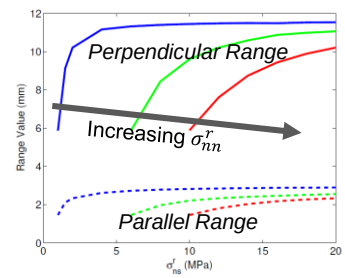




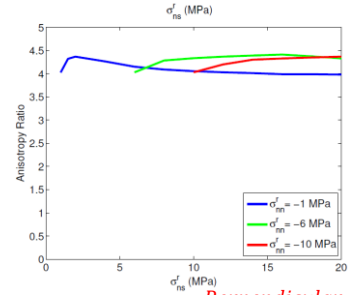


Variogram Analysis of DDM Fractures





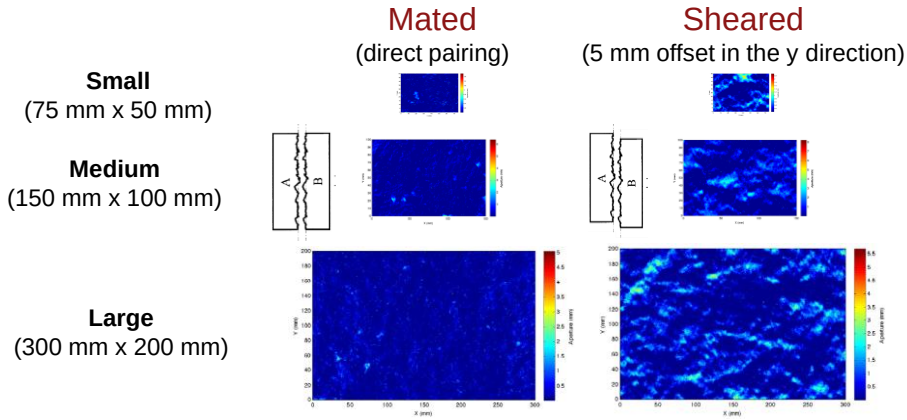
- Perpendicular >> parallel range
- Variogram Range:
  - increases with σ^r_{ns}
  - decreases with σ^r_{nn}
- Anisotropy ratio is stress independent
  - Granite: 4 - 4.5
  - Sandstone: 3 - 3.5



$$Anisotropy\ Ratio = \frac{Perpendicular}{Parallel}$$

Wedge Fracture Surfaces (Ishibashi et al., 2015)

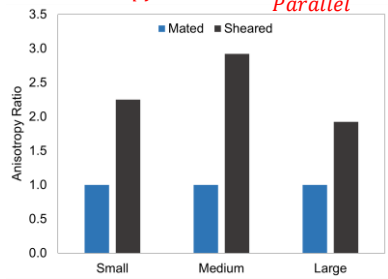
- Fracture surfaces are generated using a wedge (Granite samples)
- 3 different length scales
- 2 surface pairing configurations: different spatial characteristics

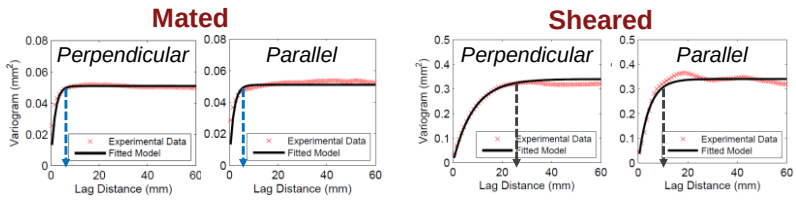


Variogram Analysis of Wedge Fractures

- Mated fractures:
  - Isotropic
  - No preferential direction
- Sheared fractures:
  - High spatial continuity in the perpendicular direction
  - Channels perpendicular to the shear offset direction

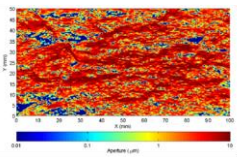
$$Anisotropy\ Ratio = \frac{Perpendicular}{Parallel}$$

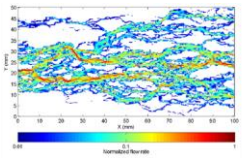


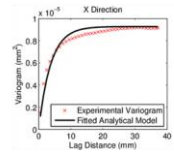


Conclusions: Fracture Characterization

- Variogram models capture spatial trends in the aperture distribution
- Variogram range:
  - higher perpendicular to the shear stress
  - increases with shear stress
  - decreases with normal stress
- Range anisotropy:
  - independent of stress
  - dependent on rock type
  - reflects the surface pairing configuration (mated vs. sheared)







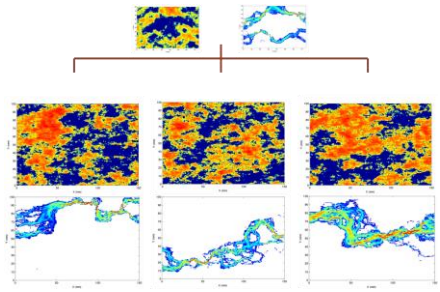
Main Conclusions

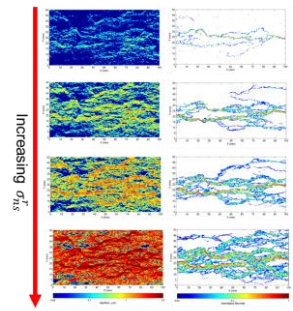
FRACTURE GENERATION WITH STRESS

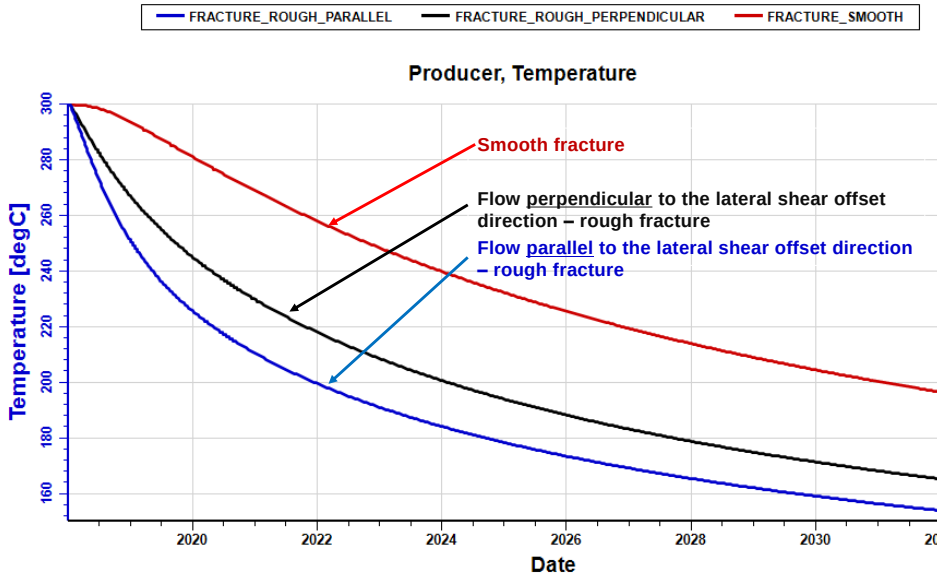
- Roughness leads to heterogeneous aperture and slip distributions
- Higher permeability perpendicular to the shear stress direction

FRACTURE CHARACTERIZATION

- Greater spatial continuity perpendicular to the shear stress
- Variogram parameters are related to the generation mechanism



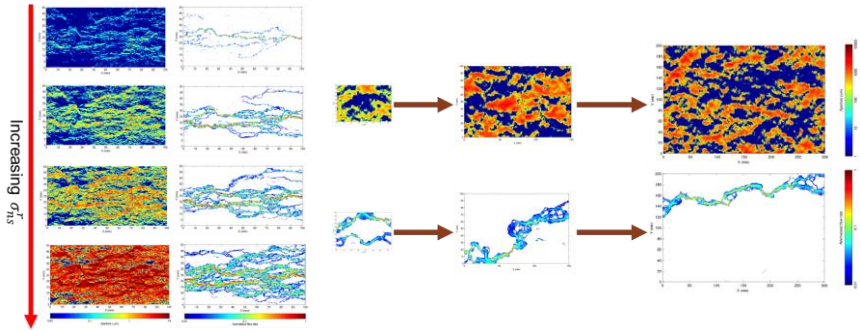




0. What kind of fractures do we want?
1. How do we create the fractures we want?
2. How do we determine what kind of fractures we've created?

Modeling and Characterization of Fracture Roughness and its Impact on Heat and Mass Transport Processes

CARLA CO, RITA OKOROAFOR AND ROLAND N. HORNE



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