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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 $\rightarrow$ production
- Flow channeling
  - Flow area
  - Heat conduction surface area

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

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 $\rightarrow$ Eliminate interpenetration of cracks

$D_n$: normal displacement (opening)
$D_s$: shear displacement (slip)
$\sigma_{nn}$: normal stress
$\sigma_{ns}$: shear stress

From Strickfaden (2009)

From Lee and Cho (2002)

Modified from Ritz et al. (2012)
**DDM Input Data**

Fracture Surface Elevation  
Fracture Trace

**Overall Procedure after Preprocessing**

**Whole Fracture Plane**  
Filtered Elevation  
DDM Model  
Get Rectangle  
Flow Model

**Rectangular Section**  
Aperture  
Aperture  
Relevant Flow
DDM Run Configurations: $\sigma_{ns}^r$ and Flow Orientation

Flow Results: $\sigma_{nn}^r$ Effect

- Higher $\sigma_{nn}^r$ increases resistance to slip, less elements open
- Most restrictive case emphasizes dominant flow paths
Flow Results: $\sigma_{\text{NS}}^\tau$ Effect

- Higher $\sigma_{\text{NS}}^\tau$ $\rightarrow$ more elements slip and open
- Most restrictive case emphasizes dominant flow paths

Flow Results: Flow Orientation Effect

- Higher flow perpendicular to $\sigma_{\text{NS}}^\tau$
- Perpendicular: channelized flow pattern
- Parallel: distributed flow pattern
- Flow patterns $\rightarrow$ heat transfer efficiency
Results Summary: Permeability vs. Stress

**Longitudinal** $\sigma_{ns}$

- Increasing $\sigma_{nn}$, $\sigma_{ns}$, flow $\sigma_{ns}$
- Critical $\sigma_{ns}$ ($\mu\sigma_{nn}$) before a permeability increase

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Defining the Representative Fracture Slip

**Fracture Slip Map**

**Fracture Slip Distribution**

- Surface roughness $\rightarrow$ 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 $\sigma_{ns}$

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

Results Summary: Permeability vs. Slip

Longitudinal $\sigma_{ns}$

- Increasing $\sigma_{ns}$
- Perpendicular vs. Parallel

- ↑ Permeability: ↓ $\sigma_{nn}$, ↑ mean slip, ↑ $\sigma_{ns}$, flow ↓ $\sigma_{ns}$
- At critical $\sigma_{ns}$: 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

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 $\sigma_{ns}$ and decreases with $\sigma_{nn}$
- Permeability is higher in the flow direction perpendicular to $\sigma_{ns}$
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

- Perpendicular >> parallel range
- Variogram Range:
  - increases with $\sigma_{\text{NS}}$
  - decreases with $\sigma_{\text{nn}}$
- Anisotropy ratio is stress independent
  - Granite: 4 - 4.5
  - Sandstone: 3 - 3.5

\[
\text{Anisotropy Ratio} = \frac{\text{Perpendicular}}{\text{Parallel}}
\]
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

Mated (direct pairing)

- Small (75 mm x 50 mm)
- Medium (150 mm x 100 mm)
- Large (300 mm x 200 mm)

Sheared (5 mm offset in the y direction)

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

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