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What is a fracture?
Why fractures matter?
What is a fracture?

- Geology
  - Ubiquitous: Fault, Fracture, Joint, Diaclase
  - Plate tectonics, sismology

San Francisco (1906)
Magnitude 8.2

San Andreas (Californie, USA)

Simpevarp (Suède)
100 m
1 m

Energy Minerals Division; Gas shale tricky to understand
Brian Cardott (EMD Gas Shale Committee member).
http://www.aapg.org/explorer/divisions/2006emd.cfm/
What is a fracture?

- Geology
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  - Plate tectonics, sismology
- Mathematical modeling
  - 2D features in 3D space (lower dimensionality)
- Hydraulics


What is a fracture?

- Geology
  - Ubiquitous: Fault, Fracture, Joint, Diaplectic
  - Plate tectonics, sismology
- Mathematical modeling
  - 2D features in 3D space (lower dimensionality)
- Hydraulics
  - Flow barriers, flow highways
  - High permeability, low storativity
  - Low surface/volume features
- Mechanics
  - Dynamic, Chaotic
  - Energy dissipation
- Physics
  - Statistics, emergence

Stauffer, D., and A. Aharony (1992), Introduction to percolation theory, second edition, Taylor and Francis, Bristol.
Why fractures matter?

- Negative fracture perception
  - Waste storage, connectivity issues
- Positive impact of fractures
  - Oil and gas recovery
  - 3D volume (geothermal energy)
  - Groundwater (India, Africa, Aquifer connectivity)
- Fractures (more generally geological complexity)
  - Source of uncertainty
  - Coexistence of services (storage, resources, environment)
- Requires CONTROL
  - Observations, Monitoring
  - Modeling
  - Data processing, calibration, assimilation
Fracture versus rock permeability

\[ K_{eq} = n \frac{\rho g a^3}{12 \mu} + (1 - na)K_m \]

\( a \): hydraulic aperture
High Fracture Densities
Extreme flow channeling
Small Permeability
Flow structures in natural fractured media
Multiple-scale Channeling and limited permeability

Fracture scale

Network scale


Bolmen channels

Stripa, Olsson [1992]

http://www.imstunnel.com/page_03.htm

80 % of flow

100 % of flow
Why are flows so channelled and permeability so limited?

FRACTURE SCALE
- Fracture roughness
- Fracture sealing/dissolution (chemistry)
- Fracture closing/opening (mechanical)

NETWORK SCALE
- Fracture length distribution
- Global connectivity (network effects)
- Effective transmissivity variability (orientations, depth)
- Local connectivity (intersections)
- Mechanical-issued correlation patterns (fracture organization)
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2D Poissonian fracture networks

\( a \): length distribution parameter
\( d \): density parameter
\( 2(\log K_1) \): fracture log-permeability variance

\[
K_N = K(d, L) \exp\left[ (d, a) \cdot \frac{(\log K_1)}{2} \right]
\]

- \( \omega = 1 \): arithmetic mean
- \( \omega = 0 \): geometric mean
- \( \omega = -1 \): harmonic mean

MODELS ARE MUCH TOO PERVIOUS

Reduction for sparse networks by tortuosity and BOTTLE NECKS

BUT

Large fractures prevent sparsity and enhance permeability

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Why are flows so channelled and permeability so limited?

FRACTURE SCALE
- Fracture roughness
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NETWORK SCALE: bottle necks versus large fractures
- Fracture length distribution
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- Mechanical-issued correlation patterns (fracture organization)
Permeability of rough fractures


Local aperture distribution
Truncated Gaussian with a bounded self-affine correlation pattern

\[
p(a/a_m) = \begin{cases} 
\frac{1}{c_{frac}\sqrt{2\pi}} e^{-\frac{(a/a_m-1)^2}{2c_{frac}^2}} & \text{ifa} \geq 0 \\
0 & \text{ifa} \leq 0 
\end{cases}
\]
Fracture aperture and transmissivity distribution shown by dashed and solid lines respectively.

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\[ p(a/a_m) = \begin{cases} \frac{1}{c_{frac}} \sqrt{2\pi} e^{-\frac{(a/a_m-1)^2}{2c_{frac}^2}} & \text{if } a \geq 0 \\ 0 & \text{if } a \leq 0 \end{cases} \]

\[ p_T(T) = \frac{1}{\sqrt{2\pi\Gamma^2}} \frac{1}{3\beta^{1/3}T^{2/3}} \exp\left( -\frac{(T / \beta)^{1/3} - \Gamma/c}{2\Gamma^2} \right) \]

\[ T \sim a^3 \]
Effective permeability $K_A$
normalized by the equivalent parallel plate permeability $K_1$

\[
\left\langle \frac{K_A}{K_1} \right\rangle
\]

\[
0,0 \quad 0,5 \quad 1,0
\]

Reduction by a factor of 2
Reduction by a factor of 4

Roughness:
Reduction factor of $K$ 2 to 4 at most
Why are flows so channelled and permeability so limited?

**FRACTURE SCALE:** reduction factor of 2 to 4 at most
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**COMBINATION FRACTURE/NETWORK**
Multi-Scale Discrete Fracture Network models (DFNs)

- Field-based DFNs
  - Power-law length distribution
  - Orientation distribution
  - Correlation patterns (mechanics)
  - Fracture density
  - Fracture roughness
  - Fracture aperture
  - Intersection structure
  - Matrix permeability

- Simplifications
  - Keep connected clusters
  - Keep large fractures

- Hydraulic simulations
  - Large scale, highly resolved
  - 3D

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Bour, O., et al. (2002), A statistical scaling model for fracture network geometry, with validation on a multiscale mapping of a large number of fractures, Journal of Geophysical Research, 107(B6).

Large number of fractures: $\sim 1 \times 10^3$

$L = 50 \, l_{\text{min}}$

fracture length, $l$

$\frac{1}{l_{\text{min}}} \ll 1$

Broad power-law length distribution $n(l) \sim l^{-a}$ with $a = 1.75$
Multi-scale DFN hydraulic simulations

- Field-based DFNs
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Flow equation
\[ \nabla \cdot a^3 \nabla h = 0 \]

Permeameter

Boundary conditions

\[ K = QL / (hS) \]
Combined fracture- and network-scale effects

**Fracture Network**

Flows with uniform apertures $K_N$

Flows with distributed apertures $K_{N,F}$

Effective permeability $K_{N+A}$

Dense Networks

$$\left\langle \frac{K_{N+F}}{K_1} \right\rangle$$

Hihgly limited effects
Effective permeability $K_{N+A}$

Sparse Networks

$$\left< \frac{K_{N+F}}{K_1} \right>$$

Reduction by a factor of 2

Reduction by a factor of 4

Single Fracture

Additional reduction by a factor of 2 to 3
Effective permeability $K_{N+F}$

Percolation Networks

\[
\left\langle \frac{K_{N+F}}{K_1} \right\rangle
\]

Reduction by a factor of 2

Reduction by a factor of 4

Additional reduction by a factor of 5 to 10
Why are flows so channelled and permeability so limited?

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COMBINATION FRACTURE/NETWORK: reduction factor of 2 to 10
Why are flows so channelled and permeability so limited?

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COMBINATION FRACTURE/NETWORK: reduction factor of 2 to 10
Mechanical induced organization of the fracture network (preliminary results)

Reduction factor of $K$: 3 to 10
Why are flows so channelled and permeability so limited?

FRACTURE SCALE: reduction factor of 2 to 4 at most
- Fracture roughness
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- Fracture closing/opening (mechanical)

NETWORK SCALE: bottle necks versus large fractures
- Fracture length distribution
- Global connectivity (network effects)
- Effective transmissivity variability (orientations, depth)
- Local connectivity (intersections)
- Mechanical correlation patterns: reduction factor of 3 to 10

COMBINATION FRACTURE/NETWORK: reduction factor of 2 to 10
Impact of Intersection length \((l_2)\)

Reduction factor of \(K\): 2 to 4

With an analytical image method adapted from Long [1985]
Why are flows so channelled and permeability so limited?

FRACTURE SCALE: *reduction factor of 2 to 4 at most*
- Fracture roughness
- Fracture sealing/dissolution (chemistry)
- Fracture closing/opening (mechanical)

NETWORK SCALE: *bottle necks versus large fractures*
- Fracture length distribution
- Global connectivity (network effects)
- Effective transmissivity variability (orientations, depth)
- Local connectivity (intersections): *reduction factor of 2 to 3*
- Mechanical correlation patterns: *reduction factor of 3 to 10*

COMBINATION FRACTURE/NETWORK: *reduction factor of 2 to 10*
Modeling frameworks
Relevant-Realistic
Simple-tractable
**Historical » modelling frameworks**

**Double Porosity**


**Discrete Fracture Network**


**Stochastic Continuum**


Multi-Scale DFN models: building simplifications

- Field-based DFNs
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  - Keep connected clusters
  - Keep large fractures

- Hydraulic simulations
  - Large scale, highly resolved
  - 3D

* Broad power-law length distribution $n(l) \sim l^{-a}$ with $l_{\text{min}} < l < L$
  Large number of fractures: $\sim 15 \times 10^3$
Equivalent Permeability, controls on the flow structure

Bottlenecks

Parallel paths

Reference Multi-Scale DFN models
Alternative modeling concepts

- Field-based DFNs
  - Power-law length distribution
  - Orientation distribution
  - Correlation patterns (mechanics)
  - Fracture density
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Discrete multiple-porosity media

- Multi-scale Fractured Media
  - Fracture structures
  - Network complexity
  - Fracture/Matrix interactions
- Hydraulic DFN MP_FRAC
  - High-resolution 3D flow simulations
  - Training basic
- Alternative modeling concepts
  - Structured Interacting Continua
  - Multiple-scale permeability
  - Discrete Double porosity
- Calibration and Testing
  - Synthetic training
  - Field testing

Elementary cell
"Structured Interacting Continua"

Multiple-scale Renormalization Group Method

Discrete Double-Porosity
D. Roubinet
Conclusions

Hydraulics in fractured media
- Large structures are essential
- Details matter!

Permeability
- Scaling and sampling
- Variable, High channeling

Modeling
- Main discrete structures
- Multi-porosity