V. Martin, J. Jaffré, and J. E. Roberts,
"Modeling fractures and barriers as interfaces for flow in porous media,"
SIAM Journal on Scientific Computing 26 5 (2005) pp 1667-1691

MODELING FRACTURES AND BARRIERS 1677

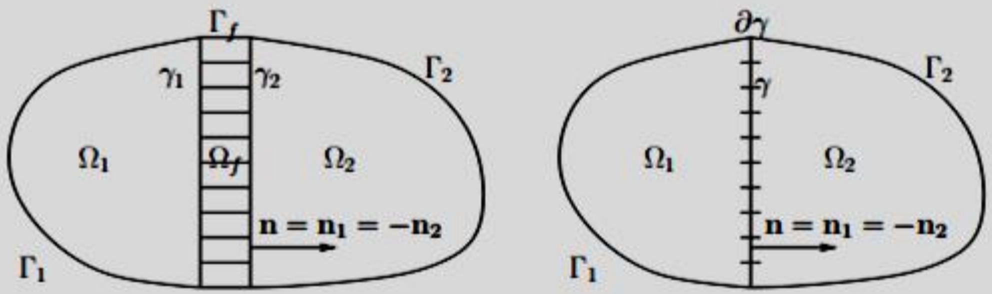


FIG. 5.1. *Left: The domain Ω with a two-dimensional fracture Ω_f that is meshed with rectangles. Right: The one-dimensional fracture γ is meshed with the projection of the two-dimensional mesh on γ_1 (or γ_2).*

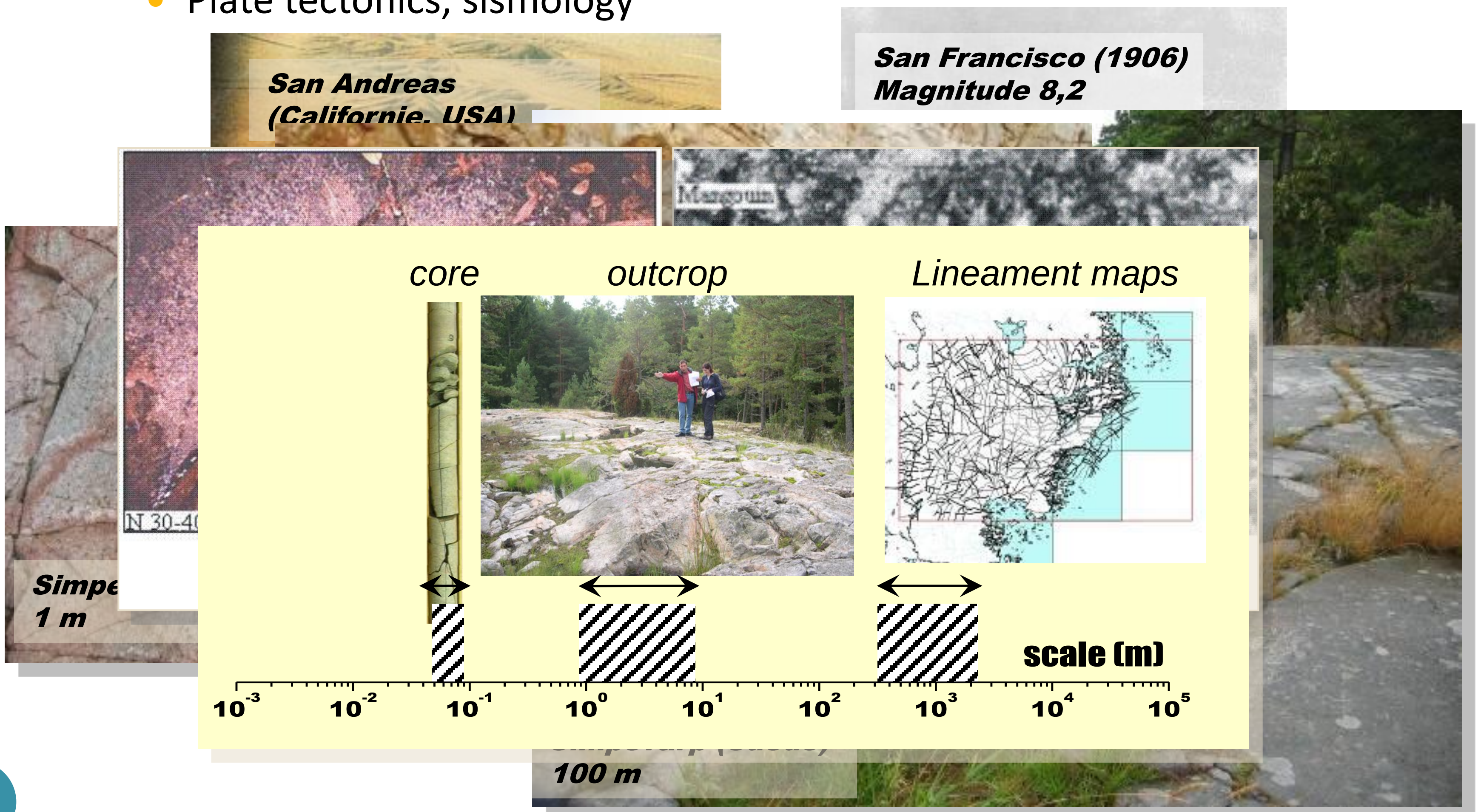
Role of flow models and simulations for assessing waste disposal and recoverable resources in FRACTURED MEDIA

Jean-Raynald de Dreuzy[1], Caroline Darcel[2], Philippe Davy[1], Jocelyne Erhel[3], Romain Le Goc[2], Julien Maillot[1, 2], Yves Meheust[1], Géraldine Pichot[3], Baptiste Poirriez[3]

1. Geosciences Rennes, UMR CNRS 6118, Univeristy of Rennes 1, Rennes, France.
2. Itasca Consultants S. A., Group HCItasca, Rennes, France.
3. IRISA/INRIA, Rennes, France.

What is a fracture?

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



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  - 2D features in 3D space (lower dimensionality)
- Hydraulics
  -
  - ity
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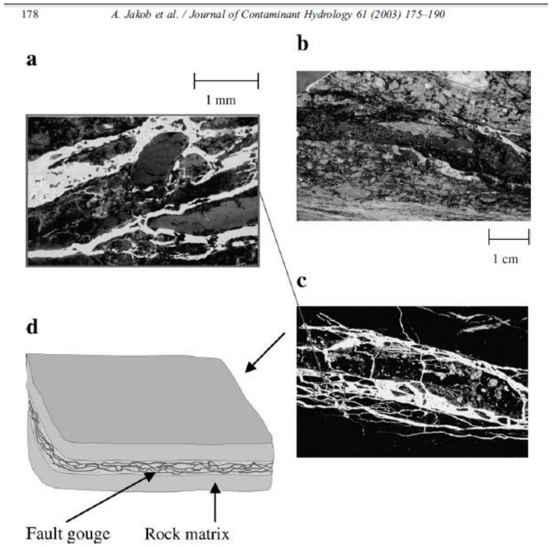
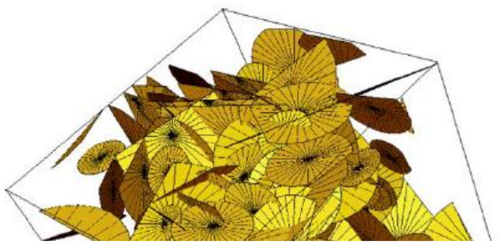
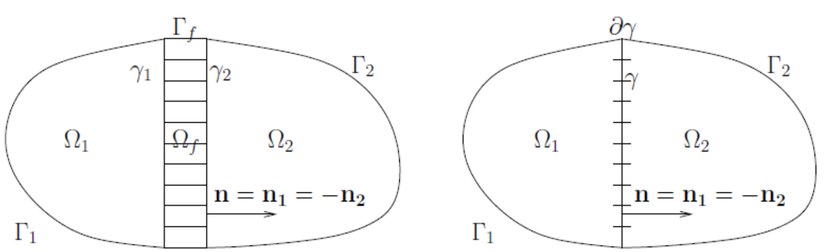




with a mixed-hybrid ... model, Computational Geosciences, 8(3).

MODELING FRACTURES AND BARRIERS 1677



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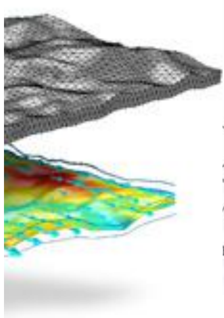
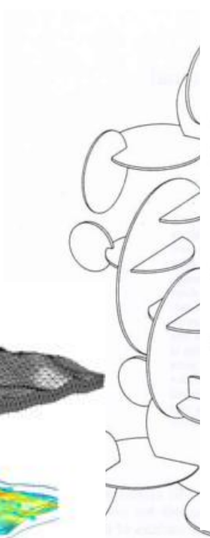
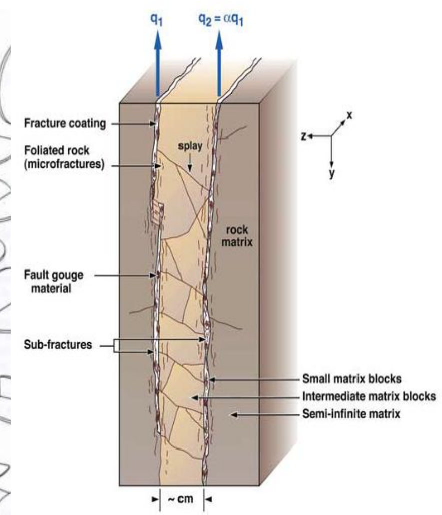




Example of a three-dimensional fracture network of disc-shaped ...

... al. (1985), A Model for Steady Fluid Flow in ...e-Dimensional Networks of Disc-Shaped Fractures, Water Resources Research, 21(8), 1105-1115.



Tsang, C. F., et al. (2008), Simple model representations of transport in a complex fracture and their effects on long-term predictions, Water Resources Research, 44(8), 13.

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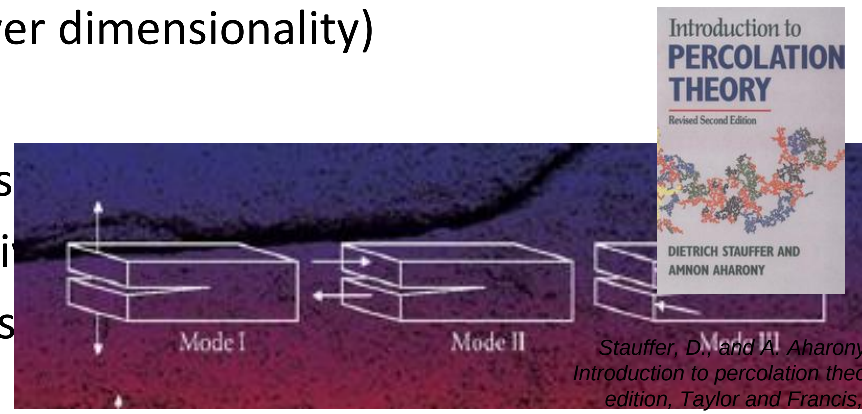
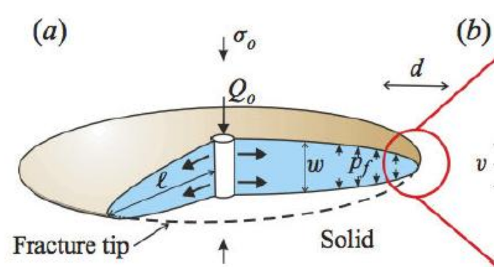
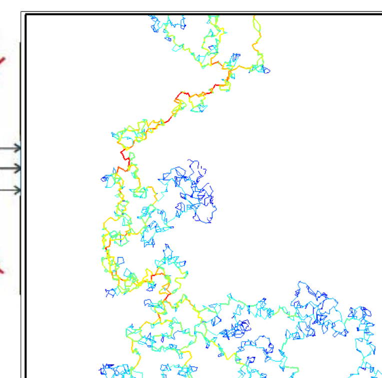
  - Ubiquitous: Fault, Fracture, Joint, Diaclase
  - Plate tectonics, sismology
- Mathematical modeling
  - 2D features in 3D space (lower dimensionality)
- Hydraulics
  - Flow barriers, flow highways
  - High permeablity, low storati
  - Low surface/volume features
- Mechanics
  - Dynamic, Chaotic
  -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



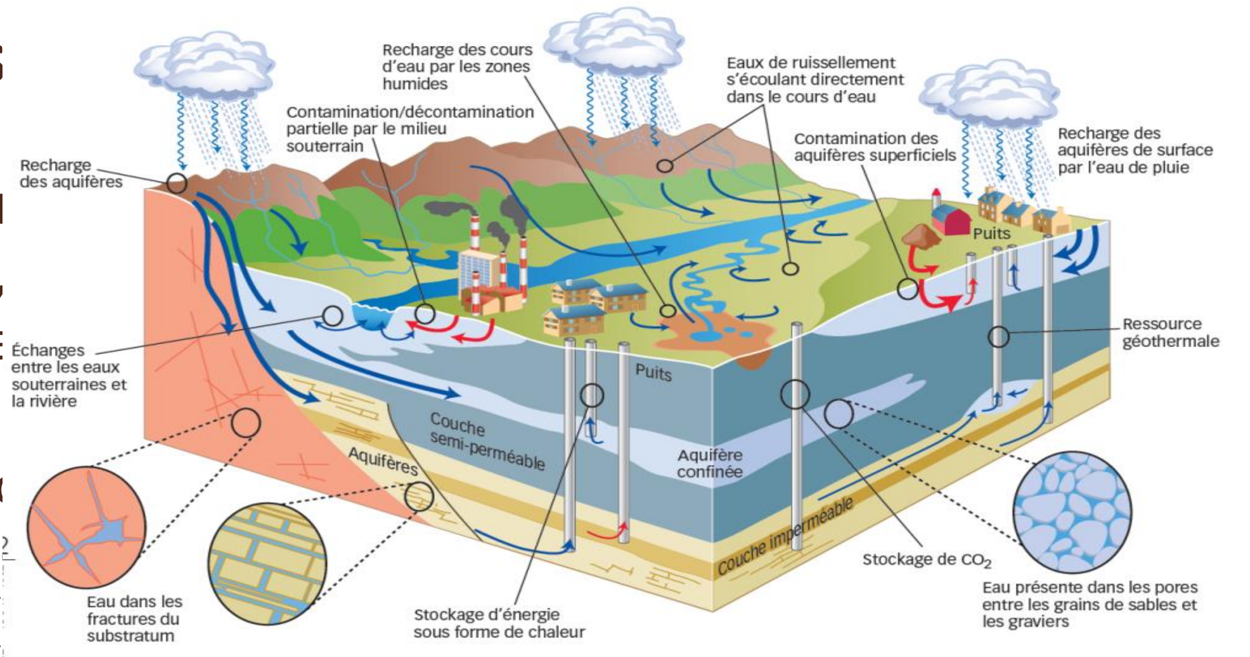
Stauffer, D., and A. Aharony (1992), Introduction to percolation theory, second edition, Taylor and Francis, Bristol.





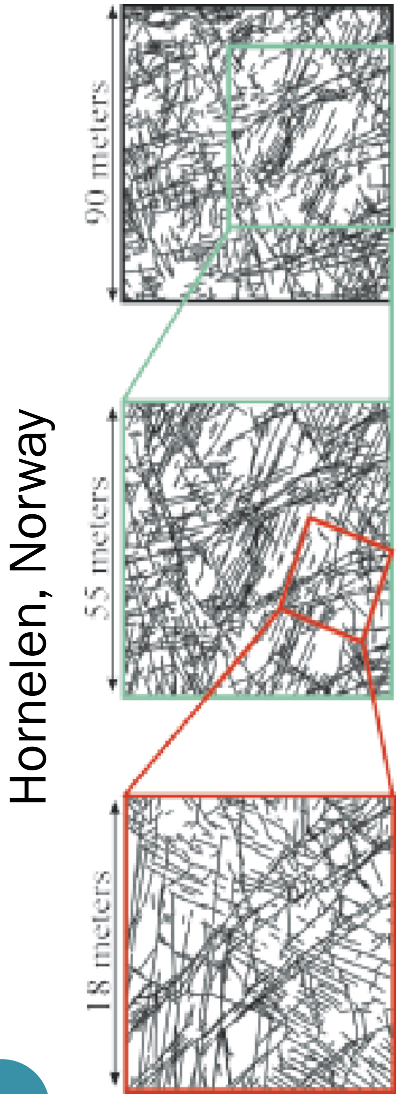
Why fractures

- Negative fractu
  - Waste storage,
  - Interacting ene
- Positive impact
  - oil and gas rec
  - 3D volume (ge
  - Groundwater (

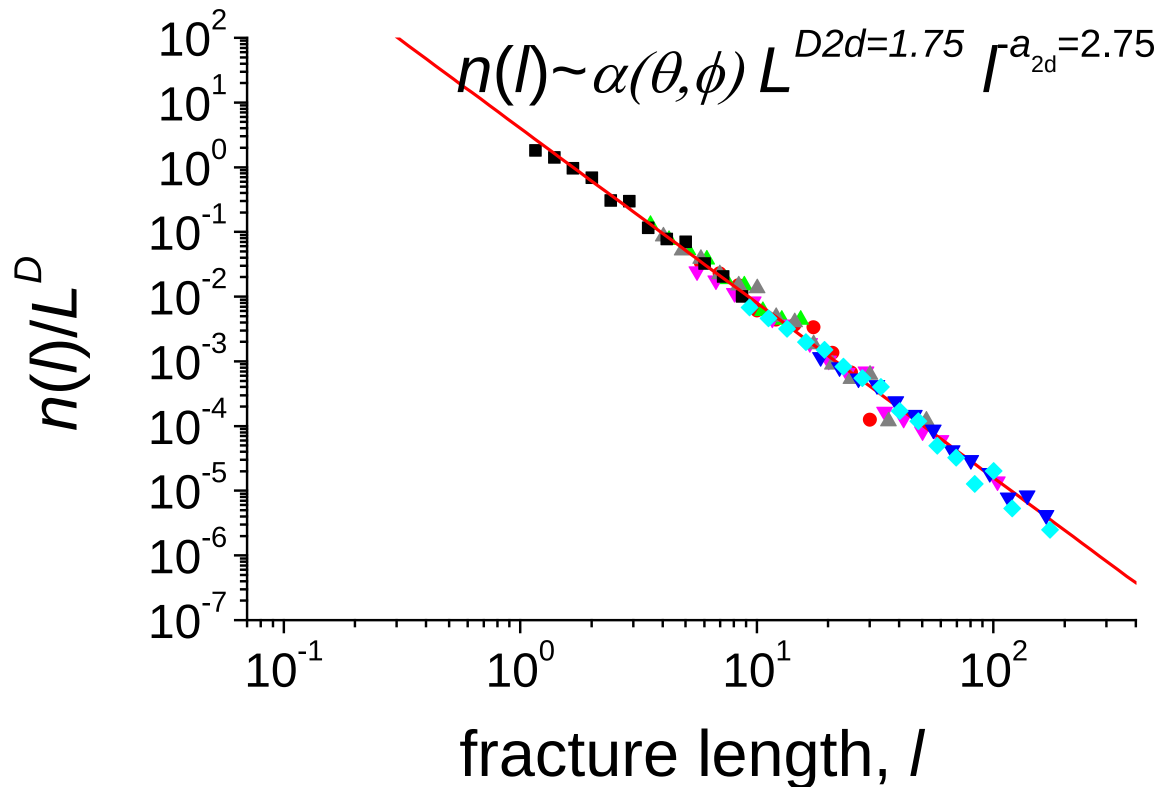


- Fractures (more generally geological complexity)
  - Source of uncertainty
  - Coexistence of services (storage, resources, environment)
- Requires CONTROL
  - Observations, Monitoring
  - Modeling
  - Data processing, calibration, assimilation

Stochastic models of fracture networks



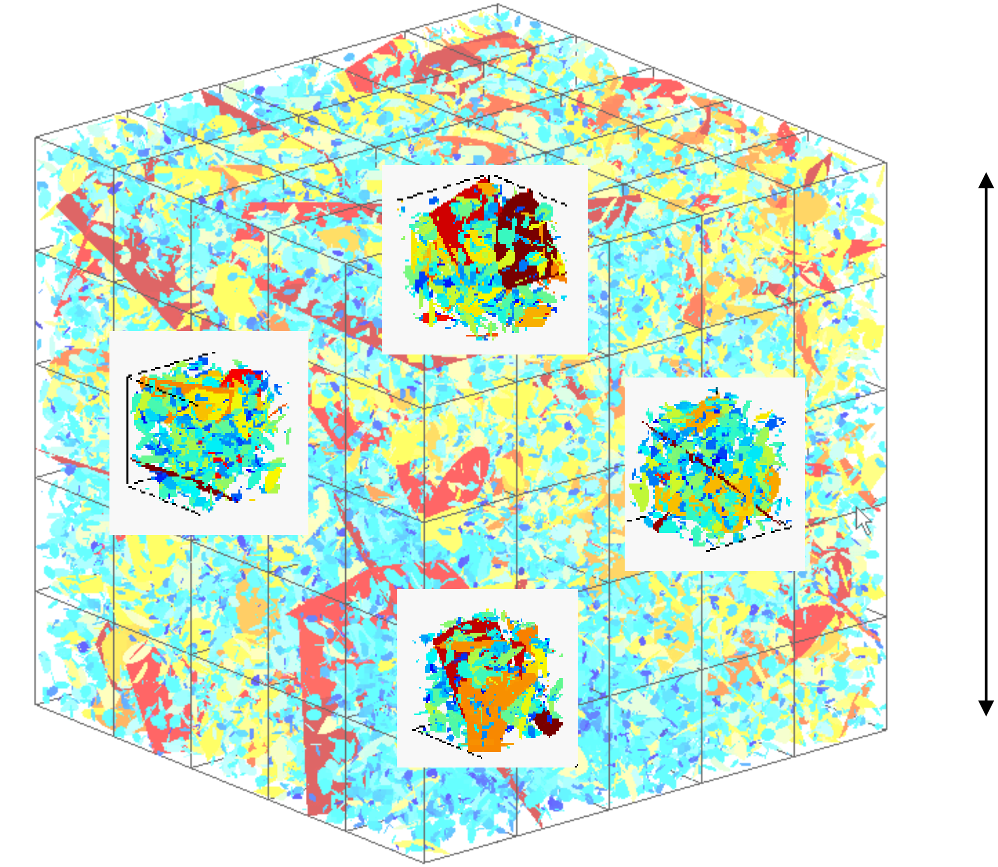
Odling, N. E. (1997), Scaling and connectivity of joint systems in sandstones from western Norway, Journal of Structural Geology, 19(10), 1257-1271.
Bour, O., et al. (2002), A statistical scaling model for fracture network geometry, with validation on a multiscale mapping of a joint network (Hornelen Basin, Norway), Journal of Geophysical Research, 107(B6).



O. Bour, Ph. Davy

Scale evolving 3D structures

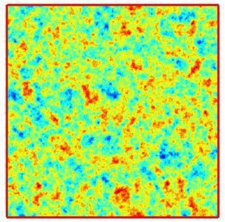
Broad power-law length distribution $n(l) \sim l^{-a}$ with $l_{min} < l < L$
Large number of fractures: $\sim 10^3$ to 10^5



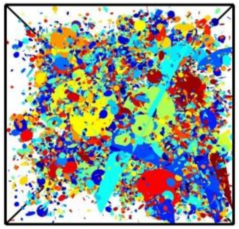
$a=3.4$
$L=50\ l_{min}$
$\sim 15\ 10^3$ fractures

Models of fluid flow in fracture networks

Fracture scale



Network scale

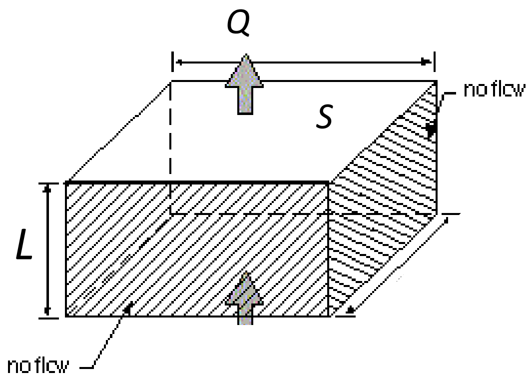


Physical equations

•*Steady-state or transient flow*

$$\epsilon V = -K\nabla h, \nabla . V = 0$$

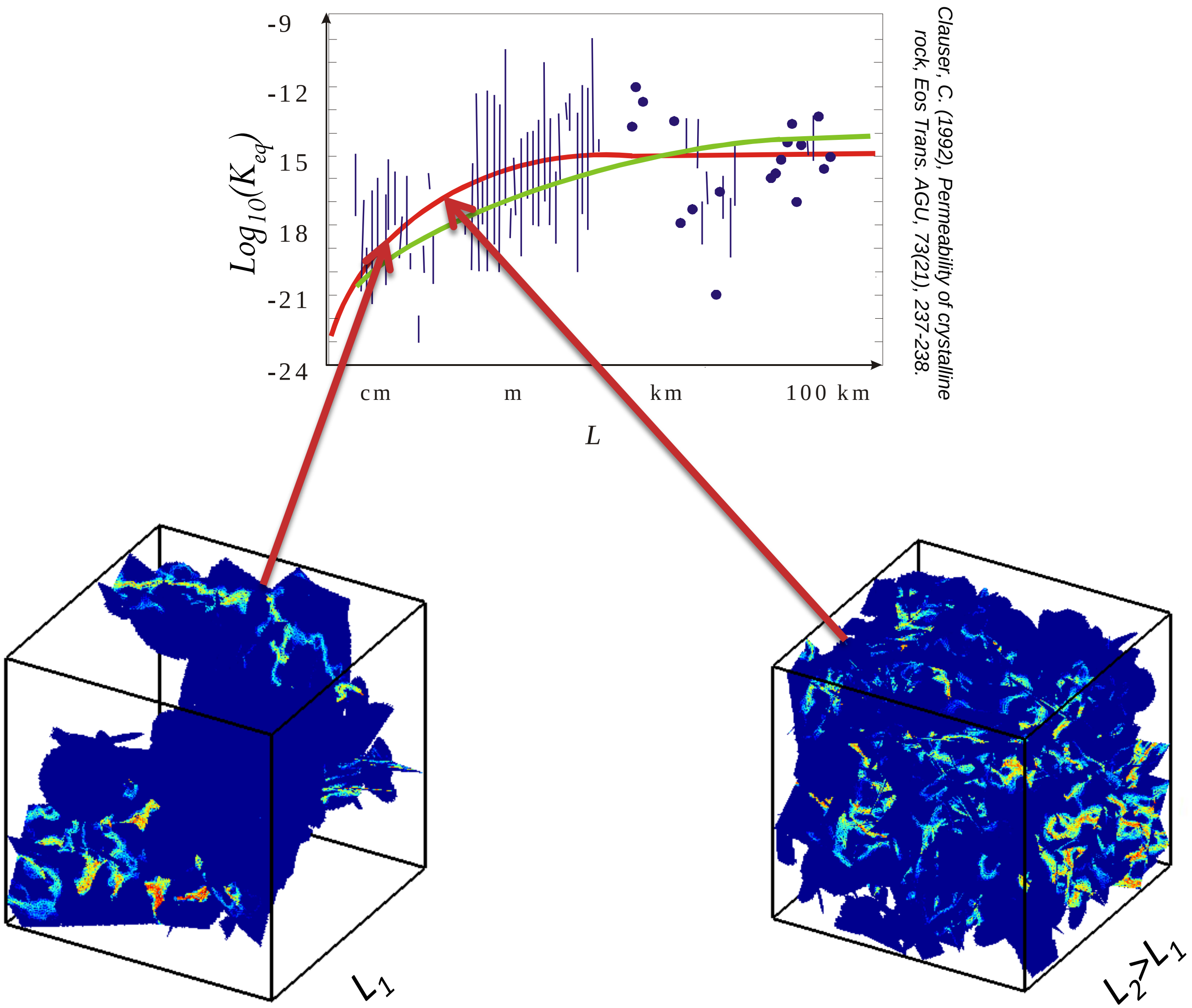
Equivalent permeability



Permeameter boundary conditions

$K_{eq} = QL/(\Delta h S)$

Permeability increase with scale



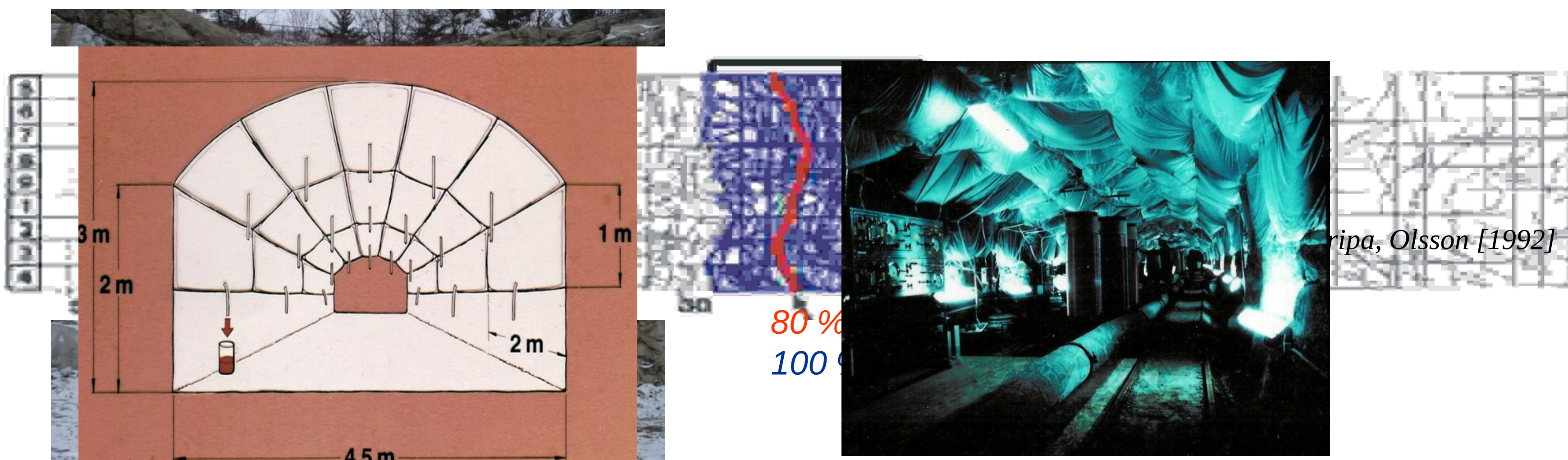
Flow structures in natural fractured media

Multiple-scale Channeling and limited permeability

Fracture scale

Stripa

Network scale



Why are flows so channelled and permeability so limited?

FRACTURE SCALE

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

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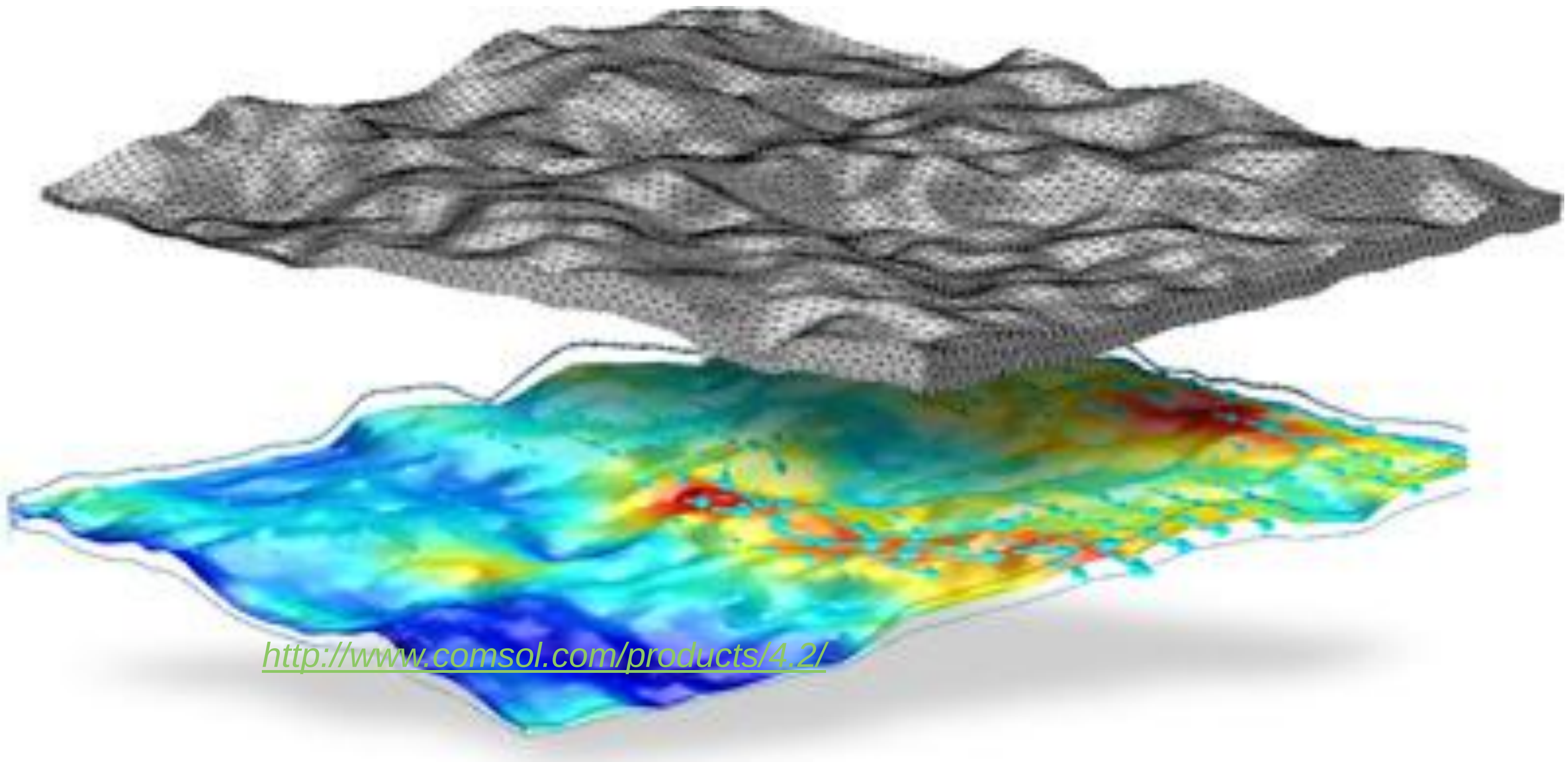
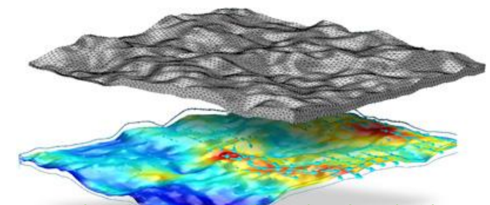
Permeability of rough fractures

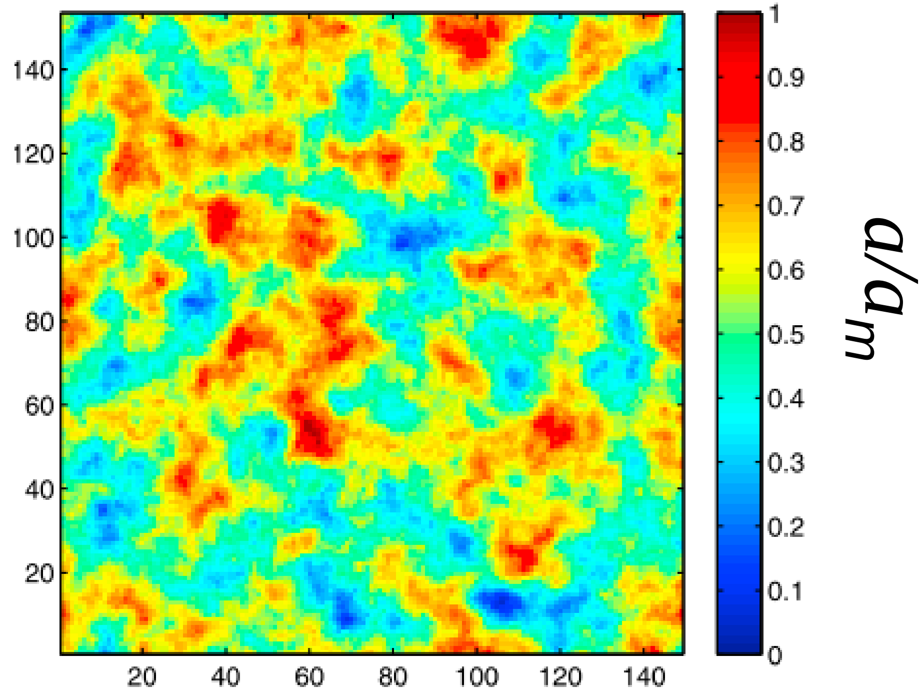


Méheust, Y., and J. Schmittbuhl (2000), Flow enhancement of a rough fracture, Geophysical Research Letters, 27(18).
Méheust, Y., and J. Schmittbuhl (2001), Geometrical heterogeneities and permeability anisotropy of rough fractures, Journal of Geophysical Research-Solid Earth, 106(B2), 2089-2102.

Local aperture distribution

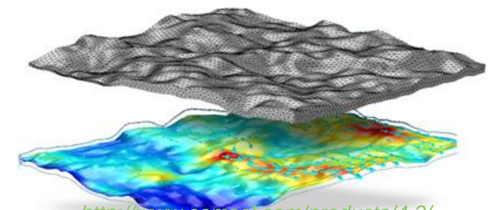
Truncated Gaussian with a bounded self-affine correlation pattern


http://www.comsol.com/products/4.2/

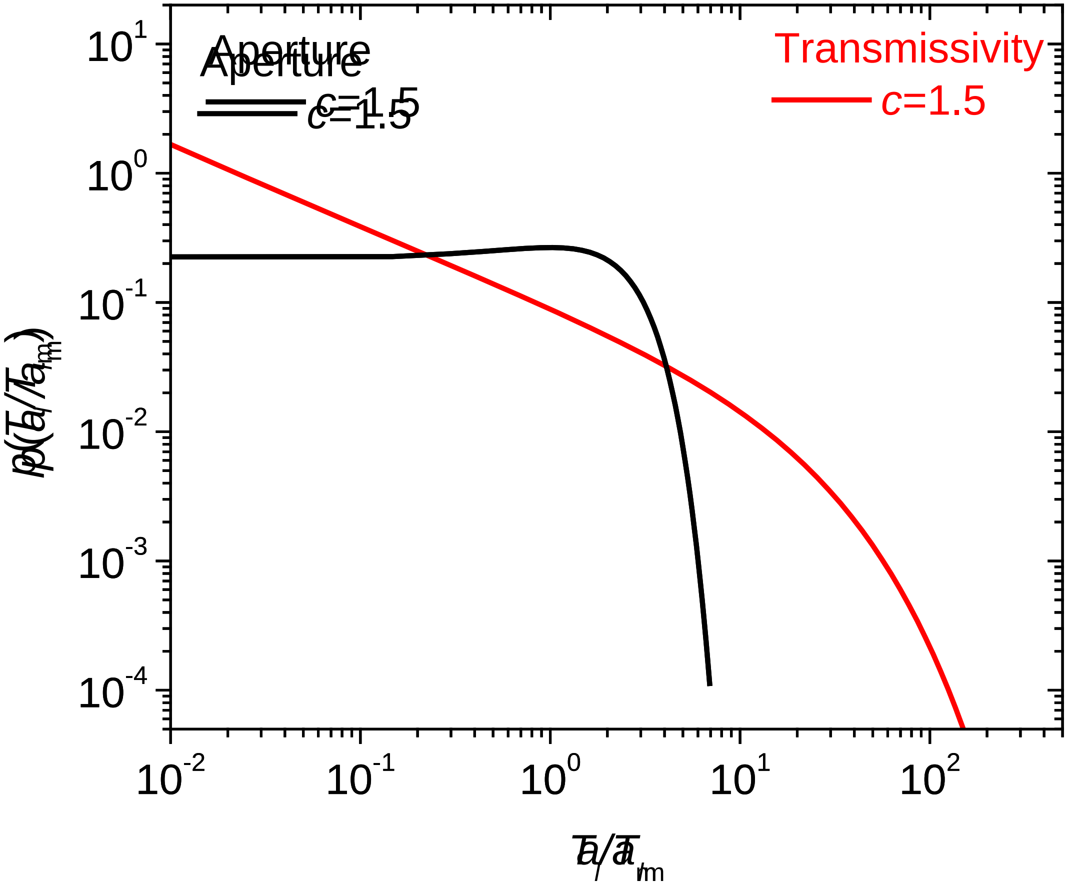


$$p\left(a/a_m\right) = \begin{cases} \dfrac{1}{c_{frac}\sqrt{2\pi}} e^{-\frac{\left(a/a_m - 1\right)^2}{2c_{frac}^2}} & if a \geq 0 \\ 0 & if a \leq 0 \end{cases}$$

From local aperture to local transmissivity



http://www.comsol.com/products/4.2/



Fracture aperture and transmissivity distribution shown by dashed and solid lines respectively.

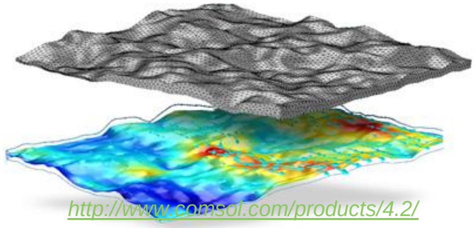
$$T \sim a^3$$

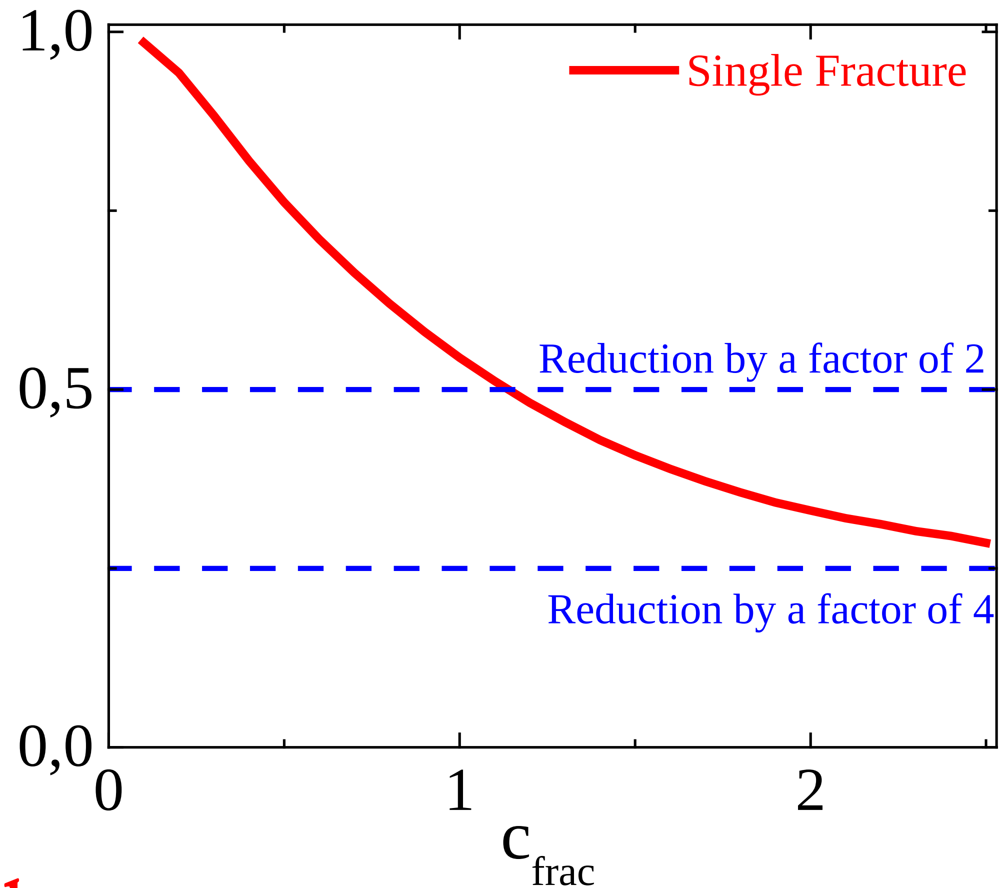
$$p(a/a_m) = \begin{cases} \dfrac{1}{c_{frac}\sqrt{2\pi}} e^{-\frac{(a/a_m - 1)^2}{2c_{frac}^2}} & if\, a \geq 0 \\ 0 & if\, a \leq 0 \end{cases}$$

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

Effective permeability K_A

normalized by the equivalent parallel plate permeability K_1





$$\left\langle \frac{K_A}{K_1} \right\rangle$$

Roughness:

Reduction factor of K: 2 to 4 at most

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2D Poissonian fracture networks

a: length distribution parameter

d: density parameter

$\sigma^2(\log K_1)$: fracture log-permeability variance

$$K_N = K(d,L)\ \exp[\omega(d,a).\sigma^2(\log K_1)/2]$$

$$K(d=d_c) \sim L^{-1}$$

$$K(d>d_c) \sim d$$

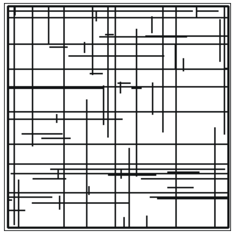
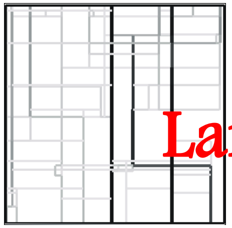
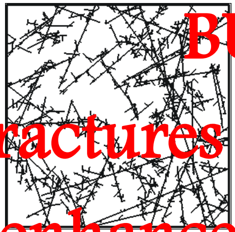
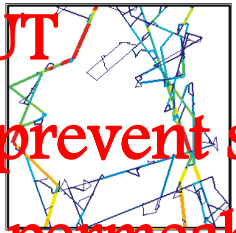
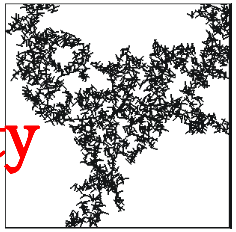
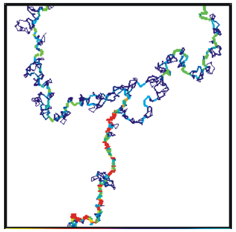
MODELS ARE MUCH TOO PERVIOUS

Reduction for sparse networks by tortuosity and **BOTTLE NECKS**

ω = 1
arithmetic mean
parallel model

ω = 0
geometric mean

ω = -1
harmonic mean
in series model

BUT

Large fractures prevent sparsity and enhance permeability

de Dreuzy, J. R., et al. (2001a), Hydraulic properties of two-dimensional random fracture networks following a power law length distribution: 2-Permeability of networks based on log-normal distribution of apertures, Water Resources Research, 37(8), 2079-2095.
de Dreuzy, J. R., et al. (2001b), Hydraulic properties of two-dimensional random fracture networks following a power law length distribution: 1-Effective connectivity, Water Resources Research, 37(8).
de Dreuzy, J. R., et al. (2002), Permeability of 2D fracture networks with power-law distributions of length and aperture, Water Resources Research, 38(12).

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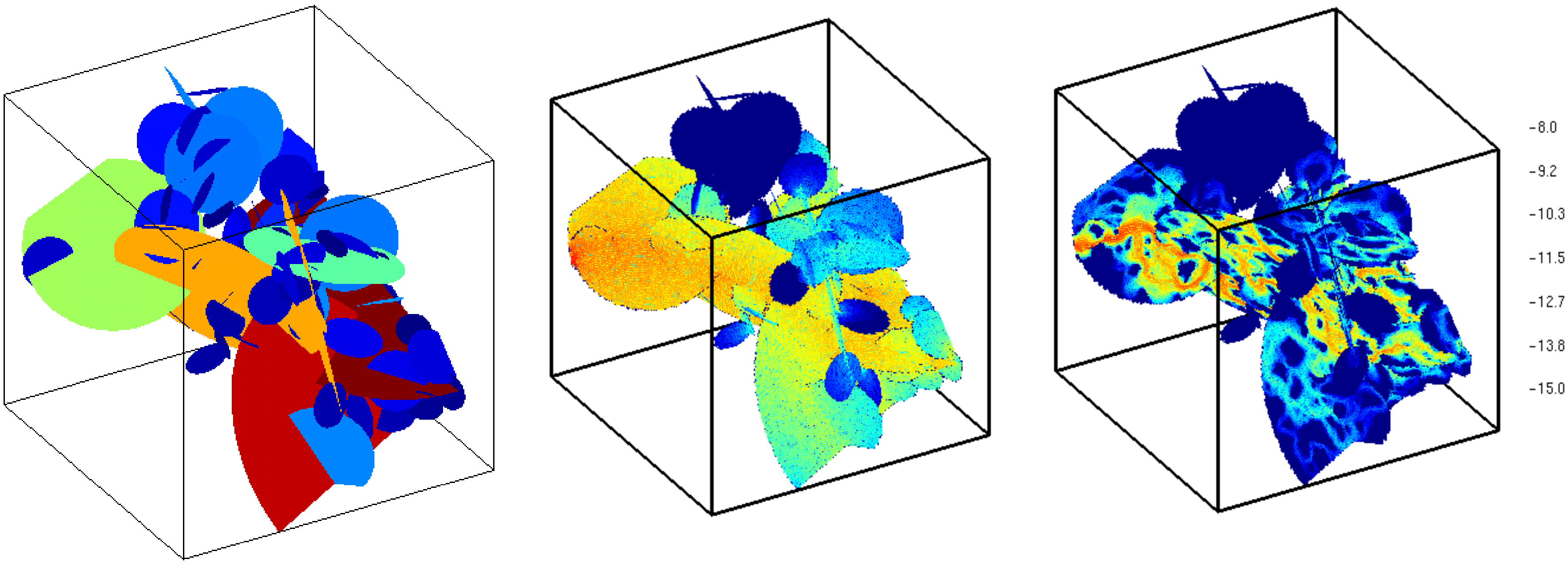
COMBINATION FRACTURE/NETWORK

Combined fracture- and network-scale effects



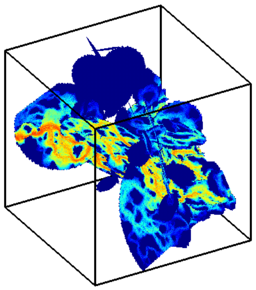
Fracture Network

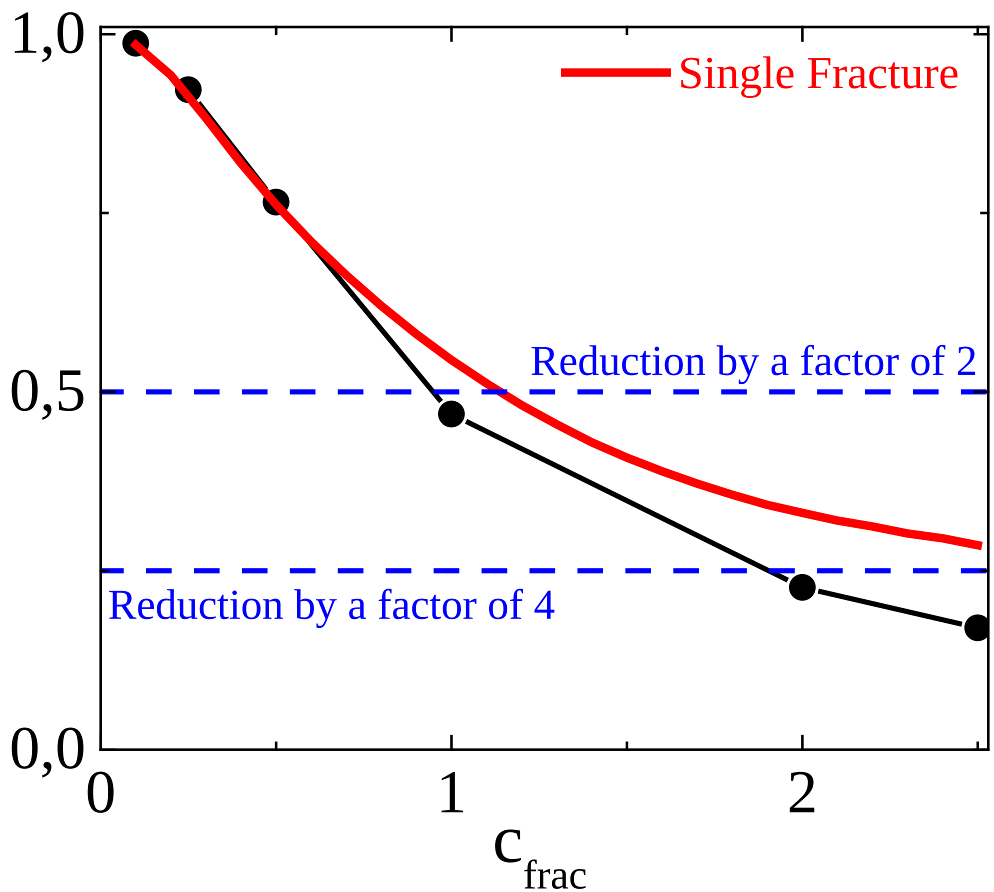
Flows with uniform apertures K_N

Flows with distributed apertures K_{N+A}

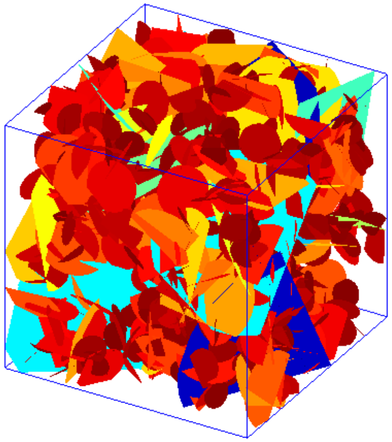
de Dreuzy, J.-R., Y. Méheust, and G. Pichot (2012), Influence of fracture scale heterogeneity on the flow properties of three-dimensional Discrete Fracture Networks (DFN), J. Geophys. Res.-Earth Surf., 117(B11207), 21 PP.

Effective permeability K_{N+A} Dense Networks



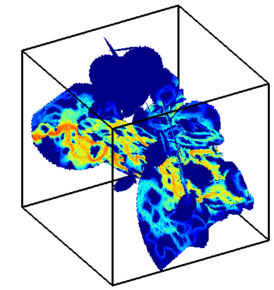


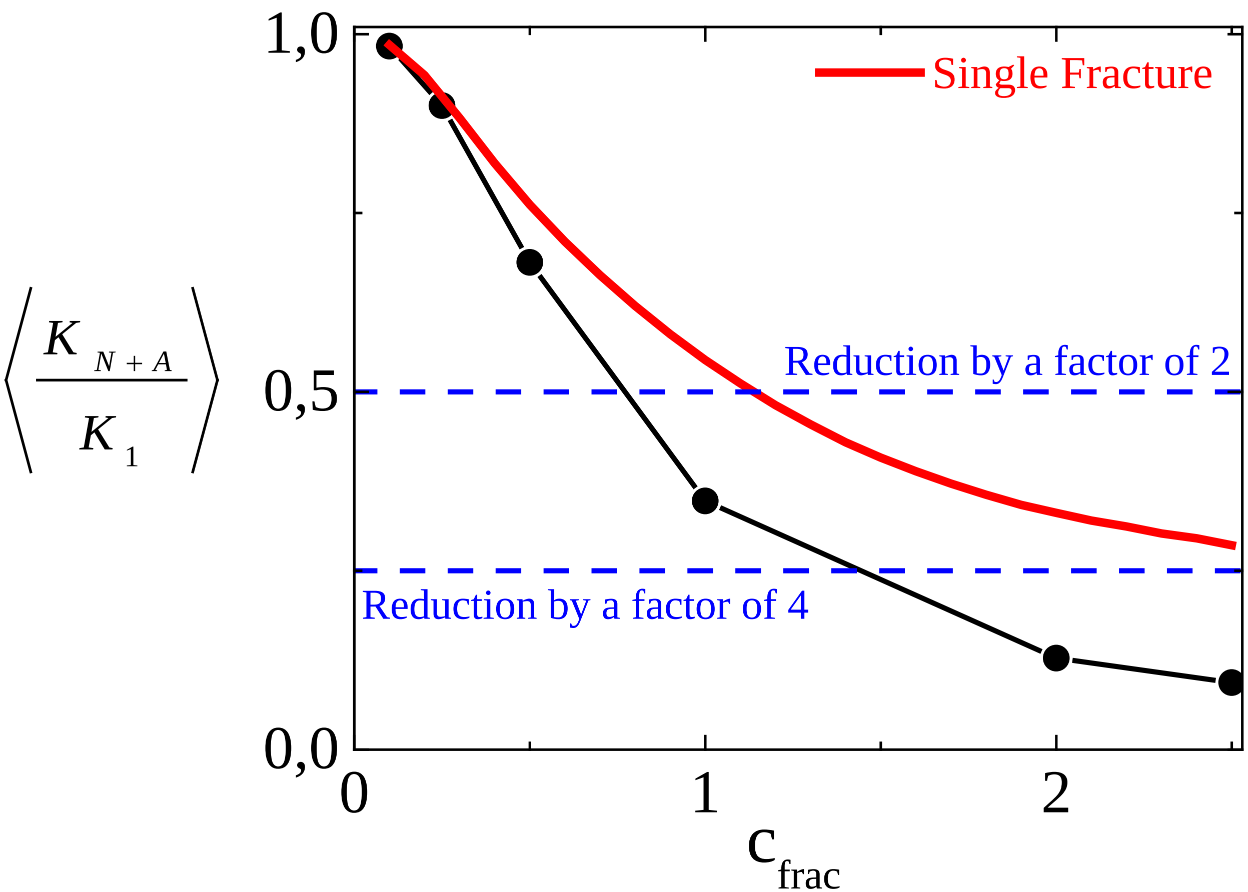
$$\left\langle \frac{K_{N+A}}{K_1} \right\rangle$$

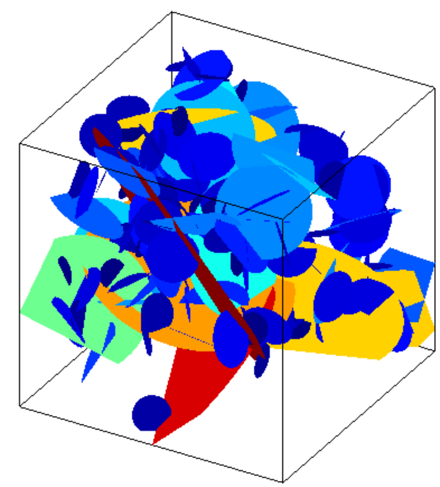


Hihgly limited effects

Effective permeability K_{N+A}
Sparse Networks

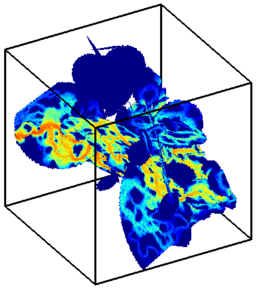


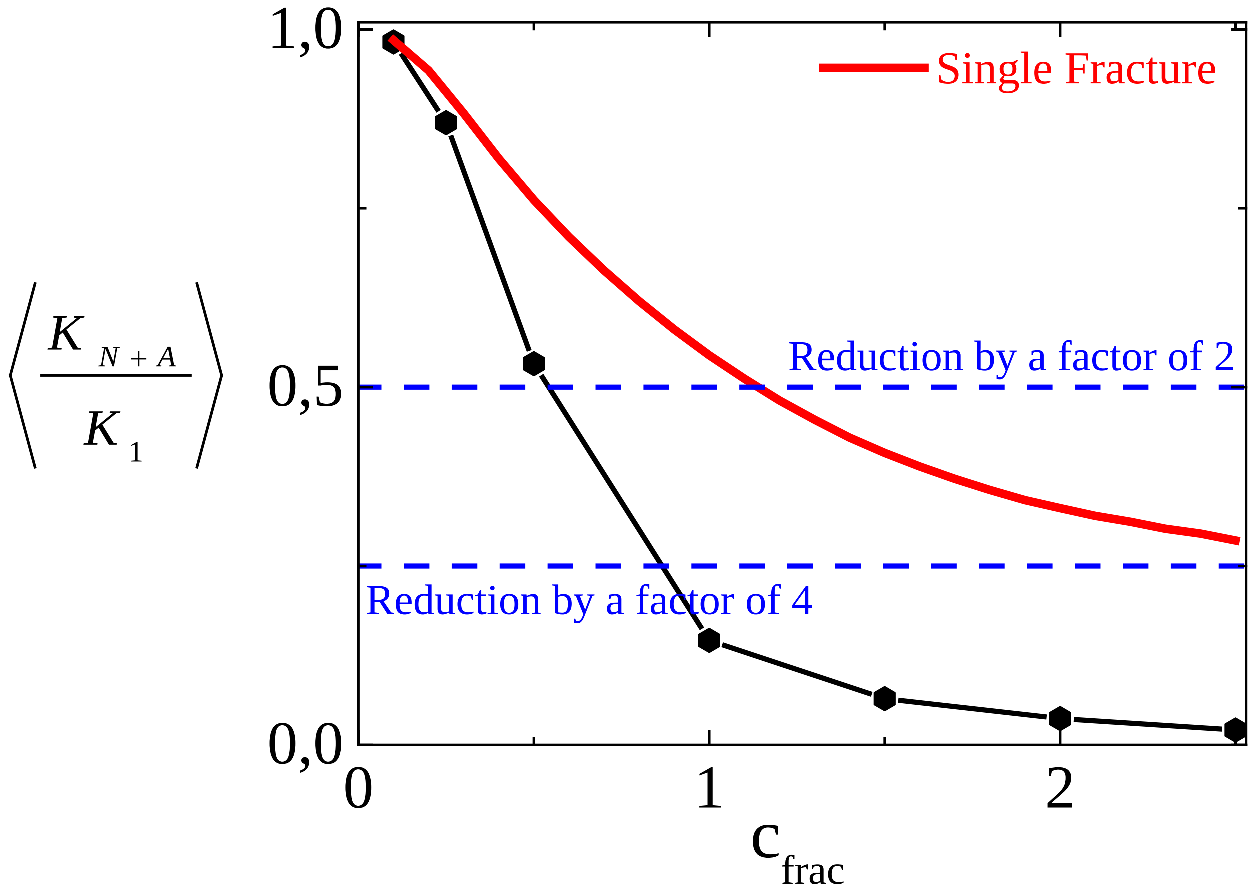


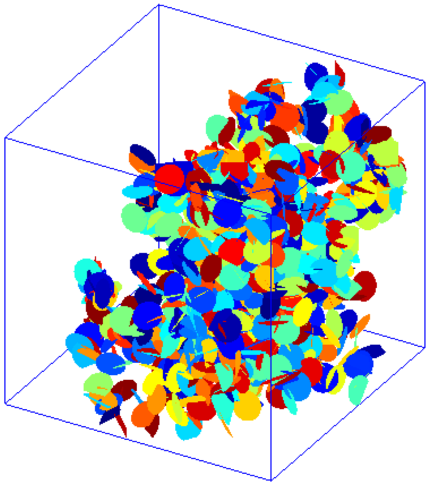


Additional reduction by a factor of 2 to 3

Effective permeability K_{N+A}
Percolation Networks







Additional reduction by a factor of 5 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)
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COMBINATION FRACTURE/NETWORK: **reduction factor of 2 to 10**

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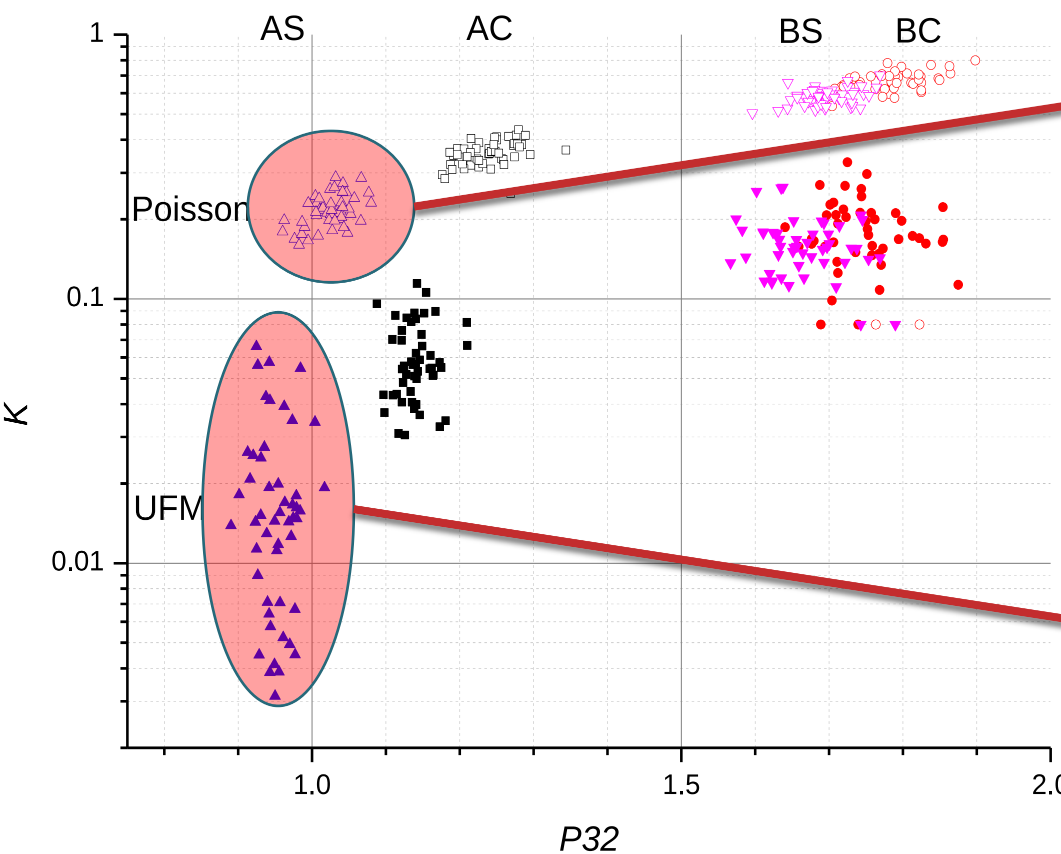
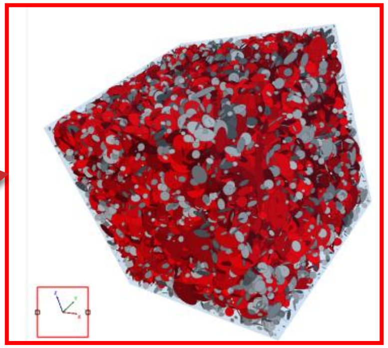
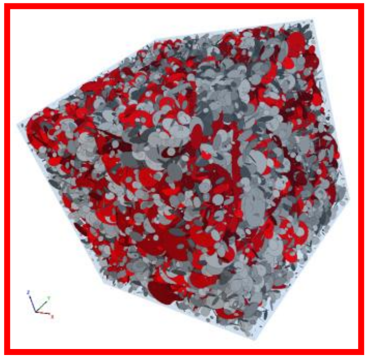
COMBINATION FRACTURE/NETWORK: **reduction factor of 2 to 10**

Mechanical induced organization of the fracture network (preliminary results)

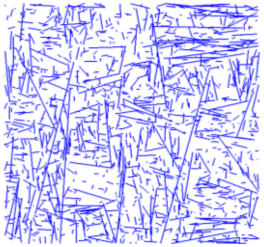




High connectivity



Low connectivity



Typical trace map view

Reduction factor of *K* : 3 to 10

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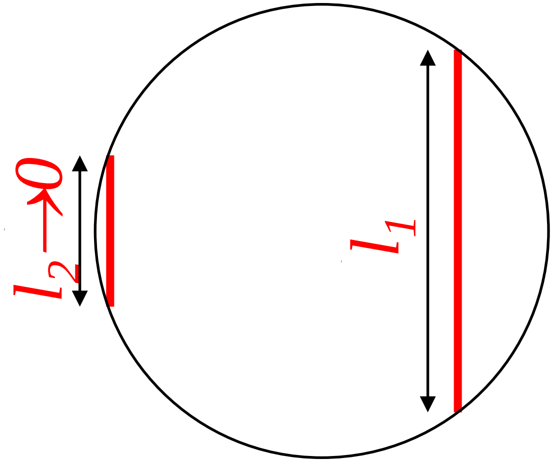
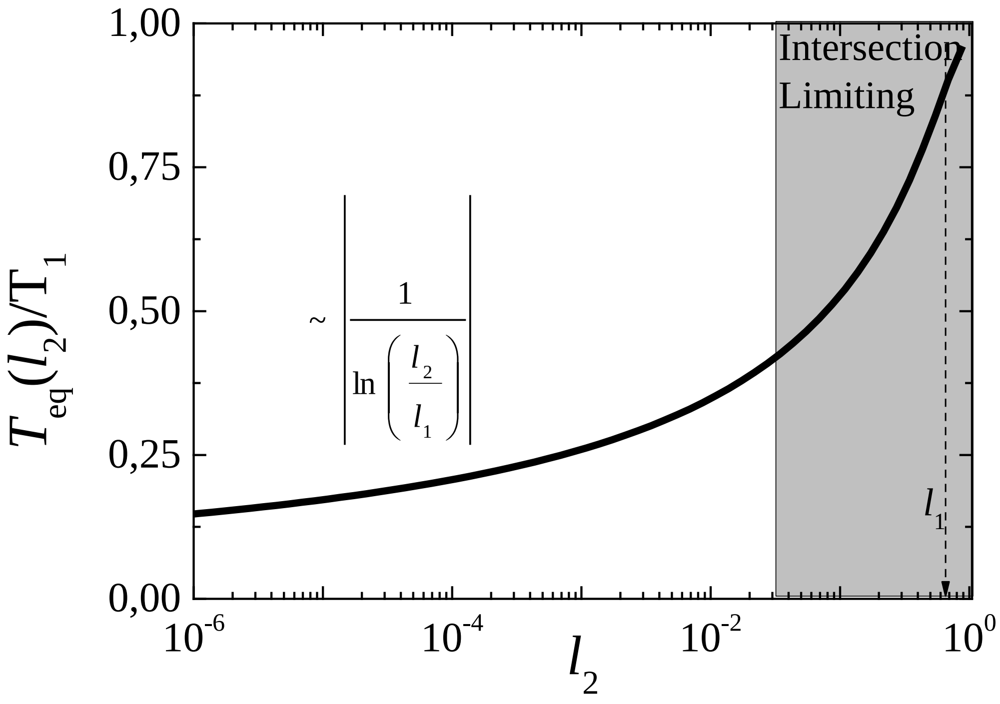
- Effective transmissivity variability (orientations, depth)
- **Local connectivity (intersections)**
- Mechanical correlation patterns: reduction factor of 3 to 10

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**

Conclusions

Model permeability of fractured media is generally too large

- Dense " Poissonian" connection create too many parallel paths
- Roughness keeps large transmissivity (keeping fractures open)

Classical reduction factors of permeability are not enough

- Roughness does not create bottle necks or disconnection
- Lack of network connectivity cannot balance large fractures

Channeling and permeability limitations come from the combination of fracture characteristics at different scales

- ✓ **Mechanical organization limits connectivity and creates bottle necks**
- ✓ **Further limitation induced by fracture roughness, intersection length and transmissivity**
- ✓ **Overall potential reductions of permeability by 1 to 3 orders of magnitude**

Why are flows so channelled and permeability so limited?

FRACTURE SCALE

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

NETWORK SCALE: **bottle necks versus large fractures**

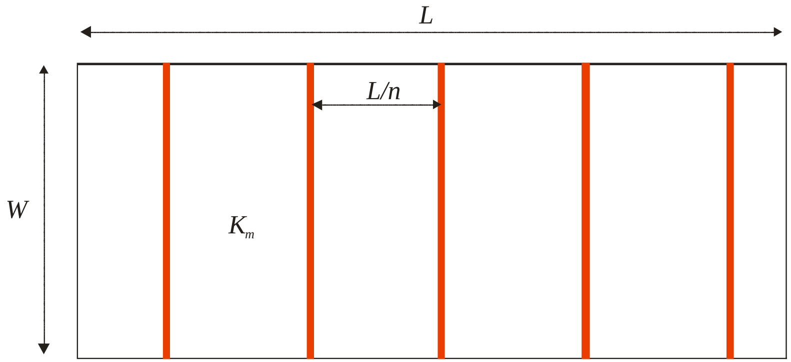
- Fracture length distribution
- Global connectivity (network effects)
- Effective transmissivity variability (orientations, depth)
- Local connectivity (intersections)
- Mechanical-issued correlation patterns (fracture organization)

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

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

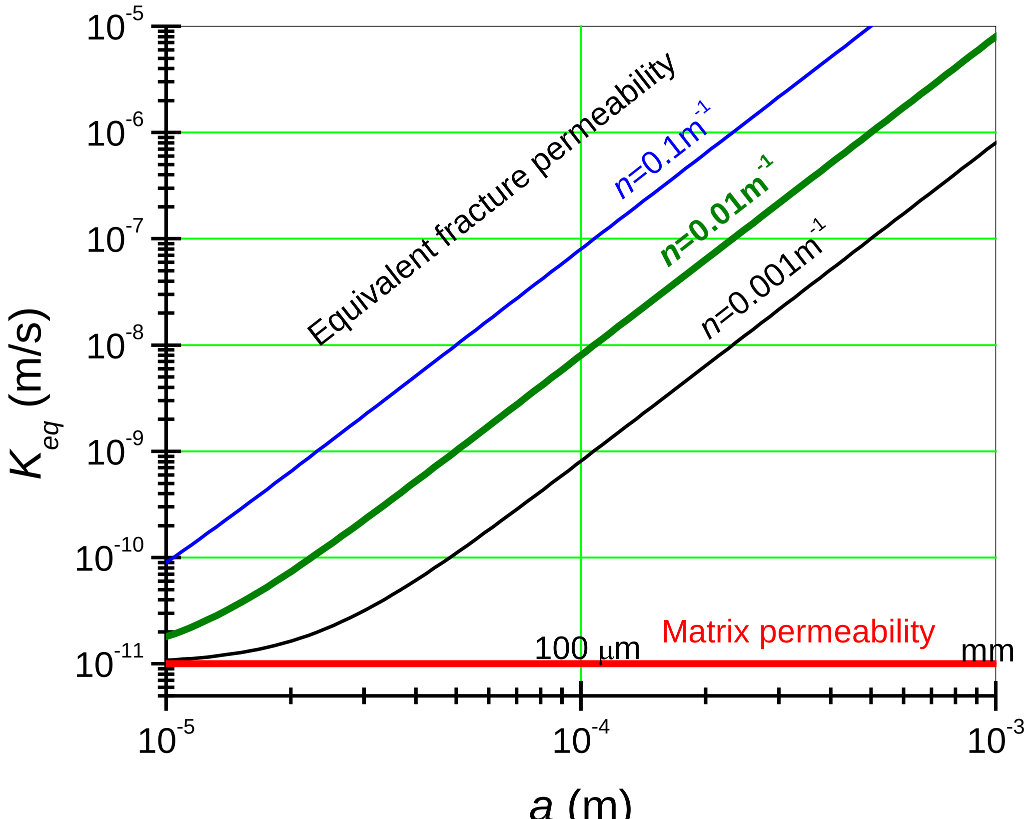

Bolmen channels 2

Fracture versus rock permeability

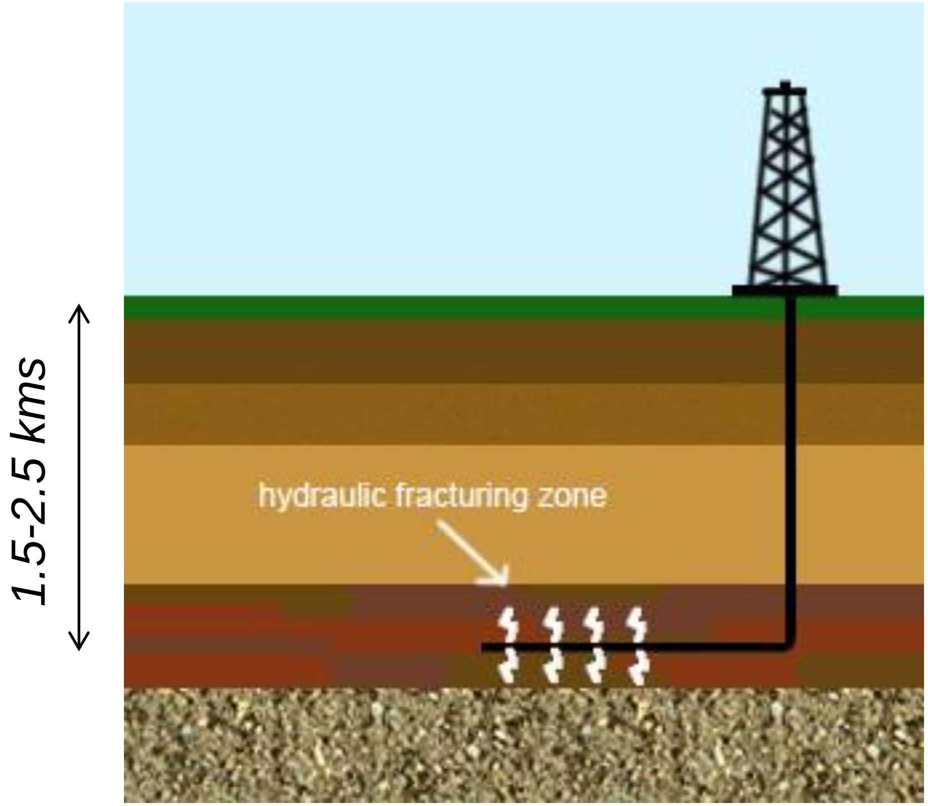


$$K_{eq} = n\frac{\rho g a^3}{12\mu} + (1 - na)K_m$$

a: hydraulic aperture



Pathways from produced shales to aquifers
Artificial and Natural Fractures

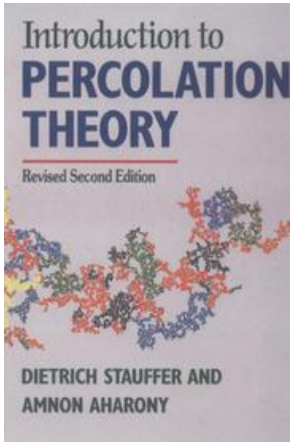


Leakage risks
- ✓ *Production well*
- ✓ *Nearby well*
- ✓ *Geological formation*

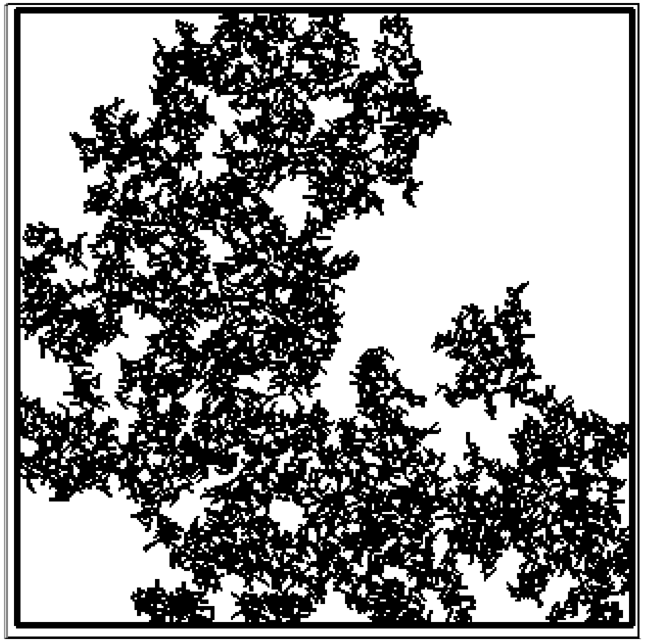
Fractures: double-sided risk and opportunity

- Geology
  - Ubiquitous: Fault, Fracture, Joint, Diaclase
  - Plate tectonics, sismology
- Mathematical modeling
  - 2D features in 3D space (lower dimensionality)
- Hydraulics
  - High permeablity, low storativity
  - Flow channels, flow barriers
  - Low surface/volume features
- Mechanics
  - Dynamical, ″chaotic ″ process
  - Plastic deformation, rupture
  - Material science, Failure
- Management
  - Issue
  - Risk (Nuclear waste disposal)
- Google
  - Health issue

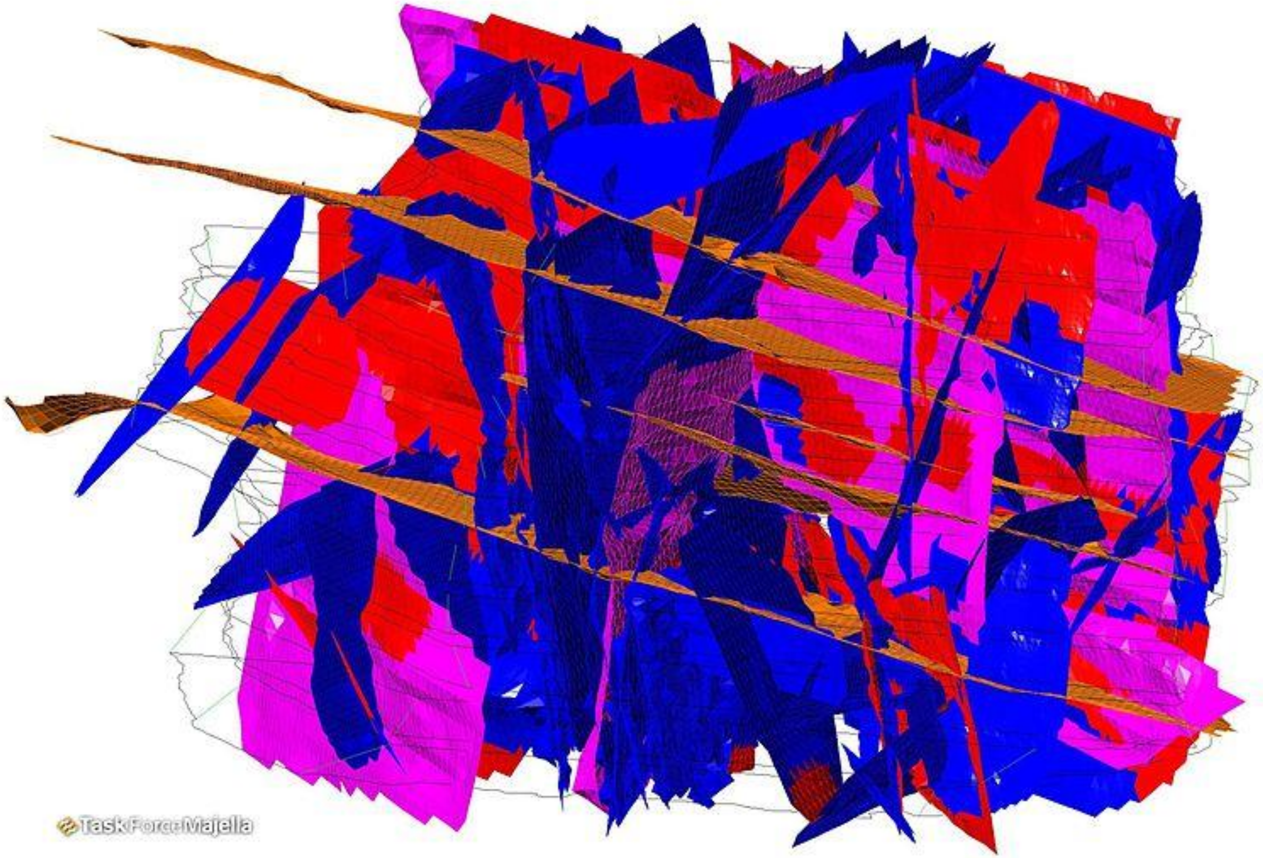
Connection by short fractures
Percolation theory



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



Classics of percolation
- ✓ *Connectivity is intrinsic*
- ✓ *Second-order phase transition*
- ✓ *Fractal structure*
- ✓ *Statistical theory*



http://en.wikipedia.org/wiki/TaskForceMajella

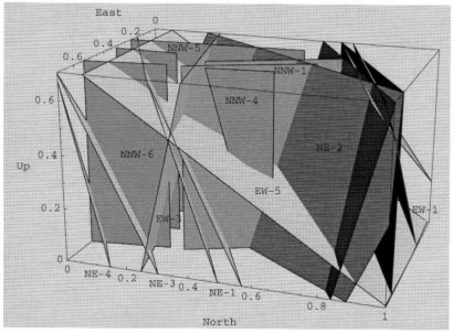
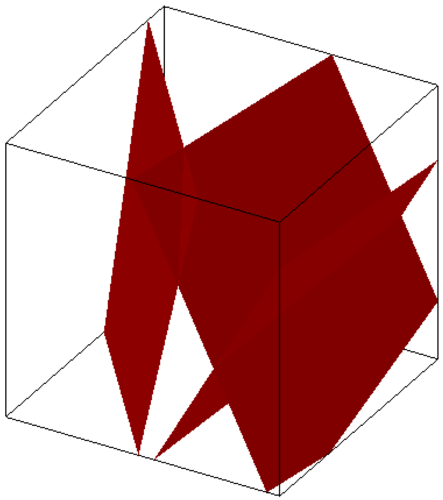
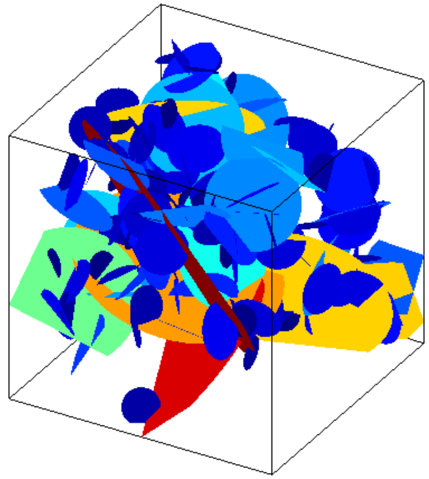
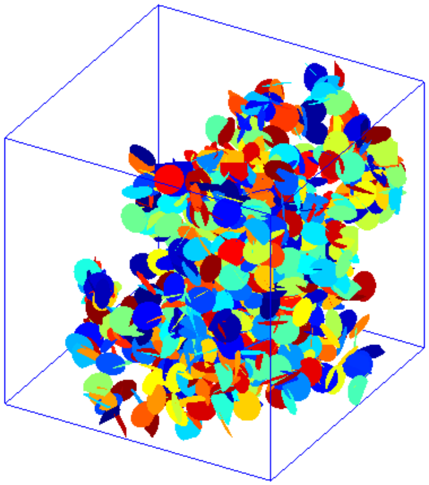
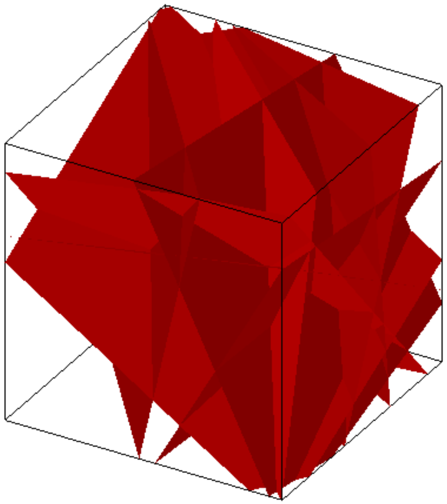
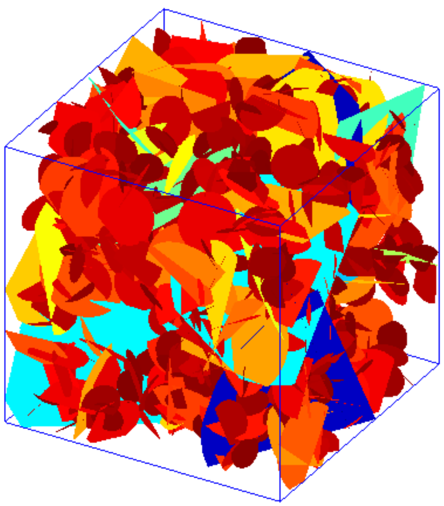
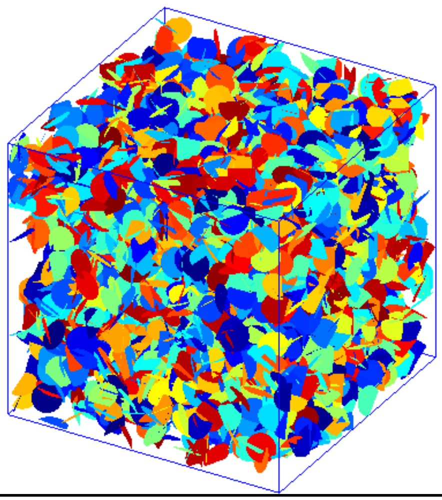
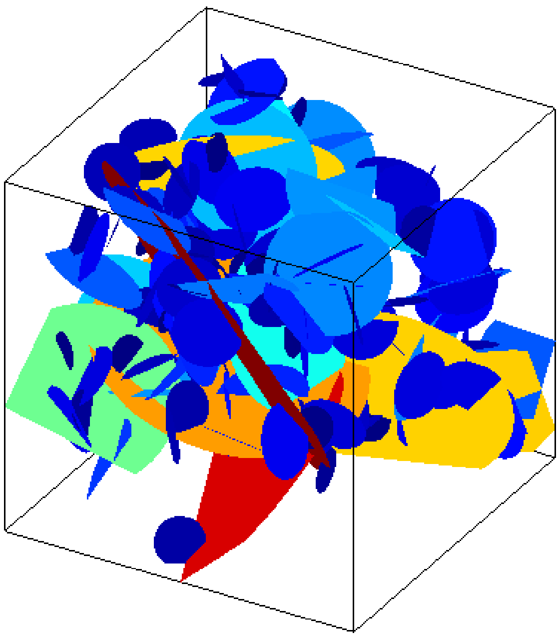


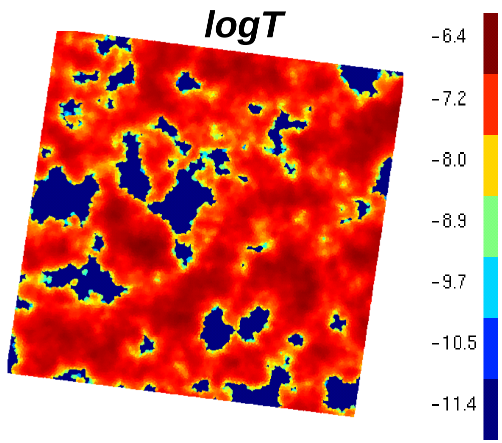
Fig. 2. All the major fracture zones found at Äspö visualized as planes. The distances on the axes are in km.

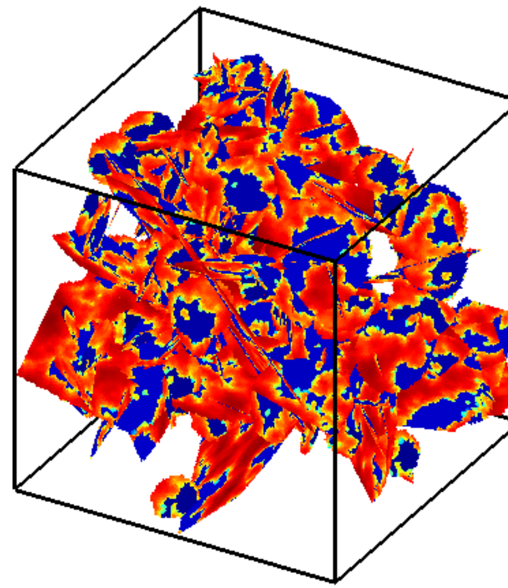
Model: Network structure

Crossing fractures "LONG"	Power-law length "DIST"	Small fractures "SHORT"	
			threshold
			"3*threshold"

Combined effects of fracture aperture and network structure on equivalent permeability?







Permeability enhancement with scale