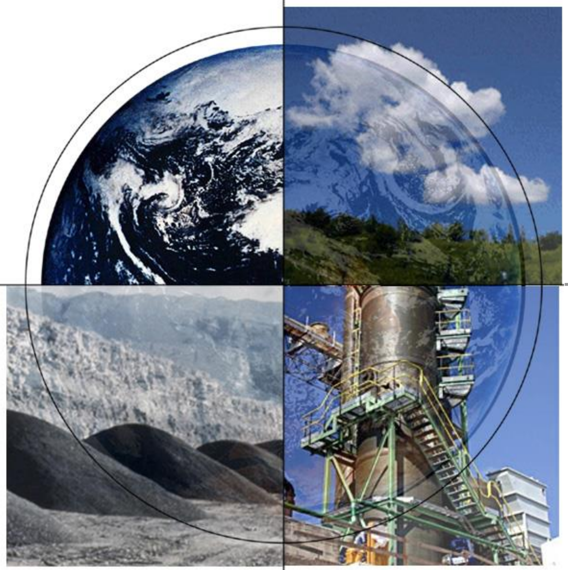
Effects of Surface Roughness on Flow through a Fracture



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Flow thru fractures and fractured formations has many applications:

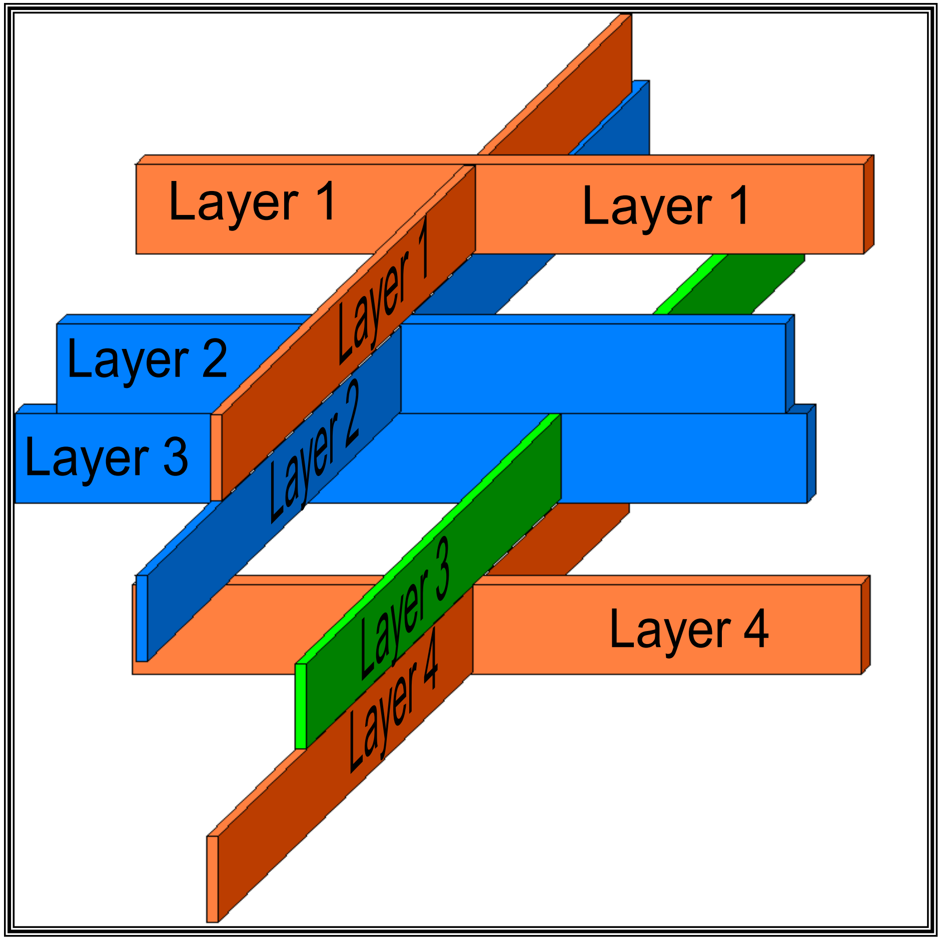
- **Natural gas production & underground storage**
- **Oil recovery**
  - Primary
  - Water flooding
  - EOR
- **Geologic sequestration of CO_2**
    - Brinefields
    - Coal beds (cleat networks)
    - Caprock integrity
- **Single phase, two phases, three phases**
- **Emulsions**

In explicit-fracture reservoir simulators (e.g., NFFLOW™), fractures often are treated as parallel planes.

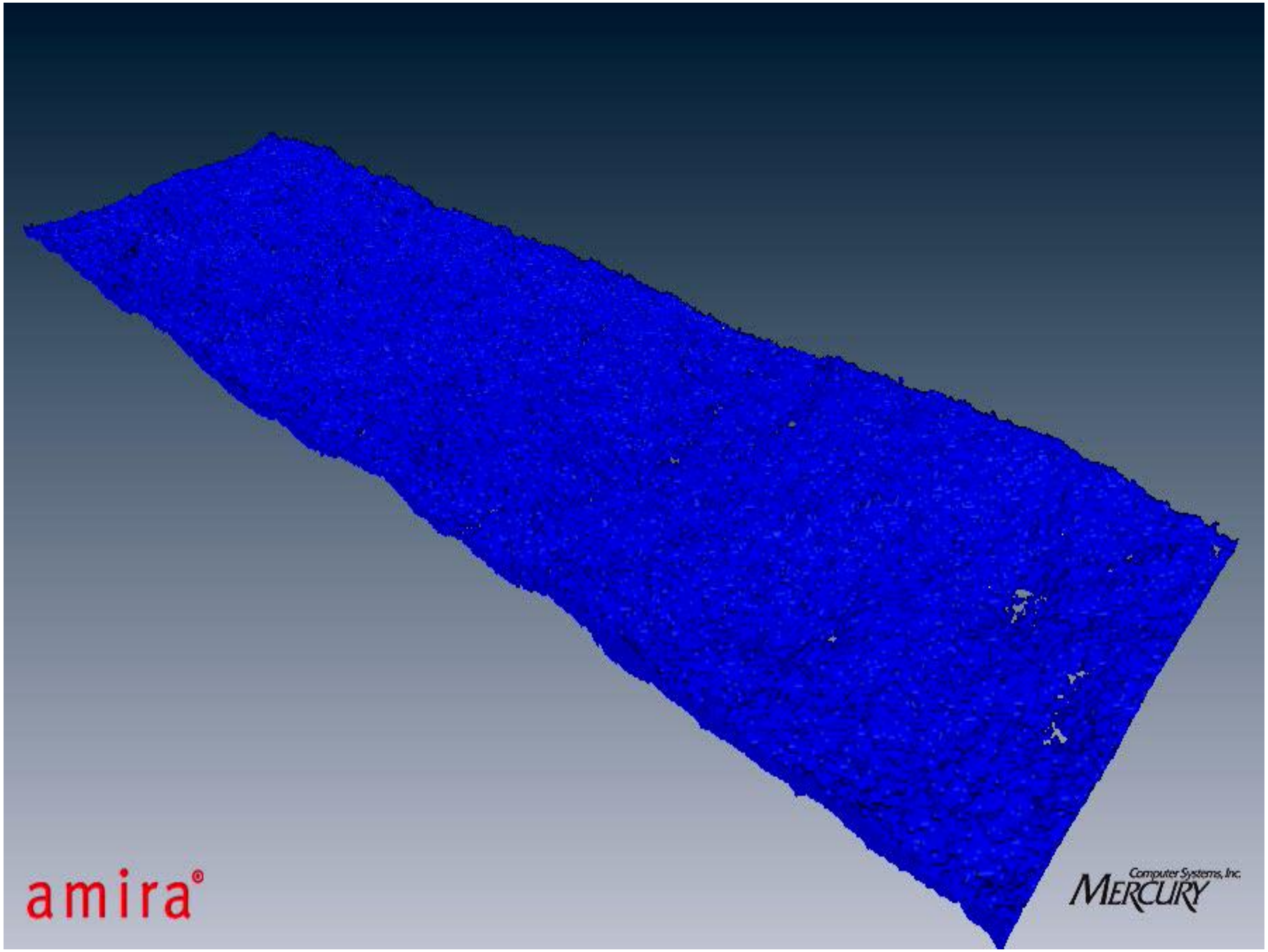
$$Q = \kappa \frac{\Delta P A}{\mu L}$$

$$Q = b_{eff}^{3} \frac{W}{12\mu} \frac{\Delta P}{L}$$

Q = volumetric flow rate
μ = fluid viscosity
ΔP = pressure drop over
L = fracture length
A = cross-sectional area of the fracture ⊥ to flow
b_{eff} = effective aperture



CT-image of fracture in sandstone



This presentation:

How does treatment of fracture-surface measurement files affect computed flows?

EXPERIMENTAL

- Berea sandstone
- Brazilian-method fracture
- Industrial-CT (computer tomography) image
- Original voxel spatial resolution = 27.3 micron
- Thresholded voxel spatial resolution : 120 micron
- Karpyn et al., J*. Colloid Interface Sci*. (2007)

COMPUTATIONAL

- Steady-state flow for single phases
- Displacement flow for two phases
- Navier-Stokes eqn.
- FLUENT™ software
- Highly refined grids— $2x10^5$ to $5x10^6$
- Volume-of-Fluids for 2-phase flow

NETL

Problem: Files from fracture-surface measurements can be too large for use as inputs to computational software.

Approach: Perform computations for several different fracture-surface smoothings.

Hope: Computational results will be independent of fracture smoothing.

Objective: minimum smoothing of CT file that produces manageable-sized file for CFD computations.

micro-CT scan file*

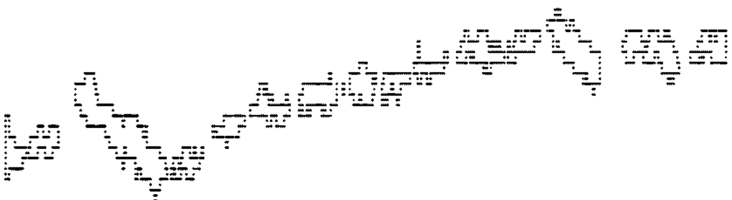
- **AutoCAD™ (via AutoLISP)**
  - Original data interpreted with an in-house code.
  - Loses voxels connected by only edges.
  - Very difficult to generate CFD mesh (all right angles).
- **amira™ (visualization software)**
  - Loses no voxels.
  - Smoothes with proprietary algorithms.
  - Large mesh file sizes.
  - Geometries 1 and 2.
- **Tgrid™ (meshing software)**
  - Further smoothing of amira geometries.
  - Reduced file size.
  - Geometries 3, 4, and 5.

*** Karypn, Grader and Halleck JCIS (2007)**

Fracture cross sections from different smoothing procedures of CT file for CFD computations.

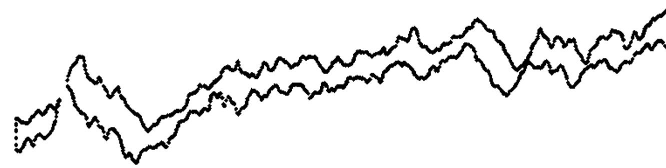
micro-CT scan file*

- **AutoCAD™ (via AutoLISP)**



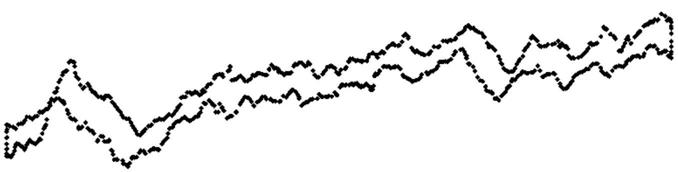
- **amira™ (visualization software)**
  - **#1**

  - **#2**



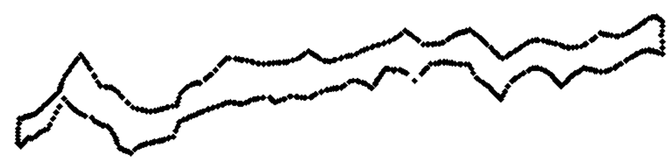
- **amira™, then Tgrid™ (meshing software)**

- **#3**



- **#4**

- **#5**



*** Karypn, Grader and Halleck JCIS (2007)**

The fracture "roughness" was fractal over length scales from ≈500 µm to ≈15 mm.

Fracture Model	b_{eff} (mm)	Vol (mm)^3	D_f**
• AutoCad	0.300	1214	2.53
• #1 Amira	0.120	1291	2.47
• #2 "	0.114	1291	2.48
• #3 " + Tgrid	0.175	1553	2.36
• #4 " "	0.241	1731	2.29
• #5 " "	0.308	1909	2.28
• Karpyn Amira	----	1472$\pm$74	----

**2.5 indicates fractal Brownian surface; D_f reduced by smoothing.

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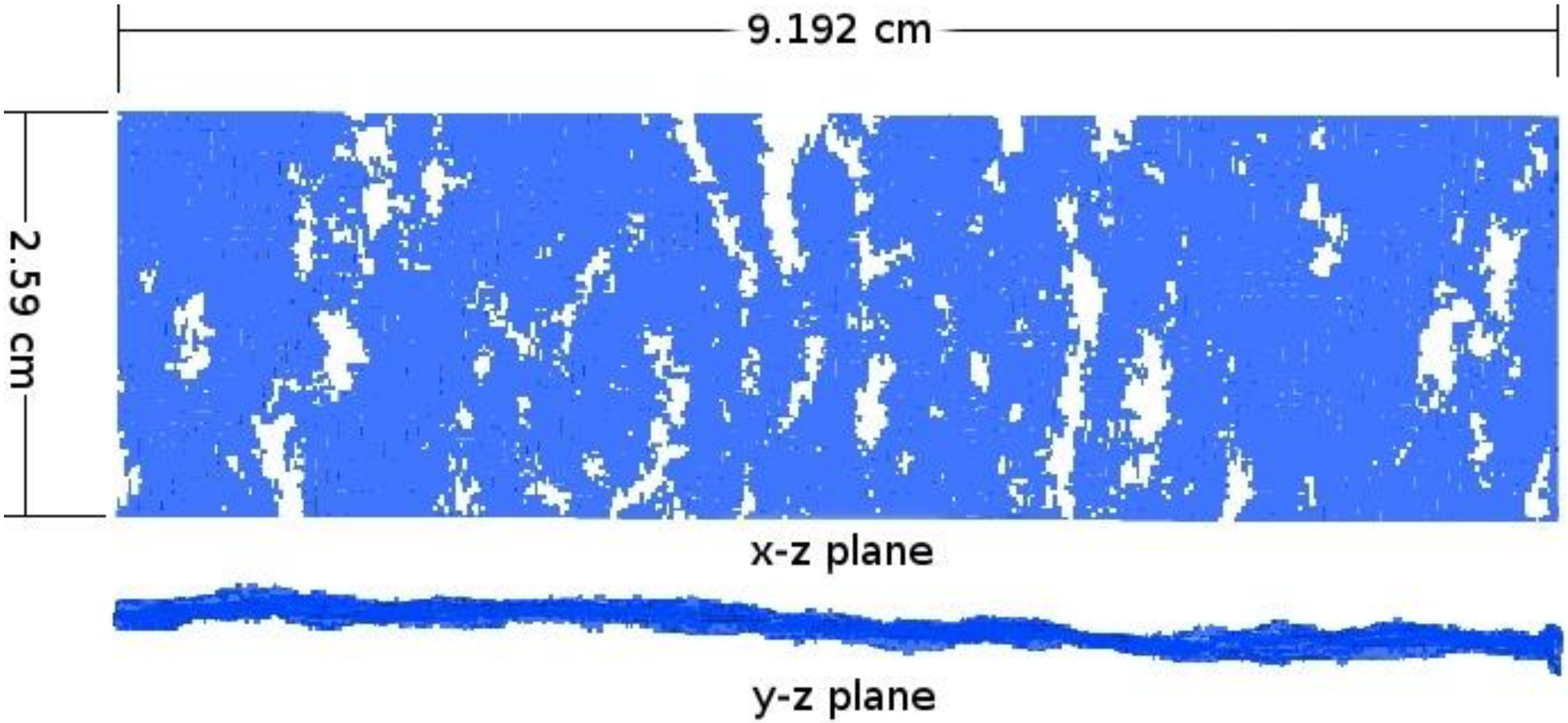
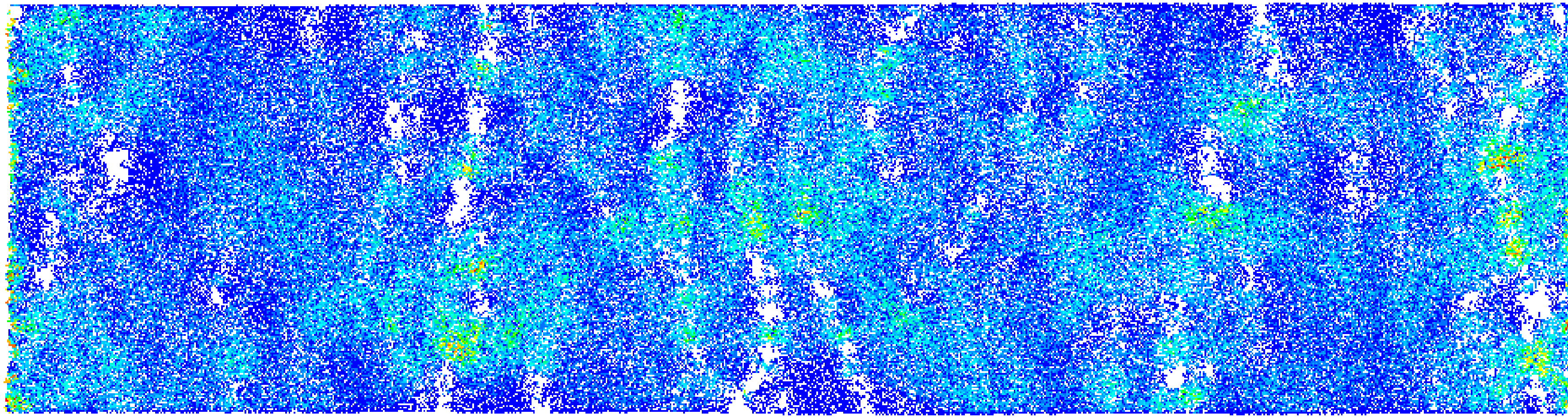
Visualized fracture



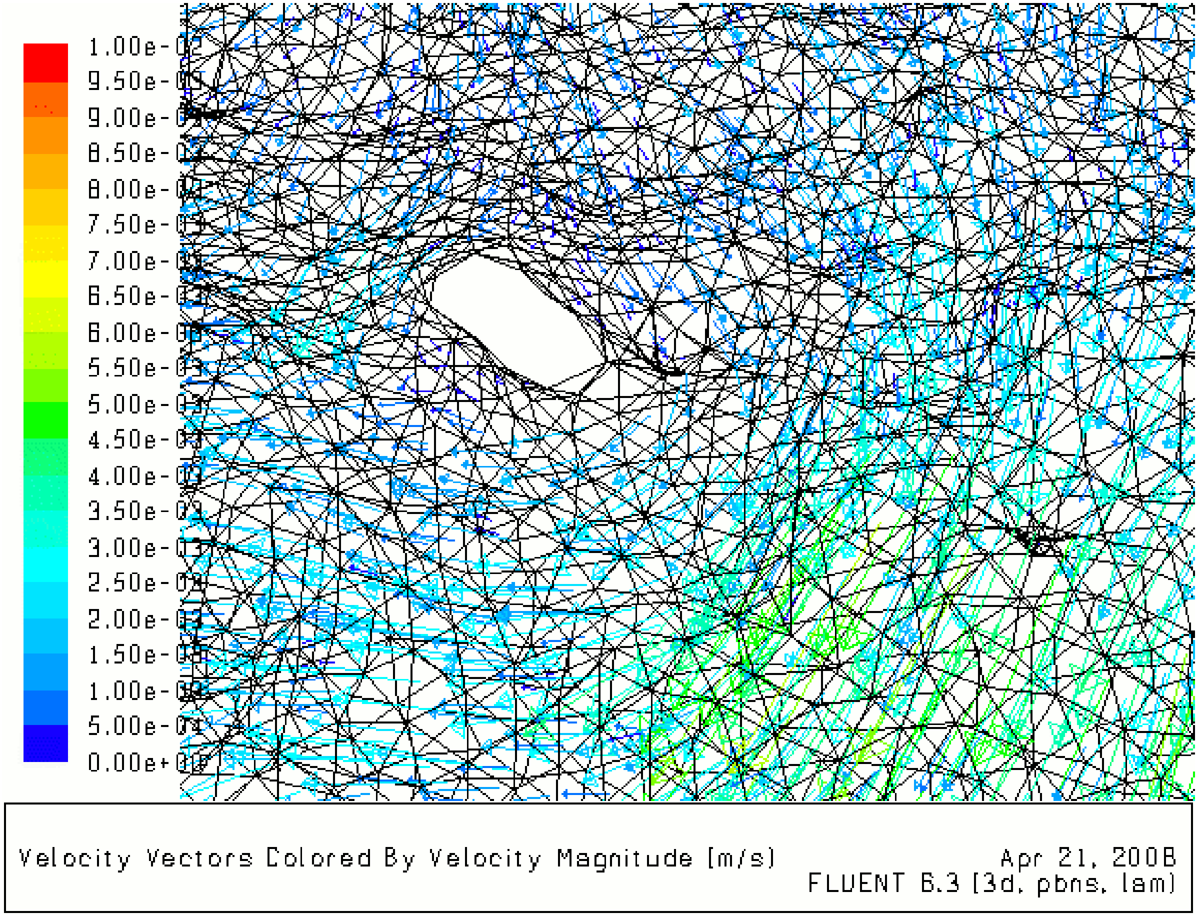
- **blue: open aperture white: asperities**

Visualized single-phase flow velocities (I)



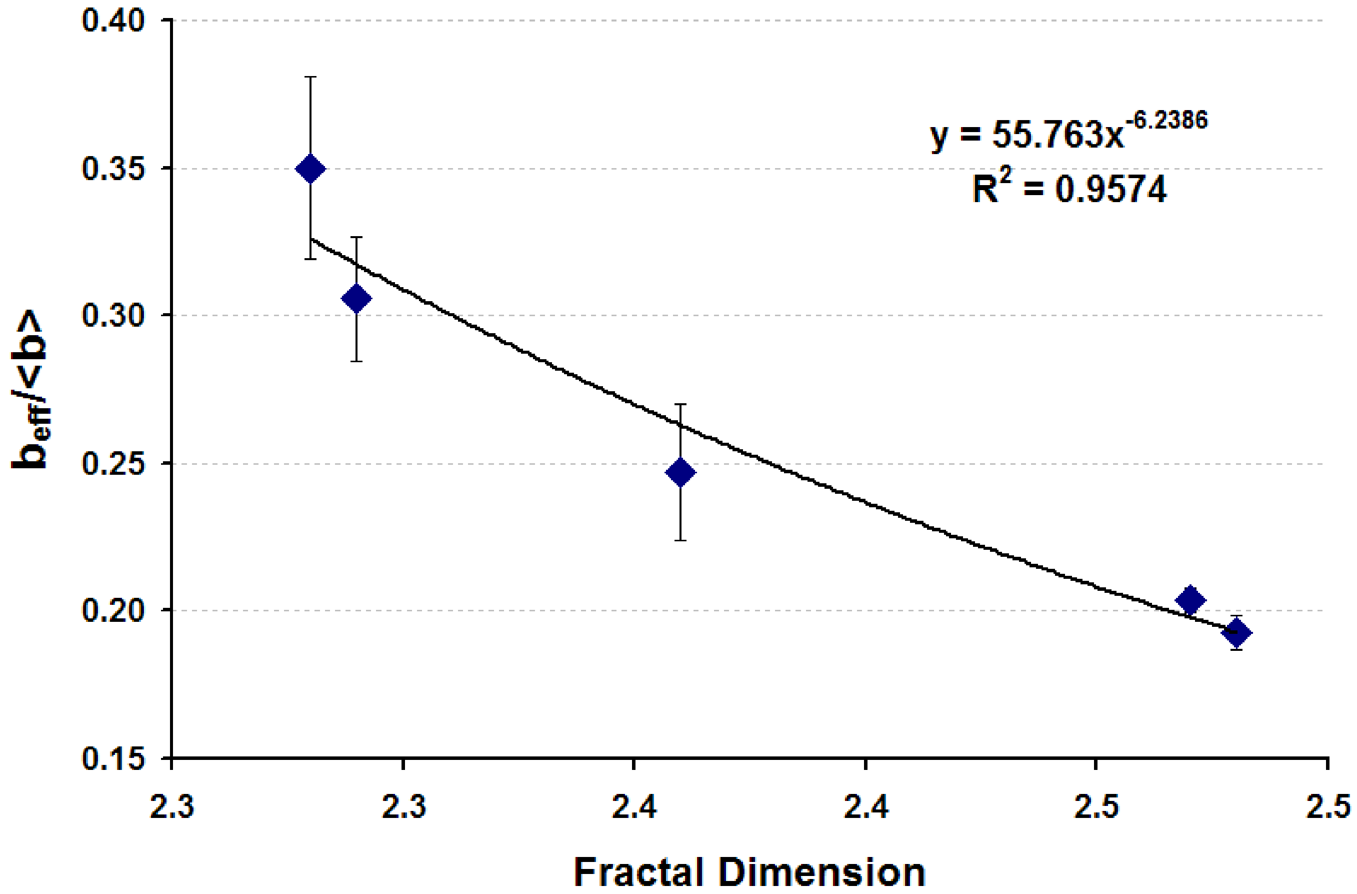
- velocity magnitudes—colored
- blue—slowest yellow—faster red—fastest
- velocity vectors—too small to see

Visualized single-phase flow velocities (II)



Black lines—gridding mesh

An apparent power-law relationship between the D_f and the effective aperture was observed.

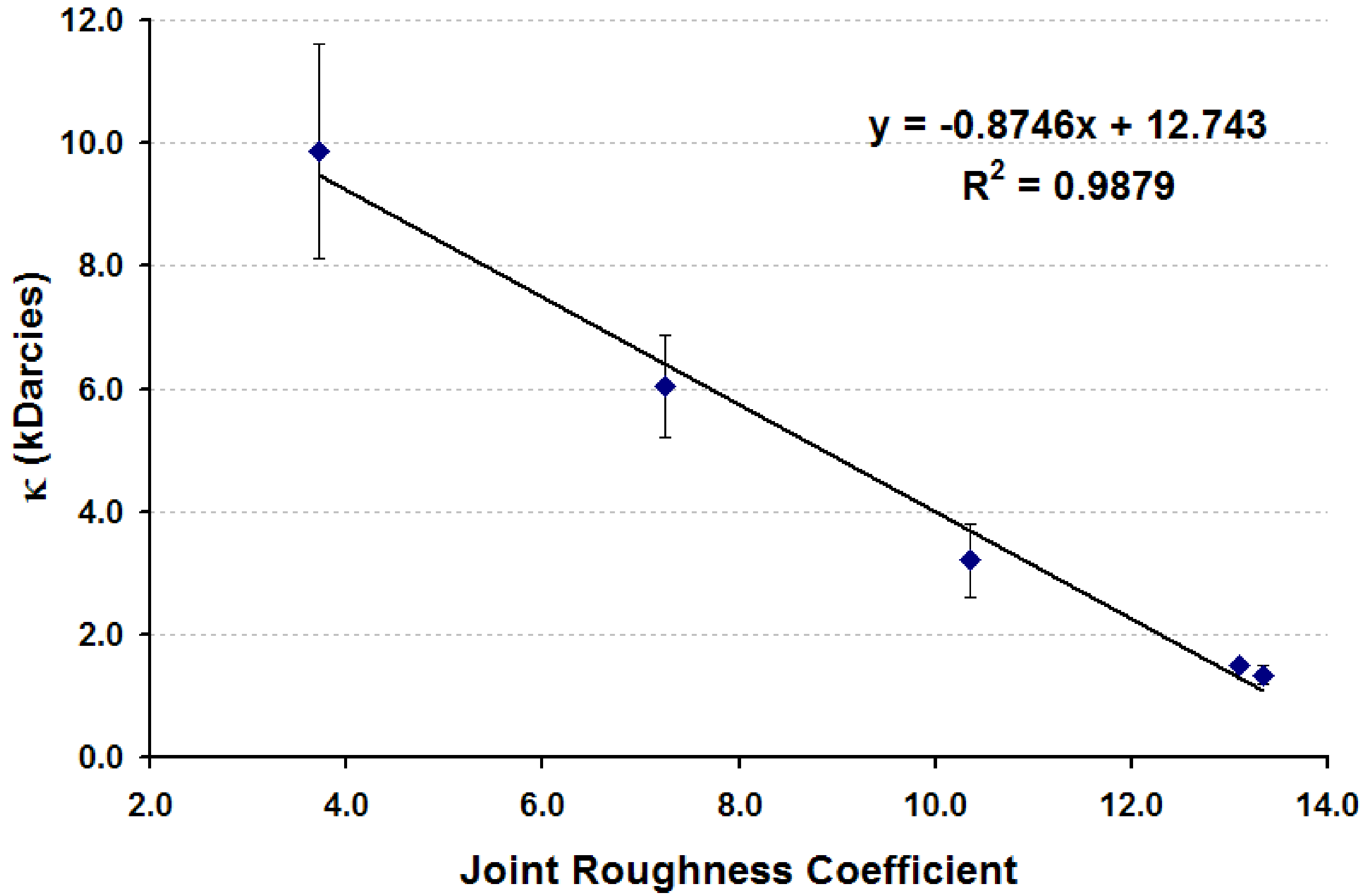


Permeability was affected by fracture smoothing.

Fracture Model	b_{eff} (mm)	Vol $(mm)^3$	κ(kdarcies)
• AutoCad	0.300	1214	0.345
• #1 Amira	0.120	1291	1.49
• #2 "	0.114	1291	1.34
• #3 " + Tgrid	0.175	1553	3.20
• #4 " "	0.241	1731	6.05
• #5 " "	0.308	1909	9.87
• Karpyn	----	1472±74	----

NETL

The "roughness coefficient" may be a practical way to estimate fracture permeability.



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The "joint roughness coefficient" (JRC) can be estimated in two different ways:

Method I

- **Determination of JRC by comparison with published profile tables.**
- **0 < JRC < 20**
- **An approximate method, suitable for field estimations.**

Method II

- **JRC = 32.2 + 32.47 log Z_2**

$$Z_2 = \left[\frac{1}{M(\Delta X)^2} \sum_{i=1}^{M} (y_{i+1} - y_i)^2 \right]^{1/2}$$

M = # intervals

Z_2 = RMS of 1st derivative of fracture wall slope

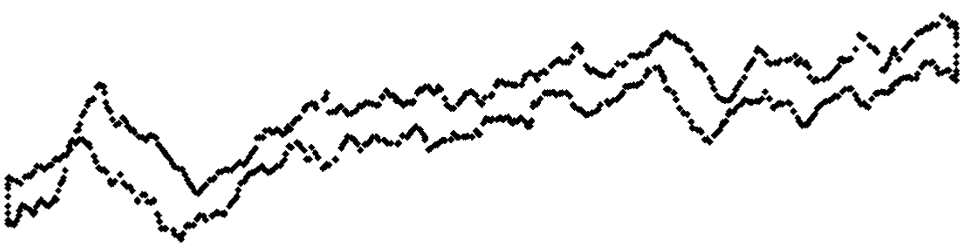
Δx = interval distance

- **Requires measurement of fracture surface.**

Use of commercial fracture-smoothing software is "necessary," but problematic.

micro-CT scan file*

- **AutoCAD™ (via AutoLISP)**
  - Real CT data, not real fracture.



Geometry 3

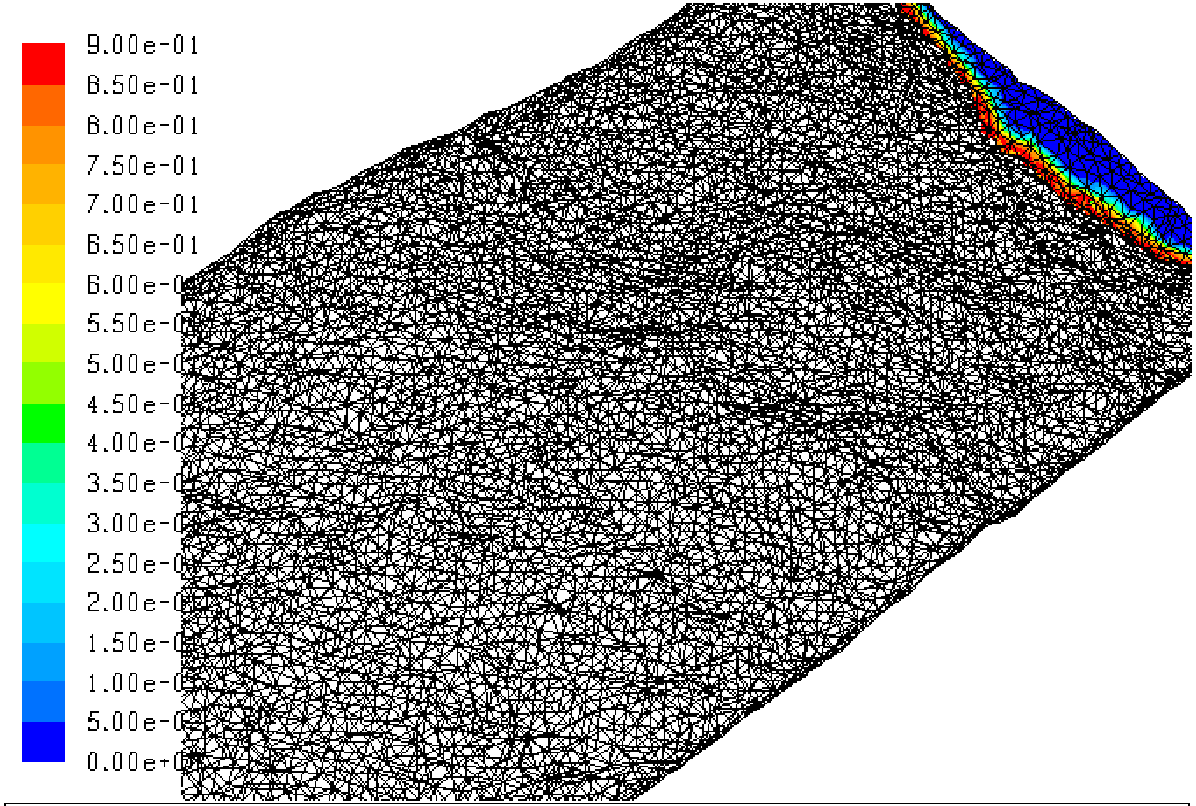
- **amira™ (visualization software)**
  - Smoothed voxels.
  - Excessive mesh file size.
- **Tgrid™ (meshing software)**
  - Geometry 3.
    - Good compromise, manageable file size.
  - Geometries 4 and 5.
    - Excessive smoothing.

Spatial resolutions of fracture geometry measurements are “ahead” of flow simulations.

Method	“Working” resolution (μm x μm x μm)		
CT	27.34	x 27.34	x 32.55
Profilometer*	2	x 2	x 10
Not given	3.1	x 3.1	x 3.1
Navier-Stokes (FLUENT)	240	x 240	x 240
2-D Network	---	x ---	x 130
Finite element	10	x 200	x 200
Level set	20(?)		
Level set	1000	X 1000	x 50

*but requires disassembly of fracture

Two-phase flow: Gas displacing brine



Contours of Volume fraction (h2o)   (Time=1.0020e-01)   Apr 15, 2008
FLUENT 6.3 (3d, pbns, vof, lam, unsteady)

Fracture Model	Processing Software	<b> (mm)	Volume (mm^3)	Closed Regions	Hurst Exponent	D_f	Z_2	JRC
Original	In-house code	0.49	1214.45	12.5%	0.47	2.53	0.287	14.58
Karpyn et al(2007)	amira	0.548±0.027	1471.65±5%	1.5%	—	—	—	—
Smoothed 1	amira	0.58	1290.68	1.1%	0.53	2.47	0.258	13.10
Smoothed 2	amira	0.59	1291.10	0.8%	0.52	2.48	0.263	13.34
Smoothed 3	amira & TGrid	0.71	1553.33	0	0.64	2.36	0.213	10.35
Smoothed 4	amira & TGrid	0.79	1730.86	0	0.71	2.29	0.171	7.24
Smoothed 5	amira & TGrid	0.88	1908.99	0	0.72	2.28	0.134	3.72

Fracture Model	Cell Count	κ (kDarcies)	b_{eff} (mm)
Smoothed 1	$5.3(10^6)$	1.49	0.12
Smoothed 2	$6.0(10^6)$	1.34	0.114
Smoothed 3	$6.4(10^6)$	3.20	0.175
Smoothed 4	$4.7(10^5)$	6.05	0.241
Smoothed 5	$2.3(10^5)$	9.87	0.308

Table 2: Fracture κ and b_{eff}.

than 10^{-3}. Computational domains of $4.8(10^4)$ to $1.3(10^6)$ nodes were used, with $2(10^5)$ to $6(10^6)$ tetrahedral and/or polyhedral cells. Larger mesh sizes were typical of the 'rougher' geometries, where the fracture walls required a higher resolution of grid spacing.

For each smoothed fracture geometry a pressure difference of 0.5, 5, and 50 Pa was modeled along the length of the fracture, with water as the working fluid. The mass flow rate through the geometries was calculated and related to κ and b_{eff} using Eqns. 3 and 4. The three calculated κ and b_{eff} for each geometry were averaged to obtain the reported values. The average velocity in the domain was determined as well, and (using the average aperture as a length scale) the Reynolds number was calculated to be less than 1 for all studied cases.

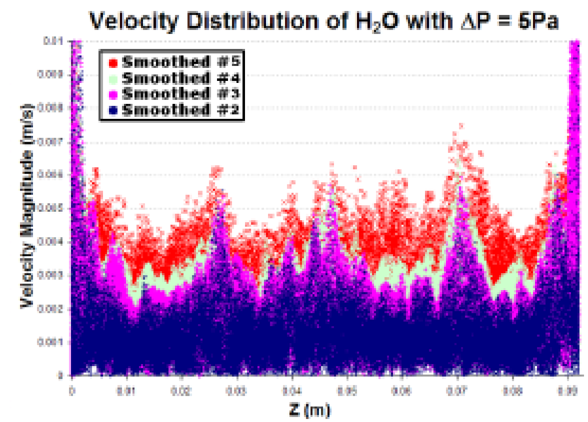
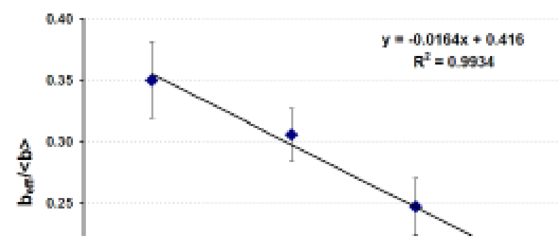
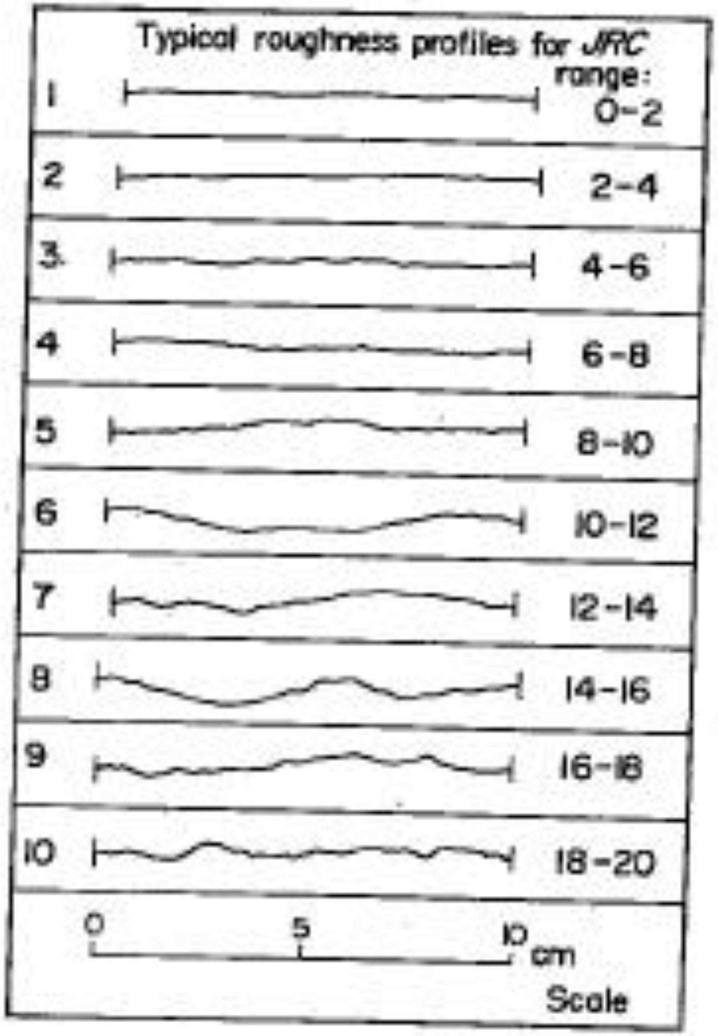


Figure 2: Distribution of velocity within four smoothed fracture geometries.




Typical roughness profiles for JRC range:
1
0-2
2
2-4
3
4-6
4
6-8
5
8-10
6
10-12
7
12-14
8
14-16
9
16-18
10
18-20
0
5
10
cm
Scale