Evaluating the effects of fracture roughness on fluid flow and solute transport: Is upscaling possible?

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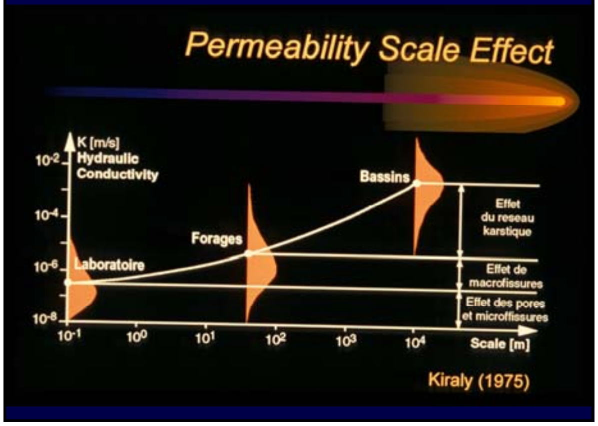
Importance?

- **Flow and transport in many or, perhaps, most rocks is fracture controlled.**
- **Black's law**
- **Scaling, if possible, could allow us to predict key hydraulic properties at larger spatial and temporal scales than we can measure readily.**

BLACK'S LAW

When dealing with fractured systems, we find that contaminants appear at places we don't expect and they appear faster than we had predicted.



FRACTURE CHARACTERIZATION

- Orientation (strike and dip, if planar)
- Spacing or density [L^{-1}]
- **Aperture**
- **Roughness (asperities)**
- **Channeling**
- Connectivity
- Skin properties

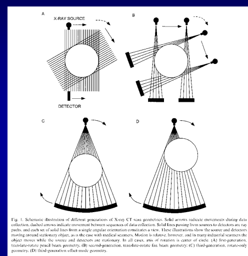
Flow and transport in fractures

- **Laboratory tests of flow**
- **Catscans (X-ray computed tomography) of roughness**
- **Evaluation of aperture and roughness statistics and scaling**
- **Evaluation of channeling**

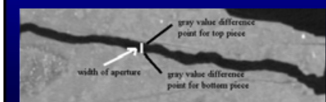
Samples tested to date include granites, sandstones, tuffs, and carbonates.

CALCULATING APERTURE FROM CT GENERATED IMAGES

Photo of scanning facility courtesy of the UTCT



From Ketcham & Carlson, 2001



FLOW IN A SINGLE FRACTURE

- Cubic law
- Modified cubic law (e.g., Lomize)
- Channelized model of flow
- Stress dependent models

LOMIZE'S MODIFIED CUBIC LAW

$$Q = \frac{1}{f}\frac{b^3 \rho_w g}{12\mu}(\nabla h)^c$$

Q = discharge $[L^3\ t^{-1}]$
f = roughness factor [-] (*1 in cubic law*)
b = aperture [L]
ρ_w = density of water $[M\ L^{-3}]$
g = gravitational acceleration $[L\ t^{-2}]$
μ = viscosity $[m\ L^{-1}\ t^{-1}]$
∇h = hydraulic gradient [-]
c = constant ≤ 1 (*1 in cubic law*)

APERTURE?

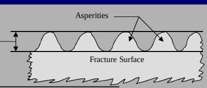
- Arithmetic mean
- Geometric mean
- Harmonic mean
- Hydraulic
- Transport

Berkowitz, Ge, Mourzenko ?

There are many methods used to calculate surface roughness

Absolute Roughness
Lomize, 1951; Louis, 1969

ε



Standard Deviation $\sigma_z = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(z_i - \bar{z})^2}$

(**Mean** $\bar{z} = 0$)

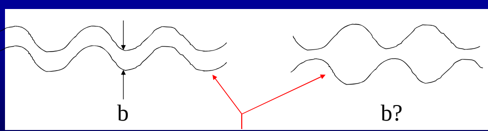
RMS Roughness (Thomas, 1999; others) $R_{rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} z_i^2}$

Center Line Average Roughness (Thomas, 1999) $R_{cla} = \frac{1}{n}\sum_{i=1}^{n}|z_i|$

Aperture Roughness Measures

Relative Roughness ε/b σ_z/b R_{cla}/b

Aperture Mismatch



Same Absolute Roughness

Empirical Relations:

	Lomize, 1951	Louis, 1969
	$C=6$	$C=3.1$
	$\left(\frac{\varepsilon}{b}\right)_{max}=0.85$	$\left(\frac{\varepsilon}{b}\right)_{max}=0.72$

$$K_{ROUGH}=K_{CUBIC}\frac{1}{\left[1+C\left(\frac{\varepsilon}{b}\right)^{1.5}\right]}$$

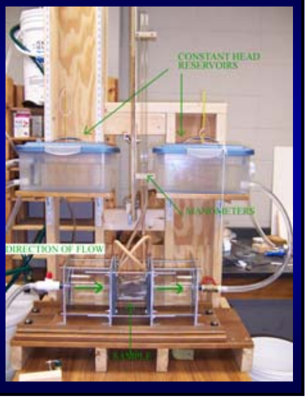
From CT scans: $\boldsymbol{R_{cla}}$ **= 0.546mm** ⟶ ε = 2.18mm, b = 0.50mm ⟶ $\left(\frac{\varepsilon}{b}\right)=4.4$

From flow tests:

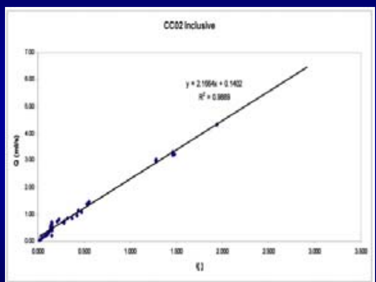
$$\frac{K_{IMPUTED}}{K_{DIRECT}}=\frac{0.143}{0.118}=1.21=\left[1+C(4.4)^{1.5}\right] \longrightarrow C=0.02$$

We need to reexamine roughness in flow in fractures!

MEASURING FLOW RATES

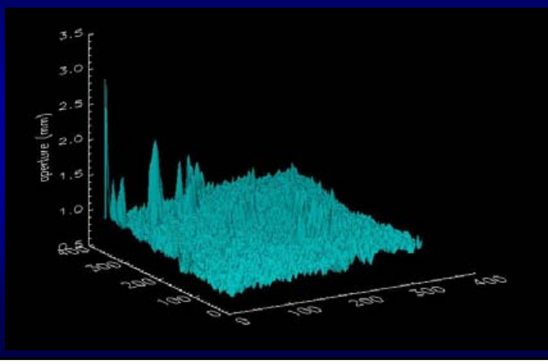


Searching for Transitional Flow



Plotting discharge versus hydraulic gradient, we expect a "rounding over" effect as inertial forces begin to dominate. In this set of tests, the flattening has yet to appear at even relatively high gradients.

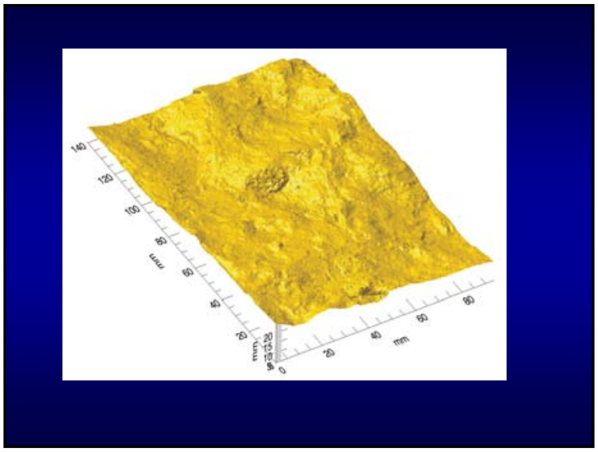
FRACTURE APERTURE

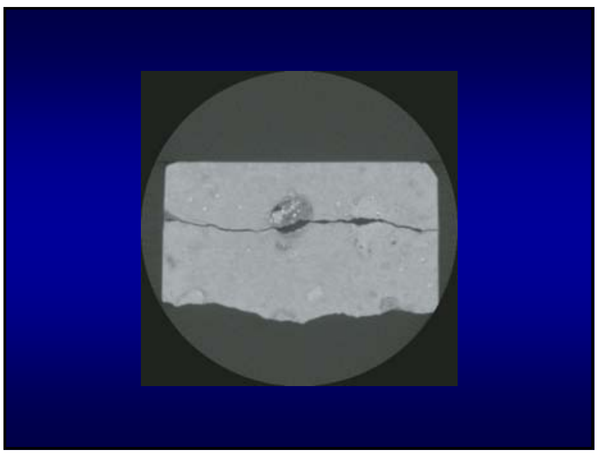


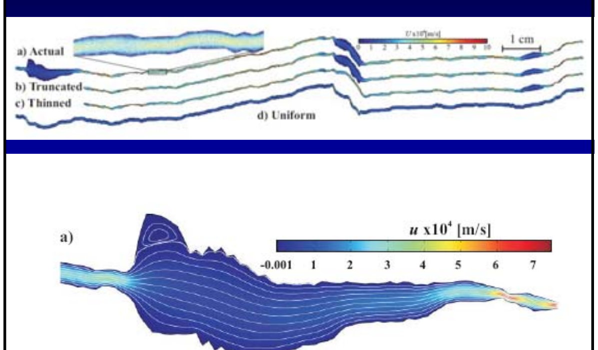
Modeling and Flow Laws

- **Local cubic law**
- **Smooth walls**
- **Parallel plates**
- **No slip**
- **No turbulence**

What does a fracture look like?

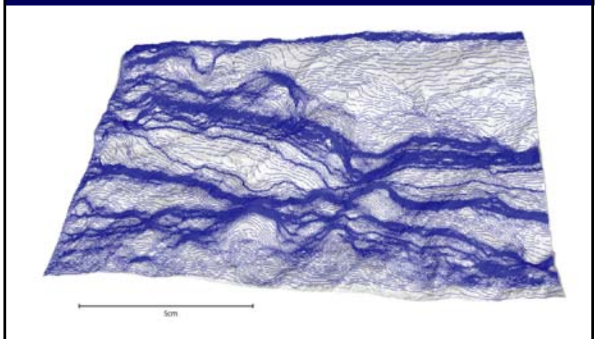




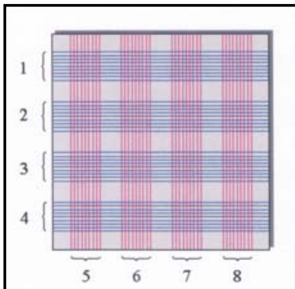


Cardenas et al, 2008

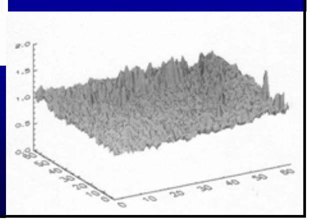
What does a fracture look like?

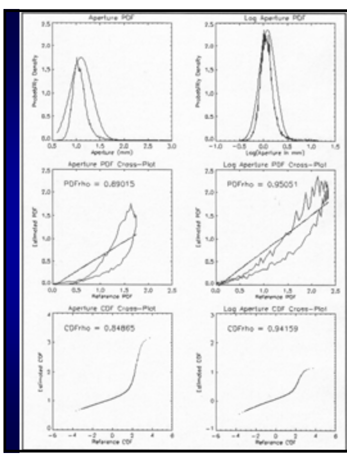


Particle Tracks for CC02-2



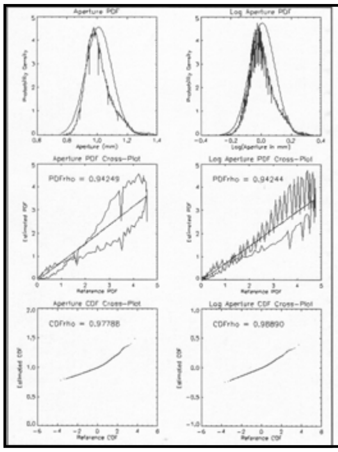
The fracture aperture determined by CT were compiled along 8 sets of 9 parallel scanlines to examine statistical properties of the fracture surfaces and apertures.





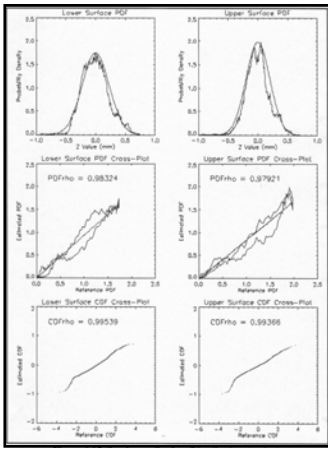
Granite apertures

- **The aperture distributions are neither normal or lognormal.**
- **There appear to be two populations of apertures.**



Sandstone aperture

- The aperture distributions are neither normal or lognormal.
- There appears to be some censoring and truncation effects and a kink. Are there two distributions?
- A binning artifact is seen in the log aperture data .



Sandstone fracture roughness

- Roughness distributions are close to normal.
- There appears to be some censoring and truncation effects and a kink .
- The statistics of the fracture surfaces are different than those of the aperture.

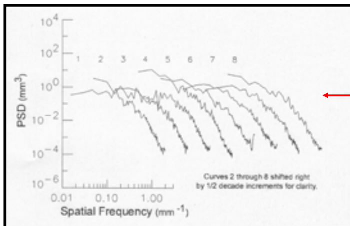
Sandstone data

Ensemble	Min	Max	Mean	Std. Dev.	GeoMean	HarMean
Apert_1	0.8177	1.1611	0.9741	0.0670	0.9718	0.9695
Apert_2	0.8387	1.2517	0.9956	0.0821	0.9924	0.9892
Apert_3	0.8661	1.2713	1.0050	0.0795	1.0020	0.9992
Apert_4	0.8896	1.2587	1.0509	0.0700	1.0485	1.0460
Apert_5	0.8474	1.1991	0.9806	0.0652	0.9784	0.9763
Apert_6	0.8725	1.2077	1.0110	0.0641	1.0091	1.0071
Apert_7	0.8143	1.2779	1.0003	0.0920	0.9962	0.9922
Apert_8	0.8816	1.3498	1.0831	0.0989	1.0786	1.0742
Min	0.8143	1.1611	0.9741	0.0641	0.9718	0.9695
Max	0.8896	1.3498	1.0831	0.0989	1.0786	1.0742
Mean	0.8535	1.2472	1.0126	0.0774	1.0096	1.0067

Each profile ensemble consisted of 2304 data points. The mean aperture was set at 1.0 mm by screw adjustment. Are the data stationary?

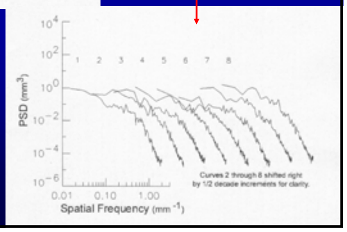
Granite data

Ensemble	Min	Max	Mean	Std. Dev.	GeoMean	HarMean
Apert_1	0.7384	1.4580	1.0109	0.1220	1.0036	0.9968
Apert_2	0.7566	1.6310	1.0856	0.1661	1.0738	1.0628
Apert_3	0.7826	1.4442	1.0931	0.1184	1.0867	1.0802
Apert_4	0.8262	2.1982	1.2091	0.2577	1.1864	1.1683
Apert_5	0.8239	1.6747	1.0968	0.1770	1.0836	1.0719
Apert_6	0.7880	1.4003	1.0414	0.1153	1.0351	1.0290
Apert_7	0.8557	1.4254	1.0956	0.1134	1.0896	1.0838
Apert_8	0.8252	2.1933	1.1654	0.2397	1.1436	1.1268
Min	0.7384	1.4003	1.0109	0.1134	1.0036	0.9968
Max	0.8557	2.1982	1.2091	0.2577	1.1864	1.1683
Mean	0.7996	1.6781	1.0997	0.1637	1.0878	1.0775



Granite aperture PSD

Sandstone aperture PSD

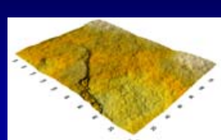


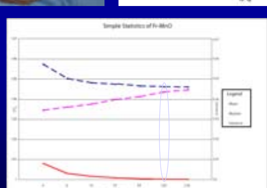
The statistics are not stationary in terms of either mean or variance even on these small scales.

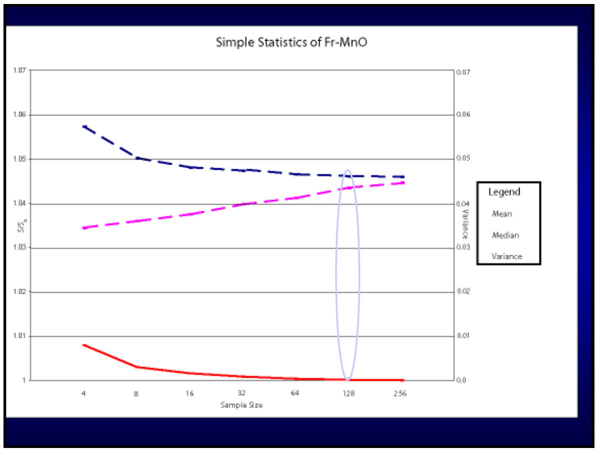
Stationarity is implicitly assumed in models of upscaling of hydraulic properties.

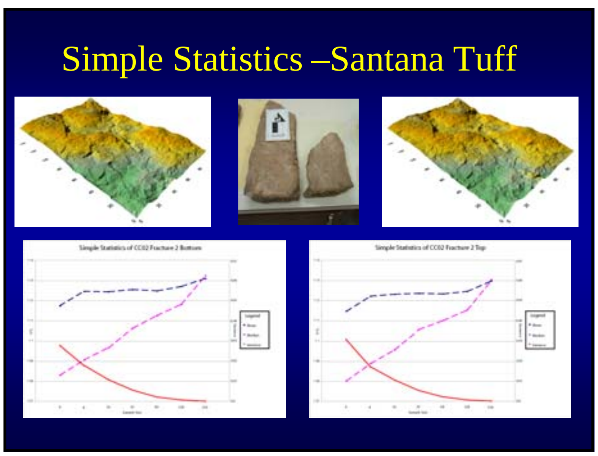
- Let's increase the sample size and scanning intensity

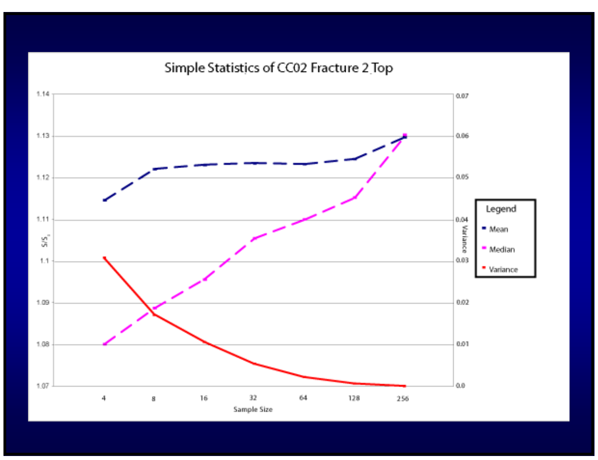
Simple statistics - granite sample

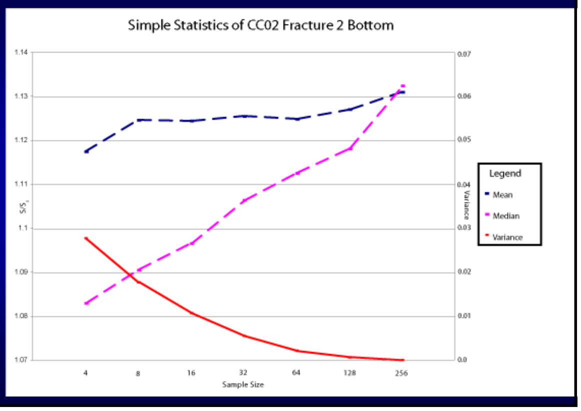




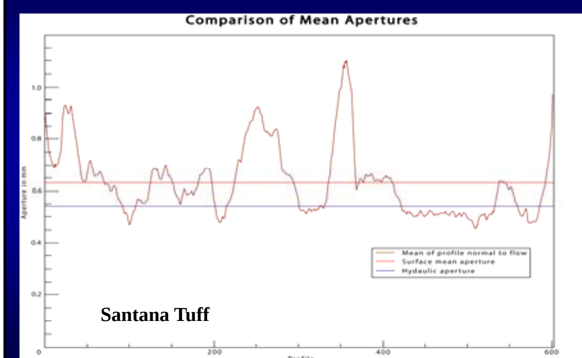

Simple Statistics of Fr-MnO
Legend
Mean
Median
Variance
Sample Size
Variance
4
8
16
32
64
128
256


Simple Statistics –Santana Tuff


Simple Statistics of CC02 Fracture 2 Top
Legend
Mean
Median
Variance
Sample Size
Variance
4
8
16
32
64
128
256



Which aperture?



Conclusions

- The widely-held assumption that the cubic law is a fair approximation for laminar flow through rough rock fractures.
- Channeling of flow occurs even at small scales.
- Roughness is important and empirical equations for handling roughness do not appear adequate.
  - The empirical correction factors of Lomize and Louis presume near-total mismatch between the surfaces and a relative roughness < 1.
  - Real rock fractures commonly have a relative roughness > 1. In fact, the asperities can be greater than the aperture.

Conclusions

- Aperture distributions may not match surface roughness distributions
- Aperture means and variances are not stationary at small scales in granite and sandstone samples with very complete data sets (2304 points).
- At a scale of 4-9 cm^2, an 0.25 mm point spacing, roughness stationarity was approached.
- The 2-D geometric mean is the best estimate of the hydraulic aperture.*

Conclusions

- Upscaling of fracture hydraulic aperture is still an open question.
- Single point or single scanline measurements of aperture should be treated with caution in predicting fluid flow and transport within fractures.
- Upscaling of transport properties is probably not yet possible.

Acknowledgments

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Future and ongoing work

(assistance needed!)

- Conduct quantitative analyses of skin properties in crystalline rocks and compare data to:
  - Rock type
  - Climate
- Consider the effects of:
  - Channeling
  - Fracture roughness
  - Density-driven flow
- Tracer tests in fractures with materials of differing sorptivity.