Viability of Rapid *in situ* Measurement of Hydraulic Properties

John L. Wilson

Dept. of Earth & Environmental Science
New Mexico Inst. of Mining & Technology
Socorro, New Mexico

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Vince Tidwell, Bob Holt & Bob Glass, Sandia Natl. Labs,
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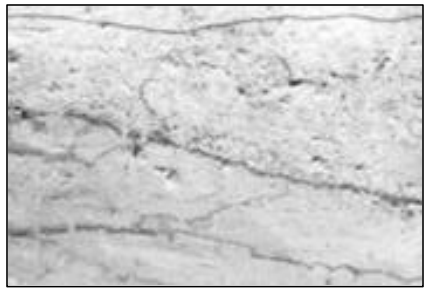
Heterogeneity



- Vadose zone characterized by heterogeneous geologic materials
- Spatial variability of unsaturated hydraulic properties influences the movement of
  - water
  - vapor
  - non-aqueous phase liquids (NAPL's).

One Approach to Characterization

- Large number of hydraulic property observations (eg, Deflaun et al., 1997)
- On typical or test materials
  - outcrops, excavations, boreholes, core and other samples
- Interpreted using models
  - geostatisical
  - geological

You could take many samples back to the lab...

Removing multiple samples for laboratory analysis is:

- expensive,
- time-consuming, and
- may not yield results representative of heterogeneous field conditions.

Simple and rapid field methods for estimating *in situ* properties

Appealing & cost-effective, but need:

- **rapid** measurements
  - > small sample volume (measurement support)
- **low cost** per data point
- **accurate** *(unbiased)* spatial statistics
  - measurements should accurately reflect the spatial variation of properties between sampled locations,
- **appropriate** instrument range
  - > relevant to the range of typical conditions
    - clastic sediments
    - low clay content (such as found at many DOE sites).

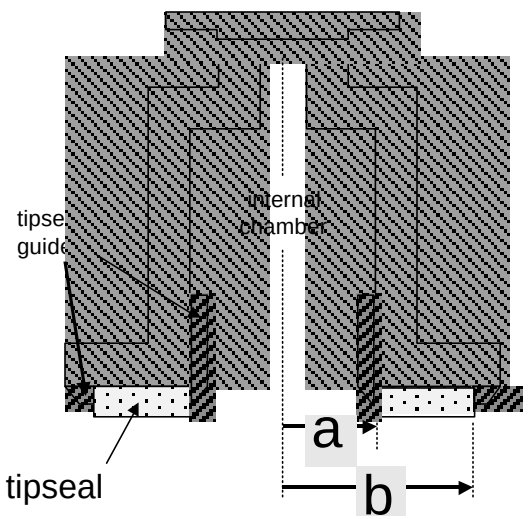
Properties of interest

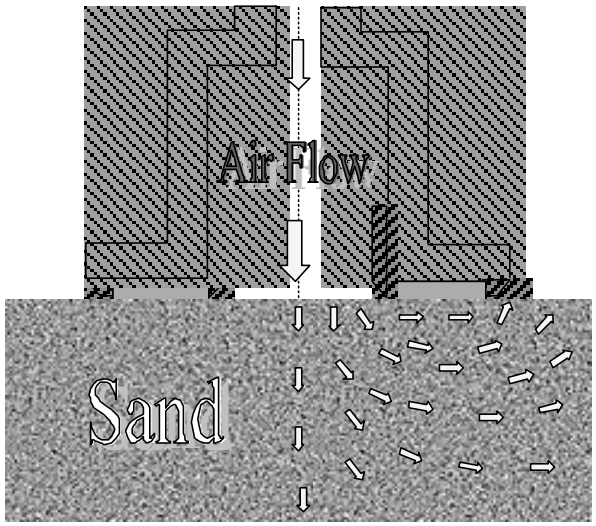
- saturated (intrinsic) permeability, k

  (or saturated hydraulic conductivity, K_s)
- porosity, ϕ.
- relative permeability, k_r (fcn. of saturation)
- pore pressure - saturation
  - – especially key parameters like air entry value

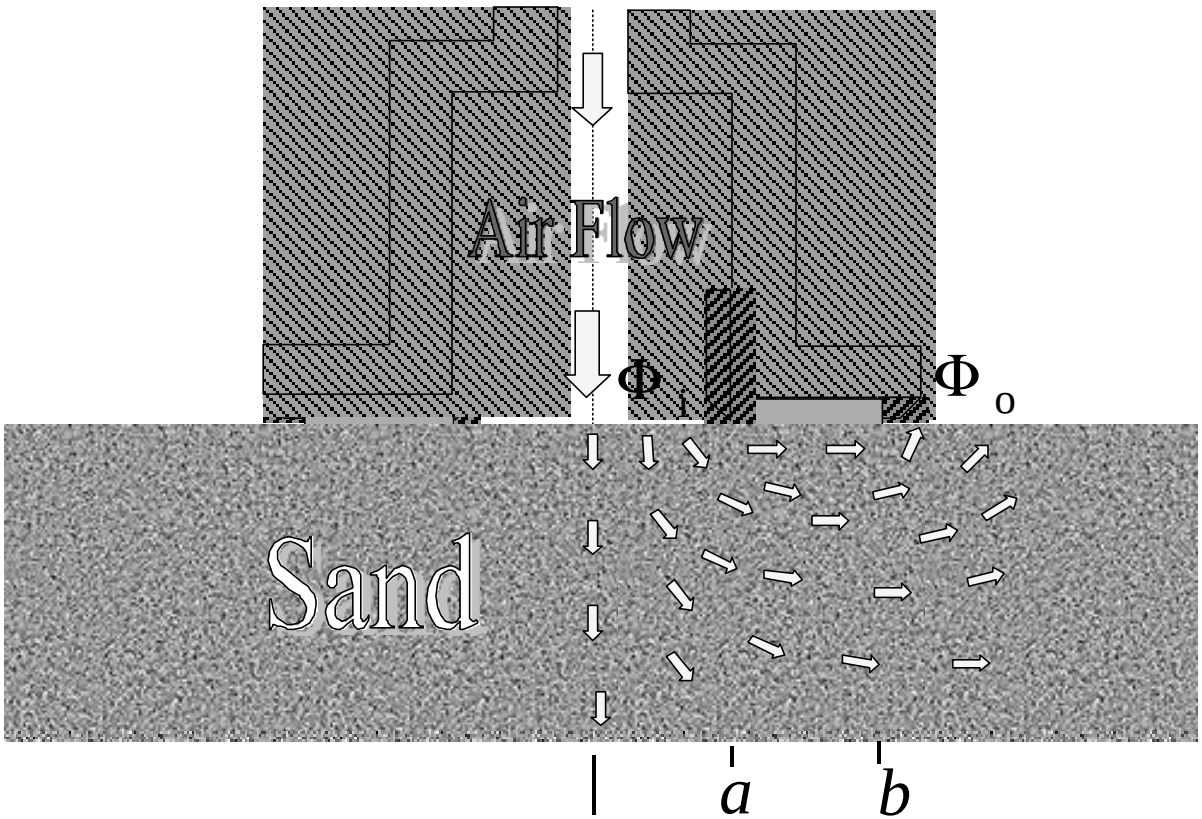
Gas Minipermeameter

- Principle (eg, Davis et al, 1994; Tidwell & Wilson, 1997):
  - Measure flow rate for applied pressure drop.
    - *Darcy's Law in a unique geometry*
  - Yields measure of (effective) intrinsic permeability:
  - Using a transient, can also give porosity.





Q and $\dot{m}$

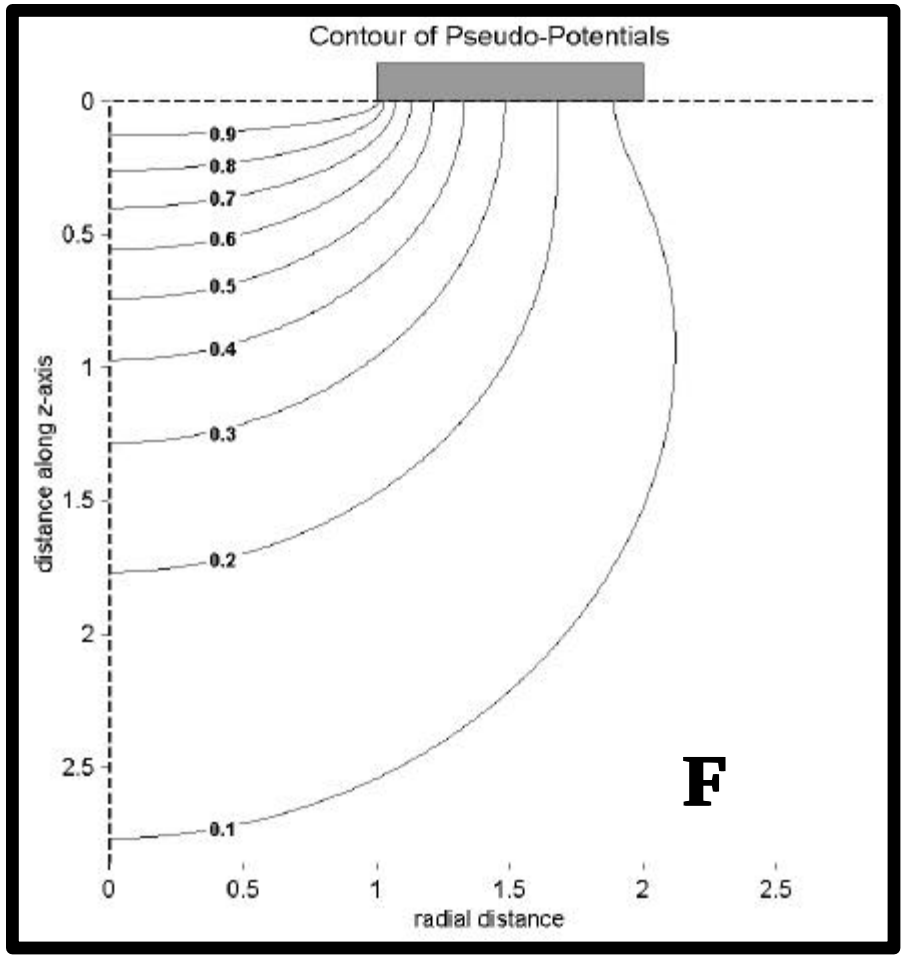


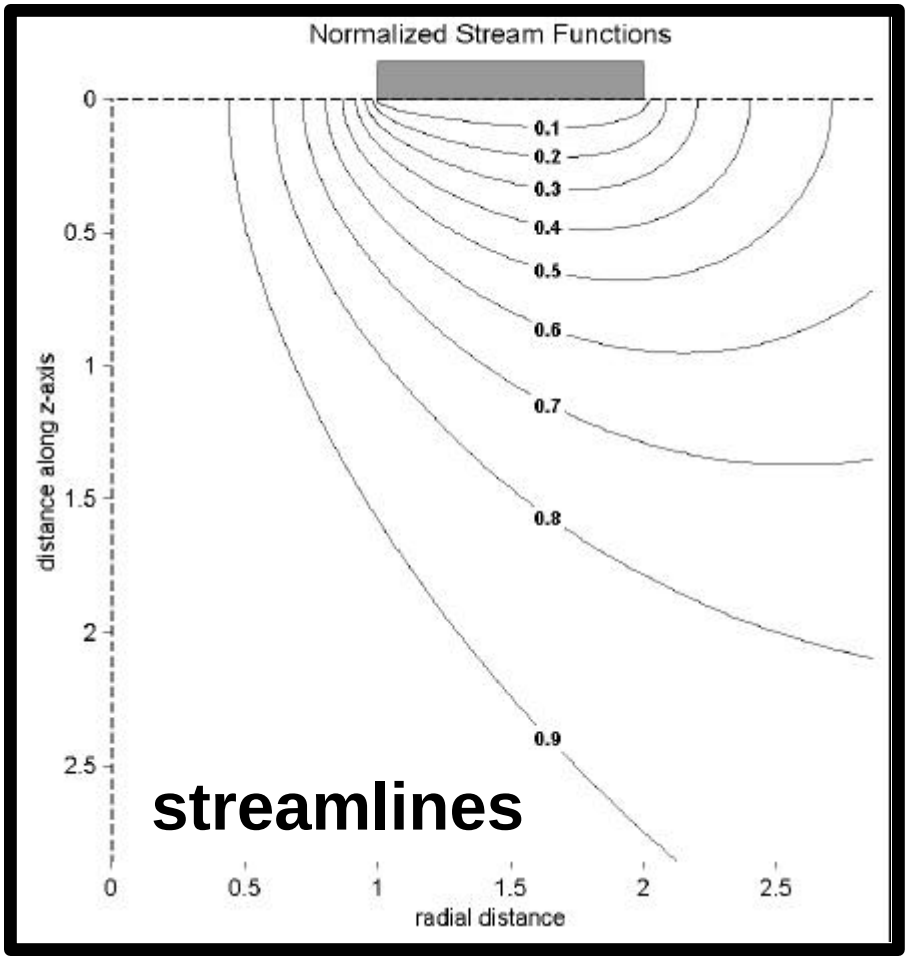
$$k_{measured} \text{ or } k_{eff} = \frac{Q\mu P_i}{0.5aG_o(b/a)[P_i^2 - P_o^2]} = \frac{\dot{m}}{aG_o(b/a)[\Phi_i - \Phi_o]},$$

where $G_o(2) = 5.10$ and $\Phi = \dfrac{M}{RT\mu}\dfrac{P^2}{2}$

(G_o from Kerr & Wilson, 2000)

Miniperm Flow Field



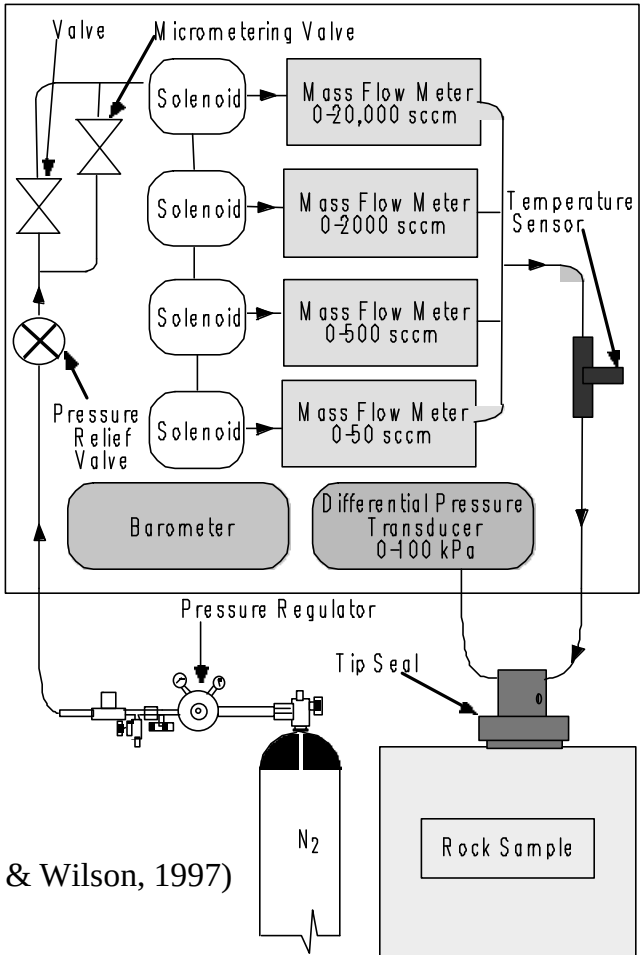


(afterWilson and Aronson, 2000)

Gas Minipermeameter

Two kinds of instruments:

Compressed Gas Tank + Mass Flow Meters:



(eg,Tidwell & Wilson, 1997)

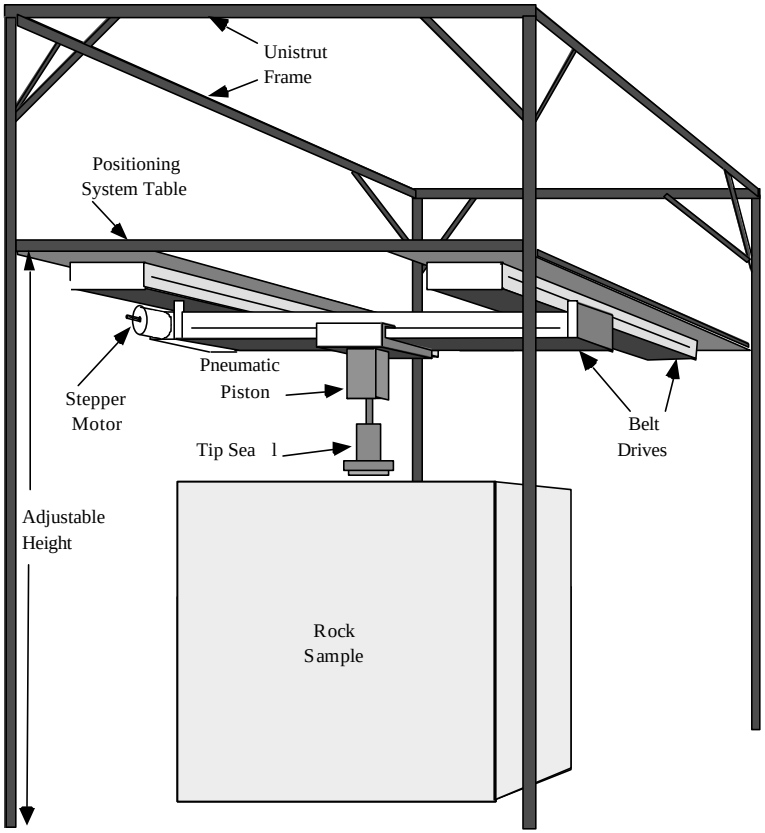
Falling Piston + "Stop Watch":

(eg, Davis et al., 1994)

Large Block Studies

X-Y Positioner

(eg,Tidwell & Wilson, 1997)

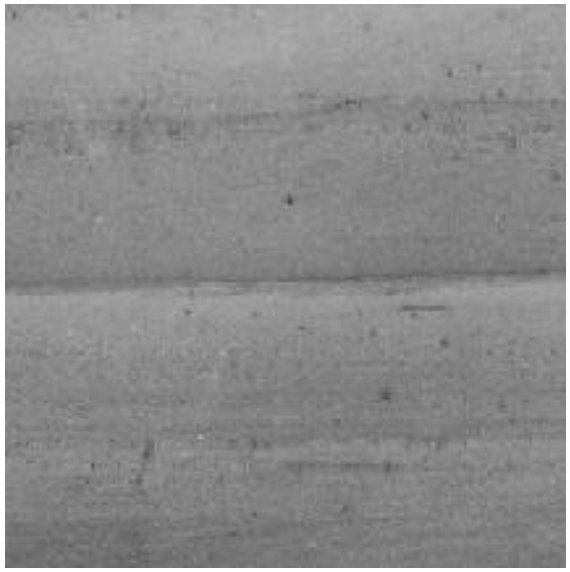


Outcrop Studies

(eg, Davis et al., 1993, 1997; Deflaun et al., 1997; Sigda et al., 1999)

Block Face Photographs

Massillon Sandstone

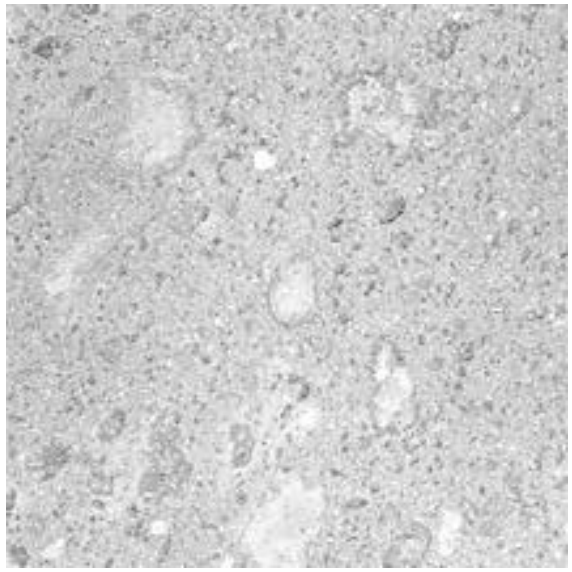


62 x 62 cm

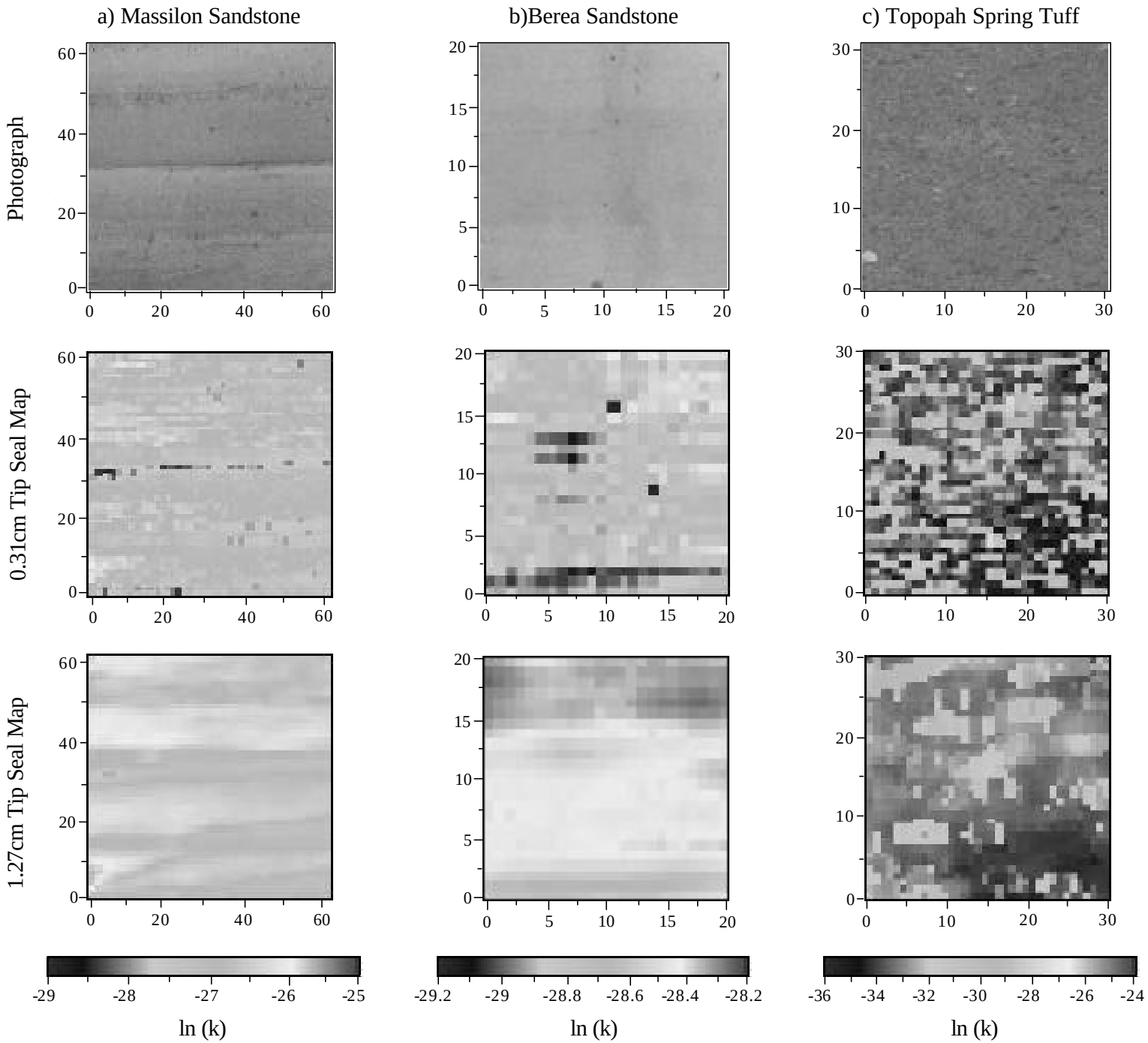
Berea Sandstone

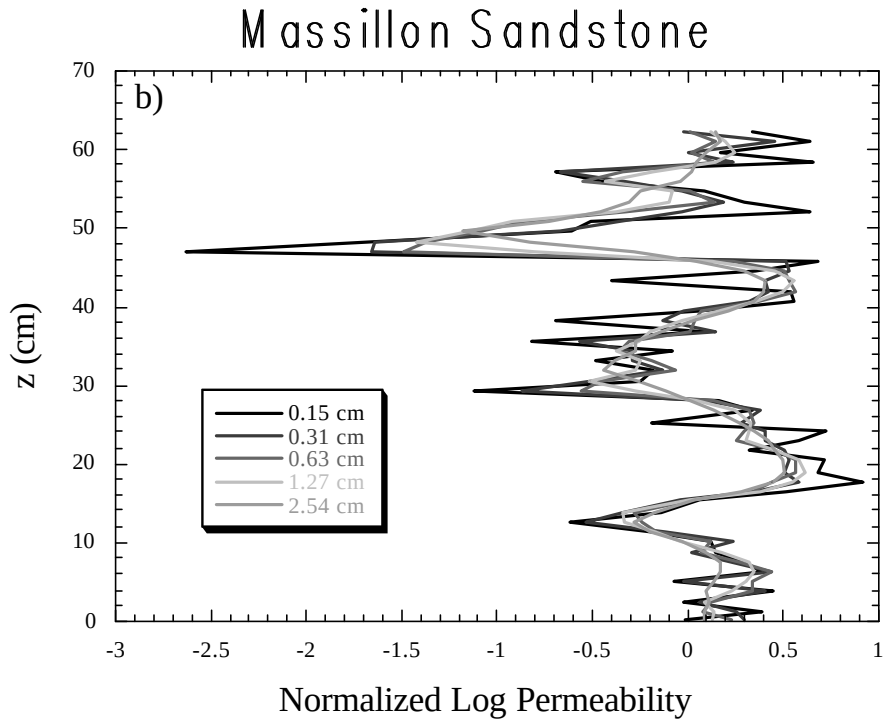
20 x 20 cm

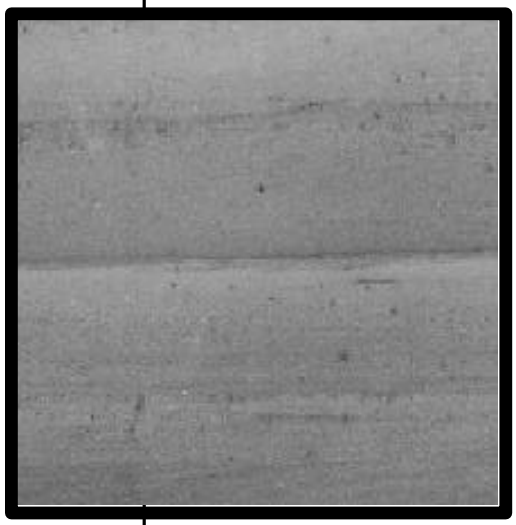
Topopah Spring Tuff



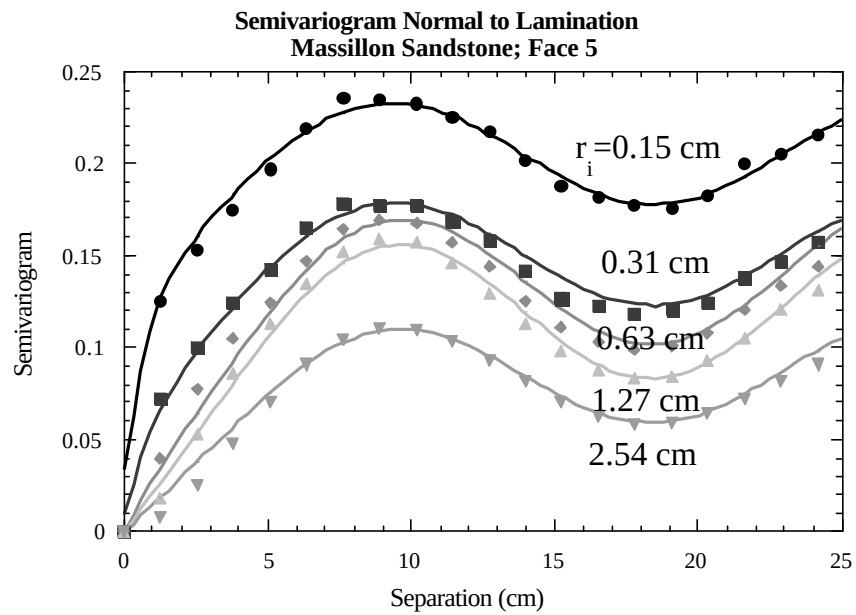
30 x 30 cm


a) Massilon Sandstone
b)Berea Sandstone
c) Topopah Spring Tuff
Photograph
0.31cm Tip Seal Map
1.27cm Tip Seal Map
ln (k)
ln (k)
ln (k)


Massillon Sandstone
b)
z (cm)
Normalized Log Permeability
0.15 cm
0.31 cm
0.63 cm
1.27 cm
2.54 cm



62 x 62 cm


Semivariogram Normal to Lamination
Massillon Sandstone; Face 5
Semivariogram
Separation (cm)
r_i =0.15 cm
0.31 cm
0.63 cm
1.27 cm
2.54 cm

Effective Permeability of an instrument

Model: power law convolution of

- point scale permeability and
- a spatial filter or weighting function
- over the volume of the sampled rock.

$$k_{eff}^{\omega} = \int_V \beta(r,z,\theta)\, k^{\omega}(r,z,\theta)\, dV \qquad \omega \neq 0$$

where $\beta(r,z,\theta)$ = spatial weighting or filter fcn [L^{-3}]

$$1 = \int_V \beta(r,z,\theta)\, dV$$

ω = averaging power (-1 for harmonic, $+1$ for arithmetic)

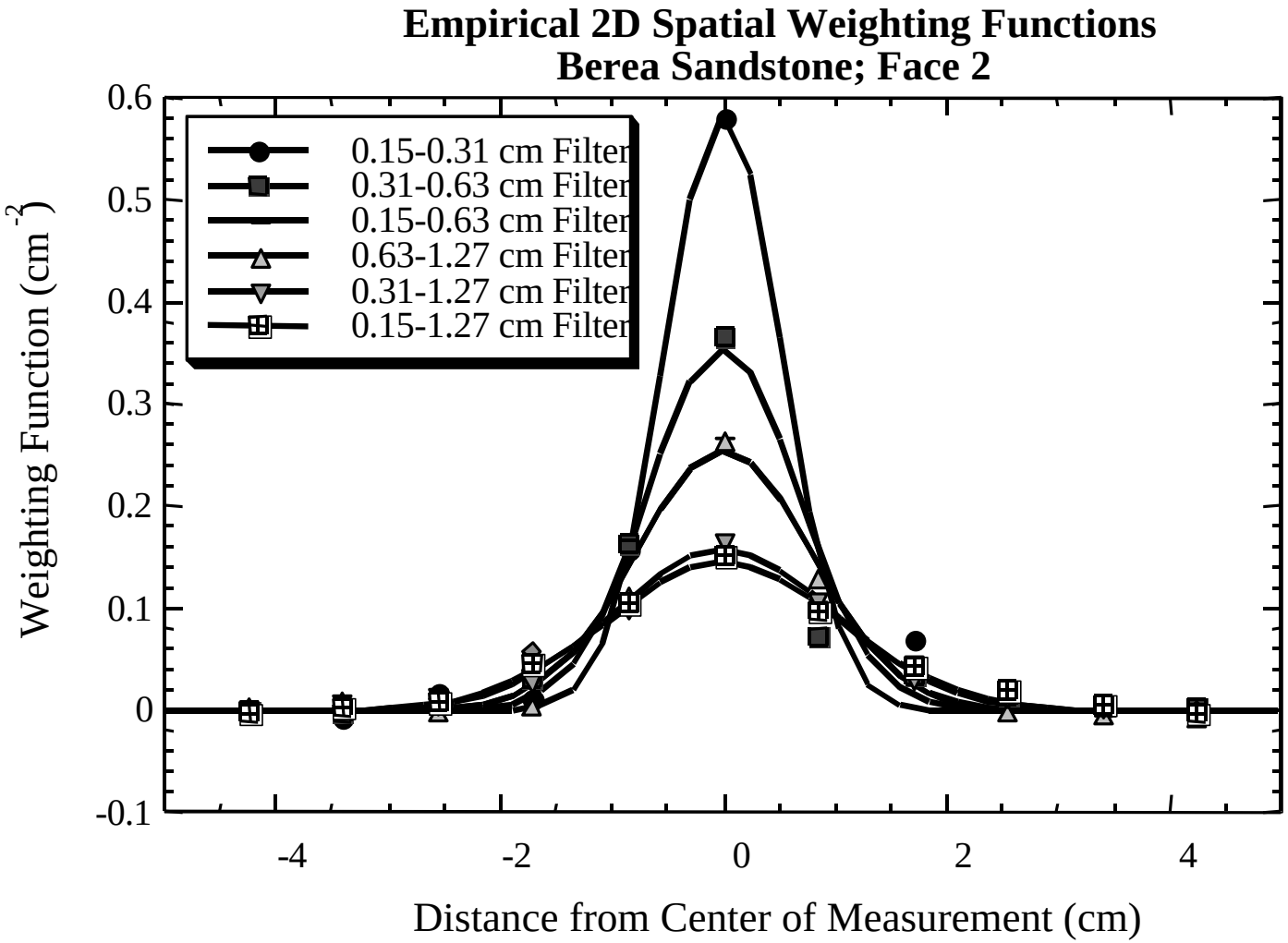
$k(r,z,\theta)$ = point scale permeability [L/T]

V = sample volume [L^3]

After Matheron, 1965; Marle, 1967; Baveye & Sposito, 1984; Cushman, 1984; Desbarats, 1992; Tidwell et. al, 1999, others. ω = 0 case not shown.

Calculating Filter Functions

- Two approaches
  - Experimental methods,
    - For example, using many measurements taken at several different scales (Tidwell et al, 1999).
  - Theoretical method,
    - New (Wilson and Aronson, 1999).
    - Uses adjoint state sensitivity analysis.
    - Can be applied to other instruments.


Empirical 2D Spatial Weighting Functions
Berea Sandstone; Face 2
0.15-0.31 cm Filter
0.31-0.63 cm Filter
0.15-0.63 cm Filter
0.63-1.27 cm Filter
0.31-1.27 cm Filter
0.15-1.27 cm Filter
Weighting Function (cm^{-2})
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-4
-2
0
2
4
Distance from Center of Measurement (cm)

Calculating Filter Functions

- Two approaches
  - experimental methods,
    - using many measurements taken at several different scales (Tidwell et al, 1999)
  - <u>theoretical method</u>
    - new (Wilson and Aronson, 1999)
    - uses adjoint state sensitivity analysis
    - can be used for any instrument

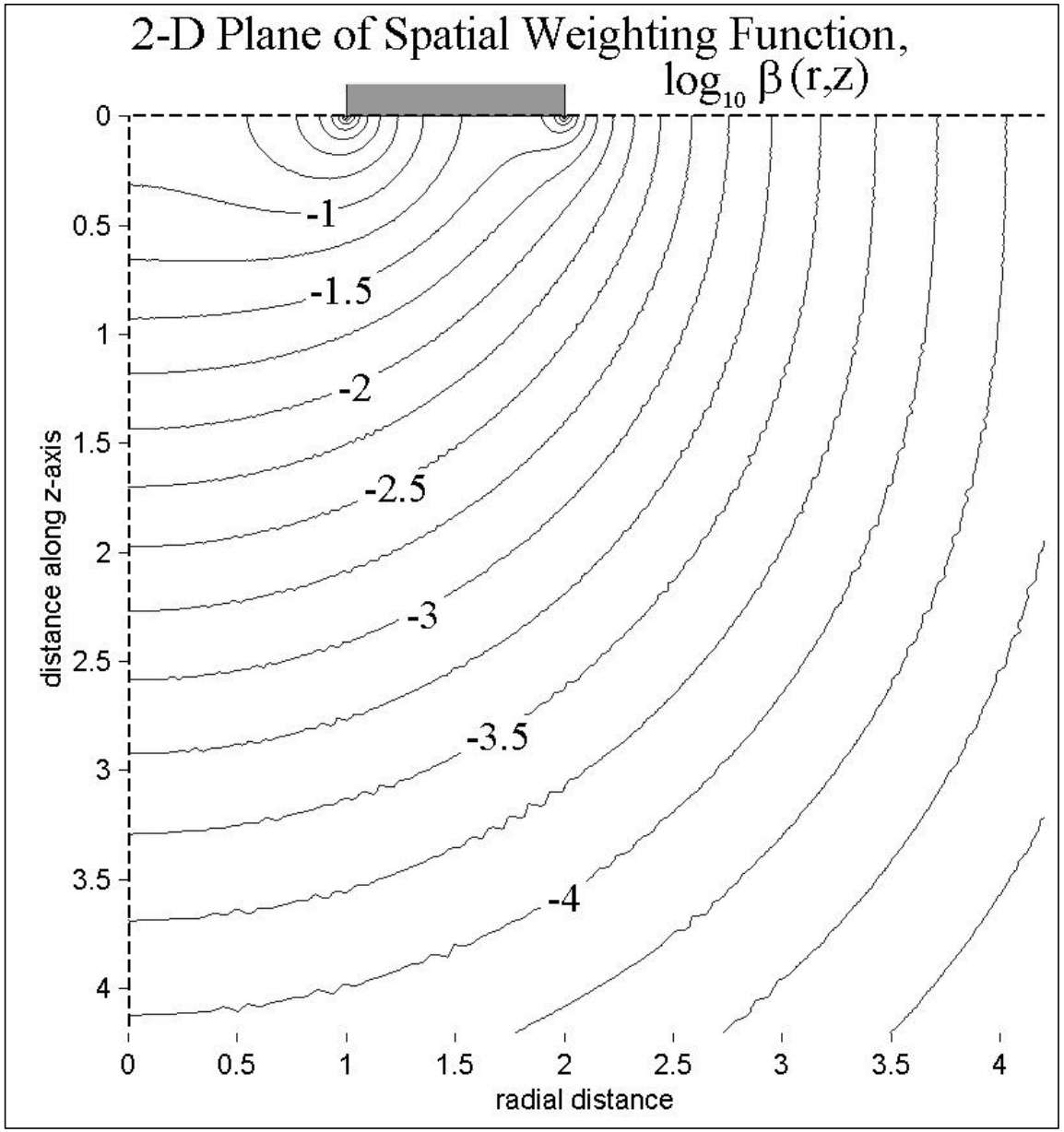
Theoretical 3D POINT WEIGHTS

Weight greater under the tip seal

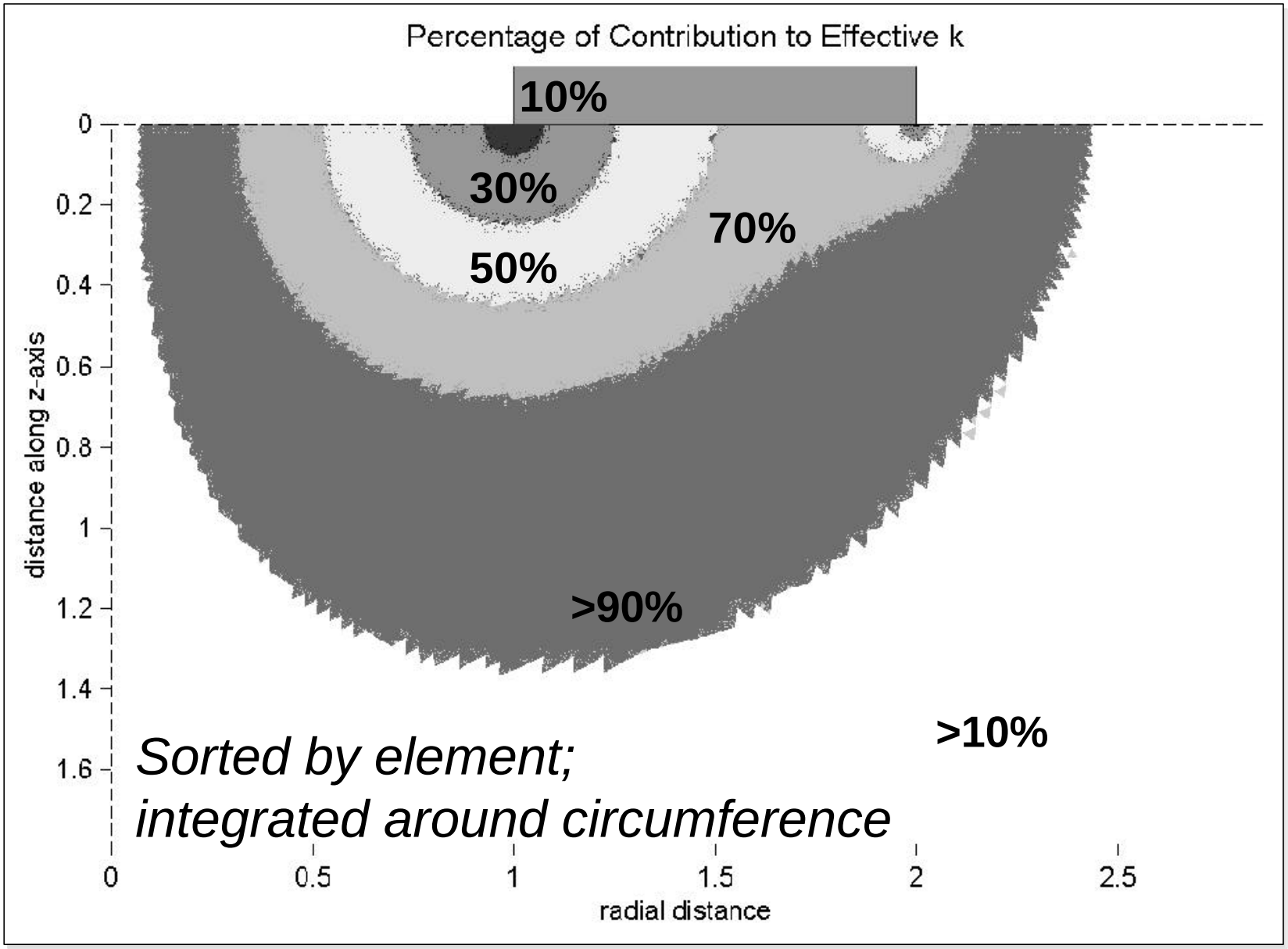
Weight greatest at inner edge, then outer edge.

Less weight along centerline

Weight drops off logarithmically



Relative Contribution



Weighting Functions

- **Indicate that**
  - **the region directly beneath the inner tip seal no-flow boundary makes the greatest contribution to the measurement.**
  - **95% of the total weight is contained in a right cylinder within a radius equal to 2.3 times the inner tip seal radius (95% inside 2.3xa)**
  - **In good agreement with previous published indirect numerical and experimental observations.**

For saturated properties we can (mostly) satisfy criteria:

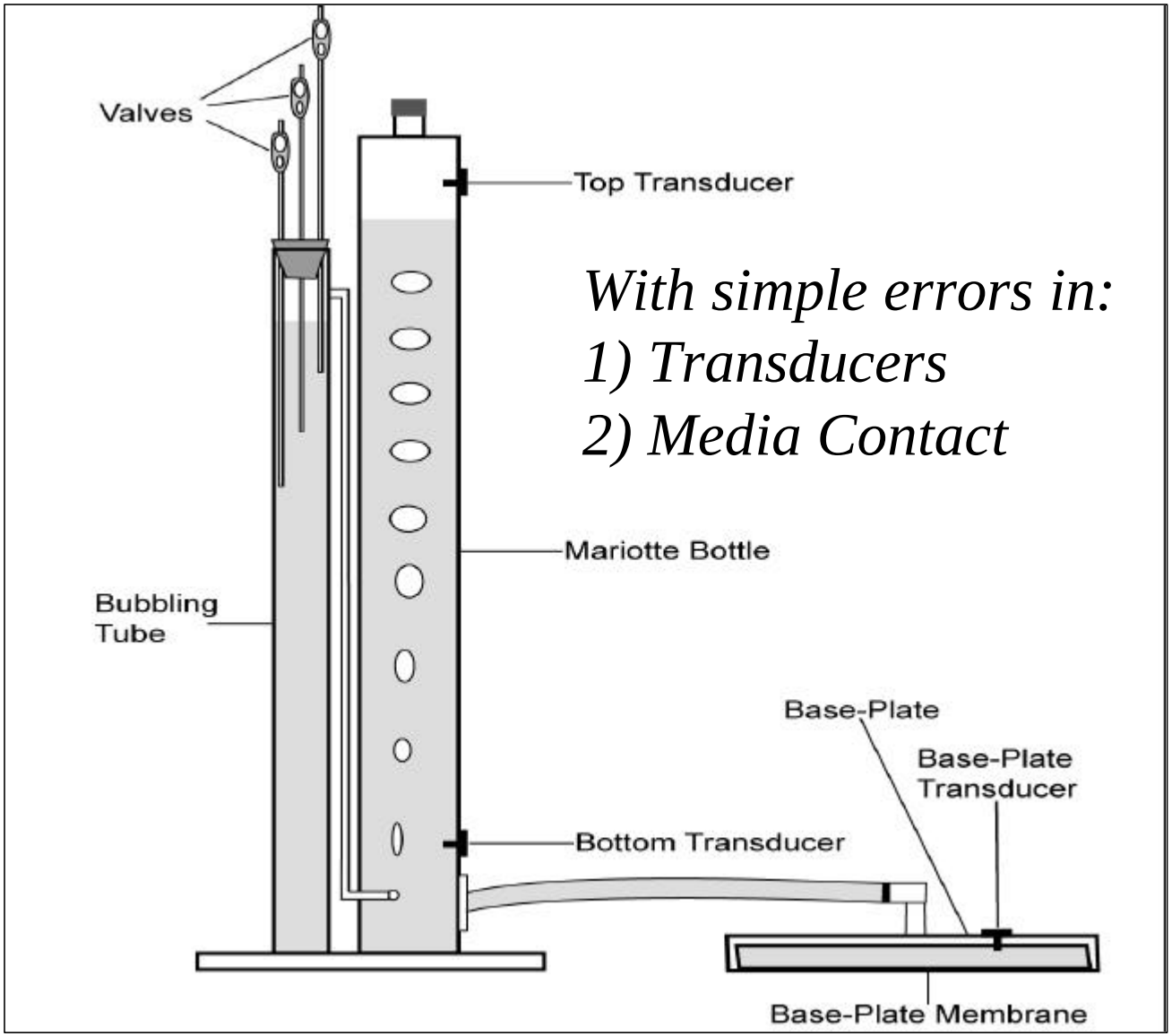
- **rapid** measurements; small sample volume
- **low cost** per data point
- **accurate** *(unbiased)* spatial statistics
  - measurements should accurately reflect the spatial variation of properties between sampled locations,
- **appropriate** instrument range

Although we have to deal with the non-uniform spatial filter function when interpreting results.

What about relative perm, k_r ?

- We've (Holt, Wilson, Glass)
  - evaluated standard instruments & methods, and
  - designed new tools.
- Let's look at the tension infiltrometer,
  - Most common field instrument.
  - Use error propagation (Holt et al., 2000)
    - to consider the effects of instrument bias
    - recalling that is a much more non-linear instrument.

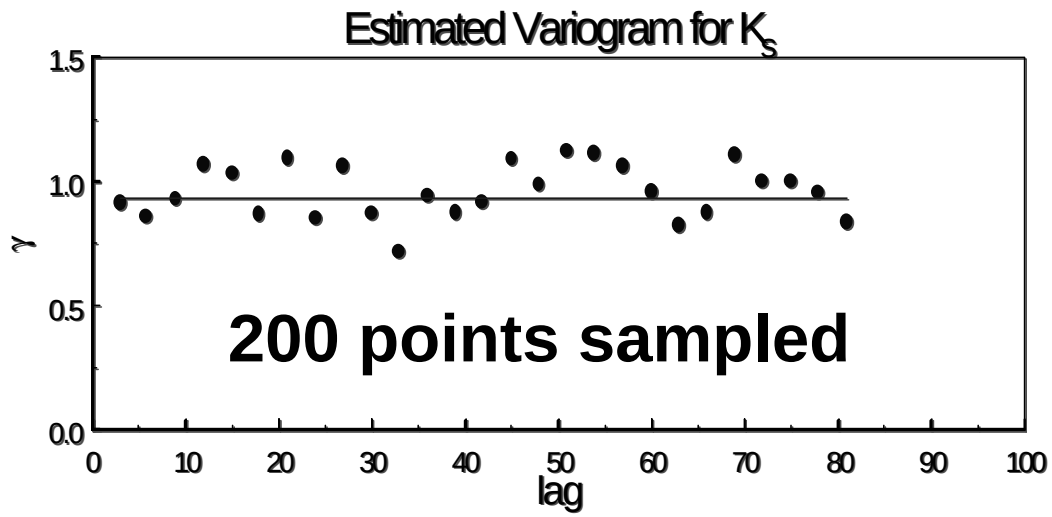
Consider the tension infiltrometer



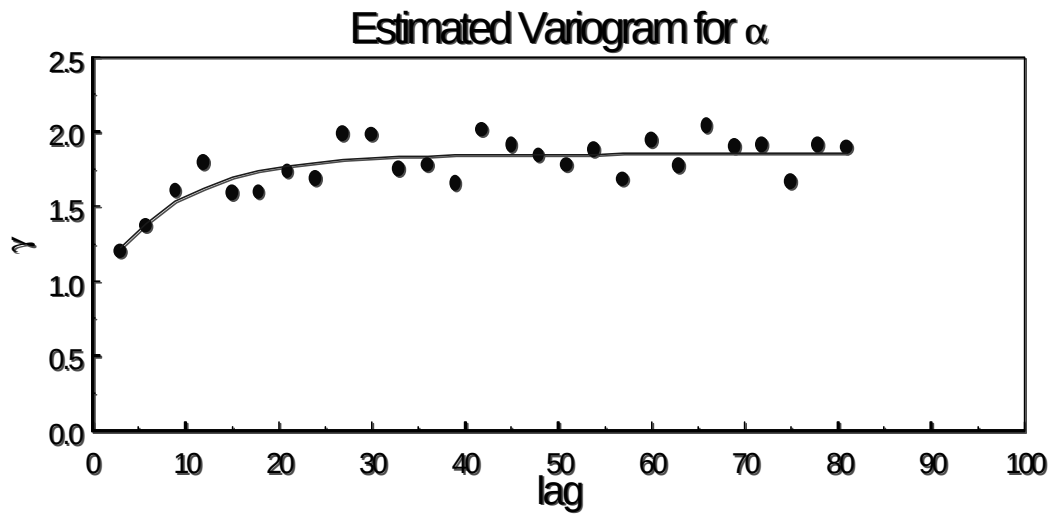
With simple errors in:
1) Transducers
2) Media Contact

Are these variograms real, or do they reflect spatial statistical bias due to an instrument bias?

Saturated Hydraulic Conductivity, K_s

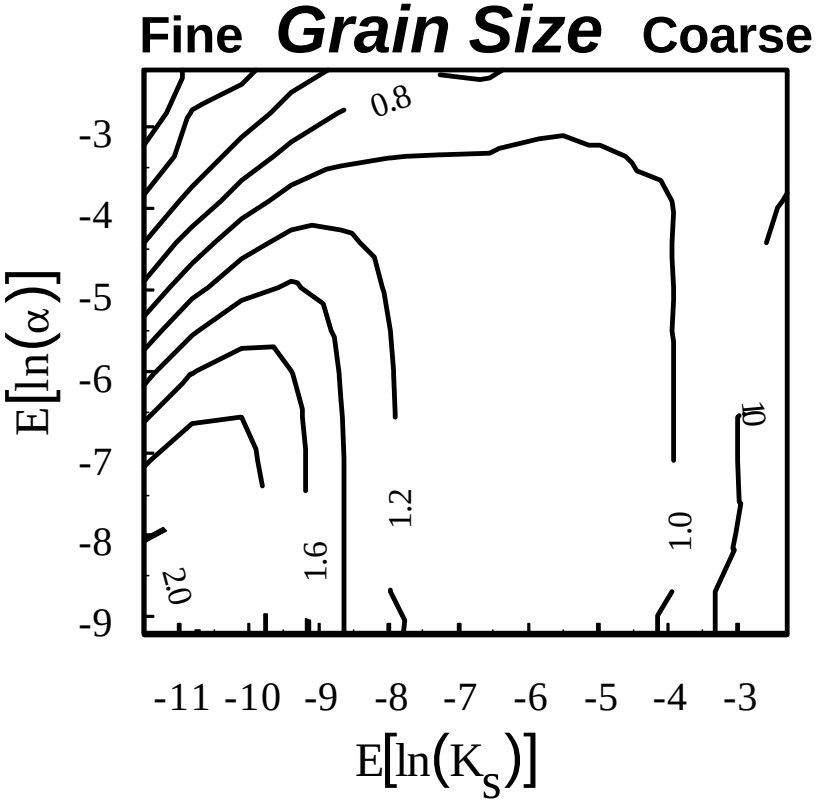


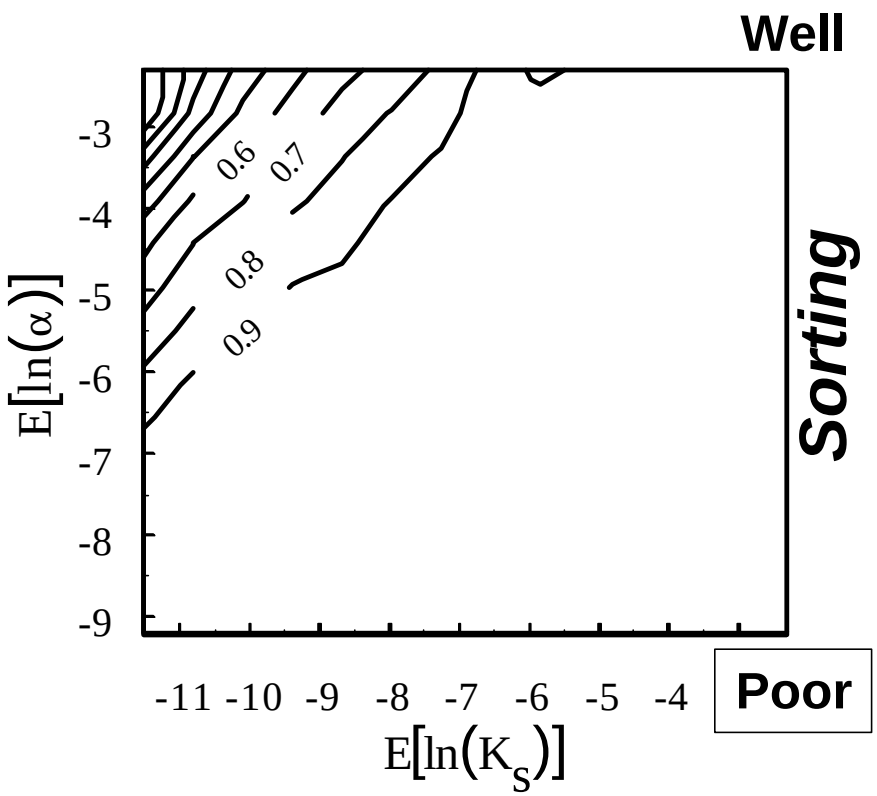
Power α in exponential k_r model



Observation errors cause spatial bias in variogram model parameters

(221 Separate Monte Carlo Simulations over Parameter Space)



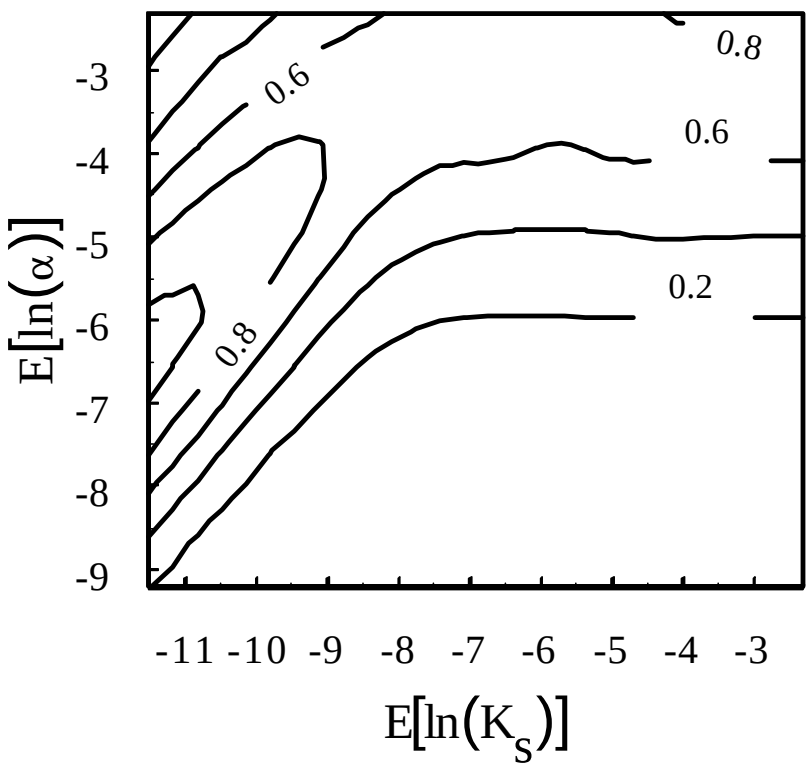


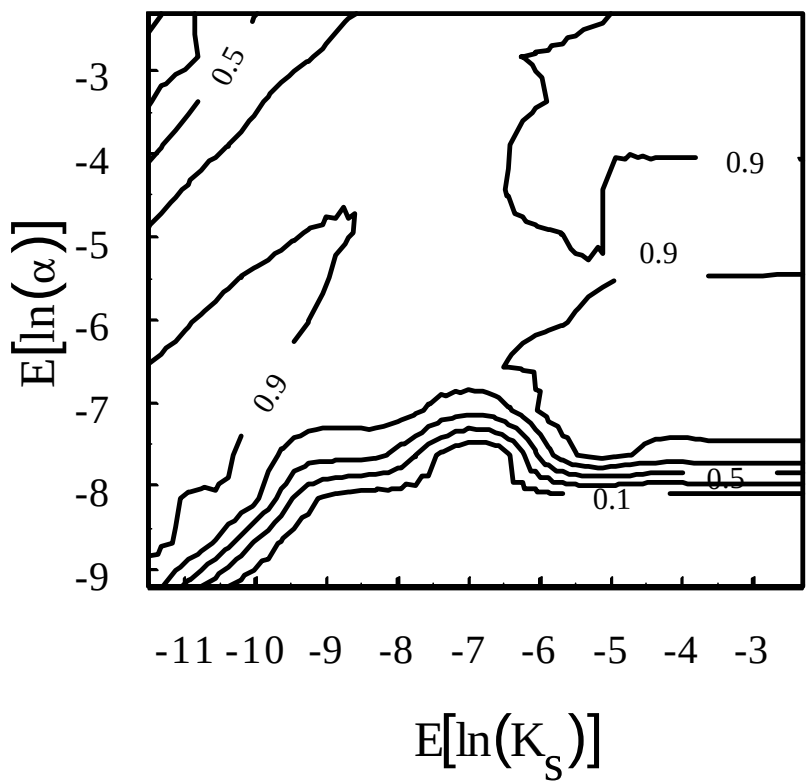
Model variance for ln(α): OVERESTIMATED

Correlation length for ln(α): UNDERESTIMATED

(from Holt et al., 2000)

Addition of inversion model error changes the spatial bias





Model variance for ln(α): UNDERESTIMATED

Correlation length for ln(α): UNDERESTIMATED

(from Holt et al., 2000)

For unsaturated properties we cannot satisfy criteria:

- **rapid** measurements are difficult
- **cost** per data point is not low
- spatial statistics are **not accurate**
  - they are spatially biased, because of non-linearity
  - measurements do not reflect the spatial variation of properties between sampled locations,
- instrument ranges are **limited**

We need alternatives.

Alternative measurements:

Estimate scaling parameters
using surrogate methods. (Holt & Glass)

- Measure parameters that scale pressure-saturation and k_r curves
  - eg, saturated hydraulic conductivity an d air-entry pressure

- Example instrument: modified mini-permeamemter
  - eg, add water-flow apparatus; measure air-entry pressure

Alternative description of spatial variability:

Replace continuous field with indicators. (Holt)

- Examples of indicators:
  - cutoffs (e.g., the median) of a continuous field, and
  - distinct (discrete) architectural elements or facies.
- Preliminary studies suggest
  - statistics of indicators are more accurately estimated,
  - even in the presence of significant instrument noise and bias.

REFERENCES:

Davis, J.M., J.L. Wilson, F.M. Phillips, and M.B. Gotkowitz, “Relationship between Fluvial Bounding Surfaces and the Permeability Correlation Structure," Water Resources Research, Vol. 33, No. 8, pp. 1843-1854, 1997.

Davis, J.M., J.L. Wilson and F.M. Phillips, “A Portable Air-Minipermeameter for Rapid In-Situ Field Measurements," Ground Water, Vol. 32, No. 2, pp. 258-266, 1994.

Davis, J.M., R. Lohman, F.M. Phillips, J.L. Wilson, and D. Love, “Architecture of the Sierra Ladrones Formation, Central New Mexico: Depositonal Controls on the Permeability Correlation Structure," Geological Society of America Bulletin, Vol. 105, No. 8, pp. 998-1007, 1993.

DeFlaun, M.F., C.J. Murray, W. Holben, T. Schreibe, A. Mills, T. Ginn, T., Griffin, E. Majer, and J.L. Wilson, "Preliminary Observations on Bacterial Transport in a Coastal Plain Aquifer," FEMS Microbiology Reviews, Vol. 20, pp. 473-487, 1997.

Holt, R.M., J.L. Wilson, and R.G.Glass, “Spatial Bias in Field-Estimated Unsaturated Hydraulic Properties,” in preparation for submittal to Water Resources Research, January, 2000. (Presented at Fall AGU, 1998.)

Kerr, G., and J.L. Wilson, “Air Minipermeameter, a New Solution Method for Axisymmetric Mixed Boundary Value Problems,” in preparation for submittal to Water Resources Research, January, 2000.

Sigda, J., L.B. Goodwin, P.S. Mozley and J.L. Wilson, , “Permeability Alteration in Small Displacement Faults in Poorly Lithofied Sediments: Rio Grande Rift, Central New Mexico," Faults and Fluid Flow, L. Goodwin and W. Haneberg (eds), AGU Monograph 113, American Geophyscial Union, Washington DC, pp. 51-68, 1999.

Tidwell, V.C. and J.L. Wilson, “Permeability Upscaling Measured on a Block of Berea Sandstone: Results and Interpretation," Mathematical Geology, Vol 31, no. 7, pp. 749-769, 1999.

Tidwell, V.C. and J.L. Wilson, “Upscaling Experiments Conducted on a Block of Volcanic Tuff: Results for a Bimodal Permeability Distribution," Water Resources Research, Vol. 35, No. 11, p. 3375-3387, 1999.

Tidwell, V.C., A.L. Gutjahr and J.L. Wilson, “What Does an Instrument Measure? Empirical Spatial Weighting Functions," Water Resources Research, Vol. 35, No. 1, p. 43, 1999.

Tidwell, V.C. and J.L. Wilson, “Laboratory Measurement of Permeability Upscaling: Results for the Topopah Spring Member of the Paintbrush Tuff," Tuff Handbook, UNESCO, New York, 1998.

Tidwell, V.C. and J.L. Wilson, “Laboratory Method for Investigating Permeability Upscaling," Water Resources Research, Vol. 33, No. 7, pp. 1607-1616, 1997.

Tidwell, V.C. and J.L. Wilson, “A Comparison of Simple Upscaling Models with Multisupport Permeability Data Measured on a Block of Berea Sandstone," Proceedings of the Third Annual Conf. on the Int'l Assoc. for Mathematical Geology, V. Pawlowsky-Glahn (Ed.),Vol. 2, pp. 737-742, CIMNE, Barcelona, 1997.

Wilson, J.L. and E.C. Aronson, “Calculating Instrument Spatial Filter Functions:
Illustrated for the Gas Minipermeameter,” in preparation for submittal to Water Resources Research, January, 2000. (Presented at Fall AGU, 1999.