Lattice Boltzmann Methods Applied to Three-Dimensional Virtual Cores Constructed from Digital Optical Borehole Images of a Carbonate Karst Aquifer

Jeff Lee[1]

Mike Sukop[1]

Kevin Cunningham[2]

[1]Earth Sciences, Florida International University
[2]United States Geological Survey, Ft. Lauderdale

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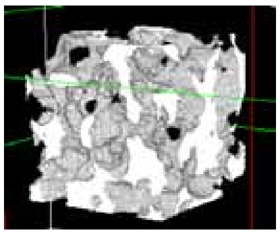
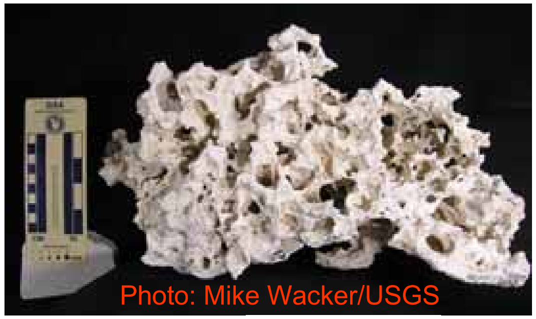
Karst

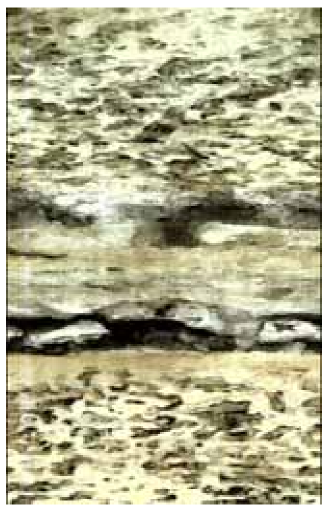
7.5 cm



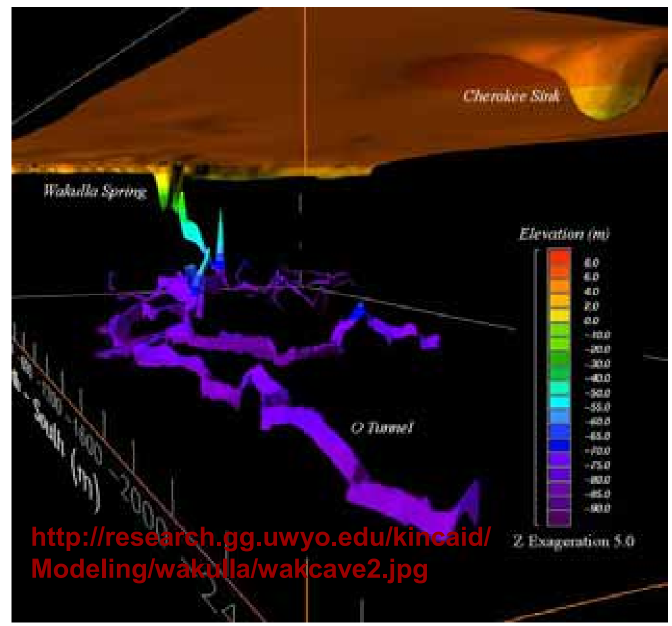


30 cm

1.7 m



17 m



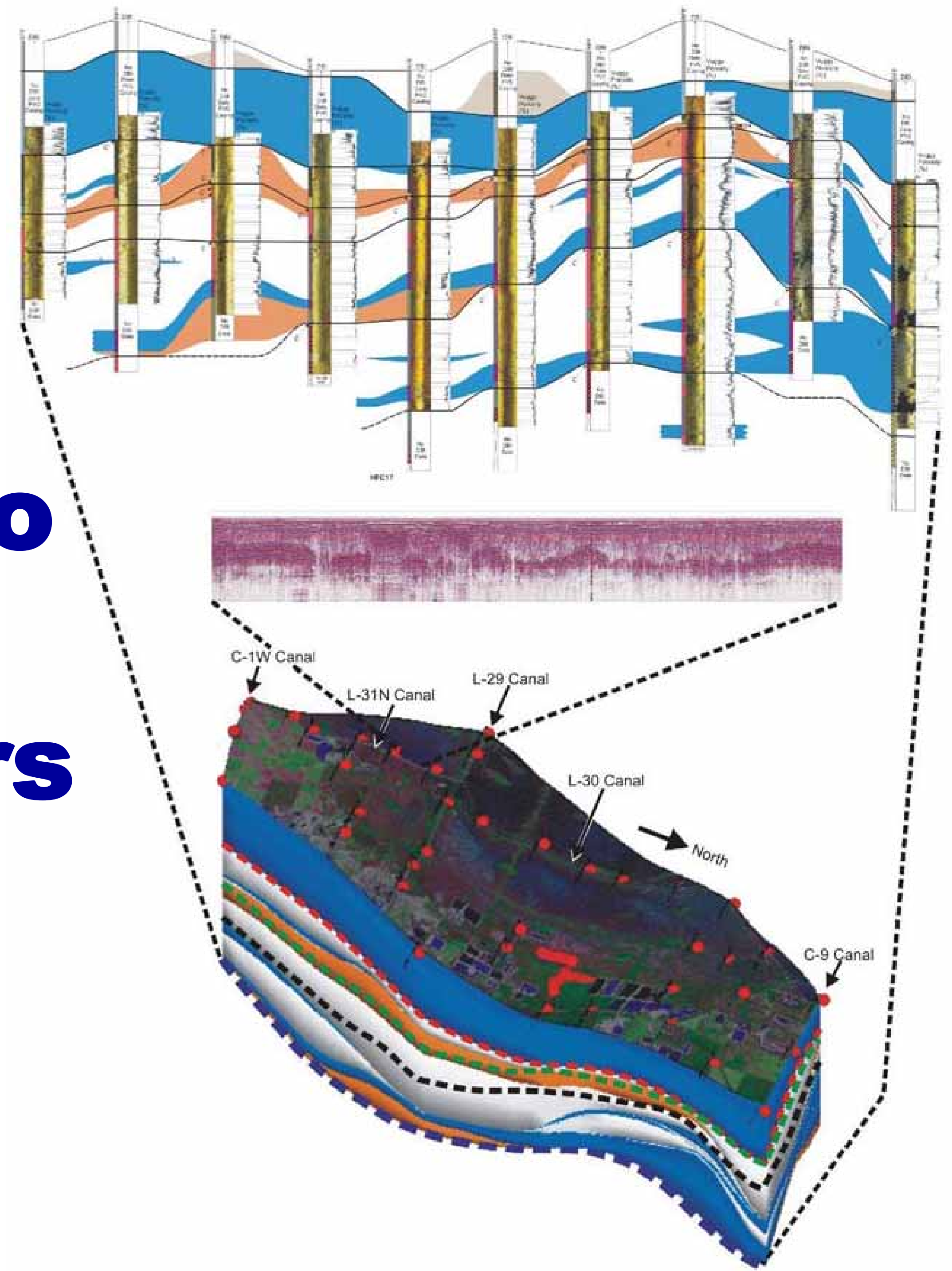
Objectives

- Project objectives:
  - Simulate virtual 3-D renderings of Biscayne aquifer macropore network based on borehole image data
  - Simulate 3-D fluid flow through macropores
  - Measure intrinsic permeability of 3-D aquifer renderings at meter-plus scales
- Long-term objective:
  - Develop LBM groundwater models for non-Darcian fluid flow through karst macroporous networks

Prior Work

- Jaquet, O. and P.Y. Jeannin, 1993. Approche geostatistque du milieu karstique, Cahiers de Géostatistque, Fascicule 3, Compte-rendu des Journées de Géostatistque, 25-26 Mai 1993, Fontainbleau, pp. 77-85
  - Consider conduit density in 200 x 200 m blocks
- Tilke, P.G., D. Allen, and A. Gyllensten, 2006, Quantitative analysis of porosity heterogeniety: application of geostatistics to borehole images, Mathematical Geology 38:2, 155-173:
  - “We assume here that …there is no vertical variation in formation properties… This assumption fails in the presence of bed boundaries. Fortunately, this is not a common occurrence in the studied borehole.”

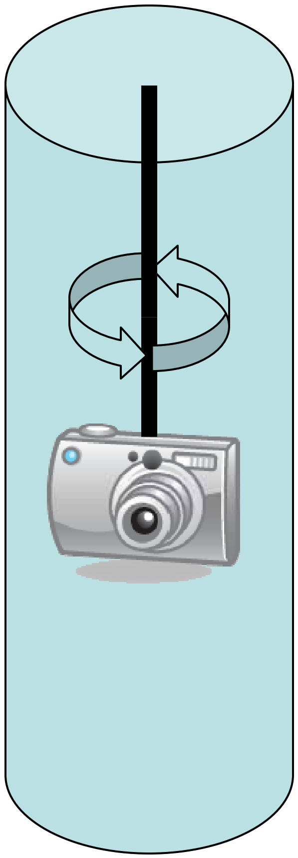
Geology to model parameters

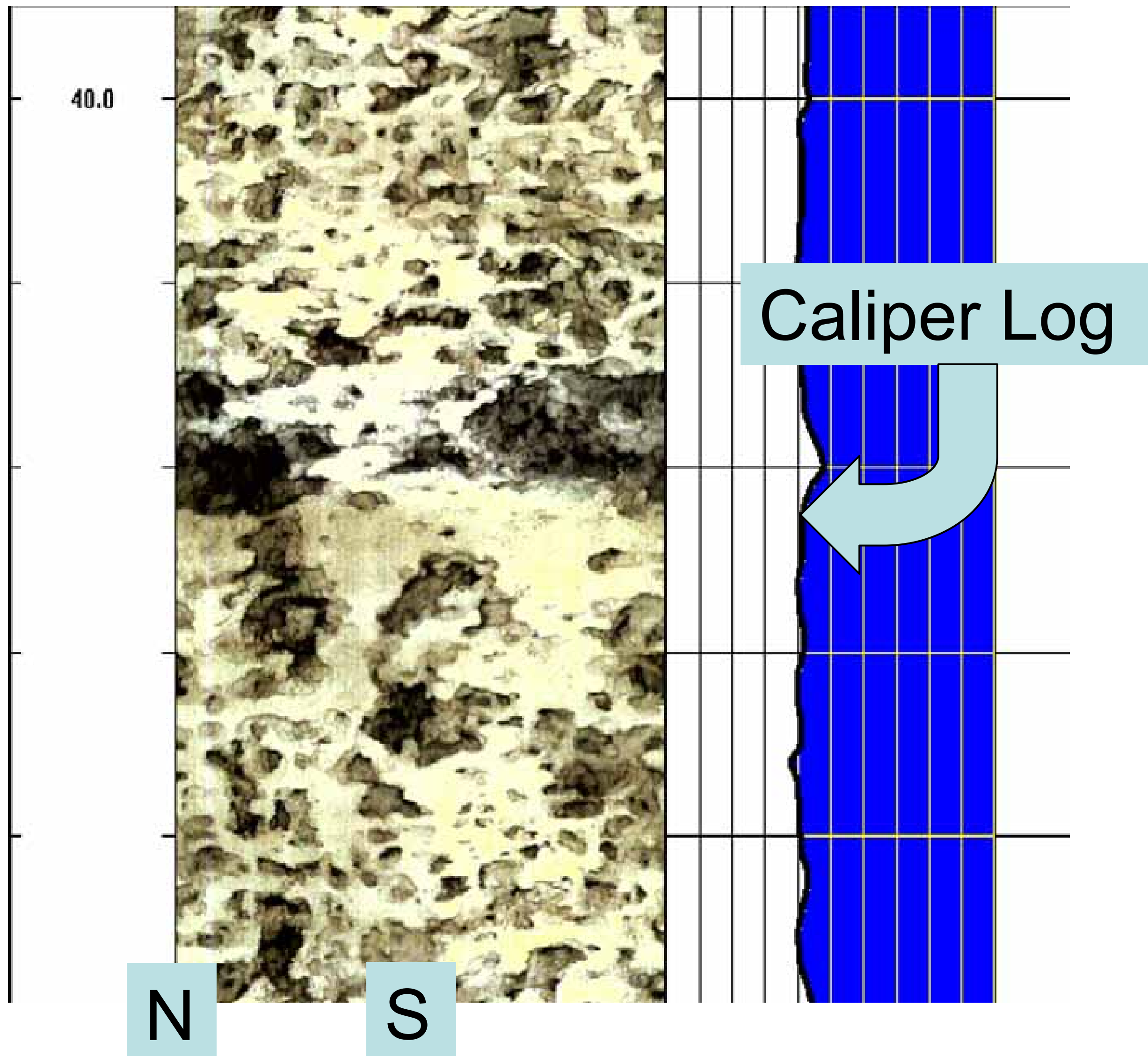


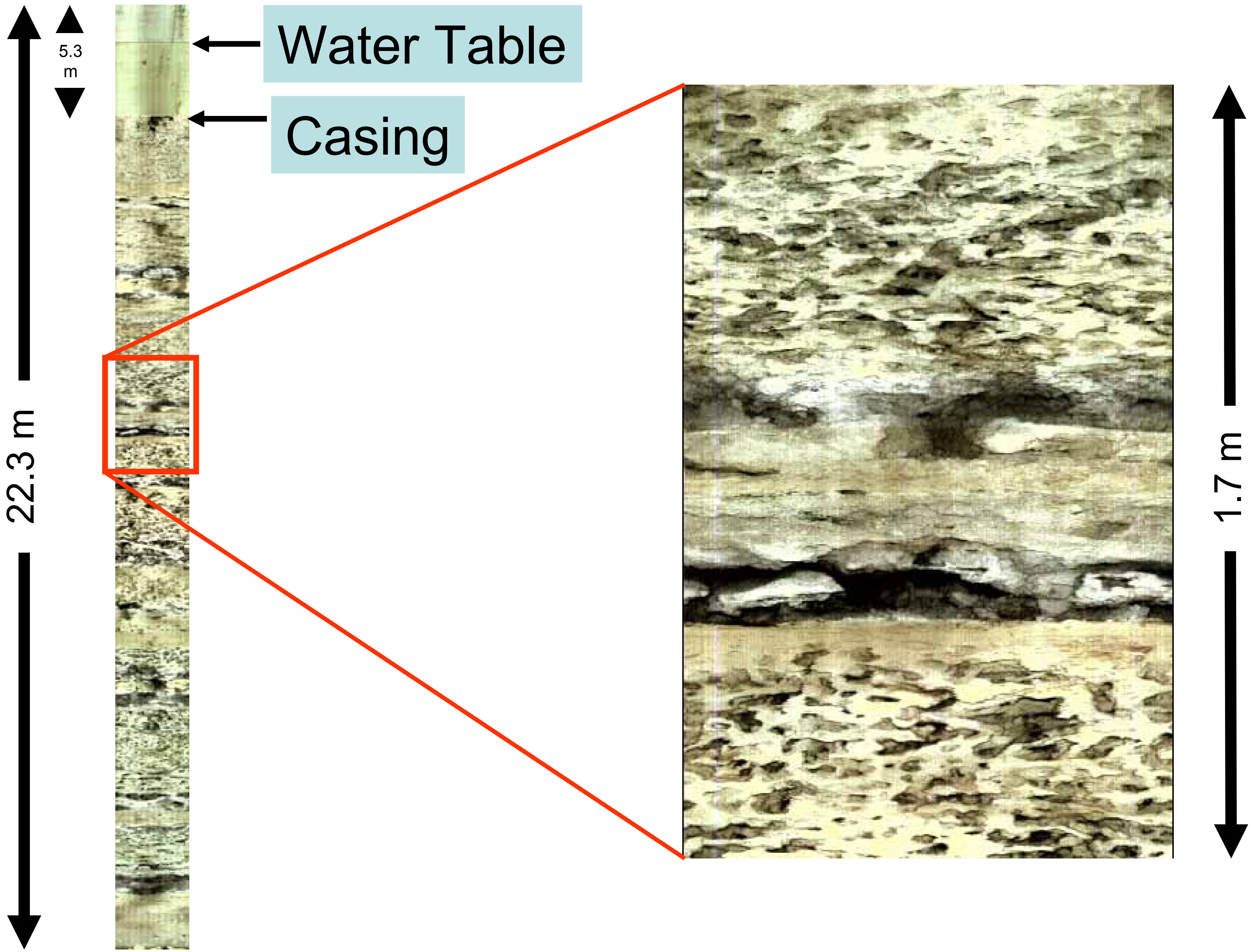
Tools

- WellCad
  - borehole imagery
- MatLab
  - RGB/grayscale/geometric
- SGeMS geostatistical software
  - map, measure, and simulate 3-D distribution of macropores and rock matrix
- 3-D LBM integrative tool: compute
  - Permeability, hydraulic conductivity
  - Scale effects
  - Non-Darcy effects

Borehole Imagery
(almost 6 M points, ~2 mm resolution)







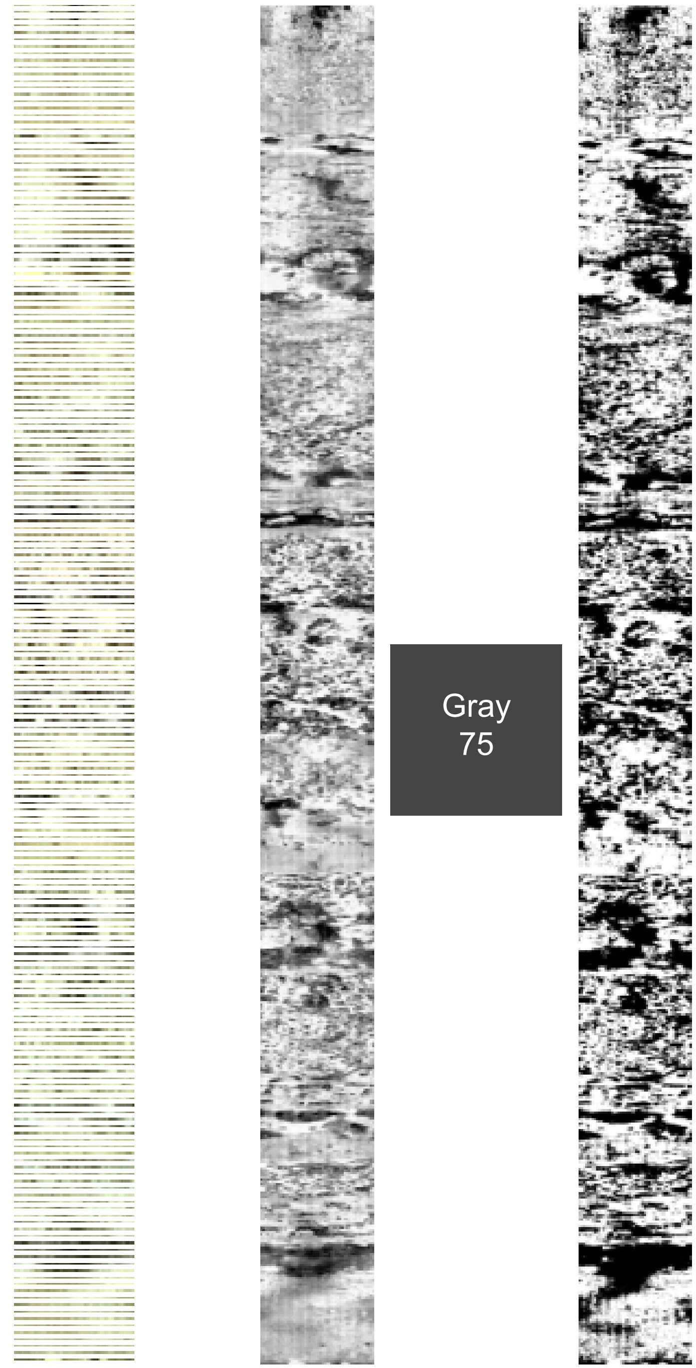
5.3 m
Water Table
Casing
22.3 m
1.7 m

RGB Data Manipulation

- Pixel RGB values from WellCad
  - RGB converted into grayscale (standard)

$$Gray = 0.3R + 0.59G + 0.11B$$

  - Threshold applied to grayscale image to obtain a black and white matrix/pore rendering

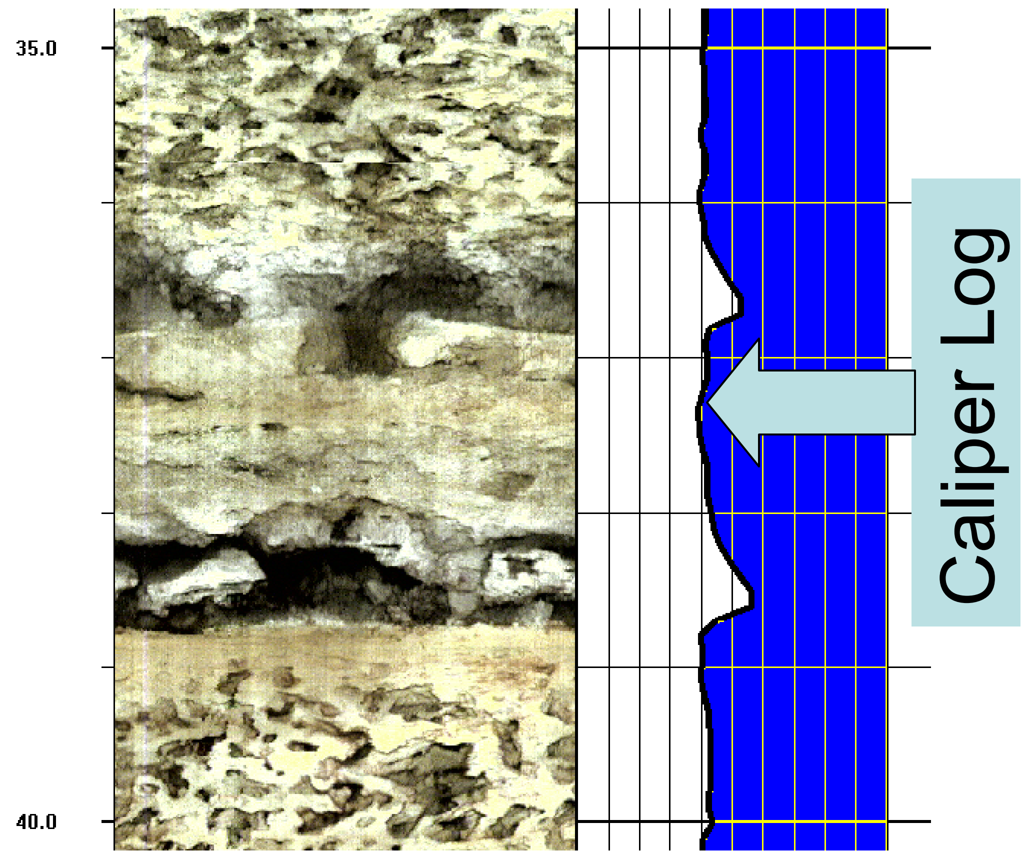


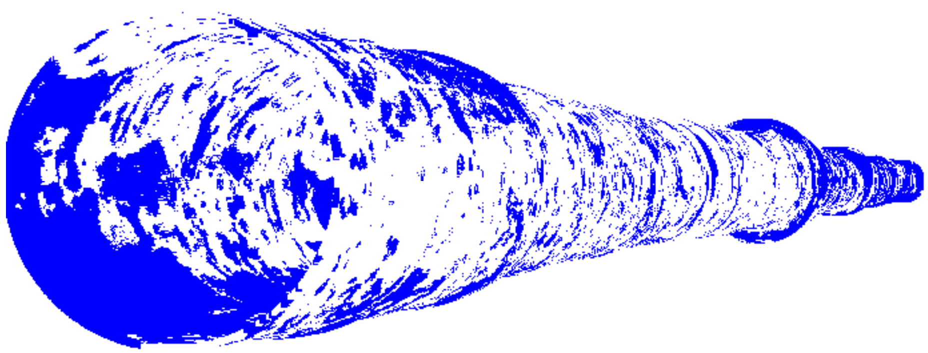
Radius interpolation and 3-D coordinate computation

- Caliper data at lower resolution
- Borehole radius computed for every pixel z coordinate
- *x*,*y* coordinates calculated:

$$x = r \sin \theta$$

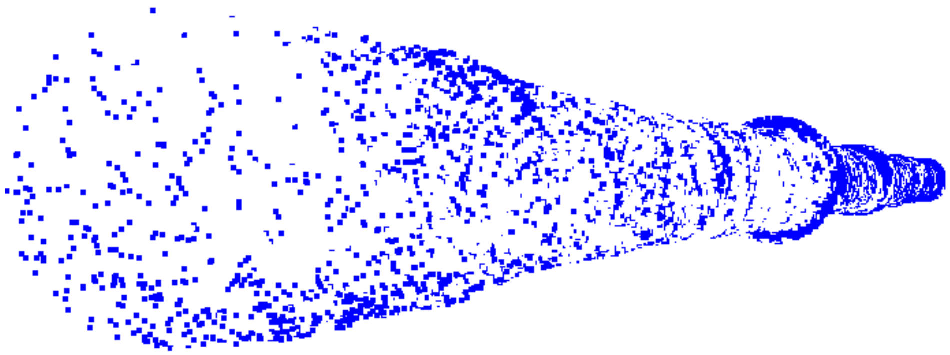
$$y = r \cos \theta$$



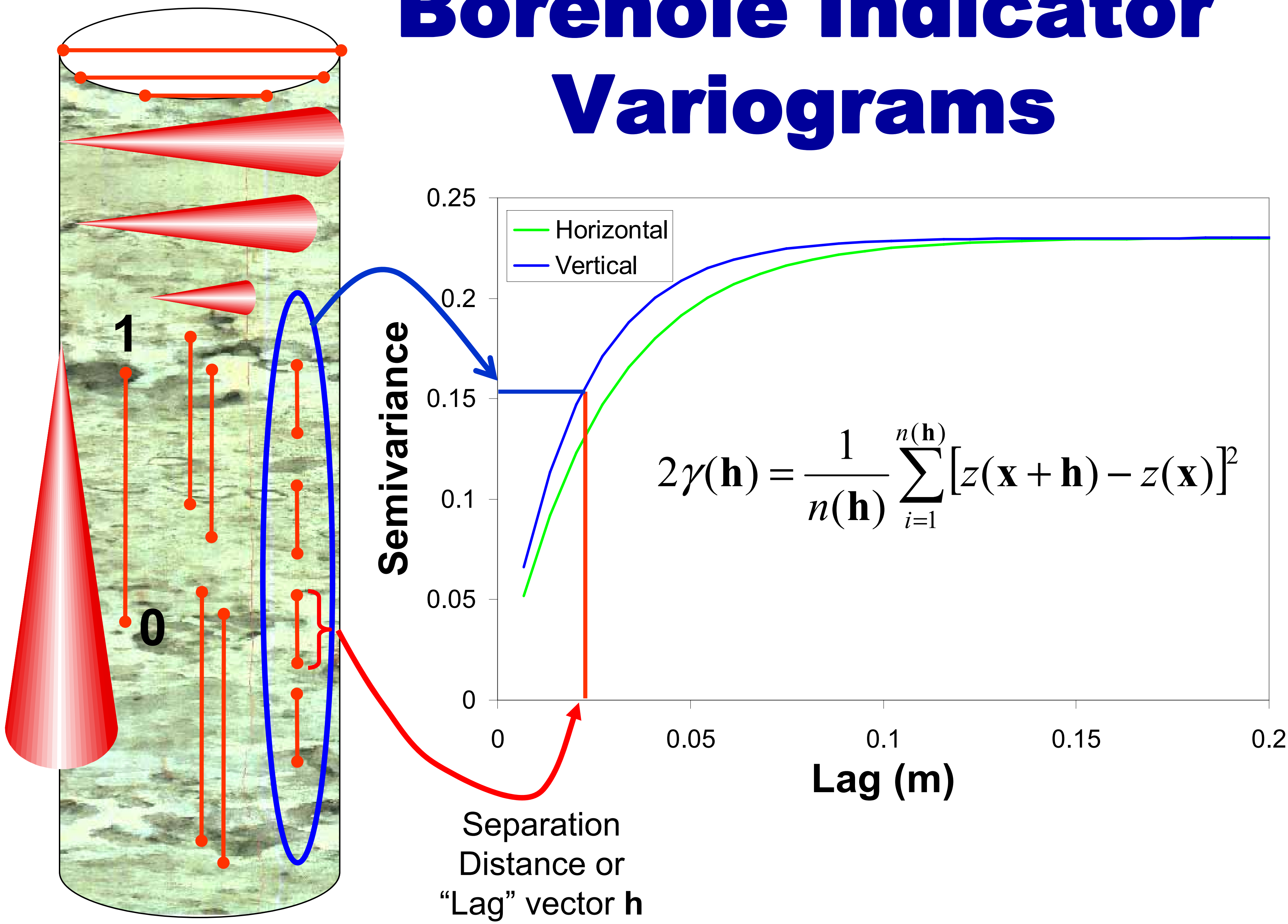


Variogram Data

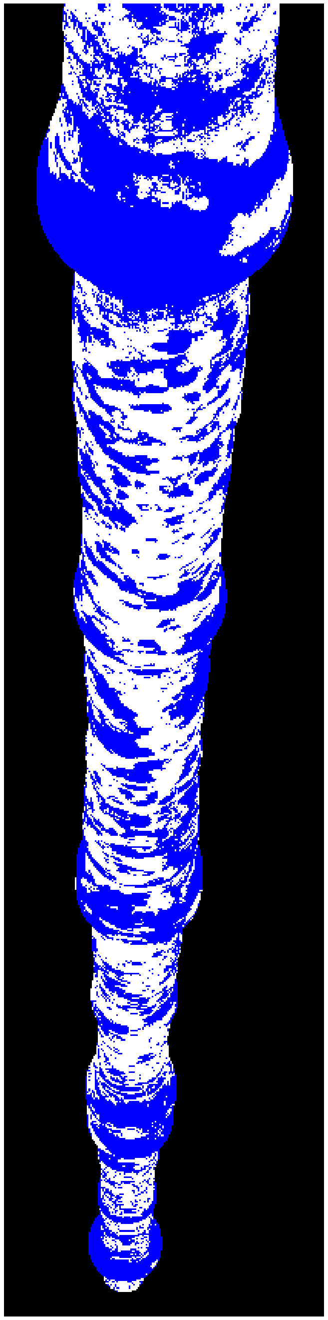
- Randomly sample 1% of original data
- 600,000 points = 1.8×10^{11} pairs!

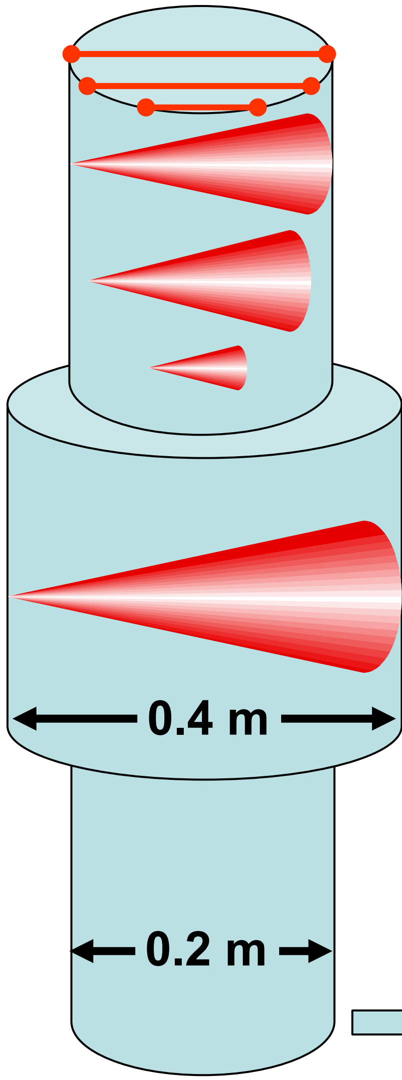


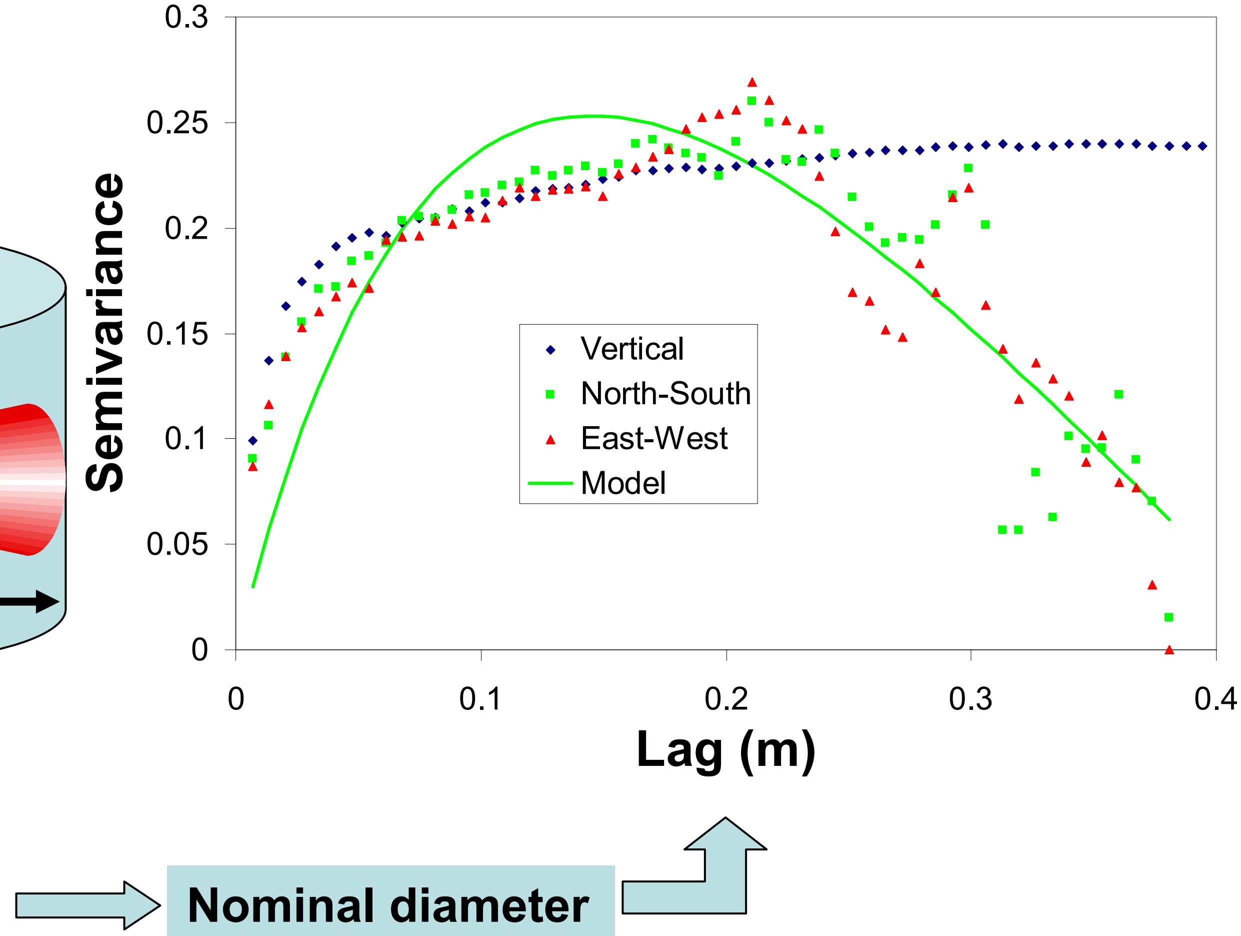
Borehole Indicator Variograms



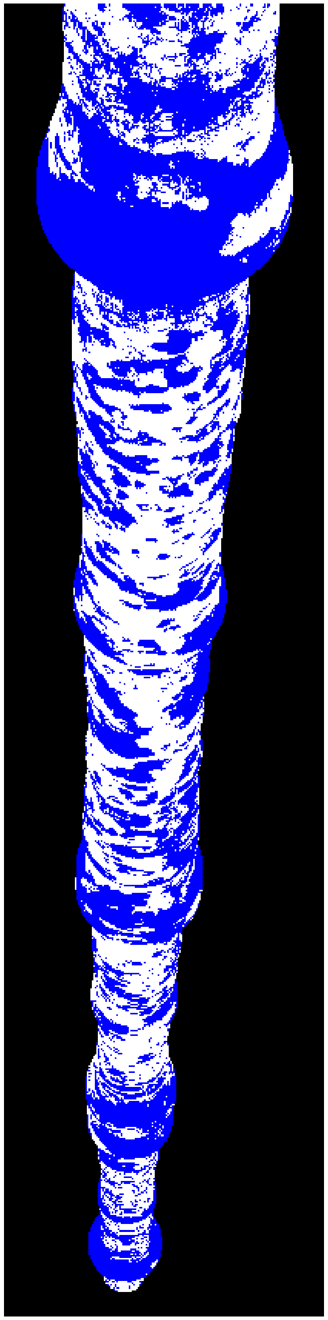
Biased Variograms

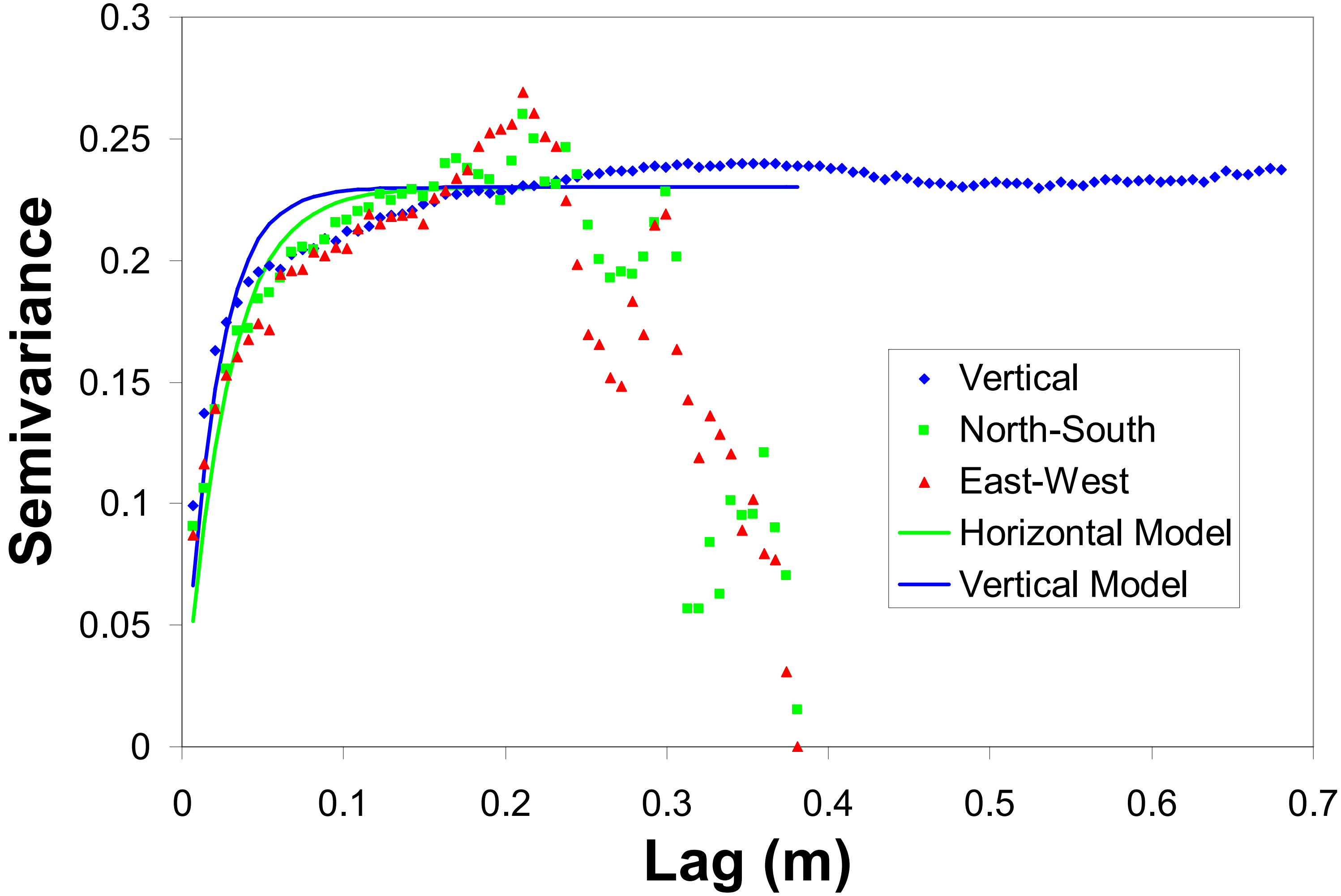






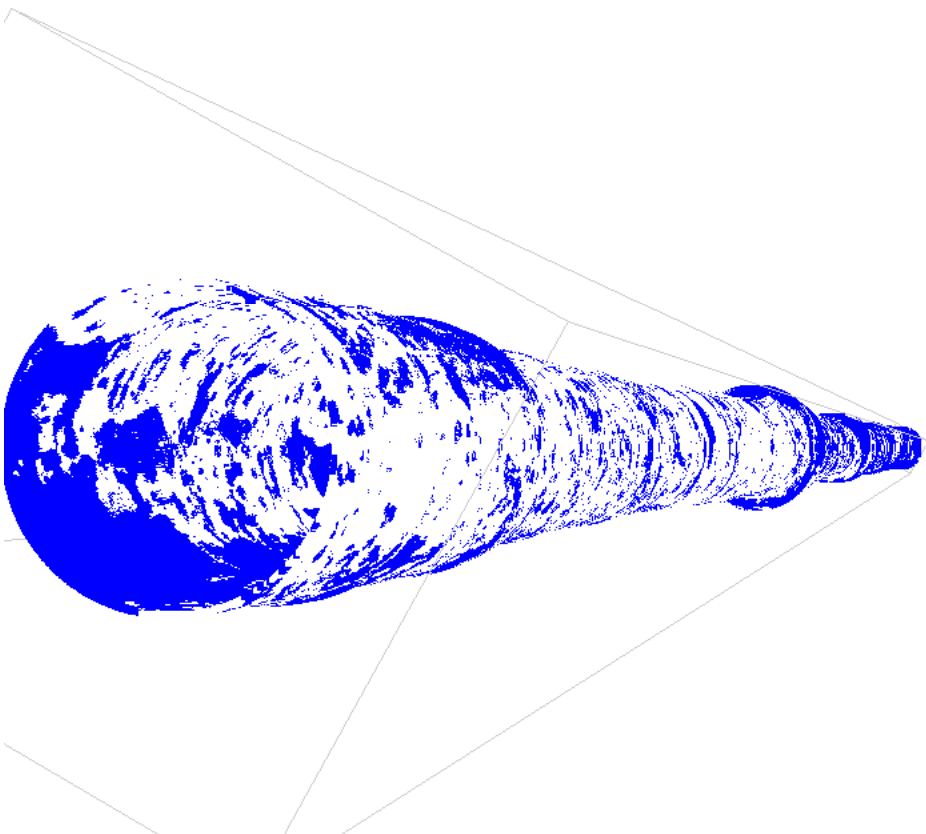
Simulation Variograms



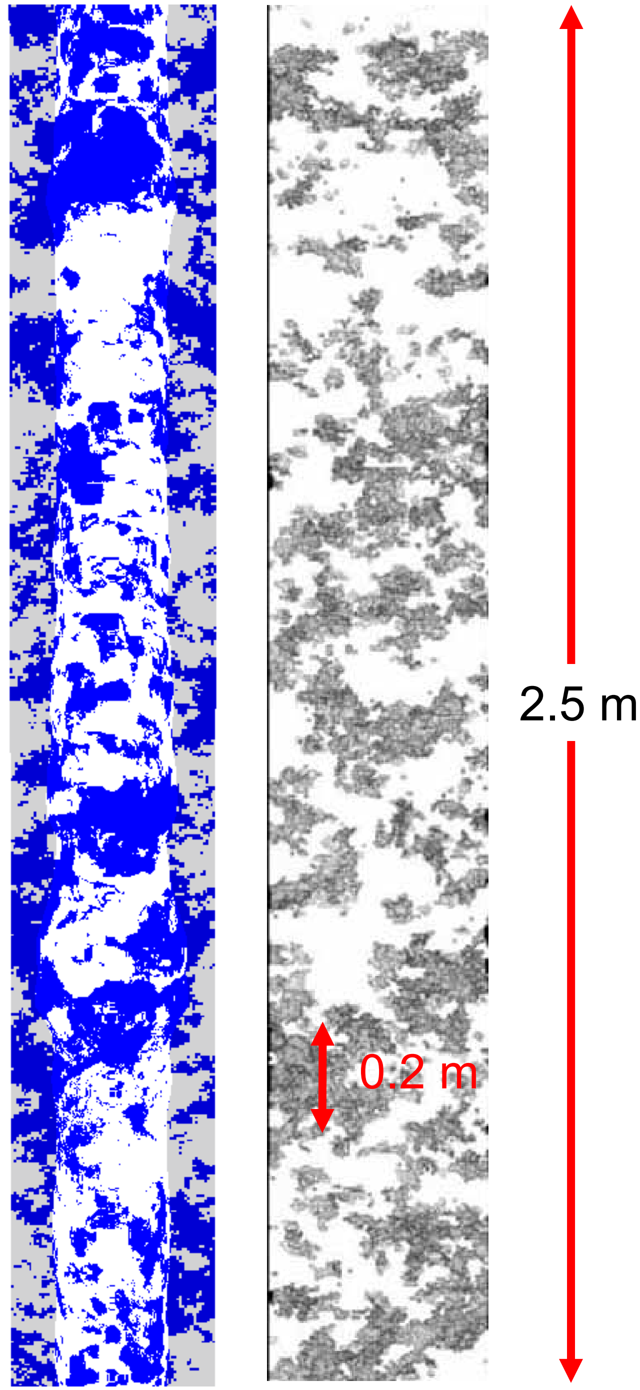


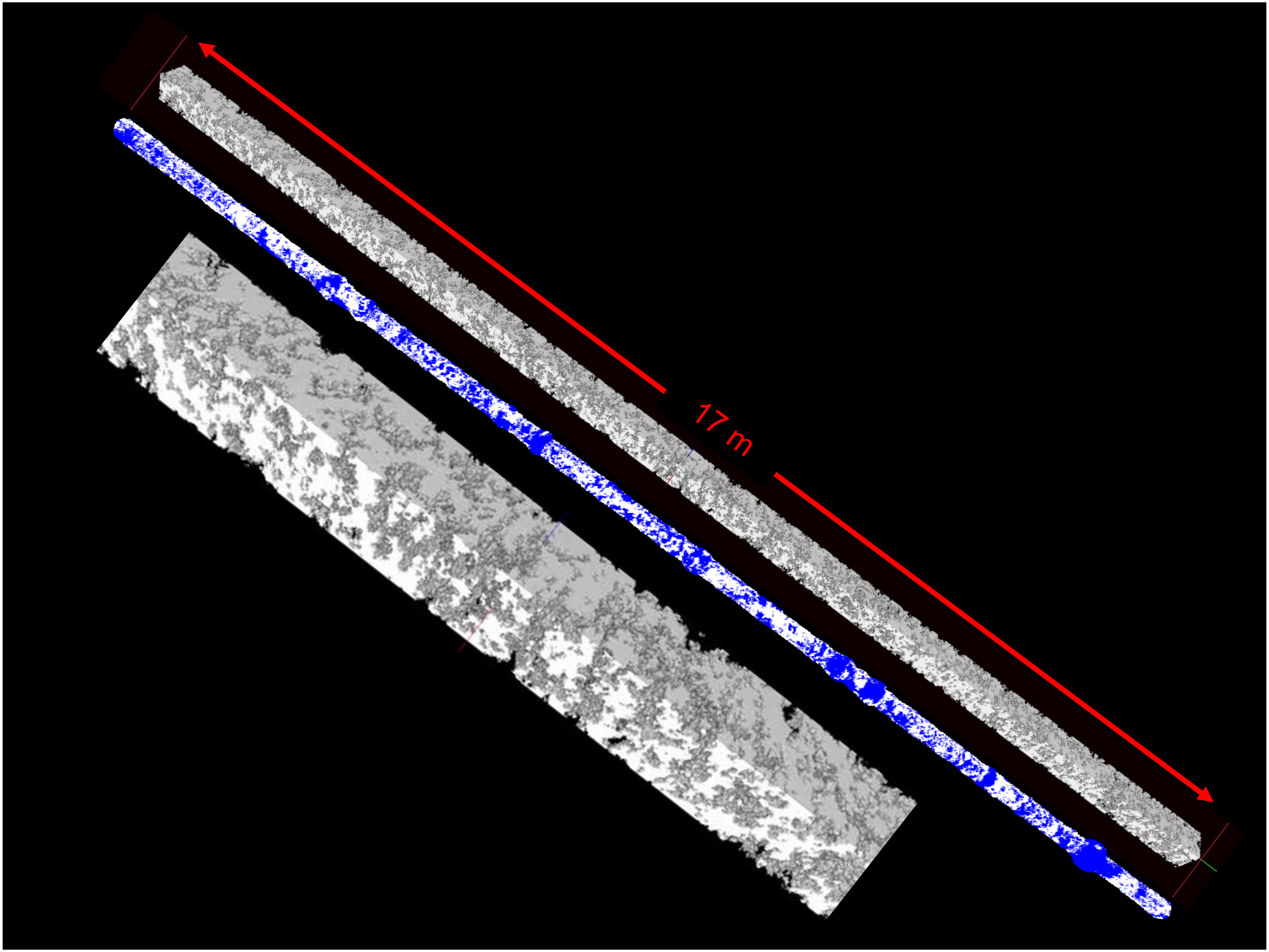
Rock Simulation

- Sequential indicator simulation
- Data honored
- Parallelepiped domain, 0.005 m resolution

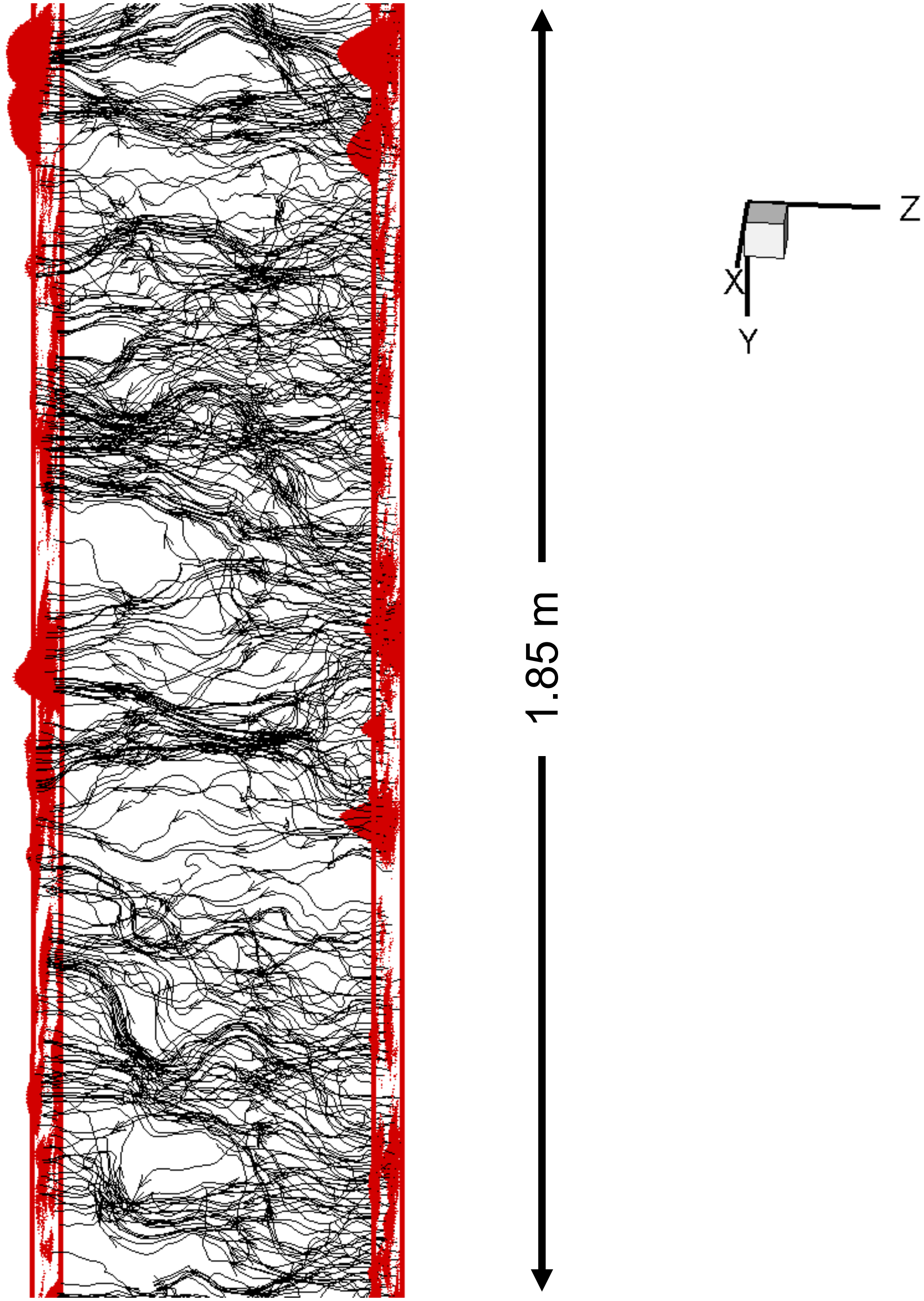


Results




17 m

Results



Results

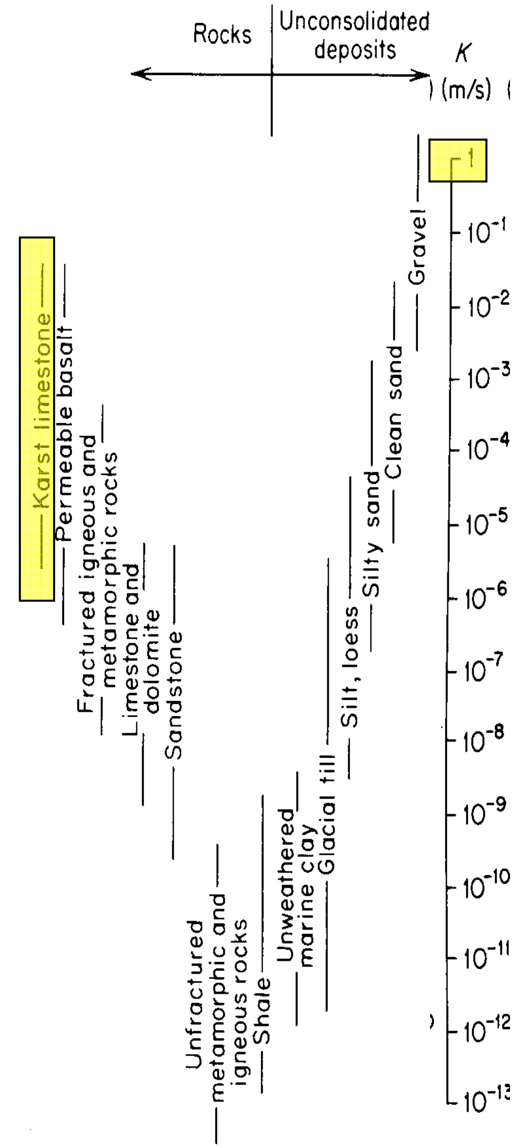
$$q = \frac{k}{\rho \nu} \frac{\Delta p}{L}$$

$$k_{physical} = k_{LBM} \left(\frac{L_{physical}}{L_{LBM}} \right)^2$$

$$K = k \frac{g}{\nu}$$

Result: 100 m/s

(much of Biscayne listed as >1000 ft/d (>0.003 m/s) (Fish and Stewart, WRI-90-4108)



Freeze and Cherry (1979) Groundwater, Prentice-Hall

Preliminary Conclusions

- Need much longer horizontal correlation length some places
  - "Non-stationary"
- Medium simulations roughly capture character of rock
- Hydraulic conductivity very high at 100 m/s