# Marine Fine-Grained Sediment Tortuosity Derived from the Analysis of Three-Dimensional Reconstructions of Organo-Clay Fabric at the Nanometer Scale*

**Jessica R. Douglas[1], Kenneth J. Curry[1], Richard H. Bennett[1,2], and Andrew Head[1]**

Search and Discovery Article #41146 (2013)**
Posted July 15, 2013

*Adapted from oral presentation given at AAPG 2013 Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 19-22, 2013


[1]The University of Southern Mississippi, Hattiesburg, MS (Jessica.Douglas@eagles.usm.edu)
[2]SEAPROBE, Inc, Picayune, MS

## Abstract

We created 3-D reconstructions of marine fine-grained sediment from serial sections and photographic mosaics obtained using a transmission electron microscope (TEM). These reconstructions show aggregations of clay domains, surrounding organic matter (OM), and "voids" where water or free gas were located prior to processing for TEM. We examined laboratory model samples with 1% OM and natural samples with high levels of OM making qualitative observations and quantitative measurements of porosity and tortuosity. Tortuosity of clay fabric is important as OM must initially be trapped in the depositional phase during early sediment diagenesis prior to becoming an OM-rich shale over geological time. Tortuosity has historically been measured at micrometer scales from 2-D electron micrographs and in some cases light optical (mm) scales by tracing a line across the X and Y planes of a micrograph around clay and organic particles and calculating the ratio of the length of that tortuous line to a straight line (shortest possible path) across the same interval. Our 3-D constructs show that structures identified as "pores" in 2-D images are actually parts of a complex matrix of channels ramifying the X, Y, and Z planes. We measured porosity and tortuosity by electronically subsampling our 3-D constructs into a series of 300 nm cubes. Porosity was measured for each cube and the orientation of each of the particles (segments of aggregates) in each cube was obtained. We used porosity and particle orientation to determine the shortest possible pathways to calculate tortuosity across a portion of the whole 3-D construct. Our technique allows us to calculate tortuosity while restricting porosity to a minimum boundary condition prior to determining the tortuous pathway. For example, using our 1% OM laboratory model sediment we measured tortuosity (ratio of measured shortest path to straight line across) through a series of 300 nm cubes with 50-100% porosity to be 1.08. Measuring tortuosity across the same sample, but restricting flow to cubes of 90-100% porosity yielded a tortuosity measure of 1.19. Tortuosity measurements can be restricted to any range of porosity that, because of the subsample cubes, corresponds to ranges of "pore" diameters none of which can exceed 300 nm. The technique currently uses data to estimate predominant particle orientation in the X, Y, or Z plane of the construct, but approximations of azimuth and inclination can be applied, thus refining the model.

# Marine Fine-Grained Sediment Tortuosity Derived from the Analysis of Three-Dimensional Reconstructions of Organo-Clay Fabric at the Nanometer Scale

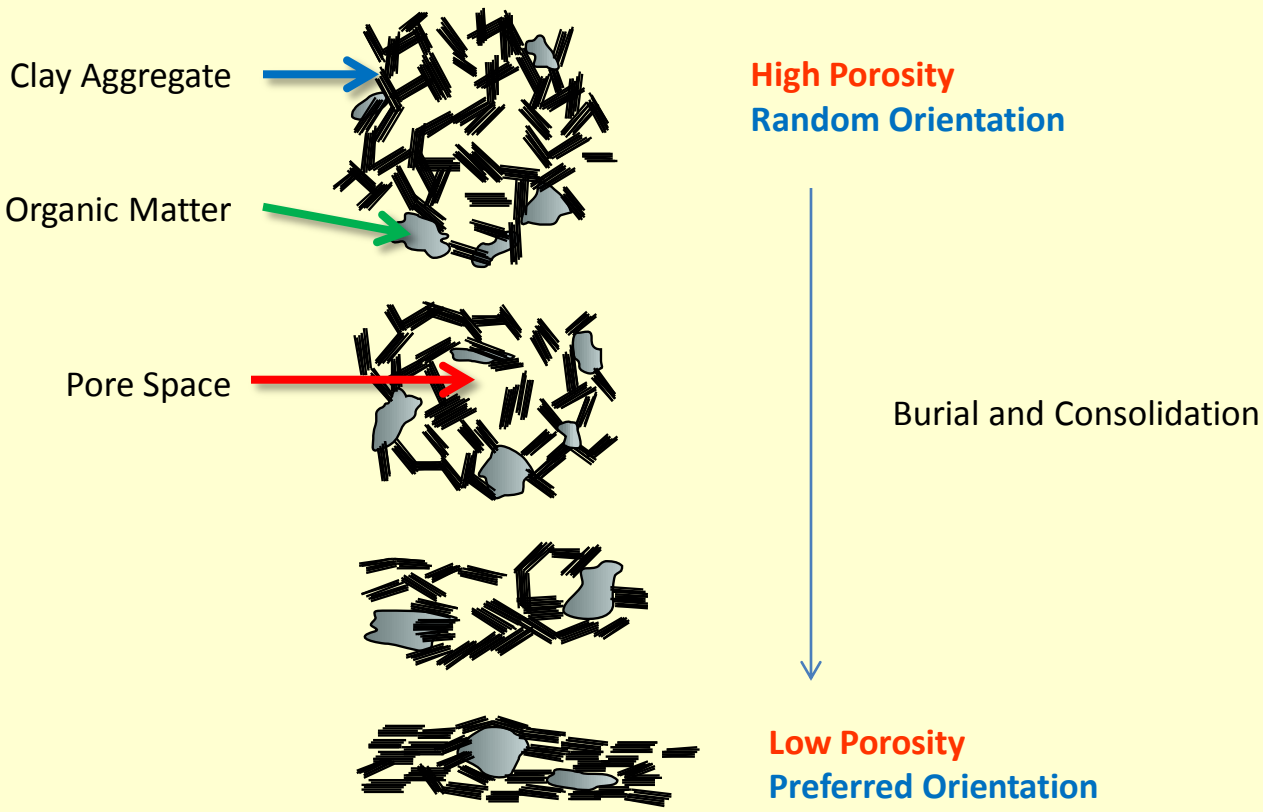
Douglas, Jessica R.[1], Kenneth J. Curry[1], Richard H. Bennett[1,2], and Andrew Head[1]
(1) The University of Southern Mississippi, Hattiesburg, MS
(2) SEAPROBE, Inc, Picayune, MS

THE UNIVERSITY OF SOUTHERN MISSISSIPPI®

SEAPROBE Inc.

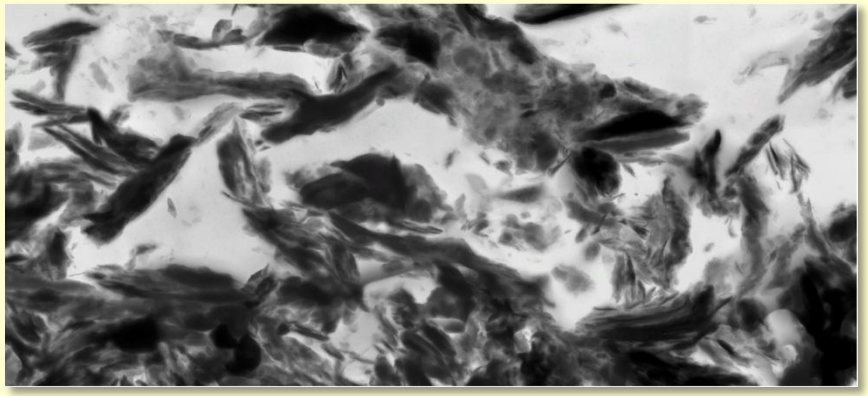
# Early Diagenesis and Organic Matter Sequestration

- An important aspect of marine clay fabric is that it traps organic matter during the depositional phase of early sediment diagenesis prior to becoming an organic rich shale over geological time.

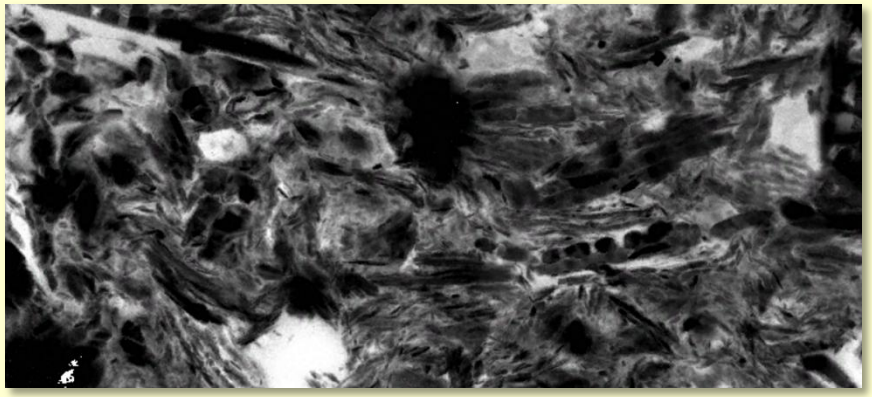


# Samples: Model and Natural

- **Model Sample**:
  - Laboratory consolidated
  - 9:1 Illite:Smectite
  - 1% chitin added as representative marine organic matter

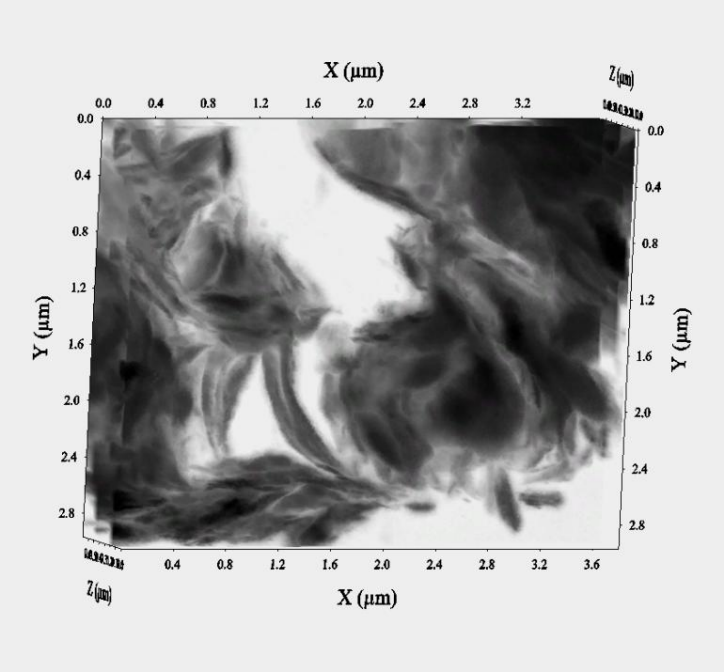


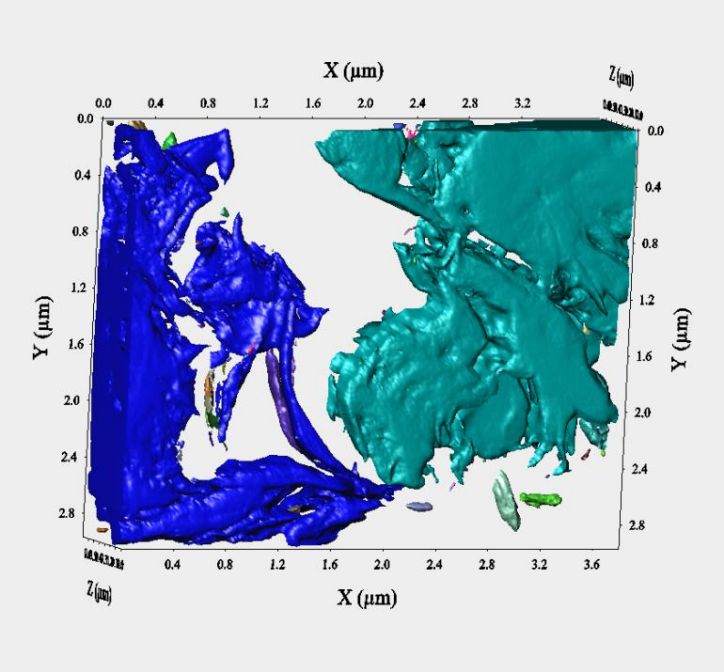
- **Natural Sample:**
  - Fecal pellet from marine polychaete worm
  - Bioturbated clay fabric
  - High organic content



# 3D Reconstructions of Marine Clay Fabric

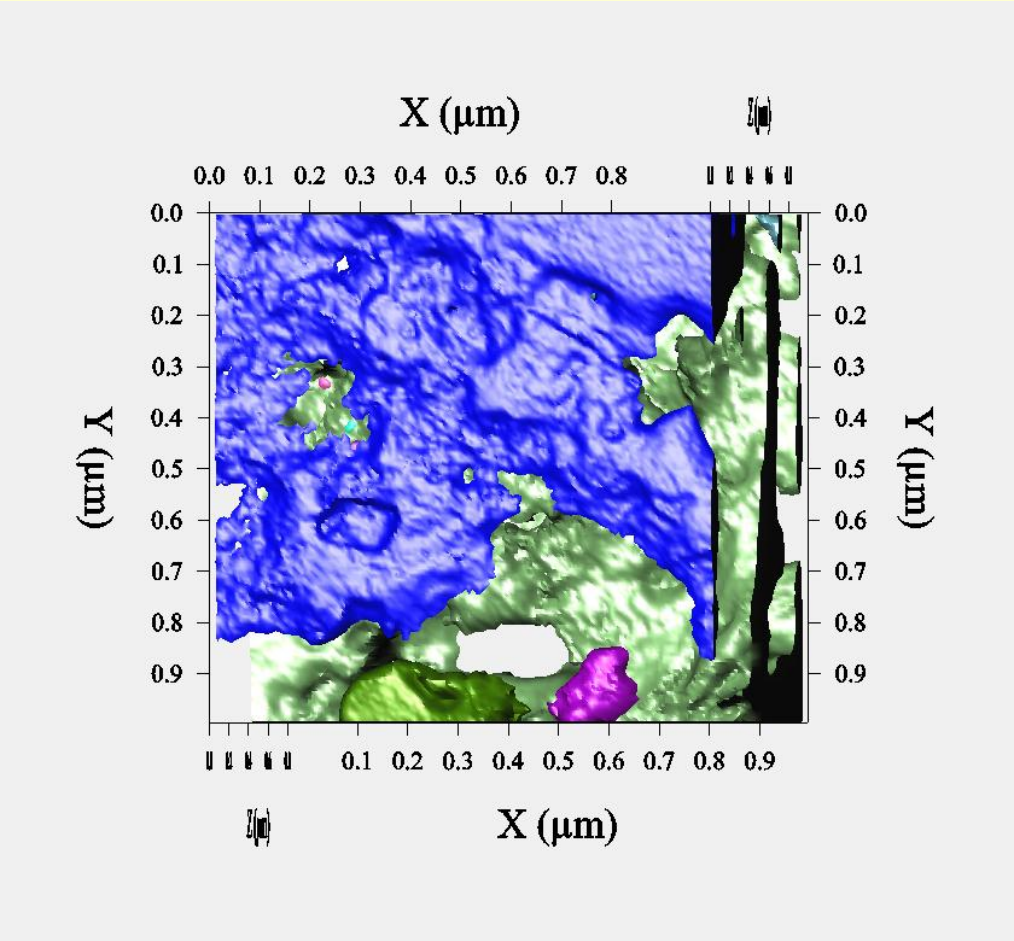
- 3D reconstructions from serial sections and photographic mosaics obtained using a transmission electron microscope (TEM).
  - Aggregations of clay domains
  - Organic matter
  - Voids (Pore space)



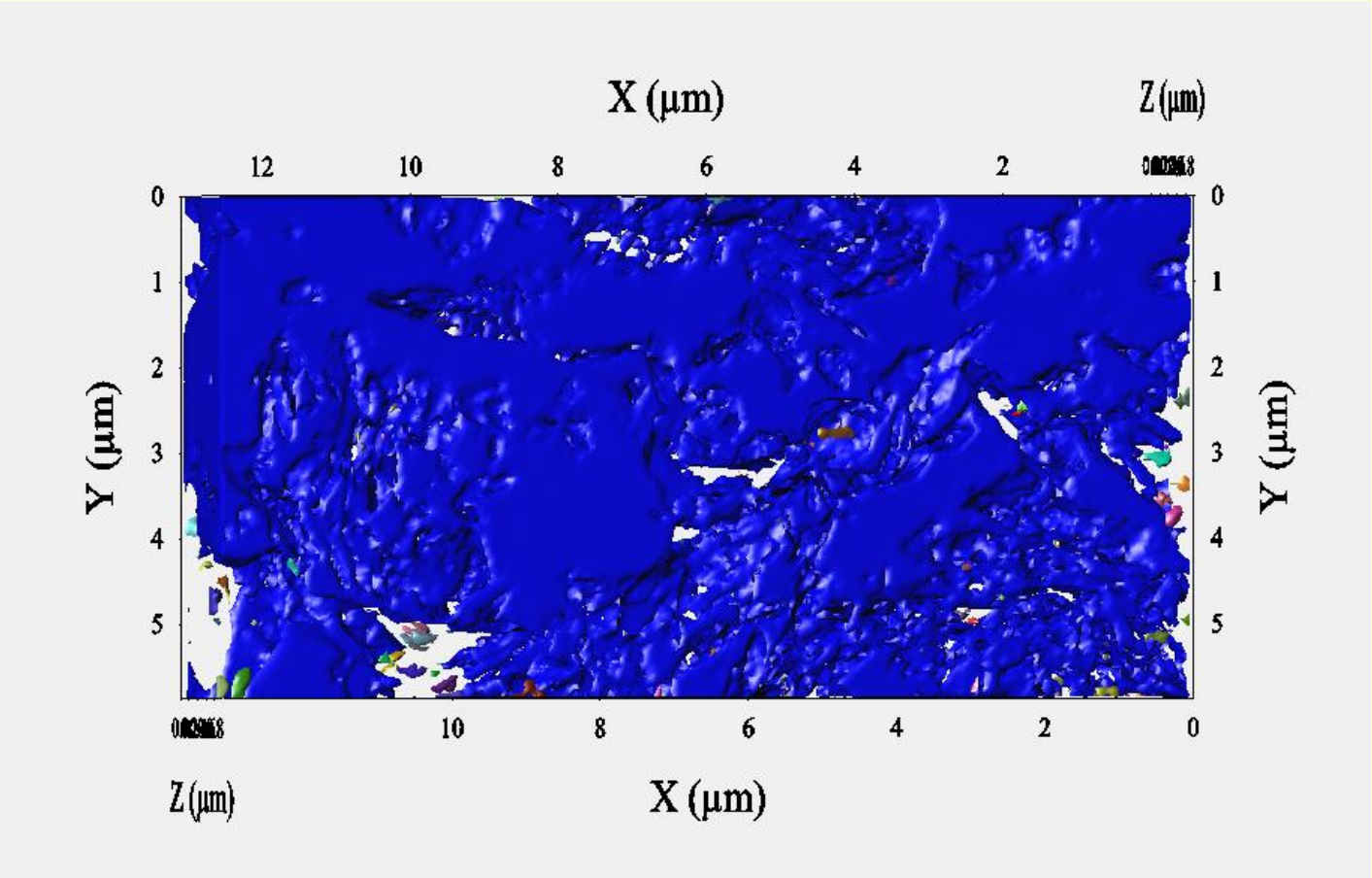
# 3D Reconstruction of Pore Network
## (Isosurface Reversed)

- “Pores” viewed in 3D constructs form  a complex matrix of channels.



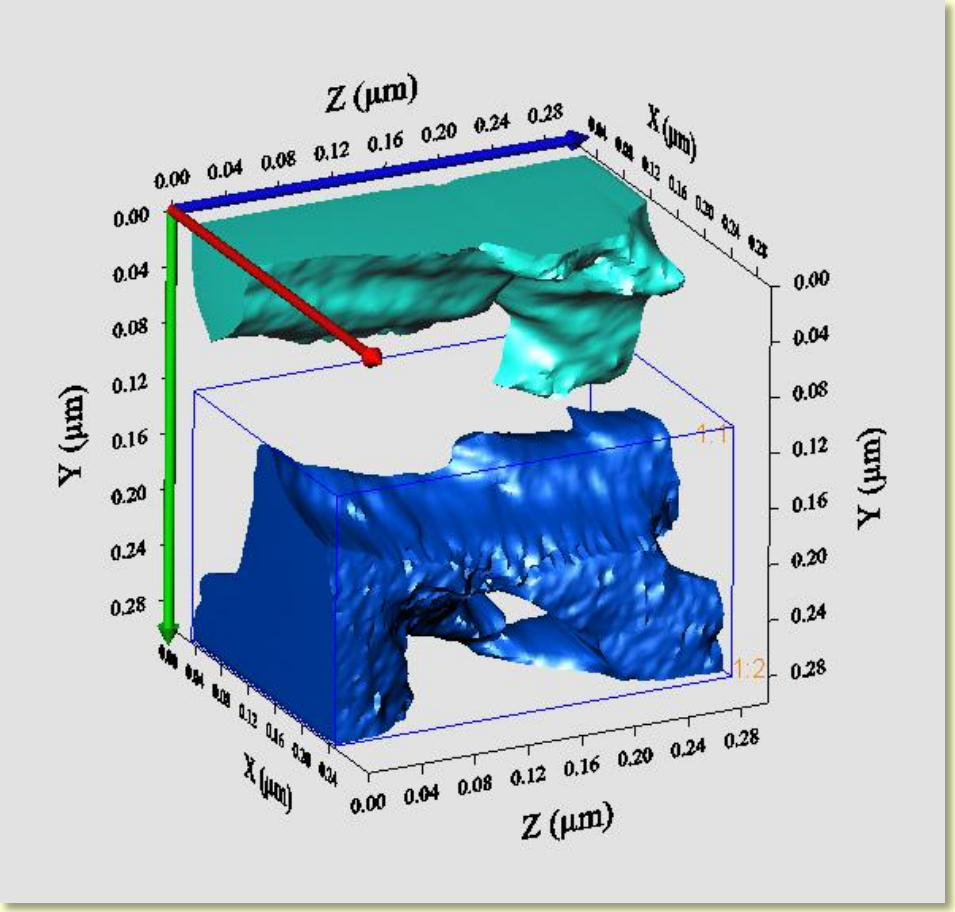
# 3D Reconstruction of Pore Network
## (Isosurface Reversed)

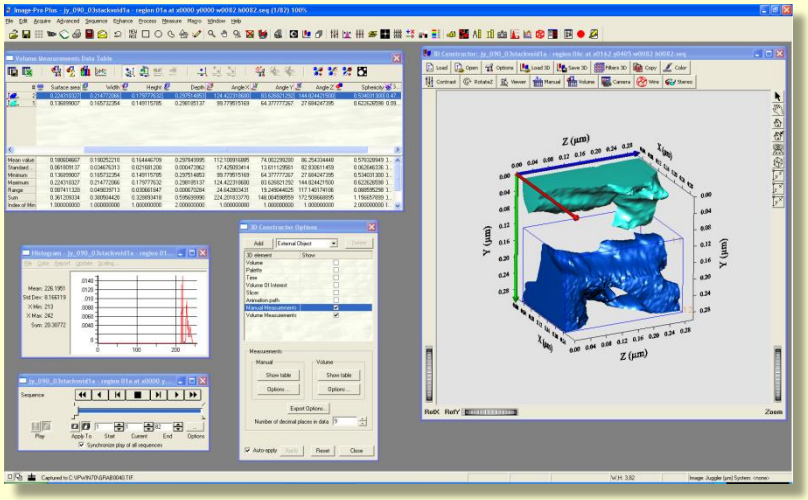
- "Pores" viewed in 3D constructs form  a complex matrix of channels.



# Measuring Porosity and Orientation

- 300 nm subsampling cubes give us measurements at a fine level throughout a whole sample.
- Porosity of each cube is a ratio of the volume of the void to the volume of the cube.
- Orientation of the void is determined by its length in the X, Y, and/or Z planes.

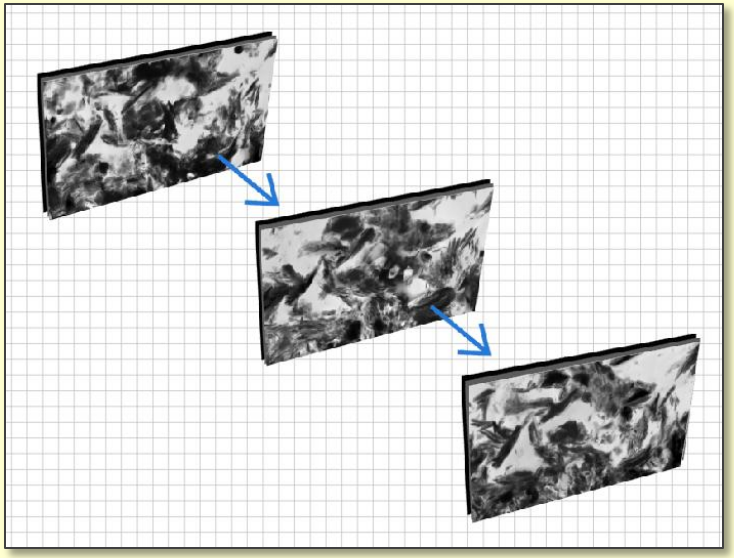


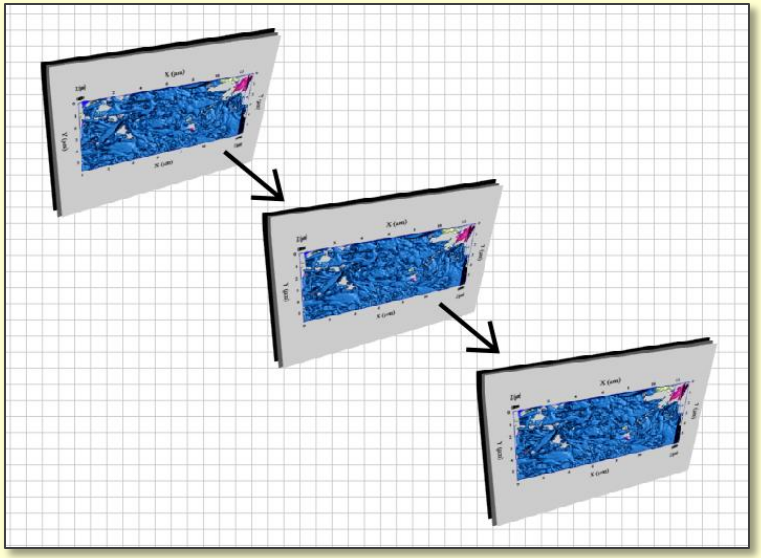



# Analysis of the Reconstructions

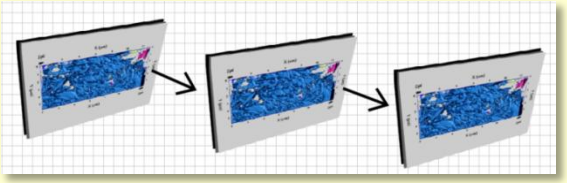
- Each subsample was segmented in the Z plane to create three regions each 300 nm deep by their respective X and Y dimensions.

| Sample | Sample Dimensions | Cube Size ($nm^3$) | Total # Cubes | # Cubes (X x Y x Z) |
|---|---|---|---|---|
| **Model Sample** | 13.1 x 5.9 x 1.0 µm | 300 | 2,451 | 43 x 19 x 3 |
| **Natural Sample** | 22.5 x 14.7 x 0.9 µm | 300 | 11,025 | 75 x 49 x 3 |

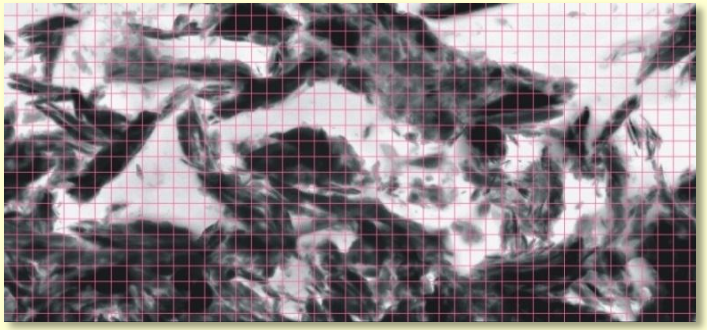


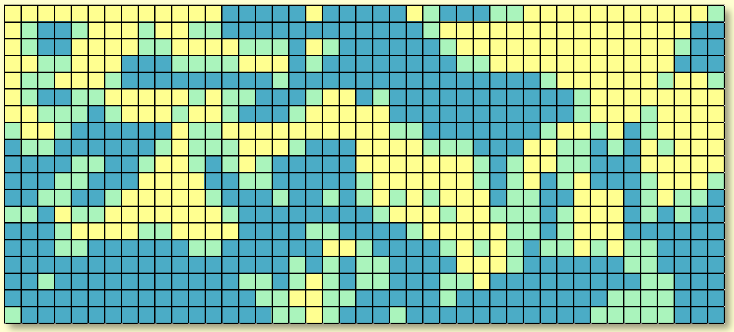


# Porosity

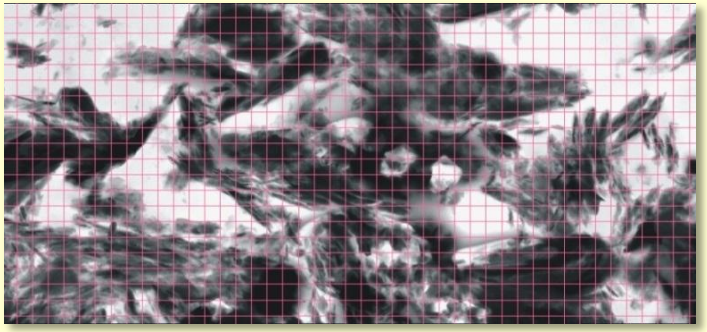


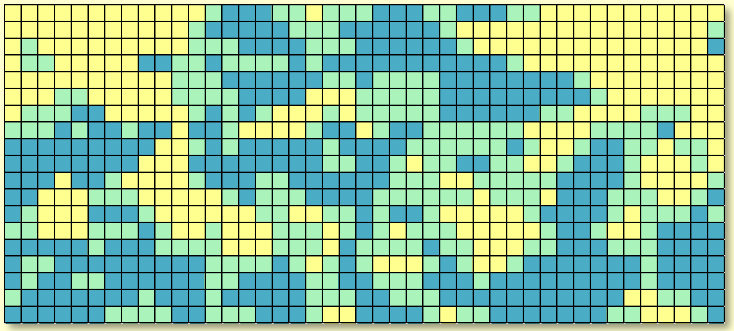
Front Region



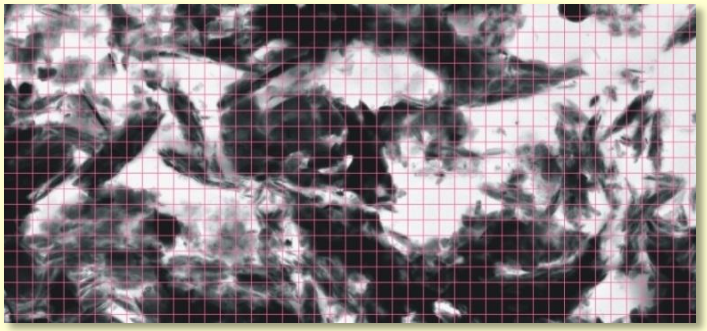


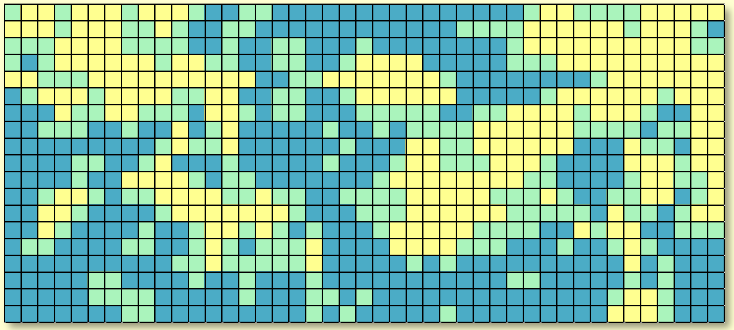
Center Region





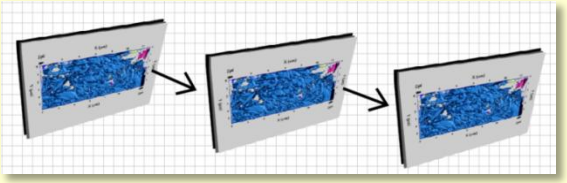
Back Region





= 86 – 100% Porosity = 56 – 85% Porosity = 00 – 55% Porosity

# Orientation



- Color coded map of porosity with void orientation overlain.

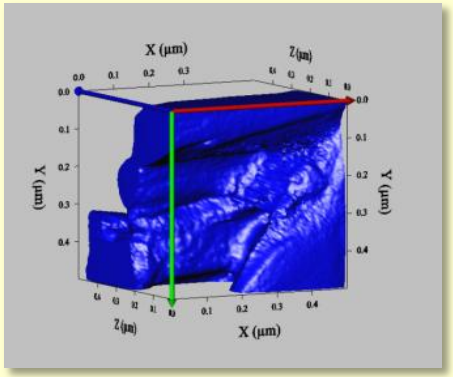
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XYZ | XZ | XYZ | XY | XY | XY | X | X | XY | XY | XY | X | Y | XY | Z | X | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY |
| XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XYZ | XYZ | Z | X | XY | XY | X | X | XY | X | Y | X | X | X | XY | XY | XY | Y | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | X |
| XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | Y | XY | XYZ | Y | X | XY | XY | XY | XY | XY | XY | X | XY | X | X | XYZ | X | X | Y | XY | XY | XY | XYZ | XYZ | XY | XY | XY | XY | XY | XY | XY |
| XY | X | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XYZ | XY | XY | X | XYZ | XY | XY | Y | XY | XY | XY | XY | XY | XY | X | Y | Y | XY | XY | X | XYZ | XYZ | XYZ | XY | XY | XY | XY | XY | XY | XY |
| XYZ | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | Y | XY | Z | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | Y | X | X | X | X | XY | XY | XY | XY | XY | XY | XY | XY |
| Z | XY | XYZ | XYZ | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | X | XY | XY | X | Z | XY | XY | XY | XY | XY | XY | XY | XY | Y | X | X | X | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY |
| XY | XY | XY | XY | XY | X | XY | XY | XY | X | XY | Y | XY | XYZ | XY | XY | XY | Y | XY | X | X | XY | XY | XY | XY | XY | XY | XY | XY | X | XY | XY | XY | XY | XY | XY | XY | XY | XY | Y | XY | XY | XY |
| XYZ | XY | XY | XYZ | XY | X | XY | XYZ | Y | Y | XY | Y | Y | XY | X | Z | X | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | Z | Z | XY | Y | XY | XY |
| Z | X | X | X | X | Z | Z | Y | X | XY | XY | XY | Y | XY | X | X | XY | XY | Z | XY | XYZ | XY | XY | X | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | Y | Y | Y | XY | XY | Z | Y | XY | XY |
| X | X | XYZ | Y | XYZ | XYZ | Z | X | XY | XY | Z | X | XY | XY | Y | XYZ | X | Z | Z | XYZ | XY | XY | XY | XYZ | XYZ | XYZ | XYZ | XY | XY | XY | XY | XY | XY | Y | Y | X | Y | XYZ | XYZ | XY | Y | XY | XY |
| X | X | Z | XY | XY | Y | XY | XYZ | XY | XY | XY | XY | Z | XY | XY | X | X | X | X | XZ | XZ | X | XY | XY | XY | XY | XYZ | XY | XY | XY | XY | XY | XY | XY | Y | Y | Z | XYZ | XYZ | XY | XY | XY | XY |
| X | Y | XY | XY | XY | XY | XY | XYZ | XY | XY | XY | XY | X | XY | XY | XY | XY | XY | XYZ | X | X | XY | XY | XY | XY | XY | XY | XY | XY | XY | X | XY | XY | X | Y | XY | XY | XYZ | XY | XY | XY | XY | XY |
| Z | Y | XY | XY | XY | X | X | X | X | XY | XY | XY | XY | XYZ | XY | XY | XY | XY | XY | X | X | XYZ | XYZ | XY | XY | XY | XY | XY | XY | XY | XY | XY | XYZ | XY | XY | Y | XY | XYZ | Z | Z | XYZ | XY | XY |
| Y | Z | XY | X | XY | Y | Y | XY | XY | XY | XY | XY | XYZ | XYZ | XY | XYZ | XY | Z | XY | XY | X | X | XYZ | XYZ | XYZ | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XY | XYZ | XY | YZ | Y | XY | XY | XY |
| X | XY | XY | XY | XY | X | Y | XY | Z | Z | Y | XYZ | XYZ | XYZ | XY | XYZ | XYZ | XY | XYZ | XY | Y | Y | XY | XYZ | XYZ | XY | XY | XY | XY | XY | X | Y | XY | XY | XY | XY | XY | XYZ | XY | XY | Y | XYZ | X |
| Y | X | XY | Z | X | X | X | X | X | Y | XYZ | XY | XY | XY | XY | XYZ | XY | XYZ | XYZ | XY | Y | X | Y | X | XYZ | X | XY | XY | XY | XY | Y | Z | XY | XY | XY | XY | XY | XY | Y | X | Y | Y | Y |
| Y | X | XYZ | Z | X | XYZ | XYZ | X | X | X | X | Z | X | X | XY | XY | X | Y | XYZ | X | X | X | XY | X | X | X | XY | XY | X | X | X | Y | XY | X | X | Z | X | XY | XY | XY | Y | Z | X |
| Z | X | XY | Y | XY | XYZ | XYZ | XYZ | Y | XZ | Y | Y | XY | XY | XYZ | X | X | Z | Y | XY | Y | XY | XY | Y | X | Y | Y | X | XYZ | X | X | X | X | X | X | Y | XYZ | XY | XY | XY | X | XYZ | XYZ |
| XYZ | X | X | Y | XY | XZ | XY | XYZ | XYZ | XY | Y | X | X | Y | Z | Y | Z | X | XY | Y | XY | XY | XY | XY | XY | Y | XYZ | XZ | X | XYZ | XYZ | XYZ | Y | X | Y | XY | XY | XY | XY | XY | Y | X | X |

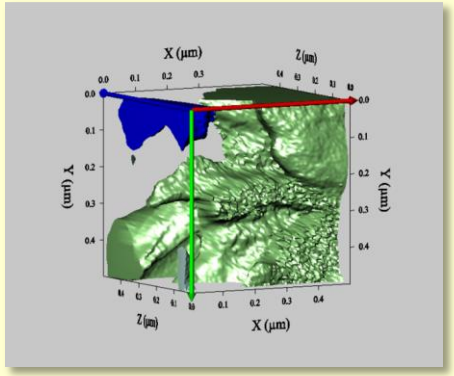
= 85 – 100% Porosity = 55 – 85% Porosity = 00 – 55% Porosity

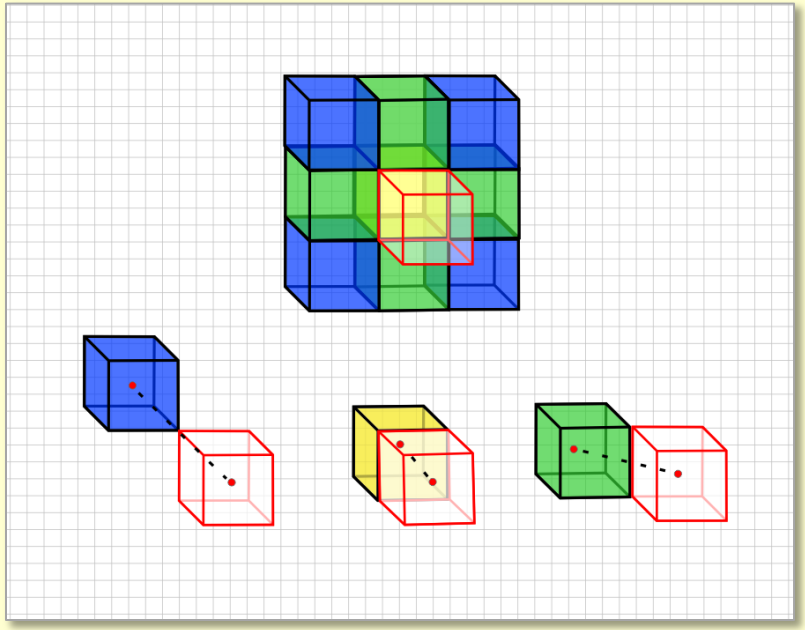
# Measuring Flow Network Tortuosity

- **Tortuosity historically measured from 2D micrographs**
  - Tracing a line across the X and Y planes of a micrograph around clay and organic particles.
  - Ratio of the length of that tortuous line to a straight line (shortest possible path) across the same interval.

- **Tortuosity measured from 3D micrographs**
  - Detailed porosity and orientation measurements are used to discover short paths across the sample.
  - Paths are constructed cube to cube by considering the closest adjacent cube in the neighboring X, Y, and Z planes.



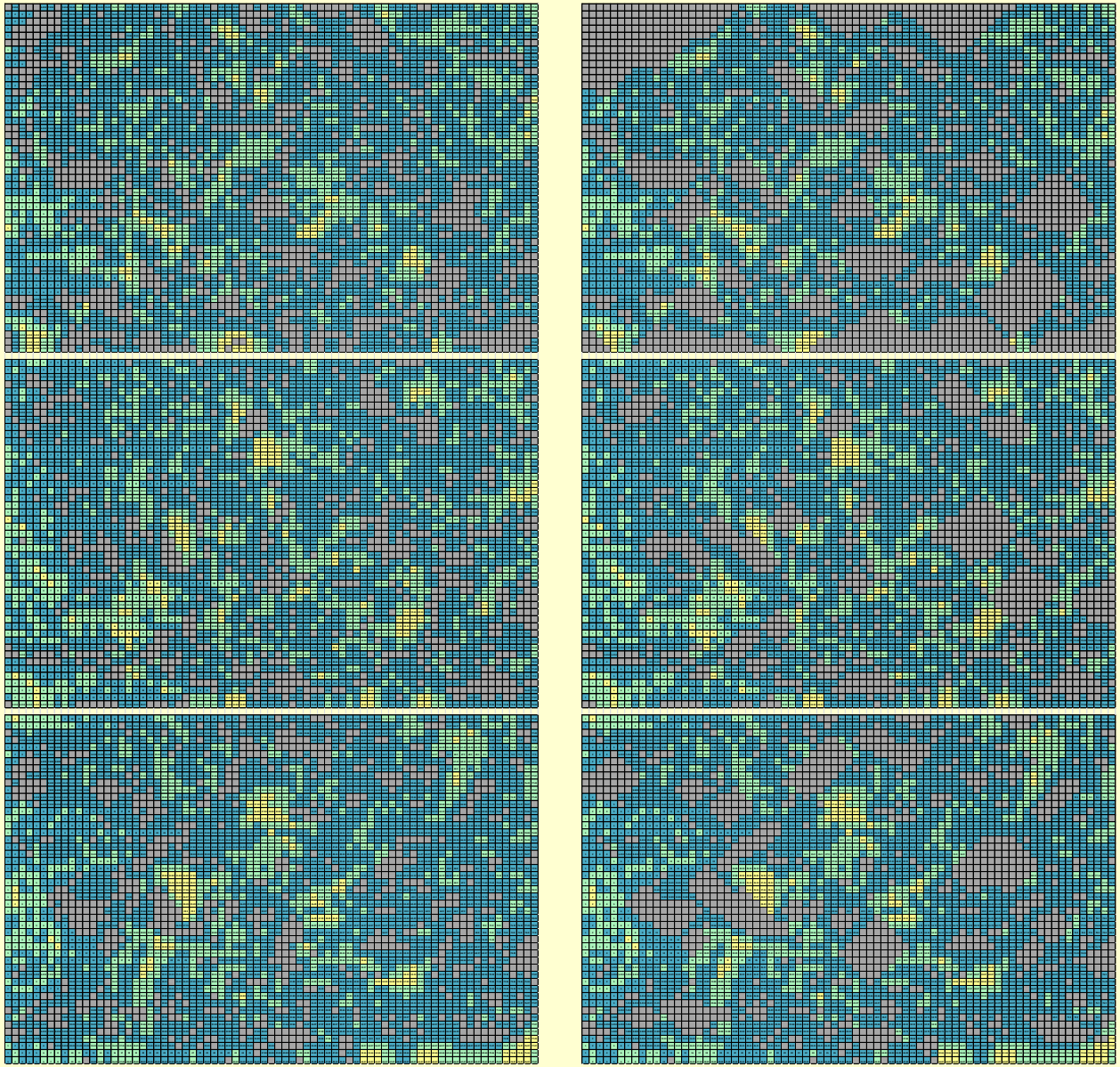



# Paths composed of cubes ranging from **10 - 100%** porosity.

3D (connected regions)

2D ( separate regions)



**Tortuosity:**
76.24/75
**1.02**

**Tortuosity:**
(76.04/75)
**1.01**

**Tortuosity:**
76.24/75
**1.02**

**Tortuosity:**
76.24/75
**1.02**

= 86 - 100% Porosity

= 56 - 85% Porosity

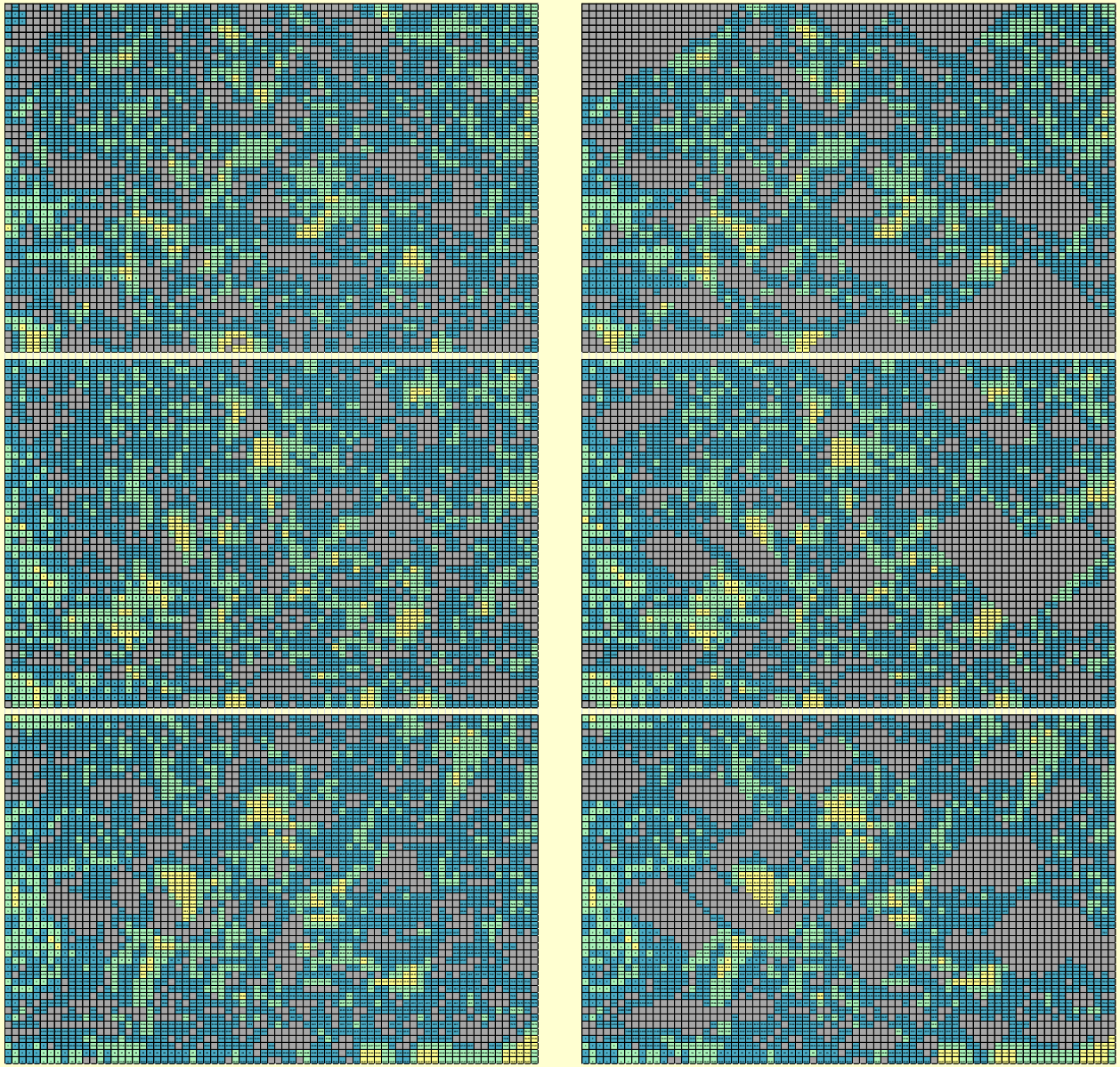
= 0 - 55% Porosity

= Blocked Path

# Paths composed of cubes ranging from **15 - 100%** porosity.

3D (connected regions)

2D ( separate regions)



**Tortuosity**:
77.49/75
**1.03**

**Tortuosity**:
76.24/75
**1.02**

**Tortuosity**:
76.24/75
**1.02**

**Tortuosity**:
76.66/75
**1.02**

= 86 - 100% Porosity

= 56 - 85% Porosity

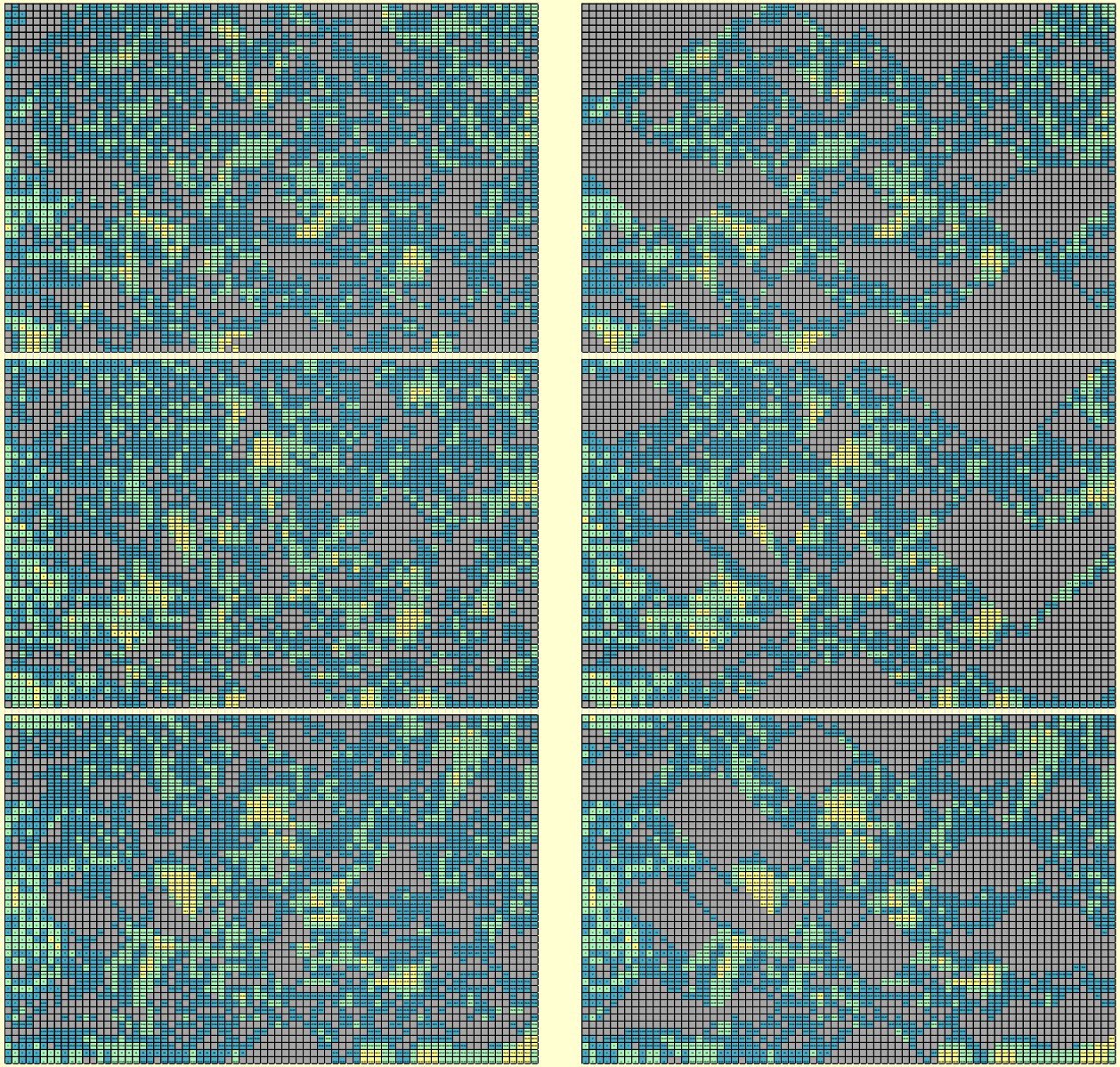
= 0 - 55% Porosity

= Blocked Path

# Paths composed of cubes ranging from **20 - 100%** porosity.

3D (connected regions)

2D ( separate regions)



**Tortuosity**:
78.31/75
**1.04**

**Tortuosity**:
76.52/75
**1.02**

**Tortuosity**:
77.07/75
**1.02**

**Tortuosity**:
79.14/75
**1.06**

= 86 - 100% Porosity

= 56 - 85% Porosity

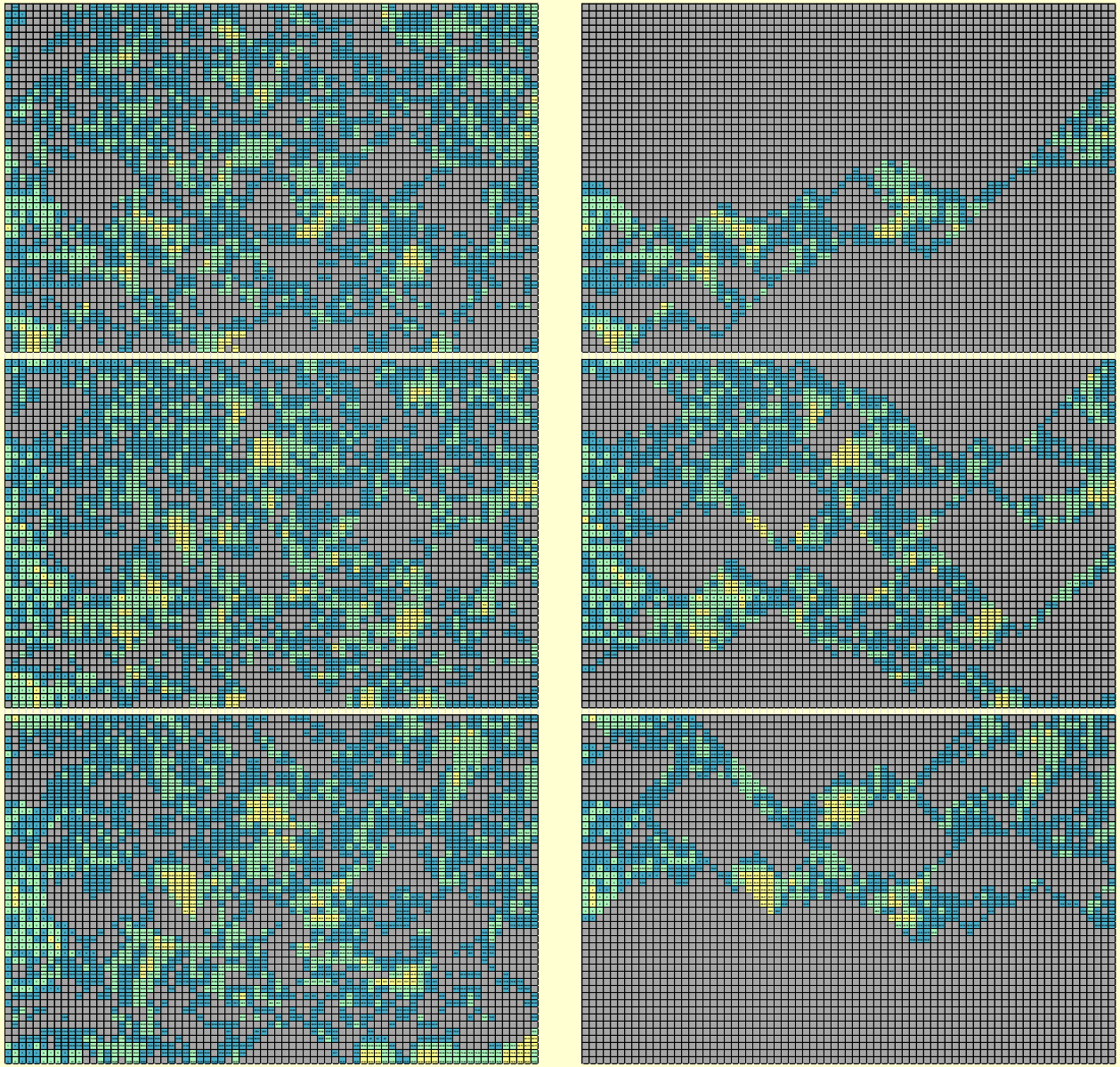
= 0 - 55% Porosity

= Blocked Path

# Paths composed of cubes ranging from **25 - 100%** porosity.

3D (connected regions)

2D ( separate regions)



**Tortuosity**:
83.70/75
**1.12**

**Tortuosity**:
77.07/75
**1.03**

Tortuosity:
79.14/75
**1.06**

**Tortuosity**:
81.63/75
**1.09**

= 86 - 100% Porosity

= 56 - 85% Porosity

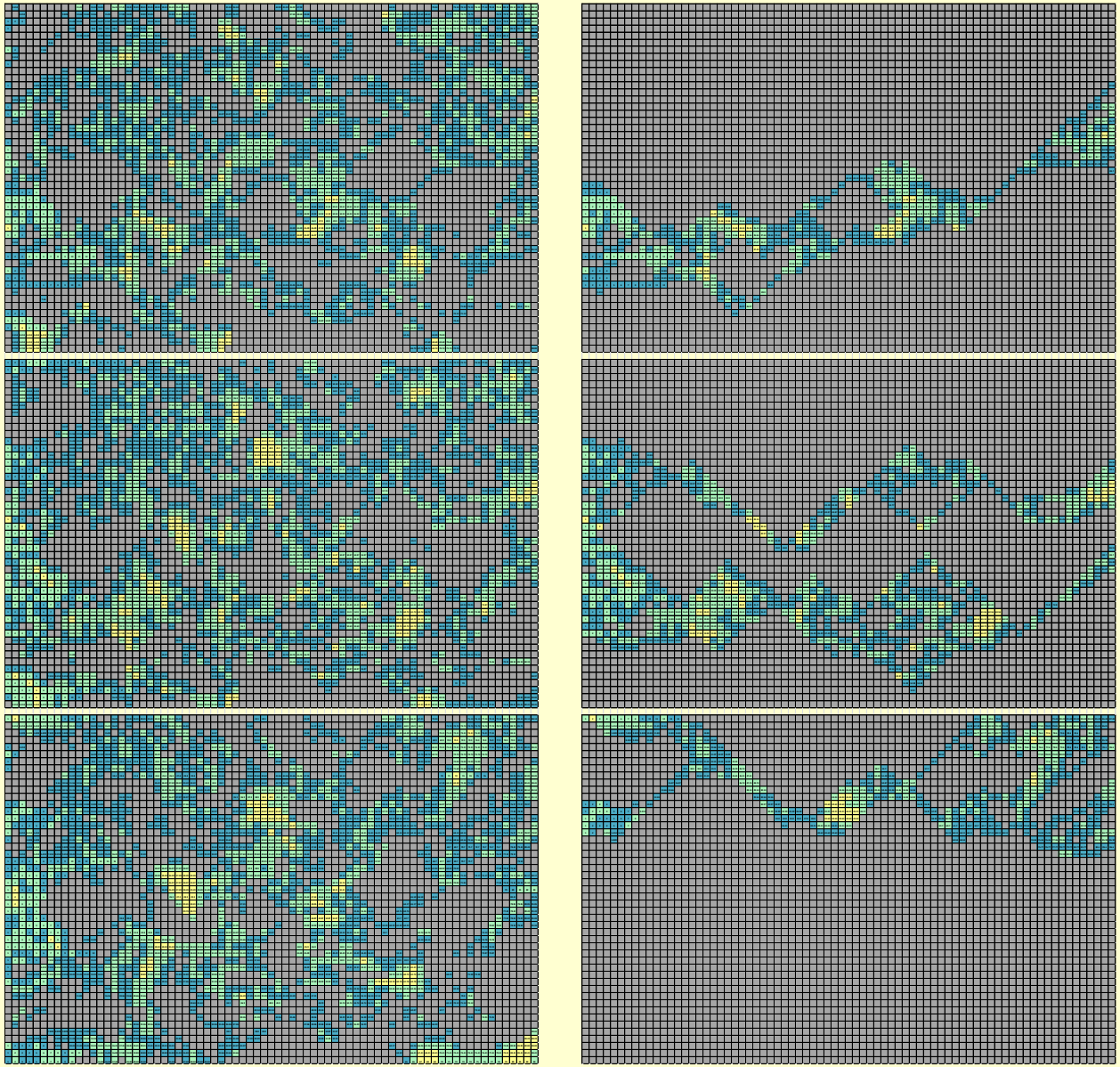
= 0 - 55% Porosity

= Blocked Path

# Paths composed of cubes ranging from **30 - 100%** porosity.

3D (connected regions)

2D ( separate regions)

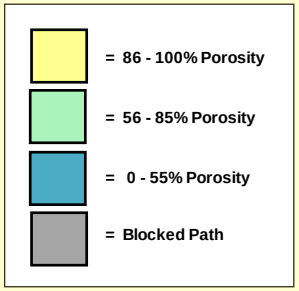


**Tortuosity**:
83.70/75
**1.12**

**Tortuosity**:
79.69/75
**1.06**

**Tortuosity**:
82.87/75
**1.10**

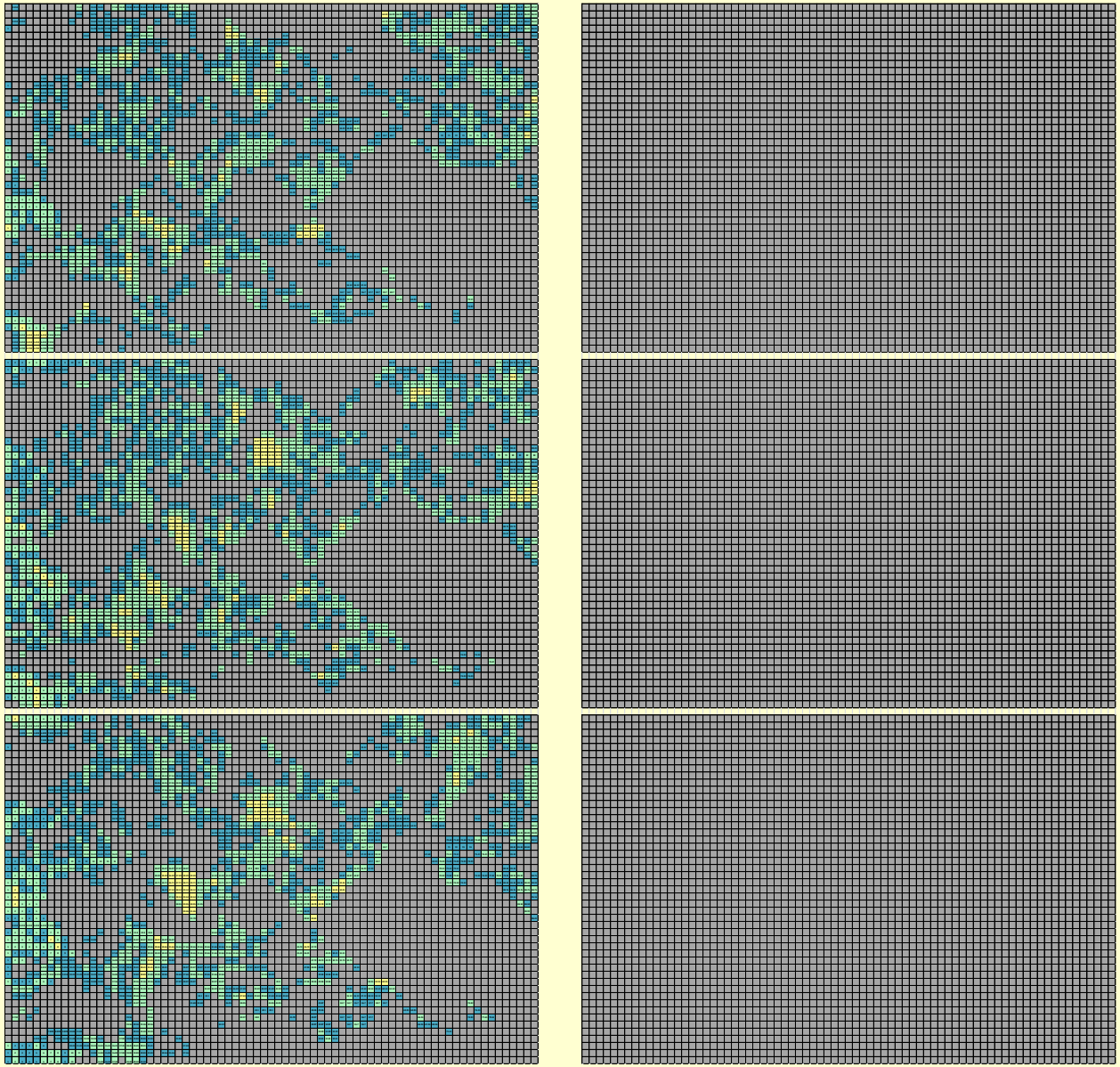
**Tortuosity**:
85.77/75
**1.14**



# Paths composed of cubes ranging from **35 - 100%** porosity.

3D (connected regions)

2D ( separate regions)



**Tortuosity**:
N/A

**Tortuosity**:
82.68/75
**1.10**

**Tortuosity**:
N/A

**Tortuosity**:
N/A

= 86 - 100% Porosity

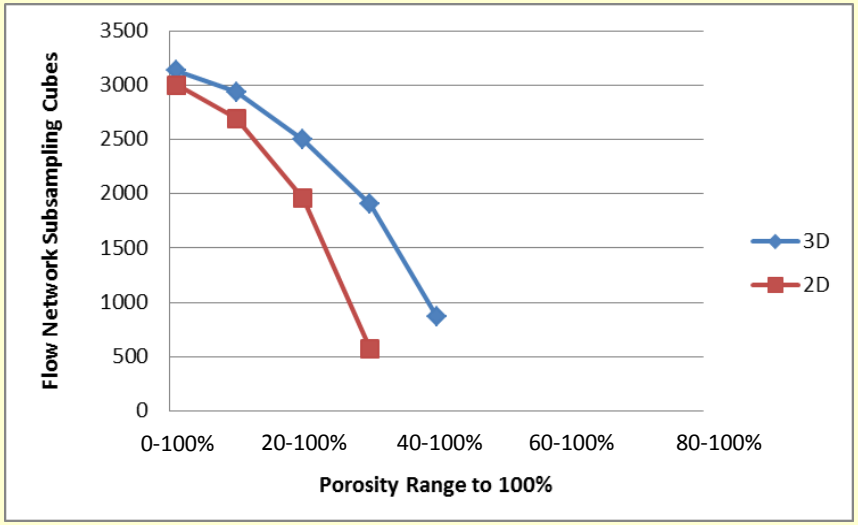
= 56 - 85% Porosity

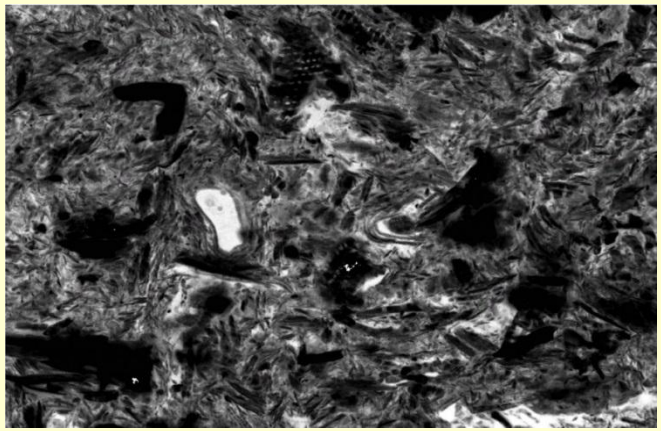
= 0 - 55% Porosity

= Blocked Path

# Flow Paths: 3D versus 2D

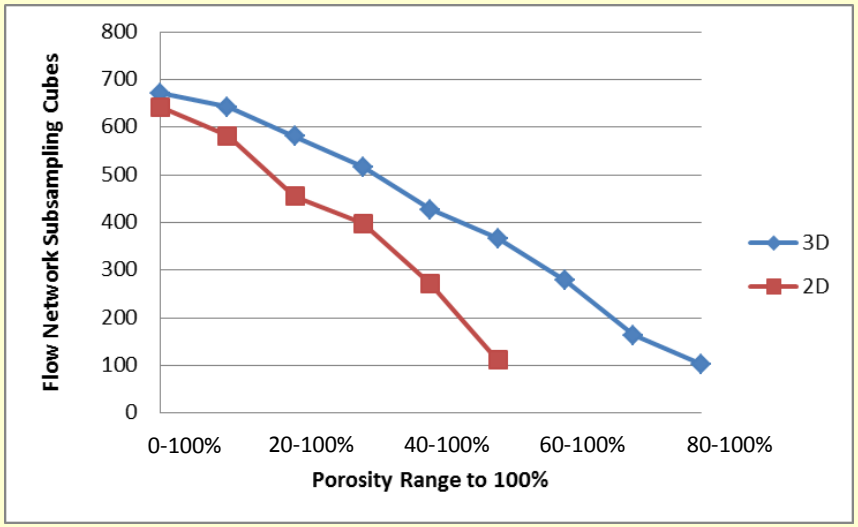
## Natural Sample

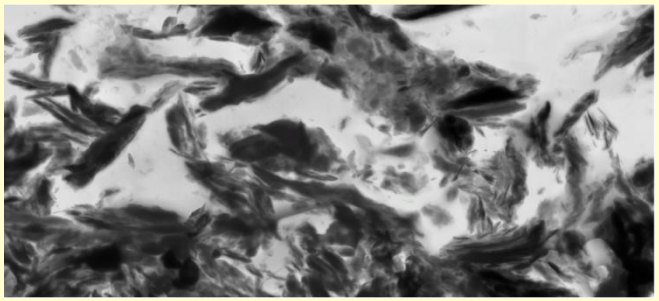


23 x 15 x 1 um

## Model Sample



13 x 6 x 1 um

# Conclusions

- 3D representations show that nano- and micrometer scale flow networks are highly intreconnected.
- Path lengths across the same sample when traced in 2D and 3D are statistically the same when a path can be traced across the sample.
- There are more path choices for 3D than 2D across restricted porosity ranges.
- Our data can impact on fluid flow modeling and our understanding of organic matter sequestration and protection.

# Acknowledgements


- National Science Foundation
  - OCE-0824566
  - OCE-0930685
  - OCE-0824569
  - OCE-0930879
- GCSSEPM
  - Ed Picou Fellowship
- Mississippi INBRE
  - 5P20RR016476-11
  - 8 P20 GM103476-11
- Colleagues
  - Kenneth Curry
  - Richard Bennett
  - Matthew Hulbert
  - Andrew Head


THE UNIVERSITY OF SOUTHERN MISSISSIPPI

COLLEGE OF SCIENCE AND TECHNOLOGY