MONet Community Science Meeting – Data tutorial on XCT

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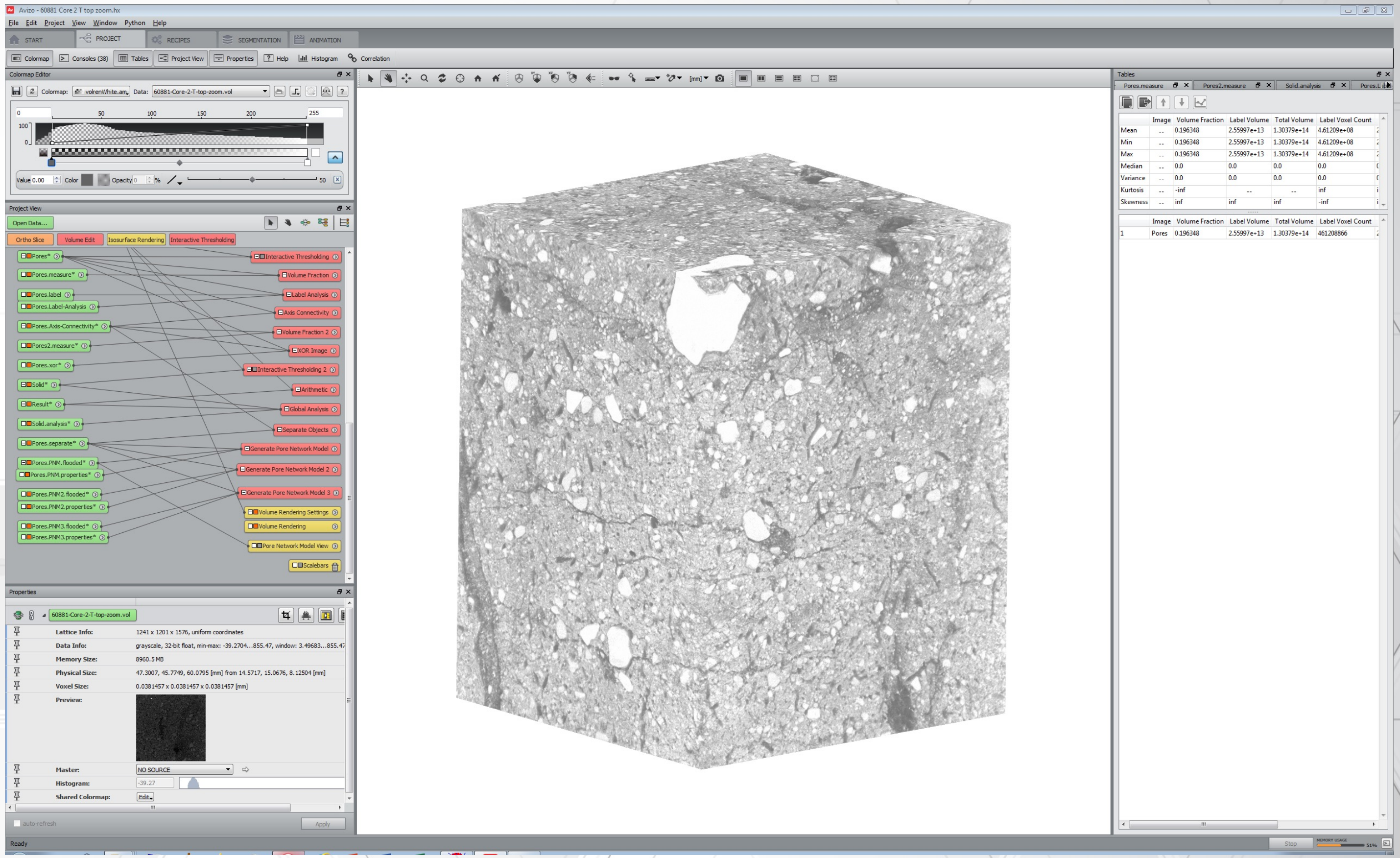
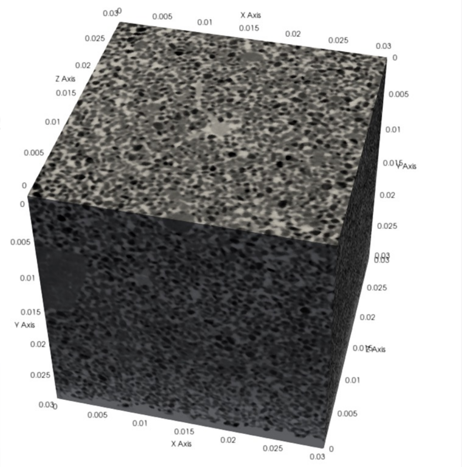
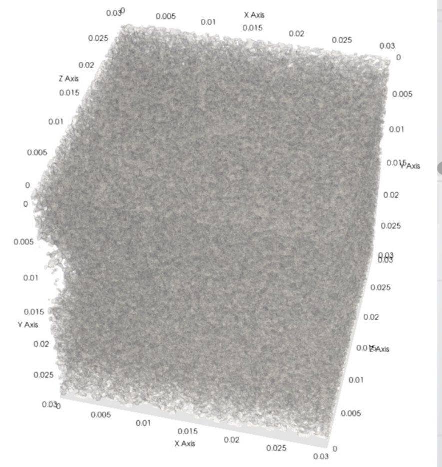






Outline

- Data types from XCT for MONet
- How do we get these: workflow
- A walk-through of our MONet-specific data analysis of soil porosity: creating/processing the raw data, other processing steps, segmentation, analyses
- Other data output formats/options, software used
- How this data can be used (examples including modeling)

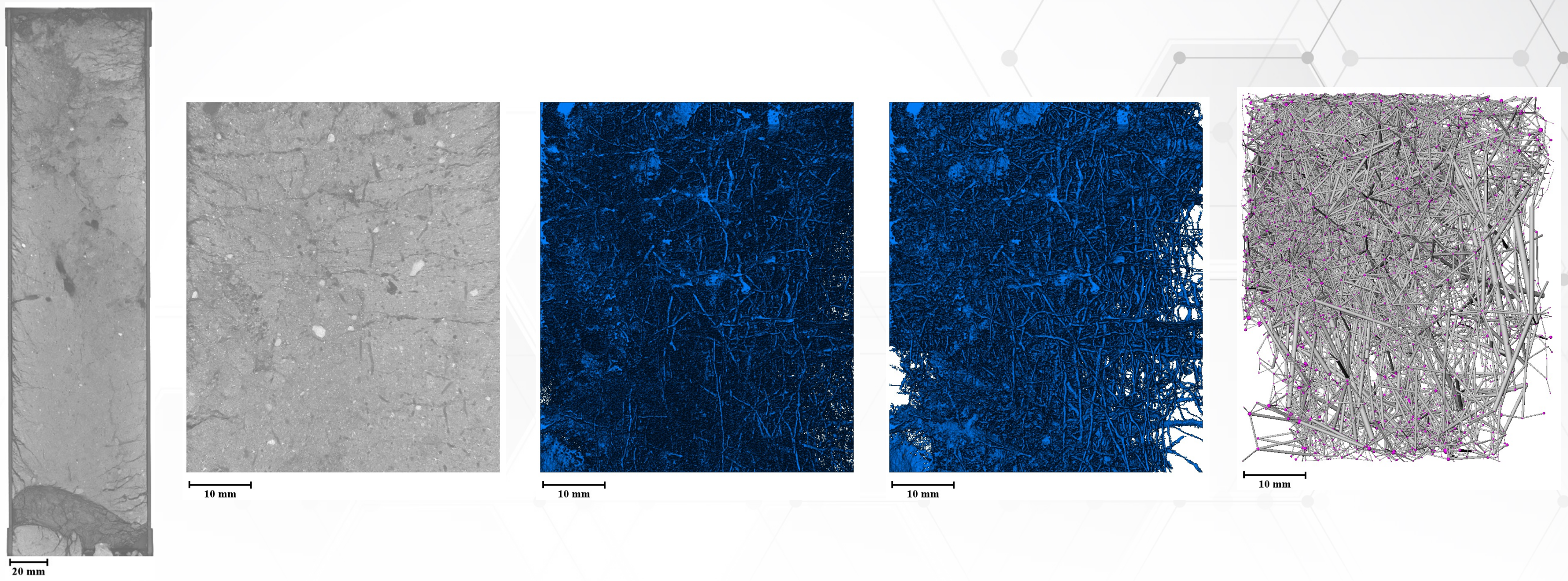
Scanning protocol

Low resolution XCT scans collected on whole core in 2 tiles (82.5 microns voxel size)

High resolution XCT scans collected on top and bottom sections (38.2 microns voxel size)

Data types for MONet

- Image data:



- Numerical data:
    - Pore size
    - Pore volume fraction
    - Pore connectivity
    - Pore size distribution
    - Bulk density
    - Permeability
    - Flow rate
    - Tortuosity

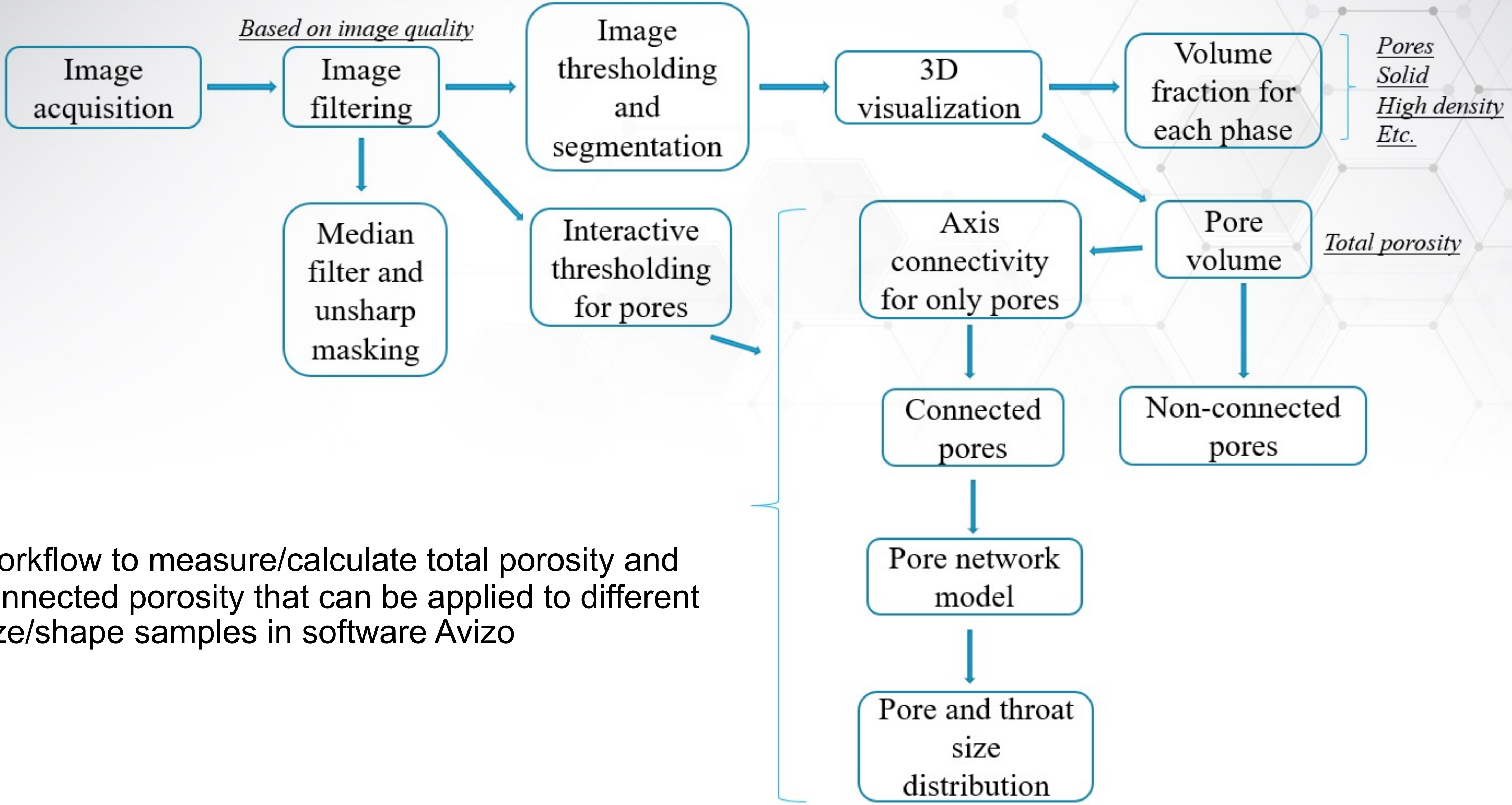
Data types for MONet: Numerical porosity data

Numerical data:

- Pore size
- Pore volume fraction
- Pore connectivity
- Pore size distribution
- Bulk density
- Permeability
- Flow rate
- Tortuosity

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1							volume (m	Area (mm	Area Fracti	Diameter (mm)				volume (m	Area (mm	Area Fracti	Diameter (mm)	
2																		
3	Pores	0.085973					0.000555	0.031101	4.07E-09	0.101964			Mean	0.001985	0.054057	1.45E-08	0.069619	
4							5.55E-05	0.004371	4.07E-10	0.047327			Min	5.55E-05	0.004371	4.07E-10	0.047327	
5							0.000222	0.015275	1.63E-09	0.075128			Max	9249.336	190975.9	0.067838	26.04379	
6							0.00444	0.187809	3.26E-08	0.203928			Median	9.22E-05	0.007635	6.76E-10	0.059606	
7	Pores.Axis	0.067838					0.006994	0.320421	5.13E-08	0.237267			Variance	15.13321	6446.432	8.14E-10	0.001437	
8			connectd p	0.789055			0.050177	1.23785	3.68E-07	0.457617			Kurtosis	5658180	5658176	5658182	69404.55	
9							0.0005	0.031401	3.66E-09	0.098445			Skewness	2378.692	2378.691	2378.693	90.81248	
10	PNM in Z						0.000111	0.008209	8.14E-10	0.059629								
11	k [µm^2]	k [d]	TotalFlowI	Tortuosity			9249.34	190975.9	0.067838	26.0438								
12	14197.26	14385.37	141710.1	1.353234			0.006328	0.2437	4.64E-08	0.229482								
13							0.025144	1.01731	1.84E-07	0.363479								
14							0.000555	0.036606	4.07E-09	0.101964				frequency	count			
15	PNM in Y						5.55E-05	0.004371	4.07E-10	0.047327			(mm)					
16	k [µm^2]	k [d]	TotalFlowI	Tortuosity			0.000444	0.02565	3.26E-09	0.094655			0-0.1		945303			
17	71.17569	72.11877	1257.678	1.808984			5.55E-05	0.004371	4.07E-10	0.047327			0.1-0.2	0.1	92624			
18							0.048179	1.67739	3.53E-07	0.45146			0.2-0.3	0.2	7860			
19							5.55E-05	0.004371	4.07E-10	0.047327			0.3-0.4	0.3	1727			
20	PNM in X						0.0005	0.030019	3.66E-09	0.098445			0.4-0.5	0.4	558			
21	k [µm^2]	k [d]	TotalFlowI	Tortuosity			0.000222	0.015041	1.63E-09	0.075128			0.5-0.75	0.5	370			
22	368.3572	373.2379	5184.799	1.582346			0.000666	0.042052	4.89E-09	0.108353			0.75-1	0.75	84			
23							0.001443	0.080395	1.06E-08	0.140207			1to5	1	47			
24							0.000111	0.008438	8.14E-10	0.059629			5to10	5	0			
25							5.55E-05	0.004371	4.07E-10	0.047327			10to25	10	0			
26	wet bulk d	2.06034					5.55E-05	0.004371	4.07E-10	0.047327			25to50	25	1			
27							0.0005	0.029642	3.66E-09	0.098445			>50	50	0			
28							5.55E-05	0.004371	4.07E-10	0.047327								
29							0.000167	0.011742	1.22E-09	0.068258								
30							0.000111	0.008506	8.14E-10	0.059629								
31							5.55E-05	0.004371	4.07E-10	0.047327								
32							0.000111	0.008438	8.14E-10	0.059629								
33							5.55E-05	0.004371	4.07E-10	0.047327								

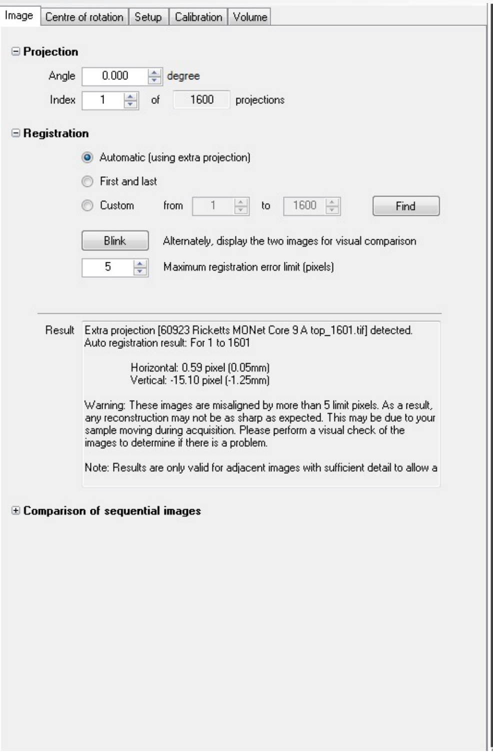
Data analysis workflow

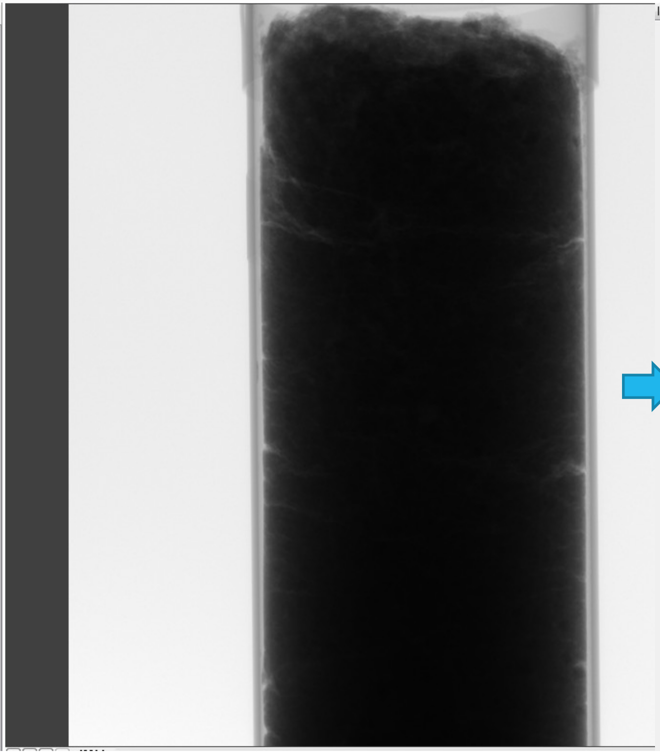


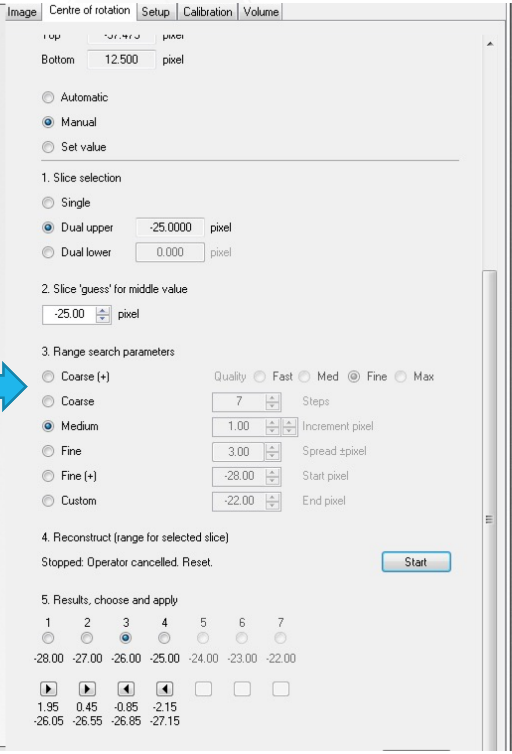
Workflow to measure/calculate total porosity and connected porosity that can be applied to different size/shape samples in software Avizo

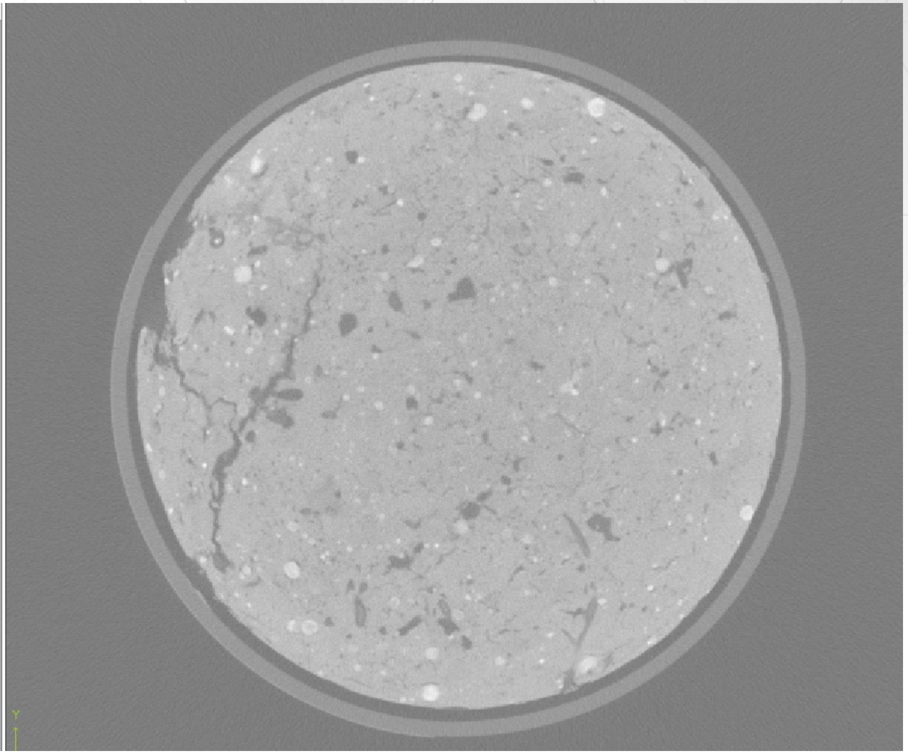
Data reconstruction

- Create 3D volume data from the individual projections
- We use CT Pro 3D (X-Tek software suite by Nikon)







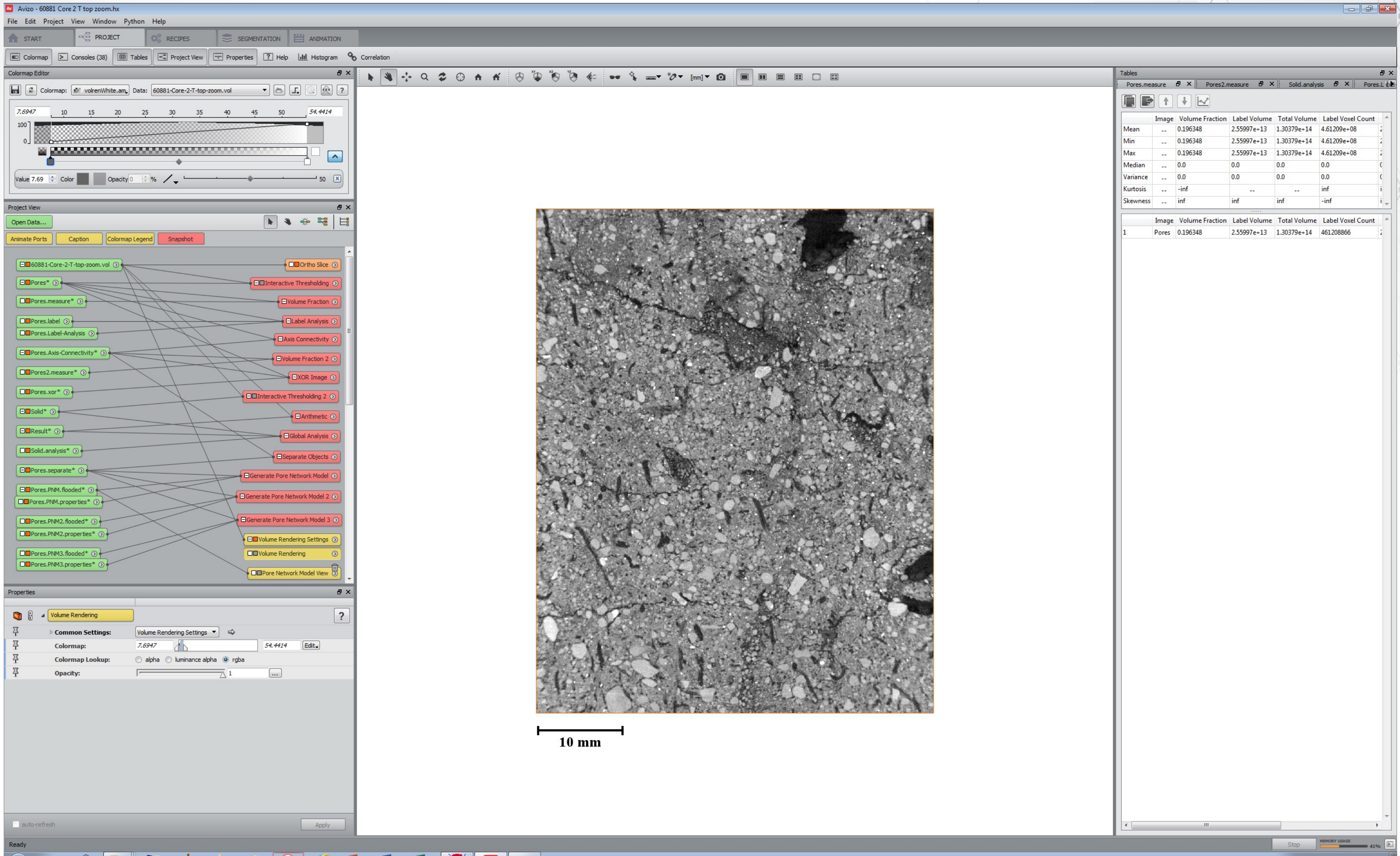


Data processing

- Importing reconstructed data into Avizo (Thermo Fisher)
- Image cropping (as necessary)
- Filtering (as necessary)
- Segmentation – see next
- Pore volume/size analysis
- Pore network analysis
- Visualization

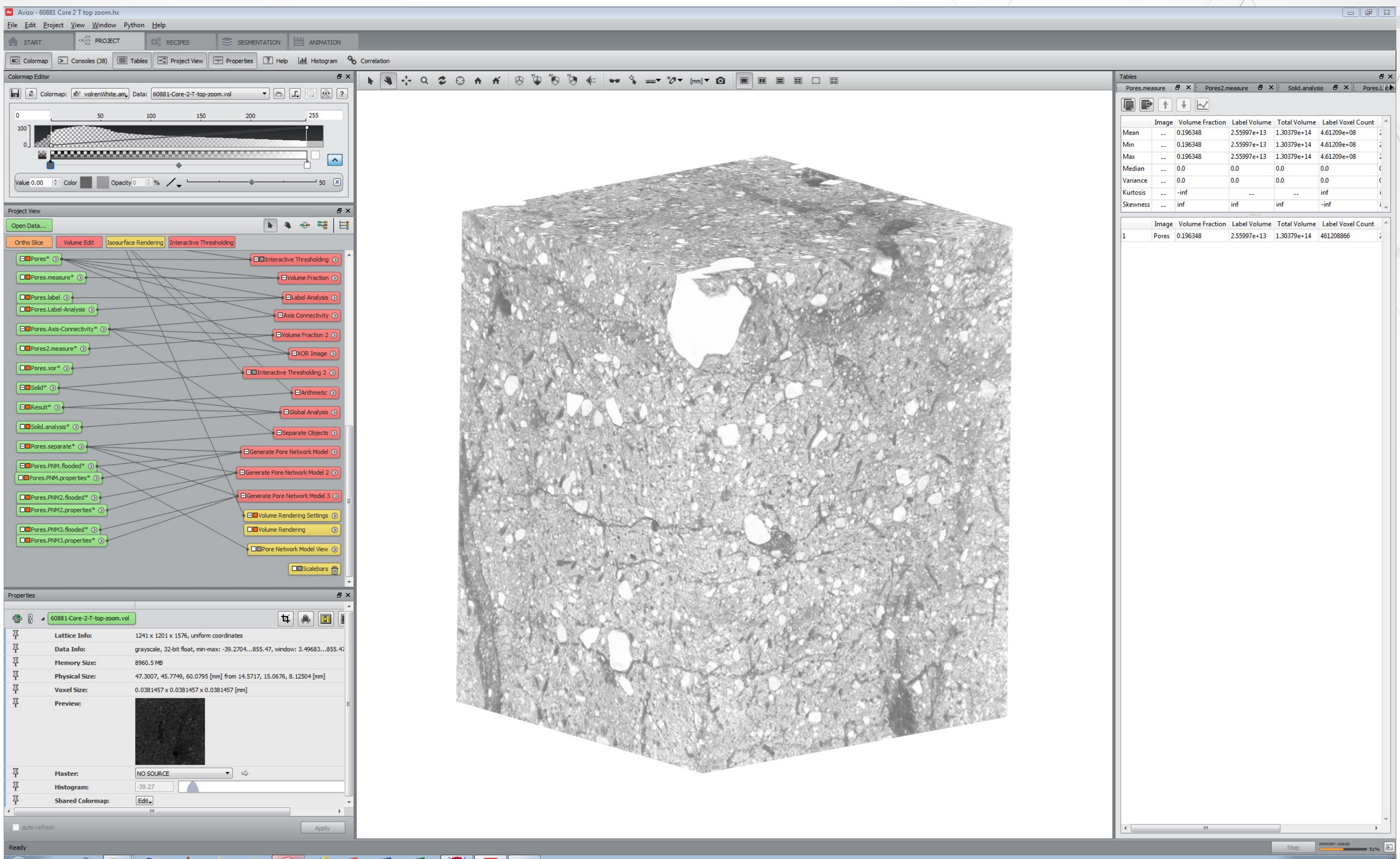
Importing the image

Reconstructed data read in as VGI volume (2D slice shown)



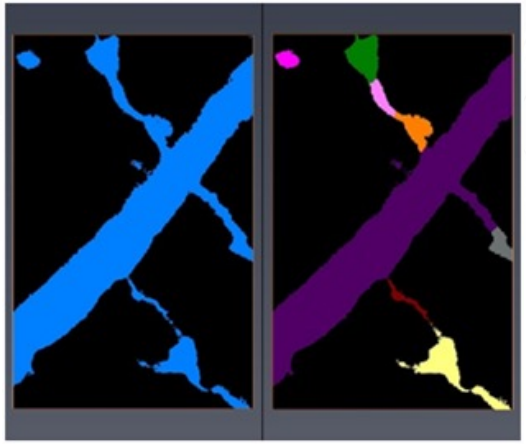
Visualization as 3D volume

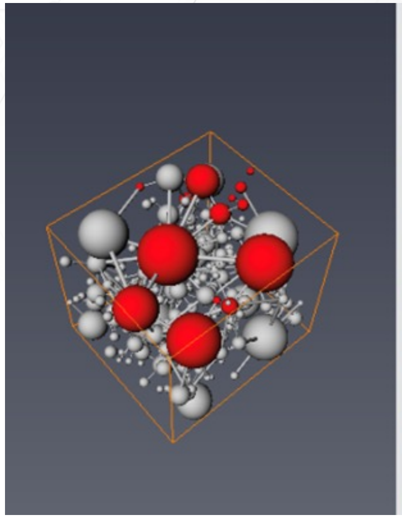
Initial look at the raw data as 3D volume



Porosity analysis – major steps

- Thresholding
- Volume fraction
- Measurement to calculate results
- Data analysis
- Pore network module (PNM-Xpore)

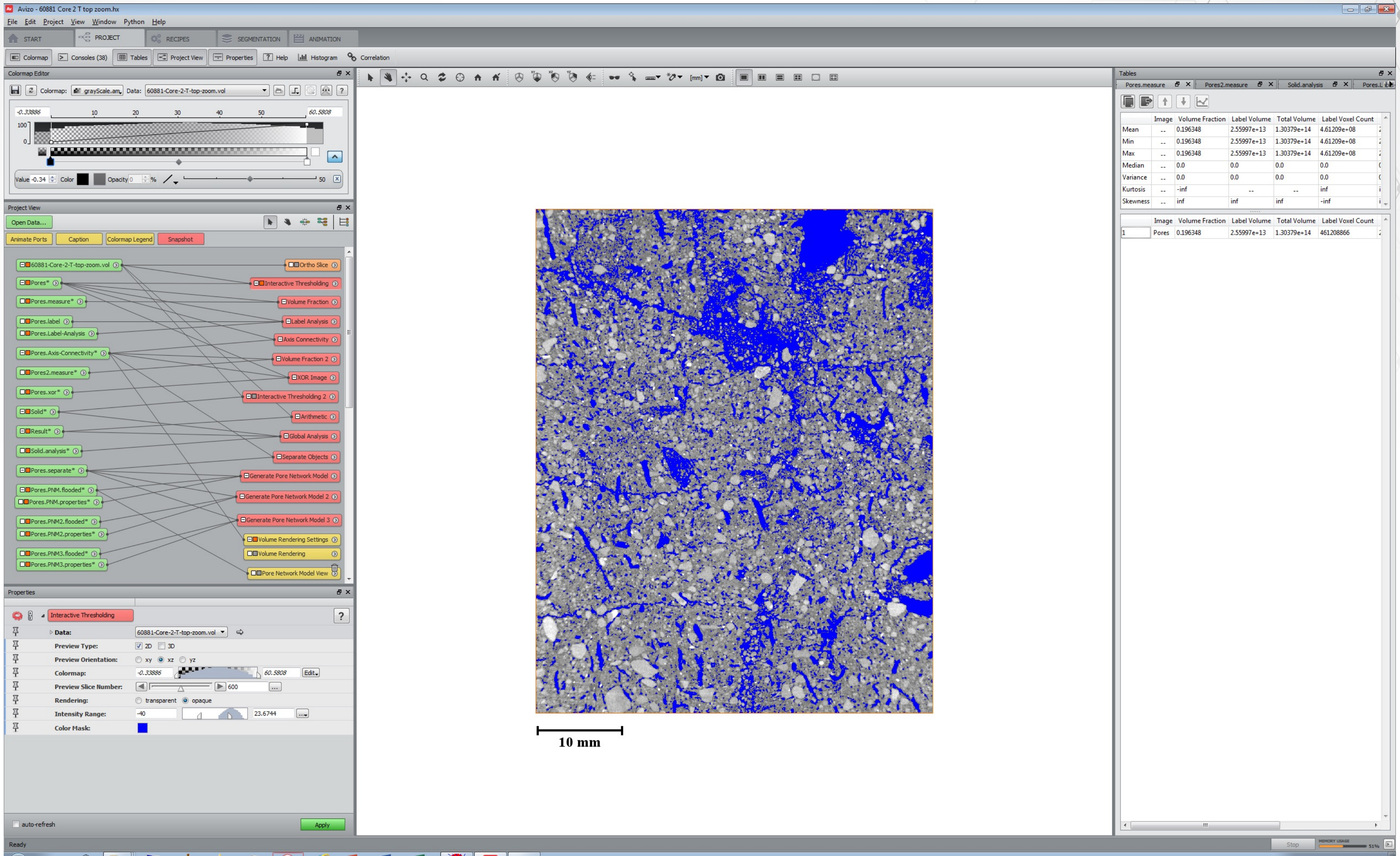




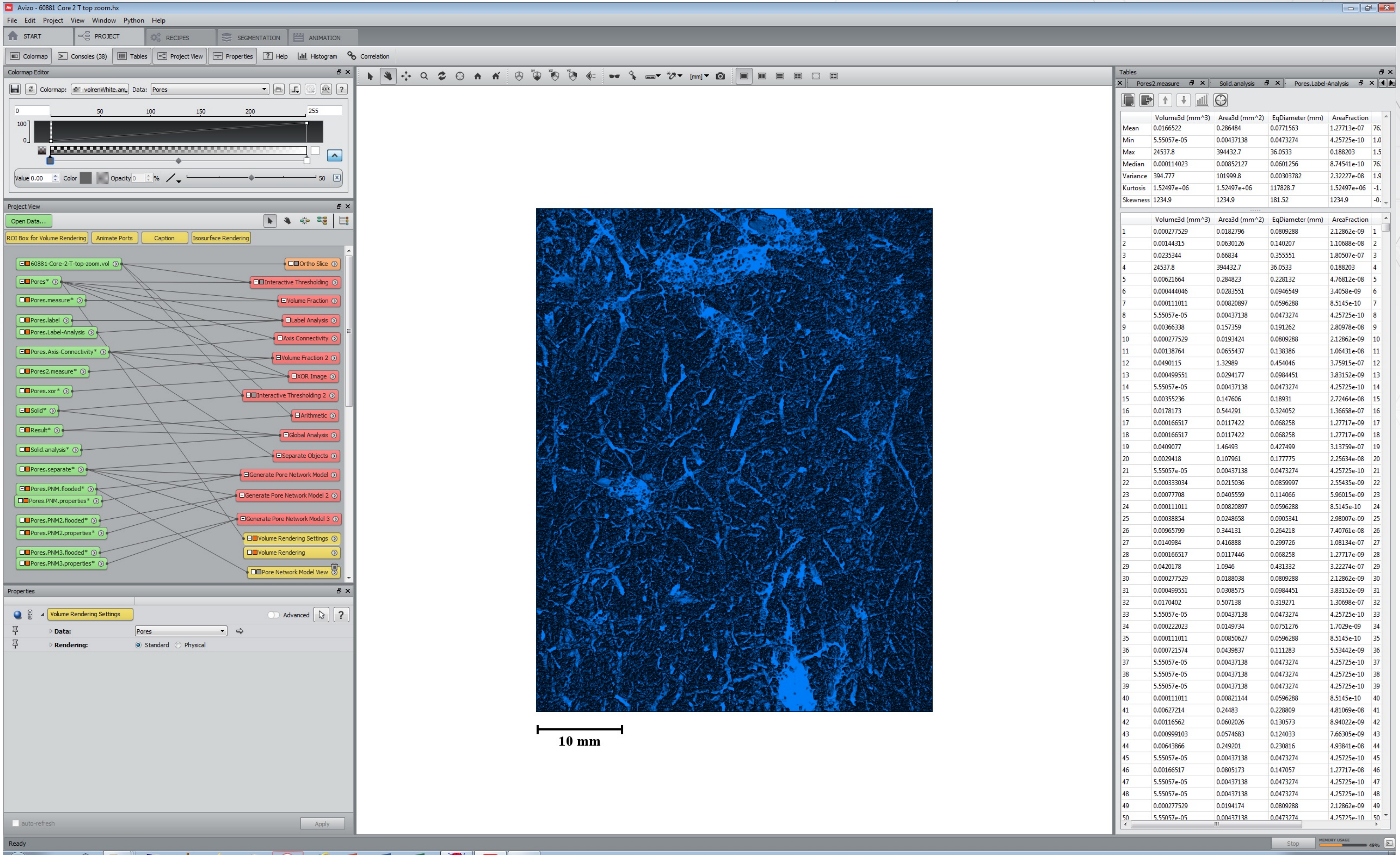
	Pore ID	Volume	Area	EqRadius
1	0	0.0780605	1.22915	0.265123
2	1	0.361577	3.40463	0.441947
3	2	0.138114	1.8833	0.320664
4	3	0.00145212	0.0639127	0.0702487
5	4	0.00497395	0.150073	0.105894
6	5	0.0012192	0.0690542	0.0662717
7	6	0.227738	2.95732	0.378834
8	7	0.0133686	0.86959	0.147231
9	8	0.537073	4.56064	0.504253
10	9	0.00510305	0.147367	0.106802
11	10	0.392412	3.24608	0.454169
12	11	0.00184743	0.110051	0.076119
13	12	0.703226	4.66303	0.551656
14	13	0.0356269	0.617245	0.204125
15	14	0.00127244	0.0578862	0.0672227
16	15	0.0140633	0.953941	0.149738
17	16	0.000535062	0.0344628	0.0503623

Image segmentation

Thresholding image for segmentation (manual or auto thresholding)



Porosity analysis – calculation of porosity numbers



Porosity analysis – additional analysis

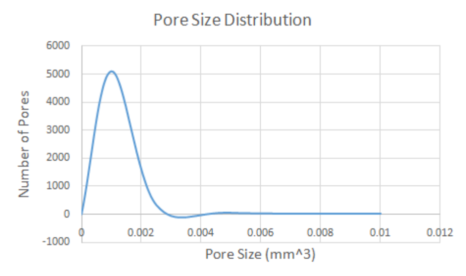
Volume 3d (mm^3)	Area 3d (mm^2)	Area Fraction	EqDiameter (mm)
0.000139044	0.0230534	3.21E-06	0.0642763
0.000123866	0.0196969	2.86E-06	0.0618469
6.02E-05	0.0113675	1.39E-06	0.0486132
0.000360536	0.0427944	8.33E-06	0.0883046
0.000373313	0.0427005	8.62E-06	0.0893356
0.00141959	0.116174	3.28E-05	0.13944
0.000600293	0.0769301	1.39E-05	0.104662
1.26E-05	0.00272518	2.90E-07	0.0288419
0.000179046	0.0196494	4.14E-06	0.0699287
8.33E-05	0.0110584	1.92E-06	0.0541867
3.28E-05	0.00572235	7.57E-07	0.0396978
4.07E-06	0.00155799	9.41E-08	0.0198142
0.00149119	0.125027	3.45E-05	0.141746
4.04E-05	0.00756834	9.34E-07	0.0425833
6.05E-05	0.00983177	1.40E-06	0.0487054
0.000146847	0.0239235	3.39E-06	0.0654569
4.55E-05	0.00834874	1.05E-06	0.0442901
0.000142731	0.0179058	3.30E-06	0.0648395
0.000101957	0.0160564	2.36E-06	0.0579614
0.000220763	0.0238131	5.10E-06	0.0749853
0.00119107	0.099855	2.75E-05	0.131516
0.000140416	0.0189657	3.24E-06	0.064487
0.000172572	0.0233842	3.99E-06	0.0690755
2.70E-06	0.0010156	6.24E-08	0.0172789
0.00144446	0.117543	3.34E-05	0.14025
2.57E-06	0.0010381	5.94E-08	0.0170001
0.00109391	0.0808837	2.53E-05	0.127838
0.00232588	0.162784	5.37E-05	0.164385
0.00184538	0.174773	4.26E-05	0.152182
1.89E-06	0.000840802	4.36E-08	0.0153304
2.02E-05	0.00549399	4.67E-07	0.0337864
2.97E-05	0.00553433	6.85E-07	0.0384094
3.33E-05	0.00746012	7.69E-07	0.0399045
0.000365938	0.0337306	8.45E-06	0.0887435
1.89E-06	0.000840802	4.36E-08	0.0153304
5.23E-05	0.00957845	1.21E-06	0.0463877
0.000795374	0.0634334	1.84E-05	0.114954
1.50E-05	0.00364637	3.48E-07	0.0306317
0.0130722	0.803633	0.000301998	0.292269
1.89E-06	0.000840802	4.36E-08	0.0153304
2.57E-06	0.0010381	5.94E-08	0.0170001
0.000147747	0.0195683	3.41E-06	0.0655904
0.00191042	0.175603	4.41E-05	0.153949
0.000625332	0.0512432	1.44E-05	0.106097
0.00173875	0.126984	4.02E-05	0.149192
0.000288034	0.0381073	6.65E-06	0.0819373
0.000330652	0.0383224	7.64E-06	0.0857941
6.15E-05	0.0104256	1.42E-06	0.0489687
2.96E-06	0.00123575	6.83E-08	0.0178109
4.81E-05	0.00868738	1.11E-06	0.0451366
0.00132312	0.0928468	3.06E-05	0.136207
4.65E-05	0.00758321	1.07E-06	0.0446079
0.000299825	0.0302504	6.93E-06	0.0830404
2.66E-06	0.000993522	6.14E-08	0.017187
1.56E-05	0.00357308	3.60E-07	0.0309769
0.00143979	0.120731	3.33E-05	0.140098
0.00167114	0.124861	3.86E-05	0.147233
3.69E-06	0.00125437	8.52E-08	0.0191676

Pore Volume %	Intensity Range Upper Threshold	Colormap Lower Threshold	Colormap Upper Threshold	Voxel Size (mm)	Dimensions of Subvolume
3.6372%	17.04	-6.4	40.88	0.0035	1150 X 548 X 1602

Filtering Options	Neiborhood	Pixel Size Excluded
	6	3

Bins- Pore Size (mm^3)	Number of Pores
0	0
0.001	5101
0.0025	332
0.005	52
0.01	22
0.02	5
0.04	1
0.08	1

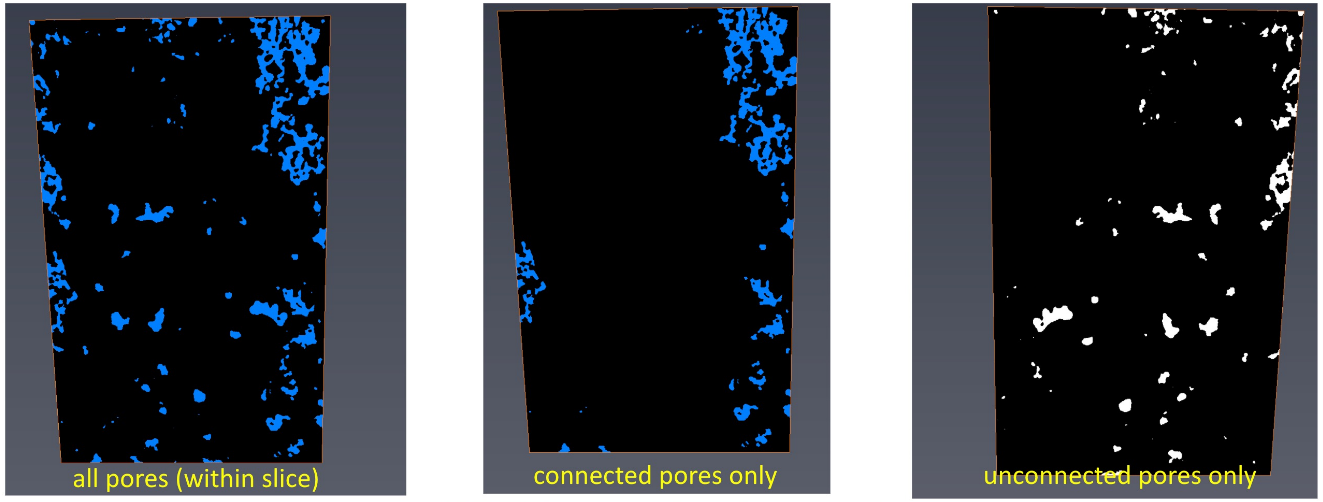
Average Pore Size (mm^3)	Min Pore Size (mm^3)	Max Pore Size (mm^3)
2.86E-04	1.8865E-06	4.38E-02



Sheet1

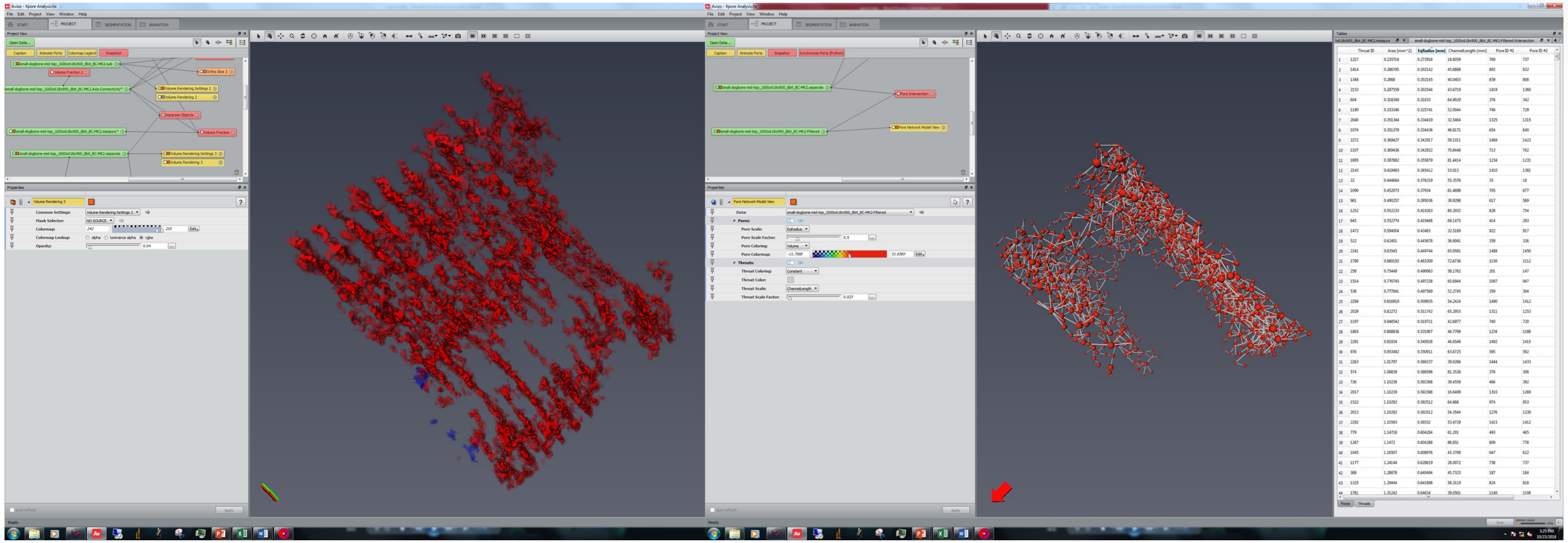
Pore Network Modeling (PNM) – major steps

- Thresholding
- Axis connectivity
- Volume fraction
- Image subtraction
- Separate objects
- Pore Network Model

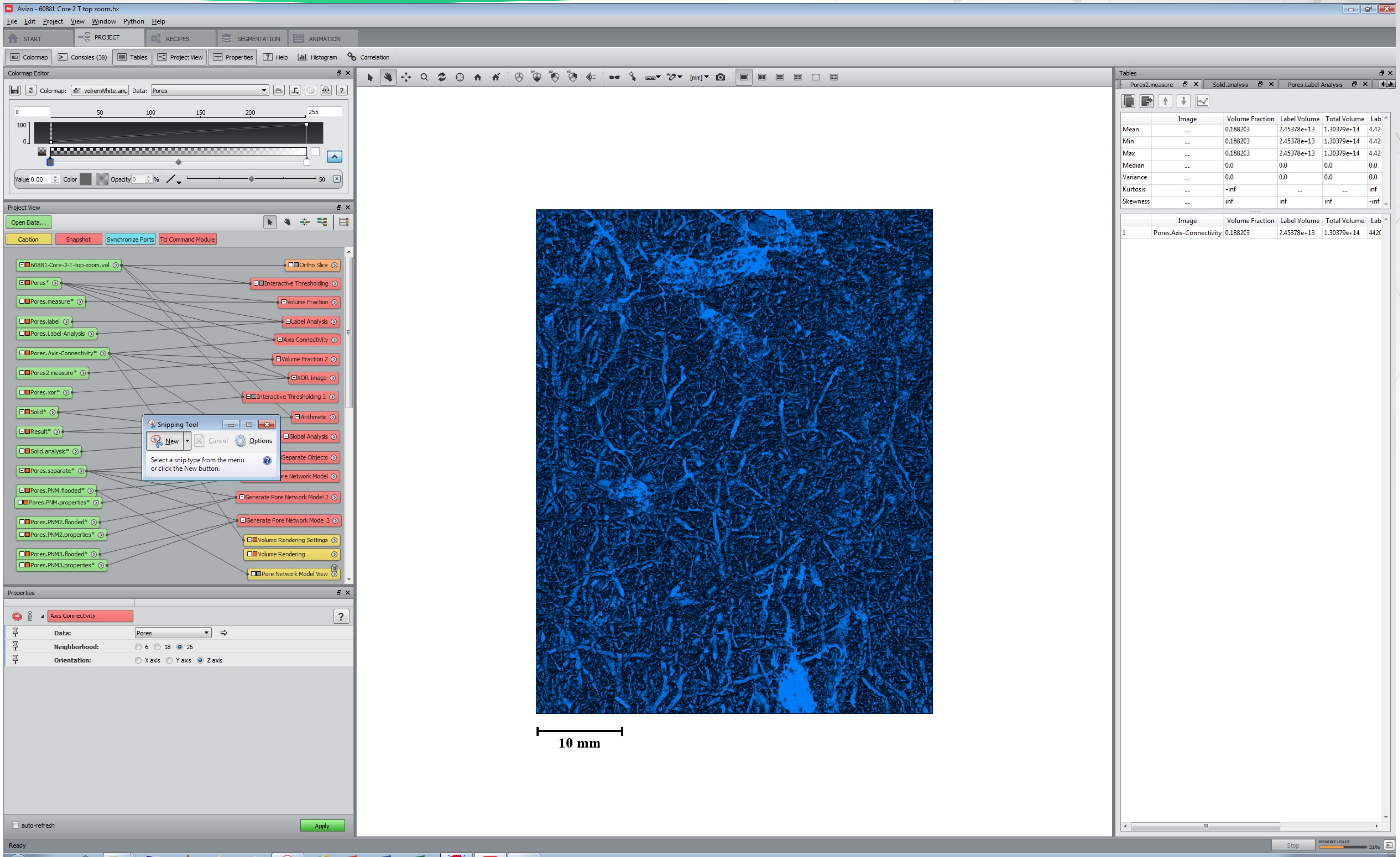


Volume Fraction	Label Volume	Total Volume	Label Voxel Count	Total Voxel Count
0.0919473	5.11411e+07	5.562e+08	5.11411e+07	5.562e+08

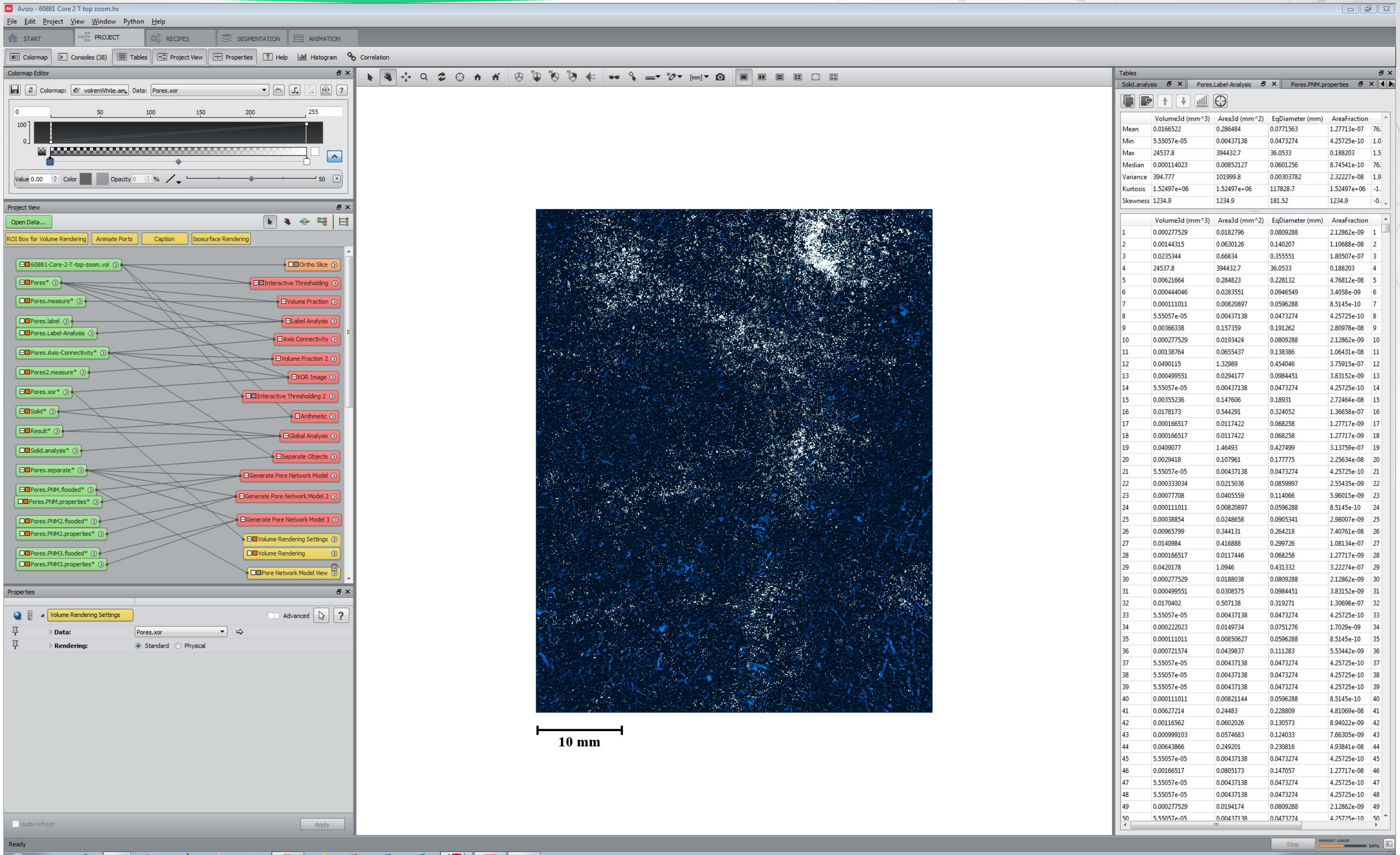
Volume Fraction	Label Volume	Total Volume	Label Voxel Count	Total Voxel Count
0.0498319	2.77165e+07	5.562e+08	2.77165e+07	5.562e+08



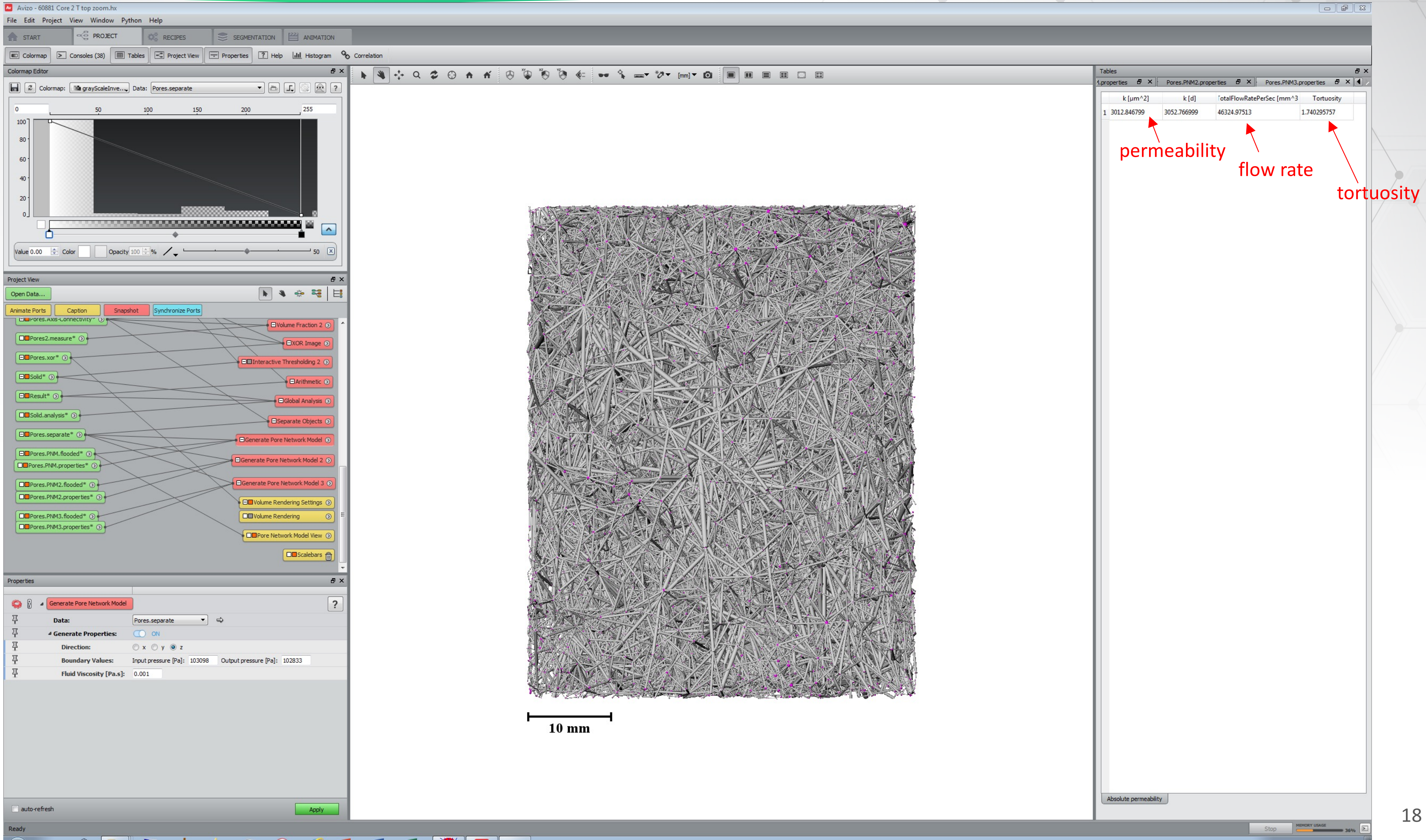
Pore Network Modeling – Axis connectivity



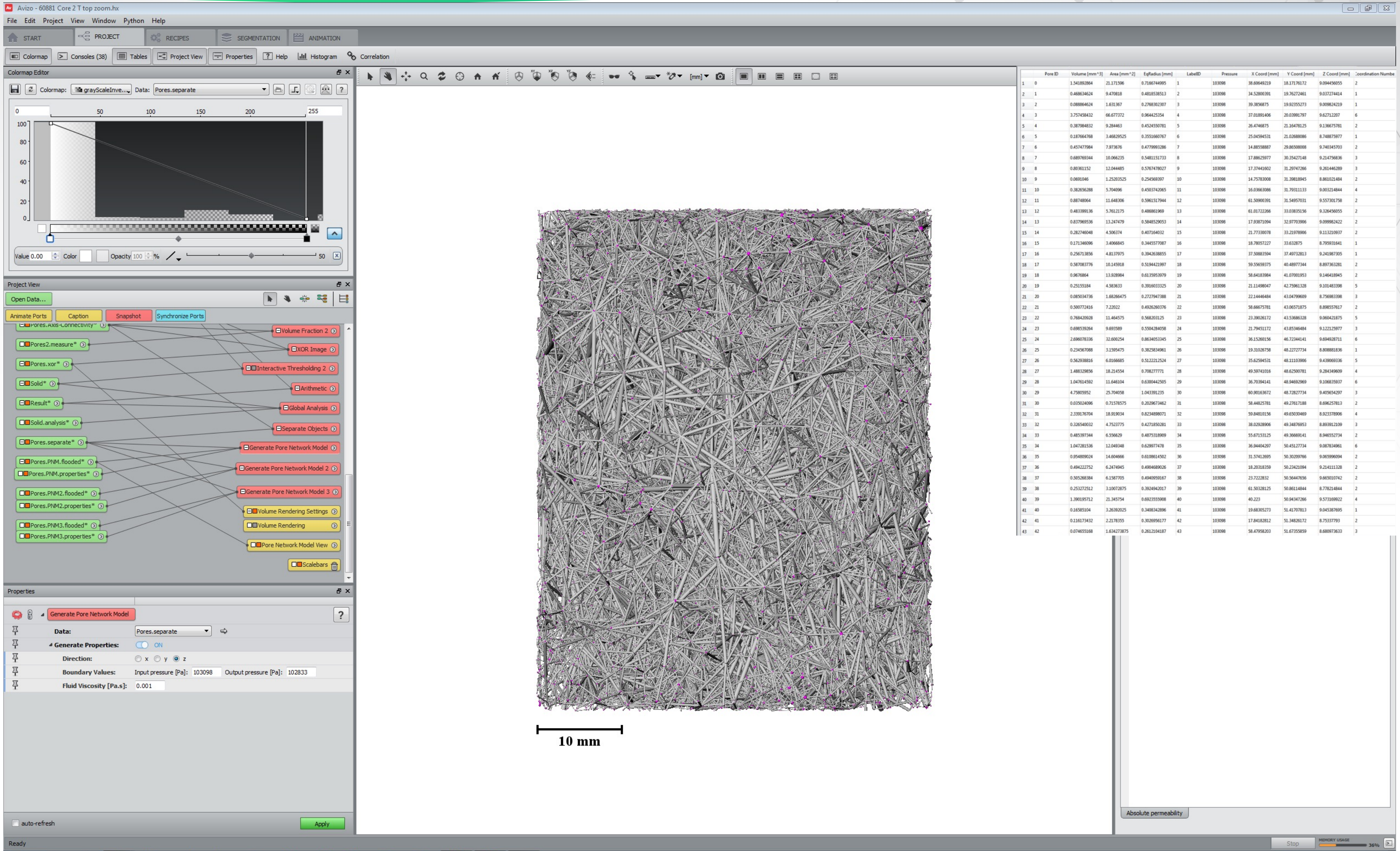
Pore Network Modeling – Volume fraction (unconnected *vs* connected)



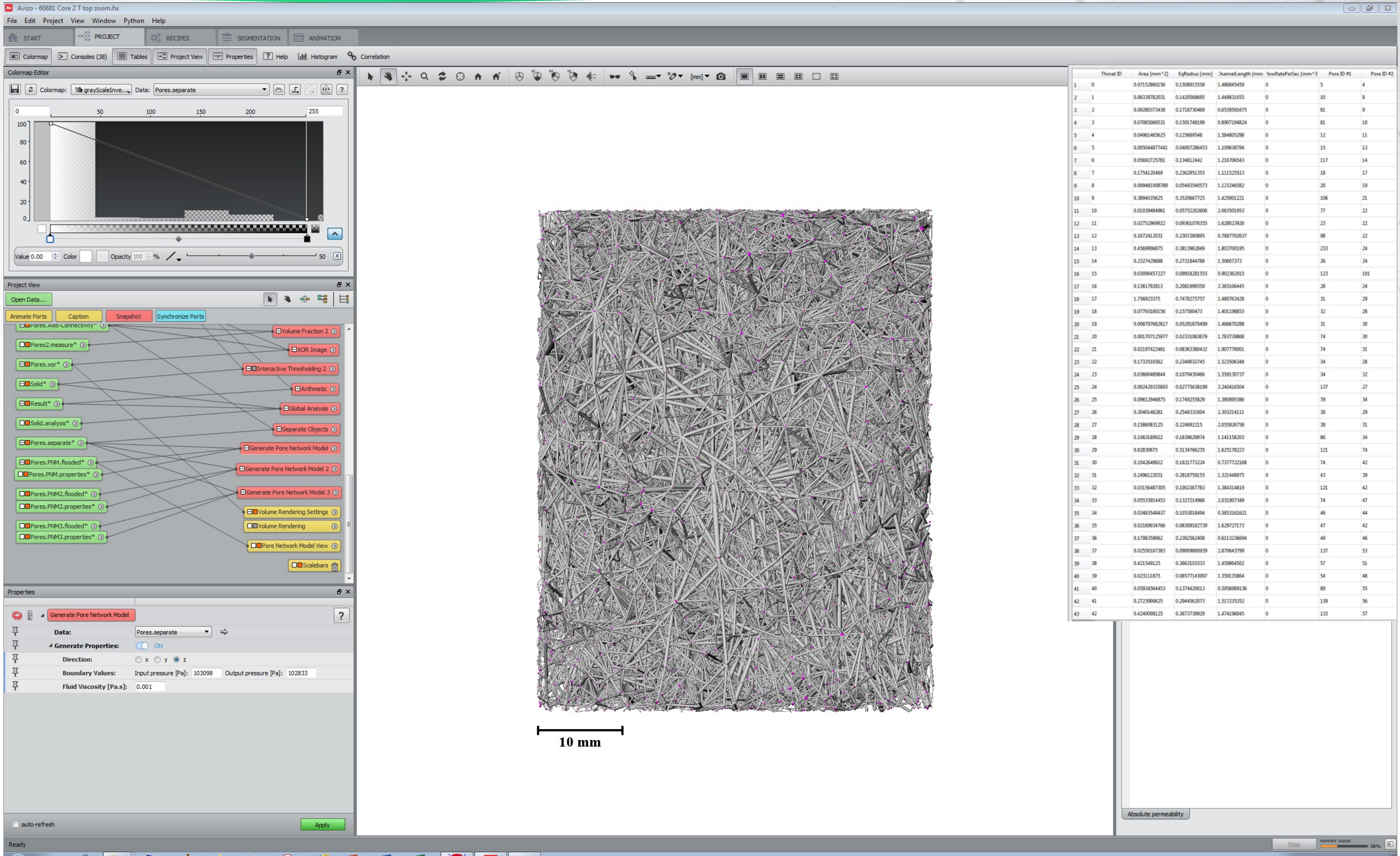
Pore Network Modeling – Calculation of results



Pore Network Modeling – Calculation of results



Pore Network Modeling – Calculation of results

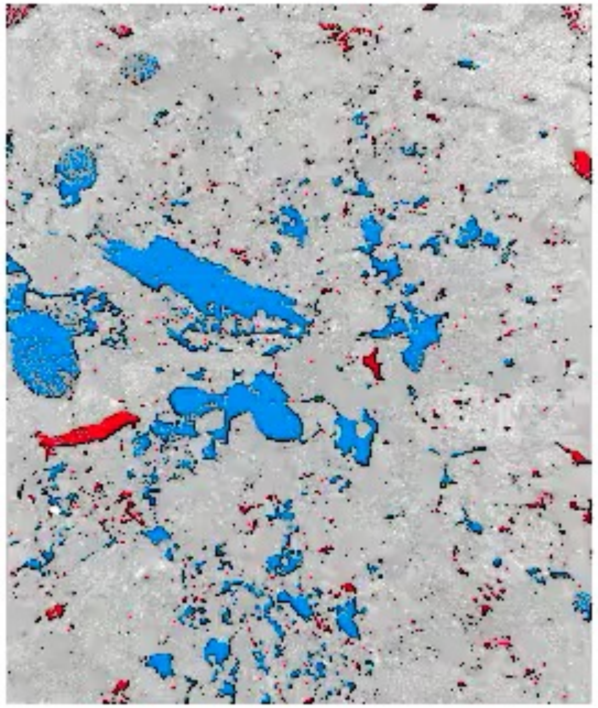


	Throat ID	Area [mm^2]	EqRadius [mm]	ChannelLength [mm	FlowRatePerSec [mm^3	Pore ID #1	Pore ID #2
1	0	0.07152860156	0.1508915558	1.486845459	0	5	4
2	1	0.06339782031	0.1420568695	1.449831055	0	10	8
3	2	0.09280373438	0.1718730469	0.6539591675	0	81	9
4	3	0.07085069531	0.1501748199	0.8907194824	0	81	10
5	4	0.04961465625	0.125669548	1.584805298	0	12	11
6	5	0.005044877441	0.04007286453	1.109638794	0	15	13
7	6	0.05692725781	0.134612442	1.216706543	0	117	14
8	7	0.1754120469	0.2362951355	1.111525513	0	18	17
9	8	0.009481008789	0.05493540573	1.123246582	0	20	19
10	9	0.3894035625	0.3520667725	1.425001221	0	106	21
11	10	0.01039484961	0.05752202606	2.063501953	0	77	22
12	11	0.02752969922	0.09361076355	1.628023926	0	23	22
13	12	0.1672412031	0.2307260895	0.7887702637	0	98	22
14	13	0.4569906875	0.3813982849	1.803700195	0	233	24
15	14	0.2327429688	0.2721844788	1.50607373	0	26	24
16	15	0.03090457227	0.09918281555	0.902362915	0	123	101
17	16	0.1361792813	0.2081999359	2.365106445	0	28	24
18	17	1.756923375	0.7478275757	1.480763428	0	31	29
19	18	0.07793160156	0.157500473	1.401198853	0	32	28
20	19	0.008797682617	0.05291870499	1.466670288	0	31	30
21	20	0.001707125977	0.02331083679	1.783739868	0	74	30
22	21	0.02197422461	0.08363380432	1.907776001	0	74	31
23	22	0.1733516562	0.2349032745	1.523506348	0	34	28
24	23	0.03660489844	0.1079430466	1.559130737	0	34	32
25	24	0.002420335693	0.02775638199	3.240416504	0	137	27
26	25	0.09612946875	0.1749255829	1.380895386	0	78	34
27	26	0.2040148281	0.2548331604	2.303214111	0	38	29
28	27	0.1586083125	0.224692215	2.055926758	0	38	31
29	28	0.1063189922	0.1839629974	1.141158203	0	86	34
30	29	0.82830675	0.5134766235	1.625178223	0	121	74
31	30	0.1042649922	0.1821773224	0.7377722168	0	74	42
32	31	0.2496122031	0.2818759155	1.321448975	0	43	39
33	32	0.03156487305	0.1002367783	1.384314819	0	121	42
34	33	0.05533914453	0.1327214966	2.031907349	0	74	47
35	34	0.03483548437	0.1053018494	0.5853161621	0	46	44
36	35	0.02169034766	0.08309182739	1.629727173	0	47	42
37	36	0.1798359062	0.2392562408	0.6113236694	0	49	46
38	37	0.02550167383	0.09009680939	2.870643799	0	137	53
39	38	0.421549125	0.3663103333	1.459864502	0	57	51
40	39	0.023111875	0.08577143097	1.359135864	0	54	48
41	40	0.05934564453	0.1374420013	0.5956989136	0	89	55
42	41	0.2723900625	0.2944562073	1.517235352	0	139	56
43	42	0.4240008125	0.3673739929	1.474196045	0	133	57

Other data output options

- Image data:
  - Animations
  - Mesh
  - STL file (3D printing)
  - …

- Numerical data:
  - Pore throats
  - Pore coordination numbers

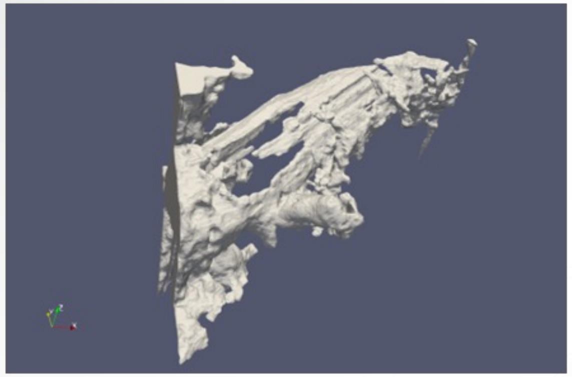


Other software

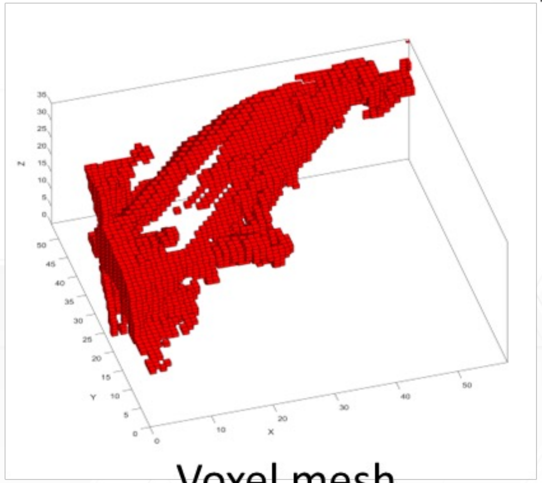
- Visual Graphics Studio, Dragonfly (license)
- ImageJ/Fiji, ParaView (free)
- Modeling:
  - OpenPNM:
    - https://openpnm.org/
    - https://github.com/PMEAL/OpenPNM
  - PoresPy:
    - https://porespy.org/
  - PFLOTRAN:
    - https://www.pflotran.org/
  - OpenFOAM:
    - https://www.openfoam.com/

How this data can be used: Example 1 – Flow & transport modeling

- Incorporate XCT segmented data to build flow and transport model



XCT image with connected pores



Voxel mesh

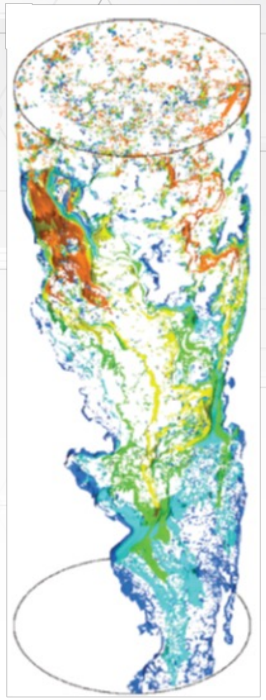


Image from Scheibe et al., 2014 WRR

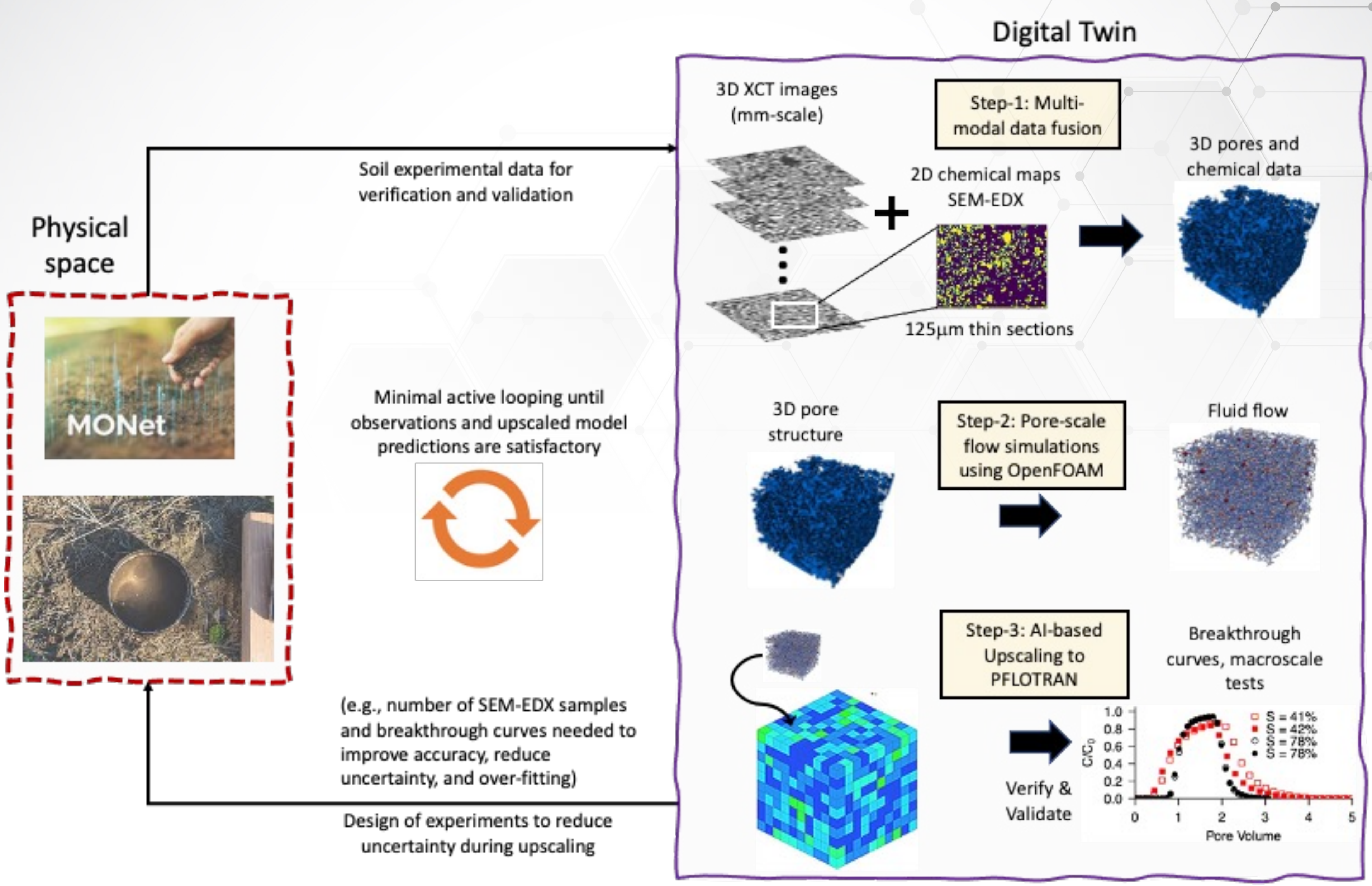
CFD model

- TETHYS

i. Multiphase simulation – VOF (volume of fluid) method
   - Multiple immiscible fluids.
   - Fluids surface tension and contact angle.

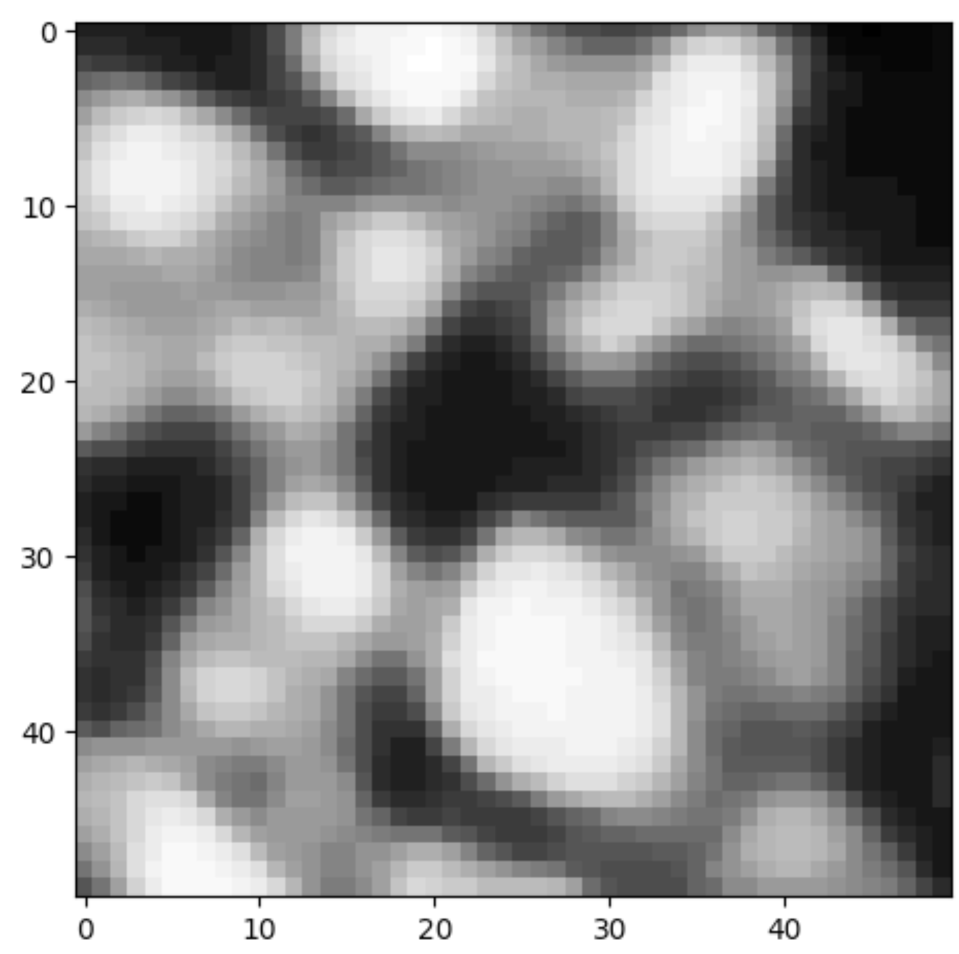
ii. Reaction engine – BIOGEOCHEM (Fang et al. 2003)
   - Individual species specified (aqueous, solid, gas, mobile, immobile).
   - Reactions: Equilibrium, Kinetic (forward/backward) or user defined.
   - Needs more robust testing and validation

How this data can be used: Example 2 – XCT to PFLOTRAN (work-in-progress)



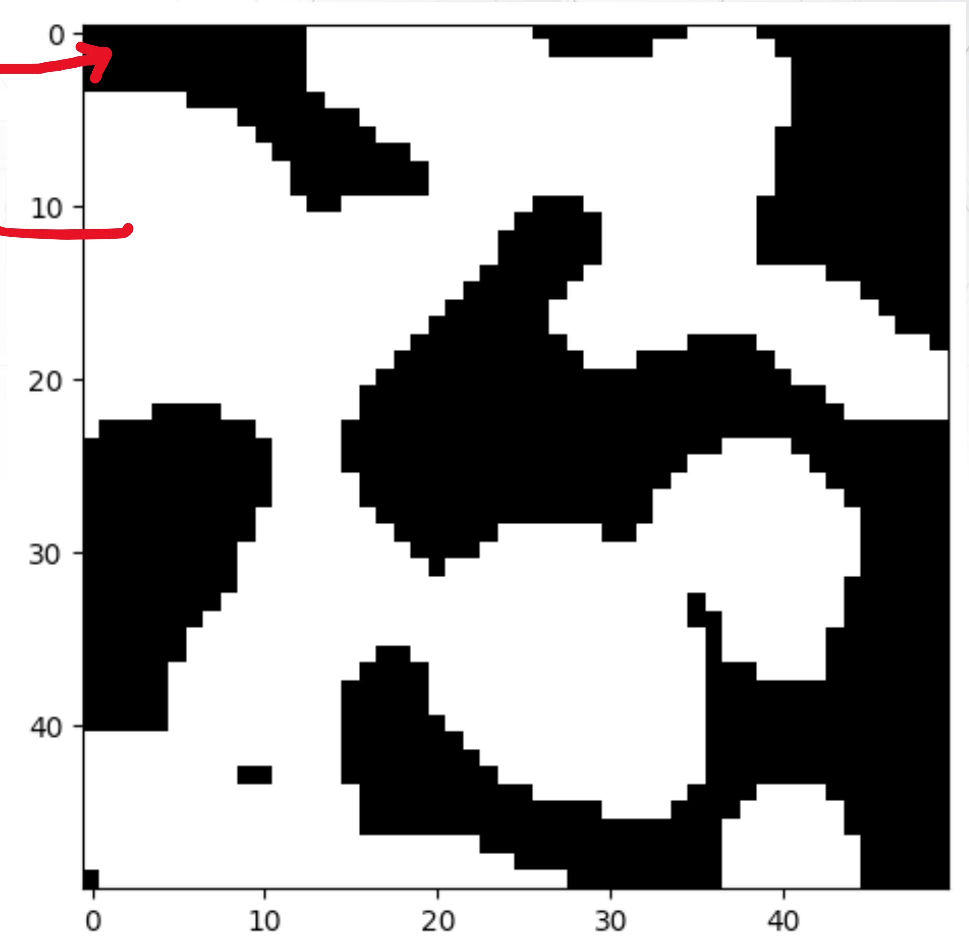
How this data can be used: Example 2 – XCT to PFLOTRAN (work-in-progress)

Raw XCT image (sub-set)



Assign material properties (e.g., permeability, porosity)

Segmented XCT image (sub-set)



How this data can be used: Example 2 – XCT to PFLOTRAN (work-in-progress)

PFLOTRAN | About | Bitbucket | Installation | Documentation | Parallel Performance | Development Team | Publications

PFLOTRAN

A Massively Parallel Reactive Flow and Transport Model for describing Subsurface Processes

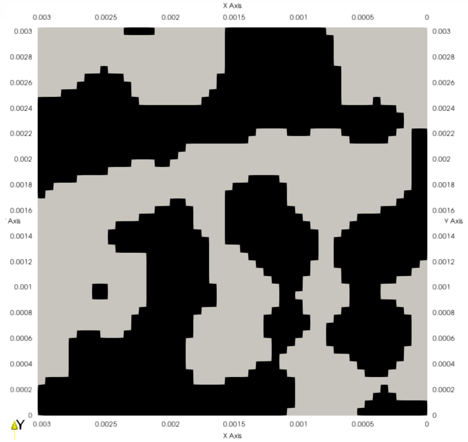
What is PFLOTRAN?

PFLOTRAN is an open source, state-of-the-art massively parallel subsurface flow and reactive transport code. PFLOTRAN solves a system of generally nonlinear partial differential equations describing multiphase, multicomponent and multiscale reactive flow and transport in porous materials. The code is designed to run on massively parallel computing architectures as well as workstations and laptops. Parallelization is achieved through domain decomposition using the PETSc (Portable Extensible Toolkit for Scientific Computation) libraries. PFLOTRAN has been developed from the ground up for parallel scalability and has been run on up to 2^18 processor cores with problem sizes up to 2 billion degrees of freedom. PFLOTRAN is written in object oriented, free formatted Fortran 2003. The choice of Fortran over C/C++ was based primarily on the need to enlist and preserve tight collaboration with experienced domain scientists, without which PFLOTRAN's sophisticated process models would not exist.The reactive transport equations can be solved using either a fully implicit Newton-Raphson algorithm or the less robust operator splitting method.

Process models:

- Flow
- Reactive-transport
- Energy balance
- Reaction sandbox

MESH



How this data can be used: Example 2 – XCT to PFLOTRAN (work-in-progress)

```
# Description: Reaction Sandbox Simple (A + B --> C + D)
# Number of reaction network parameters: D = 7
# Sobol-based GSA: N * (2D+2) samples for first and second-order indices

#=============================================================================
SIMULATION
  SIMULATION_TYPE SUBSURFACE
  PROCESS_MODELS
    SUBSURFACE_TRANSPORT transport
      MODE GIRT
    /
  /
END
#=============================================================================

SUBSURFACE

#========================== constraints ======================================
# modify these initial concentration
CONSTRAINT initial
  CONCENTRATIONS # [mol/L]
    Aaq  1.d-3   F
    Baq  5.d-4   F
    Caq  1.d-10  F
    Daq  1.d-10  F
    Eaq  1.d-10  F
  /
  IMMOBILE     # [mol/m^3 bulk]
    Xim  1.d-4
    Yim  1.d-10
  /
END

#========================== chemistry ========================================
CHEMISTRY
  PRIMARY_SPECIES
    Aaq
    Baq
    Eaq
    Caq
    Daq
  /
  IMMOBILE_SPECIES
    Yim
    Xim
  /
```

Carbon degradation modeling using PFLOTRAN

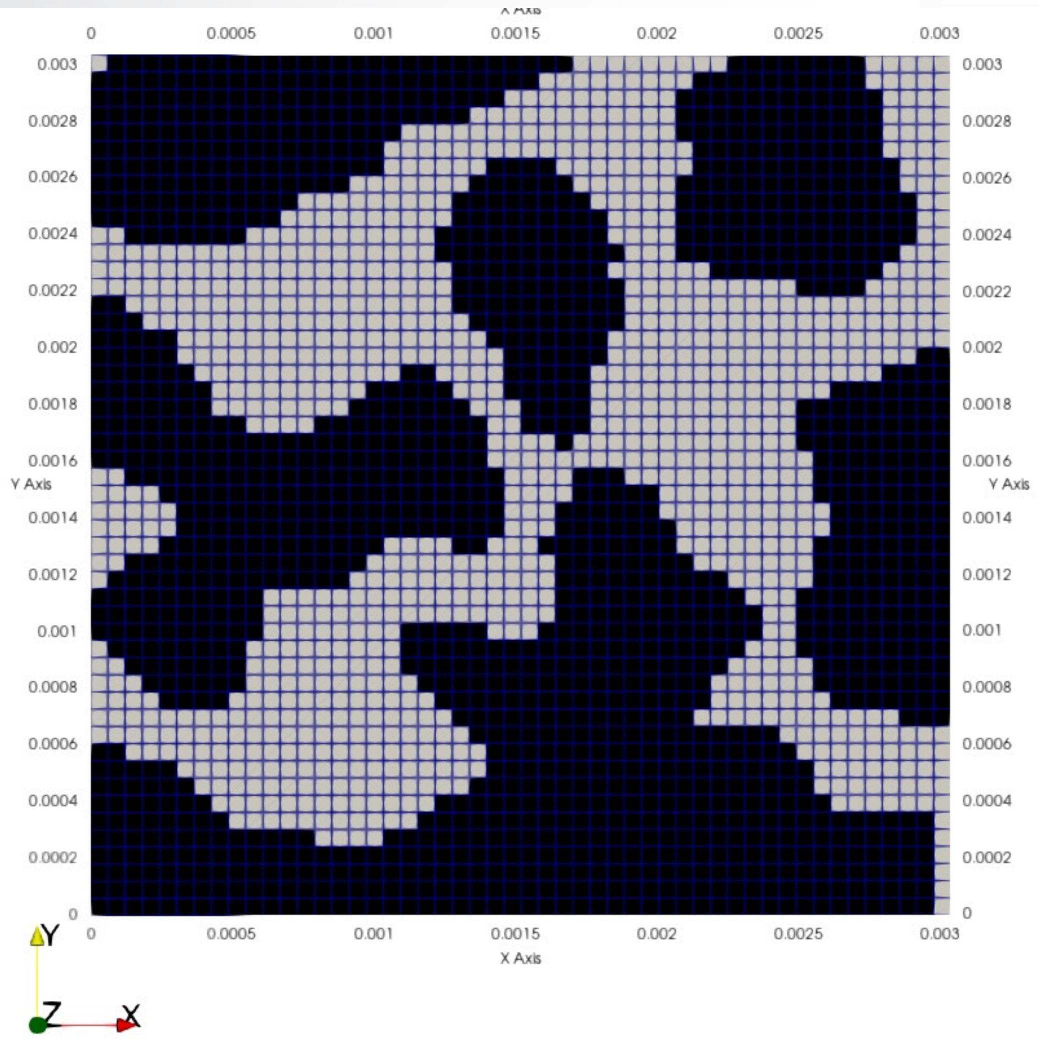
Process models:

- Flow
- Reactive-transport
- Energy balance
- Reaction sandbox

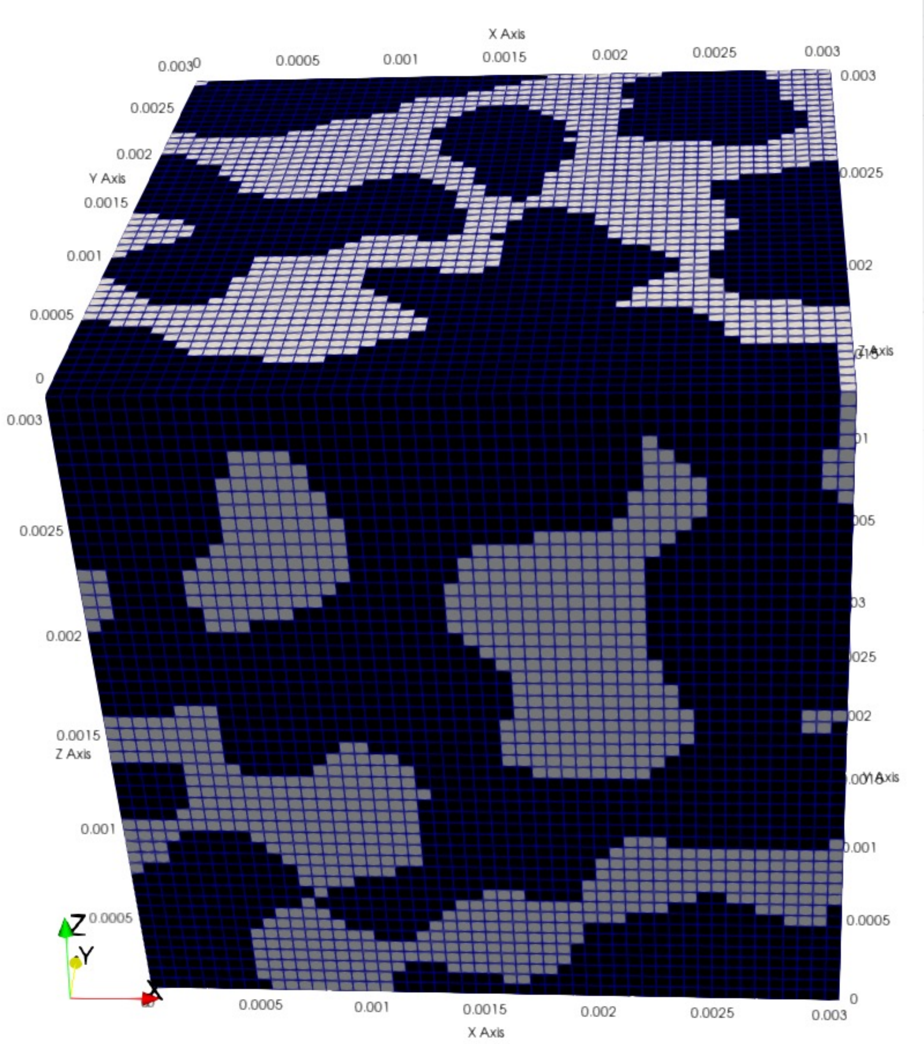
Example:
PFLOTRAN input deck for numerical simulations

How this data can be used: Example 2 – XCT to PFLOTRAN (work-in-progress)

2D view of the mesh for PFLOTRAN

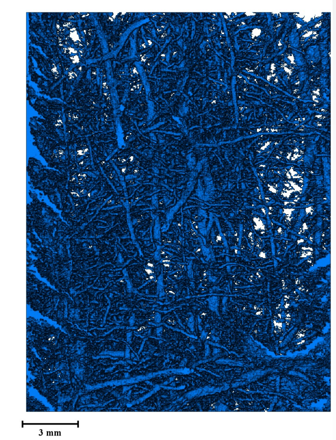


3D mesh for PFLOTRAN

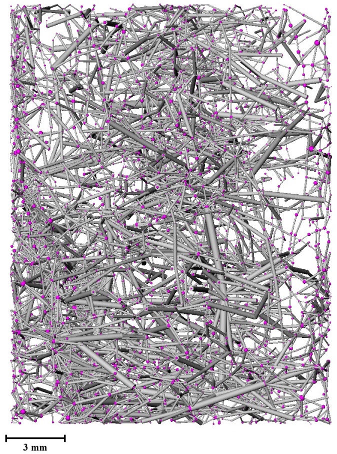


How this data can be used: Example 3 – Pore network modeling

XCT (AVIZO)

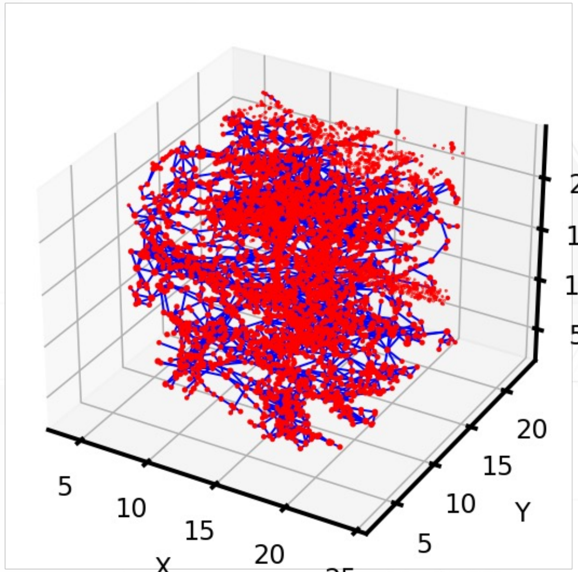


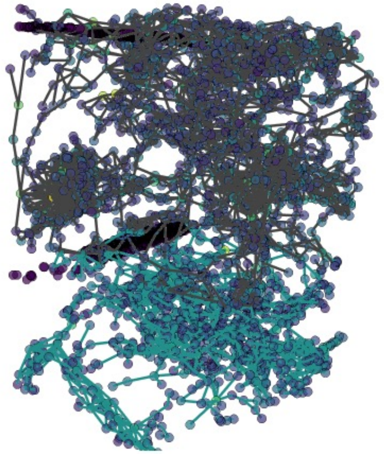
Connected pores



Pore Network Model

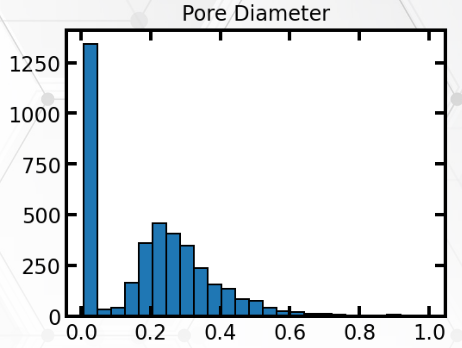
OpenPNM



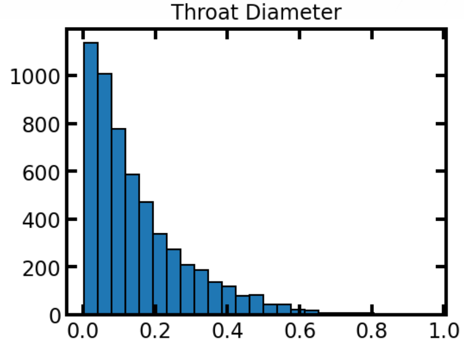


Reconstructed pore network

Probability distribution functions

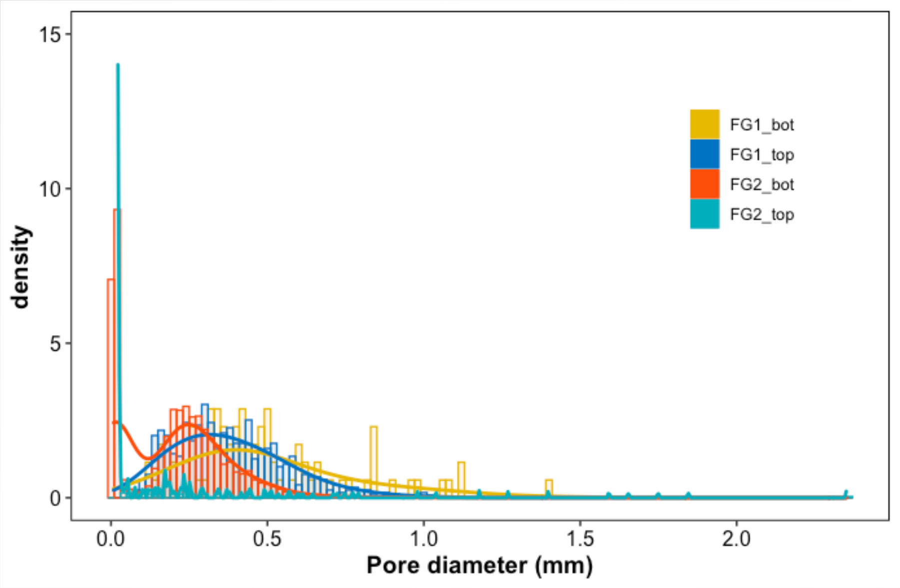


(mm)



(mm)

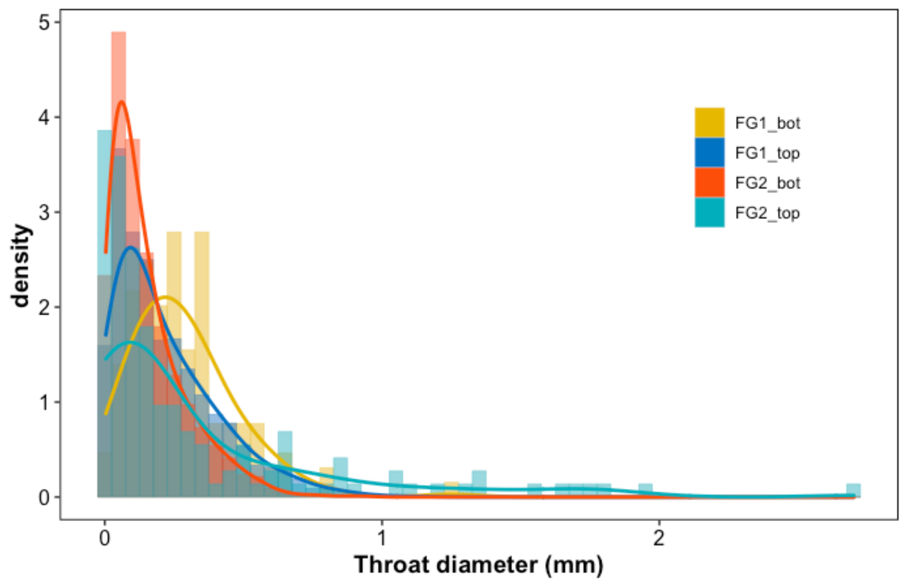
Example 3 - Geometry of pore network informs probability distribution functions (PDFs)

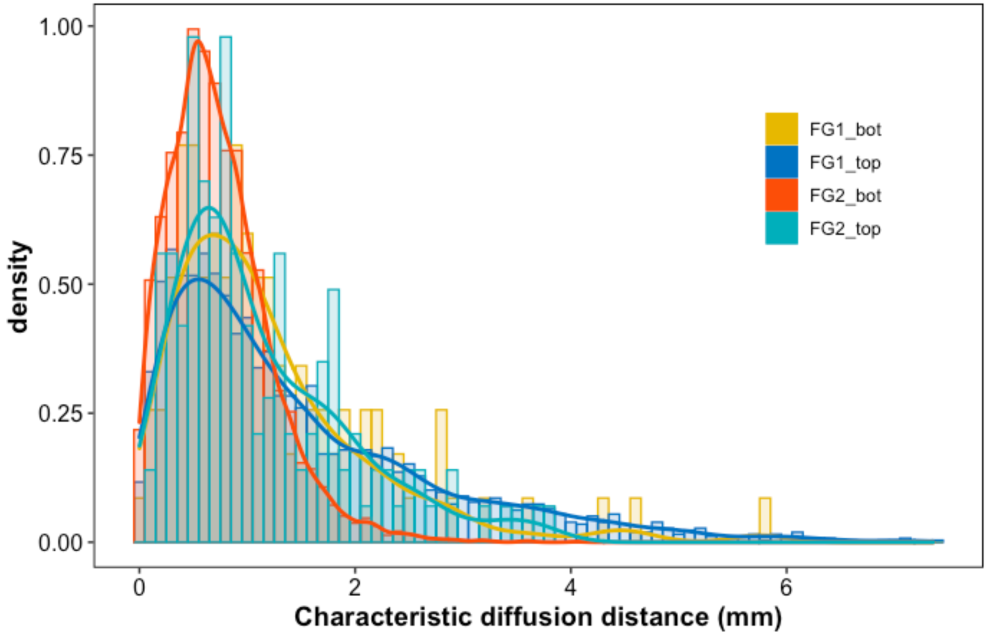


- Diffusion length calculated from pore diameter

$$L_{i,j} = L - (r_{pore,i} + r_{pore,j})$$

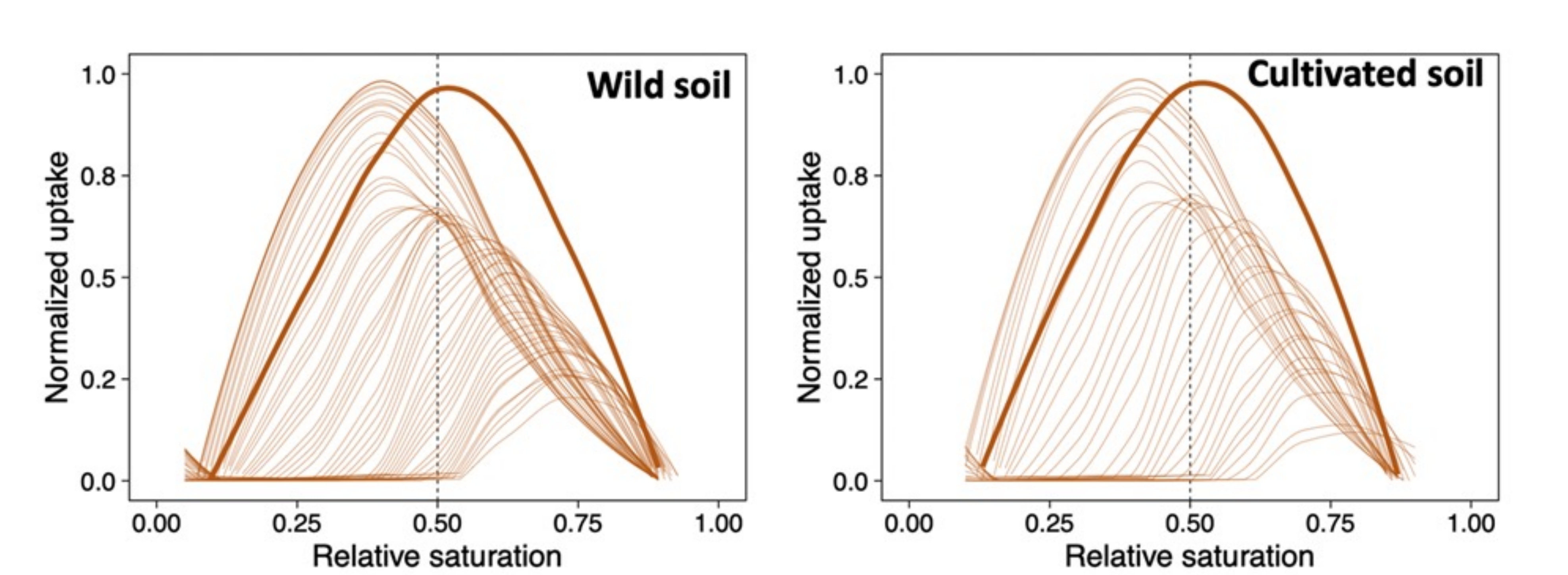
- Longer diffusion length for Cultivated soil due to its finer pore sizes and less pore connectivity





Example 3 - Implementation of porosity and SOM information in reactive transport modeling

Diffusion limited SOM decomposition kinetics



Soil respiration as normalized C uptake vs relative soil saturation compared for a “wild” and a cultivated soil. Soil respiration appears reduced in the cultivated soil relative to the “wild” due to reduced pore network connectivity.

References

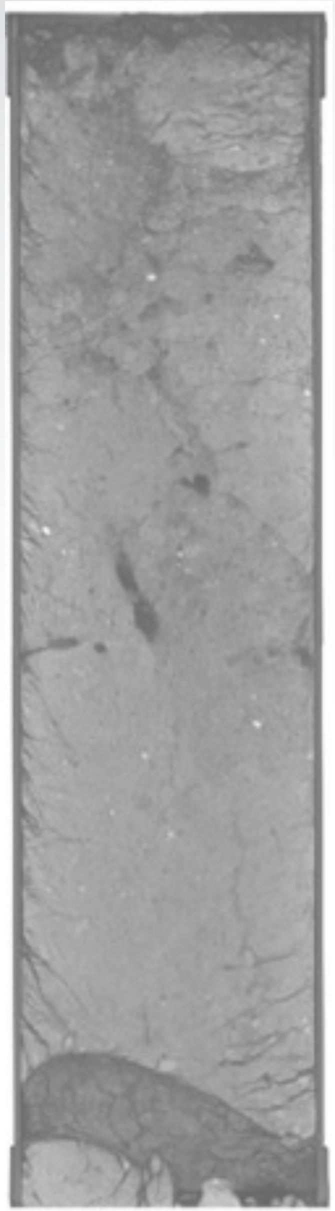
- Avizo: https://www.thermofisher.com/us/en/home/electron-microscopy/products/software-em-3d-vis/avizo-software.html
- ImageJ/Fiji: https://imagej.nih.gov/ij/download.html and https://fiji.sc/
- Modeling:
  - OpenPNM:
    - https://openpnm.org/
    - https://github.com/PMEAL/OpenPNM
  - PoresPy:
    - https://porespy.org/
  - PFLOTRAN:
    - https://www.pflotran.org/
  - OpenFOAM:
    - https://www.openfoam.com/

Questions?

EMSL

Extras

Our methodology to estimate bulk density from CT data



Estimate of bulk density is based on formula from Tanaka *et al.*, *Earth Planets Space*, **63**, 103–110, 2011:

$$HU = \frac{1000(\mu - \mu_w)}{\mu_w},$$

where HU means Hounsfield Units, μ is the grey value of a given voxel and μ_w is the grey value of water for our scan. μ_w was obtained from finding the average grey value of water in a previous scan with similar conditions. Then we used *HU*s to estimate the bulk density for a given pixel through the formula

$$\rho = \frac{0.677}{1000} HU + 1.0756.$$

Finally, we averaged the bulk densities for all pixels that are soil or pore (excluding wall porosity) to find the overall average bulk density of the scan.

Wet bulk density: $\approx$1.50 $\frac{g}{cm^3}$

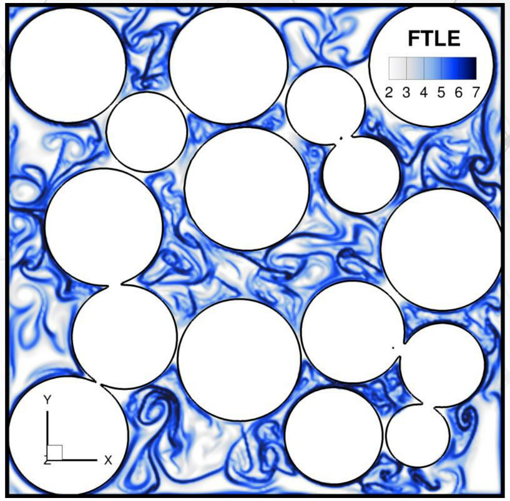
CFD - A bigger picture

Objective: Address the critical gap in our ability to translate molecular understanding and data to parameters for ecosystem-scale reactive transport models.

1. Spatial heterogeneity:

E.g., How convective water flow distributes soluble nutrients through the heterogeneous pore space?

- A direct visualization of 3D distribution with temporal evaluations
- A full spectrum of data set for detailed analysis

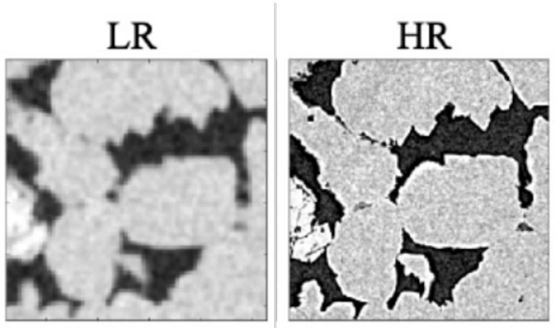


Finn 2013 Thesis

2. Spatial resolution:

Overall porosity measured from XCT data differs from that obtained in lab measurement

- Micro-continuum approach (*Scheibe et al., 2014 WRR, Soulaine et al., 2017 JFM*)
- Multi-resolution simulation framework (*Fukami et al. 2018 JFM*)
- Identify key spatial scales for specific physical/chemical/biological processes



Jackson et al. 2022 PRApplied

Question: How to translate the pore-scale dataset to reach-scale simulations?

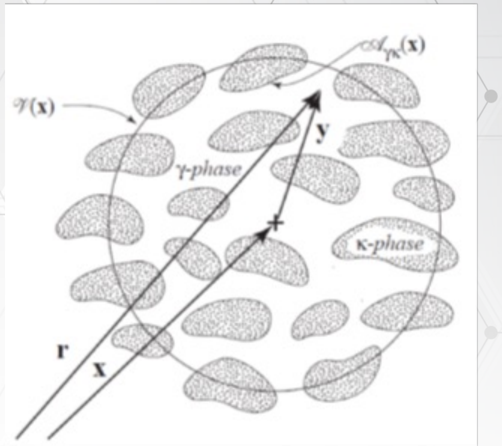
1. **Volume averaging:** equations that are valid for a particular phase can be spatially smoothed to produce equations valid everywhere
(Whitaker 1996; Soulaine et al., 2017 JFM; Wood, He and Apte, 2020 ARFM)

The volume average theorem for any quantity ψ in the fluid (γ) phase:

$$\langle \psi_\gamma \rangle = \frac{1}{V} \int_{\mathbf{r} \in \mathscr{V}_\gamma(\mathbf{X})} \psi_\gamma(\mathbf{r}) dV(\mathbf{r})$$

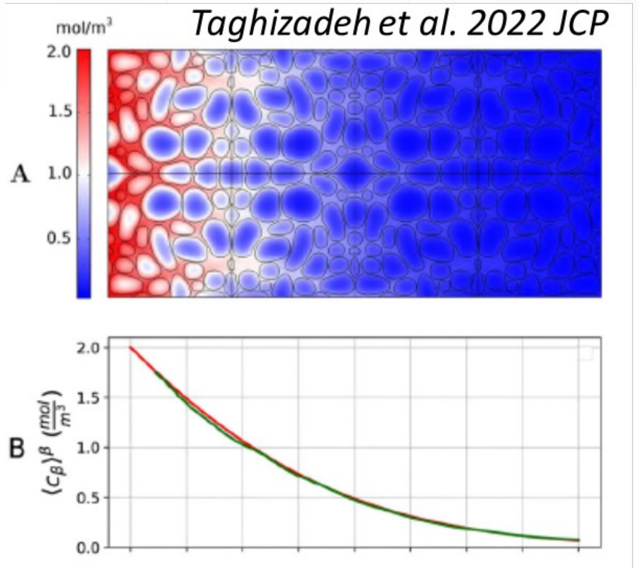
where V is the total volume in the averaging domain.

Whitaker 1996

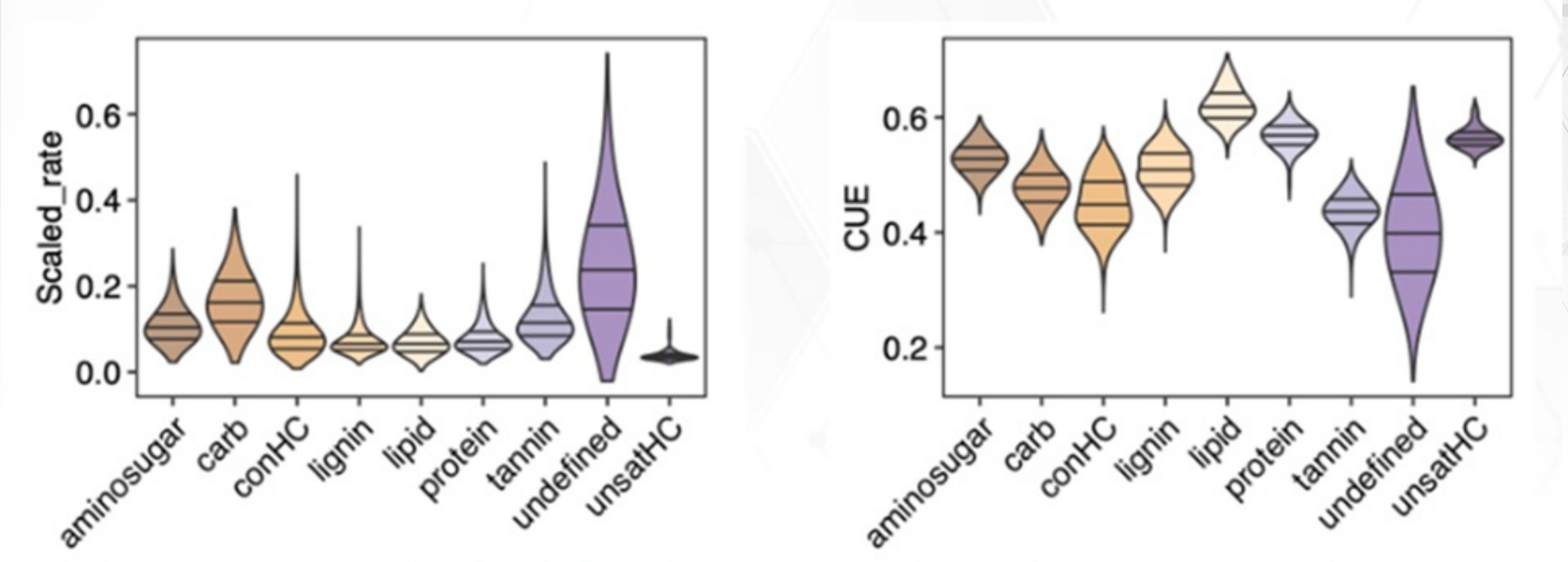


2. **Machine learning approach** (*Taghizadeh et al. 2022*)
   - Use a combination of formal upscaling and data-driven machine learning for explicitly closing a nonlinear transport and reaction process in multiscale tissues.
   - Utilize the datasets generated from high-resolution and the multi-resolution pore-scale simulations to train the ML networks to solve the nonlinear upscaling problem.

Taghizadeh et al. 2022 JCP



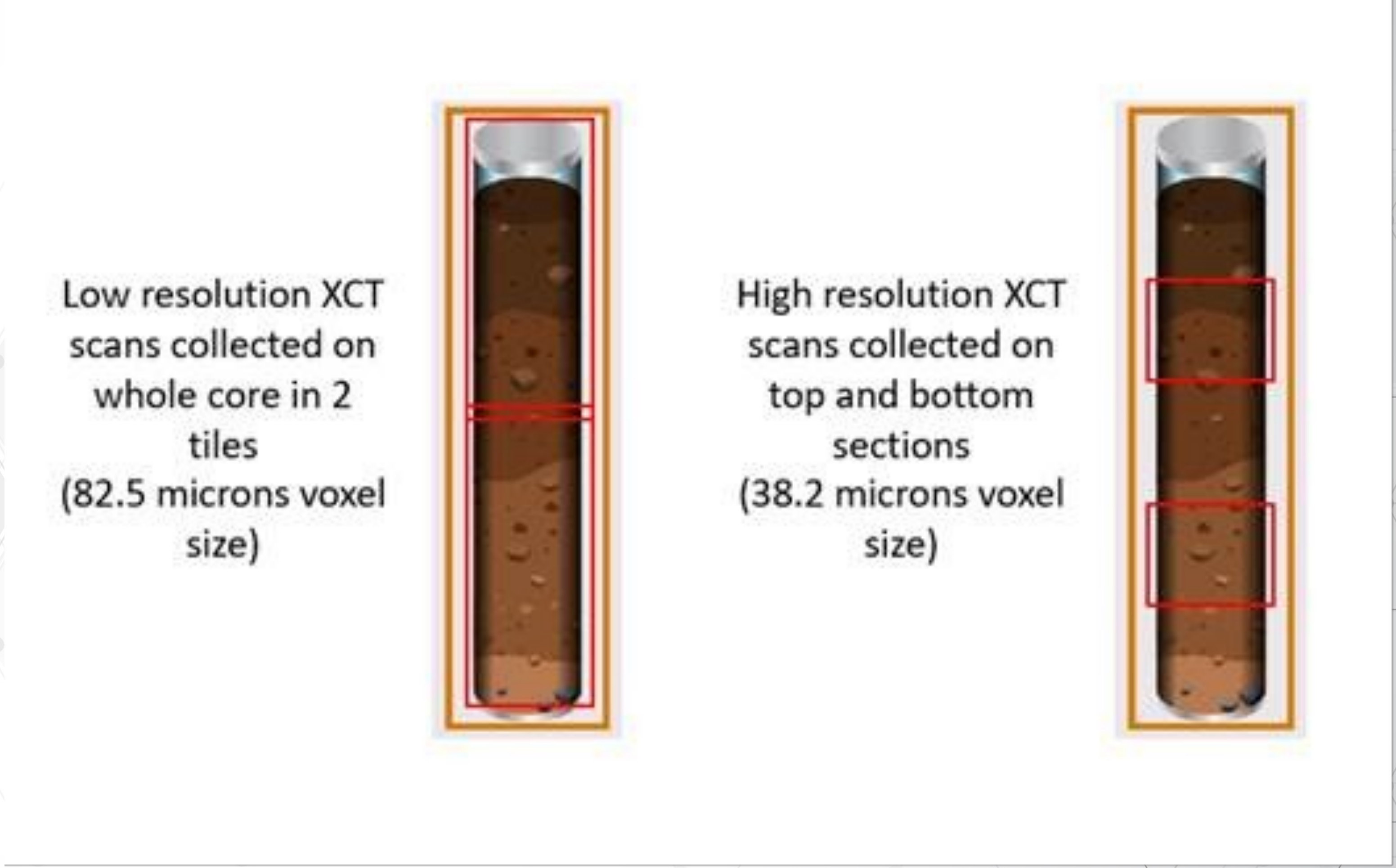
Example 2 – Connection to chemical information



Scaled rate and carbon use efficiency (CUE) were calculated based on molecular information on SOM from FTICR-MS data. Variations in SOM properties can lead to differences in the rate and efficiency of decomposition.

XCT analysis on a typical MONet soil core at EMSL

Tamas Varga



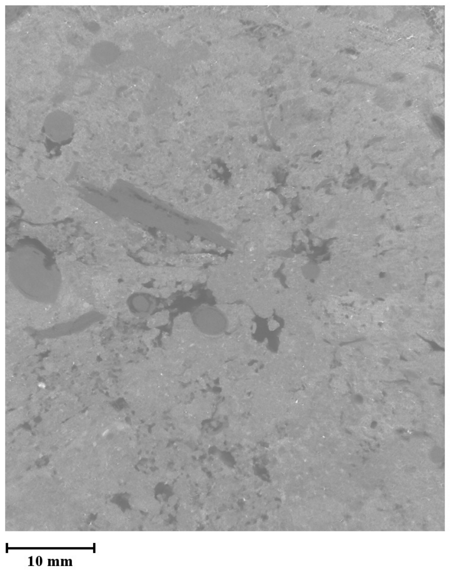
Whole core (merged low-resolution data on top and bottom sections)

Tomographic image of whole core in XZ plane view

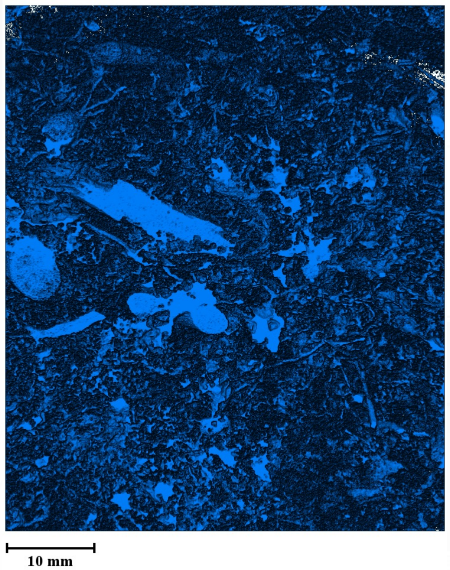
The two lower-resolution (82.5 micron voxel size, estimated spatial resolution 165 microns) scans are used to get the overall image of the whole 1-ft tall core. This image has been stitched together from two tiles as suggested in the title.

Scan conditions:
X-ray power: 105 kV and 325 μA
Projections: 1600
Frames/projection: 2
Exposure time: 500 ms
Filter: 0.5-mm Cu foil
Voxel size is 82.5 microns

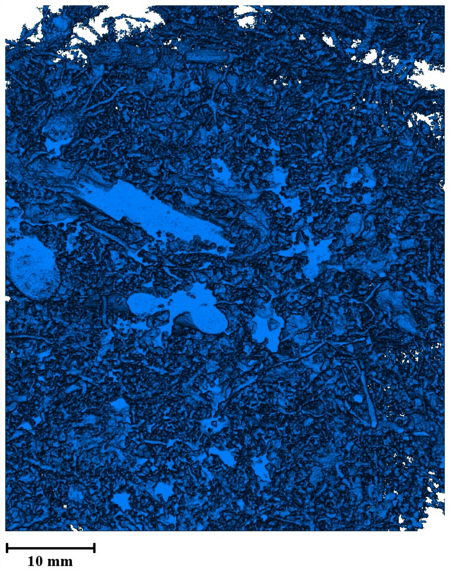
Higher-resolution scan (with 38.2-micron voxel size) on the top section of core



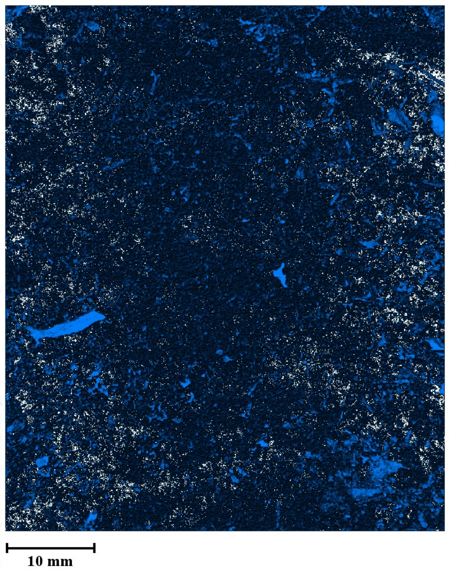
Reconstructed, cropped volume



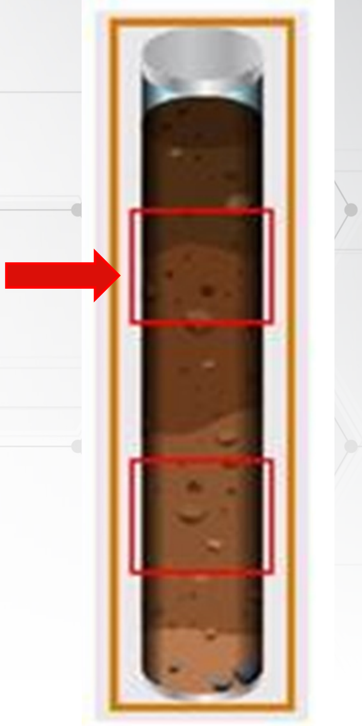
Visualizing all pores



Only connected pores



Only unconnected pores



- Total Porosity: 10.97 %
- Connected Pores Percentage: 89.75 %
- Wet Bulk Density: $\approx 2.05 \frac{g}{cm^3}$

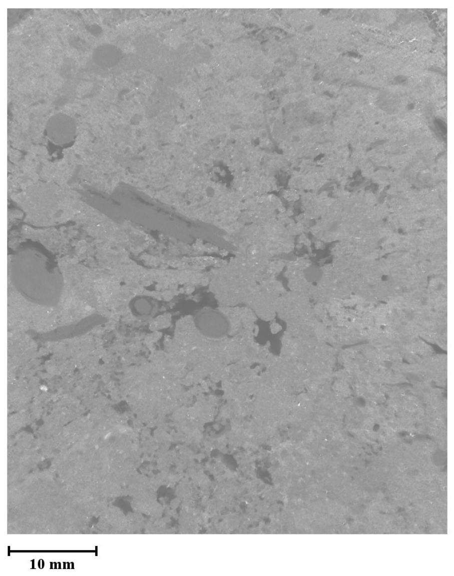
- Mean Pore size: 0.06448 mm
- Min Pore size: 0.047327 mm
- Max Pore size: 29.63071 mm
- Median Pore size: 0.047338 mm
- Variance Pore size: 0.001942 mm
- Mean Pore Volume: 0.005736 mm^3

Cropped volume size analyzed here:

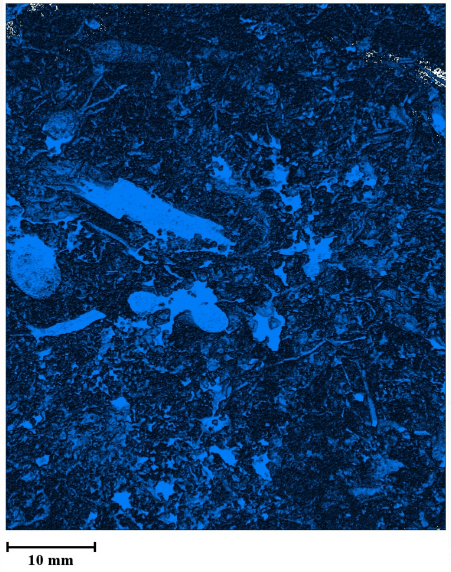
50x45x60 mm

XZ plane view, clip

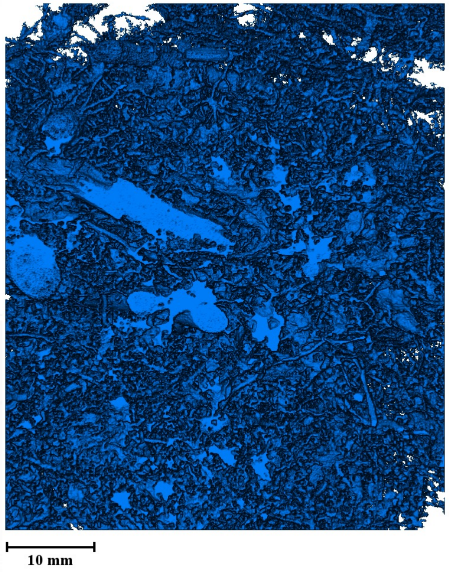
Pore network modeling (PNM) results on higher-resolution data from top section of core



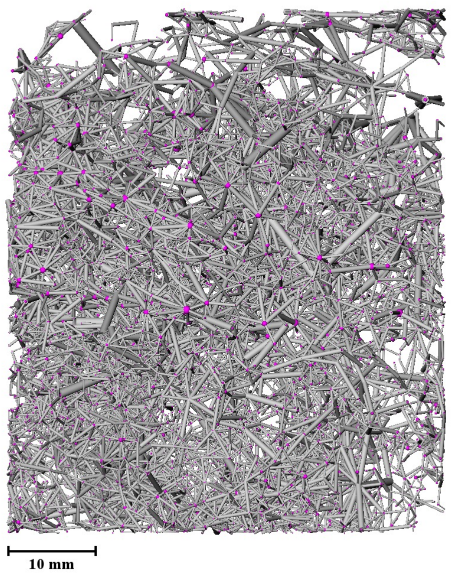
Reconstructed, cropped volume



Visualizing all pores



Only connected pores



PNM

Pore Network Model in Z-direction

- Absolute permeability: 109.69 μm^2
- Total flow rate: 1102.00 mm^3
- Tortuosity: 1.80

Pore Network Model in Y-direction

- Absolute permeability: 2882.55 μm^2
- Total flow rate: 50706.88 mm^3
- Tortuosity: 1.52

Pore Network Model in X-direction

- Absolute permeability: 379.04
- Total flow rate: 5450.30 mm^3
- Tortuosity: 1.76

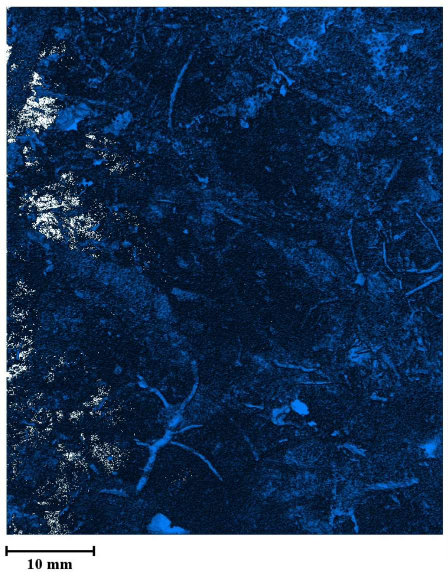
Input pressure: 103098 Pa,
Output pressure: 102833 Pa,
Fluid viscosity: 0.001 Pa.s

Cropped volume:

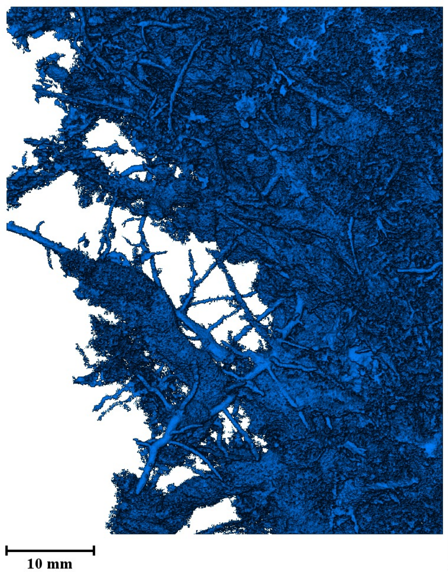
50x45x60 mm

Higher-resolution scan (with 38.2-micron voxel size) on bottom section of core

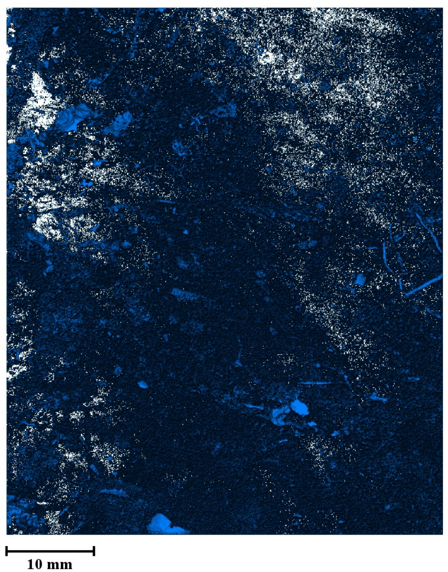
Raw volume



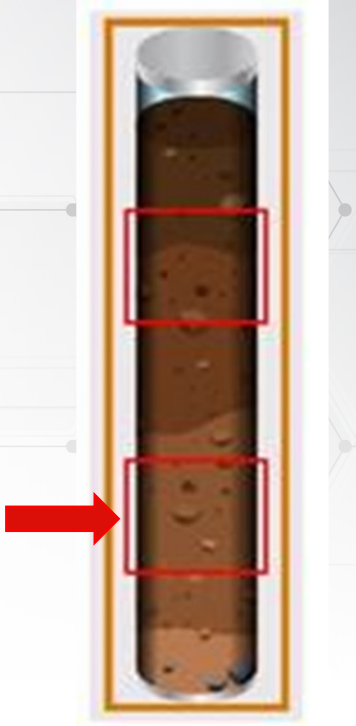
Visualizing all pores



Only connected pores



Only unconnected pores



- Total Porosity: 10.22 %
- Connected Pores Percentage: 89.06 %
- Wet Bulk Density: $\approx 2.48\ \frac{g}{cm^3}$

- Mean Pore size: 0.060224 mm
- Min Pore size: 0.047327448 mm
- Max Pore size: 28.8251591 mm
- Median Pore size: 0.047327455 mm
- Variance Pore size: 0.000824662 mm
- Mean Pore Volume: 0.002673 mm^3

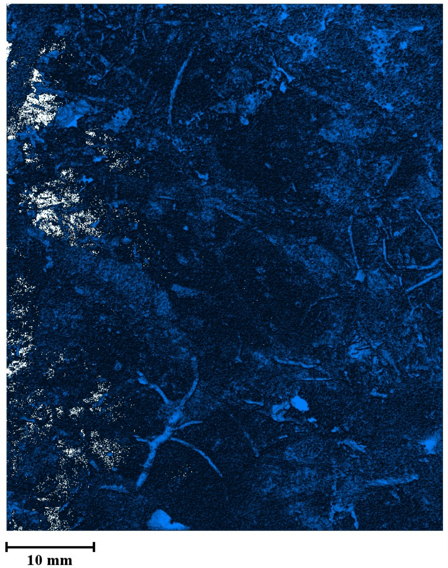
Cropped volume:

50x45x60 mm

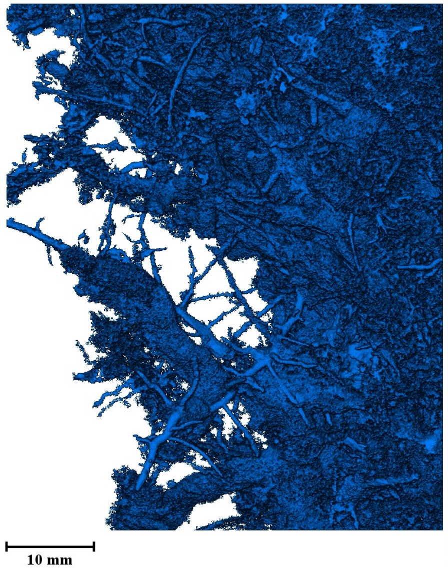
XZ plane view, clip

Pore network modeling (PNM) results on higher-resolution data from bottom section of core

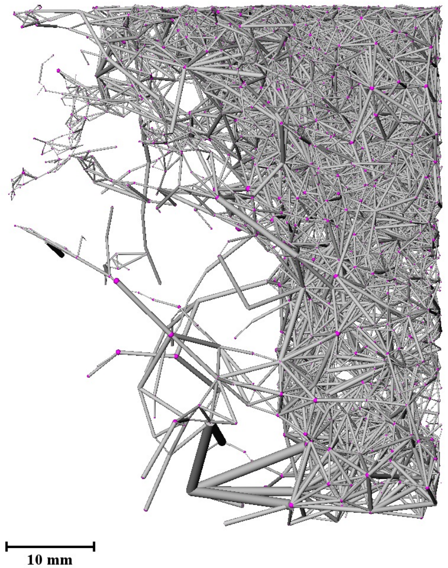
Raw volume



Visualizing all pores



Only connected pores



PNM

Pore Network Model in Z-direction

- Absolute permeability: 601.66 μm^2
- Total flow rate: 6016.31mm^3
- Tortuosity: 1.64

Pore Network Model in Y-direction

- Absolute permeability: 751.03 μm^2
- Total flow rate: 12886.47 mm^3
- Tortuosity: 1.60

Pore Network Model in X-direction

- Absolute permeability: 11.76 μm^2
- Total flow rate: 169.91 mm^3
- Tortuosity: 1.63

Input pressure: 103098 Pa,
Output pressure: 102833 Pa,
Fluid viscosity: 0.001 Pa.s

Cropped volume:

50x45x60 mm

Pore size distribution for top and bottom sections from high-resolution data

Size (mm)	count
0-0.1	979856
0.1-0.2	57796
0.2-0.3	6842
0.3-0.4	2186
0.4-0.5	923
0.5-0.75	693
0.75-1	172
1-5	105
5-10	0
10-25	0
25-50	1
>50	0

Top section

Size (mm)	count
0-0.1	1003966
0.1-0.2	41578
0.2-0.3	2282
0.3-0.4	431
0.4-0.5	143
0.5-0.75	124
0.75-1	22
1-5	26
5-10	1
10-25	0
25-50	1
>50	0

Bottom section

Scan conditions for higher resolution scans:
X-ray power: 105 kV and 325 μA
Projections: 3142
Frames/projection: 2
Exposure time: 708 ms
Filter: 0.5-mm Cu foil
Voxel size is 38.2 microns