EMSL

MONet XCT Working Group

Overview of XCT workflow and data

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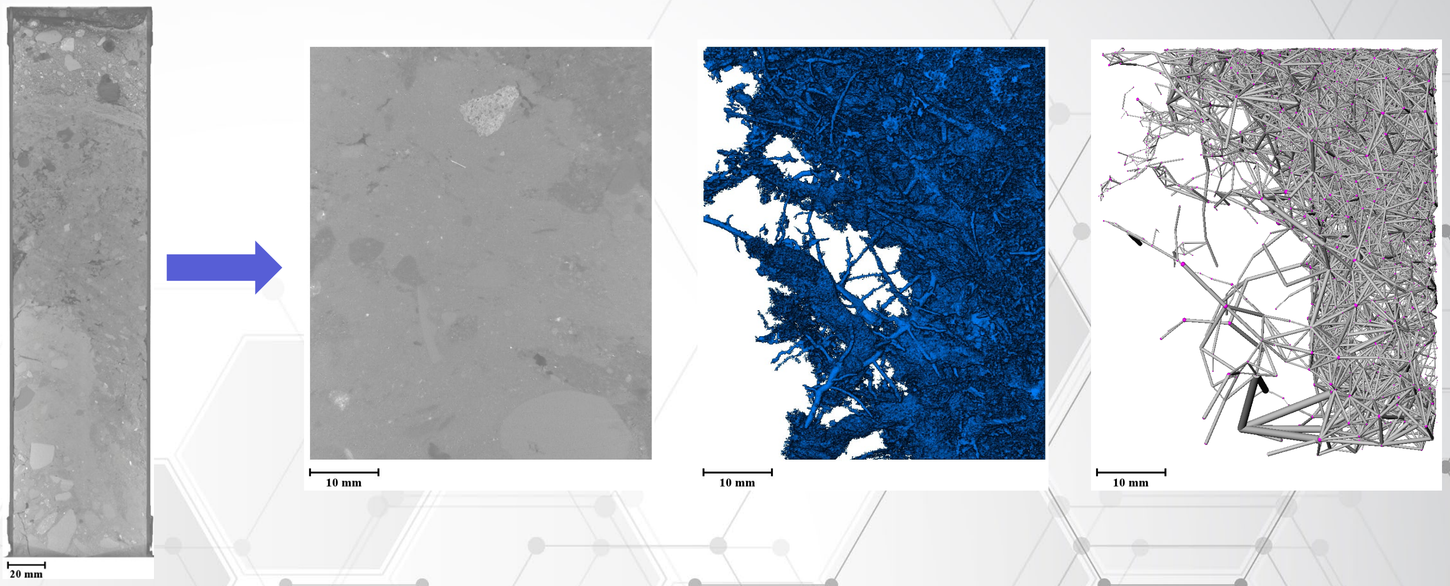
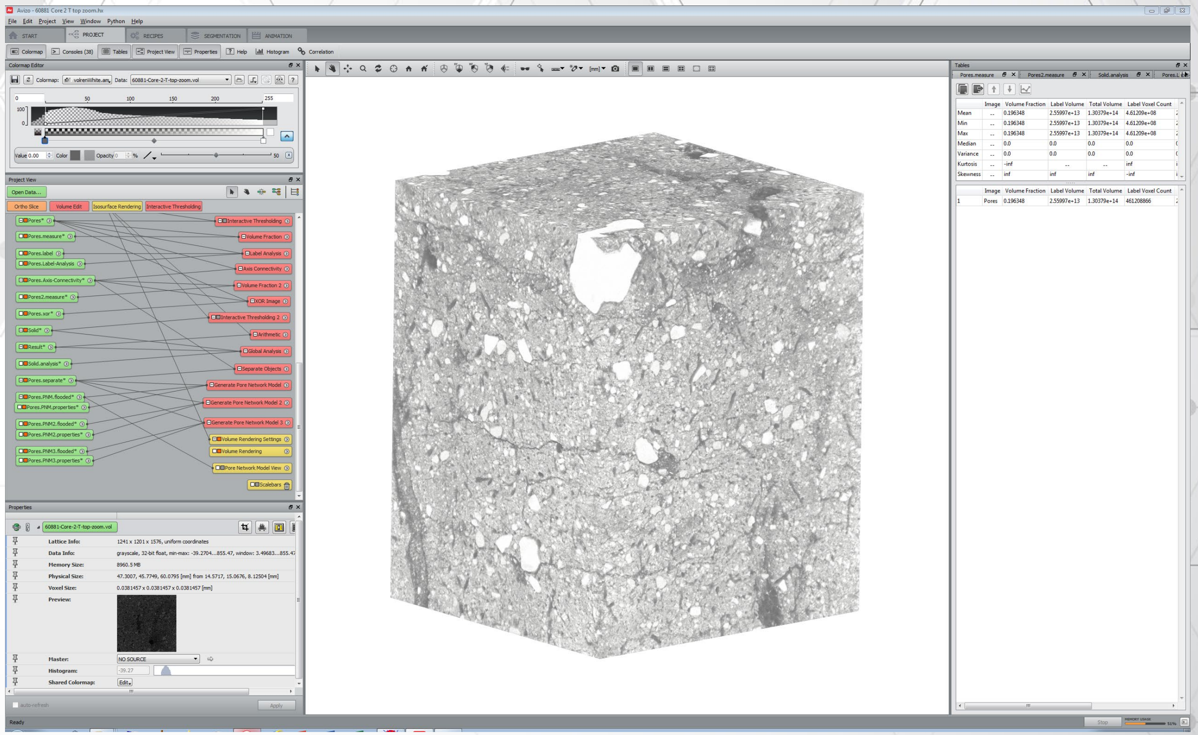
Sep 19, 2024





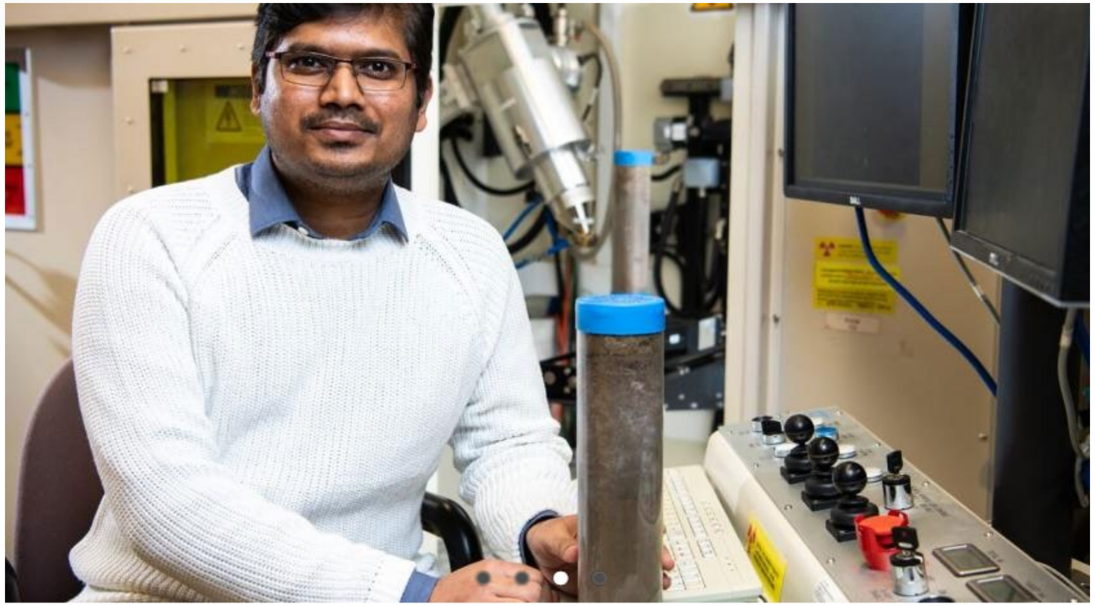
Outline

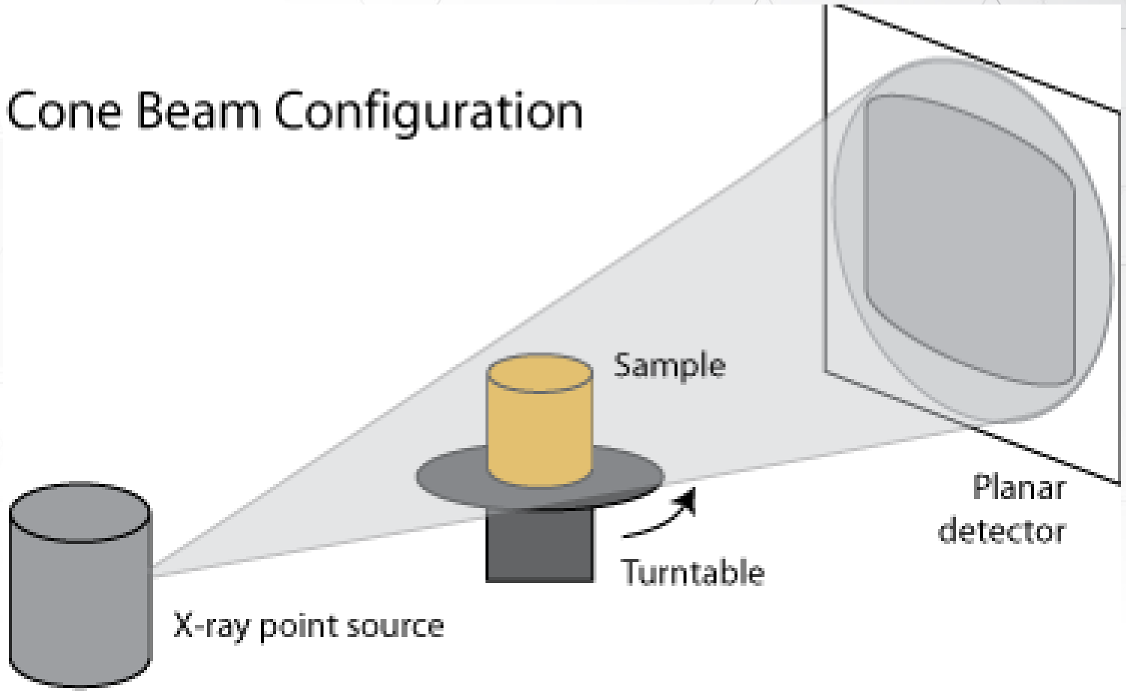
- Brief intro to X-ray Computed Tomography (XCT)
- MONet XCT workflow
- MONet XCT data types
- Other data output formats/options, software used

What is XCT?

- Non-destructive x-ray imaging to examine/visualize the internal microstructure of objects
- Output: a series of radiographs computationally reconstructed as 3D volume (CT)
- Materials are differentiated in image data based on their electron density (x-ray absorption); difference in x-ray absorption results in different gray level (color) intensity in the image

How does our x-ray CT work?



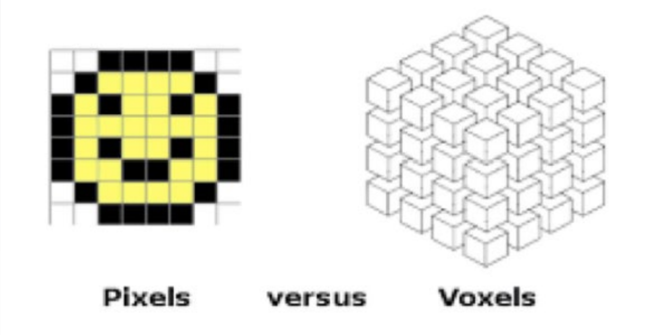


http://serc.carleton.edu/images/research_education/geochemsheets/techniques/_1172960774.png

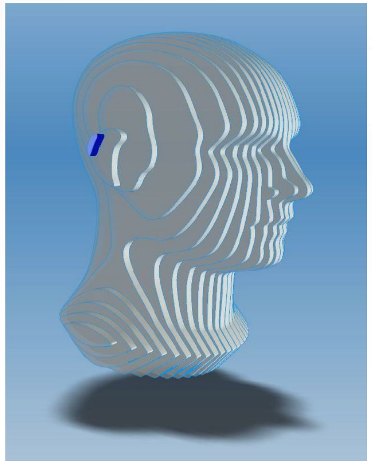
https://www.emsl.pnnl.gov/science/instruments-resources/x-ray-computed-tomography

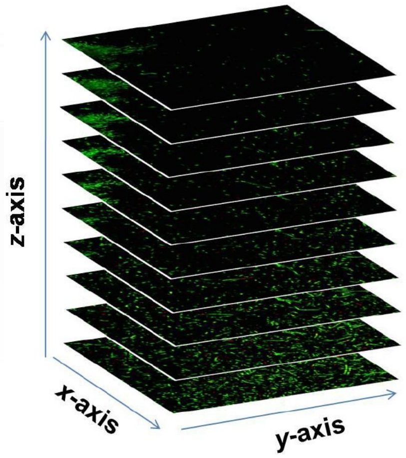
A few key terms

- Voxels (size), volume data

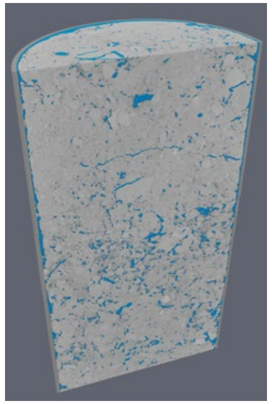


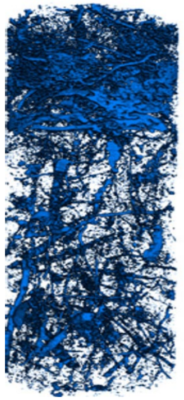
- Slices/stacks





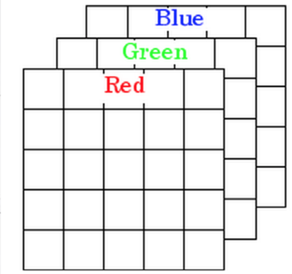
- Segmentation



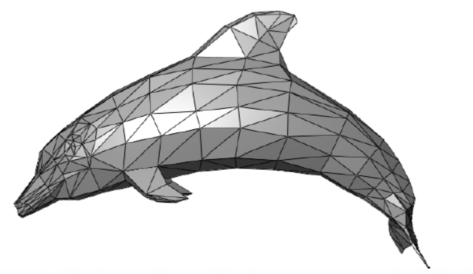


- Gray-scale vs. RGB

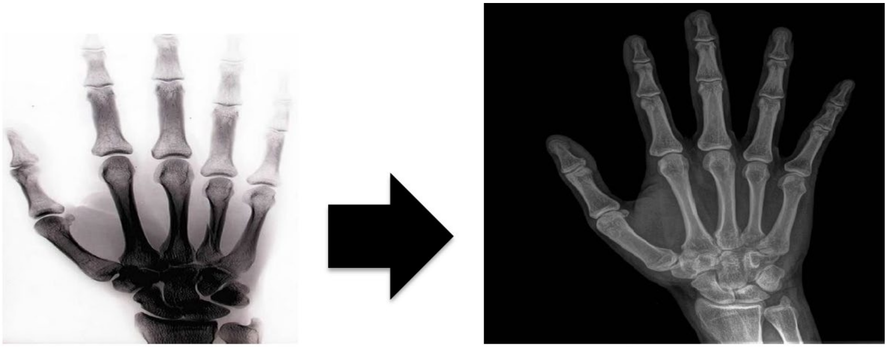
88	82	84	88	85	83	80	93	102
88	80	78	80	80	78	73	94	100
85	79	80	78	77	74	65	91	99
38	35	40	35	39	74	77	70	65
20	25	23	28	37	69	64	60	57
22	26	22	28	40	65	64	59	34
24	28	24	30	37	60	58	56	66
21	22	23	27	38	60	67	65	67
23	22	22	25	38	59	64	67	66



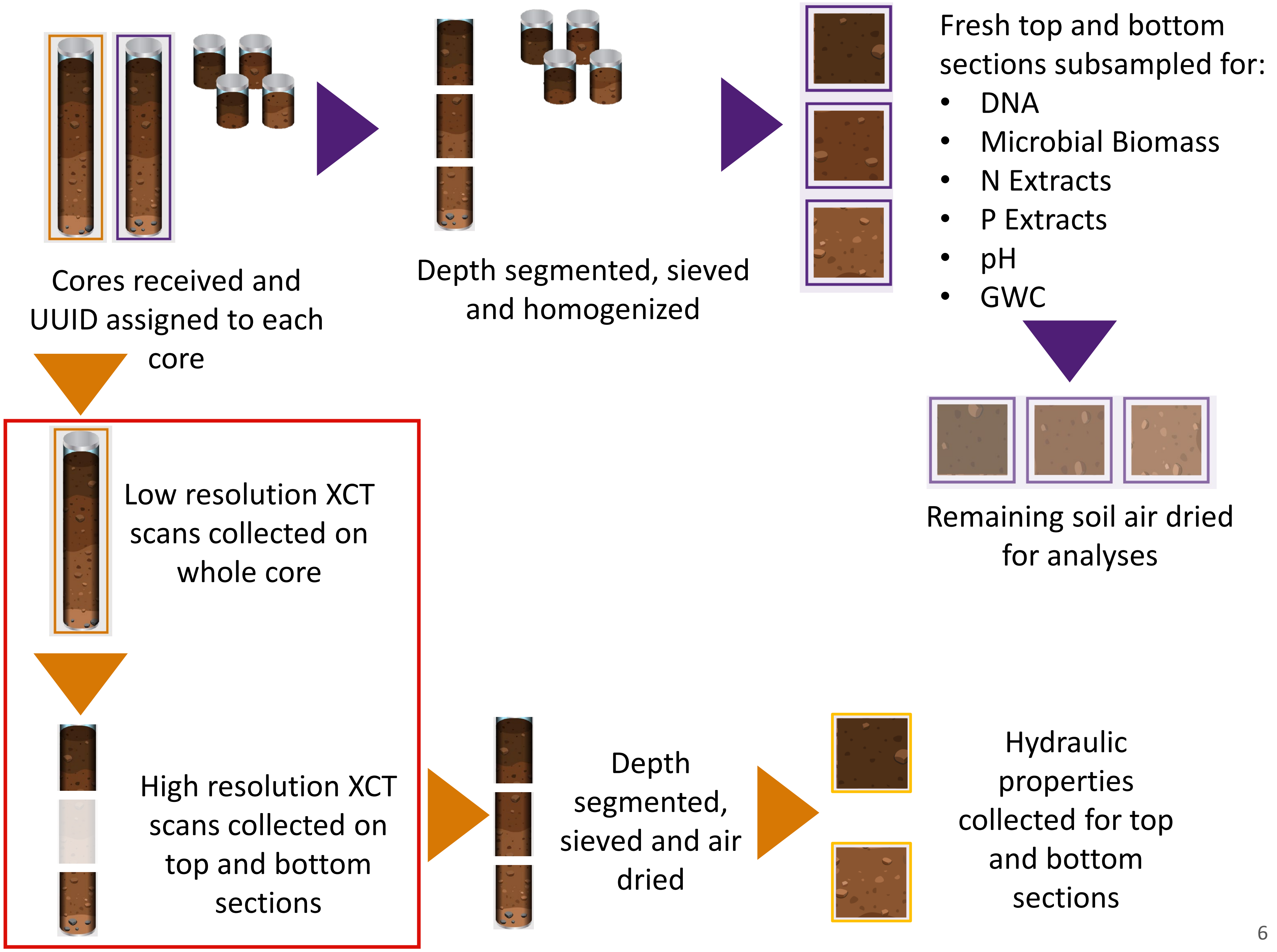
- Mesh



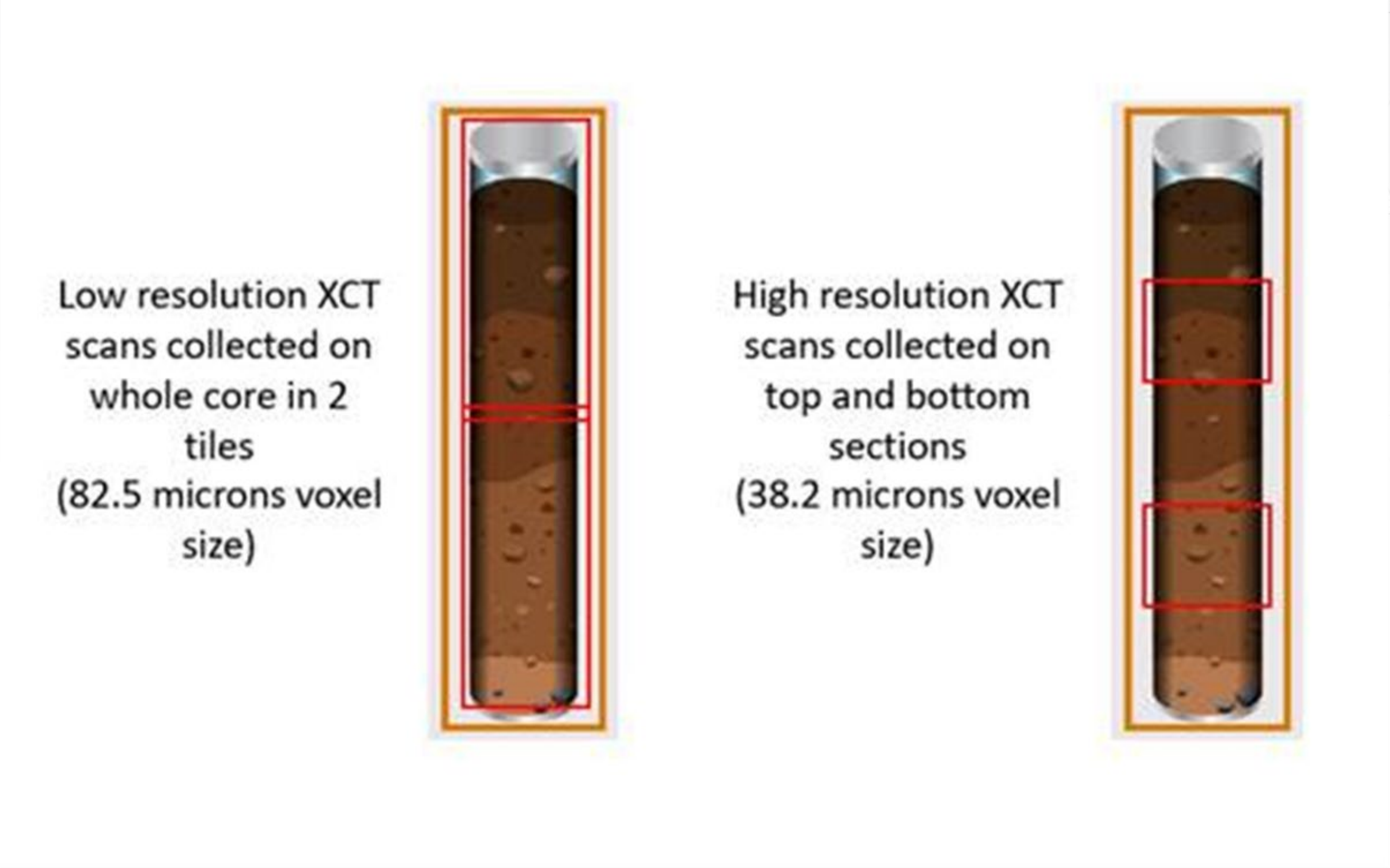
- Radiograph



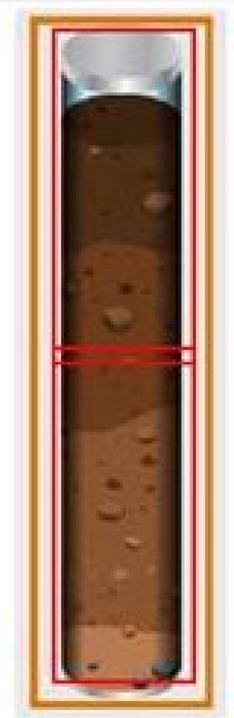
MONet core processing workflow



Scanning protocol



Whole core (merged low-resolution data from 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 merged 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 / 325 µA

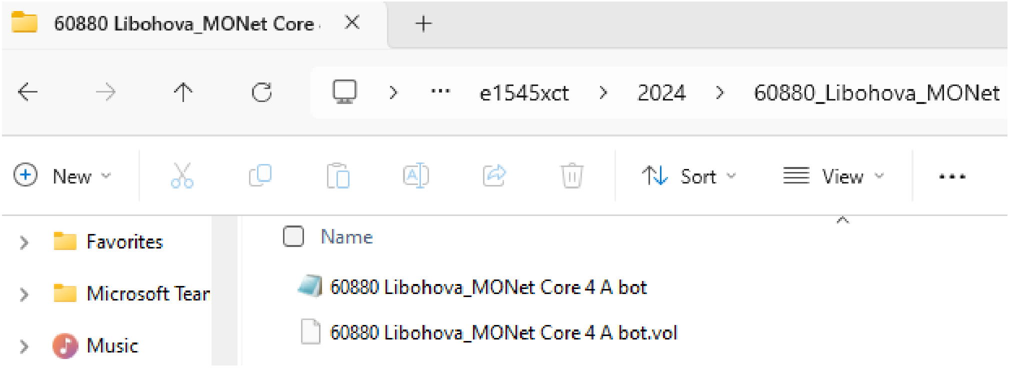
Projections: 1600

Frames/projection: 2

Exposure time: 500 ms

Filter: 0.5-mm Cu foil

Voxel size: 82.5 µm

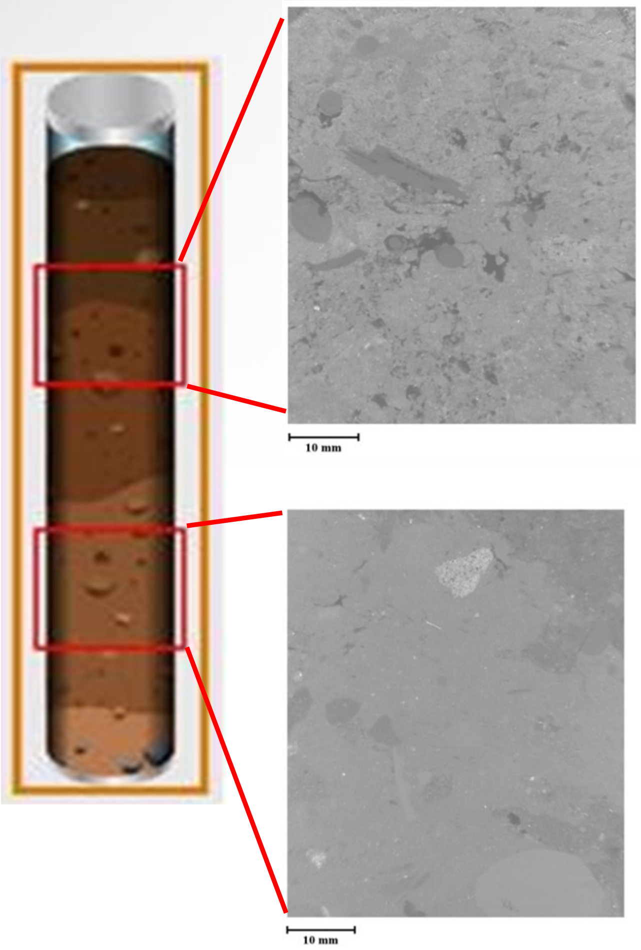


Higher-resolution scans

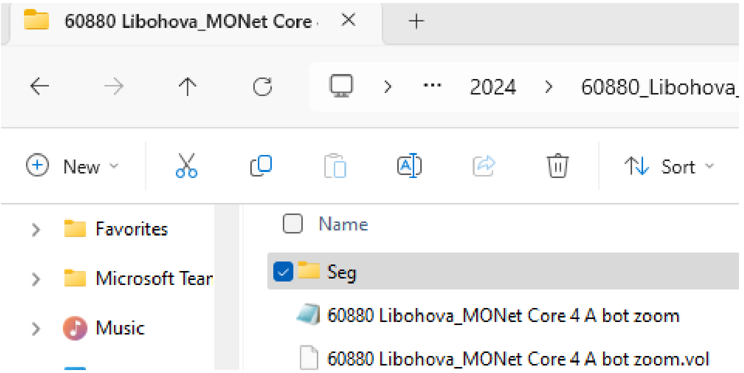
The two higher-resolution (38.2-micron voxel size, estimated spatial resolution 76.4 microns) scans are used to perform full pore network characterization. These images cannot be stitched together into one.

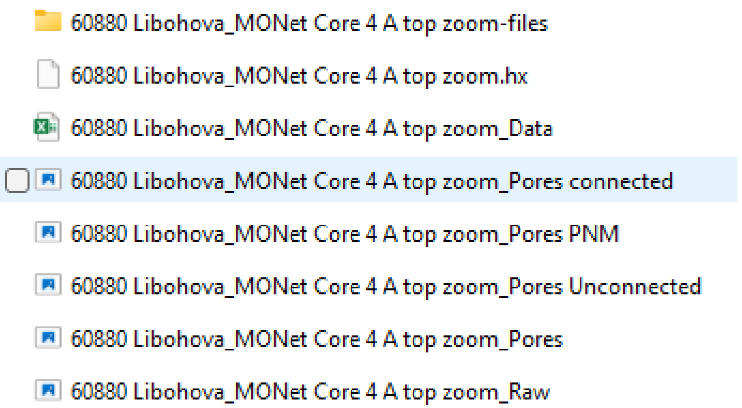
<u>Scan conditions:</u>

X-ray power: 105 kV / 325 µA
Projections: 3142
Frames/projection: 2
Exposure time: 708ms
Filter: 0.5-mm Cu foil
Voxel size: 38.2 µm



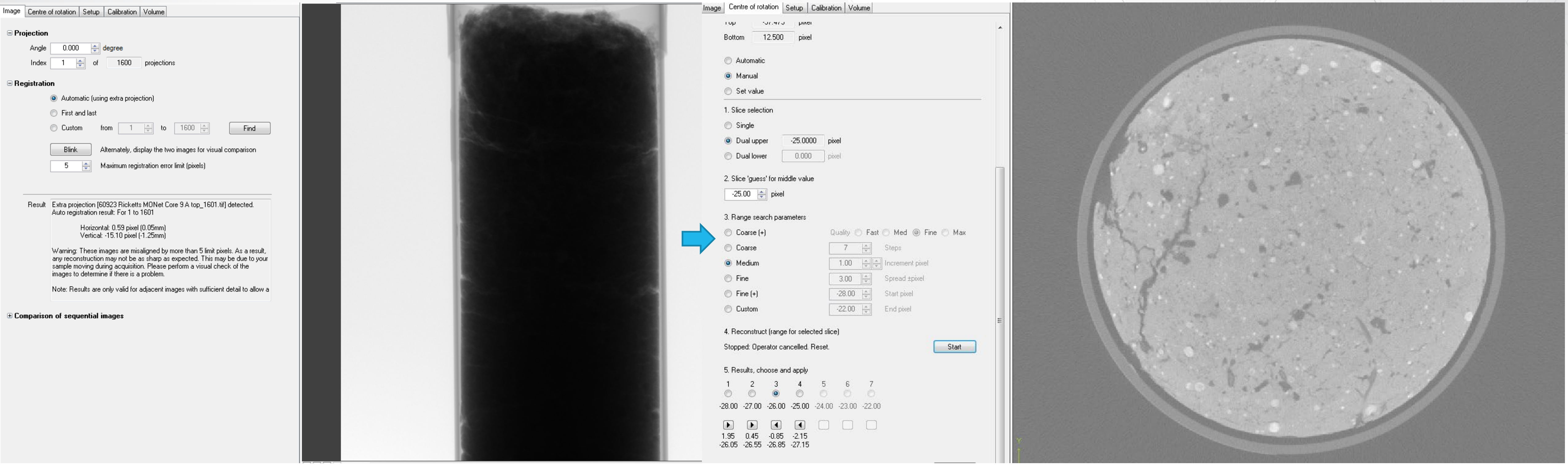
<u>Tomographic images of top and bottom sections of core in XZ plane view</u>



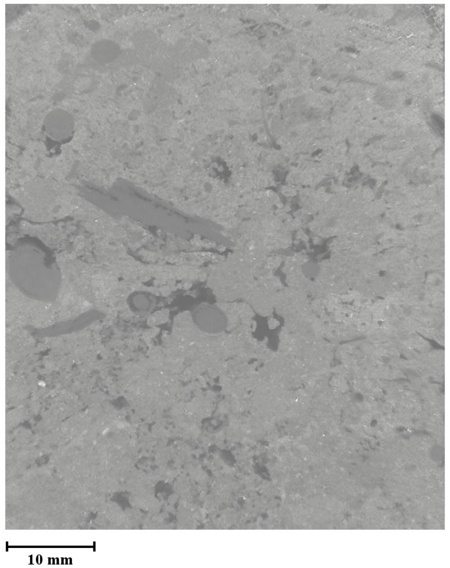


3D image reconstruction

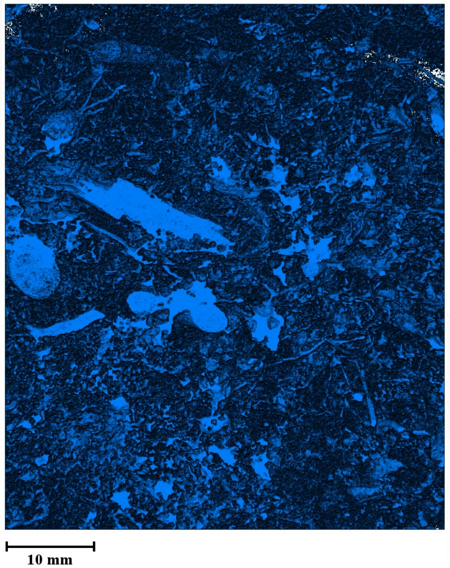
- Create 3D volume data from the individual projections
- We use CT Pro 3D (X-Tek software suite by Nikon)



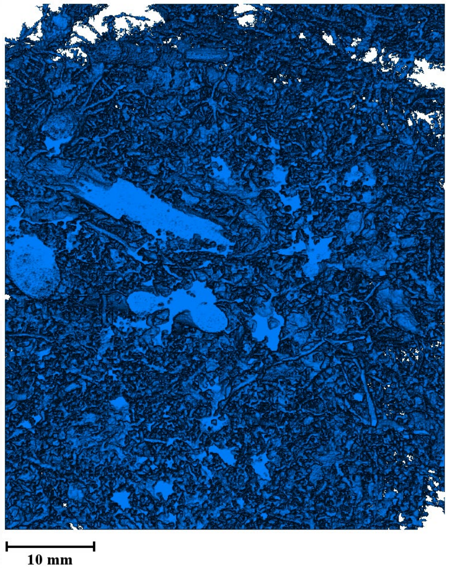
Higher-resolution scan (with 38.2-micron voxel size) on the top section of core



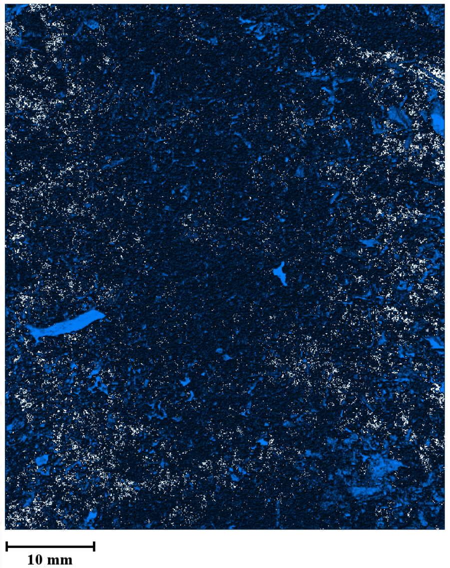
Reconstructed, cropped volume



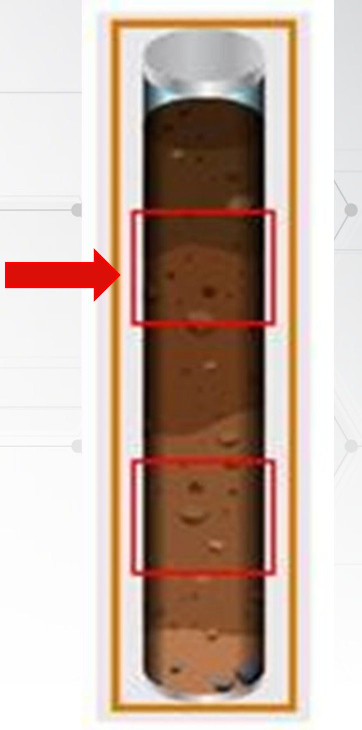
Visualizing all pores



Connected pores only



Isolated pores only



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

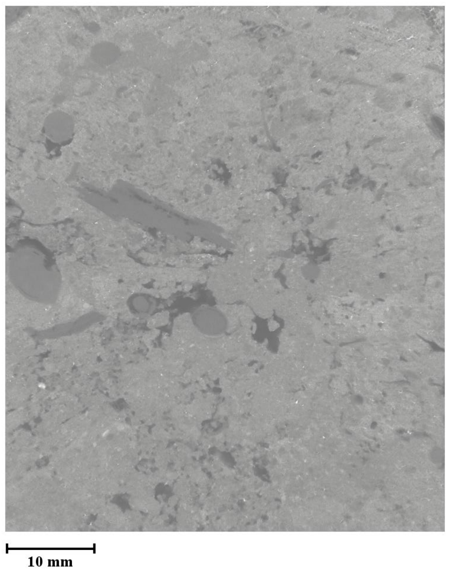
- Mean Pore size: 0.06448 mm
- Min Pore size: 0.047327 mm
- Max Pore size: 29.63071 mm
- Median Pore size: 0.047338 mm
- Variance Pore size: 0.001942 mm
- Mean Pore Volume: 0.005736 mm^3

Cropped volume size analyzed here:

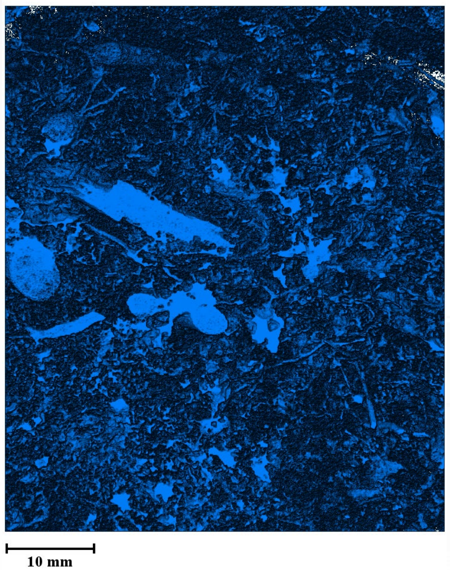
50x45x60 mm

XZ plane view, clip

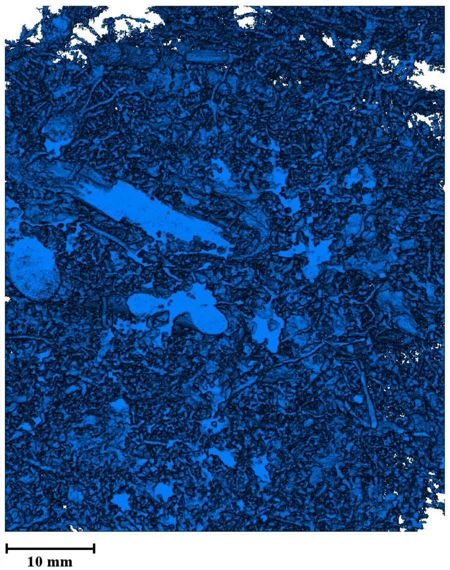
Pore network modeling (PNM) results on higher-resolution data from top section of core



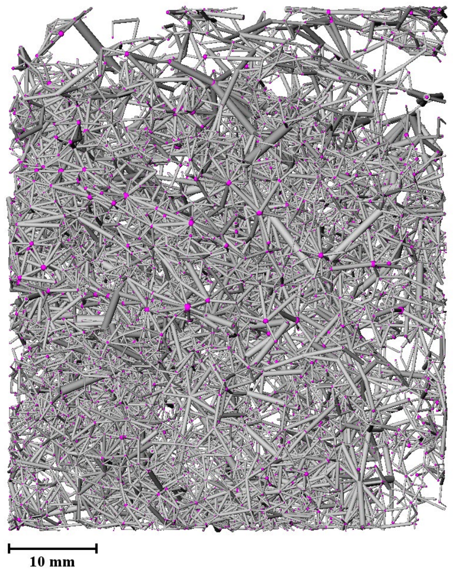
Reconstructed, cropped volume



Visualizing all pores



Connected pores



PNM

Cropped volume:

50x45x60 mm

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

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

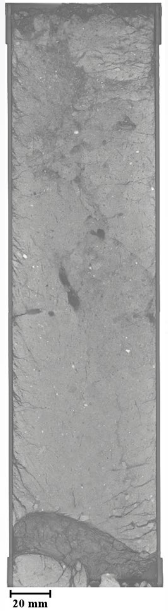
- Absolute permeability: 2882.55 μm^2
- Total flow rate: 50706.88 mm^3
- Tortuosity: 1.52

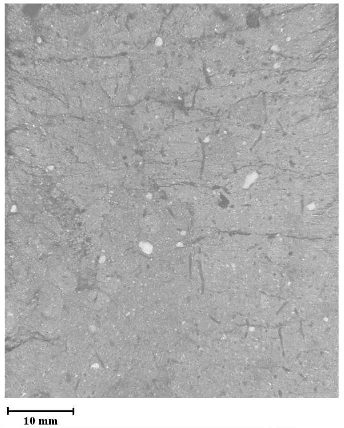
Pore Network Model in X-direction

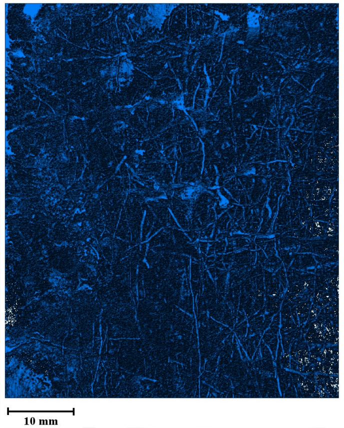
- Absolute permeability: 379.04 μm^2
- Total flow rate: 5450.30 mm^3
- Tortuosity: 1.76

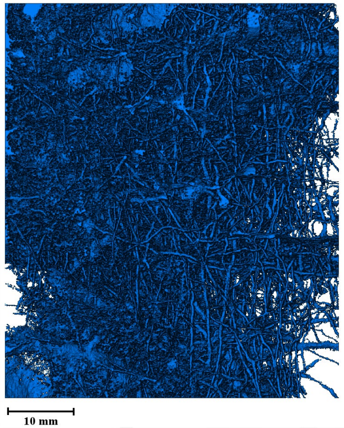
Data types for MONet

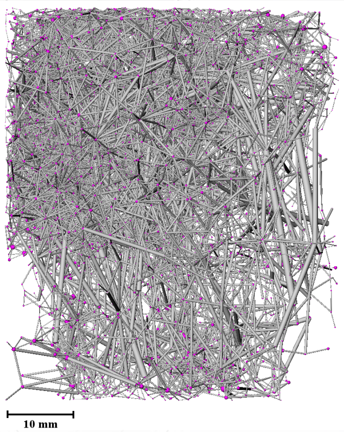
- Image data:

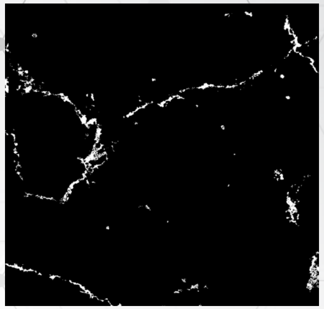








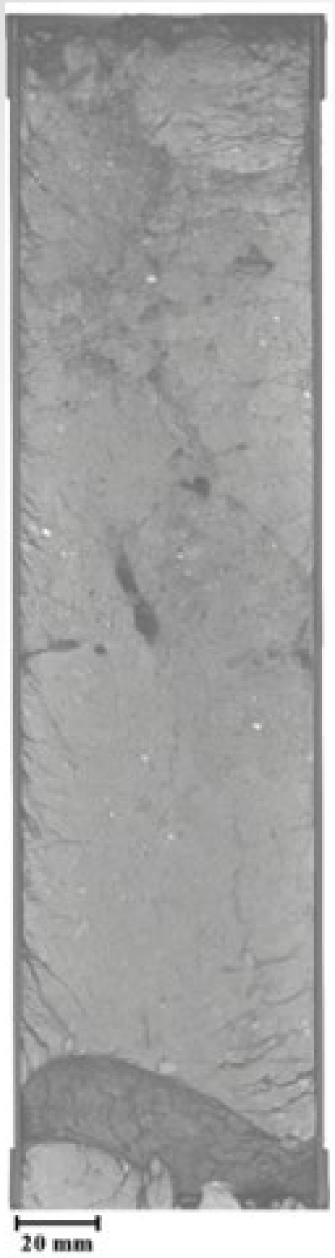




New: binary stacks!

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

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.

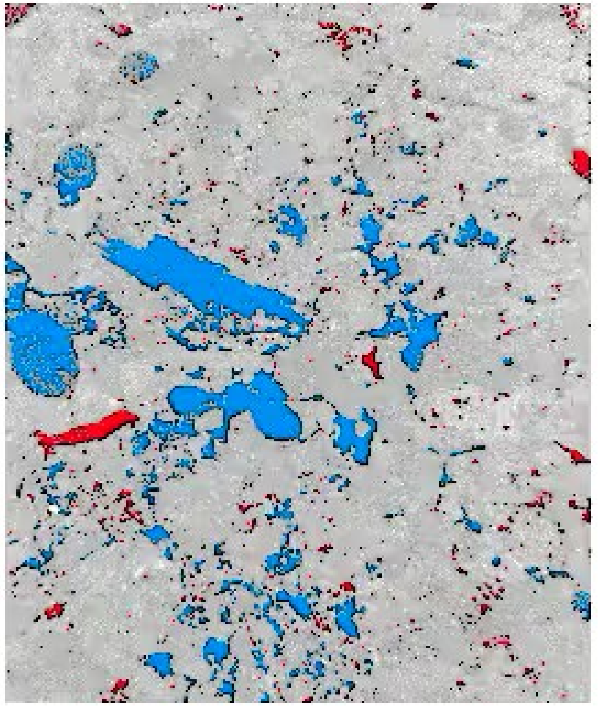
Wet bulk density: ≈1.50 $\frac{g}{cm^3}$

Data processing

- Importing reconstructed data into Avizo (Thermo Fisher)
- Image cropping
- Filtering
- Segmentation
- Pore volume/size analysis
- Pore network analysis
- Numerical output
- Visualization

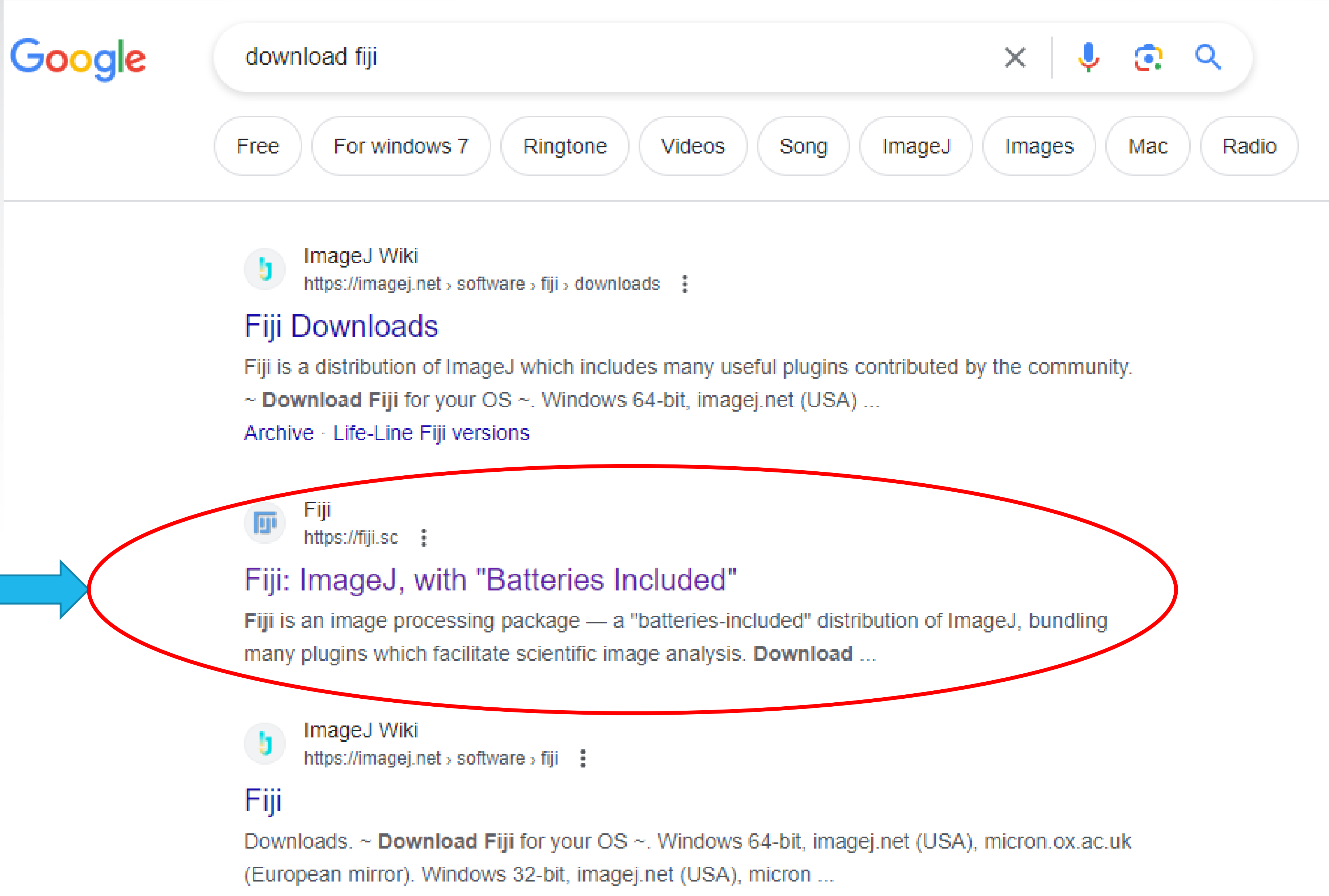
Other data output options

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

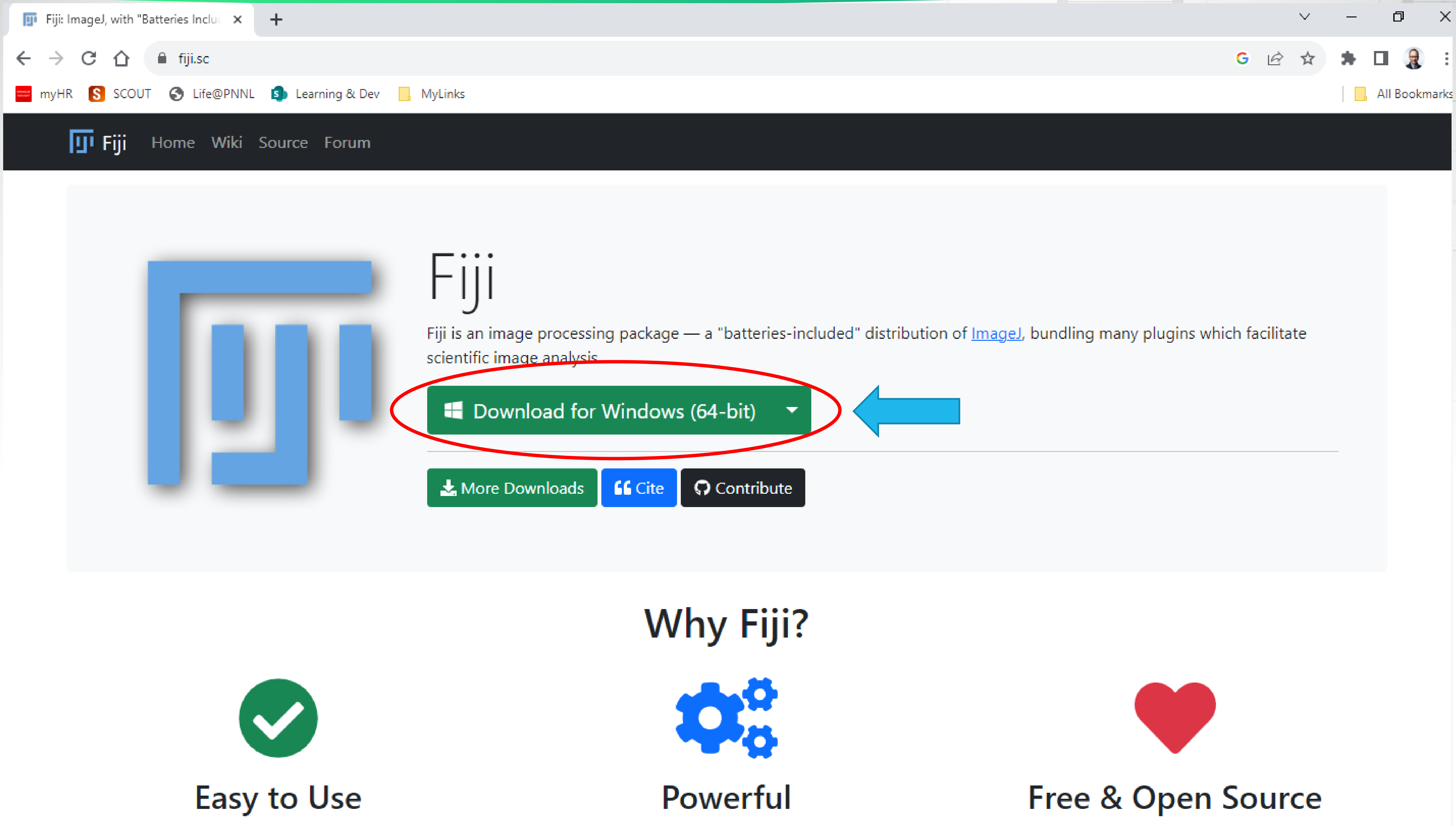


- Numerical data:
  - Pore throats
  - Pore coordination numbers

Viewing raw and segmented data (ImageJ/Fiji)

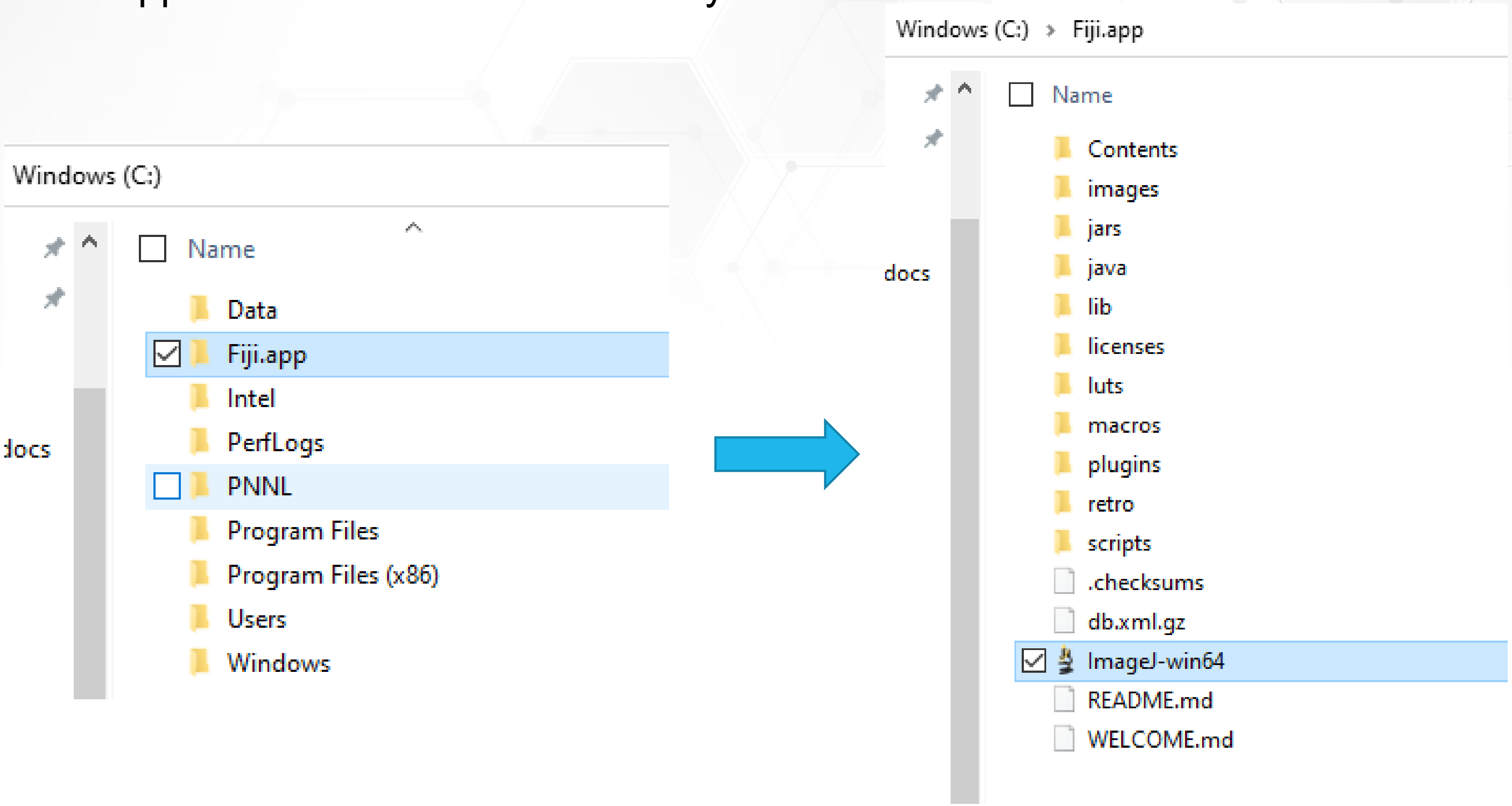


Install Fiji

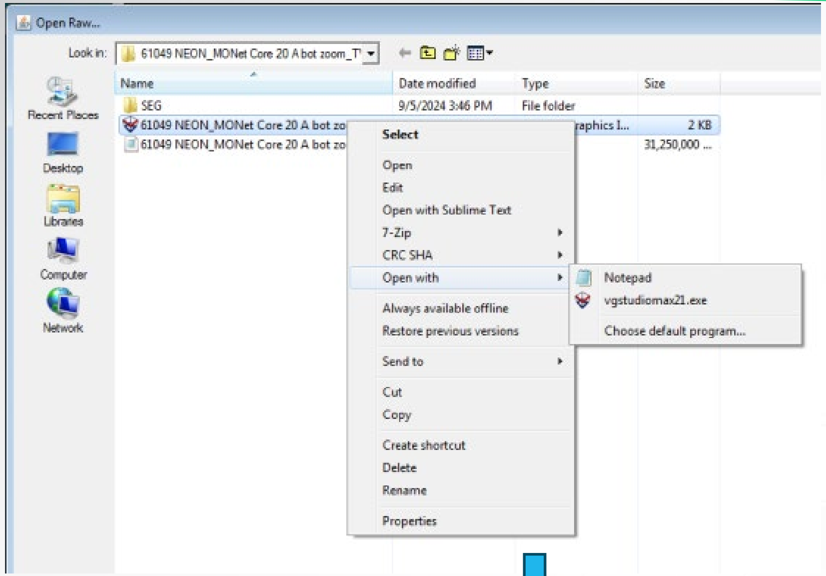


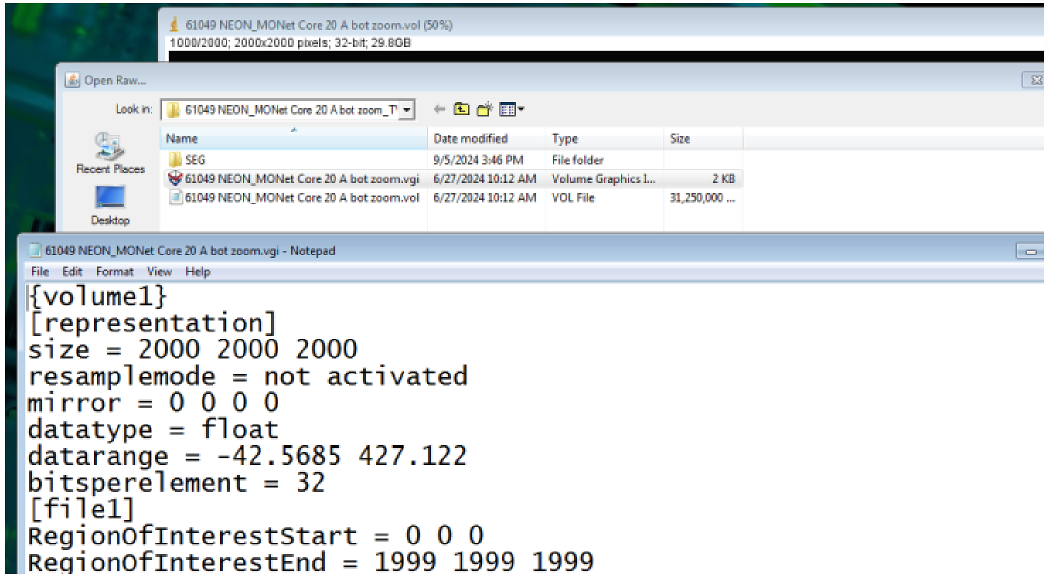
Install Fiji – cont.

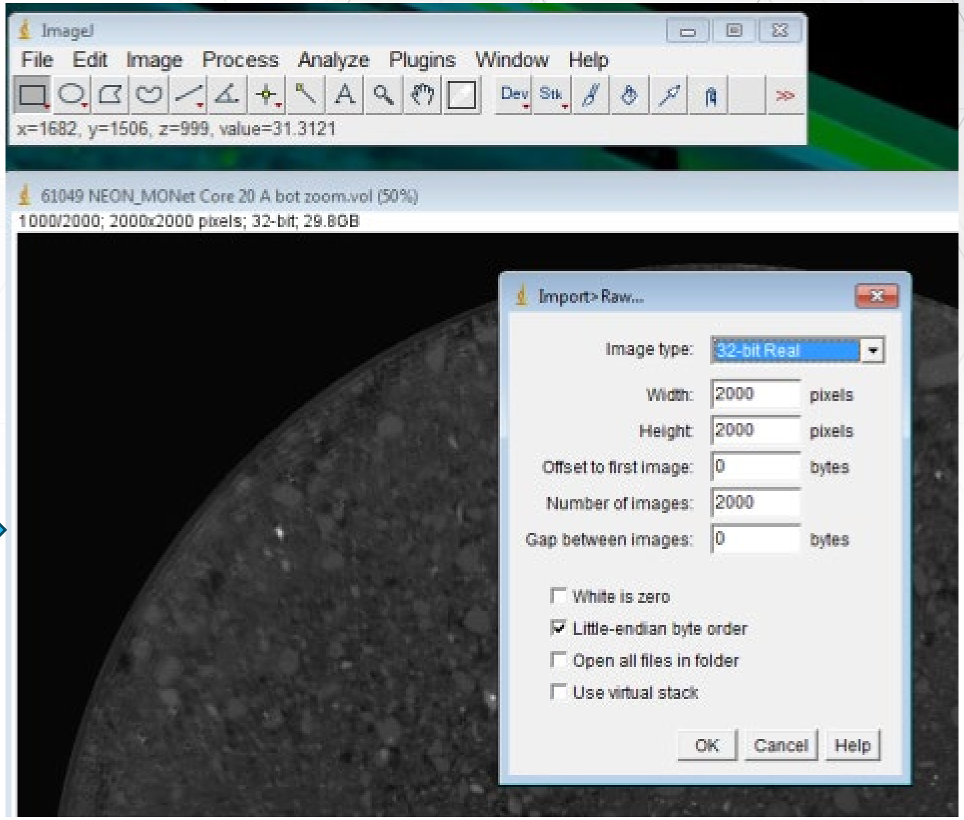
- Copy Fiji.app folder from zip file to C drive
- Run application file “ImageJ-win64”
- Allow for Java installation as offered (if you do not already run Java 1.8)
- Once app started, run updater
- You can pin this application file to taskbar for easy access



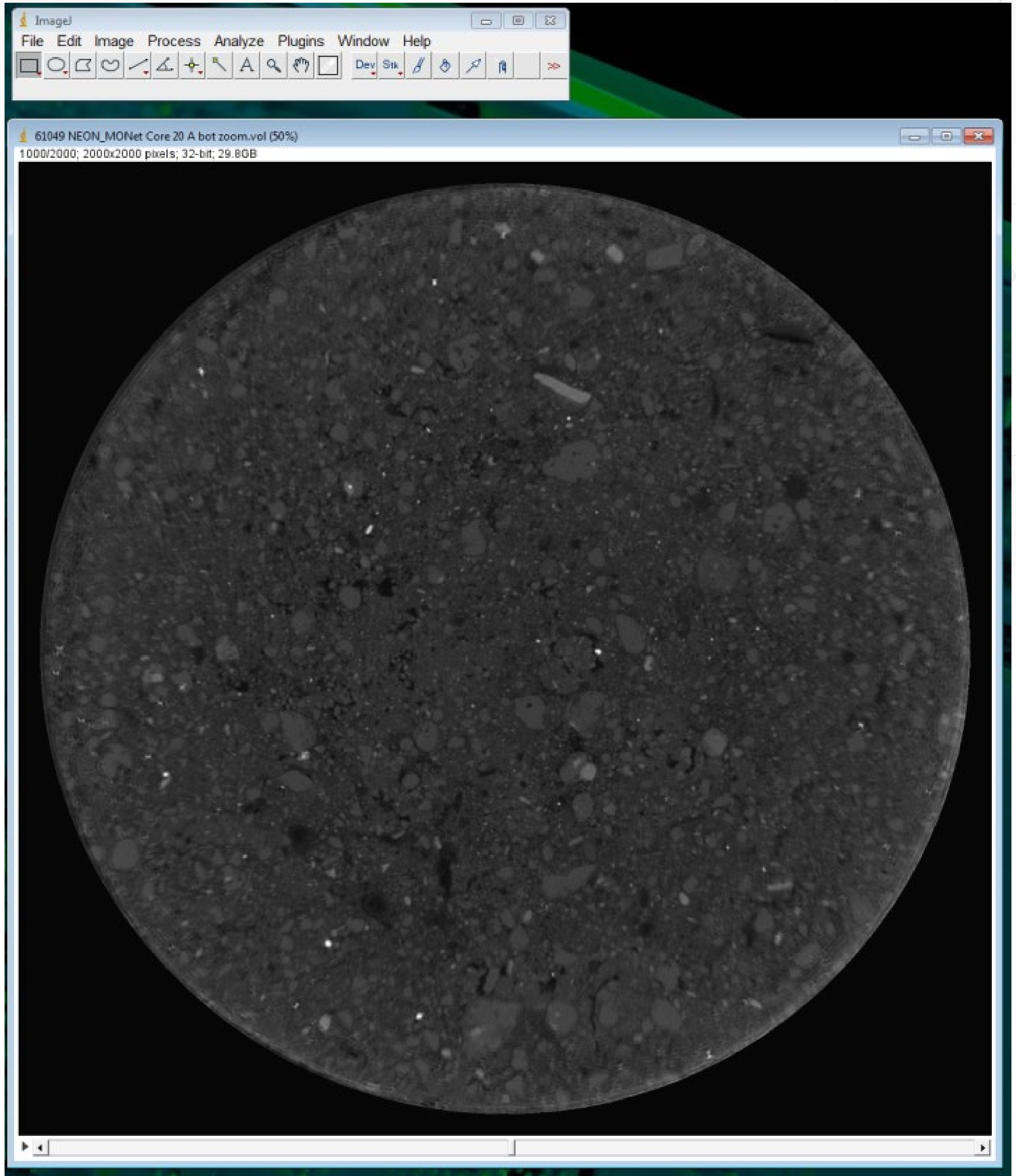
Importing raw scan data (.vol file)



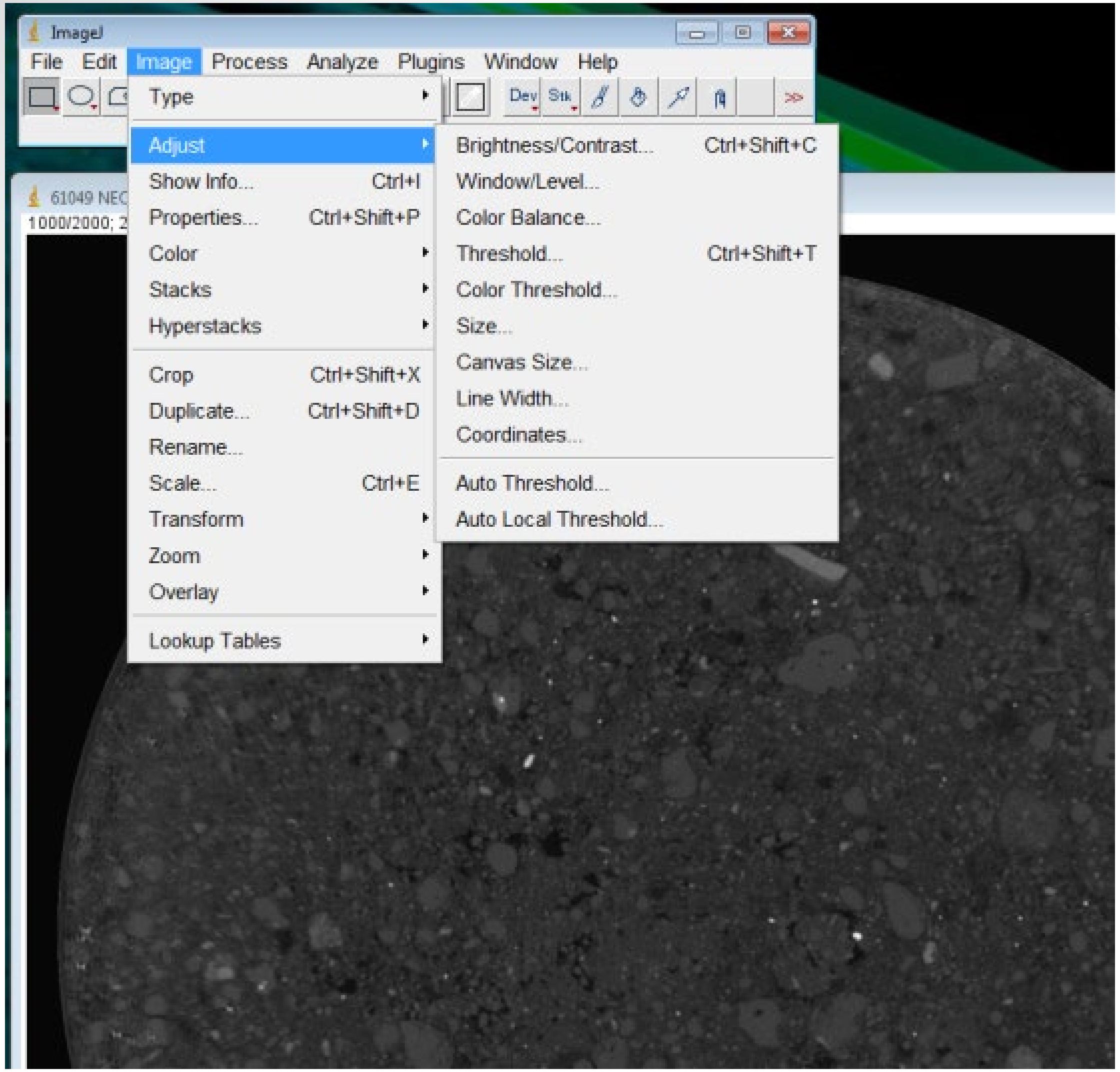


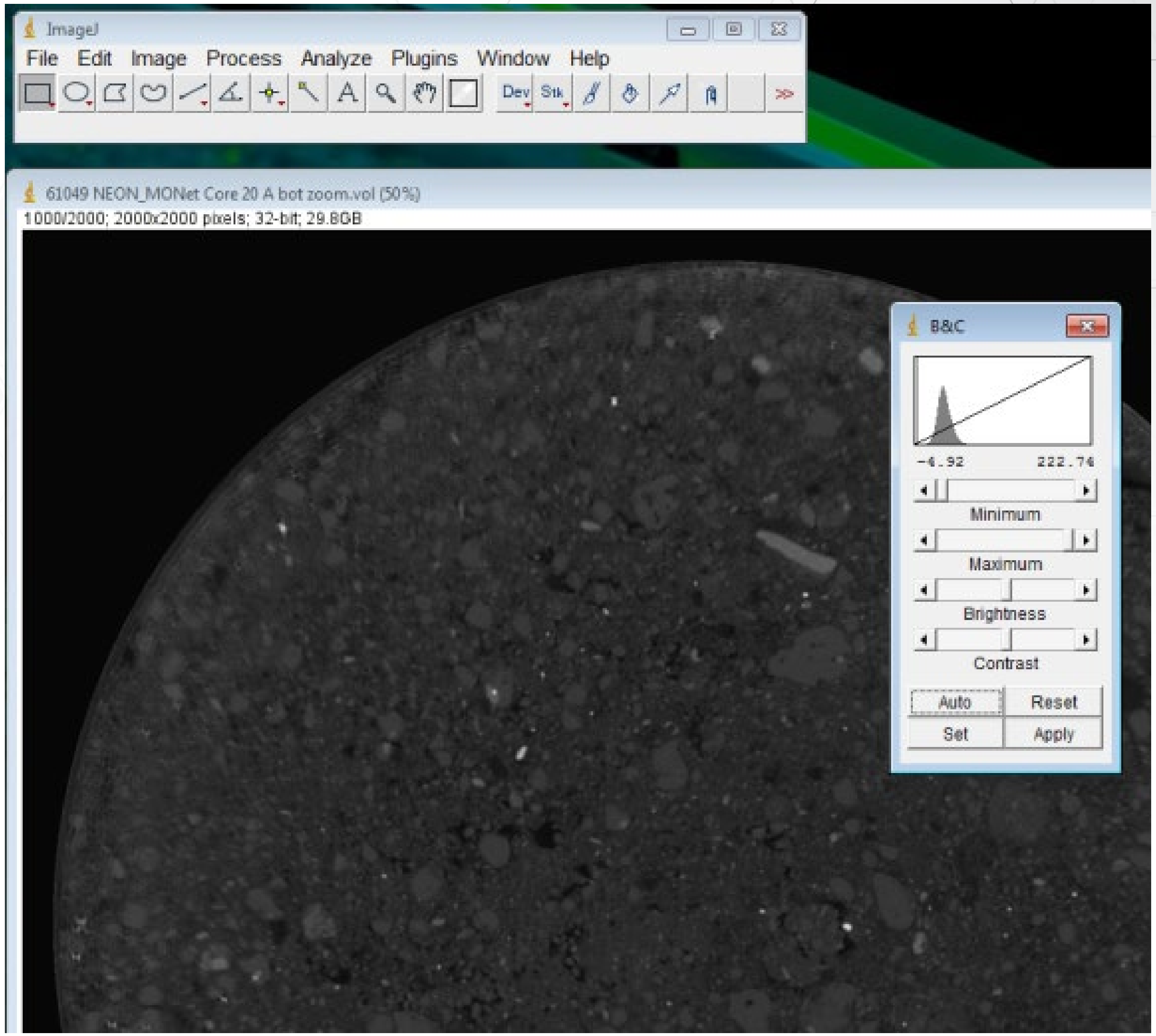


Importing data – cont.

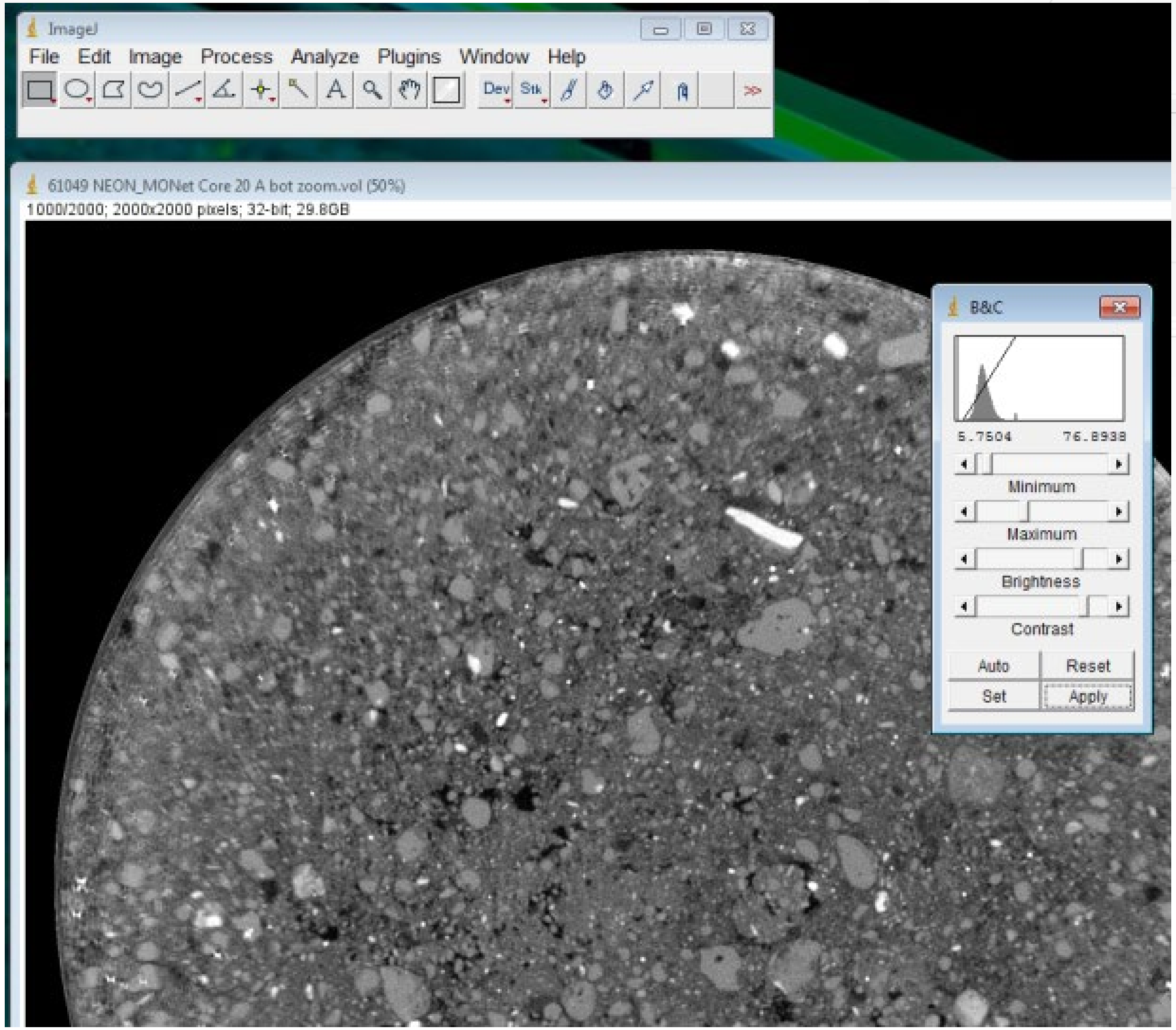


Enhancing image contrast

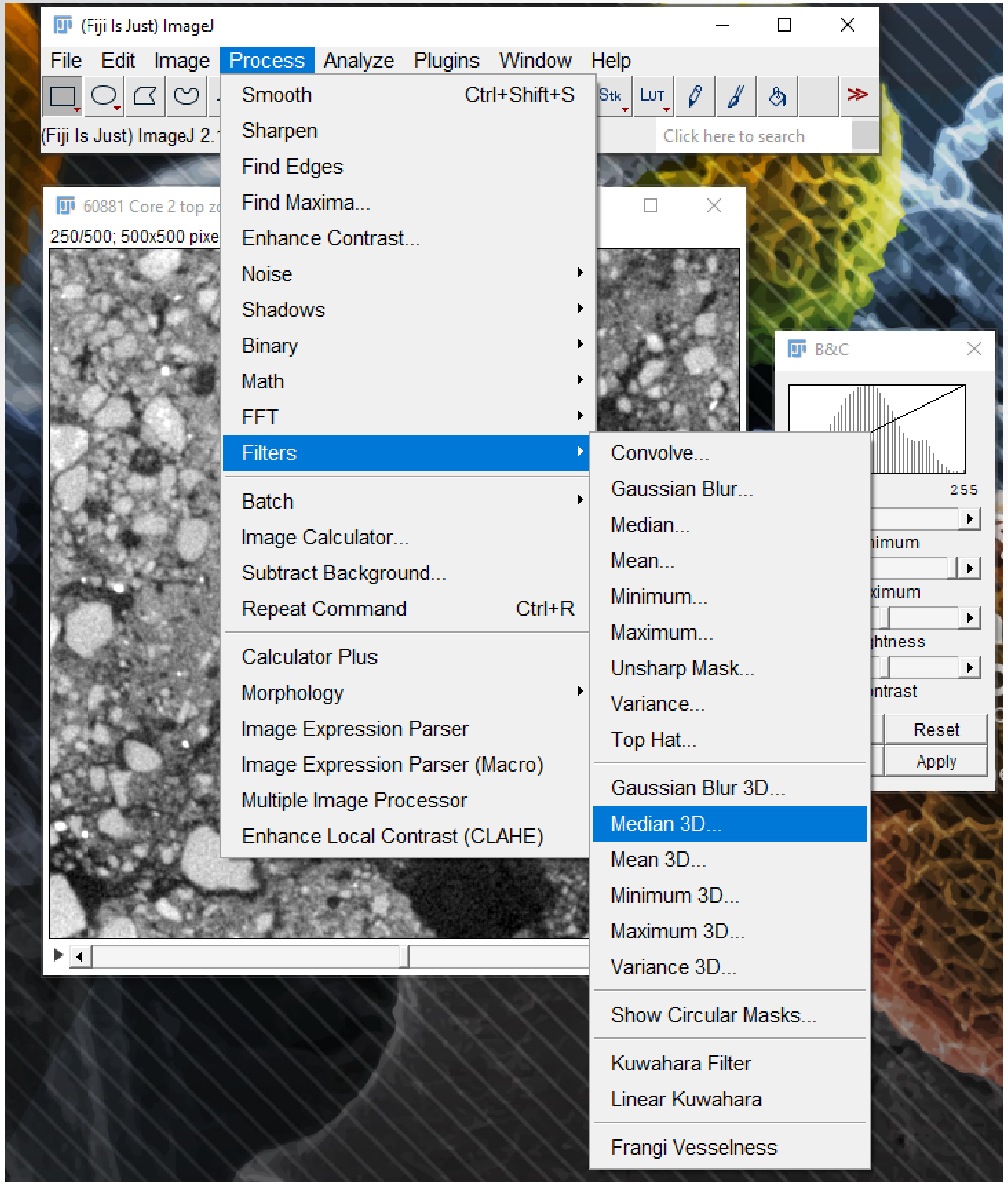




Enhancing image contrast – cont.



Filtering



(Fiji Is Just) ImageJ
File
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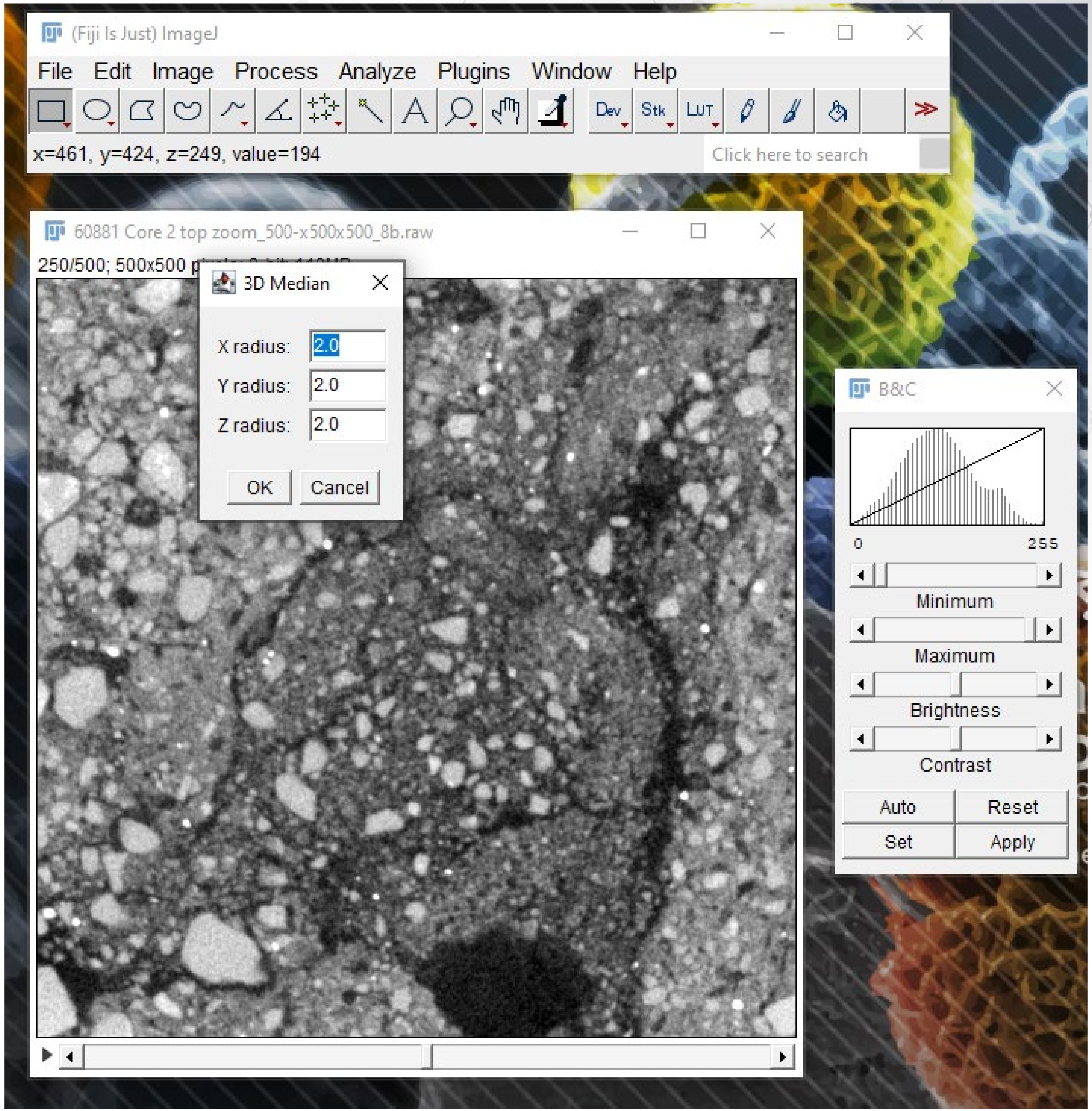
Smooth Ctrl+Shift+S
Sharpen
Find Edges
Find Maxima...
Enhance Contrast...
Noise
Shadows
Binary
Math
FFT
Filters
Batch
Image Calculator...
Subtract Background...
Repeat Command Ctrl+R
Calculator Plus
Morphology
Image Expression Parser
Image Expression Parser (Macro)
Multiple Image Processor
Enhance Local Contrast (CLAHE)
Convolve...
Gaussian Blur...
Median...
Mean...
Minimum...
Maximum...
Unsharp Mask...
Variance...
Top Hat...
Gaussian Blur 3D...
Median 3D...
Mean 3D...
Minimum 3D...
Maximum 3D...
Variance 3D...
Show Circular Masks...
Kuwahara Filter
Linear Kuwahara
Frangi Vesselness
Click here to search
250/500; 500x500 pixe
B&C
255
Reset
Apply



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250/500; 500x500
3D Median
X radius: 2.0
Y radius: 2.0
Z radius: 2.0
OK
Cancel
B&C
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Maximum
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Contrast
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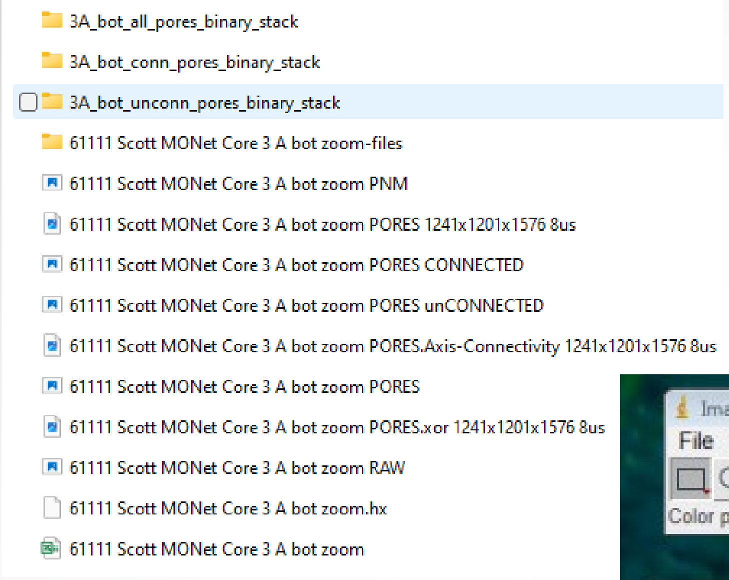
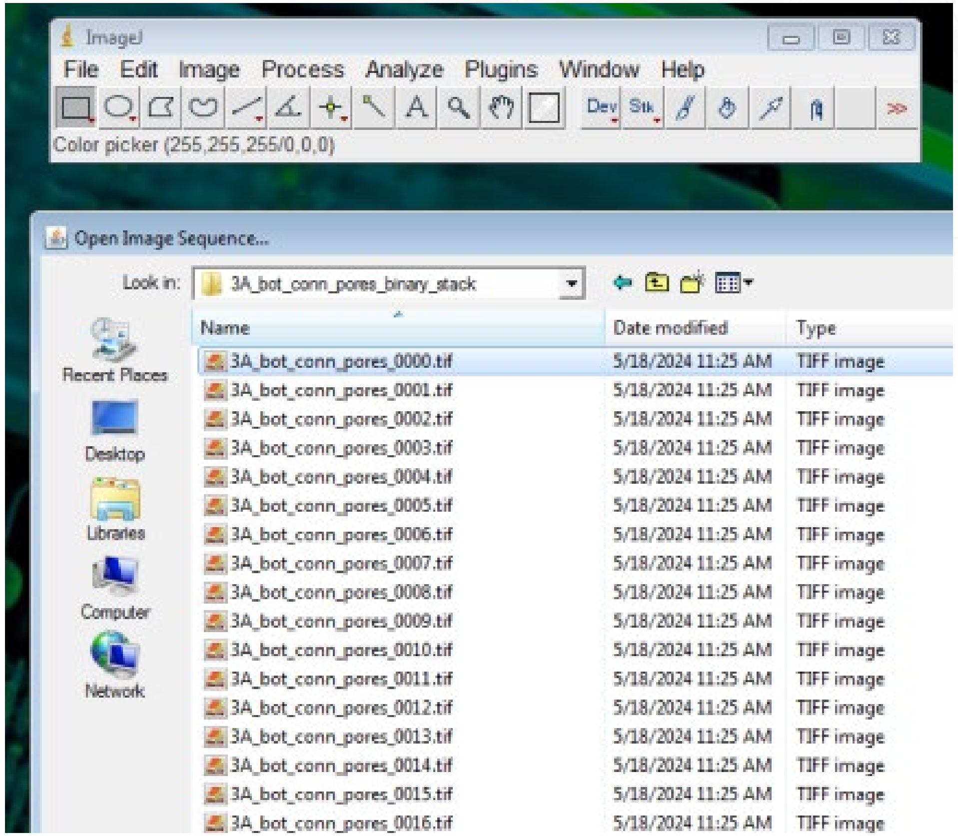
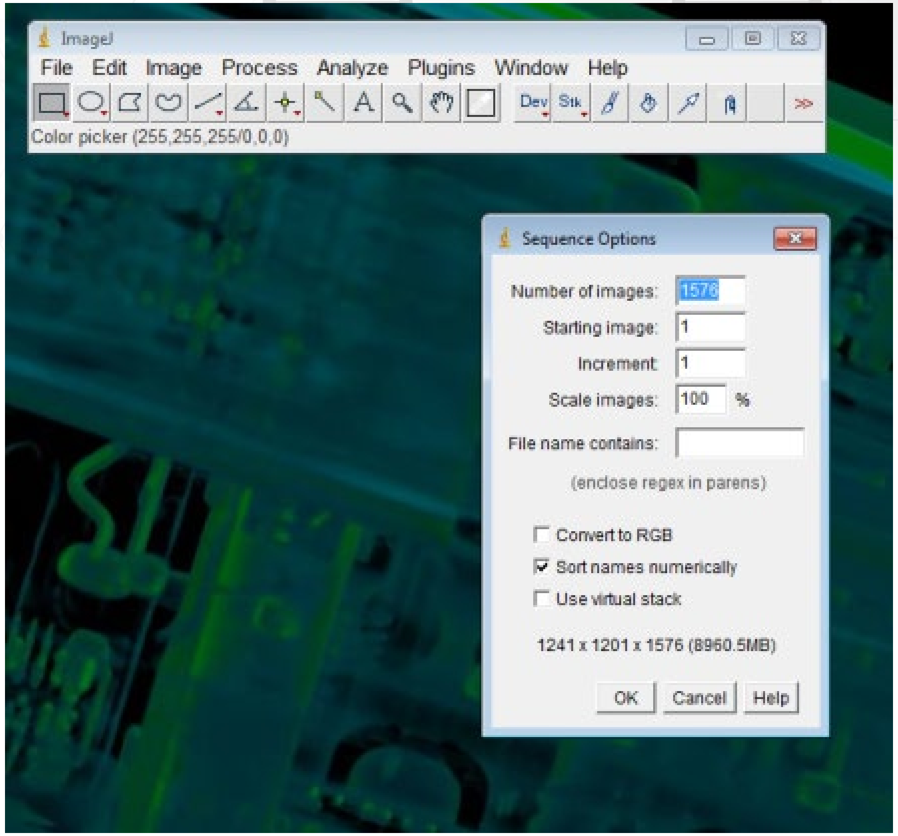
Set
Apply

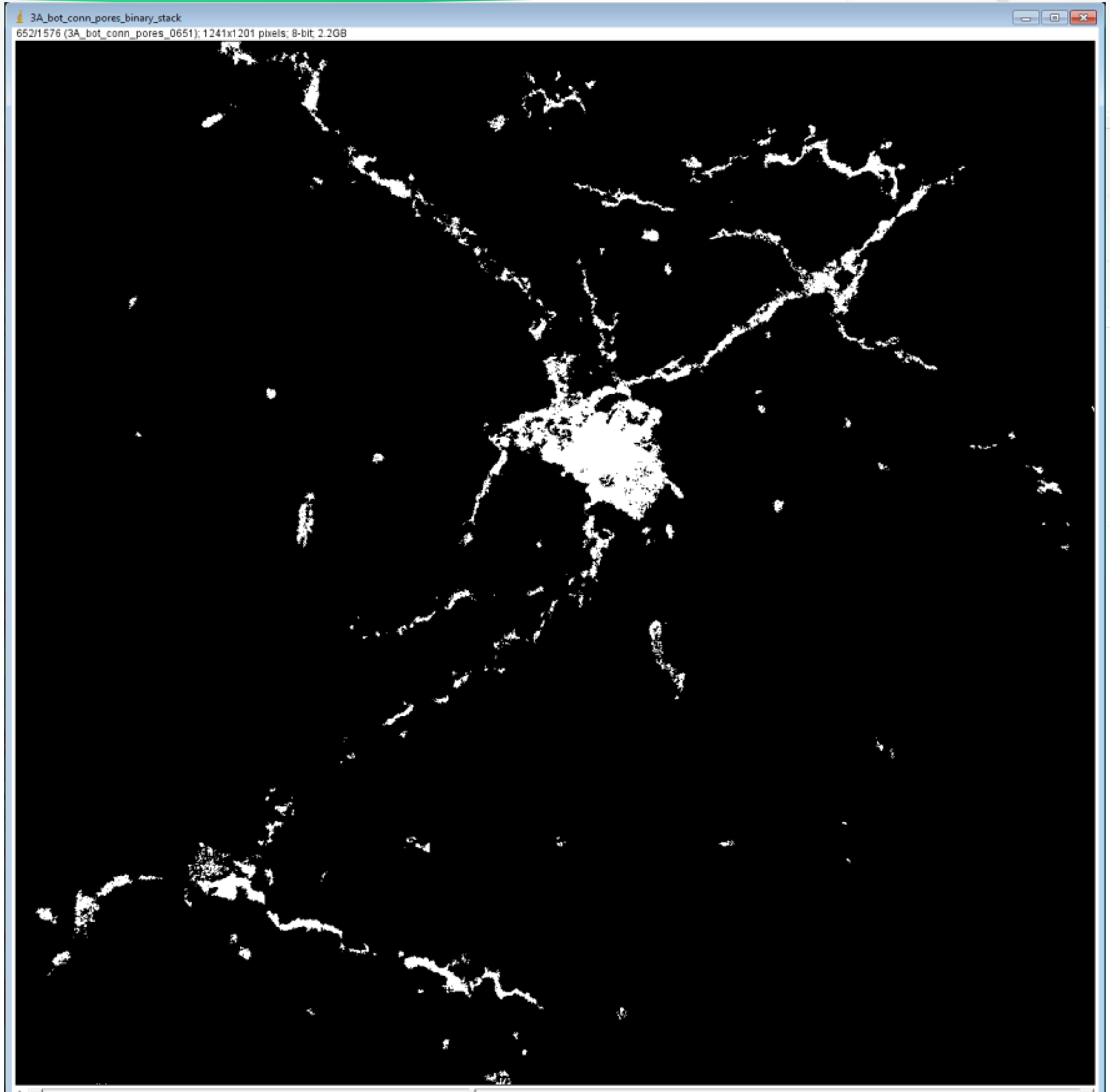
Importing segmented, binary image stack





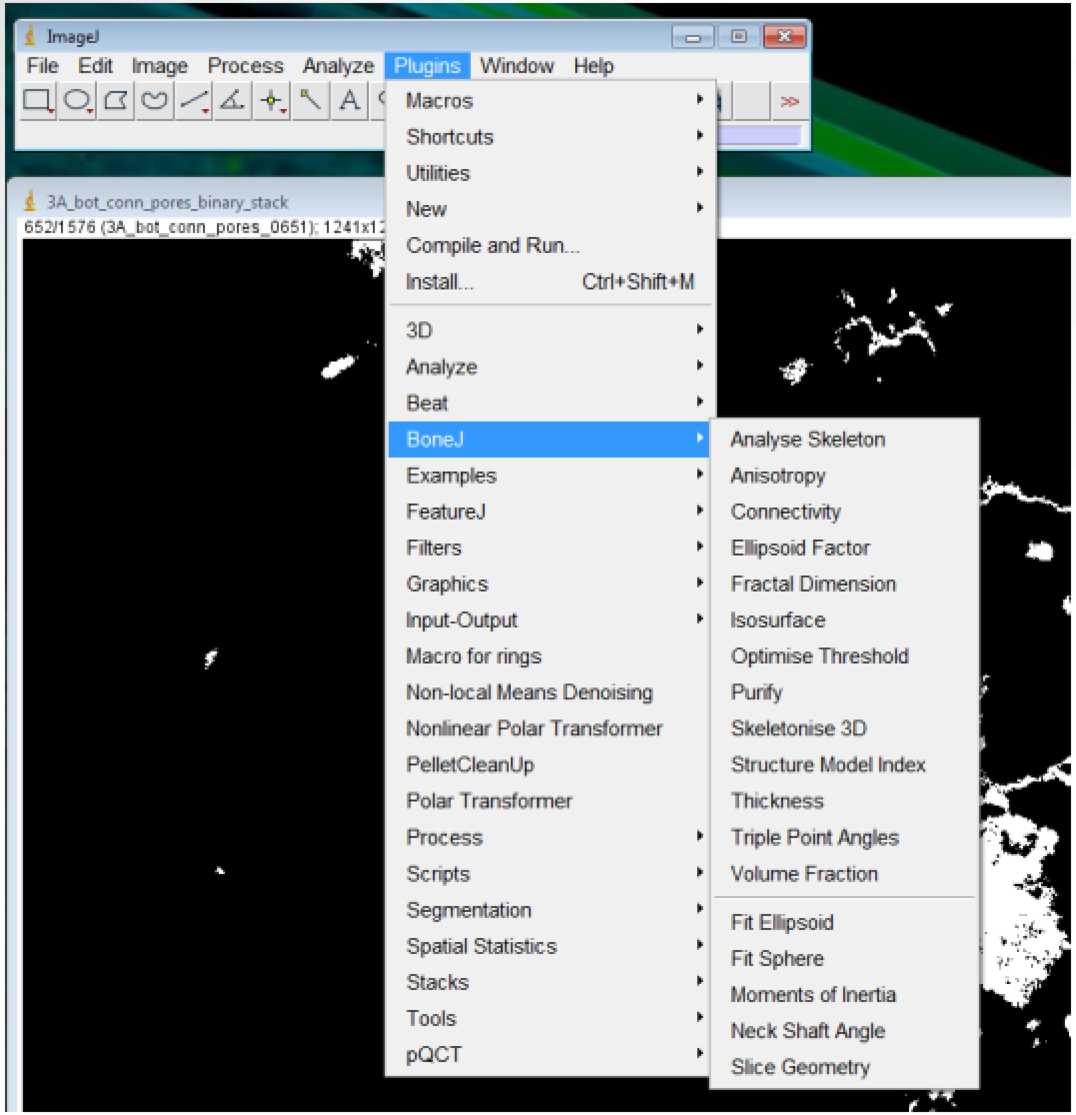


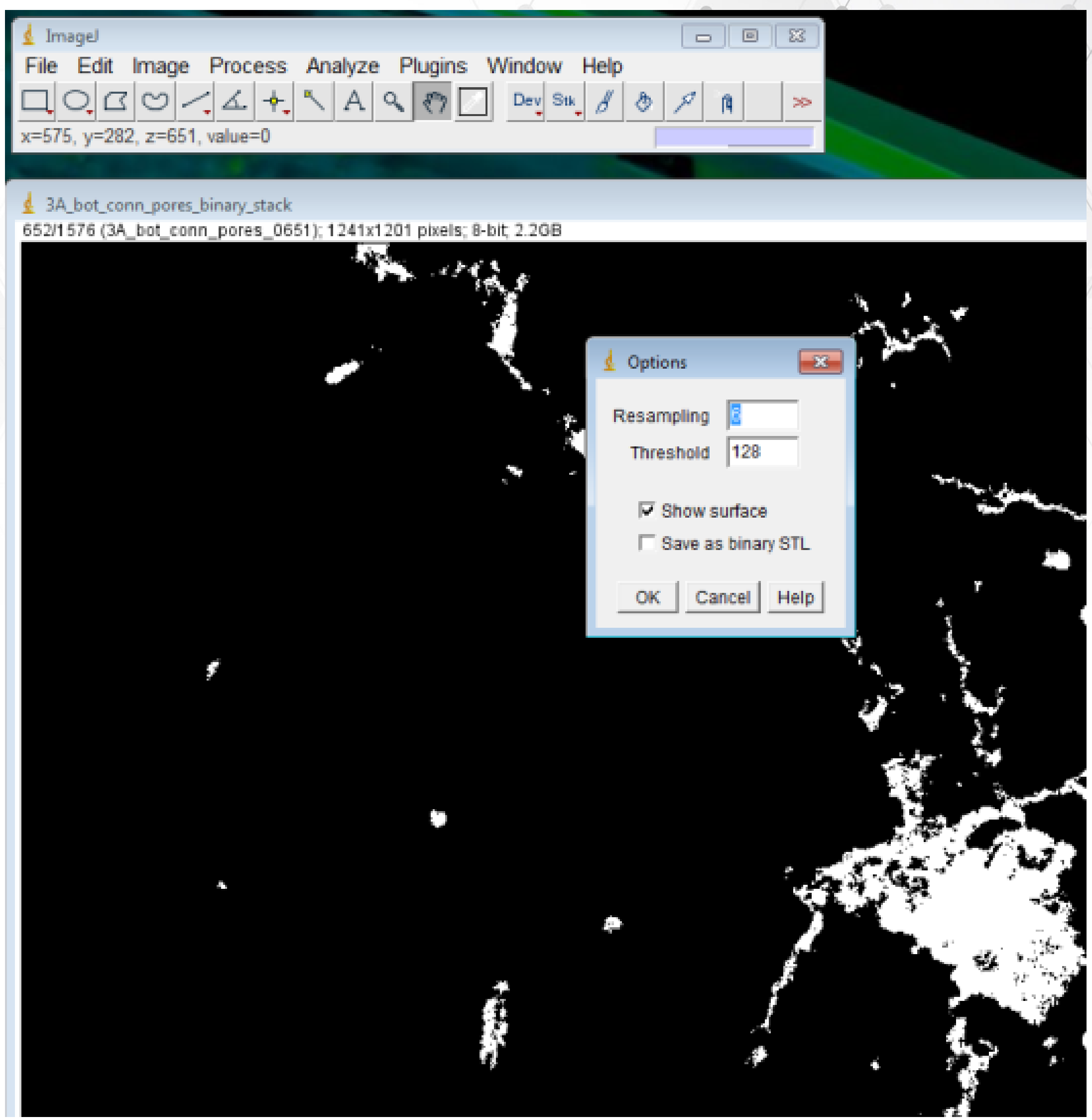
Importing stack – cont.



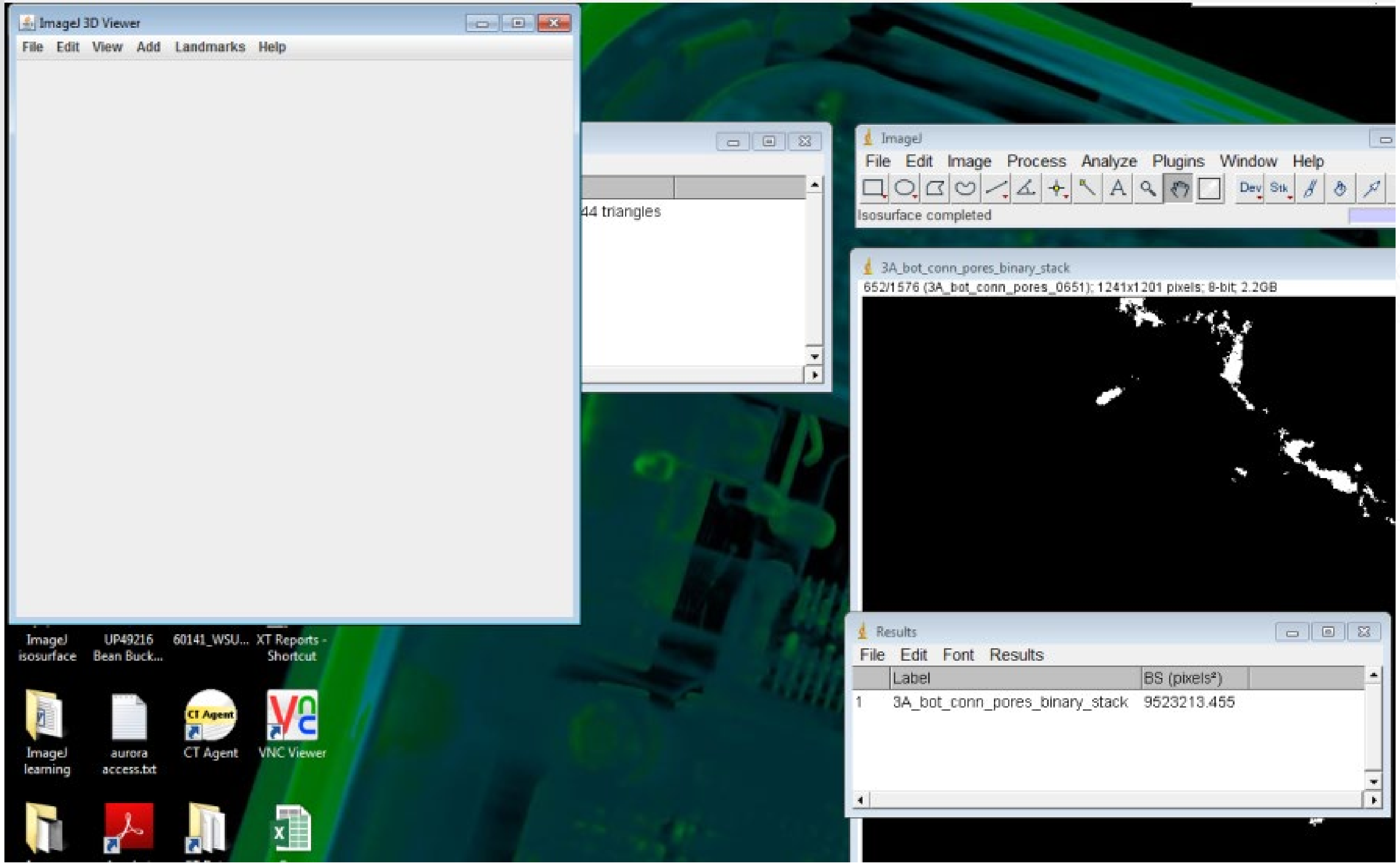
Creating STL file from segmented, binary image data

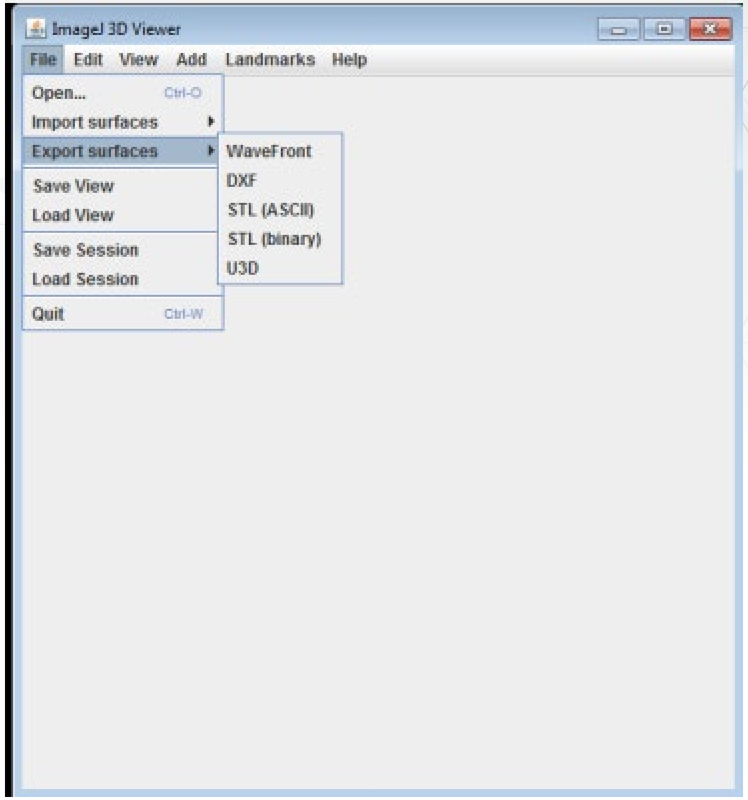
- Step-by-step process from binary stack (previous slide) to .stl in ImageJ



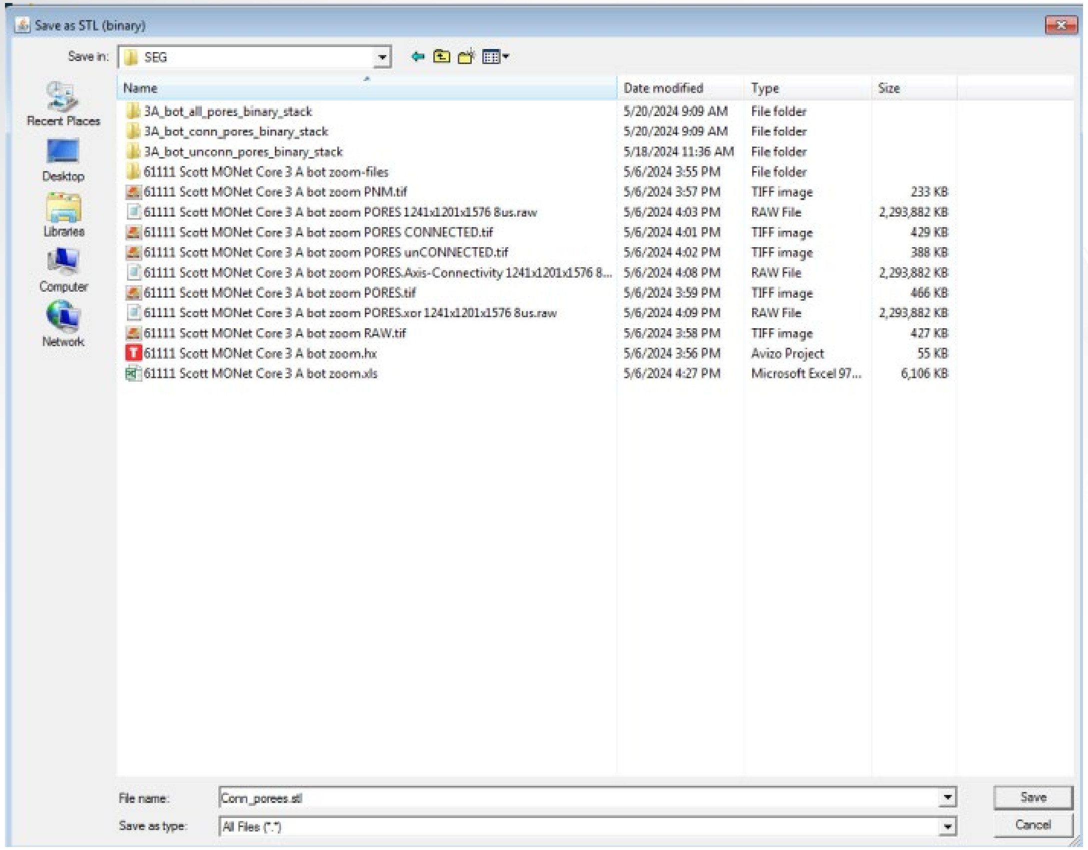


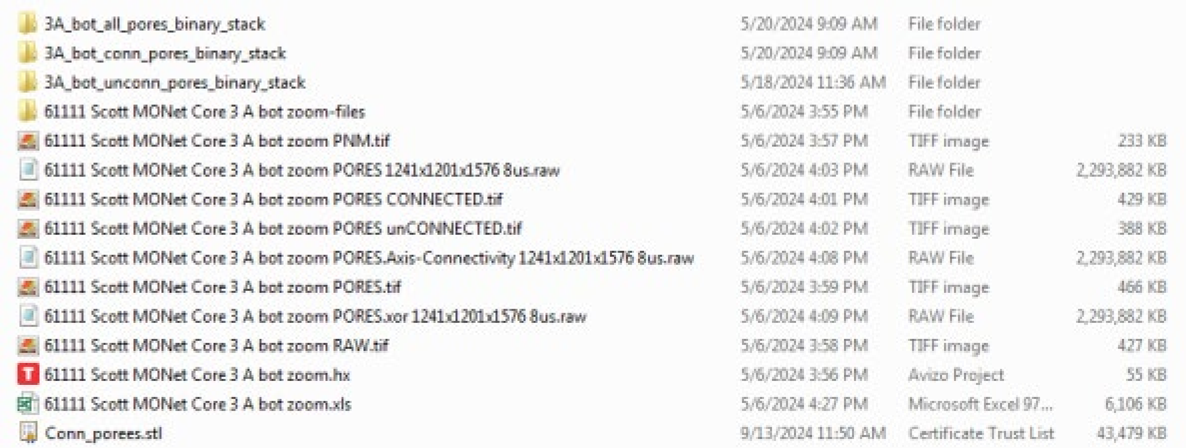
Creating STL file from segmented, binary image data – cont.





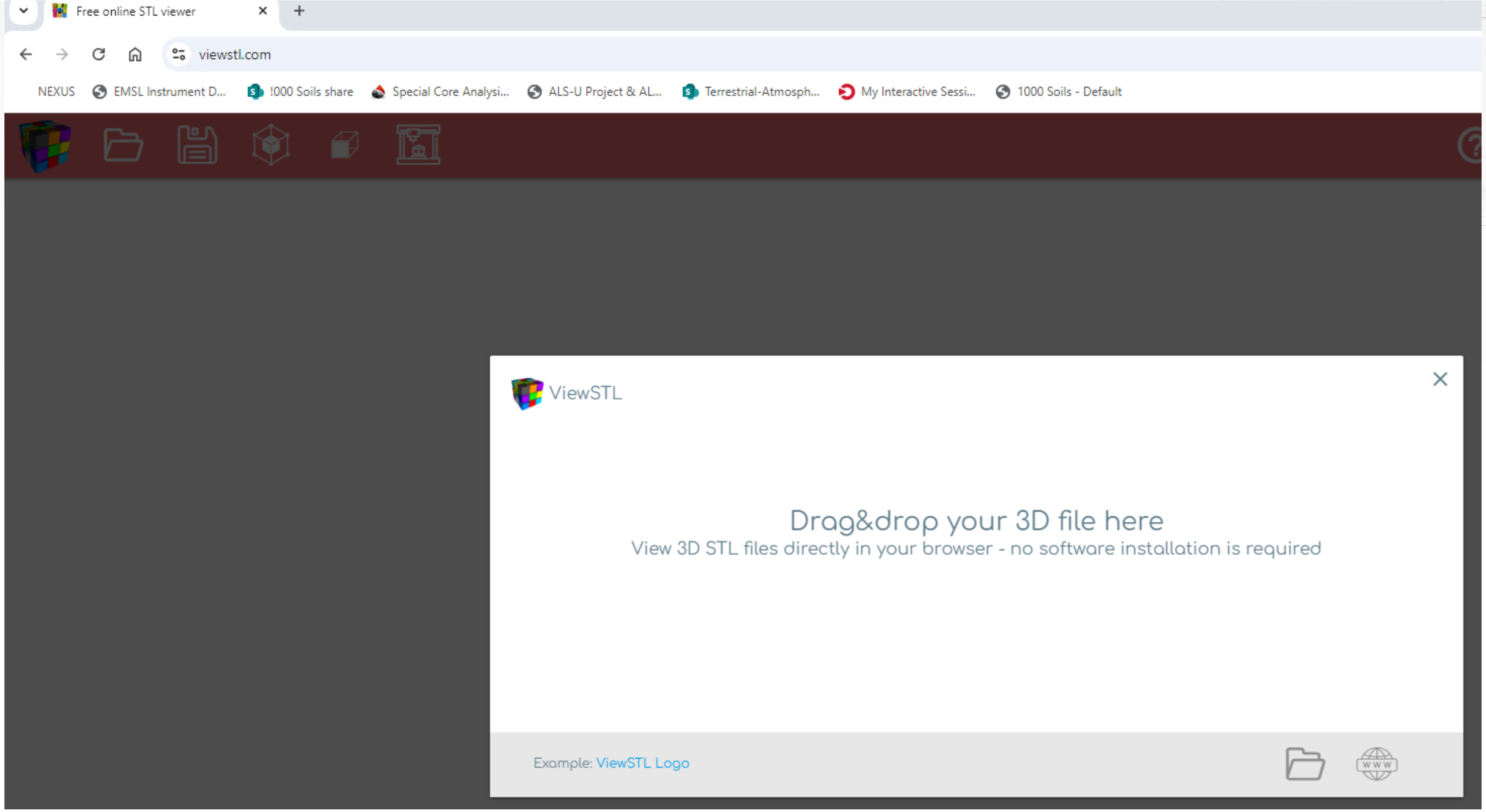
Creating STL files from segmented, binary image data – cont.





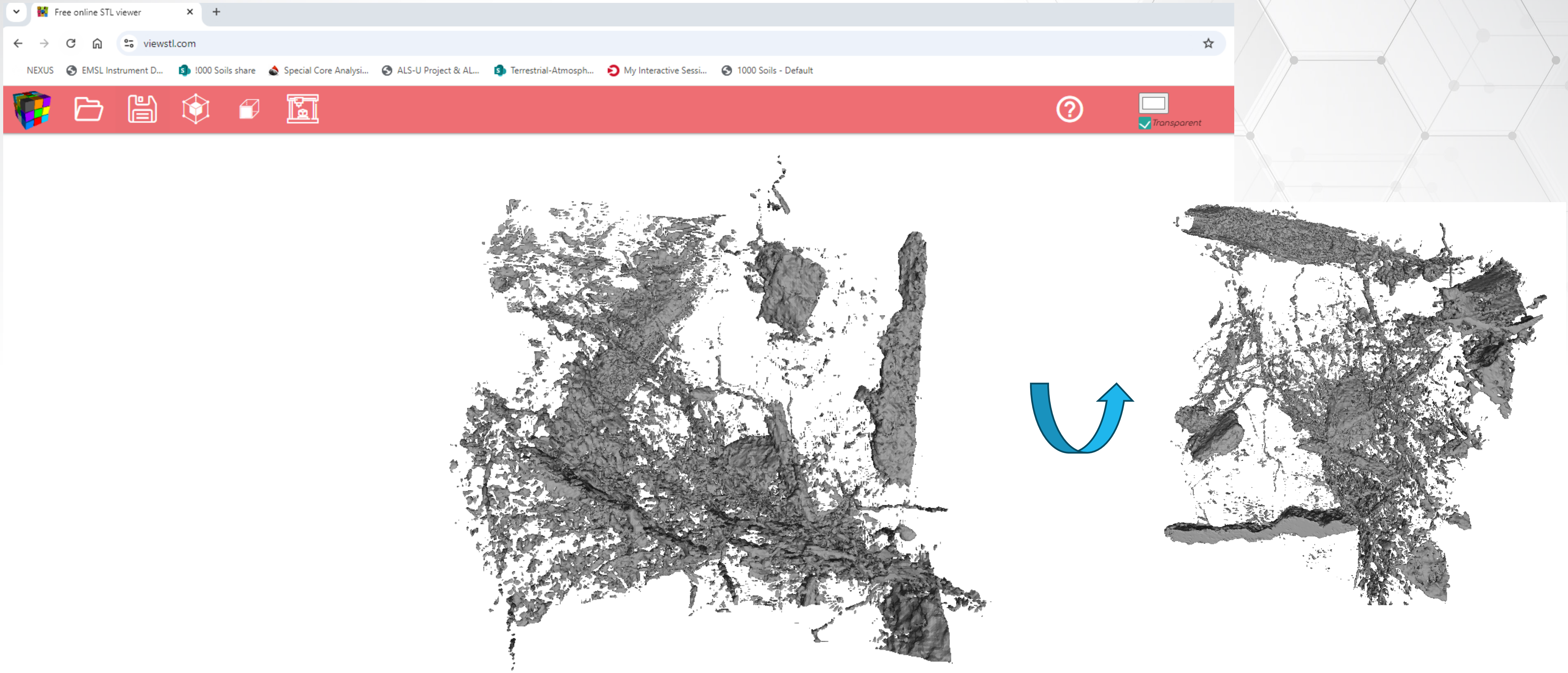
Viewing STL files

- STL Viewer: https://www.viewstl.com/



Viewing STL files

- STL Viewer: https://www.viewstl.com/



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/
- ParaView: https://www.paraview.org/download/
- Modeling:
  - OpenPNM - Pore Network Modeling Framework in Python:
    - https://openpnm.org/
    - https://github.com/PMEAL/OpenPNM
  - PoresPy - Quantitative Image Analysis of Porous Materials:
    - https://porespy.org/
  - PFLOTRAN – A massively parallel subsurface flow and reactive transport code:
    - https://www.pflotran.org/
  - OpenFOAM - A free, open source CFD software:
    - https://www.openfoam.com/

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/

Thank you!

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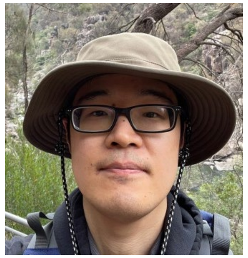
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K. Thibault

... and many more

Questions?