Ocean and Earth Science,
National Oceanography Centre
Southampton

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Optimal X-ray micro-CT image-based methods for porosity and permeability quantification in heterogeneous sandstones

Ben Callow

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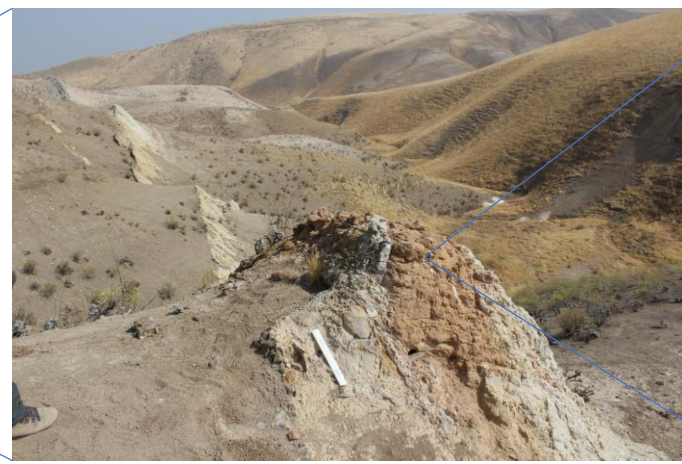
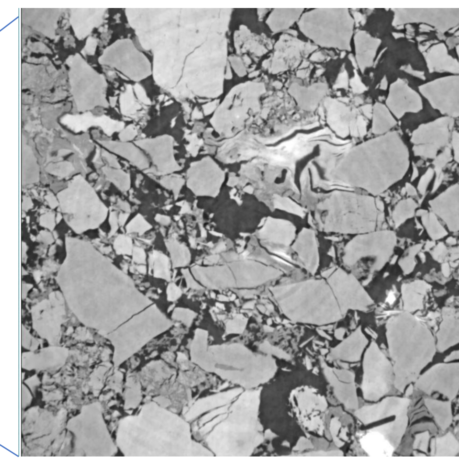

Ismael Falcon-Suarez, Jonathan Bull & Sharif Ahmed

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 654462

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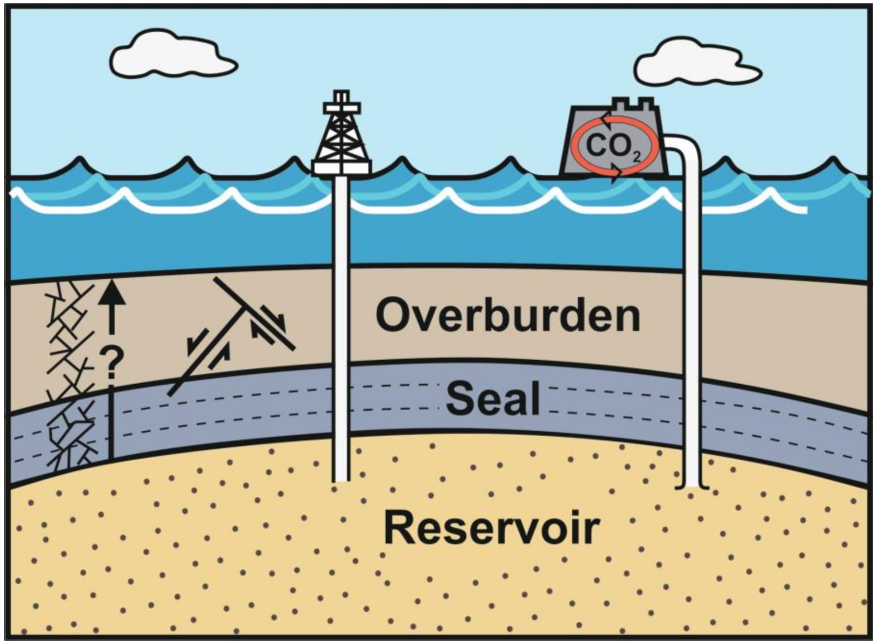
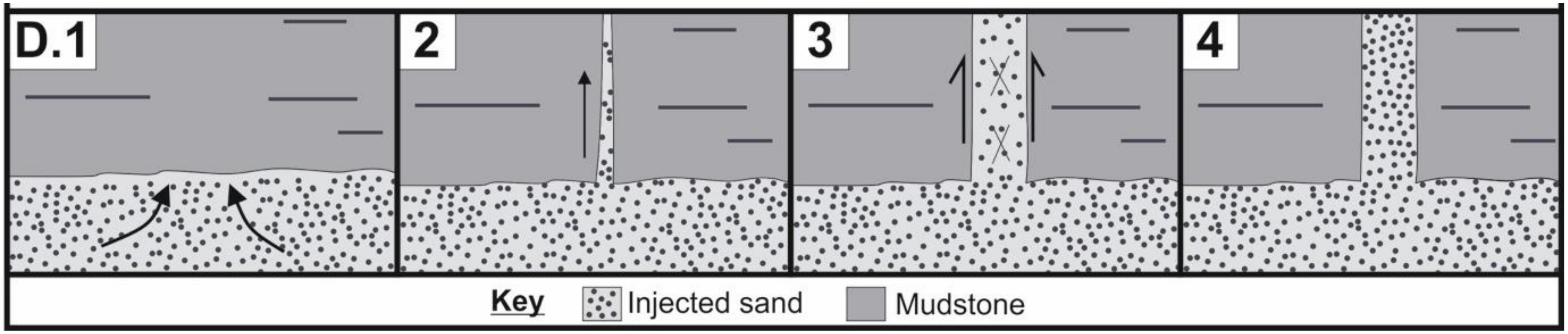
MOTIVATION: CO_2 LEAKAGE IN THE SUBSURFACE



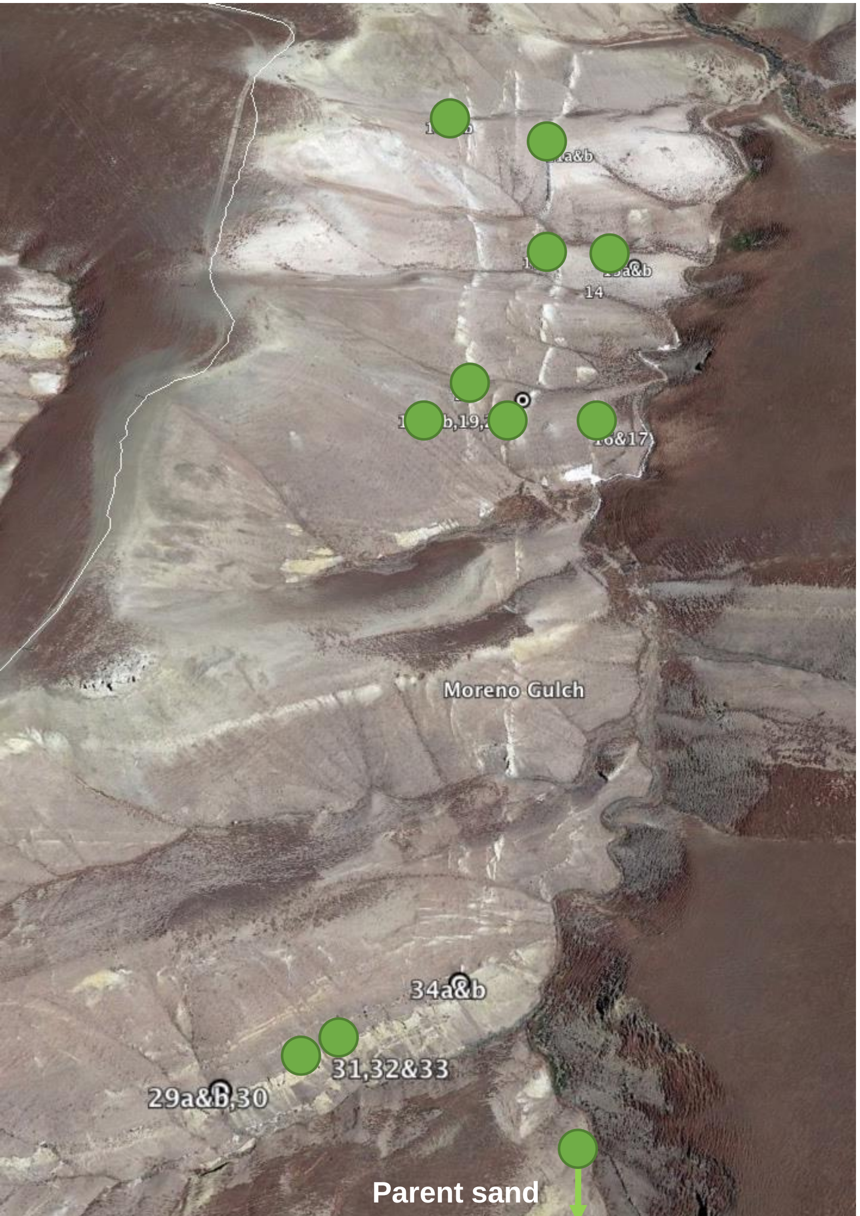
1. Faults
2. Drilling wells
3. Fluid-escape structures:
   - Sandstone intrusions

We want to sample these sandstone intrusions to quantify permeability and improve our models…

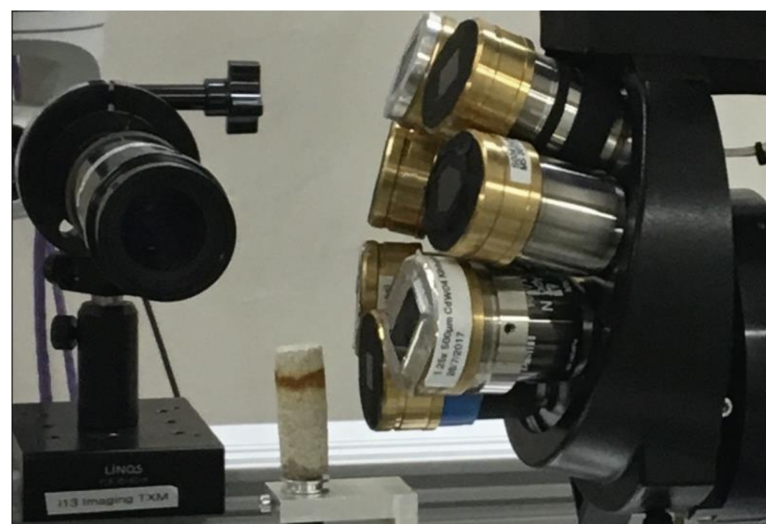


Adapted from Cobain et al. 2015

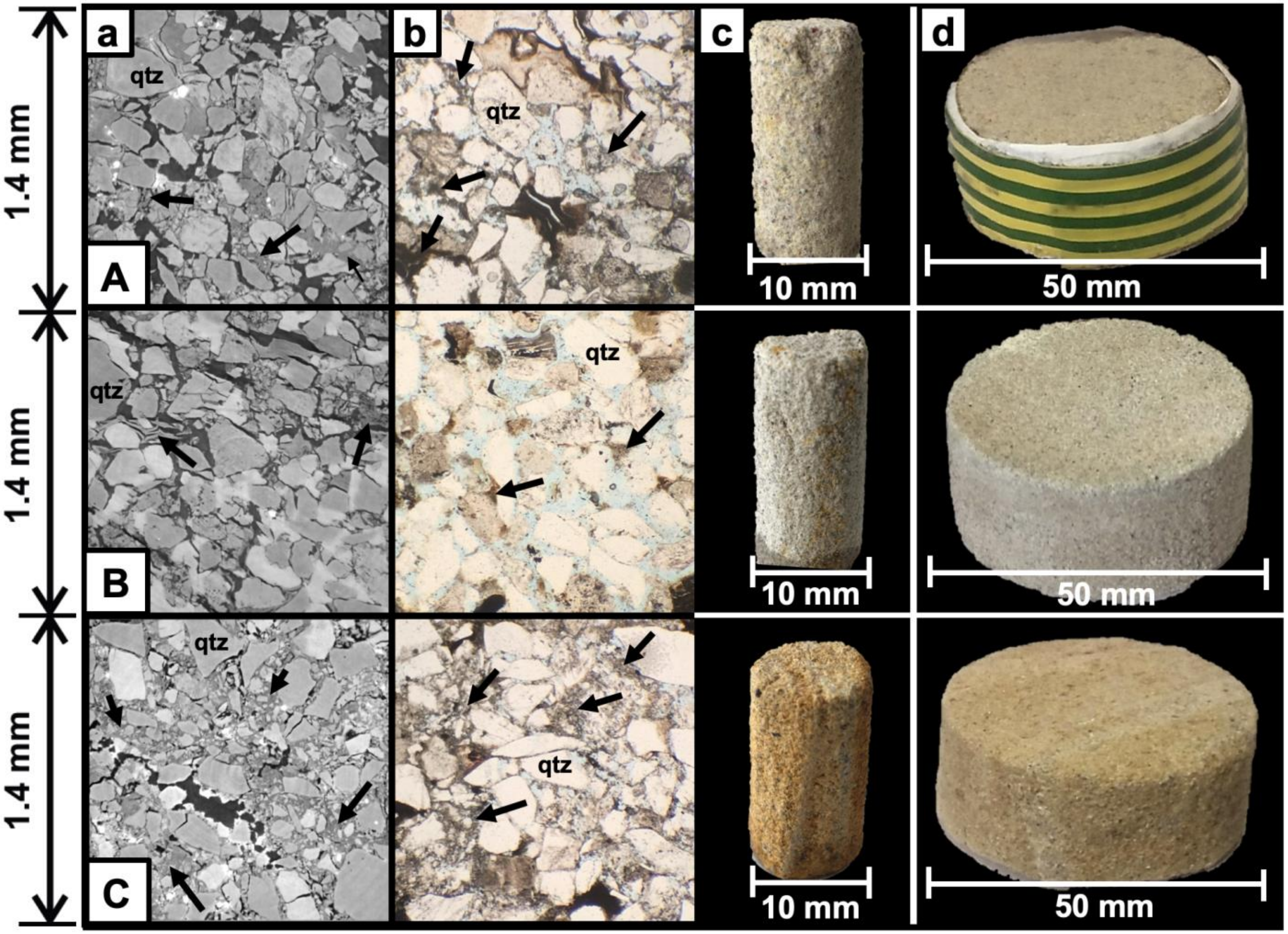
X-RAY MICRO-CT EXPERIMENT – MAY 2018



Analysed samples at Diamond Synchrotron Beamline I13-2, Oxford.

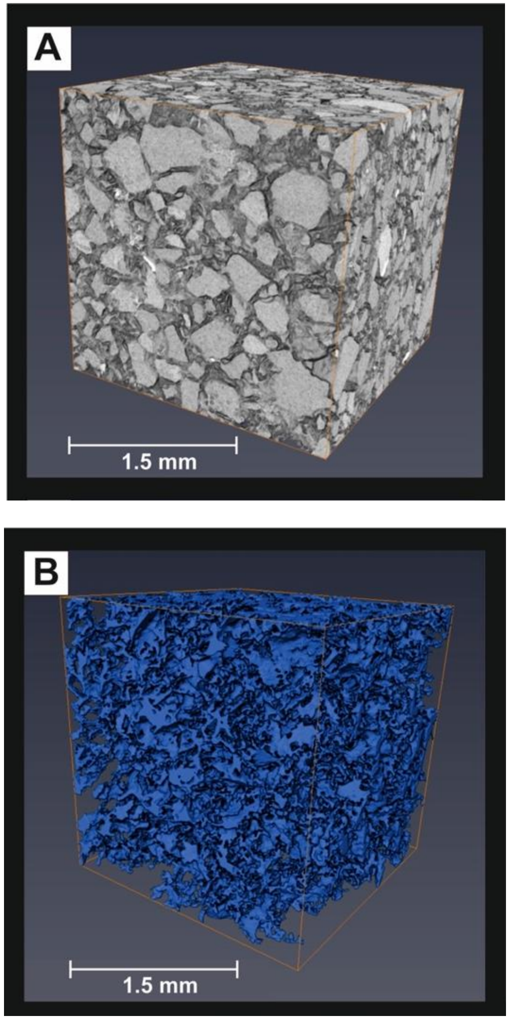


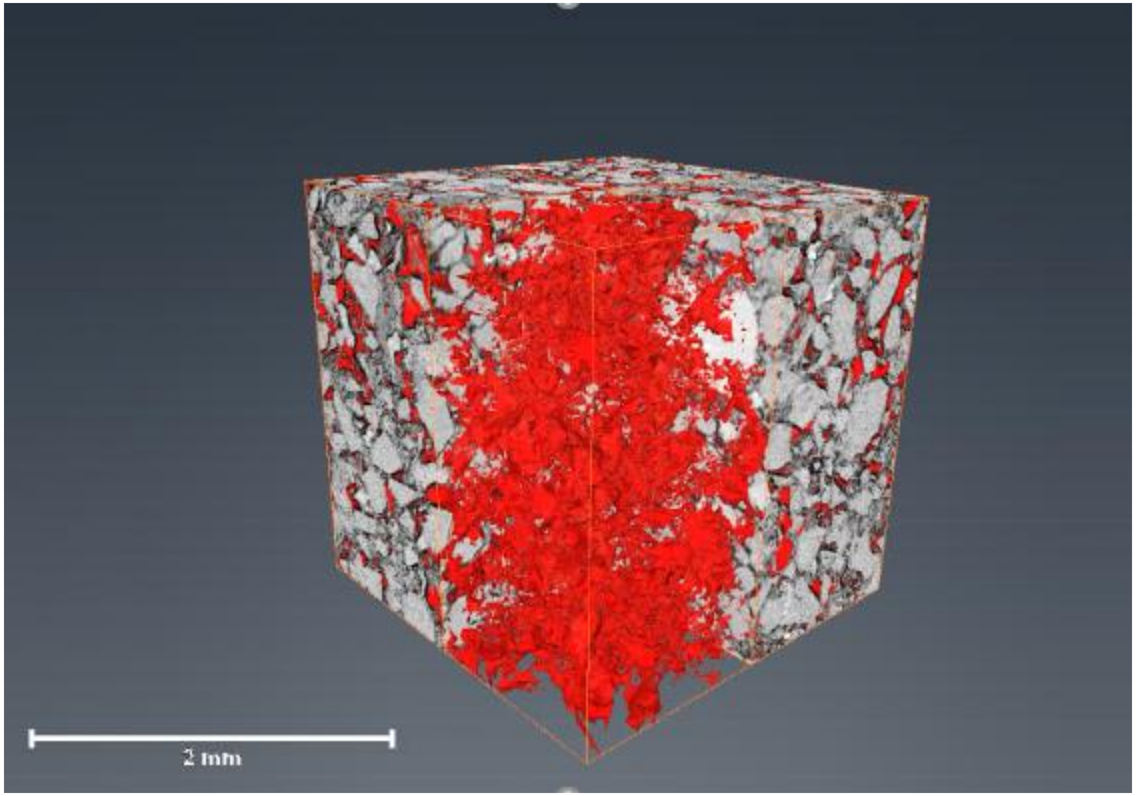
FLUID-ESCAPE SYSTEM



- Heterogeneous sandstones: 15-25 % clay and cement volume.
- 10 mm diameter samples analysed using X-ray micro-CT.
- 50 mm diameter samples analysed using laboratory measurements.

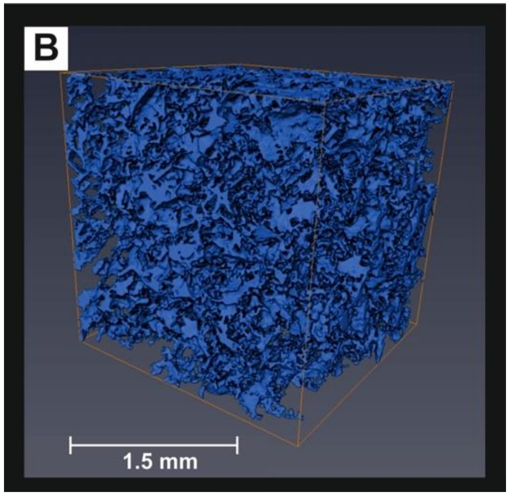
METHOD – TOTAL & CONNECTED POROSITY

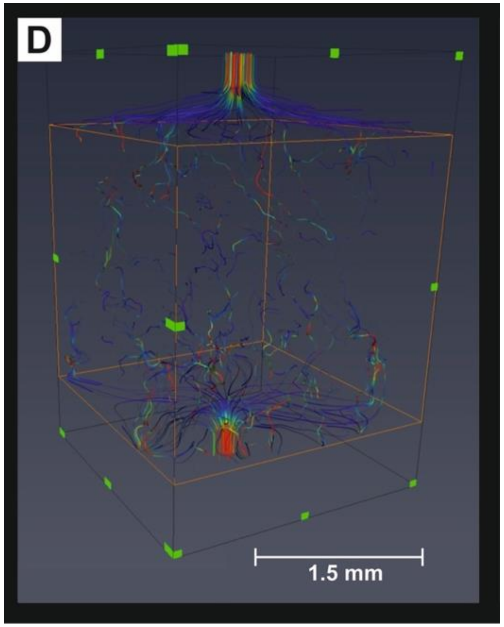


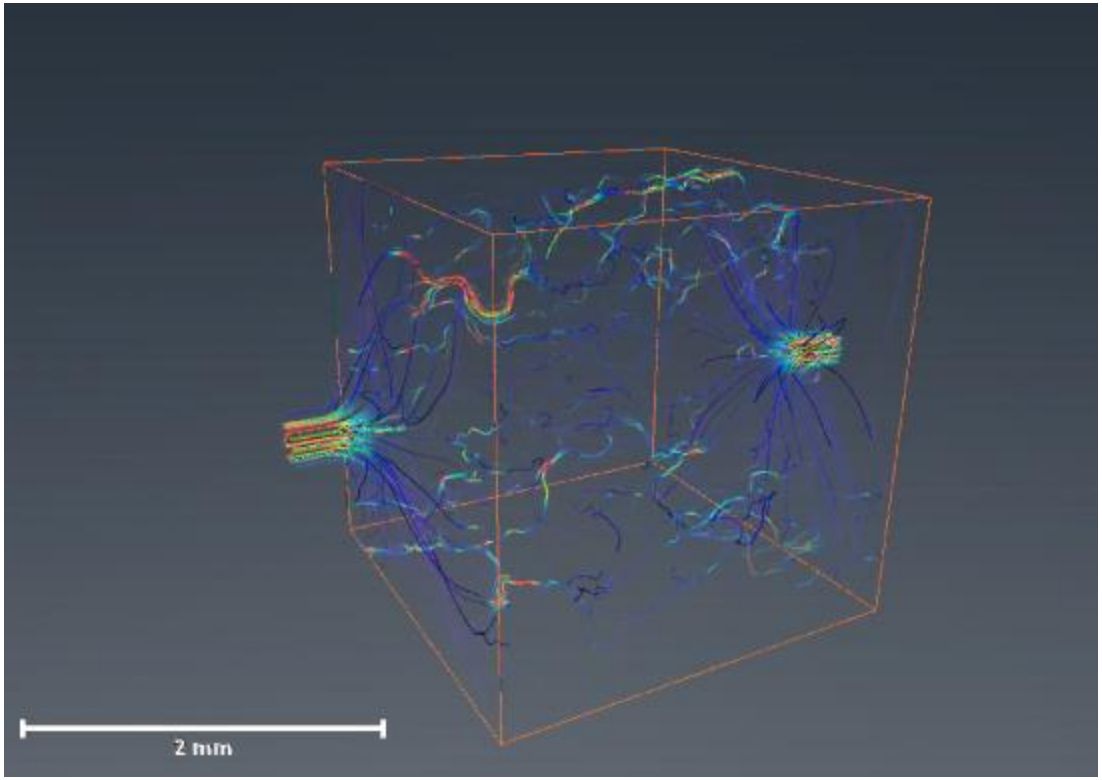


- Connected porosity obtained from the sub-volume

IMAGE-BASED FLUID-FLOW SIMULATIONS





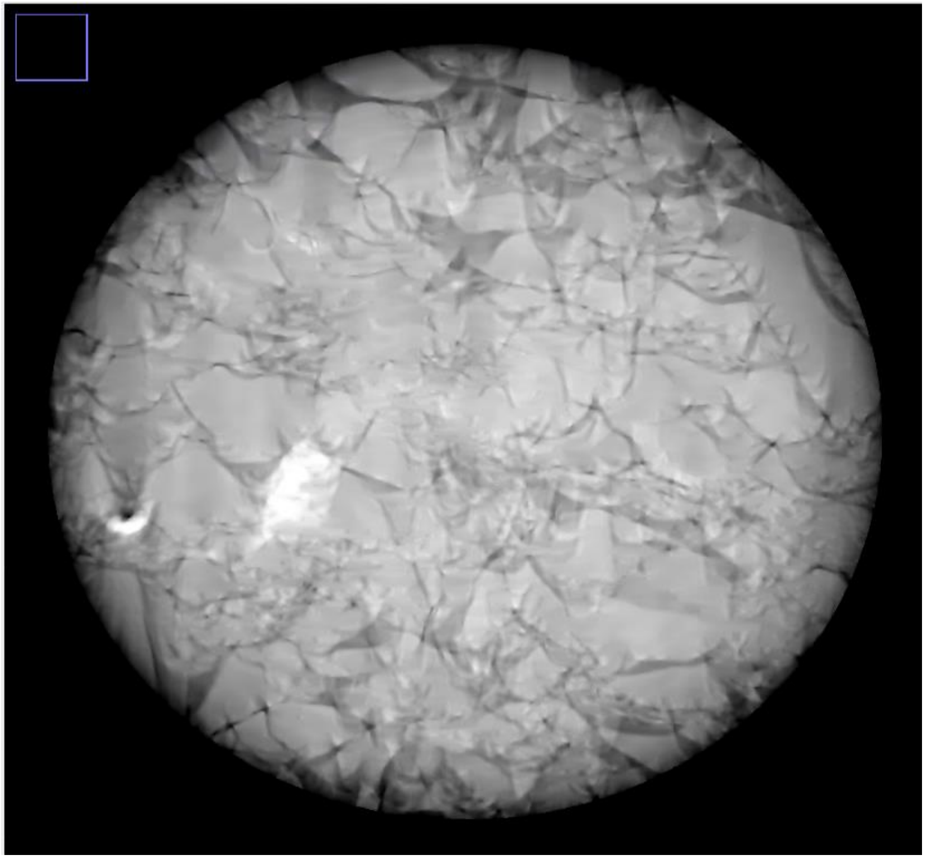


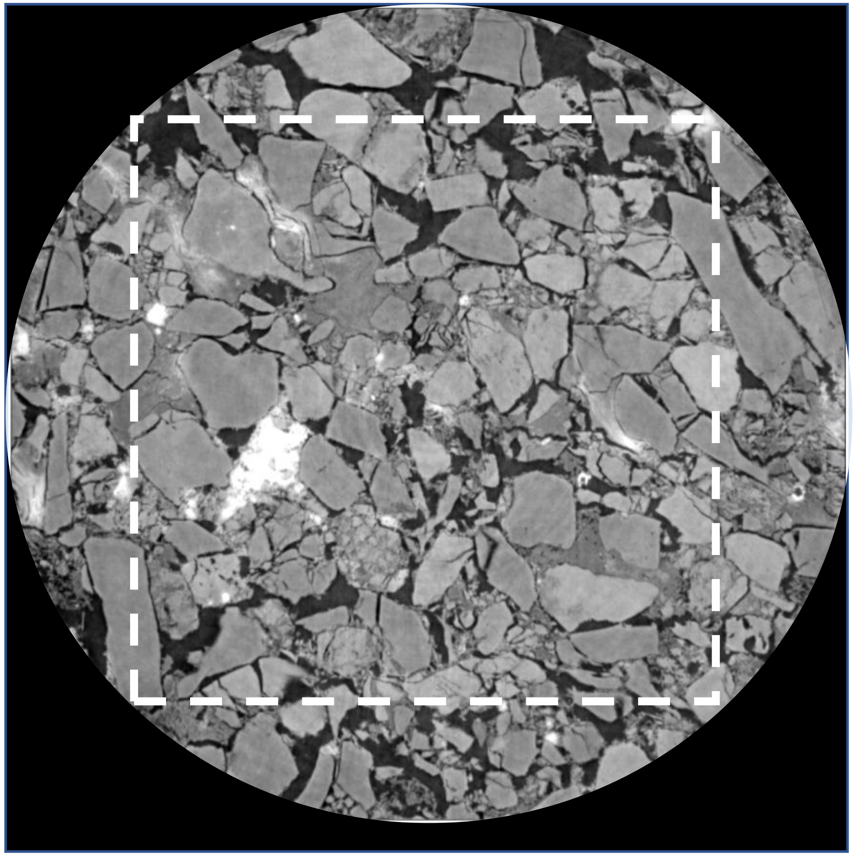
- Absolute permeability simulation

OUTLINE X-RAY CT METHODOLOGY WORKFLOW

1. Image reconstruction
2. Image segmentation
3. Fluid simulation comparison
4. Representative Volume
5. Image Resolution

1. IMAGE RECONSTRUCTION





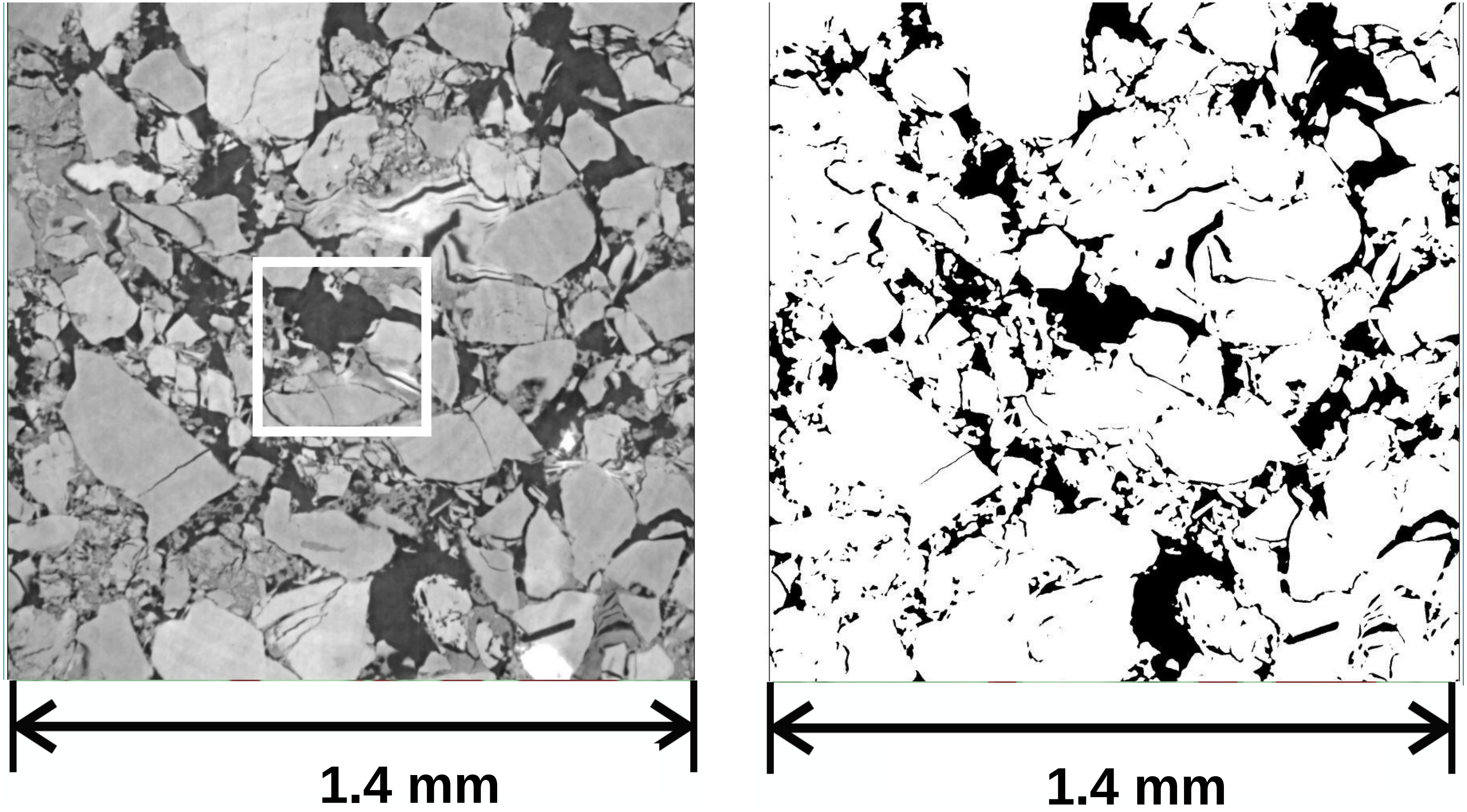
- Correct COR (Centre of Rotation)
- No beam hardening
- Filtering of noise and ring artefacts

- 5GB file
- 1400^3 voxel volume
- 8 bit image (16 also possible)

X-RAY CT METHODOLOGY WORKFLOW

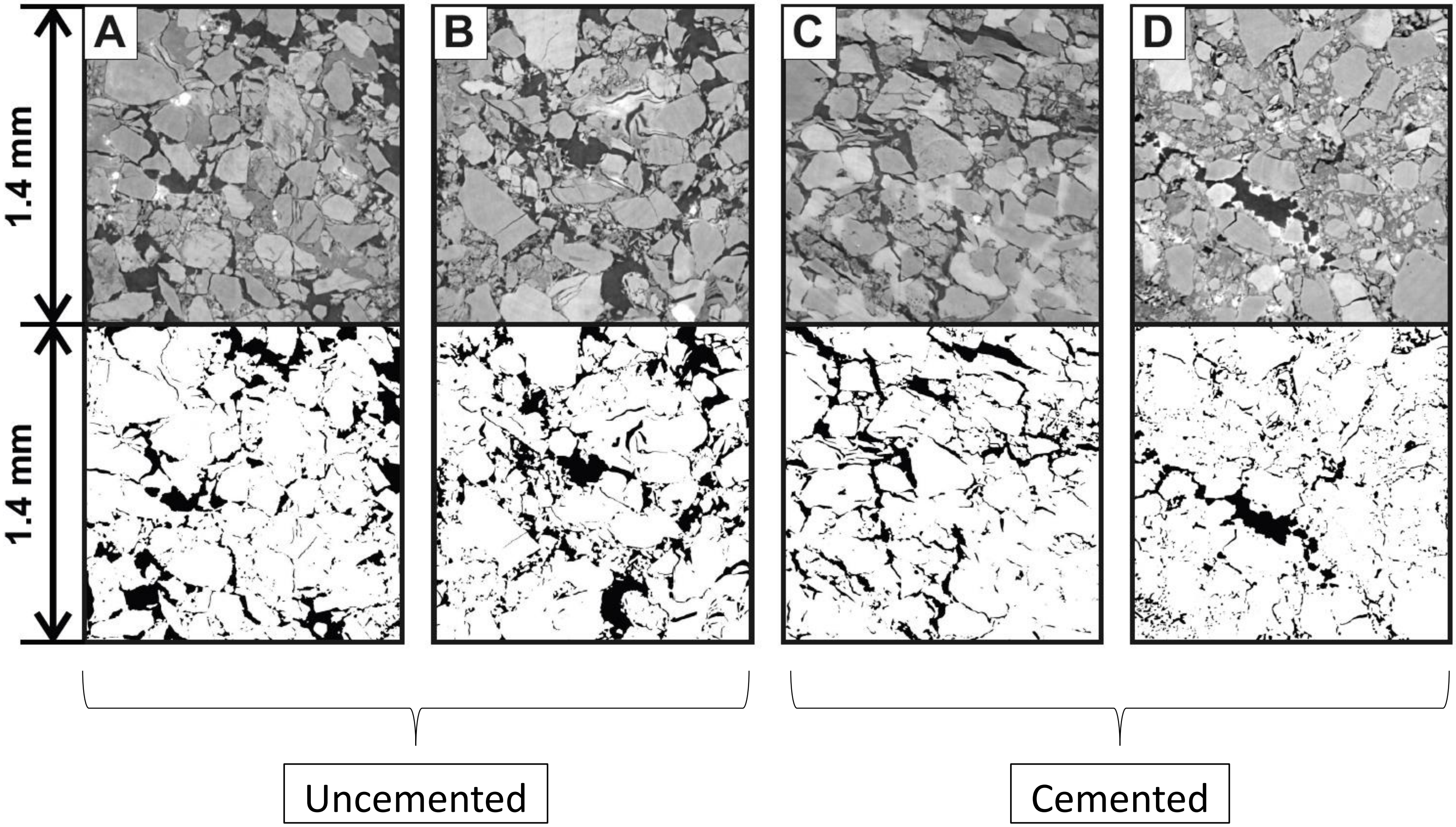
- ✓ Image reconstruction
2. Image segmentation
3. Fluid simulation comparison
4. Representative Volume
5. Image Resolution

2. IMAGE SEGMENTATION – 2 PHASES

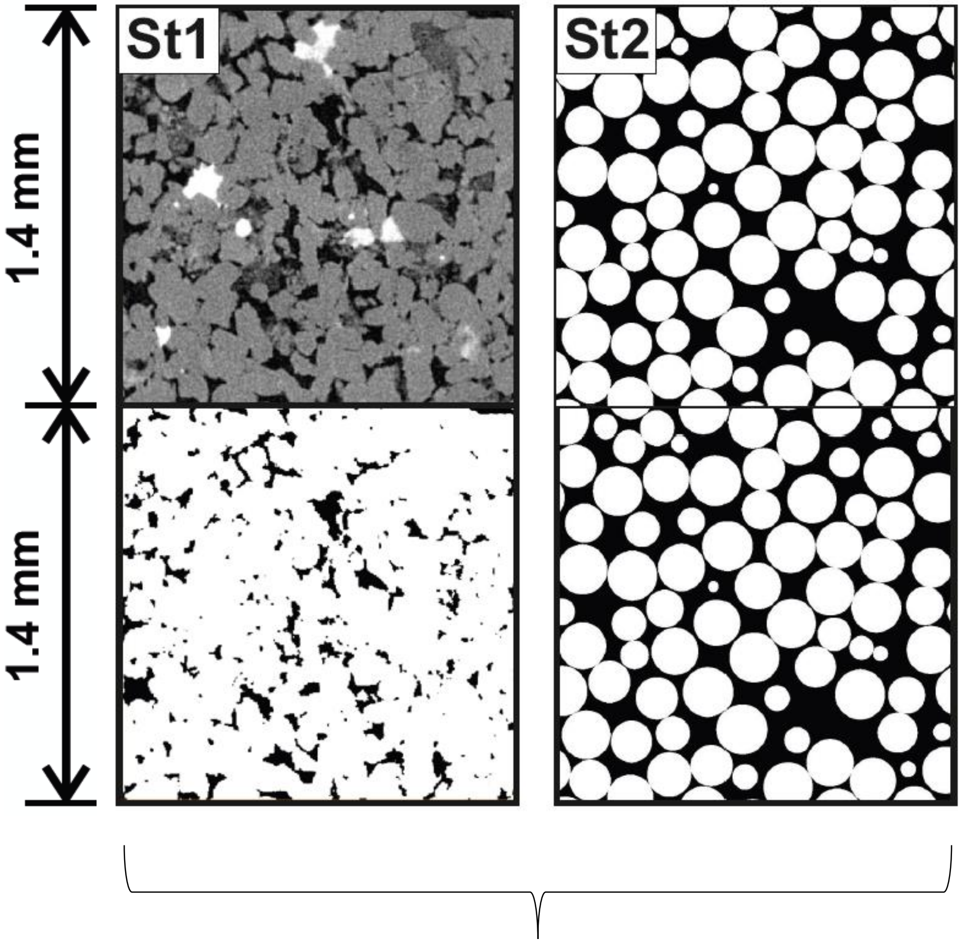


- Accurate segmentation achieved using trainable 3D Weka - FIJI.
- Training on 100^3 voxel volume
- Tiling algorithm applied to reduce memory requirements

2. IMAGE SEGMENTATION – 2 PHASES

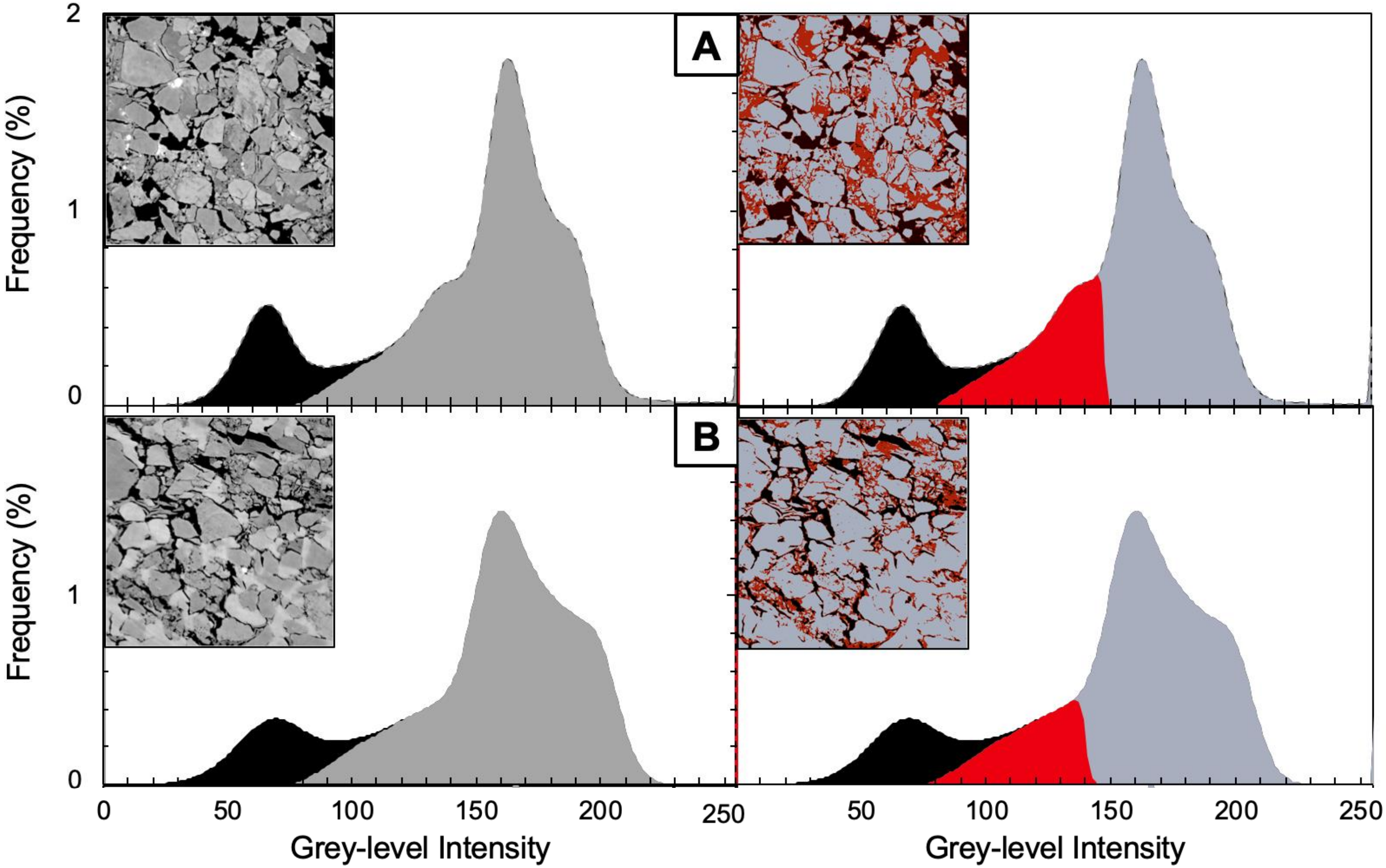


2. IMAGE SEGMENTATION – 2 PHASES



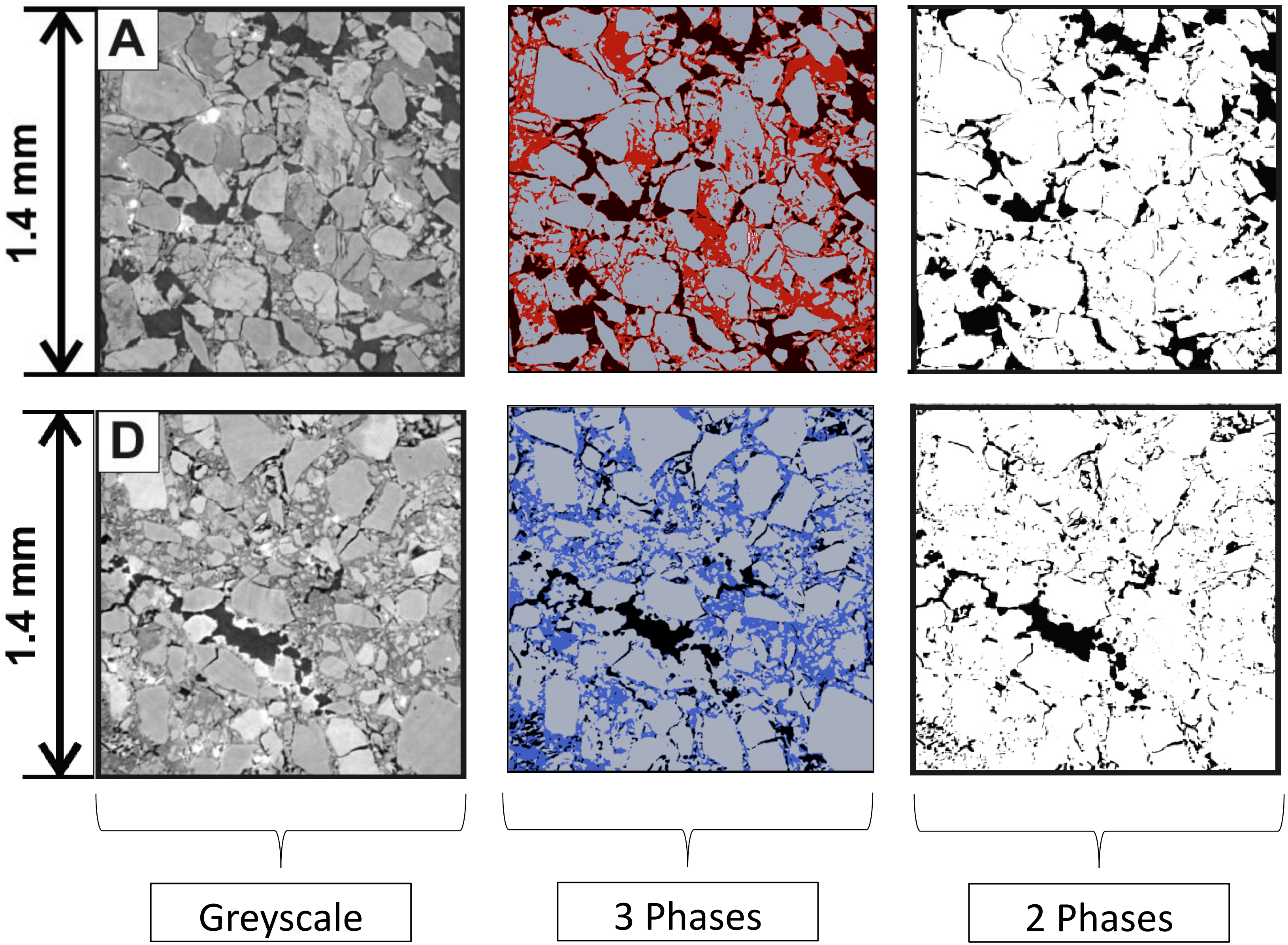
Standards

2. IMAGE SEGMENTATION – 3 PHASES



- A clay and cement phase is also defined, which is assigned to the pore phase for porosity calculations, and the solid phase for permeability calculations.

2. IMAGE SEGMENTATION – 3 PHASES

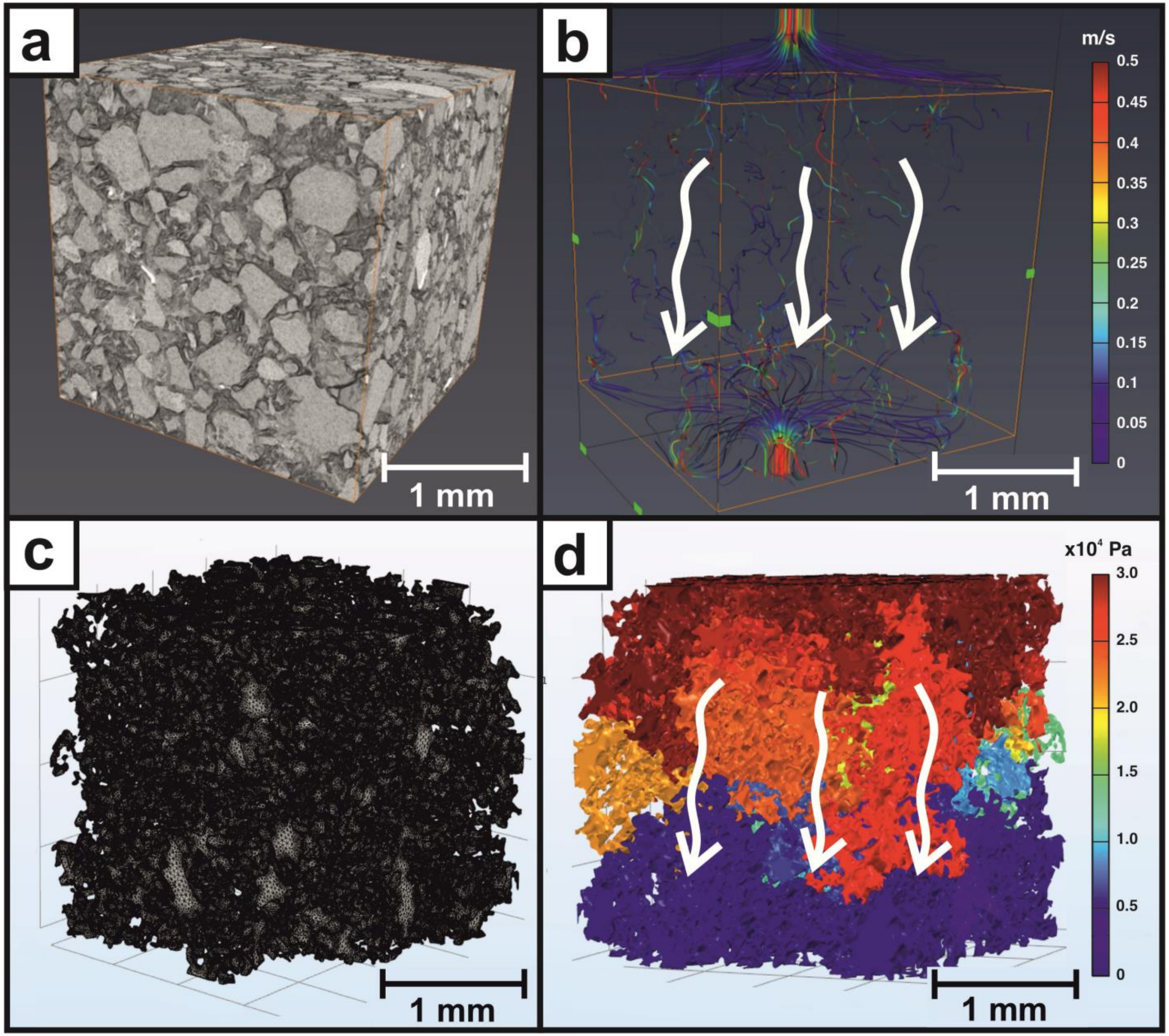


X-RAY CT METHODOLOGY WORKFLOW

- ✓ Image reconstruction
- ✓ Image segmentation

3. Fluid simulation comparison
4. Representative Volume
5. Image Resolution

3. PERMEABILITY SIMULATION COMPARISON



Voxel Based Solver (VBS)

vs

Tetrahedral Mesh

3. PERMEABILITY SIMULATION COMPARISON

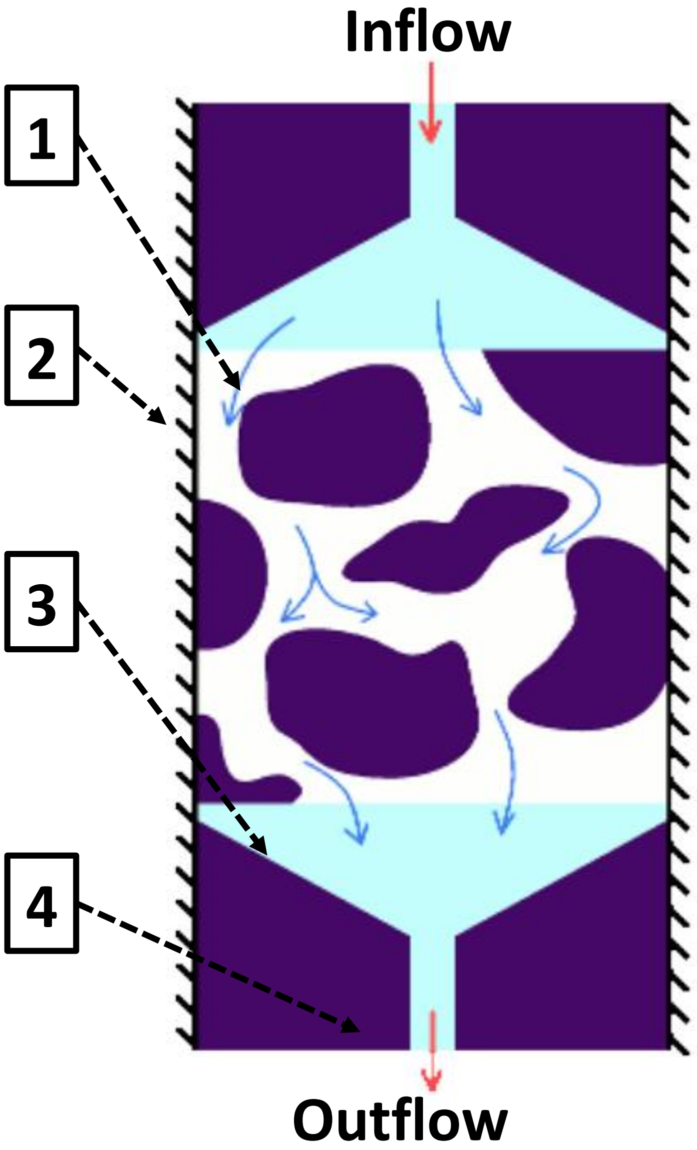
- Experiment simulation based on Stokes equations.

$$\left.\begin{array}{r}\mu\nabla^2\mathbf{u}-\nabla\mathrm{p}=0\\ \nabla\cdot\mathbf{u}=0\end{array}\right\},$$

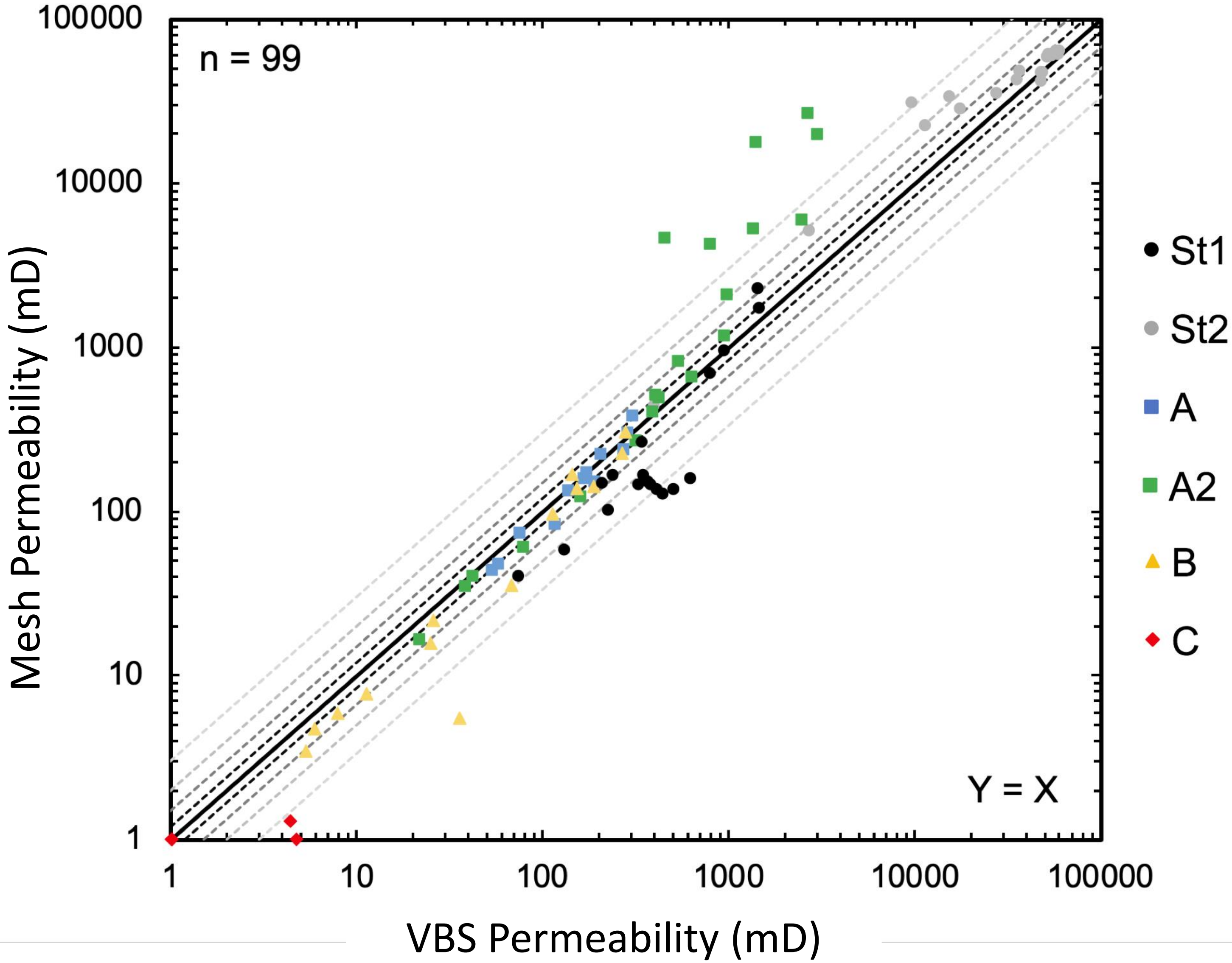
$$k=\frac{\mu L Q}{\Delta P A},$$

<u>Boundary conditions:</u>

1. No-slip condition at fluid-solid interfaces
2. Solid phases added perpendicular to main simulated flow direction
3. Stabilization zone created where pressure is quasi static
4. Input pressure, output pressure and flow rate user defined.

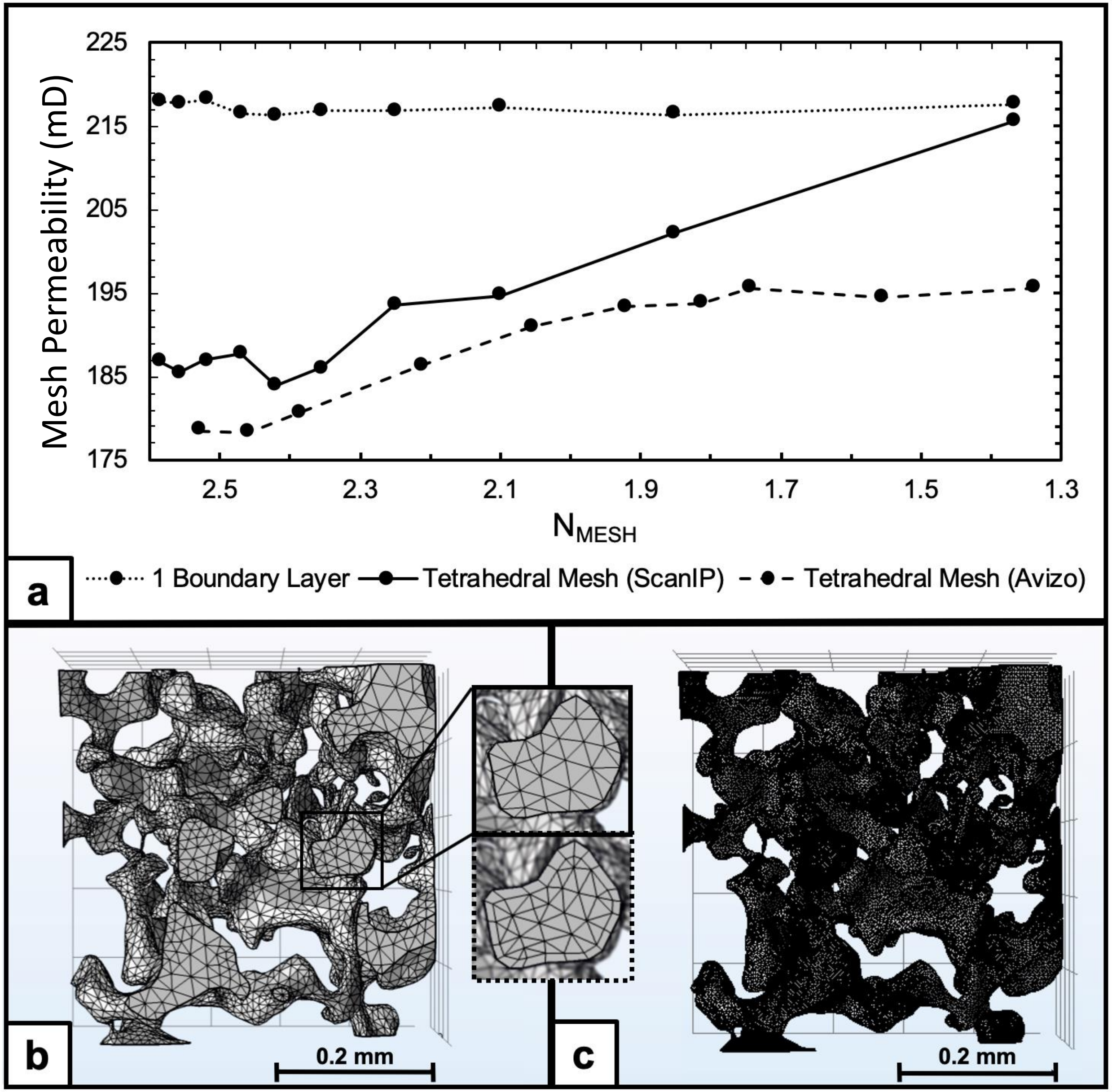


3. PERMEABILITY SIMULATION COMPARISON



- Two simulation methods are reasonably comparable between 10-1000mD range.

3. DEPENDENCY OF MESH DENSITY



$$N_{\mathrm{MESH}} = \frac{E_l}{\Delta x},$$

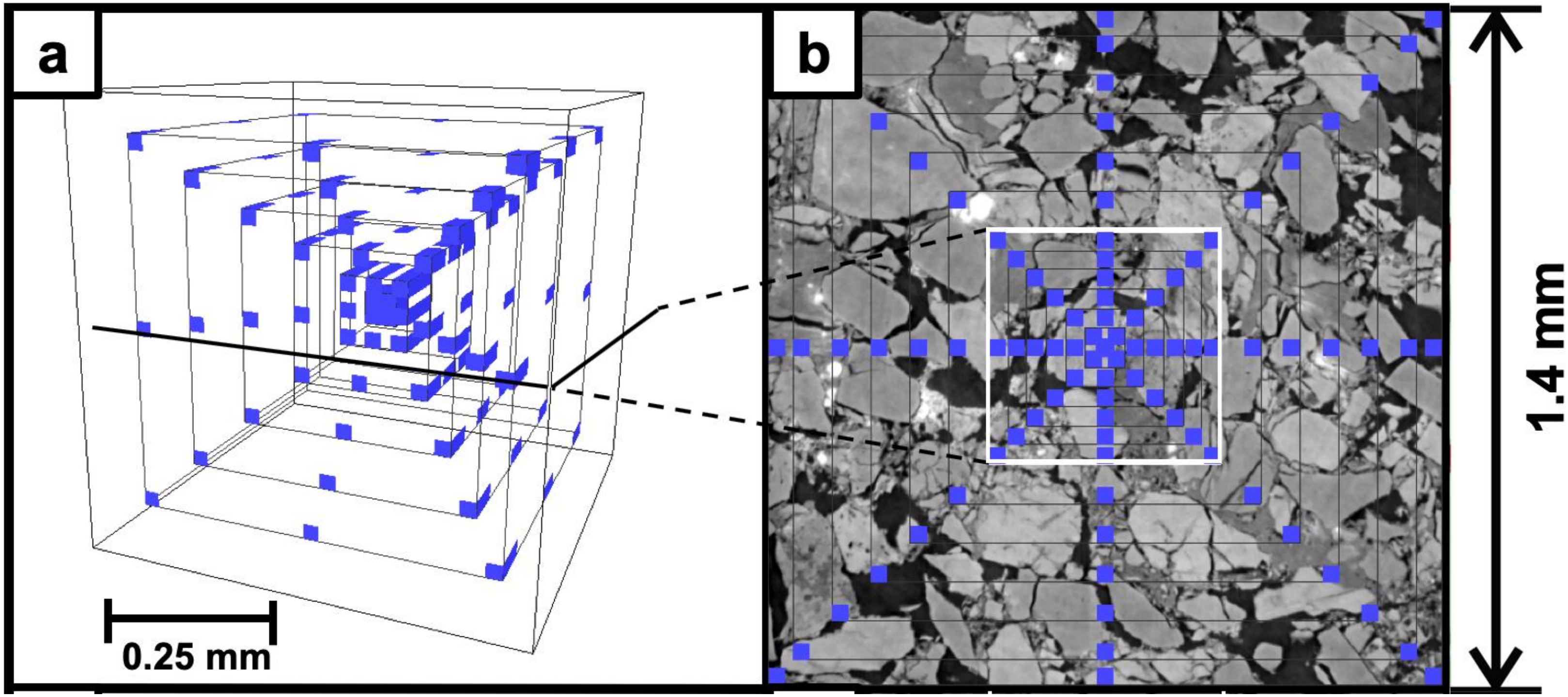
- Decreasing N_{MESH} = Increased mesh density.
- 1 Boundary Layer mesh is most desirable, but is not possible for larger volumes due to software limitations.
- N_{MESH} = 2.6 = 300,000 mesh elements
- N_{MESH} 1.3 = 1,950,000 mesh elements

X-RAY CT METHODOLOGY WORKFLOW

- ✓ Image reconstruction
- ✓ Image segmentation
- ✓ Fluid simulation comparison

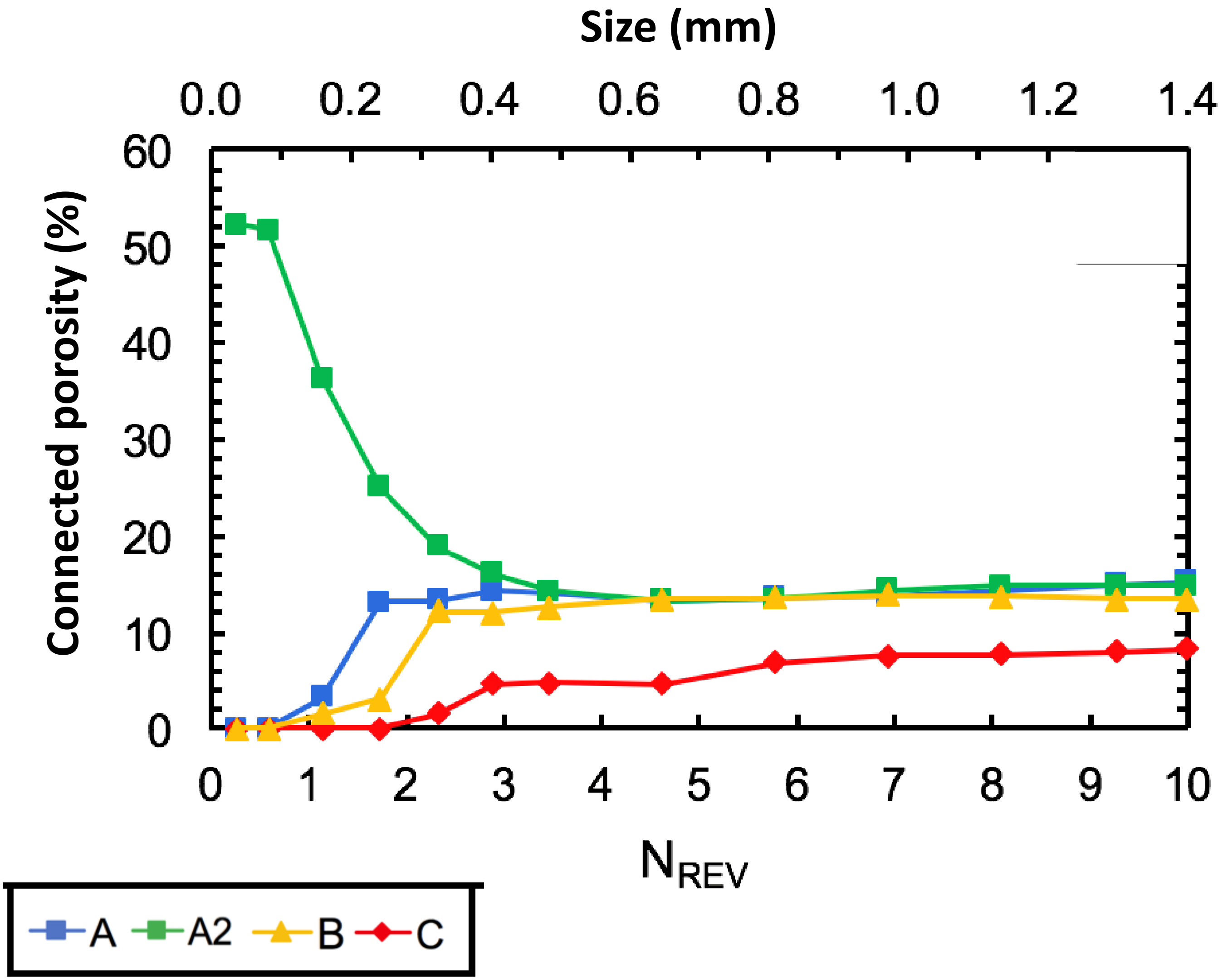
4. Representative Volume
5. Image Resolution

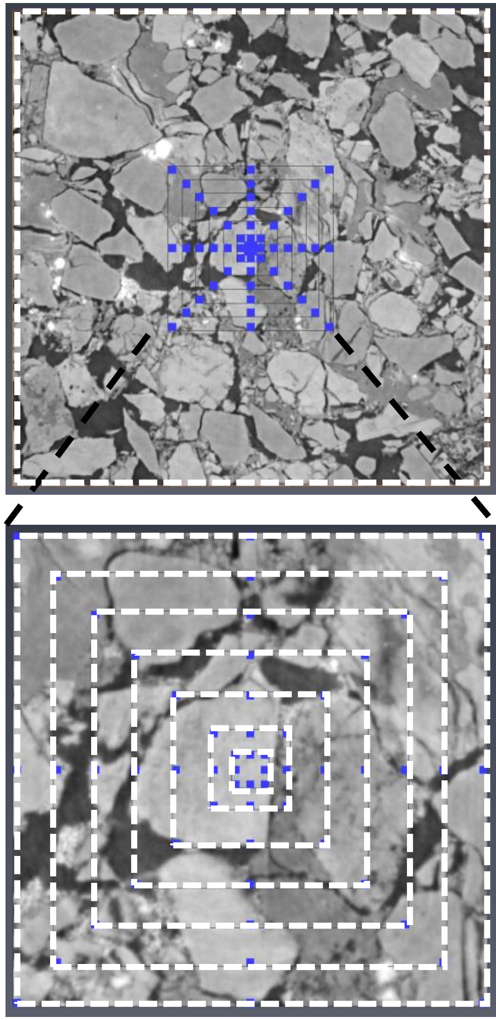
4. REPRESENTATIVE VOLUME



- Pore properties are acquired from a number of different volume sizes, to demonstrate the optimum representative elementary volume size (REV).

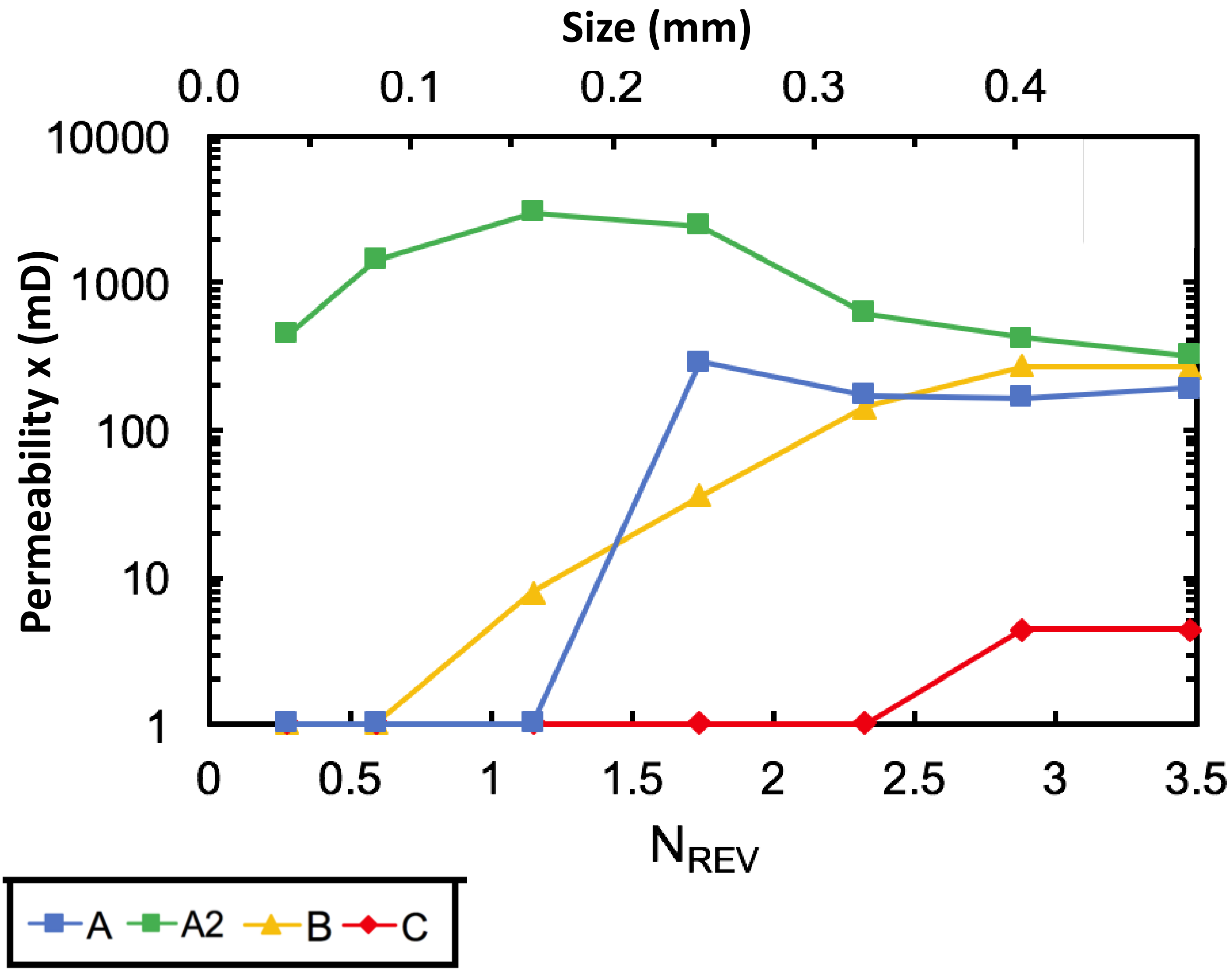
4. REPRESENTATIVE VOLUME

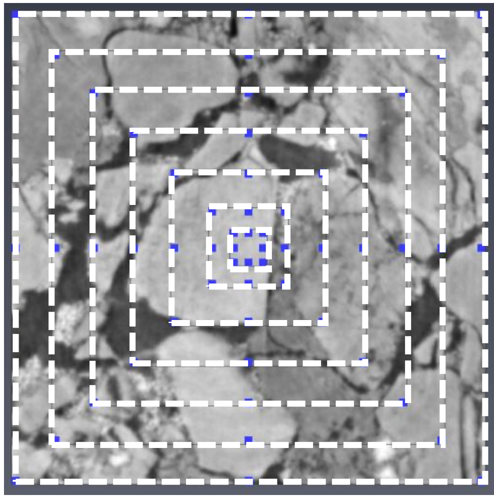




1 N_{REV} = 1 grain diameter = 140 µm

4. REPRESENTATIVE VOLUME





1 N_{REV} = 1 grain diameter = 140 µm

N_{REV} of 3.5 = 600^3 voxel volume

X-RAY CT METHODOLOGY WORKFLOW

✓ Image reconstruction

✓ Image segmentation

✓ Fluid simulation comparison

? Representative Volume

5. Image Resolution

5. IMAGE RESOLUTION

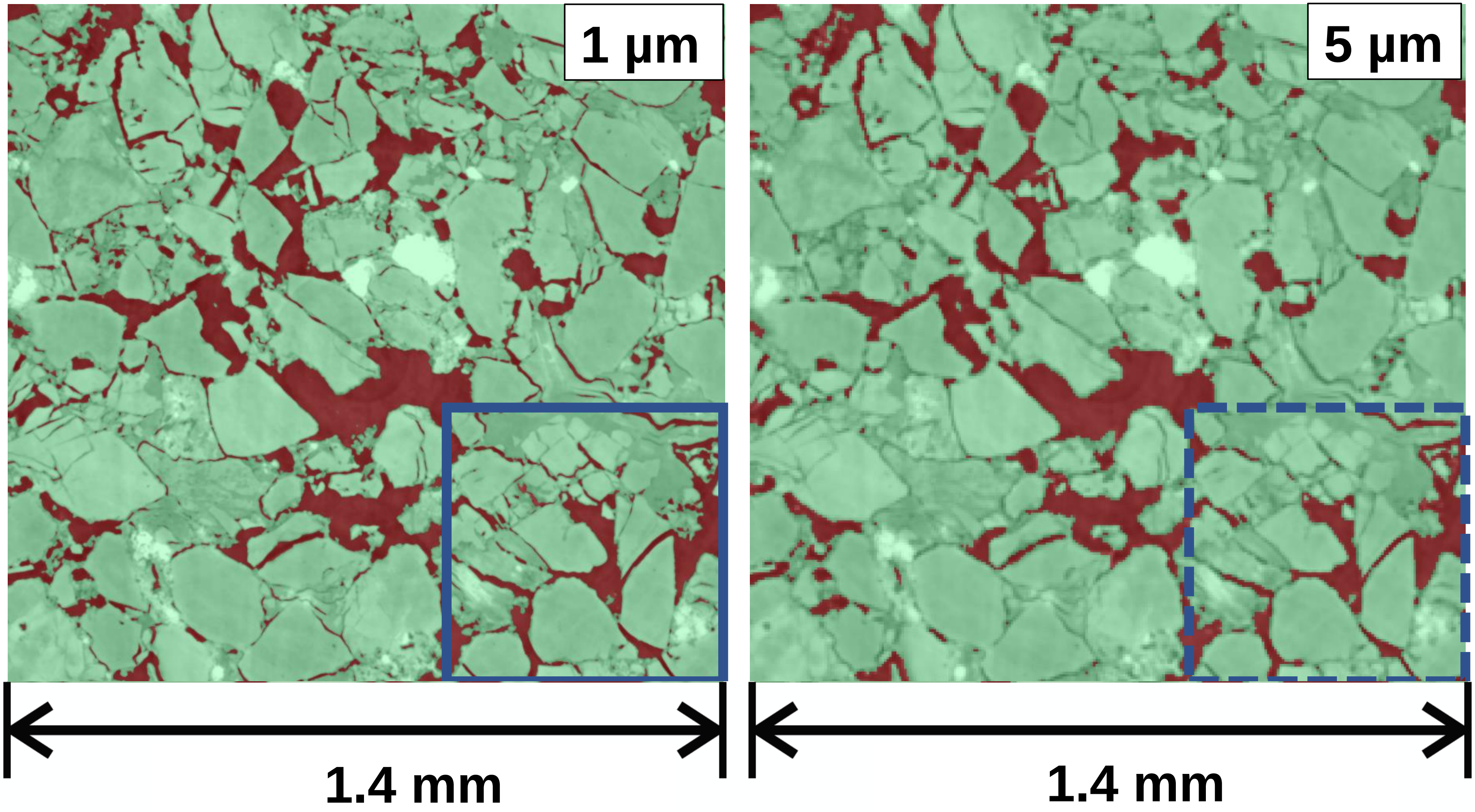
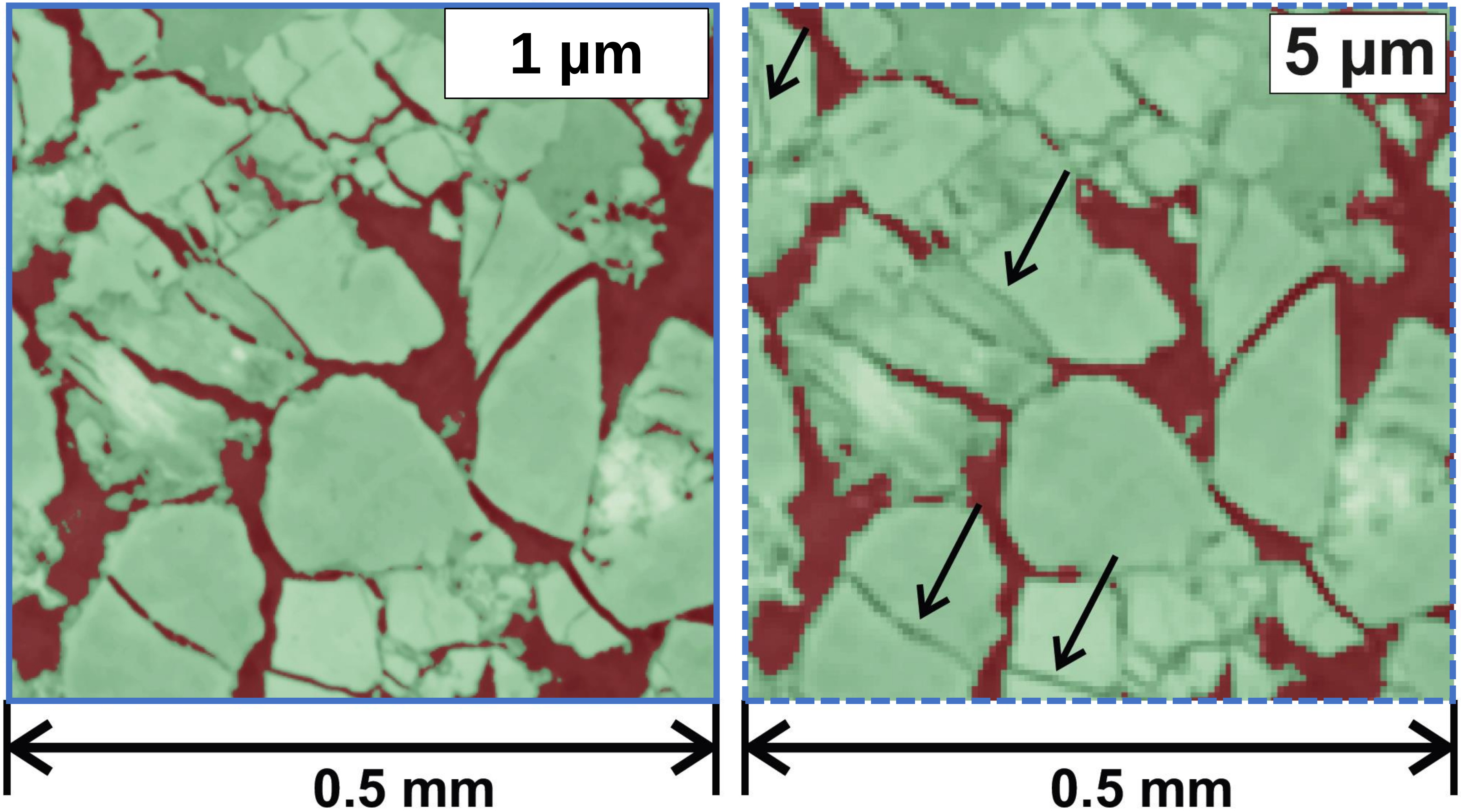
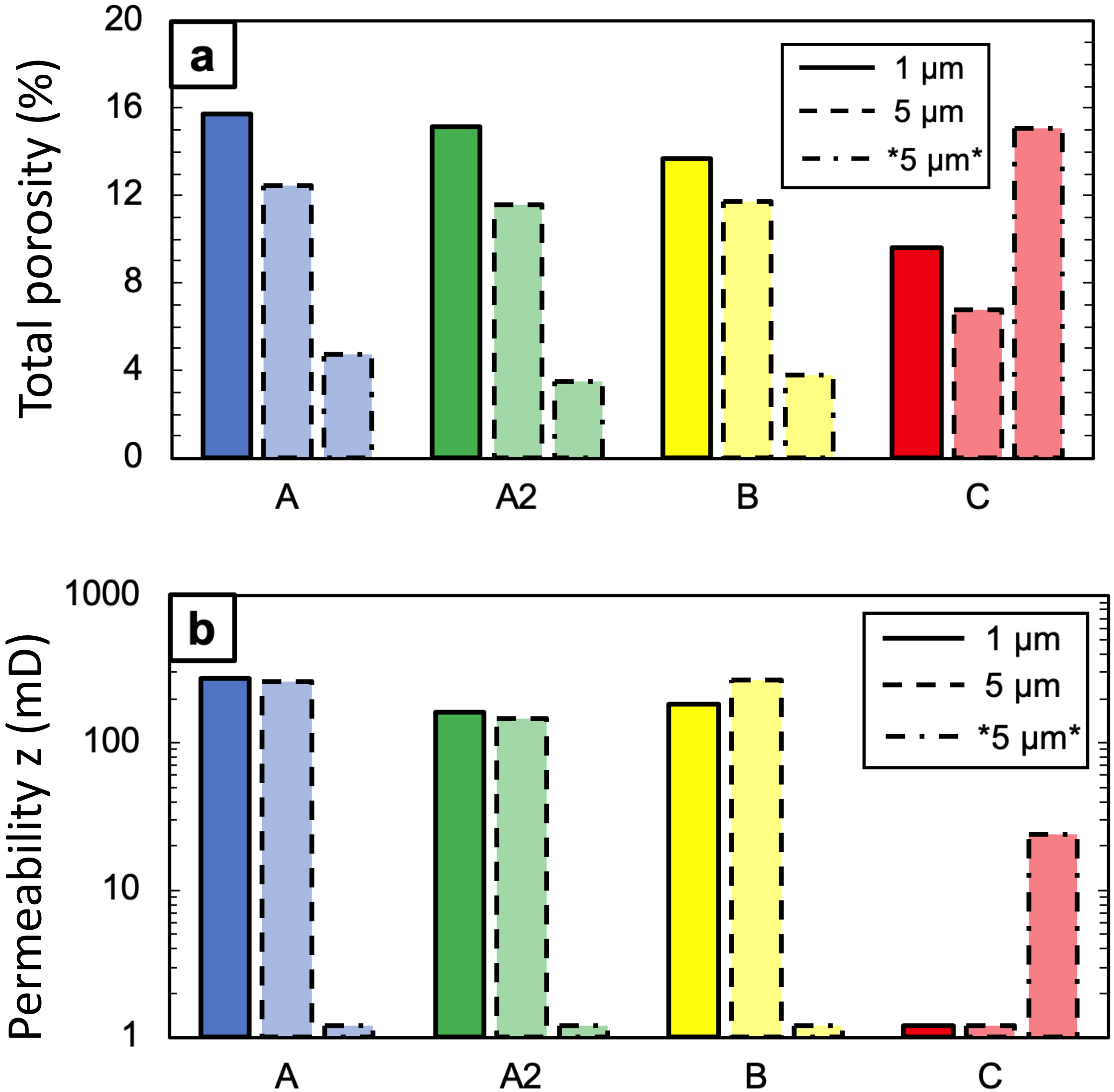


IMAGE RESOLUTION



5. IMAGE RESOLUTION



- Coarsening the image resolution to 5 µm causes porosity underestimation due to omission of the smallest intergranular pores.

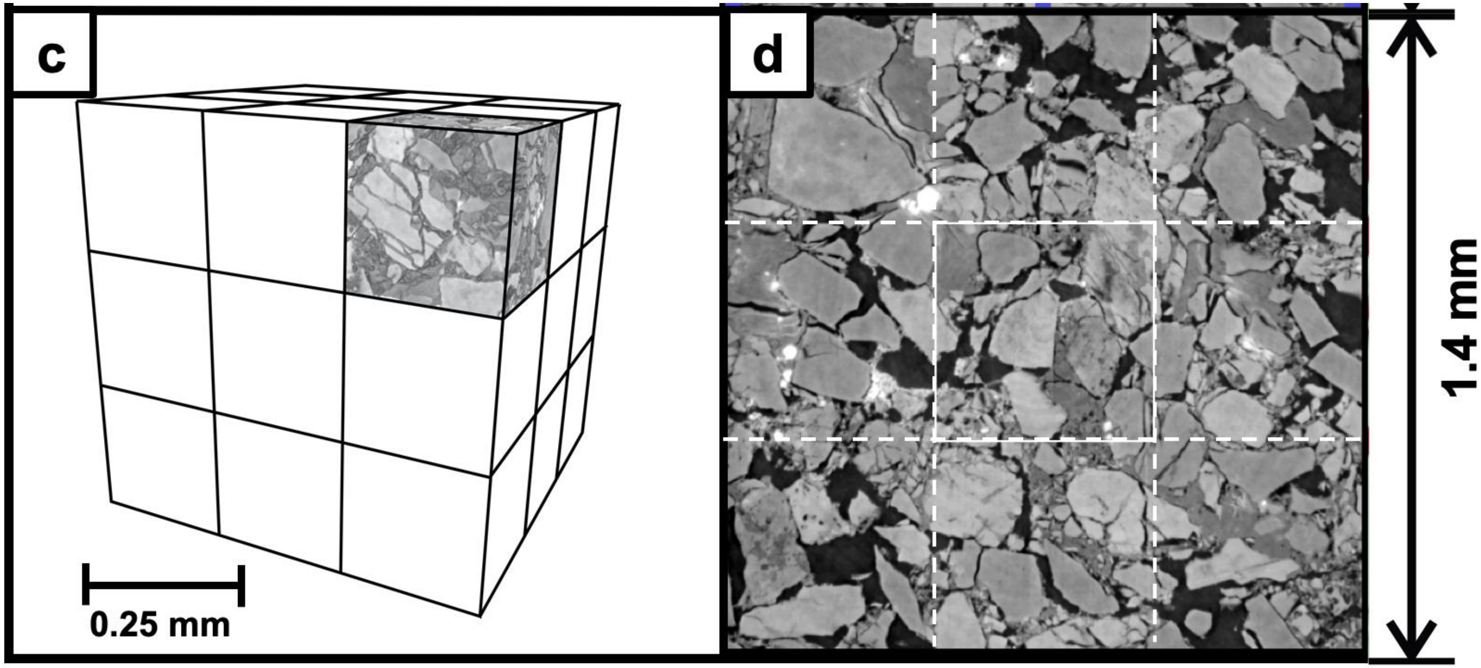
Application of the 1 µm Weka segmentation classifier to the 5 µm image produces very erroneous results

X-RAY CT METHODOLOGY WORKFLOW

- ✓ Image reconstruction
- ✓ Image segmentation
- ✓ Fluid simulation comparison
- ? Representative Volume
- ✓ Image Resolution

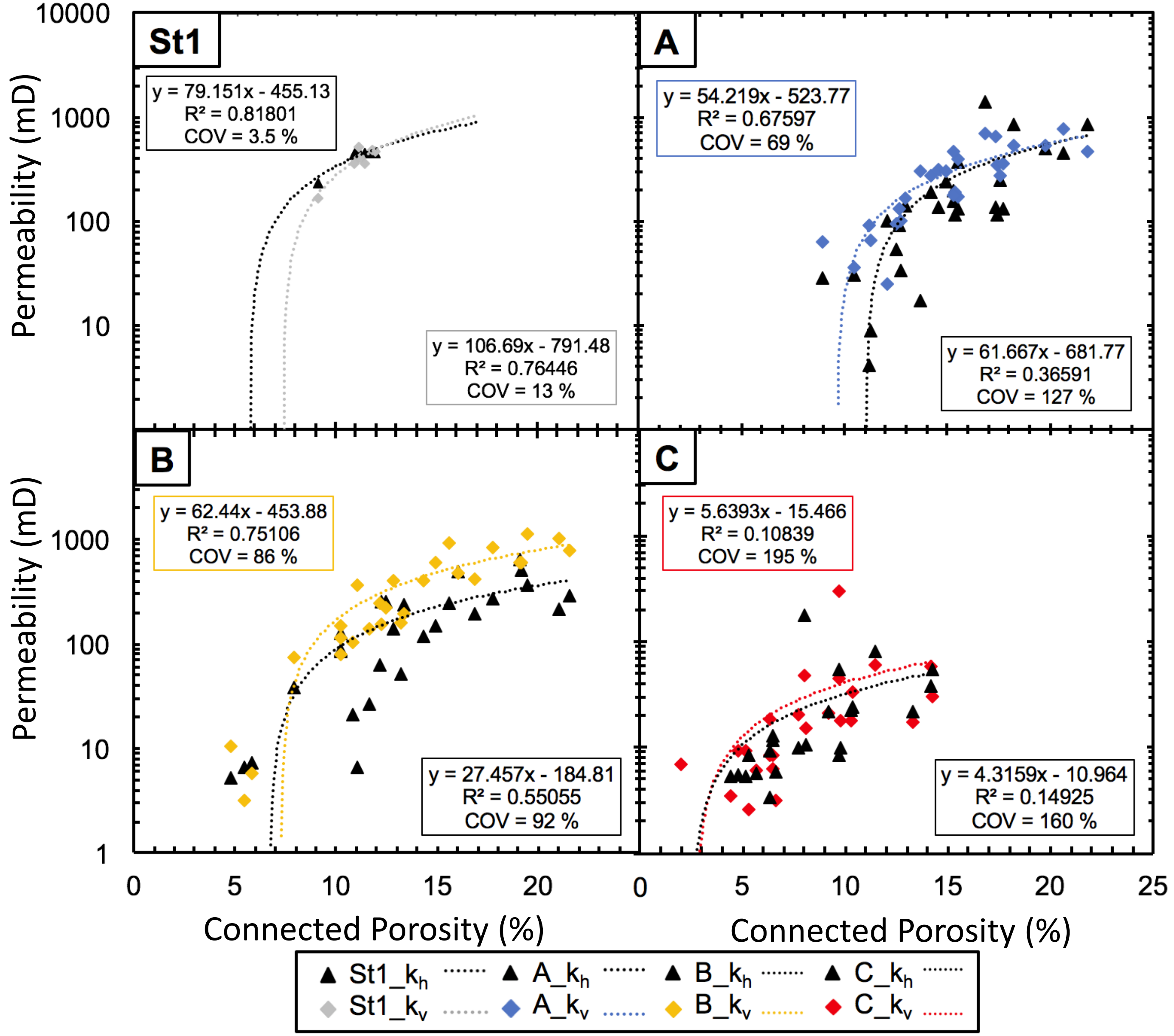
6. Image Resolution vs Volume size trade-off

6. UPSCALING – ARITHMETIC MEAN

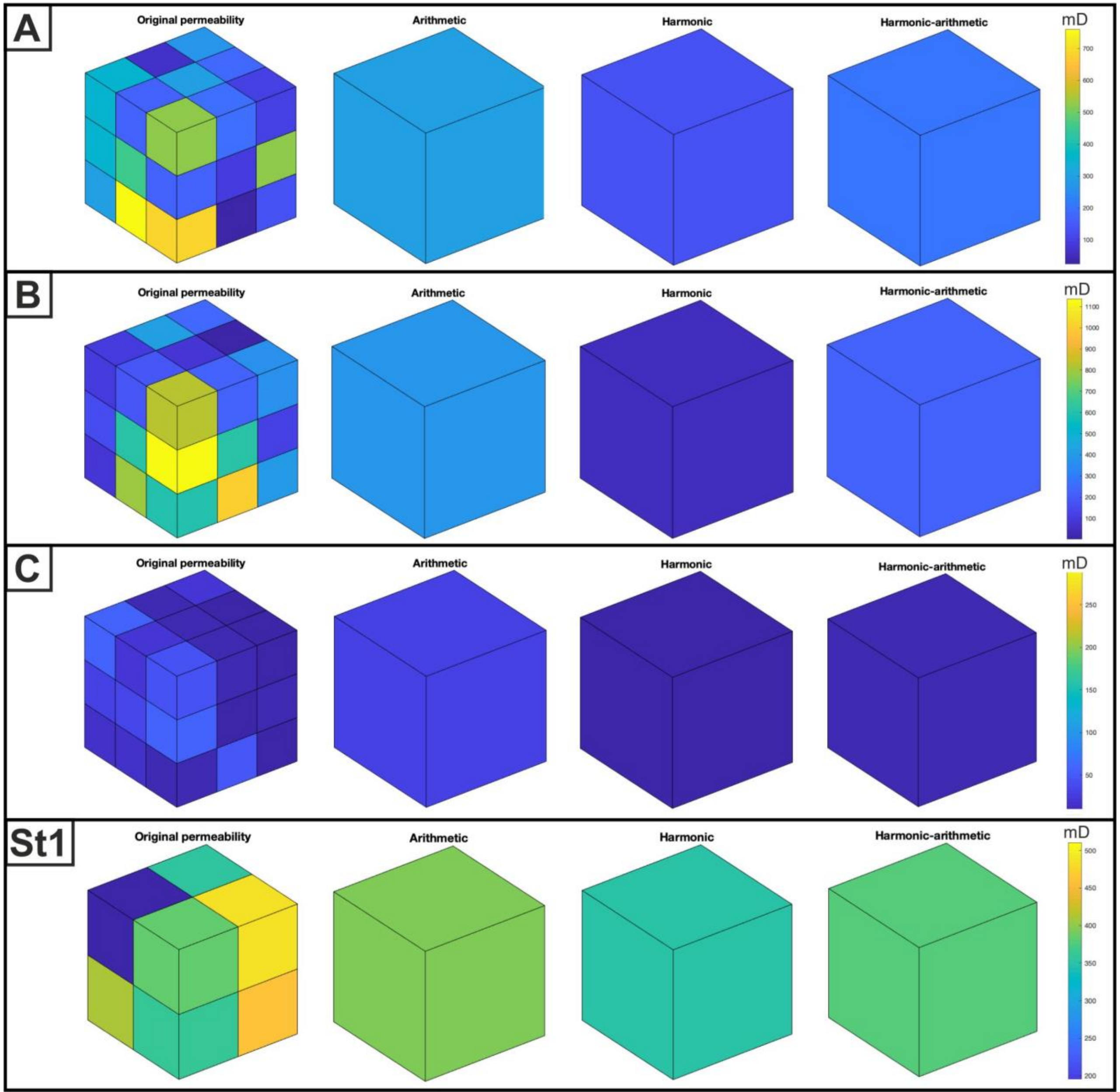


- Permeability calculations are acquired from a number of different sub-volume sizes, to determine whether a REV size is achieved?

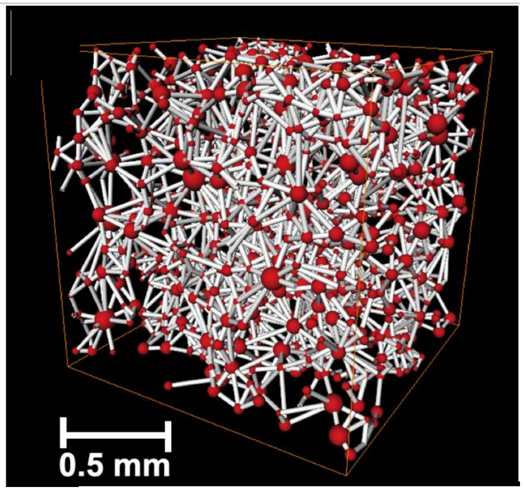
6. UPSCALING – ARITHMETIC MEAN



6. UPSCALING – ARITHMETIC & HARMONIC MEAN

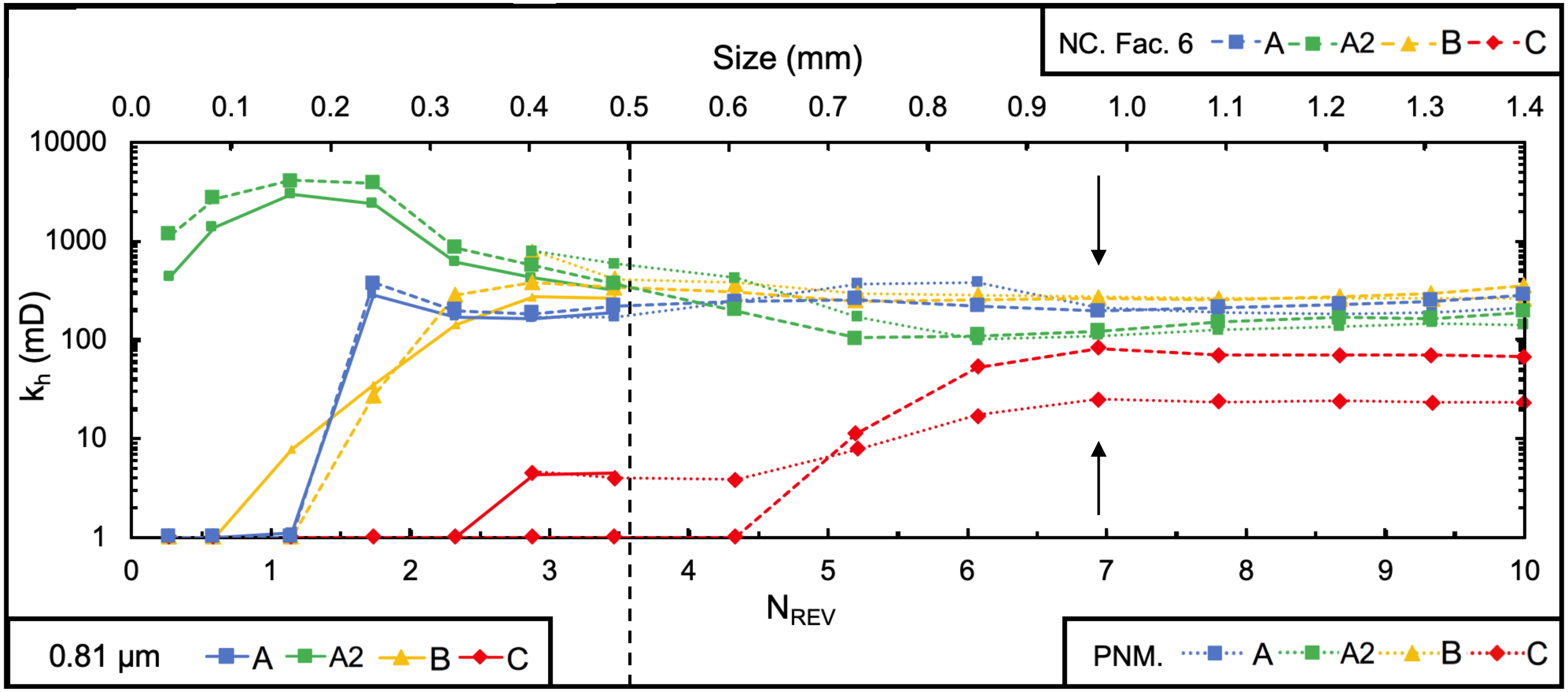


6. UPSCALING – PORE NETWORK MODELLING

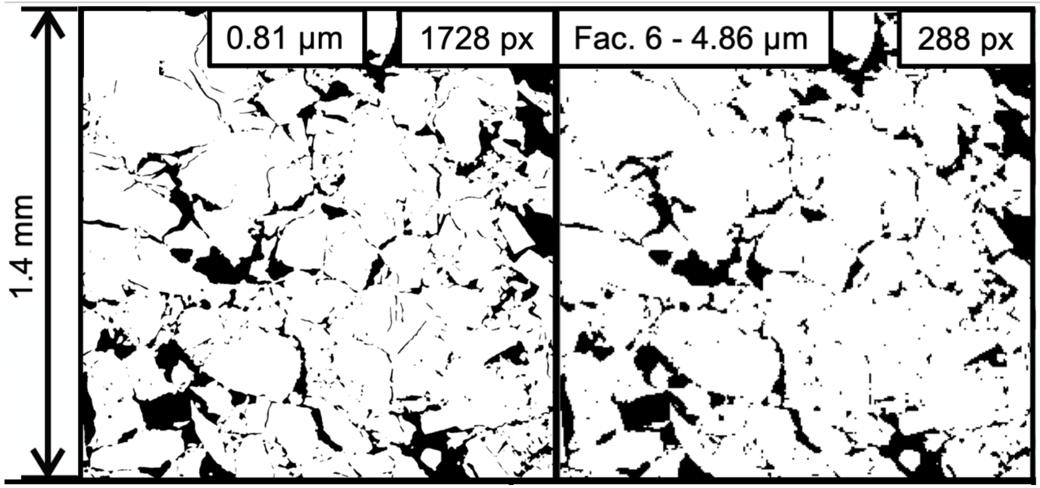


$$Q = \sum (Pi - Pj) g_{ij},$$

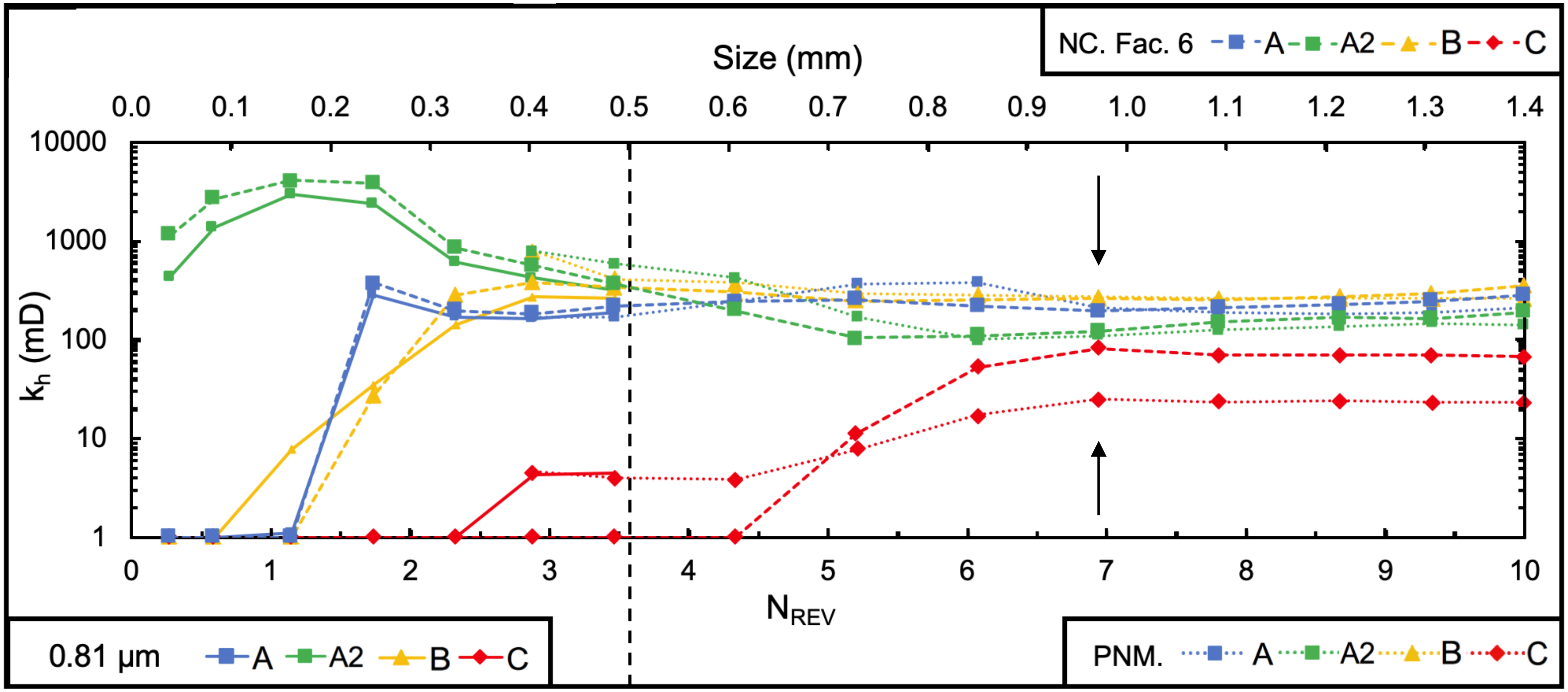
- PNM allows a REV to be achieved (dotted line).
- REV is determined as NREV ≥ 7 for all samples.



6. UPSCALING – NUMERICAL COARSENING



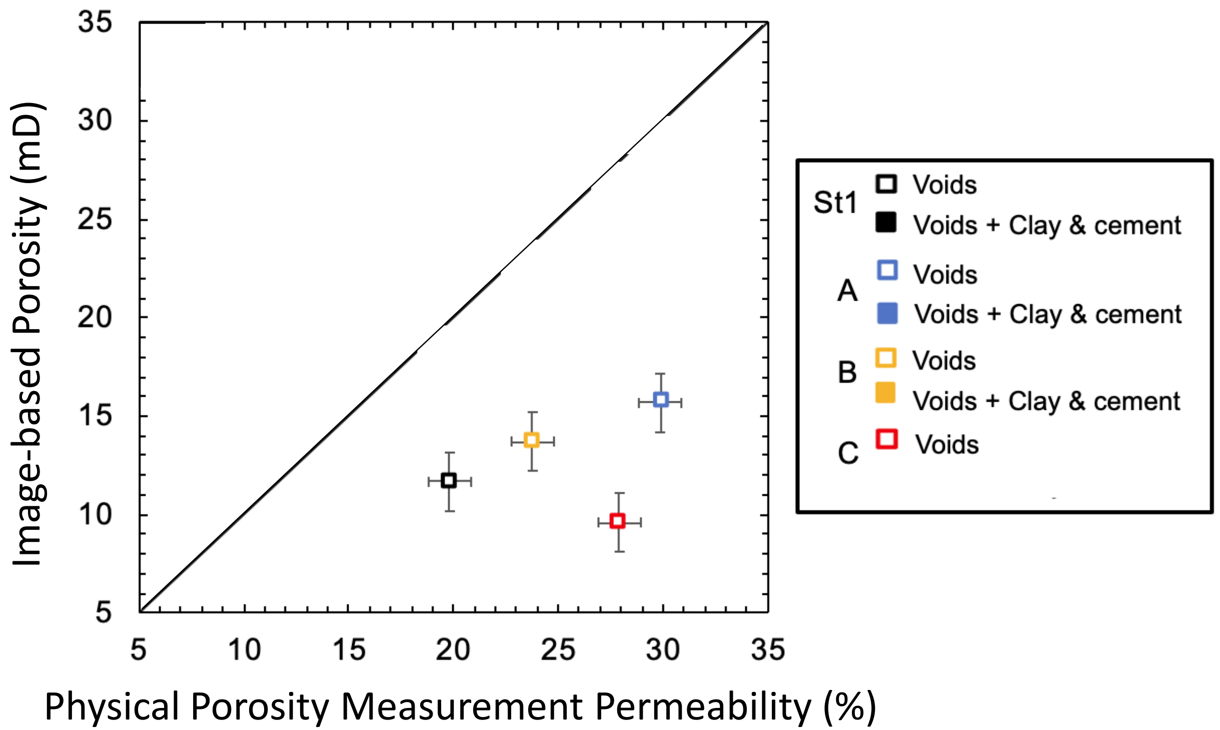
- Numerical coarsening also allows a REV to be achieved (dashed line).
- REV is determined as NREV ≥ 7 for all samples.



X-RAY CT METHODOLOGY WORKFLOW

- ✓ Image reconstruction
- ✓ Image segmentation
- ✓ Fluid simulation comparison
- ✓ Representative Volume
- ✓ Image Resolution
- ✓ Upscaling

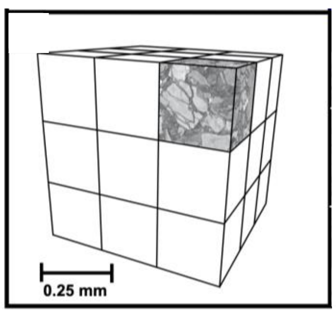
CONCLUSION - POROSITY

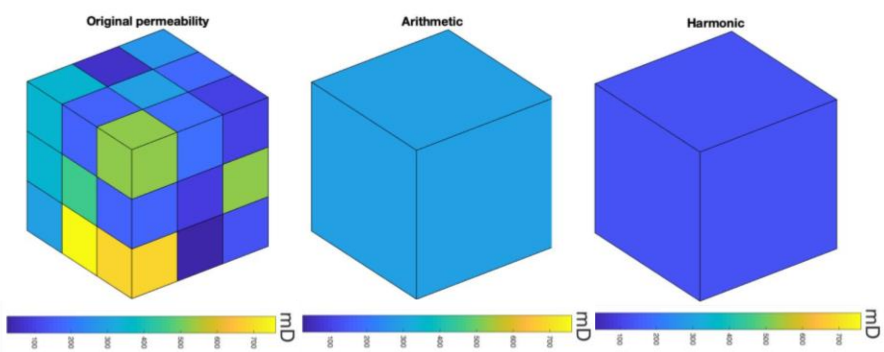


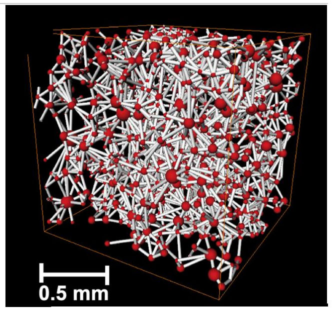
Sample Porosity	A	B	C	St 1
Intergranular Pore Phase (%)	15.7	13.7	9.6	11.7
Pore phase + clay & cement intragranular pores (%)	29.0	23.1	27.1	15.8
Physical Measurement (%)	29.9	23.8	27.9	19.8

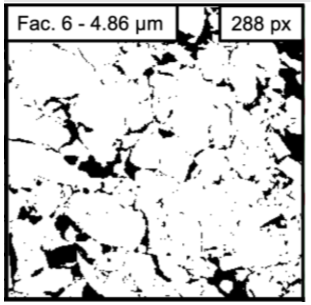
CONCLUSION – ABSOLUTE PERMEABILITY

Sample Absolute Permeability	A	B	C	St 1
One Subvolume (mD)	25-760	3-1137	0-296	164-511
Upscaling - Numerical Coarsening (mD)	355	479	57	n/a
Upscaling - Pore Network Modelling (mD)	291	500	23	235
Upscaling—Arithmetic mean (mD)	294	379	28	393
Upscaling—Harmonic mean (mD)	136	39	<1	350
Physical Measurement (mD)	83	25	50	275









Conclusion

1. Clay minerals and cement which are porous and impermeable, should be segmented as a separate phase.
2. Porosity and permeability are both highly sensitive to segmentation method, image resolution and volume size.
3. Upscaling approaches can assist in overcoming the trade-off between image resolution and sample size.
4. The workflow devised should ensure a more robust, reliable and repeatable methodology for X-ray micro-CT image processing and image-based modelling of heterogeneous sandstone rock.

Thank you for listening

- Callow et al. 2020 – '*Optimal X-ray micro-CT image based methods for porosity and permeability quantification in heterogeneous sandstones*' *Geophys. J. Int.* ***223***, *1210–1229*, doi: 10.1093/gji/ggaa321

- Email: Ben.Callow@ugent.be

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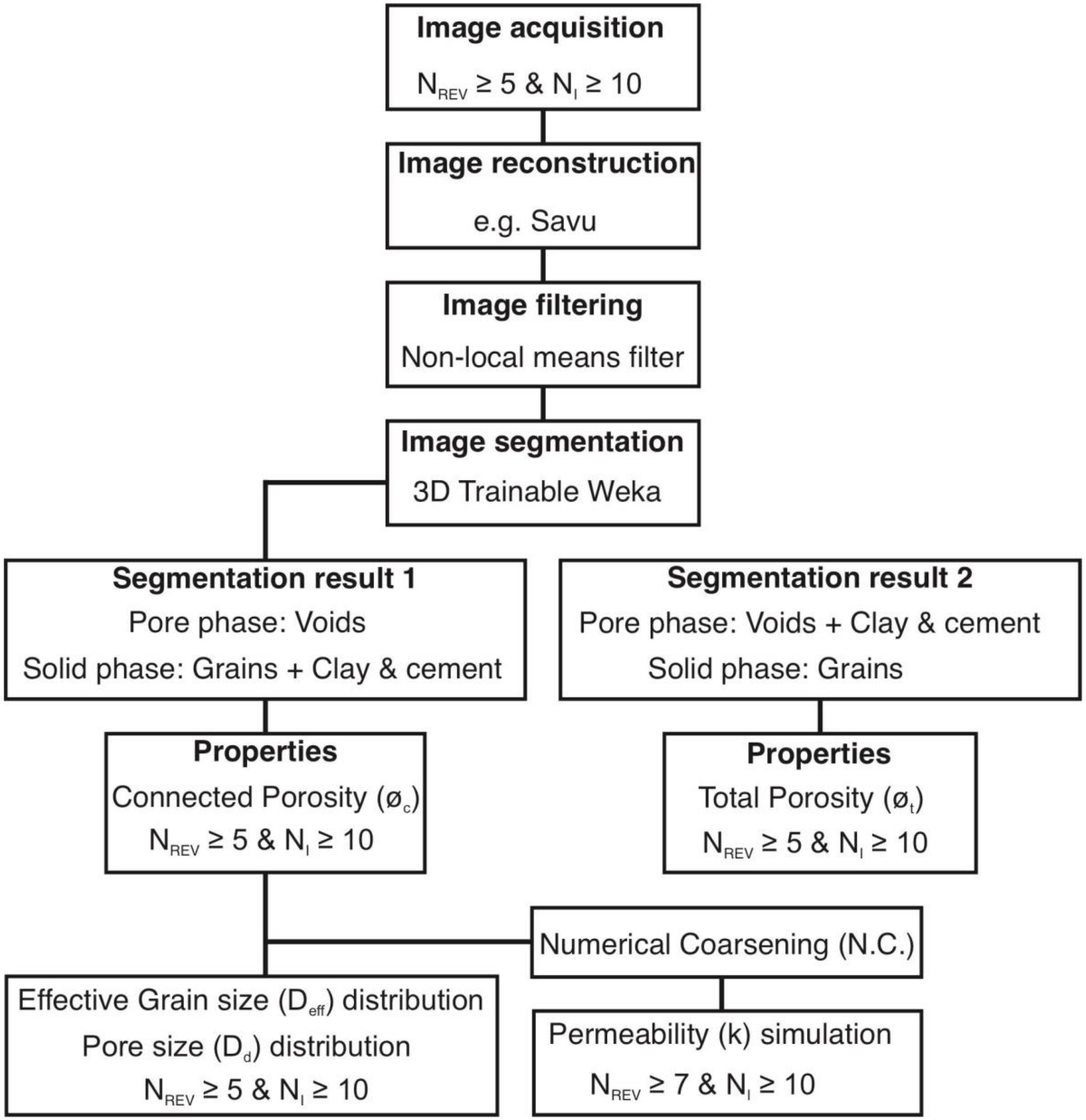
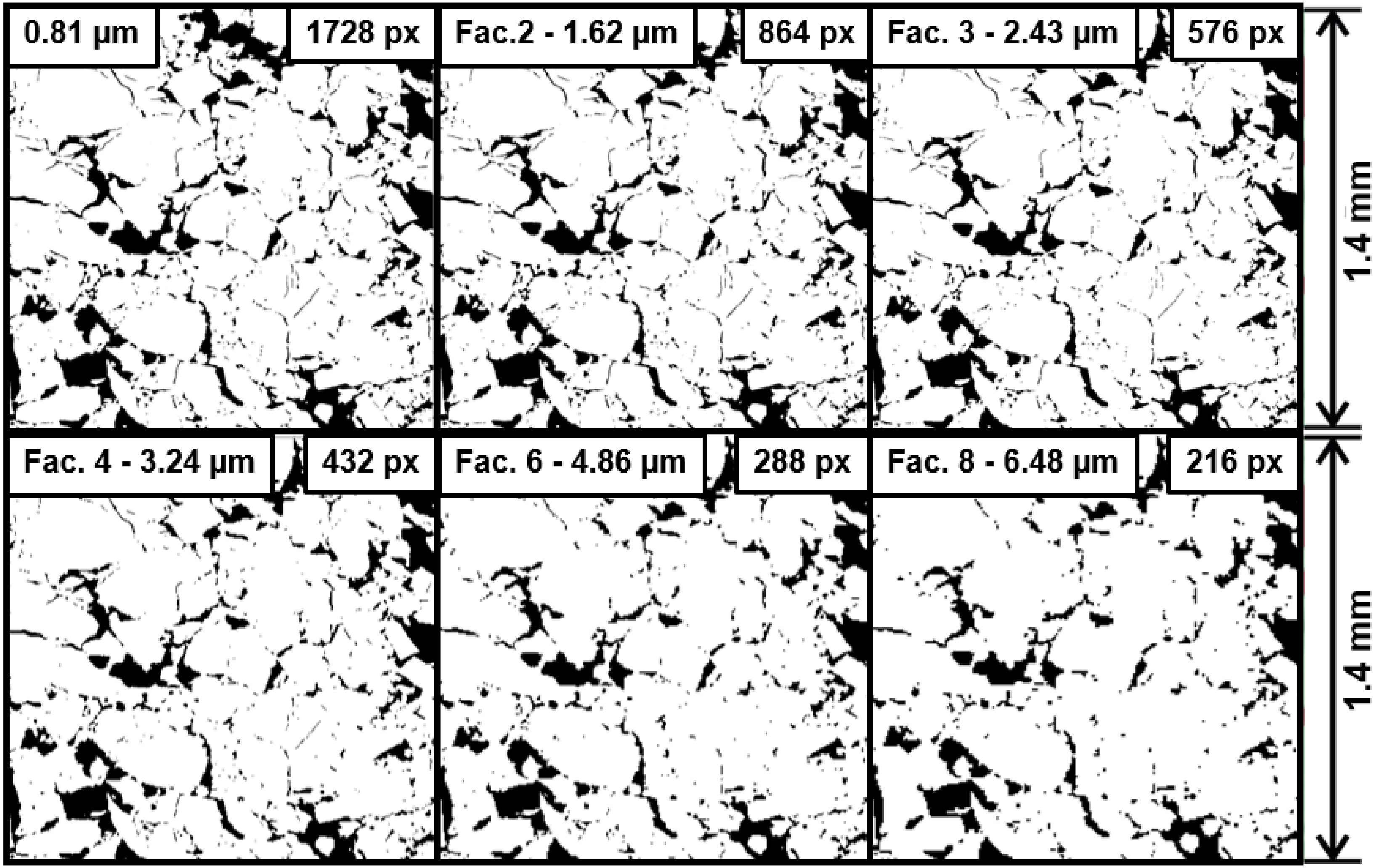
Additional Slides

Full Workflow

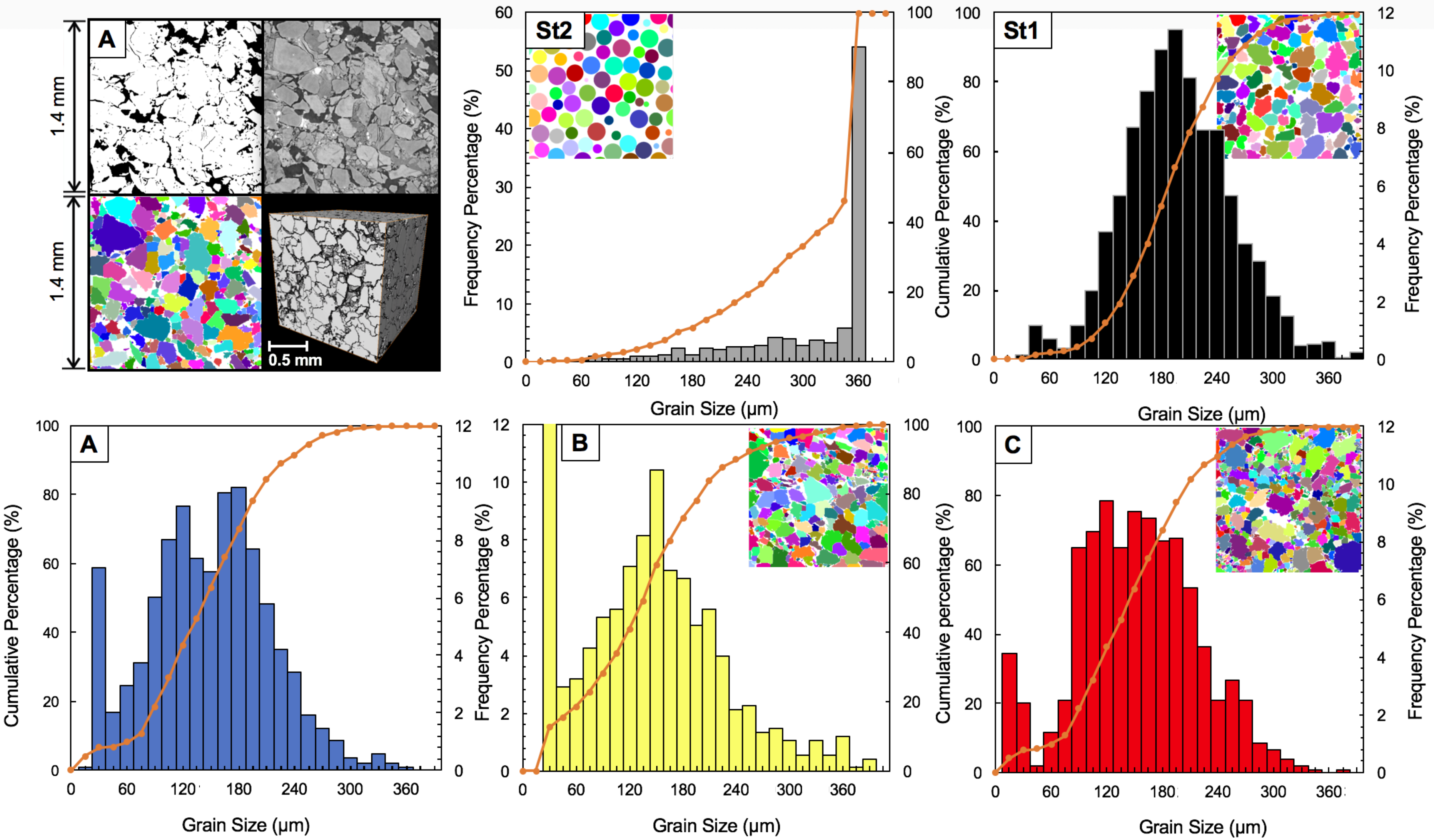


Numerical Coarsening



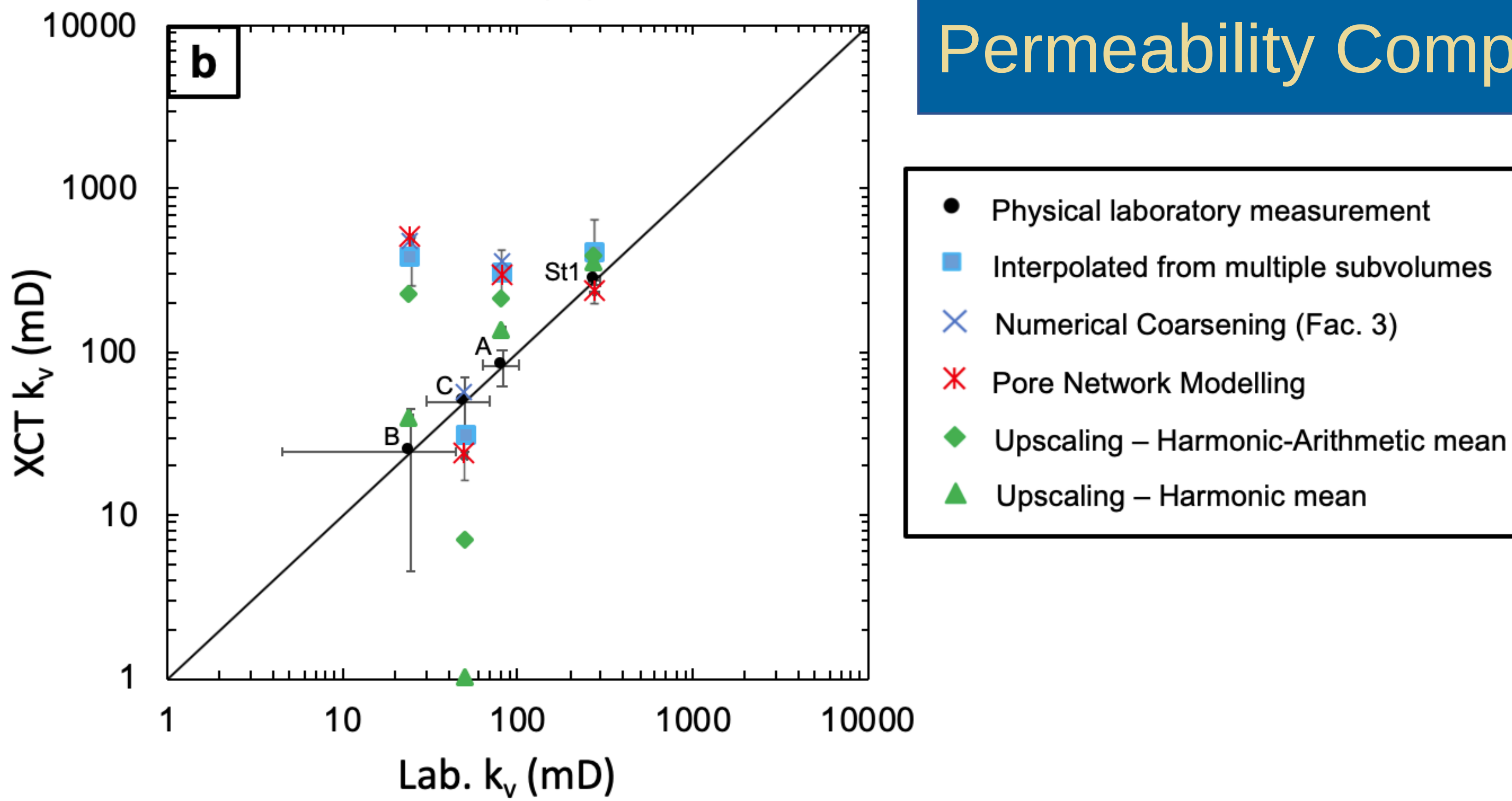
Numerical coarsening ‘after’ segmentation

Grain Size



A
1.4 mm
1.4 mm
0.5 mm
St2
Frequency Percentage (%)
Cumulative Percentage (%)
Grain Size (μm)
St1
Frequency Percentage (%)
Grain Size (μm)
A
Cumulative Percentage (%)
Grain Size (μm)
B
Frequency Percentage (%)
Grain Size (μm)
C
Cumulative percentage (%)
Frequency Percentage (%)
Grain Size (μm)

Permeability Comparison



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Equations

$$\left.\begin{aligned}\mu\nabla^2\mathbf{u}-\nabla \mathrm{p}=0\\ \nabla\cdot\mathbf{u}=0\end{aligned}\right\}, \tag{4}$$

where $\mathbf{u}$ is the fluid velocity vector, p is the simulated fluid pressure and μ is the dynamic viscosity of the fluid.

Once eq. (4) is solved through convergence of the simulation and the volumetric flow rate (Q) is calculated, the permeability (k) can be estimated from Darcy's law:

$$\boldsymbol{k}=\frac{\mu\boldsymbol{L}\,\boldsymbol{Q}}{\Delta\boldsymbol{P}\,\boldsymbol{A}}, \tag{5}$$

The number of mesh elements per unit volume (mesh density) can influence the output value of absolute permeability. The number of mesh elements used for a sample volume can be defined as:

$$N_{\mathrm{MESH}}=\frac{E_l}{\Delta x}, \tag{6}$$

where E_l is the mean edge length of a tetrahedral mesh element and Δx is the image voxel size. Decreasing values of N_{MESH} correspond to an increased mesh element density. A N_{MESH} value of one represents a sample volume with tetrahedral elements equal in length to the image voxel size.

The permeability of the network is calculated using Darcy's law (eq. 5), whereby total flow rate is deduced from a linear system of equations of flow rate between each pore:

$$Q=\sum(Pi-Pj)\,g_{ij}, \tag{7}$$

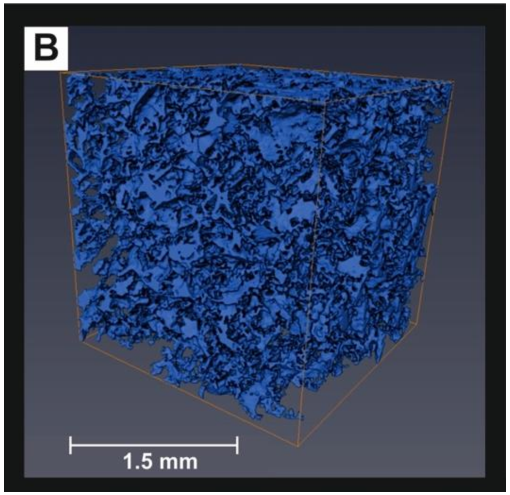
where Q is the volumetric flow rate, P is the pressure in each pore pair i,j and g_{ij} is the hydraulic conductance of the throat between each pore pair i,j, given by:

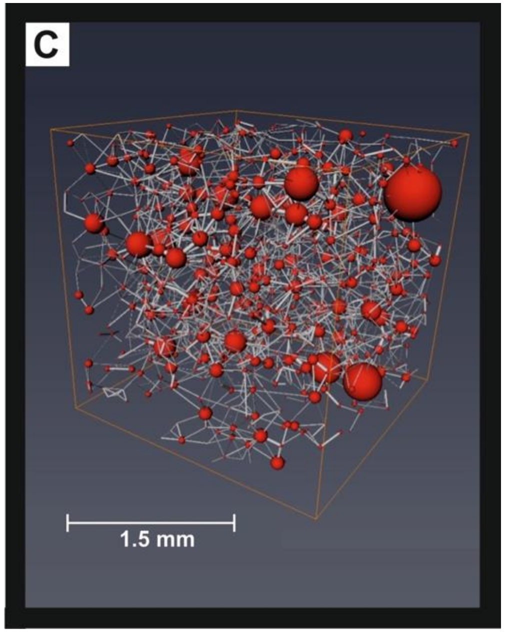
$$g_{ij}=\left(\frac{\pi}{8\mu}\frac{r_{ij}^4}{l_{ij}}\right), \tag{8}$$

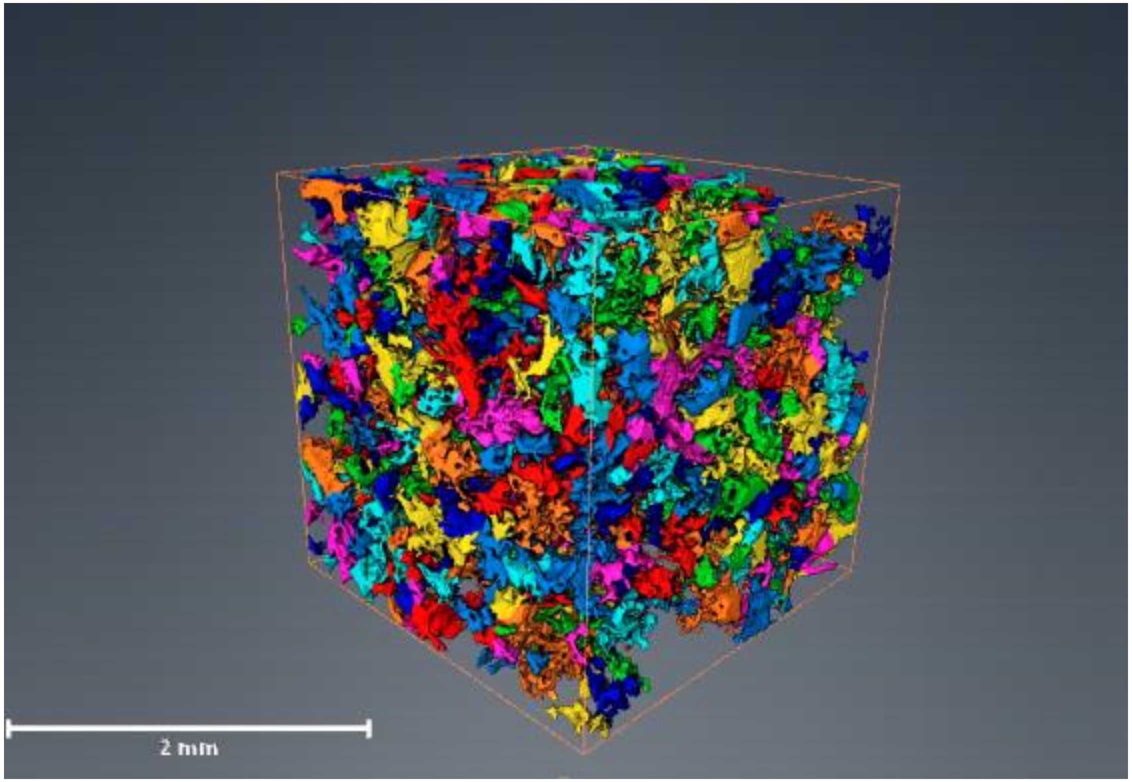
where μ is fluid viscosity, and the throats are represented by cylindrical pipes of radius r and length l between each pore pair i,j.

It is assumed that the PNM is filled with a single-phase, incompressible fluid, with steady state, laminar flow, with mass conservation for each pore body (Avizo 2018).

METHOD – PORE NETWORK MODELLING

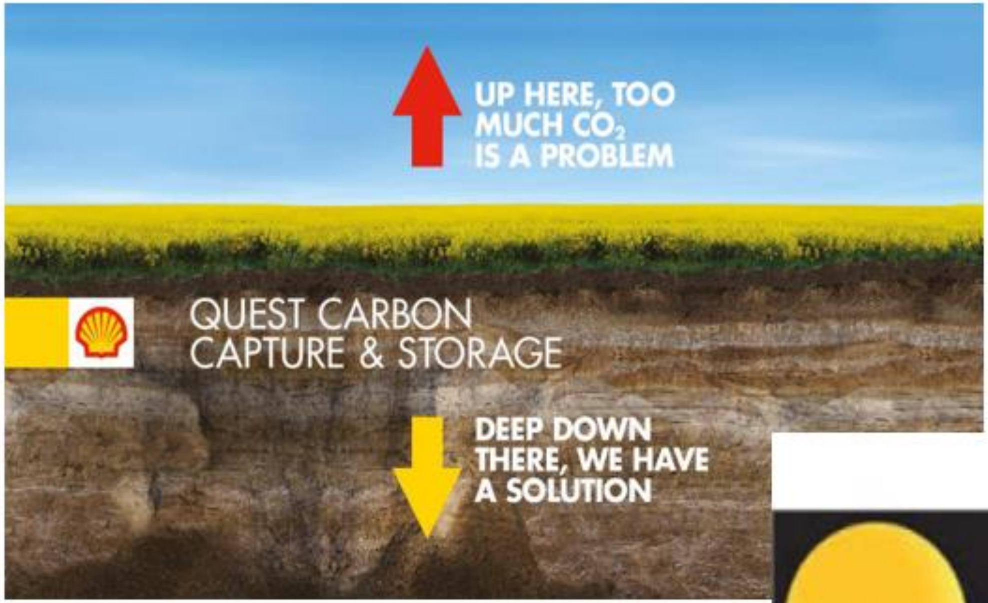






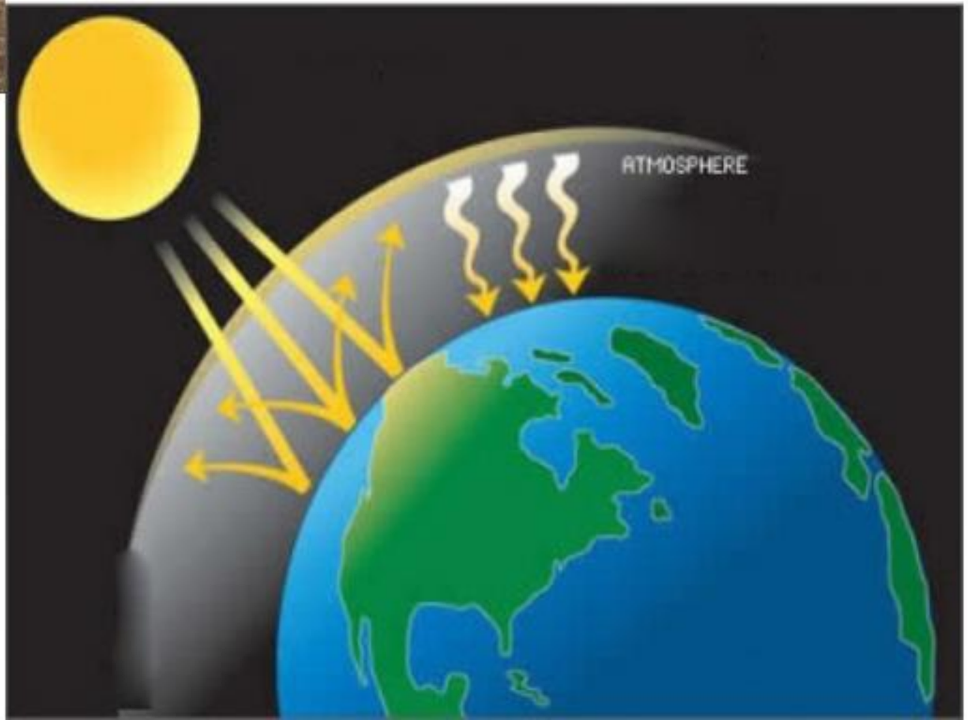
- A pore network model is derived from the connected pore volume

Context



- Growing field of carbon capture and storage
- Way of reducing carbon dioxide (Greenhouse gas) in the atmosphere

The Greenhouse Effect



- Large proportion of our energy comes from the burning fossil fuels
- Increased CO_2 emissions in the atmosphere
- Problems: Increased sea level rise, ocean acidification and increased extreme weather events