Generalized network modelling of two-phase flow

Ali Raeini, Branko Bijeljic and Martin Blunt

Department of Earth Science and Engineering
Imperial College London

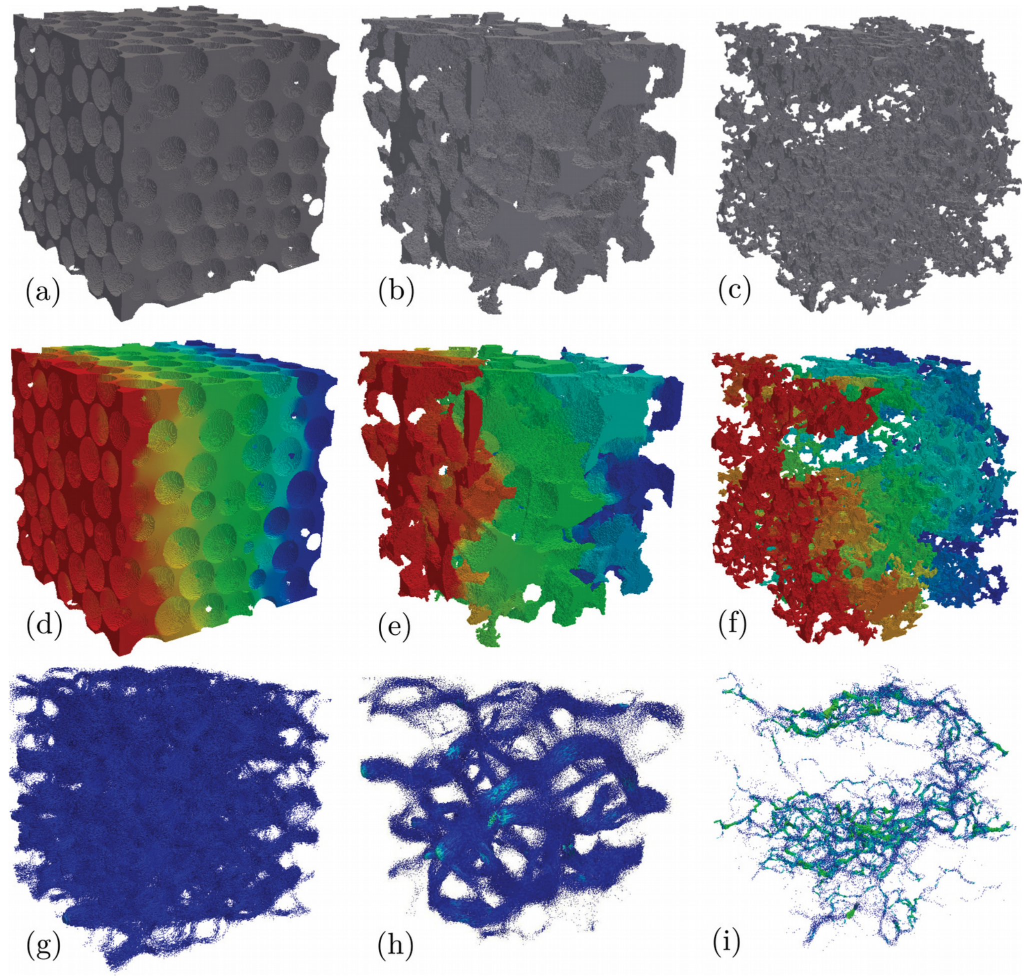
Warwick University, November 2016

Imperial College London

Outline

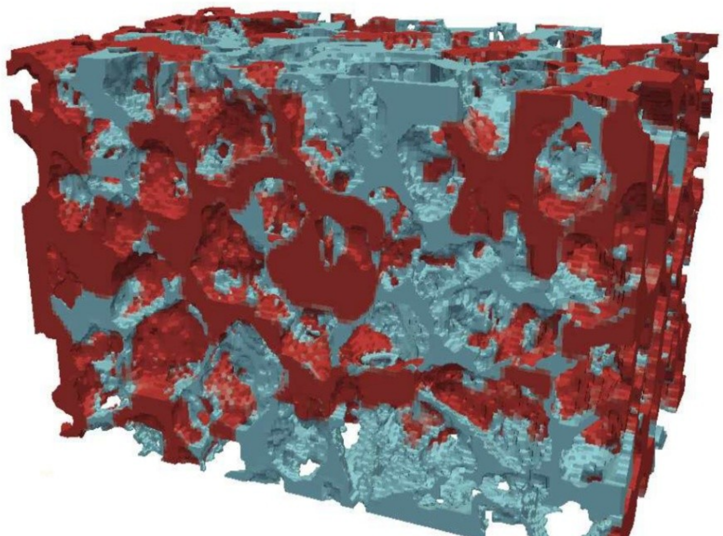
- Background
  - Direct simulation and conventional network modelling
- Generalized network modelling
  - Network extraction
  - Flow simulation
  - Validation
- Conclusion and future work

Single-phase flow computations

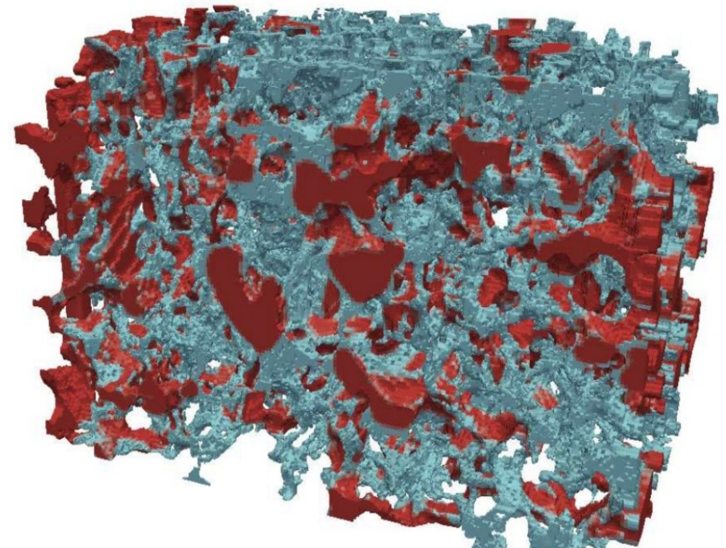


Simulation time: 12 hours on a single workstation (16 processors)

Direct simulations are computationally expensive



LV60A



Berea

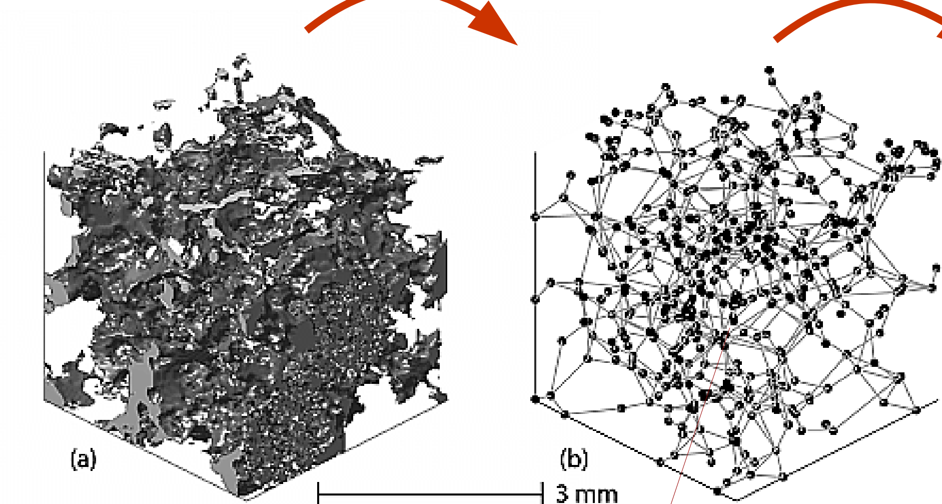
- Simulations on <u>1milion</u> cells took ~ 1 week on 24 processors, for a relatively high <u>capillary number of 10^{-5}</u>
- Simulation time increases as we decrease the capillary number
- Two-phase flow REV-size is about <u>1 billion</u> grid-blocks

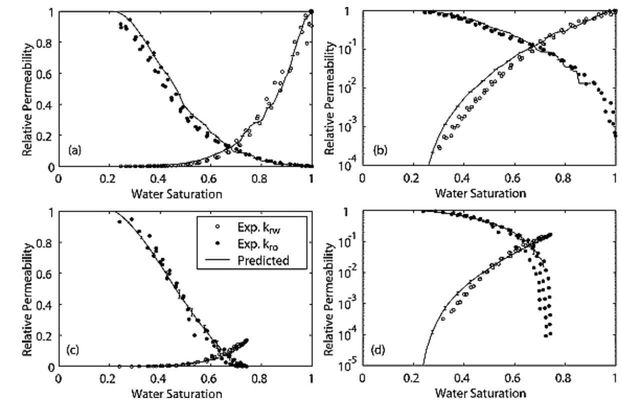
Background:
upscaling from pore-scale to Darcy-scale:

Network extraction **Flow simulation**

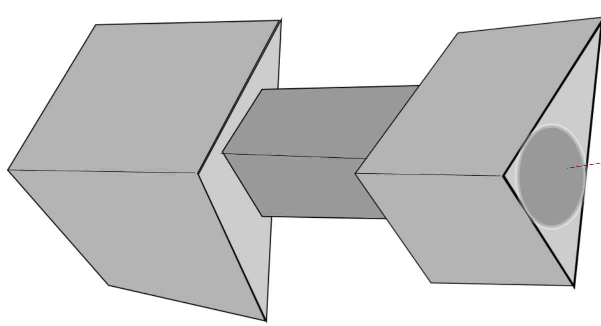
Reservoir simulation

Rock image

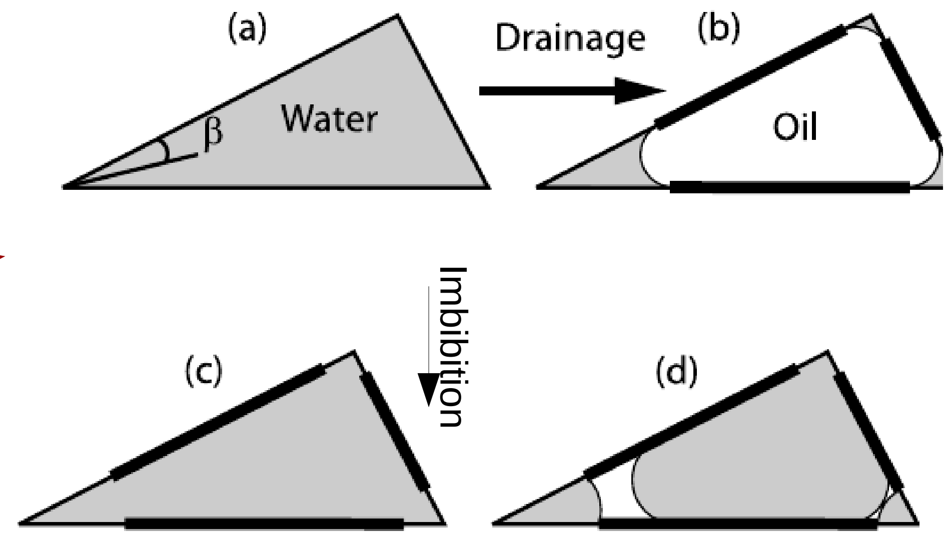




Reservoir Forecast



Conventional network elements

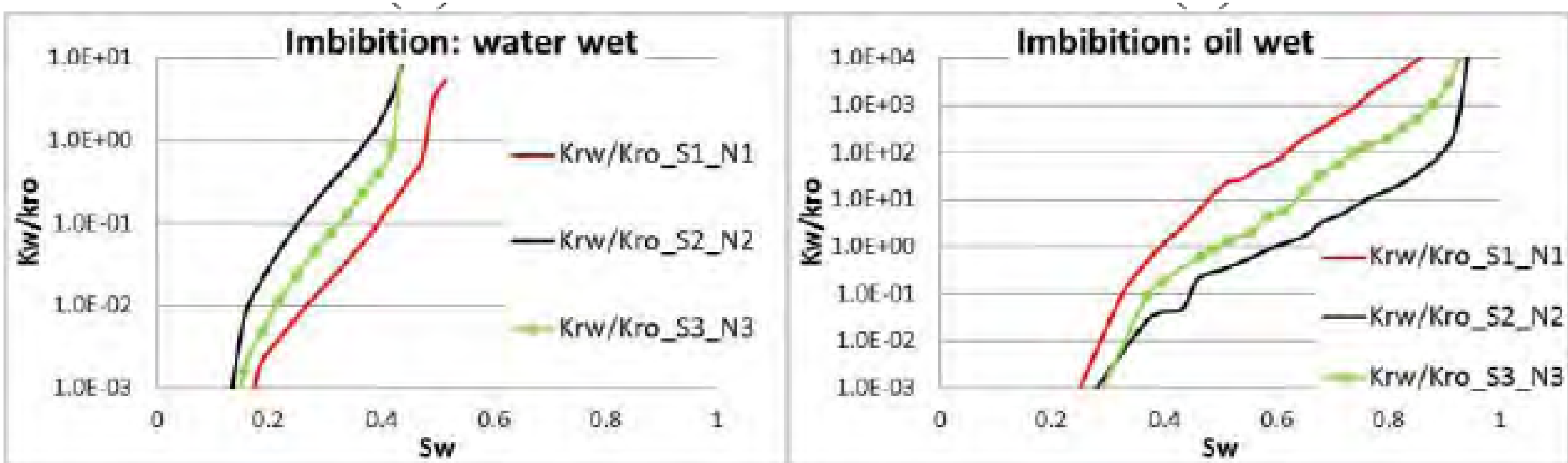


Water-wet

Oil-wet

Valvatne et al (2004)

Background – conventional network model drawbacks



Igor Bondino (Total) et al. SCA (2012):

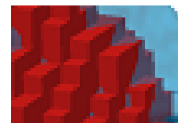
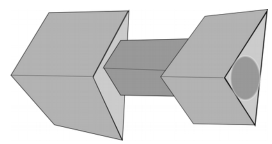
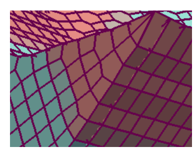
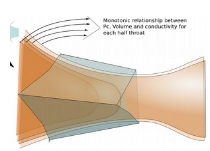
- **different network extraction algorithms give significantly different results for the same fluid/rock system**

Source of the problem:
Oversimplification of the pore-space

Summary: **conductances** and **volumes** may not be assigned correctly to **capillary radii** and hence causing uncertainty in the flow modelling predictions

Background: Sources of uncertainty

Description of the pore space:

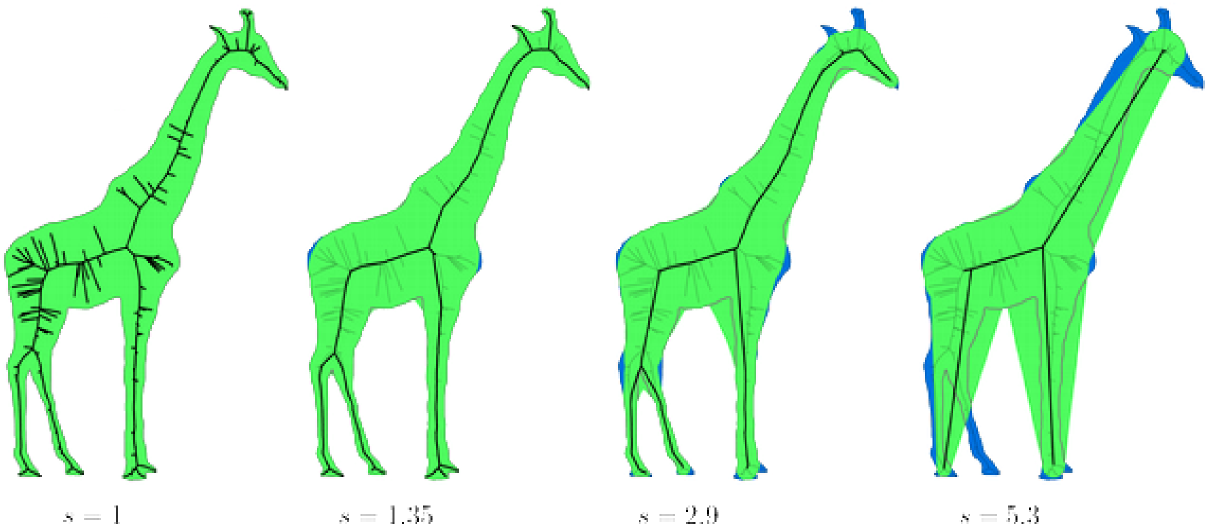
	Discretization		resolution	Error	uncertainty
Segmentation / noise	stair-case		high	$O(\delta x)$ to $O(\delta x^2)$	Low to high
Conventional pore network	stair-case		low	$O(\delta x)$, Refinement not possible	High
Direct simulations	linear		high	$O(\delta x^2)$	Low to medium
Generalised networks	linear		medium	$O(\delta x^2)$, Refinement not implemented	Low to medium

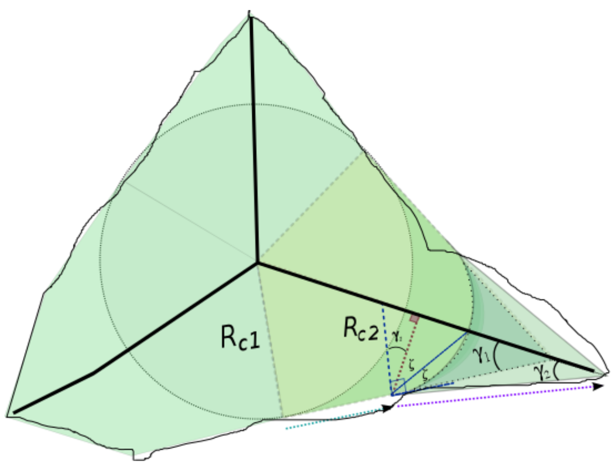
Fluid/rock properties:

- Contact angle distribution
- Clay / micro-porosity identification

Mathematics behind network extraction

There is a one-to-one relationship between any 3D geometry and its medial surface → no information loss → no additional uncertainty due to oversimplification of the pore space

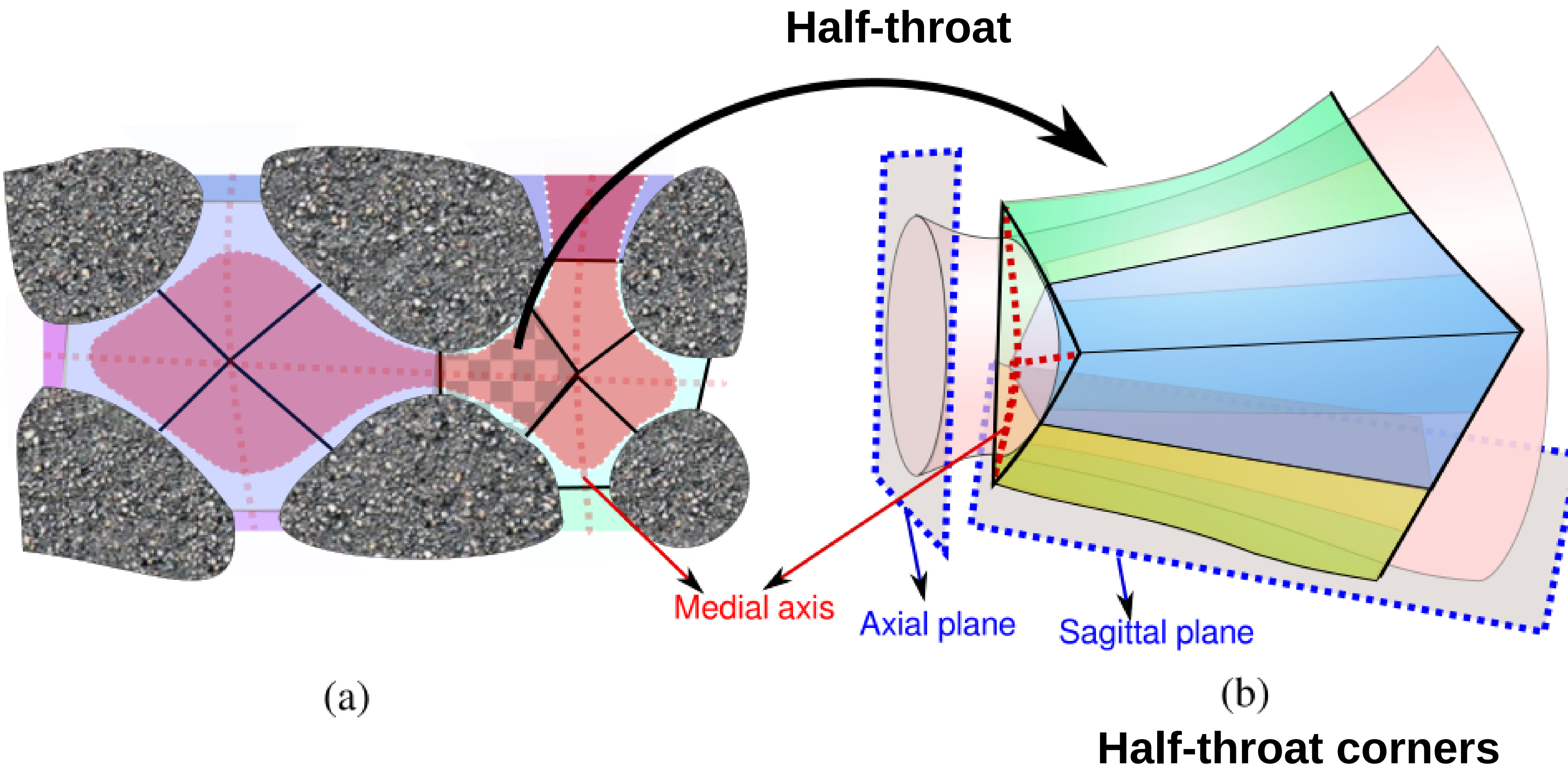




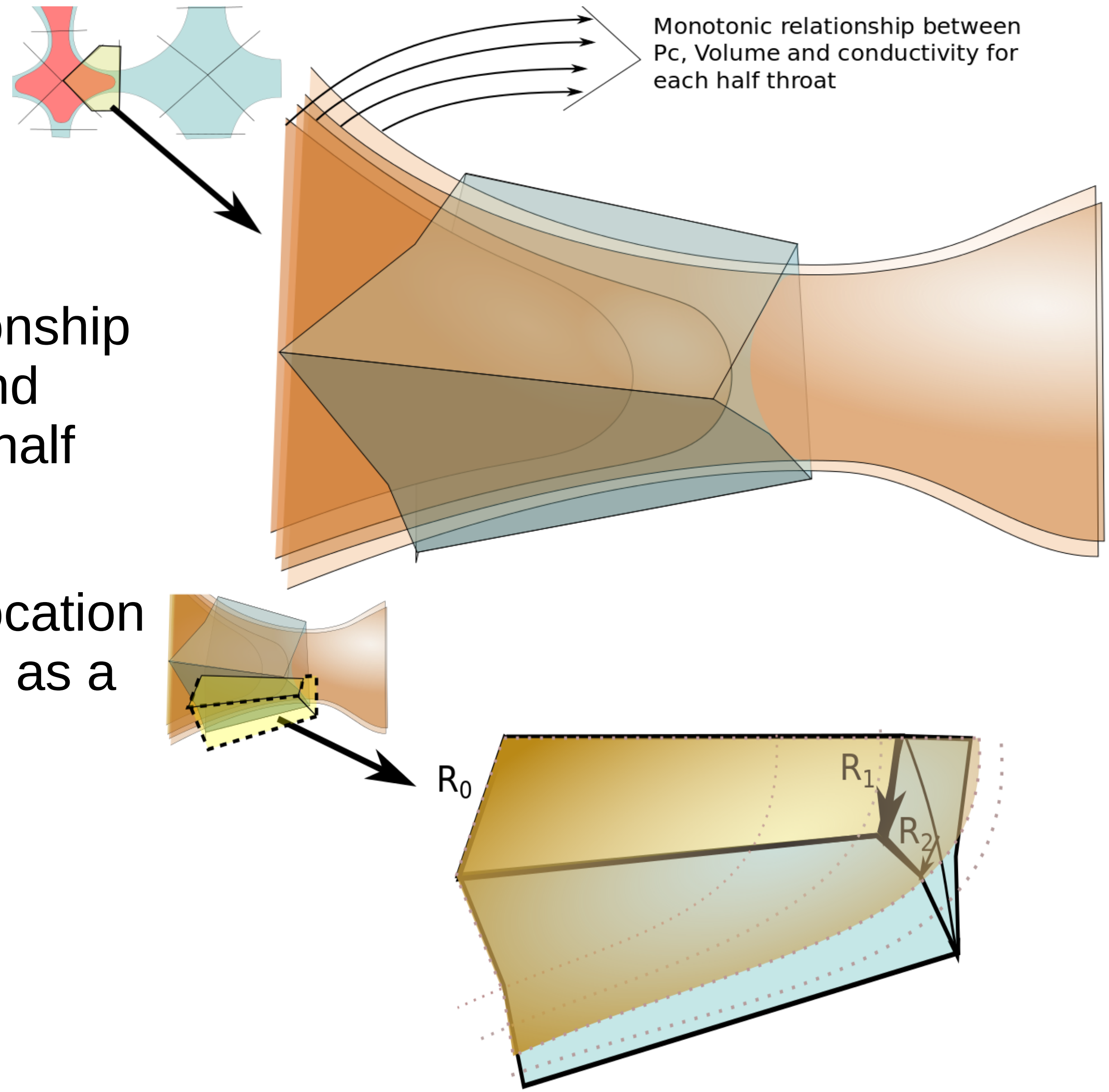
Picture from: http://www.agg.ethz.ch/research/medial_axis

- **Generalized pore network can be viewed as a coarse medial-surface representation of the pore space**

Background – generalised network model



Flow simulation:
interface tracking + post-processing



There is a one-to-on relationship between capillary radius and interface location for each half throat

→ allowing the interface location to be recorded and tracked as a single scalar variable

Generalized network modelling - summary

- **The necessary parameters are extracted directly from the micro-CT image as tabulated functions and used in a generalized network flow simulator:**

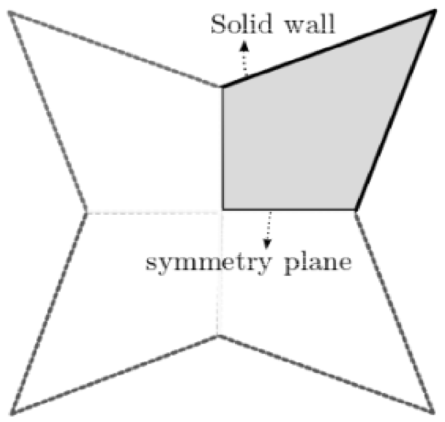
-

  - MS-P theory is used to relate **Pc** to Volume (**Sw**) for each pore/throat
    - The necessary parameters: pore/throat radius and corner angles. → extracted directly from the micro-CT image
  - Direct simulation is used to compute throat **conductivities**
  - Effect of contact angle and other fluid properties is added during flow simulation.

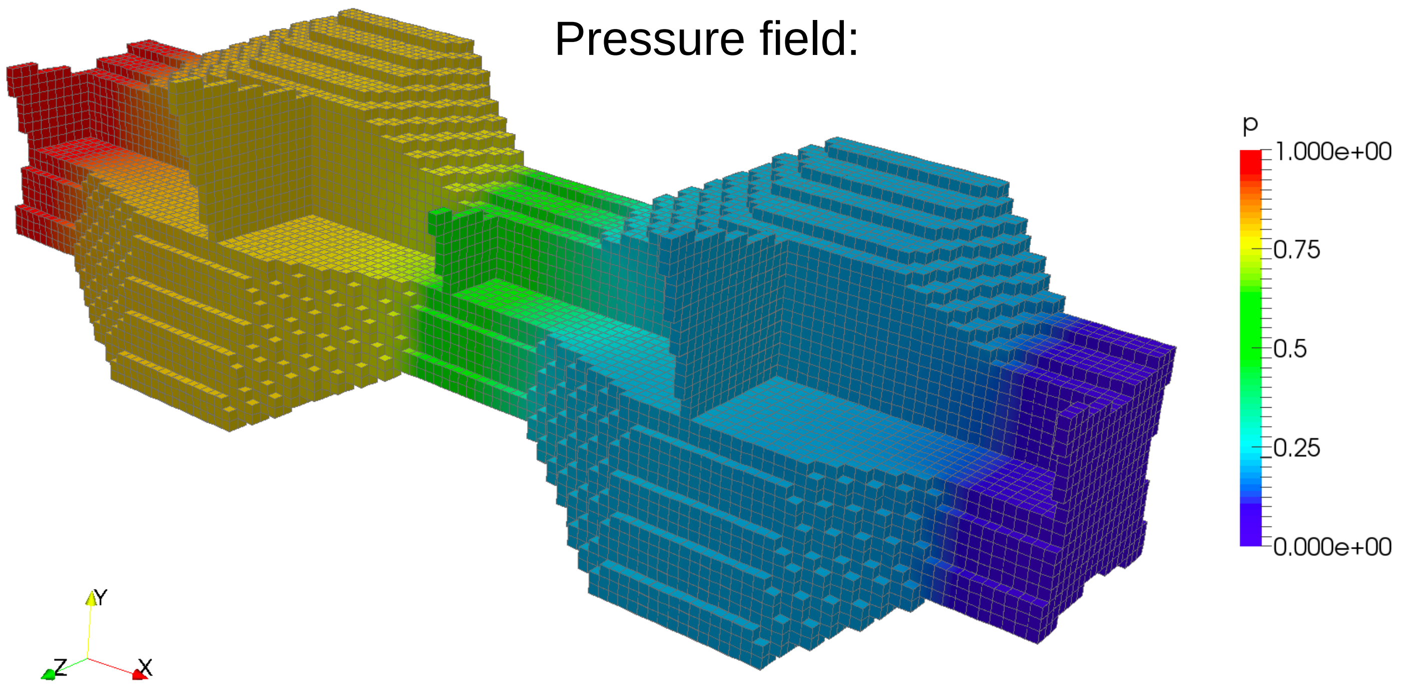
Generalised pore-network **extraction**
Parametrisation of pore space

Pore-space converted into voxelated (micro-CT) format, on which Navier-Stokes equations are solved: and converted into generalised network format

Cross-section:

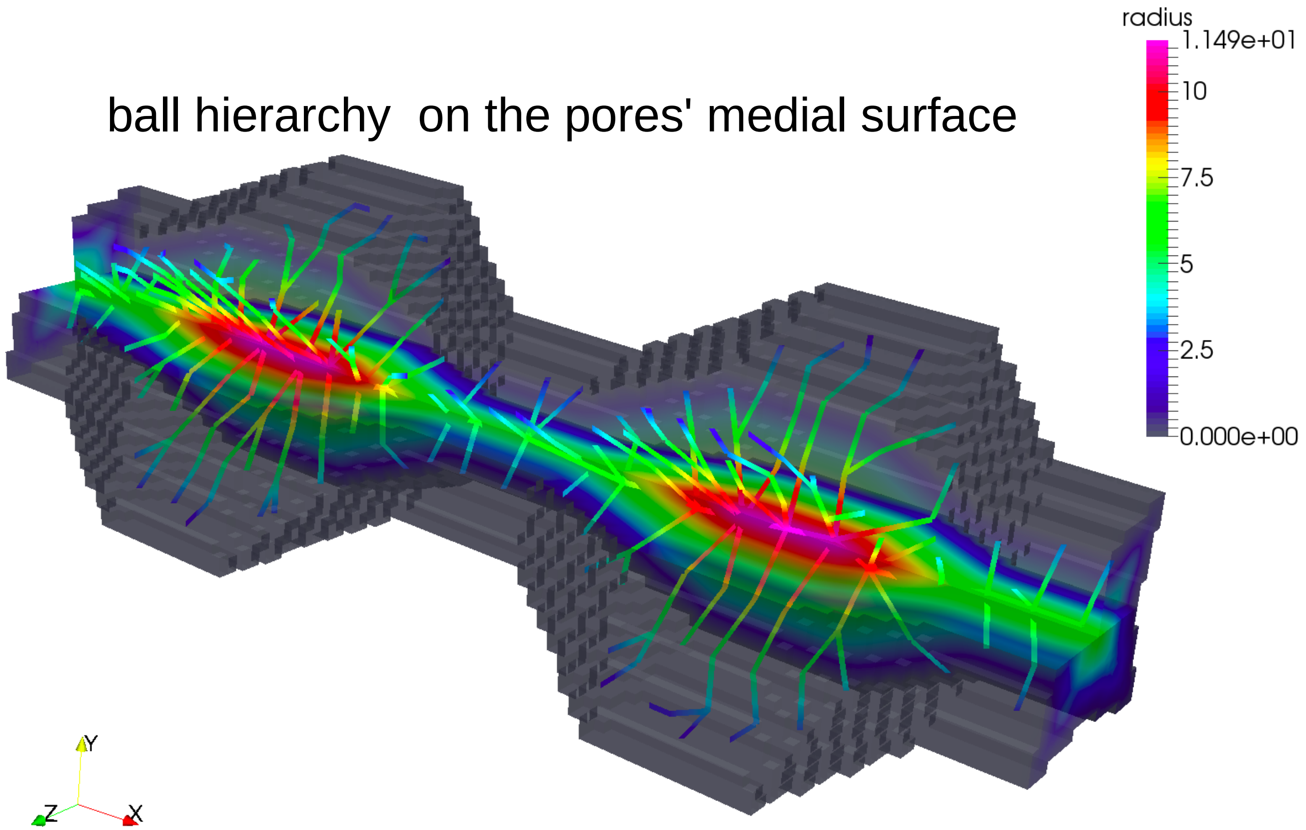


Pressure field:



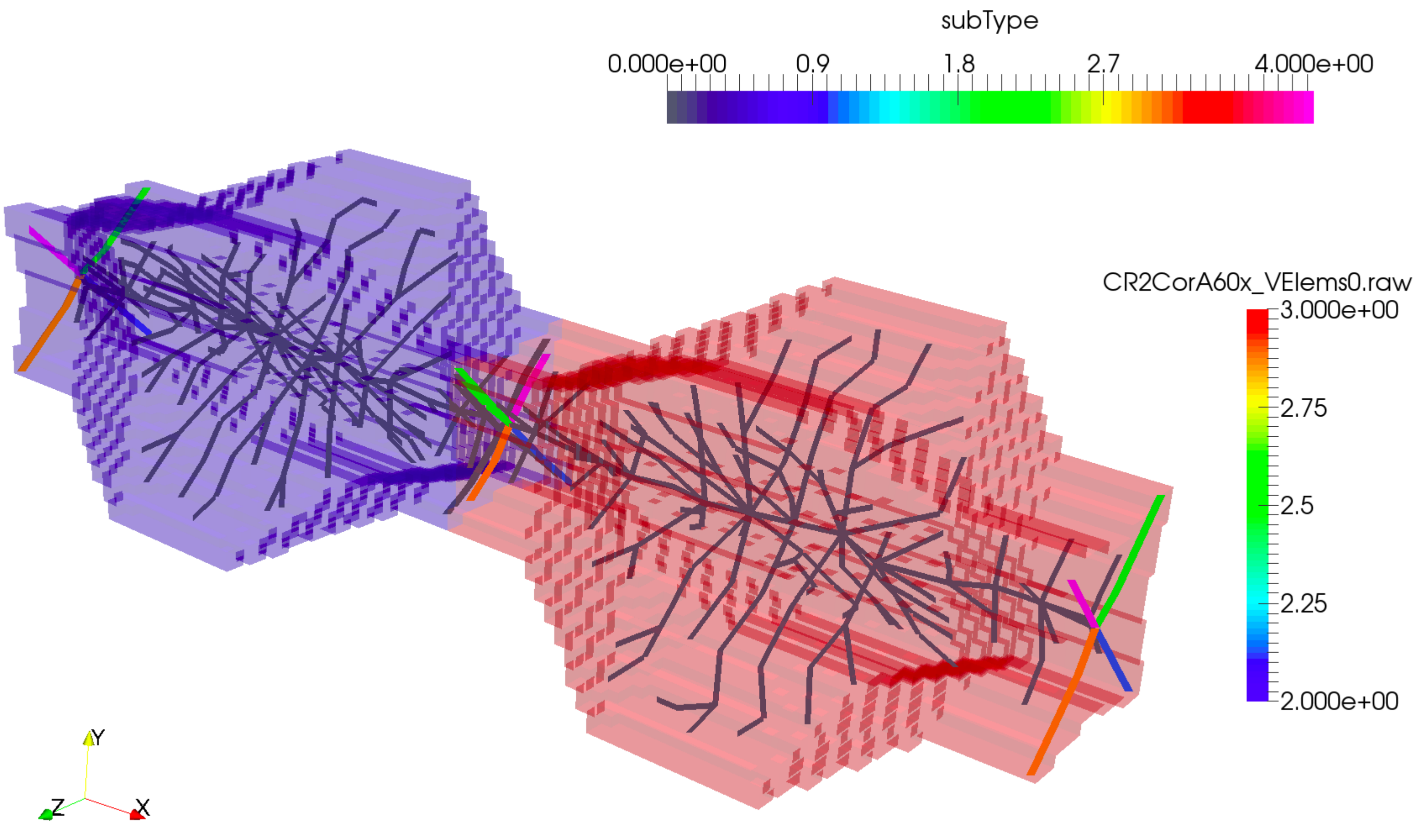
Parametrisation of pore space

Step2.
2.1. Extract ball hierarchy (medial surface),
2.2. find local maxima of the radius and
2.3 Assign a pore index to each of the local maxima



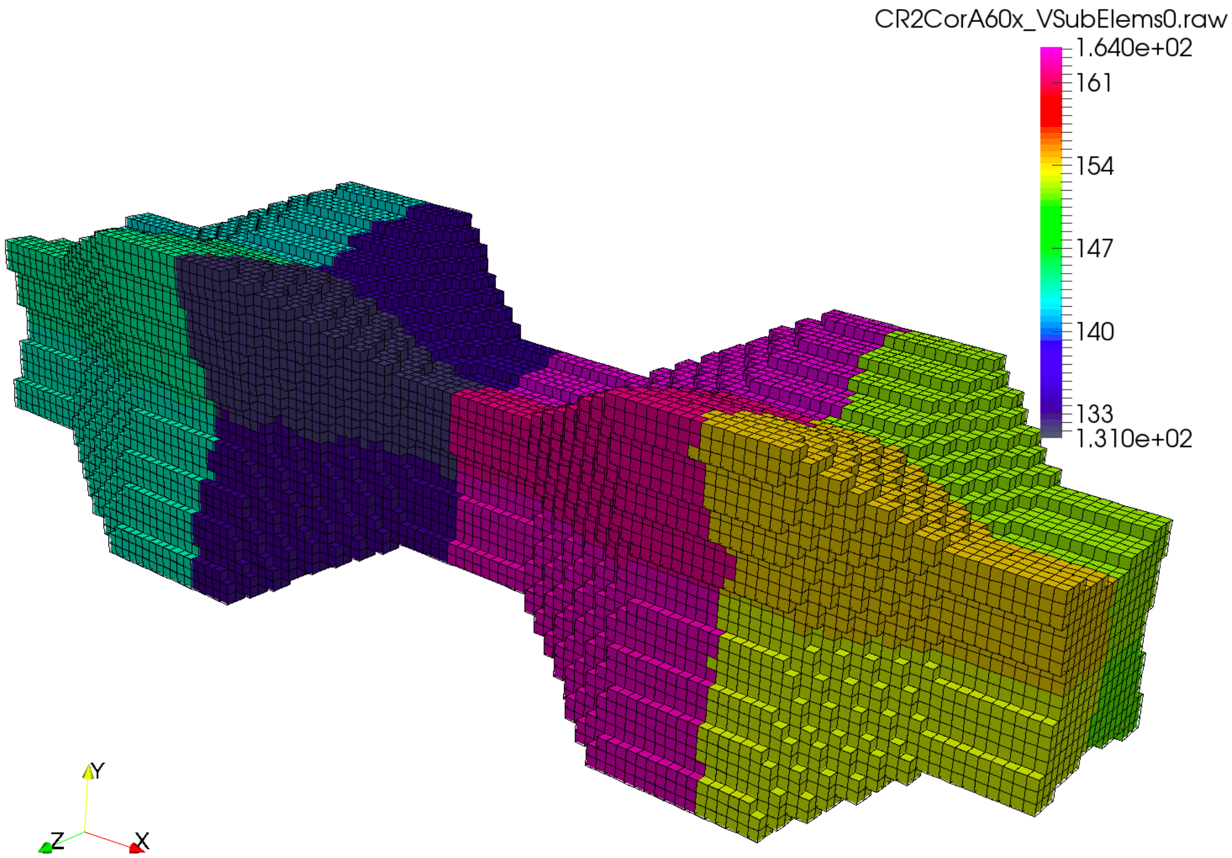
Parametrisation of pore space

Step 3.0. Find pore-to-pore connections (throats)
Step 3.1. Identify and label individual corners on the throat medial axis



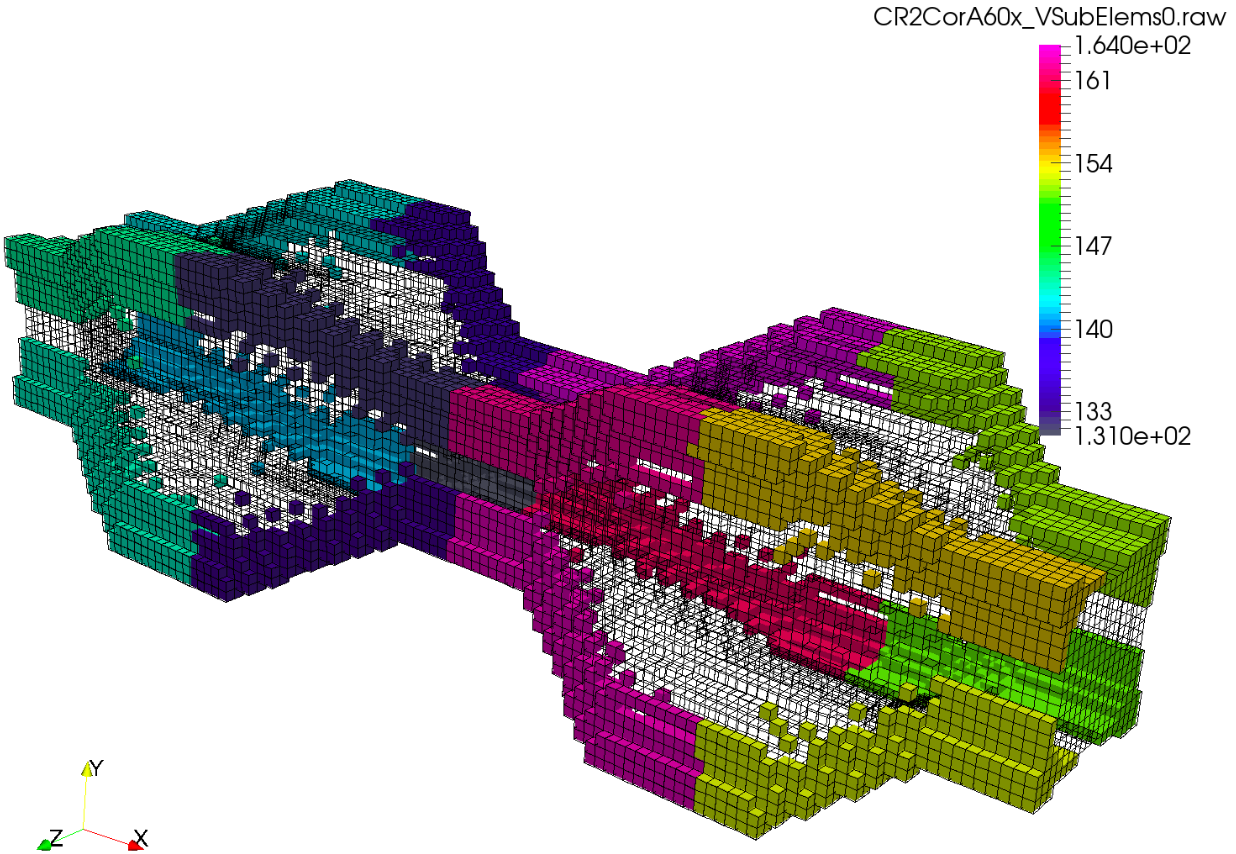
Parametrisation of pore space

Step 3.1. Map corner labels to the original image and analyse direct simulation results for each corner at Level 0



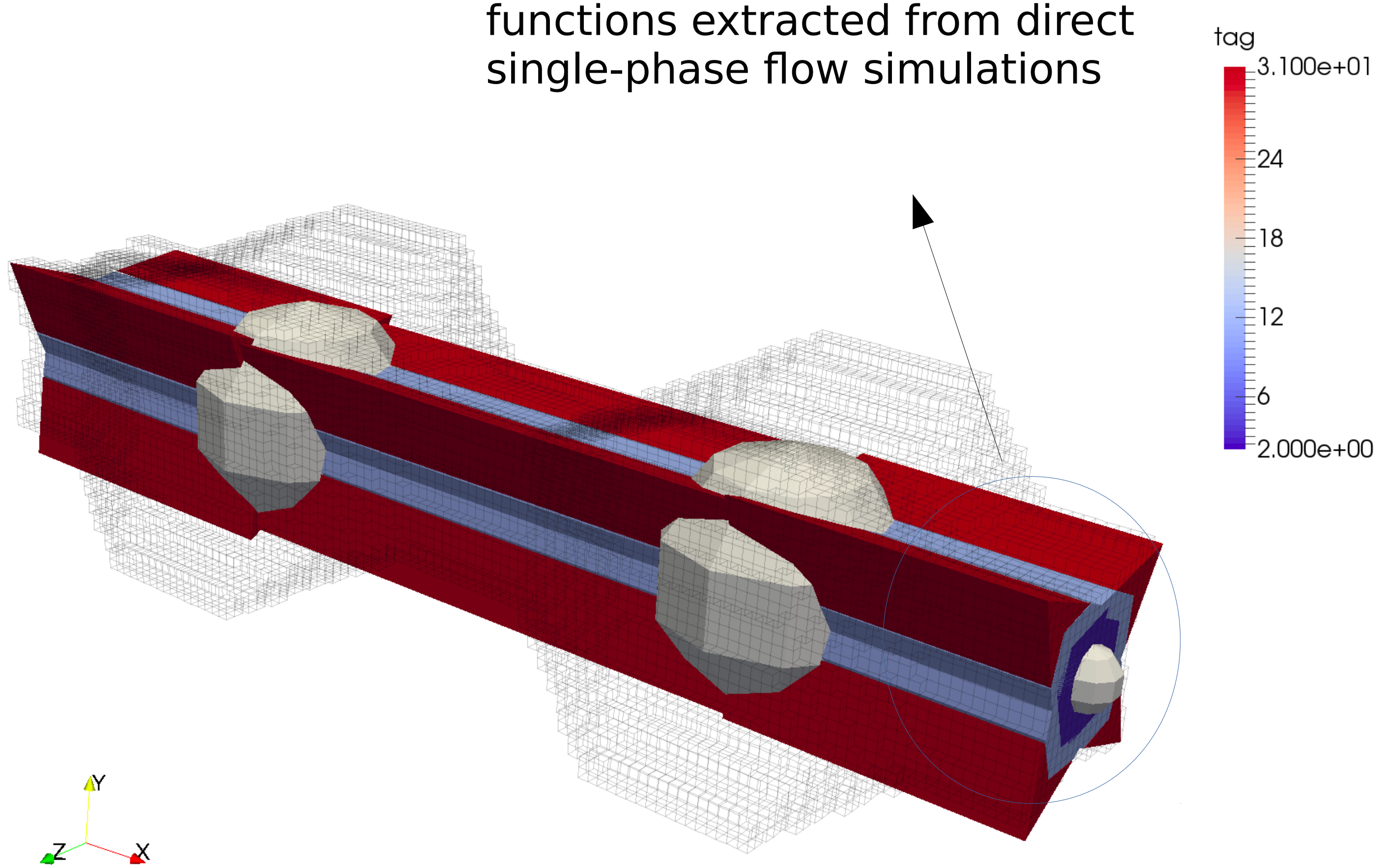
Parametrisation of pore space

Step 3.3. More balls from throat centres are deleted from corners to analyse direct simulations at Level 2

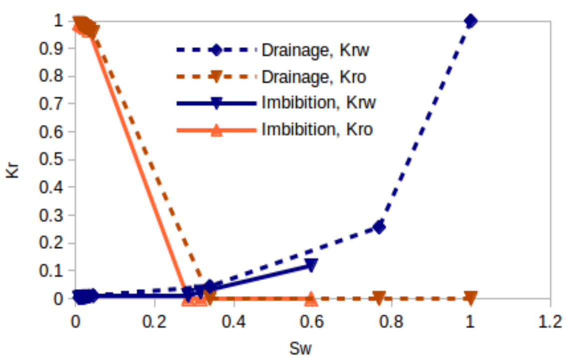


Comparison - generalized network extraction

Corner conductivities are calculated from tabulated functions extracted from direct single-phase flow simulations

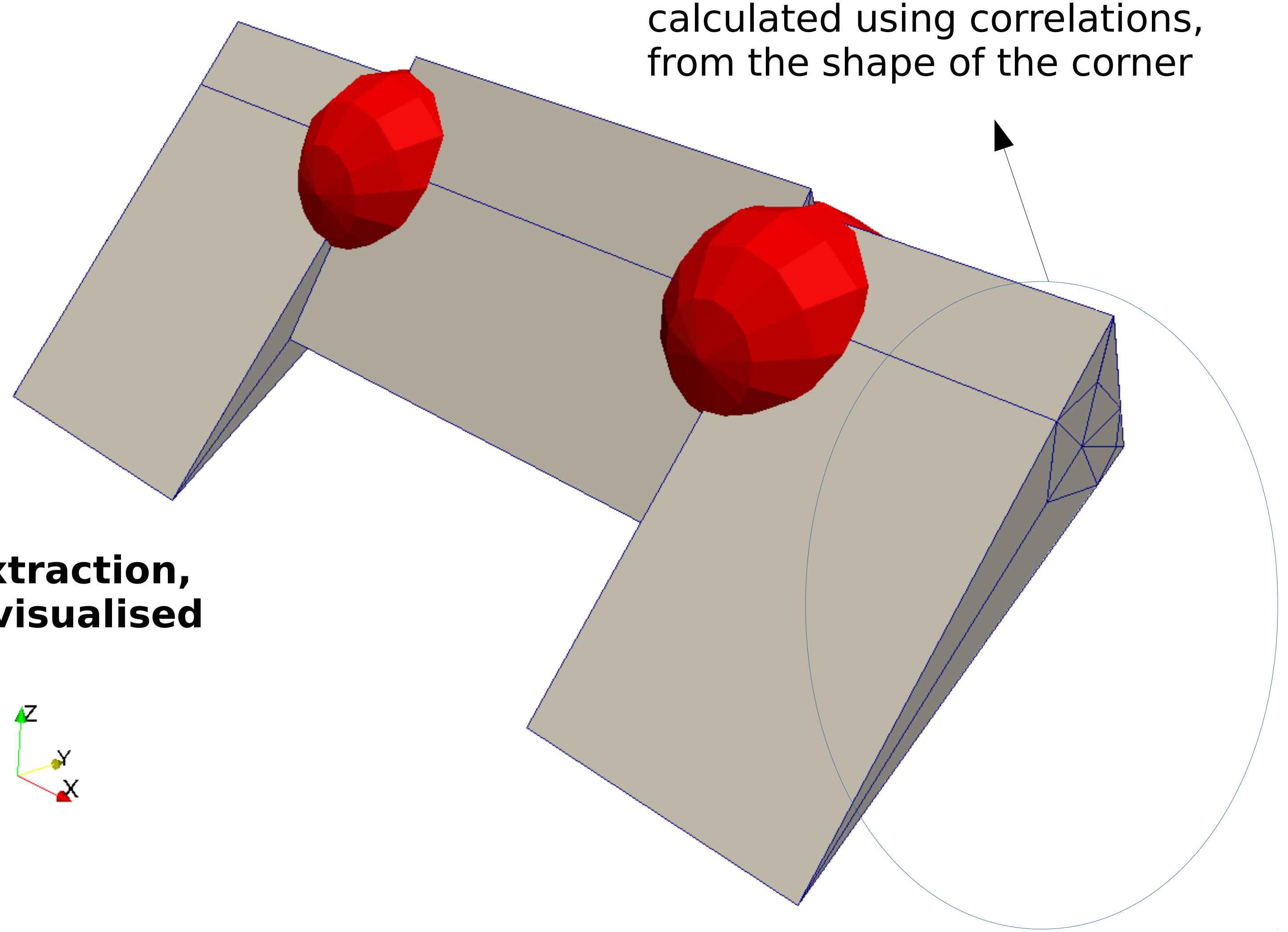


Generalised network simulation results – validation in progress



Comparison - conventional network extraction

Corner conductivities are calculated using correlations, from the shape of the corner



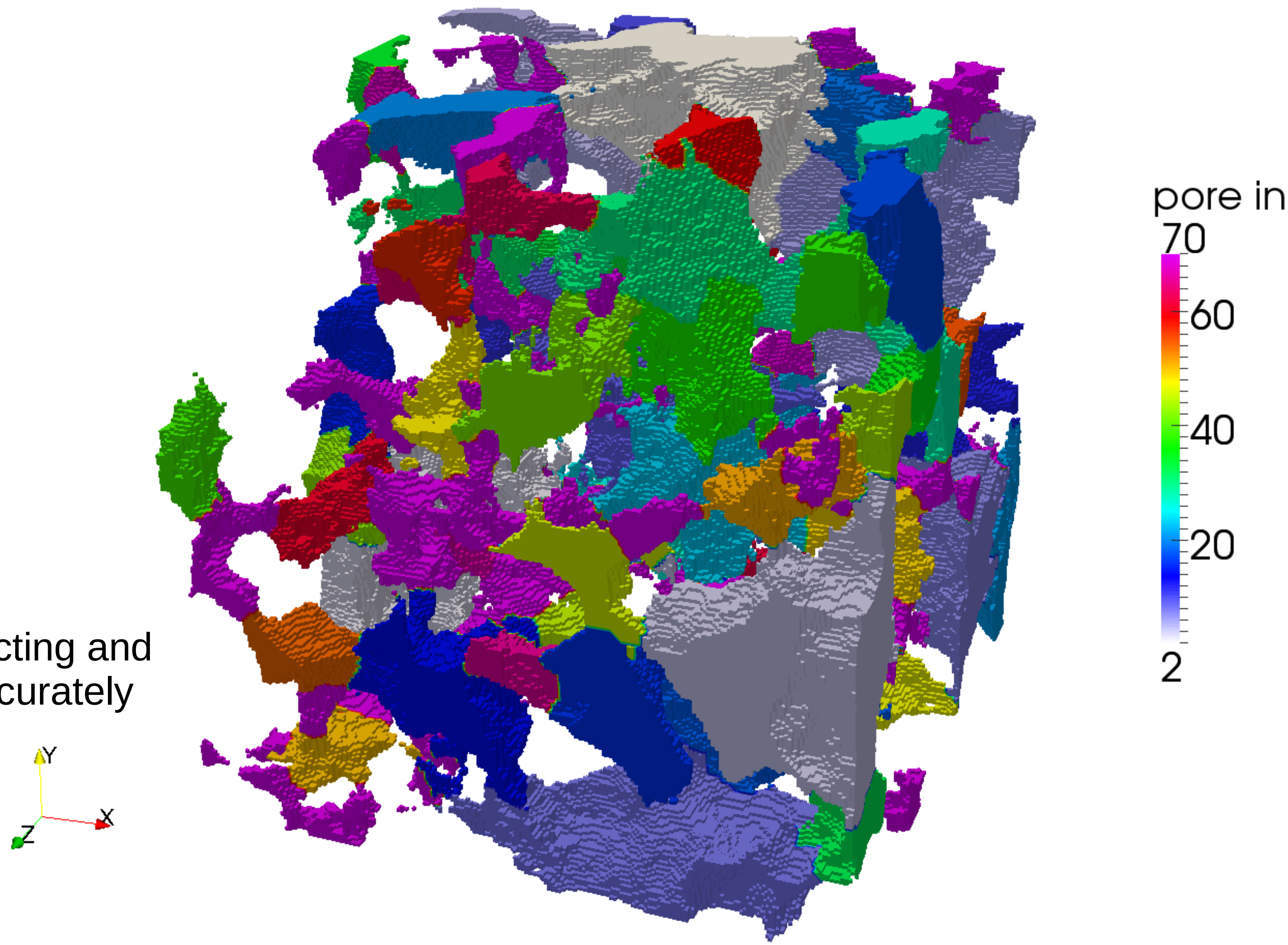
Conventional network extraction, Only throat corners are visualised

Network extraction demonstration – Berea sandstone

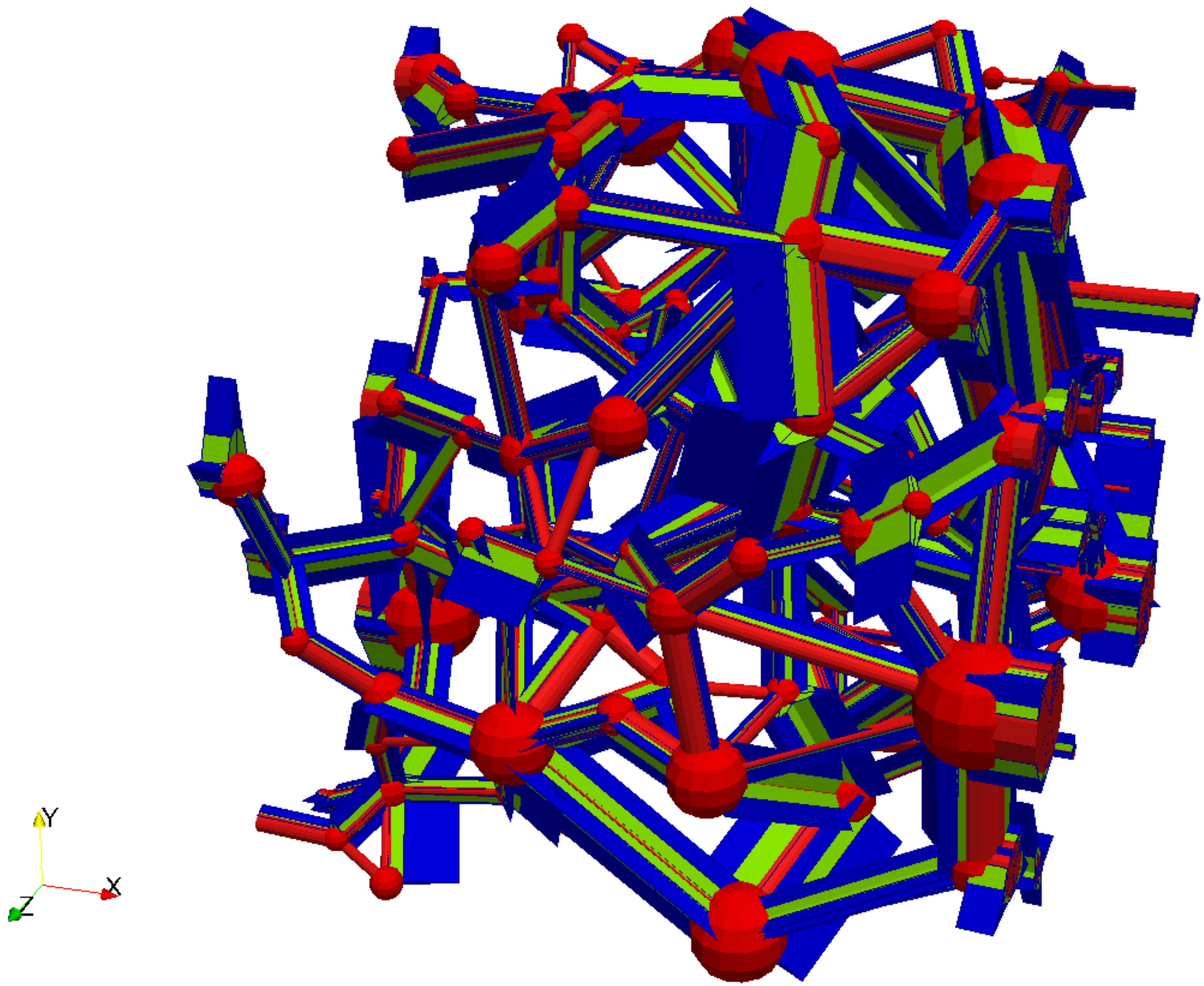
Element Indices

✔High resolution

➔ Important for detecting and analysing corners accurately

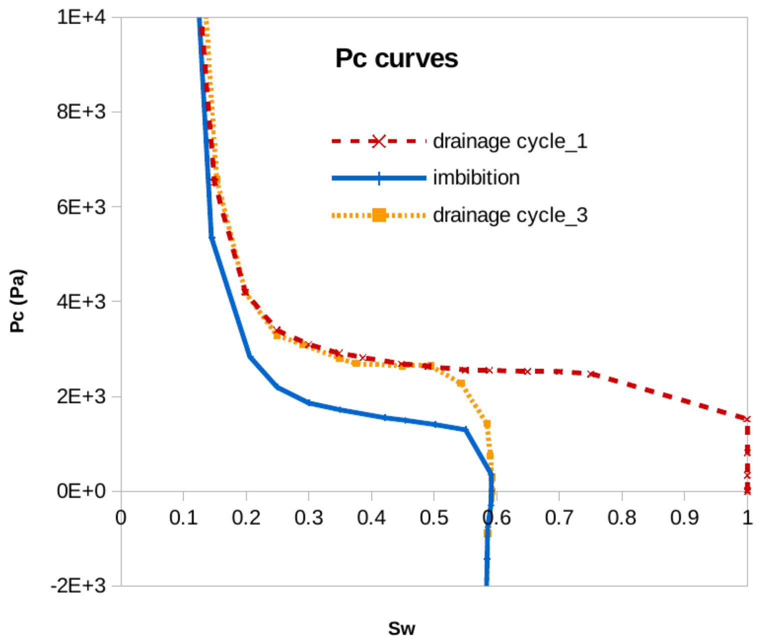


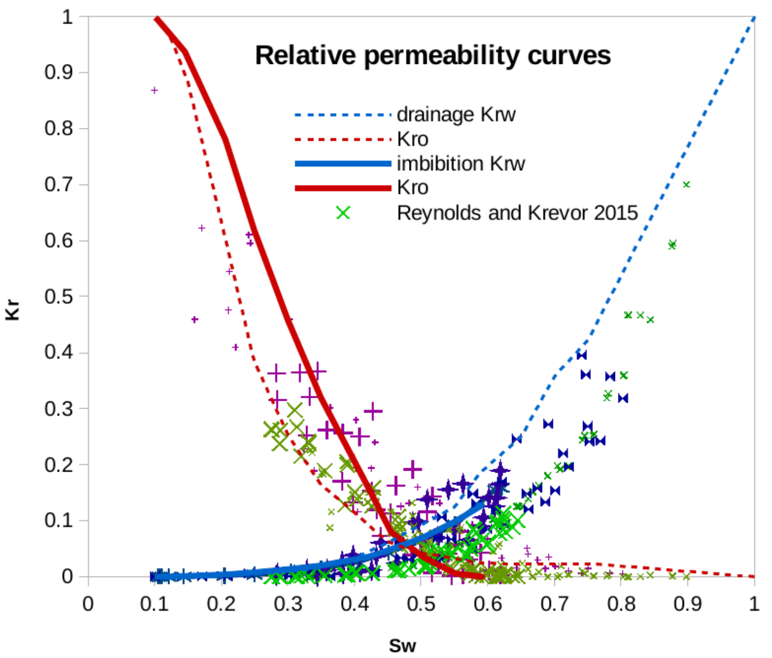
Generalised network in flow simulator, a primitive visualization

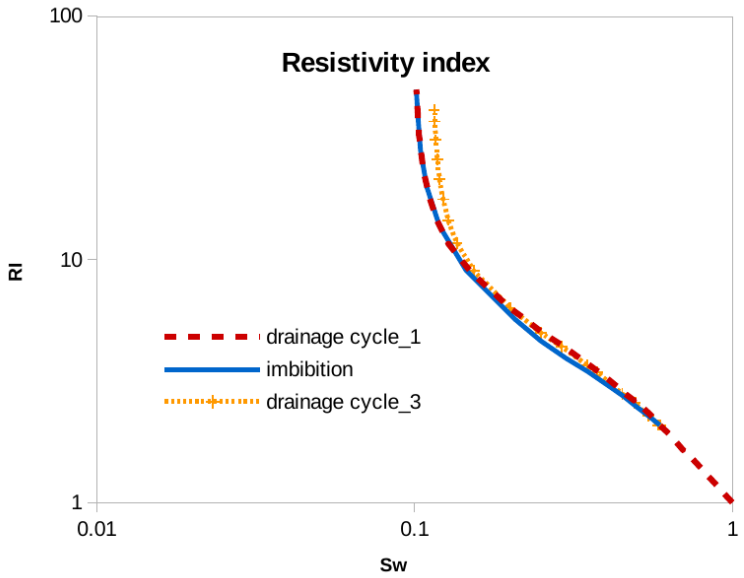


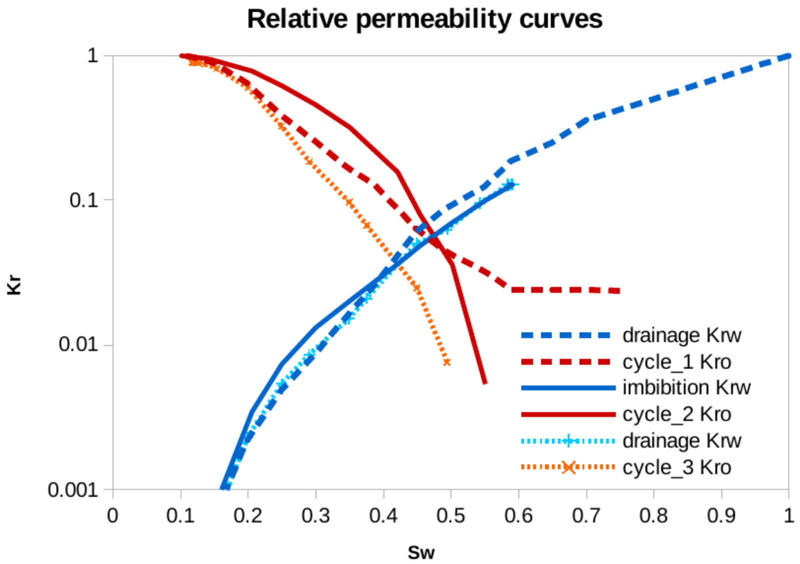
Relative permeability predictions – **water-wet**

Bentheimer sandstone (from IC-PSM website, 1000^3 @ 3um)



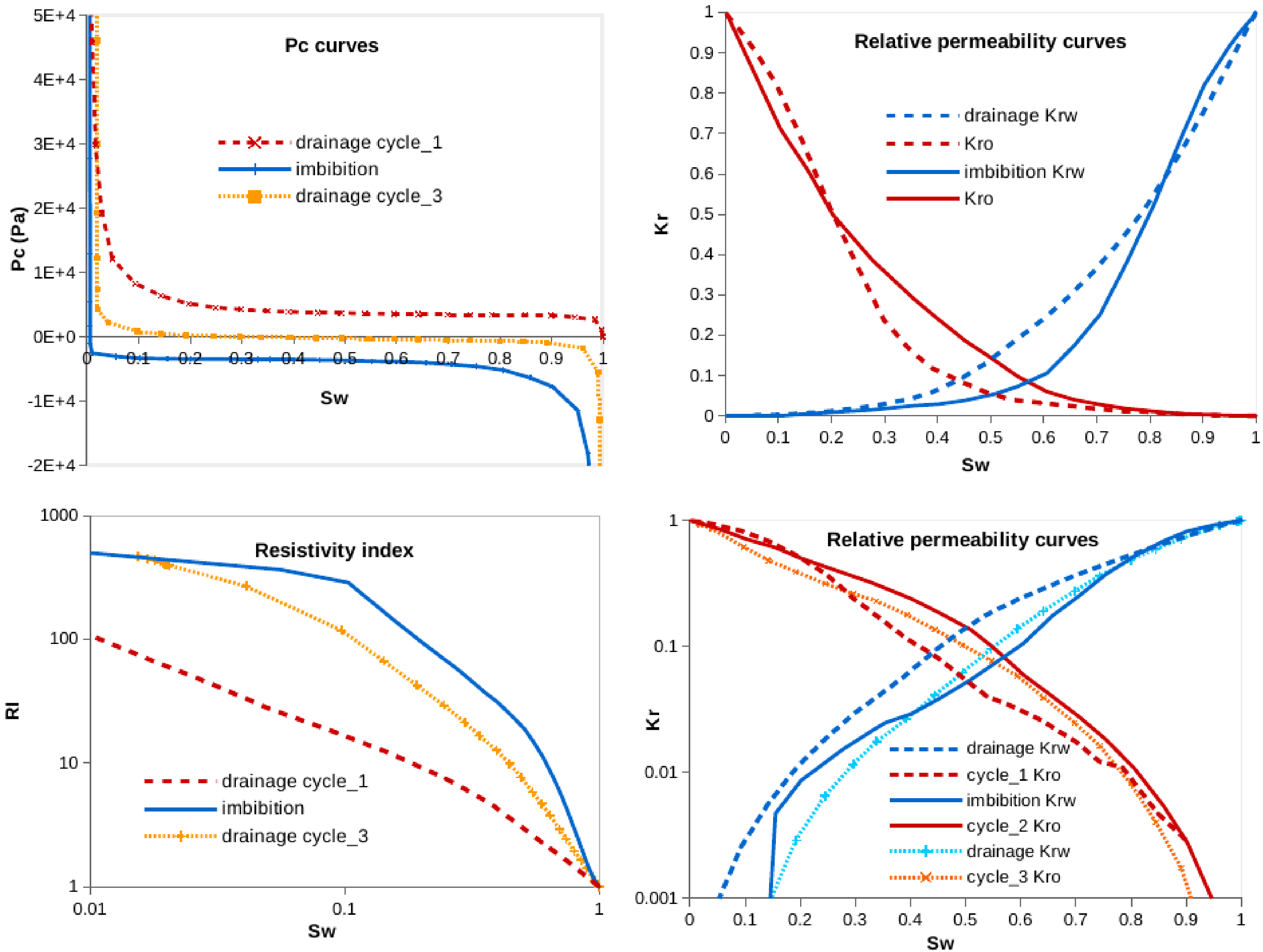






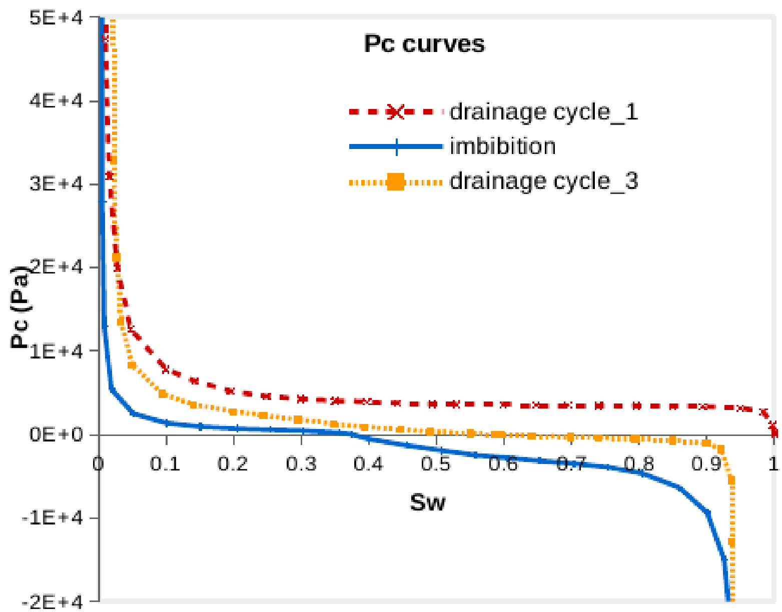
Relative permeability predictions – o**il-wet**

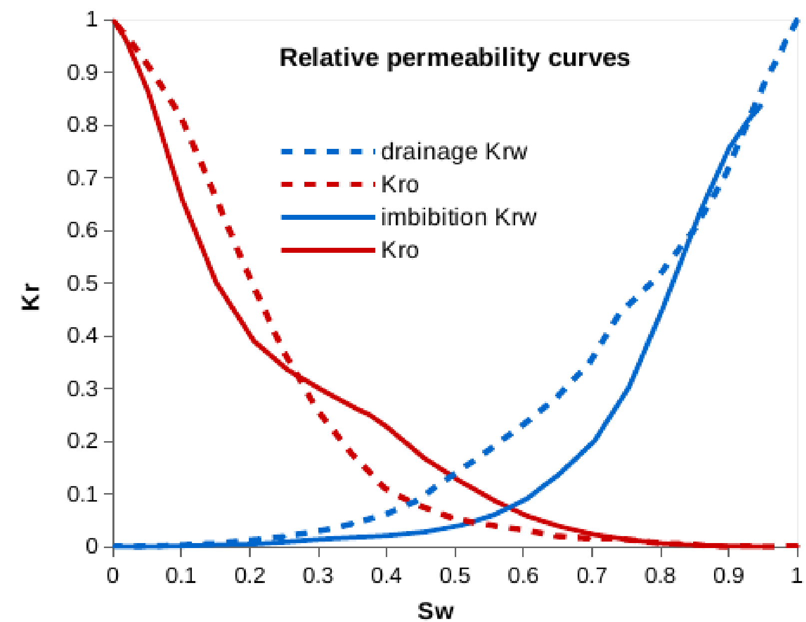
Bentheimer sandstone (from IC-PSM website, 1000^3 @ 3um)

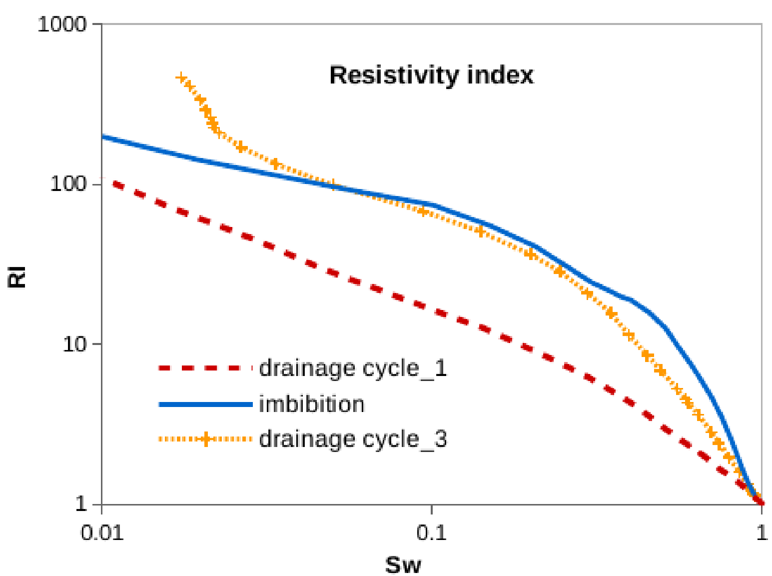


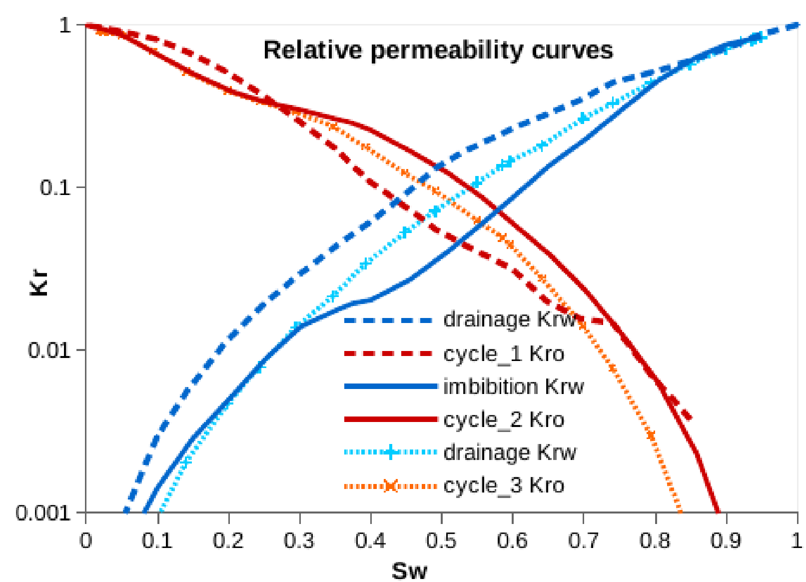
Relative permeability predictions – **mix-wet**

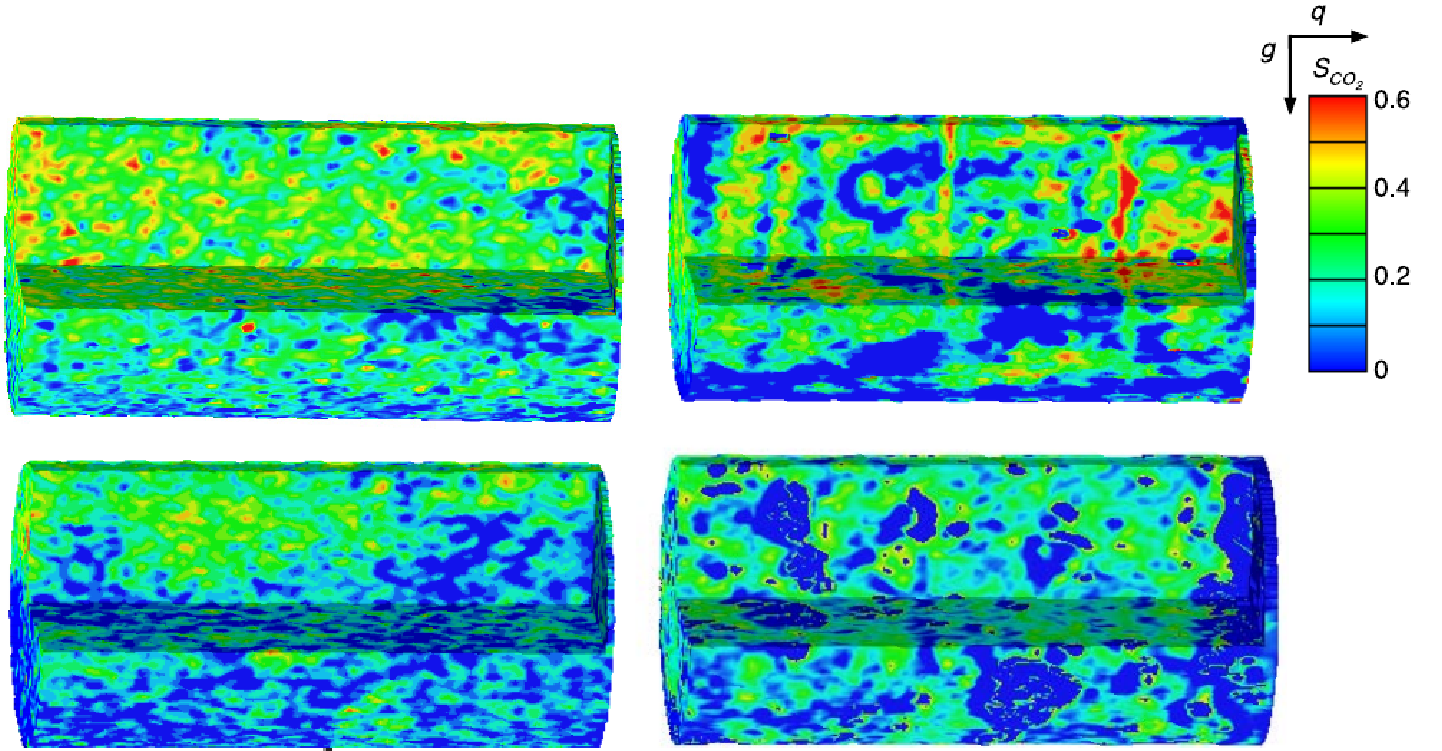
Bentheimer sandstone (from IC-PSM website, 1000^3 @ 3um)

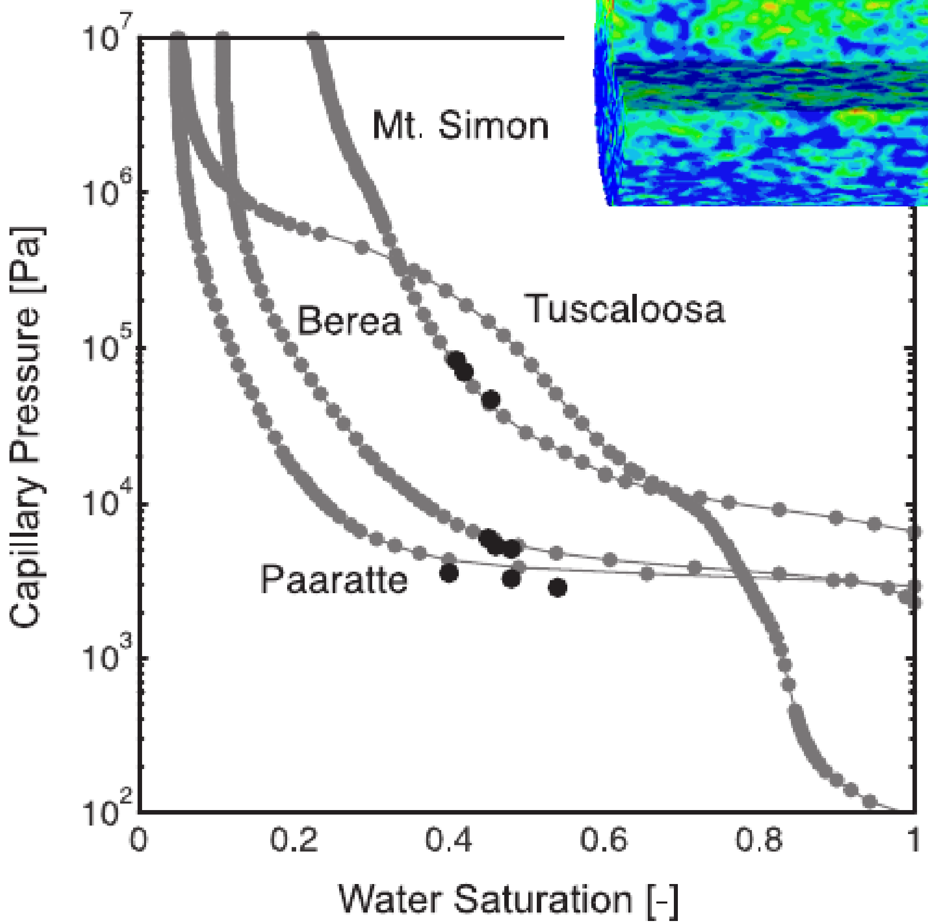








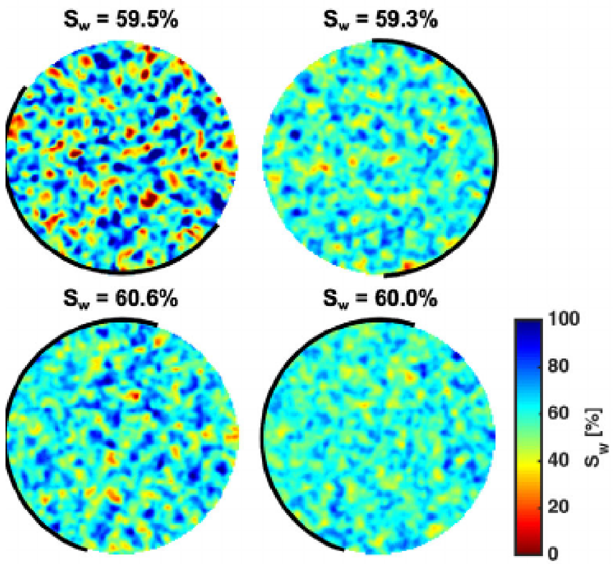




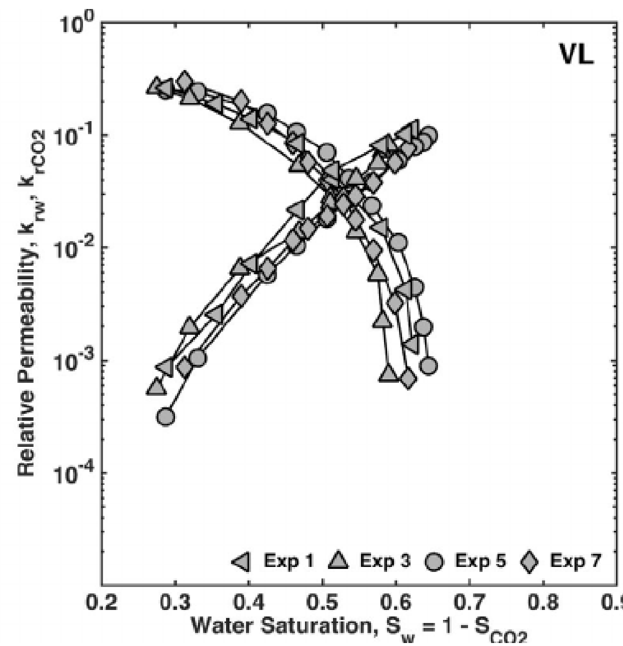
Capillary heterogeneity at core scale

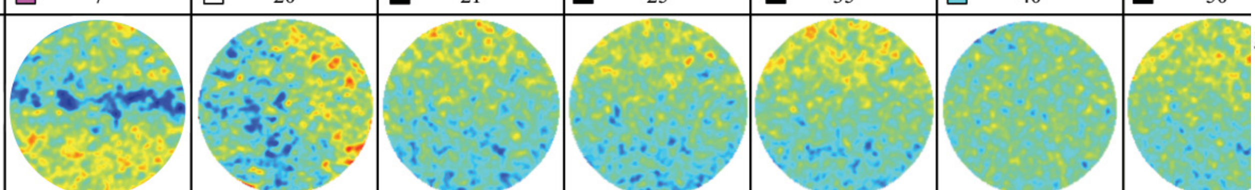
Krevor et al (2012)

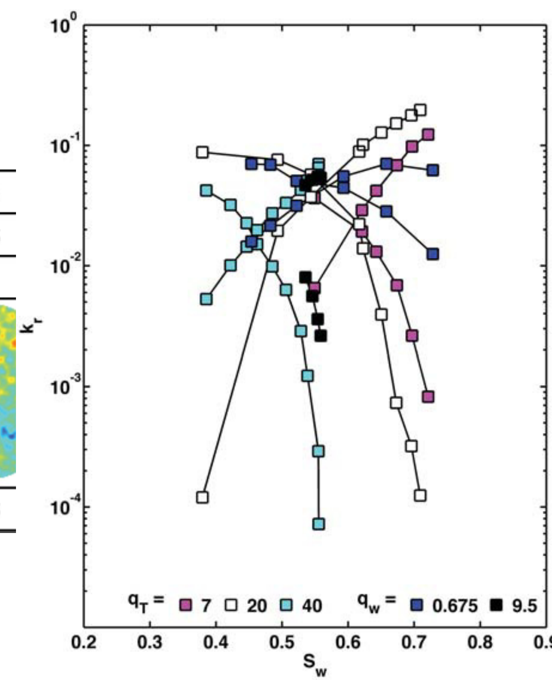
Experimental relative permeability measurement



saturation map

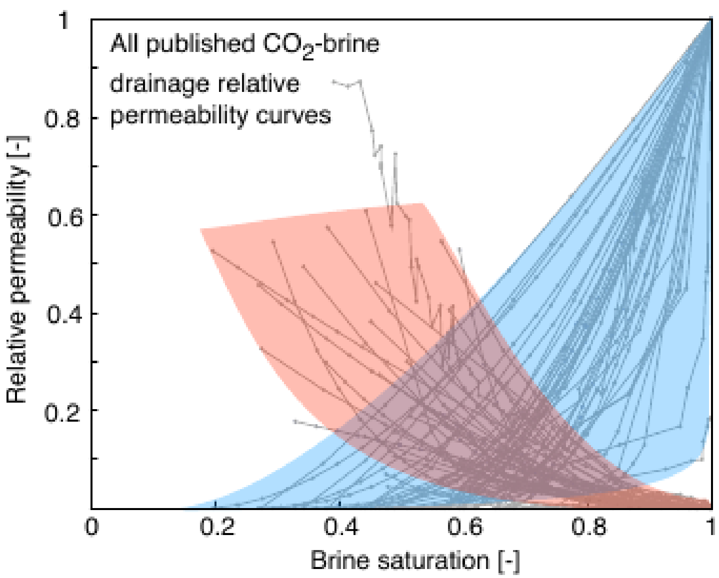


f_{N2}	0.943	0.511	0.54762	0.62	0.72857	0.1	0.81
q_{N2} (ml/min)	6.6	19.489	11.5	15.5	25.5	4.0	40.5
q_T (ml/min)	7	20	21	25	35	40	50
1 0.5 S_w 0 (S_{N2} = 1)							
S_w (%)	54.7	54.3	55.8	55.6	53.3	55.1	52.5

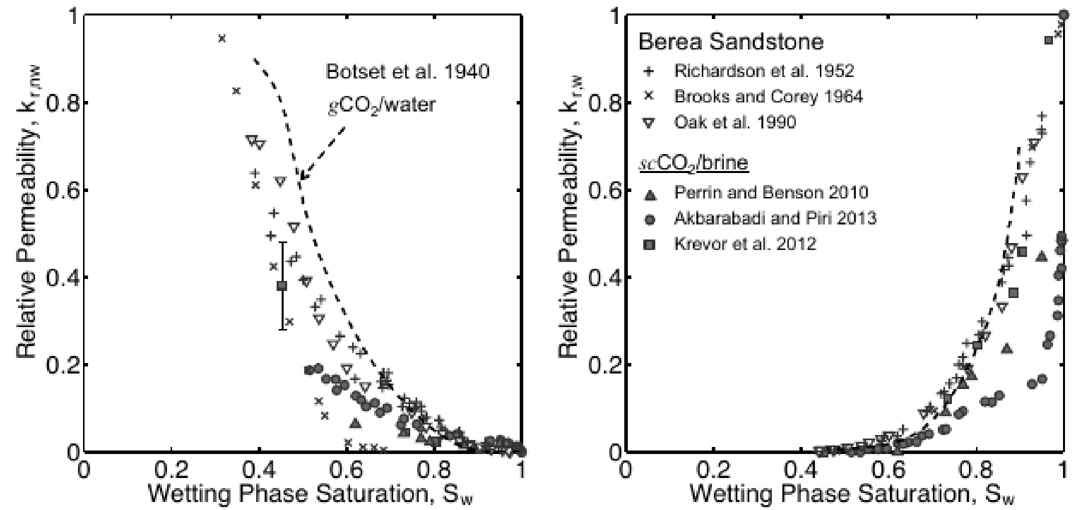


Reynolds and Krevor (2015)

Experimental relative permeability measurement

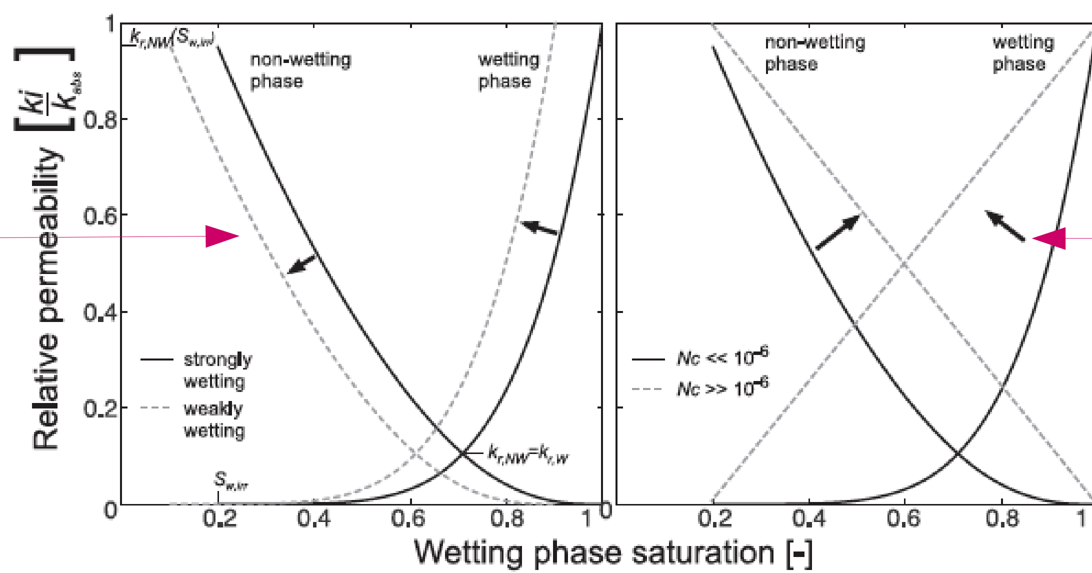


Different rocks, CO2-brine



Berea sandstone, CO2-brine

Effect of wettability



Effect of capillary number

Credit: GCCSI report no. 2 relative permeability (2013)

Validation with direct simulations - **star-shaped** pore-throat system

Star-shaped geometry parameters:
Corner Angle : 45 degrees

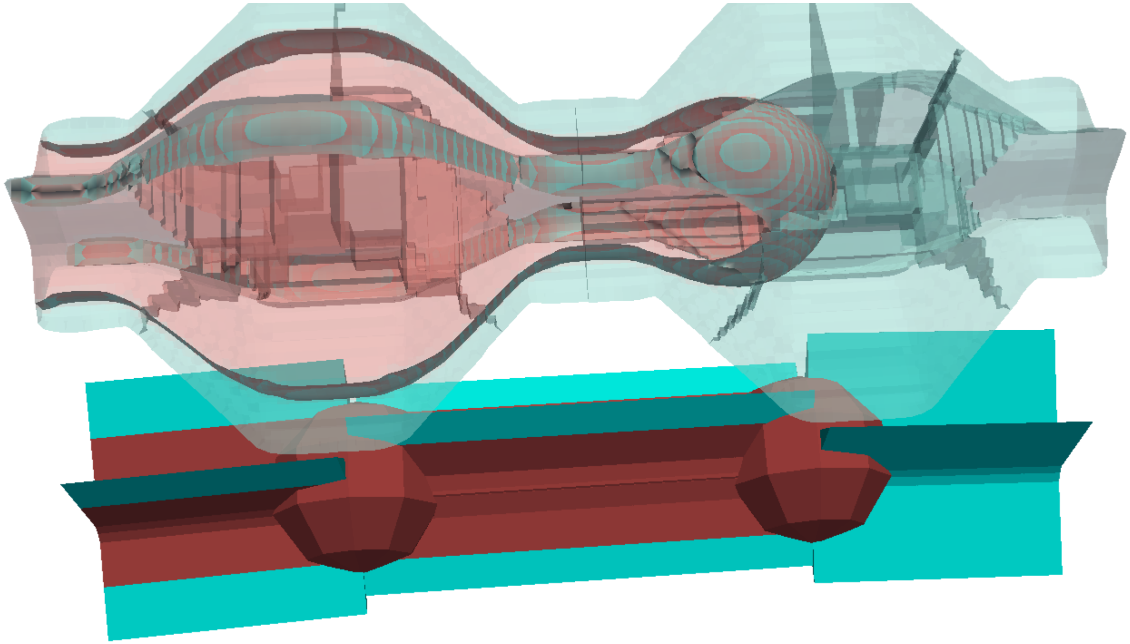
$R_{pore}/R_{throat} = 2.25$

$R_{pore}/L_{throat} = 1.25$

Direct simulation
simulations run on 12 processors
Simulation time:

3-4+ hours for R_{throat} /δx =5

2-3+ days for R_{throat} /δx =10

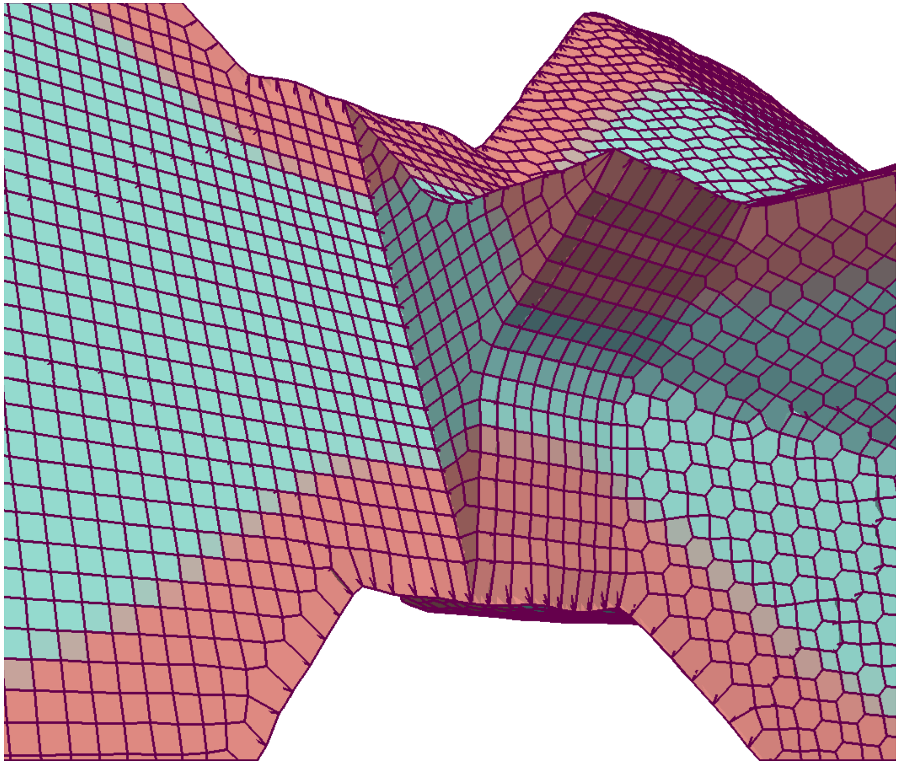


Network model
Simulation time: **less than 1 second**

Note: network model visualization is primitive, the actual calculations are done based on a fixed 4-segment linear interpolation scheme for each half corner

Improvements to direct simulations:

- Mesh quality improvements:



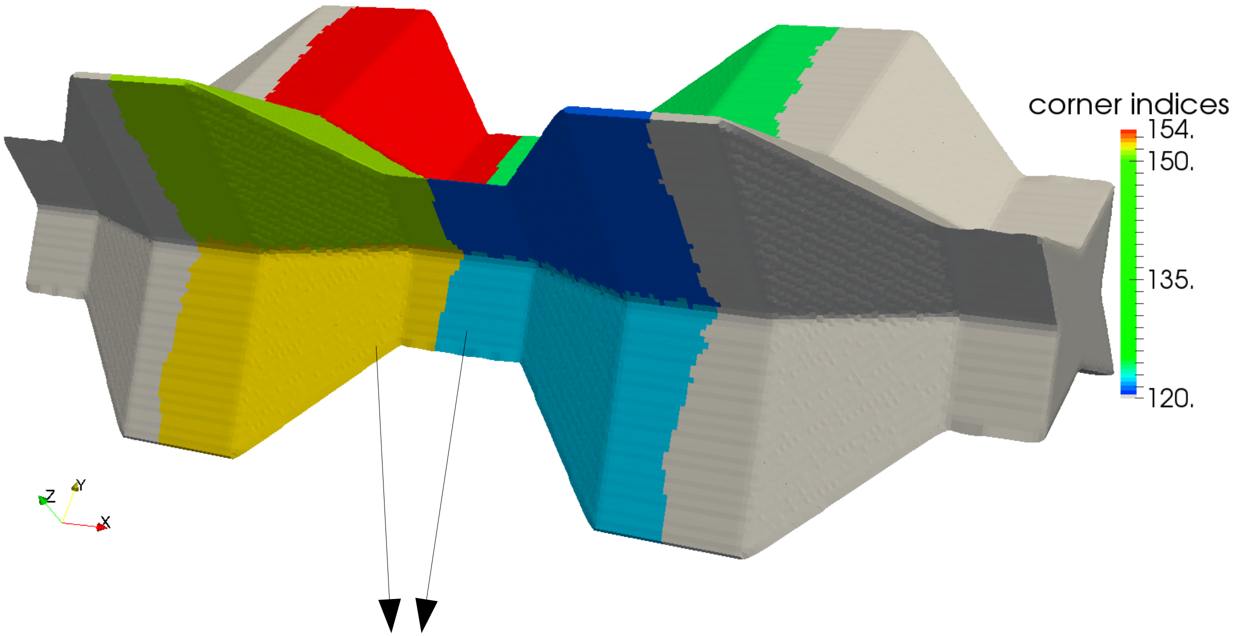
- Improved surface tension model using explicit interface reconstruction

Thanks to **Mosayeb Shams** for sharing his code, **Arthur Moncorgé** and **Stephane Zaleski** for their feedback and advice

Post-processing direct simulations

Corner Indices from network extraction are used directly as input control-volumes during direct simulations,

The code that is used for computing relative permeability curves is used to analyse individual corners extracted from rock images.



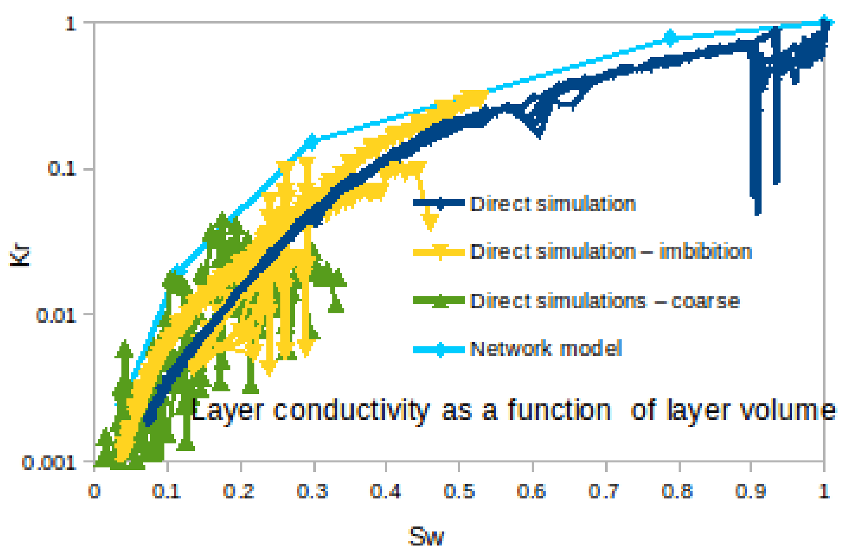
Each throat (pore-to-pore connection) is divided to 8 half throat corners during network extraction stage

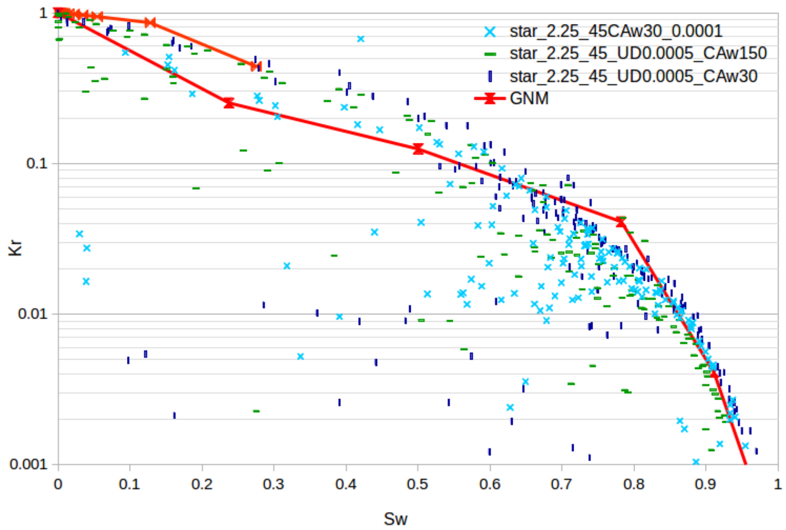
Validation of network flow simulator code saturation/conductivity computations

Layer saturation/conductivities depend on:

- **Corner cross-sectional shape**
- **Variation of the cross-sectional area along the pore-to-pore connection**
- **Flow pattern / rates**

Direct simulations, star-shaped, drainage, piston-like invasion followed by layer flow,

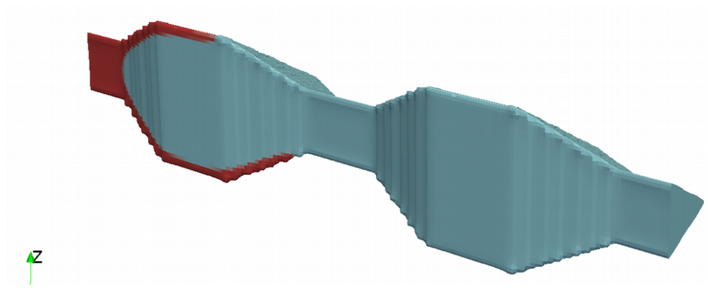




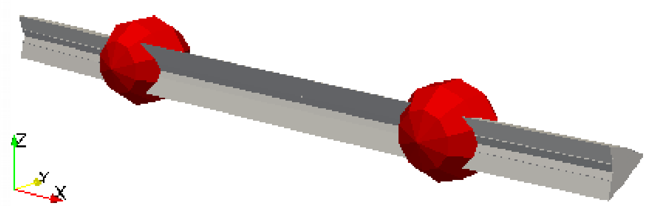
Parameters to be studied:
(Compute their Pc-volume-conductivity relationship)

- Contact angle
- Corner angle
- Longitudinal interface curvature
- Different pore geometries

Triangular geometry:



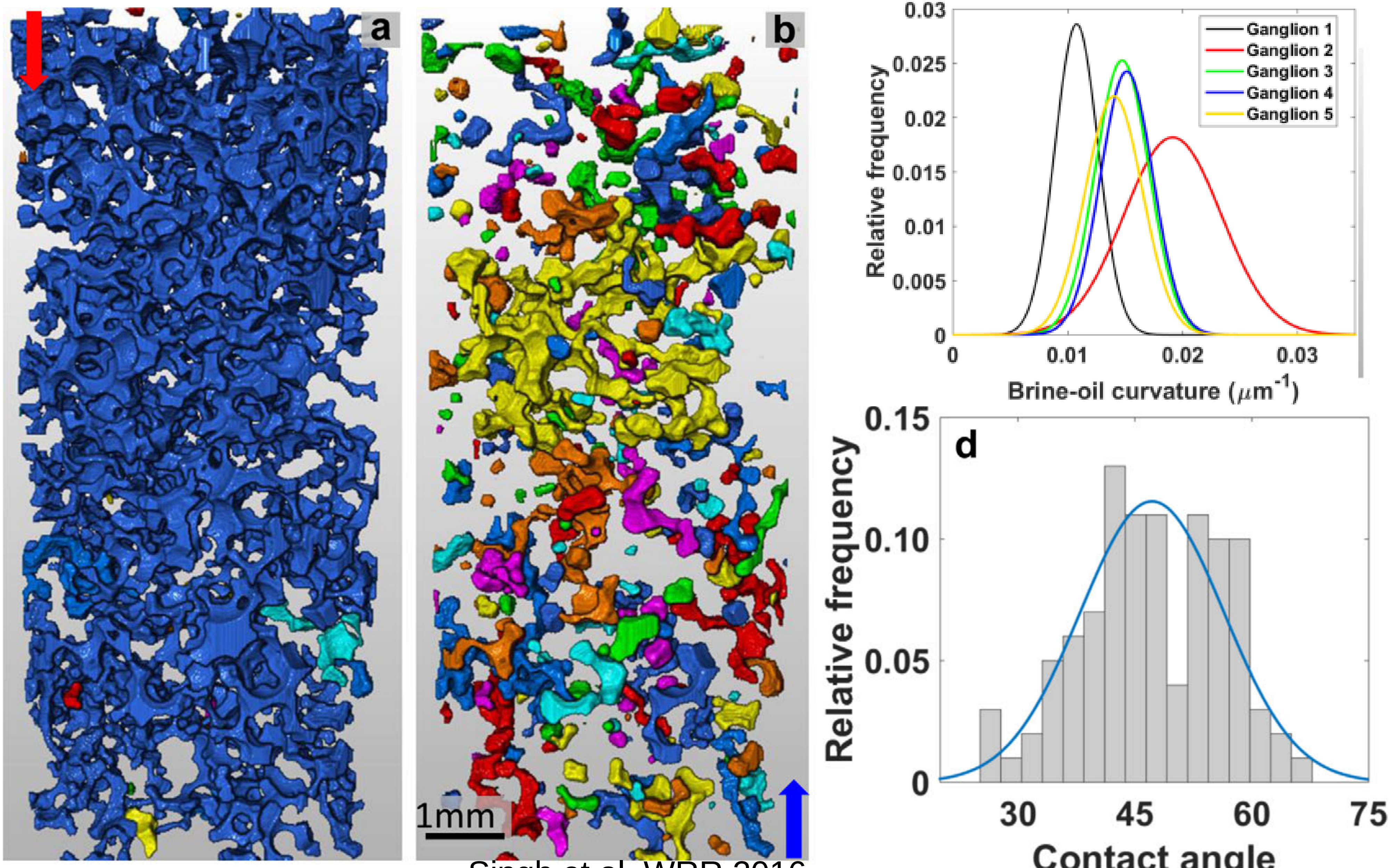
Direct simulation:



Network model:

- More Complex test cases to verify cooperate-pore filling algorithm
-
- Run direct simulations on small, but high resolution micro-CT images

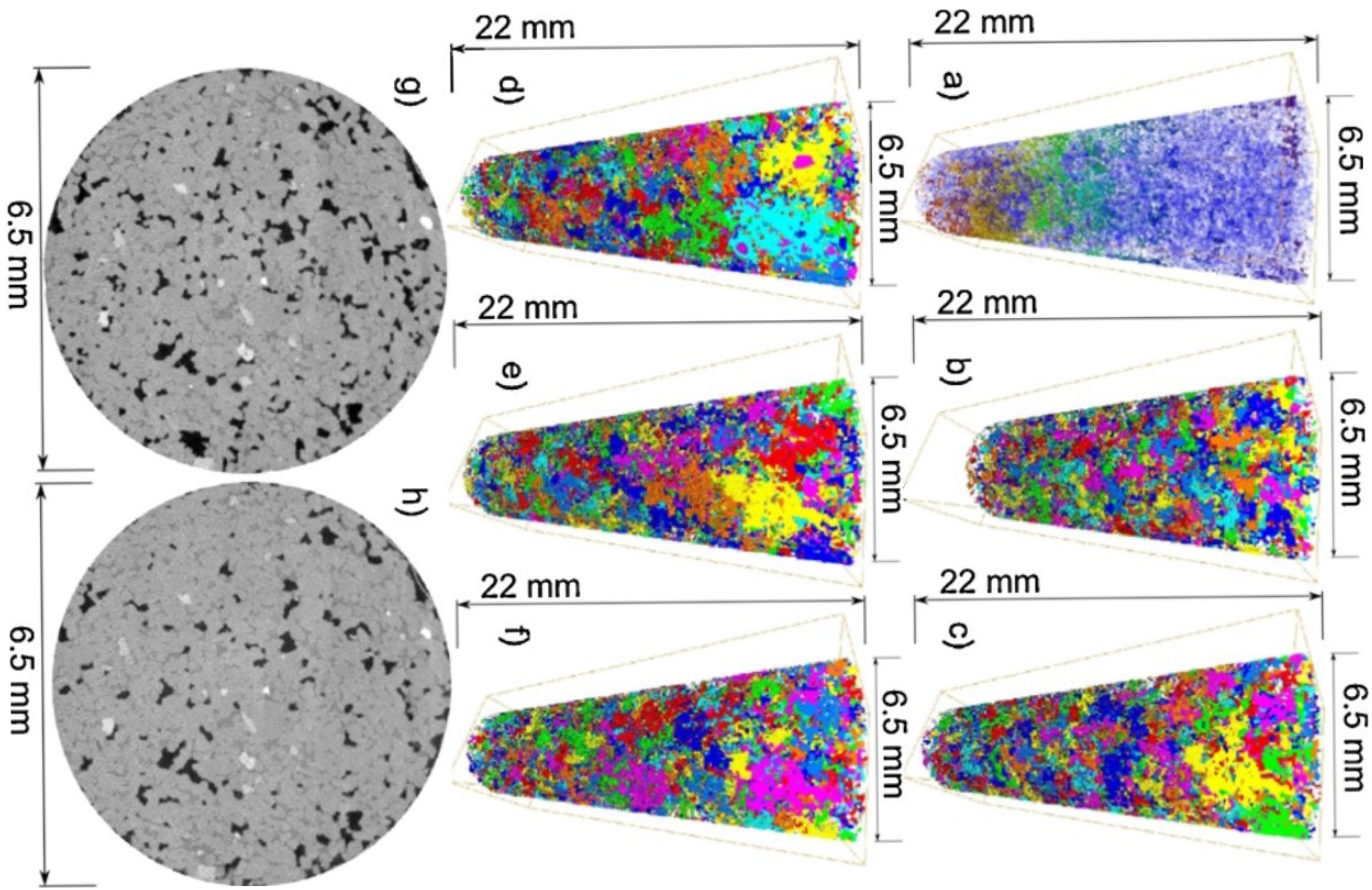
Curvature and contact angle measurements using high resolution micro-CT imaging



Singh et al, WRR 2016

Validation using experimental mesurements

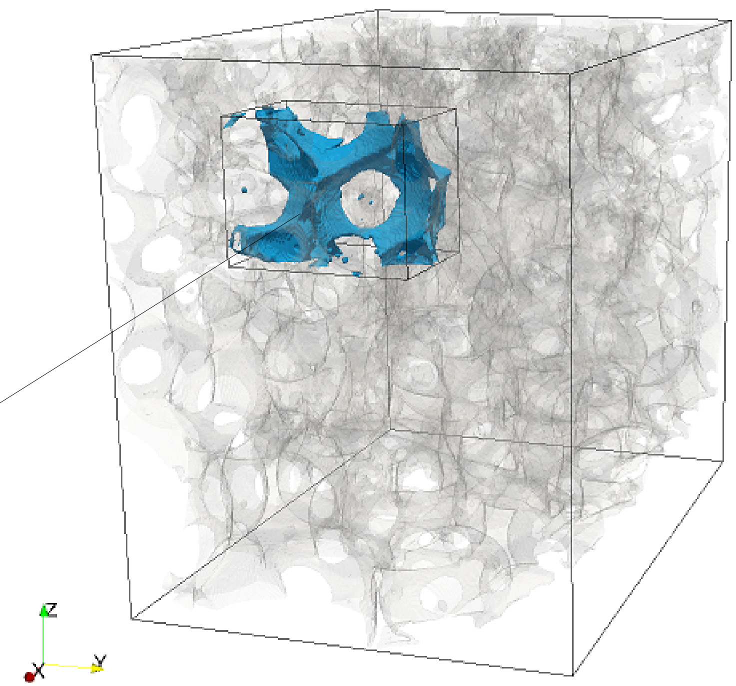
Multi-phase micro-CT imaging experiments
each experiment repeated 5 times → uncertainty quantification



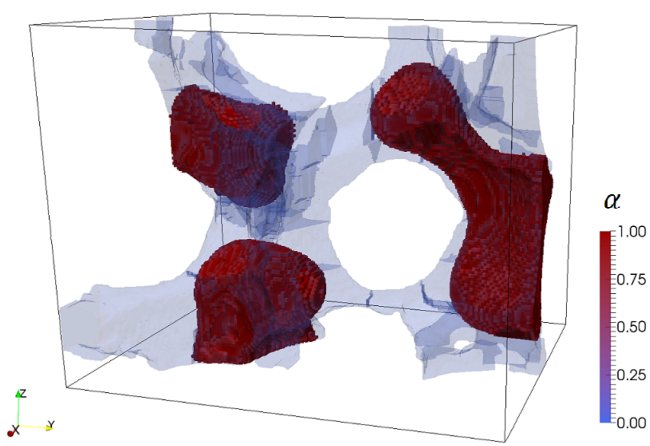
(Andrew et al, 2014)

Simulations on High resolution micro-CT images

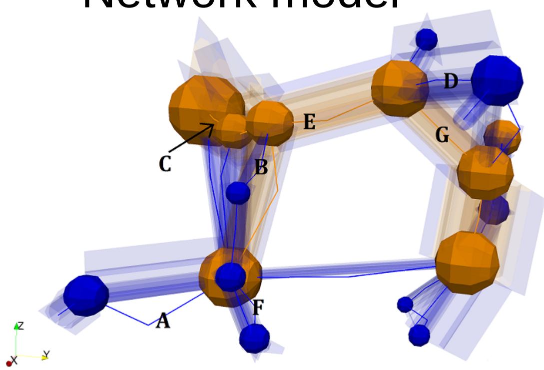
Small sample taken from the larger-scale image:



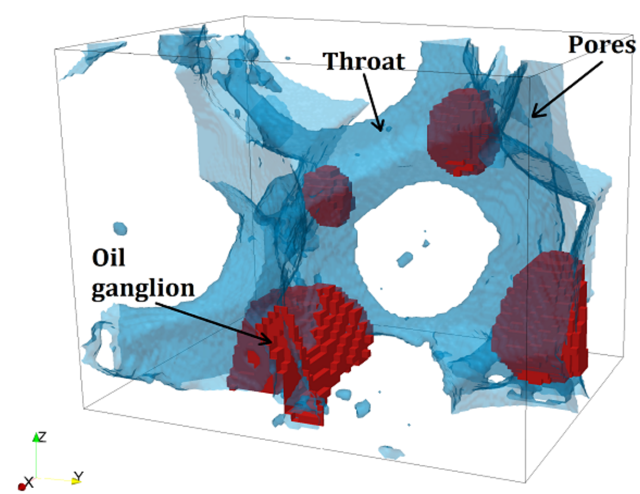
Direct simulation
(Lingru Zheng, MSc thesis, July 2016):



Network model



Multi-phase micro-CT image:



Conclusion, network modelling

- The computations are comparable in accuracy with direct simulations and in speed with network models (a gain of about 6 orders of magnitude in performance)

- Corner extraction and connectivity-tracking provides richer computations and predictions and gives us the opportunity to have a pore-by-pore comparison on complex micro-CT images

- Further work is needed to quantify the range of uncertainties/variations in experimental measurements and compare them with network model predictions

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Thank you for your attention