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2023 Annual Meeting of the Imperial College Consortium on Pore-Scale Modelling and Imaging

Predictive multi-scale network models with micro-porosity

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12th January 2023

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Outline

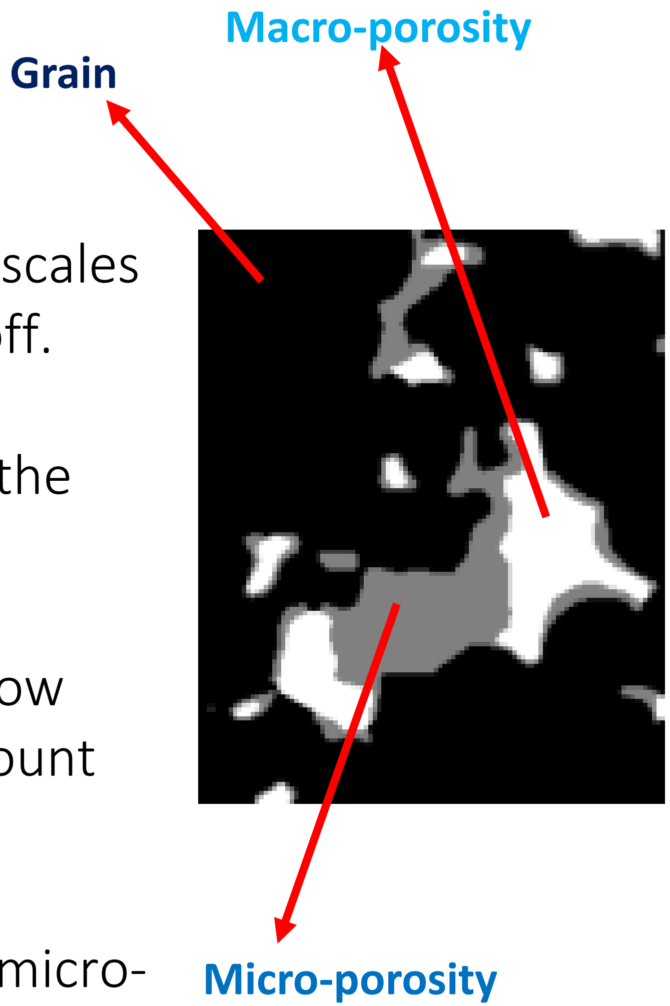
❖**Incorporating micro-porosity in pore network models:**

- Identification of micro-links using micro-porosity from differential imaging.
- integrate micro-links and the macroscale network in terms of topology.
- Characterisation of micro-links.
- Results for single-phase flow incorporating all scales.
- Incorporating micro-links in two-phase flow using Leverett J-Function, Corey model and Archie equation.
- Developing a model for capillary pressure for all wettabilities.
- Sample results for two-phase flow.
- Incorporating flow through connected micro-porosity.

❖ **Application to characterizing single-phase and two-phase flow in a water-wet Estaillades sample by Ying Gao et al. [2020].**

Micro-porosity

- In pore-scale imaging, it is often not possible to visualize pores of all scales present in one experiment due to the resolution/sample size trade-off.
- This sub-resolution pore space for some rocks such as Estaillades or the reservoir sample is a significant fraction of the total porosity.
- Before we can apply our successful calibration and prediction workflow (Foroughi et. al, Phys. Rev. E, 2020 & Transp., 2021), we need to account for the connectivity provided by micro-porosity.
- Differential imaging makes it possible to identify micro-porosity in a micro-CT experiment and to quantify its porosity.



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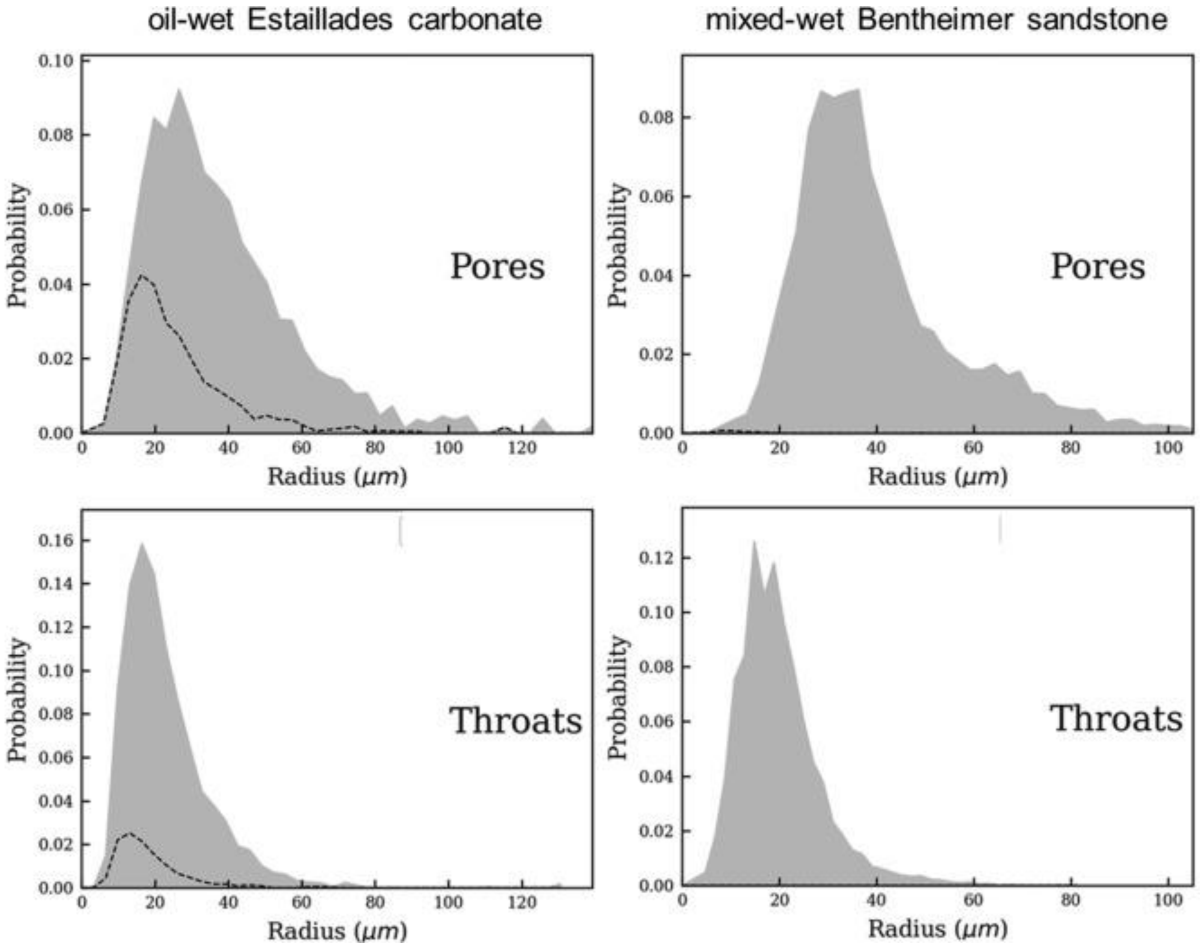
Importance of micro-porosity

Pore and throat size distribution in Estaillades and Bentheimer samples. The dashed black curve corresponds to isolated elements which are connected through micro-porosity.

Including micro-porosity in our model to have correct connectivity and accessibility is essential.



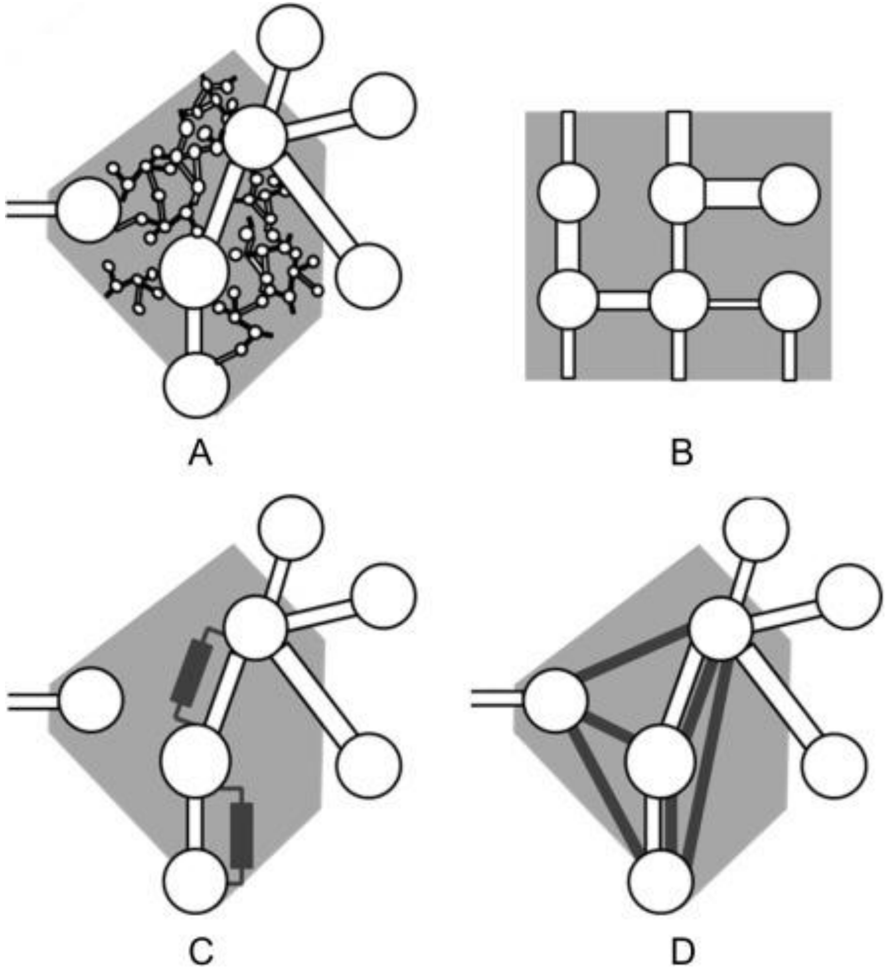
Lin et al., *Chemical Engineering Science*, 2020.

Resolved Porosity: **0.11** **Total Porosity:** **0.288±0.013**

Micro-porosity in pore network modelling

Multiscale or dual pore network models are the way to incorporate micro-porosity in pore-scale modelling.

The important criteria for multiscale PNM are computational efficiency, and allowing micro-porosity to contribute in flow both in presence and absence of macro-porosity.



Schematic description of existing DPNM methods, Bultreys et al., *Advances in Water Resources*, 2015.

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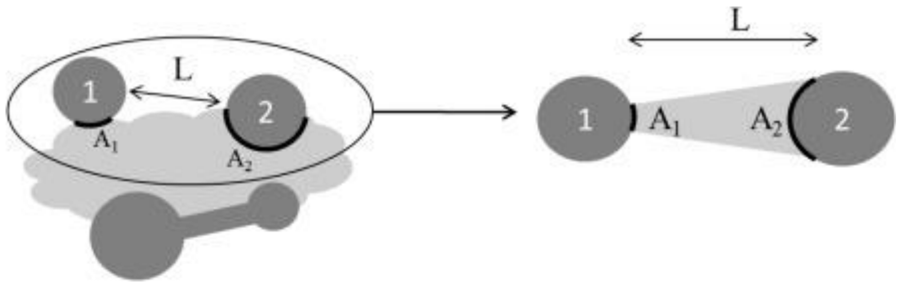
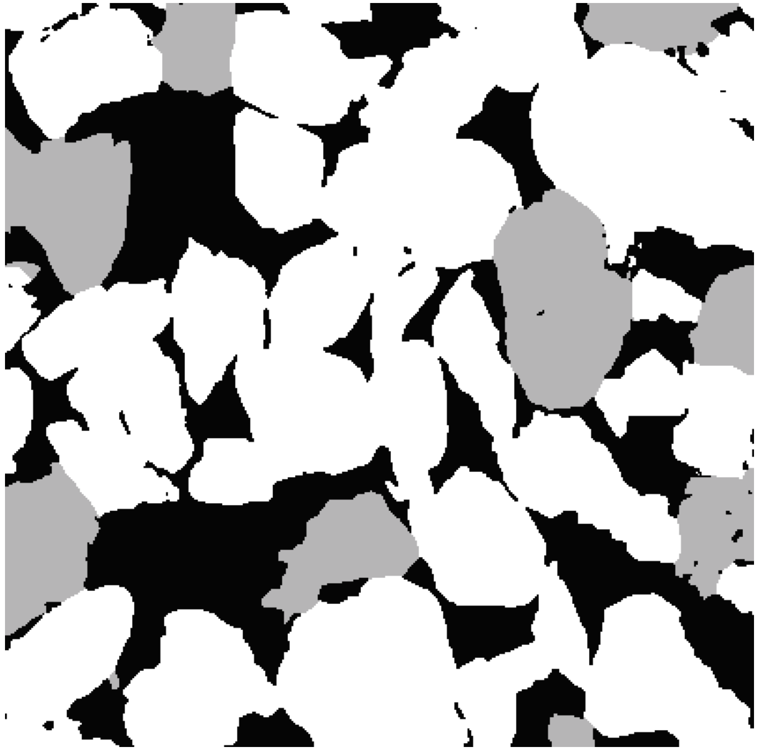
Characterizing micro-porosity as throats

Black is inter-granular pore space, grey is microporous grain, white is solid grains.



Bultreys et al., *Advances in Water Resources*, 2015.

Based on this Ruspini et al. developed a multiscale pore network model, *Transport in Porous Media,* 2021.



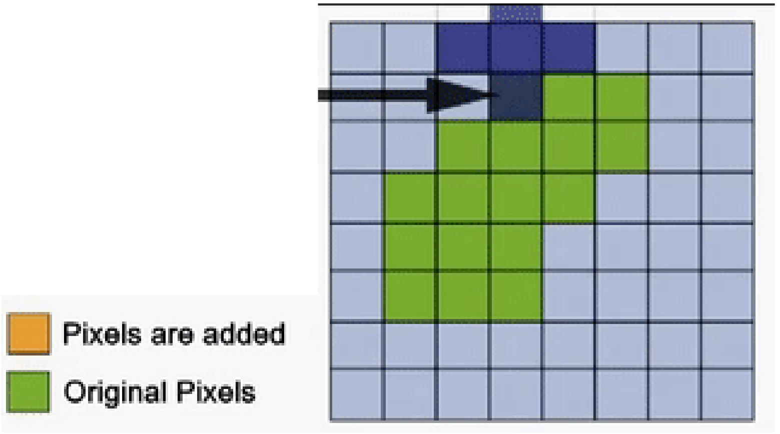
Mehmani and Prodanović., *Advances in Water Resources*, 2011.

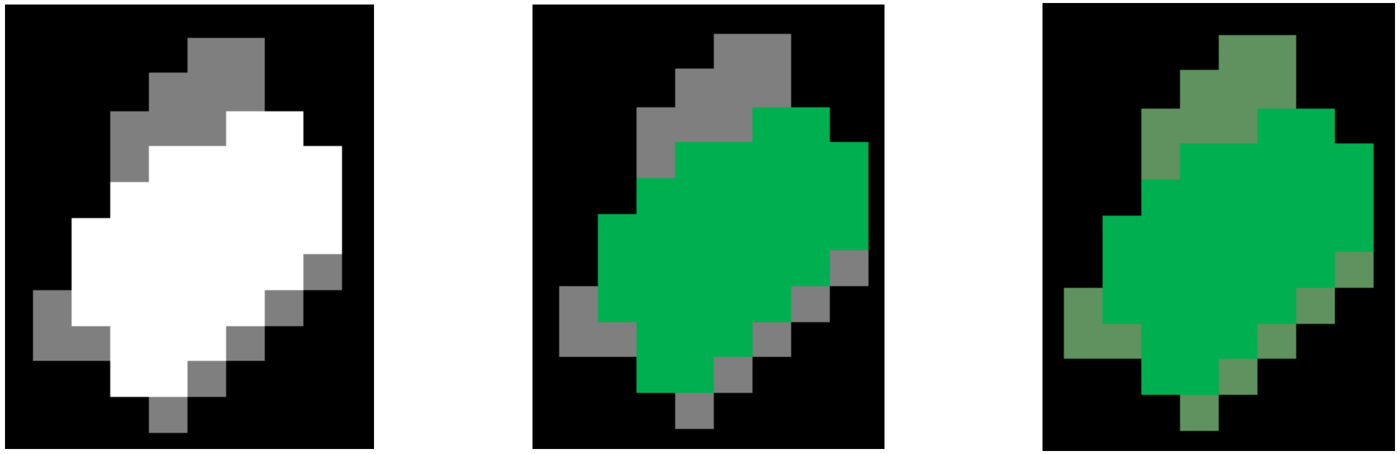
Differences compared to previous work in this area

- An automatic algorithm has been used to detect the micro-links based on a voxel-by voxel porosity map from micro-porosity derived from differential imaging. Micro-porosity is used to detect the possible connection between macro-network pores. Physical properties such as length, volume and conductivity will be assigned to these links.
- Empirical models will be used to characterise unresolved porosity instead of nanometre level scanning. This empirical model give us the opportunity to consider different wettability systems.
- We can model cases where the macro-porosity has no connectivity and allow flow across the network in micro-porosity only.

Workflow

- Assign the nearest two pores to each voxel containing micro-porosity in the image based on a automatic dilation algorithm.





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Workflow

- Assign the nearest two pores to each voxel containing micro-porosity in the image based on a automatic dilation algorithm.
- Based on the differential imaging results and previous step results assign micro-porous regions to micro-throats.
- Based on average porosity and volume of the region assign conductivity and volume to each micro-throat.
- Provide average macroscopic properties to micro-throats: volume and conductance as a function of imposed capillary pressure.
- Modify the flow model to consider a network with micro-throats.

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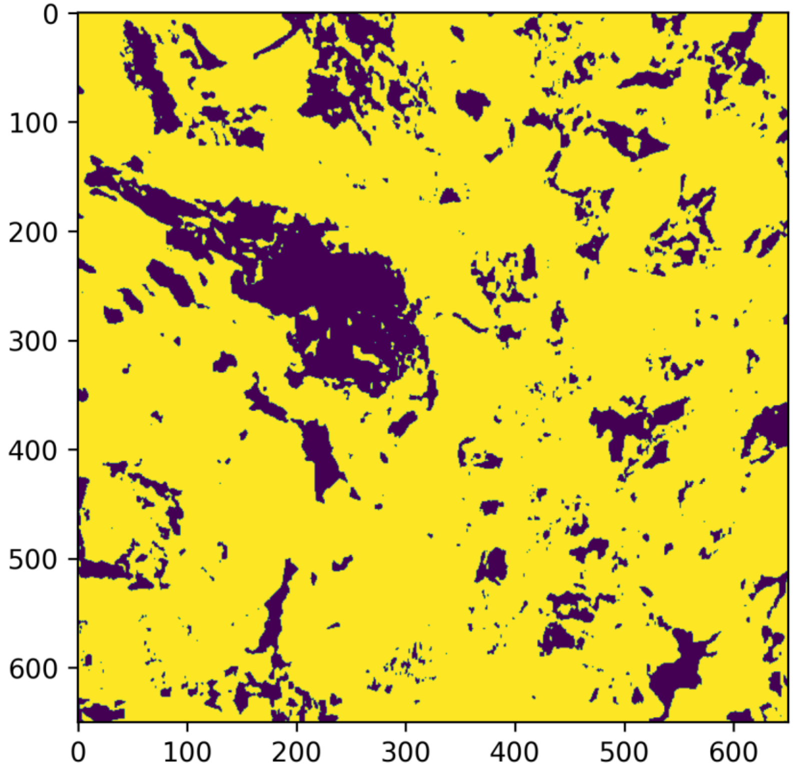
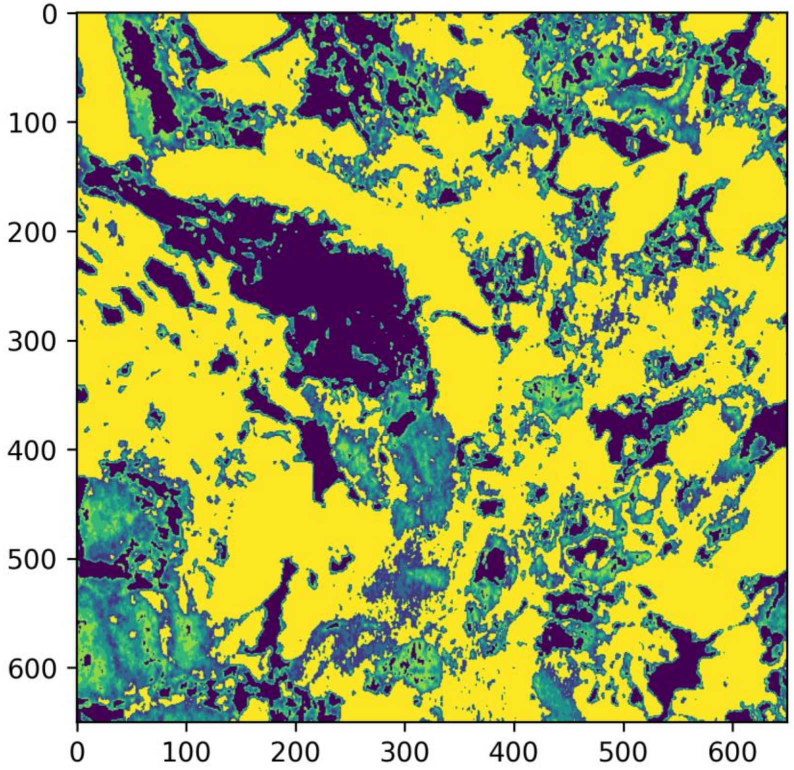
Assessment of micro-porosity in an Estaillades Sample



Pore structure used for pore network extraction

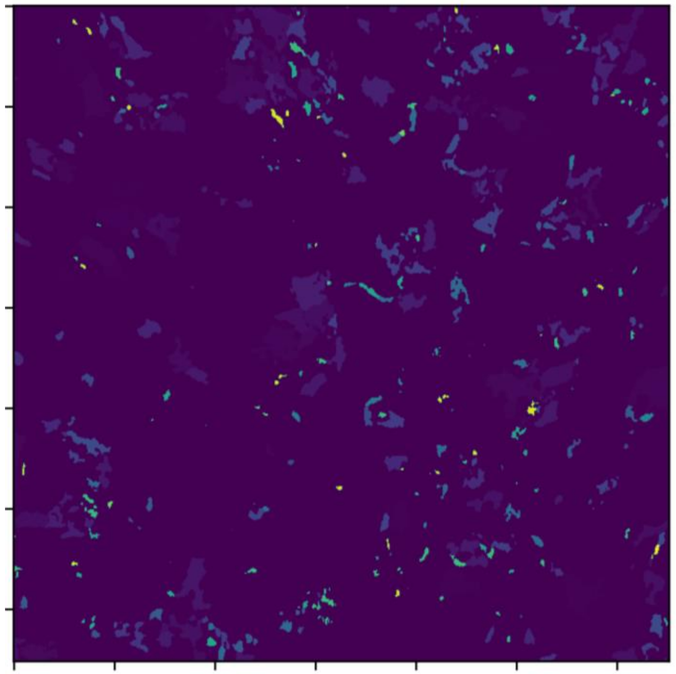


Micro-porosity results obtained from differential imaging

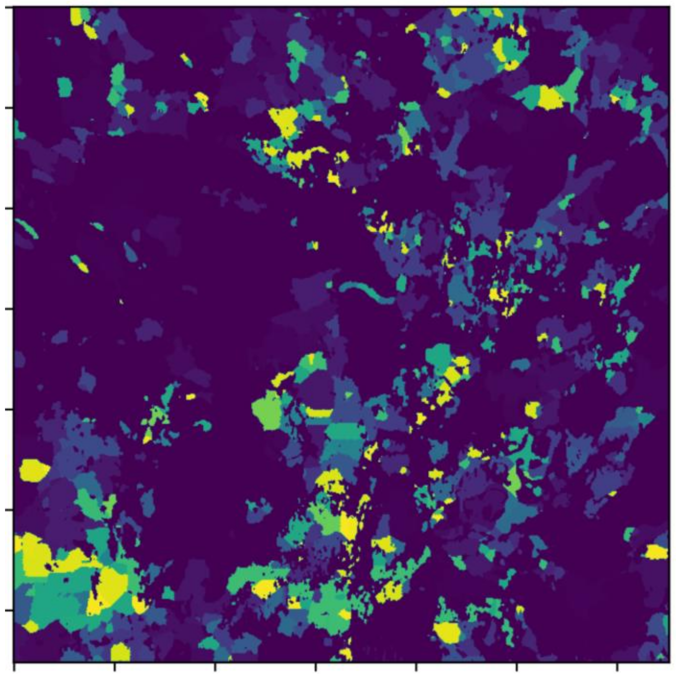
Characterizing micro-porosity as throats

- Detection of two nearest pores to each micro-porous voxel based on a dilation process.

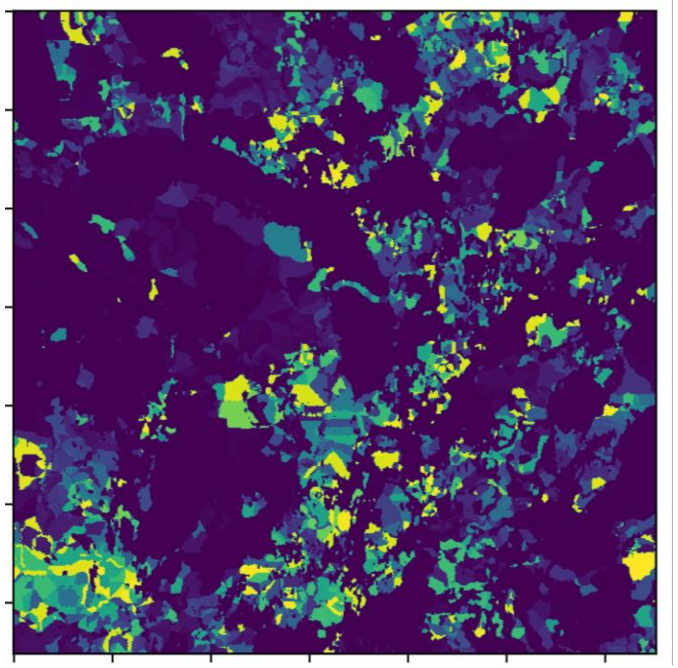
- These maps help us detect properties of the micro-link shared between two pore indices (if it exists).



Pore number map obtained from pore network extraction



Nearest pore label to each micro-porous voxel is identified.



Next nearest pore label to each micro-porous voxel is identified.

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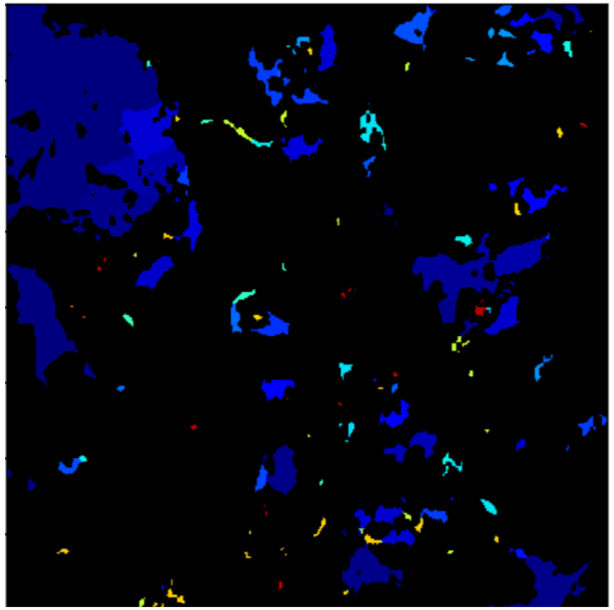
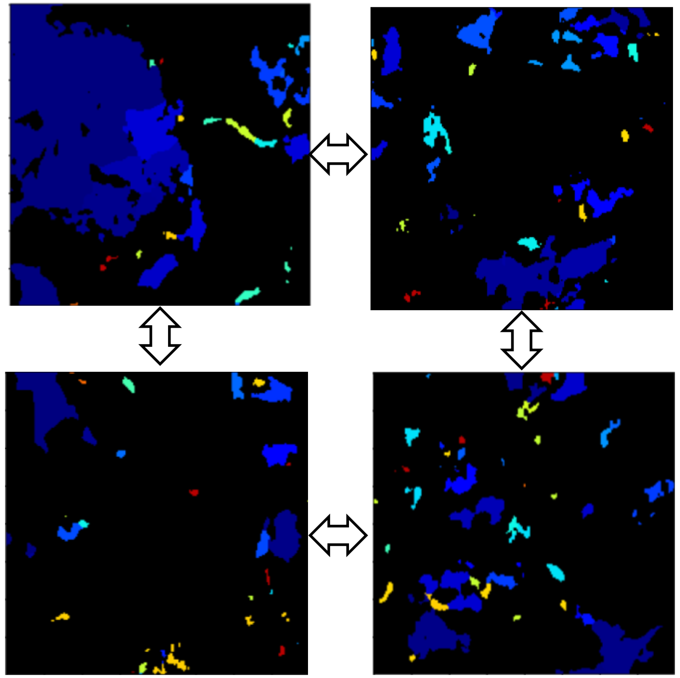
Challenge in characterisation of micro-links for large sample

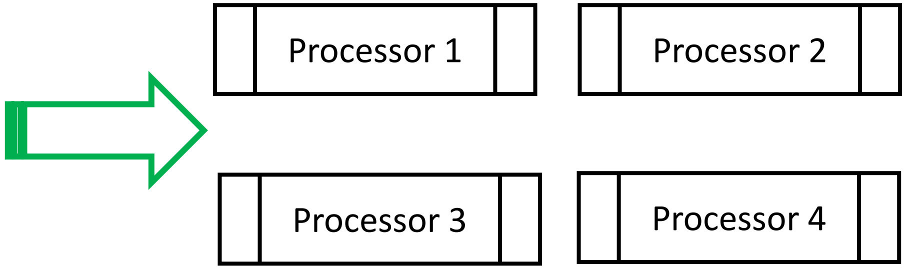
The process of micro-link characterisation would become computationally challenging both in terms of **computational speed** and **memory** management for large samples.

- Dilation algorithm is time consuming and requires speed up. The dilation algorithm is a recursive process in which pore label is transferred to neighbouring microporous voxels iteratively. As this process is local, increasing computational speed is possible by **parallel computation.**





For my workstation with 32 threads the computational time can be decreased by factor of 32!



Challenge in characterisation of micro-links for large sample

- Another challenging step is memory management for finding micro-links based on two microporous pore labels from the dilation step. As finding all micro-links for the whole image in one step is not possible due to **memory restrictions**, we do this process **sequentially** and in each step a part of whole image has been selected. **In this way we can manage up to 2000 cubed images and more.**

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Micro-link characterisation

Each micro-porous voxel that has two assigned pore numbers *i* and *j* has label $l_{i,j}$. The summation of volume of these voxels give us the micro-link, $l_{i,j}$, volume. mpv stands for micro-porous voxel.

Micro-link Volume	$V_{l_{i,j}} = \sum V_{mpv}^{k}$
Micro-link Cross sectional Area	$A_{l_{i,j}} = \frac{V_{l_{i,j}}}{D_{i,j}}$
Micro-link porosity	$\phi_{l_{i,j}} = \frac{\sum \phi_{mpv}^{k}}{N}$
Permeability based on Carman-Kozeny	$k = \frac{1}{180} \frac{d_g^2 \phi^3}{(1-\phi)^2}$

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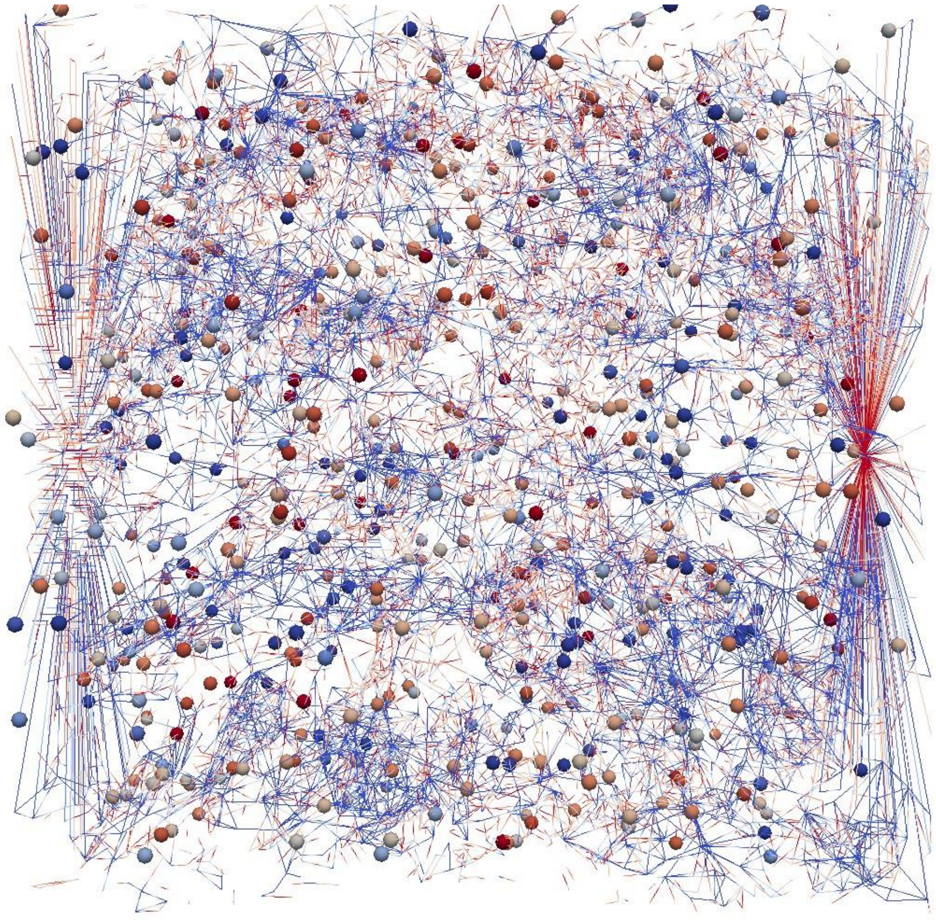
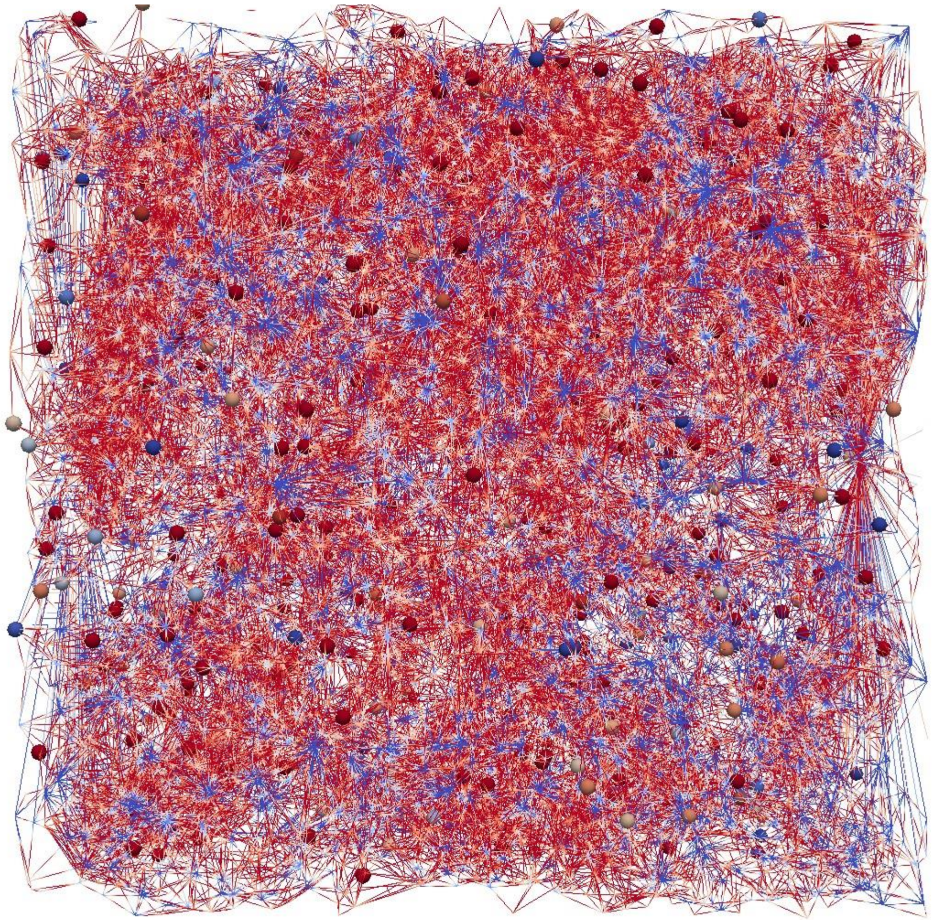
Multiscale network topology by including micro-links



No. Pores: 15672,   No. throats: 17884

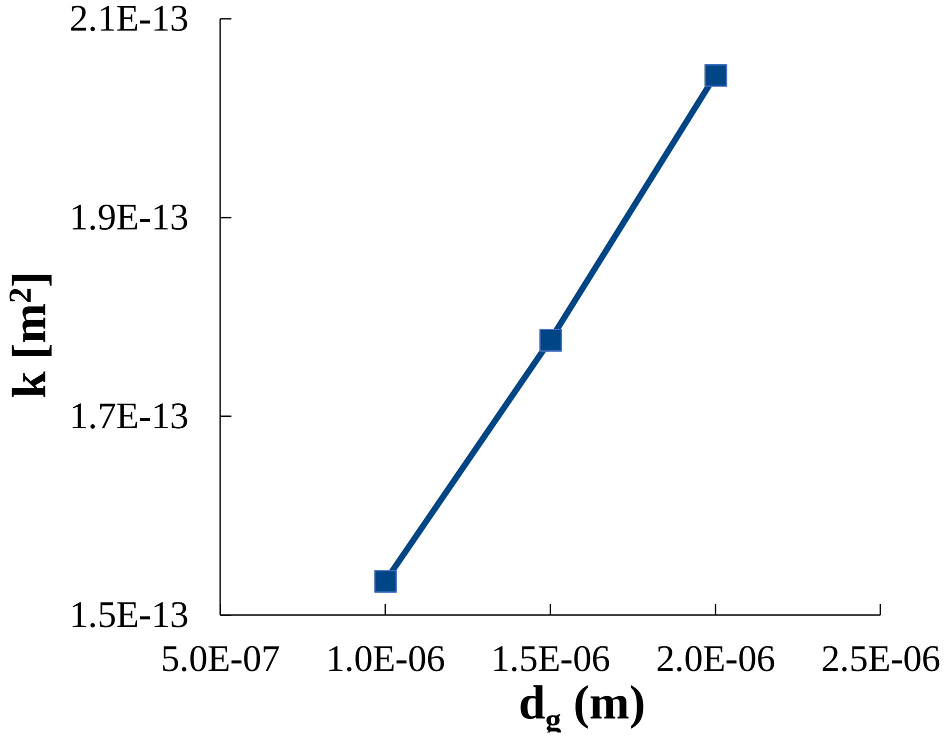


After adding 78995 micro-links

Single phase flow results (the Estaillades Sample)

For micro-links the permeability which is calculated from the Kozeny-Carman equation is imported from the file. In our modelling d_g is a matching parameter.

	Porosity	Permeability (m^2)	Formation Factor
Network based on macro-porosity	0.125	1.23×10^{-13}	227
Micro-porosity incorporated network	0.293	1.70×10^{-13}	114
Direct modeling	-	$2.06\pm0.43\times10^{-13}$	-
Experiment	0.293	$1.75\pm0.11\times10^{-13}$	-



Bijeljic et al., *arXiv:1807.07611, Multimodal Functions as Flow Signatures in Complex Porous Media*

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Two-phase flow modelling

For two-phase flow modelling we need to assign the capillary pressure and relative permeability for micro-links. For this purpose we use empirical equations in the literature.

For capillary pressure we use the Leverett J-function, power-law model and our recently-developed model for all wettabilities (Foroughi et al., 2022) and for relative permeability we use the Corey model:

$$P_c(S_w) = J(S_w)\frac{\sigma \cos\theta}{\sqrt{k/\phi}}$$

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Two-phase flow modelling

Parameter	Equation	Used model
Leverett j-function	$P_c = \frac{J(S_w)\sigma}{\sqrt{k/\phi}}$	-
Assumed analytical relation for J	$J(S_w) = J_0 S_e^A$	$J(S_w) = 0.25 \times S_e^{-1}$
Normalized saturation	$S_e = \frac{S_w - S_{wi}}{1 - S_{wi}}$	$S_{wi} = 0$
Corey model for water rel. perm.	$k_{rw} = k_{rwMax} S_e^{nw}$	$k_{rw} = S_e^2$
Corey model for oil rel. perm.	$k_{ro} = k_{roMax}(1 - S_e)^{no}$	$k_{ro} = 0.9 \times (1 - S_e)^{2.5}$
Archie model for resistivity Index	$R_t = \frac{1}{S_w^n} \frac{aR_w}{\phi^m}$	$R_t = \frac{1}{S_w^n} \frac{R_w}{\phi^{1.9}}$

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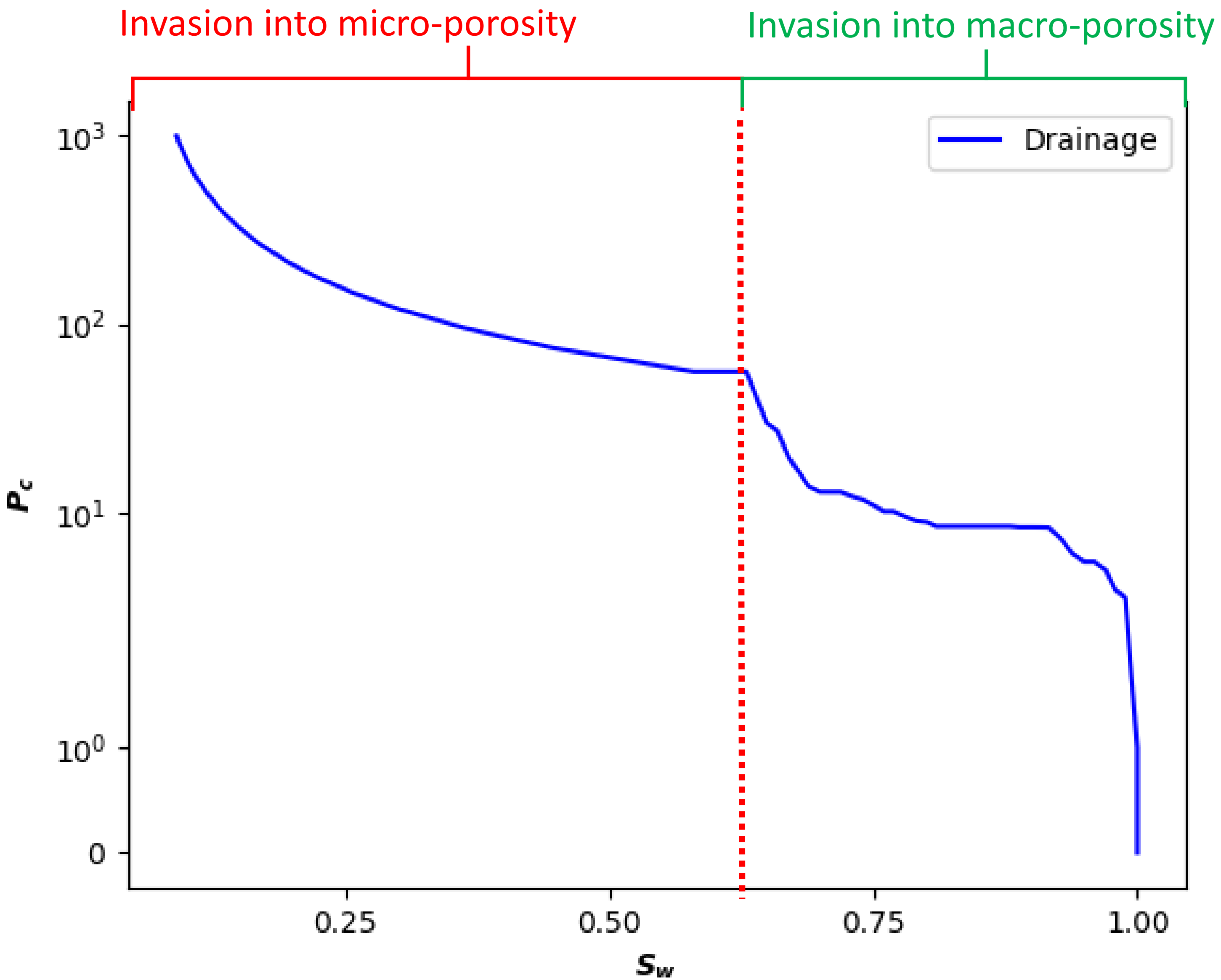
Capillary pressure for primary drainage

J_0 = 0.25

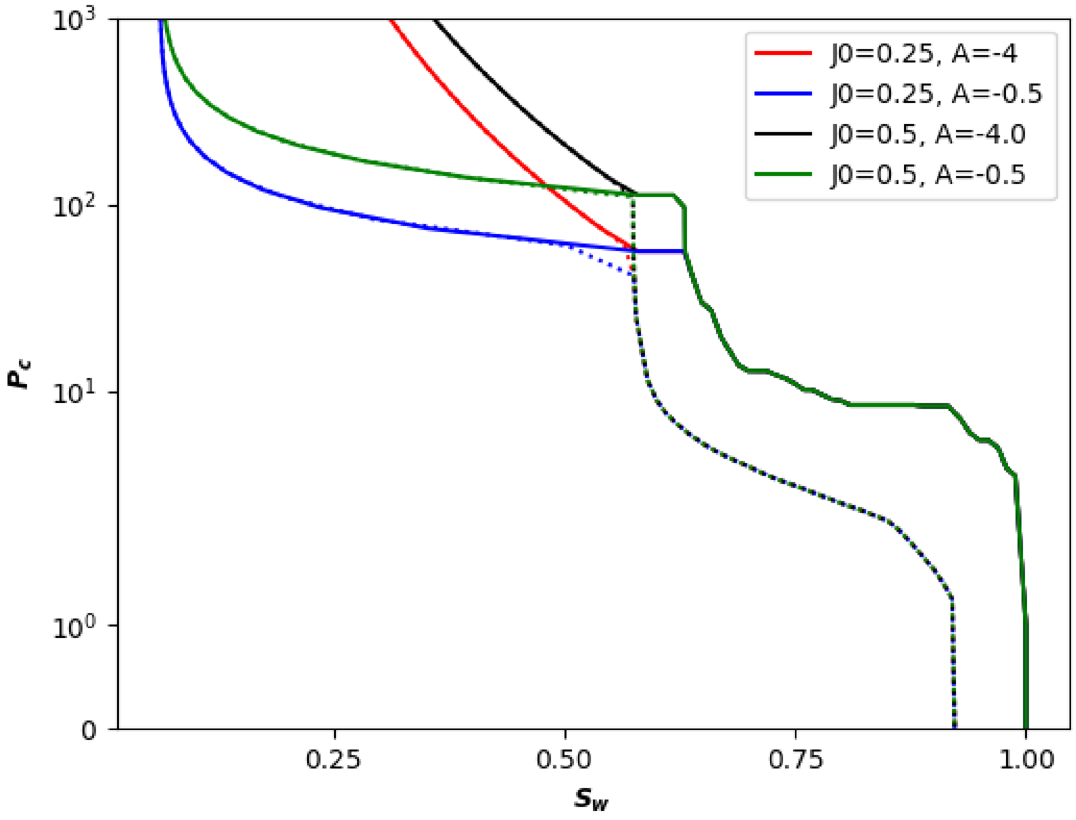
A = −1

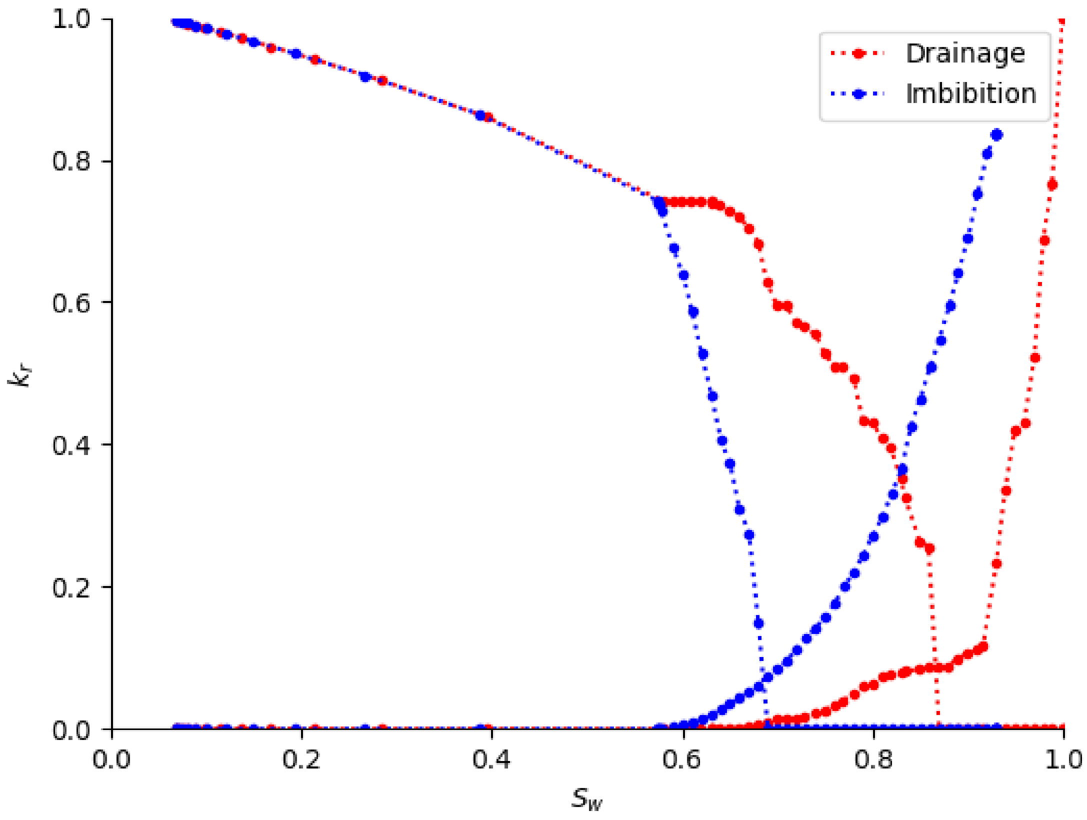
$$J(S_w) = J_0 S_e^A$$



Capillary pressure for primary drainage and imbibition

Capillary pressure results for both drainage and imbibition. Same Leverett J-function for both drainage and imbibition (no hysteresis). Relative permeability results for one set of parameters reported.





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Capillary pressure models and limitations

Brooks and Corey model:

$$S_e = \frac{S_w - S_{wi}}{1 - S_{or} - S_{wi}} \qquad P_c = P_{ct}(S_e)^{\frac{1}{\lambda}}$$

Van Genuchten model:

$$P_c = 1/\alpha \left(S_e^{-1/m} - 1\right)^{1-m}$$

These two models are restricted to water-wet systems. A power law model by Skjaeveland et al. 2000 presented for mixed-wet system:

$$P_c = c_w/S_e^{a_w} + c_o/(1 - S_e)^{a_o}$$

Limitation: it is not possible to explicitly determine saturation from capillary pressure.

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A closed form expression proposed for capillary pressure

"*A Closed-form Equation for Capillary Pressure in Porous Media for All Wettabilities*"

published in *Transport in Porous Media*

$$S_e = \frac{S_w - S_{wi}}{1 - S_{or} - S_{wi}} \qquad P_c = A + B\, tan\left(\frac{\pi}{2} - \pi S_e^C\right)$$

$$S_e = \left(\frac{1}{\pi}\left(\frac{\pi}{2} - \tan^{-1}\frac{P_c - A}{B}\right)\right)^{1/C}$$

This model can match different capillary systems range(from water-wet, mixed-wet and oil-wet).

Also saturation can be obtained explicitly from capillary pressure.

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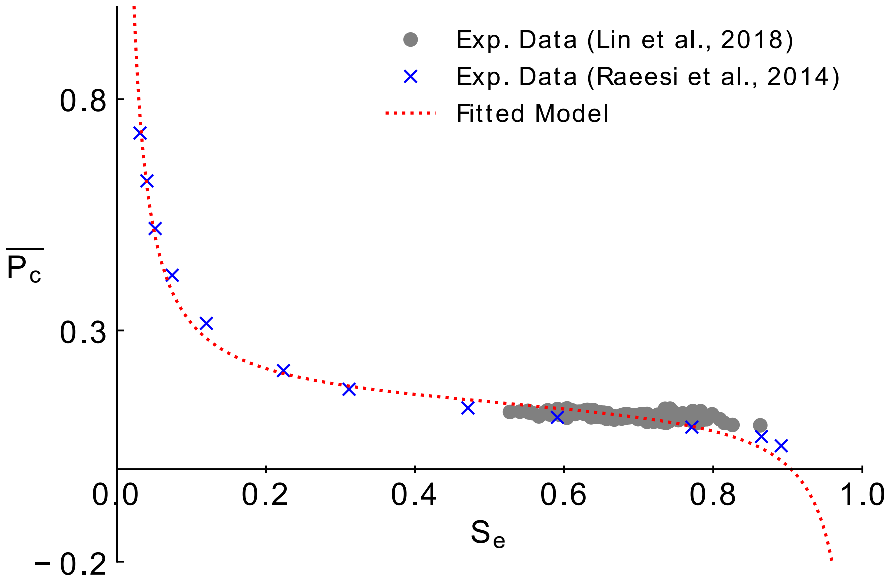
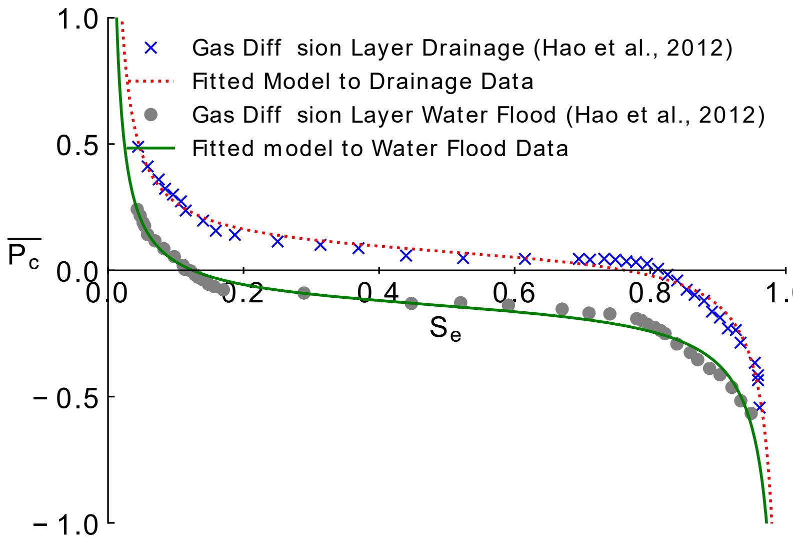
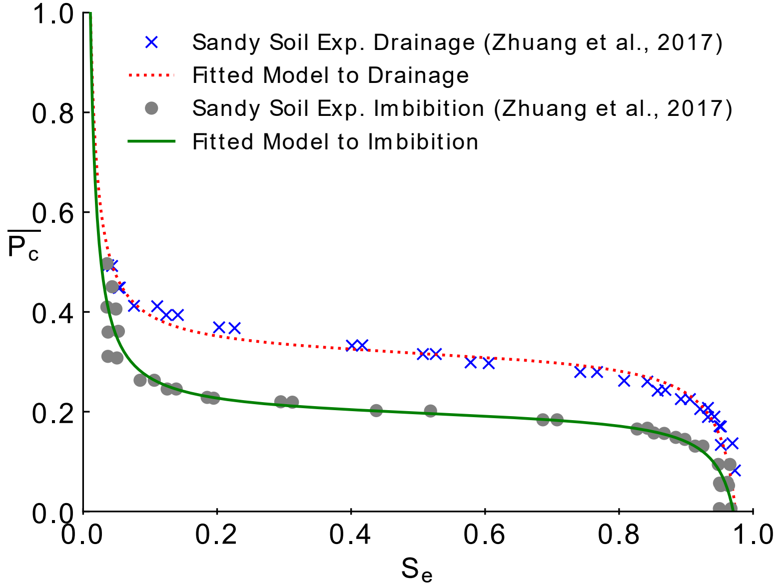
Fitting the proposed model to the experimental data (water-wet, oil-wet, and mixed-wet)

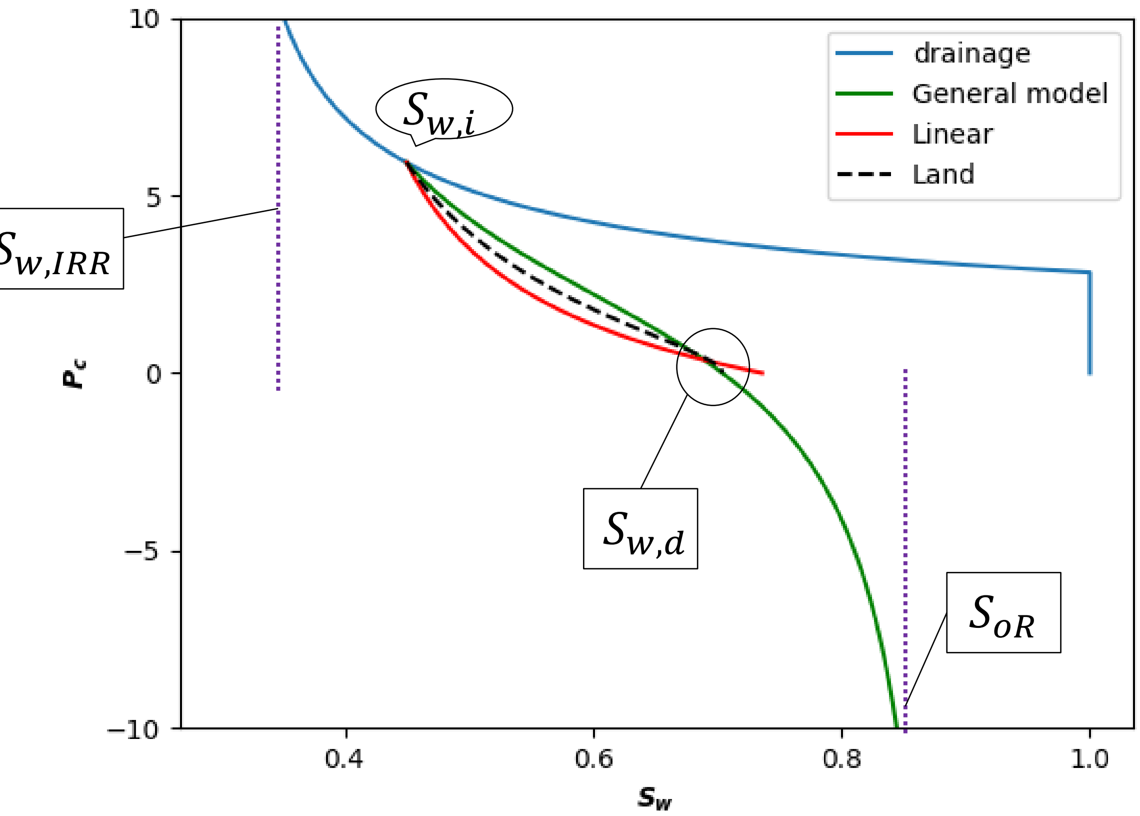
The model is matched accurately to **29 datasets** in the literature for **water-wet**, **mixed-wet** and **hydrophobic** media, including **rocks, soils, bead** and **sand packs** and **fibrous materials** with **over four orders of magnitude** difference in **permeability** and **porosities** from **20%** to nearly **90%**.



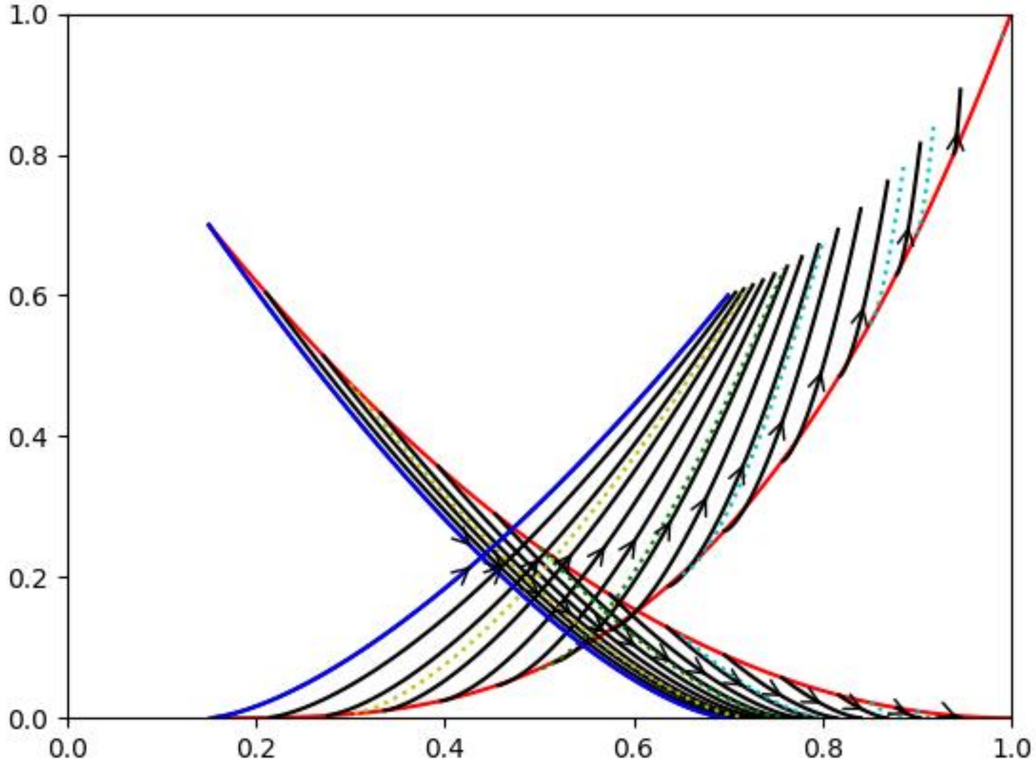




Including hysteresis in the model



$$C_d = \frac{1}{S_{o,d}} - \frac{1}{S_o^{Max}} \qquad C_r = \frac{1}{S_{or}} - \frac{1}{S_o^{Max}}$$



Scanning curves obtained based on Killough model

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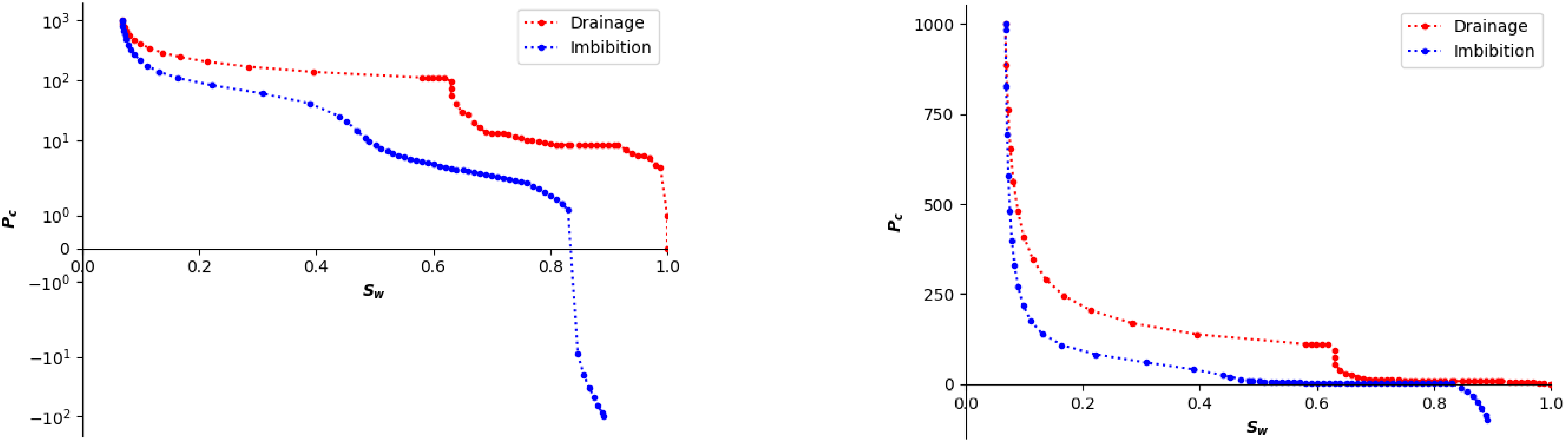
Capillary pressure for primary drainage and waterflooding including hysteresis (WW)



Water-wet system with zero contact angle. S_{wi} = 0.1, S_{or} = 0.1, A = 0.5 , B = -0.5 for Brooks-Corey model and for Killough model α =2.0 and λ=0.9. and Land coefficient C=5.

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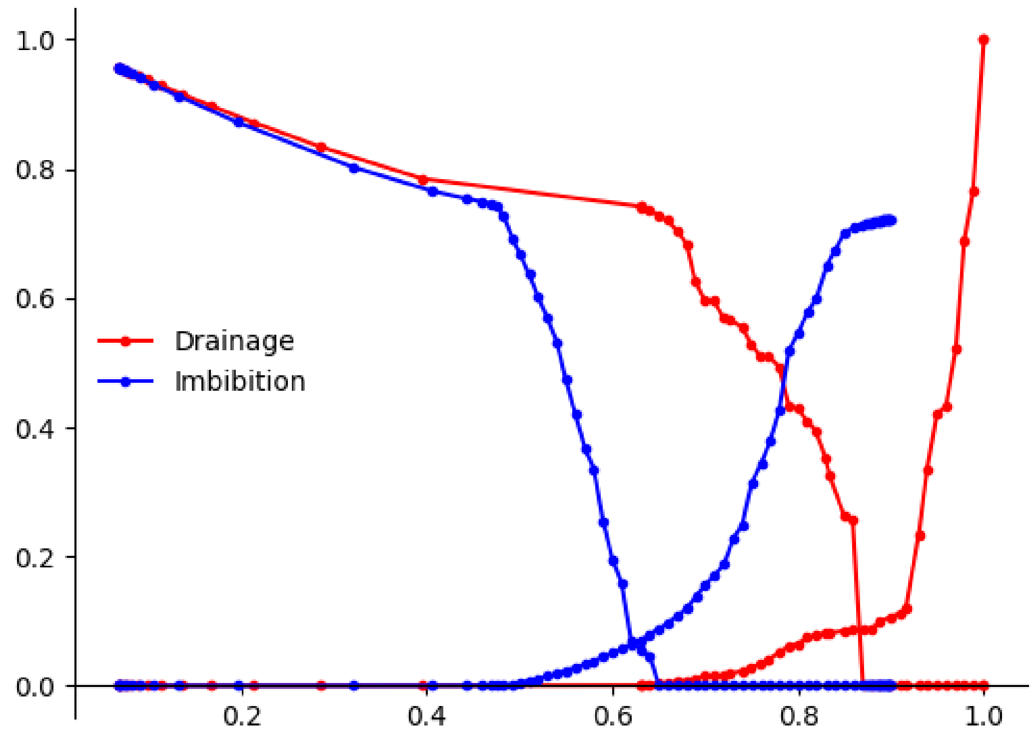
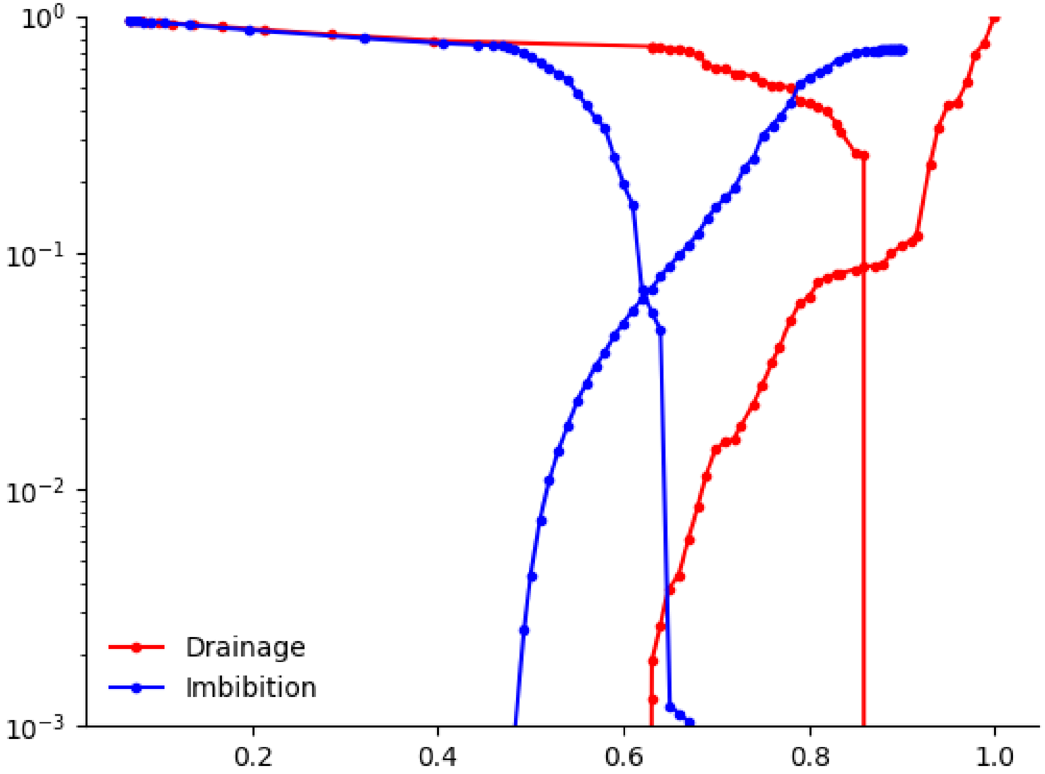
Relative permeability for primary drainage and waterflooding including hysteresis





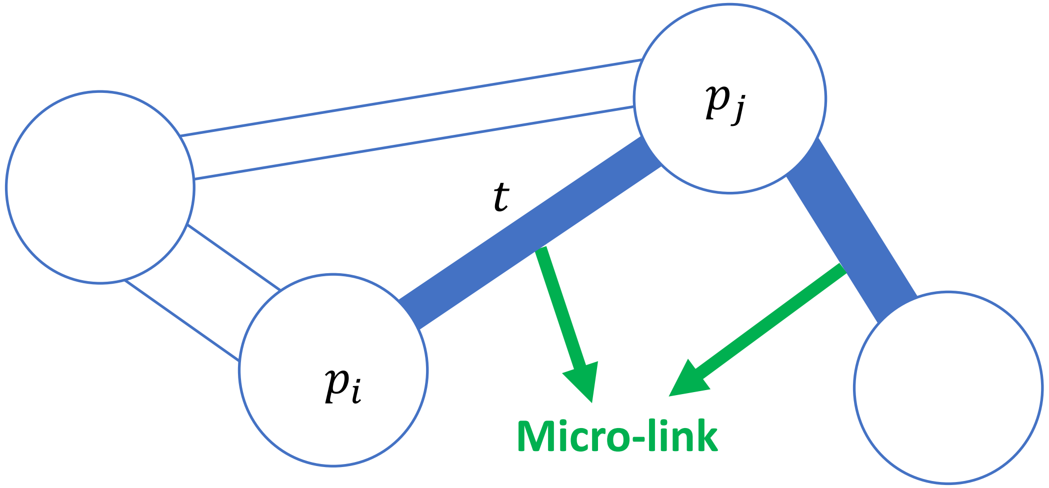
Flow between two micro-links with a macro-pore in between

How do we deal with micro-porosity containing one phase, while the pore contains another phase? Need to allow flow across micro-porous links, bypassing the pores. Critical in the sample where the macro-pore space is not connected.

We need to consider this in our model. For this purpose the conductivity between pore i and j is defined as follows:

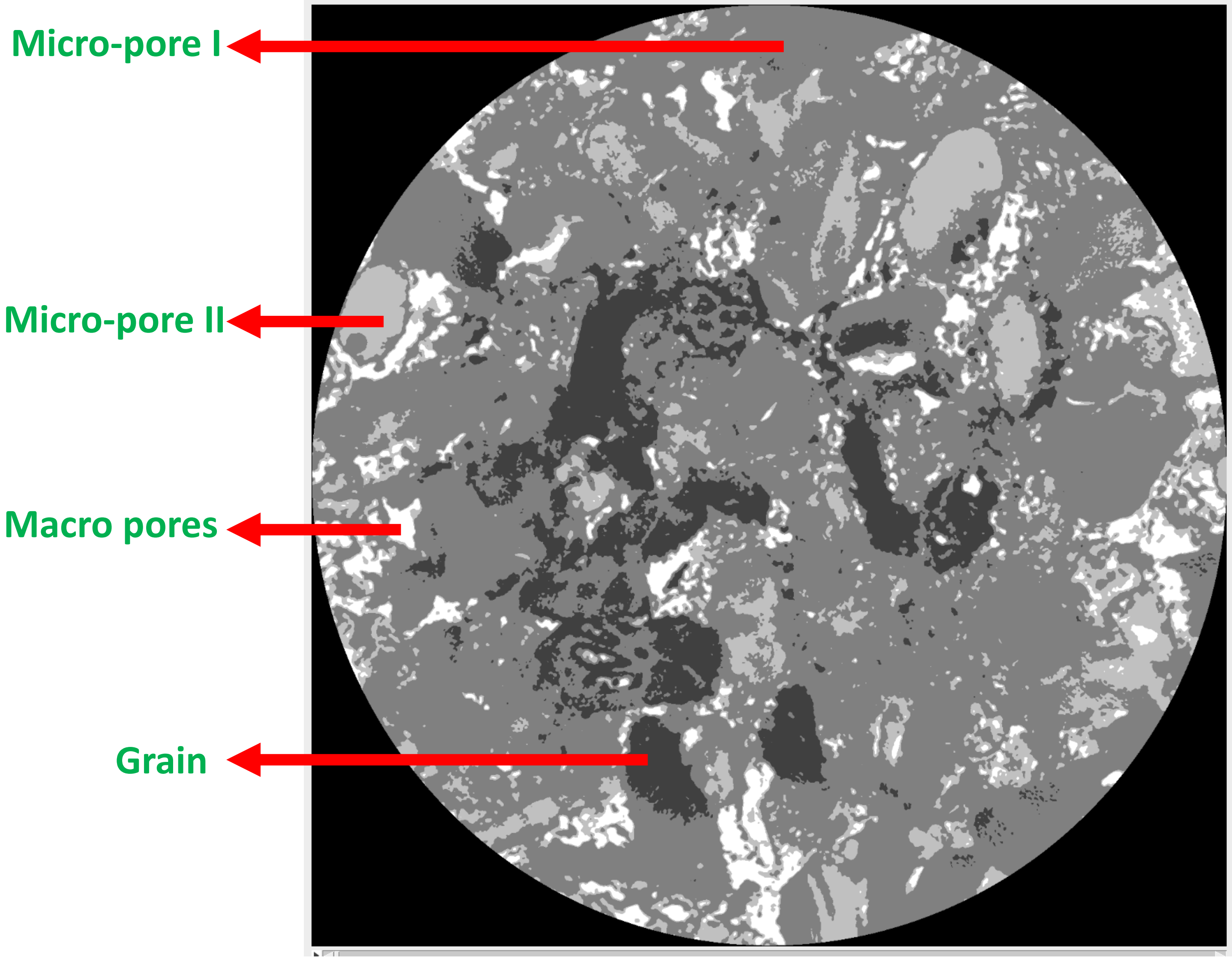
$$\frac{L_{ij}}{g_{p,ij}} = \min\left(\frac{L_i}{g_{p,i}} + \frac{L_t}{g_{p,t}} + \frac{L_j}{g_{p,j}}, \frac{L_j + L_i + L_t}{g_{p,t}}\right)$$

This relation has been used for both flow and electrical conductivity



Estaillades water-wet sample by Gao et al. [2020]

- Sample porosity is $28.4 \pm 0.5\%$
- Macro-pores is 6.9%
- Micro-porosity (unresolved) is 21.5%
- Sample size $1582 \times 1582 \times \ 2789$
- Voxel size $3.58\ \mu m$
- **Macro-pores are not connected**
- **Different sample and image than the test case previously presented.**
- $Ca \ = \ 7.3 \times 10^{-6}$
- Permeability $1.06 \pm 0.02 \times 10^{-13}\ m^2$
- Micro-pore I has 0.568 volume fraction with porosity 0.260.
- Micro-pore II has 0.096 volume fraction with porosity 0.70.



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Conclusions and Future work

- Including micro-porosity in the pore network model leads to correct saturation and pore volume.
- Also it is essential to improve our prediction of connectivity and permeability. Furthermore it has important effect on accessibility to elements of network.
- A new closed-form model for capillary pressure has been proposed that can work for all type of wettability.
- Consider flow though micro-porosity by modifying the conductivity term.
- Sensitivity analysis on effect of micro-porosity in pore network modelling
- We will continue to apply this methodology along with our wettability optimization workflow to our datasets including **Estaillades (by Gao, 2020 and Lin, 2021) and a reservoir sample (Yihuai Zhang)**.

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Acknowledgments

We gratefully acknowledge funding from the **Shell Digital Rocks** program at Imperial College London.

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Thank you for your attention!