



Determining Hydrogen Relative Permeability by a Hybrid Experimental-Pore Scale Modelling Approach

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Shell’s net carbon intensity

Also, in this content we may refer to Shell’s “net carbon intensity” (NCI), which includes Shell’s carbon emissions from the production of our energy products, our ‘suppliers’ carbon emissions in supplying energy for that production and our customers’ carbon emissions associated with their use of the energy products we sell. Shell’s NCI also includes the emissions associated with the production and use of energy products produced by others which Shell purchases for resale. Shell only controls its own emissions. The use of the terms Shell’s “net carbon intensity” or NCI is for convenience only and not intended to suggest these emissions are those of Shell plc or its subsidiaries.

Shell’s net-zero emissions target

Shell’s operating plan and outlook are forecasted for a three-year period and ten-year period, respectively, and are updated every year. They reflect the current economic environment and what we can reasonably expect to see over the next three and ten years. Accordingly, the outlook reflects our Scope 1, Scope 2 and NCI targets over the next ten years. However, Shell’s operating plan and outlook cannot reflect our 2050 net-zero emissions target, as this target is outside our planning period. Such future operating plans and outlooks could include changes to our portfolio, efficiency improvements and the use of carbon capture and storage and carbon credits. In the future, as society moves towards net-zero emissions, we expect Shell’s operating plans and outlooks to reflect this movement. However, if society is not net zero in 2050, as of today, there would be significant risk that Shell may not meet this target.

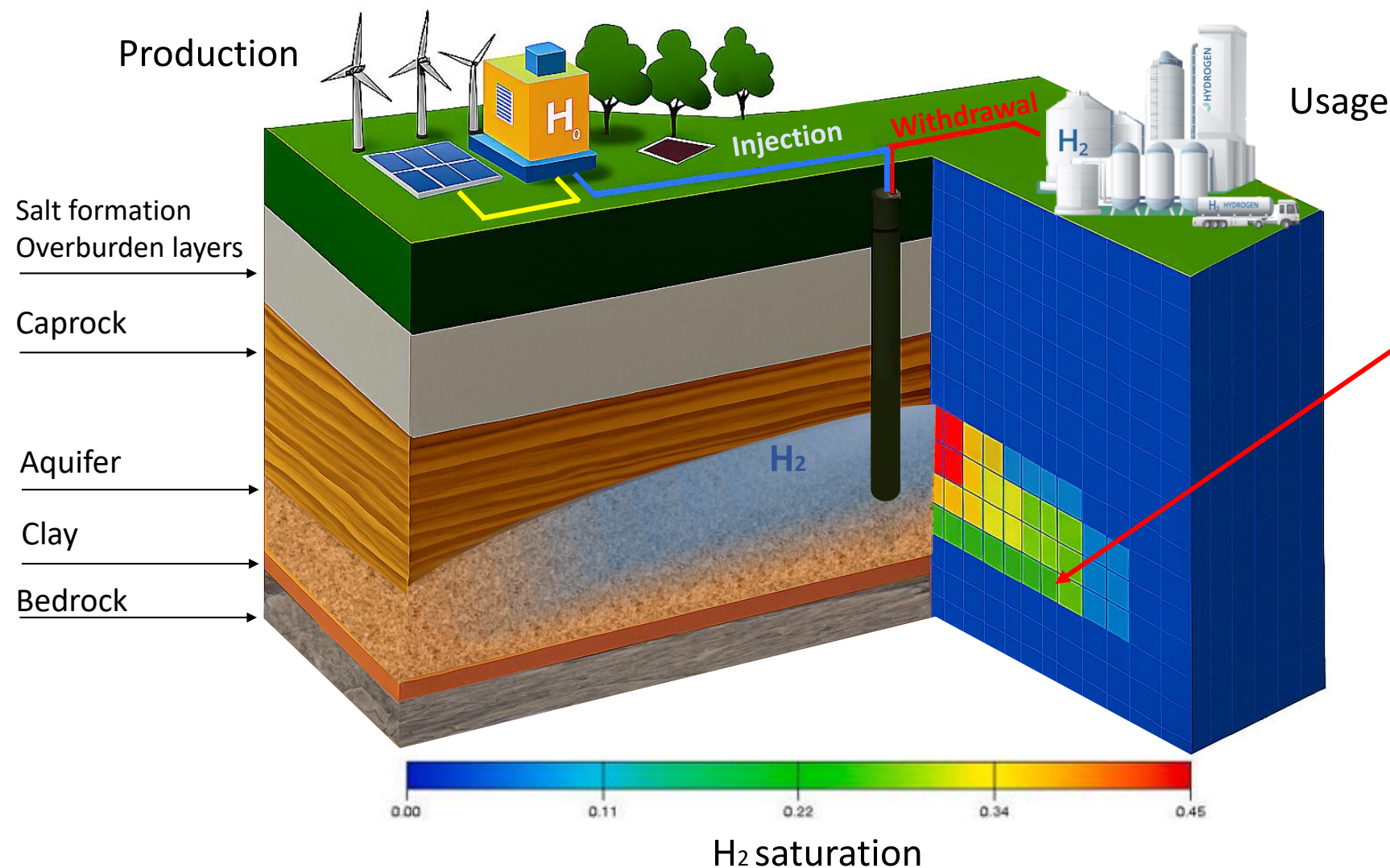
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This content may contain certain forward-looking non-GAAP measures such as adjusted earnings and divestments. We are unable to provide a reconciliation of these forward-looking non-GAAP measures to the most comparable GAAP financial measures because certain information needed to reconcile those non-GAAP measures to the most comparable GAAP financial measures is dependent on future events some of which are outside the control of Shell, such as oil and gas prices, interest rates and exchange rates. Moreover, estimating such GAAP measures with the required precision necessary to provide a meaningful reconciliation is extremely difficult and could not be accomplished without unreasonable effort. Non-GAAP measures in respect of future periods which cannot be reconciled to the most comparable GAAP financial measure are calculated in a manner which is consistent with the accounting policies applied in Shell plc’s consolidated financial statements.

The contents of websites referred to in this content do not form part of this content.

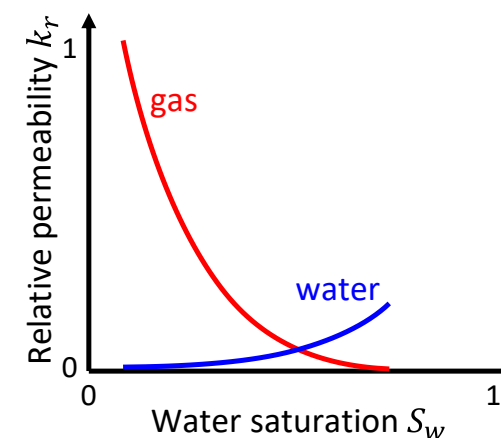
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Underground Storage of Hydrogen

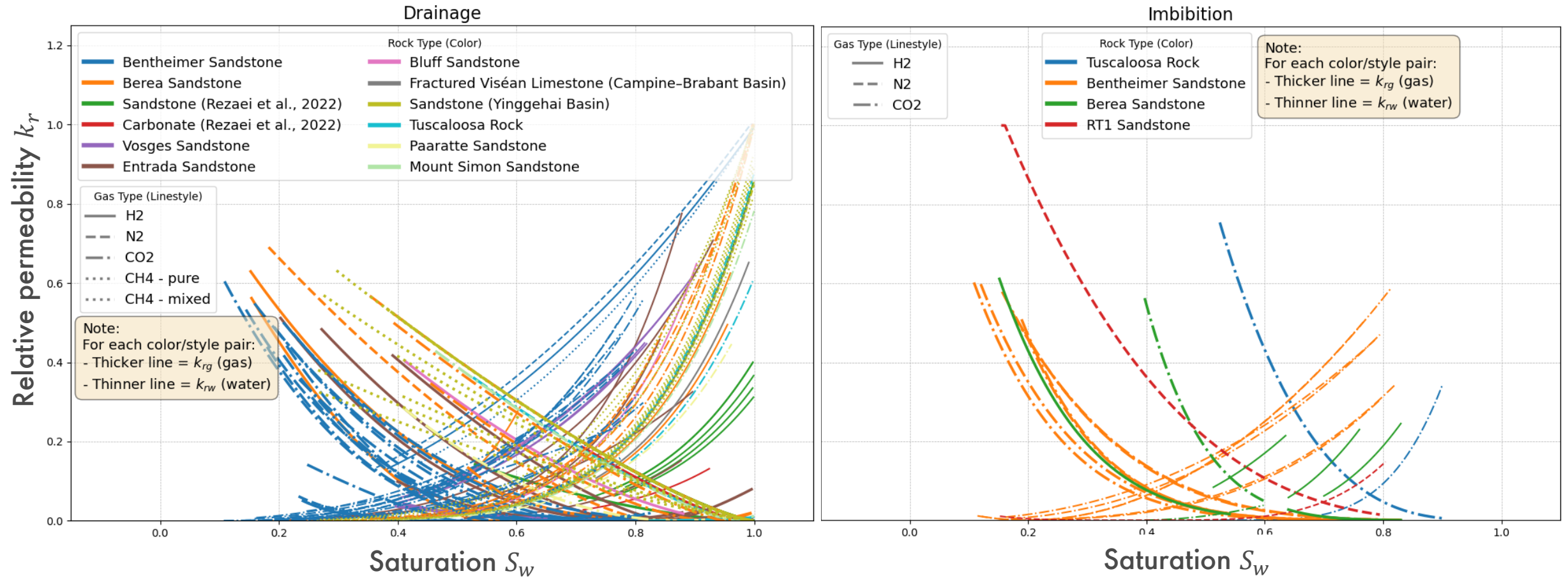


Gridded Reservoir Model

- Porosity ϕ
- Permeability K
- 2-phase flow $v_i = -k_{r,i} \frac{K}{\mu_i} \frac{dp_i}{dx}$
- Relative permeability k_r



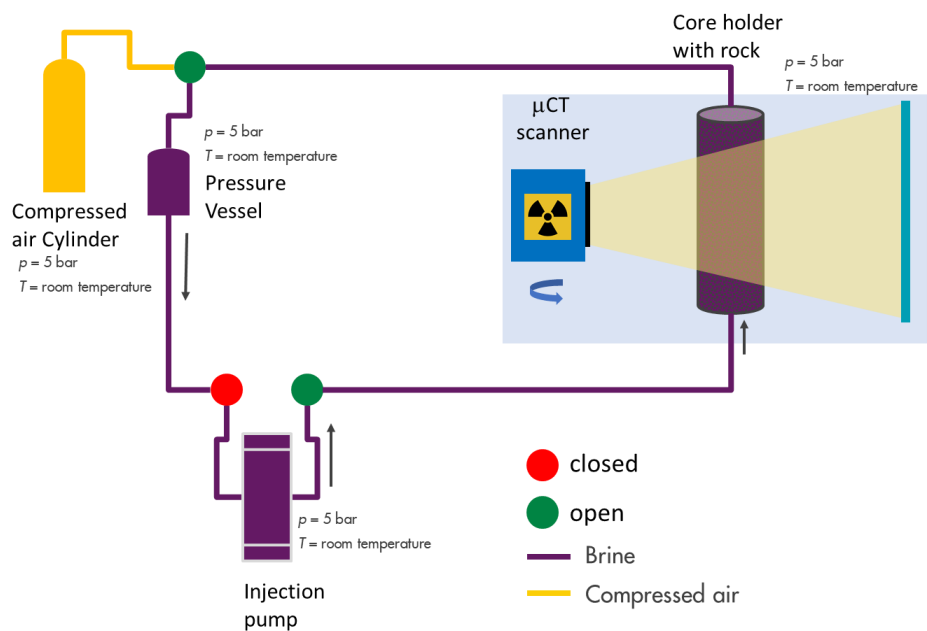
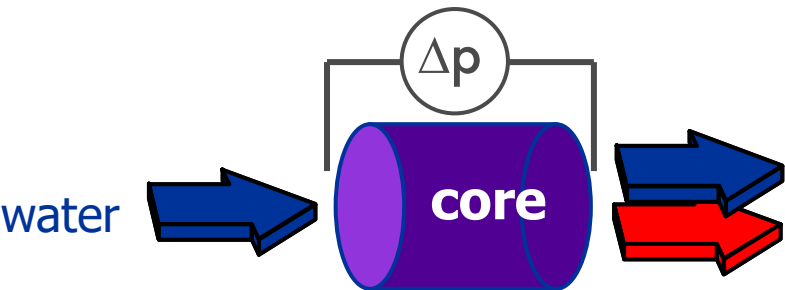
Relative Permeability Data in the Literature



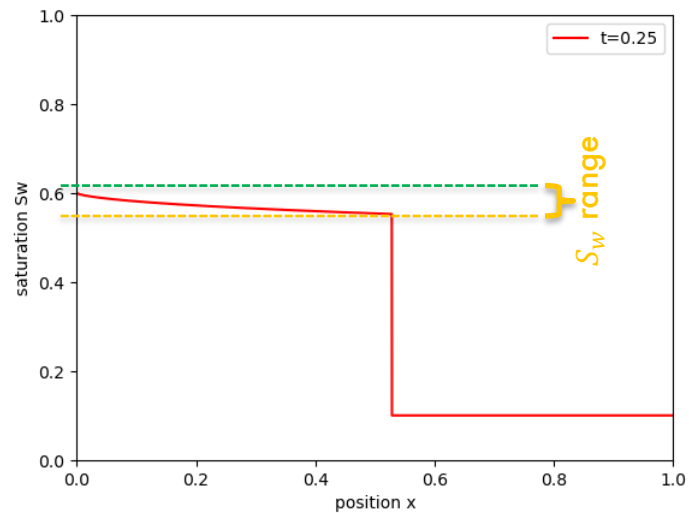
- Inconsistency in protocols → inverse modelling [Core2Relperm](#)
- Limited mobile saturation range

Classical Unsteady-State vs. Micro-CT Flow Experiment

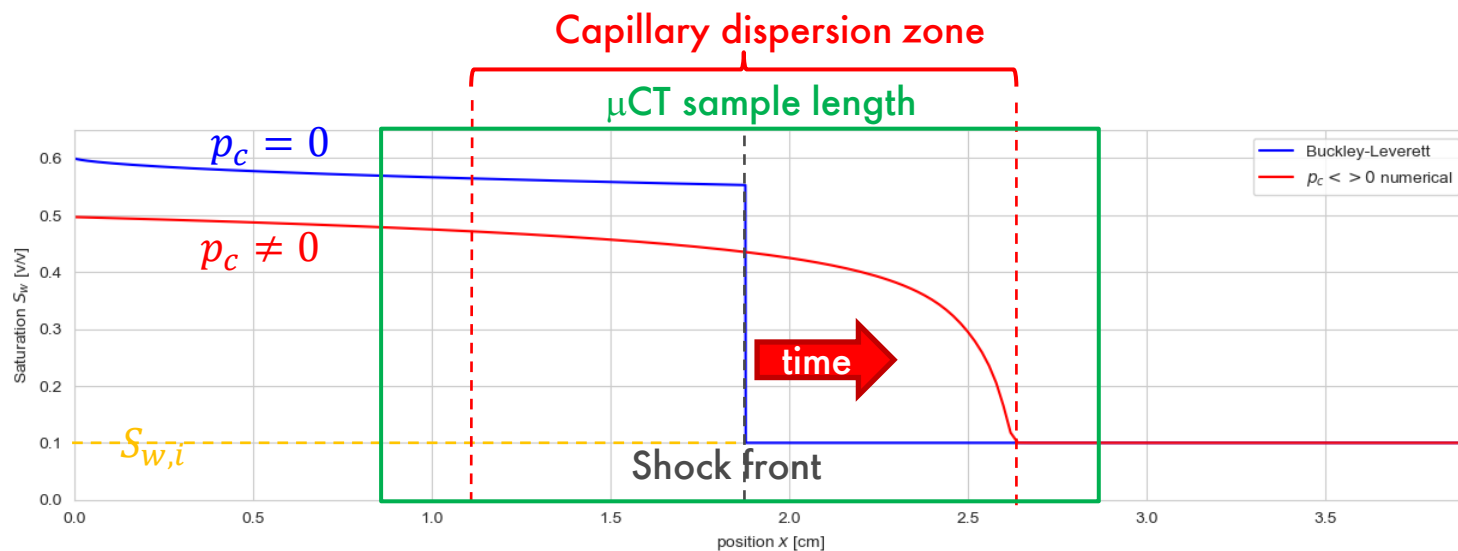
Unsteady-state (USS) Method



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○ Limited mobile saturation range

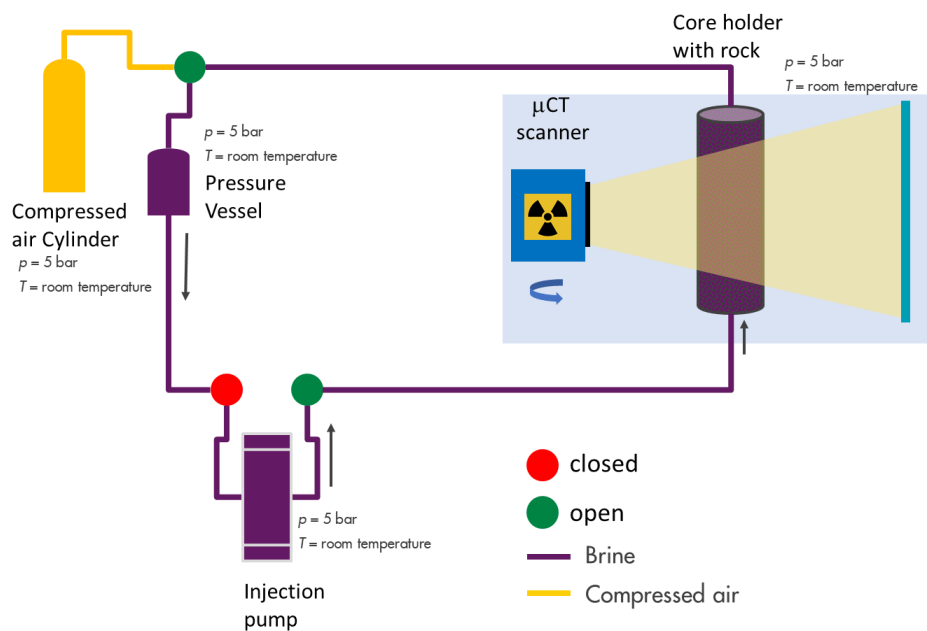
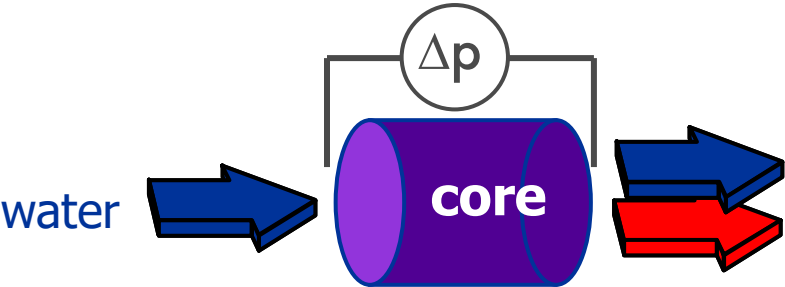


← Conventional USS-SCAL sample length →

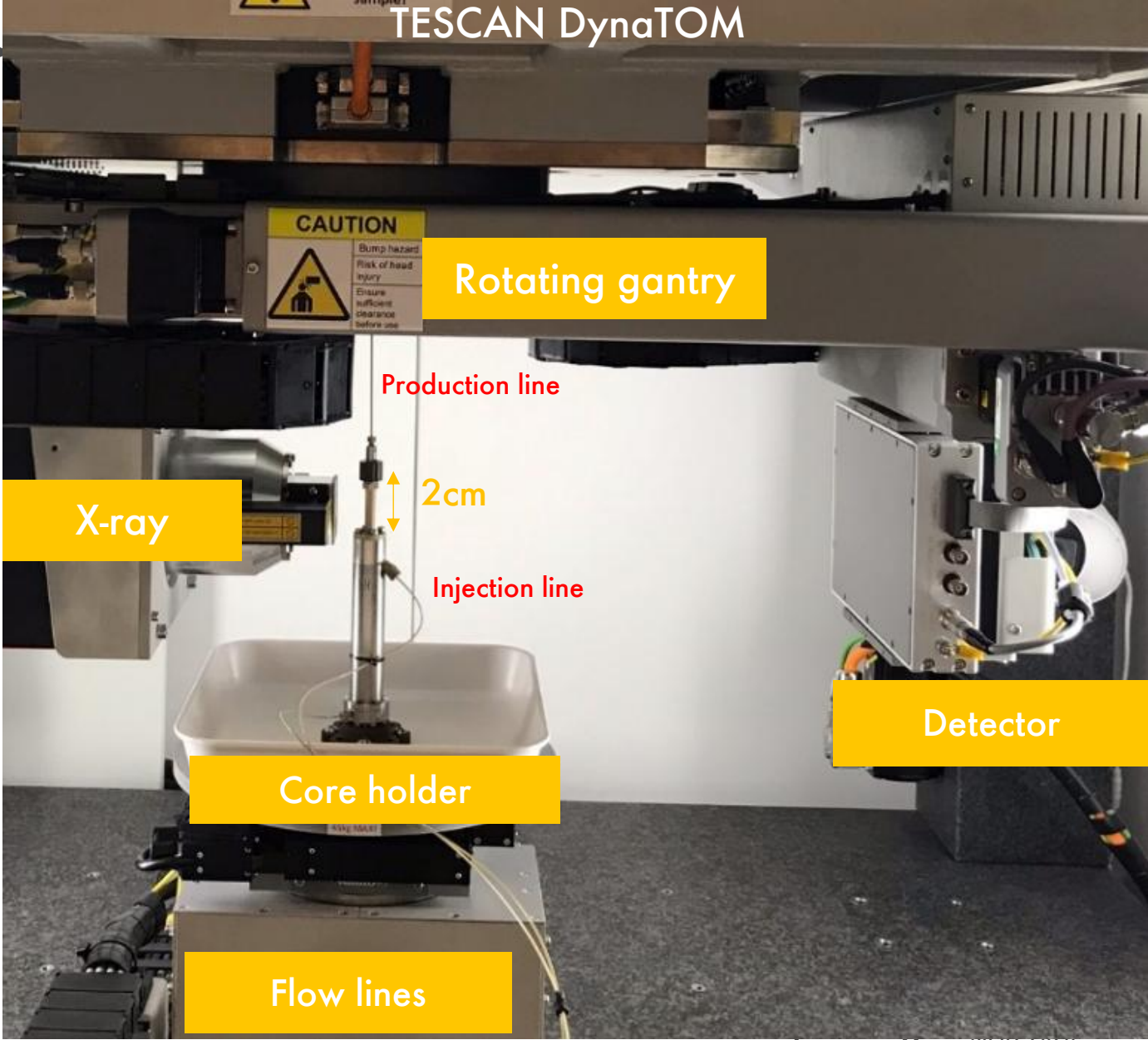
30.09.2026

Classical Unsteady-State vs.

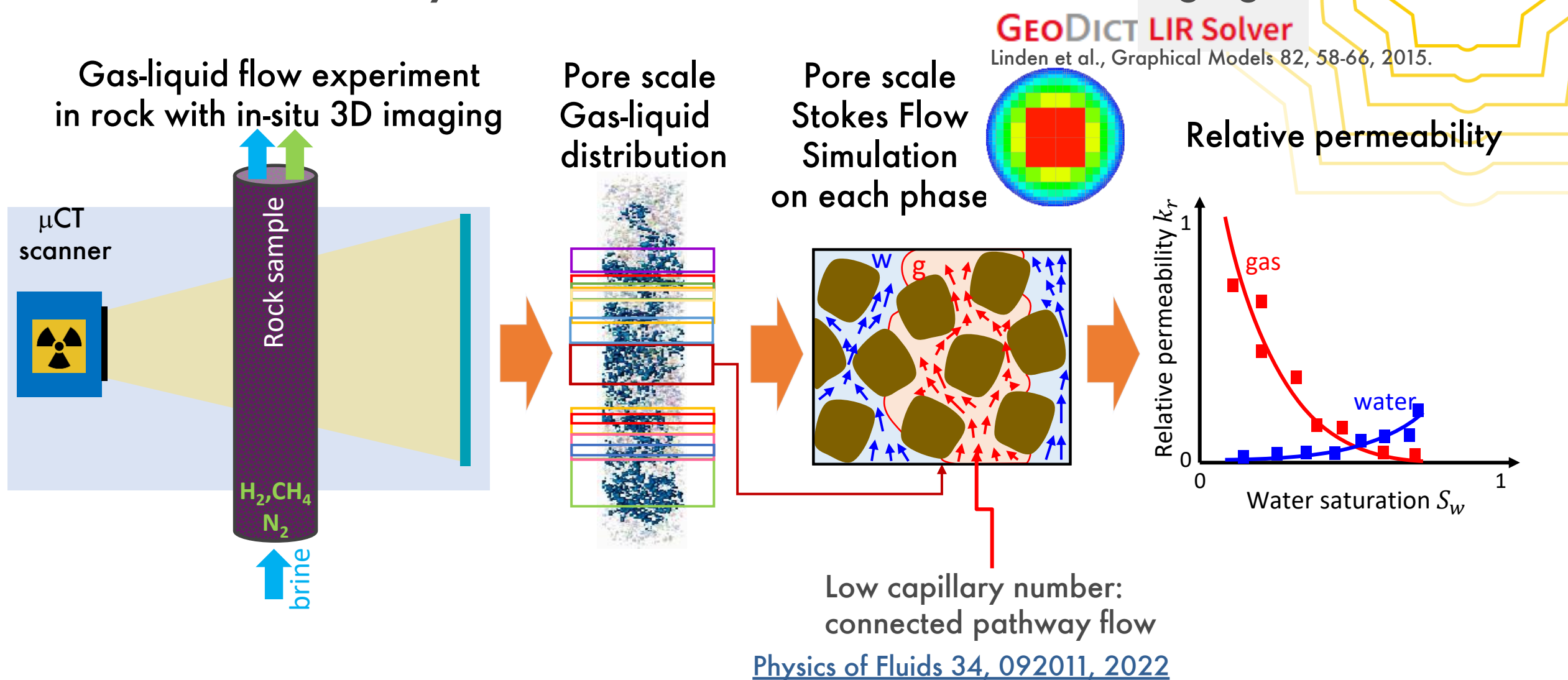
Unsteady-state (USS) Method



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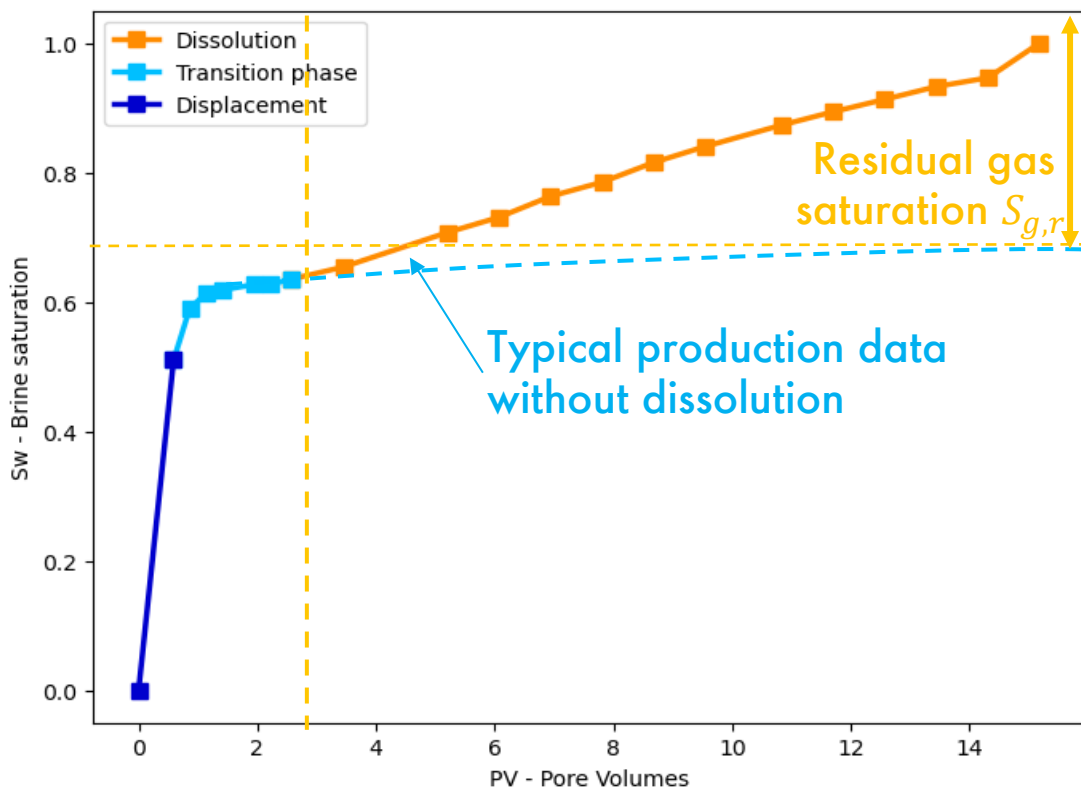
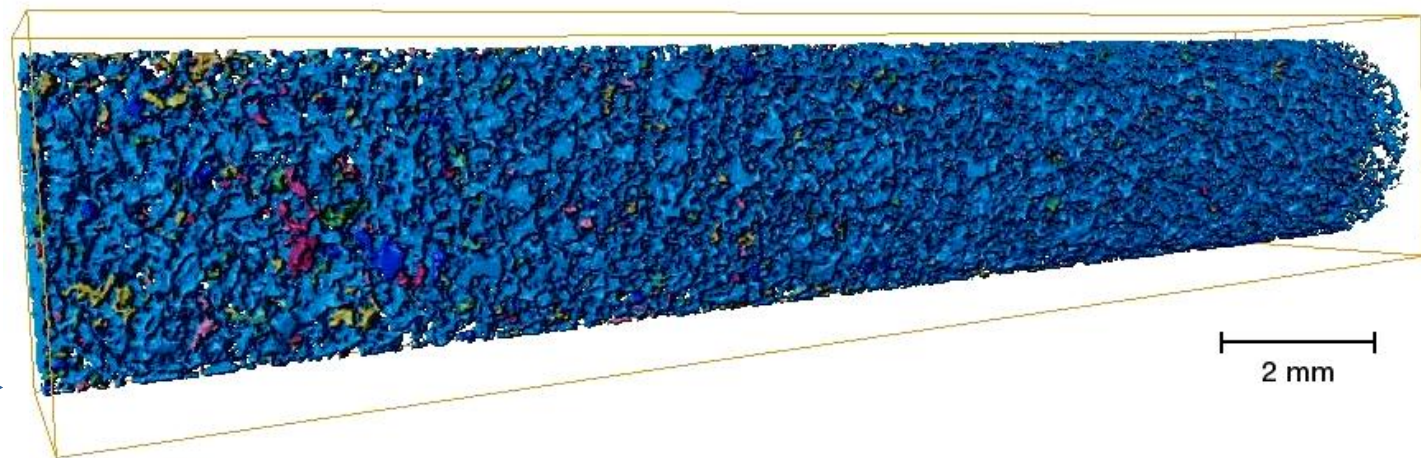
Relative Permeability from Stokes Flow Simulations on Imaging Data



Micro-CT Flow Experiments

Displacement-dominated

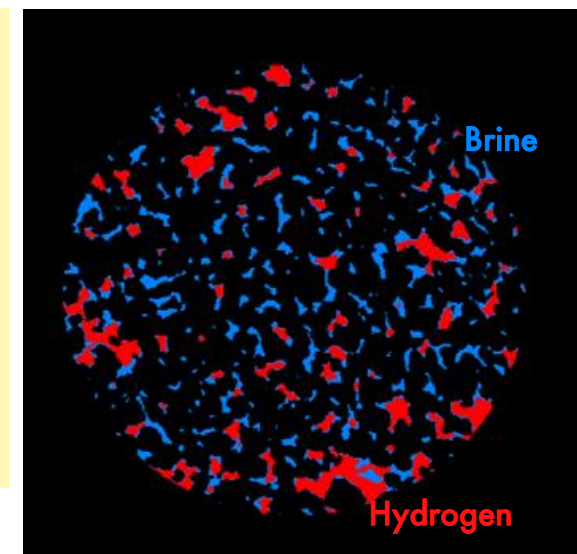
Dissolution-dominated
(caused by ripening)



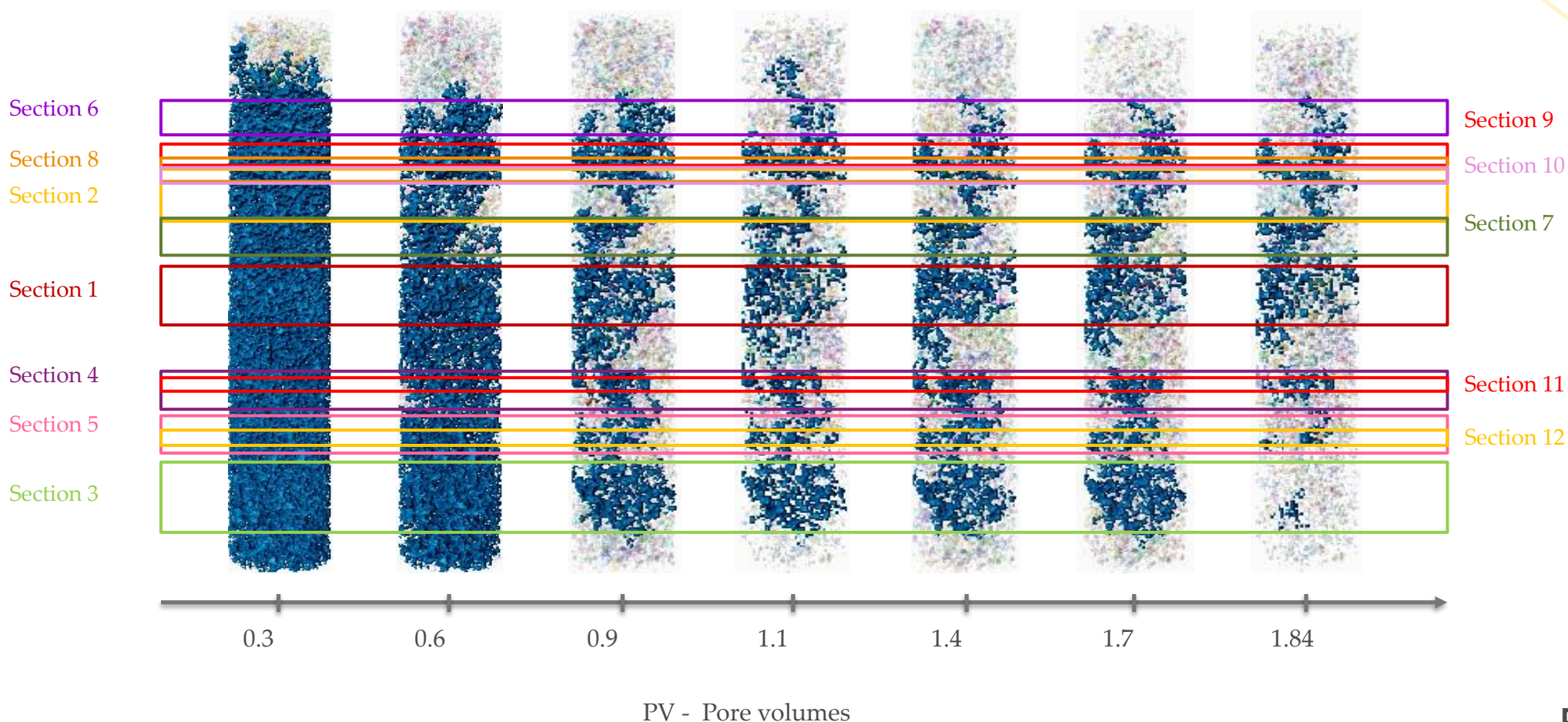
Bentheimer sandstone, 4 mm x 20 mm

4 experiments:

- Compressed air (mainly N₂)
- Methane
- Hydrogen-1, 2 (repeat)

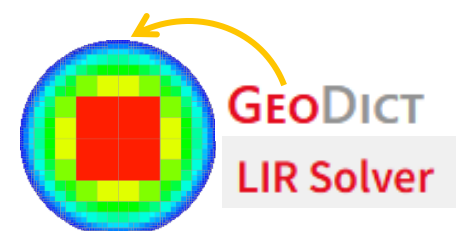
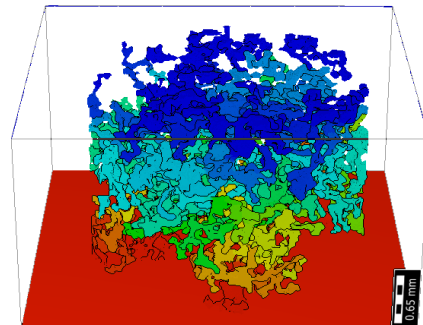


Relative Permeability from Stokes Flow Simulations on Imaging Data



Stokes Flow Sim.

$$-\vec{\nabla} p + \mu \nabla^2 \vec{u} = 0$$

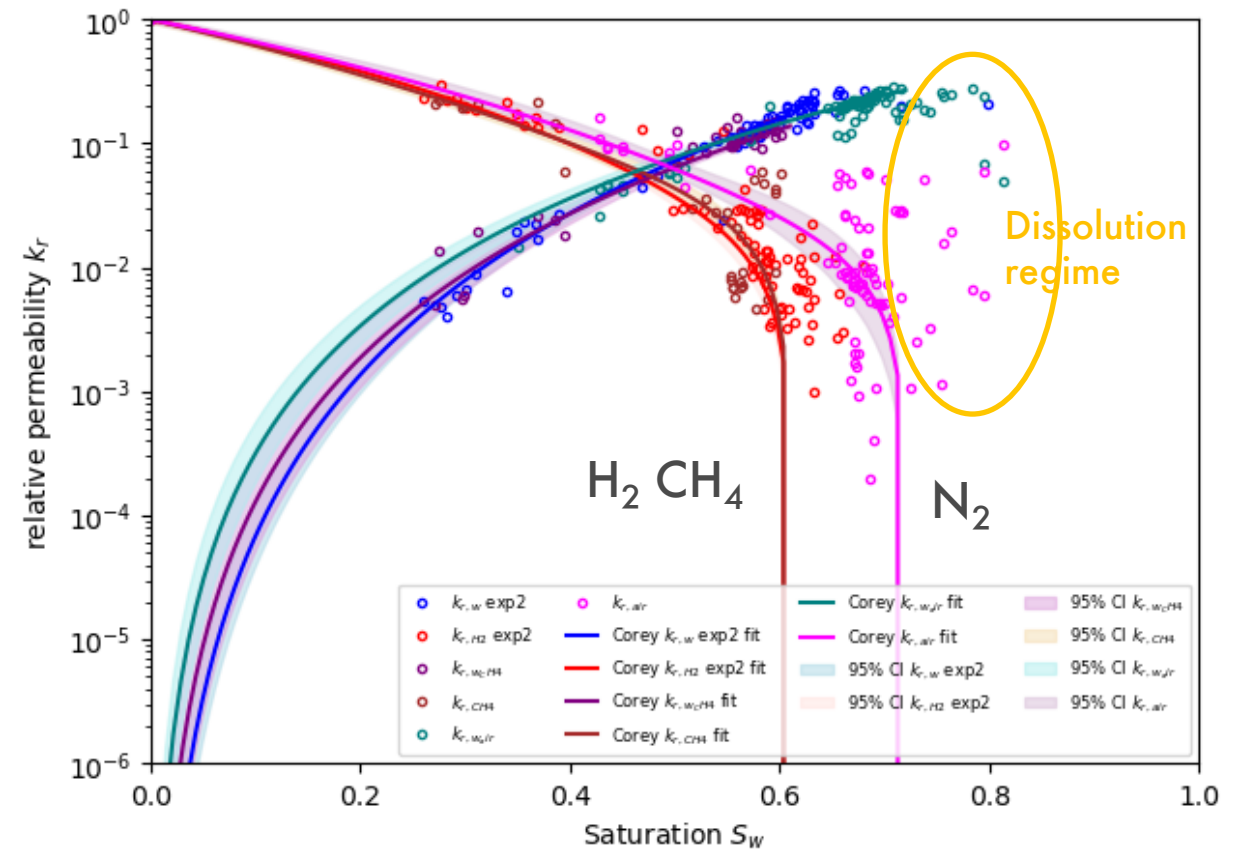
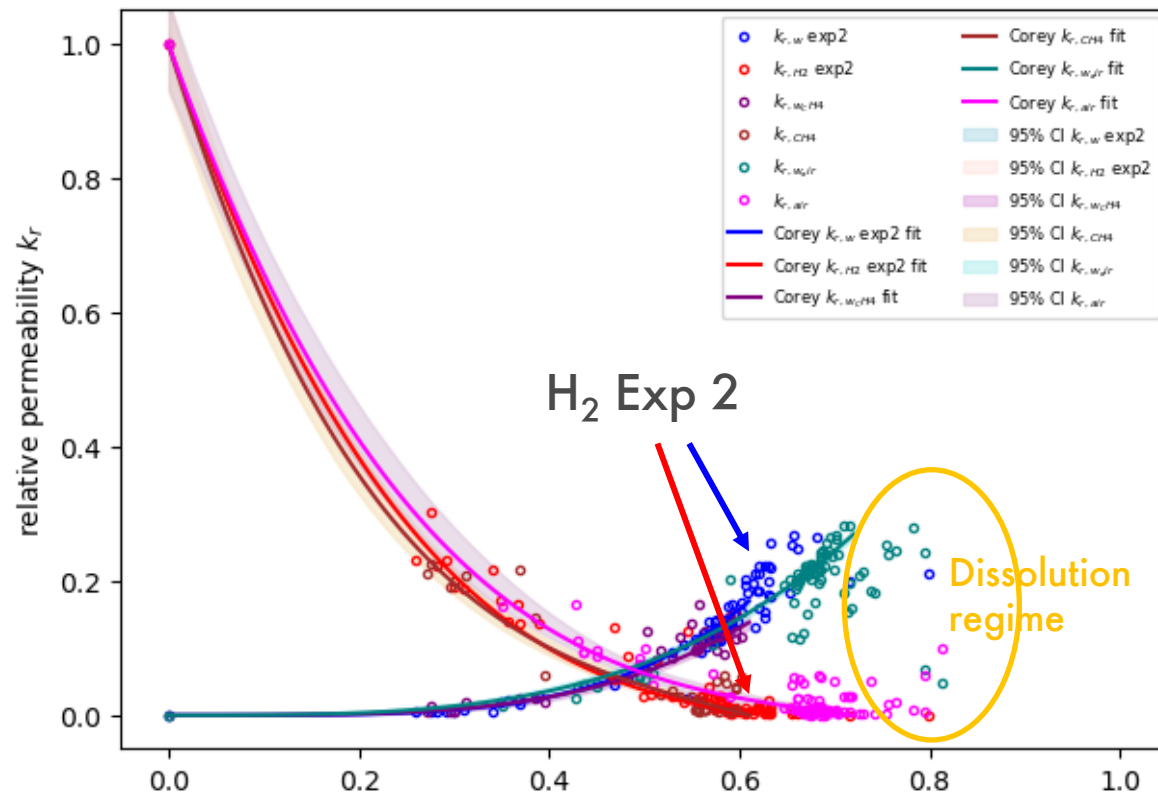


$$k_{r,g/w} = \frac{K_{g,w}}{K_{abs}}$$

Relative permeability

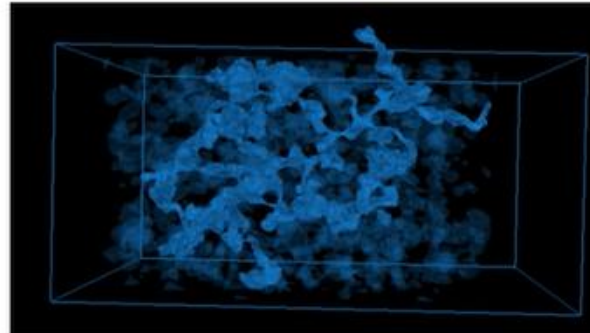
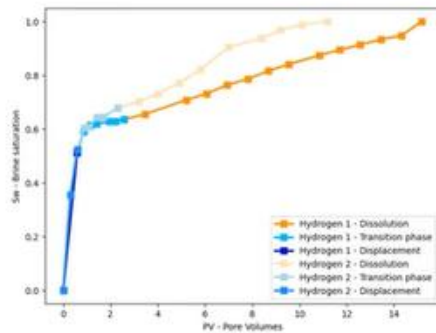
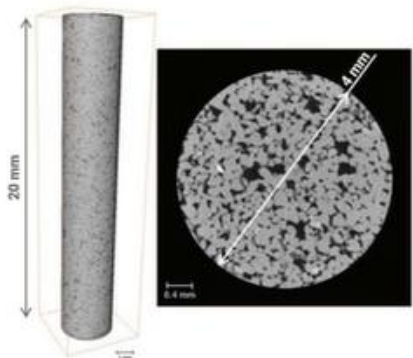
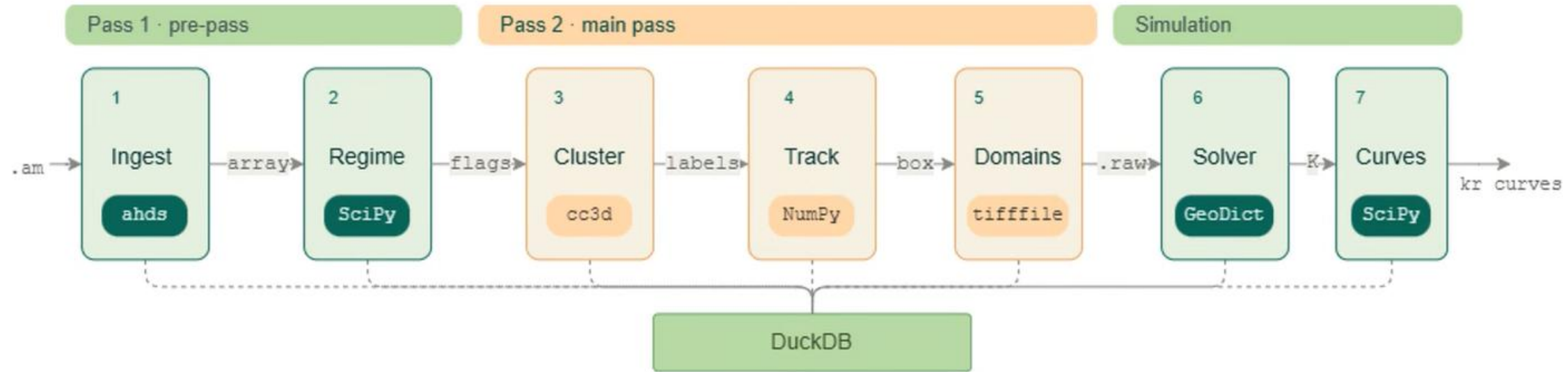
Comparison of 3 Gasses: Relative Permeability (MSc Eleonora Parente)

Differences between gases **NOT** significant, only difference is S_{gr} for N_2

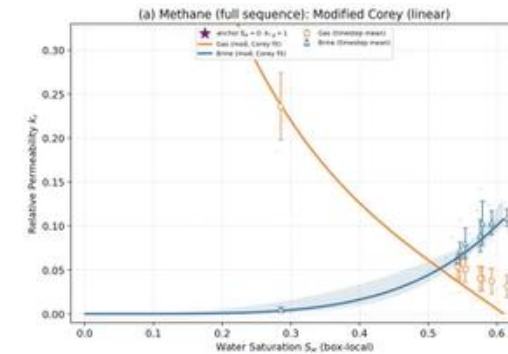


MSc thesis [Politecnico di Milano](#), [Universitat Politecnica de Catalunya](#)

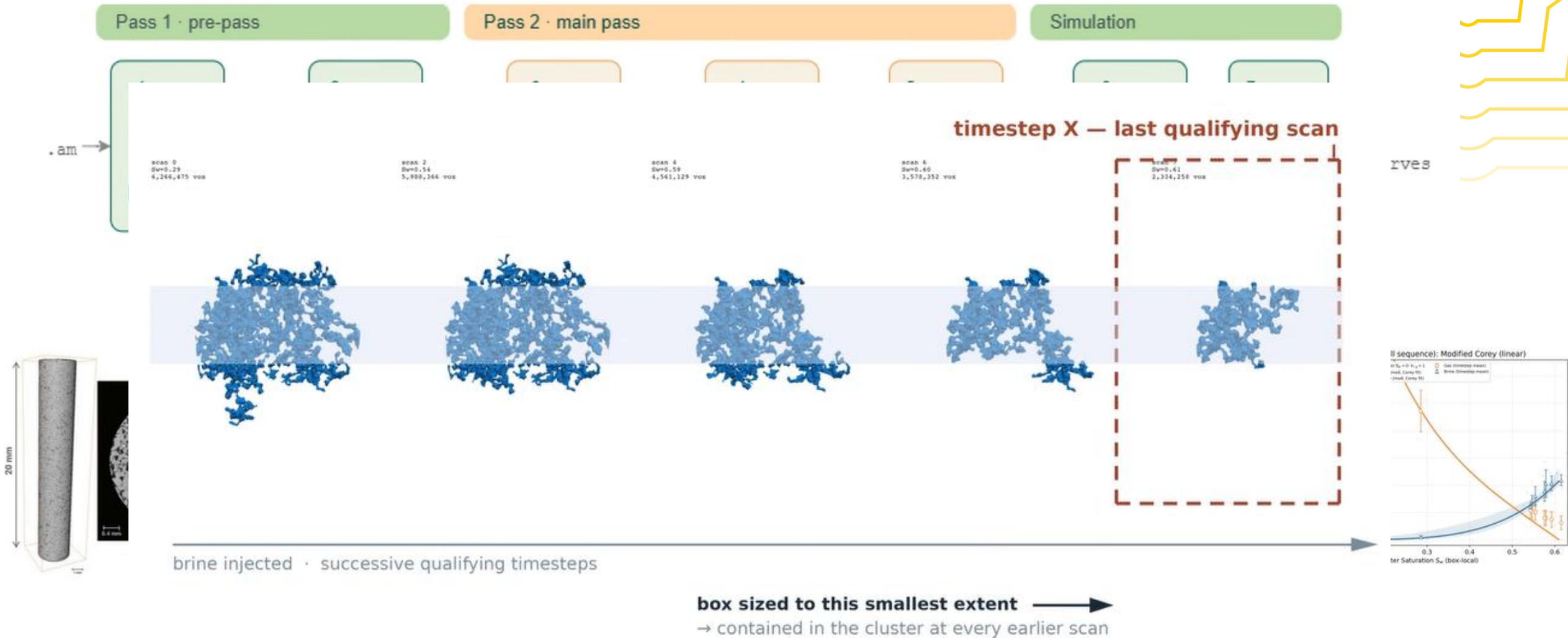
Automating Processing Pipeline (MSc Sveta Radeva)



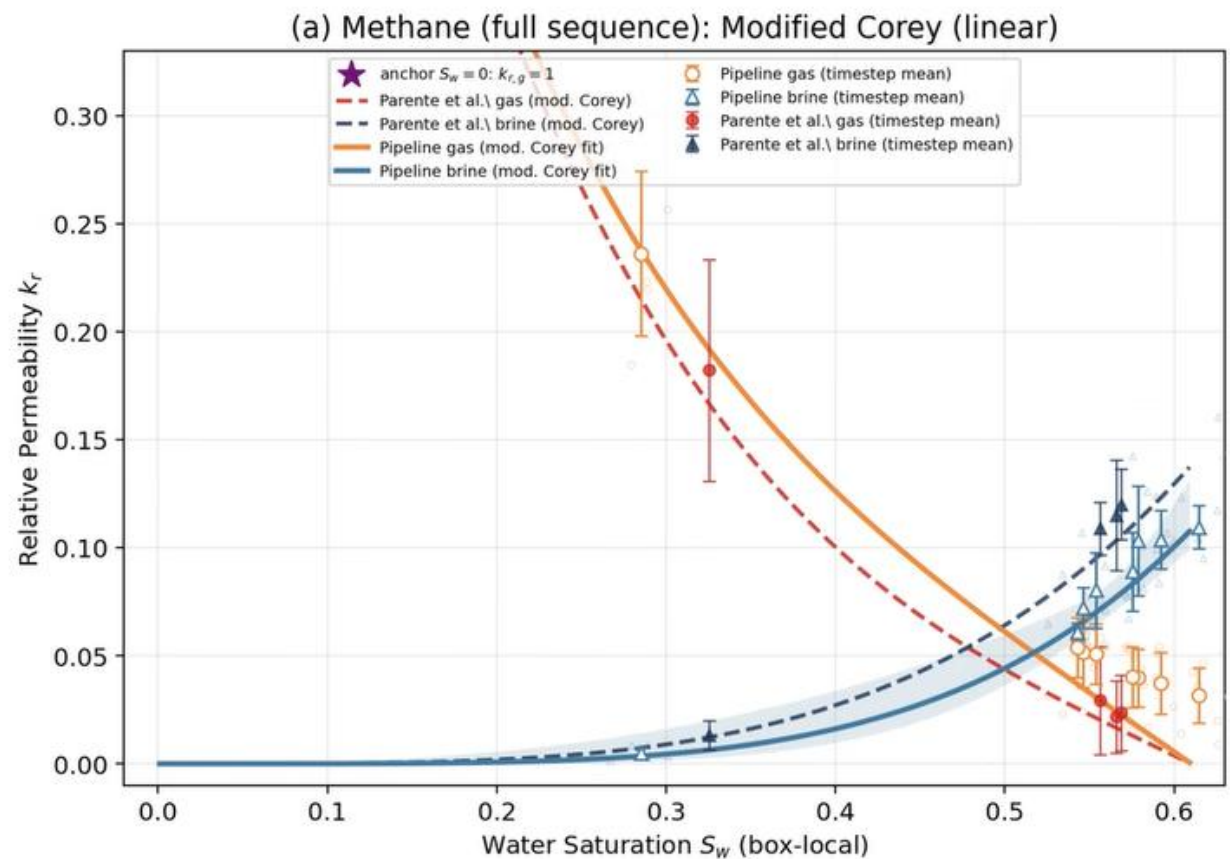
GEODICT
The Digital Material Laboratory



Automating Processing Pipeline (MSc Sveta Radeva)



Automating Processing Pipeline (MSc Sveta Radeva)



Thesis Figure 6.3(a) — modified Corey, against box-local water saturation

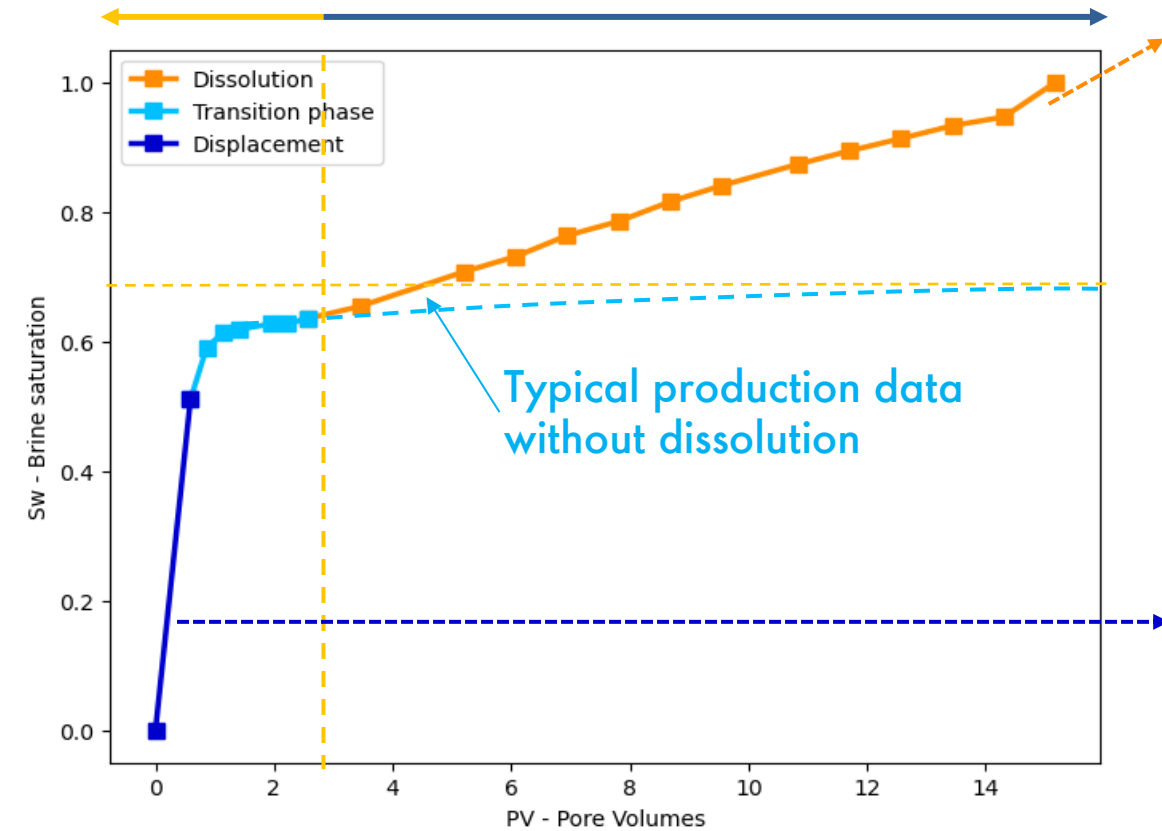
Scan · S_g (vol.)	pipeline g / w	baseline g / w
0 · 0.649	0.236 / 0.005	0.182 / 0.013
1 · 0.410	0.051 / 0.072	0.029 / 0.109
2 · 0.408	0.054 / 0.061	0.022 / 0.115
3 · 0.401	0.051 / 0.080	0.024 / 0.120
4* · 0.366	0.040 / 0.103	—
5* · 0.369	0.040 / 0.089	—
6* · 0.344	0.037 / 0.104	—
7* · 0.313	0.032 / 0.110	—
8* · 0.270	0.031 / 0.147	—
9* · 0.240	0.027 / 0.171	—
10* · 0.211	0.019 / 0.186	—
11* · 0.135	0.014 / 0.320	—

mean $k_{r,g} / k_{r,w}$ per timestep · scans 4–11 extend past the baseline (*)

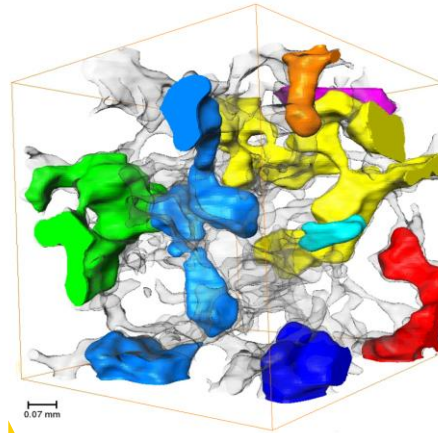
Differences Between Displacement and Dissolution

Displacement-
dominated

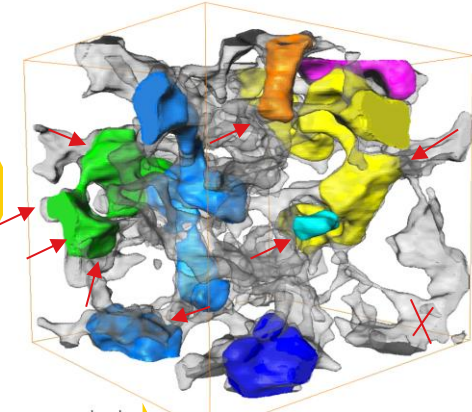
Dissolution-dominated
(caused by ripening)



Dissolution

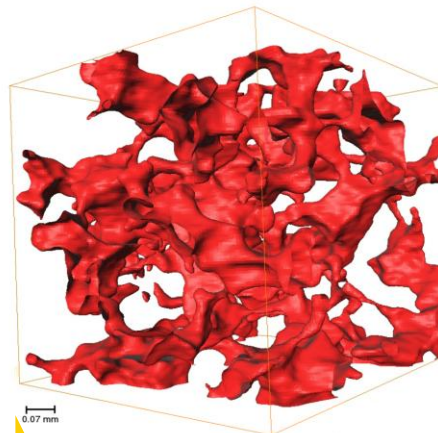


Gas clusters shrinking

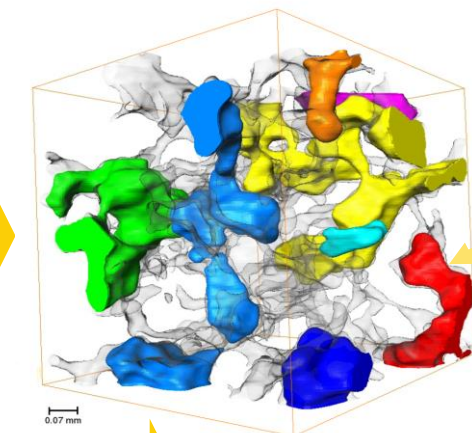


Curvature
Interfacial area

Displacement



Change in topology of gas



Euler characteristic χ

Trapped gas
Residual gas

Differences Between Displacement and Dissolution: Minkowski Functionals

4 Minkowski functionals

$$M_0^n = \text{volume} \rightarrow \text{saturation } S_W \quad M_0^n = \lambda(\Omega_n) = \int_{\Omega_n} dr$$

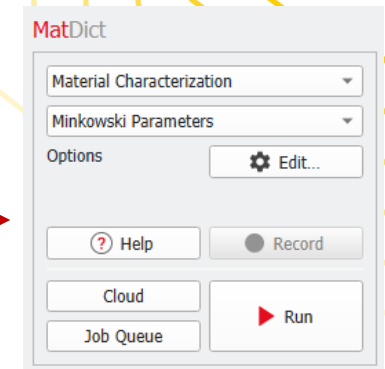
$$M_1^n = \text{interfacial area } A_{nw} \quad M_1^n = \lambda(\Gamma_n) = \int_{\Gamma_n} dr$$

$$M_2^n = \text{mean curvature } \kappa \quad M_2^n = \int_{\Gamma_n} \left(\frac{1}{R_1} + \frac{1}{R_2} \right) dr$$

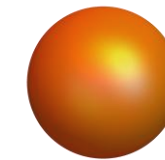
$$M_3^n = \text{Gauss curvature} = 2\pi\chi \quad M_3^n = \int_{\Gamma_n} \frac{1}{R_1 R_2} dr = 2\pi\chi$$

→ Geometric State Function of Capillarity

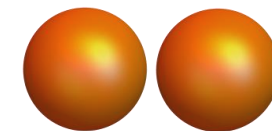
- Avizo
- QuantimPy
- GeoDict →



$$\chi = V - E + F$$



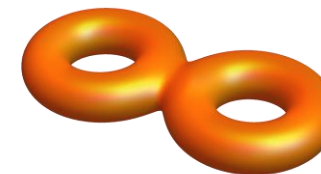
$$\chi = 1 - 0 = 1$$



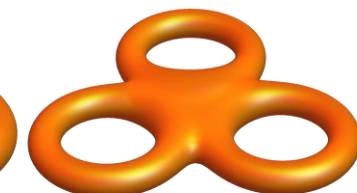
$$\chi = 2 - 0 = 2$$



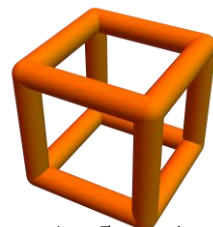
$$\chi = 1 - 1 = 0$$



$$\chi = 1 - 2 = -1$$



$$\chi = 1 - 3 = -2$$

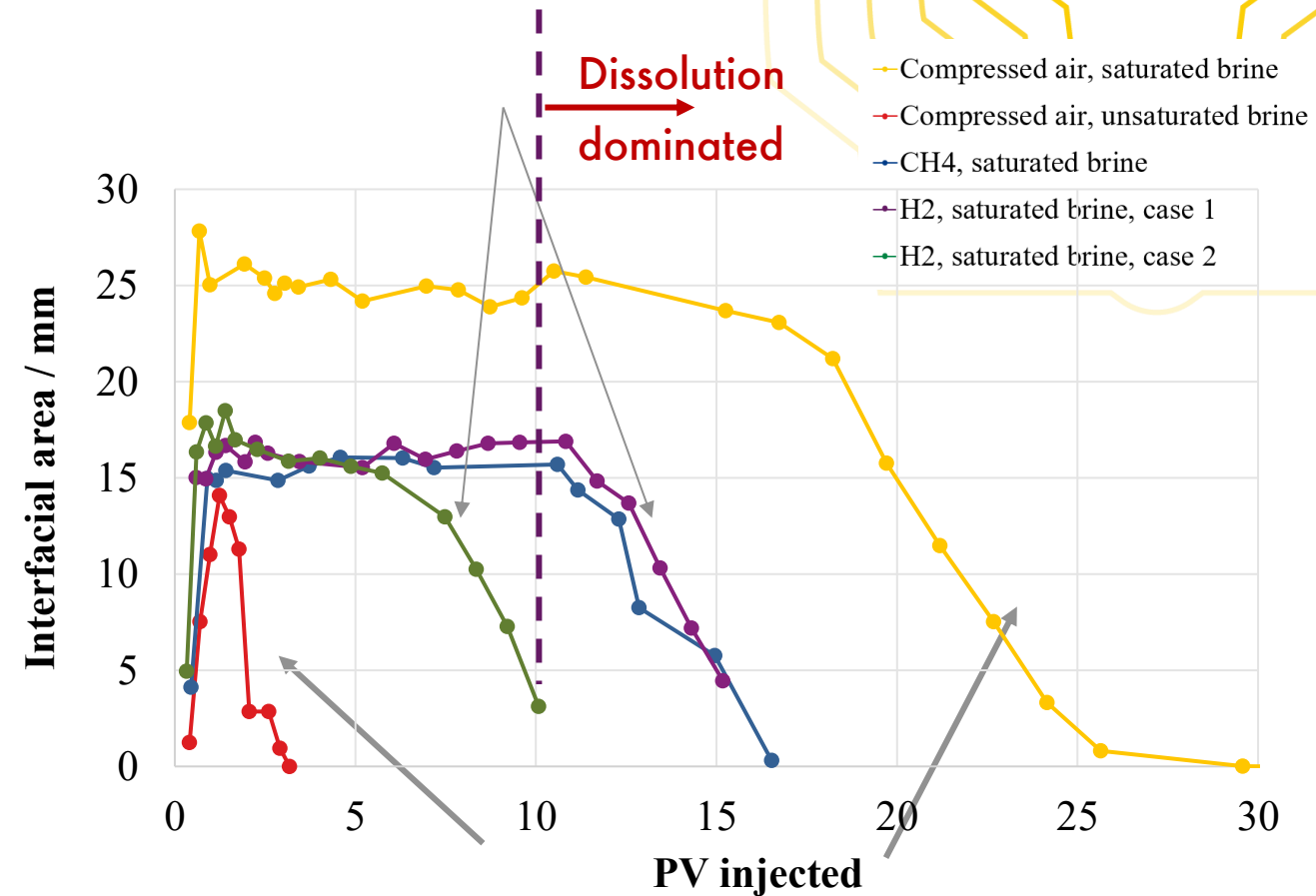
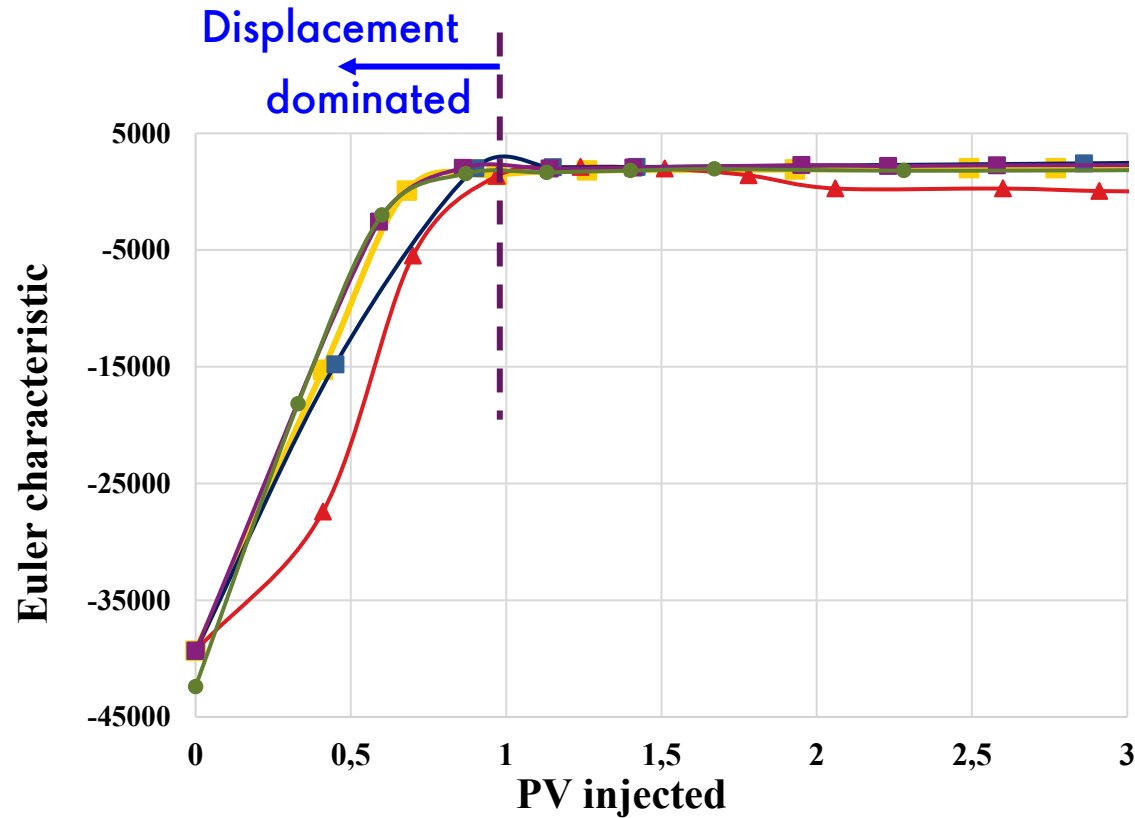


$$\chi = 1 - 5 = -4$$

[Phys. Rev. Fluids 3\(8\), 084306, 2018.](#)

[Transport in Porous Media 130, 305-335, 2019.](#)

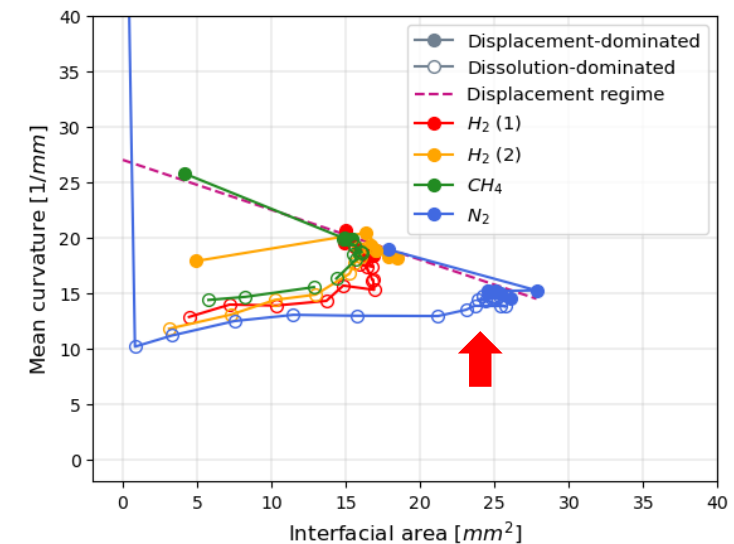
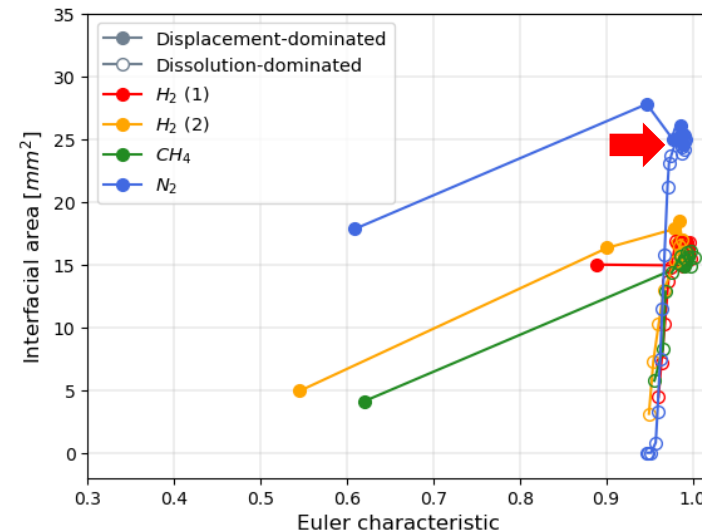
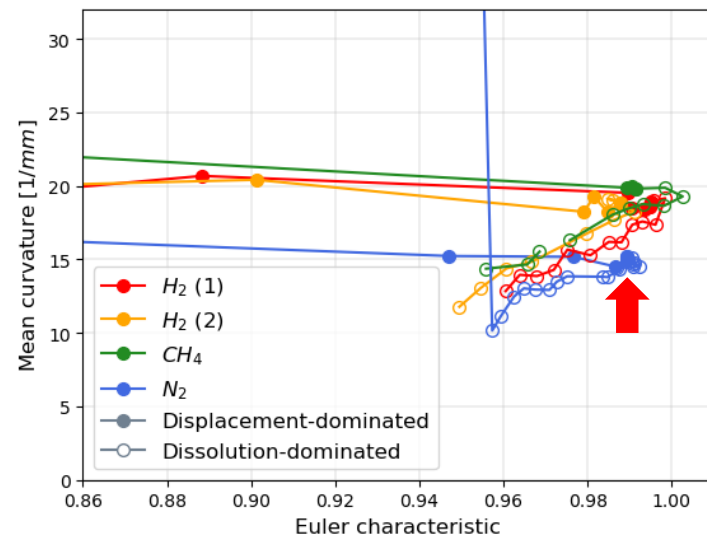
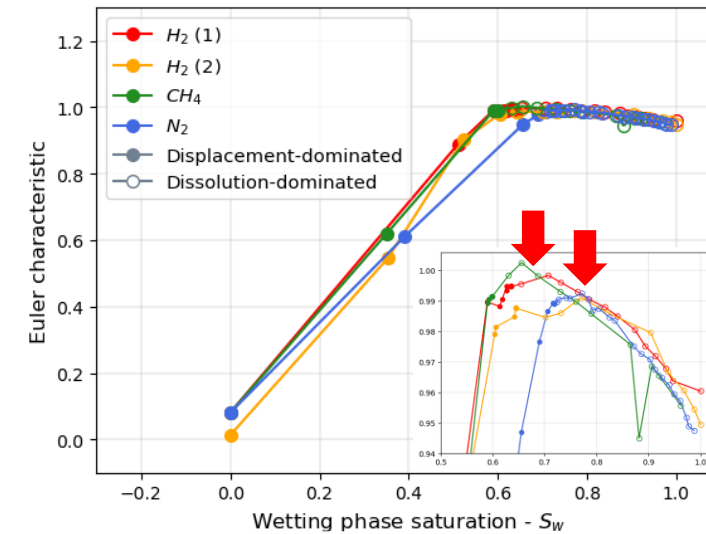
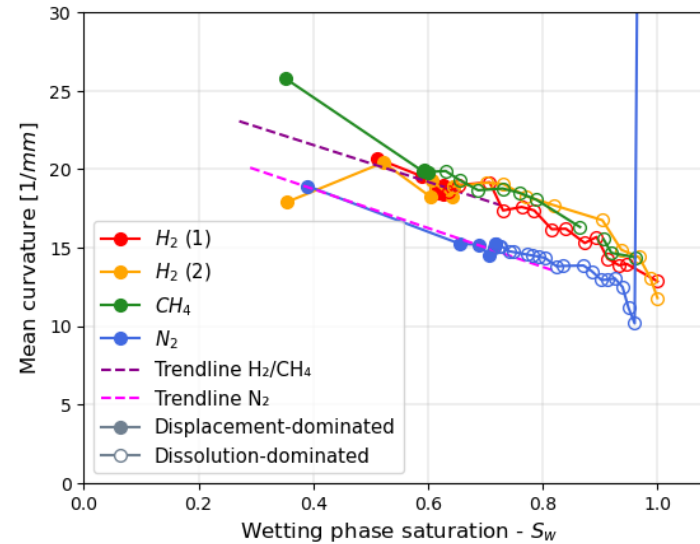
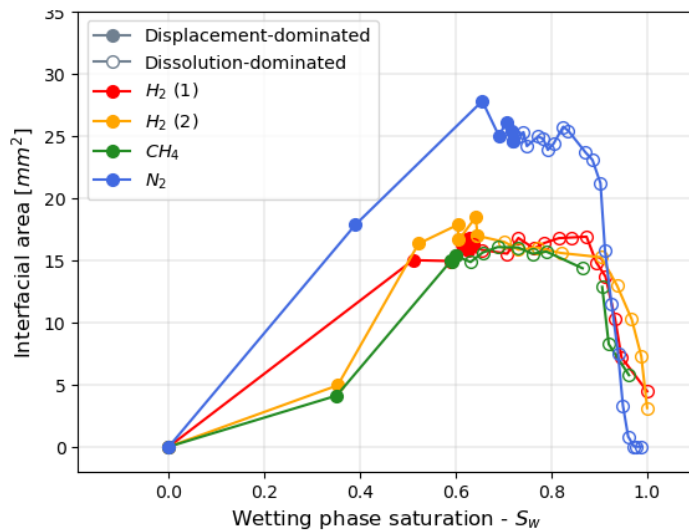
Differences Between Displacement and Dissolution: Minkowski Functionals



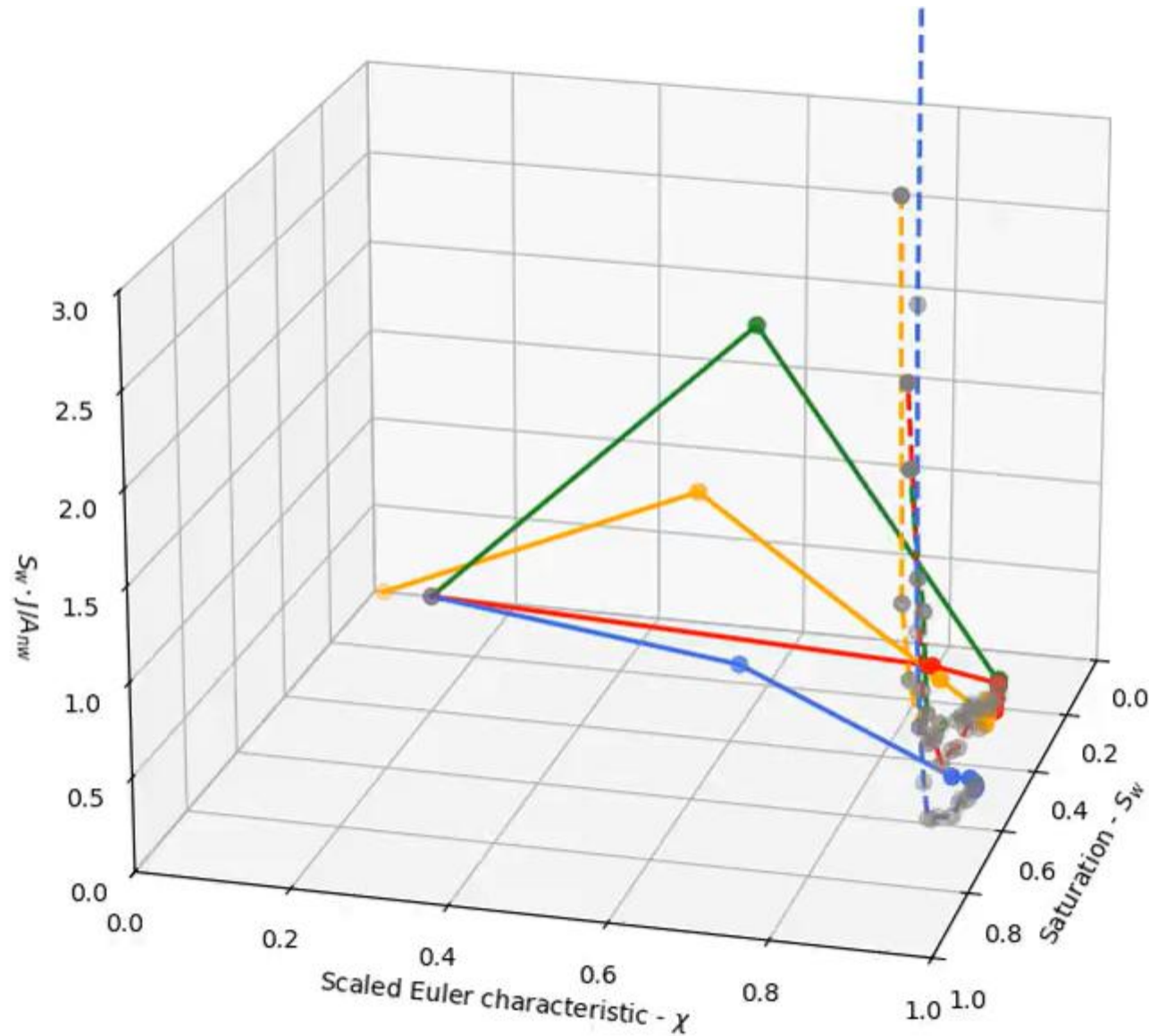
- End of displacement-dominated regime is upper limit to S_{gr}
- Beginning of dissolution-dominated regime is lower limit to S_{gr}

Clear trend of dissolution dominated regime with saturation level of brine

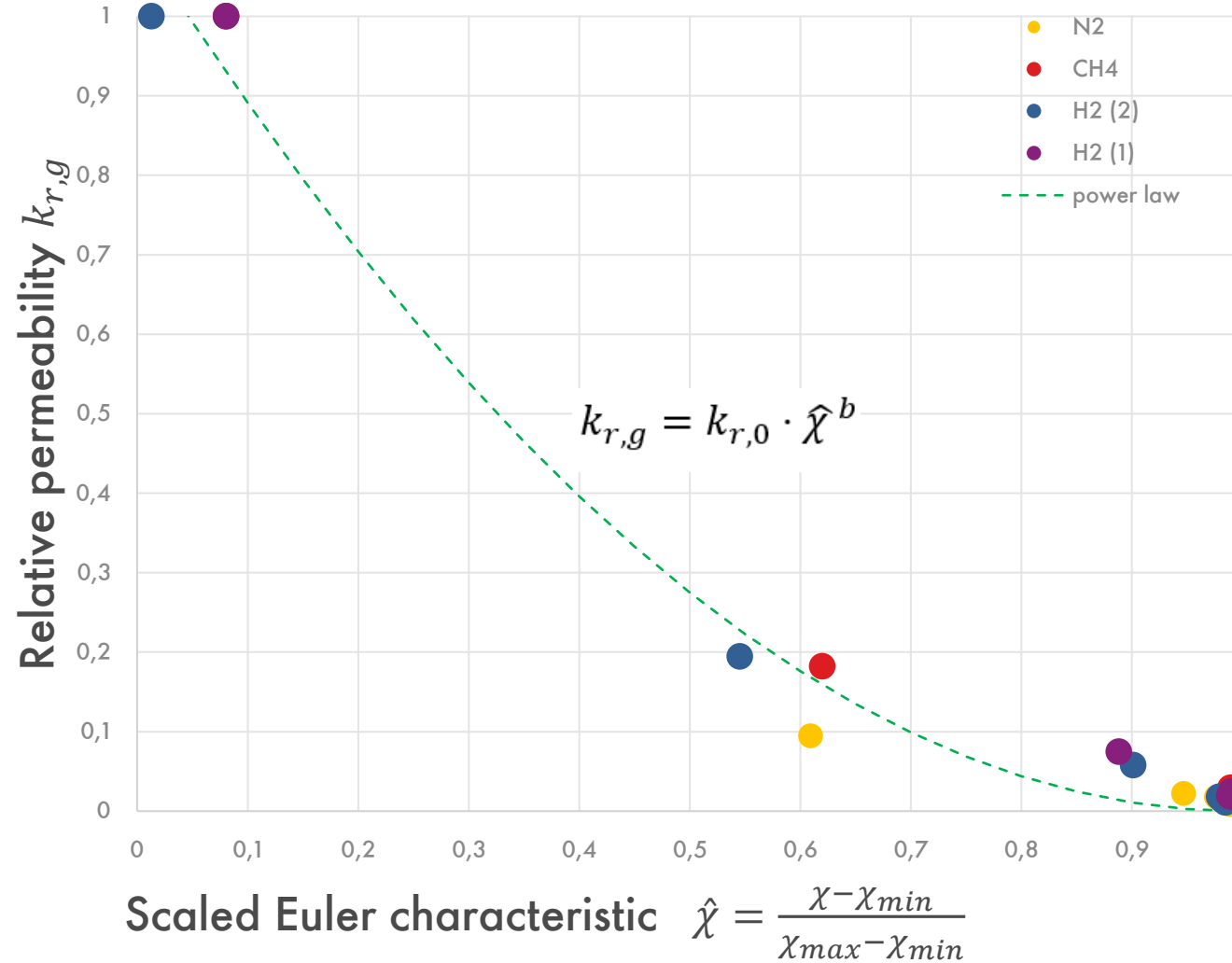
Differences Between Displacement and Dissolution: Minkowski Functionals



Differences Between Displacement and Dissolution: Minkowski Functionals



Relative Permeability @ Displacement Regime – Same population for 3 Gases



- $S_{g,r}$ for N₂ may or may not be different
- But same trend of $k_{r,g}$ with $\hat{\chi}$
- Same population of data

Summary & Conclusions

GEODICT LIR Solver

- Hybrid micro-CT flow experiments + Stokes flow simulations → relative permeability for gasses
- Wider mobile saturation accessible than in traditional SCAL experiments
- Lower residual gas saturation in N₂ experiment
 - lies within typical repeatability
 - need more repeats to understand whether significant or not
- Relative permeability differences between H₂, CH₄, N₂ not significant, form same population in $k_{r,g}(\hat{\chi})$
- Characterization of flow regimes with Minkowski functionals

[International Journal of Hydrogen Energy 229, 154730, 2026.](#)

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Math2Market is gratefully acknowledged for support with LIR solver and Python automation

Q&A

