25th Imperial Consortium on Pore-Scale Modelling and Imaging

Pore-scale Characterisation of Hydrogen Storage During Imbibition and Reflooding

Sepideh Goodarzi, Branko Bijeljic and Martin J. Blunt

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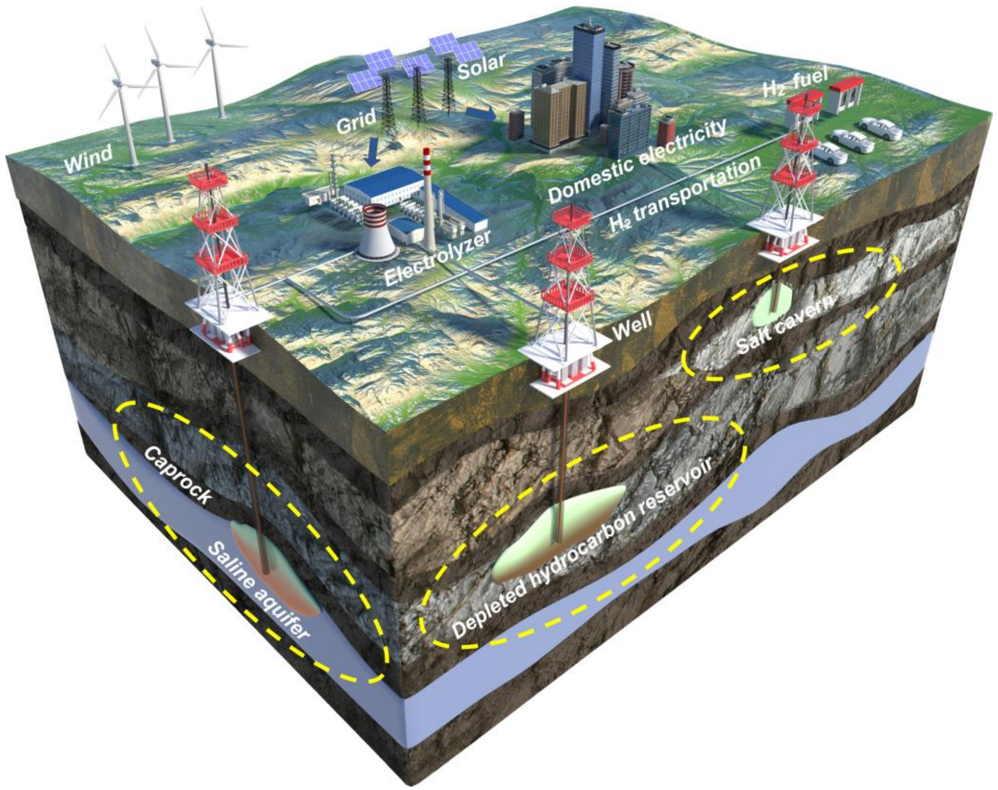
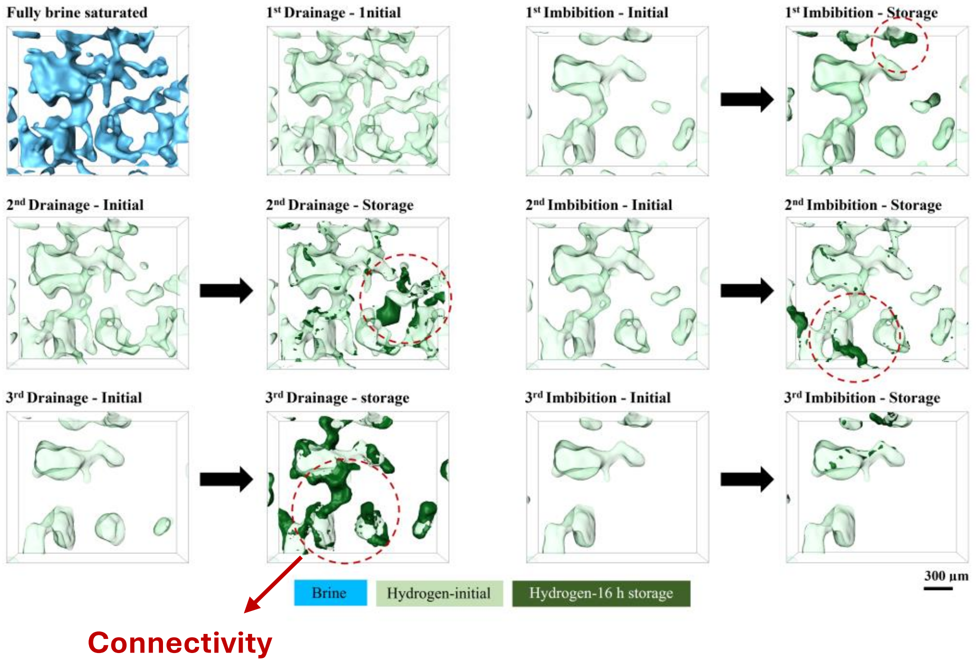
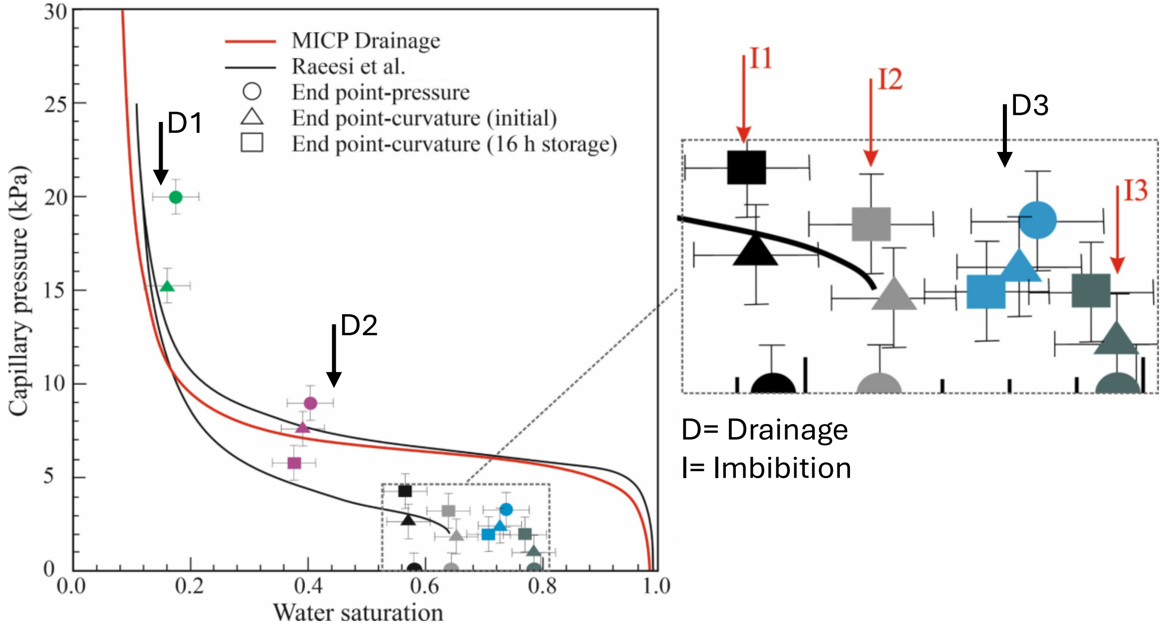
Motivation and aim



- Significant reorganisation of gas can occur over periods ranging from hours to months and across distances from millimetres to centimetres. I will study the **impact on residual saturation and capillary pressure hysteresis.**
- Time-dependent effects of Ostwald ripening on capillary pressure hysteresis and trapping during cyclic injection and withdrawal will be quantified.
- The emphasis in this talk in on **multiple cycles of imbibition and drainage by displacement at constant pressure** to quantify changes on hydrogen distribution, and specifically the increase in connectivity, allowing for additional displacement after Ostwald ripening.

Key insights from previous experiment work

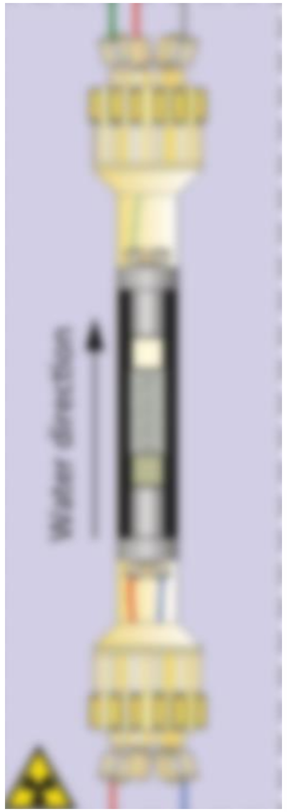




- Once flow has stopped, the **gas redistributes within the pore space** without altering the overall volume.
- This rearrangement leads to **better gas connectivity** and, in most cases, the growth of a single, large connected ganglion.
- The capillary pressure measurements are not consistent with traditional hysteresis models. Repeated drainage and imbibition cycles led to **lower residual saturations**.

Multiple water flooding after gas injection

Repeat experiment to confirm the additional connectivity induced by Ostwald ripening: transport of dissolved gas in the aqueous phase.



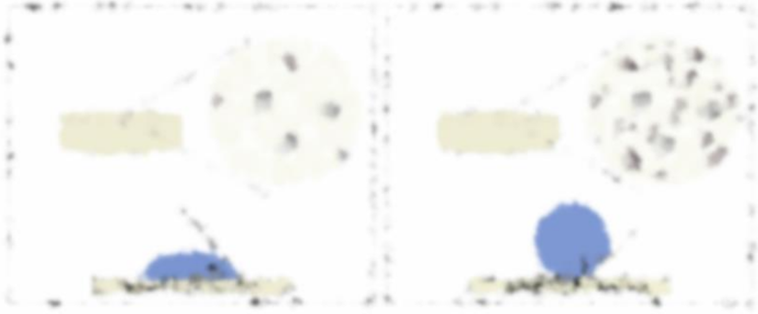
Step 1: **Hydrogen flooding** → Gas Injecting From top → Bottom-to-top scan

Step 2: **1st water flooding** → Brine Injecting From bottom → Bottom-to-top scan → storage → Bottom-to-top scan (**4 days**)

Step 3: **2nd water flooding** → Brine Injecting From bottom → Bottom-to-top scan → storage → Bottom-to-top scan (**4 days**)

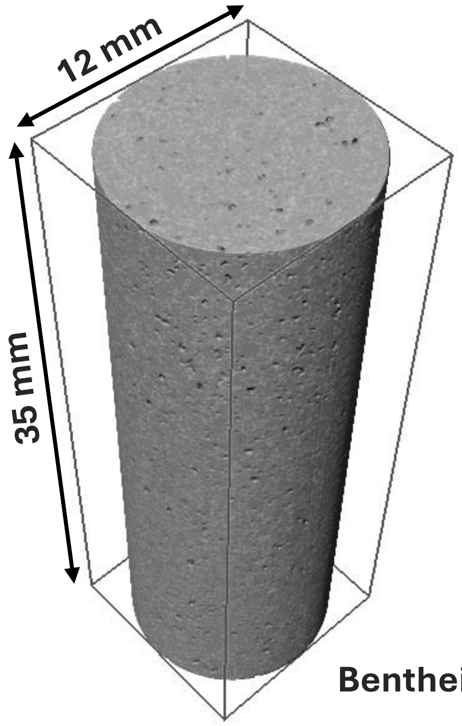
Step 4: **3rd water flooding** → Brine Injecting From bottom → Bottom-to-top scan → storage → Bottom-to-top scan (**4 days**)

P= 4 MPa

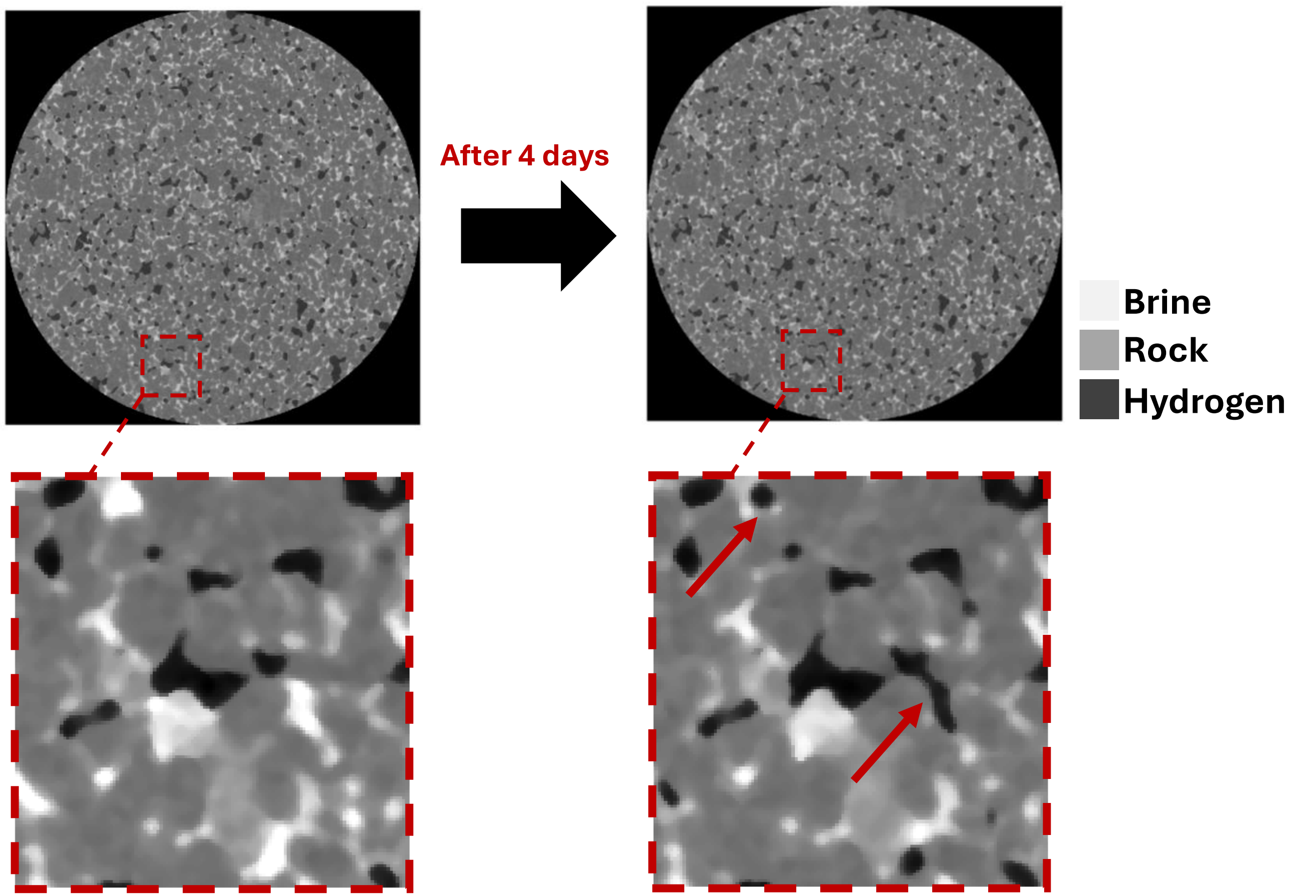


Gas rearrangement observed after waiting 4 days

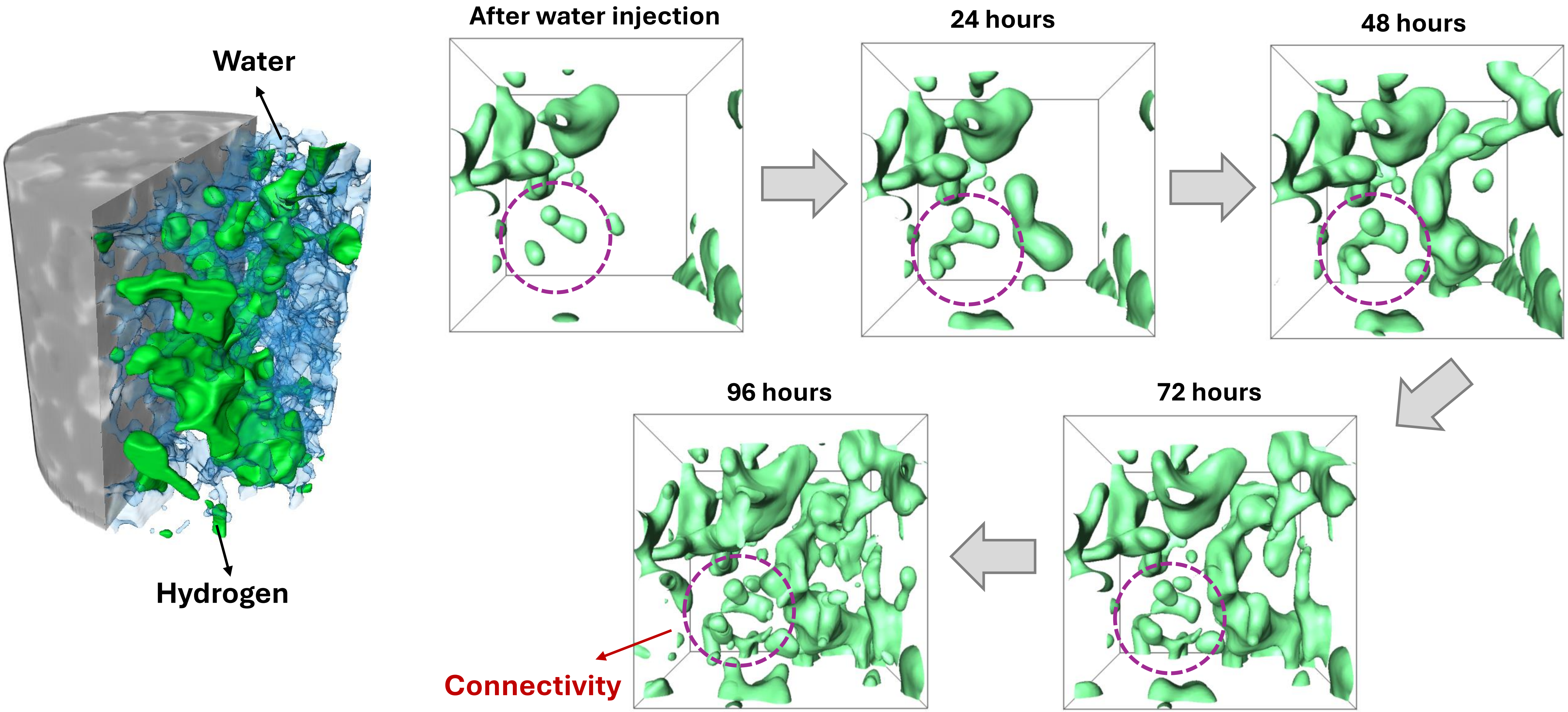
- Imaging was performed using a **Heliscan**, equipped with a flat panel detector.
- The detector delivered three-dimensional images featuring a voxel size of **9.3 µm** and **4.6 µm.**



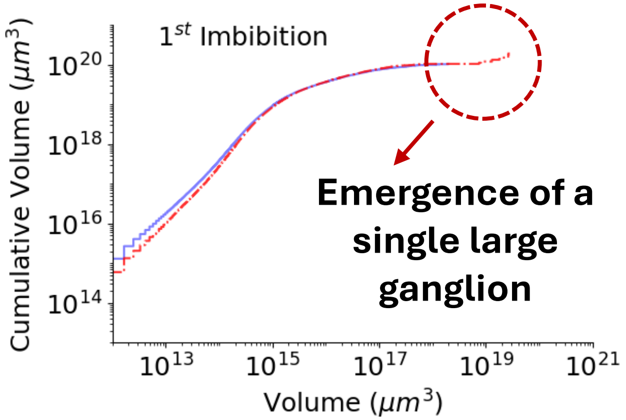
Bentheimer sandstone

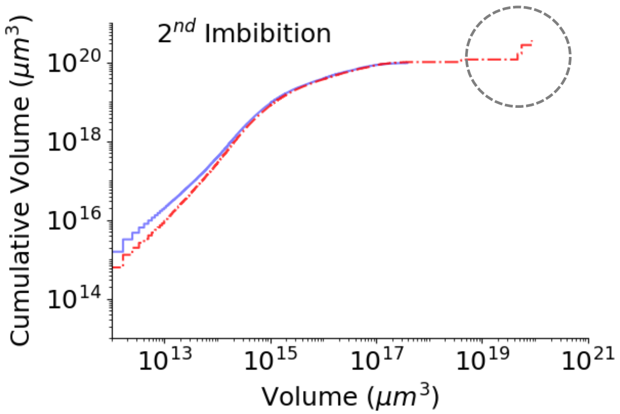


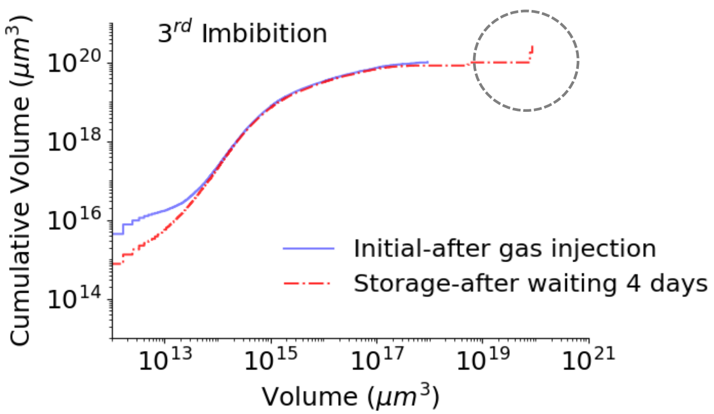
Hydrogen connectivity improved over 96 hours



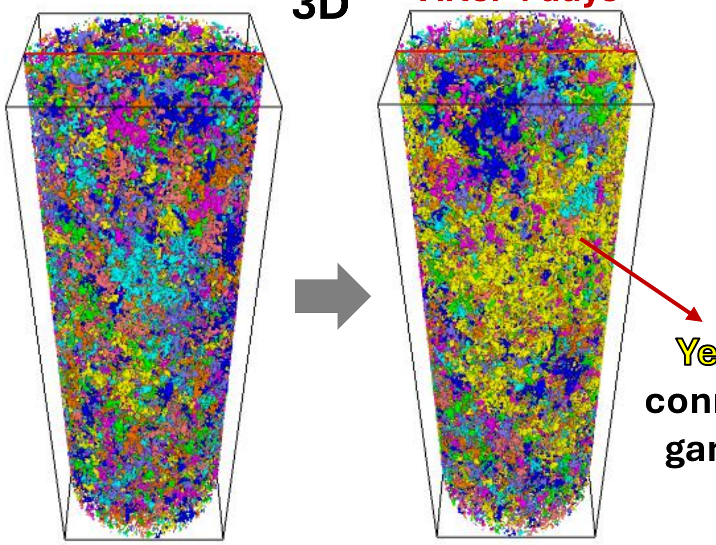
Withdrawal through a connected pathway





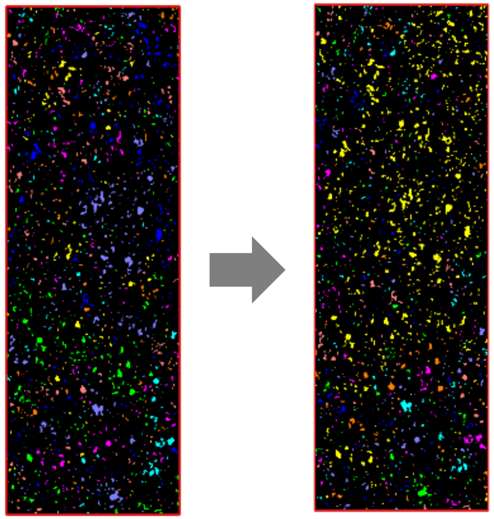


3D **After 4 days**



Yellow: connected ganglion

2D **After 4 days**



Euler Characteristic 1/mm³		
	Initial	**4 days Storage**
1st Imbibition	28	23
2nd Imbibition	22	21
3rd Imbibition	26	19

Increase in connectivity

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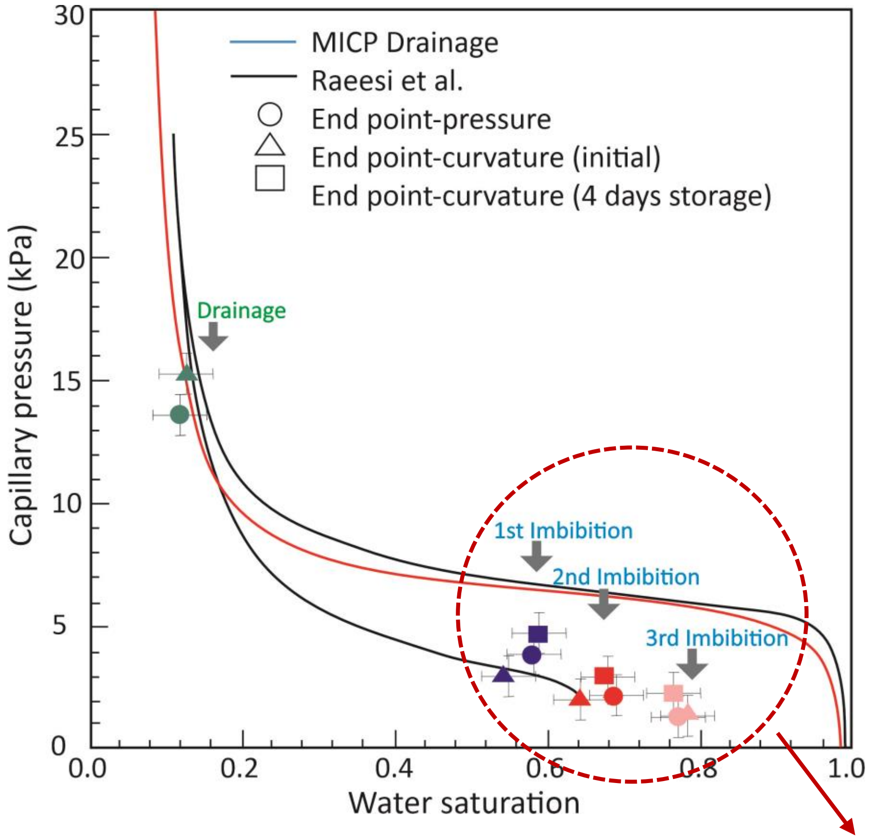
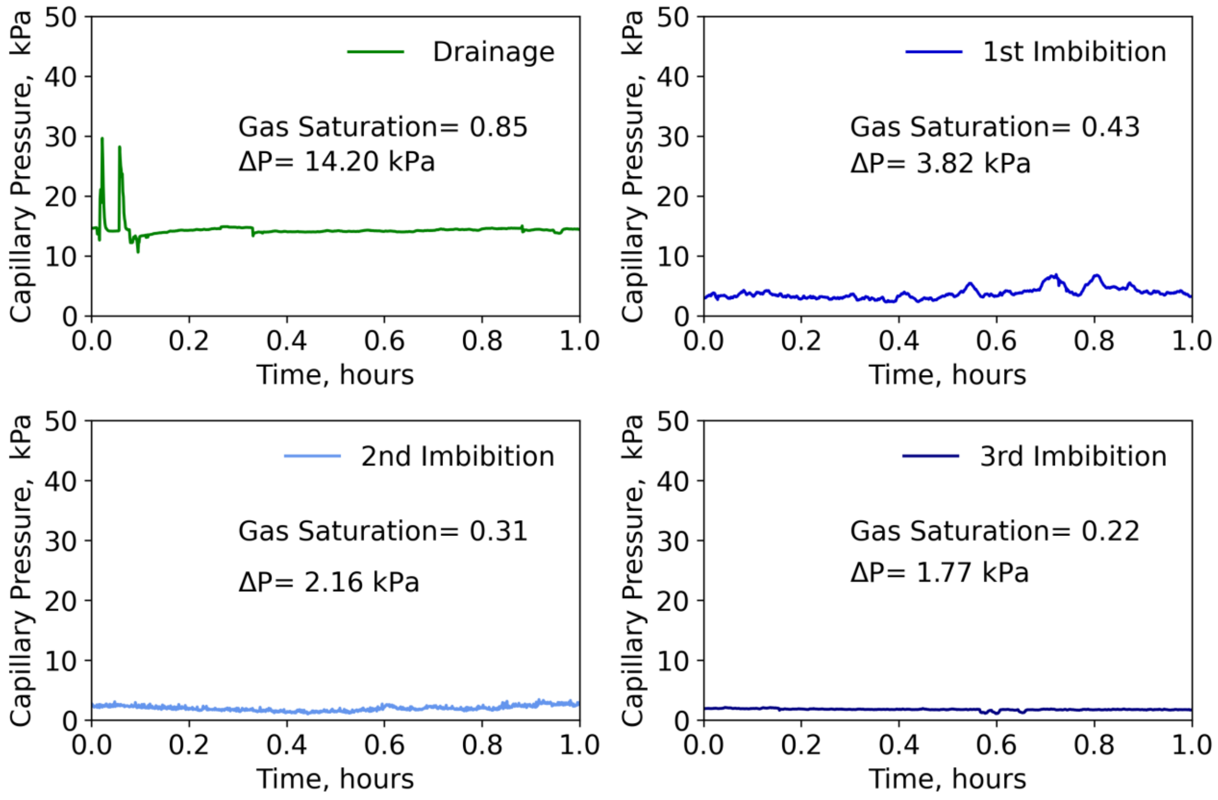
Reduction in capillary pressure

- End points capillary pressure measured for both drainage and imbibition.
- The capillary pressure measurements are not consistent with traditional hysteresis models.

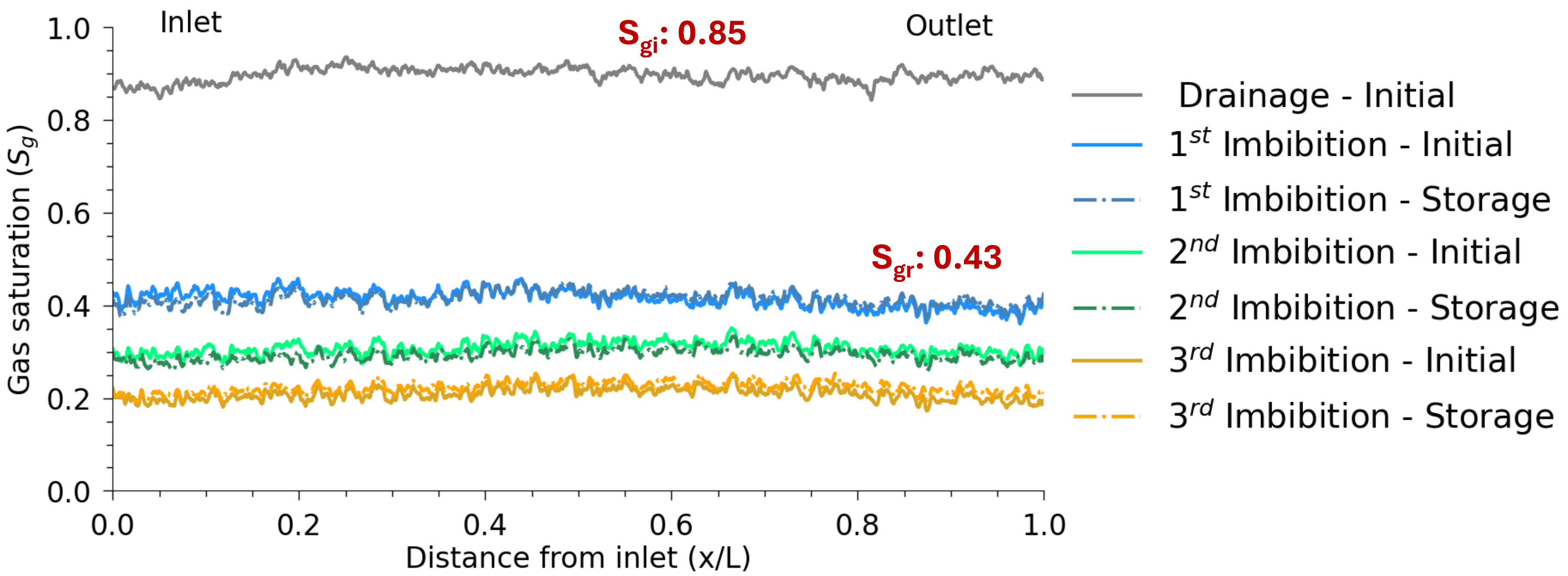


MICP: Lin et al. (2018). Water Resources Research, vol. 54, no. 9, pp. 7046–7060.
Raeesi et al. (2014). Vadose Zone Journal, vol. 13, no. 3.

Lower residual saturations



Uniform gas saturation profile



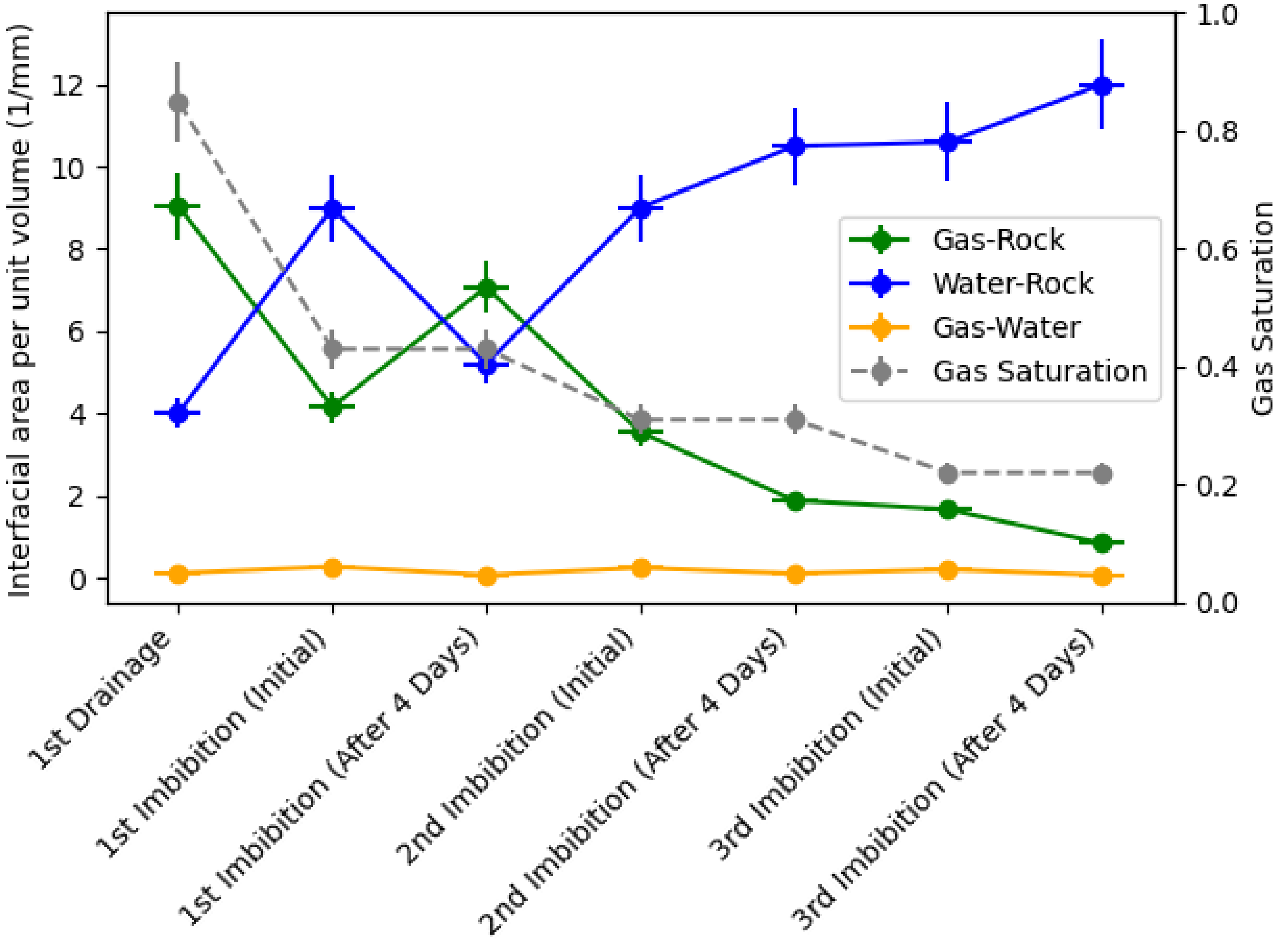
- Mixing **re-equilibrated brine** with hydrogen under high-pressure.
- Using **porous plates** resulted in uniform gas saturation after injection and withdrawal.
- **No additional gas displacement** or production occurs during storage.

Bentheimer is water wet

- Water-wet nature of the sample, as indicated by the consistently **higher water-rock interfacial area** (blue) compared to the gas-rock interfacial area.

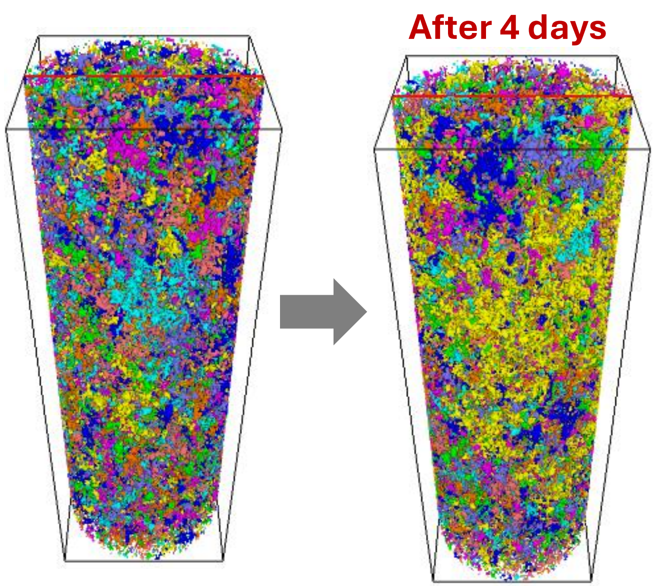
- The **gas-rock interfacial area (green) consistently decreased**: reflects the displacement of gas from regions in contact with the solid surface.

- **Gas saturation decreased** over the three cycles of water injections (S_g= 0.43-0.31-0.22).

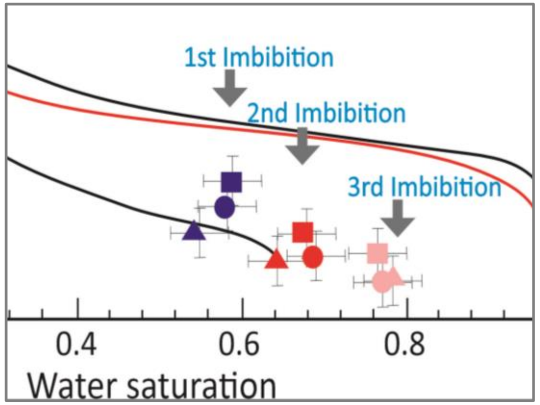


Conclusions

- The average hydrogen saturation achieved was 87%, while the residual hydrogen saturation averaged approximately 40%.
- After a 4-day no-flow period, gas redistributed within the pore space without altering the overall volume, a process attributed to Ostwald Ripening.
- This redistribution improved gas connectivity, enabling hydrogen withdrawal through a continuous pathway.
- The capillary pressure measurements are not consistent with traditional hysteresis models. Repeated imbibition led to lower residual saturations.



Future work:
- Conduct experiments under high-pressure and high-temperature conditions.
- Looking at true equilibrium for long residence times in the subsurface.
- Use the experimental results as a benchmark and validation for pore-scale models (Ademola).



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Thank you