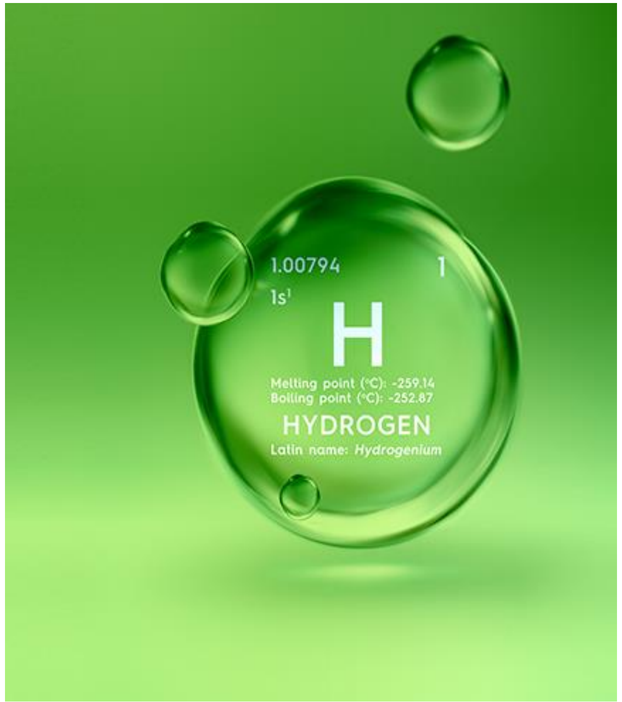

Trapping, Hysteresis and Ostwald Ripening in Hydrogen Storage

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Objectives of the project

- Fundamentals of dynamic hysteresis in multiphase flow
- A better characterization of multiphase flow properties, looking at both the effects of saturation path and flow rate.
- Potentially applicable to other situations including CO_2 and H_2 storage.
- Investigating hydrogen storage and use in different rock geometries.

Background

- **Saturation, Interfacial area, Mean curvature** and **Gaussian curvature** give a full characterisation of geometry.
- Capillary pressure depends on both the saturation and saturation history.
- **X-ray imaging techniques** enable us to use this theory by measuring these four functions.
- **UHS** can be considered as a long-term energy storage solution (inject into the surface reservoir and withdrawn).
- **Porous formations** are good places for GT storage and use.

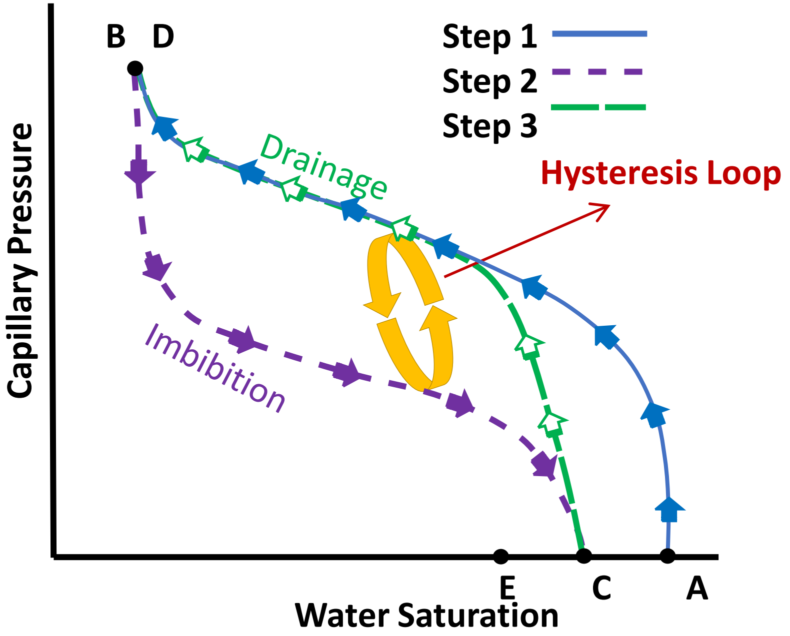
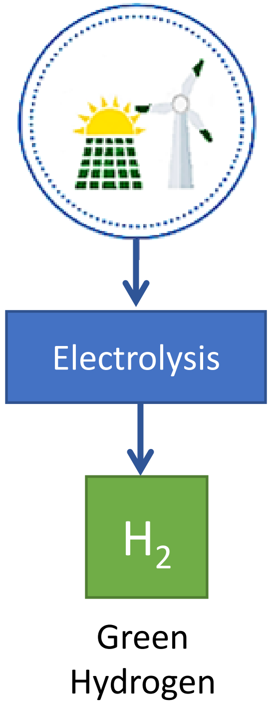


Figure 1: Two-phase flow hysteresis of the gas-water system during drainage and imbibition steps.



Two-phase hydrogen experiment

- Investigate the hysteresis of a two-phase hydrogen-brine system at unsteady-state conditions.
- **Meso-scale, 12 mm diameter core and repeated H_2 and brine injection.**
- Lab-based micro-CT, using a Zeiss Versa XRM-500 X-ray microscope.

Table 1: Capillary number for unsteady state H2-Brine experiment, $Ca_{ij} = \frac{\mu_i q_i}{\sigma_{ii}}$.

Flooding Step	Ca_{wg}	Ca_{gw}	Flowrate(ml/min)
Water	5.8E-09	-	0.06
Gas	-	1.9E-07	2.00
Gas	-	3.9E-08	0.40
Gas	-	7.7E-09	0.08

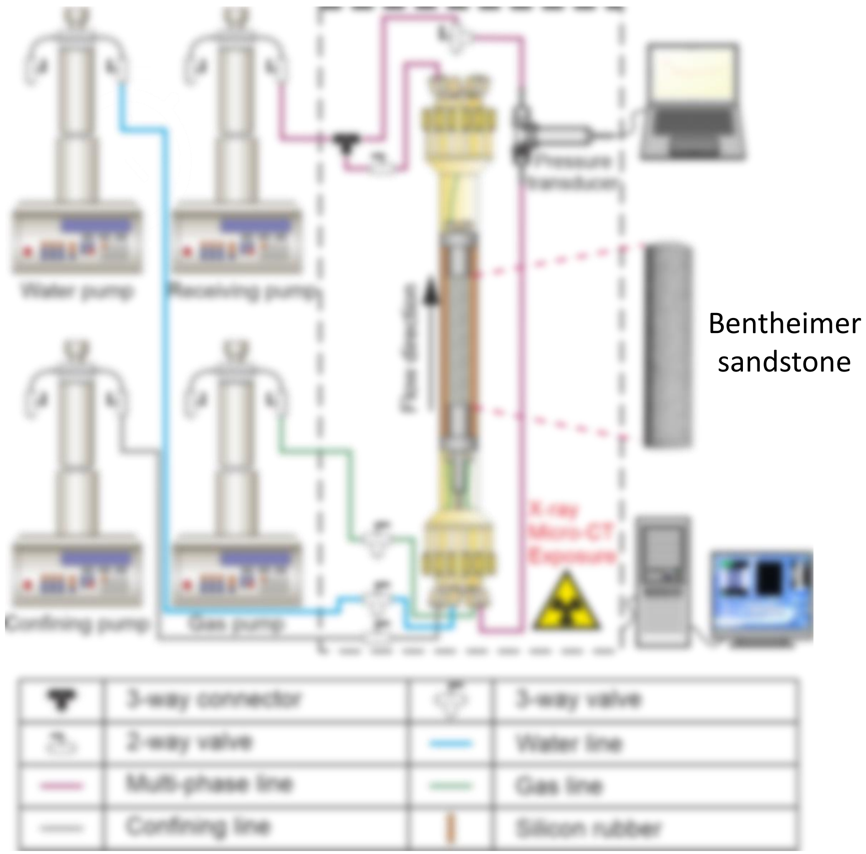


Figure 2: Schematic diagram for the two-phase gas-water experiment.

Dry, normalised and segmented images

- Using Non-Local Means filter with Watershed segmentation technique.
- Image resolution is 5.86 µm.

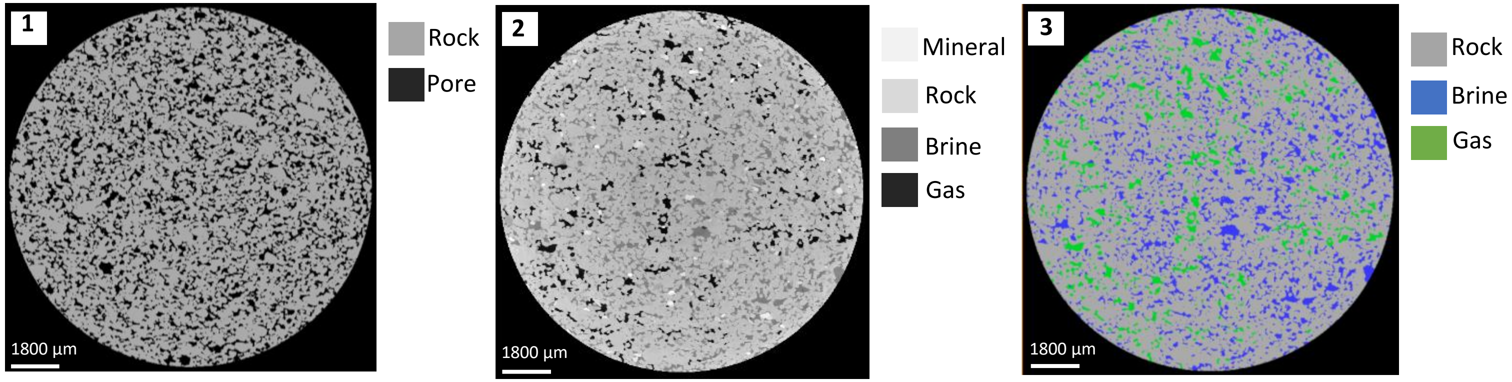


Figure 3: Dry(1), normalised(2) and segmented(3) two-dimensional slices of three-dimensional images of the Hydrogen-brine experiment.

Table 2: Procedure of the sample scanning.

Scan	Steps	Section
1st	Dry scan	1-6
2nd	Fully saturated	1-6
3rd	**1st Drainage**	**1-6**
4th	after16hrs	2 , 5
5th	**1st Imbibition**	**1-6**
6th	after16hrs	2 , 5
7th	**2nd Drainage**	**1-6**
8th	after16hrs	2 , 5
9th	**2nd Imbibition**	**1-6**
10th	after16hrs	2 , 5
11th	**3rd Drainage**	**1-6**
12th	after16hrs	2 , 5
13th	**3rd Imbibition**	**1-6**
14th	after16hrs	2 , 5
15th	after 1day	1-6

Imaging of gas saturation for all cycles

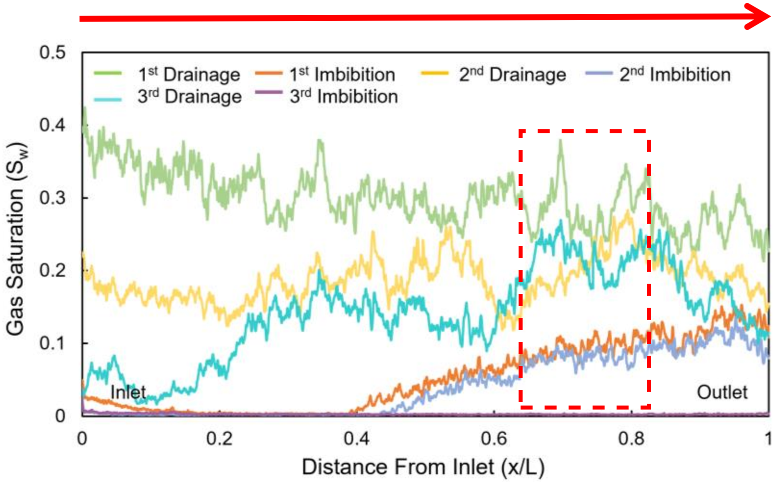
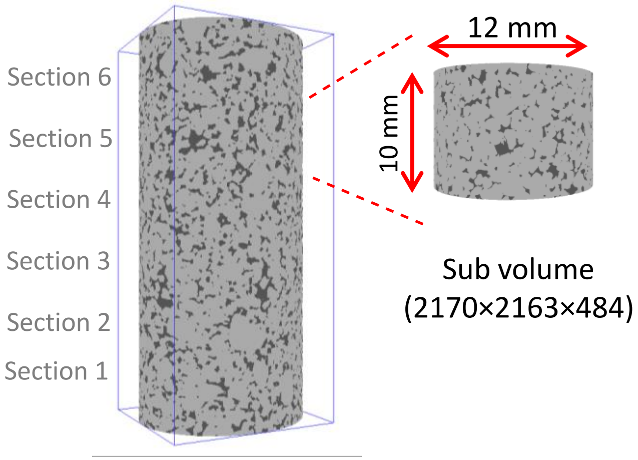


Figure 4: Fluid saturation profiles of gas during 3 cycles during imbibition and drainage.



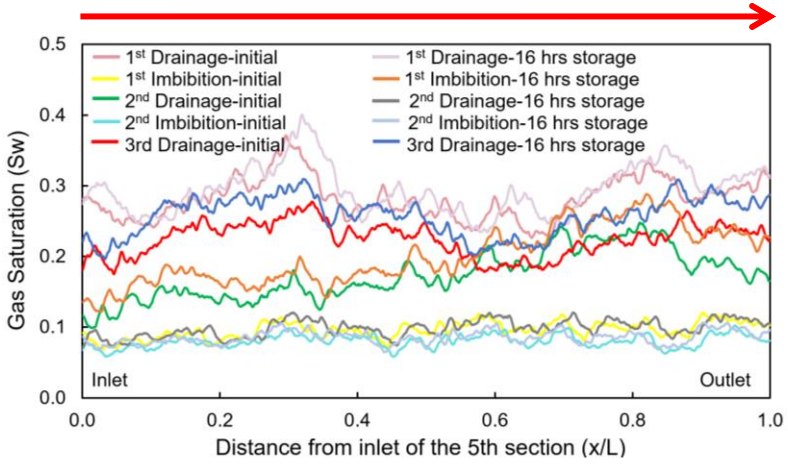
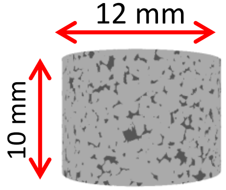


Figure 5: Saturation profiles of water during 3 cycles for a sub volume.

- Hydrogen is dissolved near the inlet when brine is injected.
- Gas saturation can increase after 16 hrs in the volume studied: gas may rise upwards from lower in the sample.
- Drainage (gas injection) leads to an increase in gas saturation.
- Not much change after water flooding.

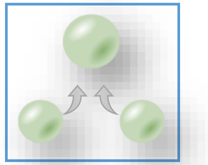
Analysis of discrete ganglia

Ganglion size distribution (cycle 1)

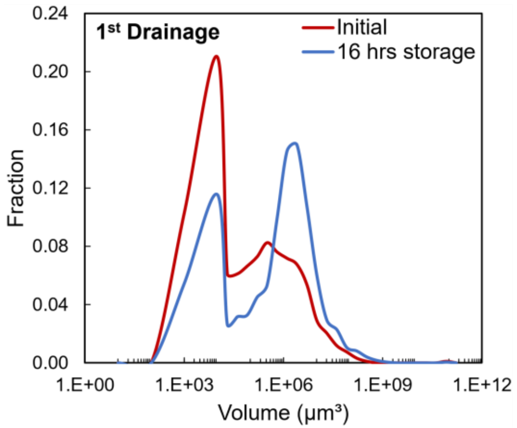


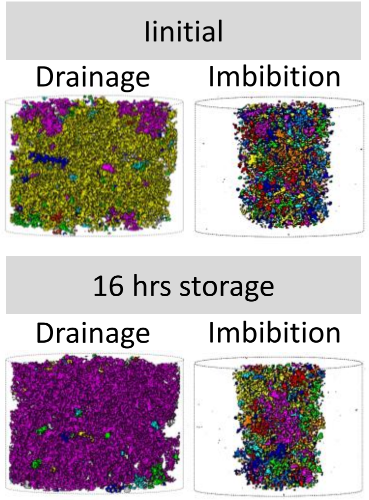
Section 5

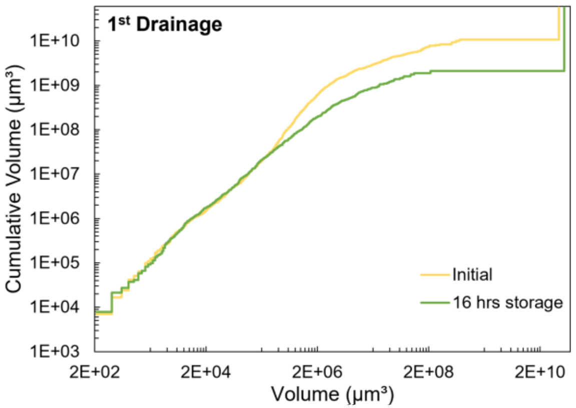
- Rearrangement and tendency for some of the smaller bubbles to disappear and add to the larger bubbles but not necessary completely in a connected ganglion
- After imbibition one big ganglia begins to dominate the volume, which makes the withdrawal of hydrogen through a connected pathway possible.

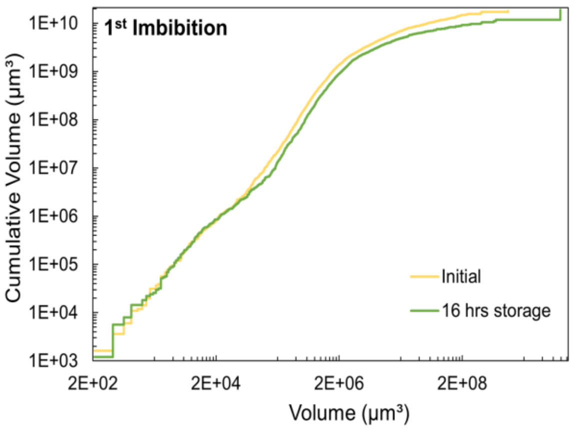


Ostwald Ripening









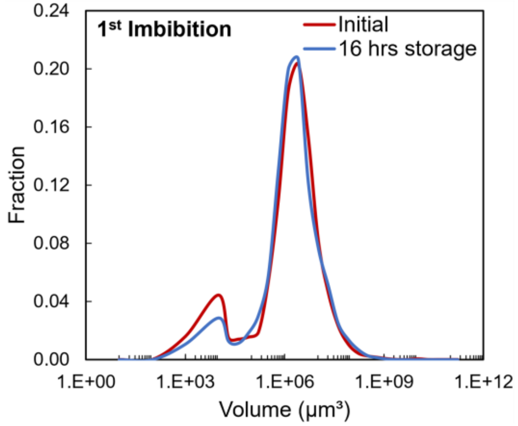
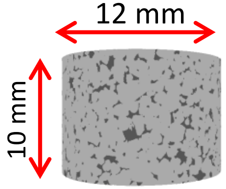


Figure 6: Ganglia size distribution of hydrogen-brine during first cycle for a sub volume.

Analysis of discrete ganglia

Ganglion size distribution (cycle 2 & 3)



Section 5

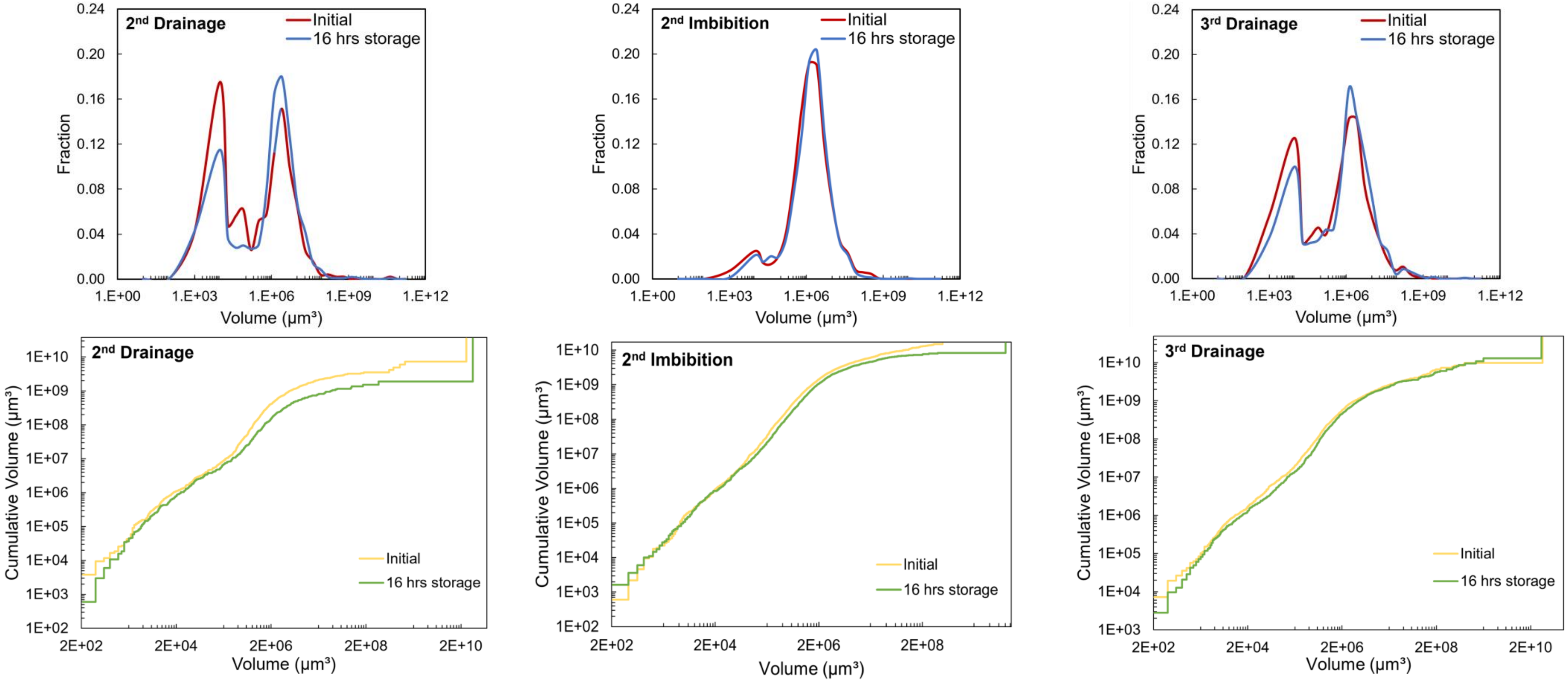
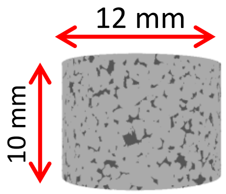


Figure 7: Ganglia size distribution of hydrogen-brine during second and third cycles for a sub volume.

Pore occupancy maps

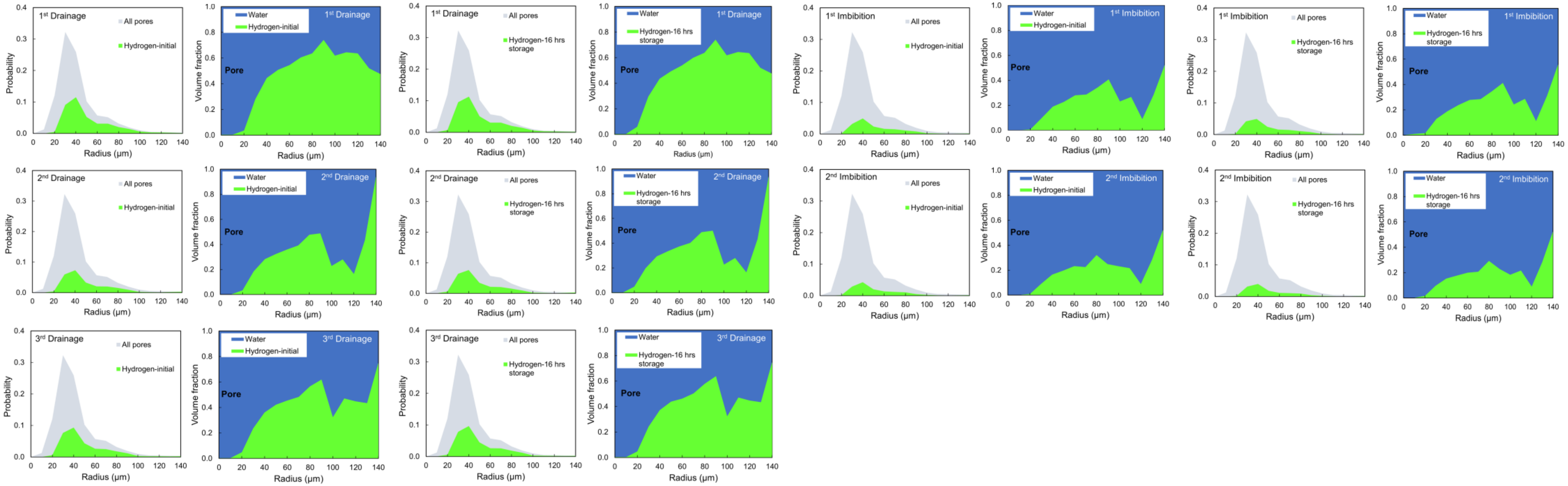


Section 5

Cycle 1

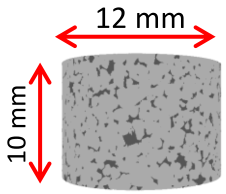
Cycle 2

Cycle 3



As expected, gas (shown in green) tends to reside in the larger pores. Both the actual distribution and occupied fractions are shown.

Throat occupancy maps



Section 5

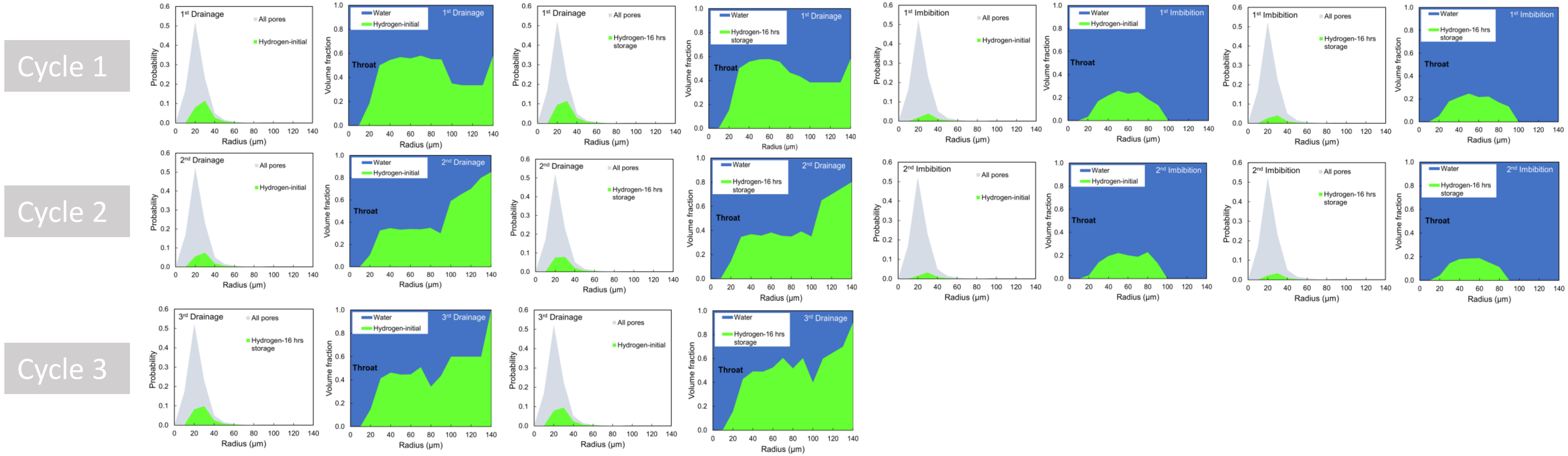
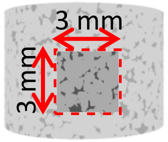


Figure 8: Histogram of the distribution of gas-filled pore elements at different stages of gas injection and the throat occupancy of the volume fraction at different radii.

Measurement of interfacial area & capillary pressure analysis



Section 5
Sub volume
(500×500×500)

- Can't rely too much on pressure because of uncertainty in the measurement.
- Capillary pressure after drainage is slightly higher than after imbibition.
- No clear trend between initial and after waiting 16hrs, can go up or down.

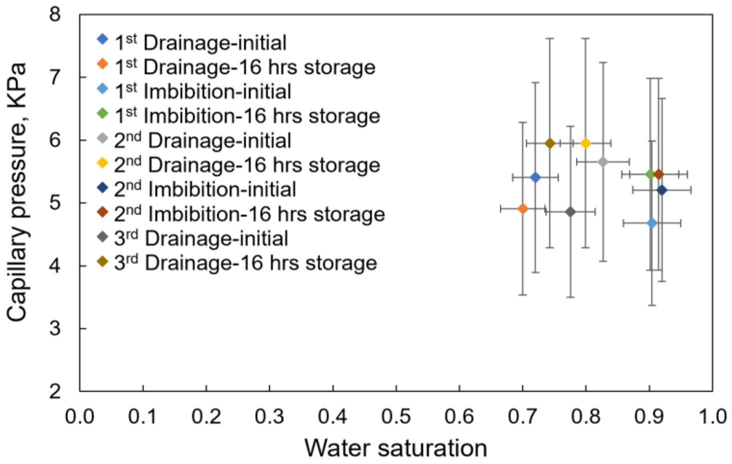


Fig 9: Capillary pressure measurements of each two phases for initial and after 16hrs.

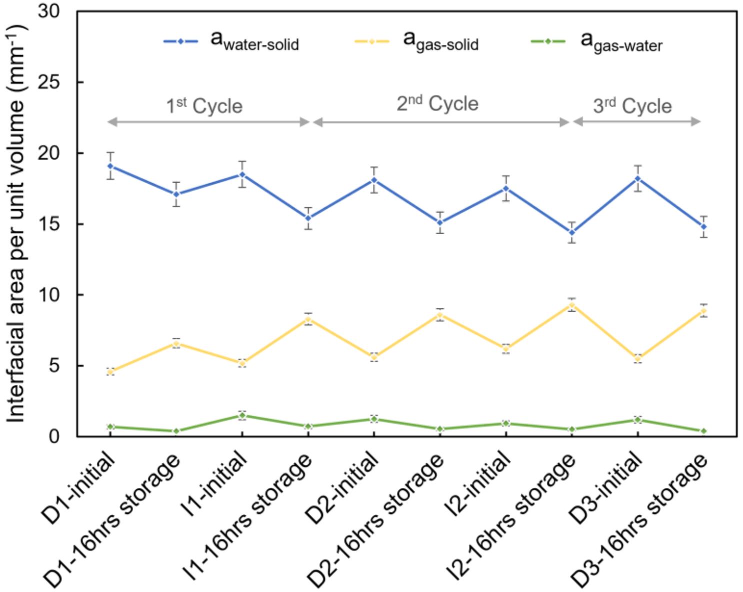


Figure 10: Interfacial area measurements of each two phases for initial and after 16hrs for 3 cycles

Improvement of the experiment protocol

- Porous plate to allow a higher initial hydrogen saturation.
- Using imposed pressures to determine capillary pressure in drainage.
- Pre-equilibrated brine to reduce the effect of dissolution.
- Higher pressure, 10 MPa, to better represent reservoir conditions.

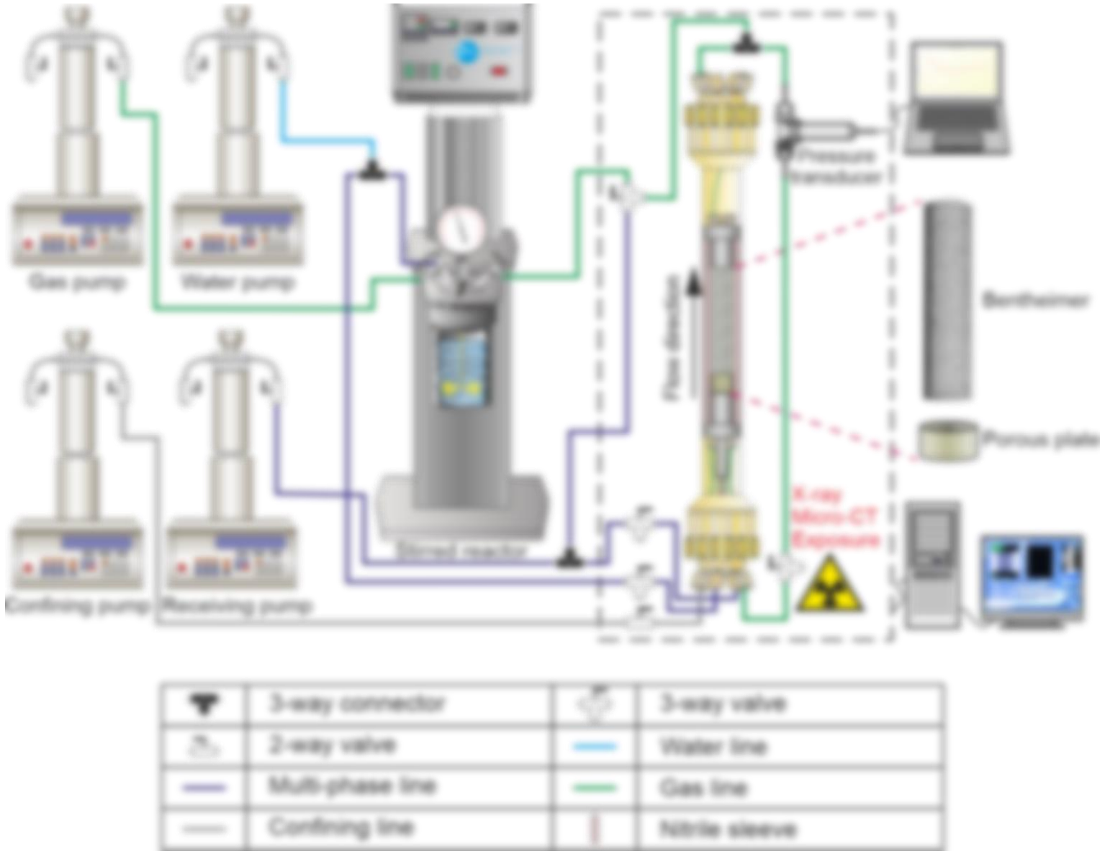
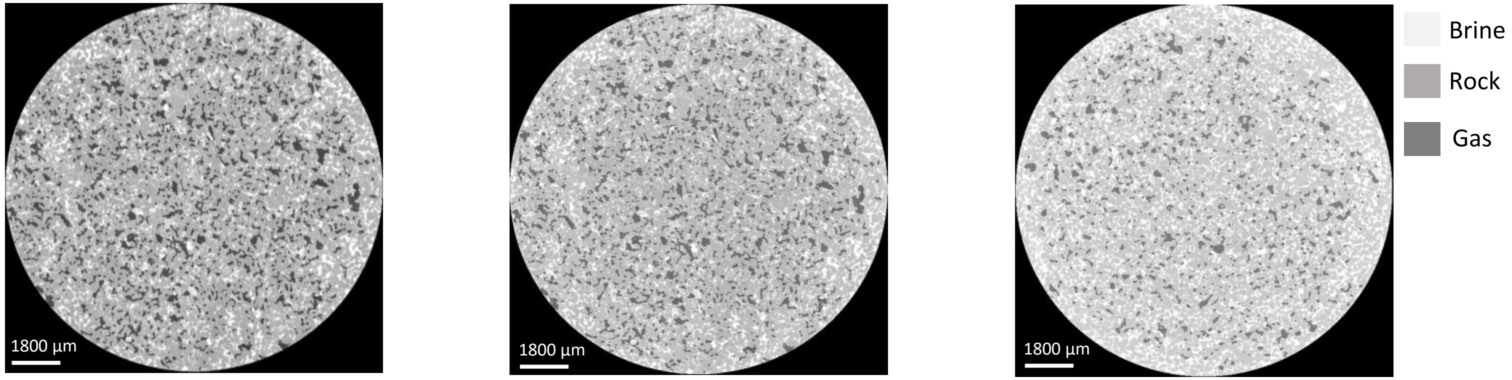


Figure 11: Schematic diagram for the two-phase gas-water experiment.

Did the experiment work?

- High Initial gas saturation after hydrogen injection
- Uniform gas saturation after injection and withdrawal



Drainage Initial | Drainage 16 hrs storage | Imbibition Initial

Figure 12: Dry two-dimensional slices of three-dimensional images of the Hydrogen-brine experiment.

Conclusions

- Studying hysteresis during hydrogen injection is the main purpose of my work.
- The relationship between saturation, area, curvature and Gaussian curvature will be measured.
- Drainage and imbibition processes in 3 cycles for a hydrogen-brine system at the unsteady state condition have been investigated.
- The gas saturation was between 30% and 40% after each gas injection near the top of the sample
- Dissolving gas in brine changes the gas saturation along the sample.
- We saw the effect of Ostwald ripening: some of the smaller bubbles disappear and are rearranged to the larger bubbles but are not necessary in a connected ganglion.

Future work

- I have looked at the carbonate sample for which I have performed a similar suite of experiments, and I am still analysing the results.
- Finishing the result analysis of Hydrogen-Brine experiment (porous plate).
- Preparing the procedure for a new set of experiment, different types of rock.
- How can we extend the experimental protocol to measure capillary pressure and relative permeability for a range of saturations, after allowing pore-scale equilibrium (Ostwald ripening)?

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Thank you