



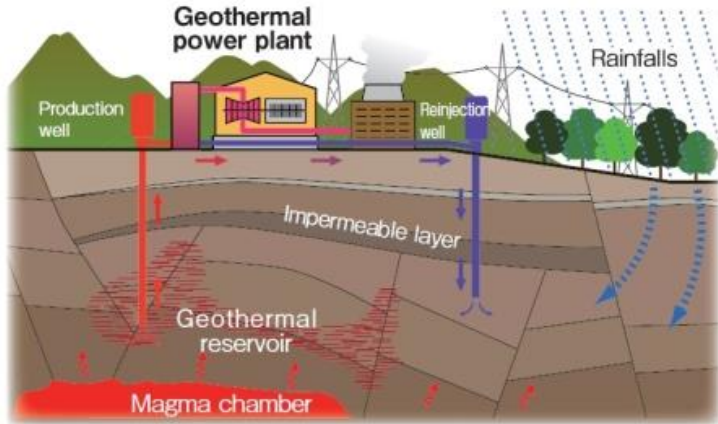
Study of the multiphase saturation distributions within a fracture

Meritxell Gran, C. Zahasky, R. Pollyea, S. Benson

Stanford University Department of Energy Resources Engineering

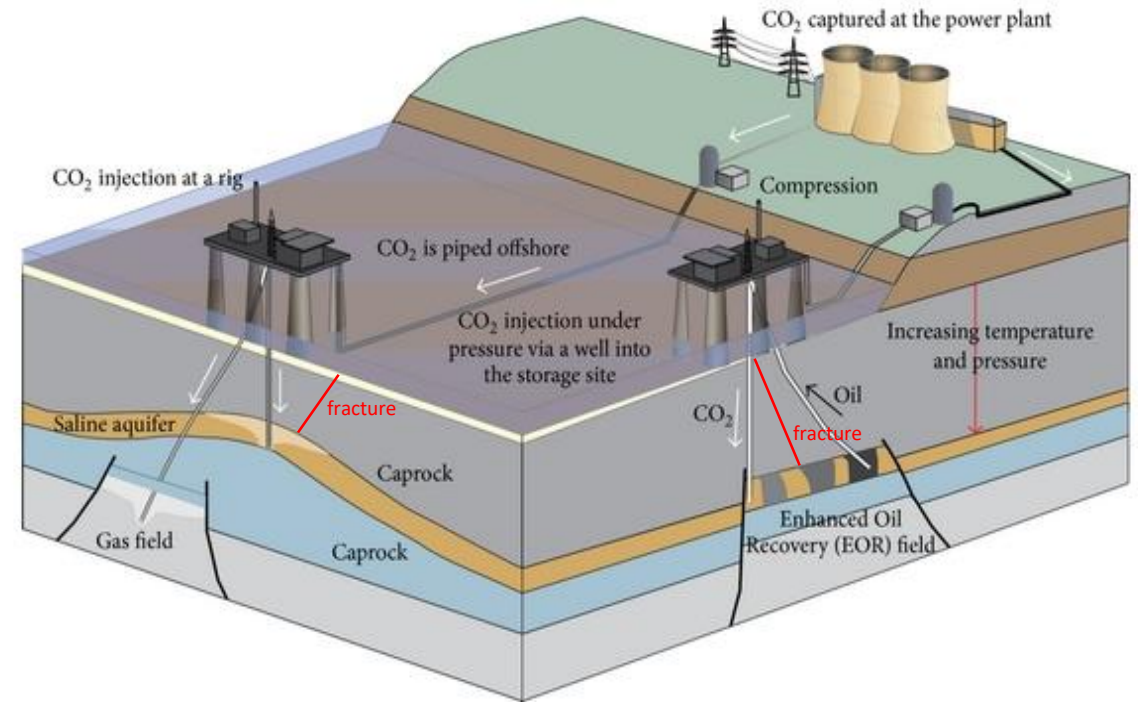
Fractures are the dominant flow paths in a wide range of environments

Geothermal energy



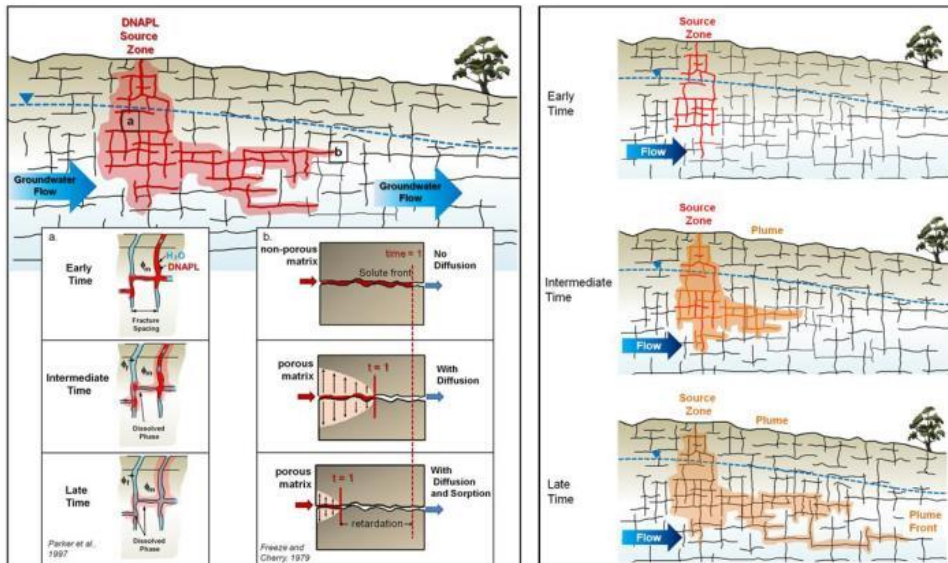
www.jogmec.go.jp

Caprock integrity-CO₂ storage



Modified from Sheng et al. 2015

Contaminant transport



Parker et al. 2012

Unsolved problems

The fundamentals of multiphase flow in fractures have been studied:

- Experimentally, mainly by means of synthetic fractures -> not much data available
- Numerically, assuming linear relative permeability curves -> large errors in the predictions

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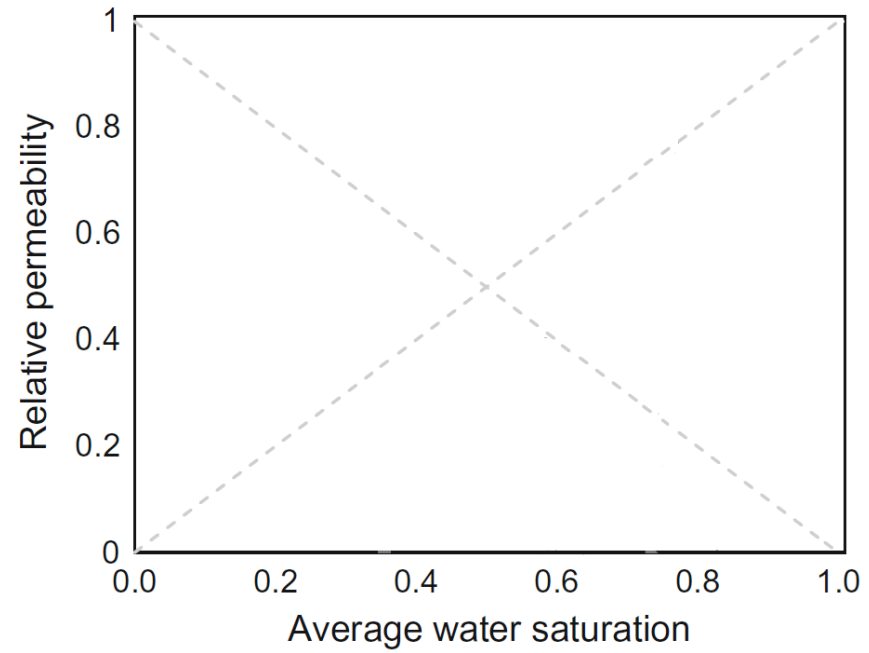
Our goal

Measure relative permeability and water saturation distribution in a natural fracture in order to:

- Analyze the behavior of liquid and gas fluxes through the fracture.
- Provide relative permeability curves for numerical flow simulation.

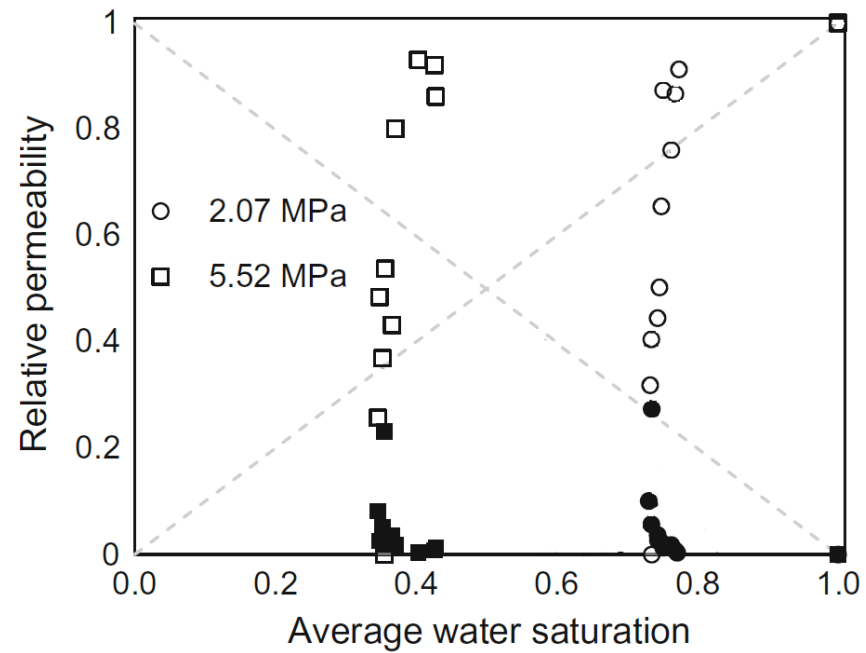
Previous work carried out in our group

Huo and Benson 2016: single saw-cut fracture in a sandstone core



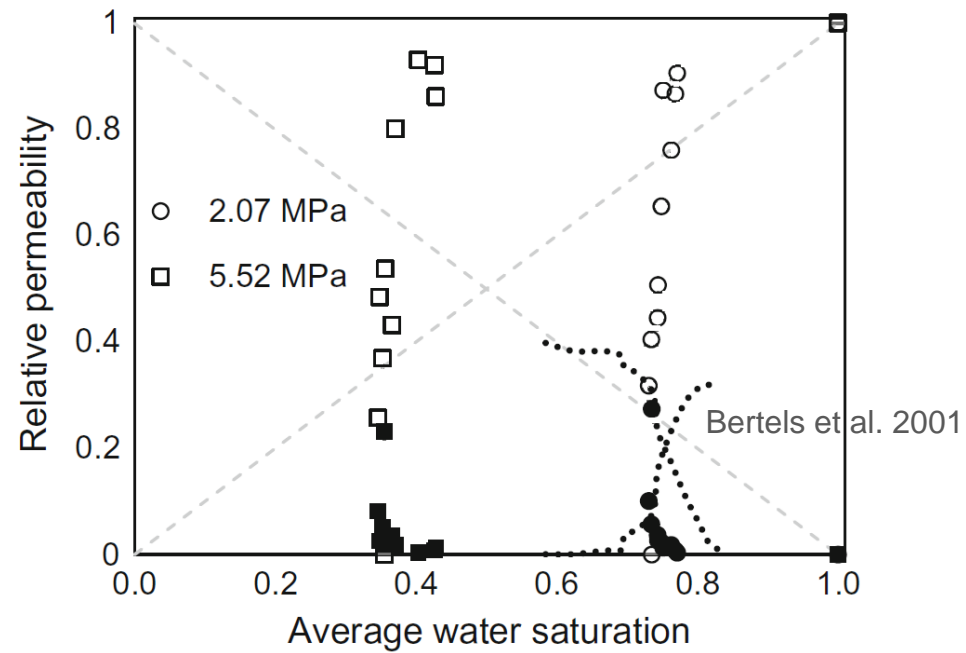
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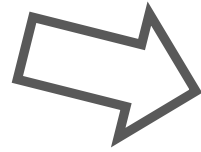
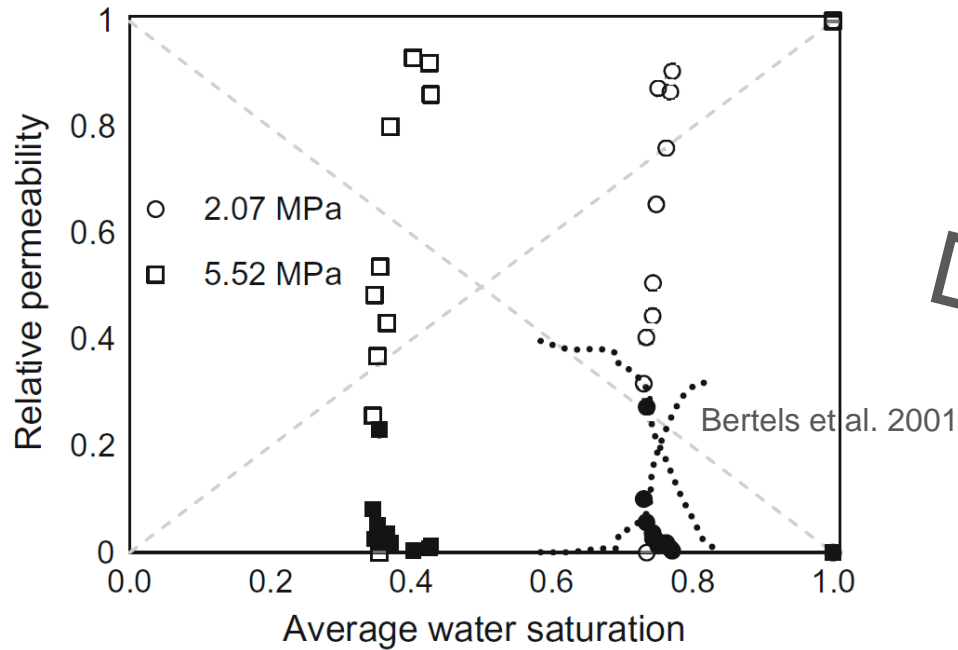
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Huo and Benson 2016: single saw-cut fracture in a sandstone core



Current project:

Columbia River Basalt Group (Washington)



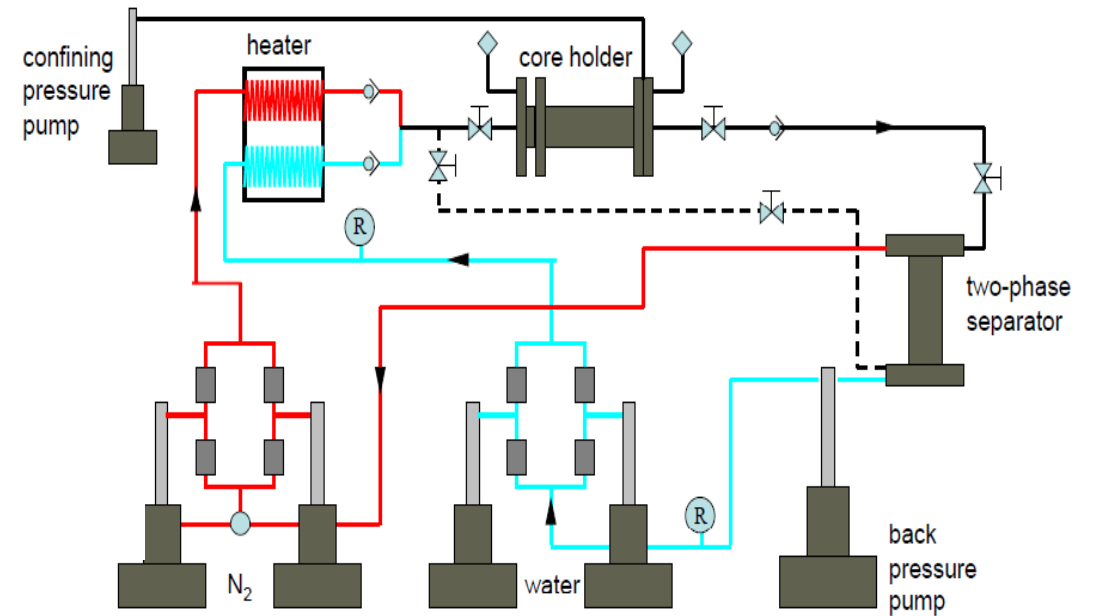
Fracture in a basalt core

Experimental techniques:

- Core flooding -> K & k_{rel}
- X-ray CT imaging -> fracture aperture
- PET imaging -> fluid saturation distribution

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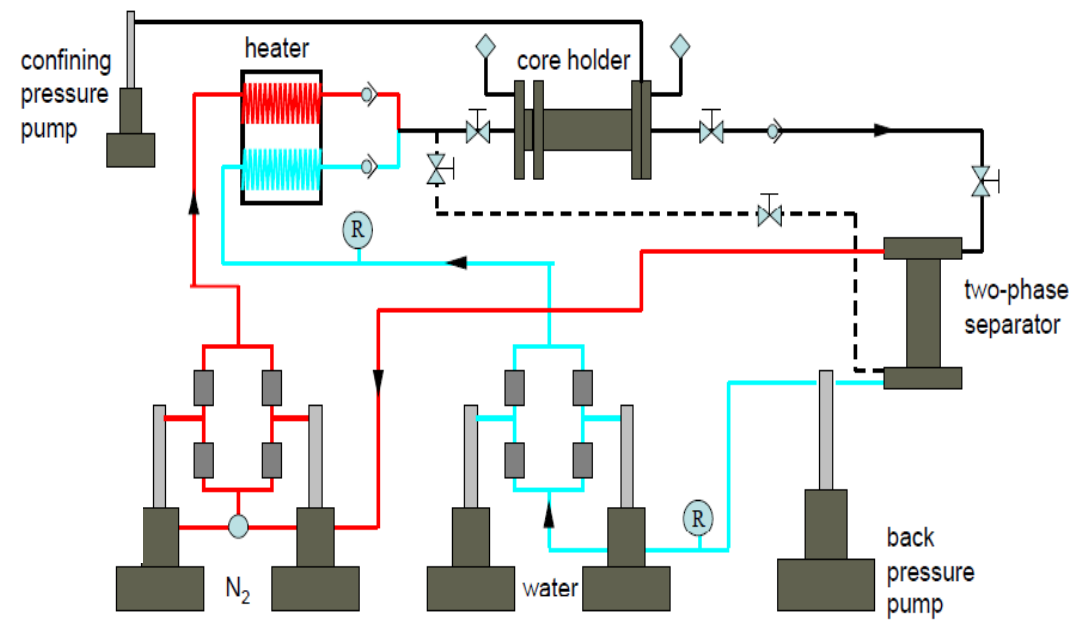


(Figure modified from Huo & Benson 2016)

300 psi and 50° C

Experimental techniques:

- Core flooding -> K & k_{rel}
- X-ray CT imaging -> fracture aperture
- PET imaging -> fluid saturation distribution



(Figure modified from Huo & Benson 2016) 300 psi and 50° C

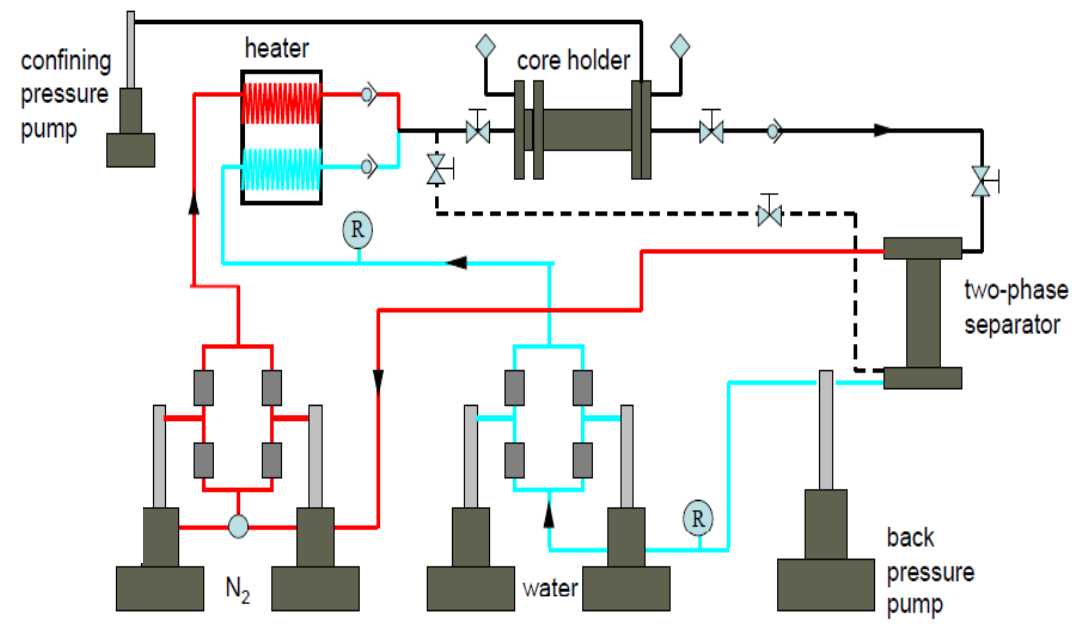
With X-ray CT, the intensity of a collimated X-ray beam passing through the core is measured by detectors located opposite the x-ray source.

Experimental techniques:

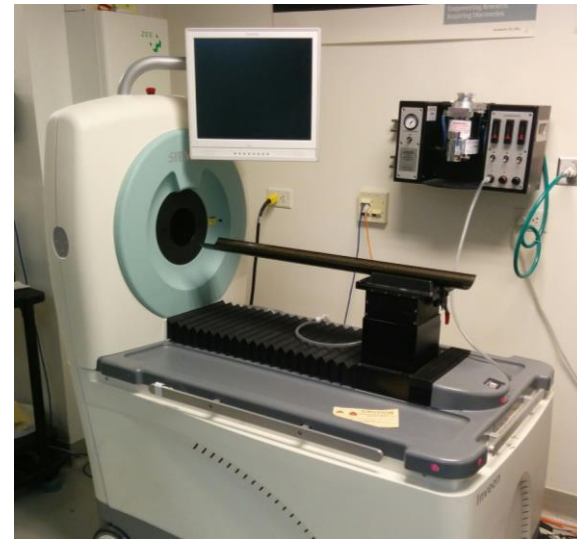
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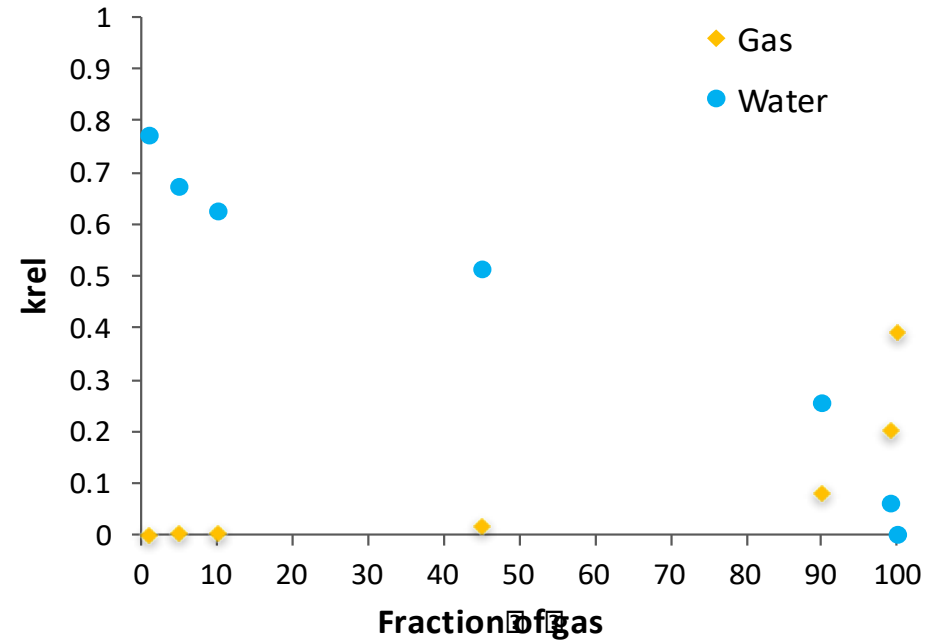
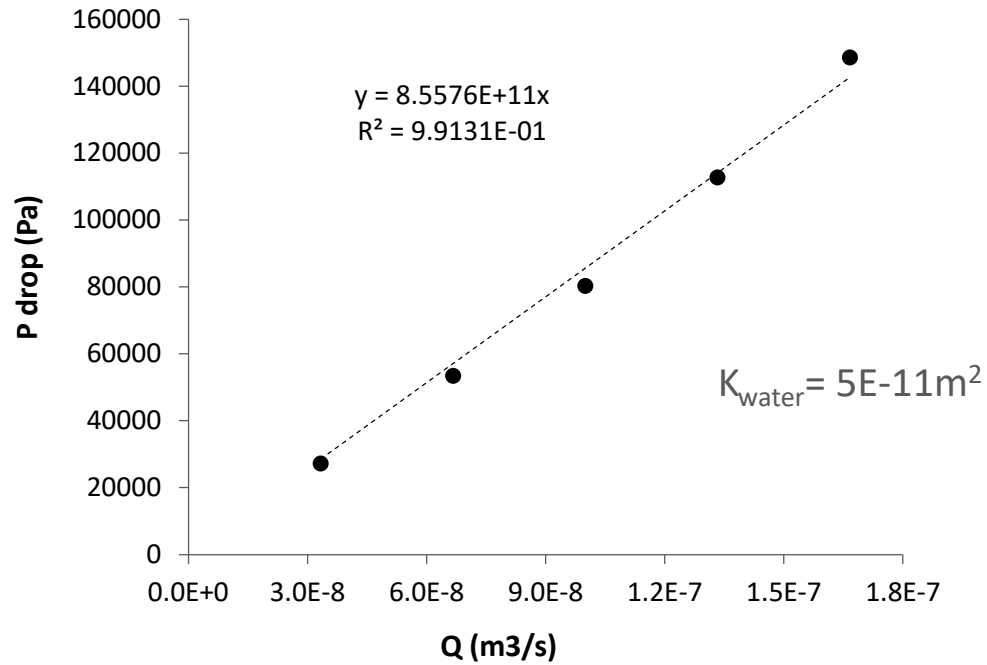


(Figure modified from Huo & Benson 2016) 300 psi and 50° C



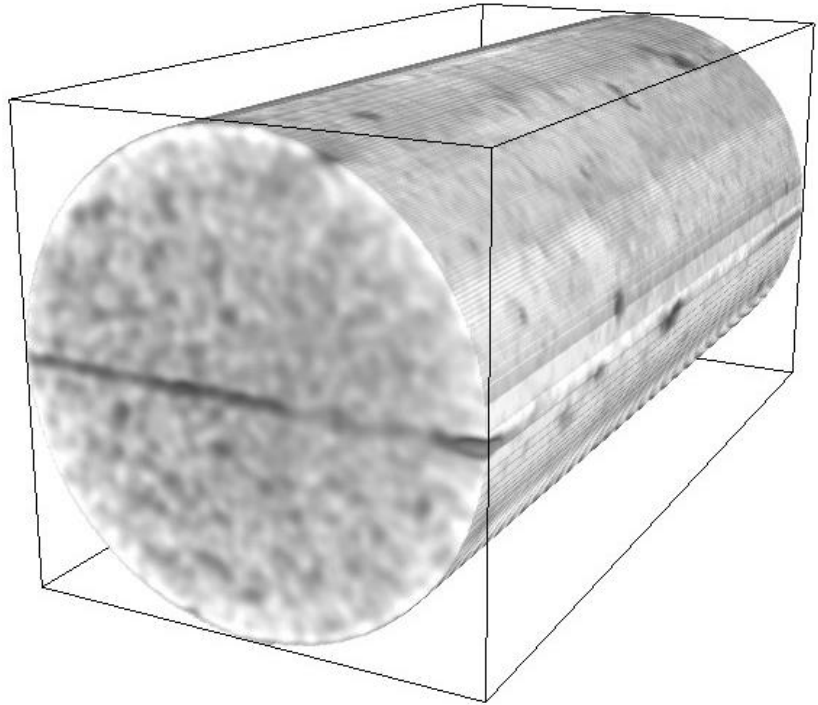
The Positron Emission Tomography: emitting radionuclides detected with an array of photon detectors surrounding the core.

Results from the core flooding -> K & k_{rel} vs fraction of gas

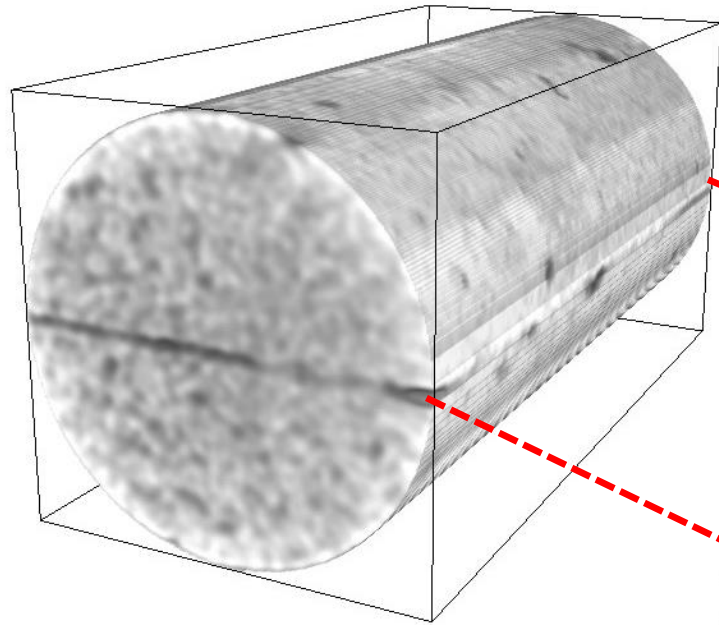


Flow shifts quickly from being dominated by water to being dominated by gas.

Results from the X-ray CT imaging -> fracture aperture (structure)

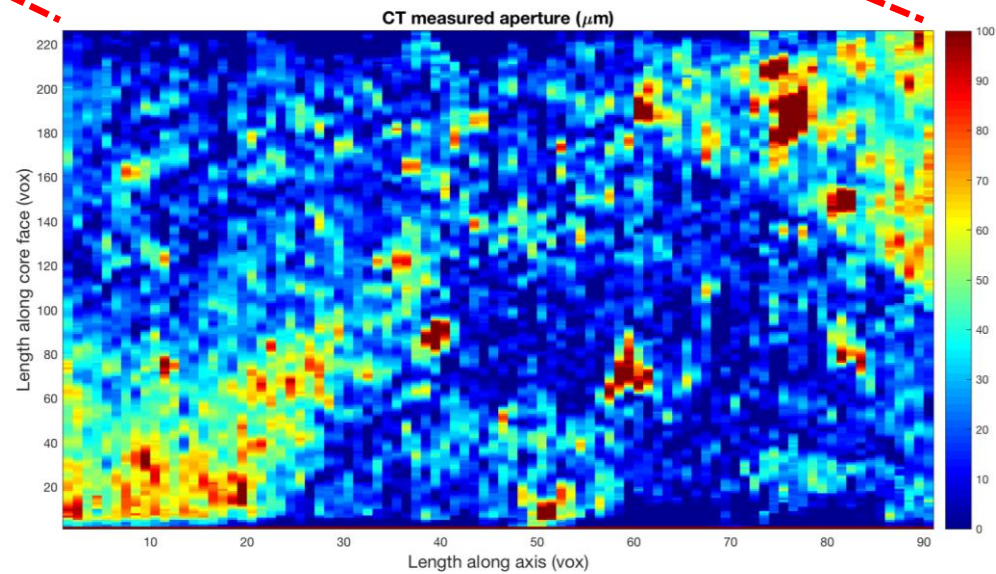


Results from the X-ray CT imaging -> fracture aperture (structure)



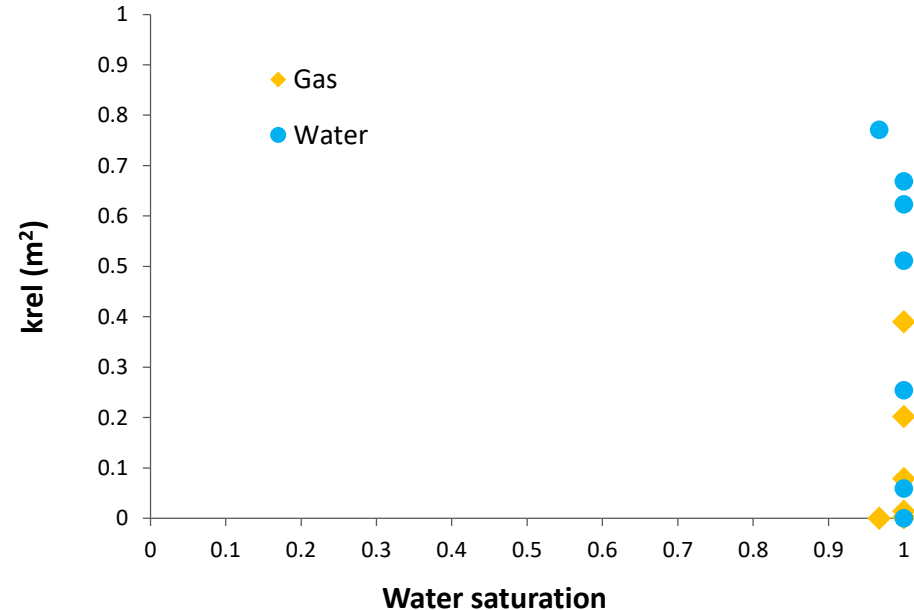
Fracture Aperture:

mean=26 μ , median=21 μ



Results from core flooding and CT combination -> k_{rel} curves

- Core flooding -> K & k_{rel}
- X-ray CT imaging -> fracture aperture



- Not true, because we know gas is pushing water out of the fracture.

- From the CT images, we can't see the gas displacing the water.

PET imaging methodology

Experiment procedure:

1. Fracture fully saturated with water (no tracer).
2. Injection of tracer mixed in the water.
3. Gas and water-tracer co-injection at different ratios.

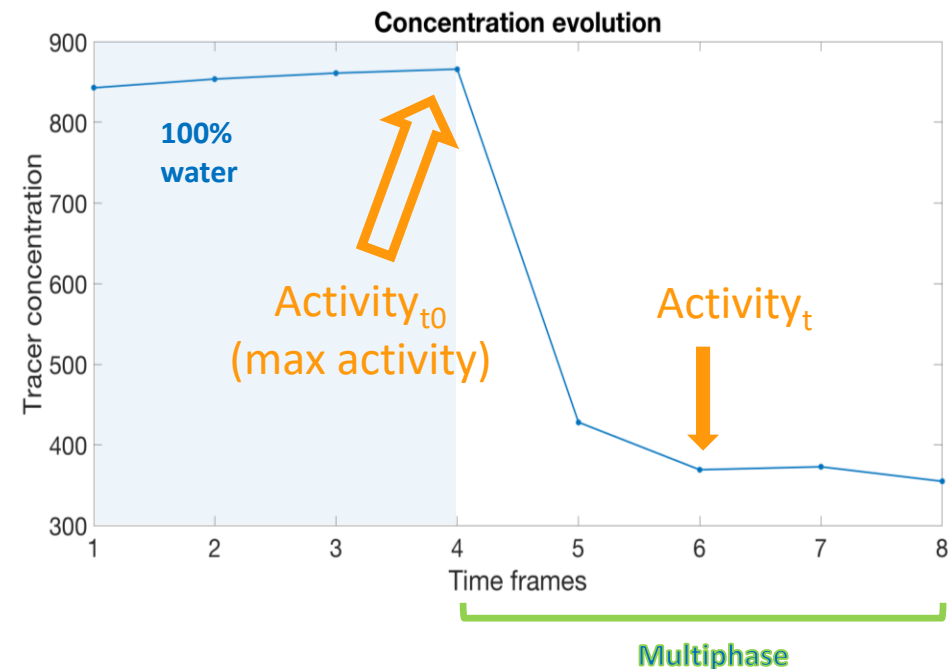
PET imaging methodology

Experiment procedure:

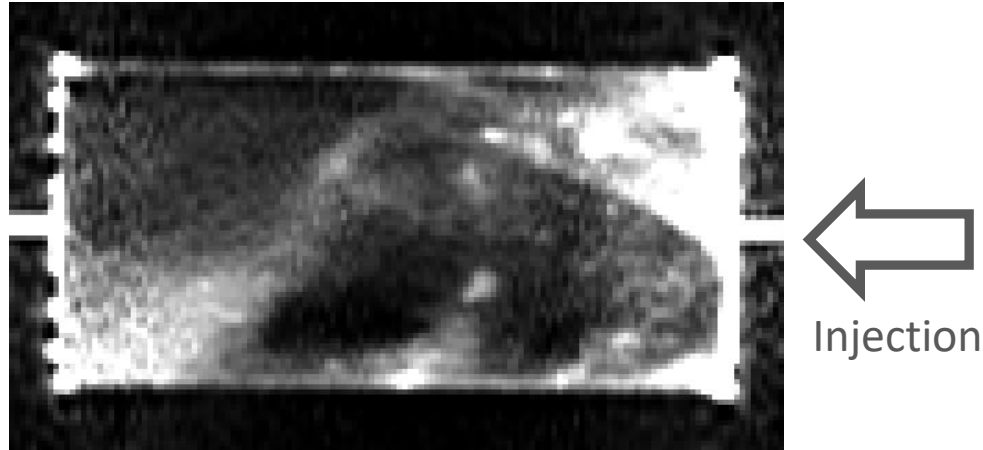
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Post-processing:

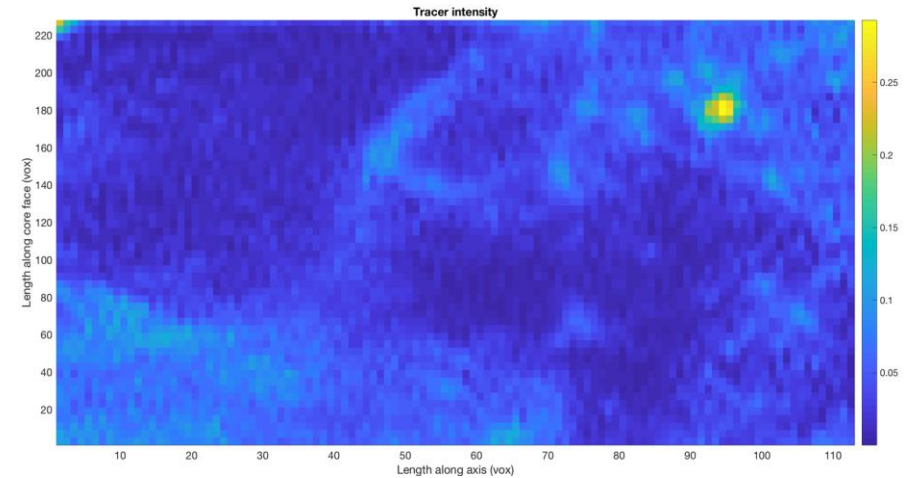
- We use the activity measured at full saturation as a reference.
- Saturations during the multiphase are calculated respect this initial (maximum) value: $S = \text{activity}_t / \text{activity}_{t_0}$



Results from PET imaging -> fluid saturation distribution (flow)



Tracer activity map



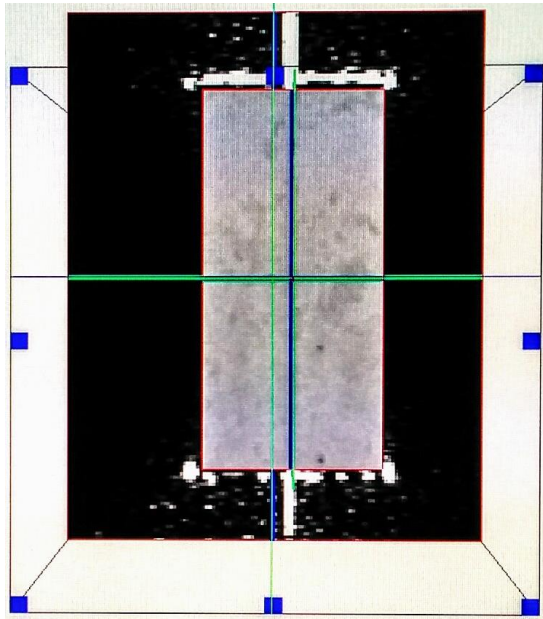
Bright areas = high tracer activity -> water presence

First attempt to calculate saturations -> we got saturations bigger than 1.

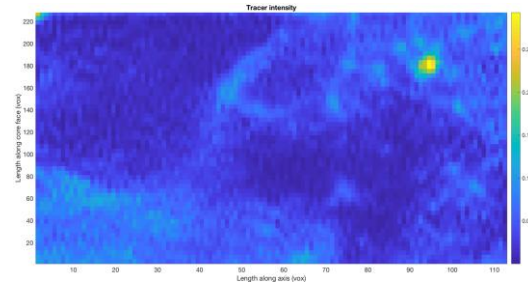
And that's because there are areas where activity increases during the multiphase injection.

Provably related with the amplitude of the fracture?

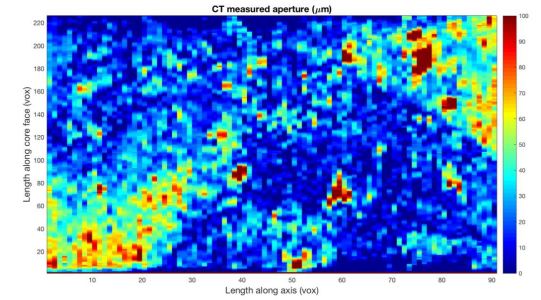
CT and PET images superposition



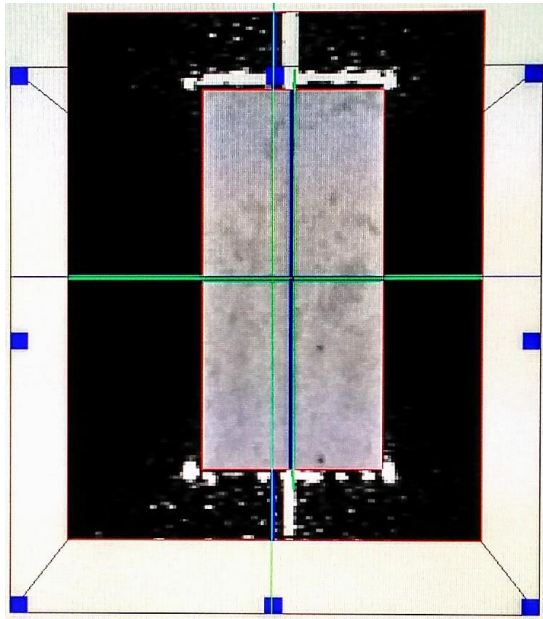
Tracer activity map (from PET)



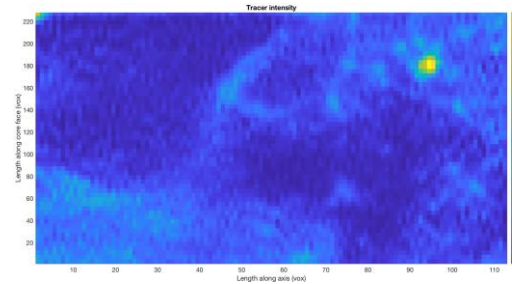
Aperture map (from CT)



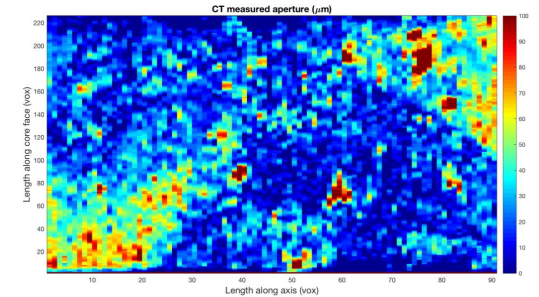
CT and PET images superposition



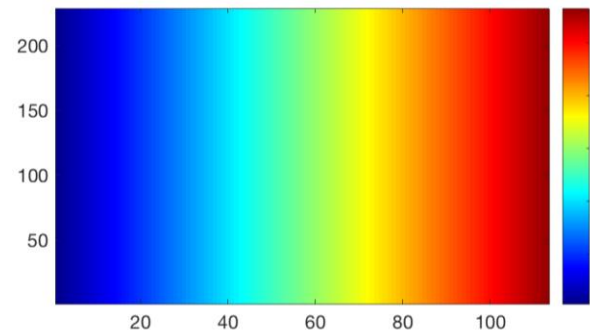
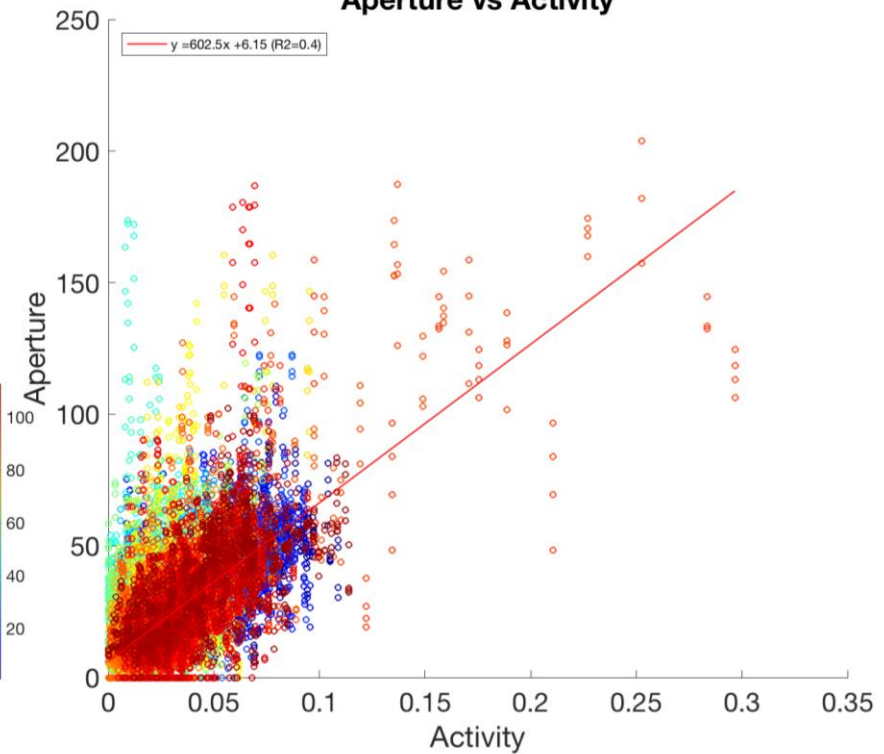
Tracer activity map (from PET)



Aperture map (from CT)



Aperture vs Activity

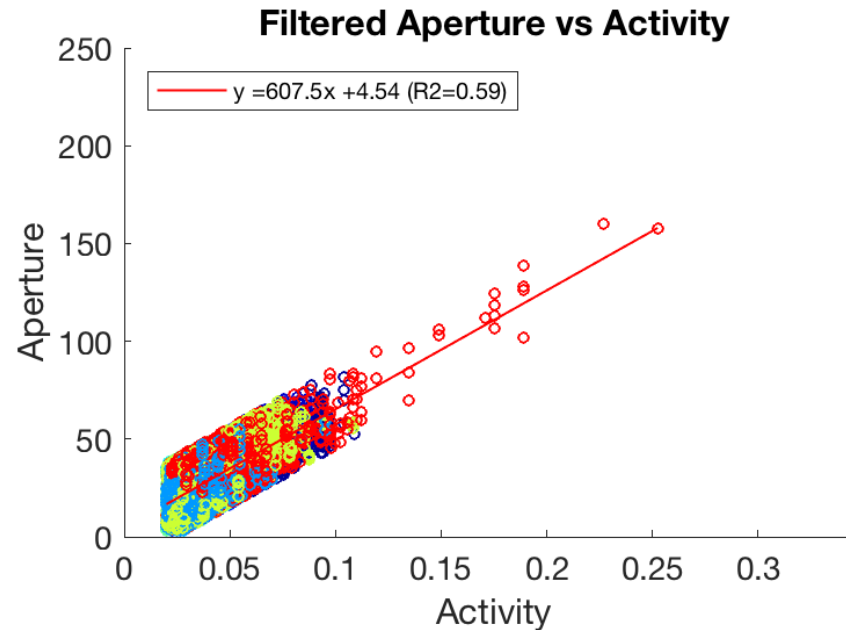


The tracer is not fully distributed through the fracture

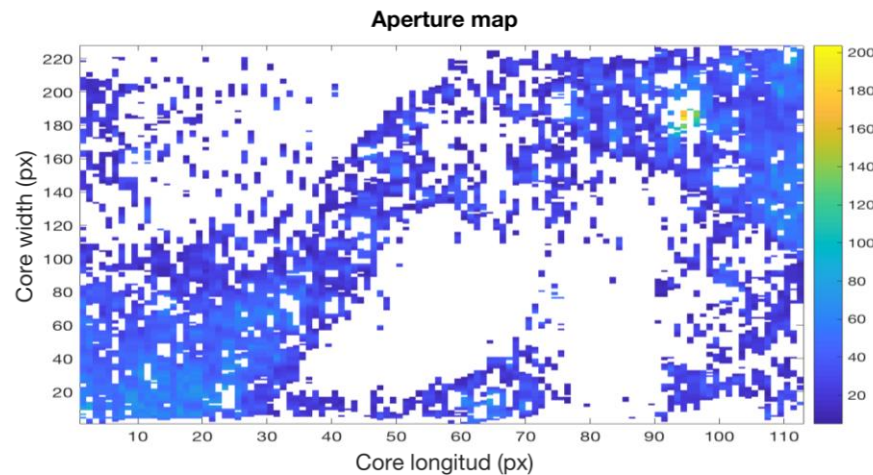
Use of filters to discard the no-flow areas

We set up 3 filters:

- 1 standard deviation
- Minimum activity=0.02
- Minimum aperture=3 μ

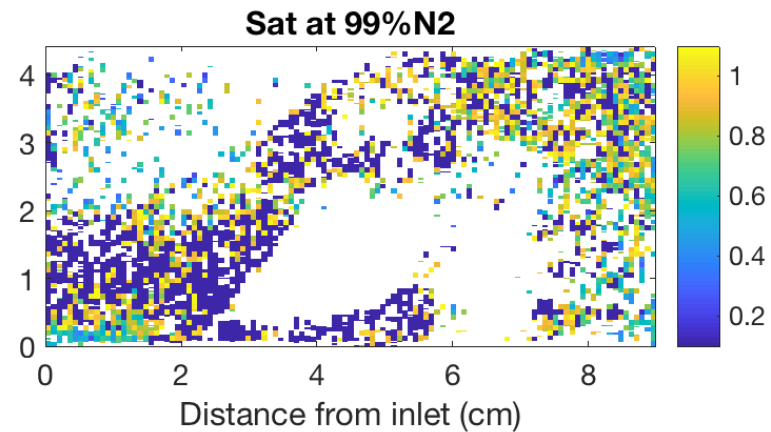
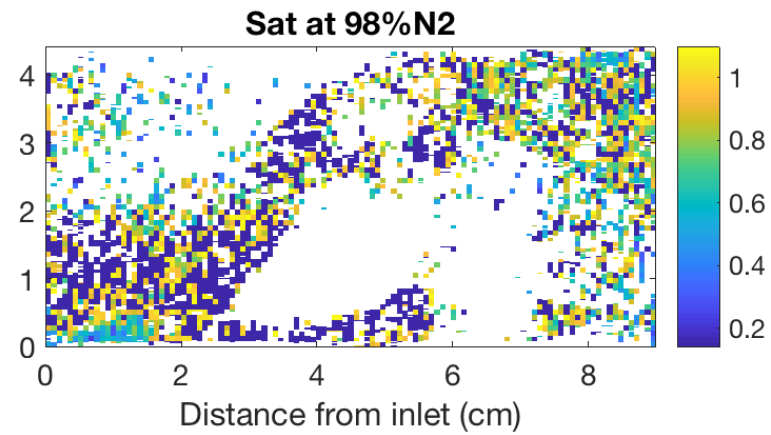
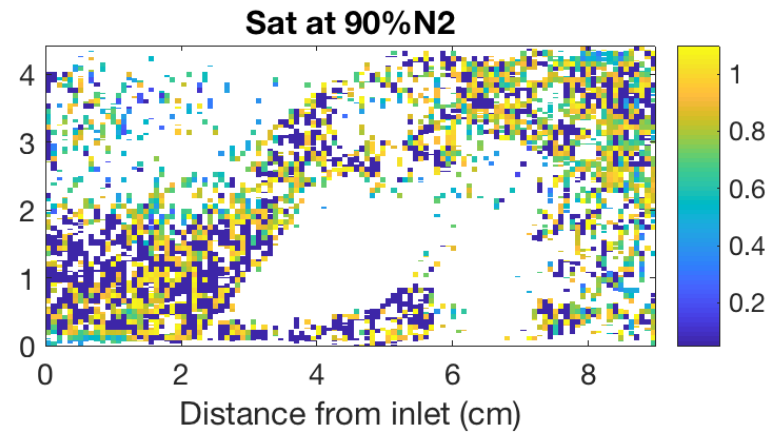


Aperture map after discarding these pixels:

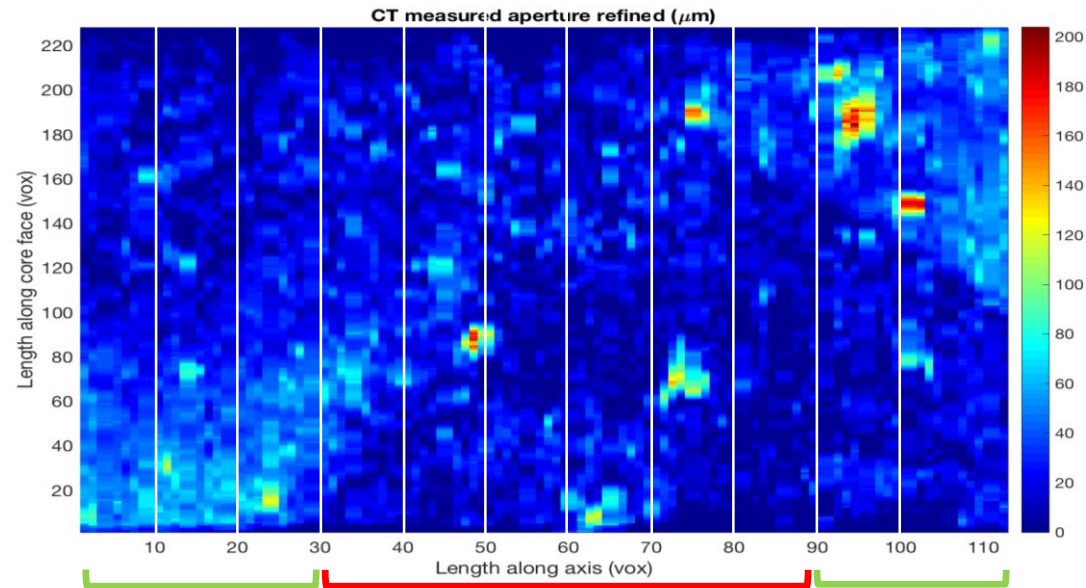


We calculate saturations again-> there are still some areas where activity increases during the multiphase injection.

Calculated saturation maps



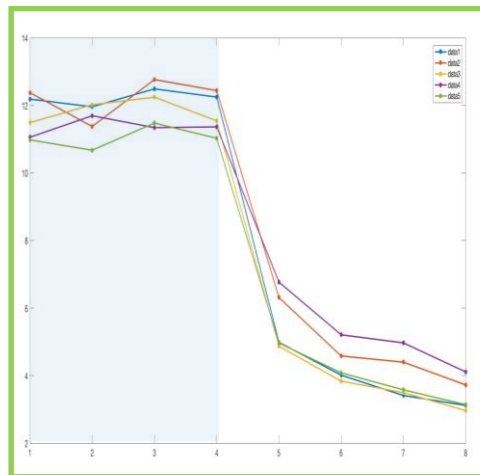
The tracer is not well distributed in the central narrow area



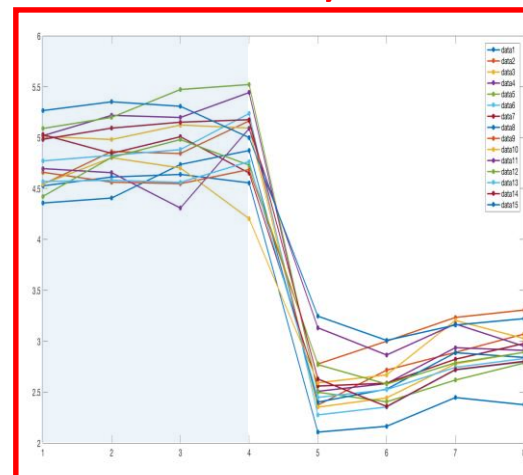
Activity evolution by slice:

Increasing activity

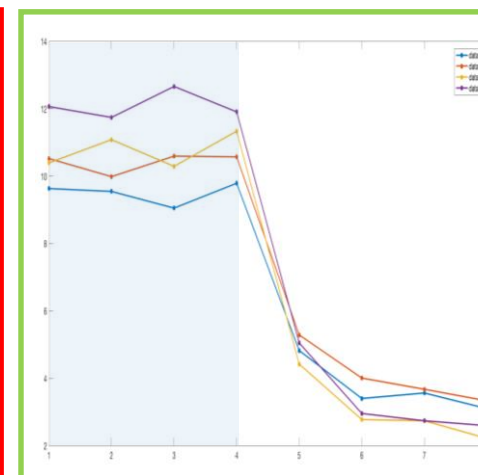
Decreasing activity



Slices 1 to 5



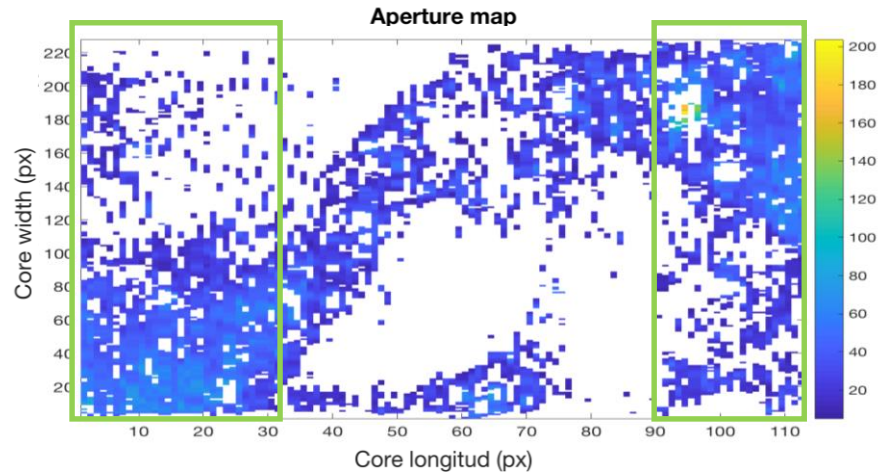
Slices 46 to 55



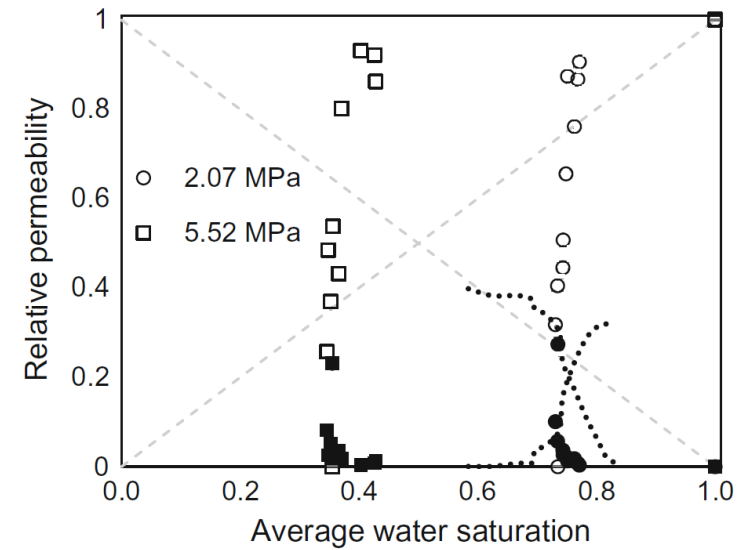
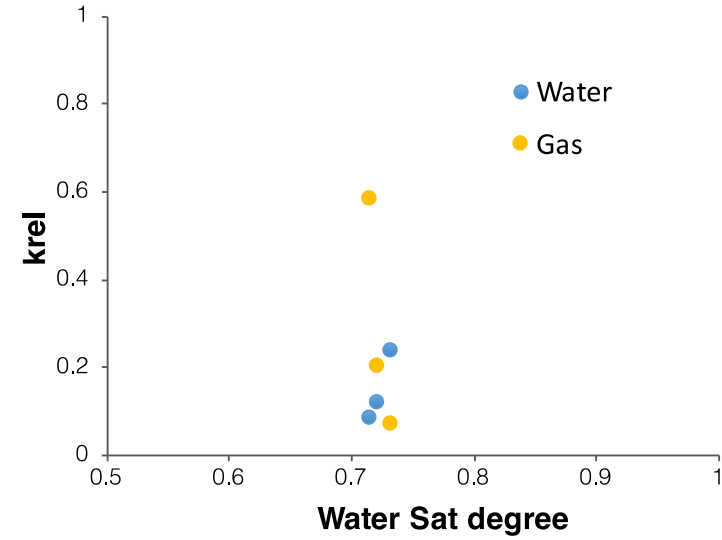
Slices 110 to 113

Decreasing activity

We obtain saturations in the selected regions

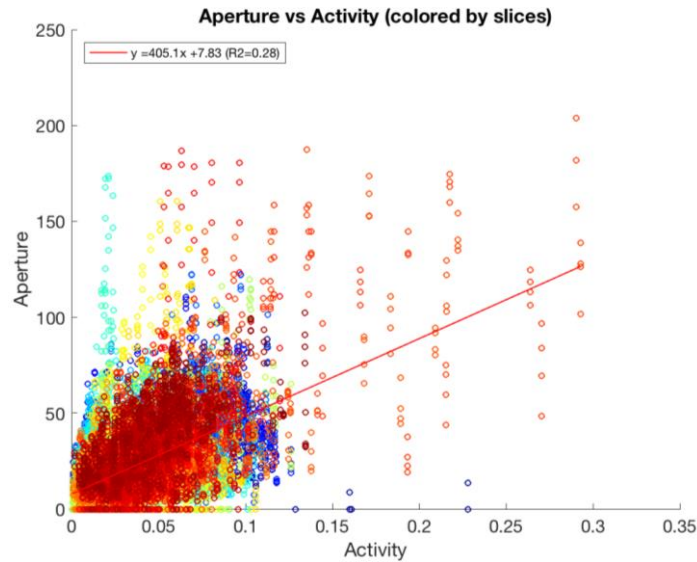


We can calculate saturations in a fracture combining CT and PET data



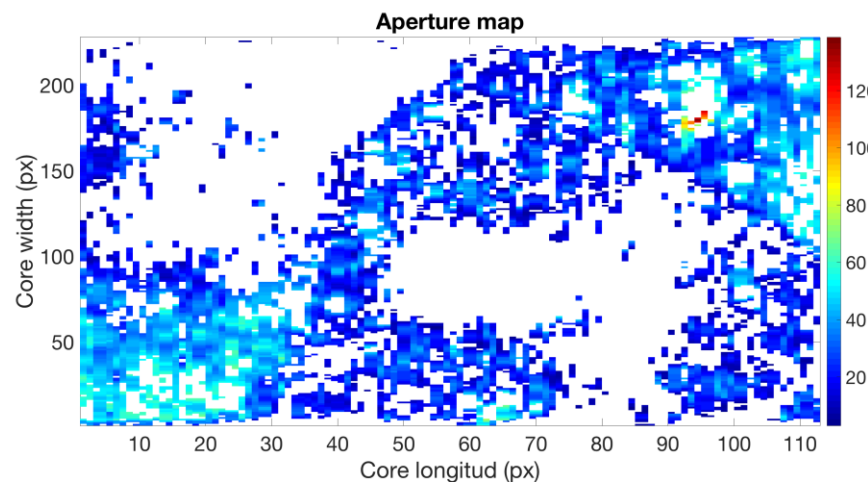
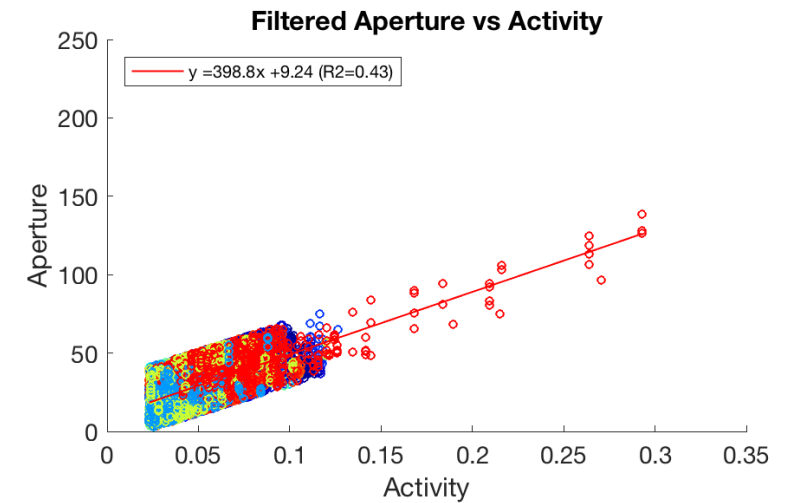
New PET experiment looking for a better tracer distribution

We repeat the experiment injecting tracer at a lower flow rate for a longer time



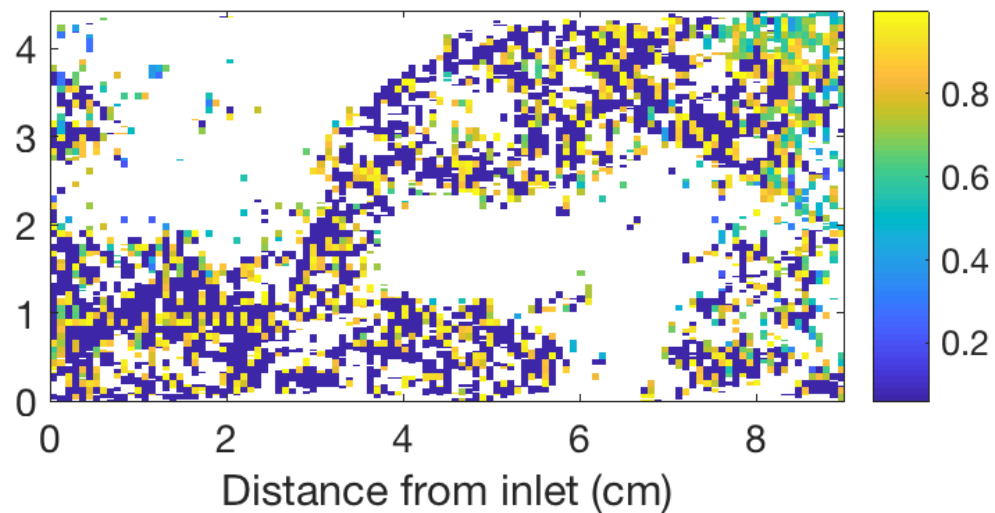
We set up 3 filters:

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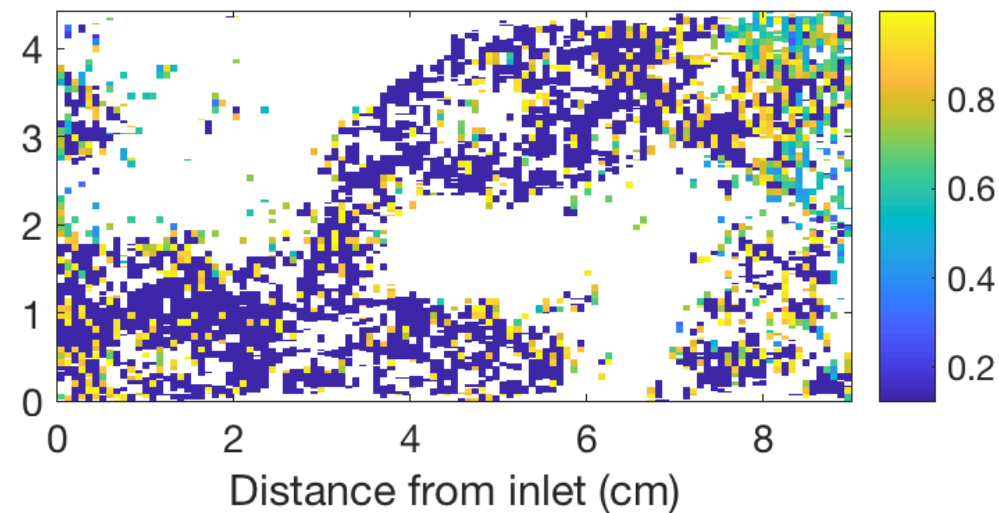


Calculated saturation maps

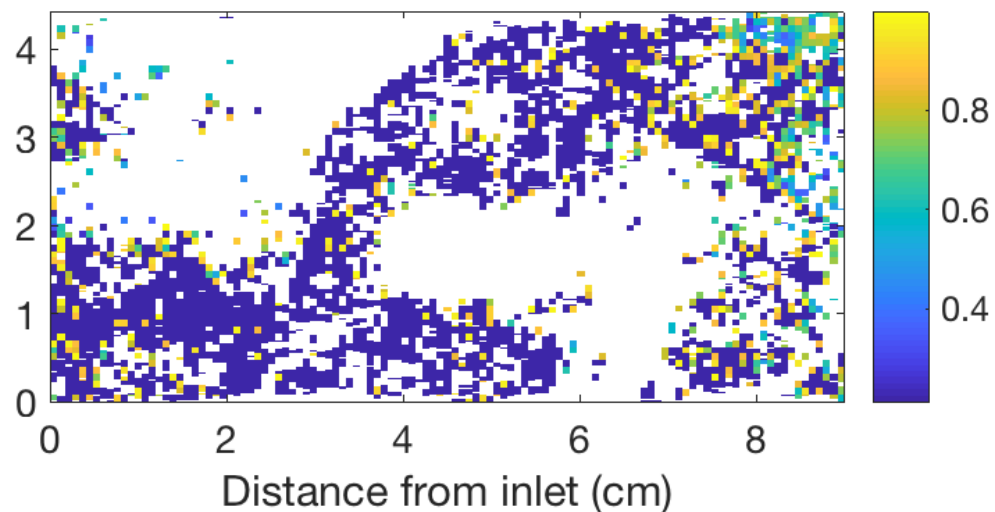
Sat at 84%N2



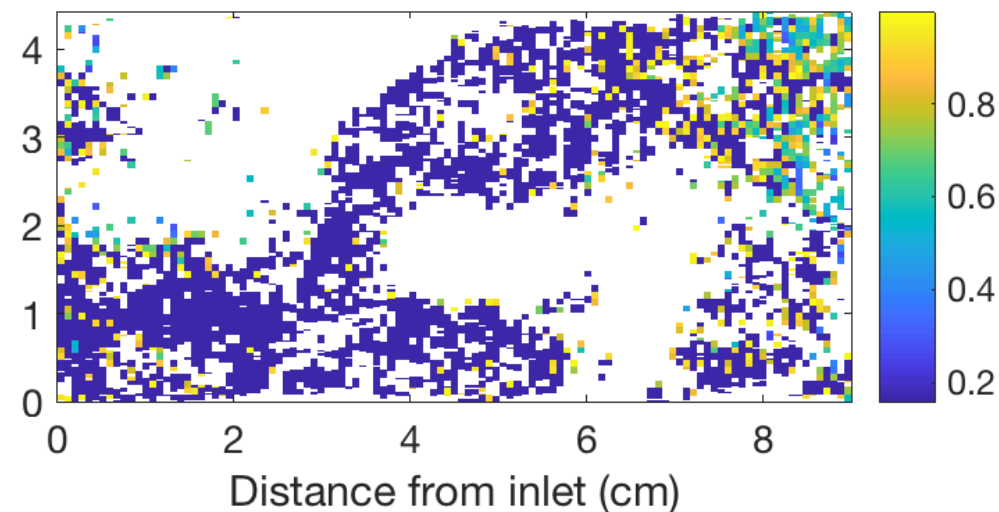
Sat at 94%N2



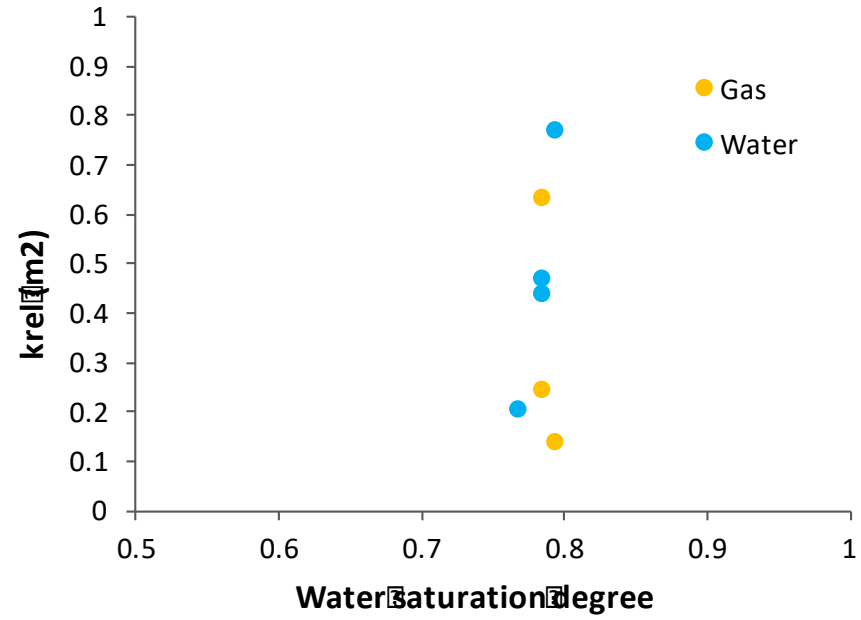
Sat at 98%N2



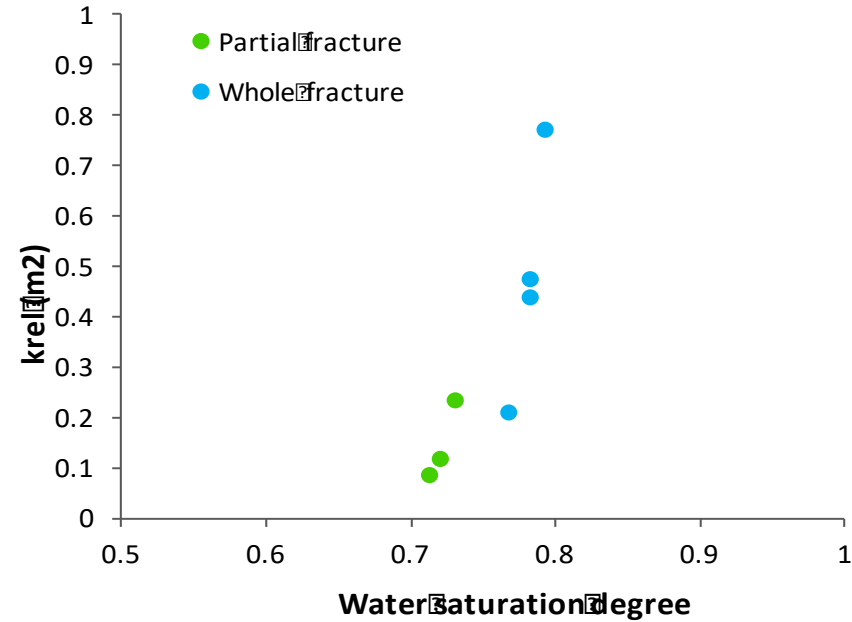
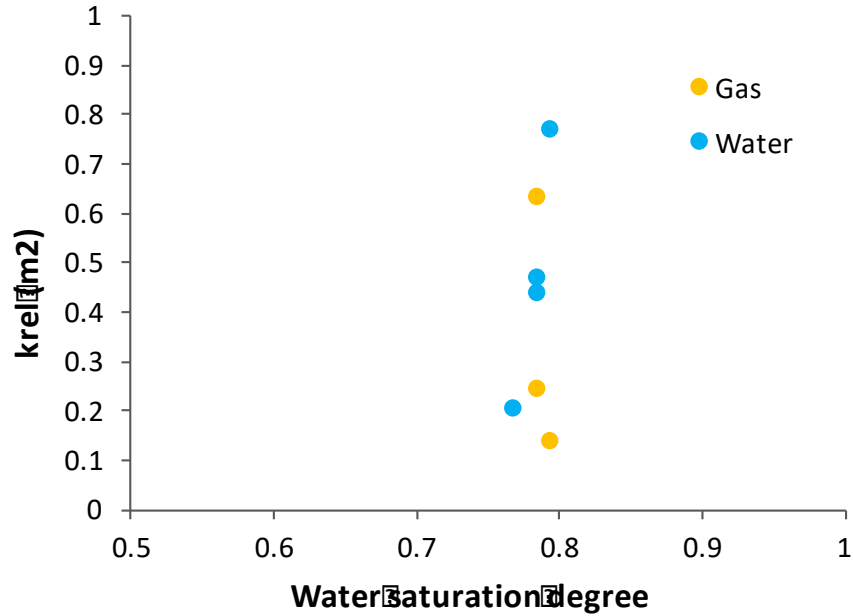
Sat at 99.8%N2



We obtain saturations for the whole main flow path



We obtain saturations for the whole main flow path



- Lower flow rates allow better fluid distribution within the fracture
- We can calculate k_{rel} curves in a fracture combining CT and PET data

Conclusions

- Combining core flooding experiments, CT and PET imaging we can calculate the relative permeability curves vs water saturation in a fracture.
- Gas flow does not displace completely the water inside the fracture.
- Multiphase flow shifts quickly from liquid to gas dominated system.
- Water flows mainly through the bigger paths not saturating immediately all the fracture.
- Not only the fracture aperture but also the injection flow rate controls the fluid distribution in the fracture.

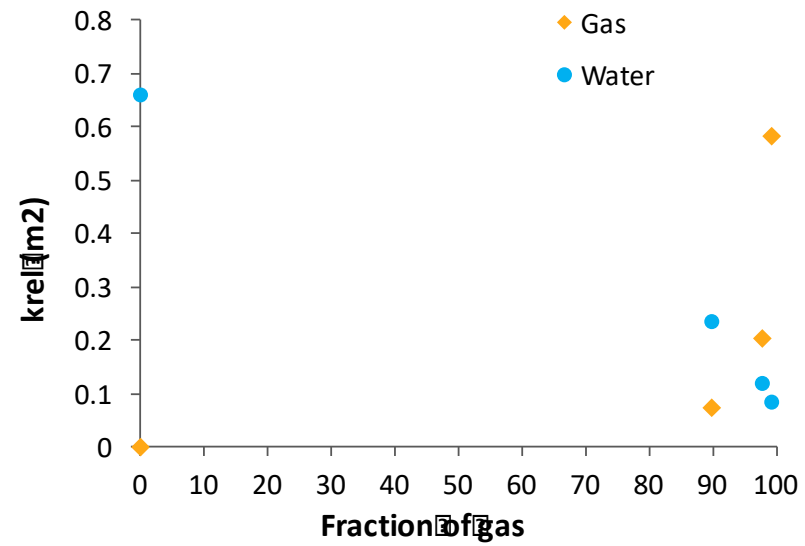
Acknowledgements

Stanford
Center for Carbon Storage



Global Climate & Energy Project
STANFORD UNIVERSITY

From march21 PET experiment



Experimental procedure



With x-ray CT, the intensity of a collimated x-ray beam passing through the core is measured by detectors located opposite the x-ray source.

Voxel size: 0.18 x 0.18 x 0.625 mm

Current of 200 mA

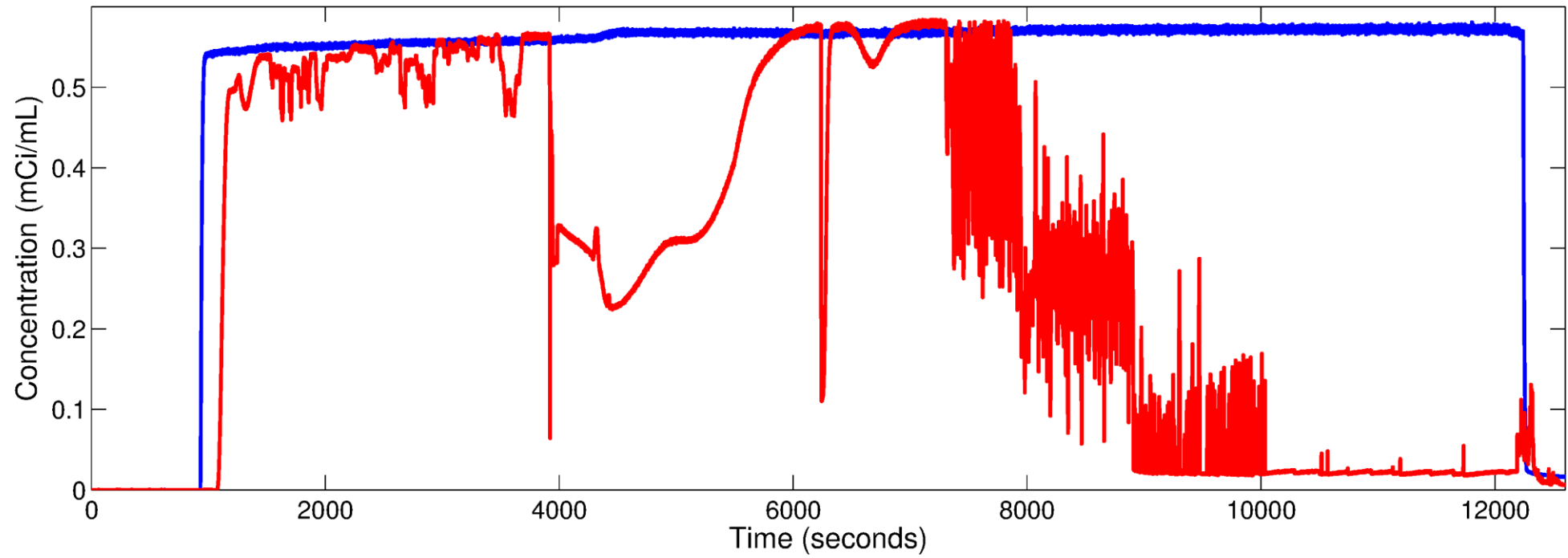
Energy level 120 kV

Experimental procedure

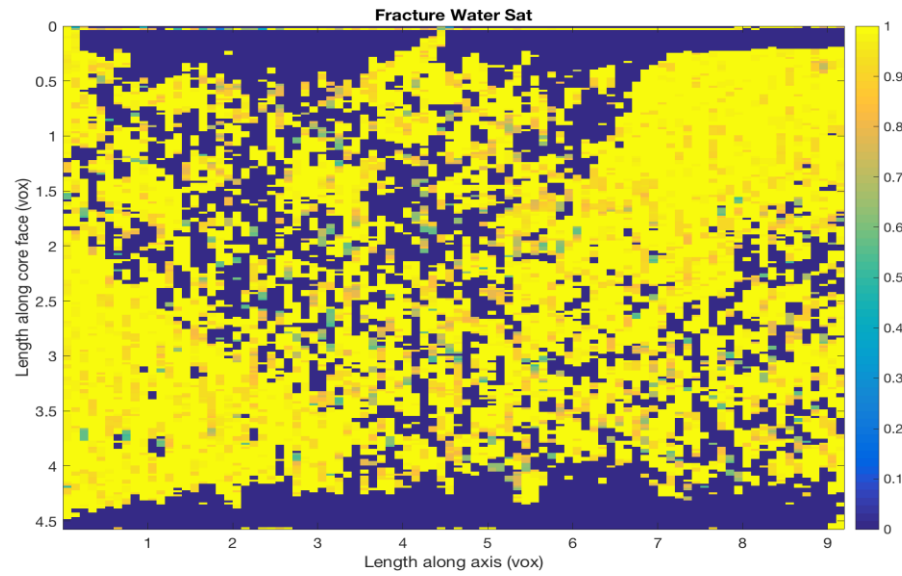
Core flooding -> K & k_{rel}

X-Ray CT images -> fracture aperture & saturation

1. CT scan -> dry fracture aperture & data for saturation calculation
2. N_2 injection at different flow rates -> gas permeability
CT scan -> gas fracture aperture
3. CO_2 injection
4. Water injection at different flow rates -> water permeability
CT scan -> water fracture aperture & data for saturation calculation
5. Multiphase injection: N_2 and water at different ratios at a constant total flow -> relative permeability versus gas fraction-saturation
CT scan -> data for saturation calculation



1% N2, 99% Water



100% N2, 0% Water

