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SCHOOL OF EARTH, ENERGY & ENVIRONMENTAL SCIENCES | Energy Resources Engineering

SCCS annual meeting – 10 May 2018

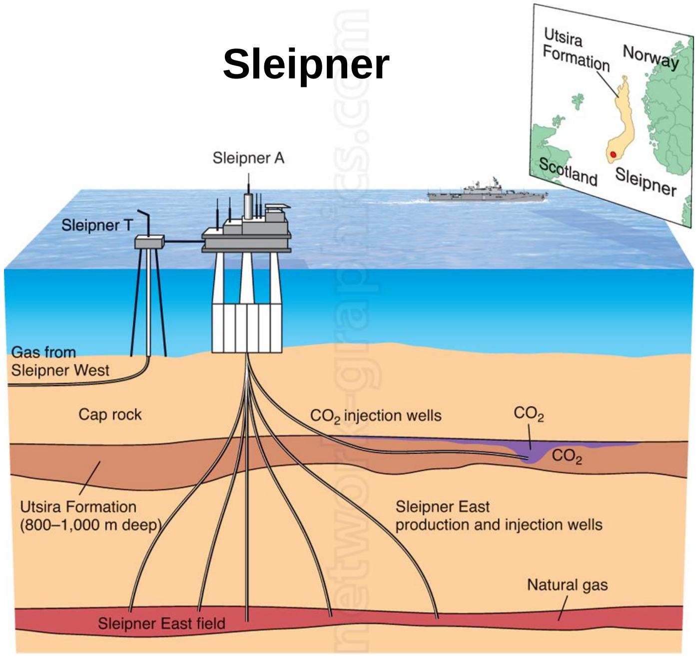
Impact of rock structure heterogeneity on residual trapping: Which structures and scales are most important?

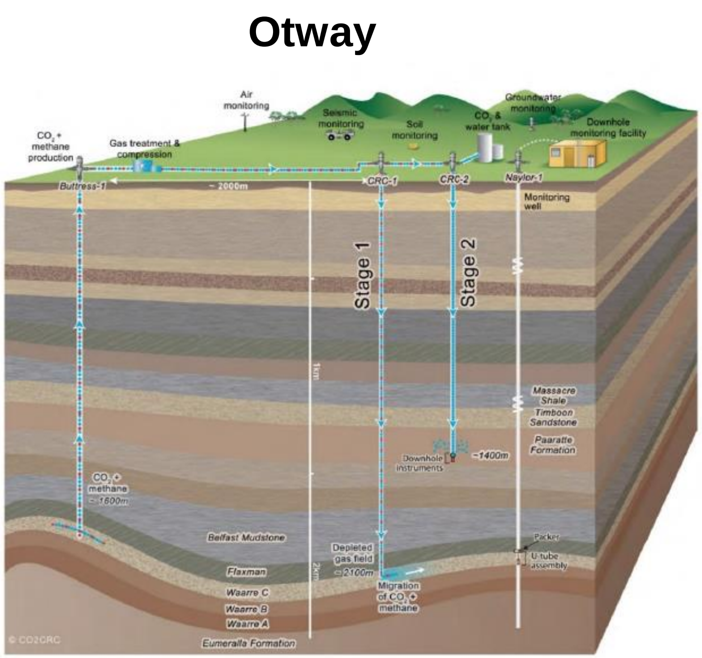
Maartje Boon, Cindy Ni and Sally Benson

Can CO_2 be safely stored in an extensively faulted heterogeneous formation?

Conventional sites with a perfect seal can safely store CO_2 :

Can we rely on secondary trapping mechanisms to safely store CO_2 at unconventional sites?





http://network-graphics.com

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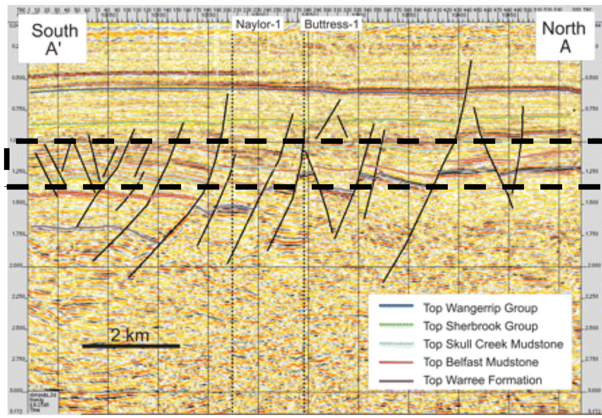
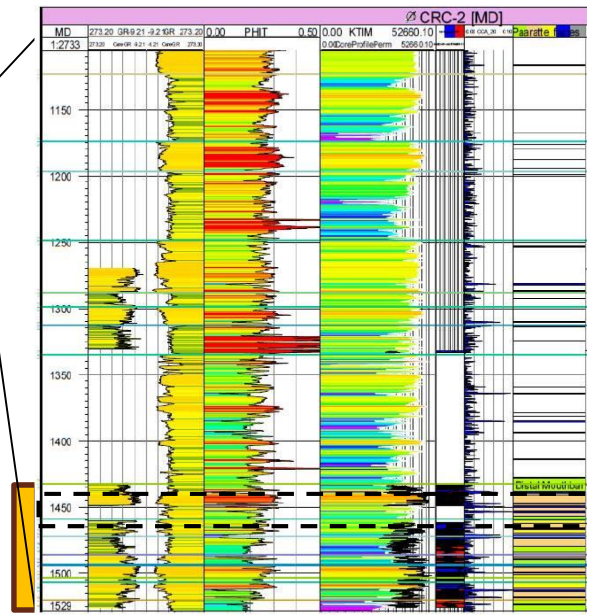
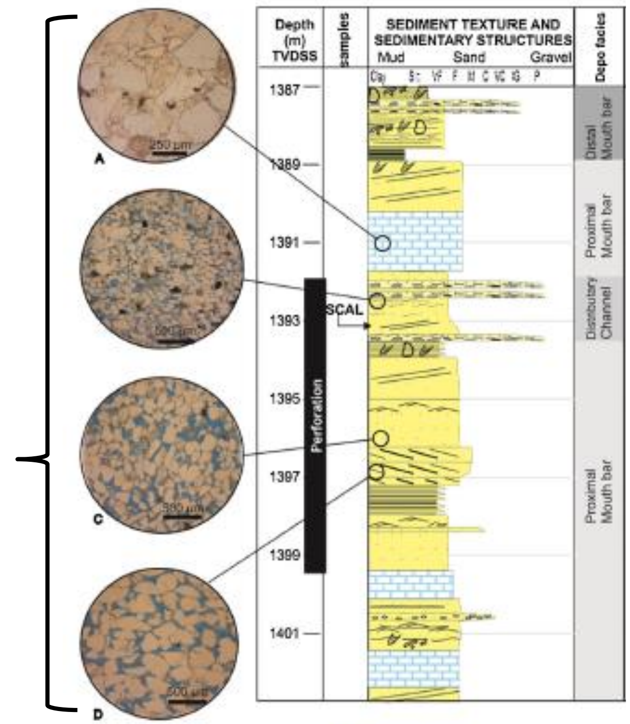
What is the impact of faults, stratigraphy, mineralogy on CO_2 sequestration?







100 m core sequence
CRC-2 CRC-3

Which structures and scales are most important for the different trapping mechanisms?

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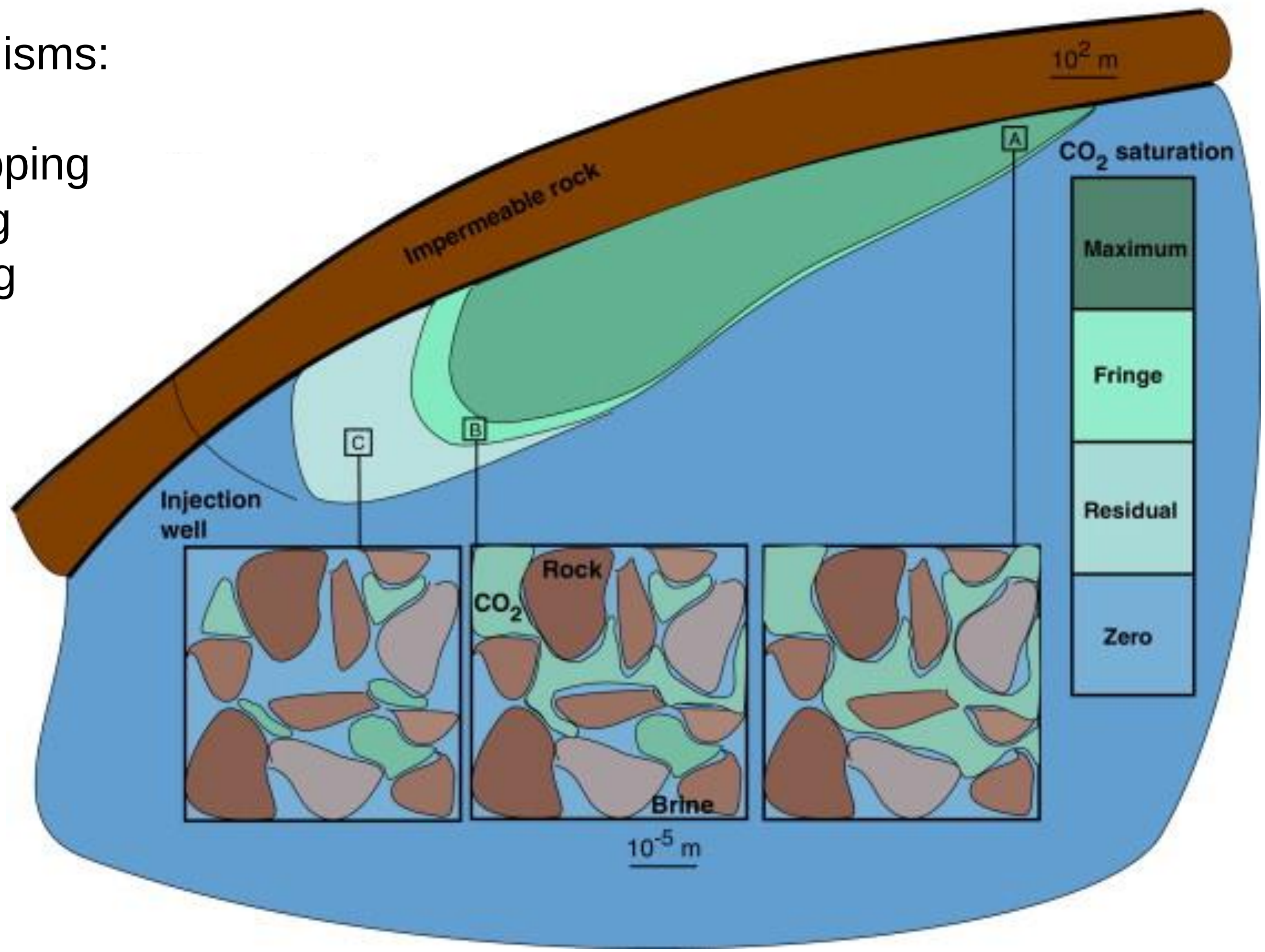
Can we rely on secondary trapping to safely store CO_2 at unconventional sites?

CO_2 trapping mechanisms:

1. Stratigraphic trapping
2. Residual trapping
3. Solubility trapping
4. Mineral trapping



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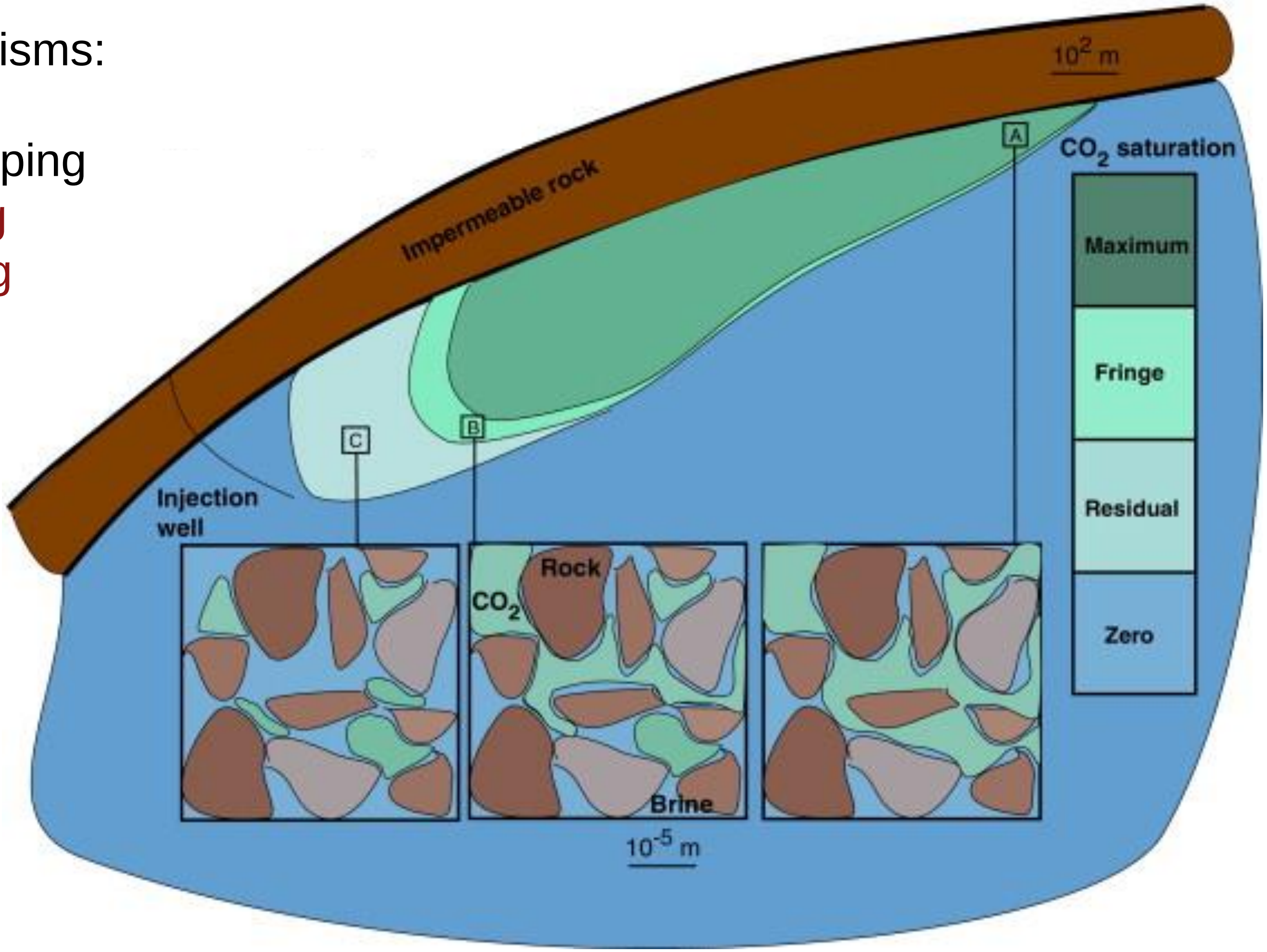
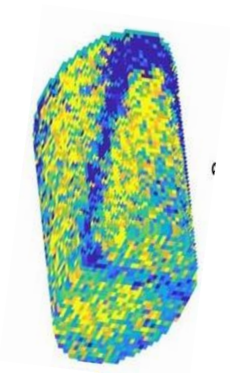


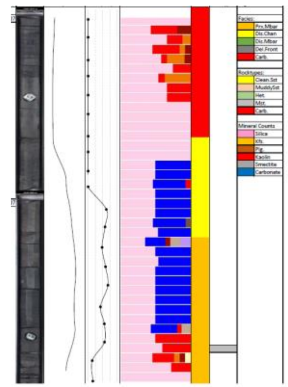
To model secondary trapping you need to take small scale heterogeneity into account:

Voxel scale



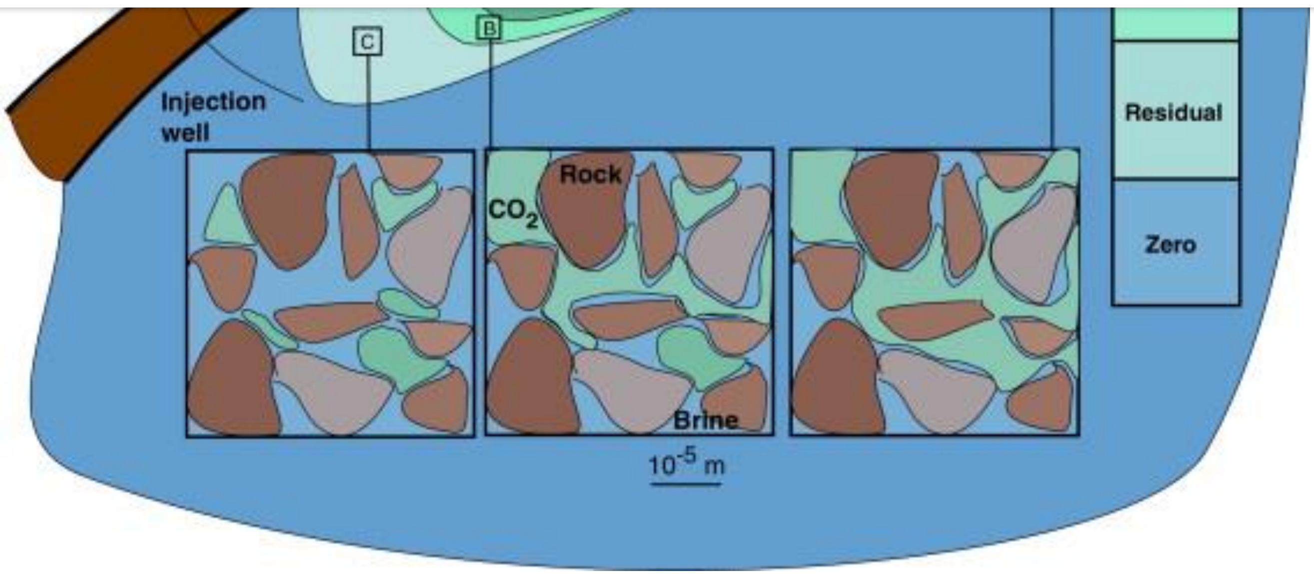
Core scale

Log scale



Outcrop scale

Field scale



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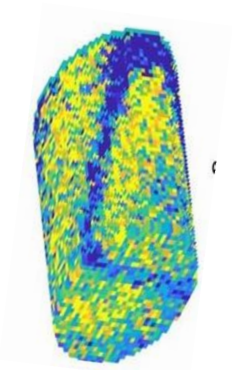

Core scale

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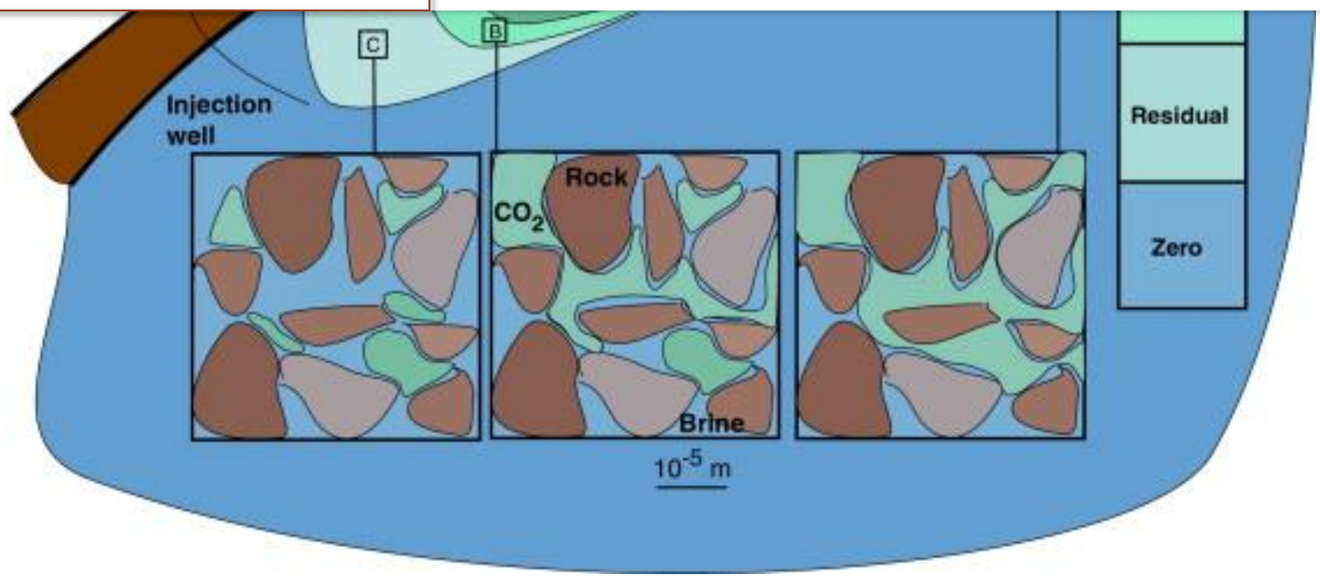

Question:

How does capillary heterogeneity at the subcore scale impact the CO_2 saturation distribution during injection?

CO_2 saturation distribution depends on viscous, capillary and gravitational forces

- Viscous forces depend on the injection rate and viscosity of the fluids.
- Capillary forces are a result of gradients in capillary pressure caused by variations in rock structure.
- Gravitational forces can lead to gravity segregation between fluids if the density difference is large.

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The capillary number gives the ratio of viscous to capillary forces

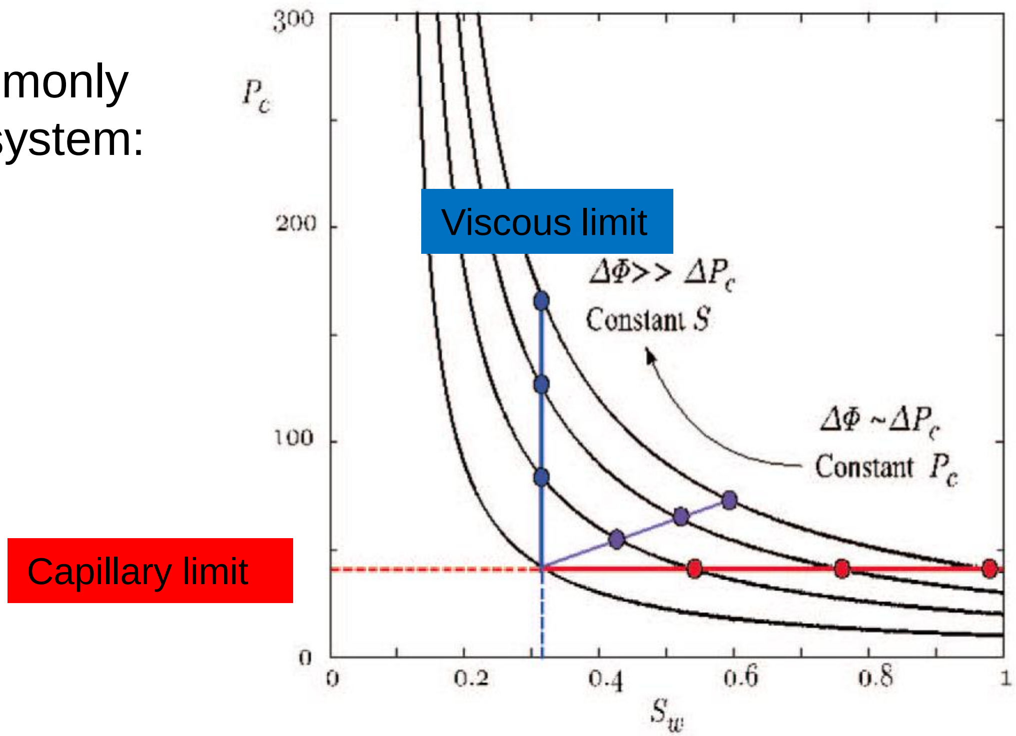
The capillary number (N_c) is commonly used to determine the state of a system:

$$N_c = \frac{v\mu}{\sigma}$$

v = Darcy velocity (m s^{-1})

μ = Viscosity (Pa s)

σ = Interfacial tension (N m^{-1})



$N_c << 10^{-5}$ = capillary dominated regime
$N_c >> 10^{-2}$ = viscous dominated regime

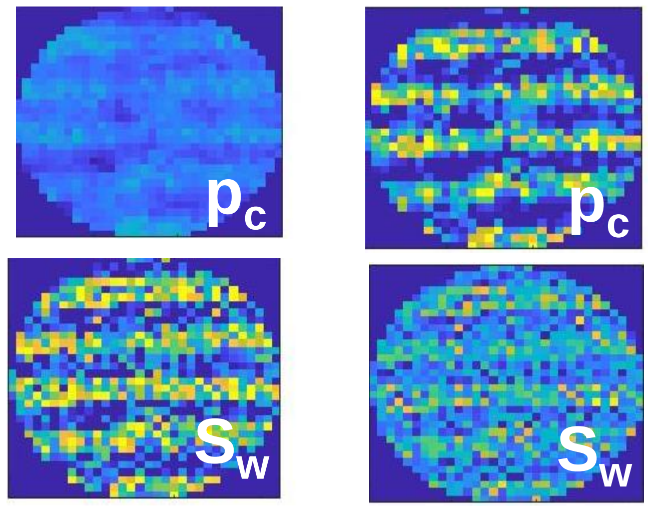
The saturation distribution impacts the relative permeability

Transition zone

Capillary limit

$N_c << 10^{-5}$

- Capillary equilibrium
- Heterogeneous saturation distribution
- Relative permeability is flow rate dependent



Viscous limit

$N_c >> 10^{-2}$

- Capillary disequilibrium
- Homogenous saturation distribution as if the core is homogeneous
- Relative permeability is flow rate independent

The saturation distribution impacts the relative permeability

Transition zone

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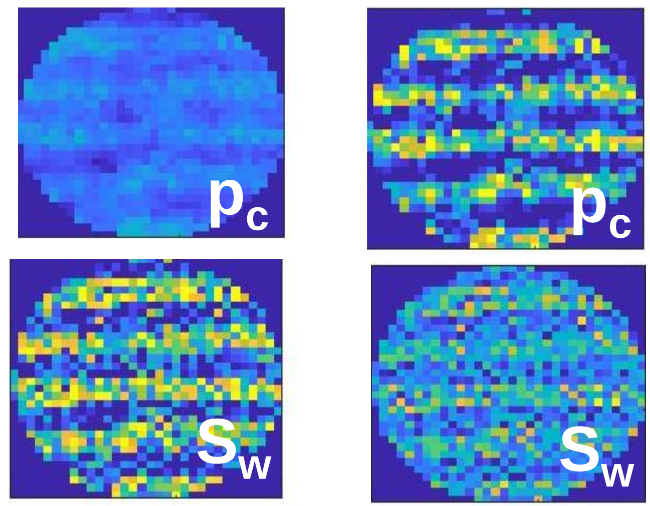


Viscous limit

$N_c >> 10^{-2}$

- Capillary disequilibrium
- Homogenous saturation distribution as if the core is homogeneous
- Relative permeability is flow rate independent

Effective relative permeability

Characteristic relative permeability

The saturation distribution impacts the relative permeability

Transition zone

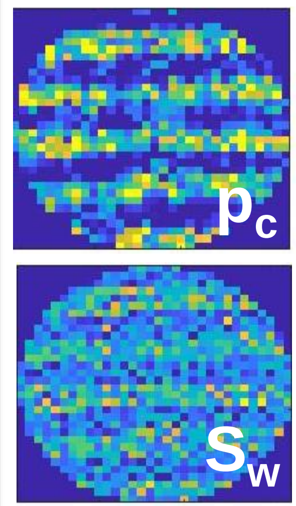
Capillary limit ⟷ **Viscous limit**

Flow rates are low in the case of CO_2 injection (capillary dominated regime):

- Experiments take a long time
- Rel perm curve changes for different conditions so many experiments are needed

Solution:

1. Use experiment in capillary dominated regime to create a subcore scale absolute permeability map.
2. Use numerical model to simulate core-flood test at different condtions.



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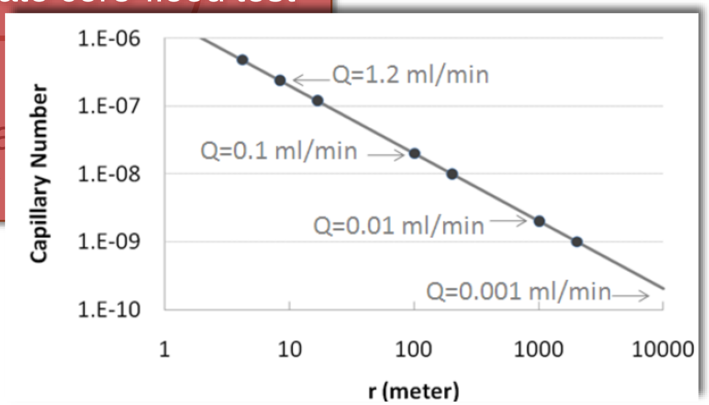
Characteristic relative permeability



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Experimental core-flood tests

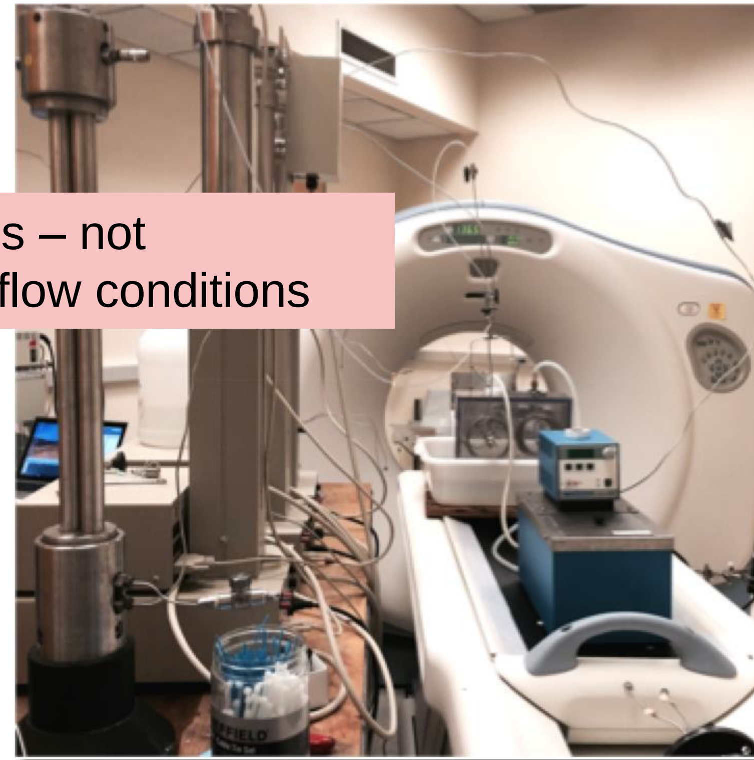
Experimental set up used at Stanford to measure multiphase flow parameters

We will measure:

- Absolute permeability
- Porosity
- Capillary pressure (MICP)
- Irreducible gas saturation (trapping)
- Relative permeability (drainage and imbibition)

It takes ~1 week per core to complete an experiment !

Experimental set up used at Stanford to measure multiphase flow parameters



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- Porosity
- Capillary pressure (MICP)
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Rock properties – not dependent on flow conditions

Are flow rate dependent!

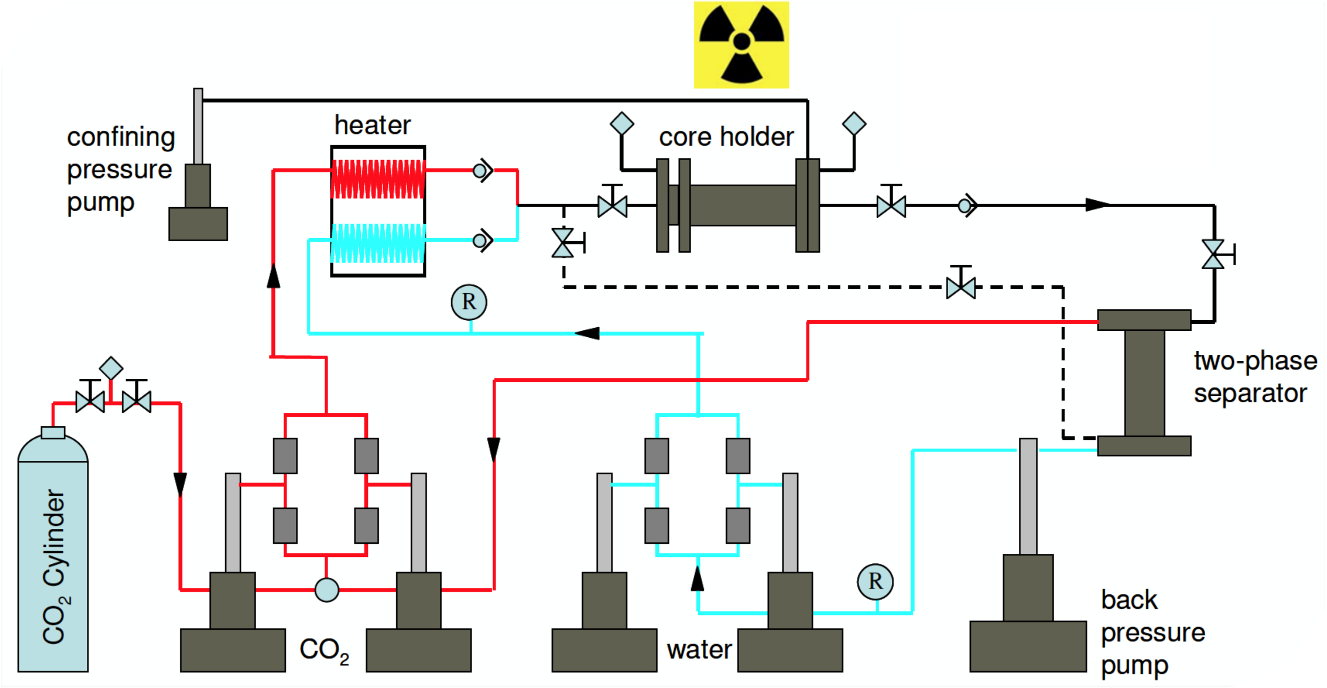
It takes ~1 week per core to complete an experiment !

Experimental procedure

CO_2 and water are co-injected into an initially water saturated core at reservoir conditions (high P, high T) and constant flow rate.

1. Drainage: stepwise increase f_{CO2} to 100% → initial CO_2 saturation
2. Imbibition: stepwise increase f_{H2O} to 100% → residual CO_2 saturation

A medical X-ray CT scanner is used to measure the CO_2 saturation once steady state is reached after each stepwise increase.



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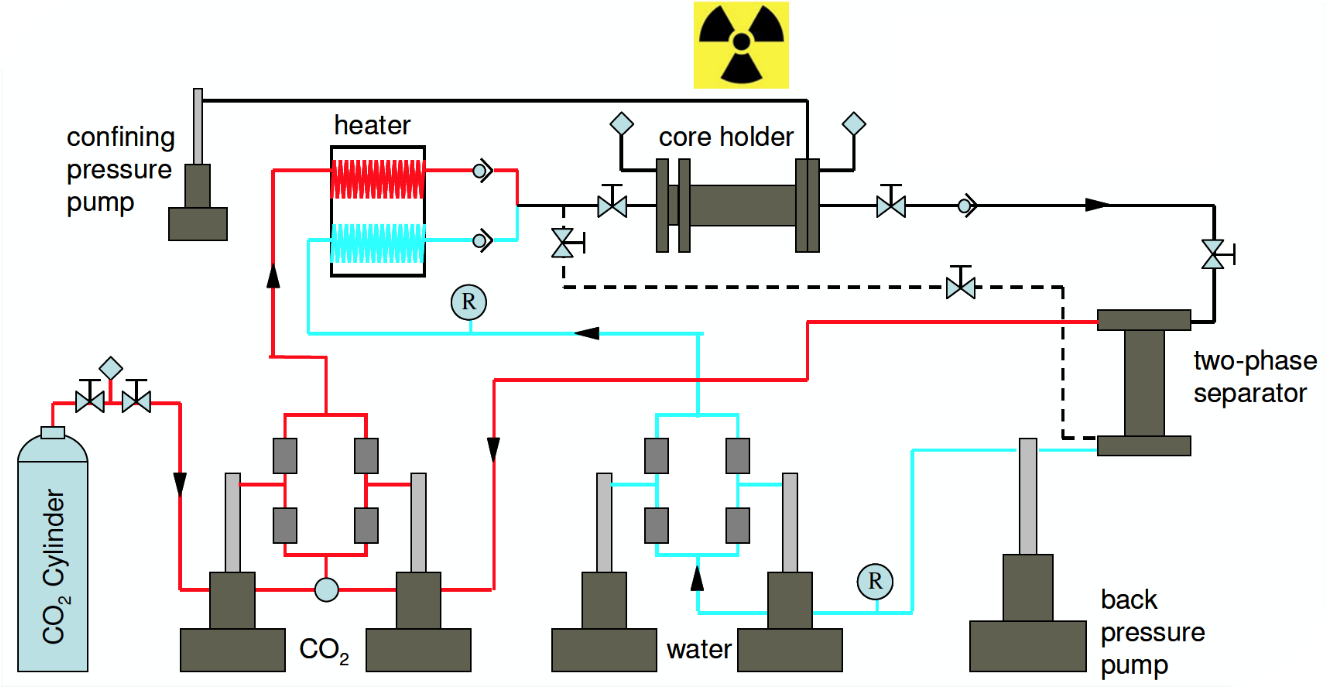


Numerical core-flood tests

Numerical simulations are used to:

- Obtain the subcore scale permeability field of the rocks used in the experiments.
- Obtain characteristic relative permeability curves of the rocks used in the experiments
- Look at the impact of different types of heterogeneity on capillary forces.

Can be used to simulate coreflood tests at different conditions

Method to obtain subcore scale absolute permeability field:

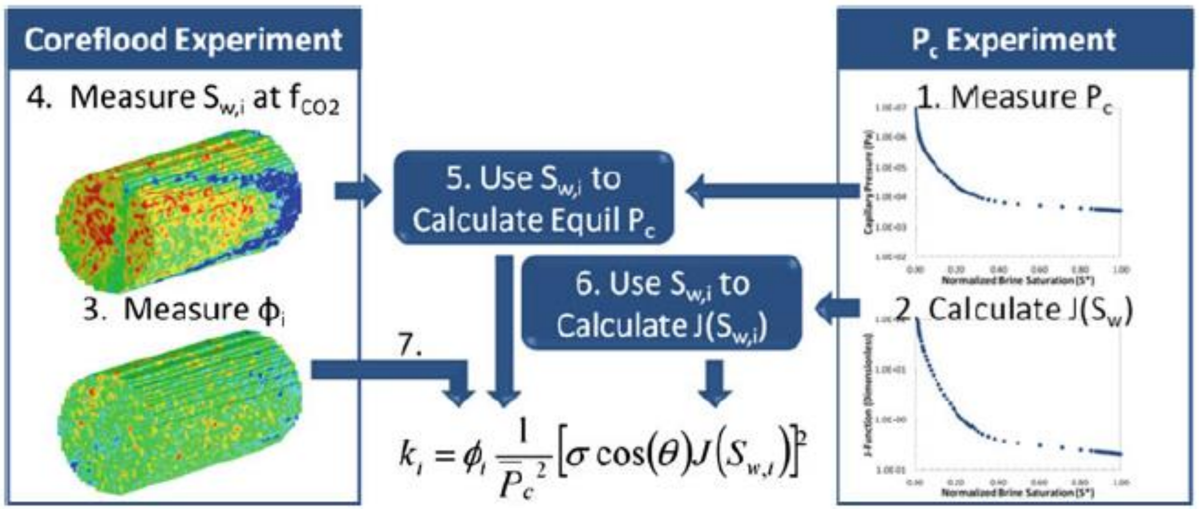


Fig. 1 Workflow of the permeability calculation procedure with steps numbered in order

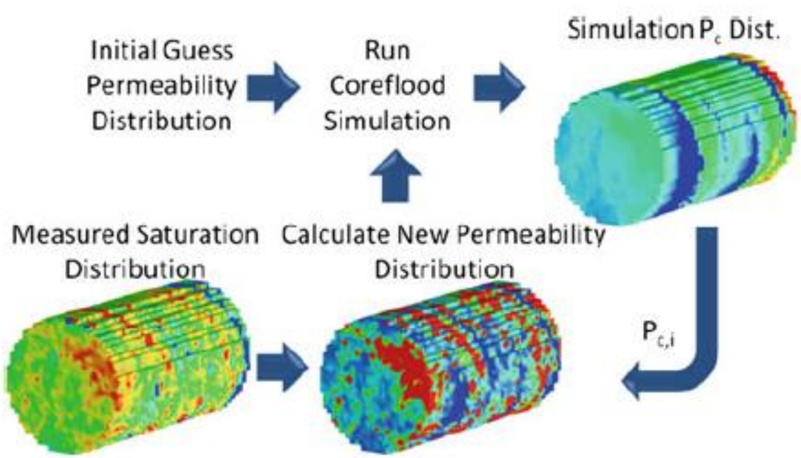


Fig. 2 Workflow of the extended iterative permeability calculation procedure

<u>Assumption:</u>

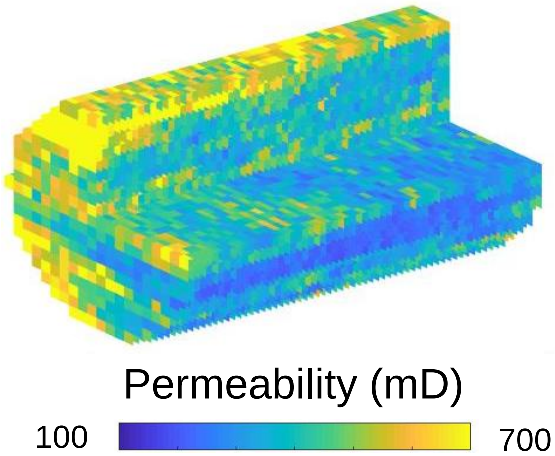
- Capillary equilibrium at the voxel scale

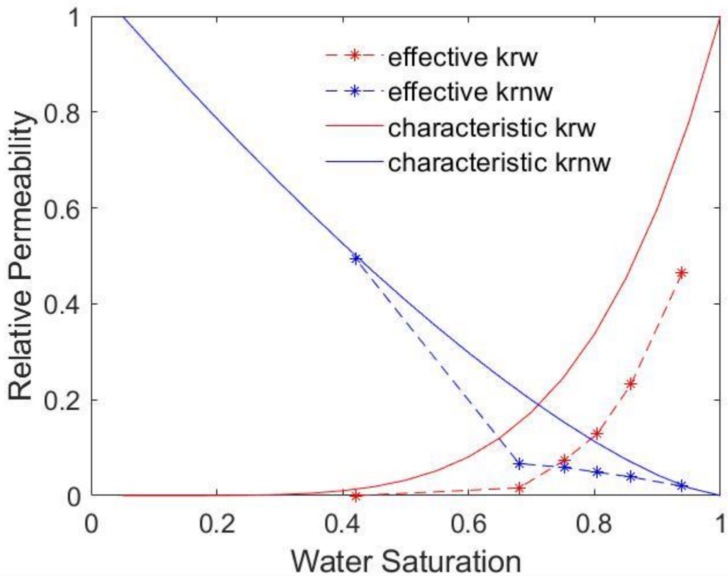
<u>Input:</u>

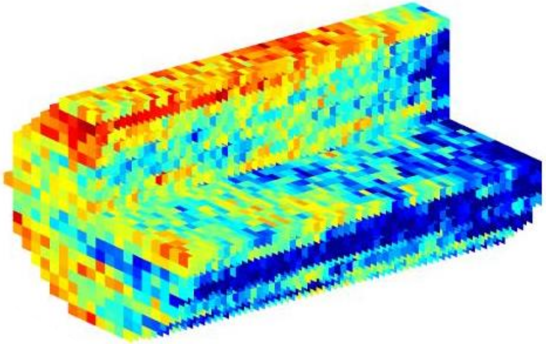
- Water saturation distribution
- Porosity distribution
- Capillary pressure curve (MICP)
- Characteristic rel. perm. curve

Can be obtained by experiment in the viscous limit or through history matching

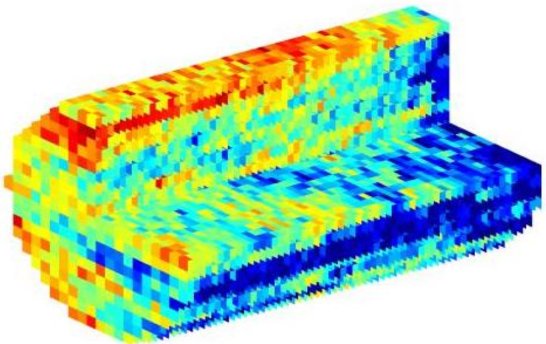
Numerically obtained absolute permeability field and characteristic relative permeability for Berea (Liver)



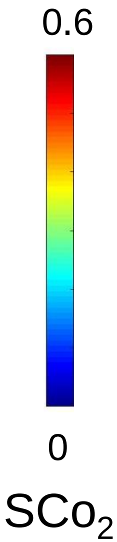




Measured CO_2 saturation



Simulated CO_2 saturation



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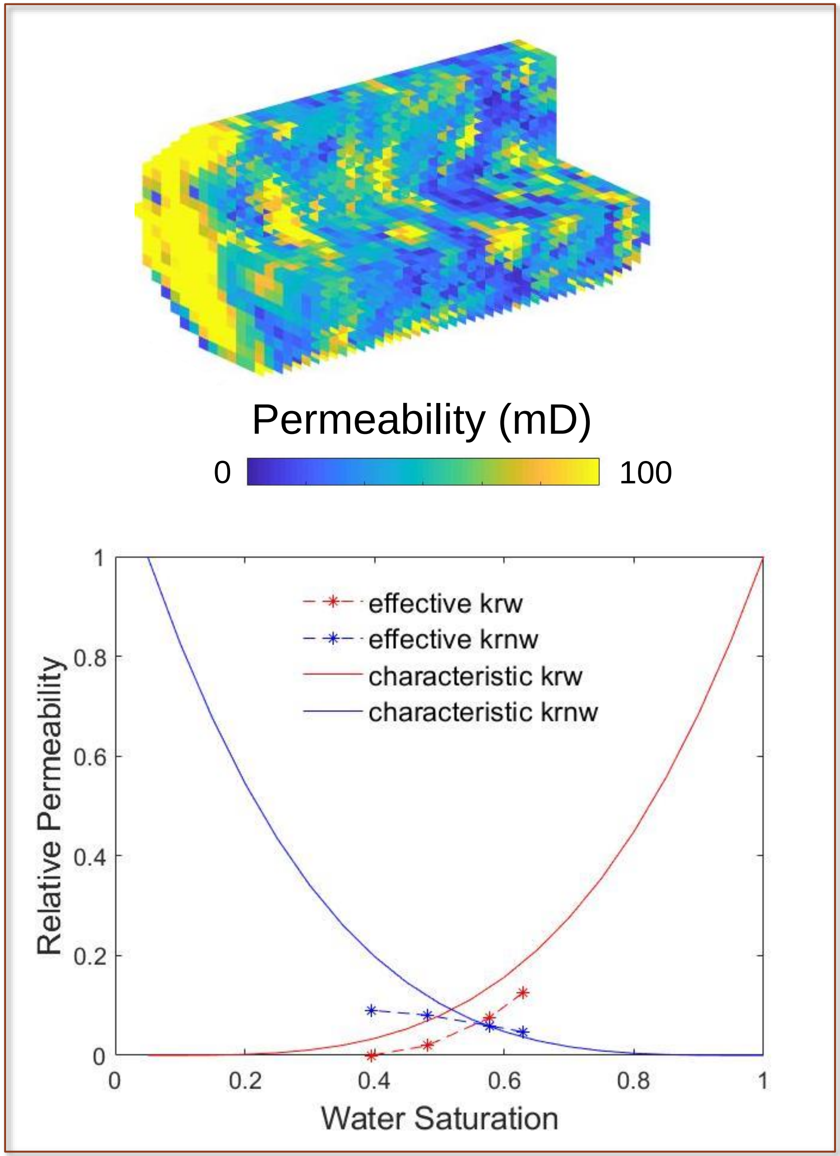
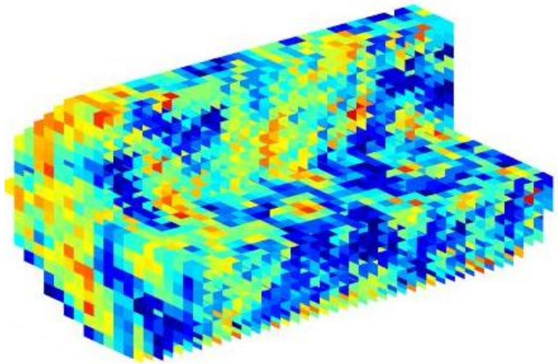
Numerically obtained absolute permeability field and characteristic relative permeability for the heterogeneous Fontainebleau





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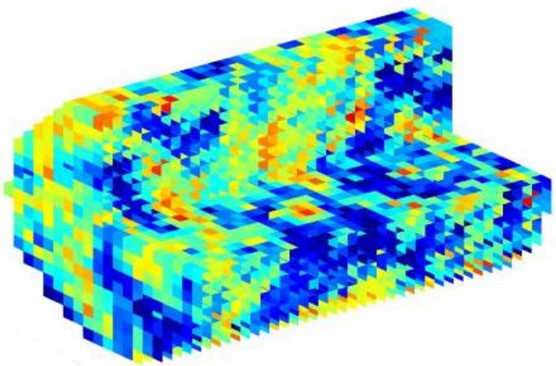
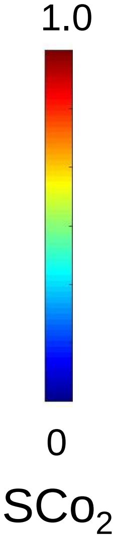


Simulated CO_2 saturation



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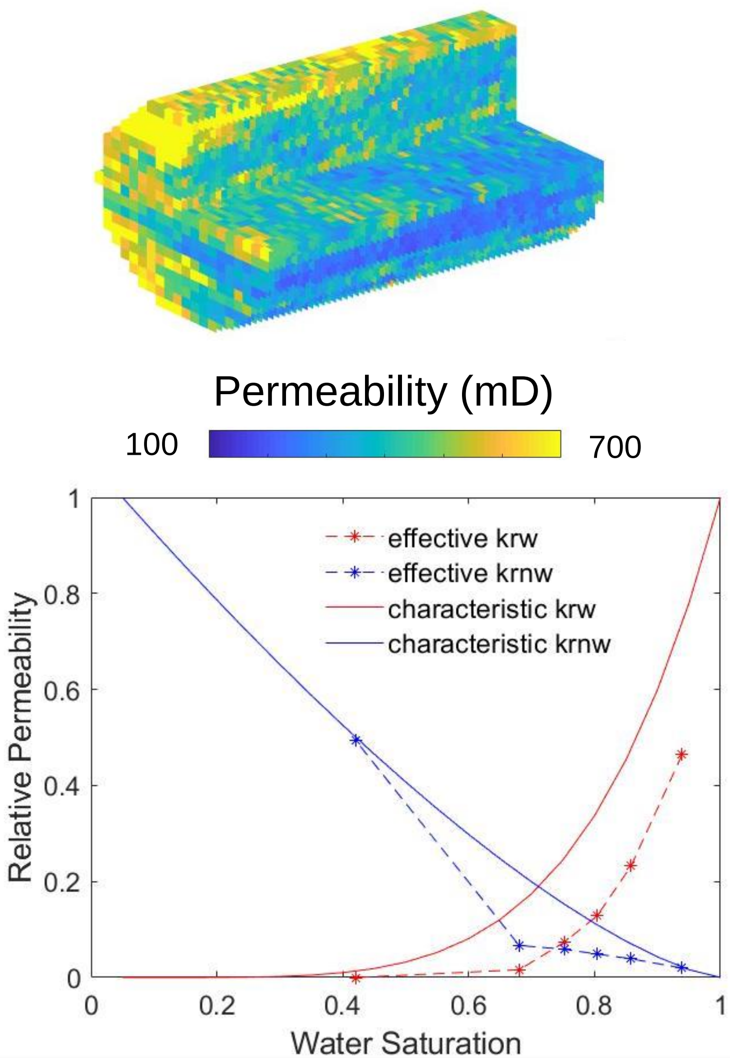
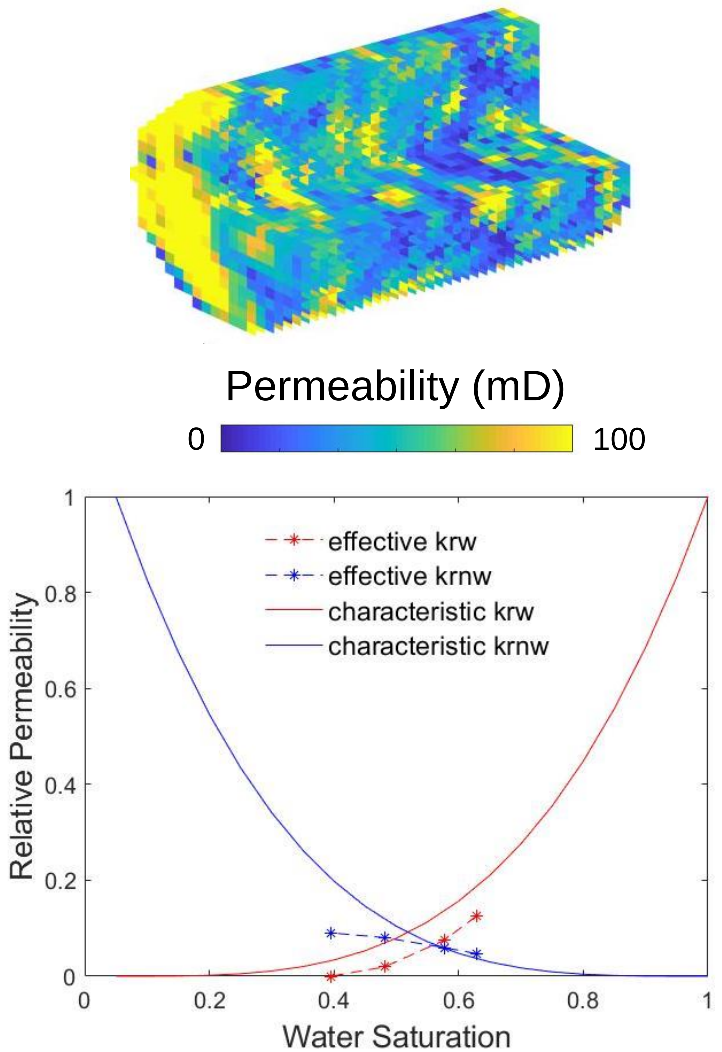
Subcore scale perm field + characteristic rel perm curve can be used to model core-flood tests at different conditions

Berea

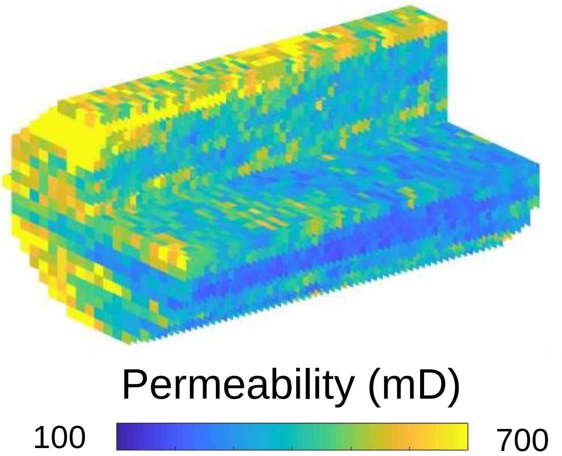


Fontainebleau



Upscale relative permeability from the voxel to the core scale

Voxel scale



+ Characteristic relative permeability

Core scale

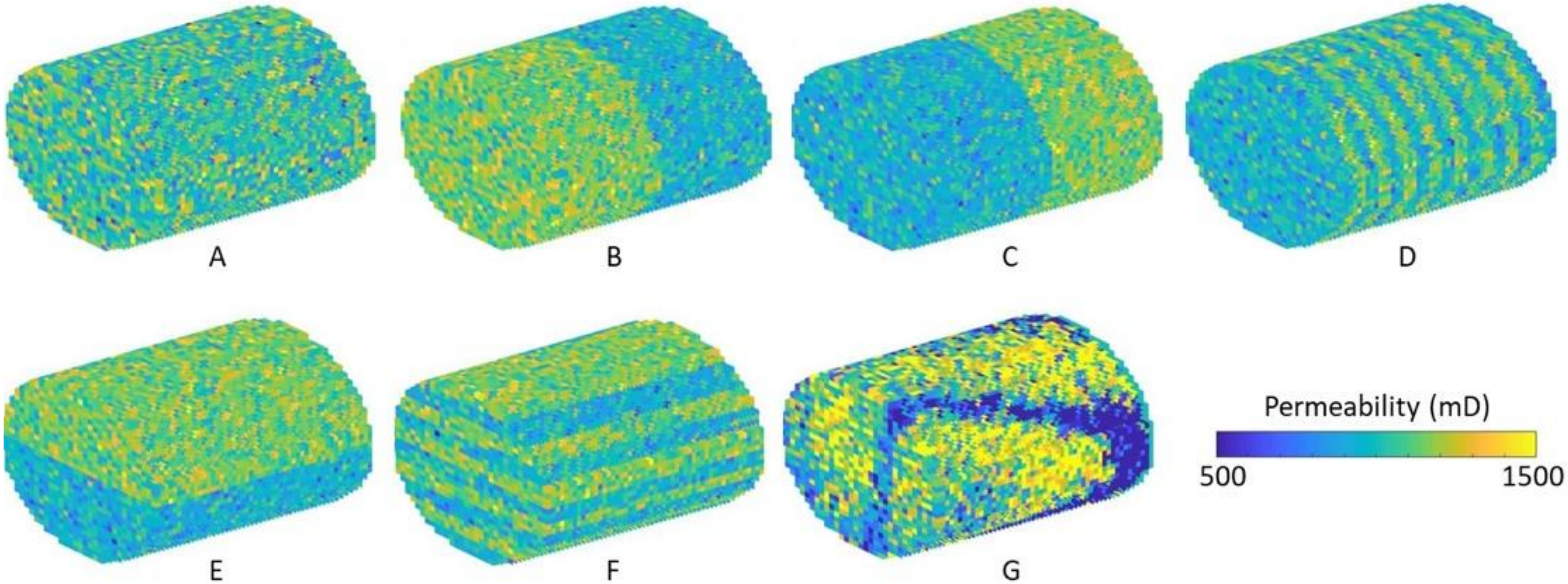
Incorporates subcore scale heterogeneities!

+ Effective relative permeabiltiy

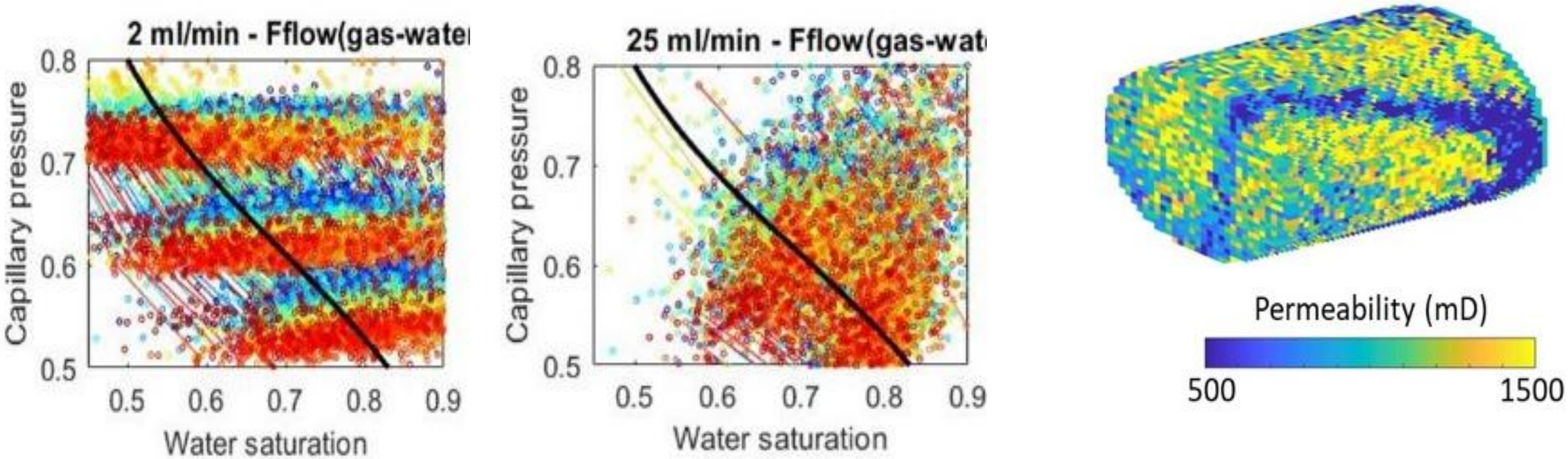
Average Permeability (380 mD)

What is the impact of subcore scale heterogeneity on capillary forces?

What is the impact of subcore scale heterogeneity on capillary forces? And how does this impact the relative permeability?

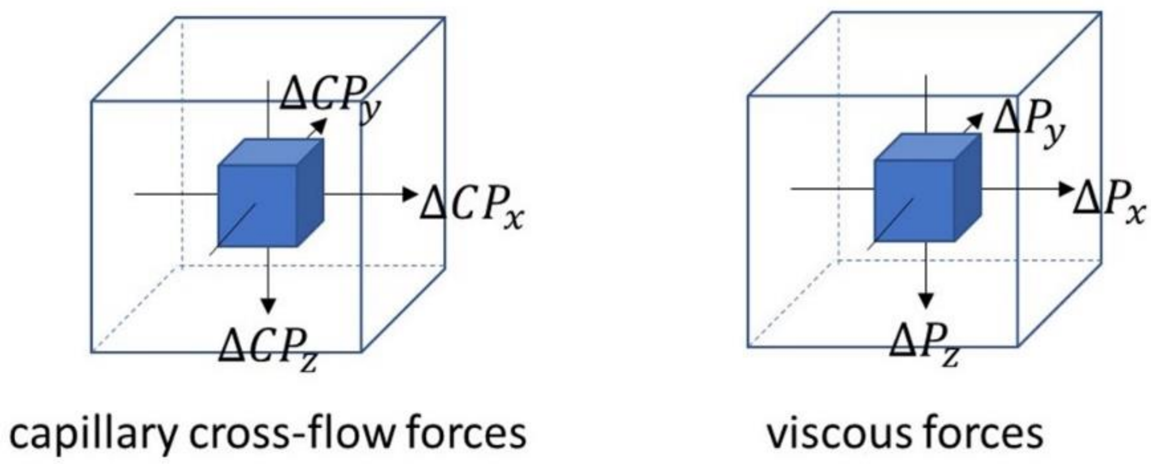


In heterogeneous systems, capillary disequilibrium can exist in the capillary dominated regime



Capillary pressure gradients can result in capillary induced flow

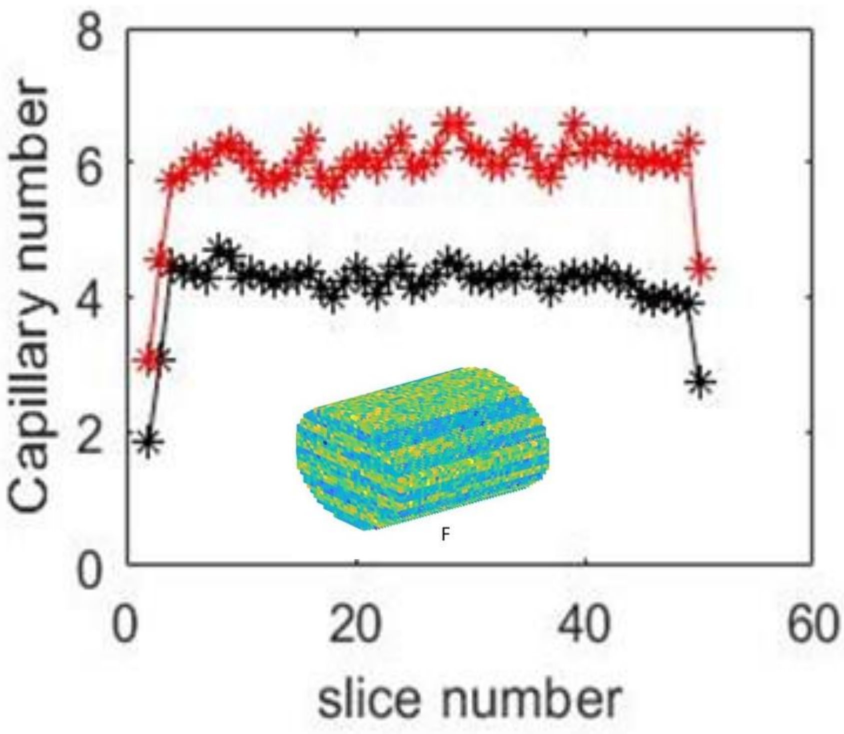
To quantify the impact of capillary induced flow a capillary cross-flow number is calculated:

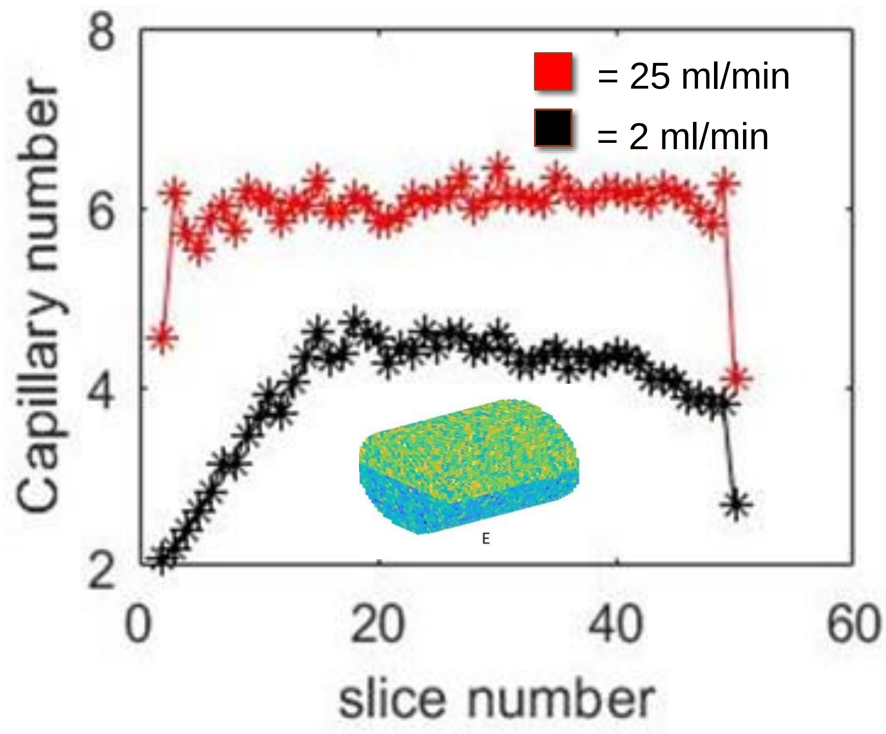


$$N_{cfp} = \frac{\sqrt{\Delta P_x^2 + \Delta P_y^2 + \Delta P_z^2}}{\sqrt{\Delta CP_x^2 + \Delta CP_y^2 + \Delta CP_z^2}}$$

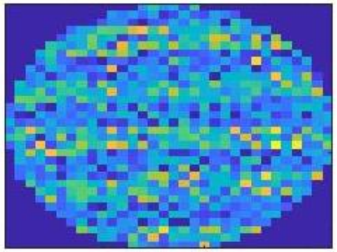
The capillary cross-flow number gives the ratio of the viscous forces to capillary cross-flow forces

Horizontal layers can lead to cross-flow





Inlet



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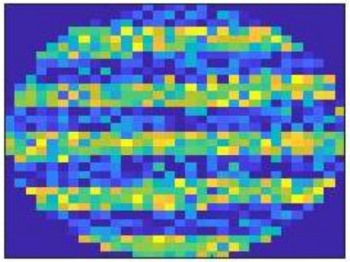

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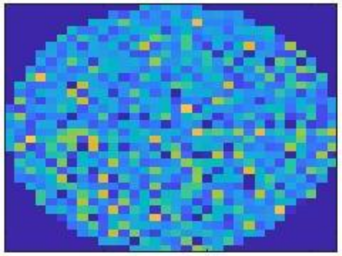

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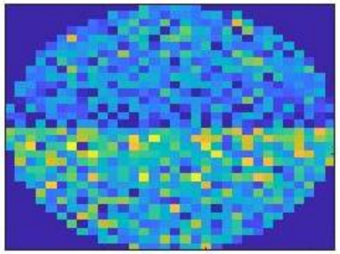
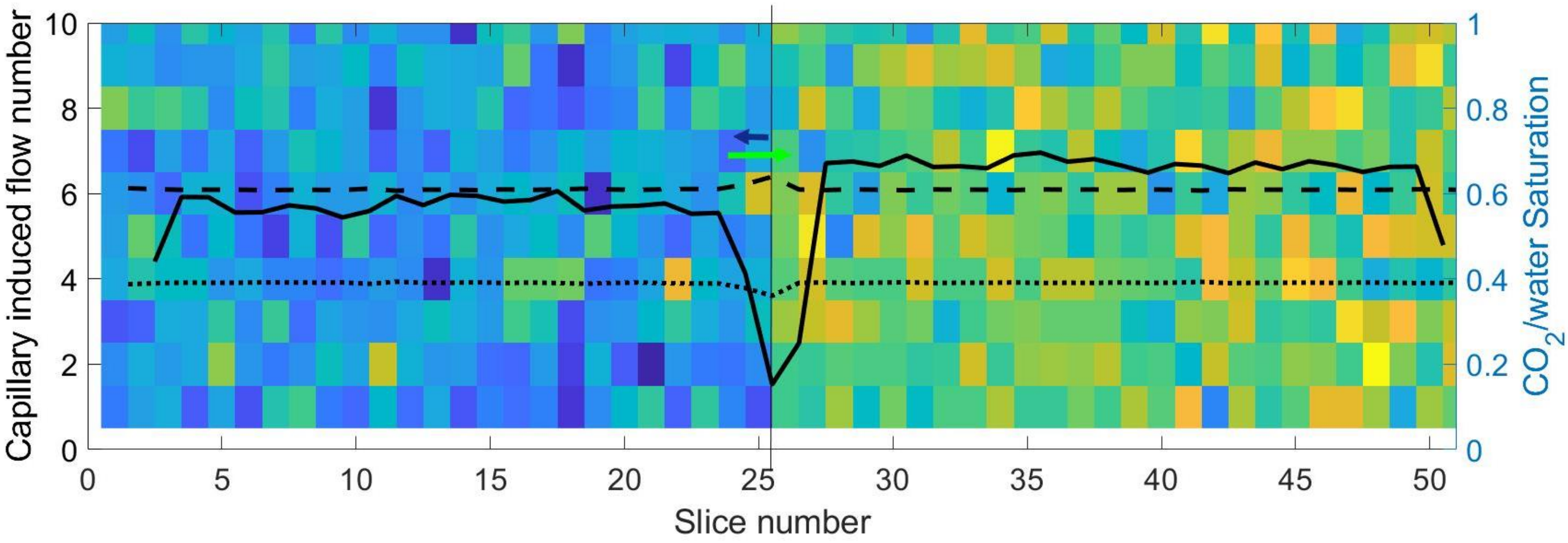


Cross-flow forces in vertically layered systems

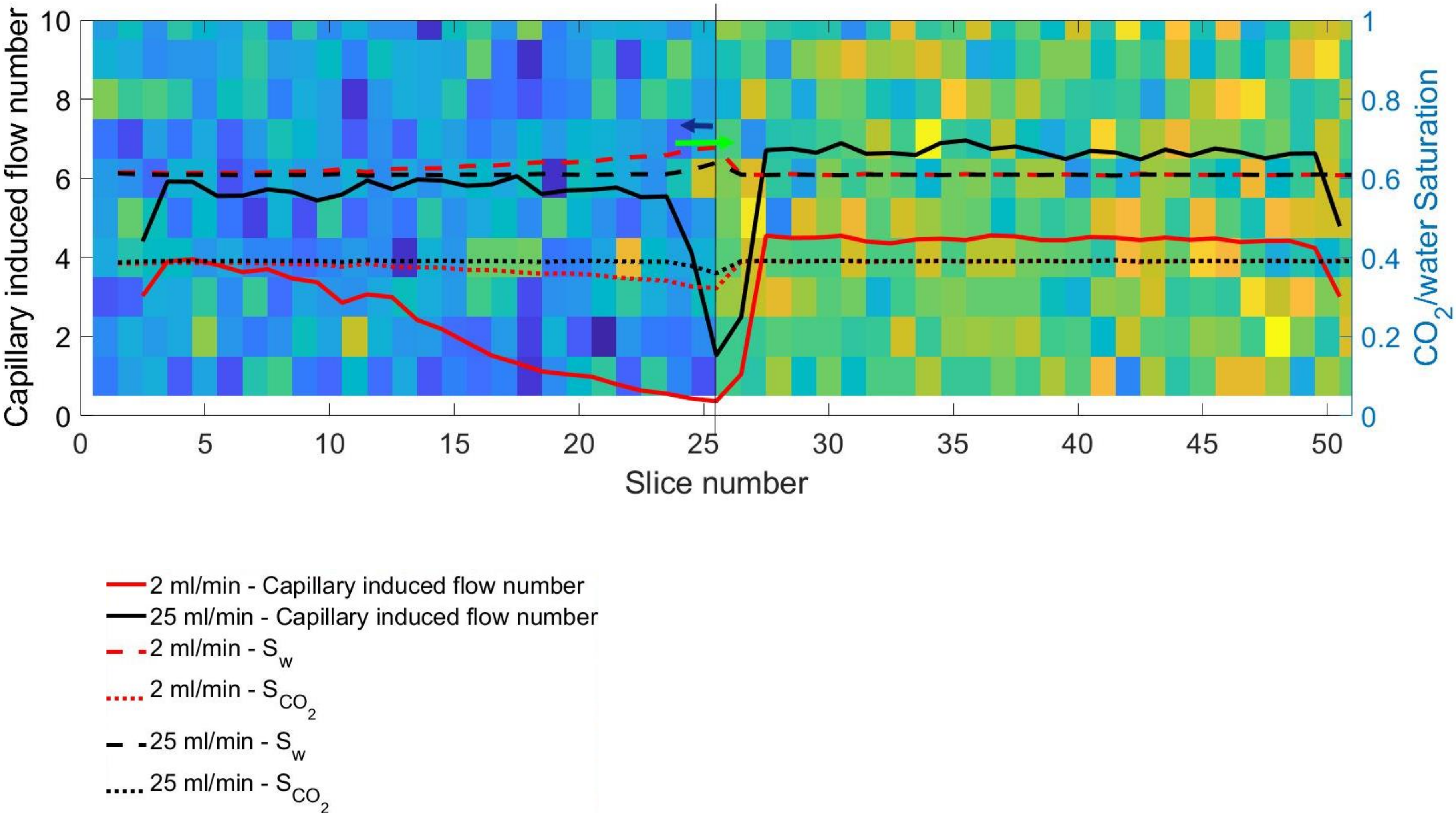


25 ml/min - Capillary induced flow number

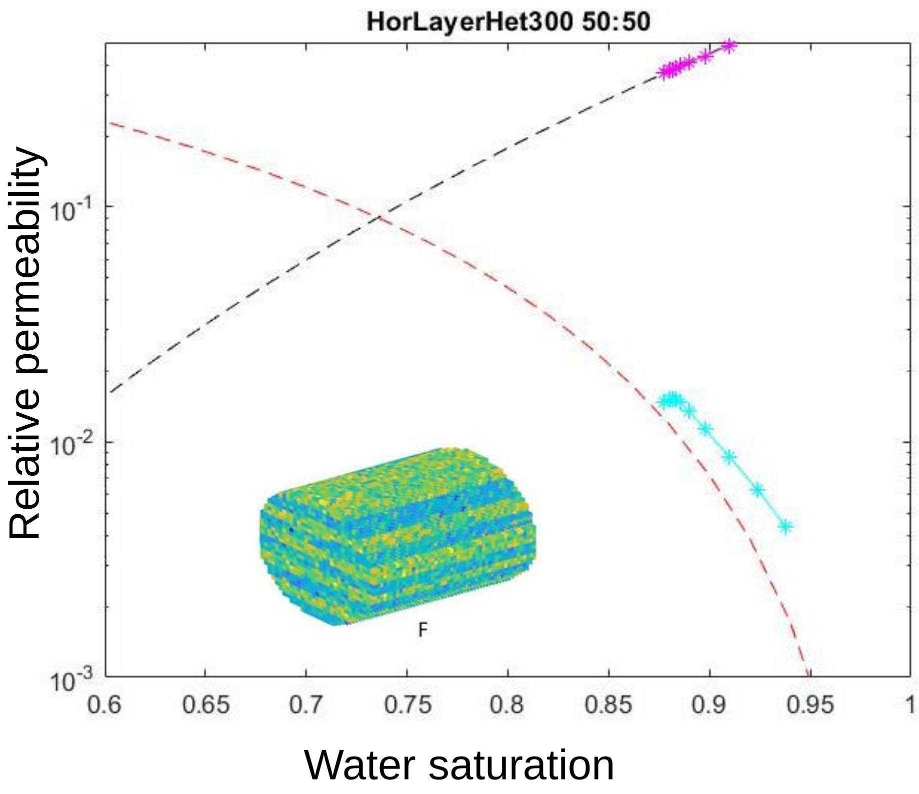
25 ml/min - S_w

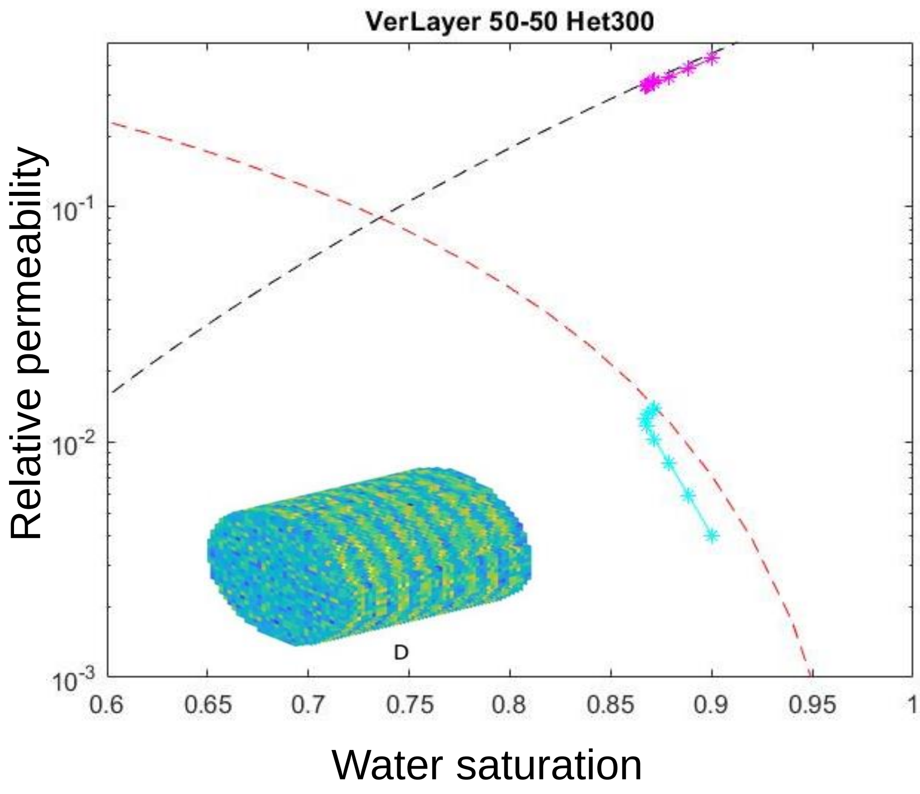
25 ml/min - S_{CO_2}

Cross-flow forces in vertically layered systems



Horizontal layers increase the effective rel perm while vertical layers decrease the effective rel perm





Conclusions

- The direction of the heterogeneity and the scale of the heterogeneity impact the cross-flow forces and, therefore, impact the capillary pressure and saturation distribution.

- Horizontal layers increase the effective relative permeability which can enhance the spreading of the plume while vertical layers decrease the effective relative permeability.

Acknowledgement

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Center for Carbon Storage