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

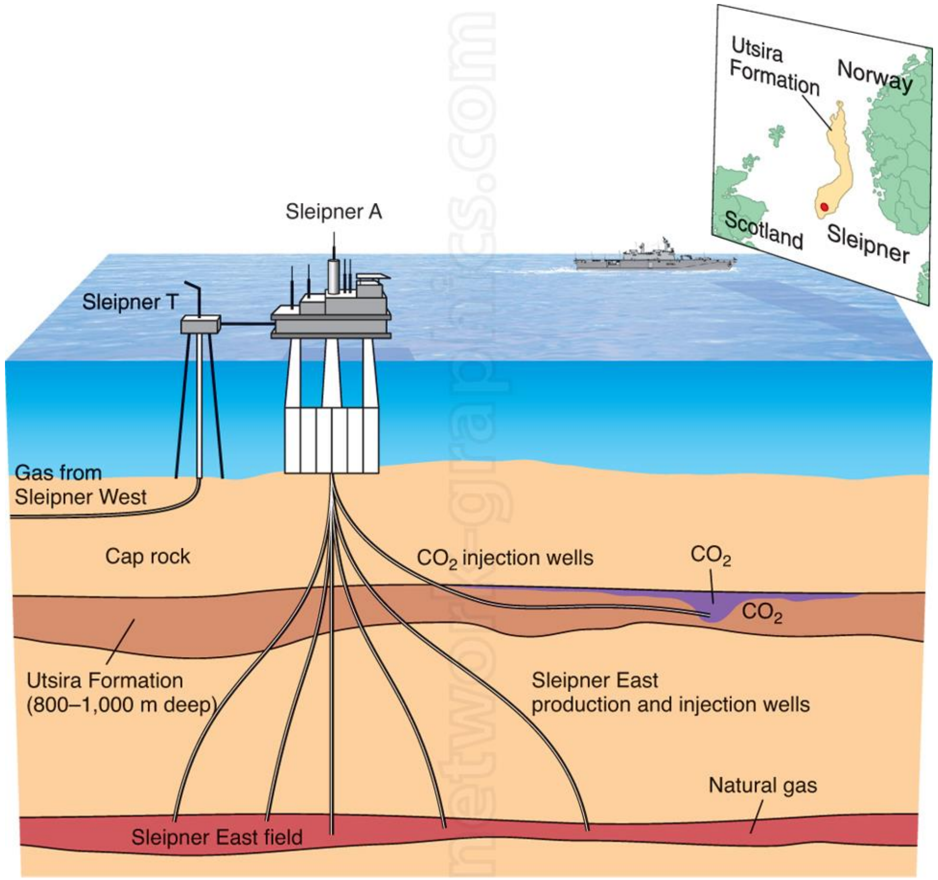
SCCS Annual Affiliates Meeting, November 19, 2020

A physics-based model to predict the impact of horizontal laminations on CO_2 plume migration

Maartje Boon and Sally M. Benson

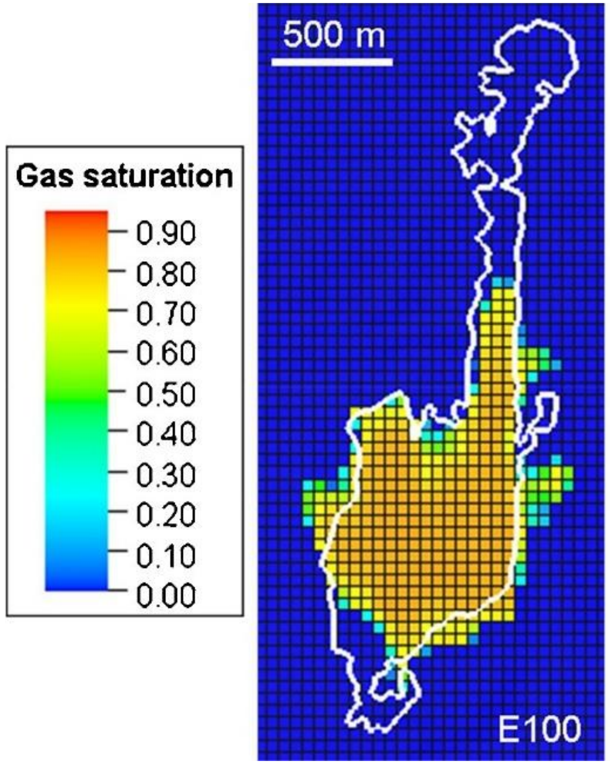
Accurate and efficient models are needed to support the safety of geologic carbon sequestration

- Lateral plume migration is often **not** well predicted by reservoir simulators where small scale rock heterogeneity is not taken into account.



http://network-graphics.com

7 years after injection started



Williams *et al.* 2018.

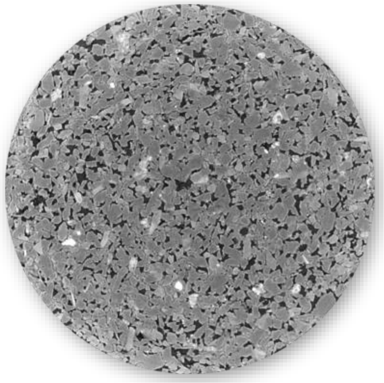
Each grid cell is 50m by 50m

How do we incorporate the impact of smaller scale heterogeneity into field scale models?

Rock structure heterogeneity exists from the pore to the meter scale and impacts the multiphase flow parameters of the rock.

- Which scales, structures are most important?

8 mm

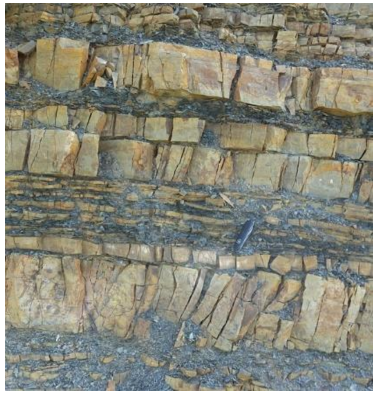


Pore scale

3.8 cm

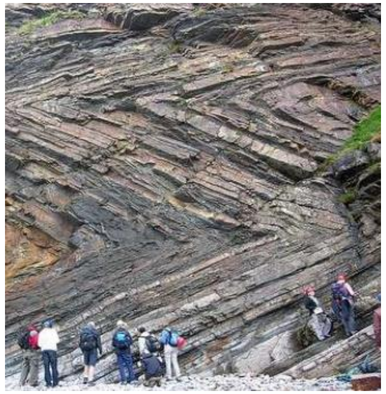
Core scale

1 m



Log scale

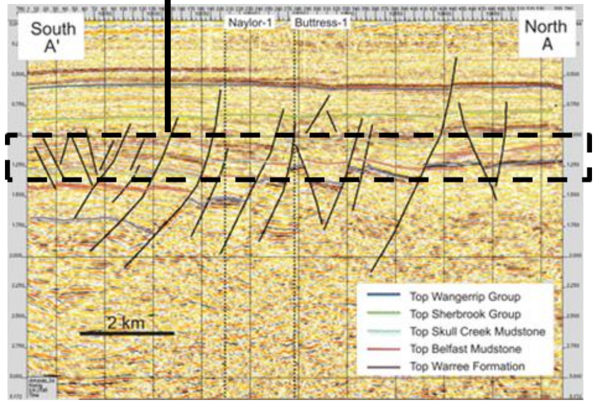
10 m



Outcrop scale

Paaratte formation

10 km



Field scale

How do we incorporate the impact of smaller scale heterogeneity into field scale models?

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Horizontal laminations

Paaratte formation

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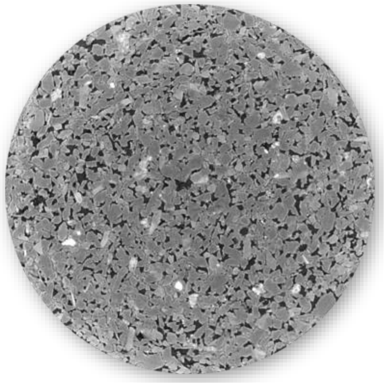

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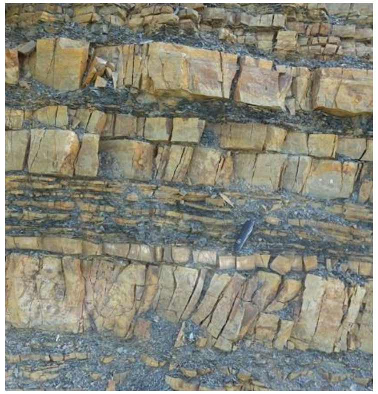
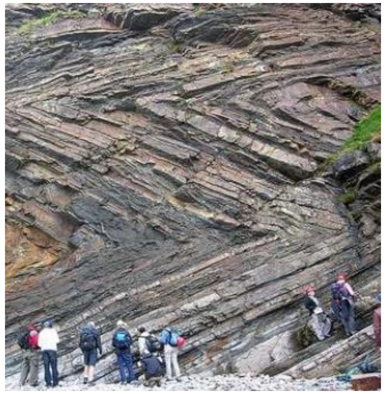


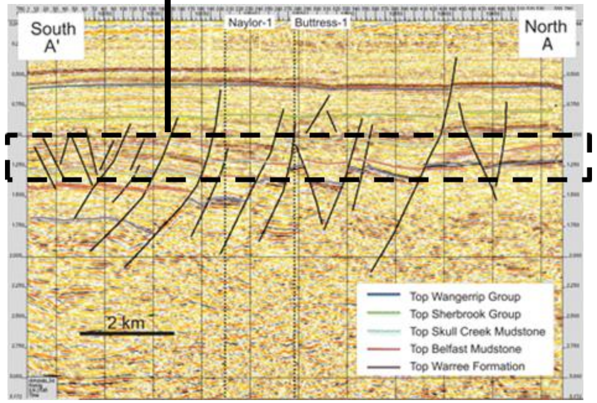
Log scale

10 m



Outcrop scale

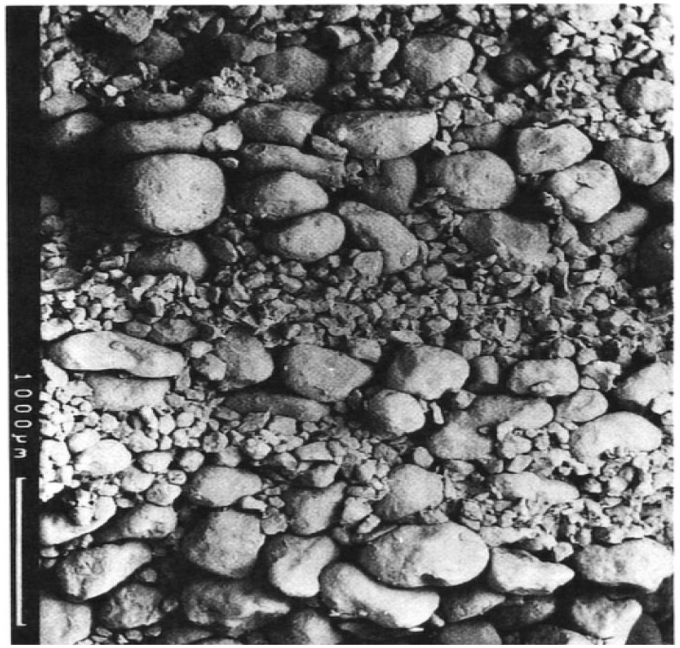
10 km



Field scale

Horizontal laminations

mm-scale



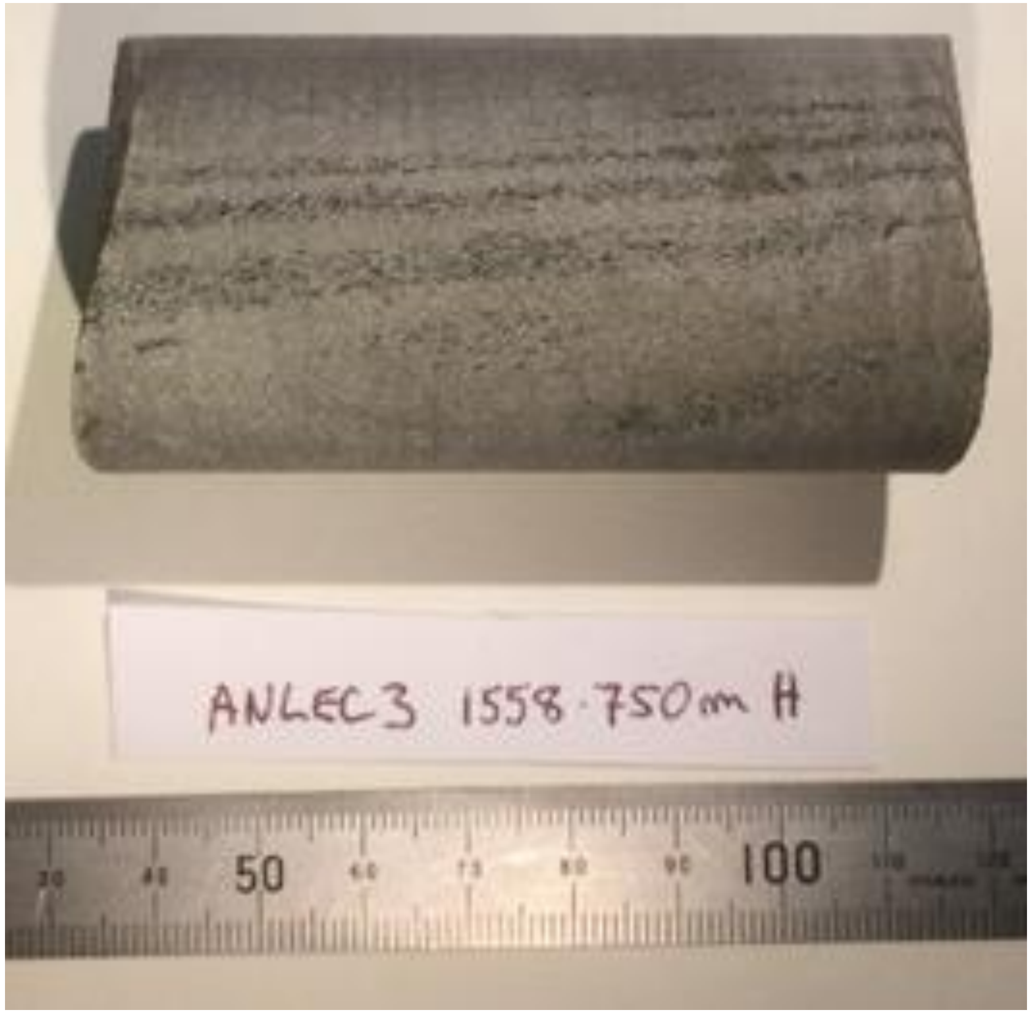
cm-scale

m-scale

Small-scale horizontal laminations impact where the CO_2 flows

Multi-phase flow experiments

Experimental observations of the CO_2 saturation distribution in a horizontally layered rock core



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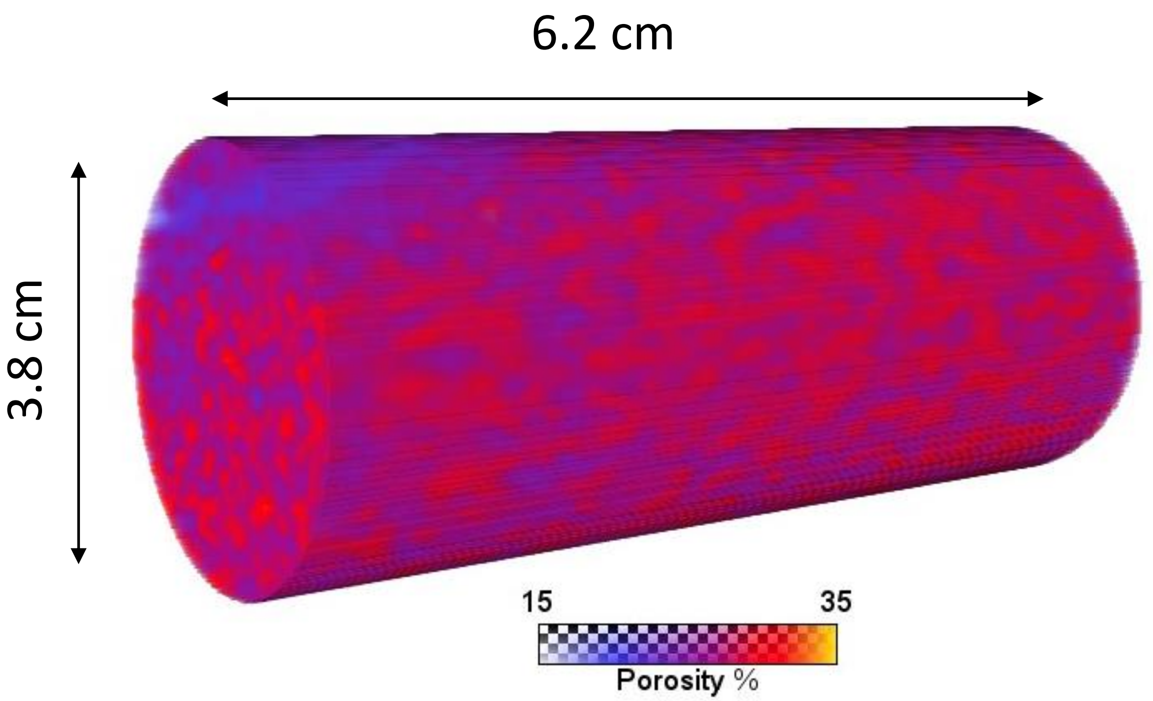
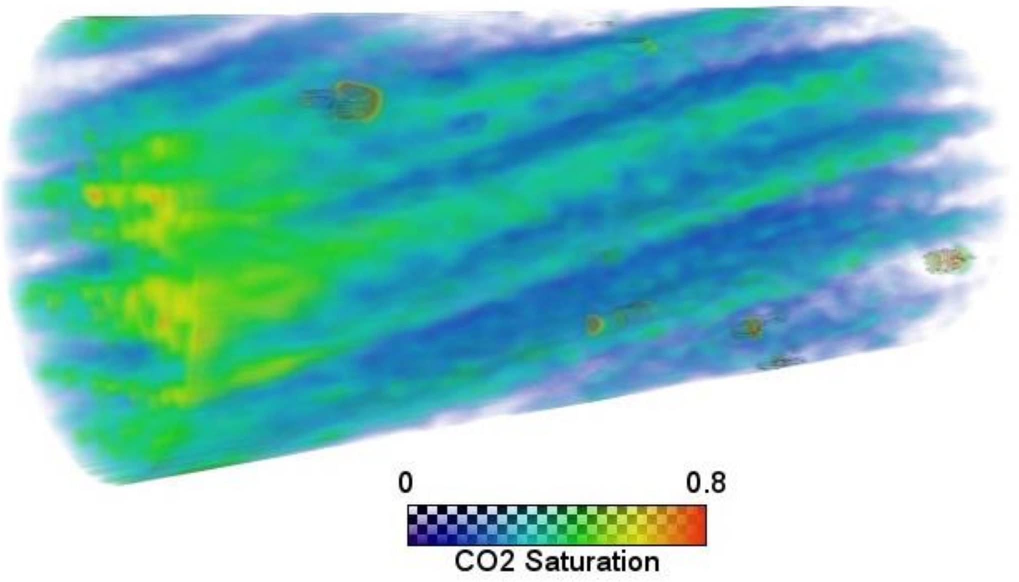


Porosity map – 27%



CO2 95% - Water 5% (3ml/min)

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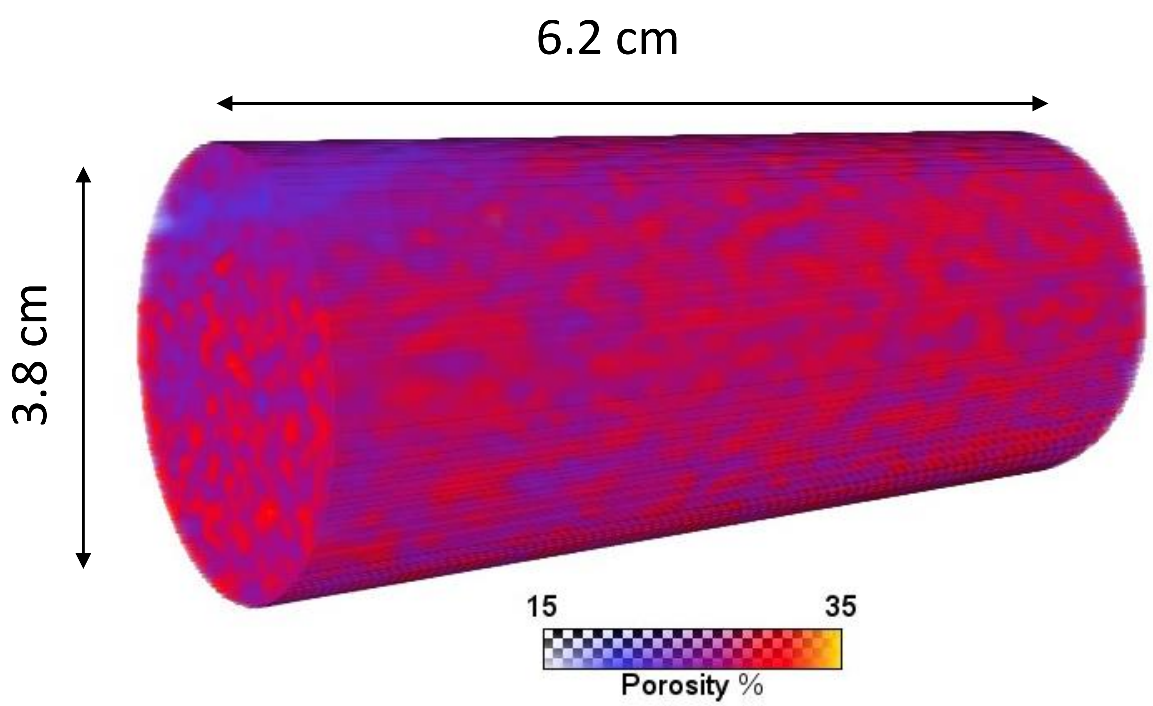

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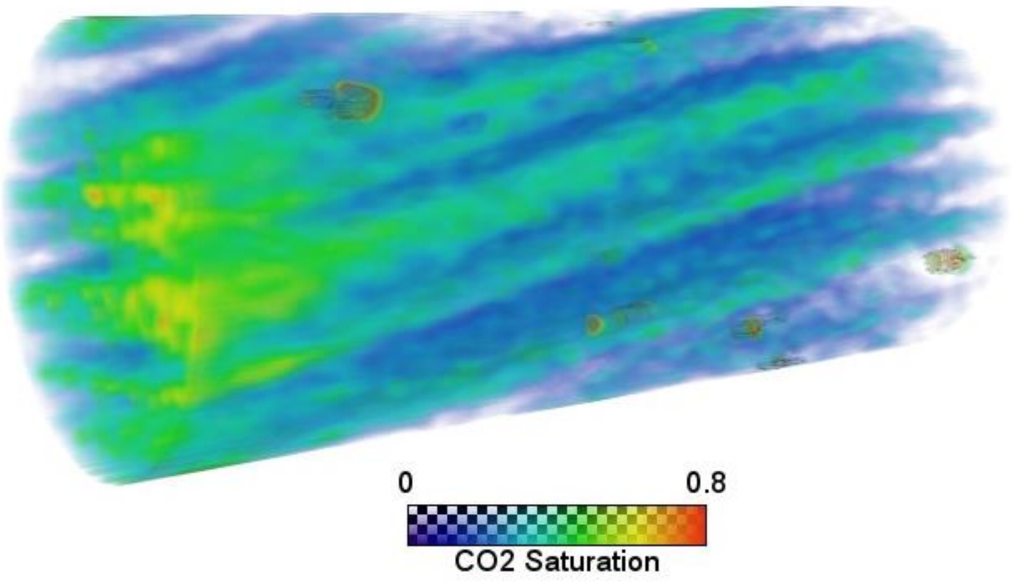
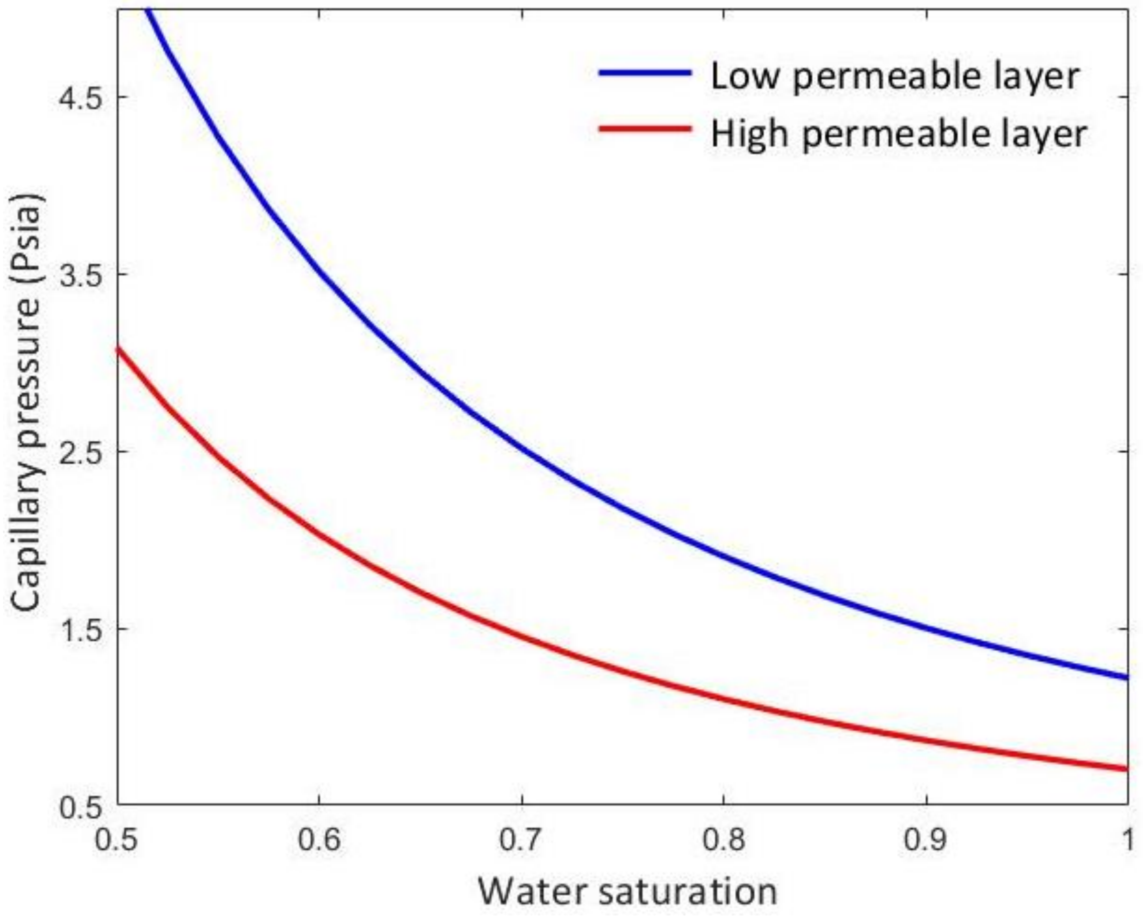


CO2 95% - Water 5% (3ml/min)

Heterogeneous saturation distributions are the result of capillary heterogeneity

Heterogeneity in the capillary pressure - saturation relationship can lead to heterogeneous saturation distributions



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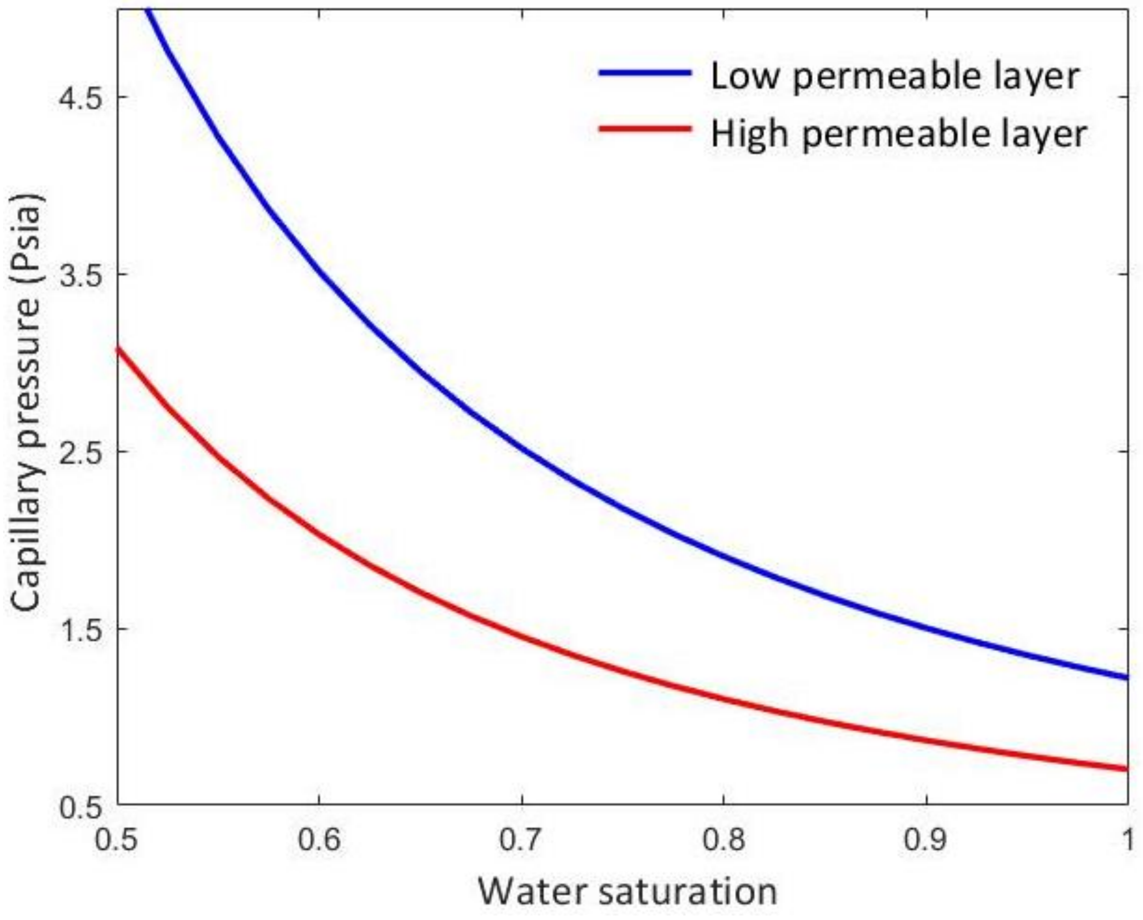

$$q_T = -\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}} + \frac{k\kappa_{rw}}{\mu_w}\right)\nabla p_w$$

Viscous

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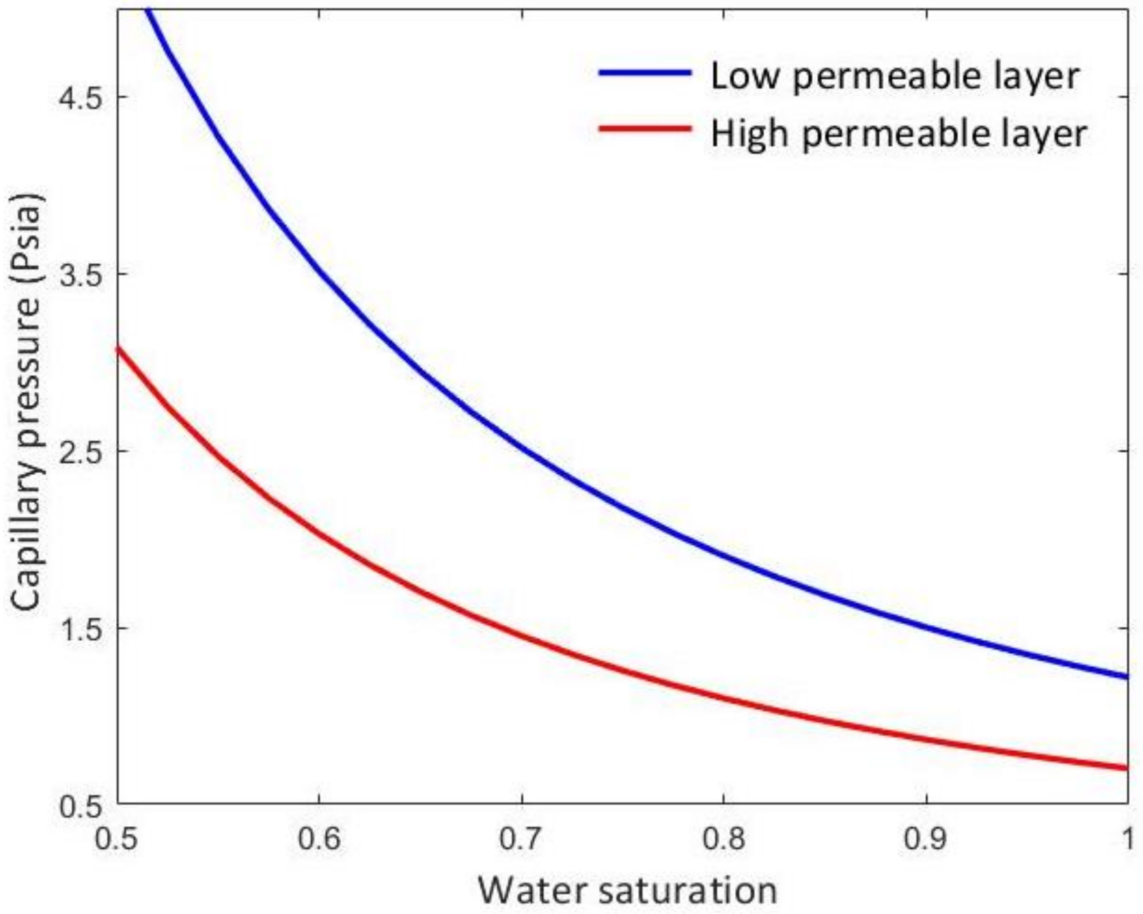

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Viscous Capillary

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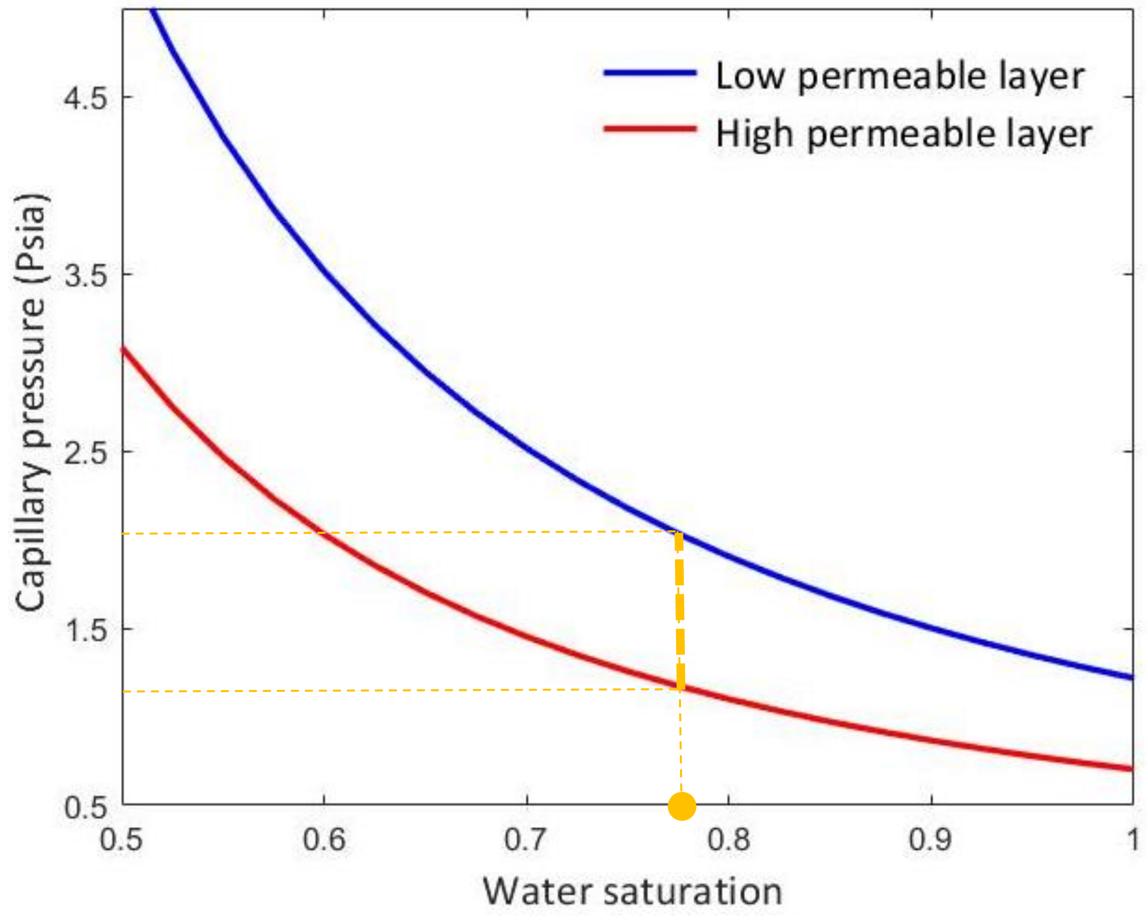

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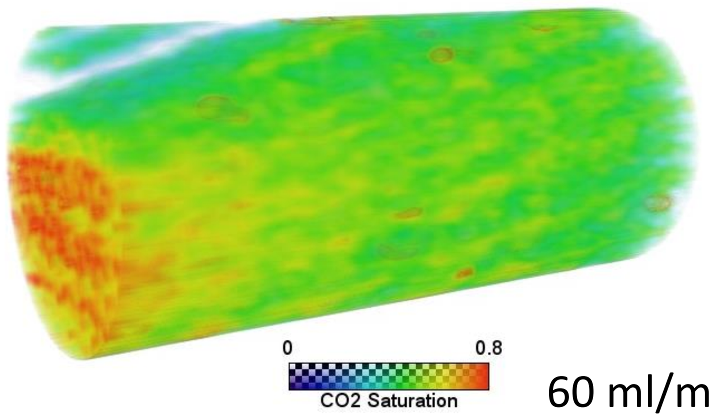
Viscous Capillary

Viscous dominated



60 ml/min

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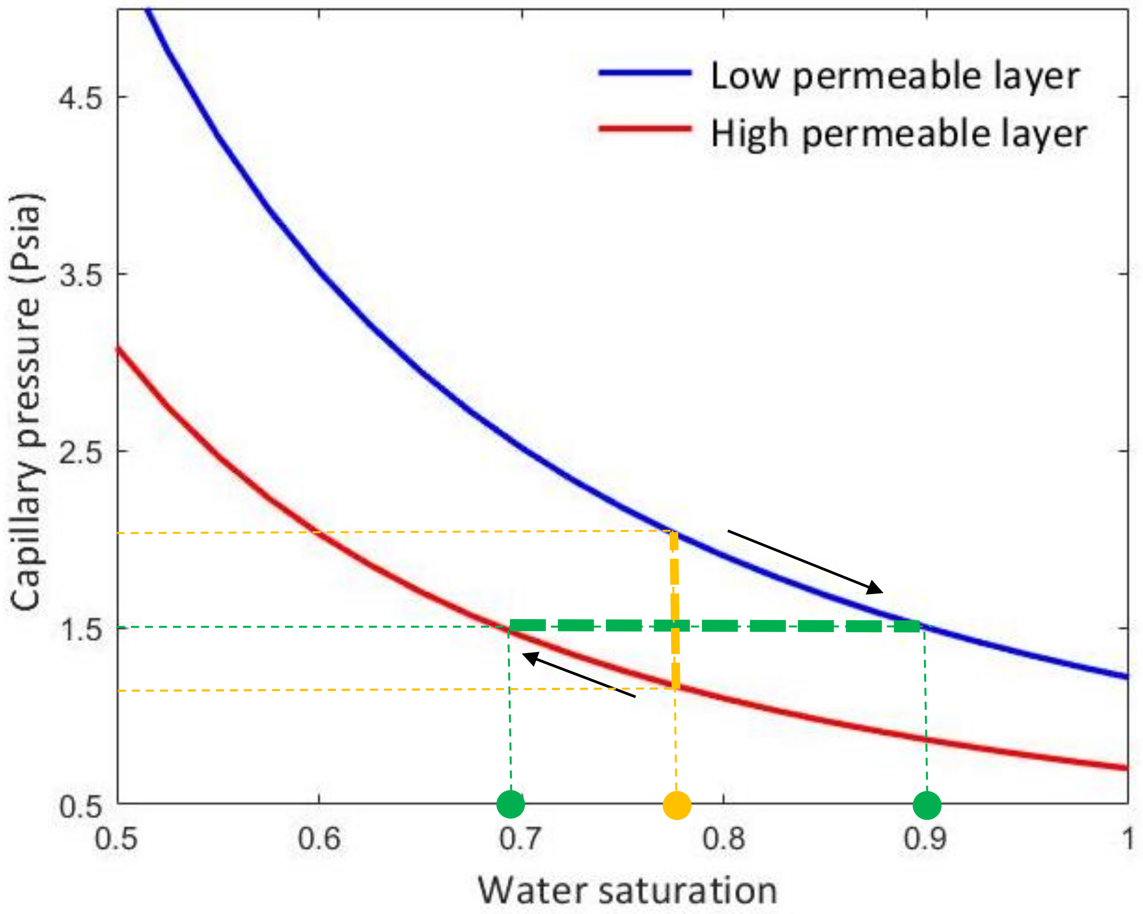

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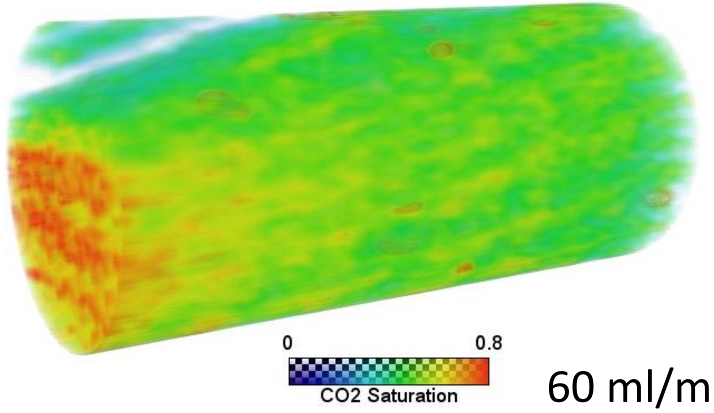
Viscous

Capillary

Viscous dominated



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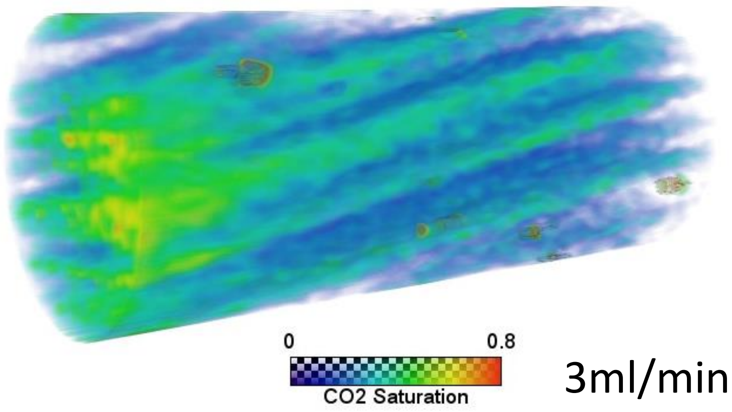
Capillary dominated



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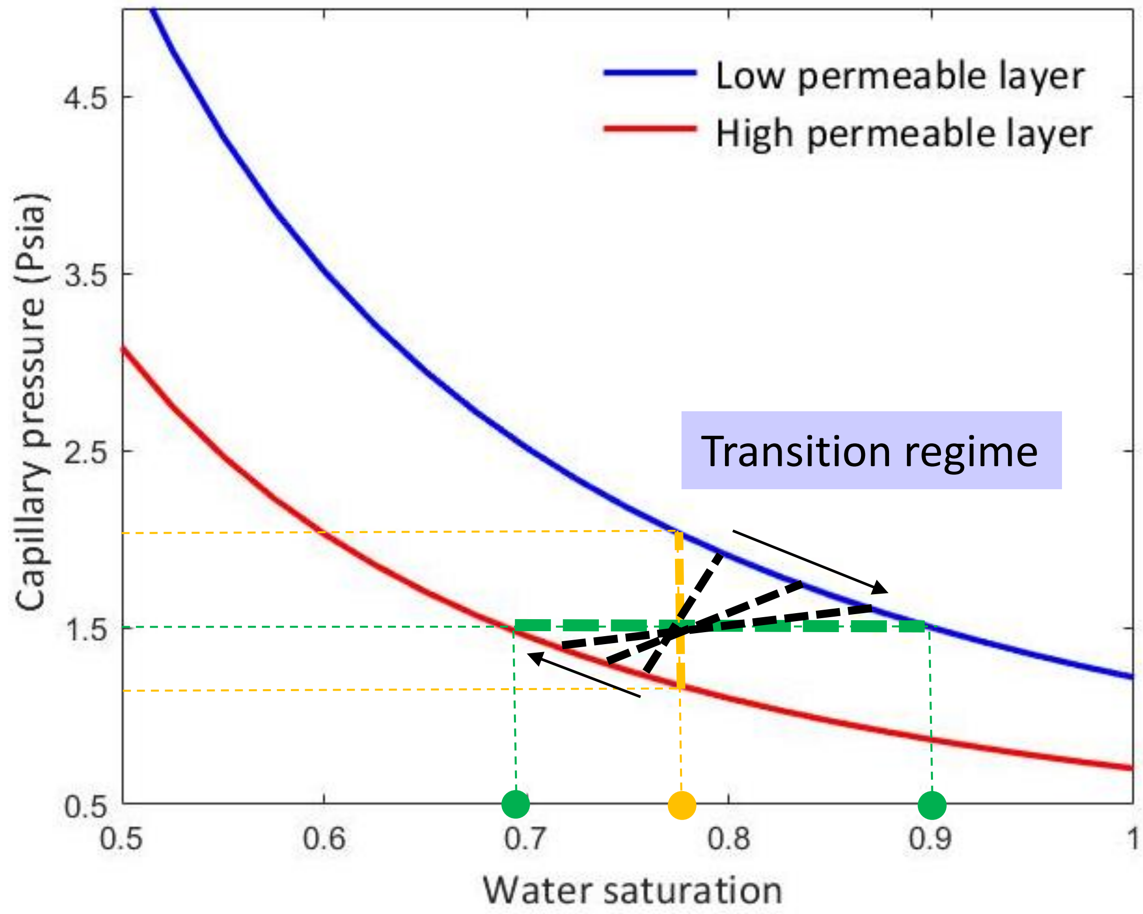

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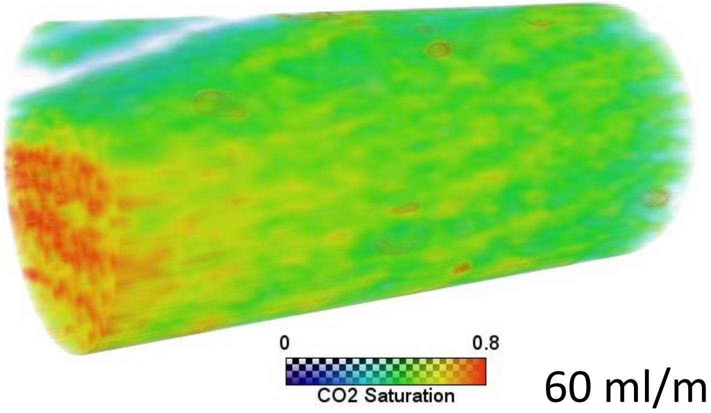
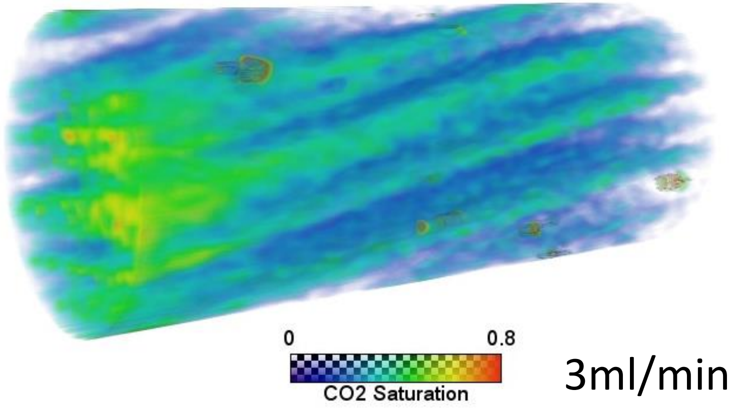


60 ml/min

Capillary dominated



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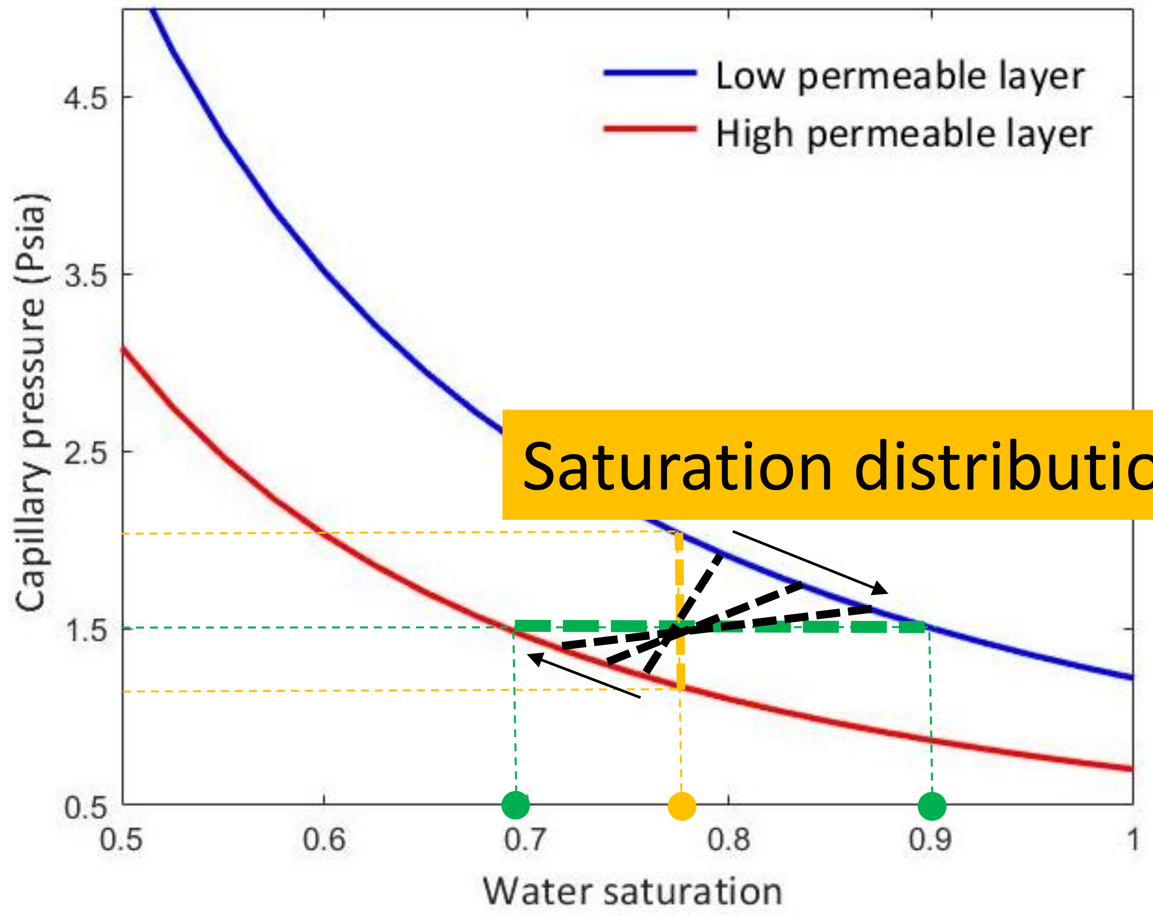

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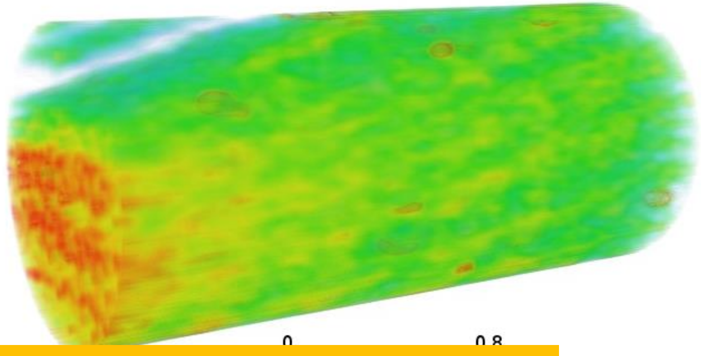
Viscous

Capillary

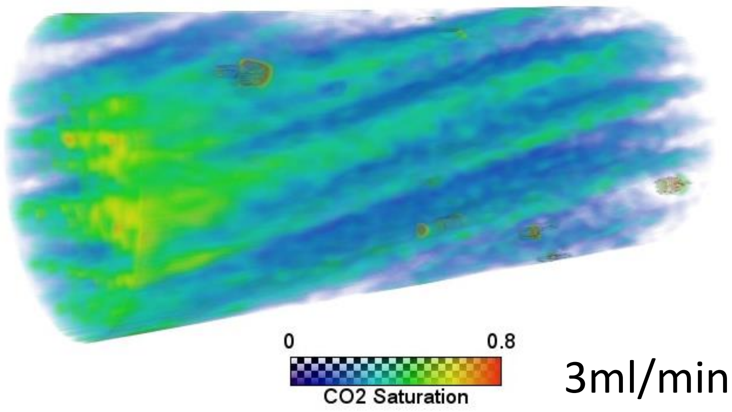
Saturation distributions are flow-rate dependent

Viscous dominated



0 ml/min

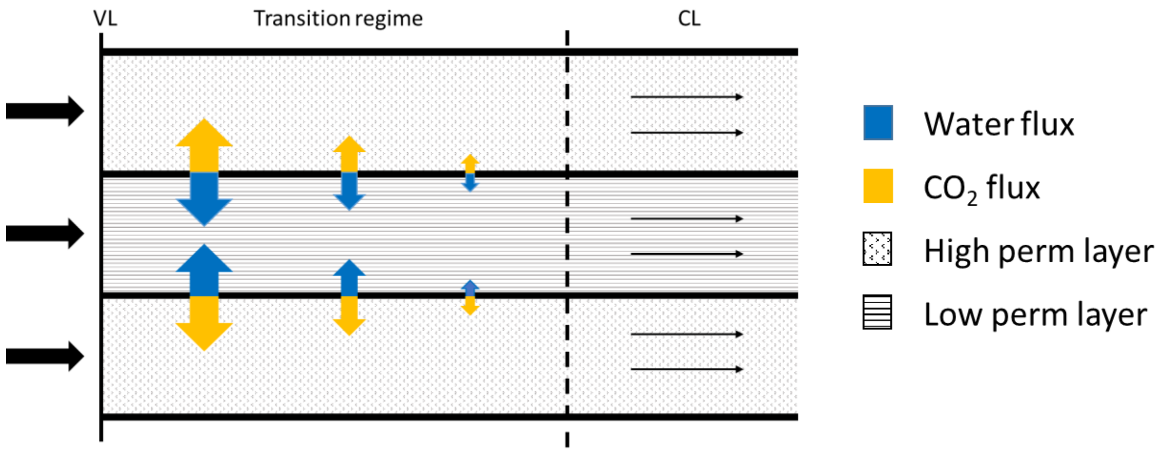
Capillary dominated



3ml/min

A physics-based model to predict the impact of horizontal laminations on CO_2 plume migration

A physics-based model to find upscaled saturation functions and incorporate them into a field-scale model



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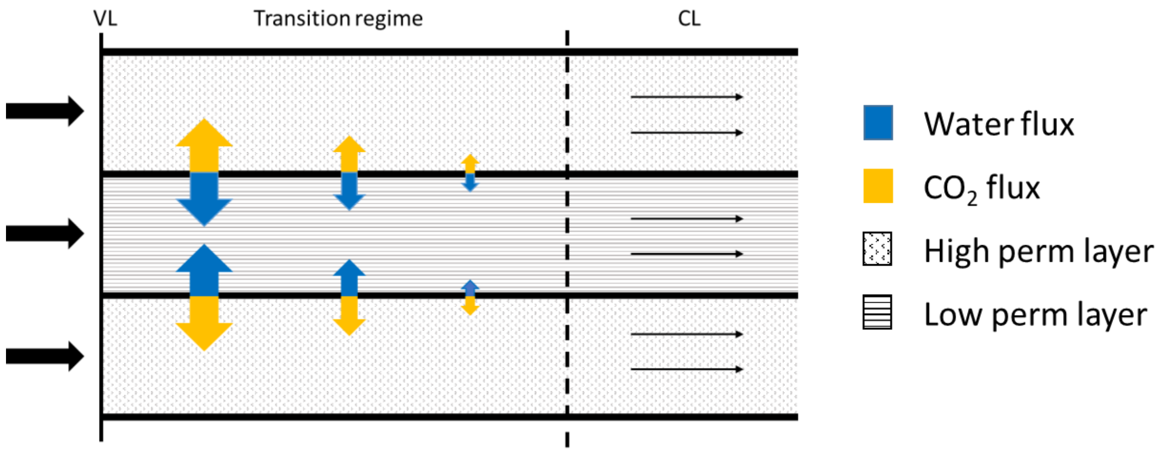
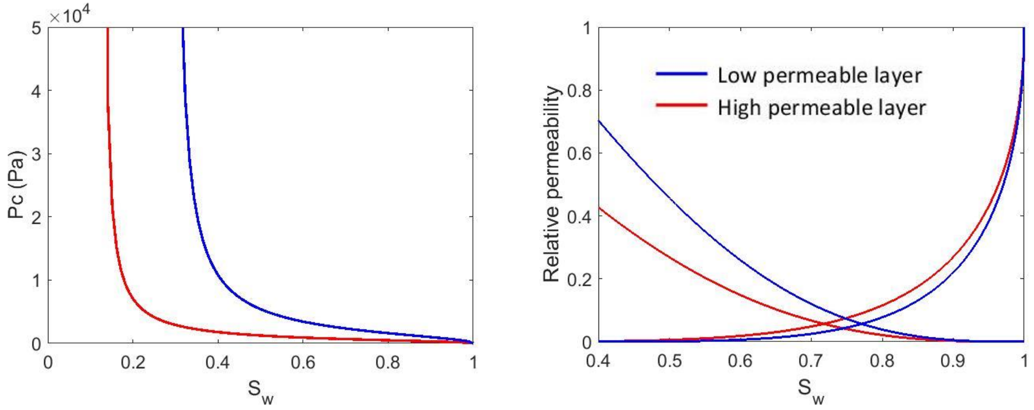


- Saturation functions are defined for each layer



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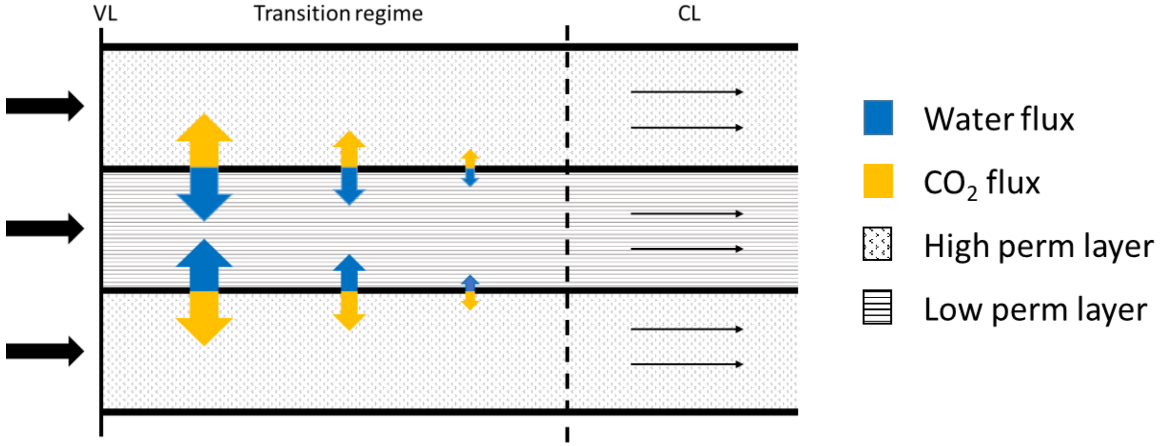

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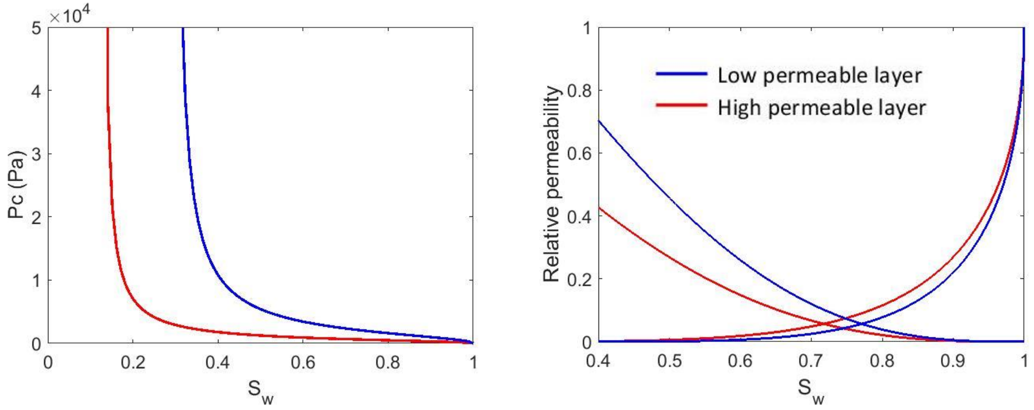

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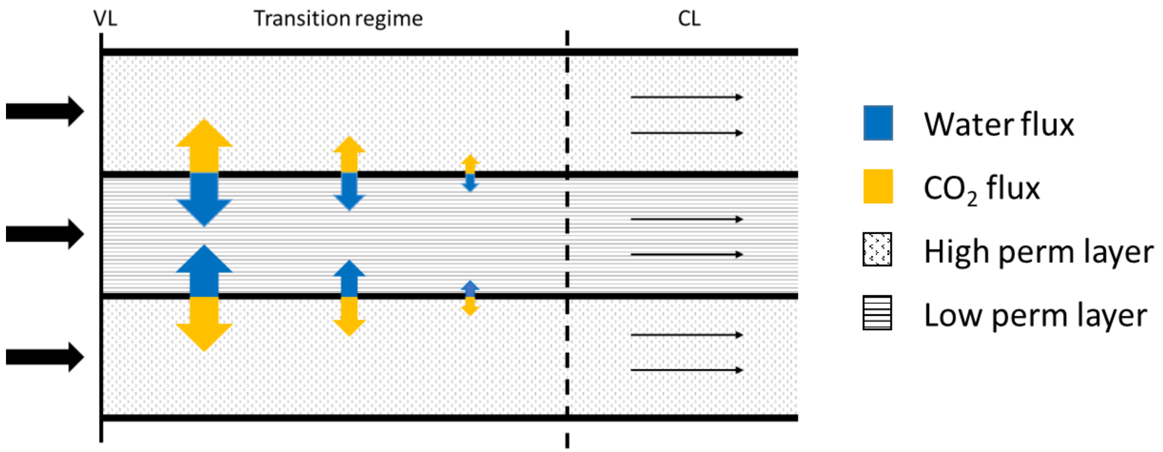
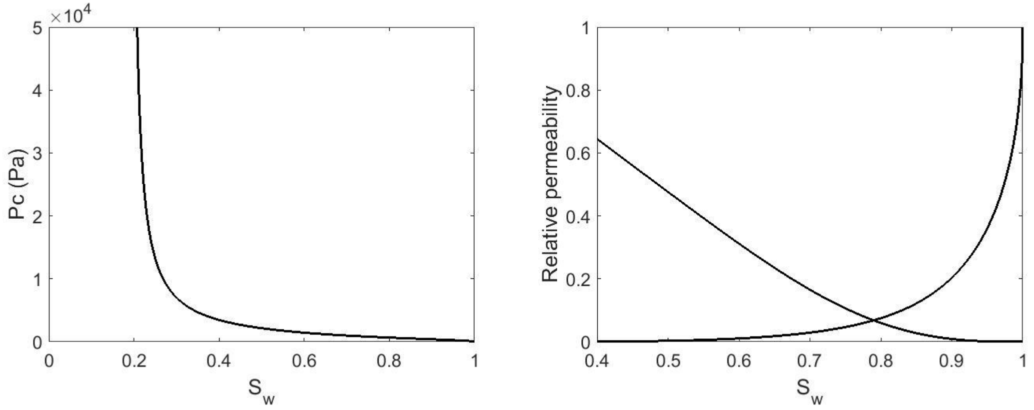


- Upscaled flow-rate dependent saturation functions



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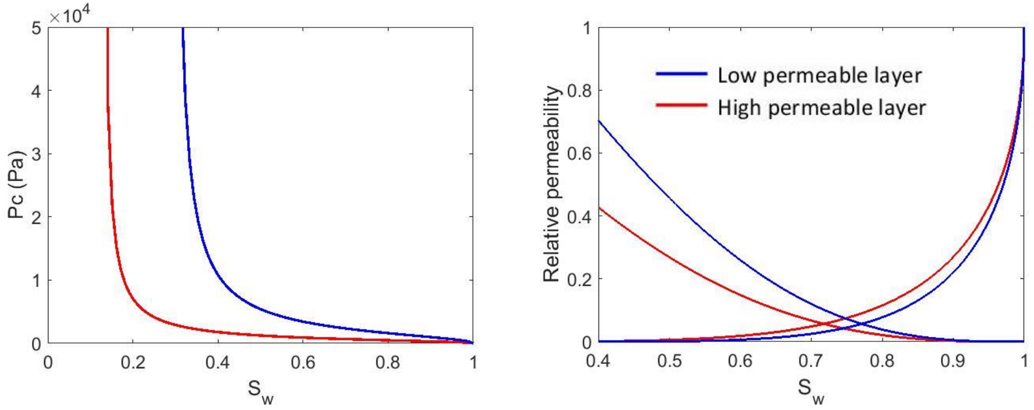

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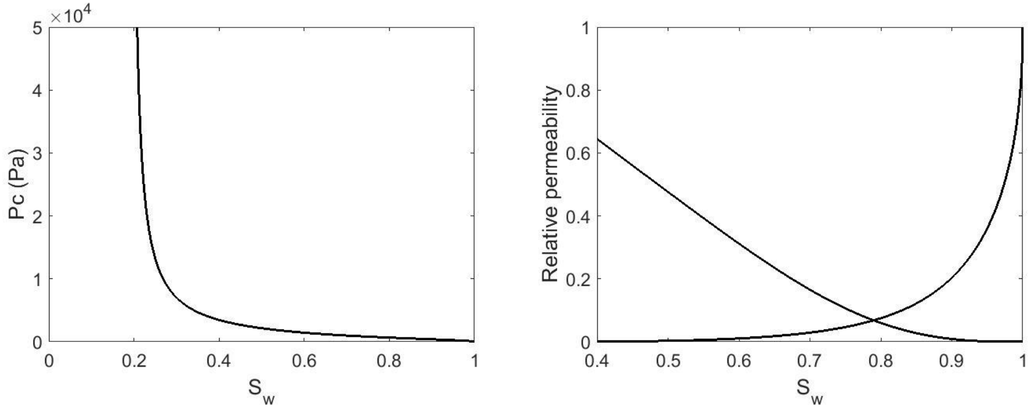

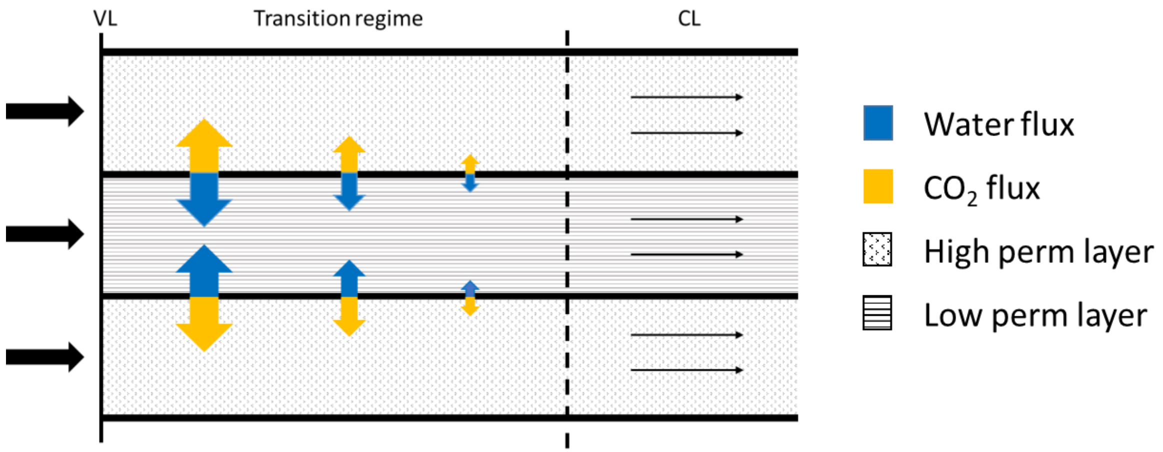

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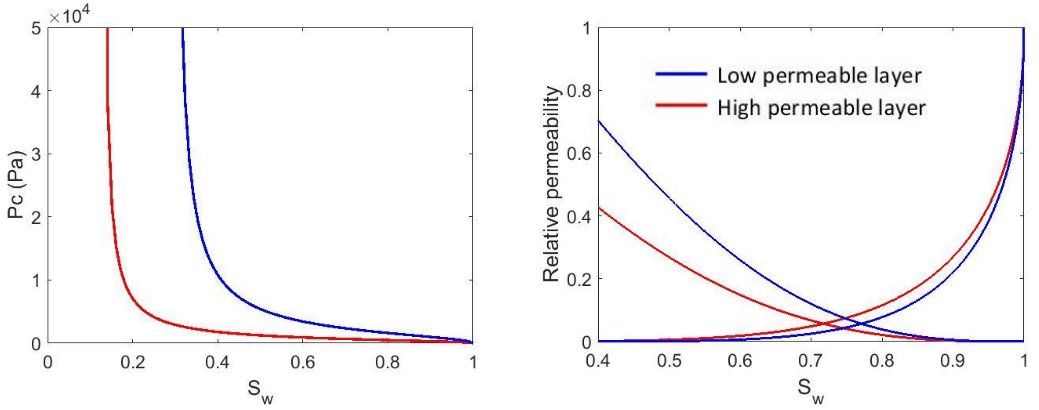
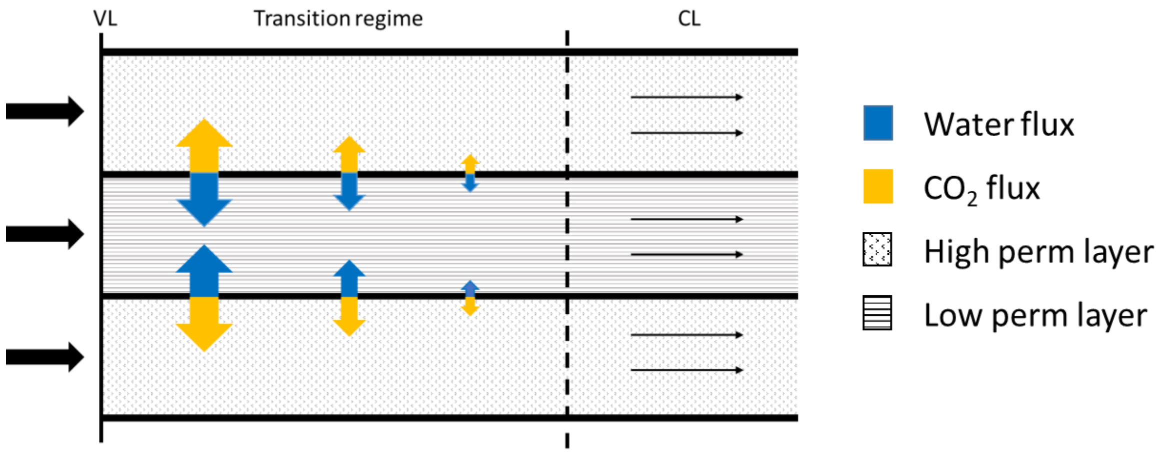


1. Derive upscaled flow-rate dependent saturation functions

A physics-based model to find upscaled saturation functions and incorporate them into a field-scale model



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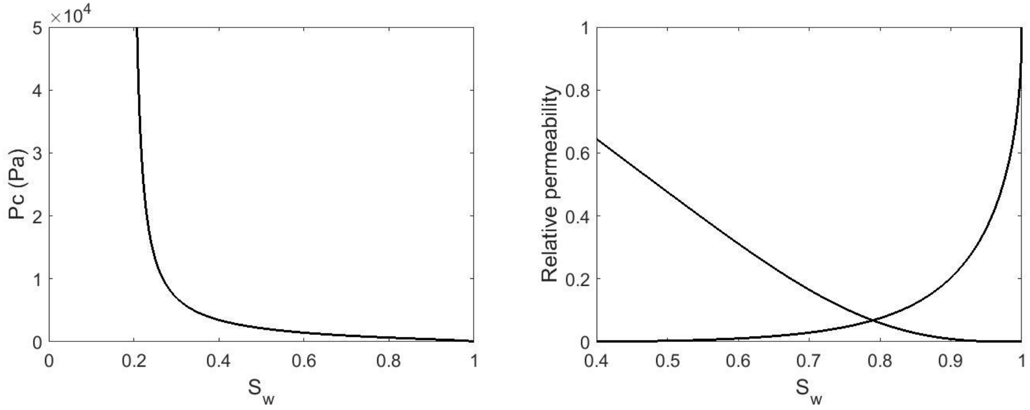

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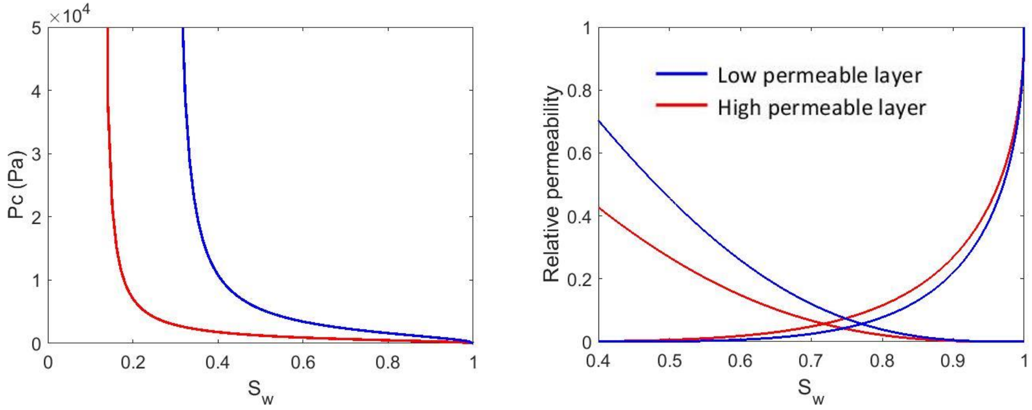
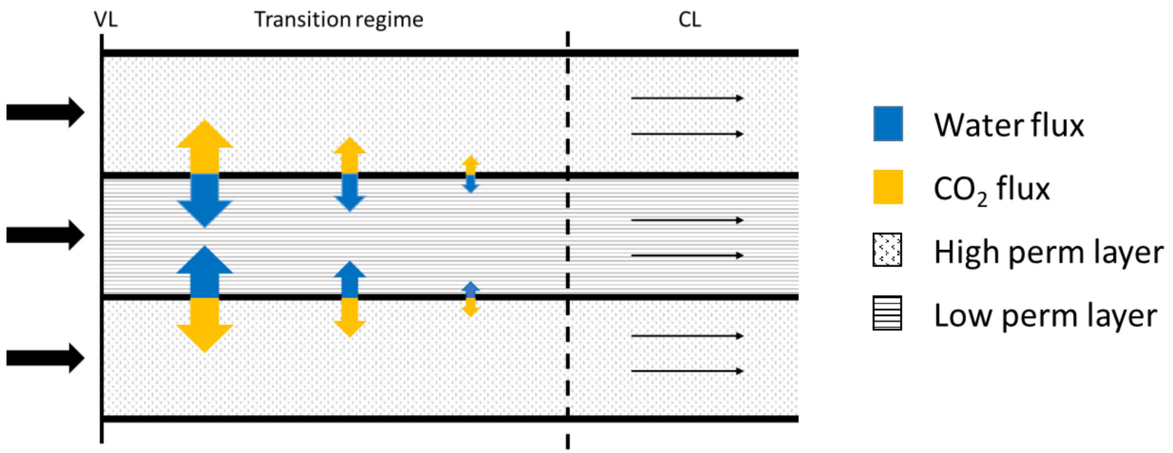


1. Derive upscaled flow-rate dependent saturation functions
2. Incorporate these functions into a field scale model

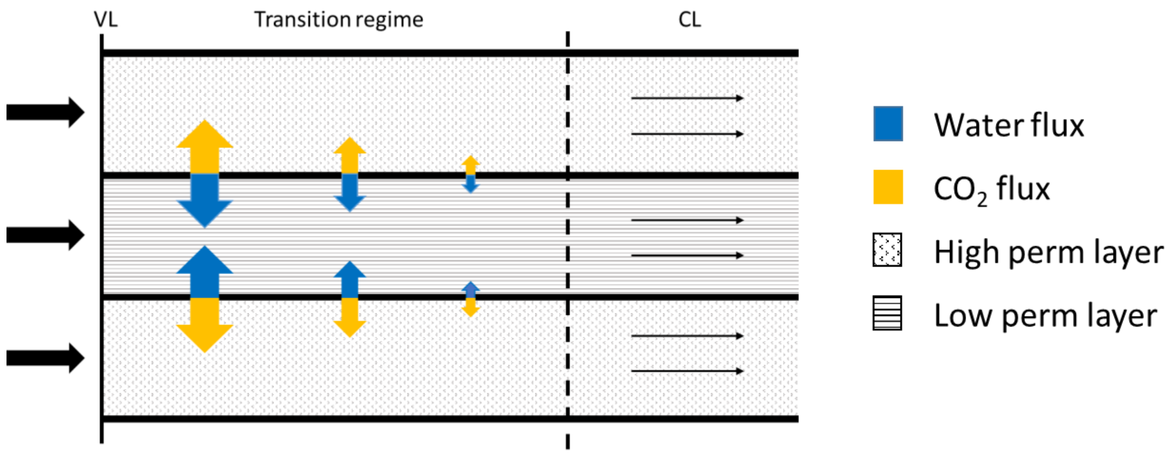
Upscaled saturation functions



Upscaled saturation functions

$$q_w = \frac{\frac{k\kappa_{rw}}{\mu_w}}{\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}} + \frac{k\kappa_{rw}}{\mu_w}\right)} q_T + \frac{\frac{k\kappa_{rw}}{\mu_w}}{\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}} + \frac{k\kappa_{rw}}{\mu_w}\right)} \frac{k\kappa_{rCO2}}{\mu_{CO2}} \frac{dp_c}{dS_w} \nabla S_w$$

$$q_{CO2} = \frac{\frac{k\kappa_{rCO2}}{\mu_{CO2}}}{\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}} + \frac{k\kappa_{rw}}{\mu_w}\right)} q_T - \frac{\frac{k\kappa_{rCO2}}{\mu_{CO2}}}{\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}} + \frac{k\kappa_{rw}}{\mu_w}\right)} \frac{k\kappa_{rw}}{\mu_w} \frac{dp_c}{dS_w} \nabla S_w$$



Upscaled saturation functions

Viscous flux

$$q_w = \frac{\frac{k\kappa_{rw}}{\mu_w}}{\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}} + \frac{k\kappa_{rw}}{\mu_w}\right)} q_T + \frac{\frac{k\kappa_{rw}}{\mu_w}}{\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}} + \frac{k\kappa_{rw}}{\mu_w}\right)} \frac{k\kappa_{rCO2}}{\mu_{CO2}} \frac{dp_c}{dS_w} \nabla S_w$$

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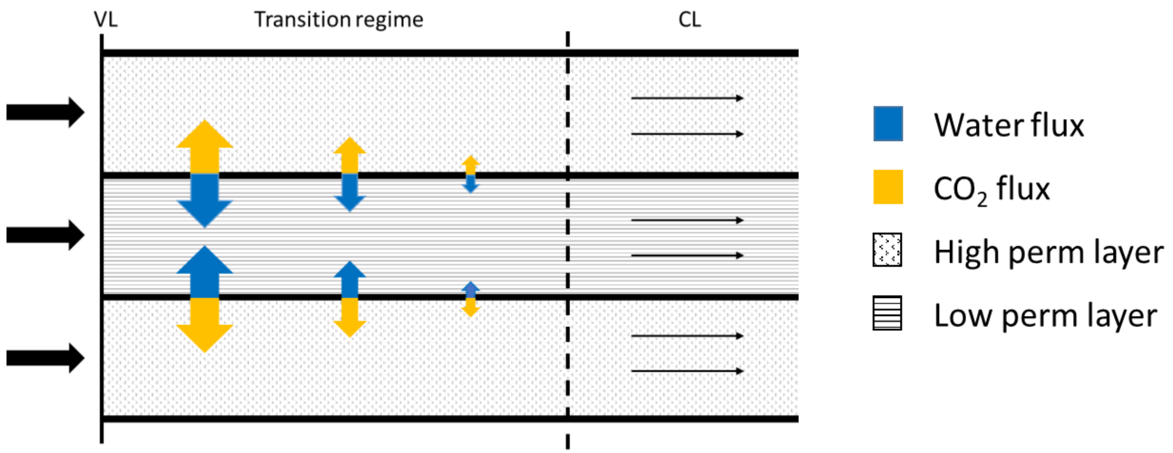

Upscaled saturation functions

Viscous flux | Capillary flux

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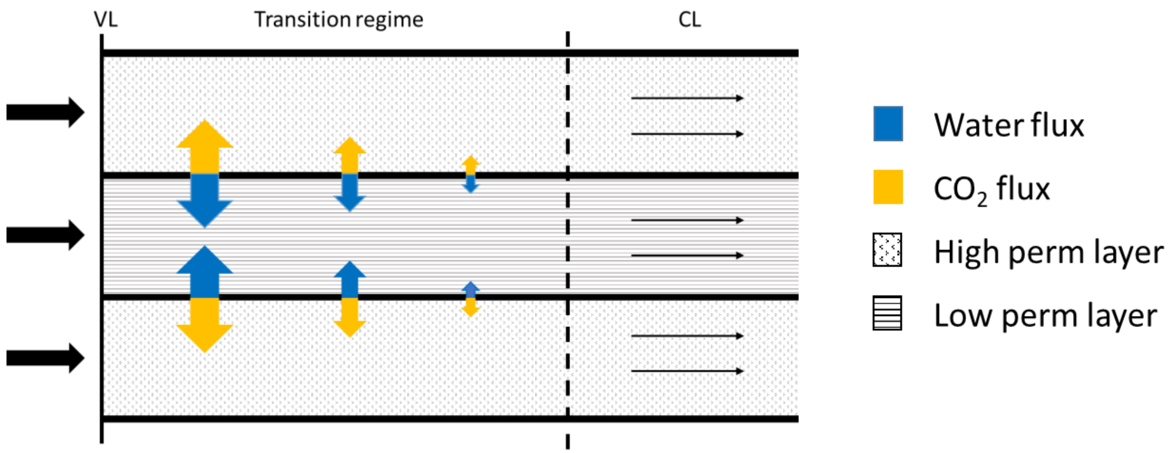

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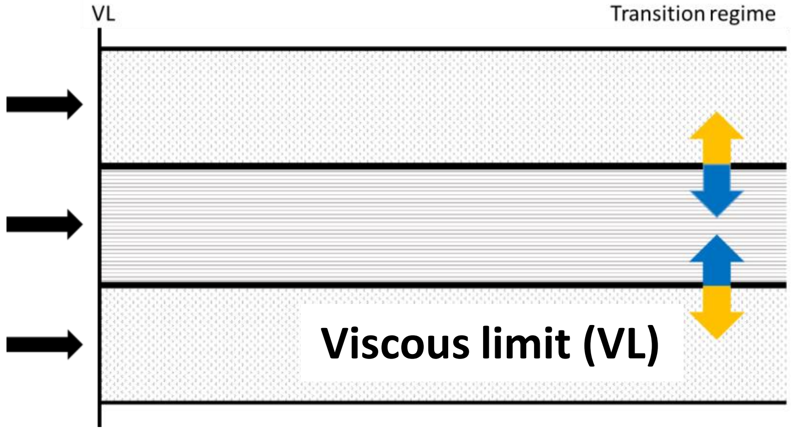

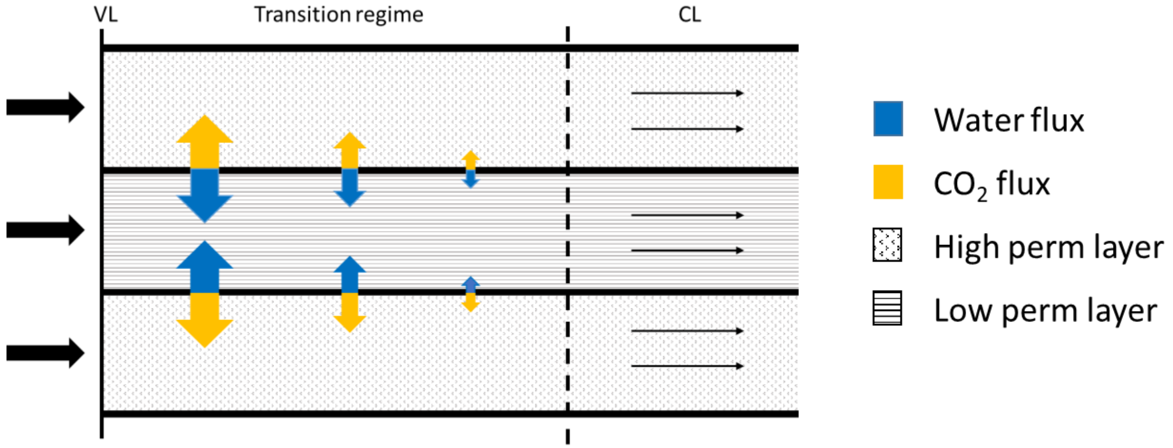

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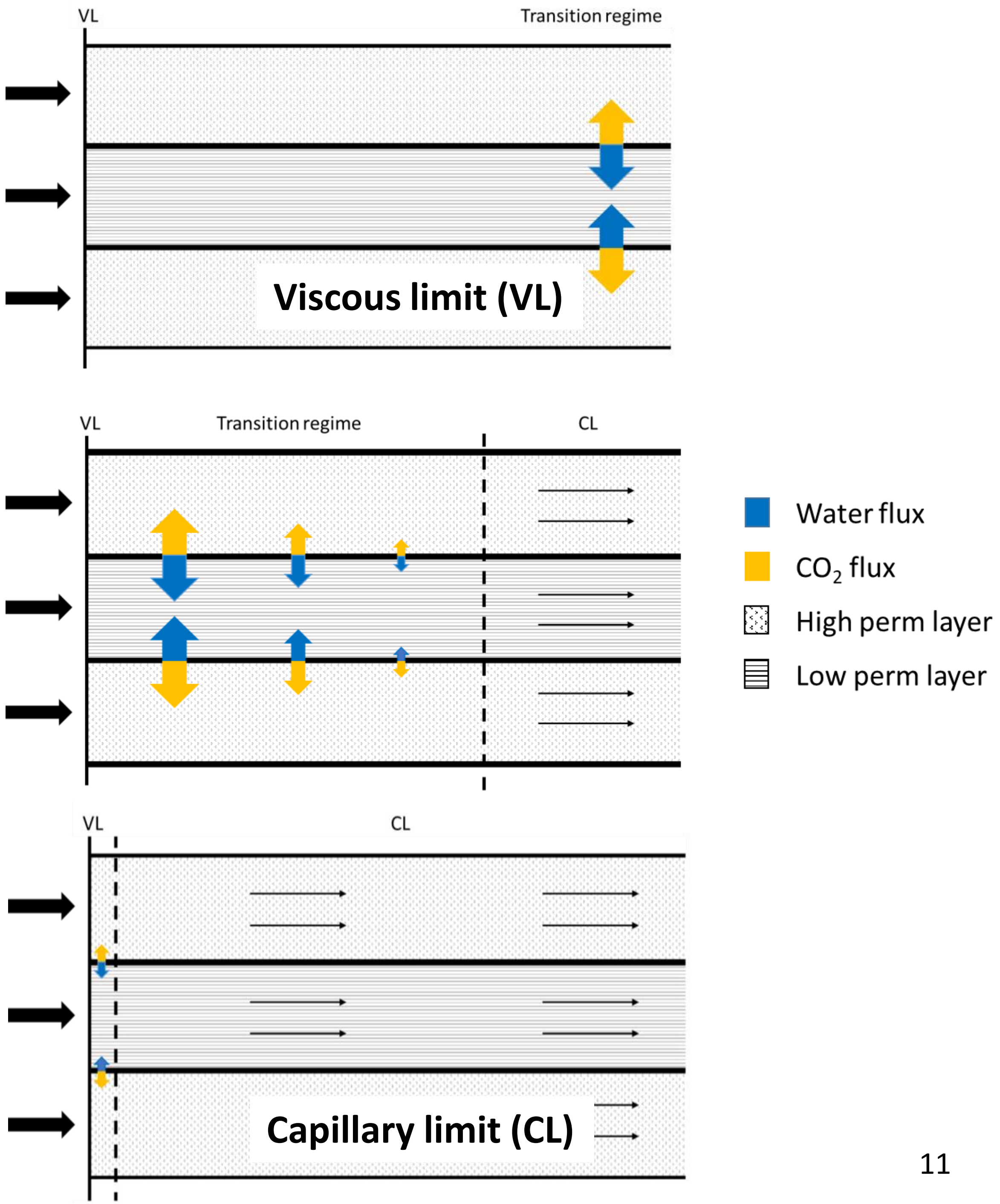
Viscous flux	Capillary flux

$$q_w = \frac{\frac{k\kappa_{rw}}{\mu_w}}{\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}} + \frac{k\kappa_{rw}}{\mu_w}\right)} q_T + \frac{\frac{k\kappa_{rw}}{\mu_w}}{\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}} + \frac{k\kappa_{rw}}{\mu_w}\right)} \frac{k\kappa_{rCO2}}{\mu_{CO2}} \frac{dp_c}{dS_w} \nabla S_w$$

$$q_{CO2} = \frac{\frac{k\kappa_{rCO2}}{\mu_{CO2}}}{\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}} + \frac{k\kappa_{rw}}{\mu_w}\right)} q_T - \frac{\frac{k\kappa_{rCO2}}{\mu_{CO2}}}{\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}} + \frac{k\kappa_{rw}}{\mu_w}\right)} \frac{k\kappa_{rw}}{\mu_w} \frac{dp_c}{dS_w} \nabla S_w$$



Upscaled saturation functions

Viscous flux | Capillary flux

$$q_w = \frac{\frac{k\kappa_{rw}}{\mu_w}}{\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}} + \frac{k\kappa_{rw}}{\mu_w}\right)} q_T + \frac{\frac{k\kappa_{rw}}{\mu_w}}{\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}} + \frac{k\kappa_{rw}}{\mu_w}\right)} \frac{k\kappa_{rCO2}}{\mu_{CO2}} \frac{dp_c}{dS_w} \nabla S_w$$

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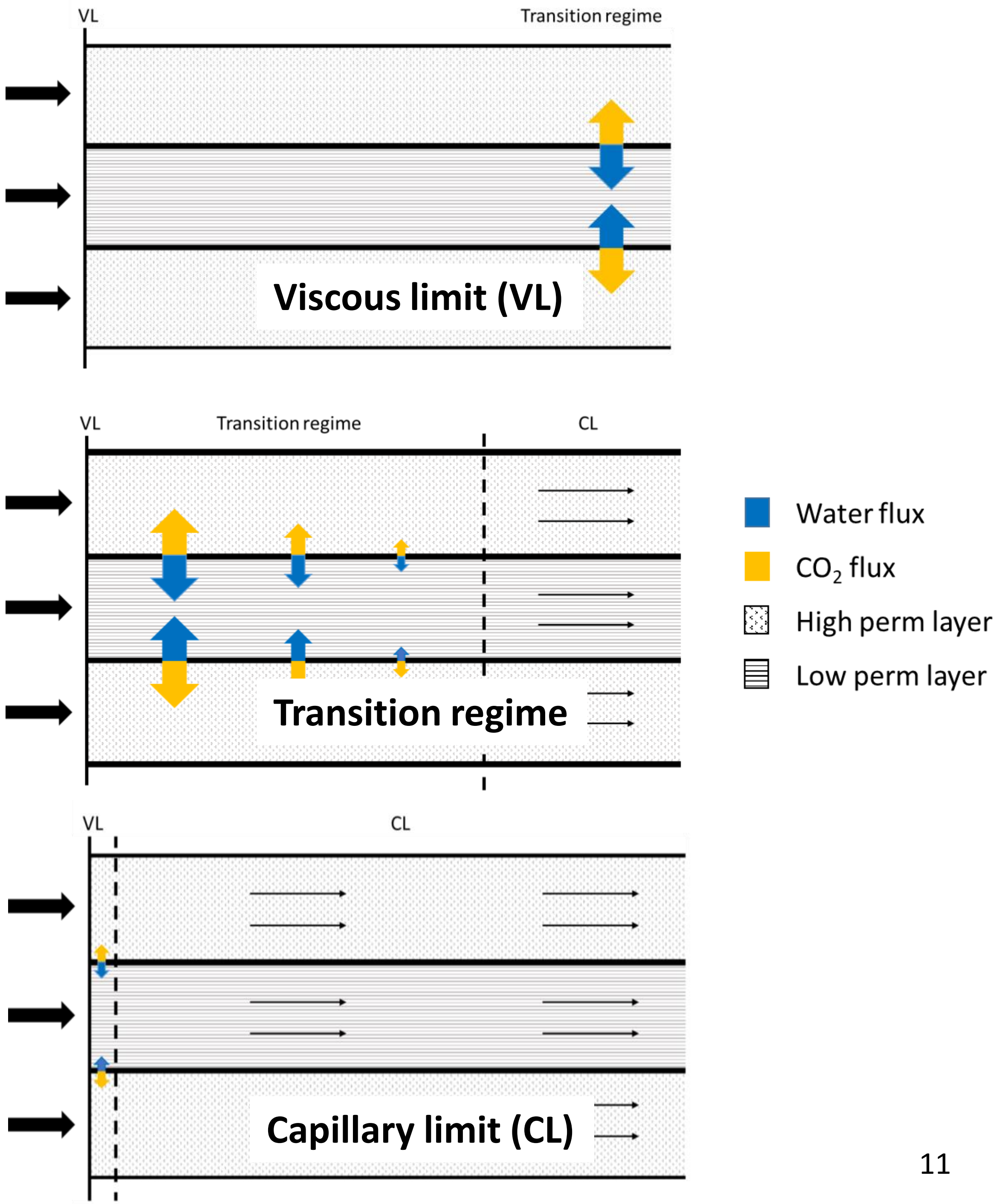


Upscaled saturation functions

Viscous flux

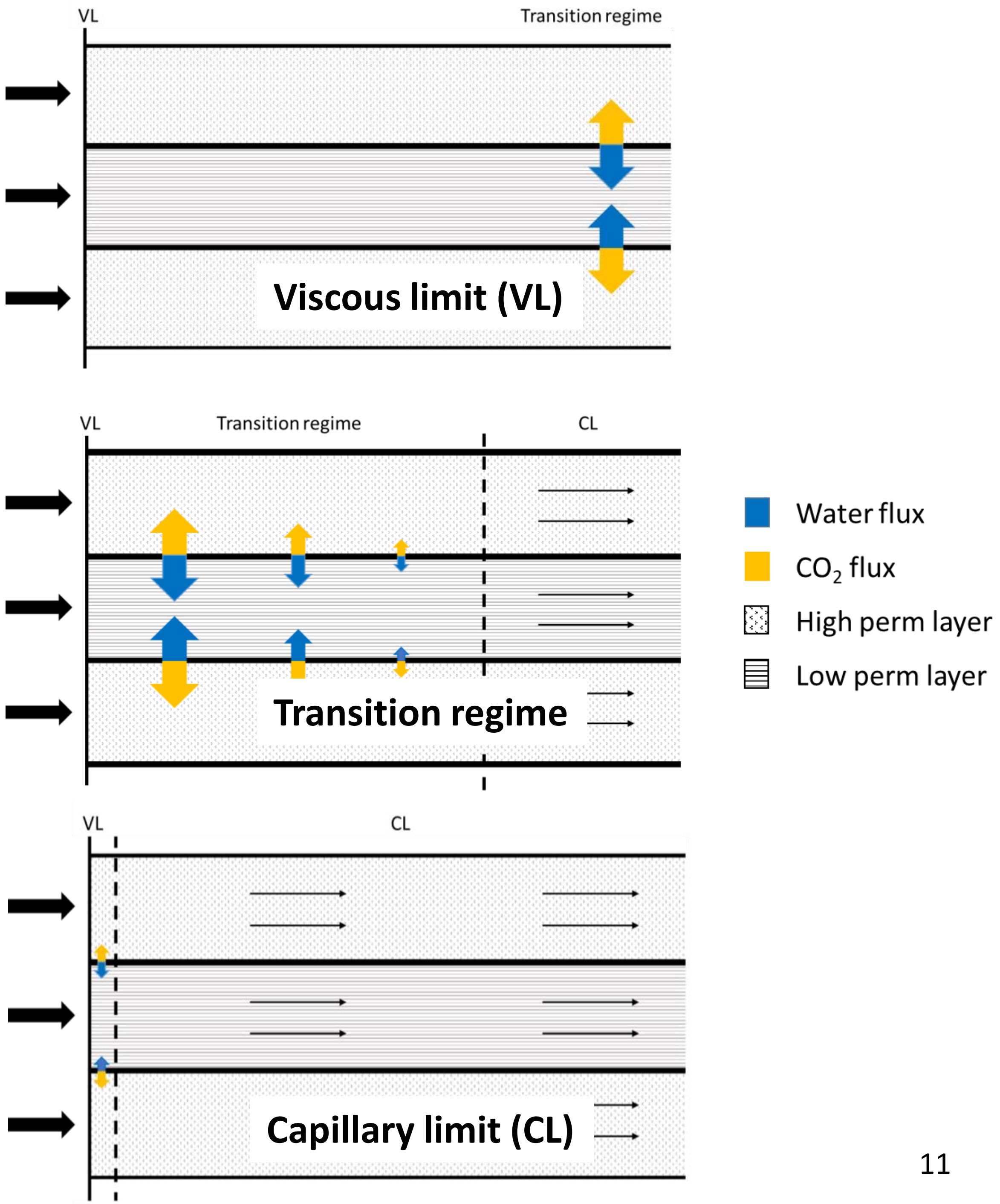
Capillary flux

$$q_w = \frac{\frac{k\kappa_{rw}}{\mu_w}}{\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}} + \frac{k\kappa_{rw}}{\mu_w}\right)} q_T$$

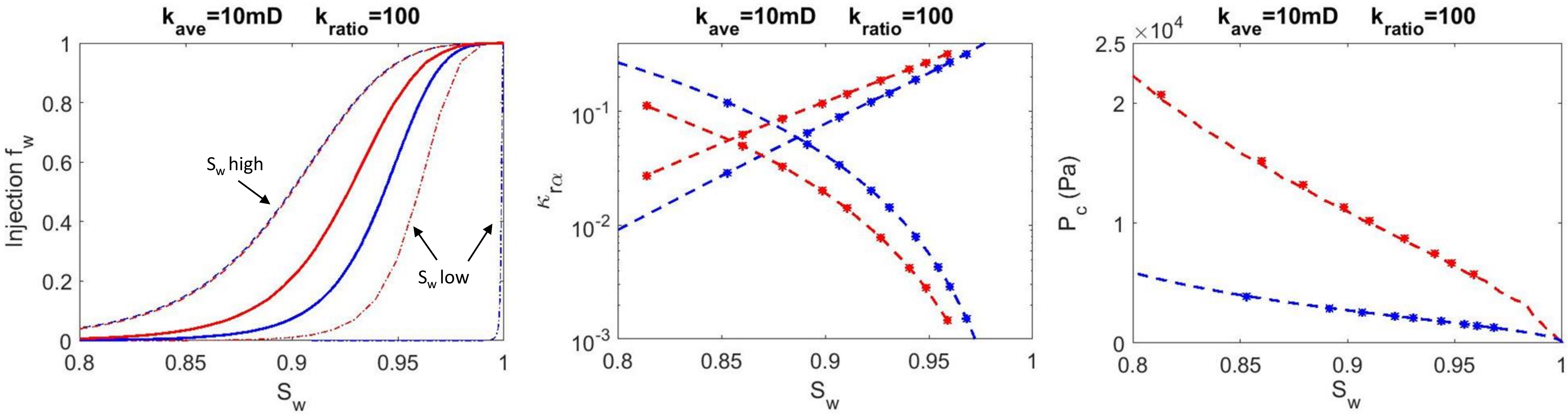
$$q_{CO2} = \frac{\frac{k\kappa_{rCO2}}{\mu_{CO2}}}{\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}} + \frac{k\kappa_{rw}}{\mu_w}\right)} q_T$$

In the VL and CL the capillary flux can be neglected

$$f_w = \frac{q_w}{q_T} = \frac{\frac{k\kappa_{rw}}{\mu_w}}{\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}} + \frac{k\kappa_{rw}}{\mu_w}\right)} \qquad f_{w_{up}} = \frac{q_w}{q_T} = \frac{\sum_{i=1}^{n}\left(\frac{k\kappa_{rw}}{\mu_w}\right)_i}{\sum_{i=1}^{n}\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}} + \frac{k\kappa_{rw}}{\mu_w}\right)_i}$$



Upscaled saturation functions in the CL and VL as a function of fractional flow



- Capillary limit (CL) → capillary pressure is constant in the system
- Viscous limit (VL) → fractional flow is the same in each layer

● ● f_w= 0.01, 0.05, 0.1, 0.2, 0.3, 0.5, 0.7, 0.8, 0.9

$$f_{w_{up}} = \frac{q_w}{q_T} = \frac{\sum_{i=1}^{n}\left(\frac{k\kappa_{rw}}{\mu_w}\right)_i}{\sum_{i=1}^{n}\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}} + \frac{k\kappa_{rw}}{\mu_w}\right)_i}$$

VanGenuchten-Mualem relationships

$$P_c = P_c\left((S_w^*)^{((-1/m)-1)}\right)^{(1-m)}$$

$$k_{rw} = (S_w^*)^{1/2}\left[1-\left((1-S_w^*)^{(1/m)}\right)^m\right]^2$$

$$k_{rnw} = (1-S_w^*)^2(1-(S_w^*)^2)$$

$$S_w^* = \frac{S_w - s_{wi}}{1-S_{wi}}$$

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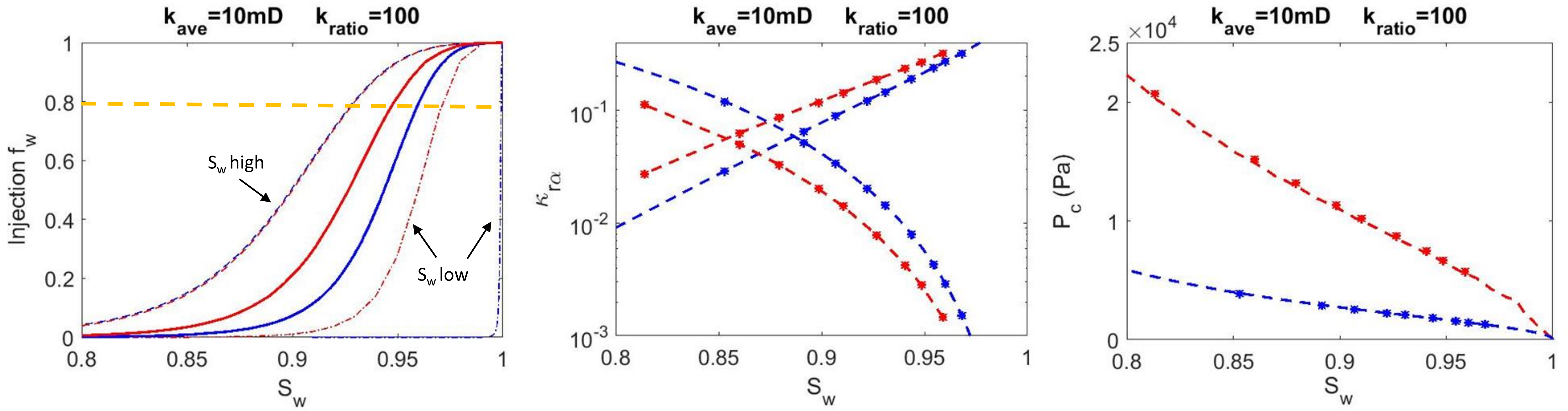

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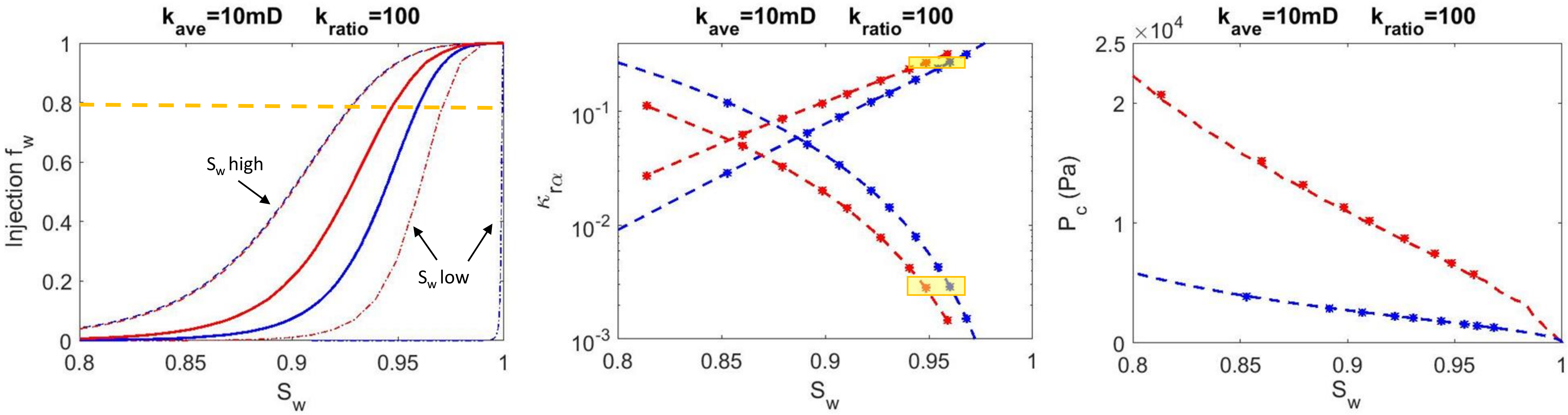

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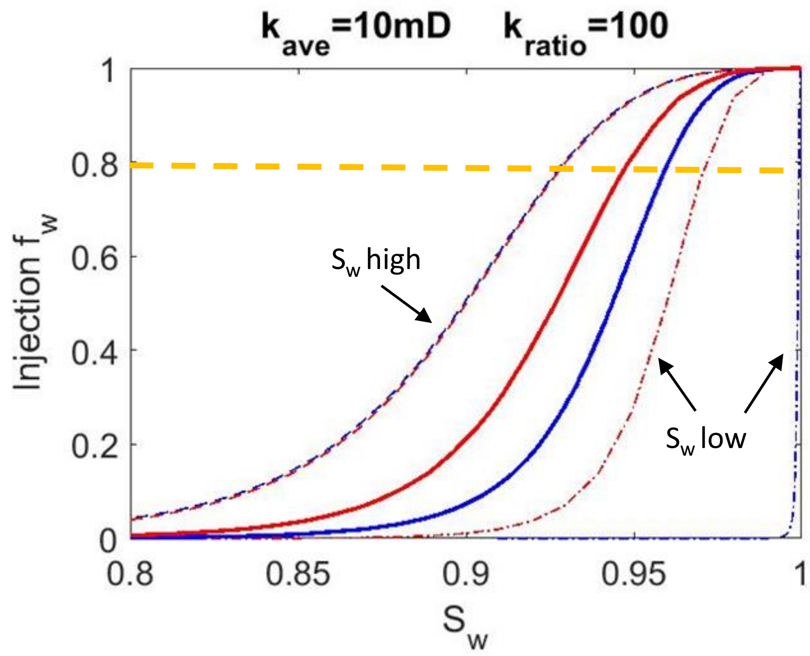

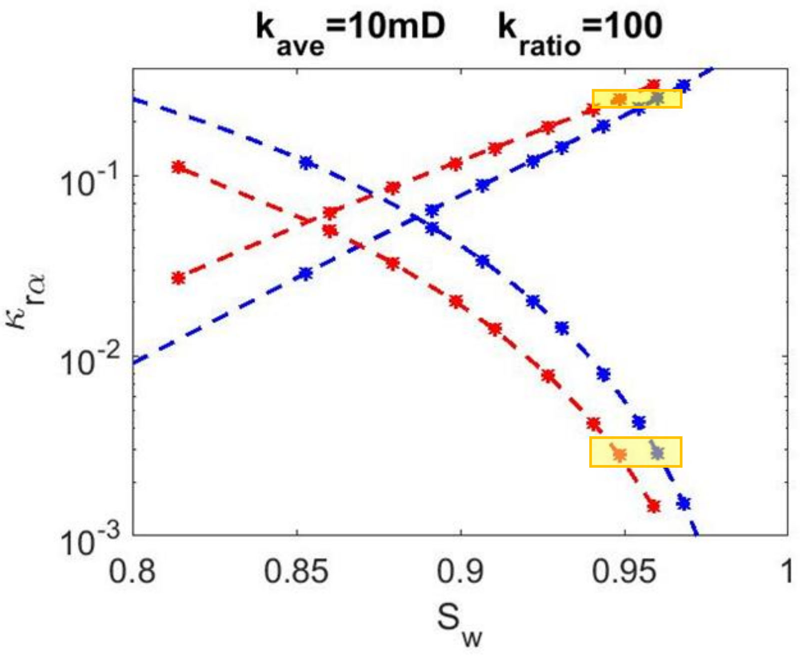

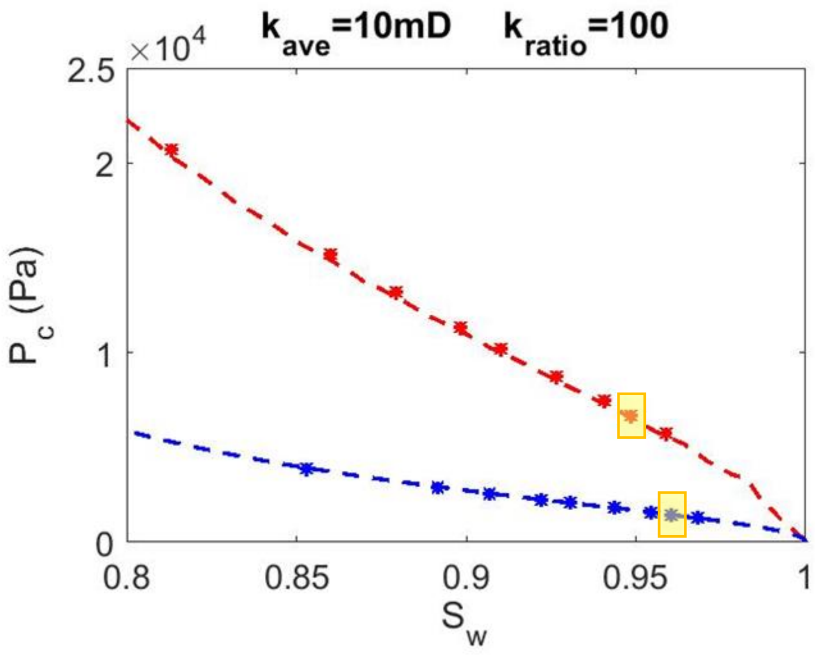

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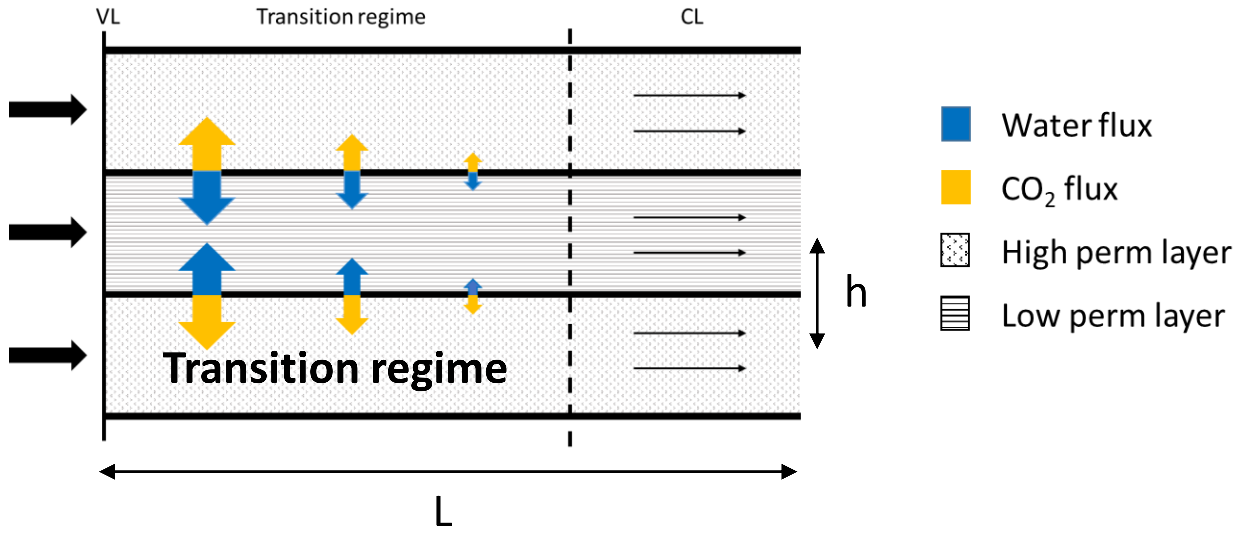
A capillary number scaling is used to find the upscaled saturation functions in the transition regime



$$q_w = \frac{\frac{k\kappa_{rw}}{\mu_w}}{\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}} + \frac{k\kappa_{rw}}{\mu_w}\right)} q_T + \frac{\frac{k\kappa_{rw}}{\mu_w}}{\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}} + \frac{k\kappa_{rw}}{\mu_w}\right)} \frac{k\kappa_{rCO2}}{\mu_{CO2}} \frac{dp_c}{dS_w} \nabla S_w$$

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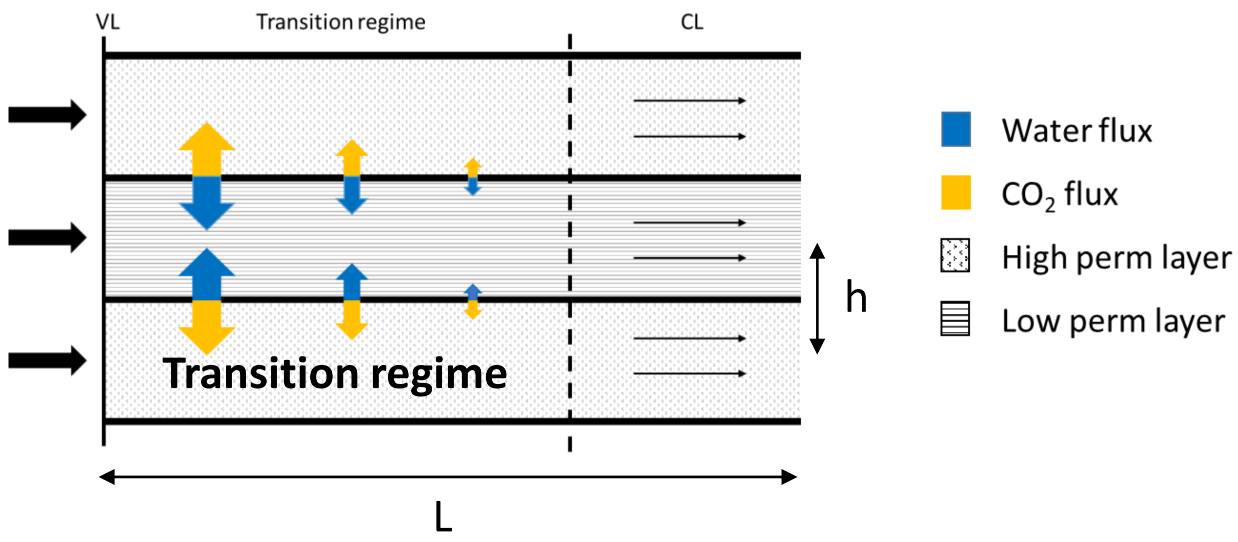

- **New capillary number that describes the viscous/capillary force balance:** $RVC = \frac{h}{L}\frac{q_{vis}}{q_{cap}}$

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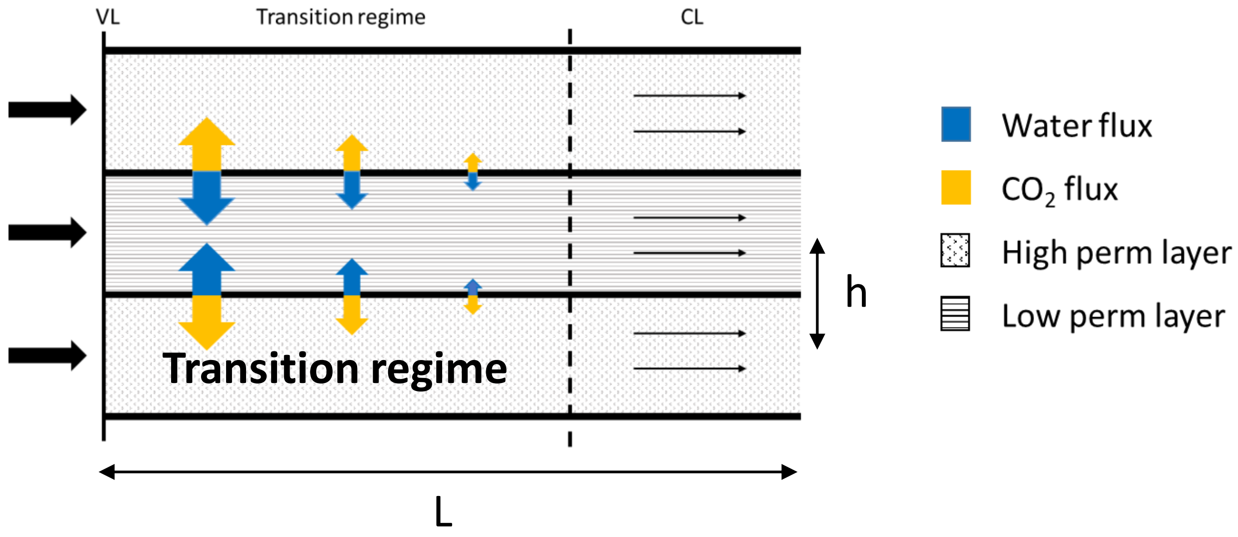

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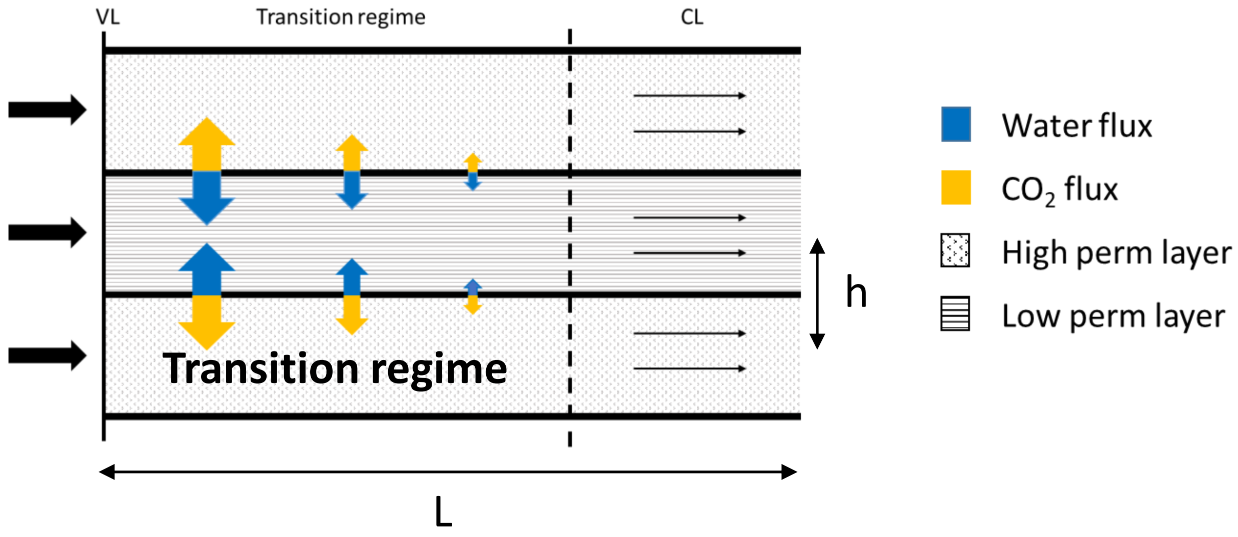

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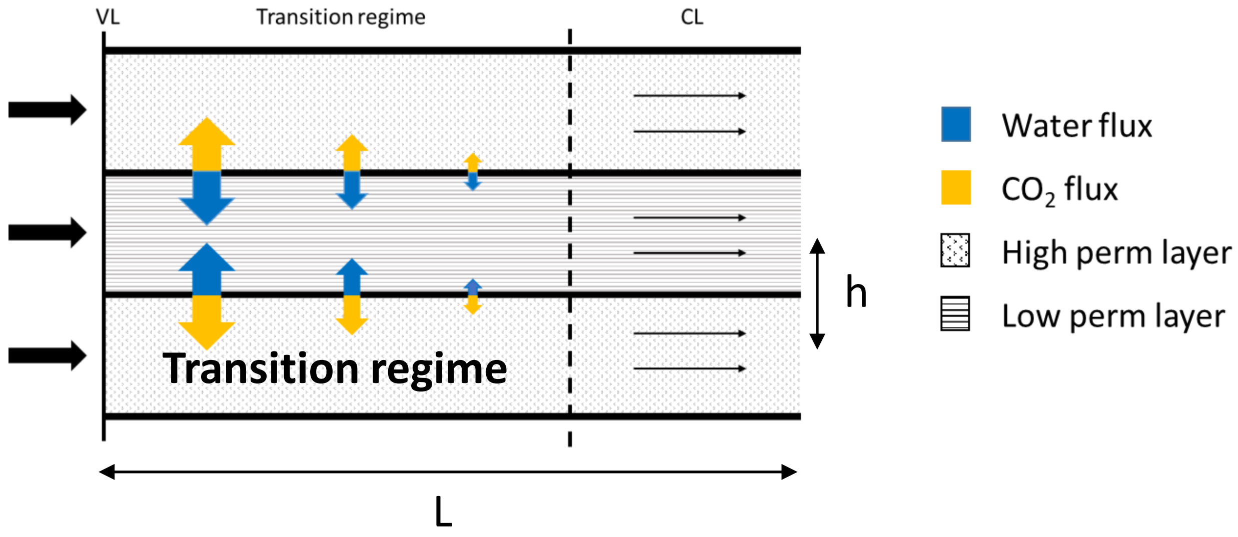

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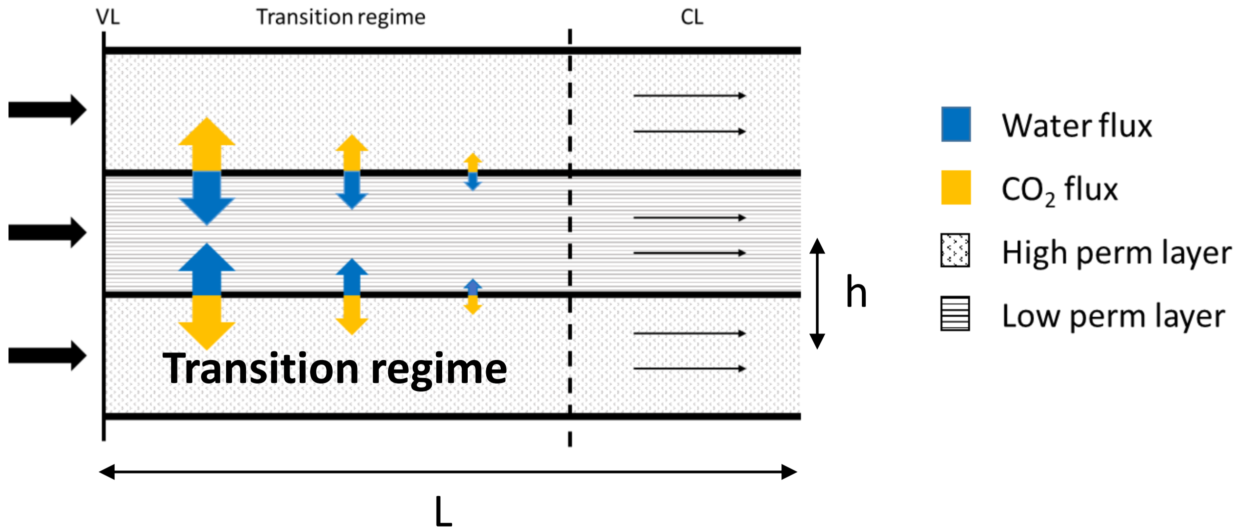
$$RVC_{water} = \frac{h}{L} \frac{q_T}{\frac{k\kappa_{rCO2}}{\mu_{CO2}} \frac{dp_c}{dx}}$$

$$RVC_{CO2} = \frac{h}{L} \frac{q_T}{\frac{k\kappa_{rw}}{\mu_w} \frac{dp_c}{dx}}$$

A capillary number scaling is used to find the upscaled saturation functions in the transition regime



$$RVC = \frac{h}{L}\frac{2q_T}{\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}}\frac{dp_c}{dz} + \frac{k\kappa_{rw}}{\mu_w}\frac{dp_c}{dz}\right)}$$

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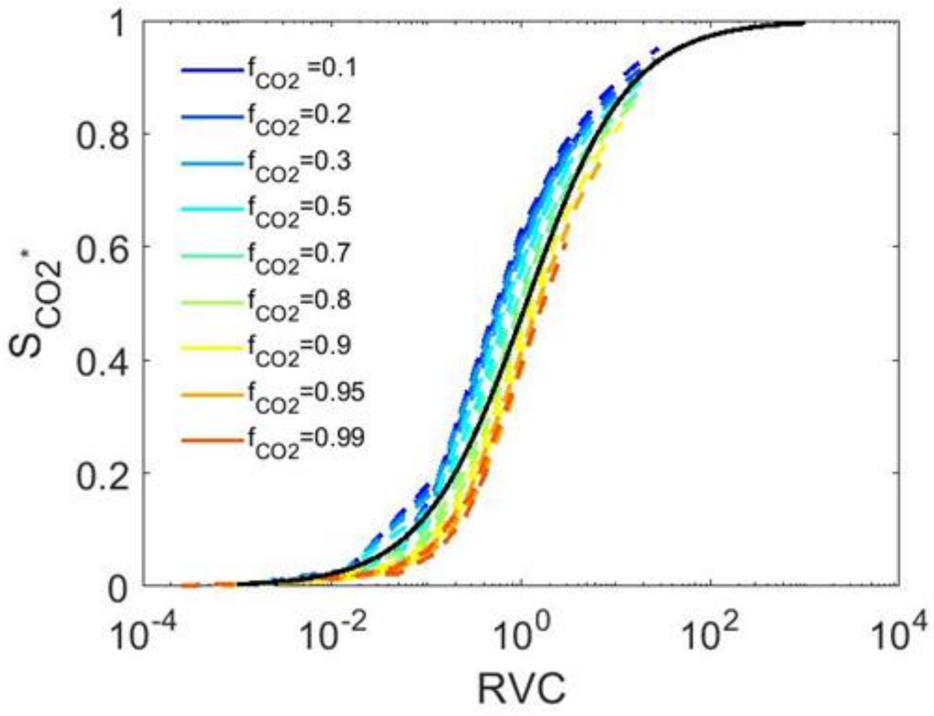
$$RVC_{water} = \frac{h}{L}\frac{q_T}{\frac{k\kappa_{rCO2}}{\mu_{CO2}}\frac{dp_c}{dx}} \qquad RVC_{CO2} = \frac{h}{L}\frac{q_T}{\frac{k\kappa_{rw}}{\mu_w}\frac{dp_c}{dx}}$$

A capillary number scaling is used to find the upscaled saturation functions in the transition regime



$$S_{CO2}^* = 1/(1 + 0.9\mathrm{RVC}\left(f_{w,}q_T\right)^{0.8})$$

$$S_{CO2}^* = \frac{S_{CO2}(f_w) - S_{CO2_{CL}}(f_w)}{S_{CO2_{VL}}(f_w) - S_{CO2_{CL}}(f_w)}$$

$$RVC = \frac{h}{L}\frac{2q_T}{\left(\frac{k\kappa_{rCO2}}{\mu_{CO2}}\frac{dp_c}{dz} + \frac{k\kappa_{rw}}{\mu_w}\frac{dp_c}{dz}\right)}$$

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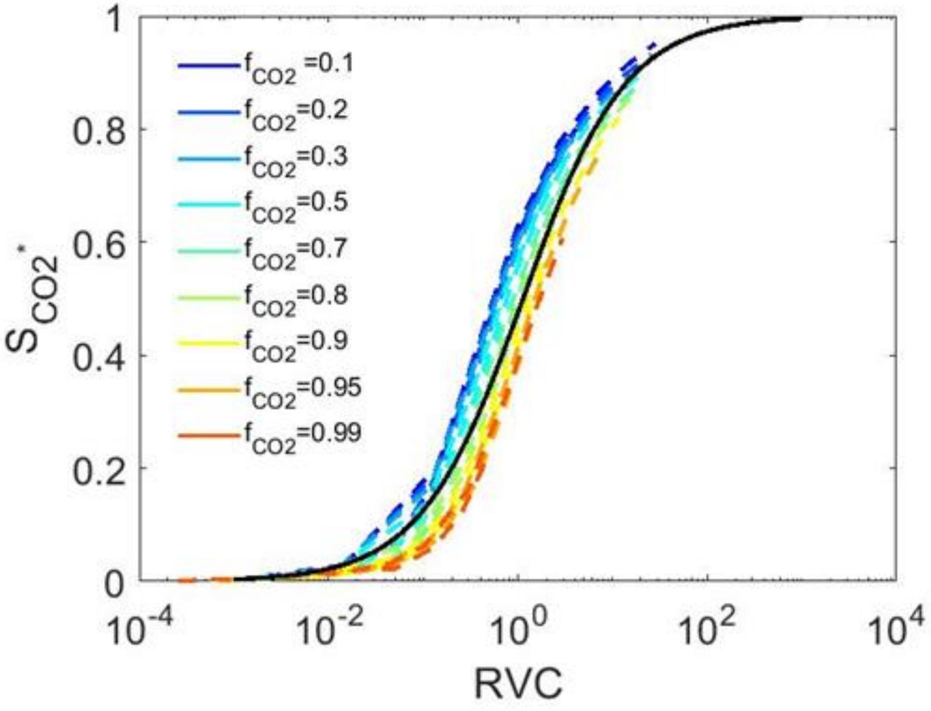

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$\Downarrow$

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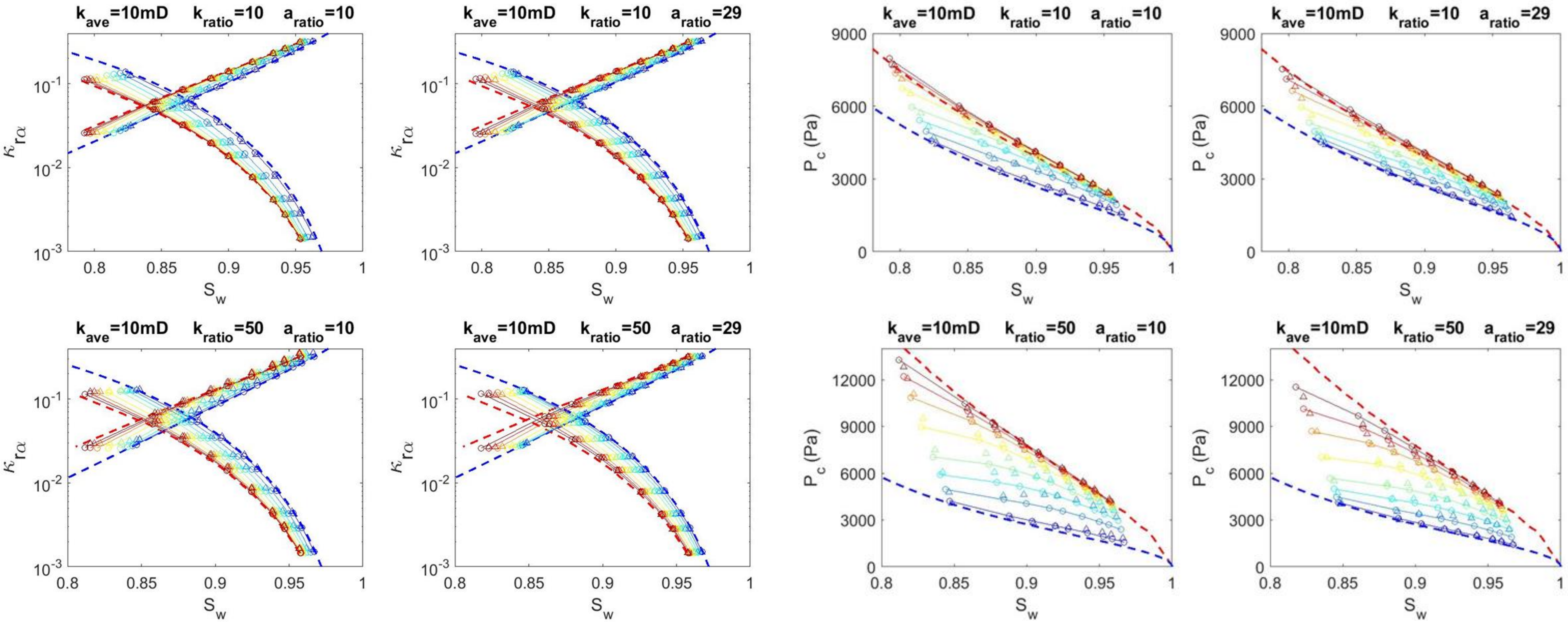
Upscaled saturation functions as a function of fractional flow and flow-rate

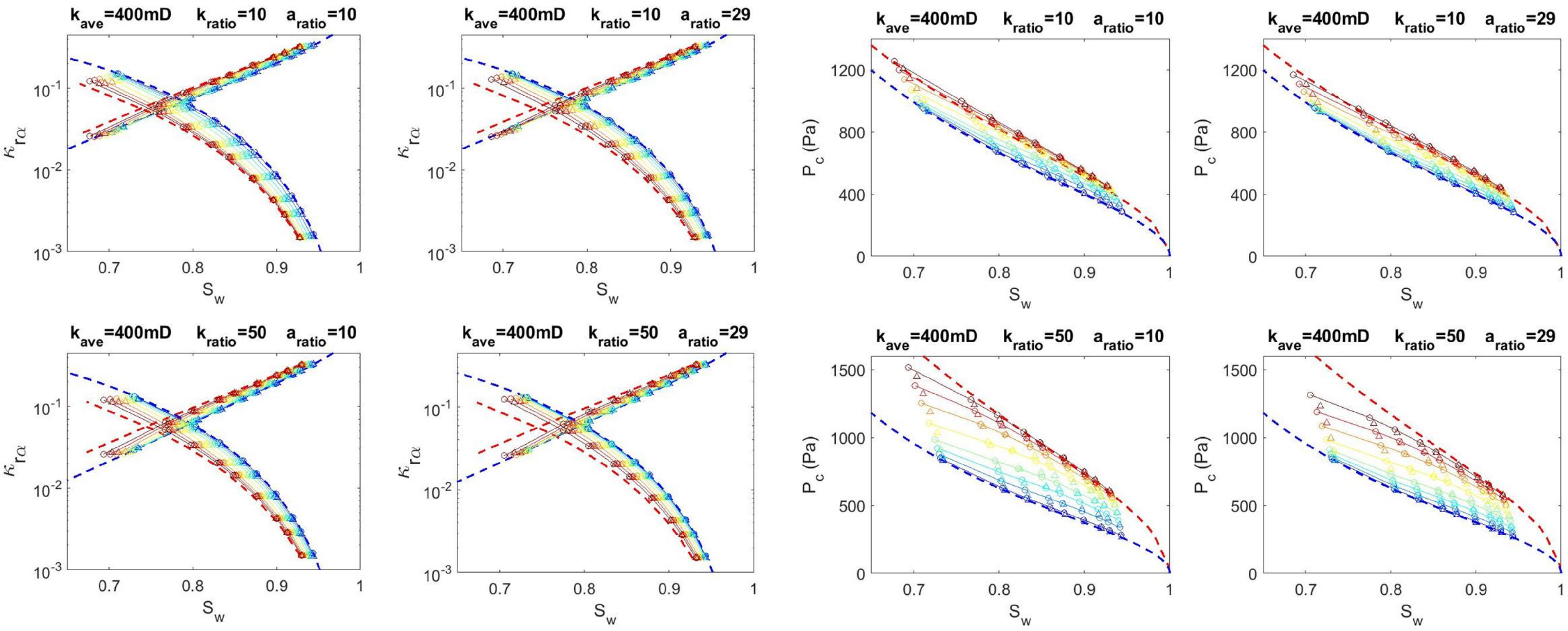


Capillary limit (CL)

Viscous limit (VL)

- The relative permeability of CO_2 increases with a decrease in flow-rate
- The transition towards the capillary limit happens at higher velocities for higher f_{CO2}

Upscaled saturation functions as a function of fractional flow and flow-rate



Capillary limit (CL)

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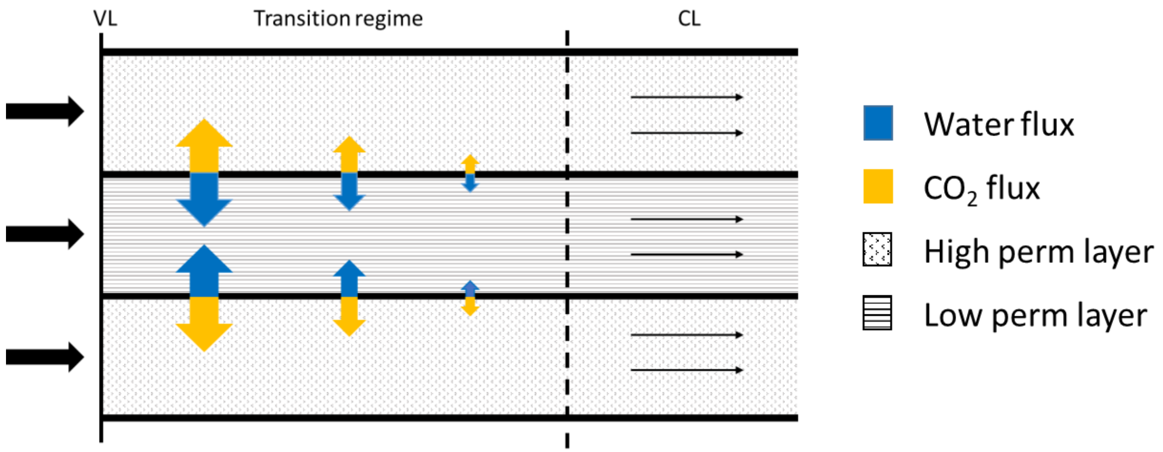
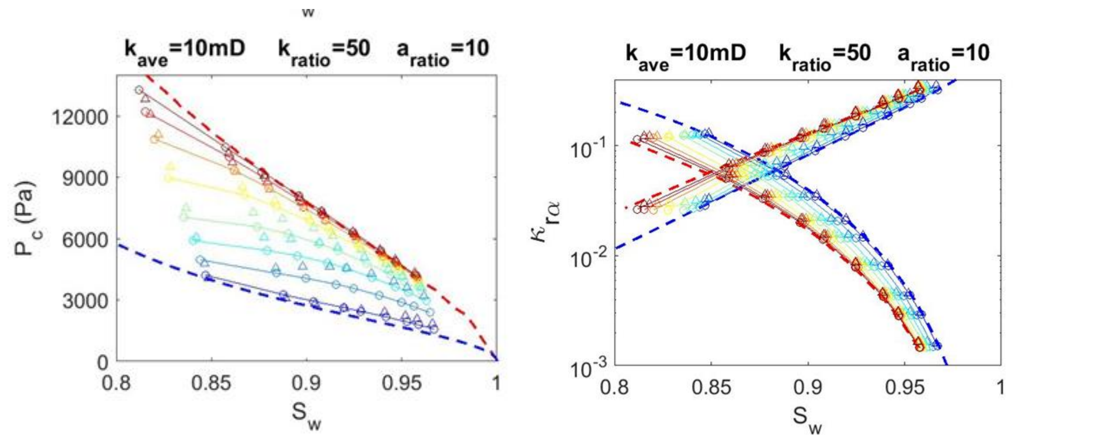
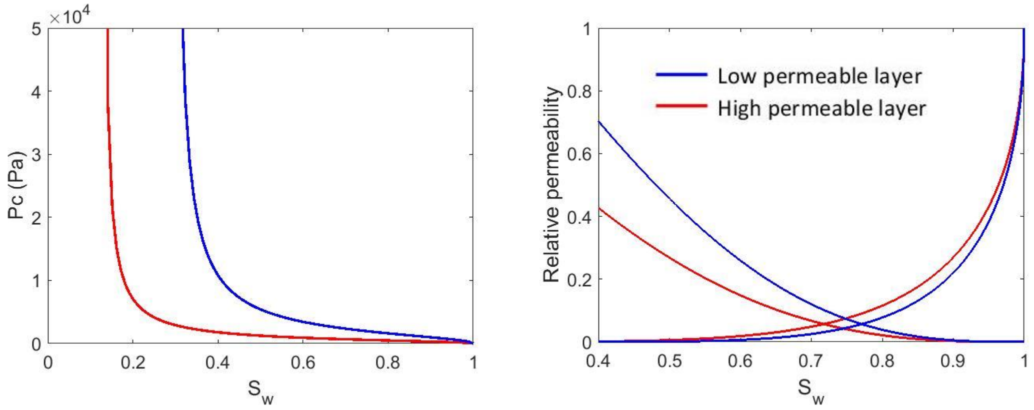
A physics-based model to find upscaled saturation functions and incorporate them into a field-scale model



- Upscaled flow-rate dependent saturation functions

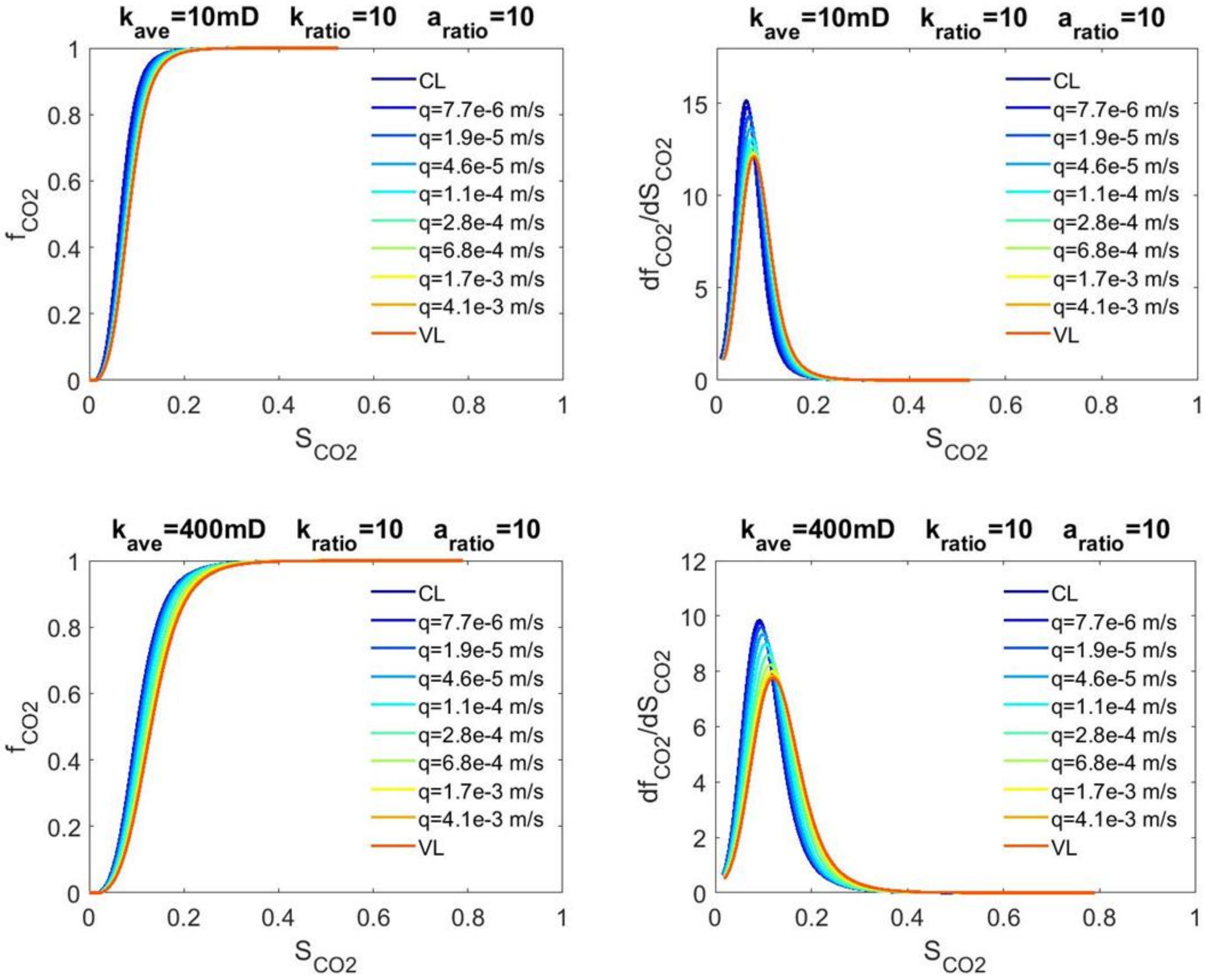


- Saturation functions are defined for each layer



1. Derive upscaled flow-rate dependent saturation functions
2. Incorporate these functions into a field scale model

An extended Buckley-Leverett solution where the fractional flow function depends both on the saturation and radial distance from the well is used to look at the field scale impact of small scale layered heterogeneity



Extended BL solution:

$$\frac{dr_D}{dt_D} = \left(\frac{\partial f_{CO2}}{\partial S_{CO2}}\right)_{r_D}$$

where,

$$r_D = \frac{r^2}{r_e^2} \qquad t_D = \frac{Qt}{\pi r_e^2 H\theta}$$

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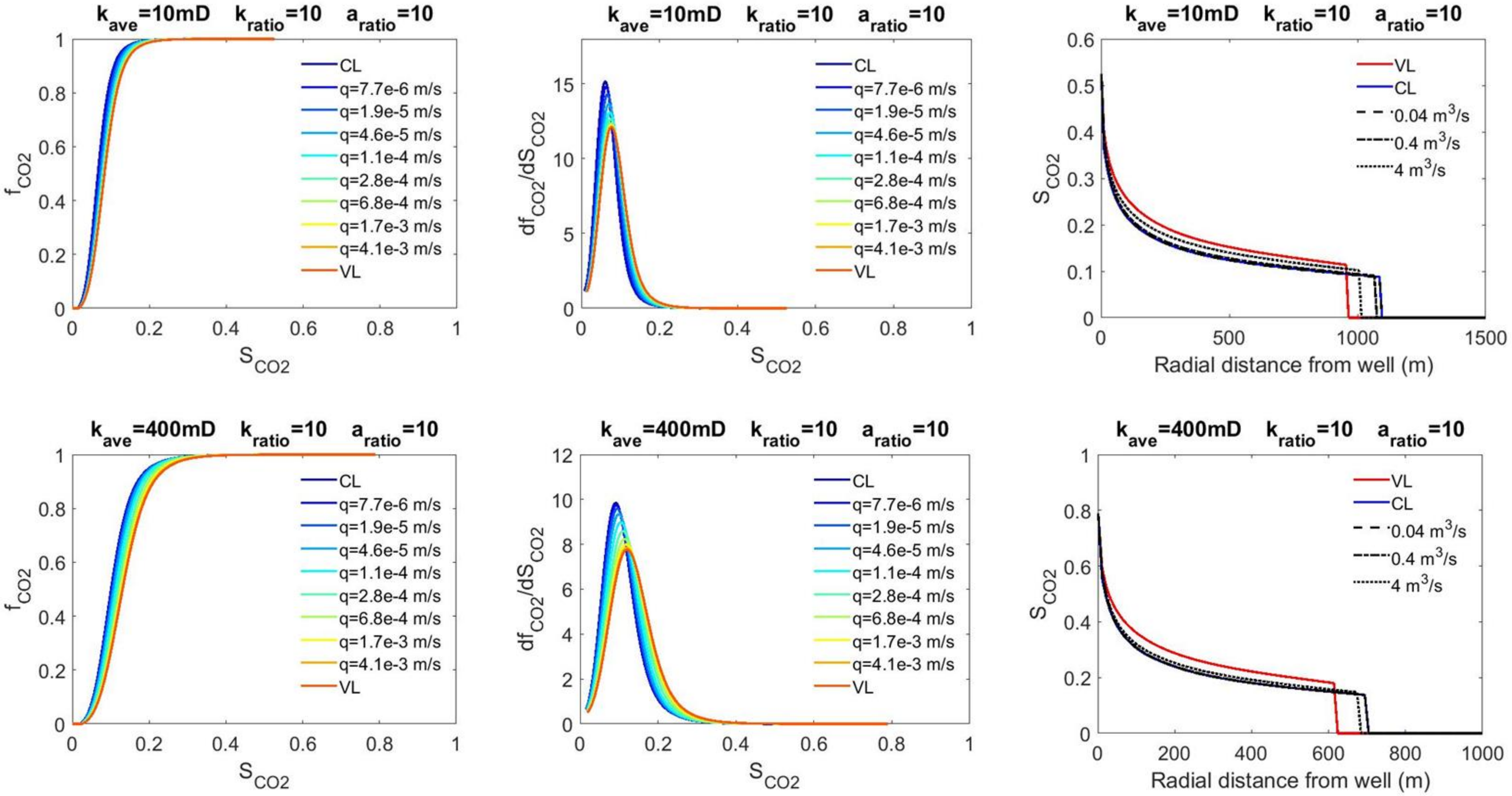

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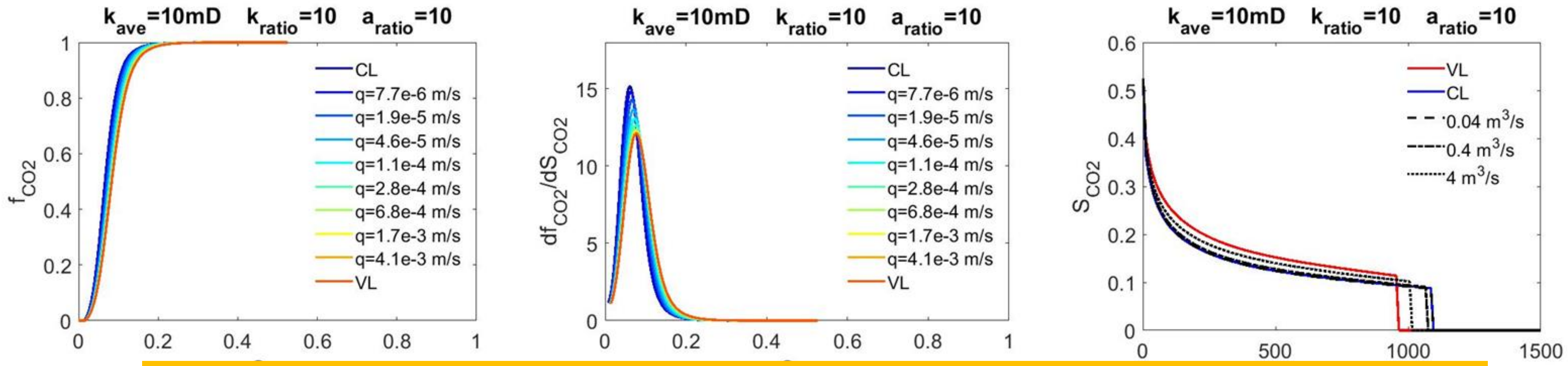
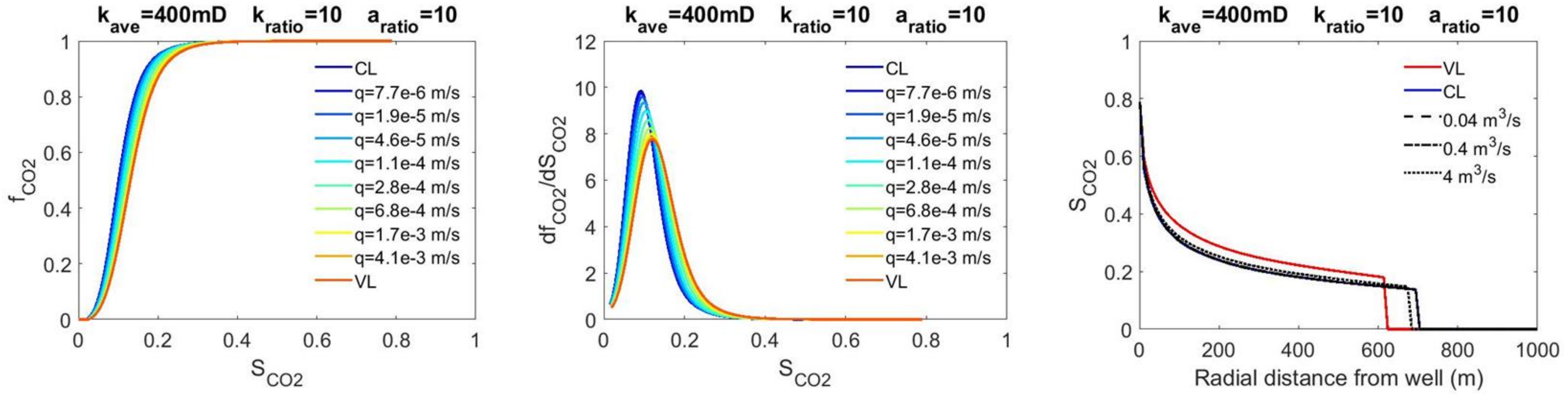
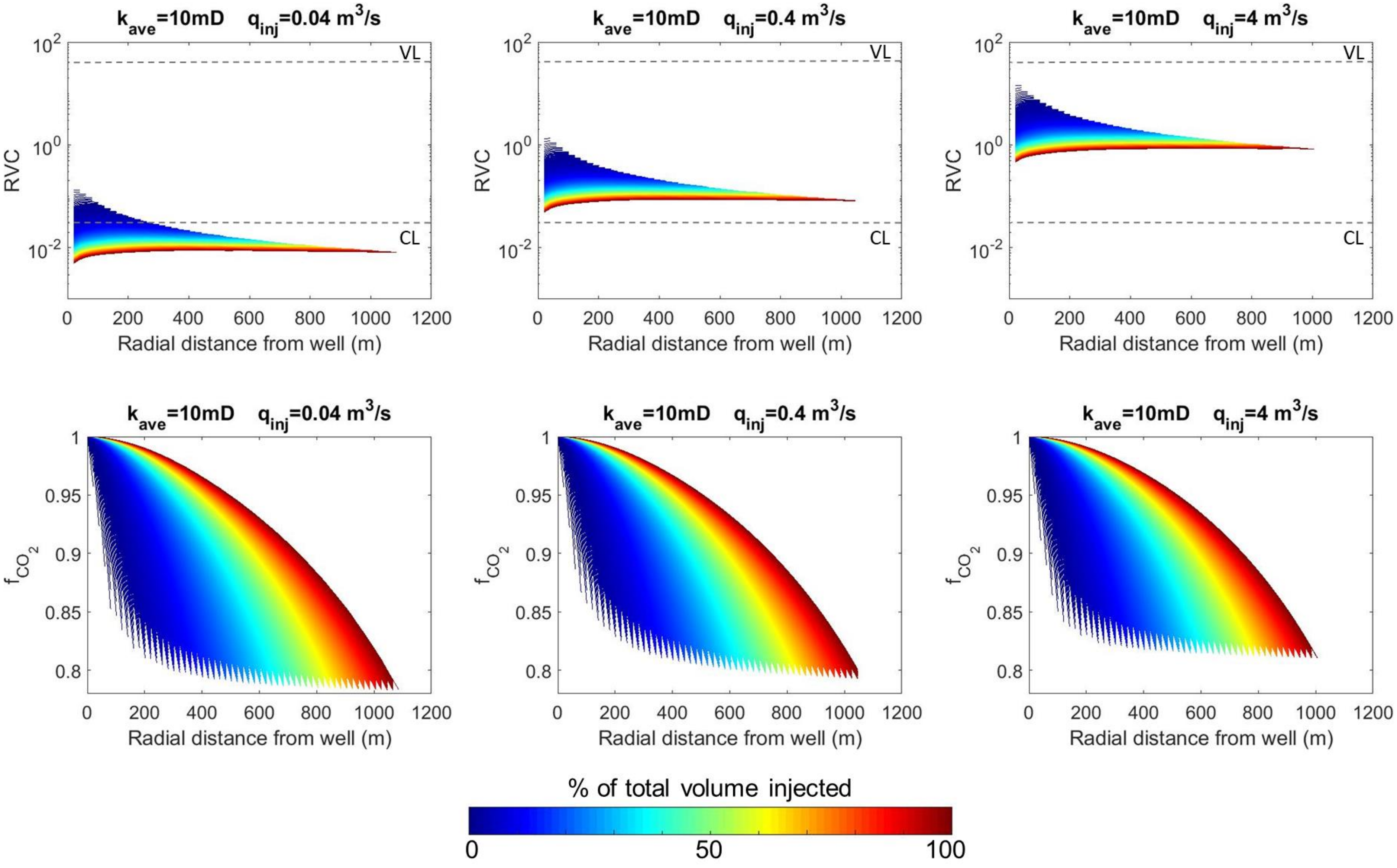


To predict the lateral extend of the plume the CL solution is a valid approximation



For injection rates and volumes commonly used at injection sites, the capillary limit is reached quickly



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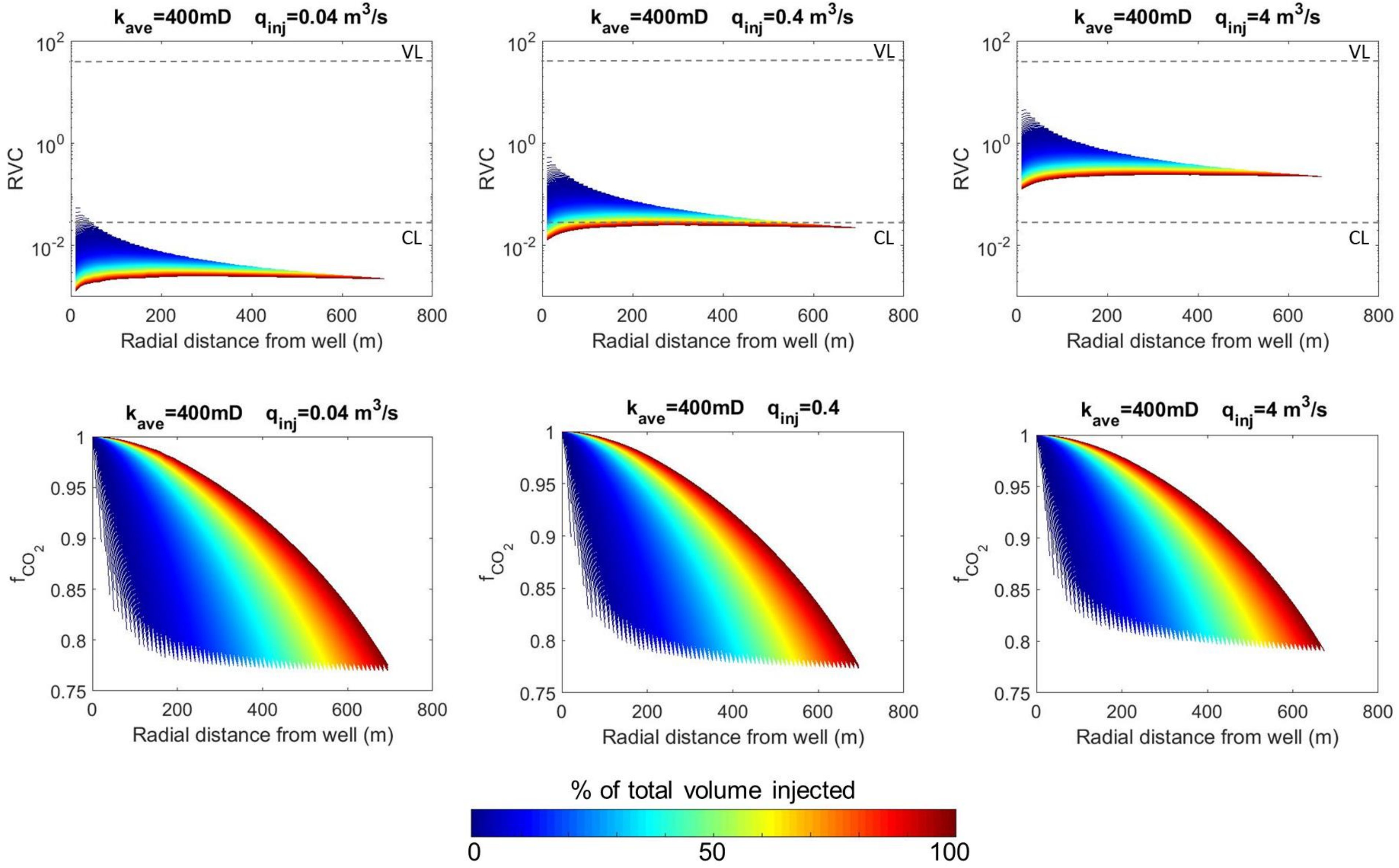


A physics-based model to predict the impact of horizontal laminations on CO_2 plume migration

Maartje Boon & Sally M. Benson

Scientific Achievement

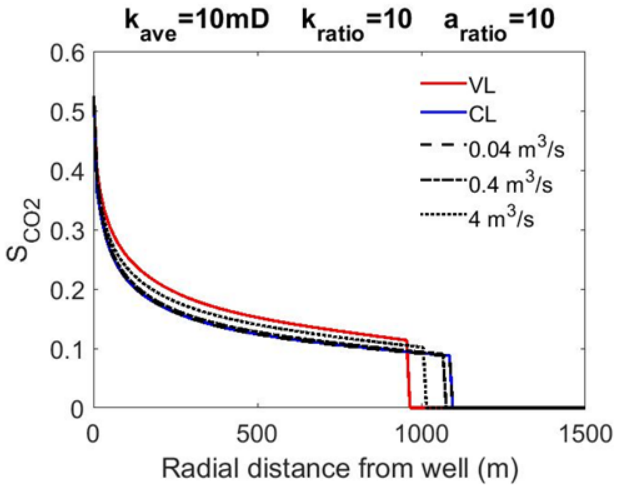
A physics-based model has been developed that can predict the impact of small-scale horizontal laminations on field-scale CO_2 plume migration.

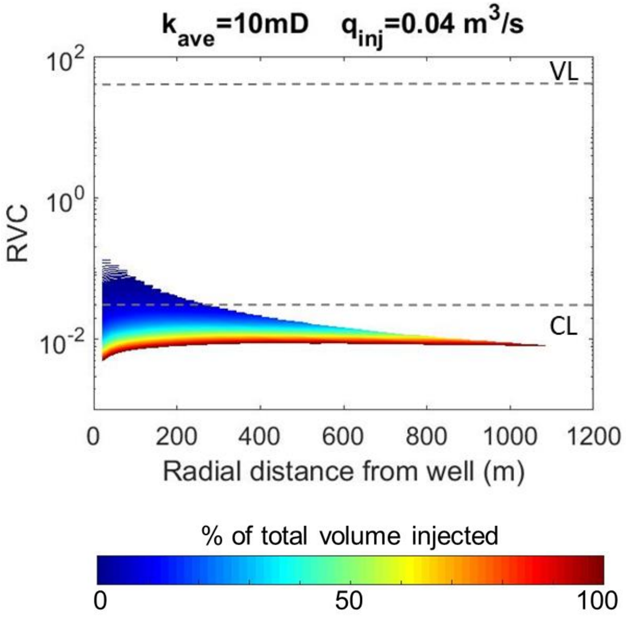
Significance and Impact

Small-scale horizontal laminations enhance the lateral migration of the plume. To incorporate this impact into field-scale models requires the use of flow-rate dependent saturation functions which is not supported by most reservoir simulators. Our model provides an easy way to investigate the impact of small-scale laminations on field-scale plume migration.

Research Details

- A new physics-based model that includes the effects of capillary and viscous forces is used to obtain effective capillary pressure and relative permeability functions over a wide range of capillary numbers.
- For this purpose a new capillary number is derived that accurately describes the viscous-capillary force balance in horizontally layered systems.
- The new model is based on the fractional flow approach and can be implemented in an extended Buckley-Leverett solution where the fractional flow function depends both on the saturation and radial distance from the well.





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