Predicting CO_2 Residual Trapping Ability Based on Experimental Petrophysical Properties for Different Sandstone Types

SCCS Annual Affiliates Meeting 2018

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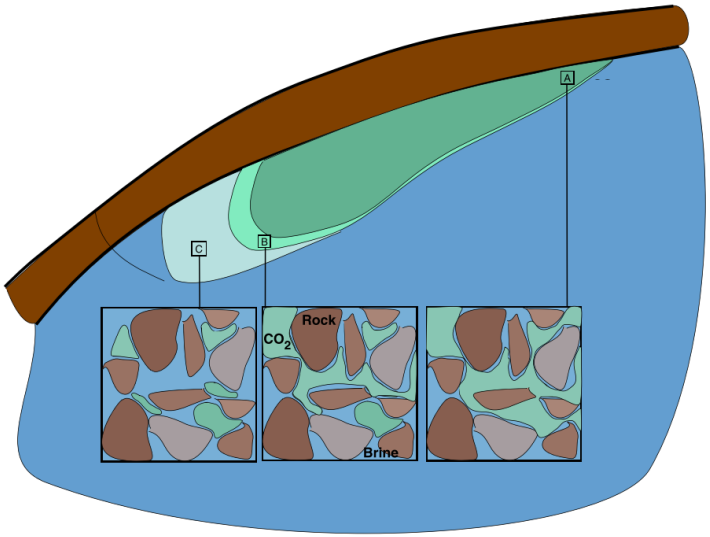
Stanford University, Energy Resources Engineering Department

Question and motivation

Why study CO_2 residual trapping ability

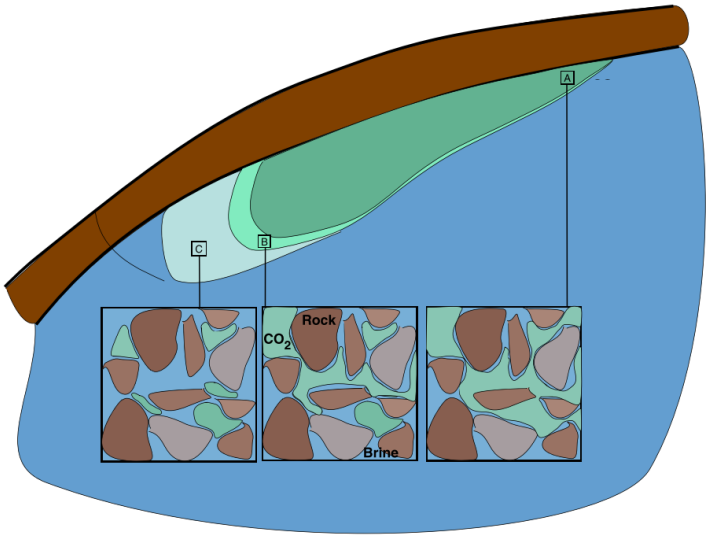
The importance of studying CO_2 residual trapping



Post-imbibition CO_2 trapping
(Krevor et al., 2015)

The importance of studying CO_2 residual trapping

- Spontaneous imbibition: low flow rates; capillary-dominated flow regime



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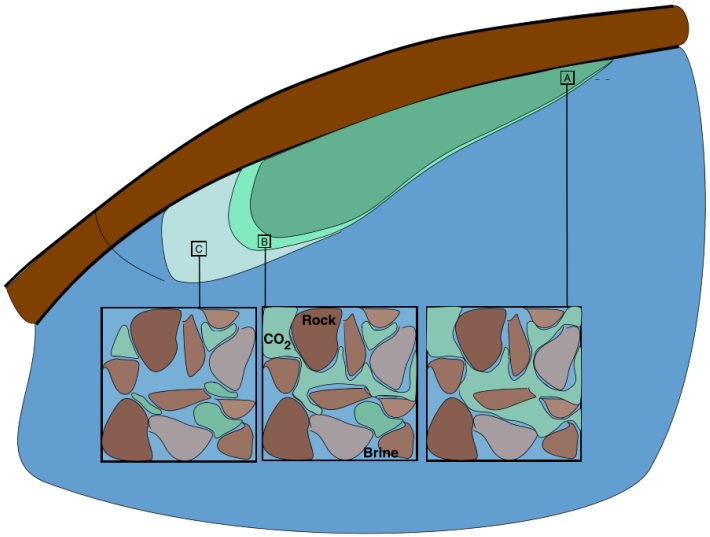

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- Can trap significant amount of CO_2

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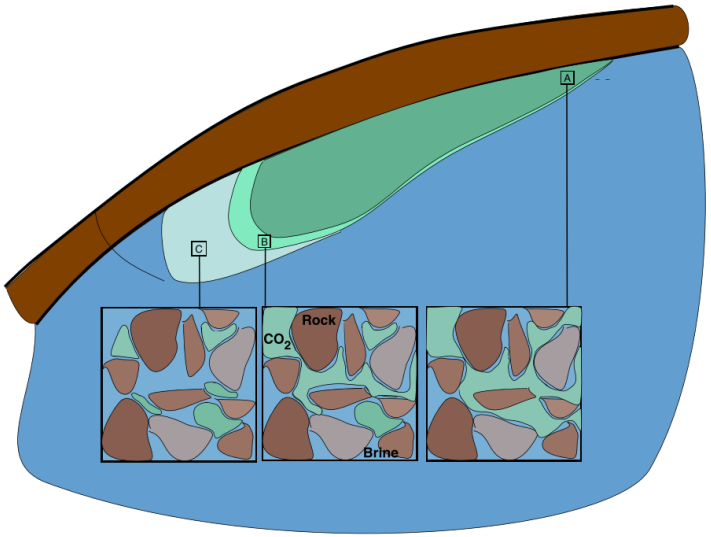

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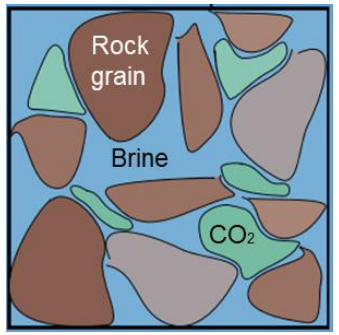

$10^{-5}m$

- Pore-scale trapping
  - Caused by pore-scale heterogeneity

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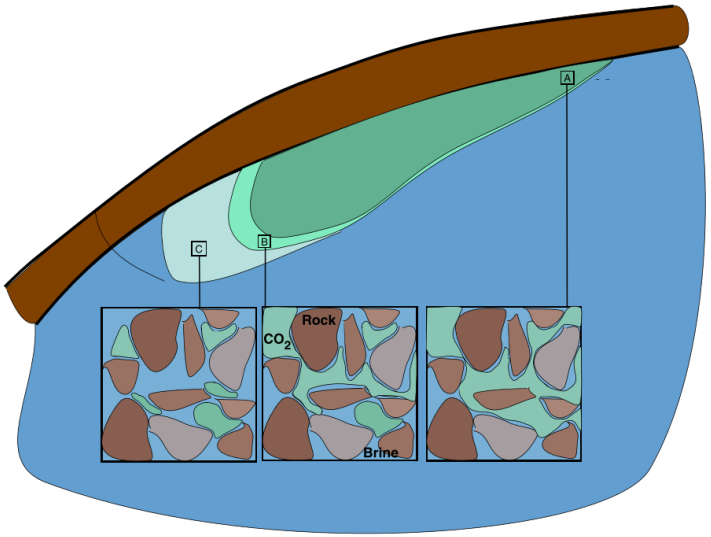

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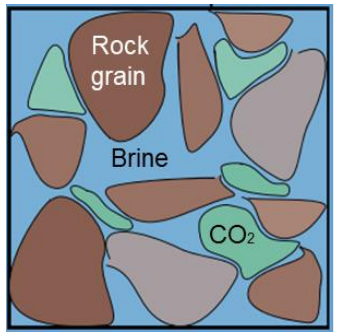

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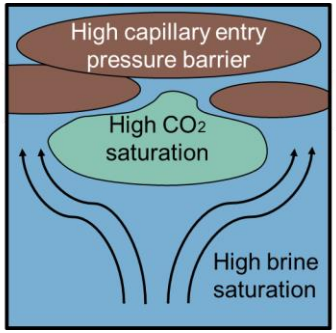
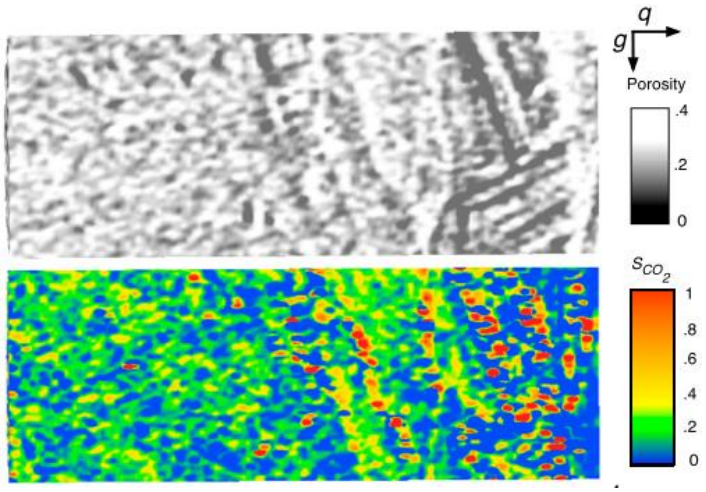


$10^{-3}m$

- Mesoscale trapping
  - Caused by millimeter-scale heterogeneity

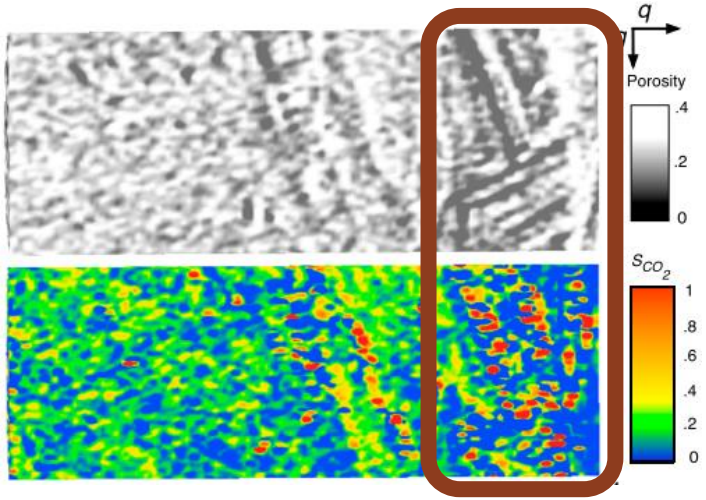
Mesoscale trapping mechanism can also trap significant amount of CO_2



Mt. Simon sandstone core
(Krevor et al., 2011)

Mesoscale trapping mechanism can also trap significant amount of CO_2

High capillary entry pressure barrier



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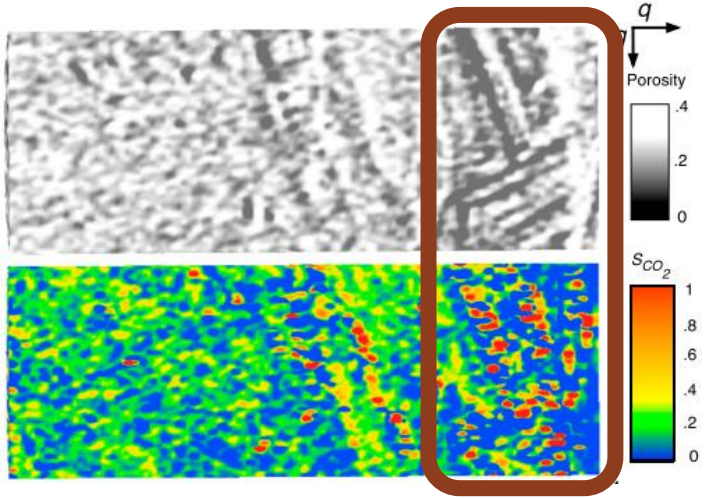

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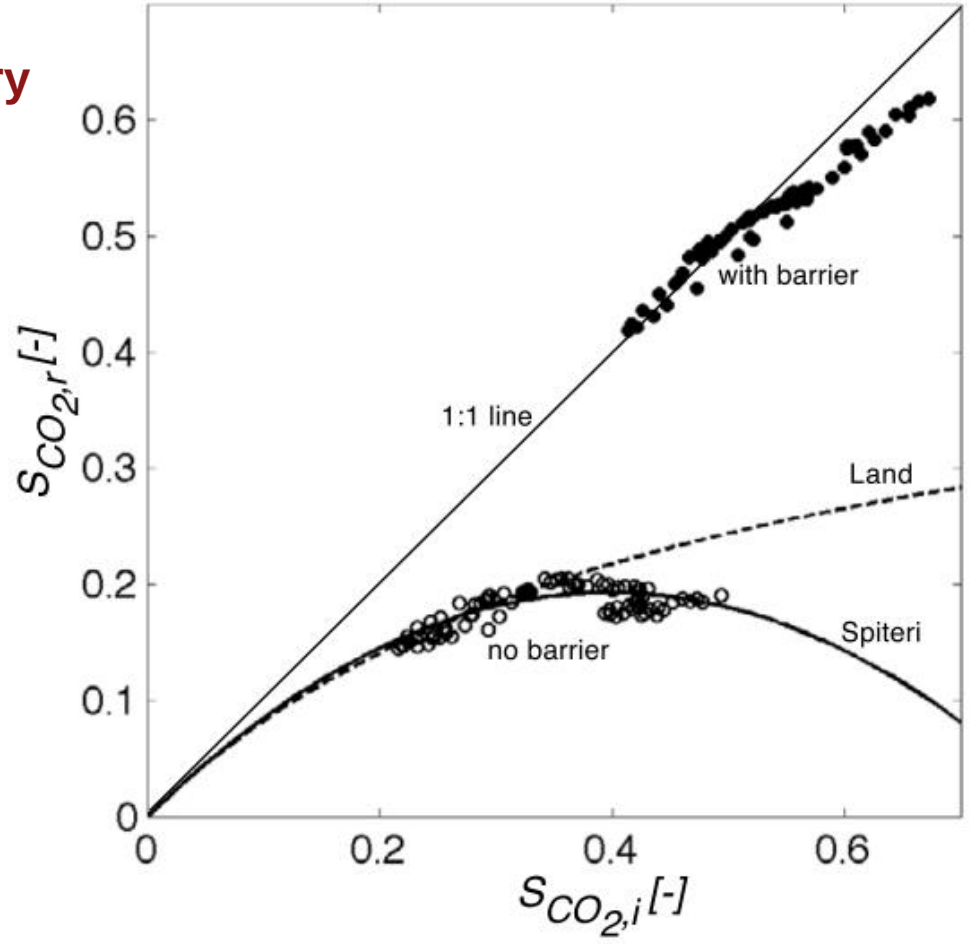

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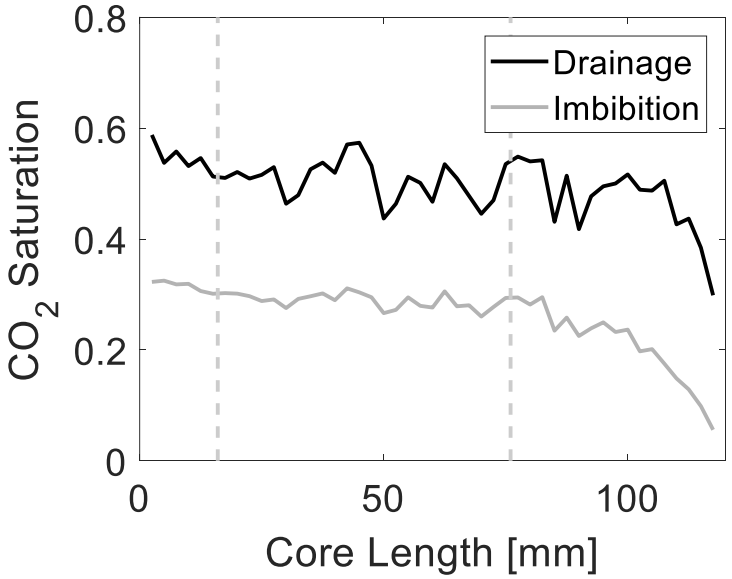

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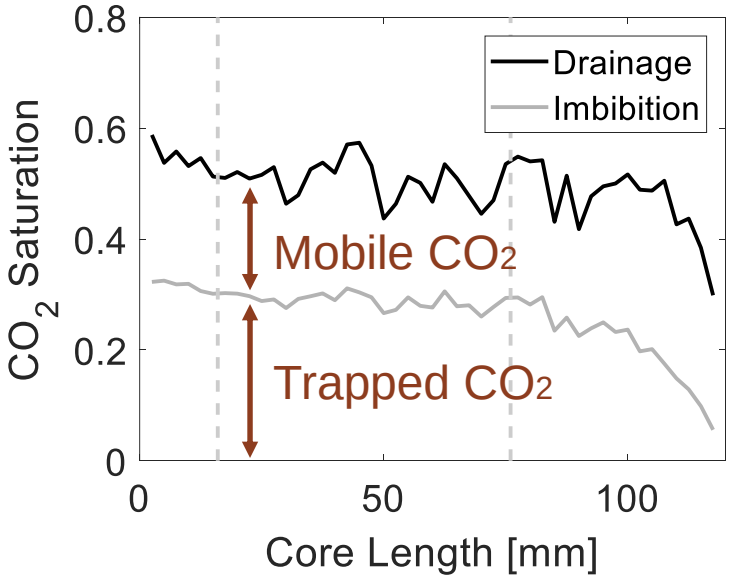

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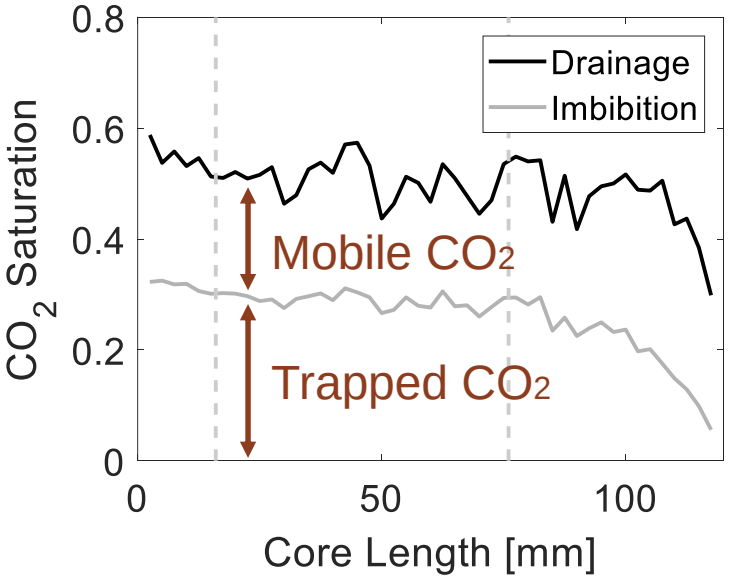

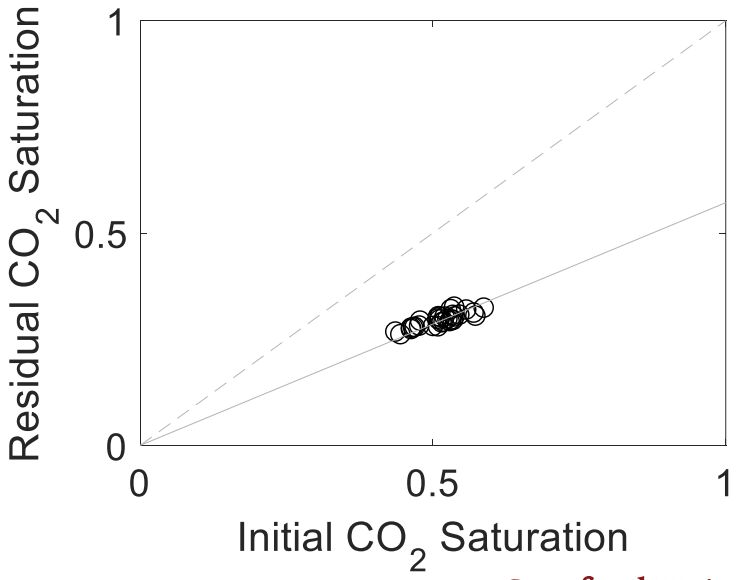

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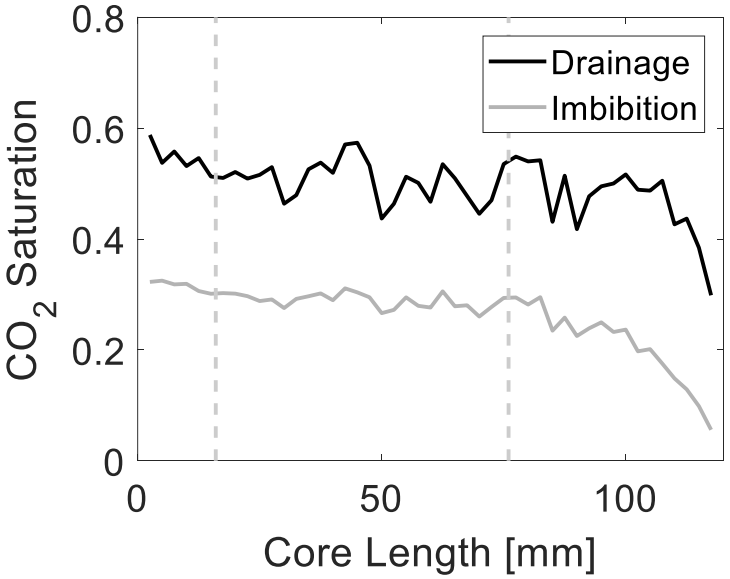

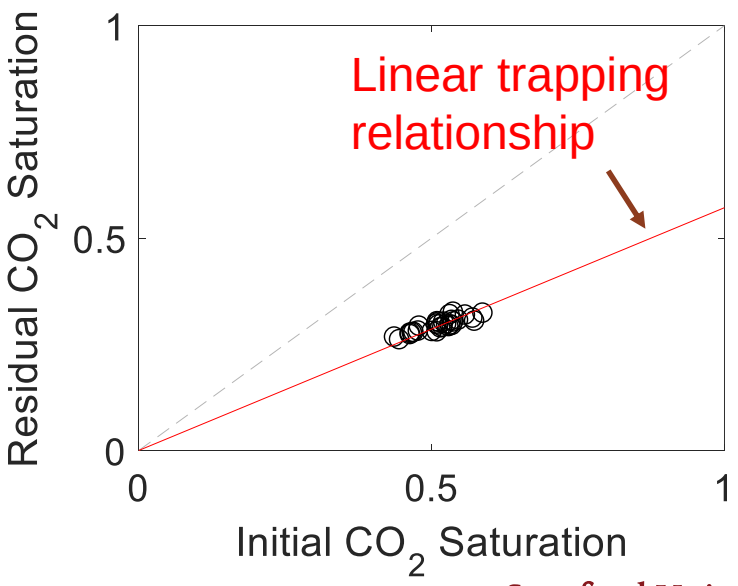

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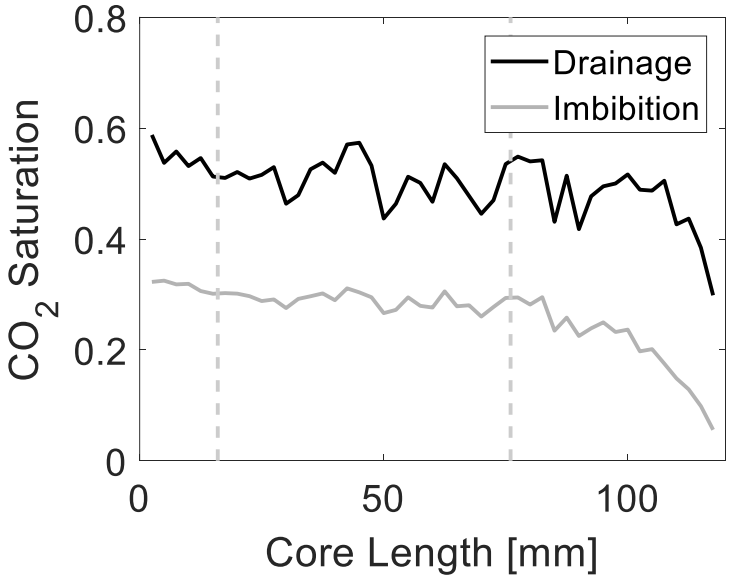
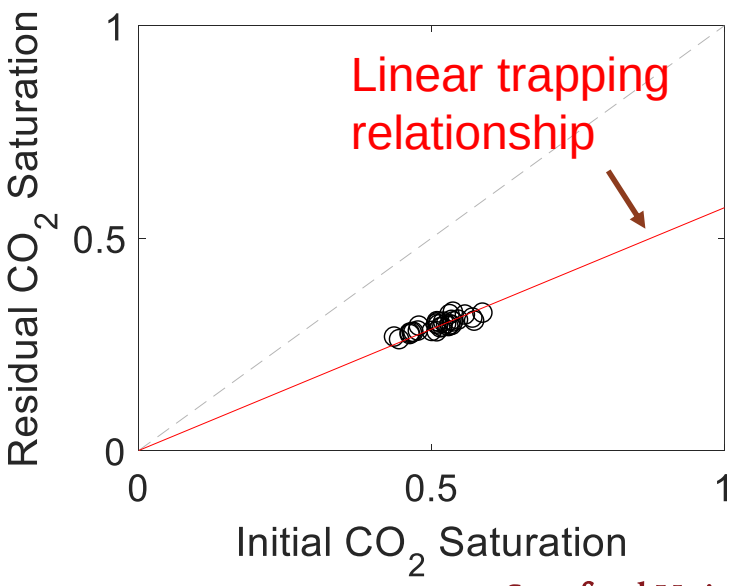
$$S_{CO_2,r} = A \cdot S_{CO_2,i}$$





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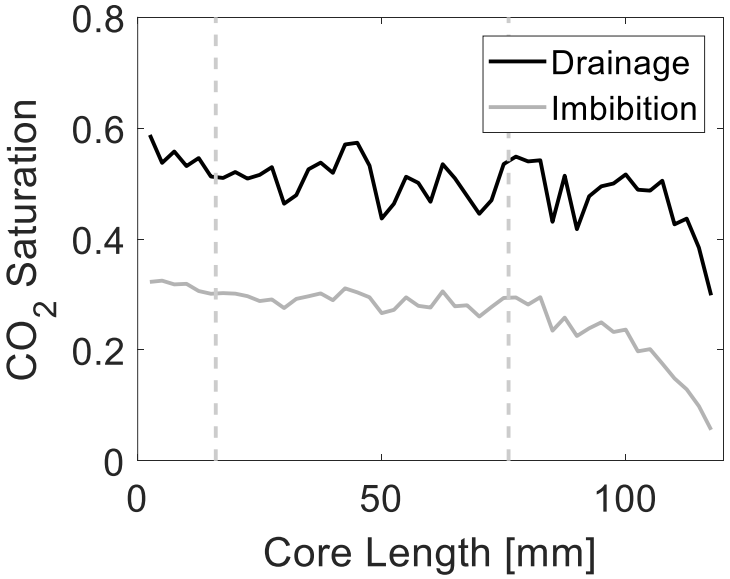

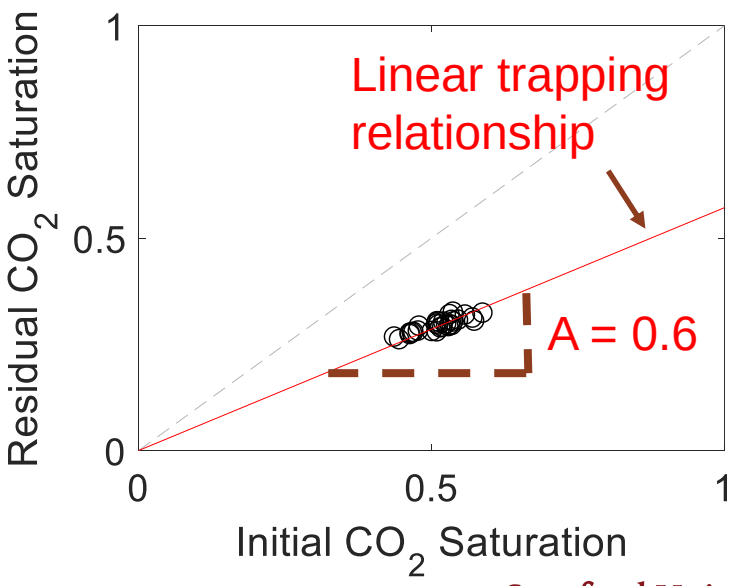

Stanford University

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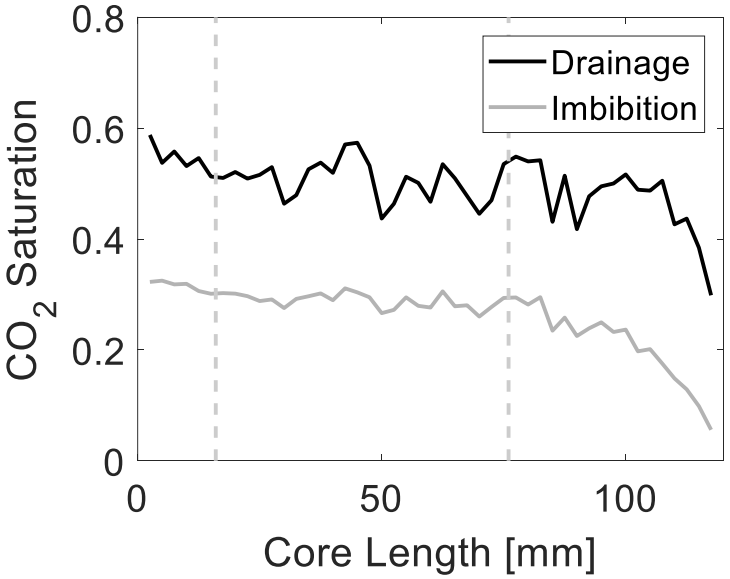

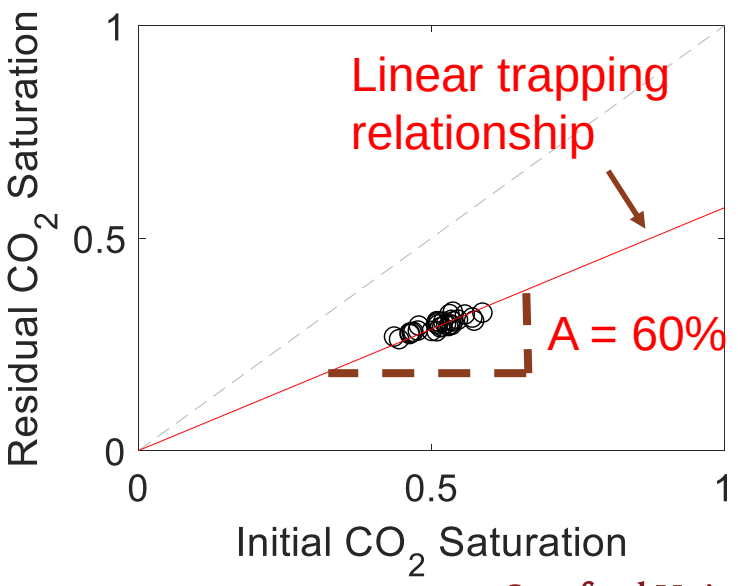

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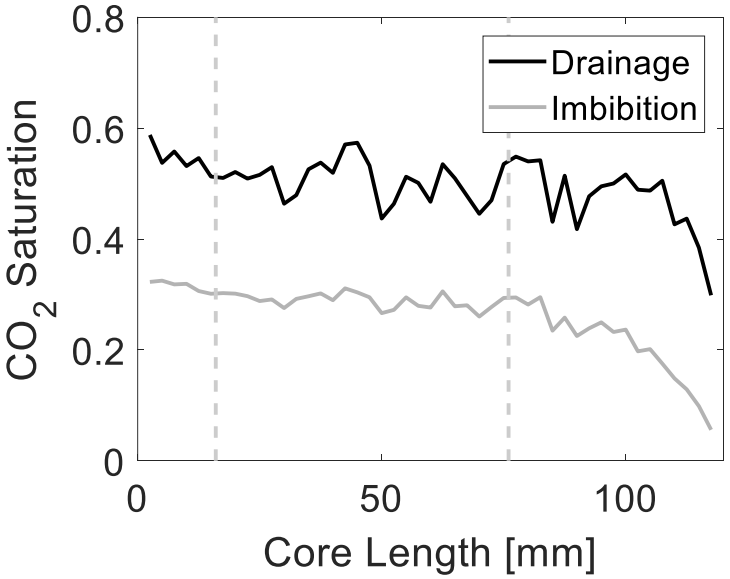

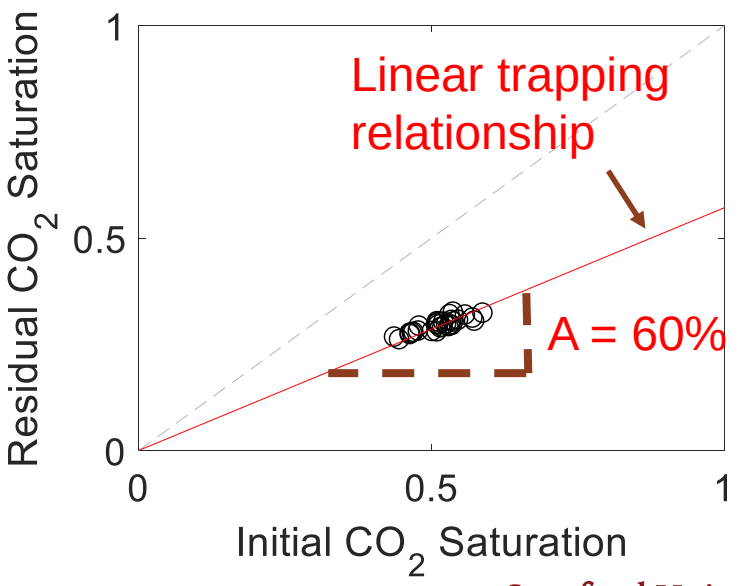

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- Residual trapping ability is important for deriving the following properties
  - CO_2 storage capacity (Niu et al., 2015)
  - Hysteretic relative permeability model (Ruprecht et al., 2014)
  - Hysteretic capillary pressure model (Pini and Benson, 2017)

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Which CO_2 residual trapping mechanism is more important, pore-scale or mesoscale?

- Based on core-scale experimental results alone?

Material and methods

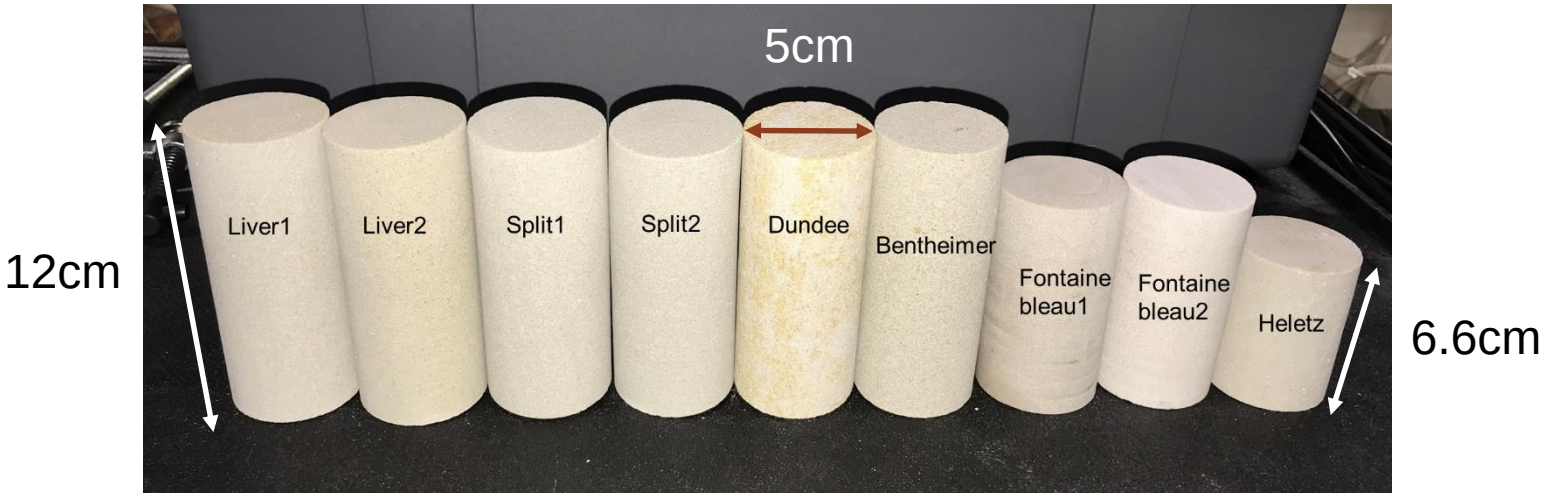
Material

Experimental and analysis methods

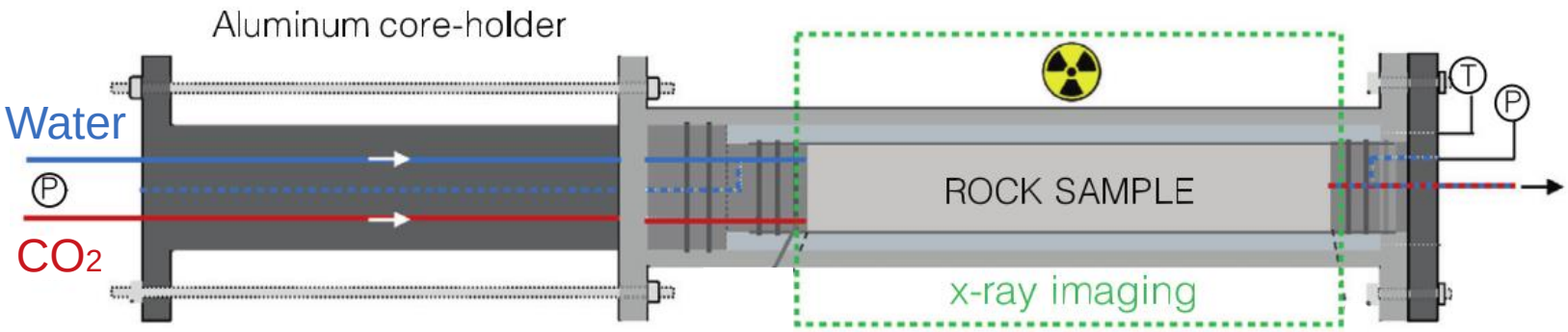
Core samples used in this study

9 cores spanning 5 sandstone types are used

- Berea
  - Liver and Split
  - Both lamination parallel (1) and perpendicular (2) to flow
- Dundee
- Bentheimer
- Fontainebleau
- Heletz



CO_2/water coreflooding experimental set-up



(Pini and Benson, 2017)

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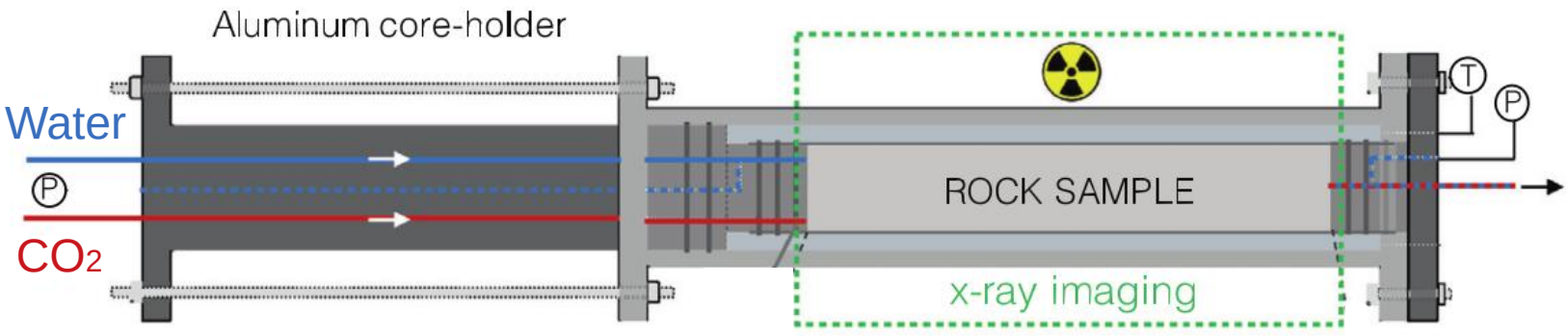

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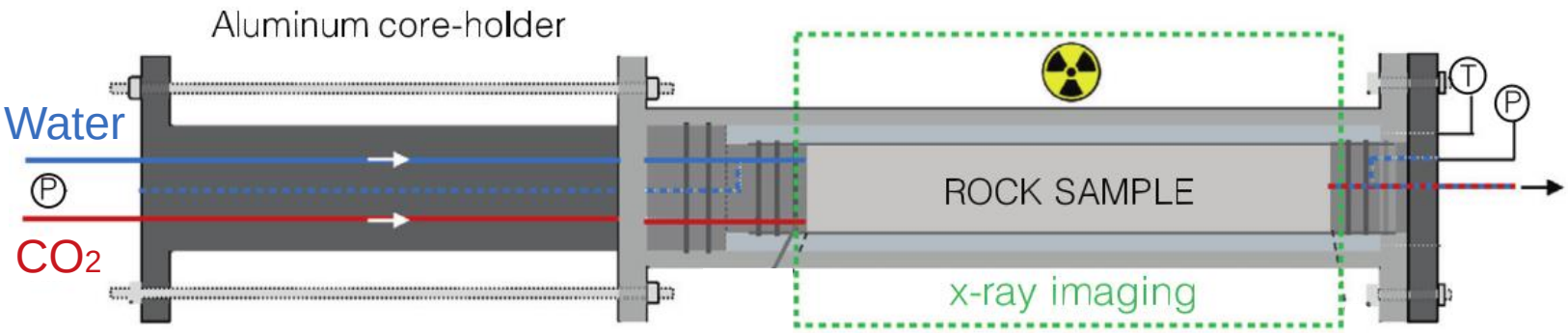
Flow rate: capillary-dominated flow regime

Capillary number < 10^{-5} (Gupta and Trushenski, 1979; Jerauld, 1997)

Properties we can measure with a coreflooding experiment



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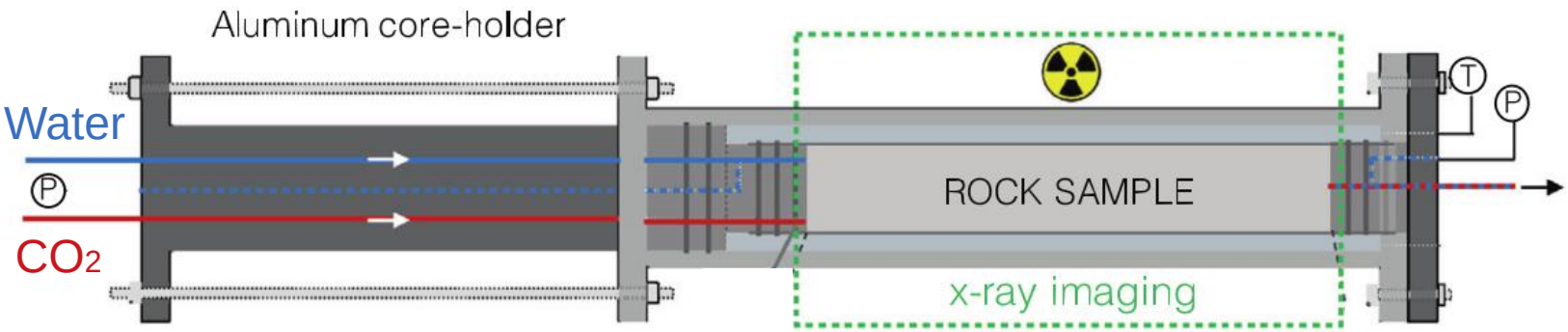

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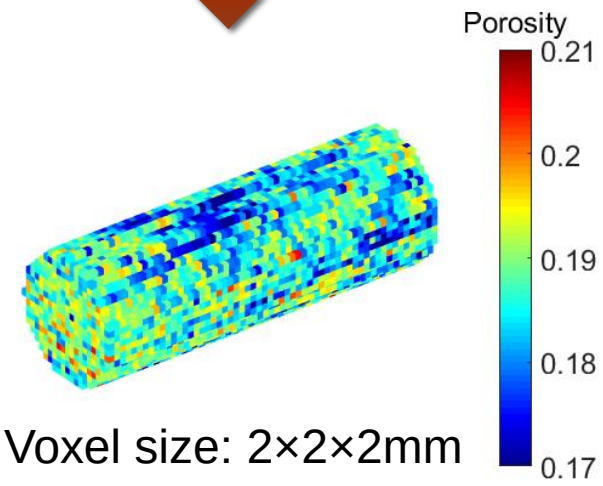

Voxel size: 2×2×2mm

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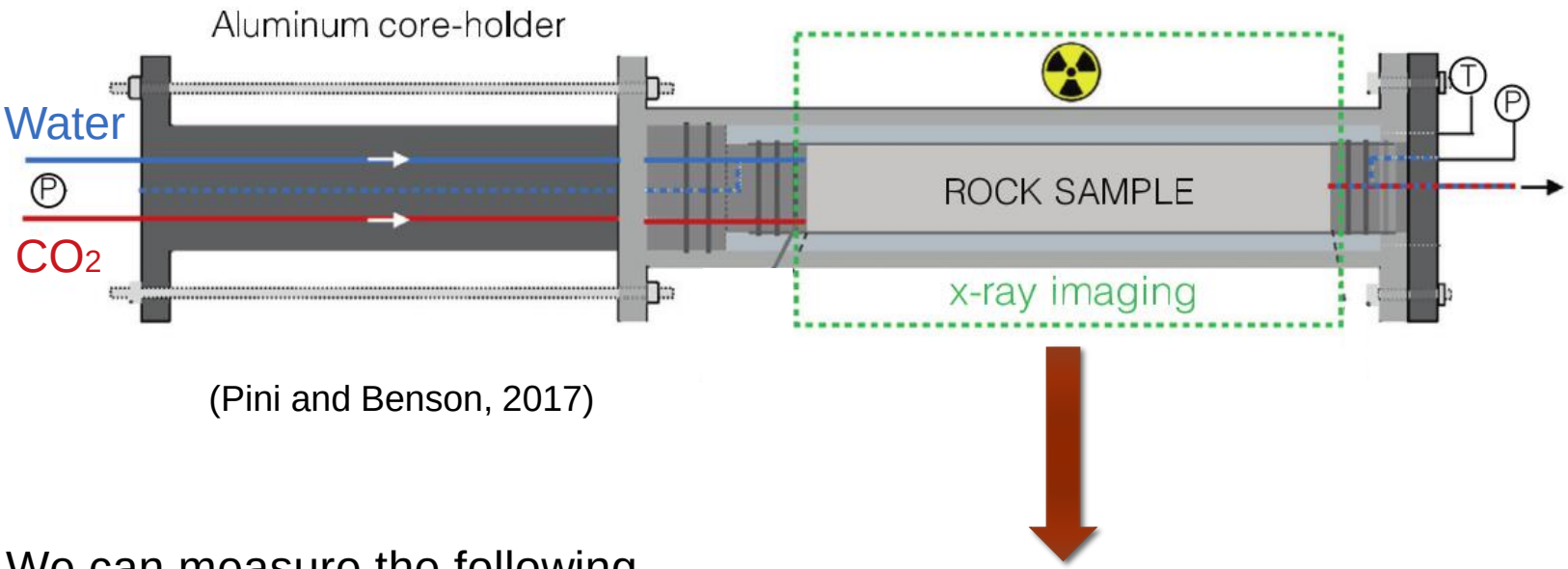

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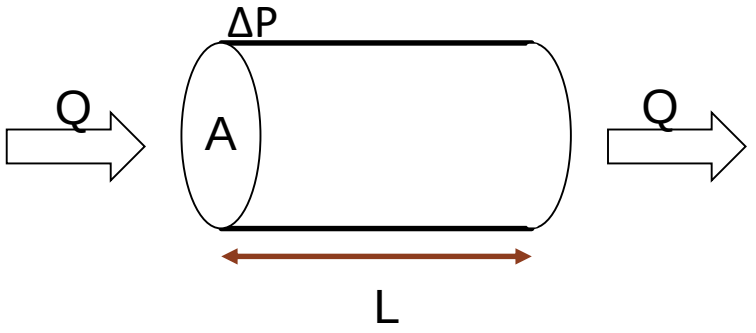

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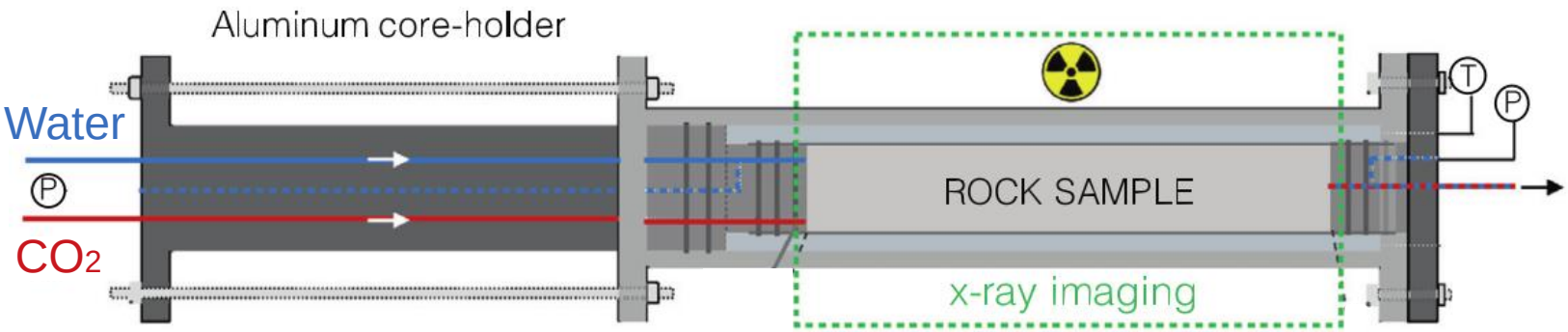

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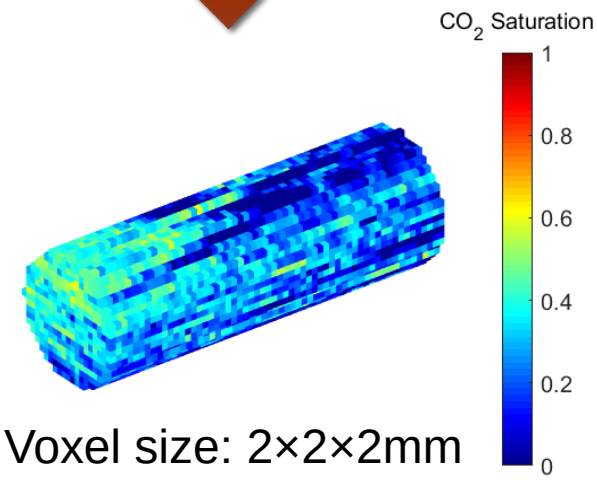

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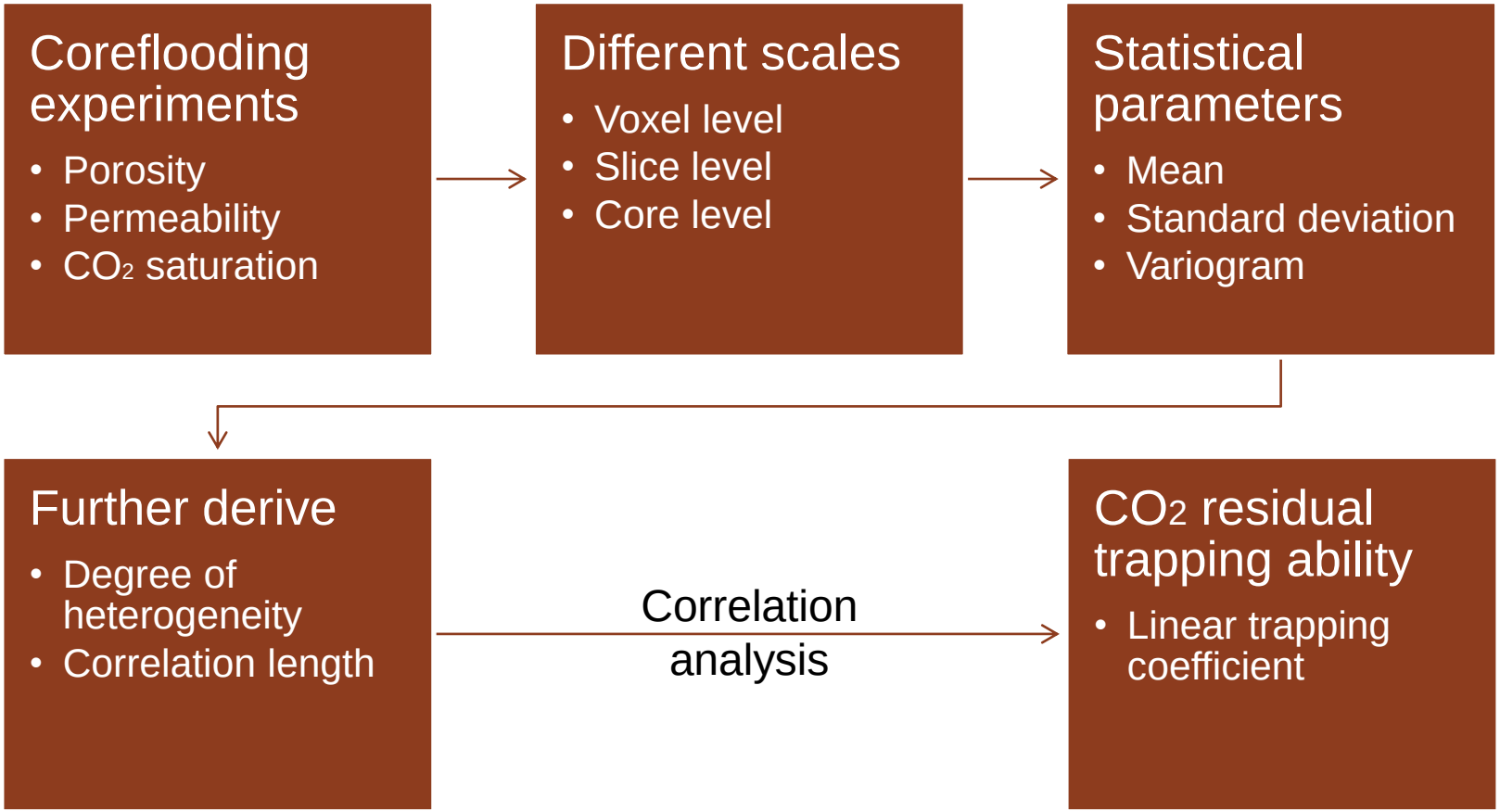
Workflow of the entire study



20 petrophysical parameters are analyzed as candidate predictors

- Porosity
- Permeability
- Correlation length in porosity field in x, y, and z direction
- Correlation length in permeability field in x, y, and z direction
- Minimum, mean, and maximum standard deviation in drainage CO_2 saturation field
- Coefficient of variation in porosity field
- Coefficient of variation in permeability field
- Dykstra-Parsons coefficient in permeability field (Dykstra and Parsons, 1950)
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- Capillary pressure curve

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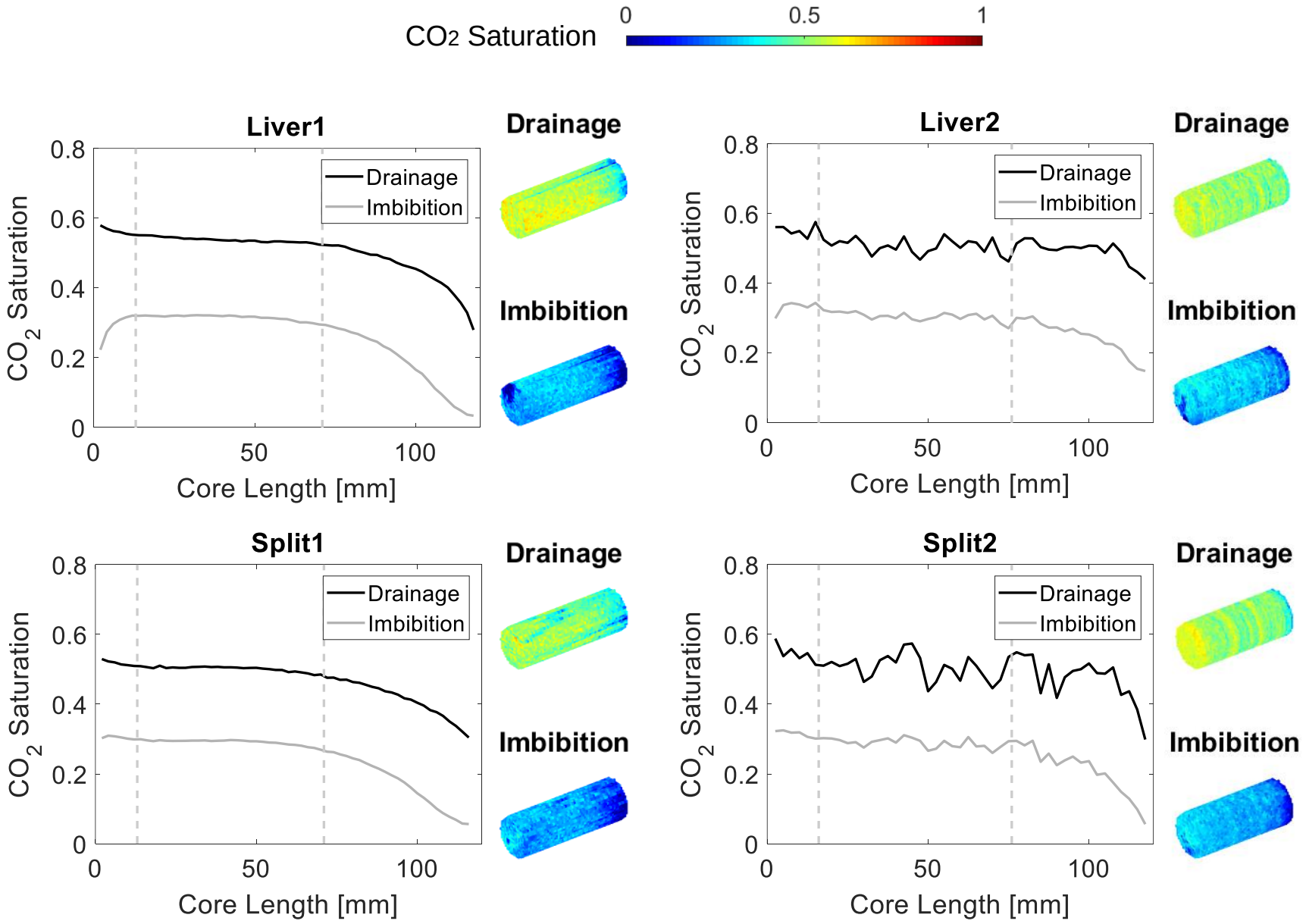
Results

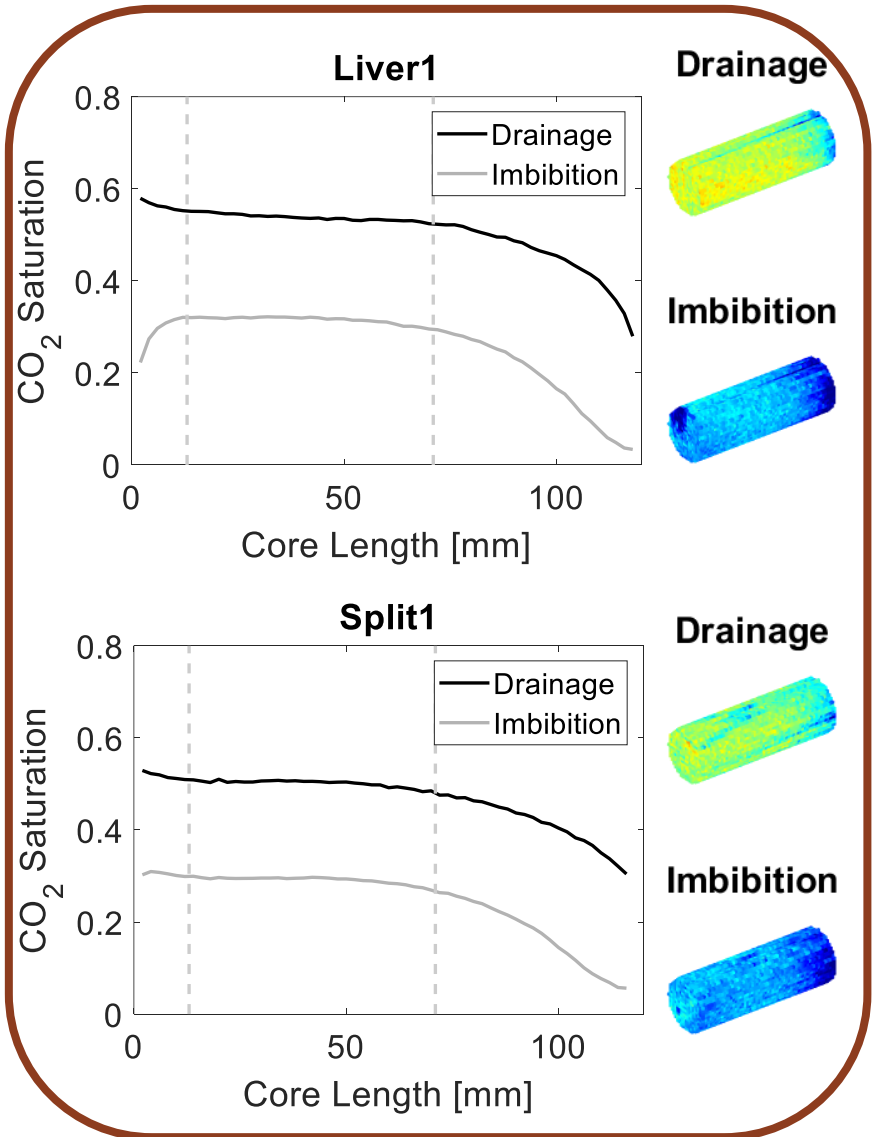
CO_2 saturation and trapping results

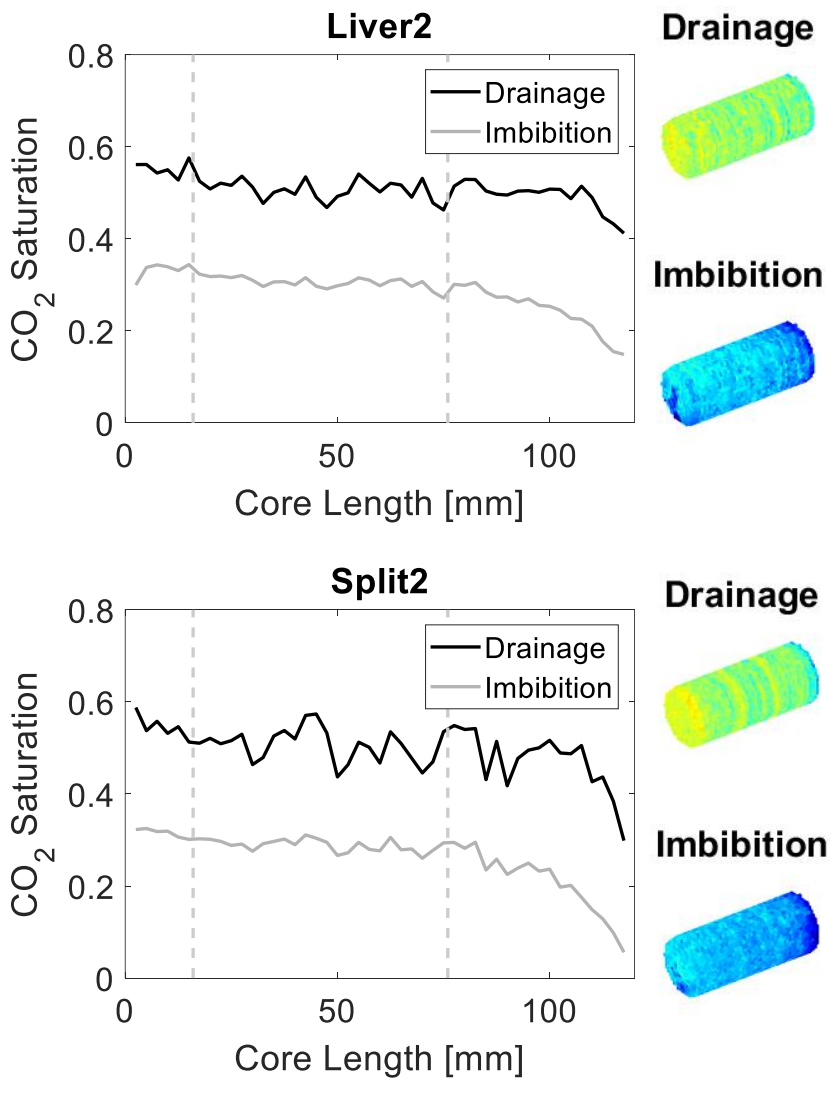
CO_2 initial and residual saturation results



CO_2 initial and residual saturation results

Berea: Lamination parallel to flow



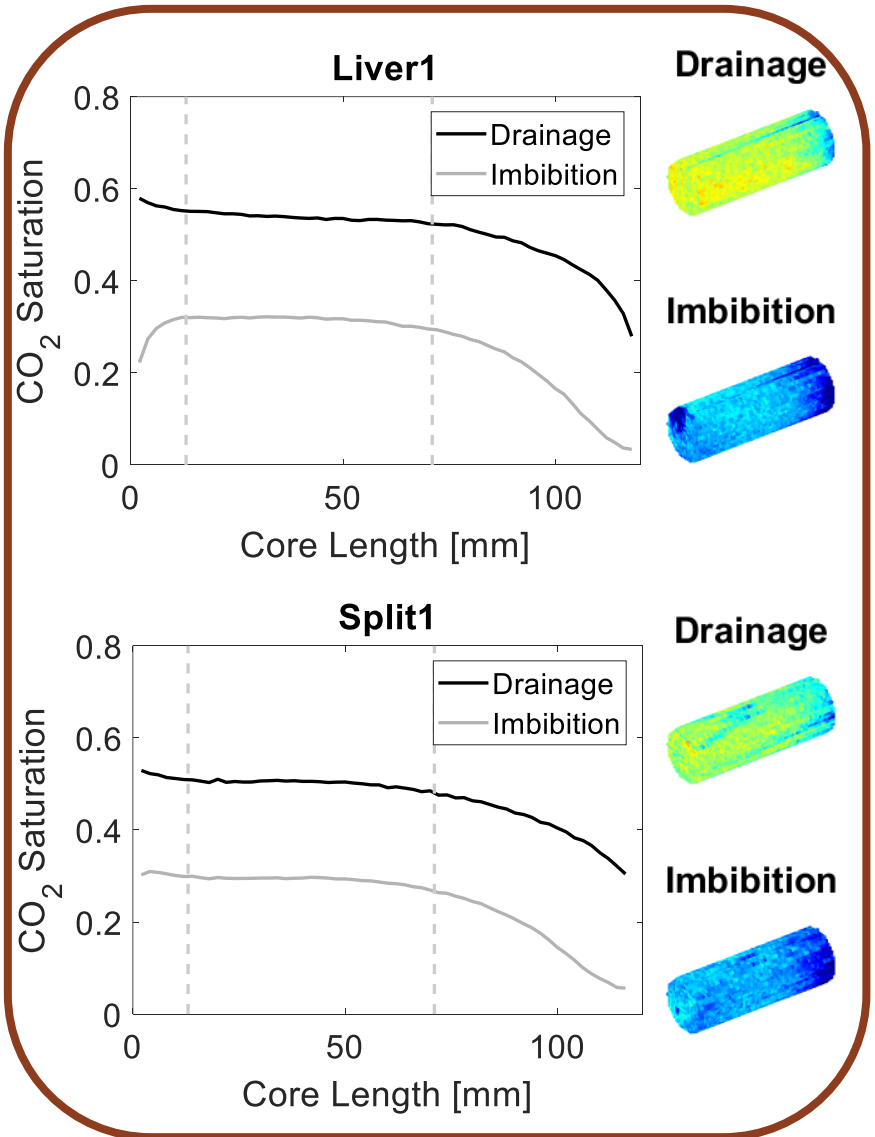


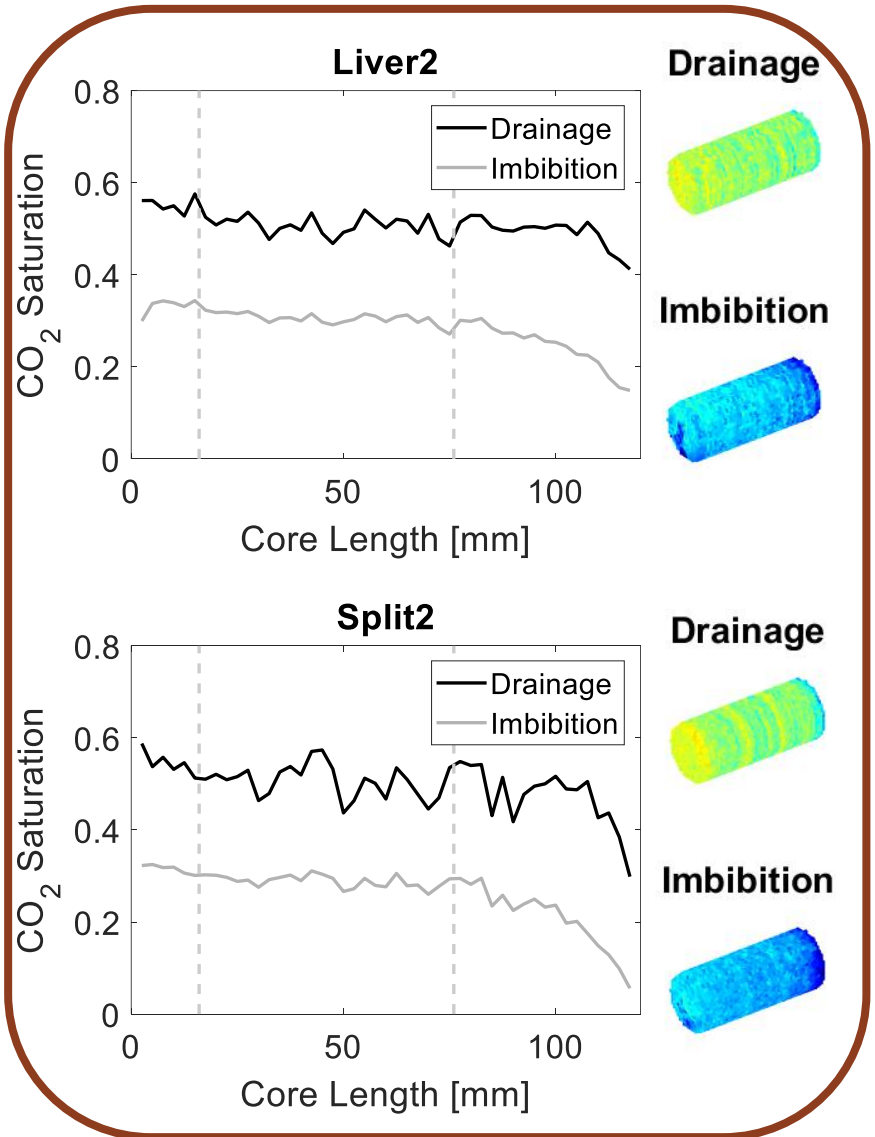
CO_2 initial and residual saturation results

Berea: Lamination parallel to flow

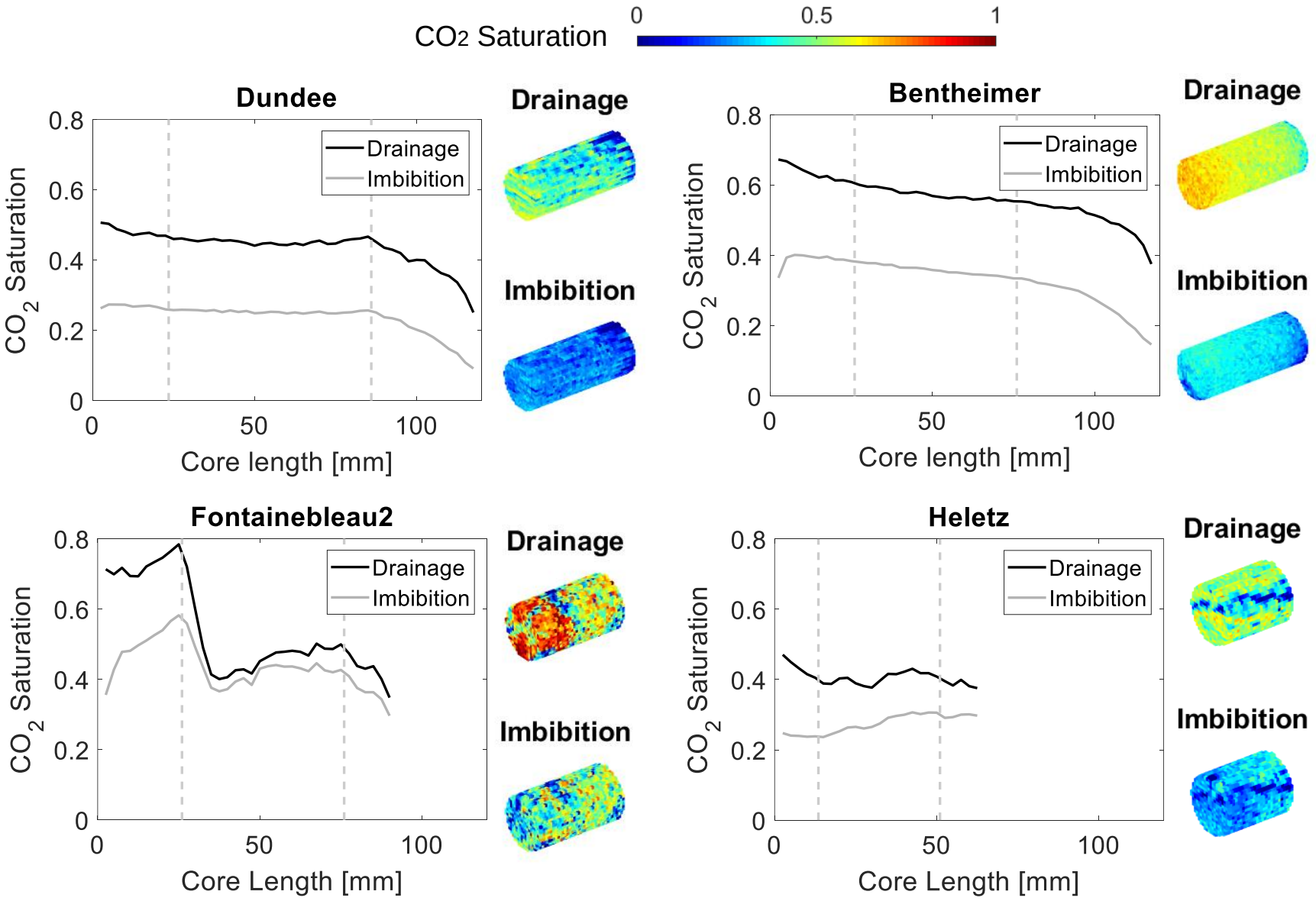
CO_2 Saturation 0 0.5 1

Berea: Lamination perpendicular to flow

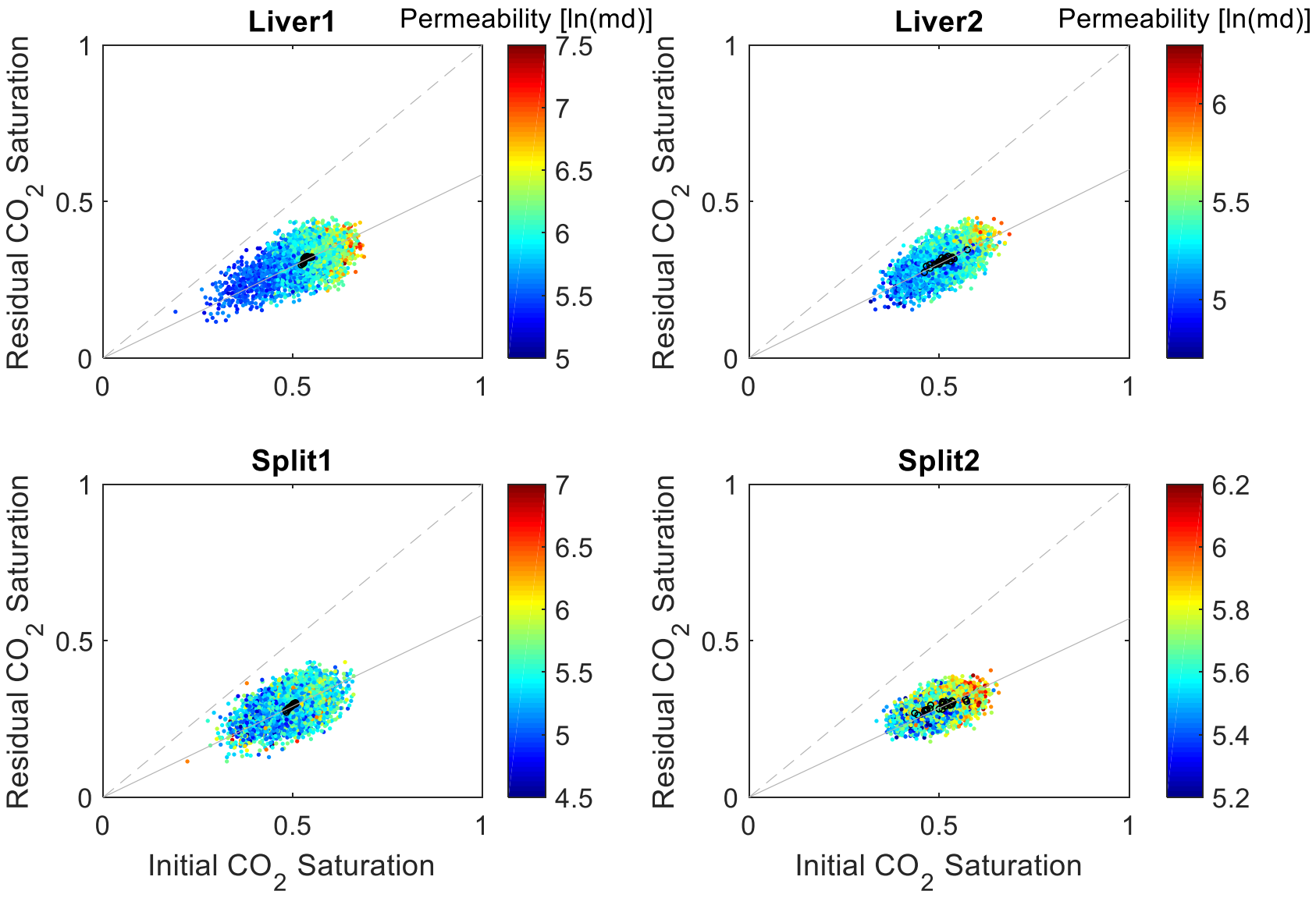




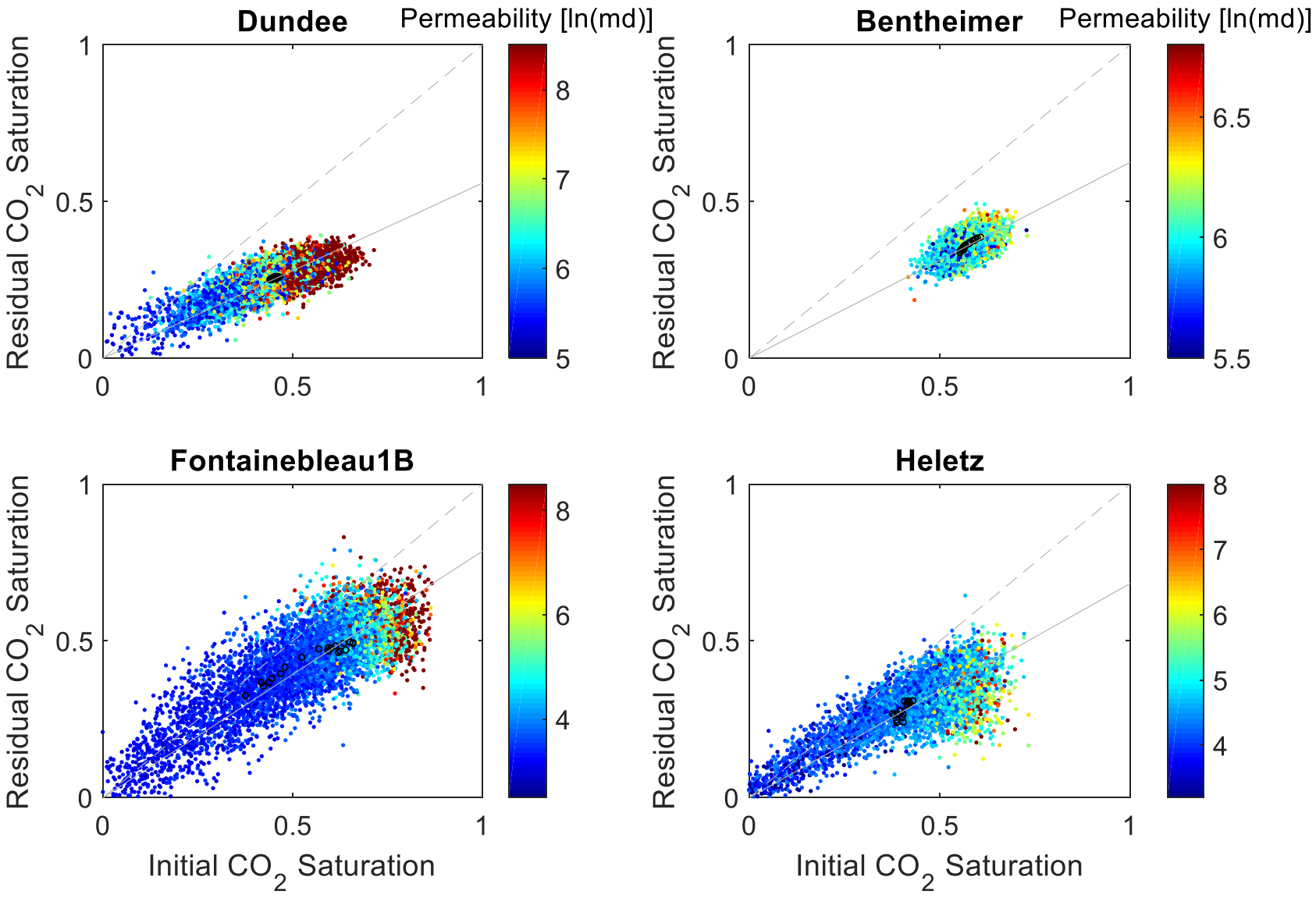
CO_2 initial and residual saturation results



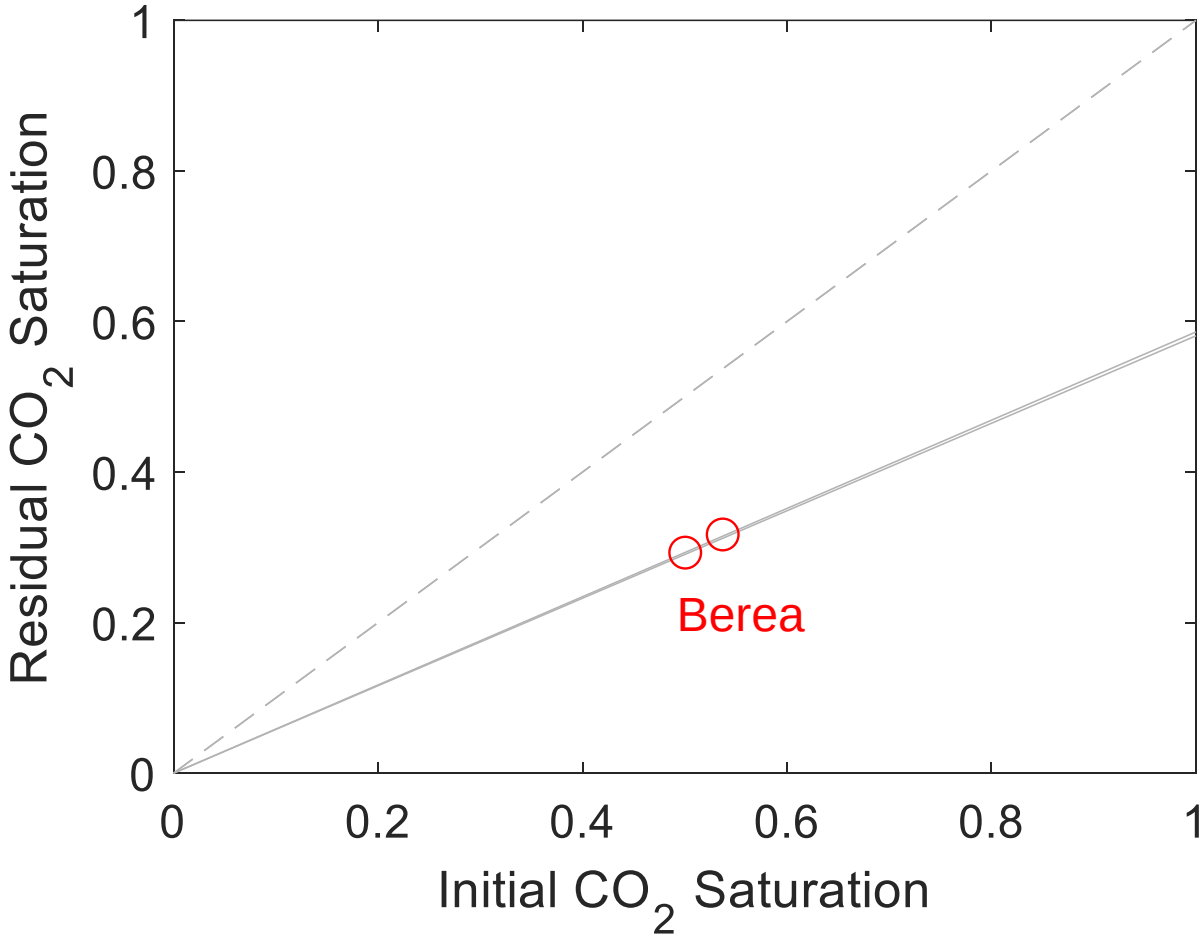
CO_2 residual trapping results



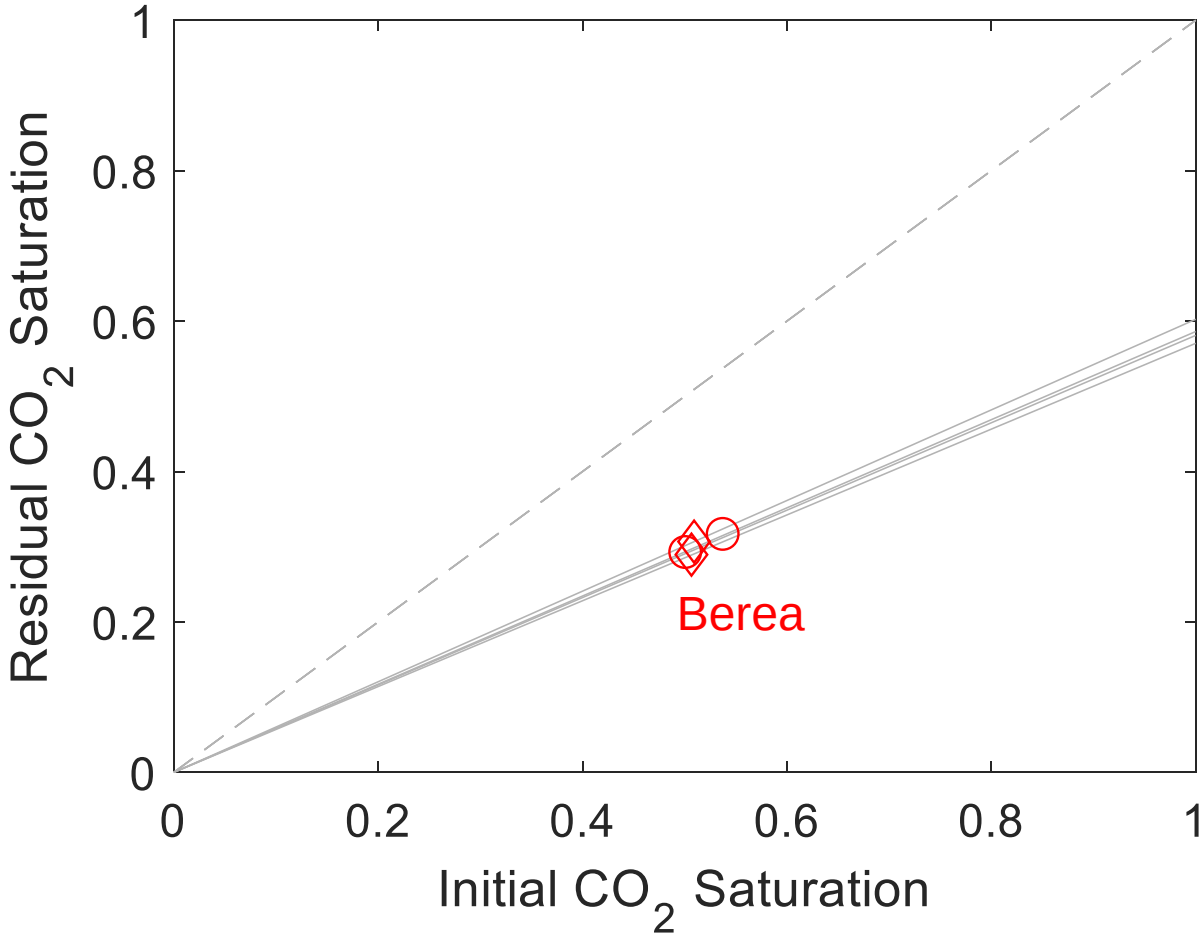
CO_2 residual trapping results



CO_2 residual trapping results



CO_2 residual trapping results



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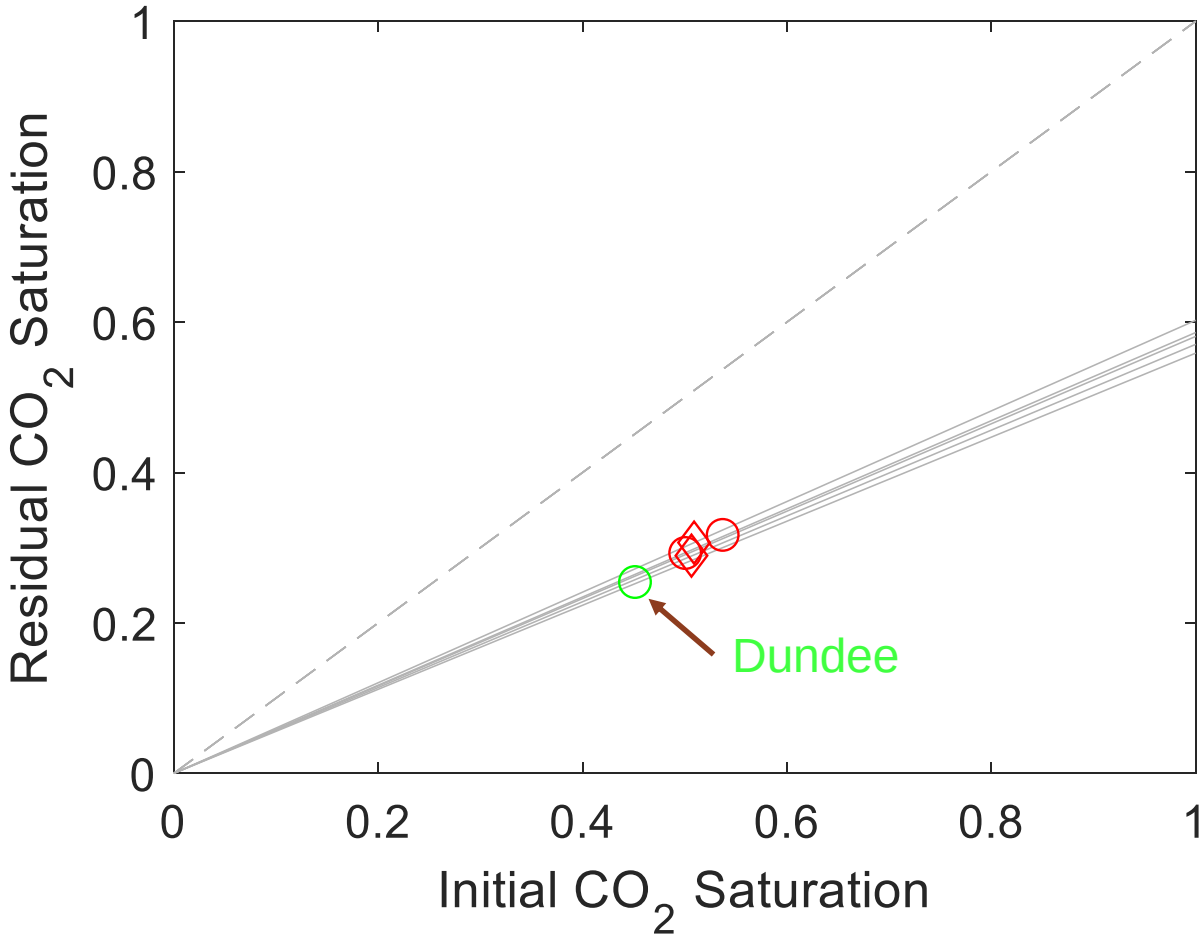

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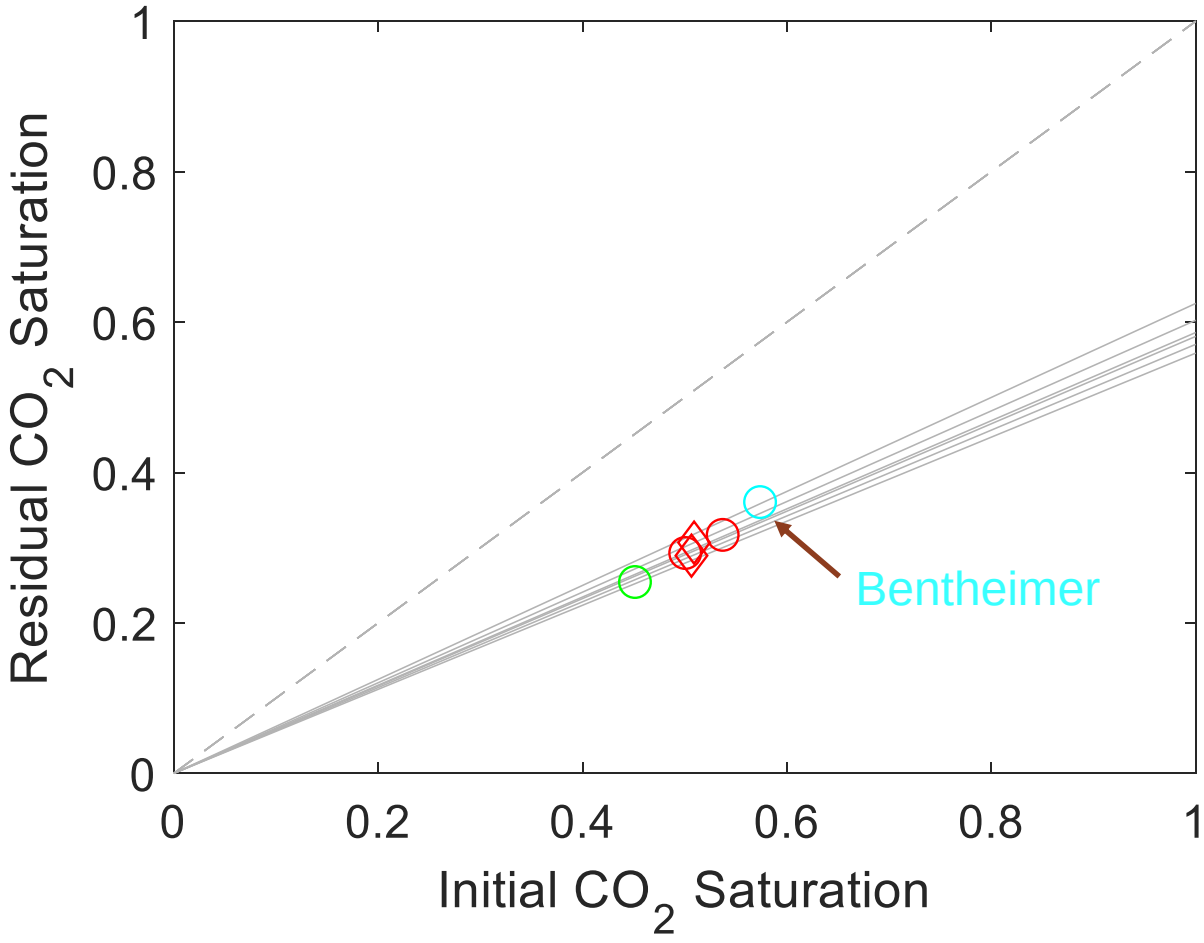

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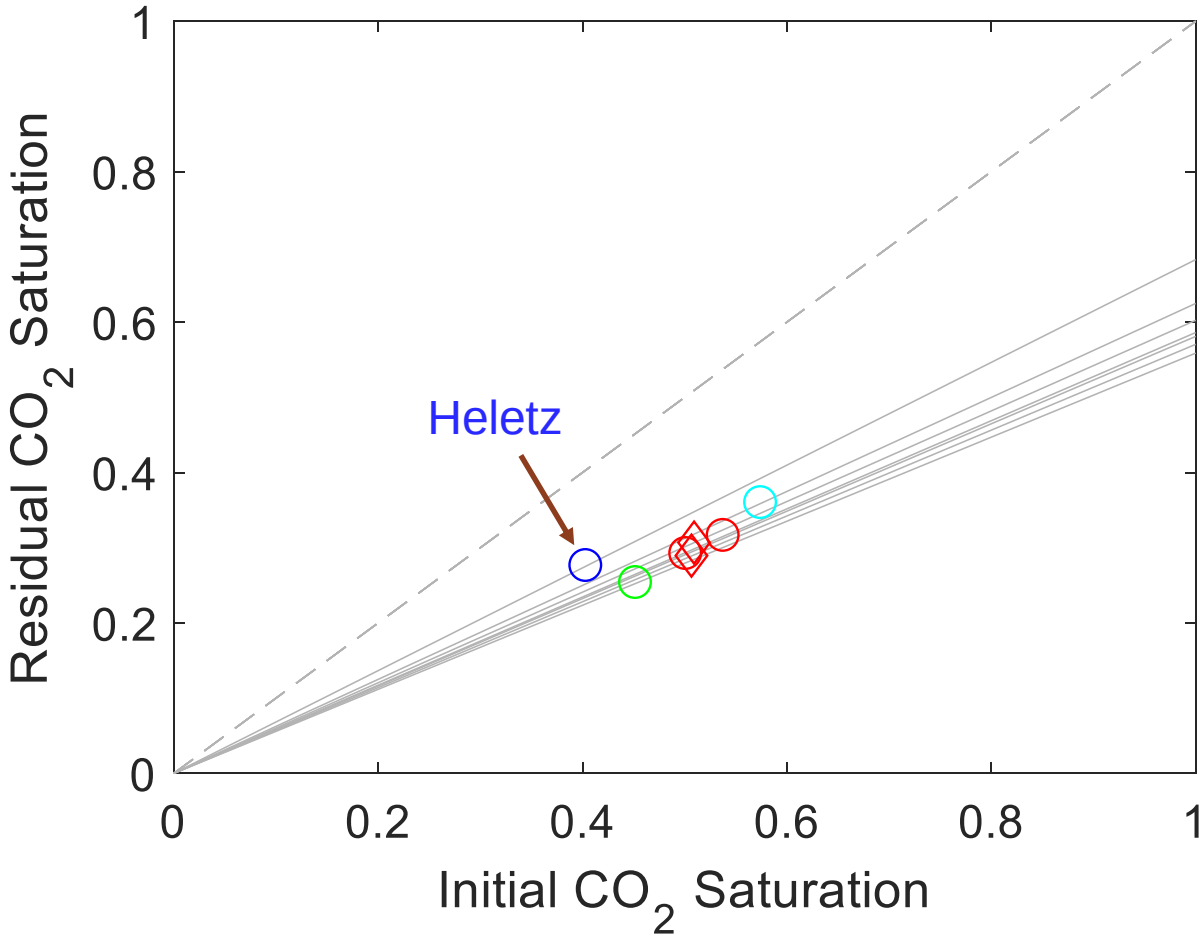

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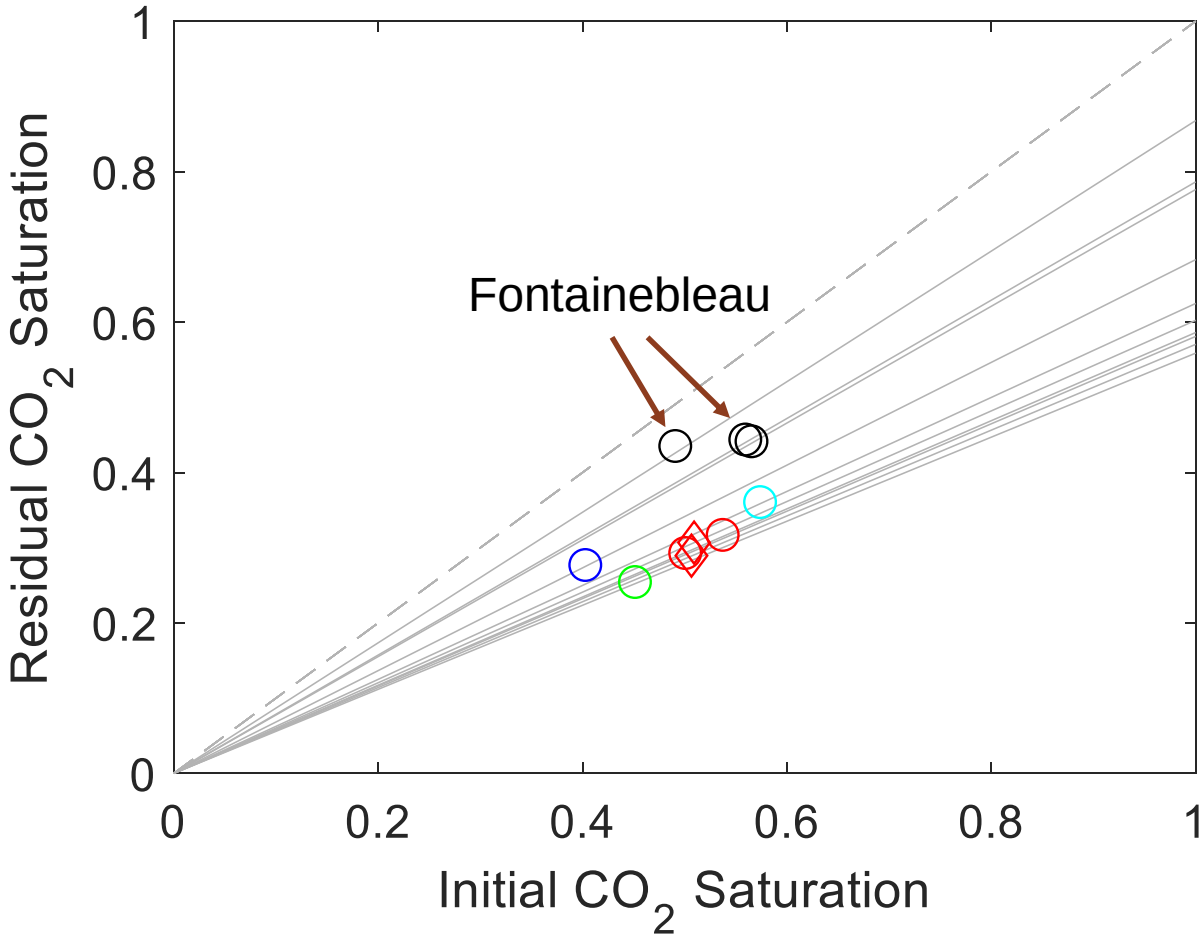

Questions this study seeks to answer

Which are the best predictors for a sandstone core's CO_2 residual trapping ability?

- Porosity?
- Permeability?
- Drainage saturation?
- Correlation length?
- Degree of heterogeneity?

Which CO_2 residual trapping mechanism is more important, pore-scale or mesoscale?

- Based on core-scale experimental results alone?

Best predictors from correlation analysis results

20 petrophysical parameters are analyzed as candidate predictors

- Porosity
- Permeability
- Correlation length in porosity field in x, y, and z direction
- Correlation length in permeability field in x, y, and z direction
- Minimum, mean, and maximum standard deviation in drainage CO_2 saturation field
- Coefficient of variation in porosity field
- Coefficient of variation in permeability field
- Dykstra-Parsons coefficient in permeability field (Dykstra and Parsons, 1950)
- Li's degree of heterogeneity parameter (Li and Benson, 2015)
- Capillary pressure curve

Best predictors from correlation analysis results

The two best predictors for a sandstone core's CO_2 residual trapping ability:

- **Porosity**
- Permeability
- Correlation length in porosity field in x, y, and z direction
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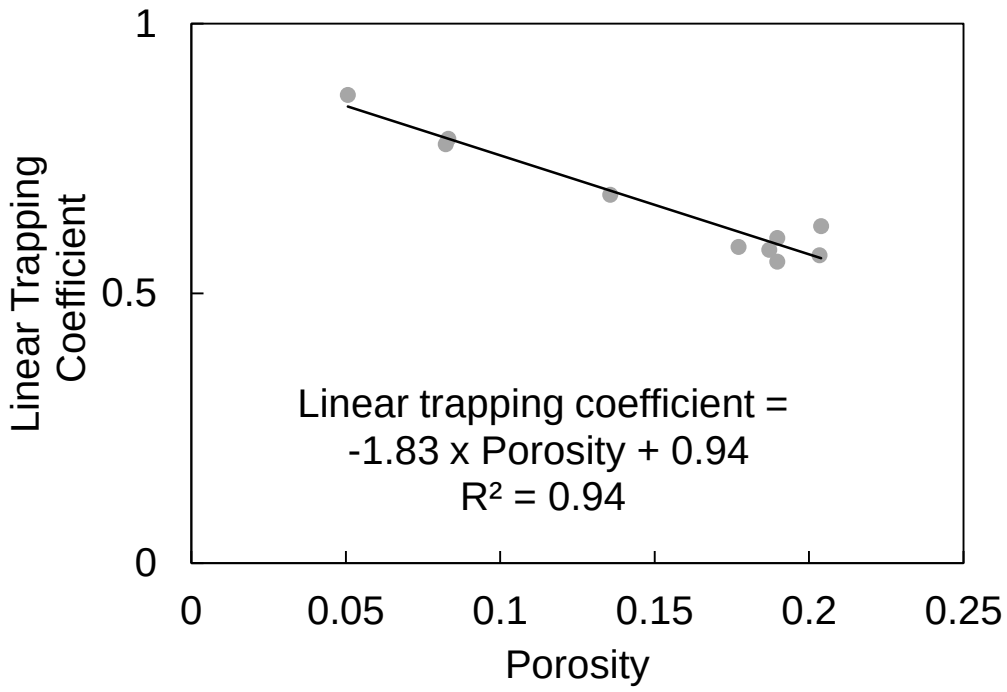

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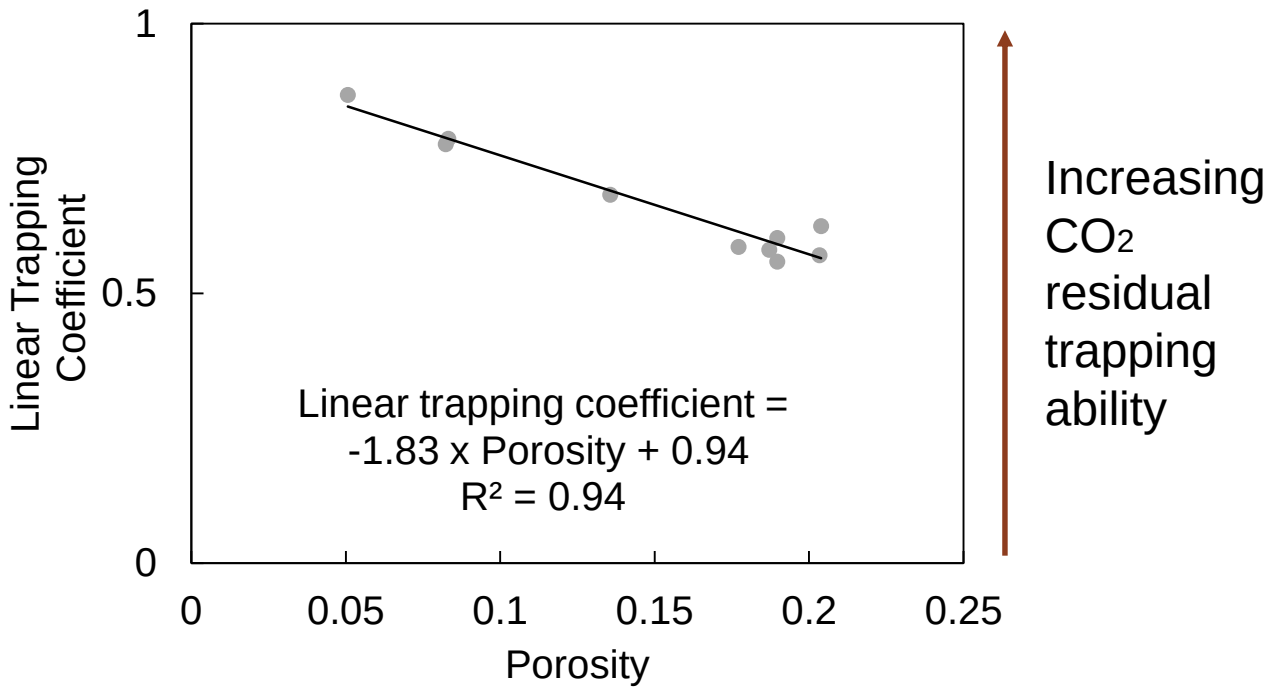

Best predictors from correlation analysis results

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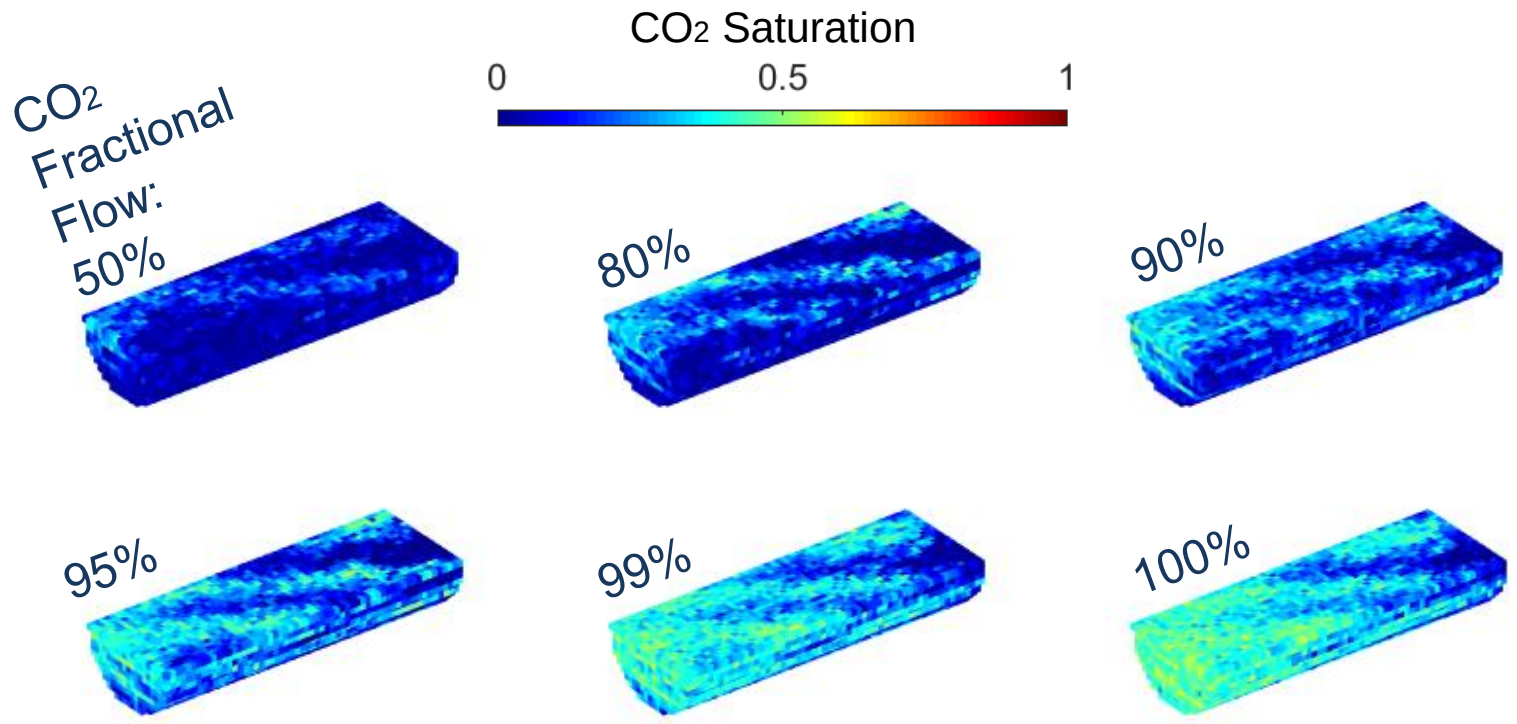
Predictor parameters derived from the CO_2 saturation field

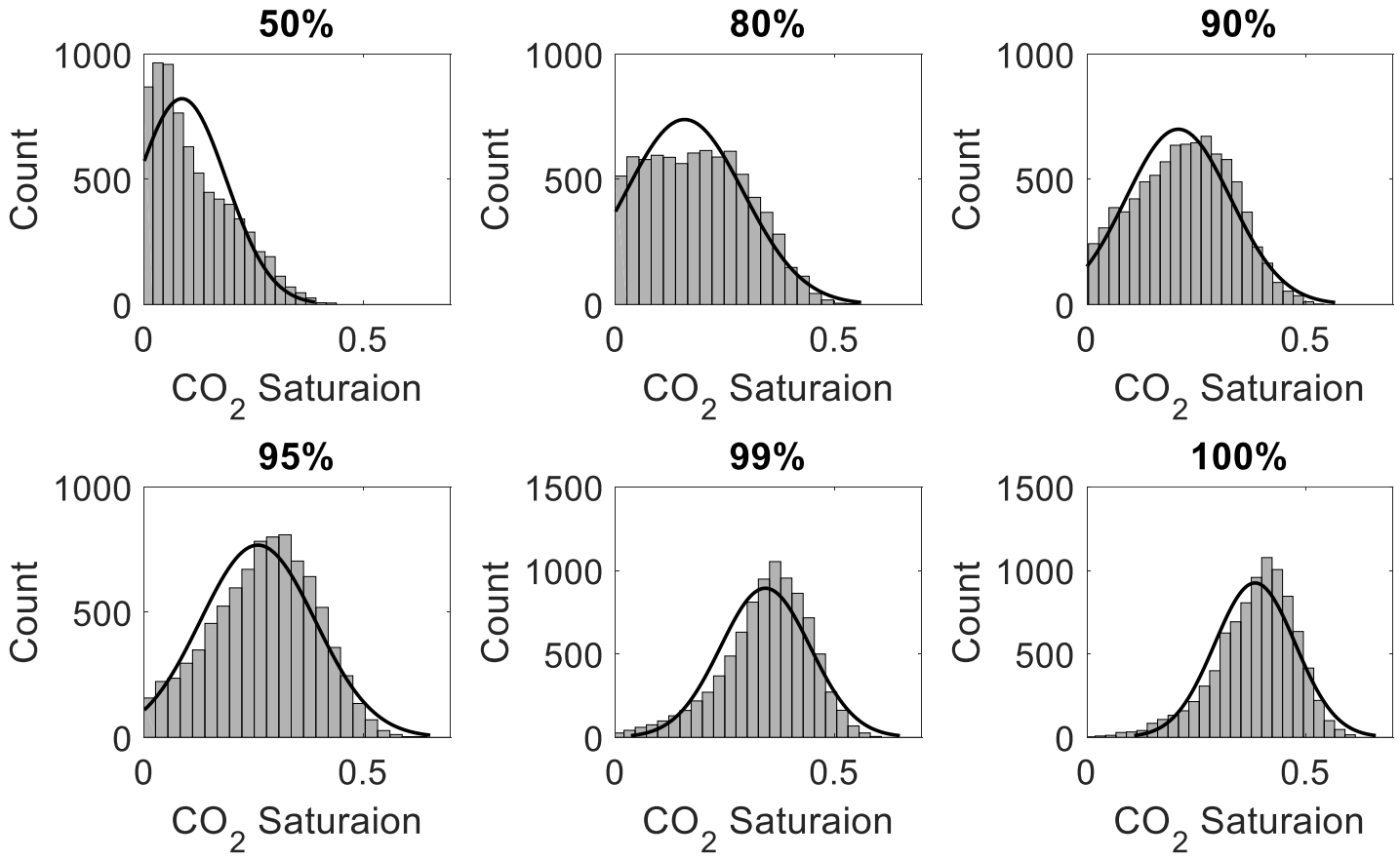
- Maximum standard deviation in drainage CO_2 saturation field



CT images of voxel-level CO_2 saturation field
for 50 – 100% CO_2 fractional flow for drainage

Predictor parameters derived from the CO_2 saturation field

- Maximum standard deviation in drainage CO_2 saturation field



Histograms of voxel-level CO_2 saturation field for 50 – 100% CO_2 fractional flow for drainage

Best predictors from correlation analysis results

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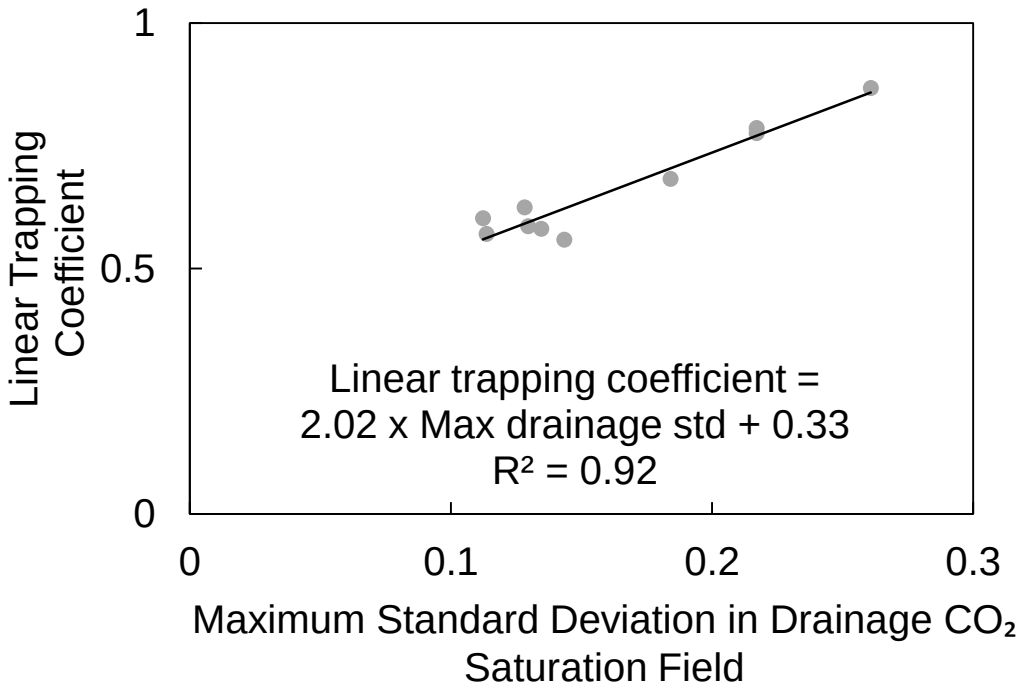

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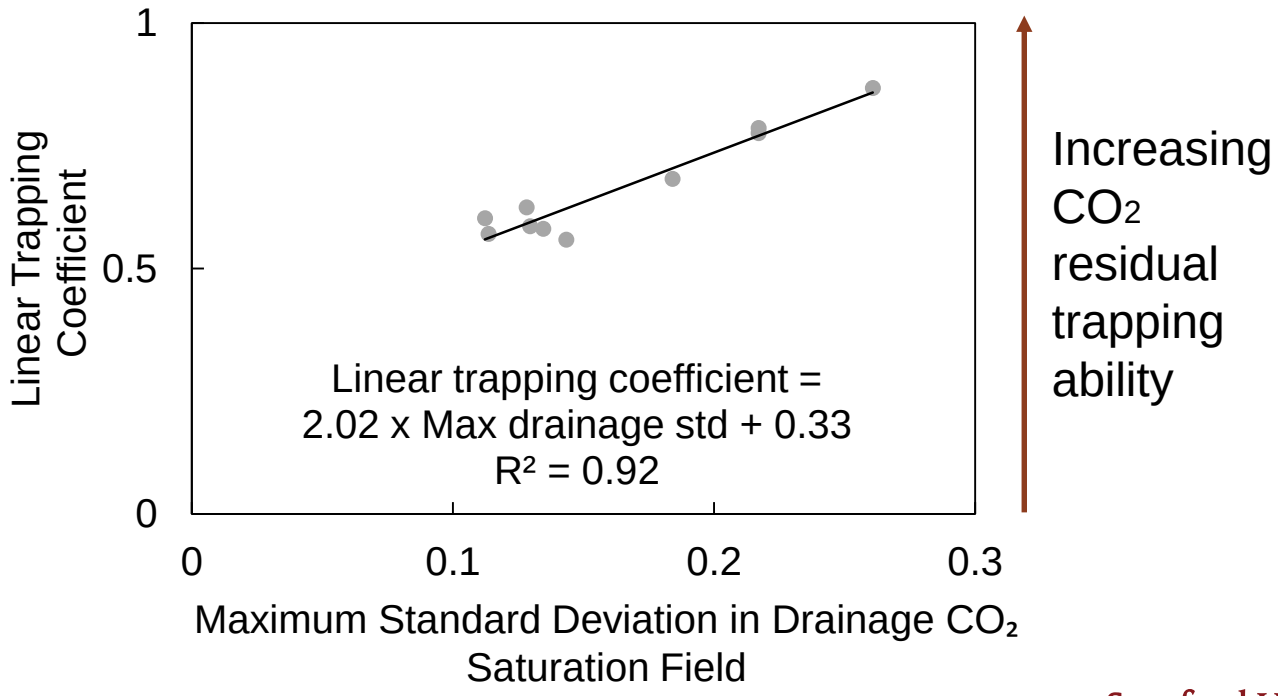

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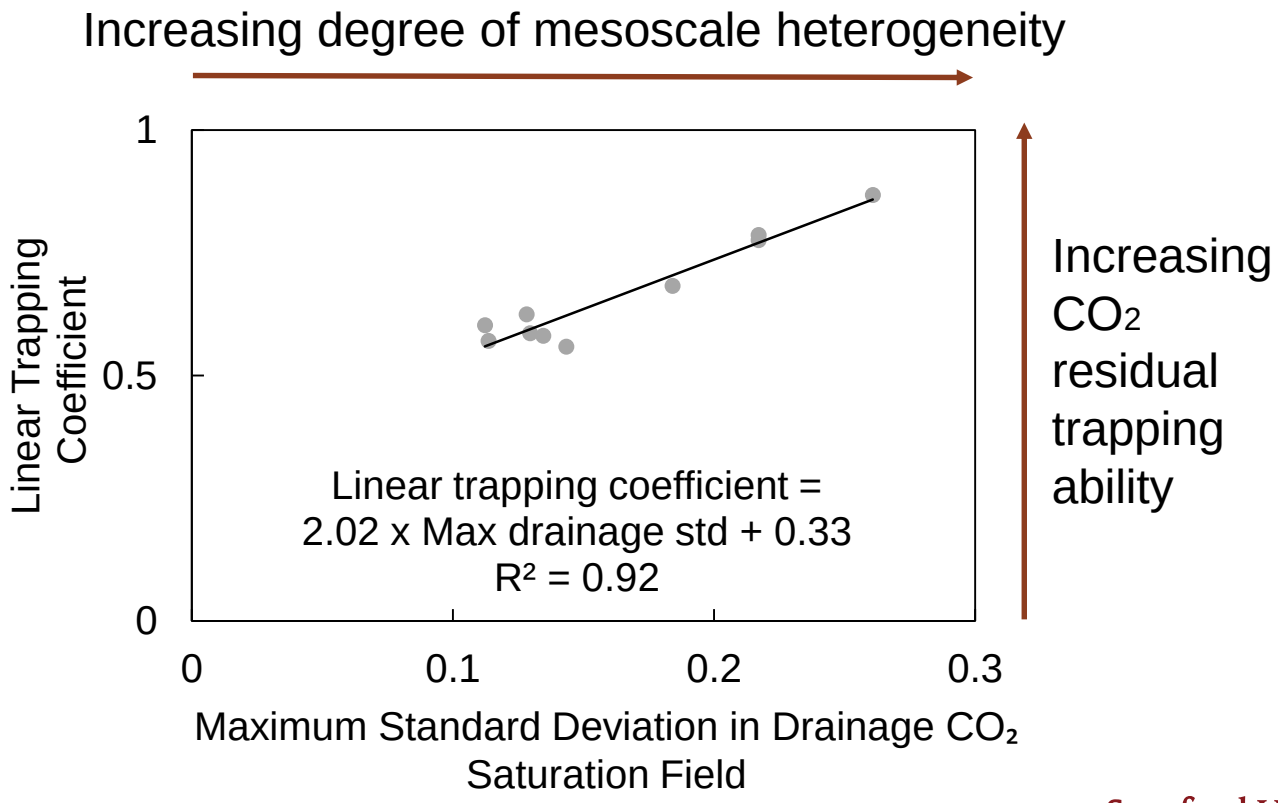

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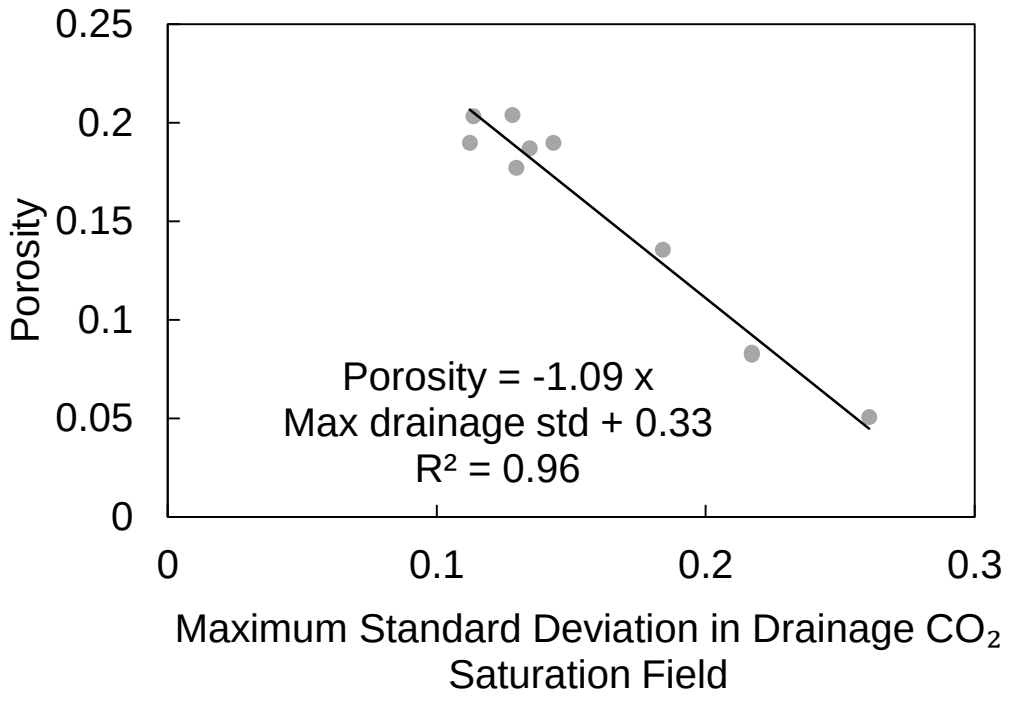

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How to infer the amount of pore-scale and mesoscale residual trapping mechanism

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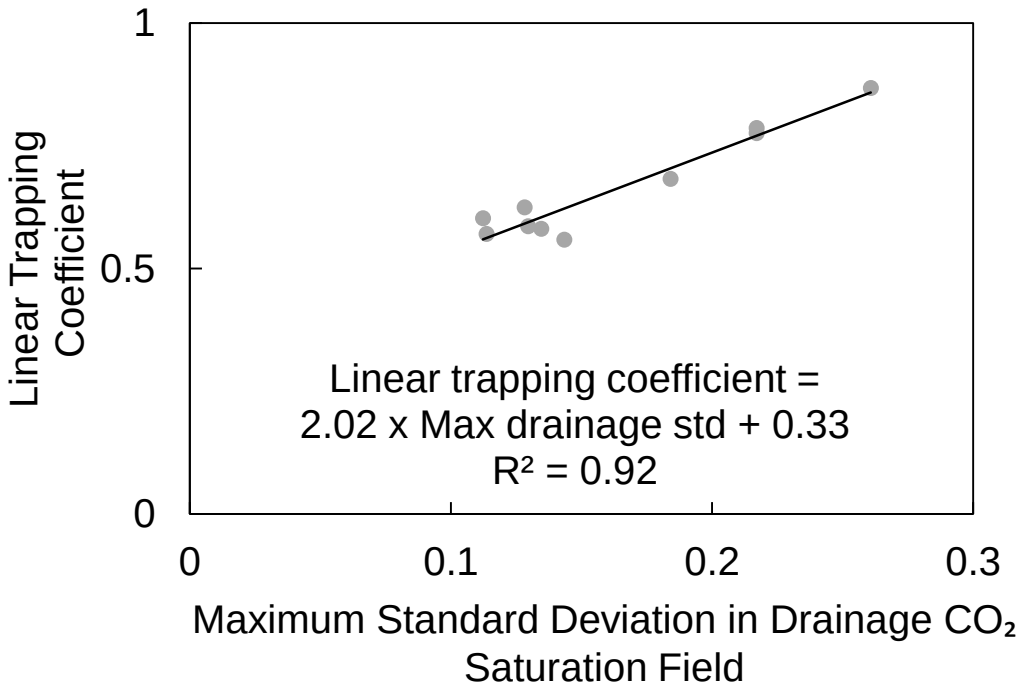
By extrapolating the following correlation relationship



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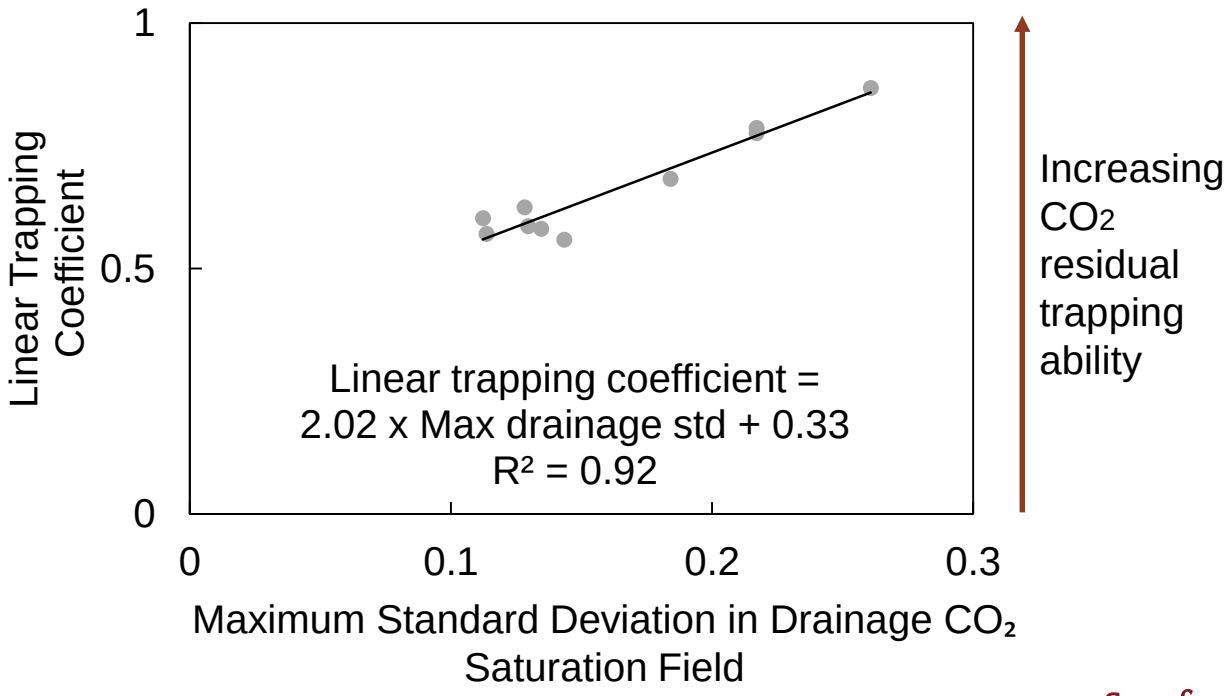

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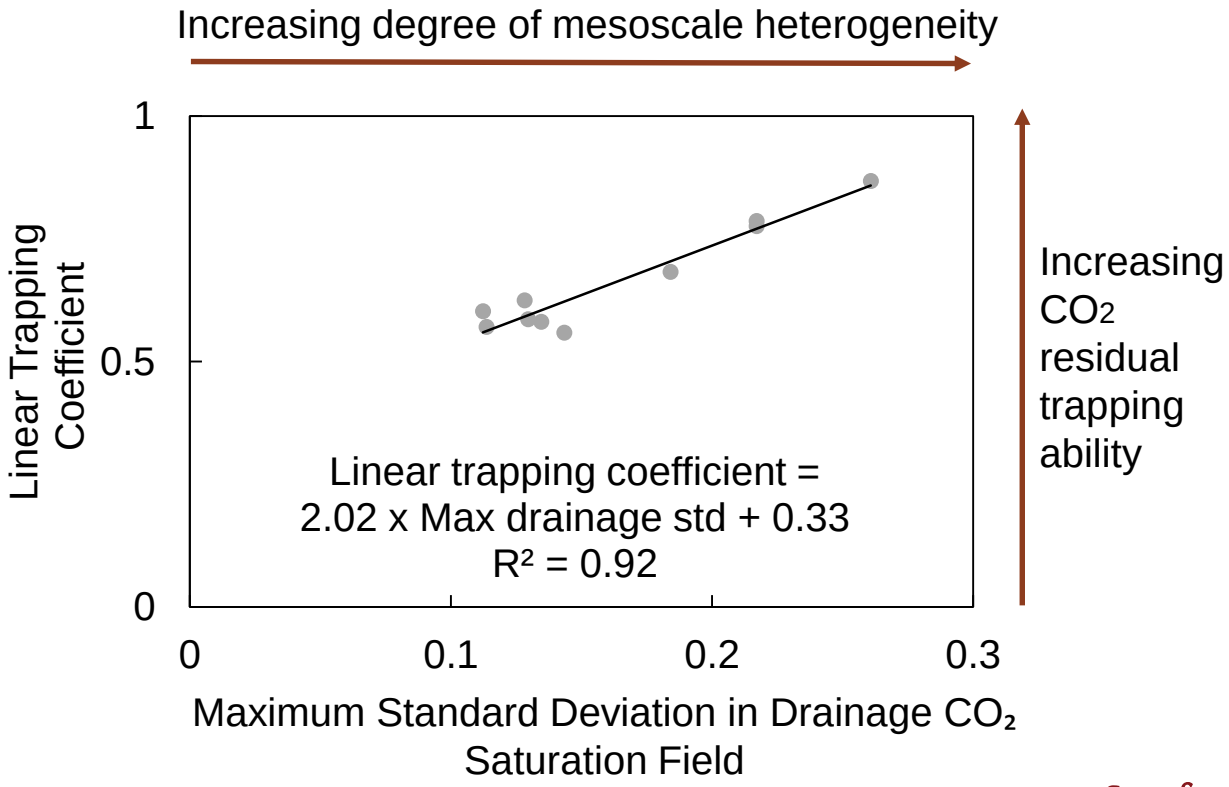

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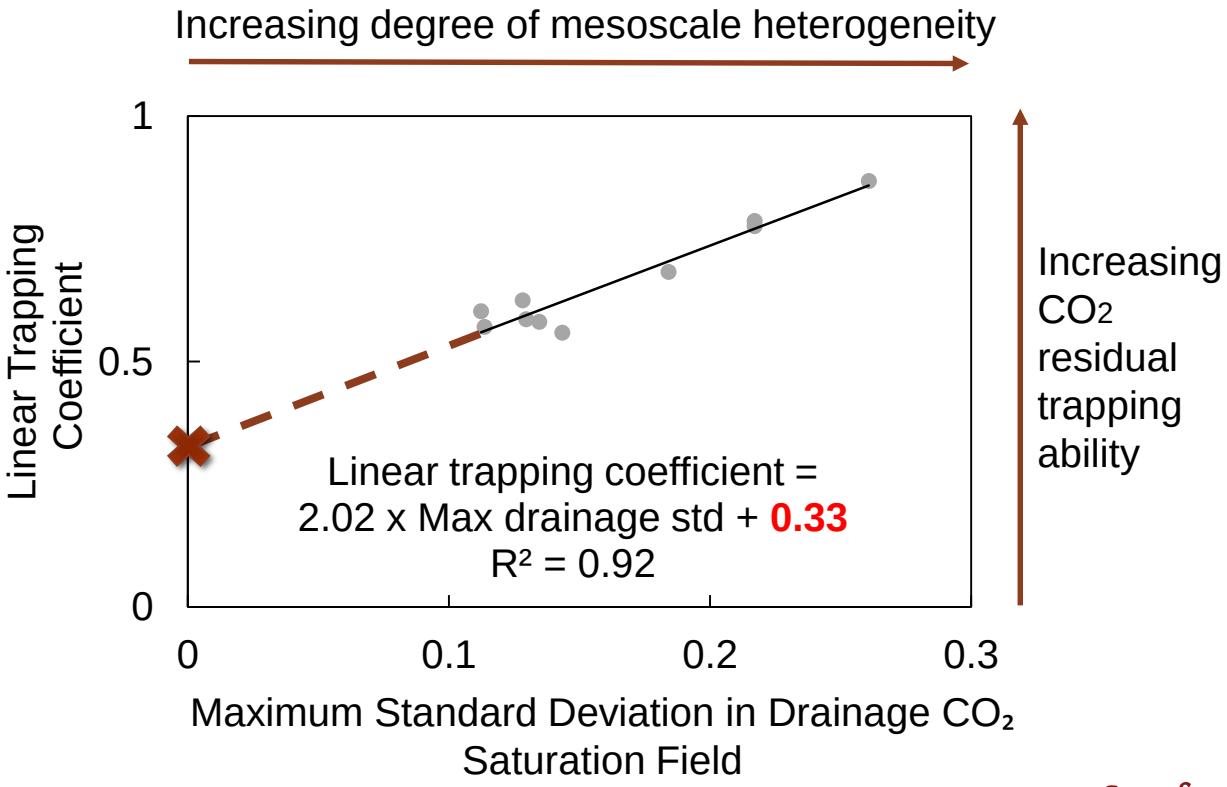
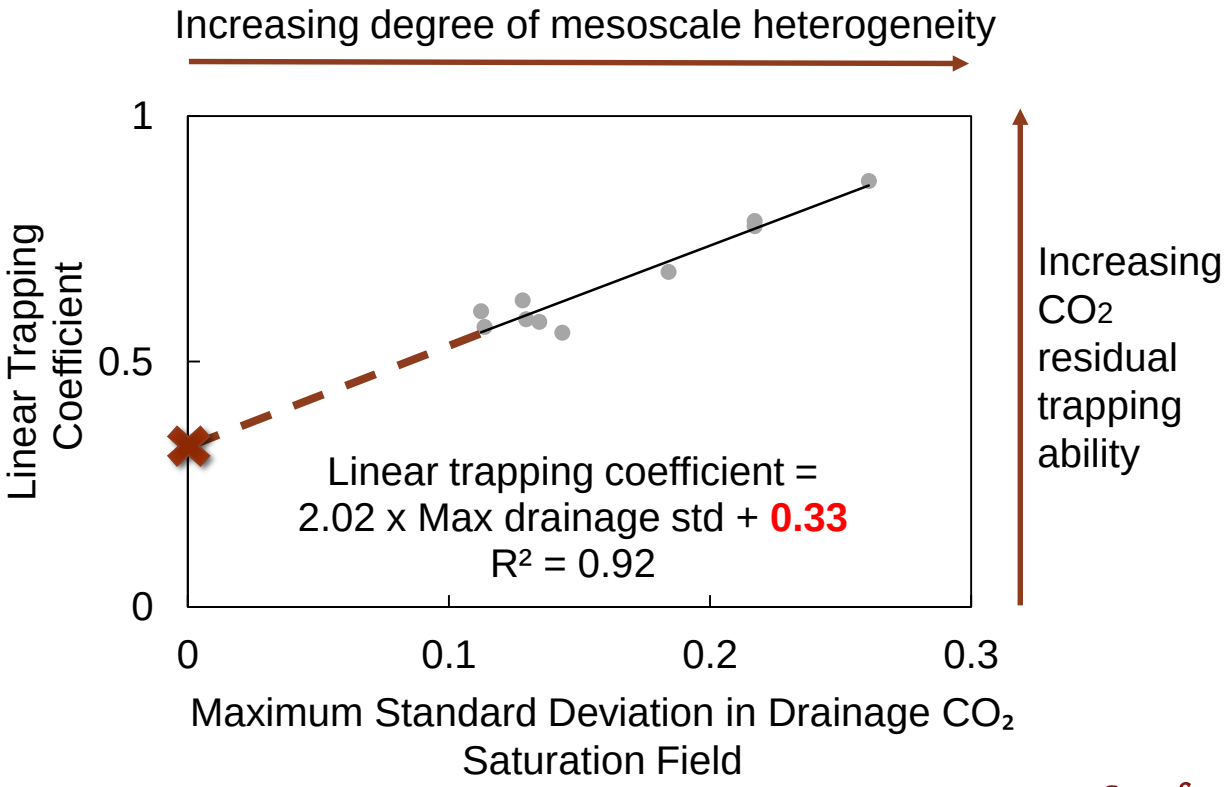


How to infer the amount of pore-scale and mesoscale residual trapping mechanism

By extrapolating the following correlation relationship

- 33% of initial CO_2 saturation is trapped by pore-scale mechanism



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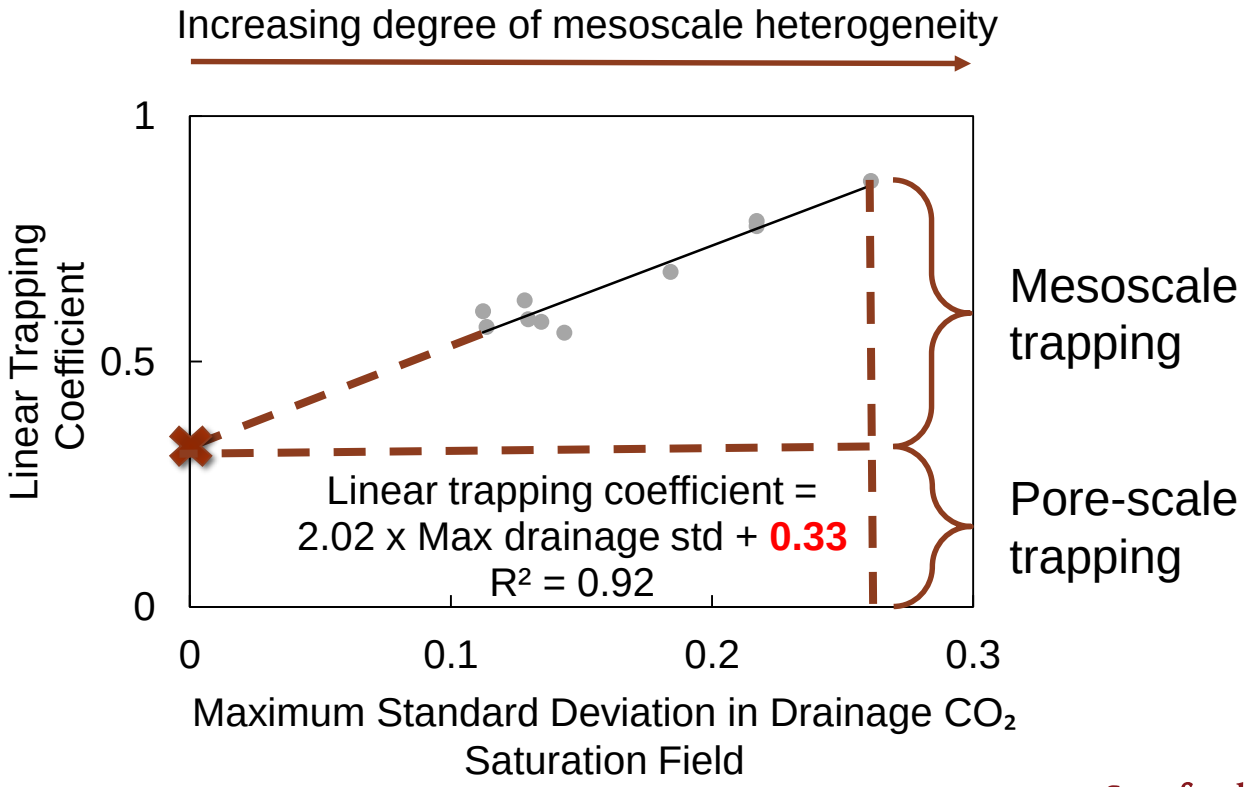
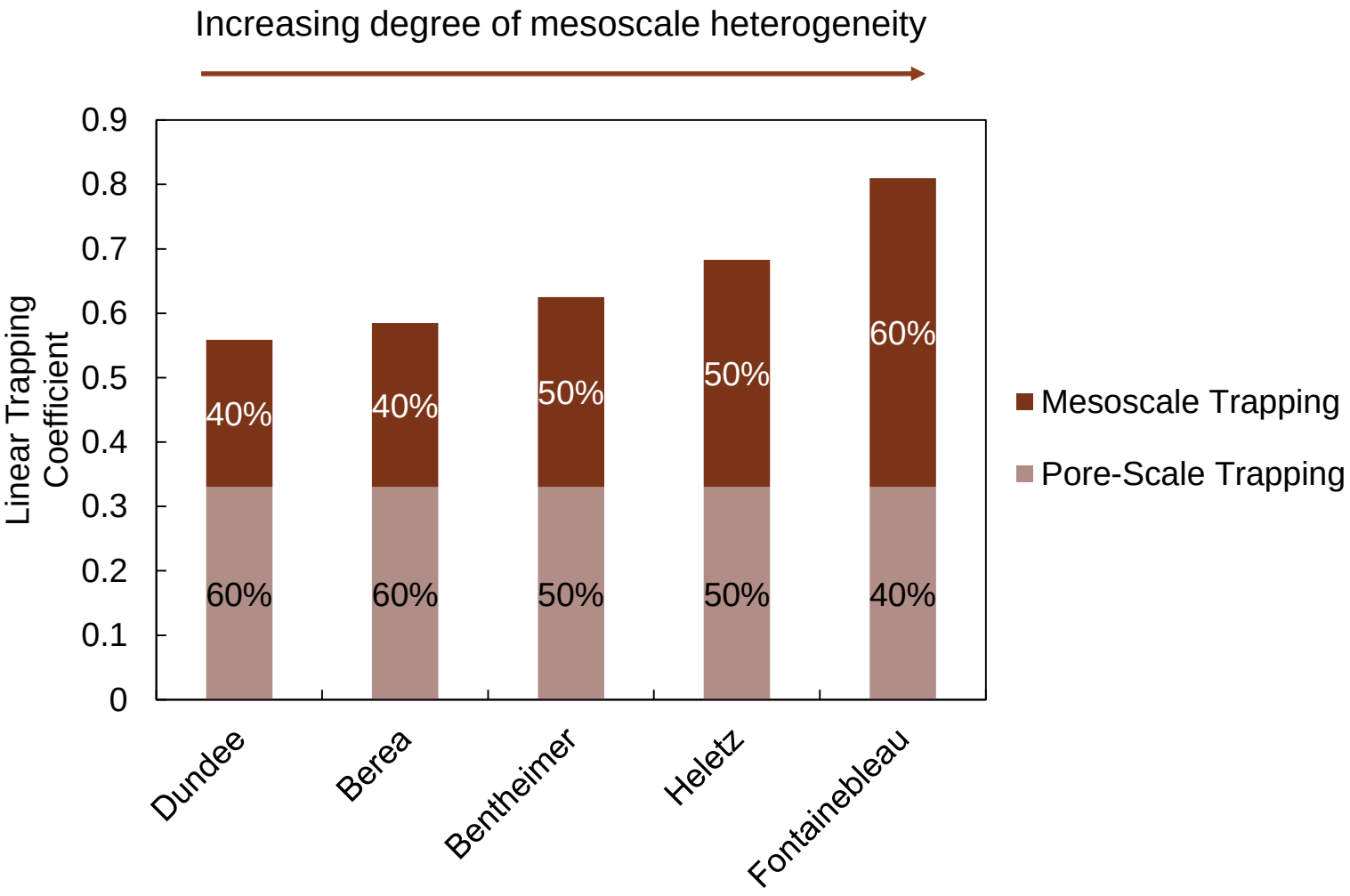


The contribution to CO_2 residual trapping from pore-scale and mesoscale trapping mechanism



Conclusions

Conclusions from experimental results

Conclusions

Which are the best predictors for a sandstone core's CO_2 residual trapping ability?

- Porosity
- Maximum standard deviation in drainage CO_2 saturation field

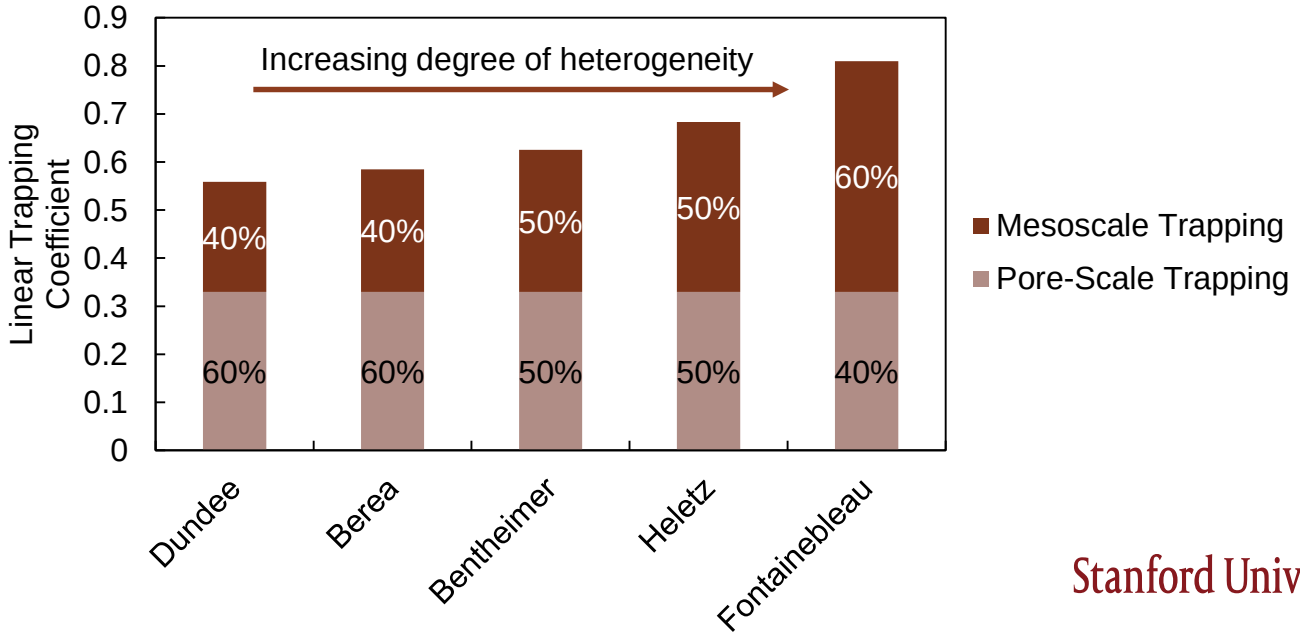
Conclusions

Which are the best predictors for a sandstone core's CO_2 residual trapping ability?

- Porosity
- Maximum standard deviation in drainage CO_2 saturation field

Which CO_2 residual trapping mechanism is more important, pore-scale or mesoscale?

- Pore-scale and mesoscale mechanism are equally important



Acknowledgement

- SCCS
- GCEP
- NCGC

Stanford Center for Carbon Storage

GCEP

Global Climate & Energy Project

STANFORD UNIVERSITY

Center for Nanoscale Controls on Geologic CO_2

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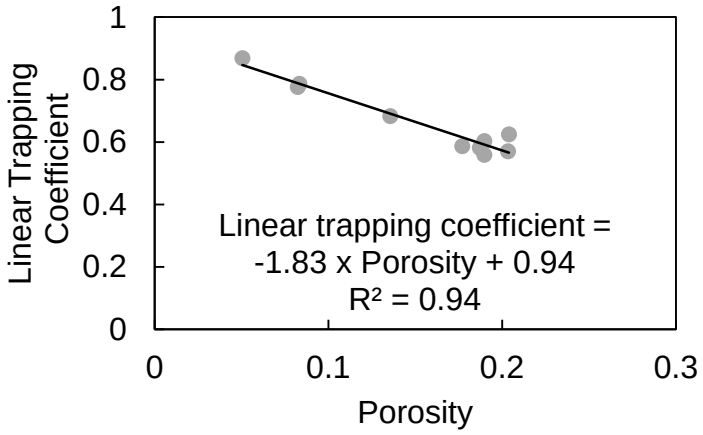
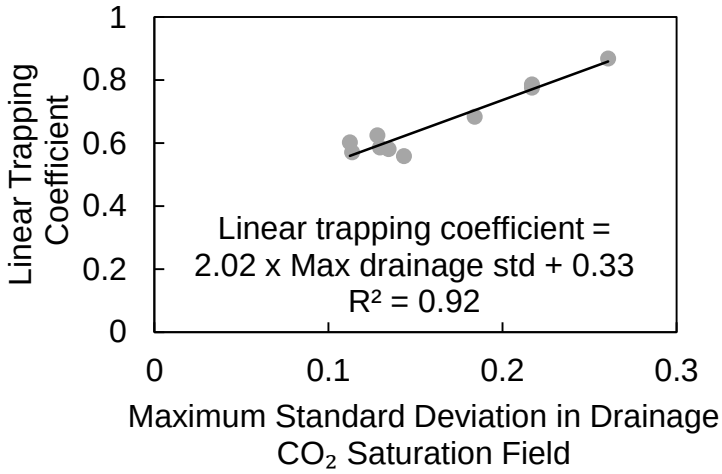
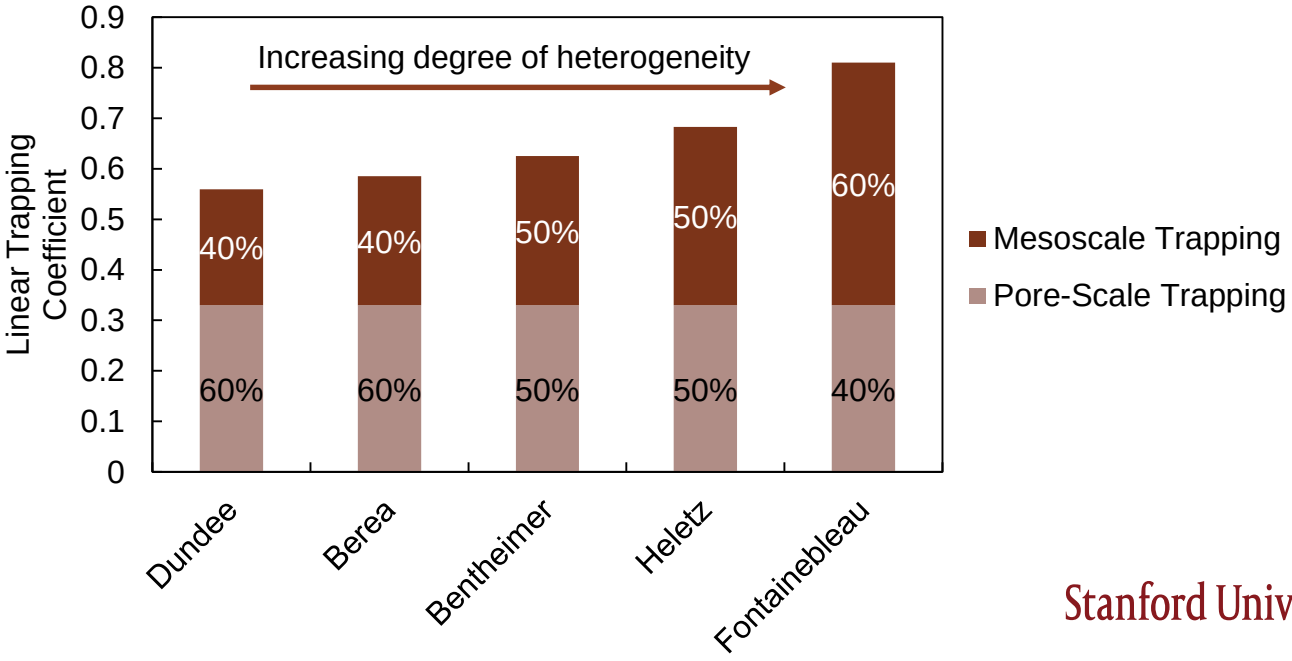
Questions?







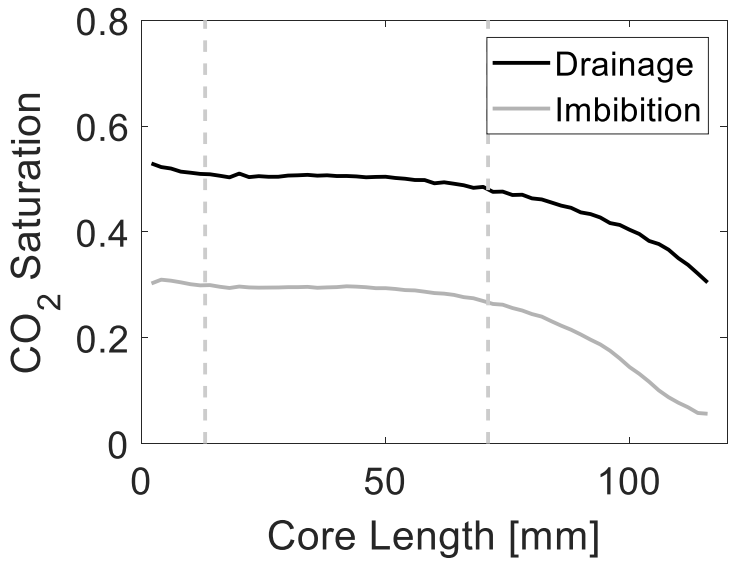
Stanford University

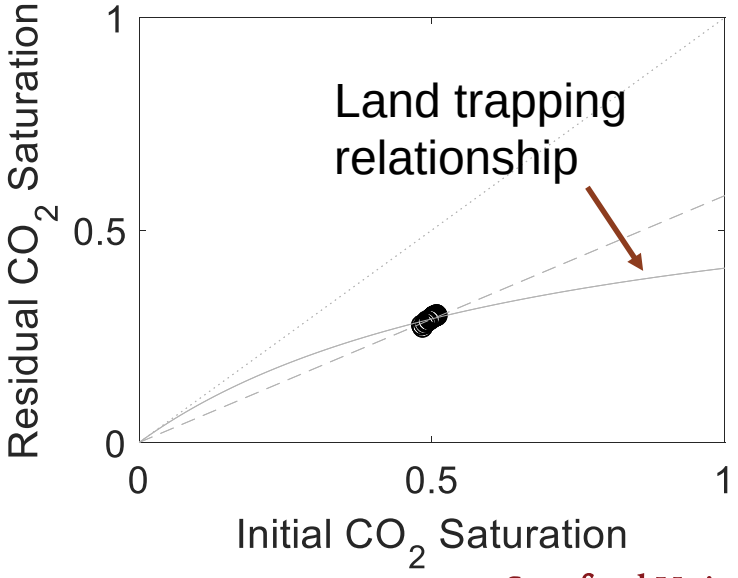
Extra slides

The importance of studying CO_2 residual trapping ability

What is CO_2 residual trapping "ability"?

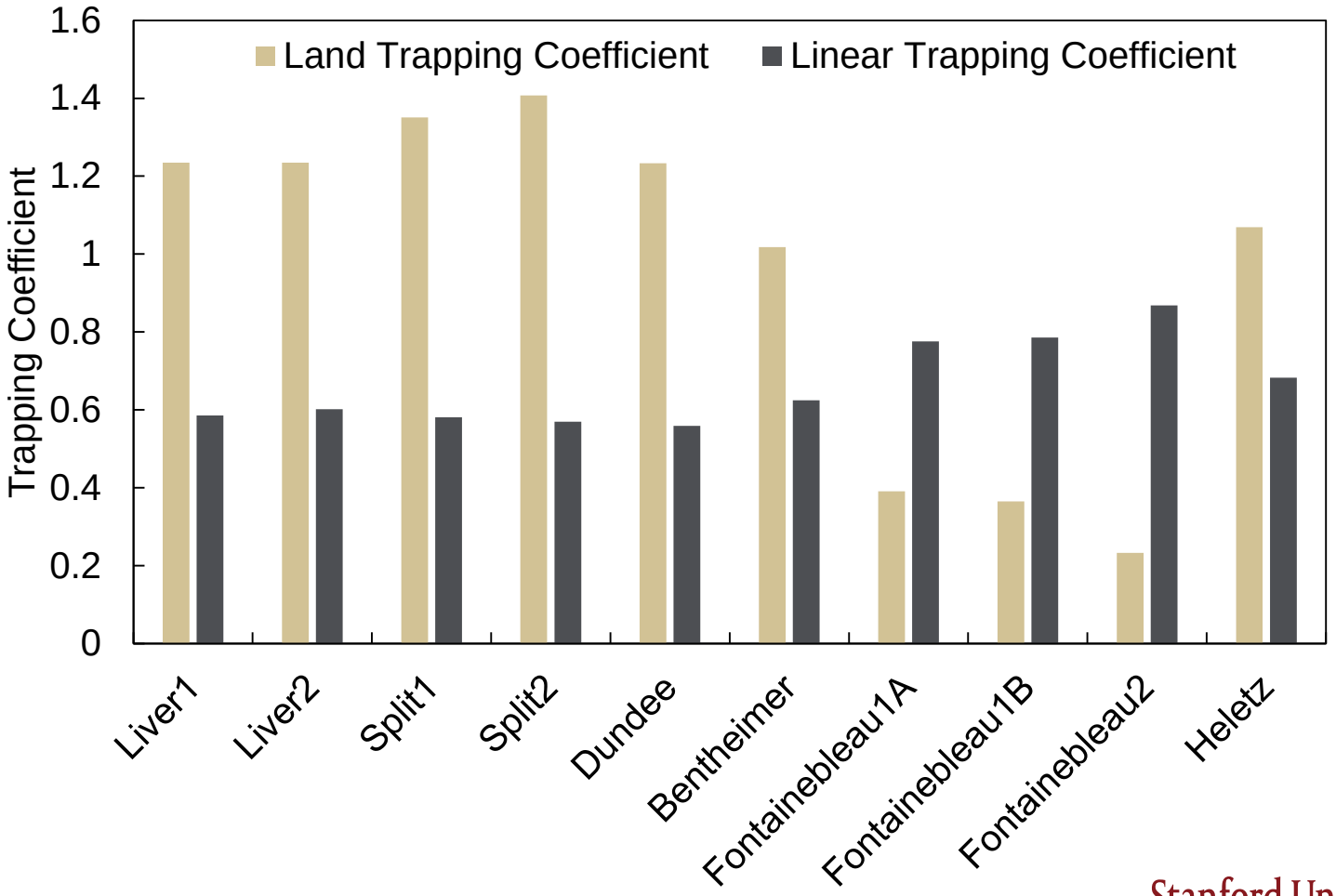
$$S_{CO_2,r} = A \cdot S_{CO_2,i} \qquad S^*_{CO_2,r} = \frac{S^*_{CO_2,i}}{1 + C \cdot S^*_{CO_2,i}}$$





CO_2 residual trapping ability correlation analysis results

CO_2 residual trapping



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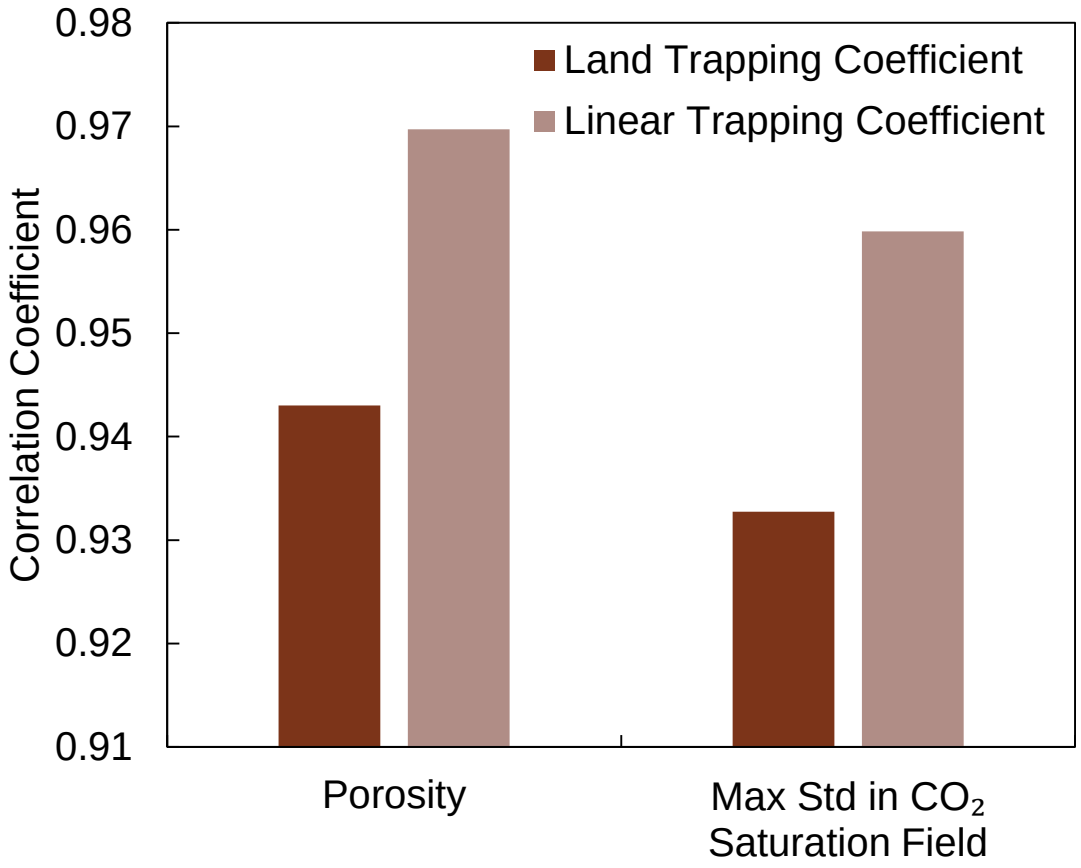
Correlation results



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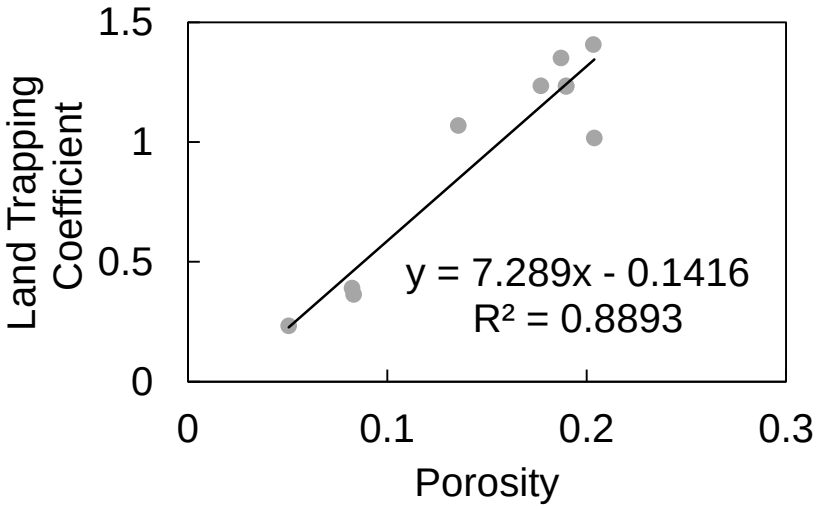
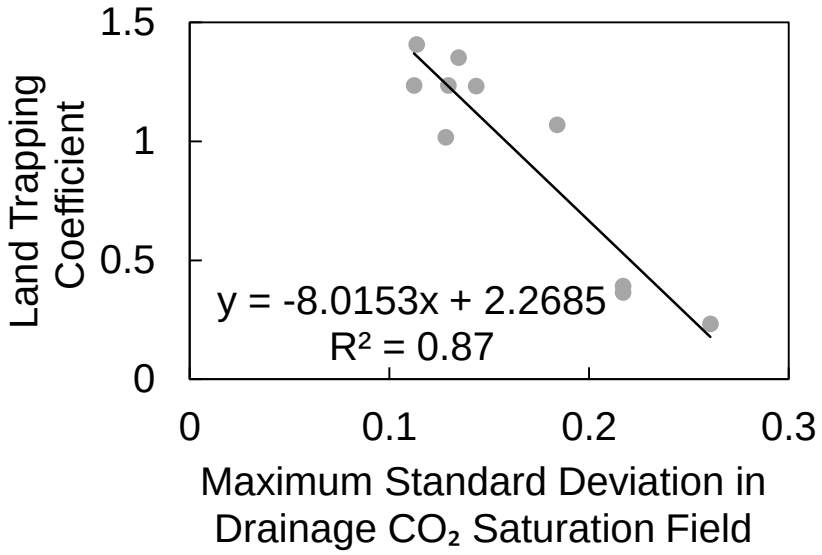
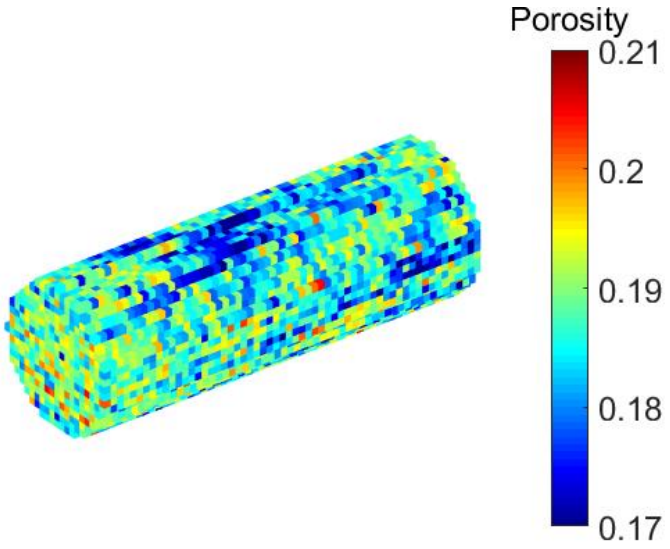




Predictor parameters derived from the porosity field

- **Porosity**
- Correlation length in porosity field in x, y, and z direction
- Coefficient of variation in porosity field



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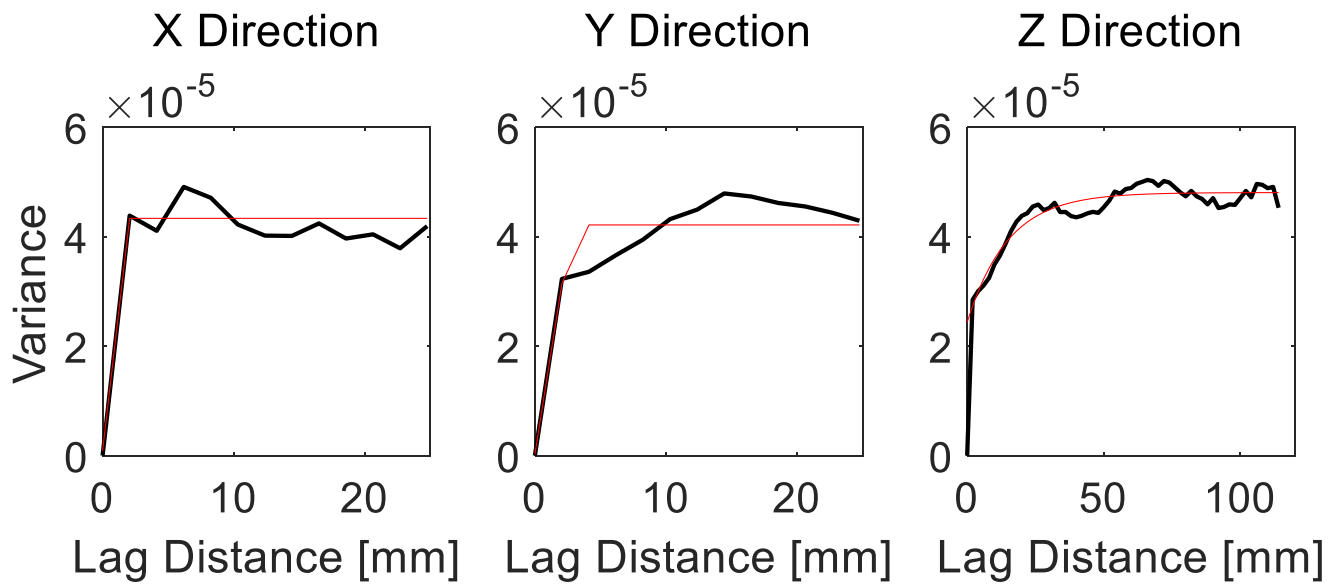

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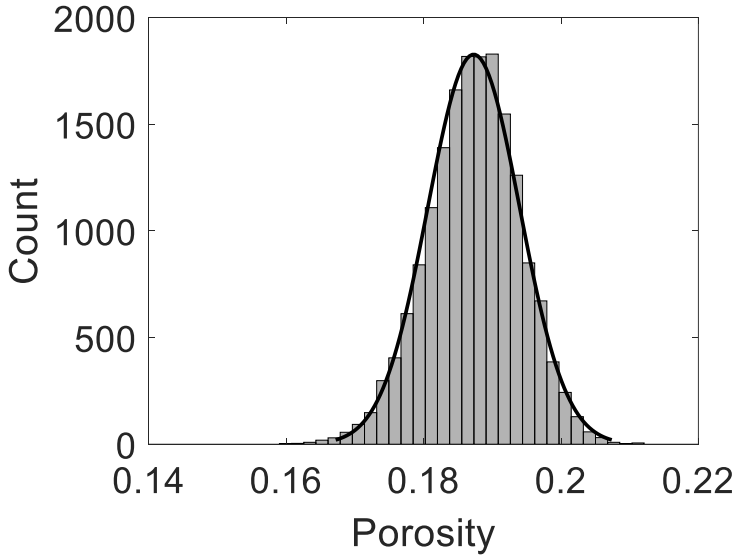
$$C_V = \frac{std(\phi)}{mean(\phi)}$$



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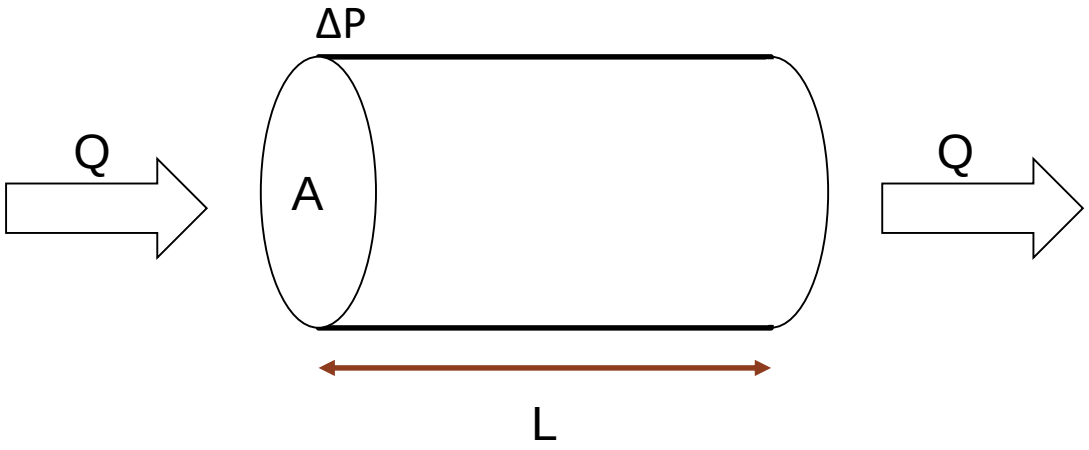

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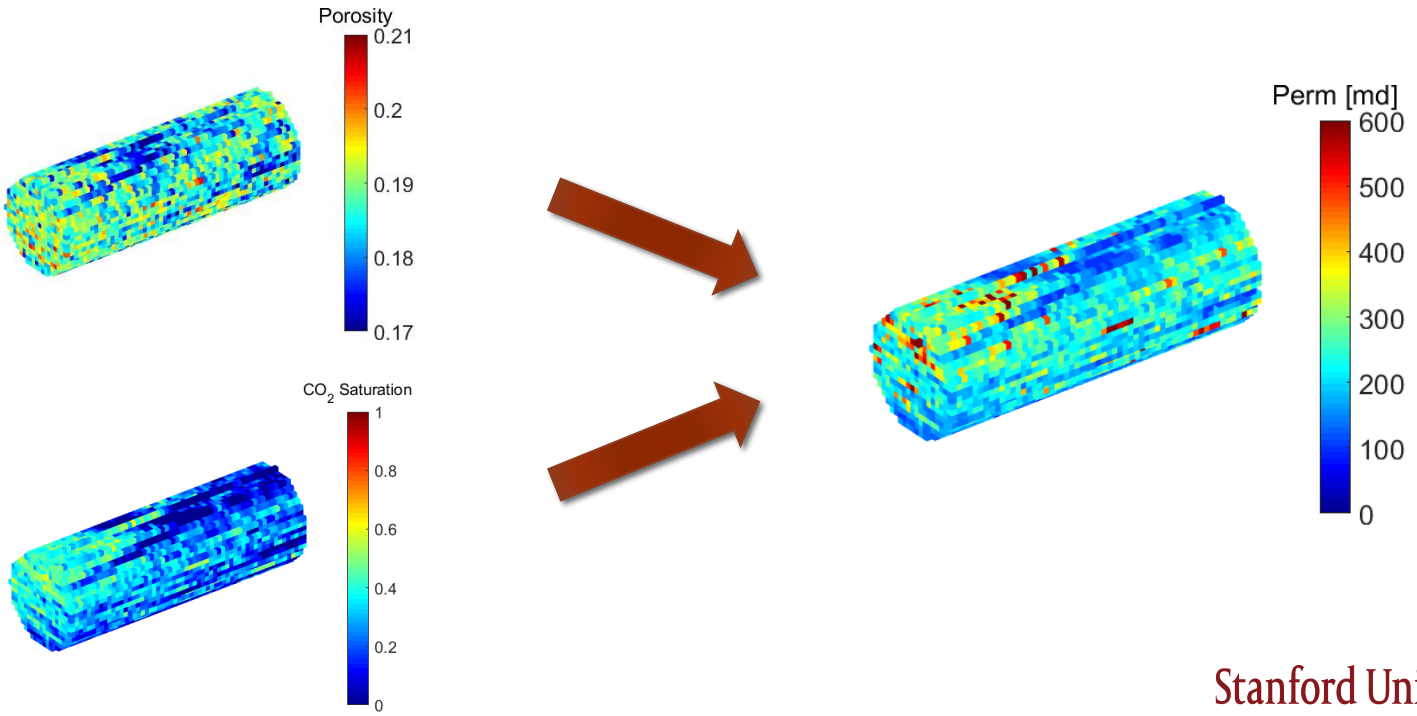

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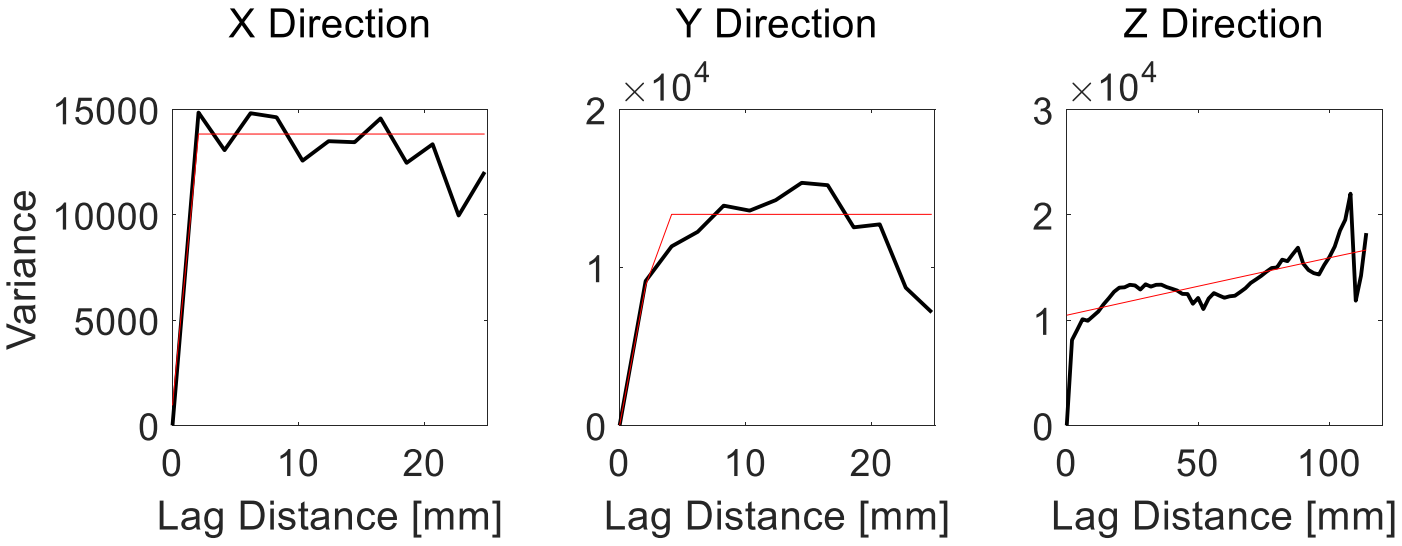

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$$C_V = \frac{std(\ln(k))}{mean(\ln(k))}$$

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$$C_V = \frac{std(\ln(k))}{mean(\ln(k))}$$

$$V_{DP} = \frac{k_{P50} - k_{P16}}{k_{P50}}$$

(Dykstra and Parsons, 1950)

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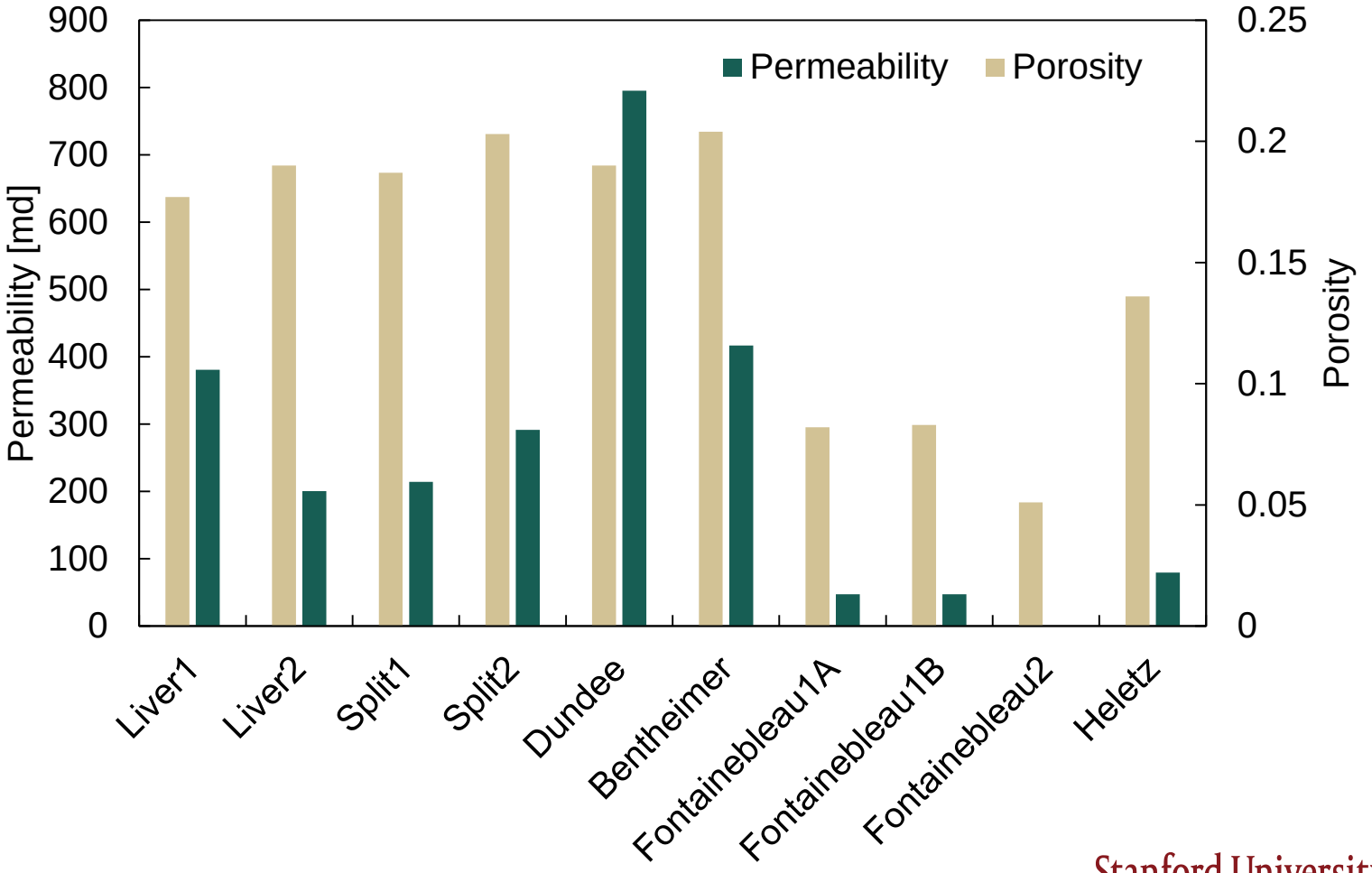
(Dykstra and Parsons, 1950)

$$\eta = \frac{std\left(\sqrt{\frac{\phi}{k}}\right)}{mean\left(\sqrt{\frac{\phi}{k}}\right)}$$

(Li and Benson, 2015)

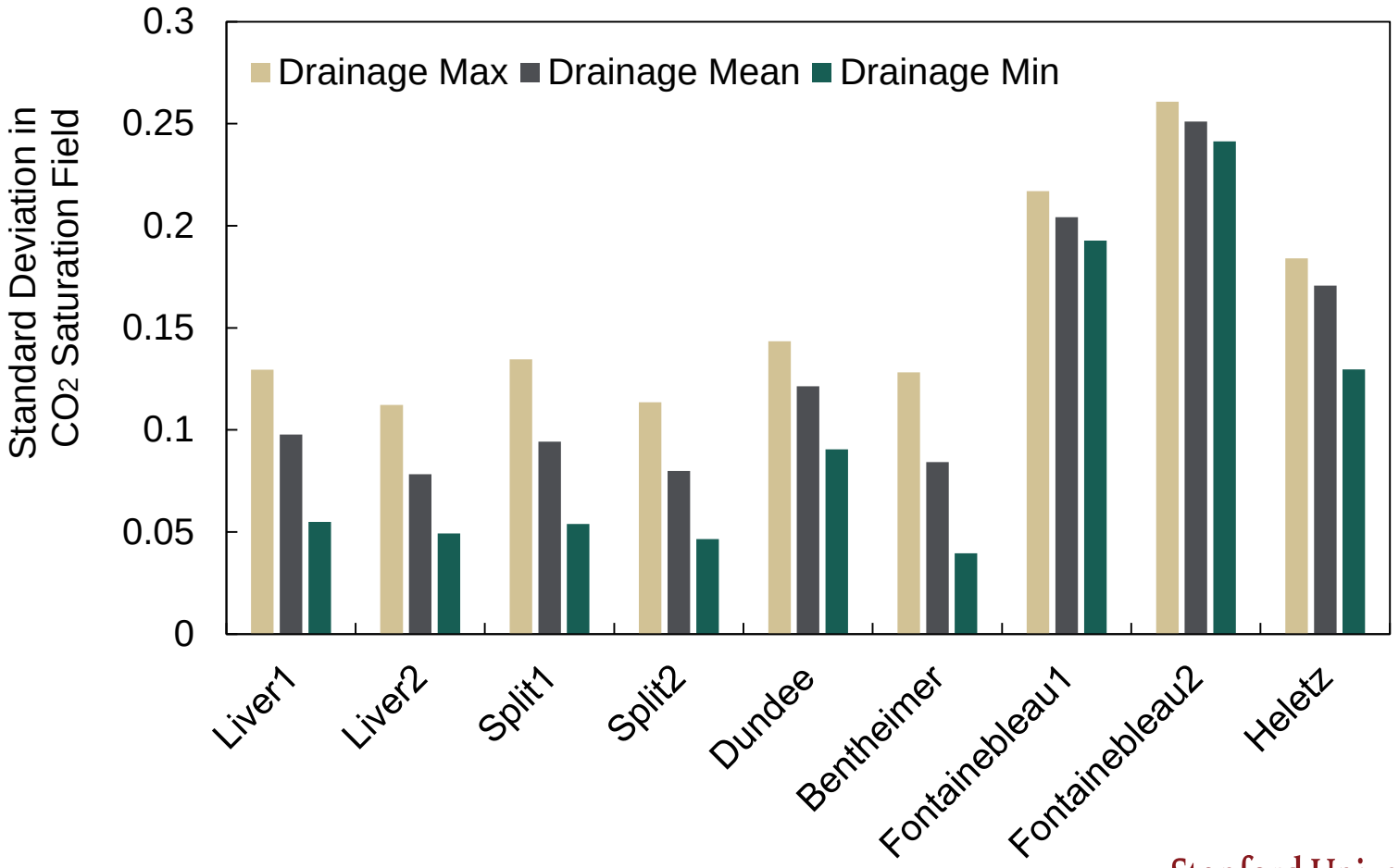
CO_2 residual trapping ability correlation analysis results

Porosity and permeability



CO_2 residual trapping ability correlation analysis results

CO_2 saturation



CO_2 residual trapping ability correlation analysis results

Degree of heterogeneity parameters