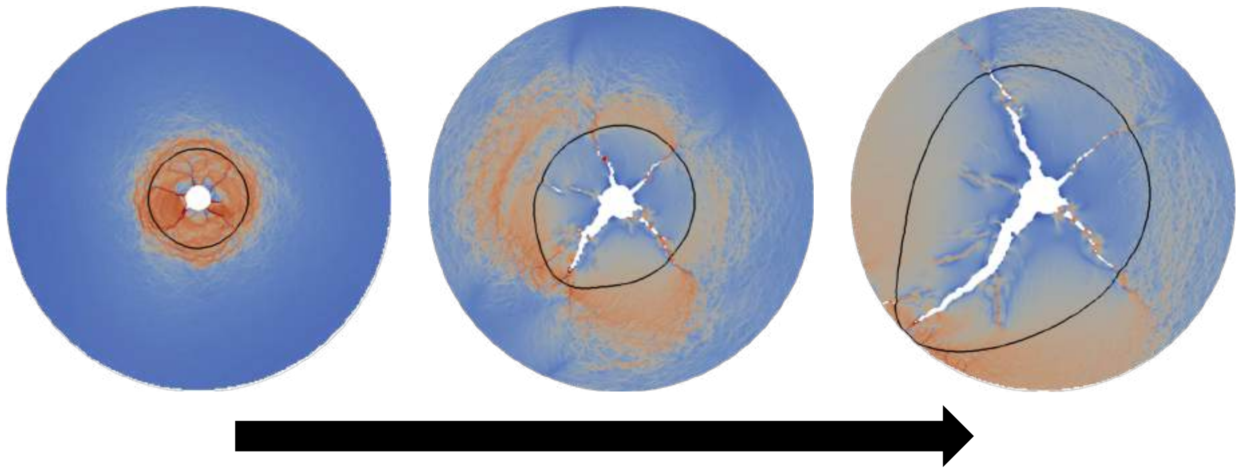
Modeling the Hydrology and Mechanics of Deformable Porous Media



Francisco J. Carrillo

FPO 2021

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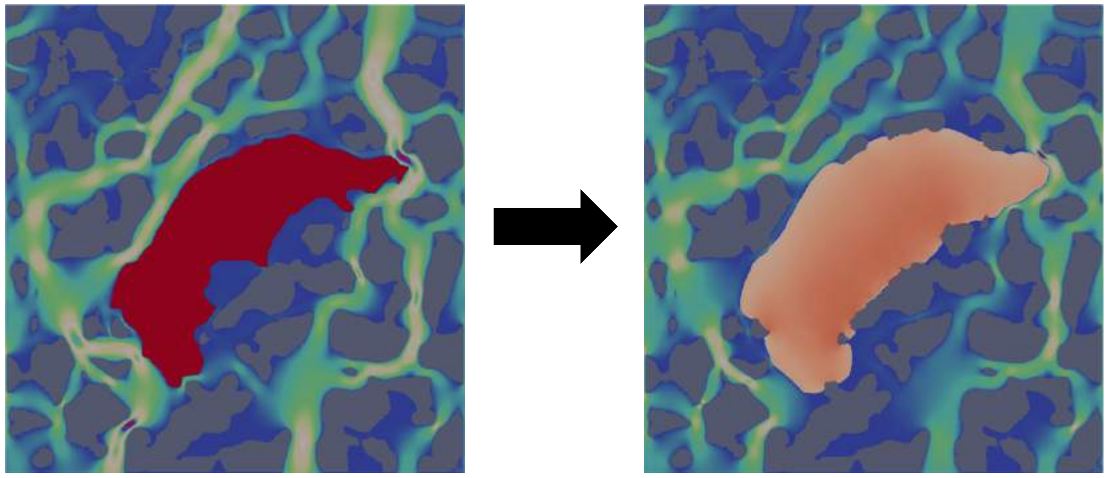
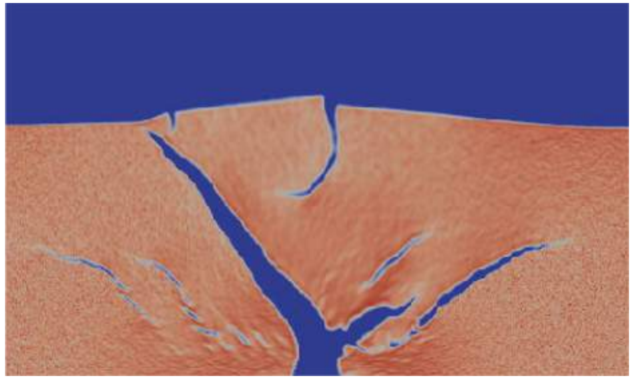
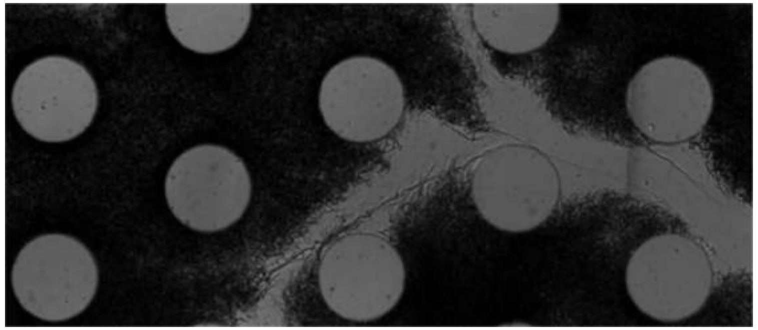


How is Fluid Flow Affected by Porous Media Dynamics and Vice Versa?

Cracking

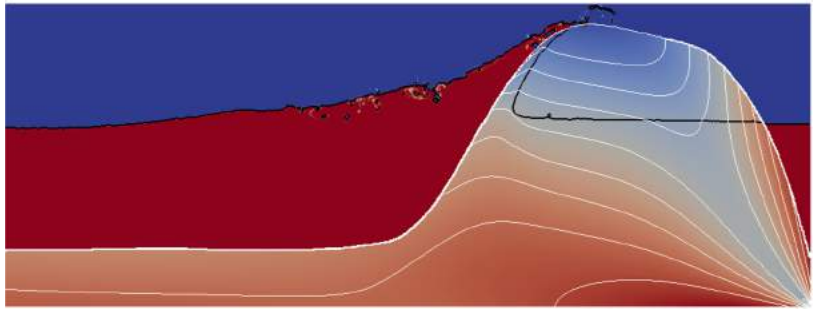


Bio-Fracturing

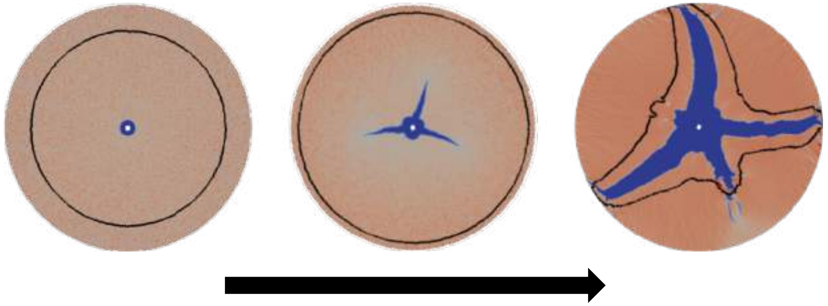


Provided by Dorothee Kurz

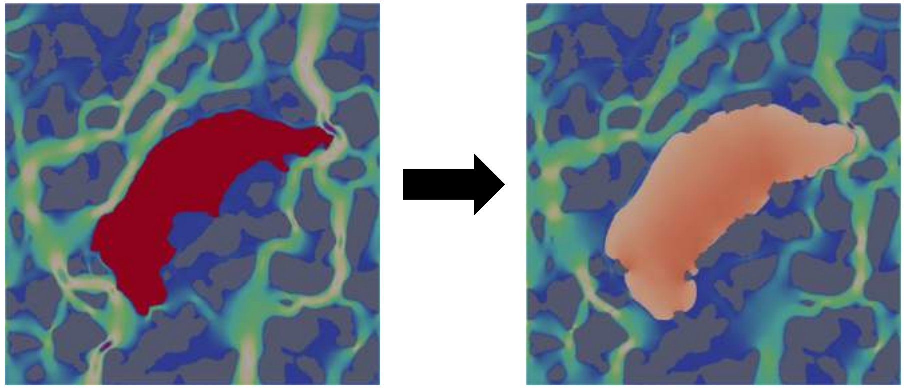
Coastal Barriers



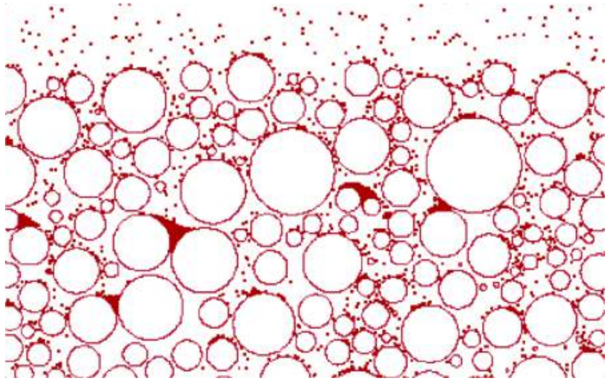
Fracturing



Clay Swelling

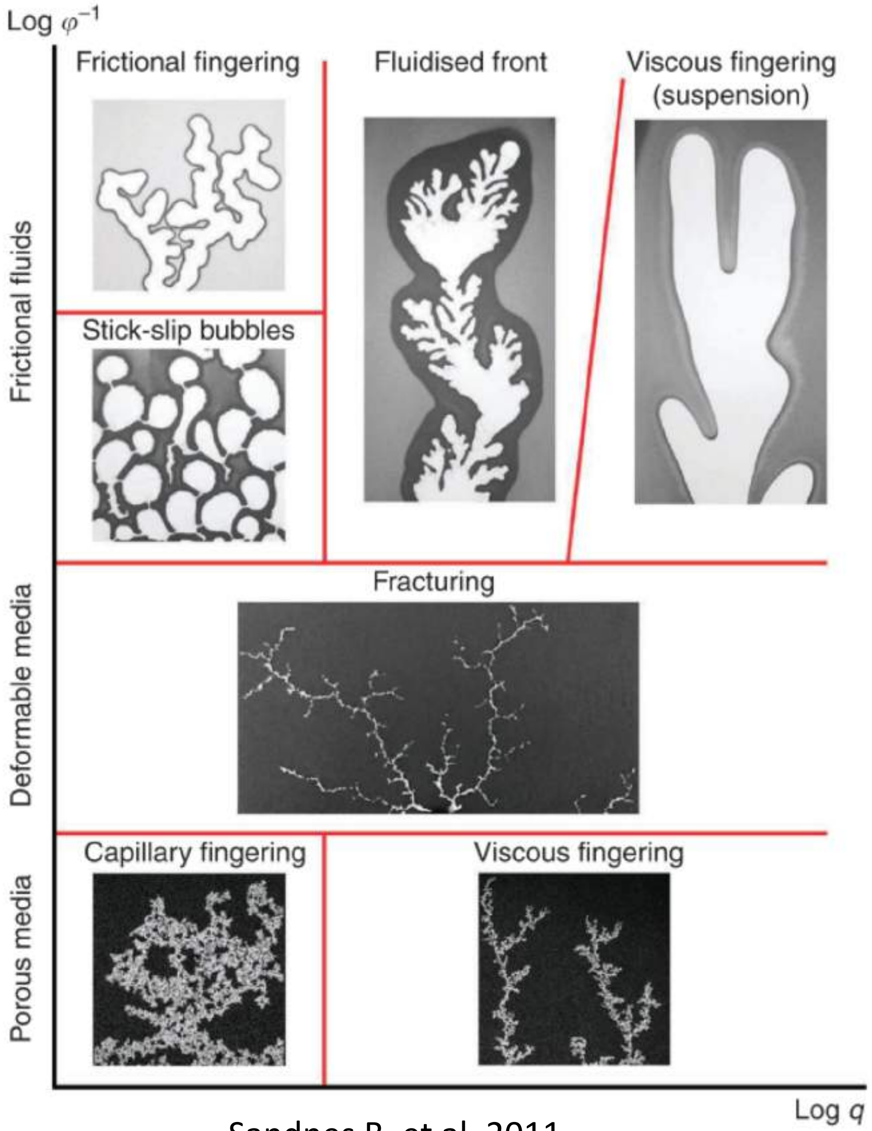


Clogging

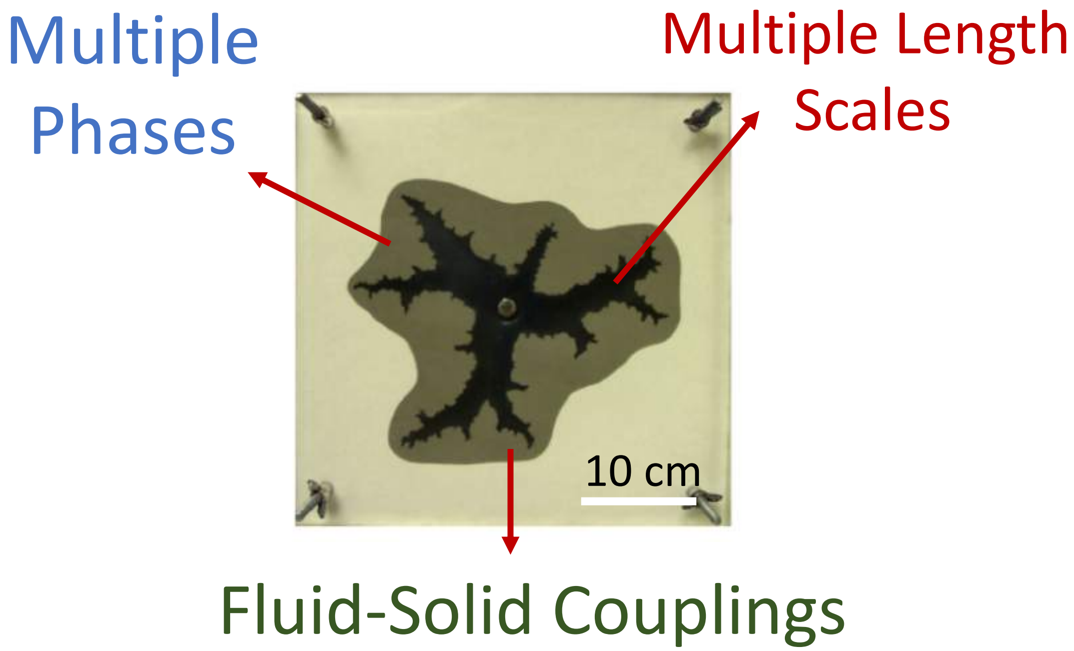


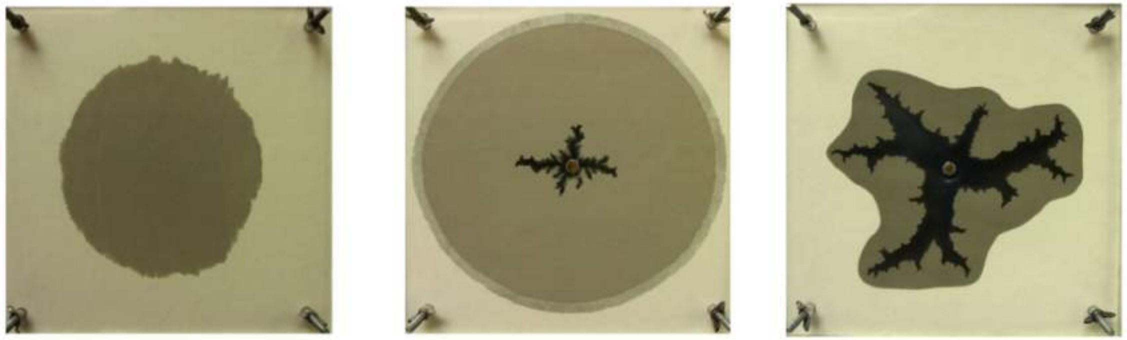
Aksu. et al. 2015

Modeling Deformable Porous Media



Sandnes B. et al. 2011





Zhang F. et al. 2013;

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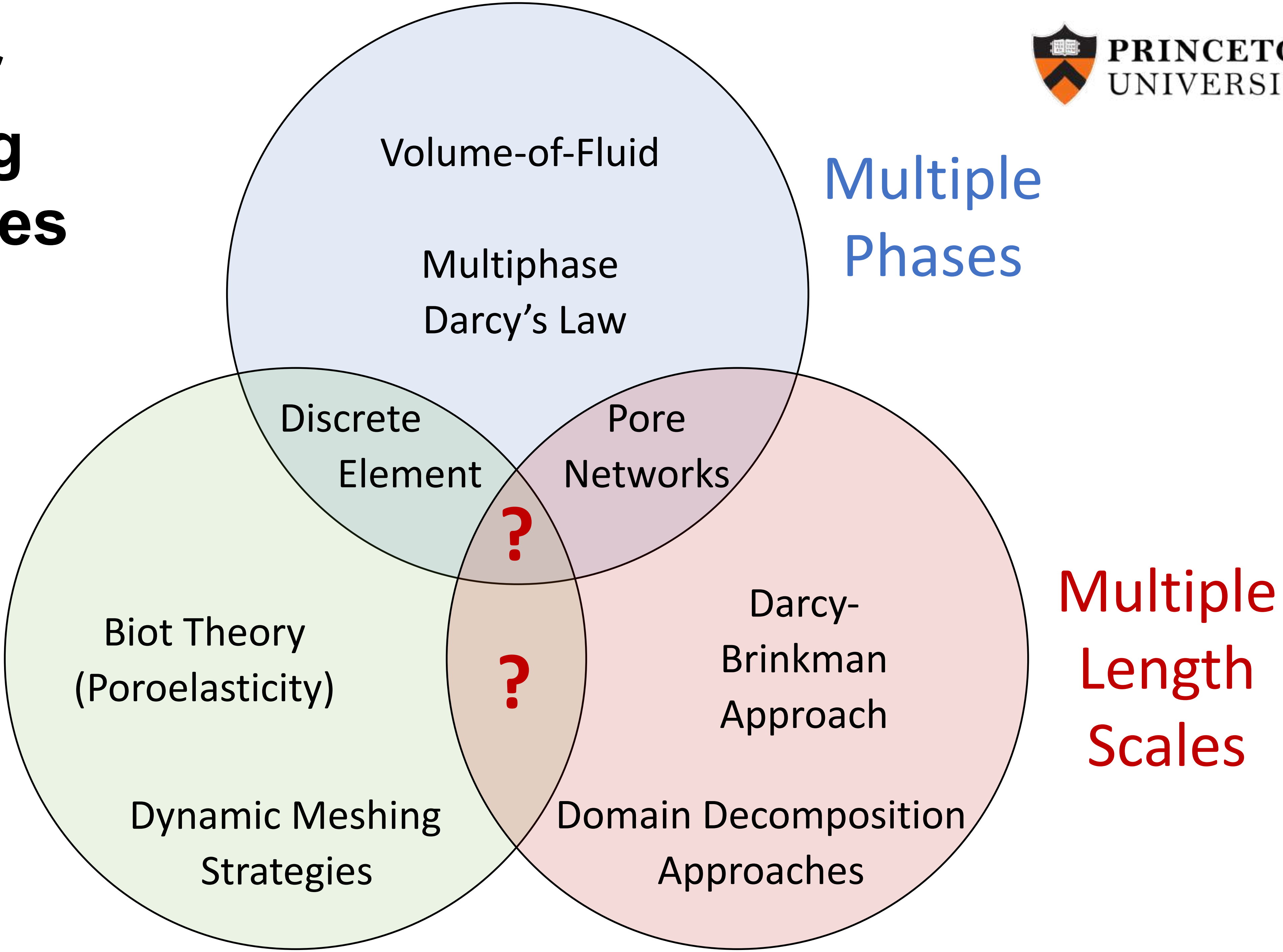
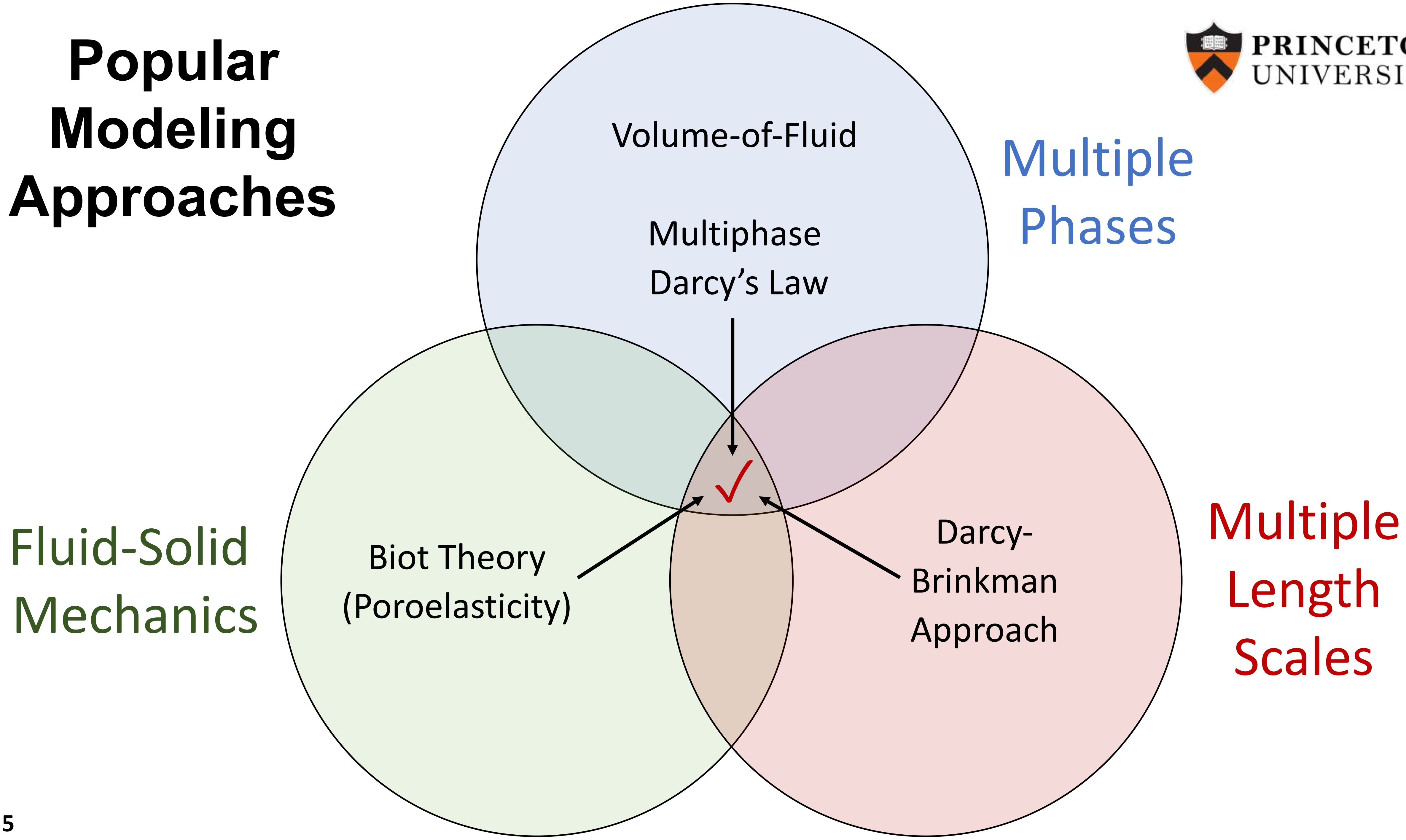
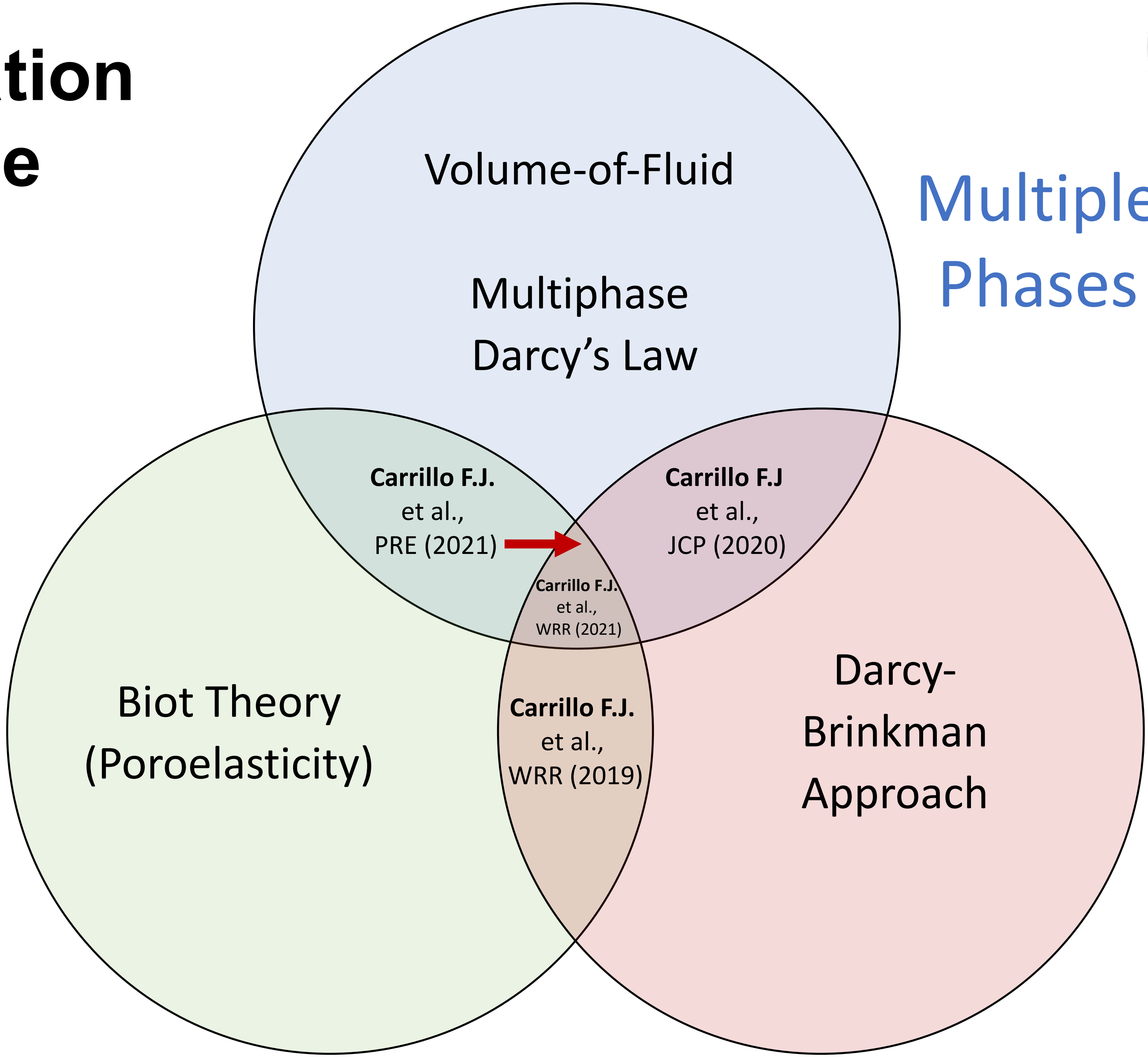
Popular Modeling Approaches



Popular Modeling Approaches



Presentation Outline



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Part 1:
Static Solids

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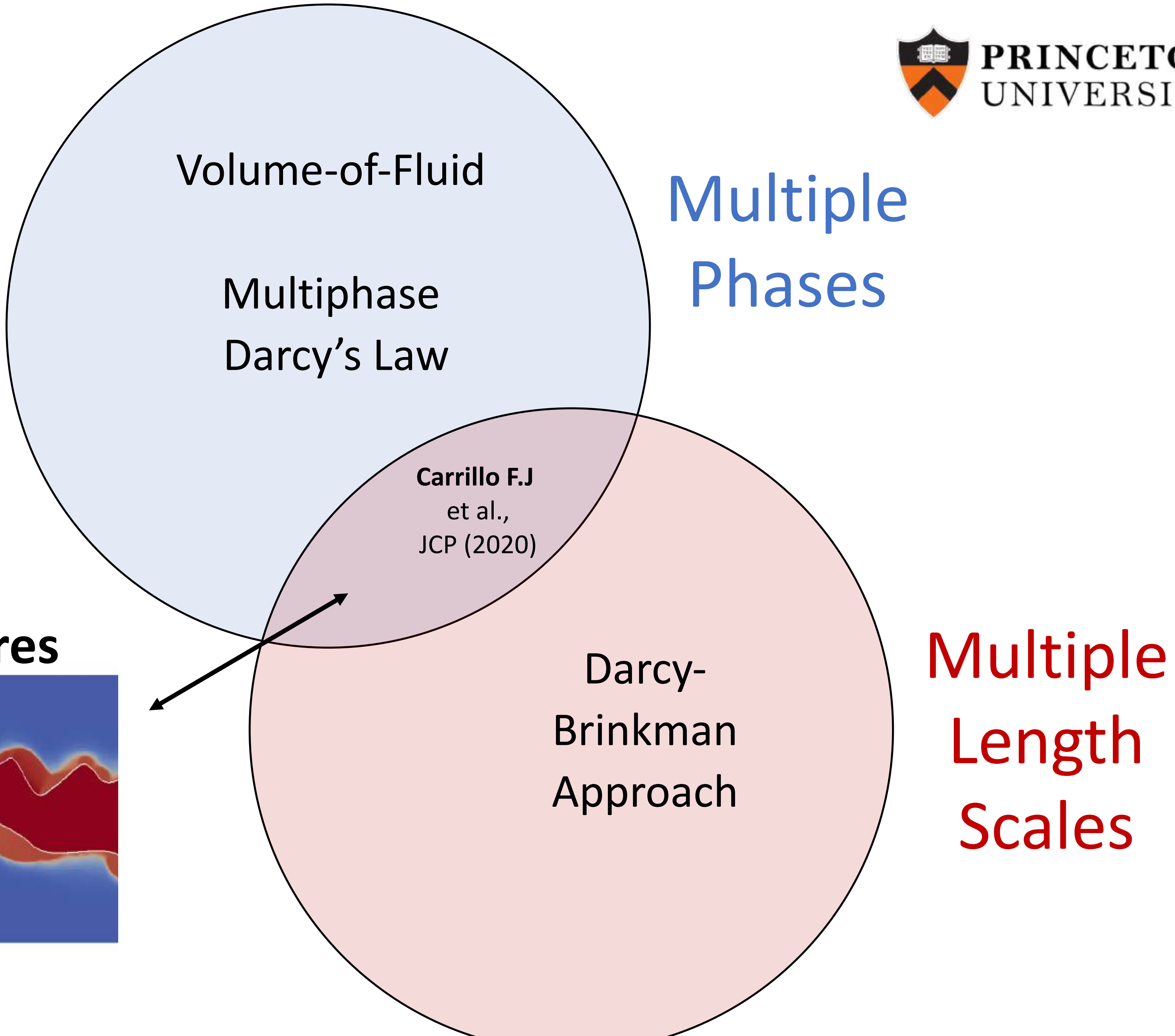
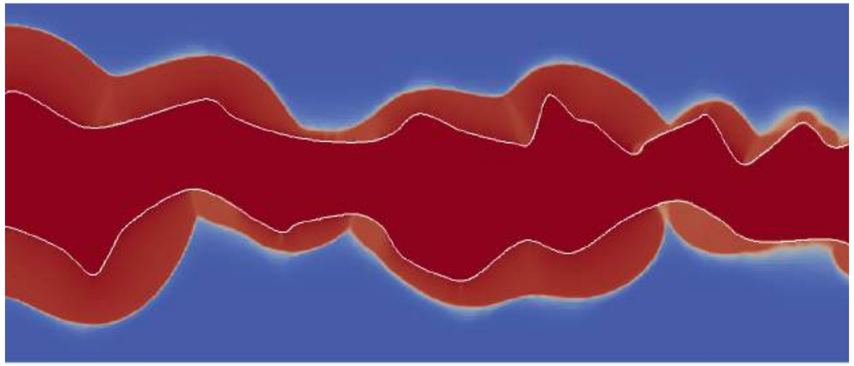
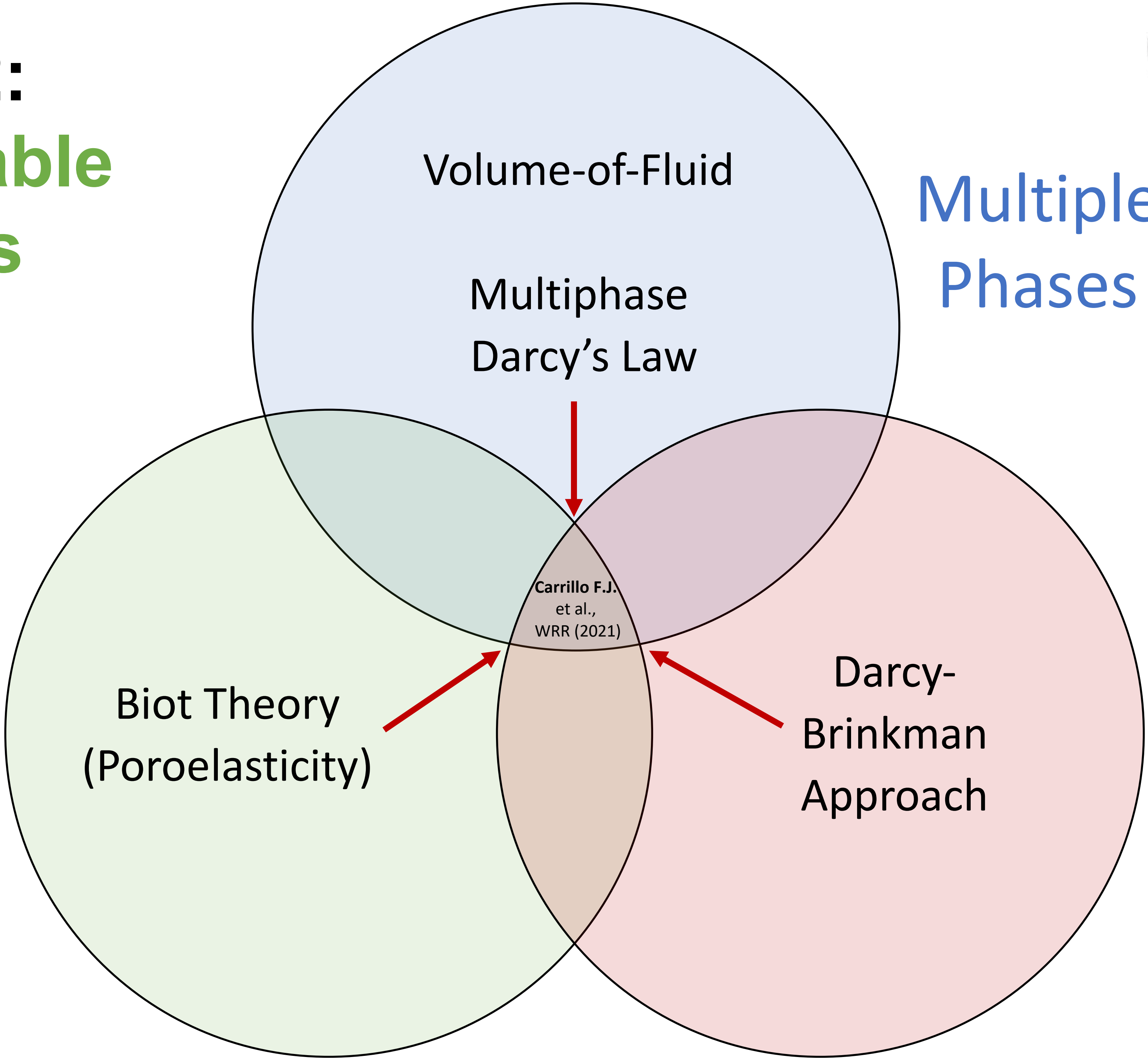


Flow in Microfractures



Part 2:
Deformable Solids



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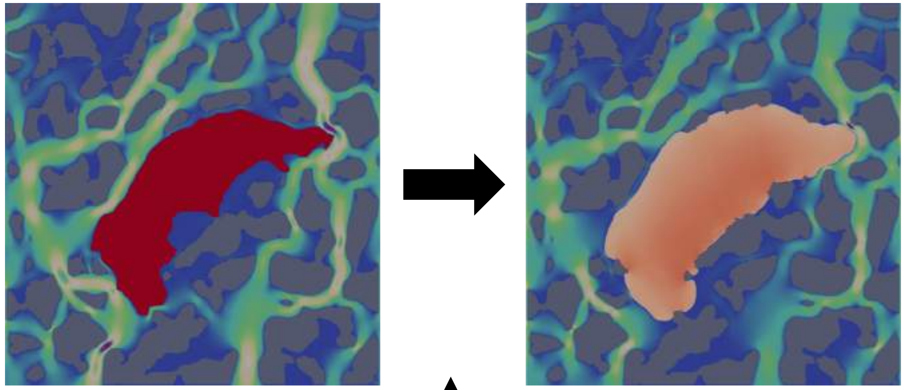
Part 3:
Clay Swelling



Fluid-Solid Mechanics

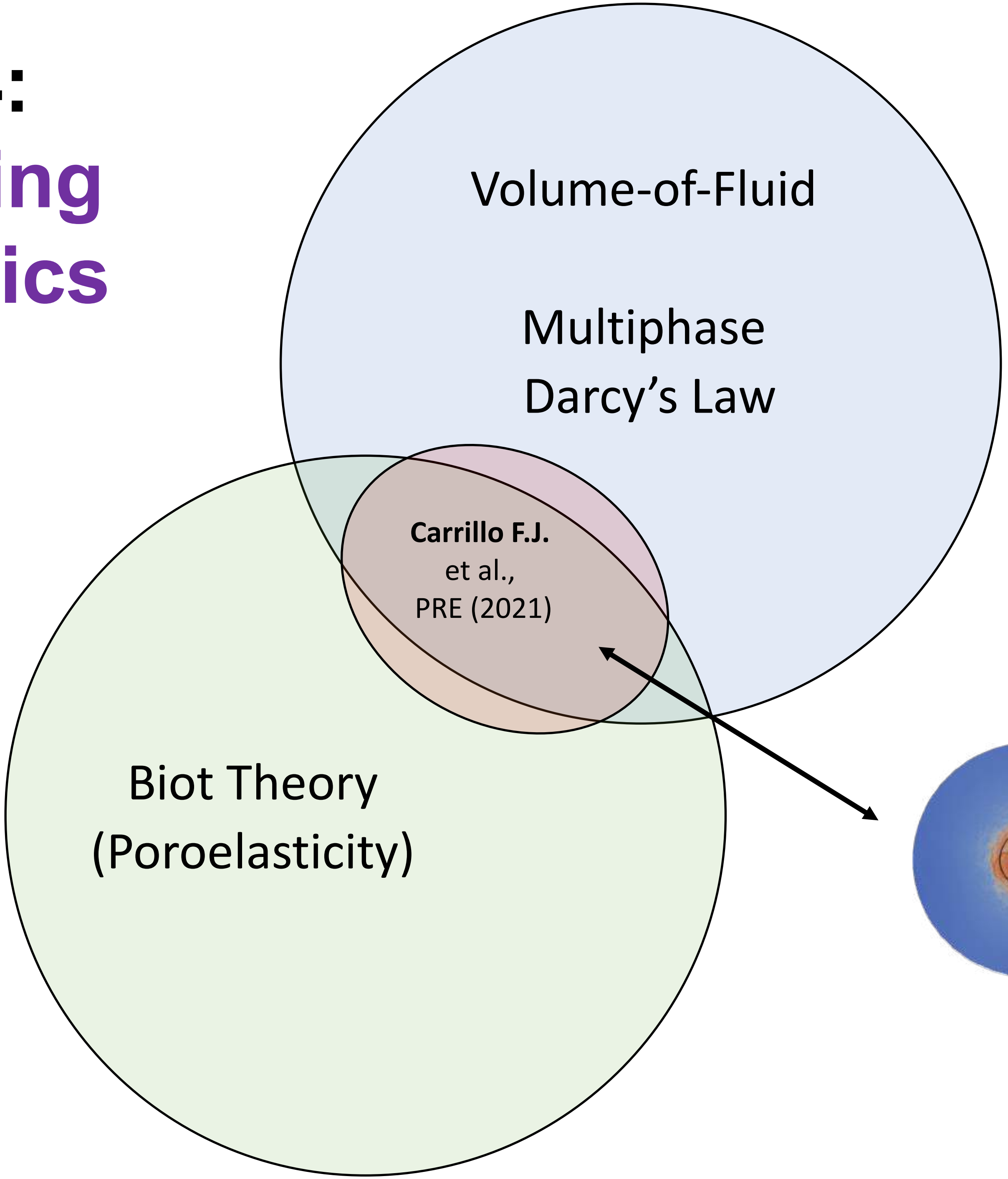
Biot Theory (Poroelasticity)

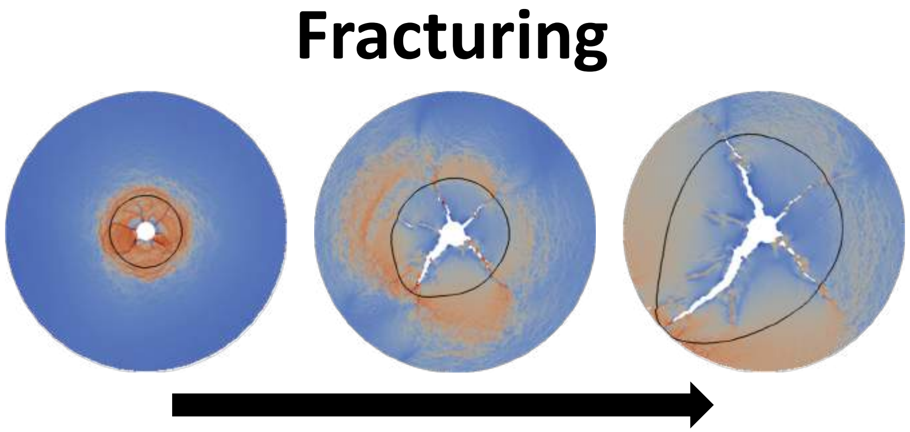
Carrillo F.J. et al., WRR (2019)

Darcy-Brinkman Approach

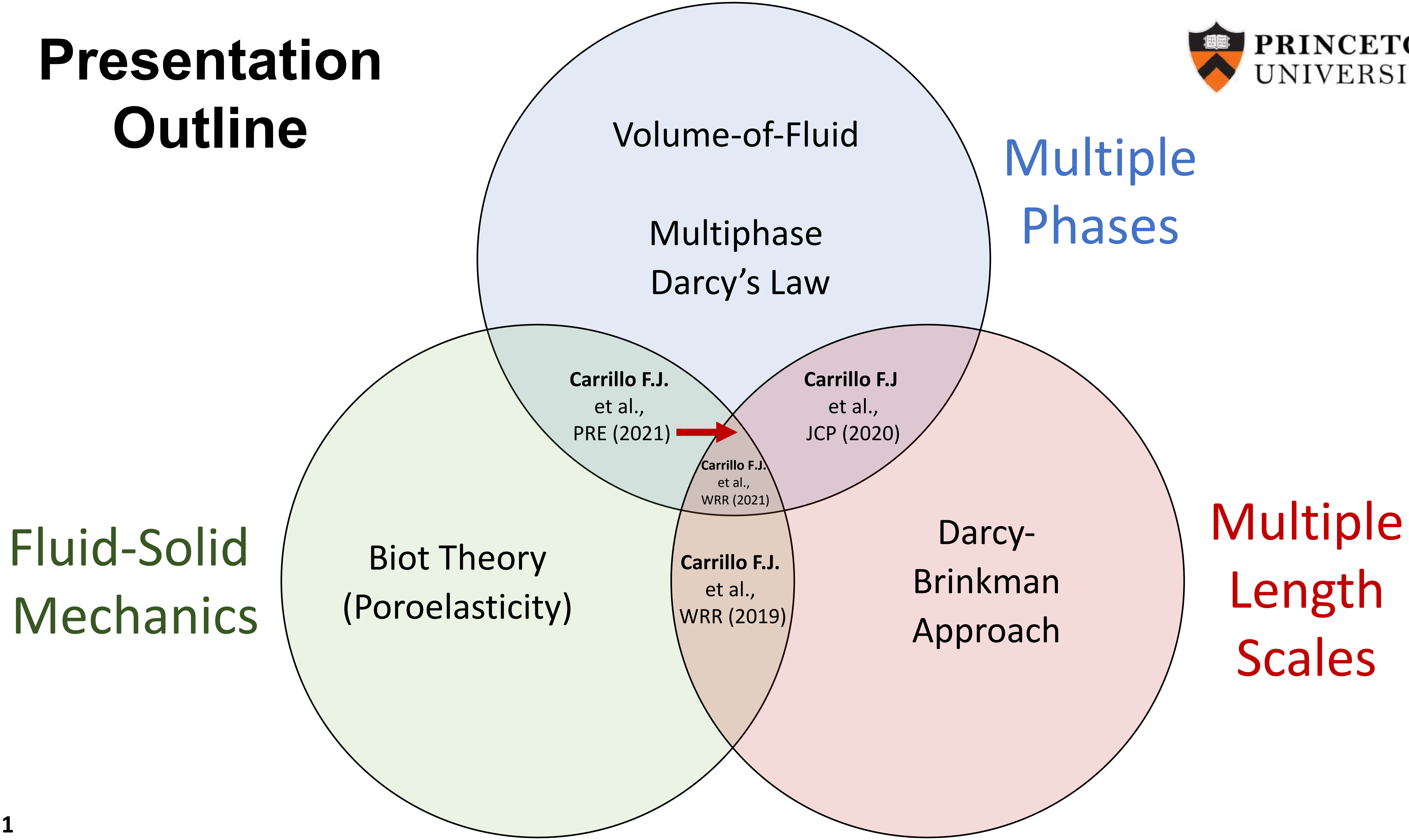
Multiple Length Scales

Part 4: Fracturing Mechanics





Presentation Outline



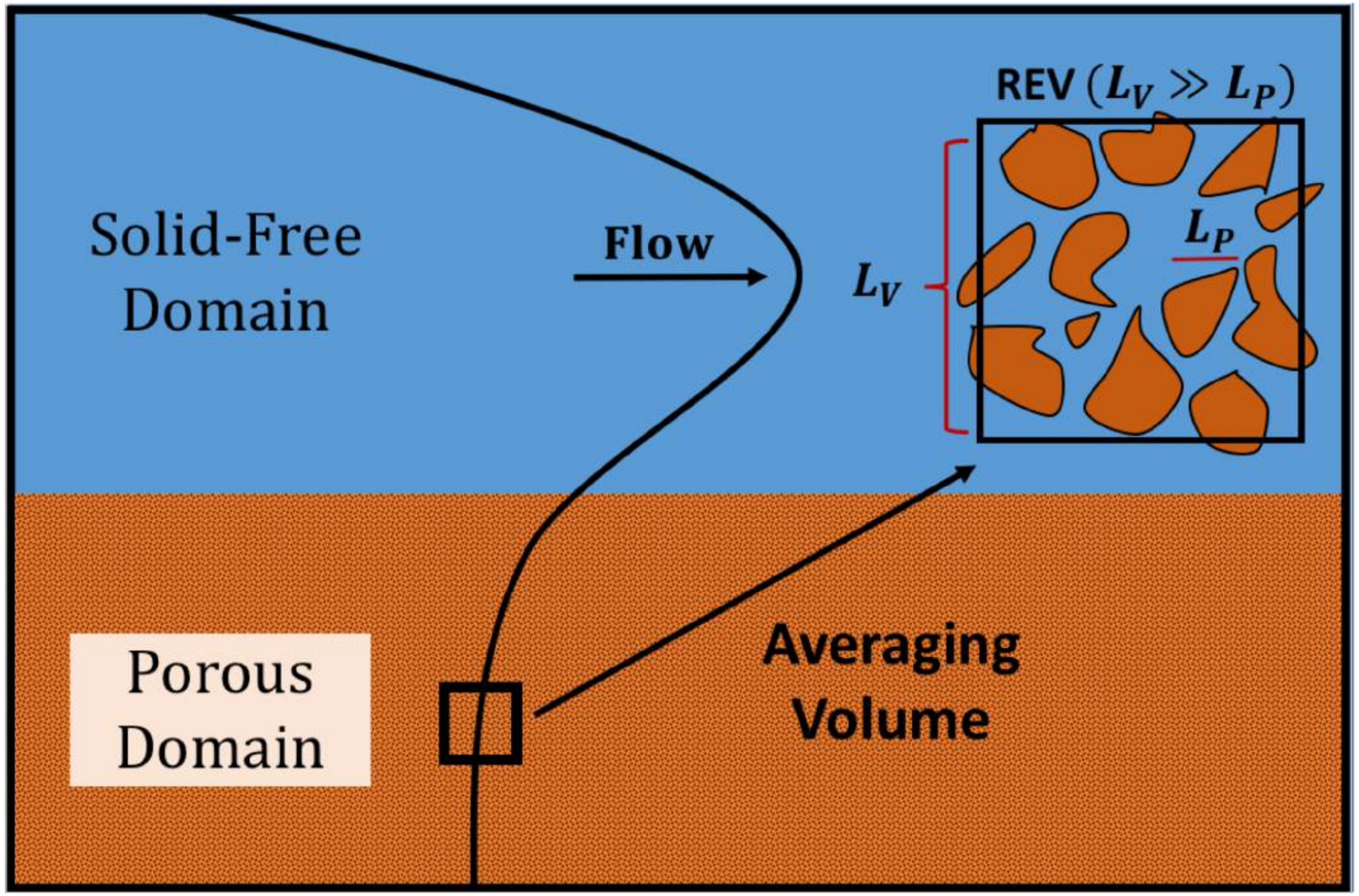
The Darcy-Brinkman Model

Navier-Stokes

$$\frac{D(\rho U)}{Dt} = -\nabla p + \nabla \cdot \tau + \rho g$$

Darcy's Law

$$\nabla p = -\frac{\mu_f}{k} U$$

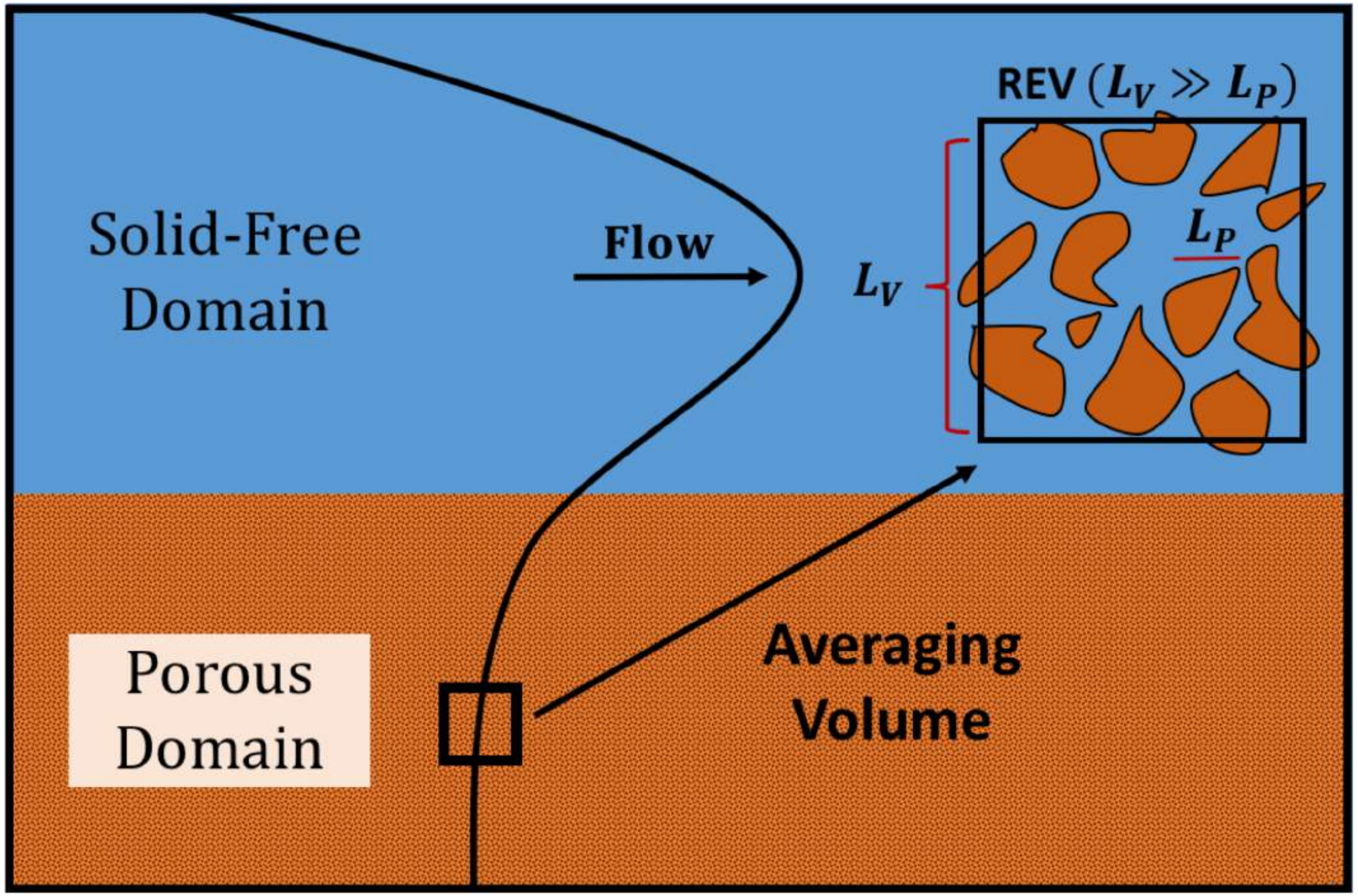


Brinkman, H. (1947)
Whitaker (1985, 1999)

The Darcy-Brinkman Model

Approximates
Navier-Stokes

Approximates
Darcy's Law



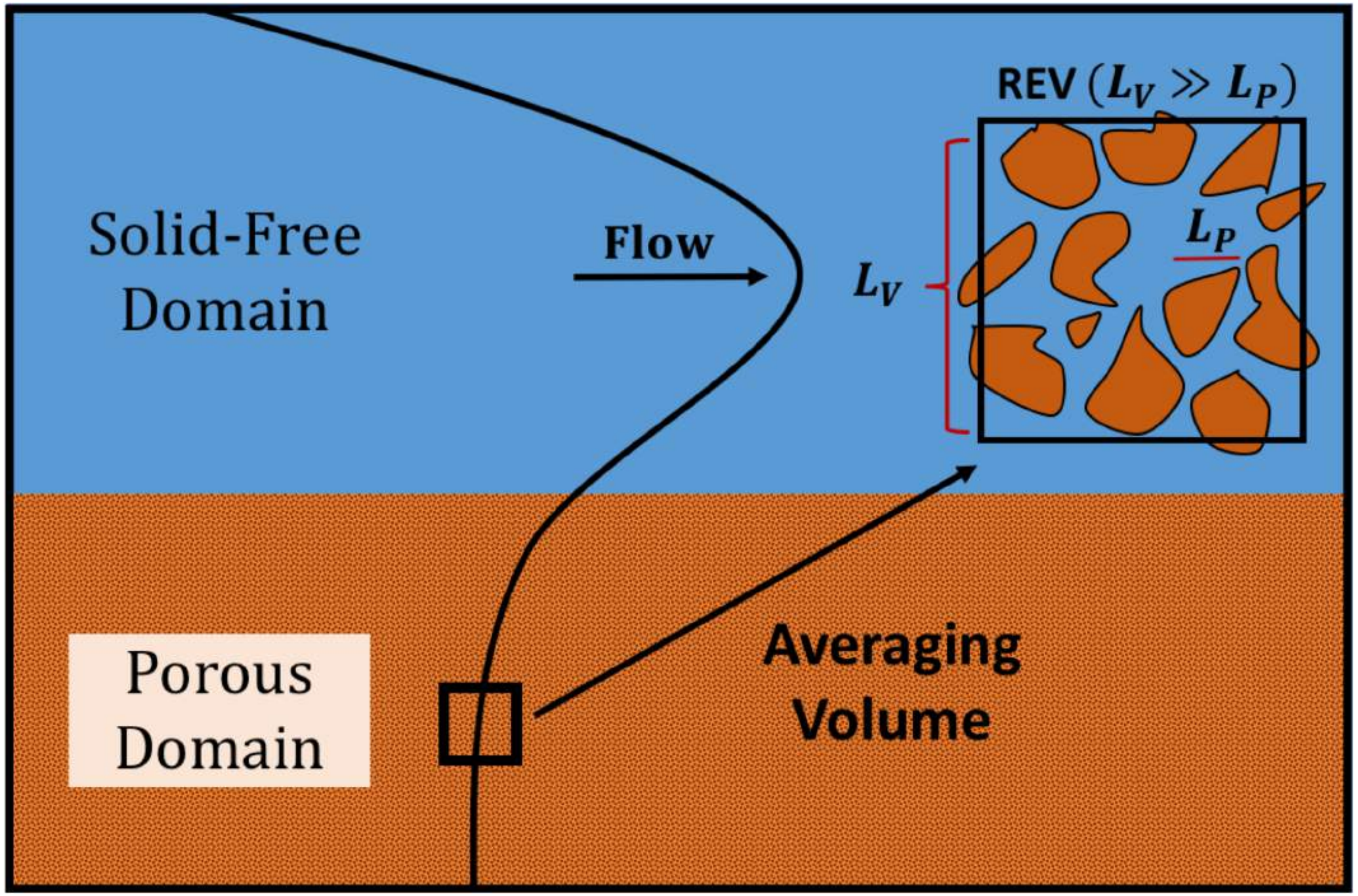
$$\frac{1}{REV}\int\left(\frac{D(\rho U)}{Dt} = -\nabla p + \nabla\cdot\tau + \rho g\right) dREV$$

Brinkman, H. (1947)
Whitaker (1985, 1999)

The Darcy-Brinkman Model

Approximates
Navier-Stokes

Approximates
Darcy's Law



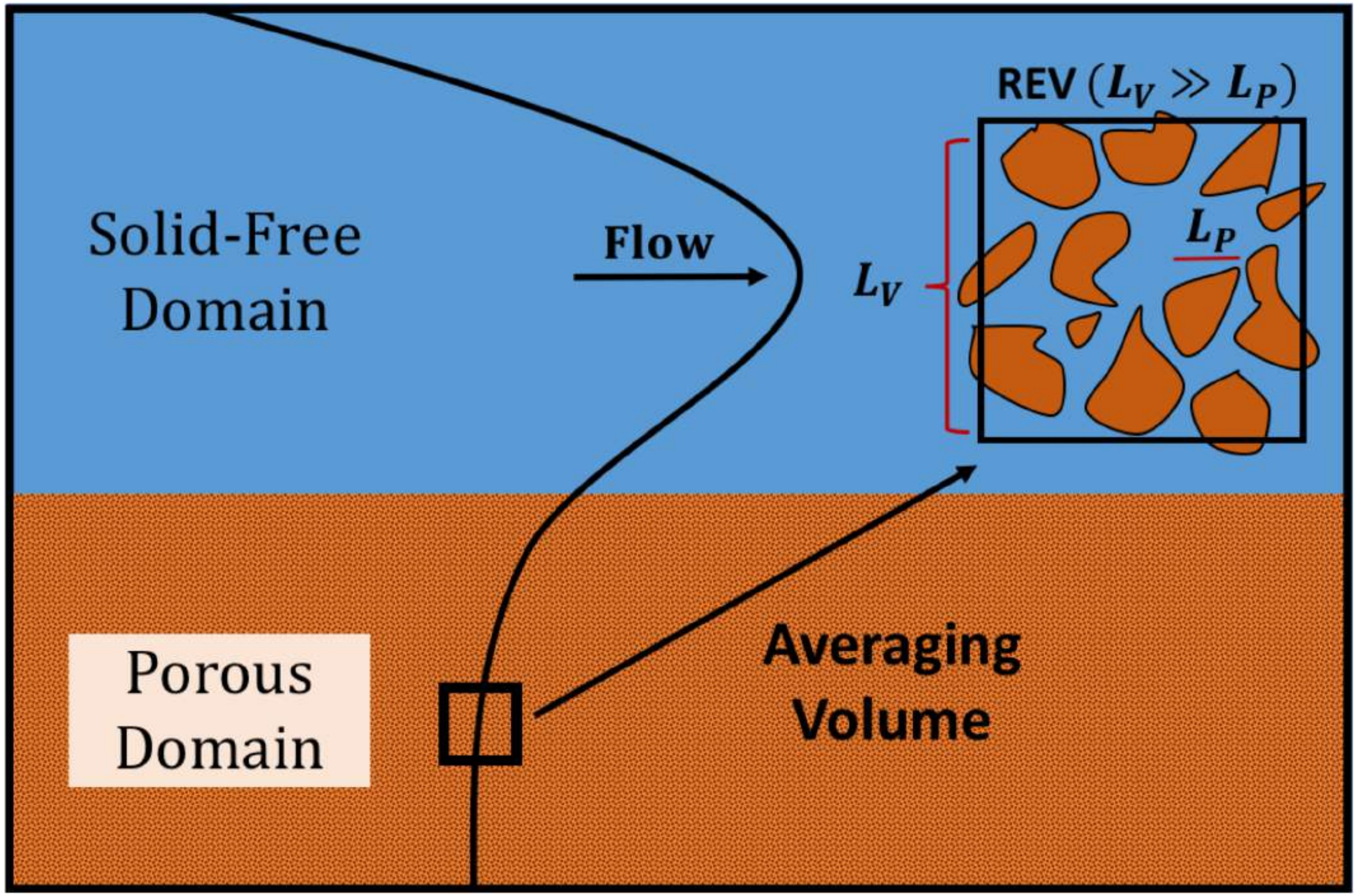
$$\frac{\overline{\mathrm{D}(\rho U)}}{Dt} = -\overline{\nabla p} + \overline{\nabla \cdot \tau} + \overline{\rho g} + \color{red}{Filter}$$

Brinkman, H. (1947)
Whitaker (1985, 1999)

The Darcy-Brinkman Model

Approximates
Navier-Stokes

Approximates
Darcy's Law



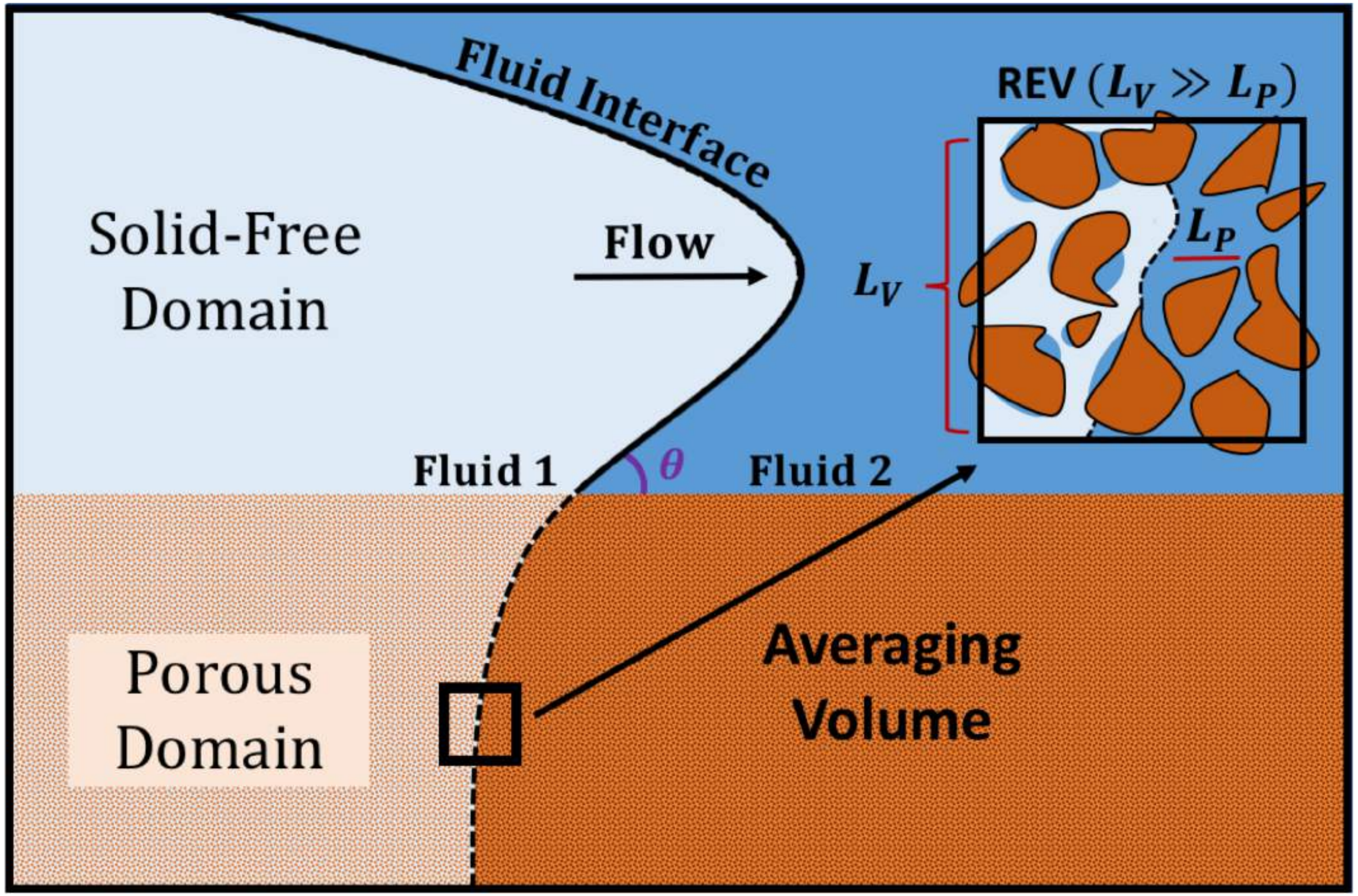
$$\overline{\frac{D(\rho U)}{Dt}} = -\overline{\nabla p} + \overline{\nabla \cdot \tau} + \overline{\rho g} - \phi_f \frac{\mu_f}{k} U$$

Neale & Nader (1974)
Brinkman, H. (1947)
Whitaker (1985, 1999)

The Extended Darcy-Brinkman Model

Approximates **Navier-Stokes**

Approximates **Multiphase Darcy's Law**



$$\frac{D(\rho_f U_f)}{Dt} = -\phi_f \nabla \bar{p} + \nabla \cdot \bar{\tau} + \phi_f \rho_f g + F_{Drag} + \phi_f F_{Capillary}$$

Carrillo F.J., Bourg I.C., & Soulaine C., *JCP* (2020)

The Model's Fluid Equations

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Averaged Mass Conservation Equation:

$$\frac{\partial \phi_f}{\partial t} + \nabla \cdot \boldsymbol{U}_f = 0$$

Averaged Saturation Conservation Equation:

$$\frac{\partial \phi_f \alpha_w}{\partial t} + \nabla \cdot \alpha_w \boldsymbol{U}_f + \nabla \cdot \phi_f \alpha_w \alpha_n \boldsymbol{U}_r = 0$$

Averaged Momentum Conservation Equation:

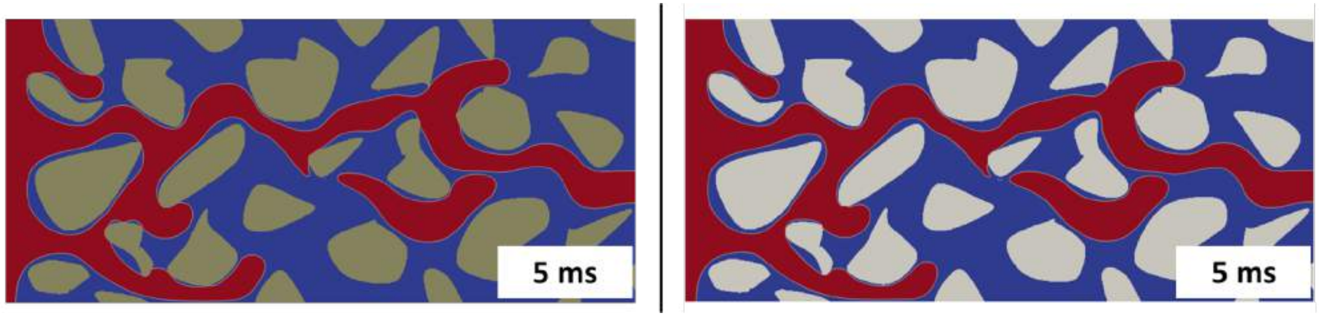
$$0 = -\phi_f \nabla \bar{p} + \phi_f \rho_f \boldsymbol{g} + \nabla \cdot \bar{\boldsymbol{\tau}} + \boldsymbol{F}_{Drag} + \phi_f \boldsymbol{F}_{c,1} + \phi_f \boldsymbol{F}_{c,2}$$

Essentially Volume-of-Fluid + Drag and Capillary Penalization Terms

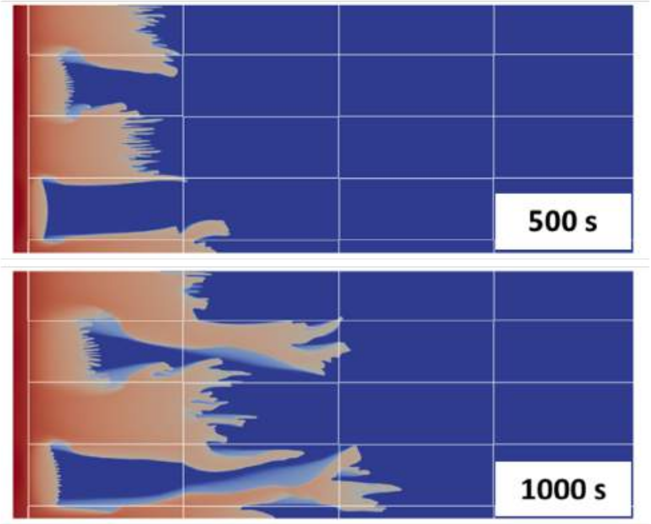
Carrillo F.J., Bourg I.C., & Soulaine C., *JCP* (2020)

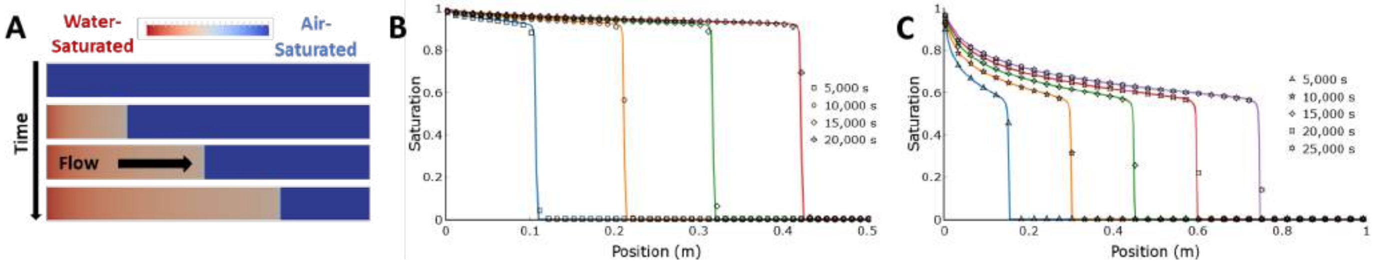
Toolbox: *hybridPorousInterFoam*

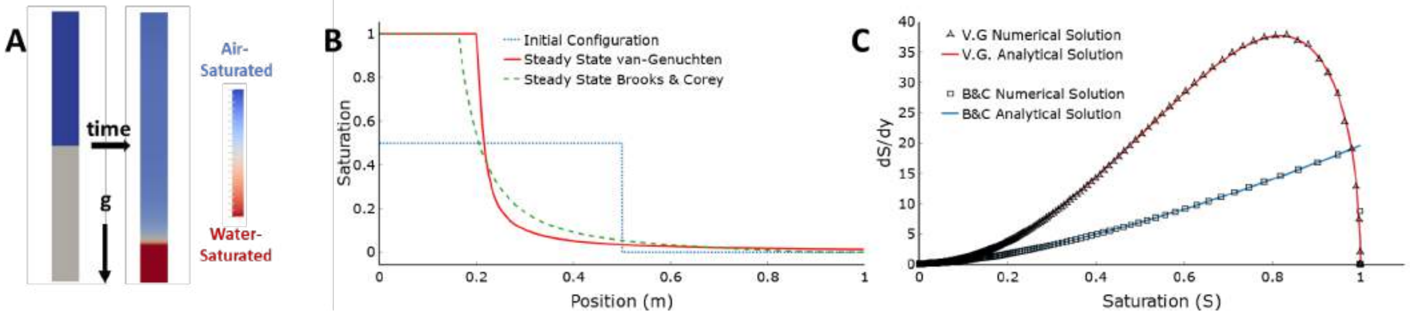
Everything implemented in OpenFoam®

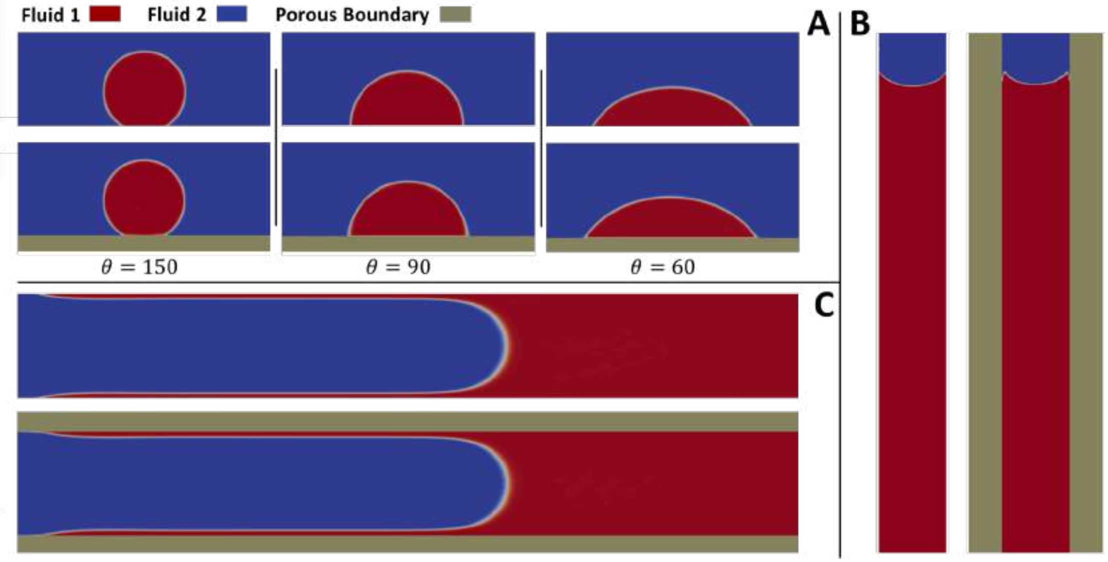


Water Flooding





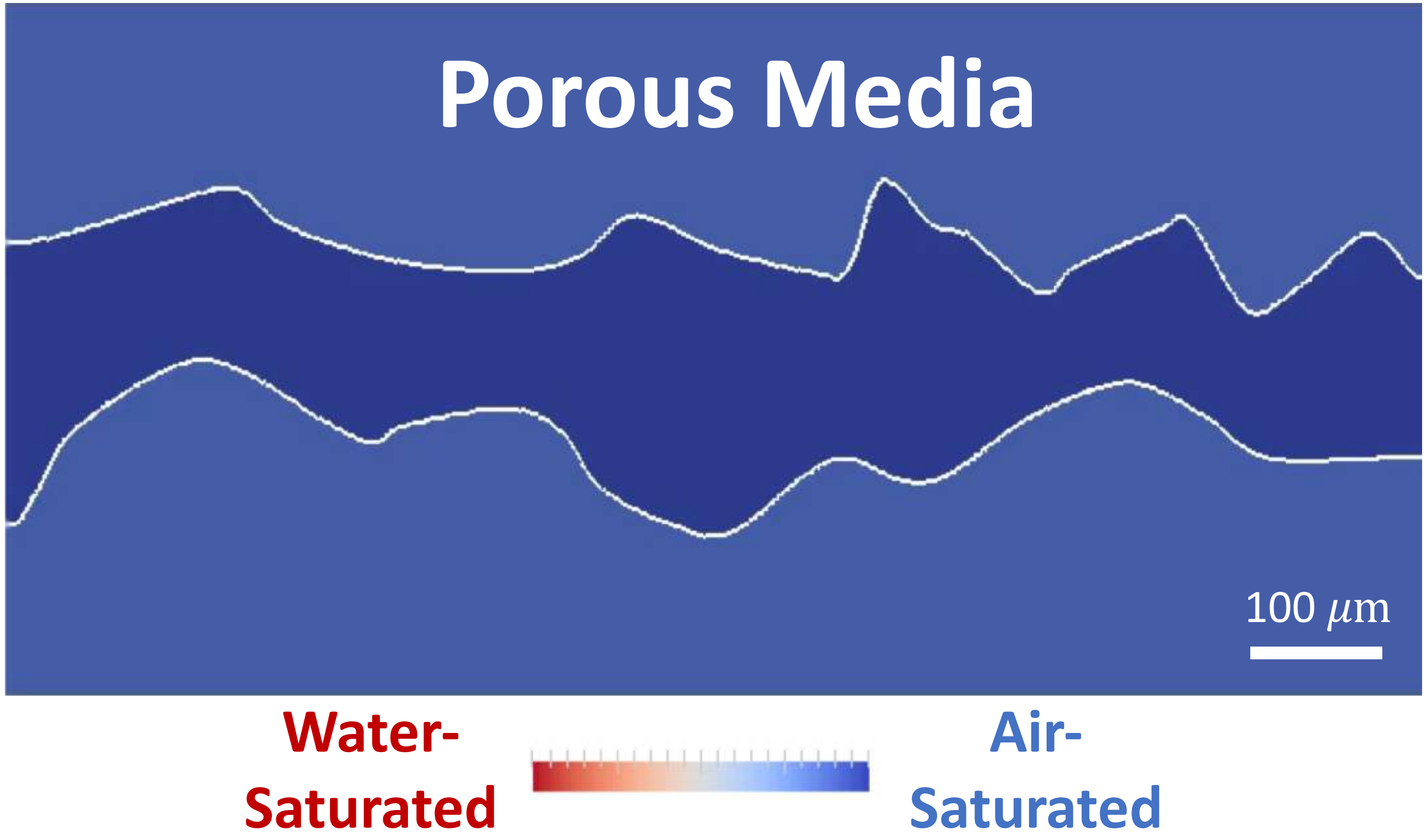




Carrillo F.J., Bourg I.C., & Soulaine C., *JCP* (2020)

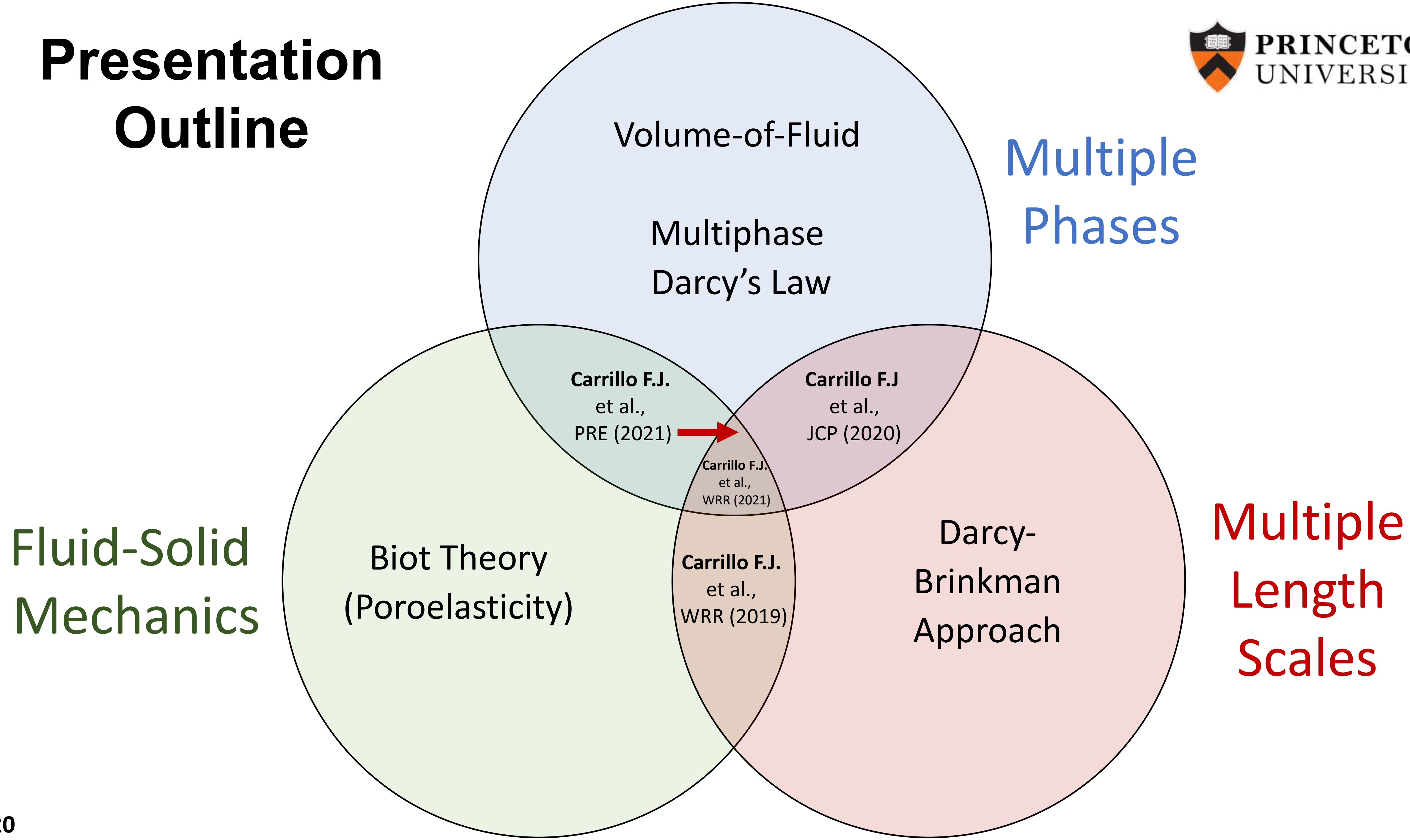
Conceptual Application:
Imbibition in Microfractures

Fracture Inlet

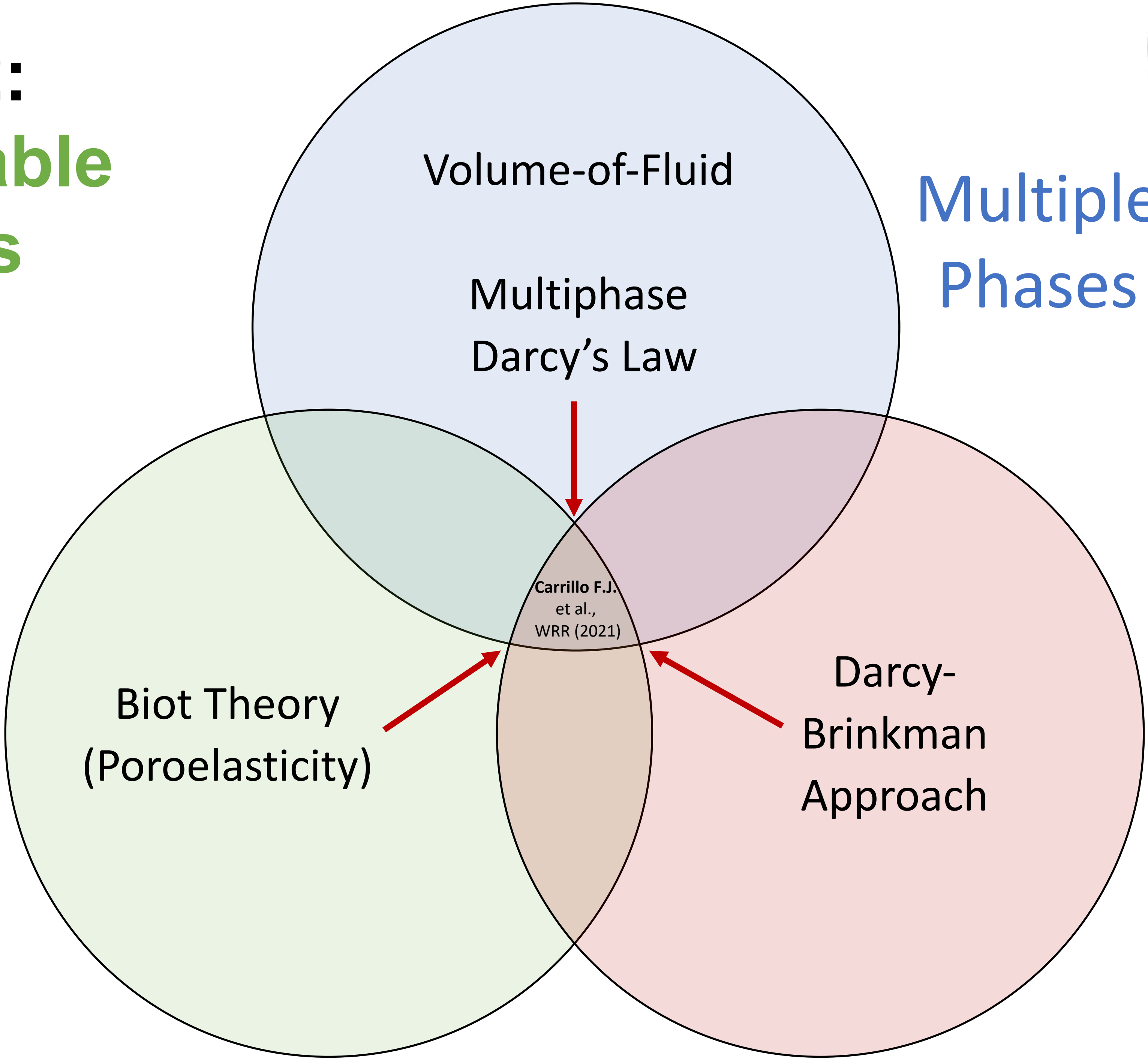


Carrillo F.J., Bourg I.C., & Soulaine C., *JCP* (2020)

Presentation Outline



Part 2:
Deformable Solids



Multiple Phases

Fluid-Solid Mechanics

Multiple Length Scales

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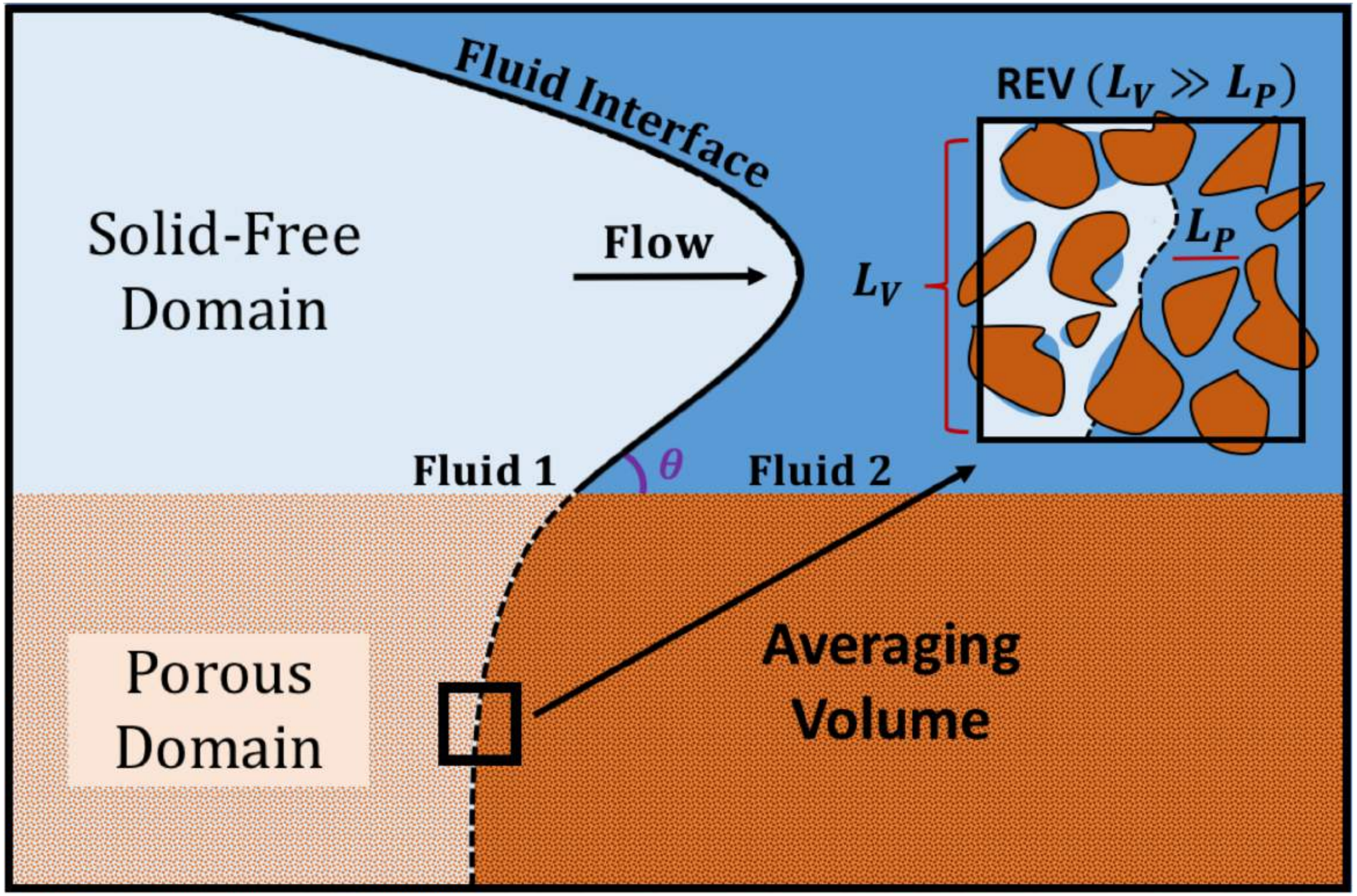
The Extended Darcy-Brinkman Model

Approximates **Navier-Stokes**

Can we make this **move?**



Carrillo F.J., & Bourg I.C.,*WRR* (2019)
Carrillo F.J., & Bourg I.C.,*WRR* (2021)

The Model's Solid Equations

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Solid Mass Conservation Equation:

$$\frac{\partial \phi_s}{\partial t} + \nabla \cdot \boldsymbol{U}_s = 0$$

Solid Momentum Conservation Equation:

$$-\nabla \cdot \overline{\boldsymbol{\sigma}}_s = -\phi_s \nabla \bar{p} + \phi_s \rho \boldsymbol{g} - \boldsymbol{F}_{Drag} - \phi_f \boldsymbol{F}_{c,1} + \phi_s \boldsymbol{F}_{c,2}$$

Combine Fluid + Solid Momentum Equations Gives Biot Theory

Carrillo F.J., & Bourg I.C.,*WRR* (2019)
Carrillo F.J., & Bourg I.C.,*WRR* (2021)

Modeling Framework: Obtaining Biot Theory

Averaged Fluid Momentum Conservation Equation:

$$0 = -\phi_f \nabla \bar{p} + \phi_f \rho_f \boldsymbol{g} + \nabla \cdot \bar{\boldsymbol{\tau}} + \boldsymbol{F}_{Drag} + \phi_f \boldsymbol{F}_{c,1} + \phi_f \boldsymbol{F}_{c,2}$$

Averaged Solid Momentum Conservation Equation:

In Porous Domain

$$+ \quad -\nabla \cdot \bar{\boldsymbol{\sigma}}_s = -\phi_s \nabla \bar{p} + \phi_s \rho \boldsymbol{g} - \boldsymbol{F}_{Drag} - \phi_f \boldsymbol{F}_{c,1} + \phi_s \boldsymbol{F}_{c,2}$$

Biot Theory! $\nabla \cdot \bar{\boldsymbol{\sigma}}_s = \nabla \bar{p} - (\phi_s \rho_s + \phi_f \rho_f)\boldsymbol{g} - \boldsymbol{F}_{c,2}$ | $\boldsymbol{F}_{c,2} = -p_c \nabla \alpha_w$

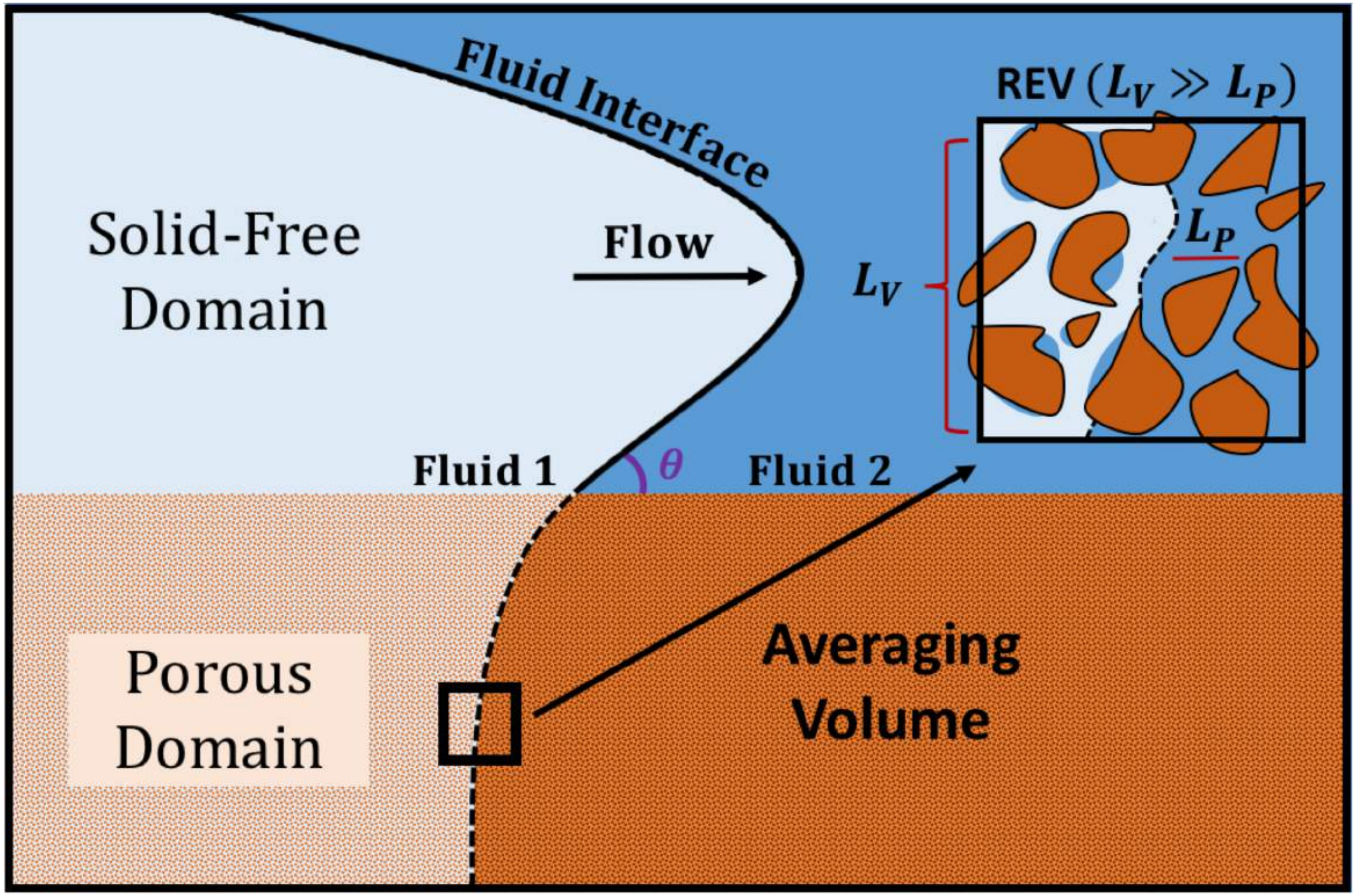
Carrillo F.J., & Bourg I.C., *WRR* (2019)
Carrillo F.J., & Bourg I.C., *WRR* (2021)

B. Jha & R. Juanes, *WRR* (2014), J. Kim et. al., *SPE* (2013)

The Extended Darcy-Brinkman Model

Approximates
Navier-Stokes

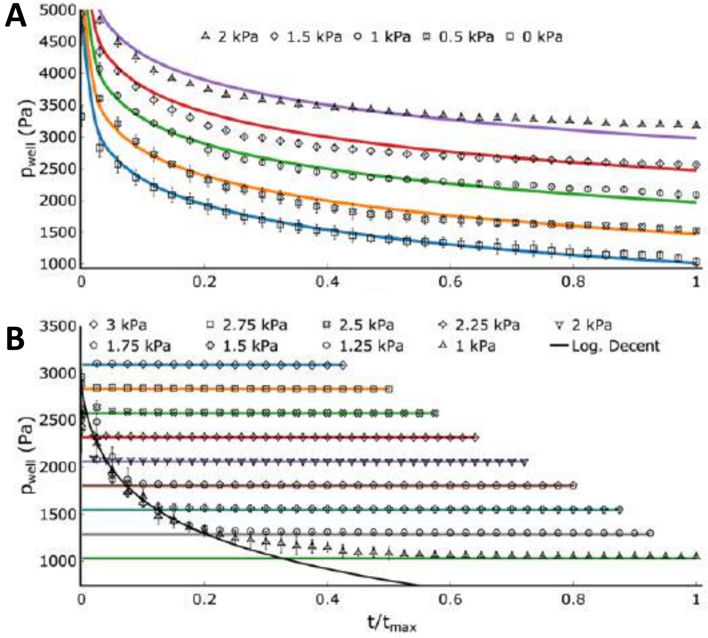
Approximates
Multiphase
Biot Theory

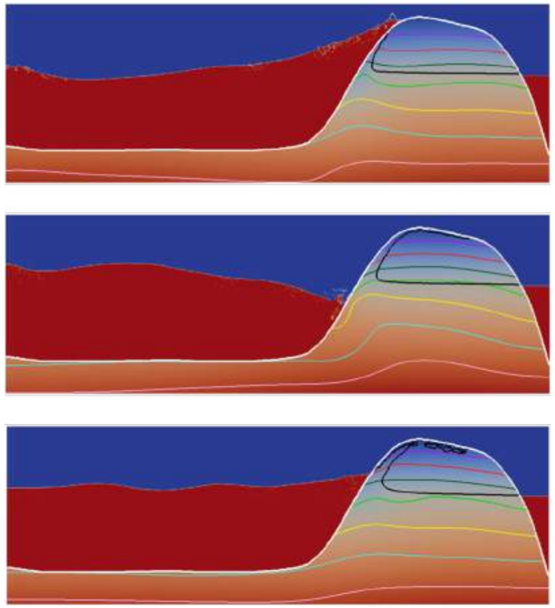


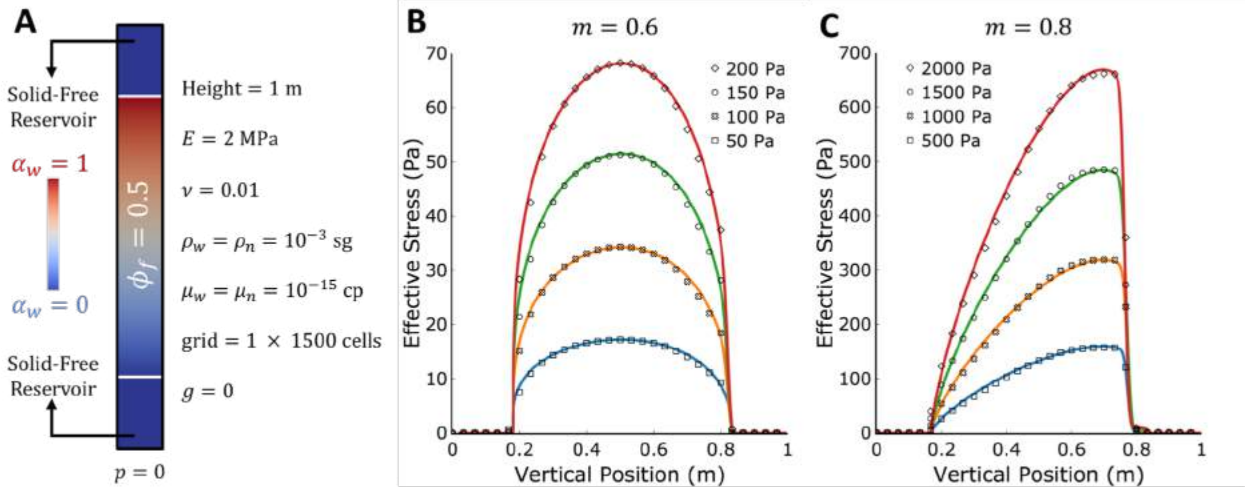
Carrillo F.J., & Bourg I.C., *WRR* (2019)
Carrillo F.J., & Bourg I.C., *WRR* (2021)

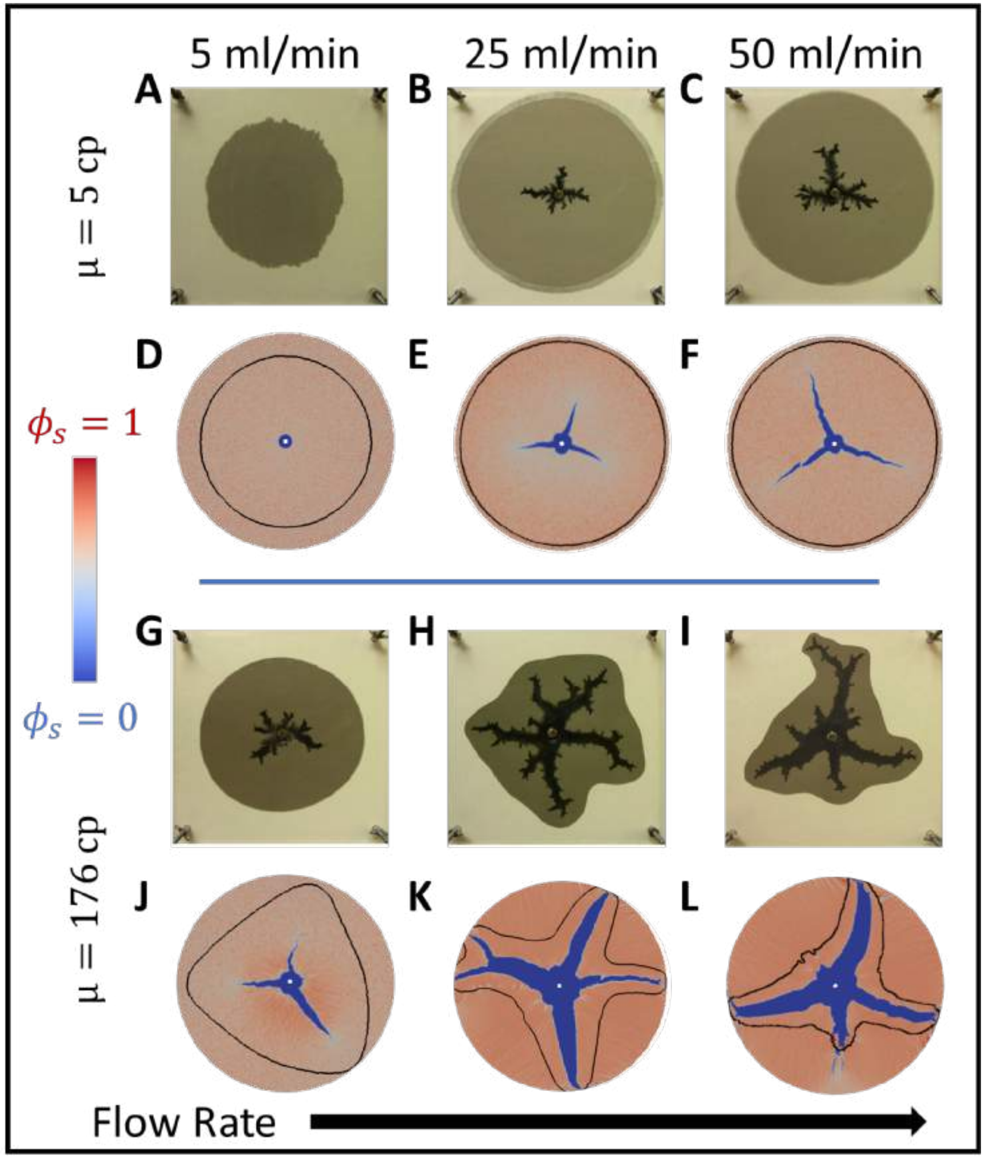
Toolbox: *hybridBiotInterFoam*

Everything implemented in OpenFoam®



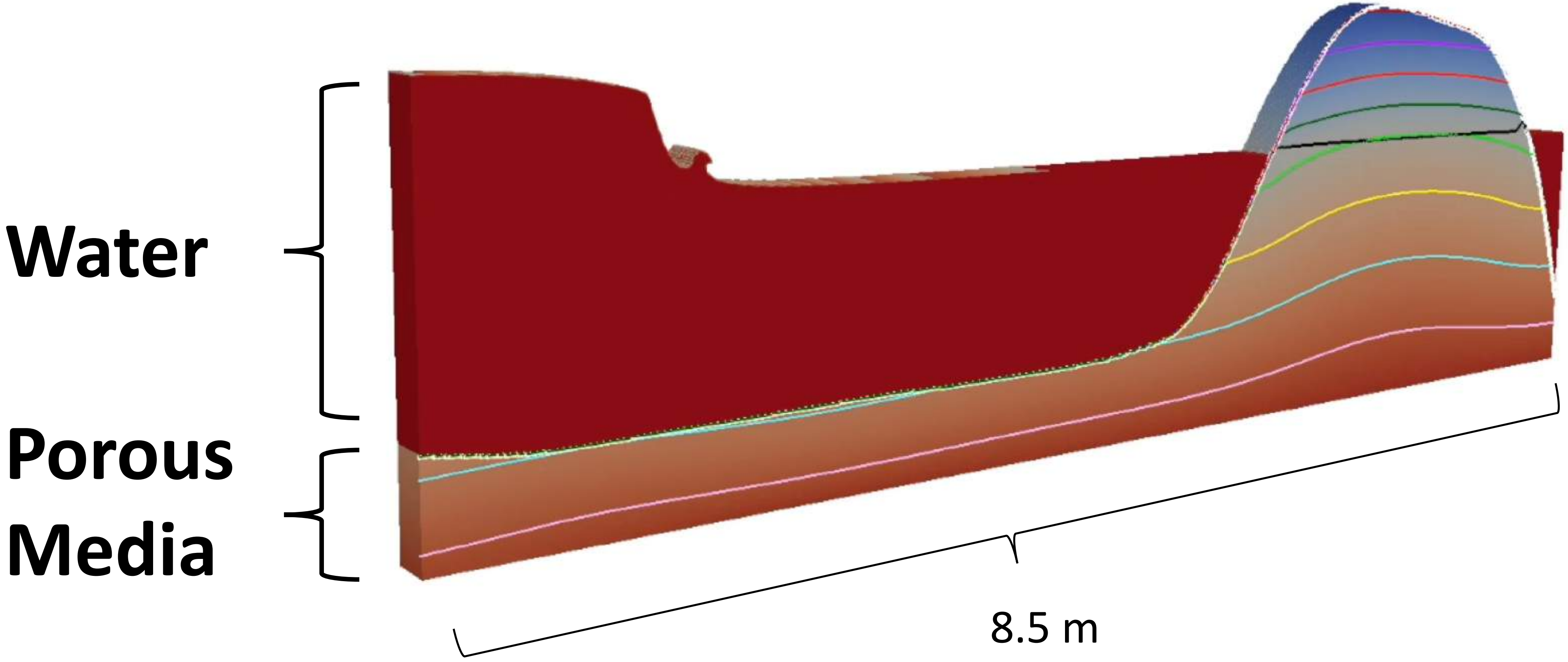






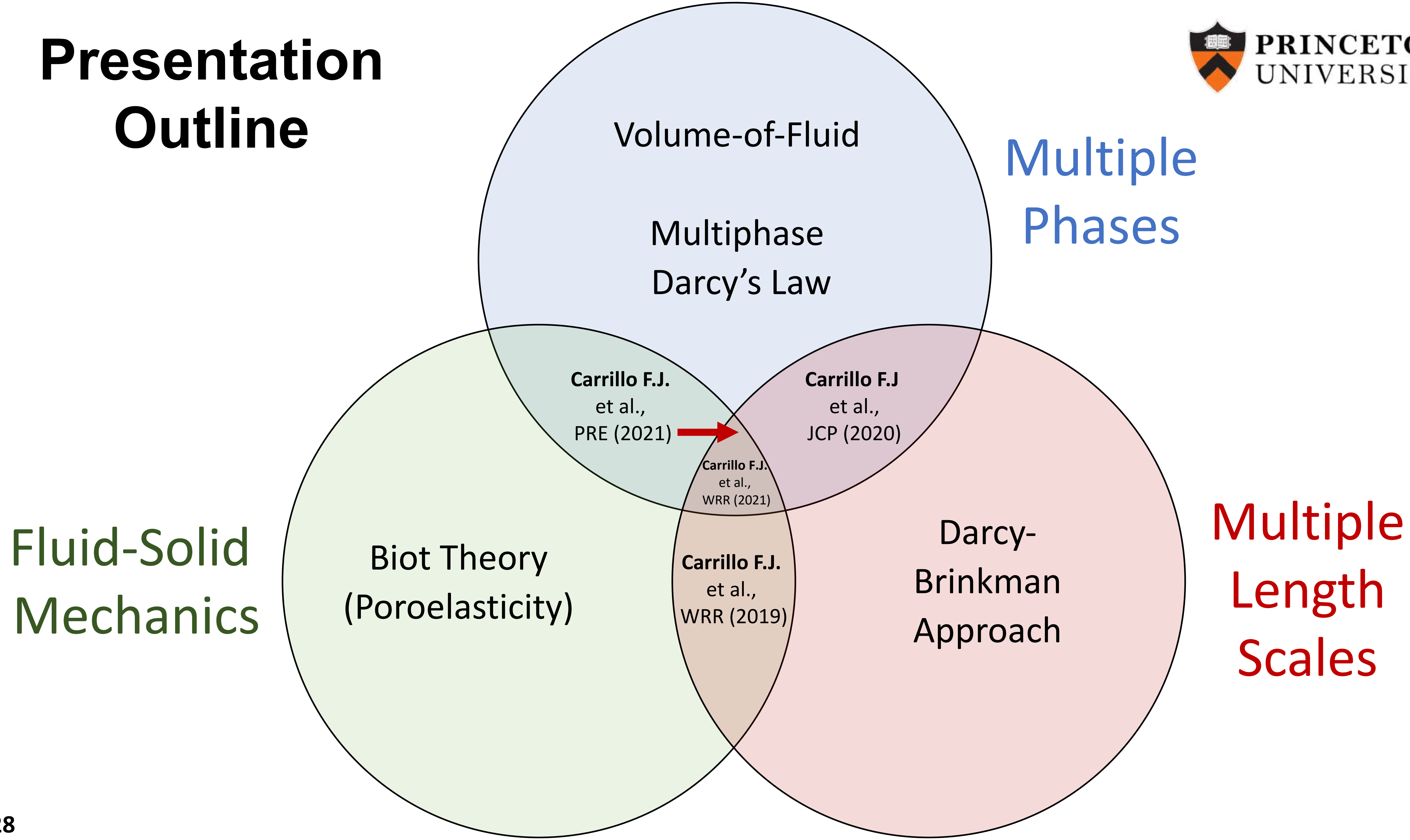
Carrillo F.J., & Bourg I.C., *WRR* (2021)

Conceptual Application:
Poroelastic Barriers



Carrillo F.J., & Bourg I.C.,*WRR* (2021)

Presentation Outline



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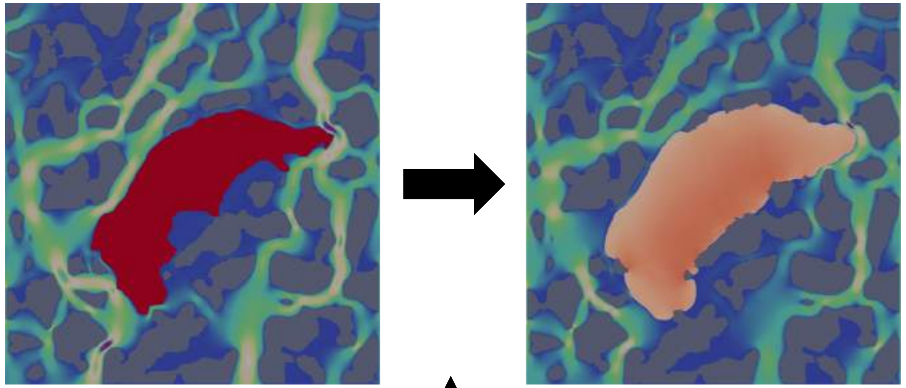
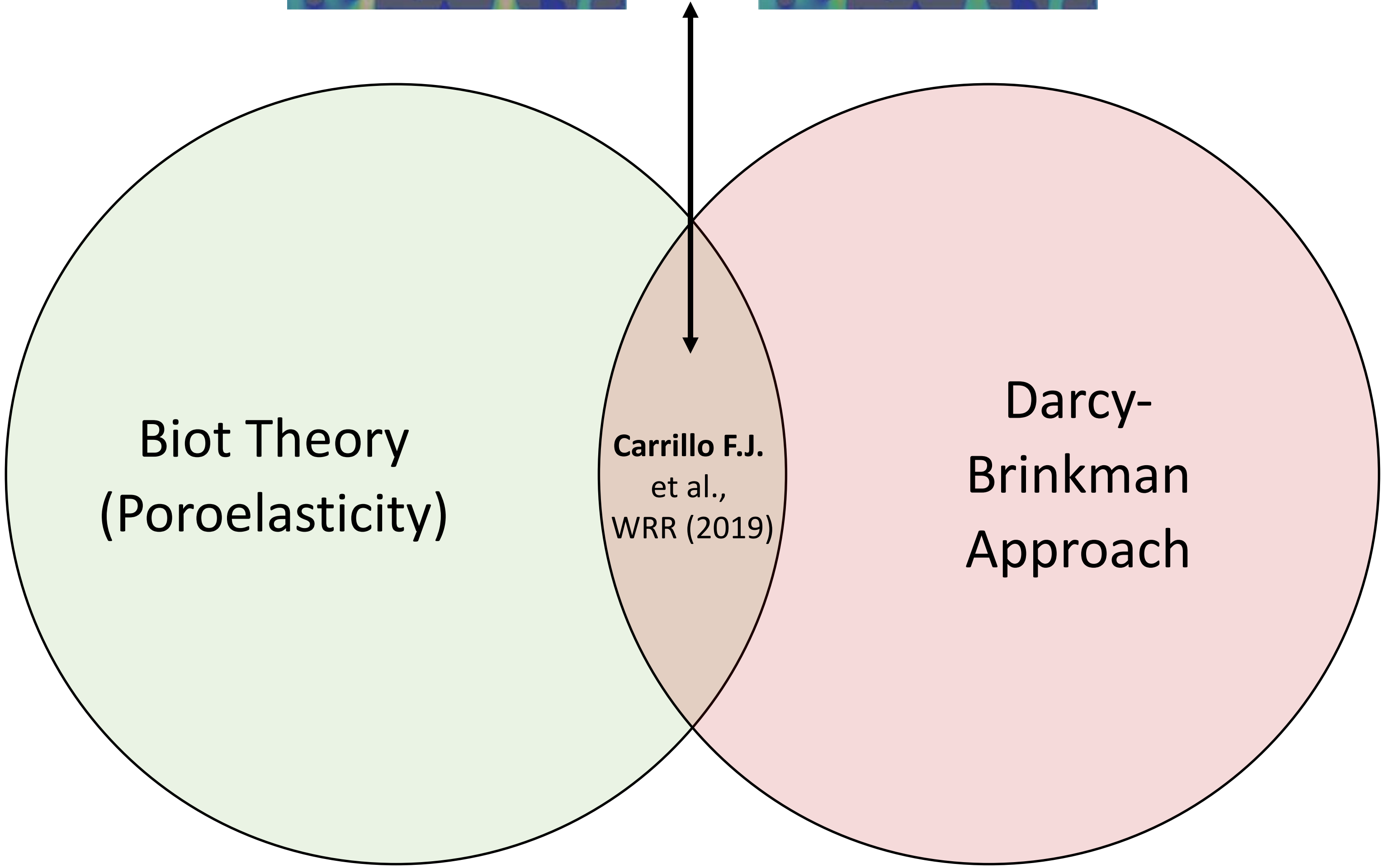
Part 3:
Clay Swelling



Fluid-Solid Mechanics



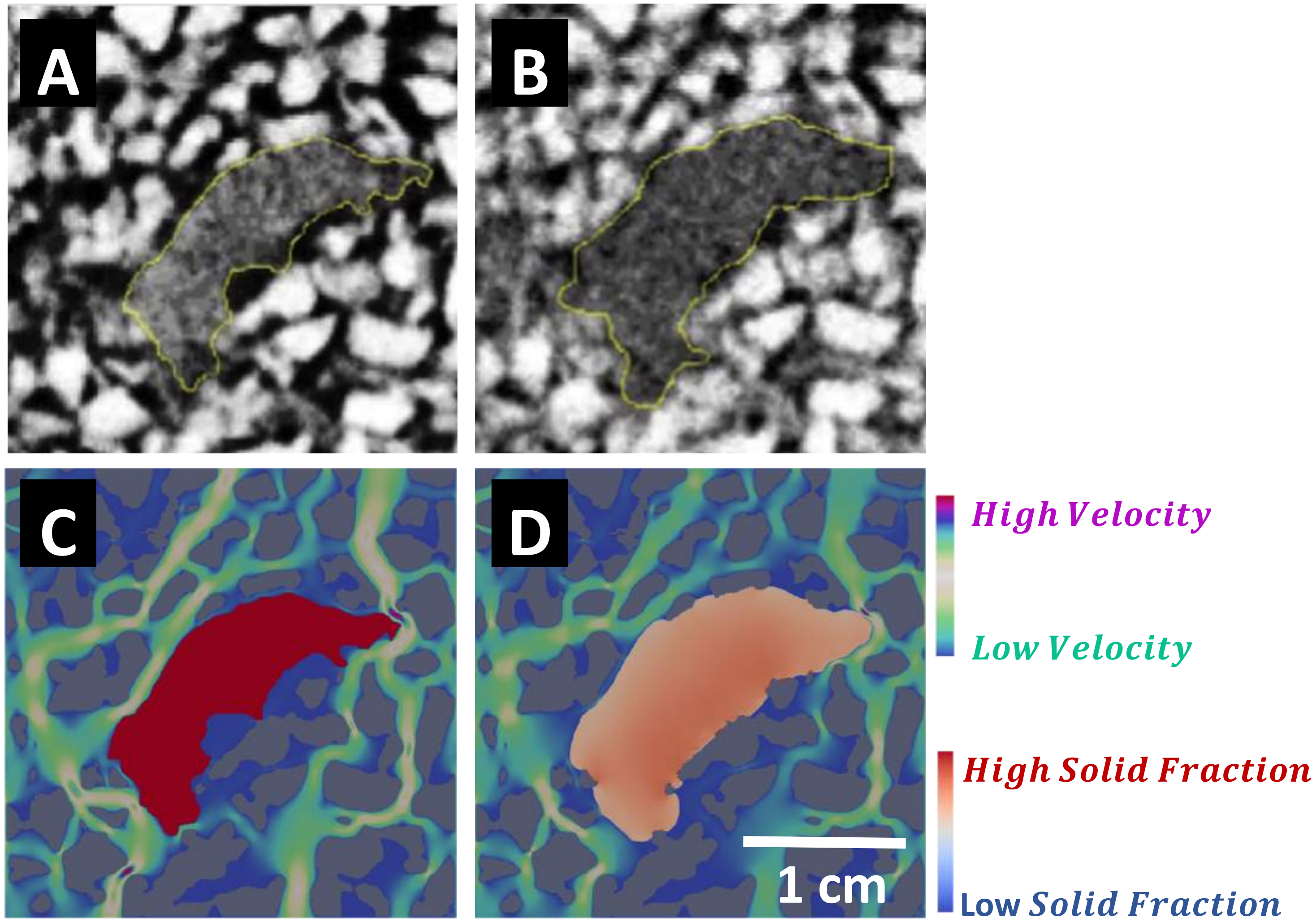
Multiple Length Scales

Applied Model: Single Phase Flow and Clay Swelling

High Salinity | Low Salinity

Experimental Scan

Simulations



Aksu. et al. 2015

Carrillo F.J., & Bourg I.C., *WRR* (2019)

Modeling Sedimentary Rock **Permeability**

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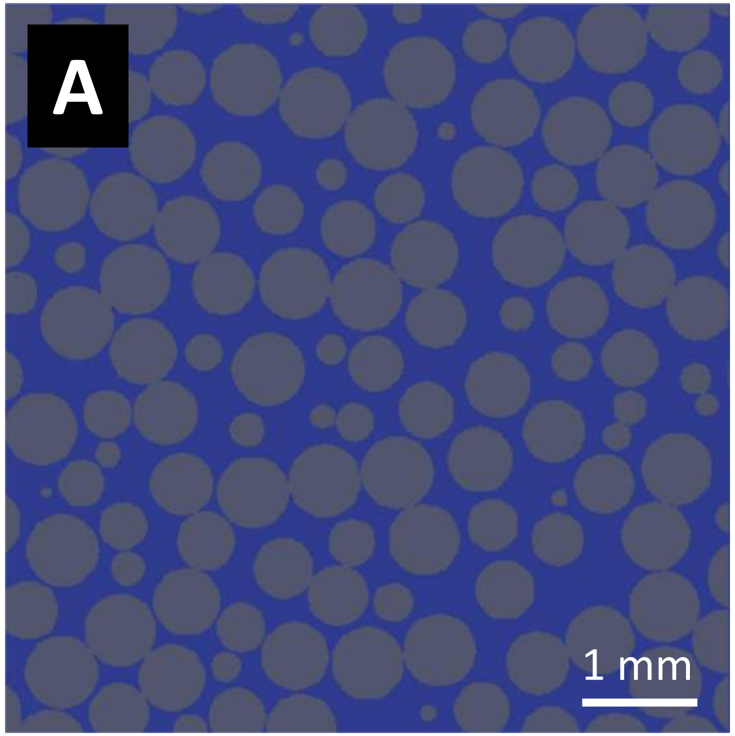
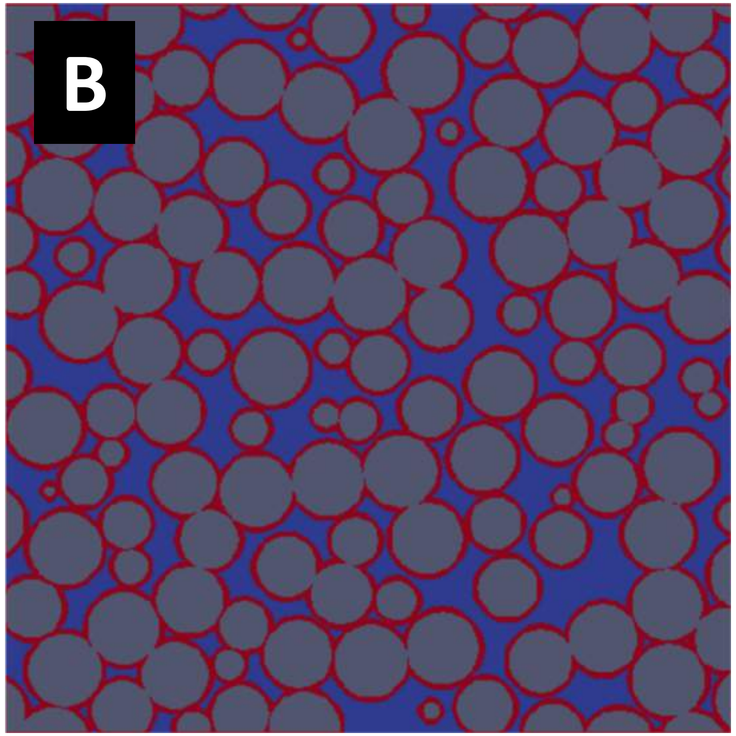
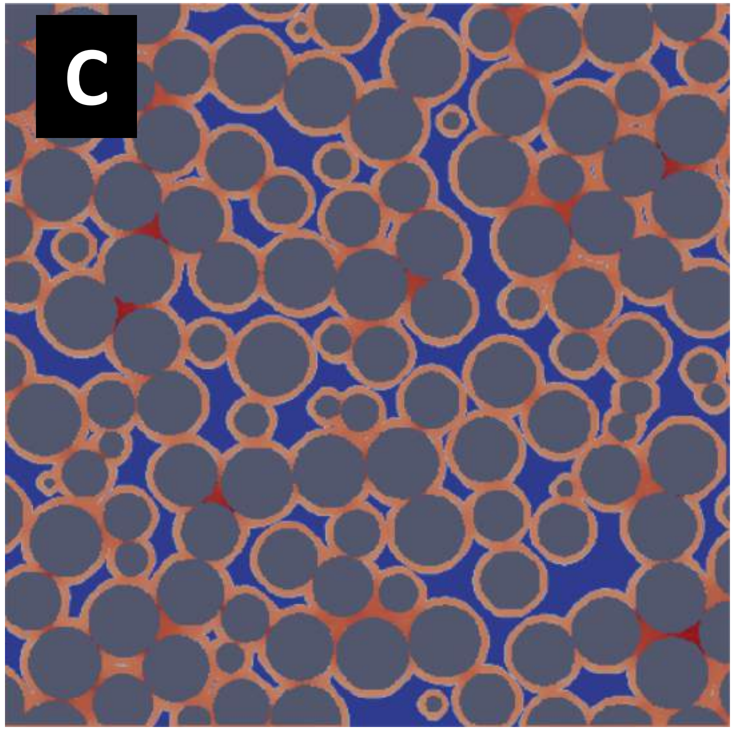
2-D spherical packed bed → Populate it with swelling clay → Induce swelling (or contraction)



Water   Coarse Grains



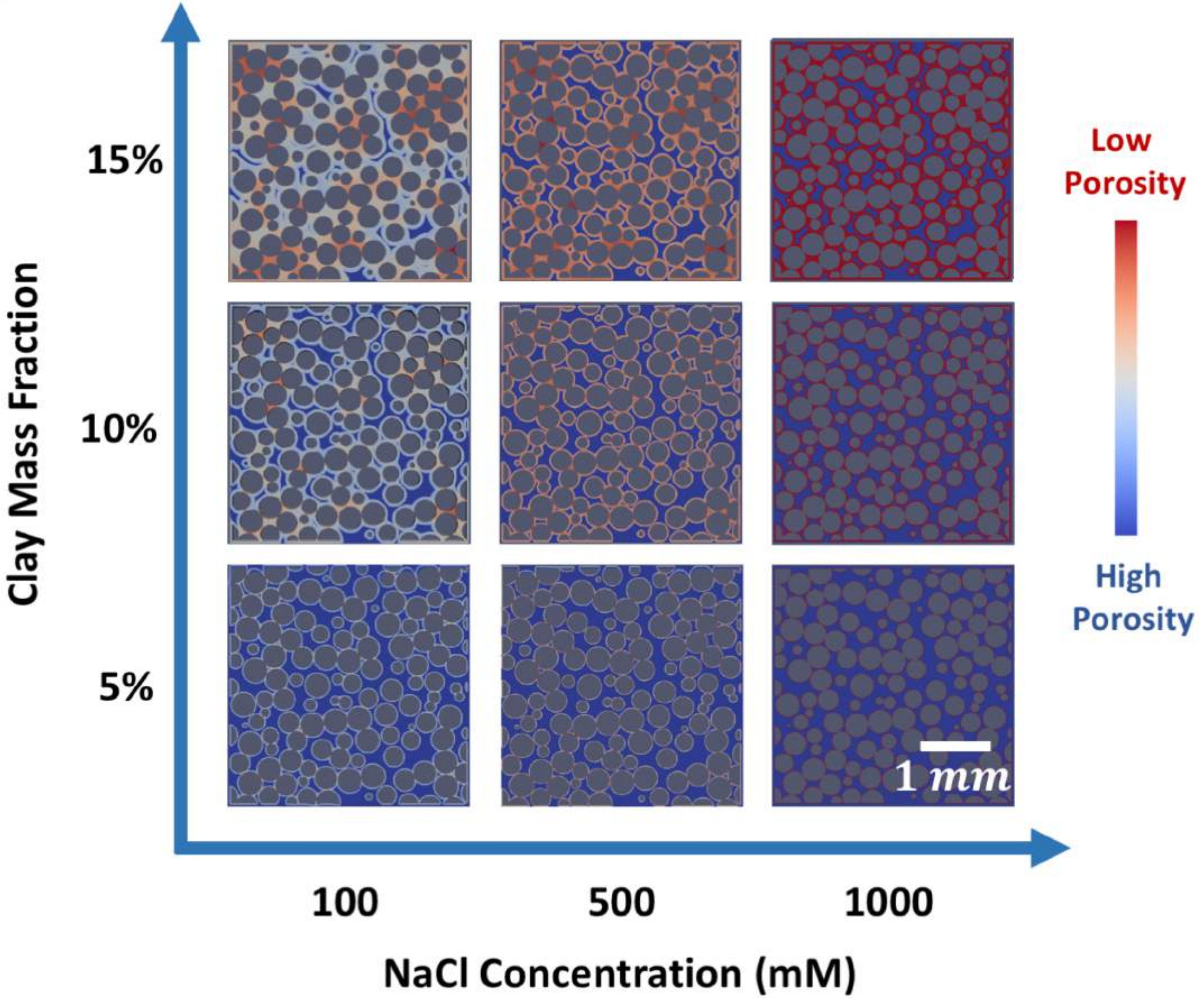
Clay



High Fluid Fraction   *High Solid Fraction*

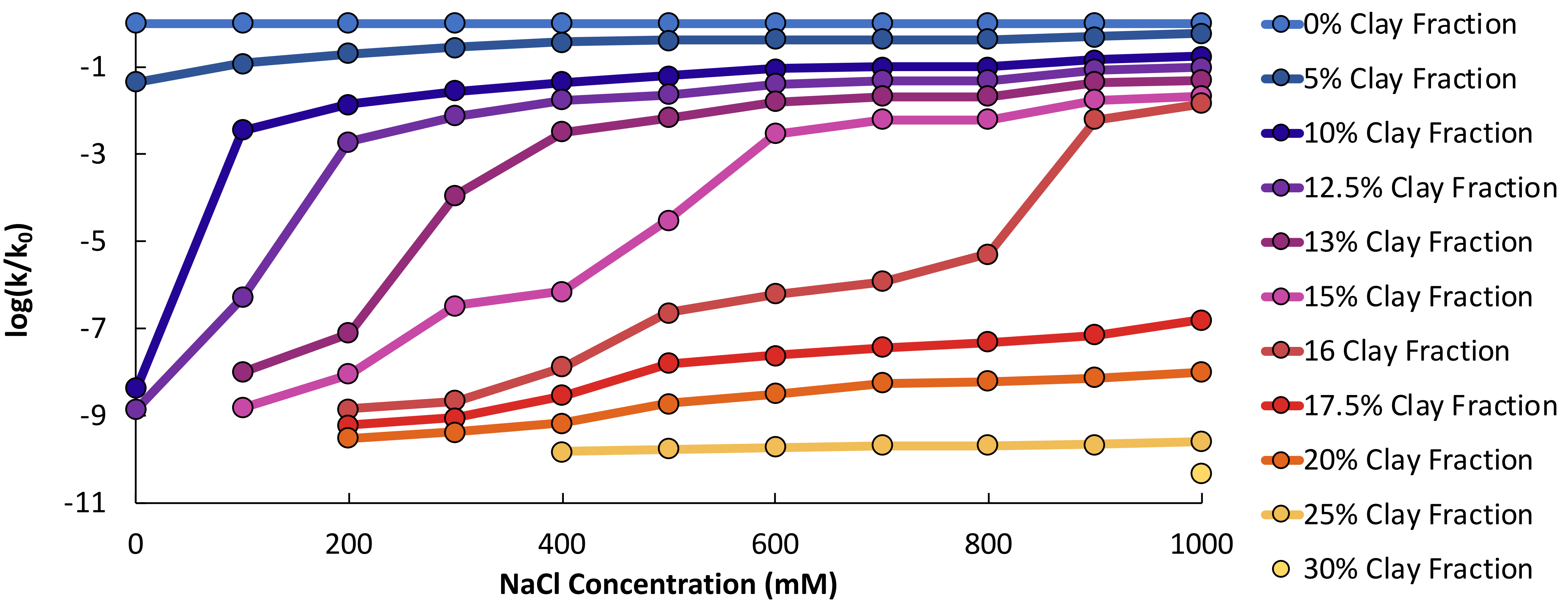
Carrillo F.J., & Bourg I.C., *WRR* (2019)

Modeling Sedimentary Rock Permeability



Carrillo F.J., & Bourg I.C., *WRR* (2019)

Modeling Sedimentary Rock Permeability



Carrillo F.J., & Bourg I.C., *WRR* (2019)

Modeling Sedimentary Rock Permeability

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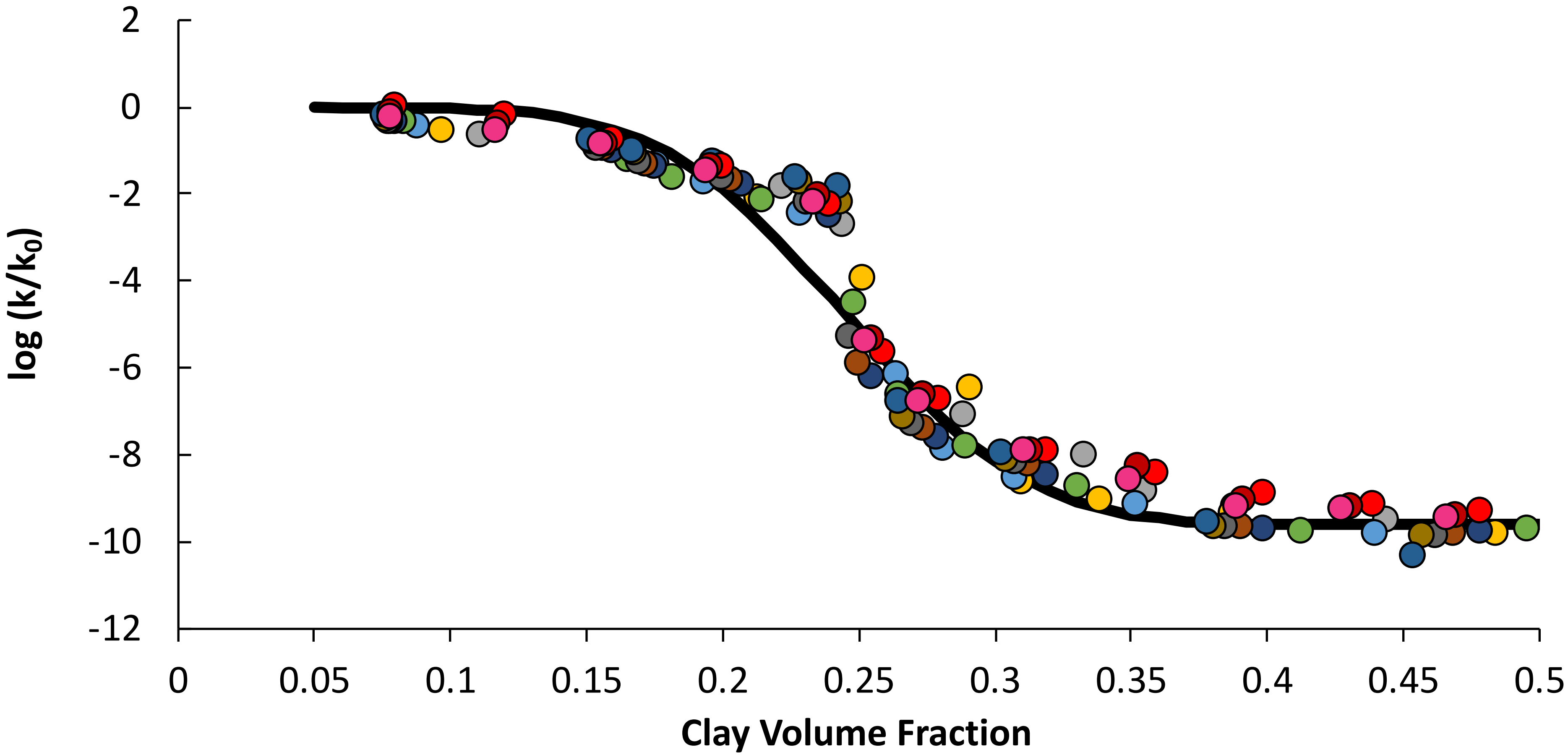
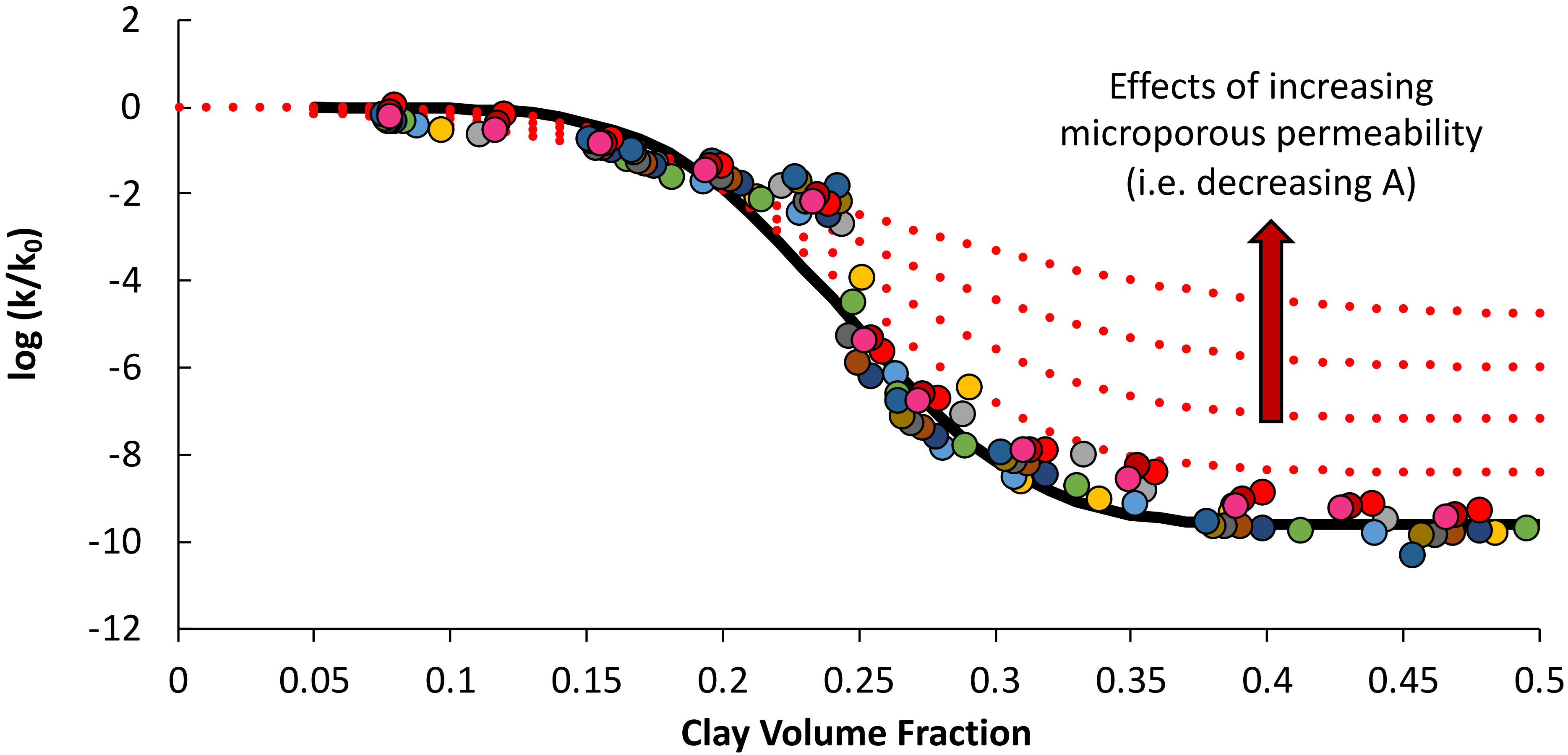


$$log\left(\frac{k}{k_0}\right) = \frac{A}{2}\left(\text{erf}\left(1.38\,A\left(V_{clay} - V^{*}_{clay}\right)\right) - 1\right)$$

Carrillo F.J., & Bourg I.C., *WRR* (2019)

Modeling Sedimentary Rock Permeability



$$log\left(\frac{k}{k_0}\right) = \frac{A}{2}\left(\text{erf}\left(1.38\,A\left(V_{clay} - V^*_{clay}\right)\right) - 1\right)$$

Carrillo F.J., & Bourg I.C., *WRR* (2019)

Modeling Sedimentary Rock Permeability

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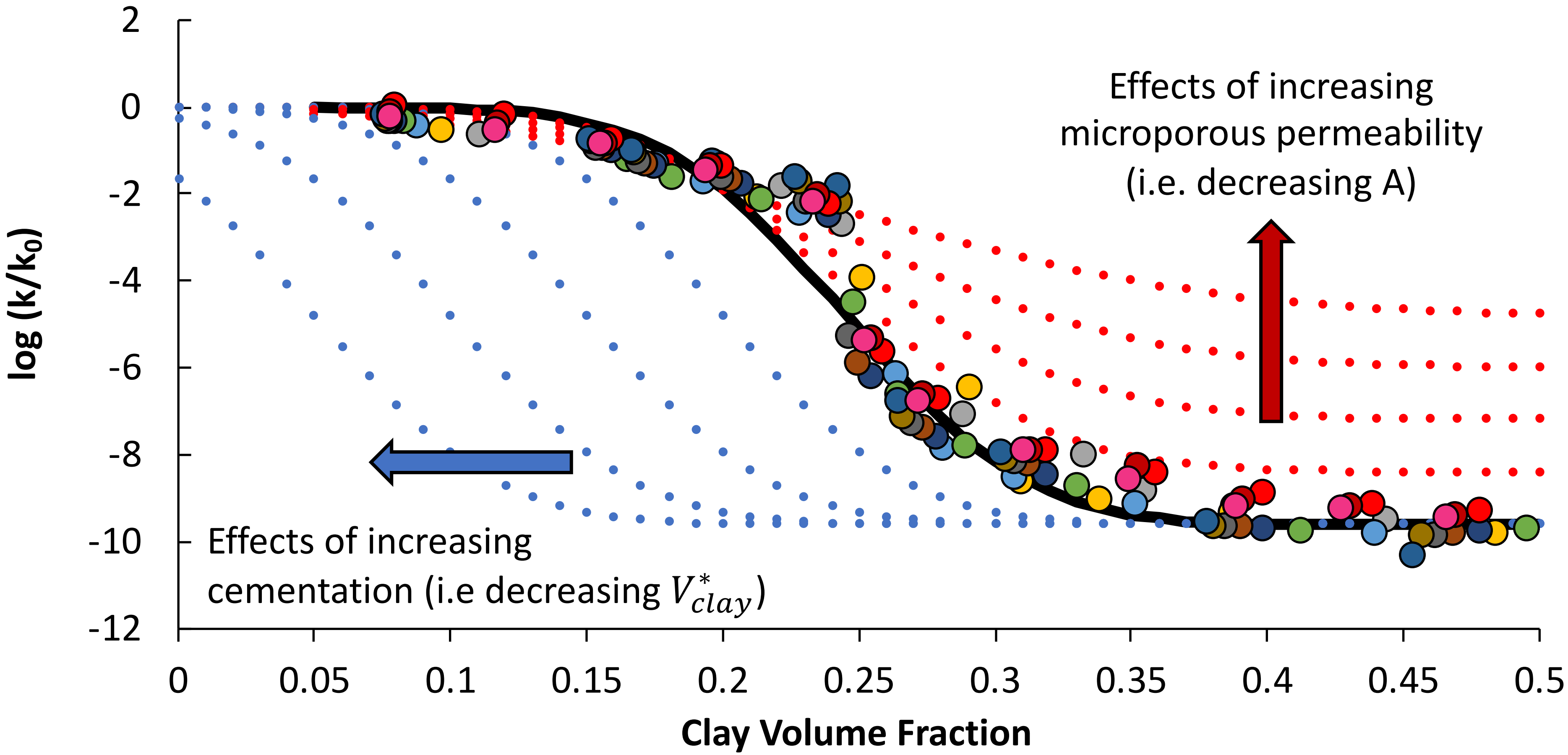
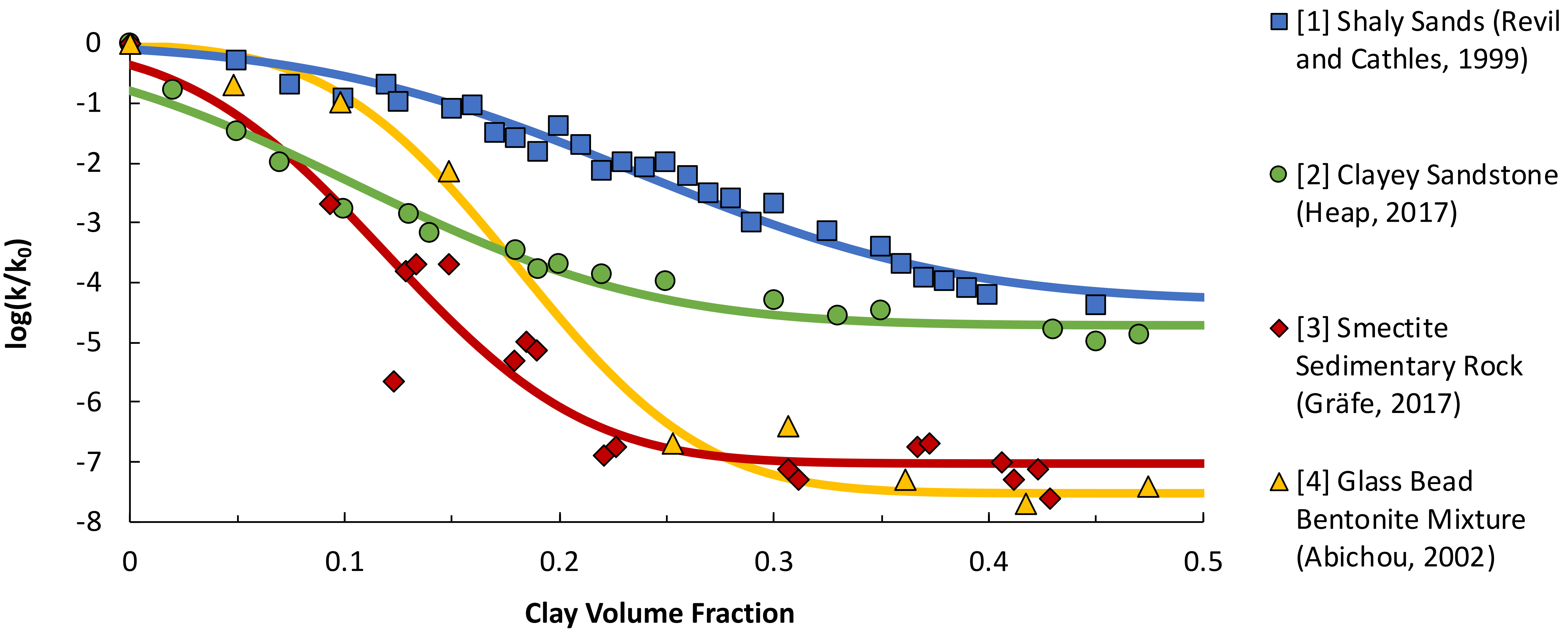


$$log\left(\frac{k}{k_0}\right) = \frac{A}{2}\left(\text{erf}\left(1.38\,A\,(V_{clay} - V^*_{clay})\right) - 1\right)$$

Carrillo F.J., & Bourg I.C.,*WRR* (2019)

Modeling Sedimentary Rock Permeability



$$\log\left(\frac{k}{k_0}\right) = \frac{A}{2}\left(\mathrm{erf}\left(1.38\,A\,\left(V_{clay} - V^*_{clay}\right)\right) - 1\right)$$

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Presentation Outline

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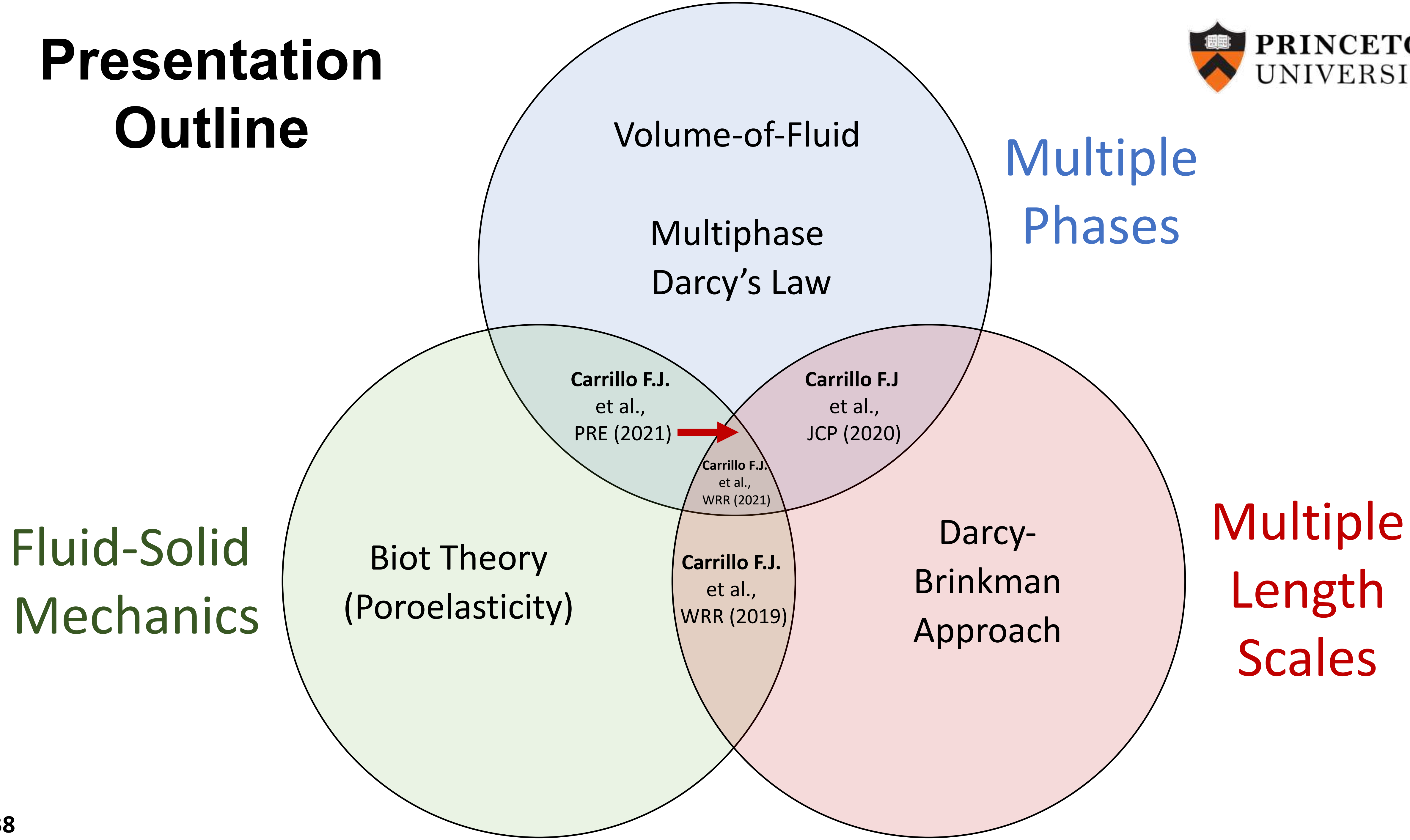
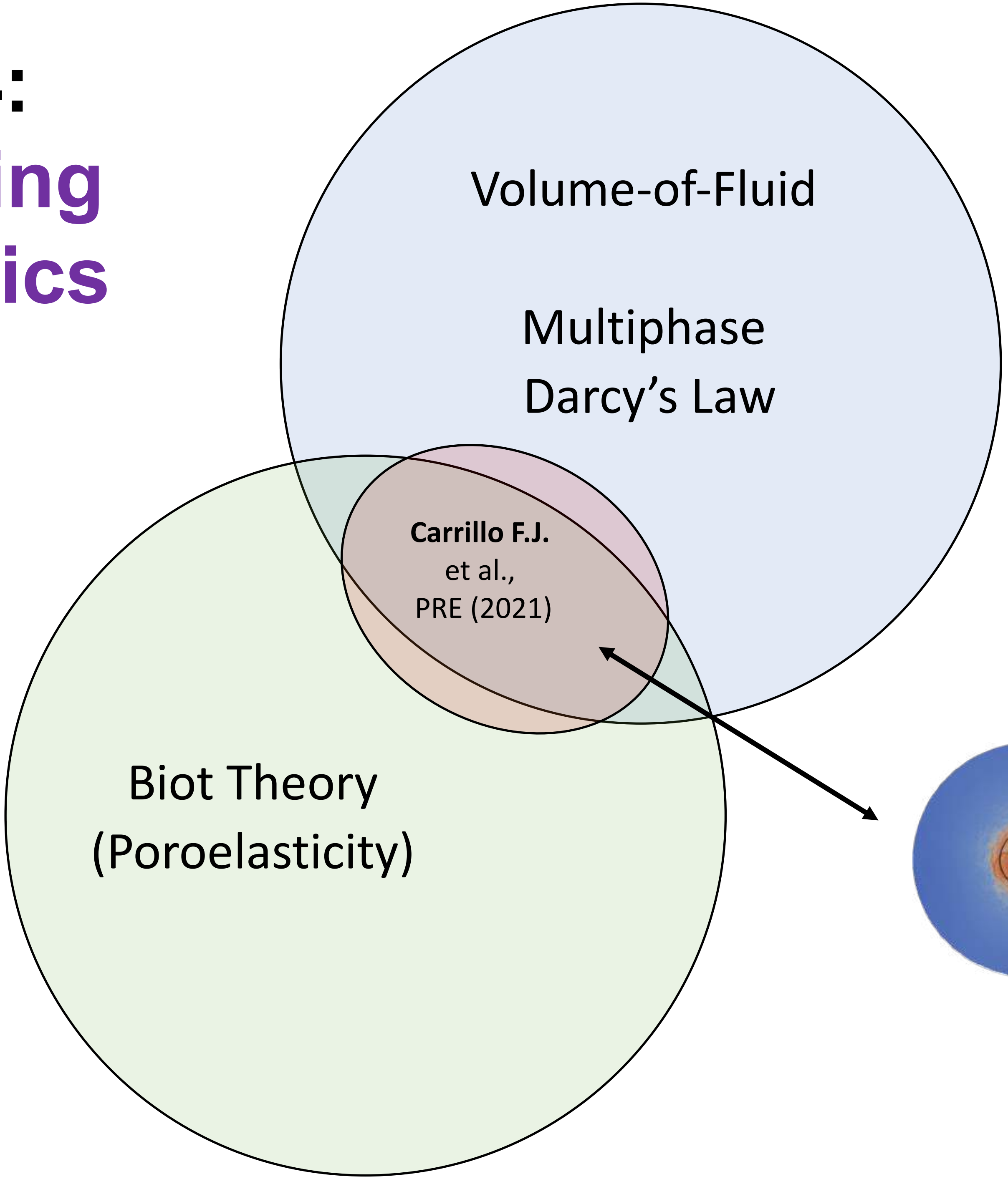


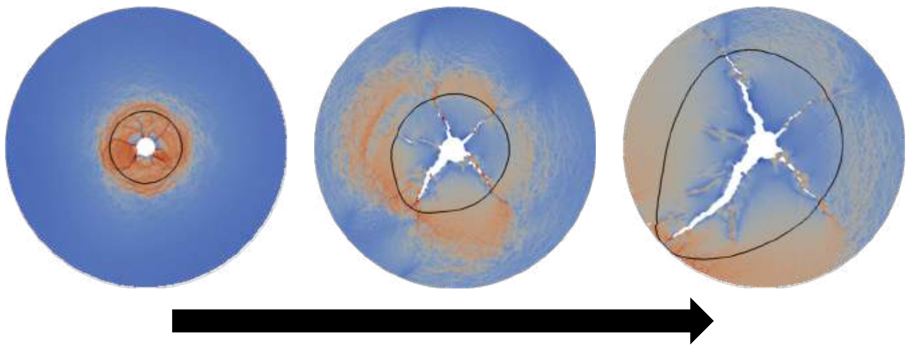
Part 4:
Fracturing Mechanics



Multiple Phases

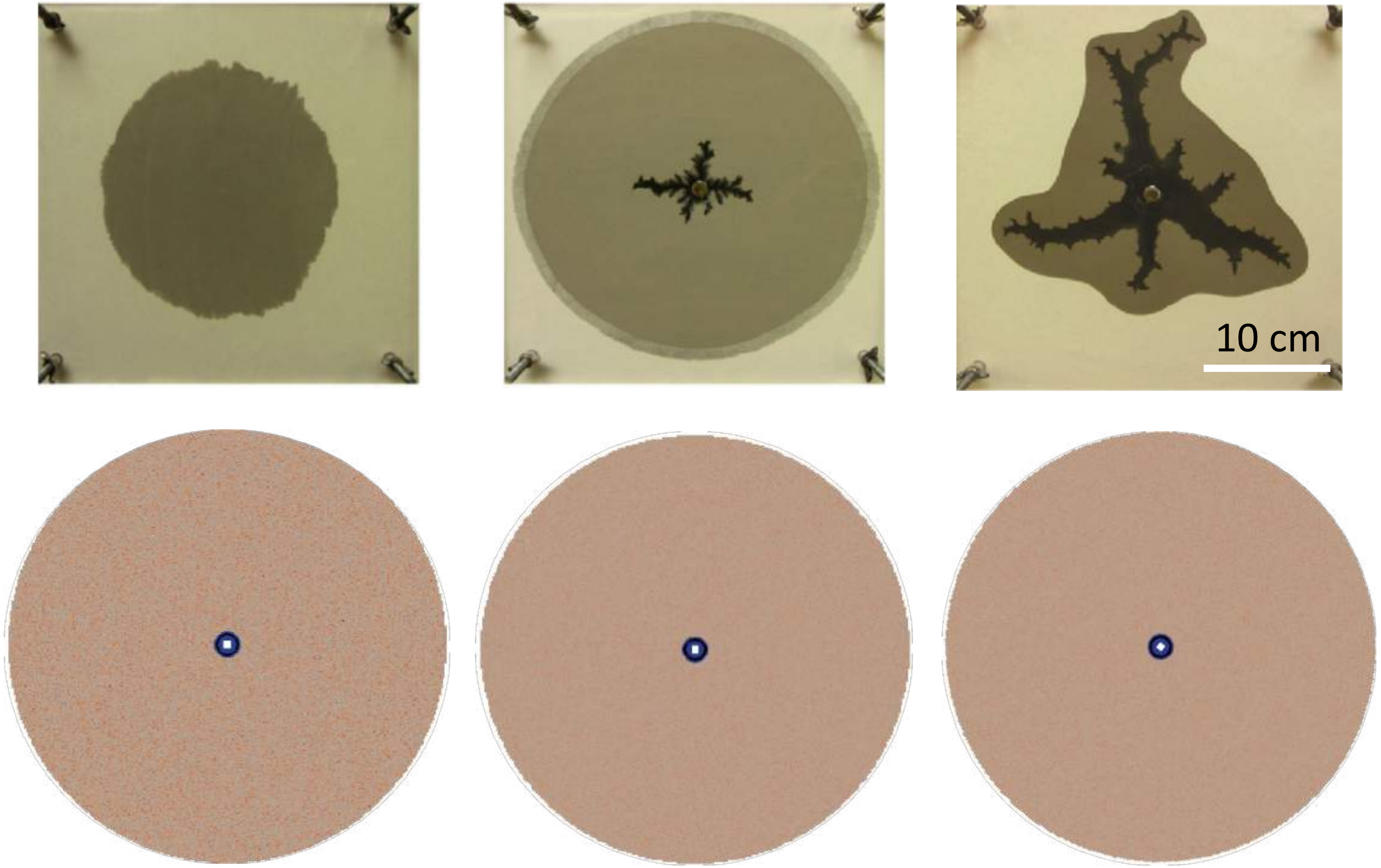
Fluid-Solid Mechanics

Fracturing



Model Applications: Fracturing

Zhang F. et al. 2013;



Low
Porosity

High
Porosity

Increasing Injection Rate

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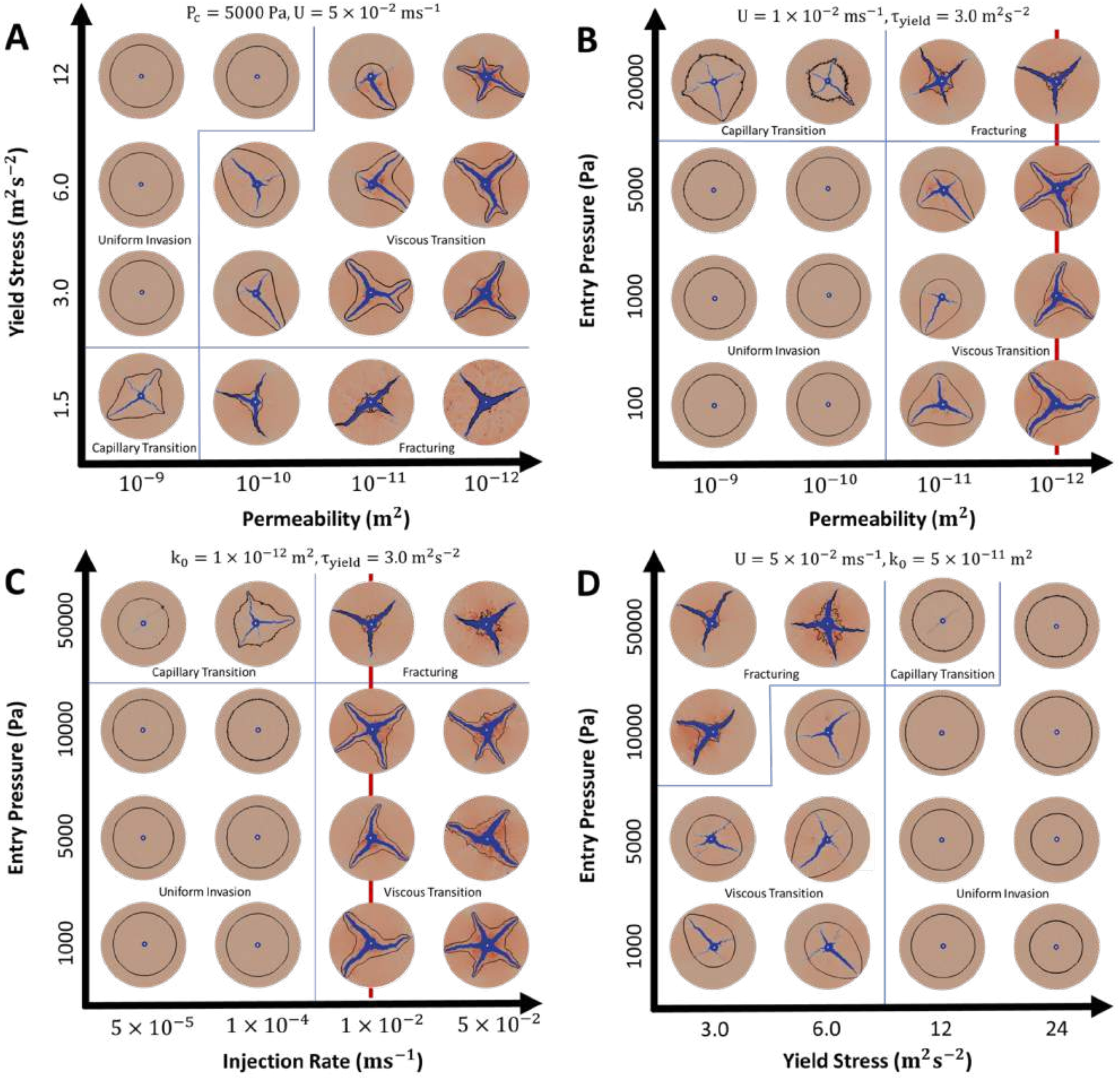
Model Applications: Fracturing



Changing the:

1) Injection flow rate
2) Permeability
3) Solid yield stress
4) Entry capillary pressure

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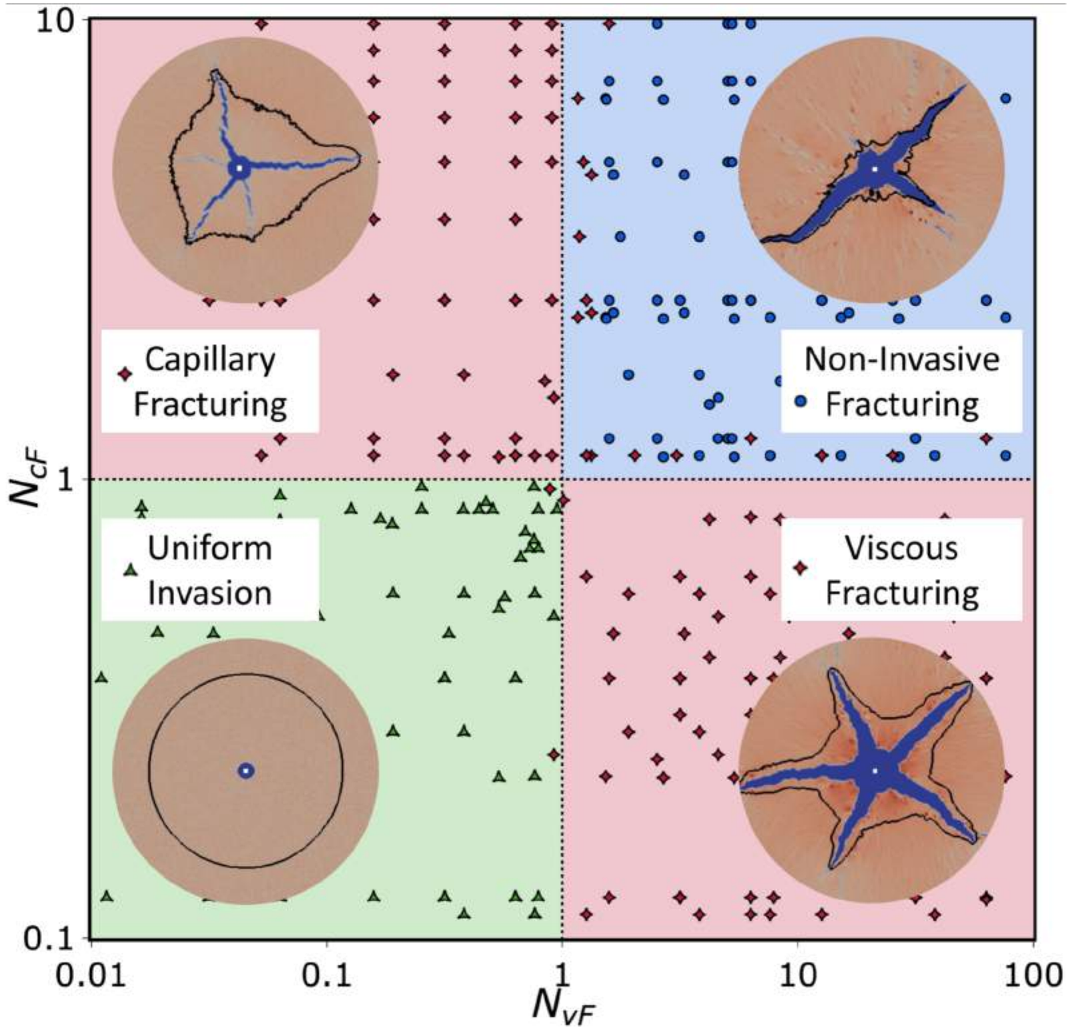
Model Applications: Fracturing



The transition from fluid invasion to fracturing ca be described by two non-dimensional numbers:

$$N_{vF} = \frac{Viscous}{Structural} = \frac{\mu UL/k}{\tau_{yield}\rho_s}$$

$$N_{cF} = \frac{Capillary}{Structural} = \frac{p_{c,0}}{\tau_{yield}\rho_s}$$

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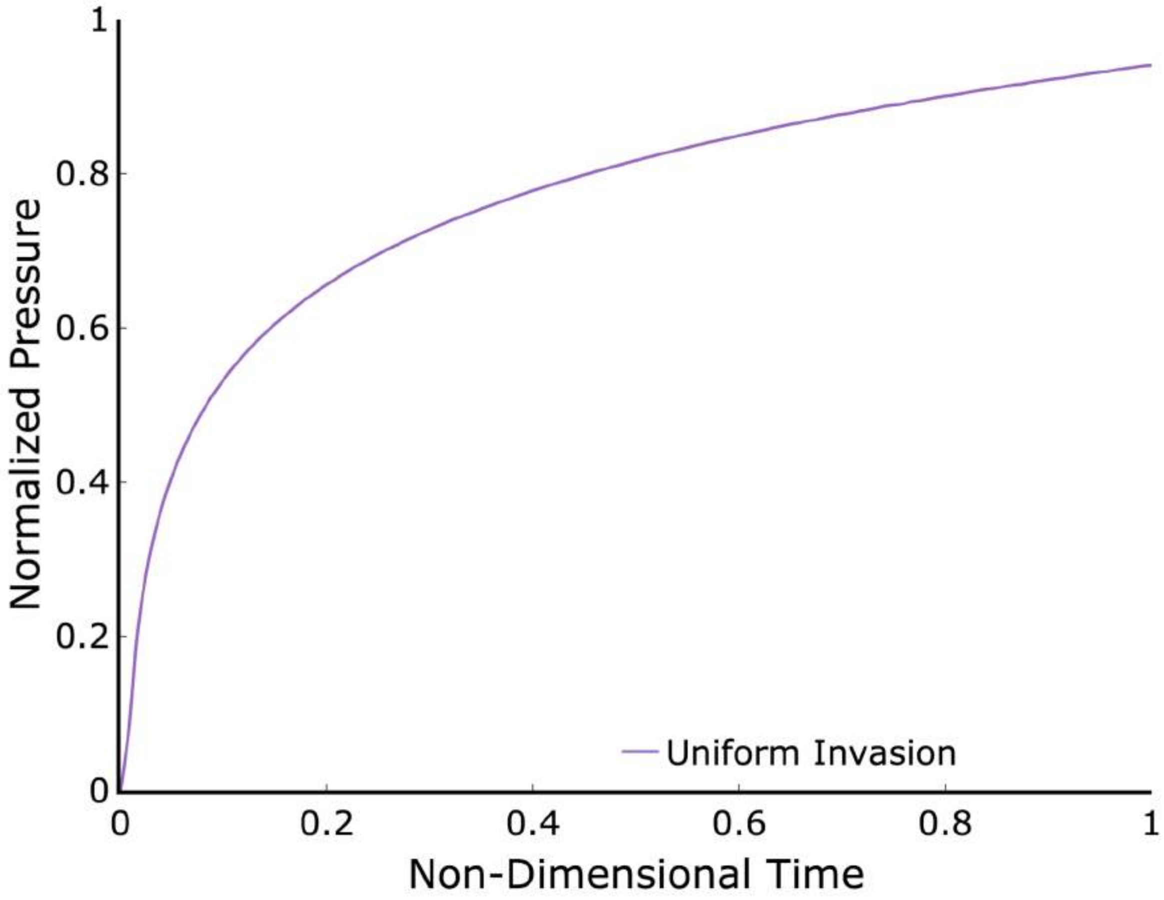
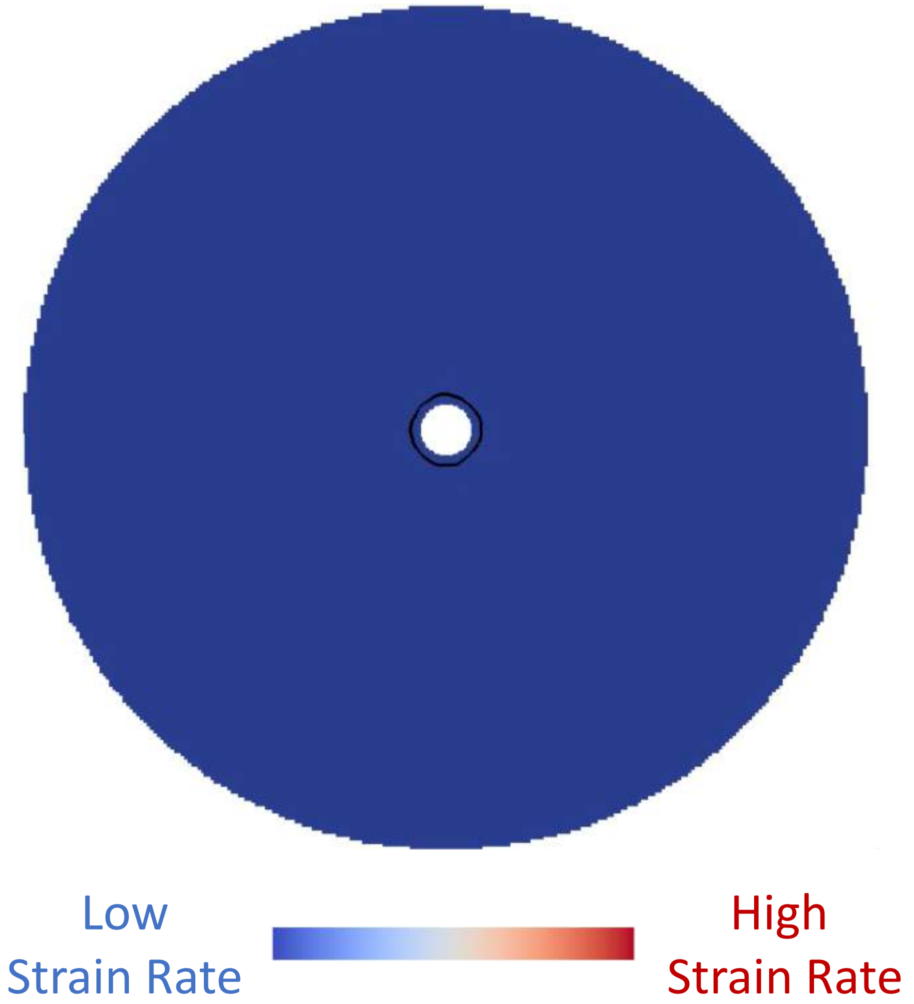
Characterization of Fracturing Types

$N_{vF} < 1$ | $N_{cF} < 1$



Uniform Invasion



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Characterization of Fracturing Types

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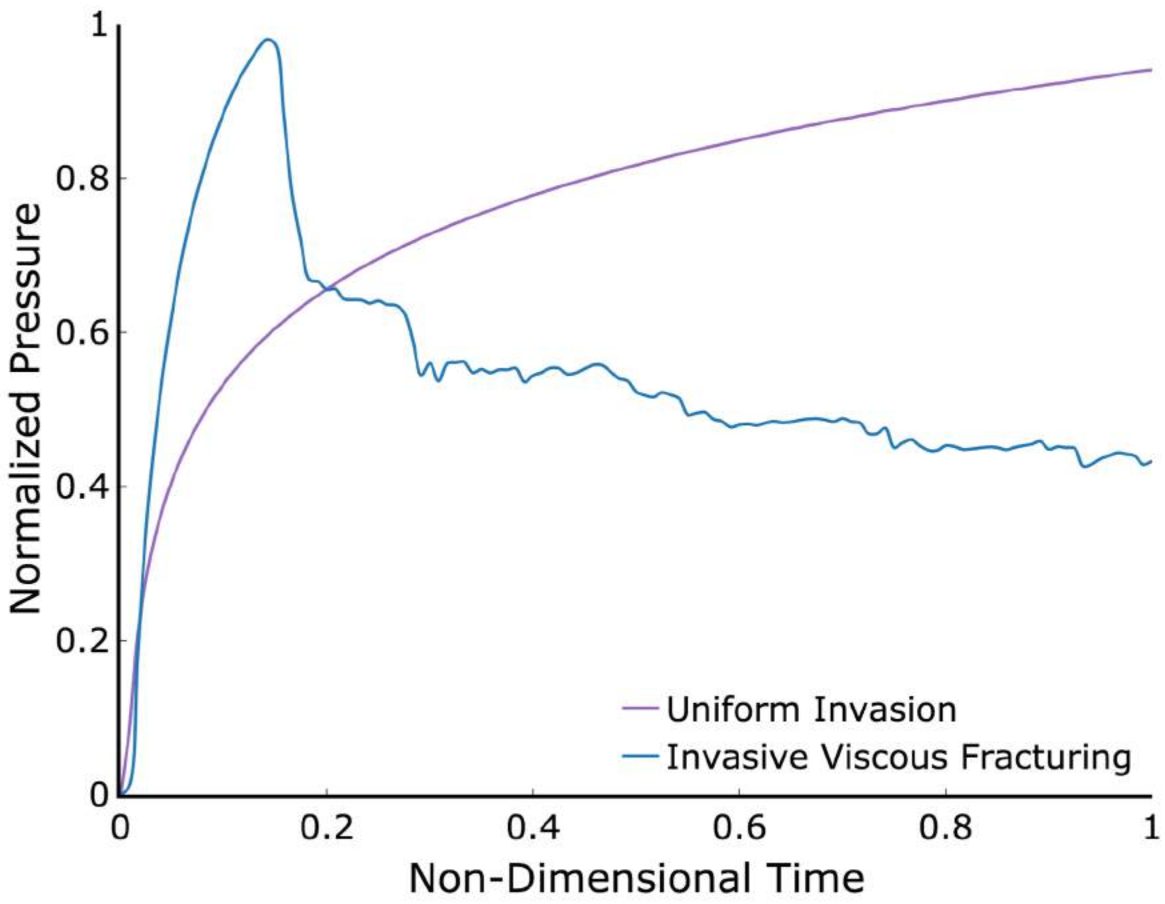
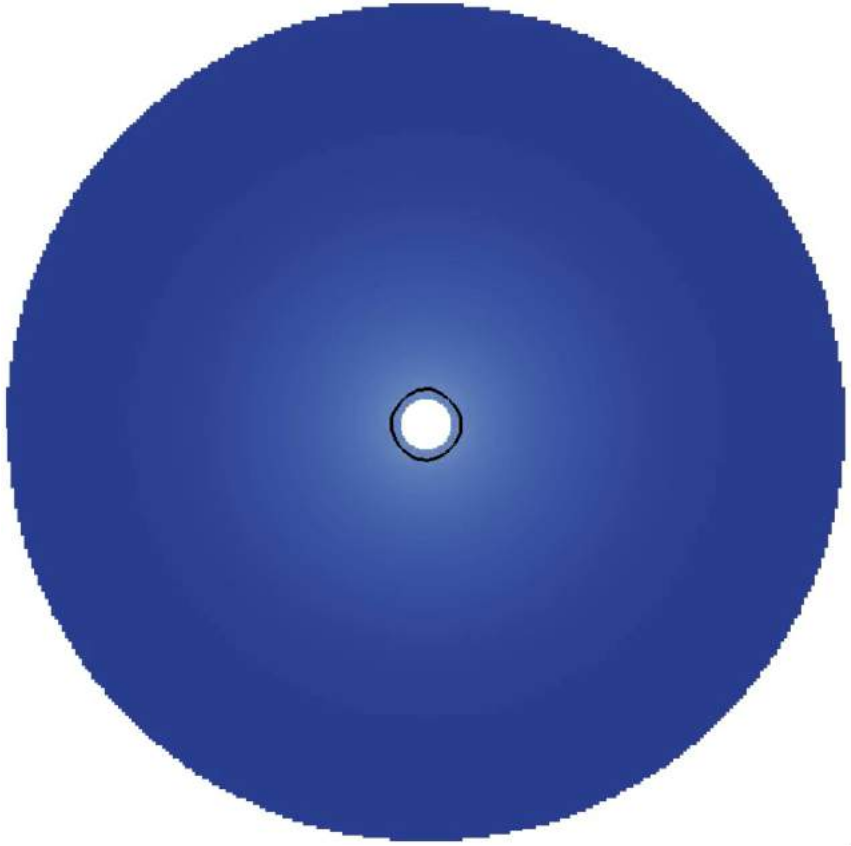
$N_{vF} > 1$ | $N_{cF} < 1$



Viscous Fracturing



Low Strain Rate

High Strain Rate

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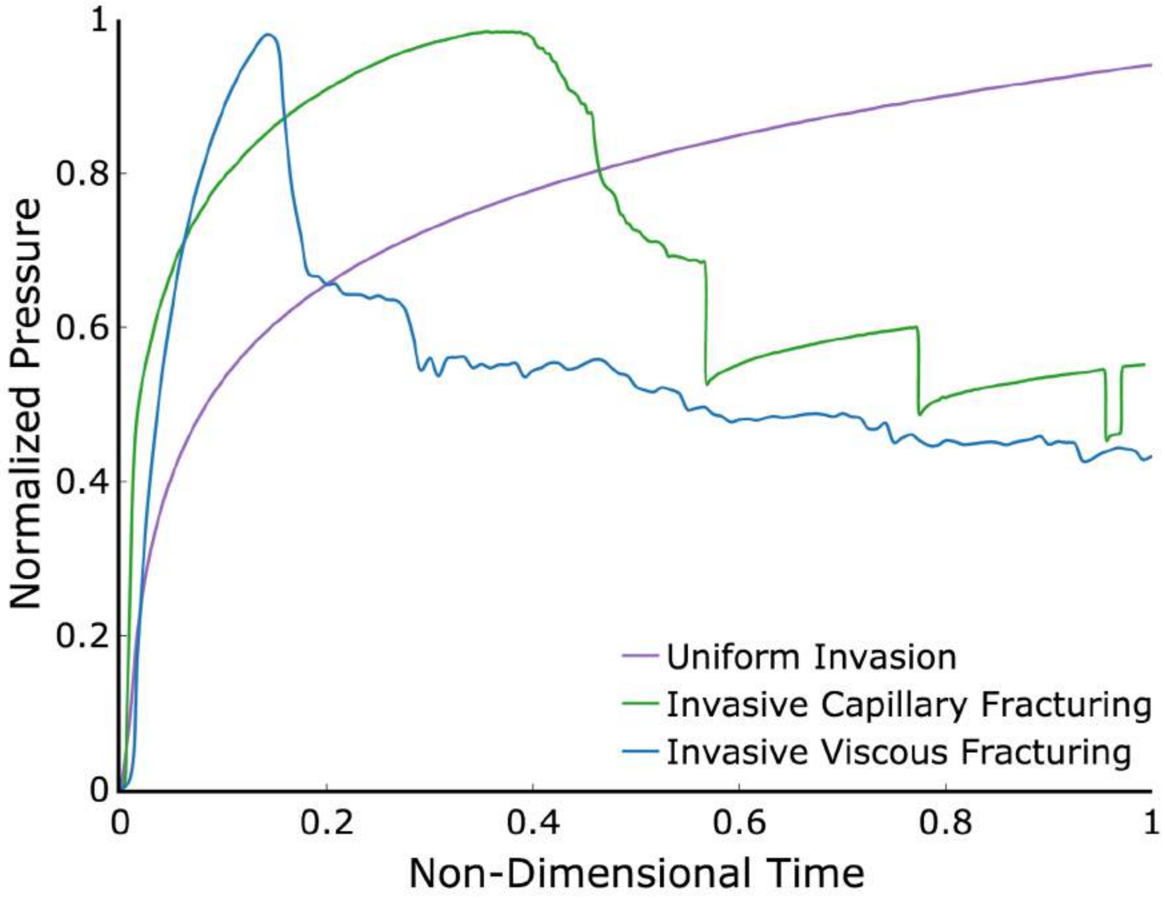
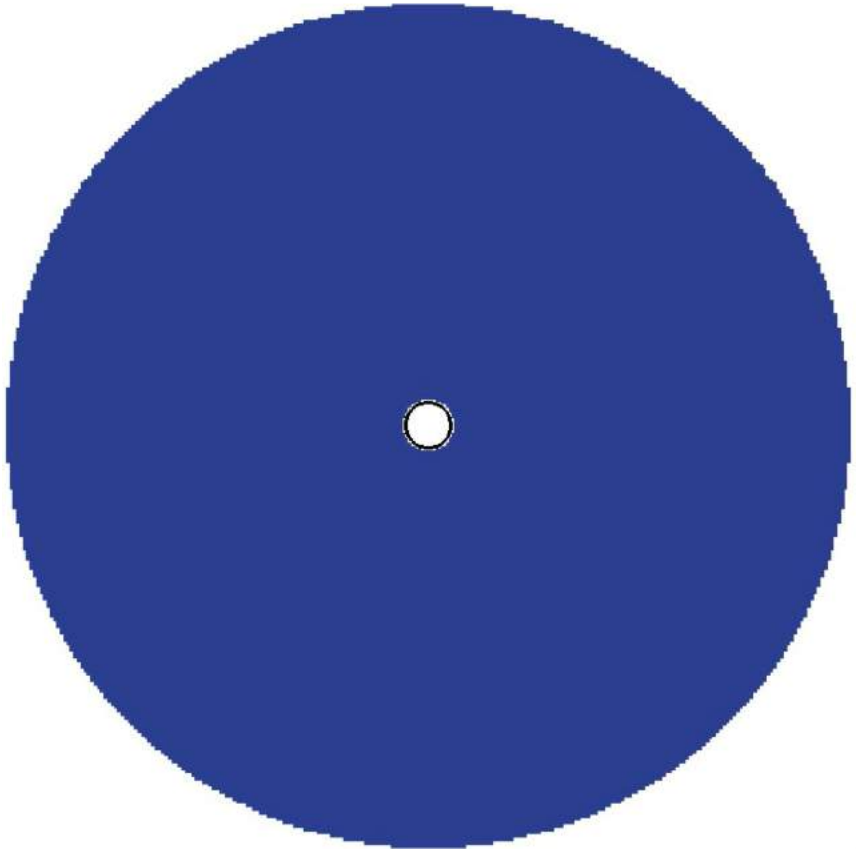
Characterization of Fracturing Types

$N_{vF} < 1 \mid N_{cF} > 1$



Capillary Fracturing



Low Strain Rate

High Strain Rate

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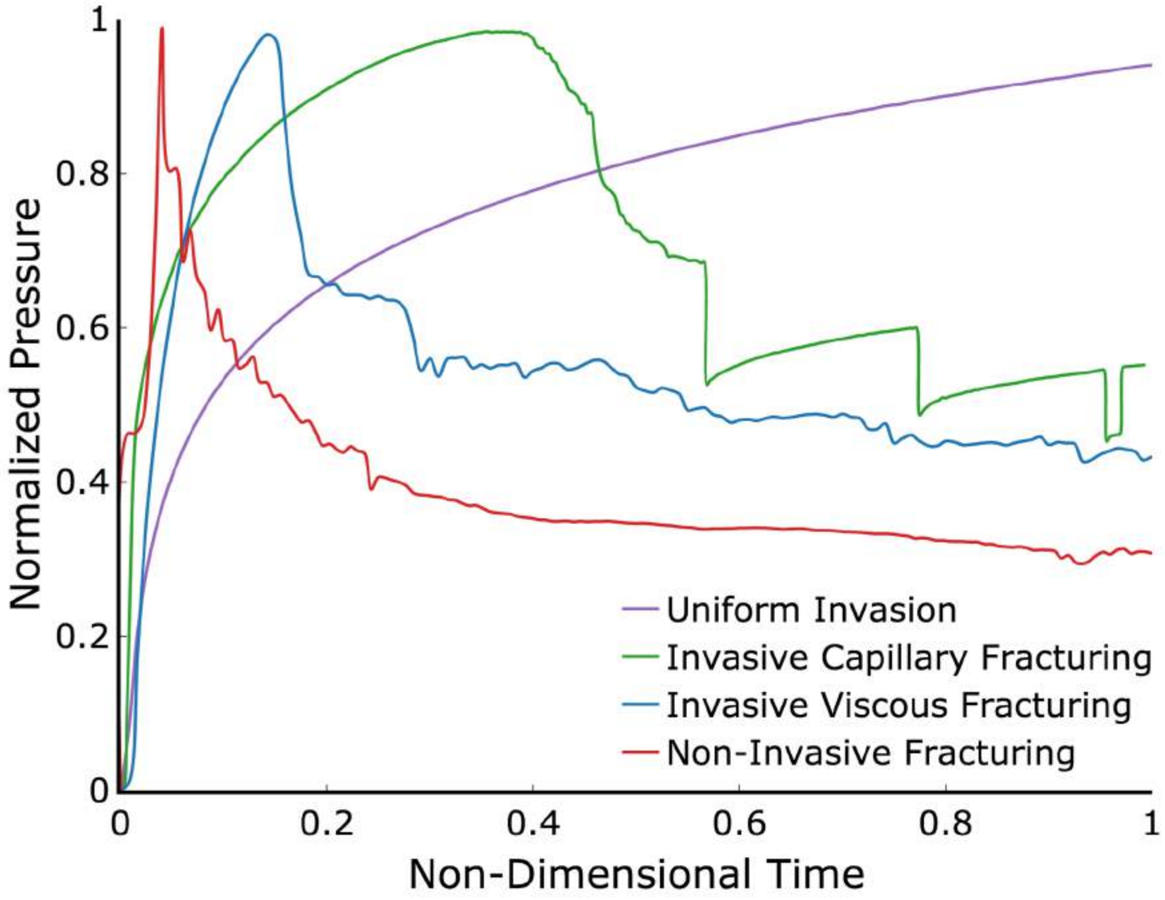
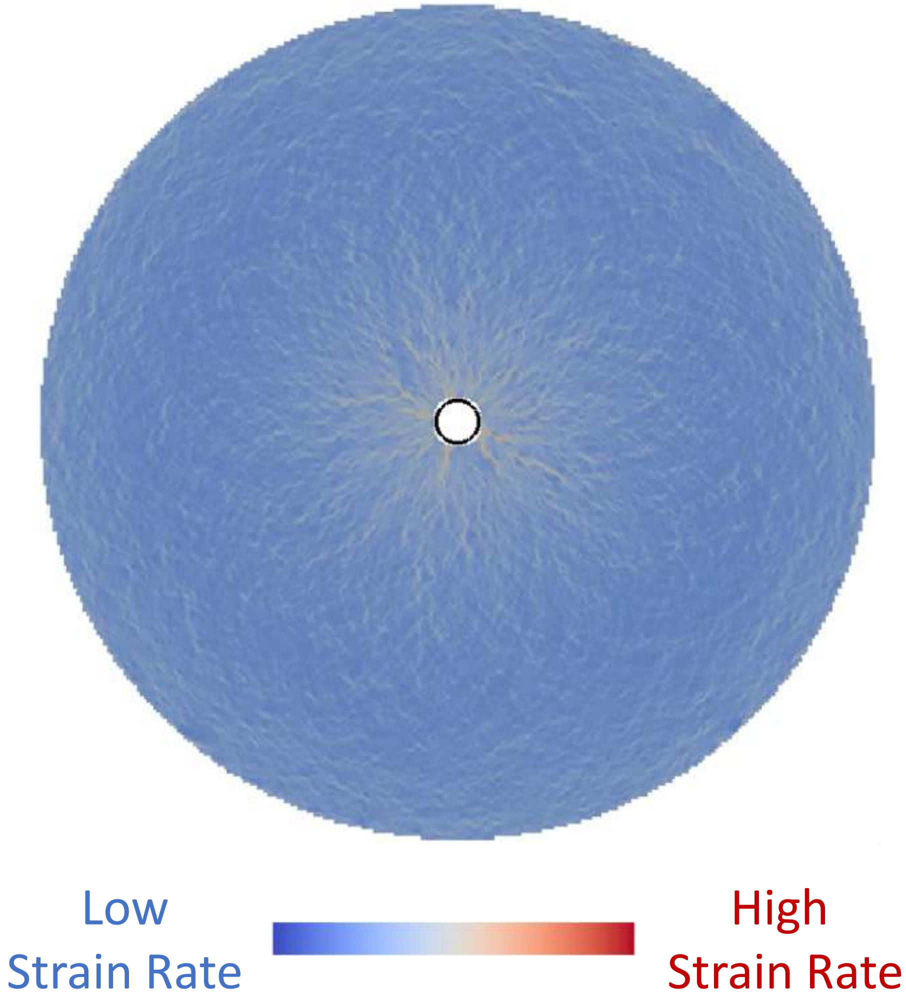
Characterization of Fracturing Types

$N_{vF} > 1 \mid N_{cF} > 1$



Non-Invasive Fracturing



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Conclusions

We developed a new framework to model multiphase flow through and around deformable porous media

The model is accessible and highly flexible with regard to its applications

The permeability of sedimentary rocks is clay-content dependent and can be described by an error function

Fracturing during drainage exhibits three different deformation regimes

Muchisimas Gracias!

Thank You!

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