Determination of Two-Phase Flow Properties with SatuDict

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Case Study

Input:

- Tomogram of Palatine Sandstone (Pfälzer Buntsandstein)

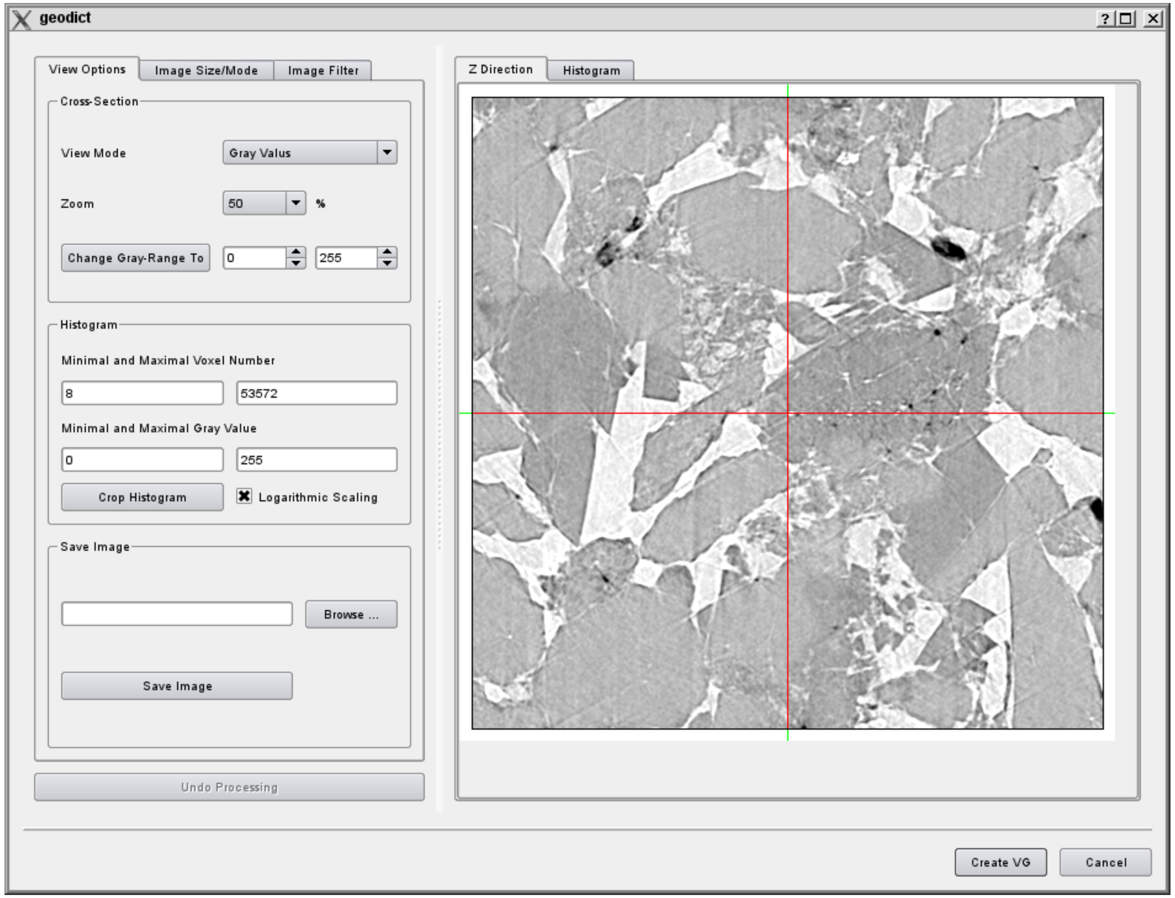
Aim: Determine (saturation dependent) permeability

Steps:

- Segmentation (ImportGeo)
- Pore size distribution (PoroDict)
- Capillary pressure curve (SatuDict)
- Permeability, fully saturated (FlowDict)
- Relative permeability, partially saturated (SatuDict)

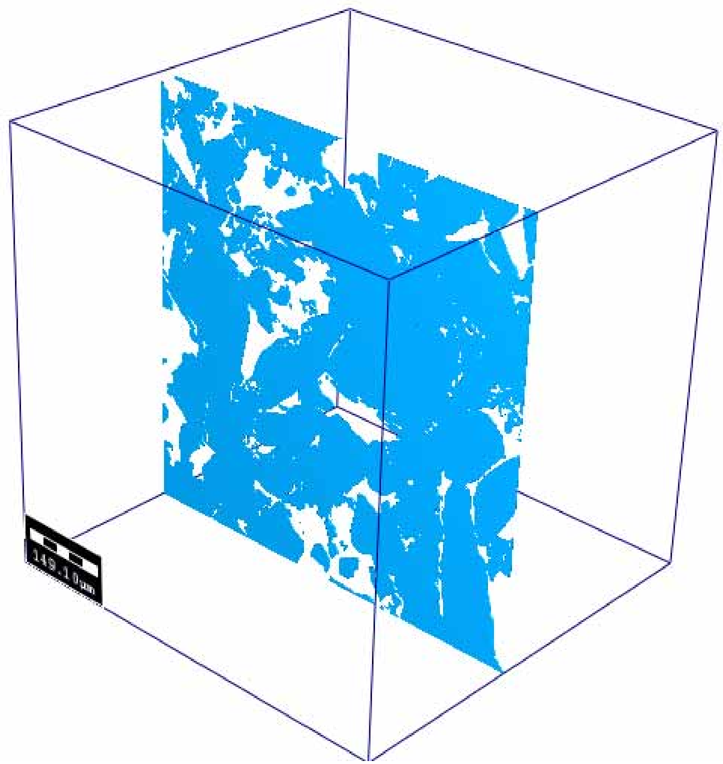
Tomogram

- F. Enzmann, Inst. for Geosciences, Uni Mainz
- Pfälzer Buntsandstein
- resolution 0.7 µm
- 1024^3 voxels



Segmentation

- Porosity 25.7 %
- Downscaled to 512³ voxels



Pore Size Distribution

Pore space : X

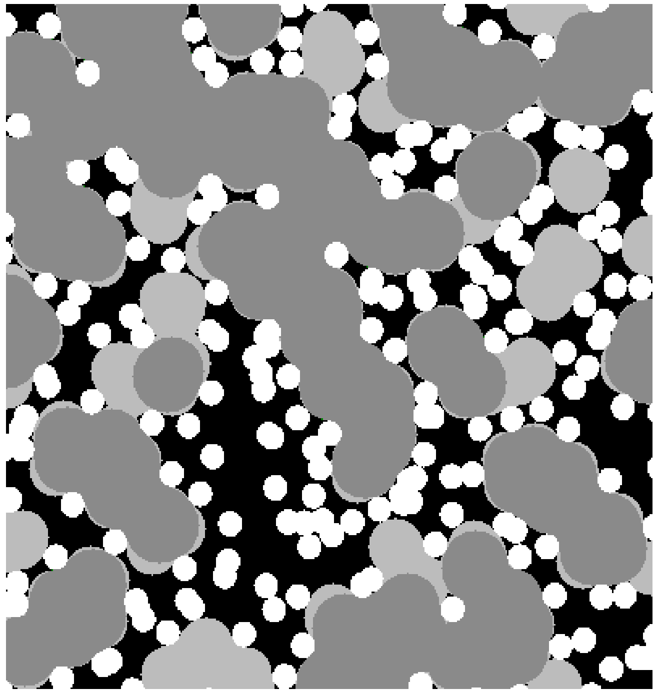
Opening of radius r :

$$O_r(X) = \bigcup_{B_{r,x} \subset X} B_{r,x}$$

Volume of pores with radius $r_1 \leq r \leq r_2$:

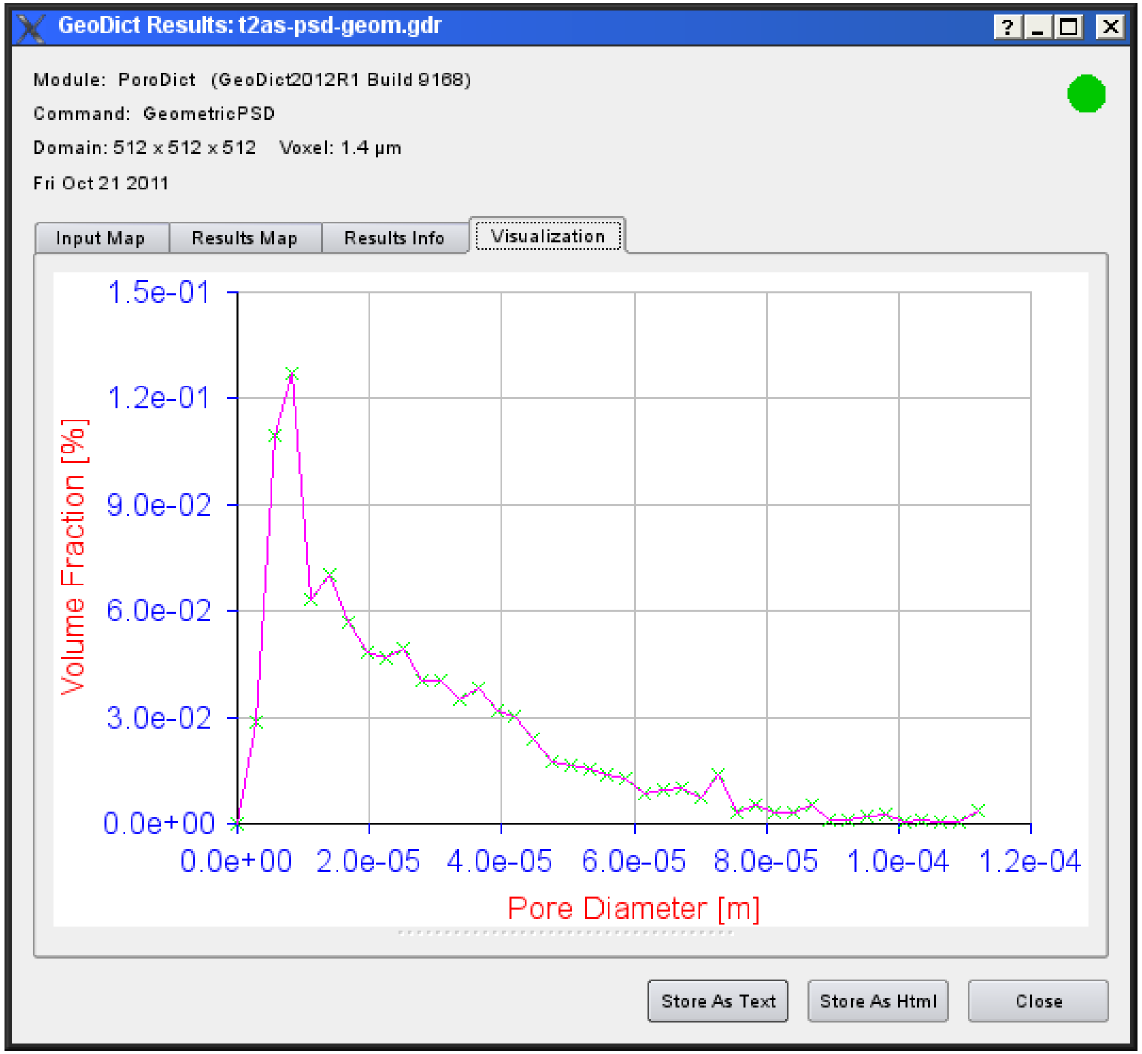
$$O_{r_1}(X) - O_{r_2}(X)$$

(PoroDict - Geometric Pore Size Distribution)



dark grey: $r \geq 20$
light grey: $16 \leq r < 20$

Pore Size Distribution (Sandstone)



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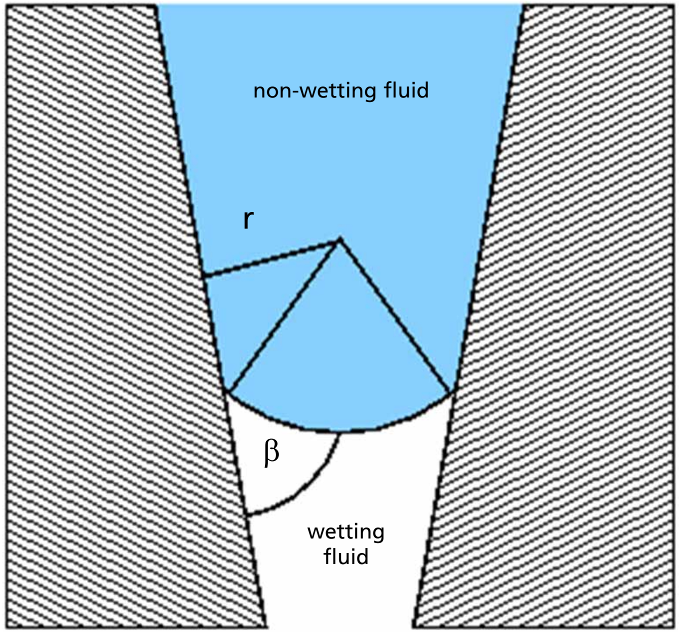
Capillary Pressure / Pore Morphology Method



- Young – Laplace equation

$$p_c = \frac{2\sigma}{r} \cos \beta$$

  (pore radius <-> cap. pressure)

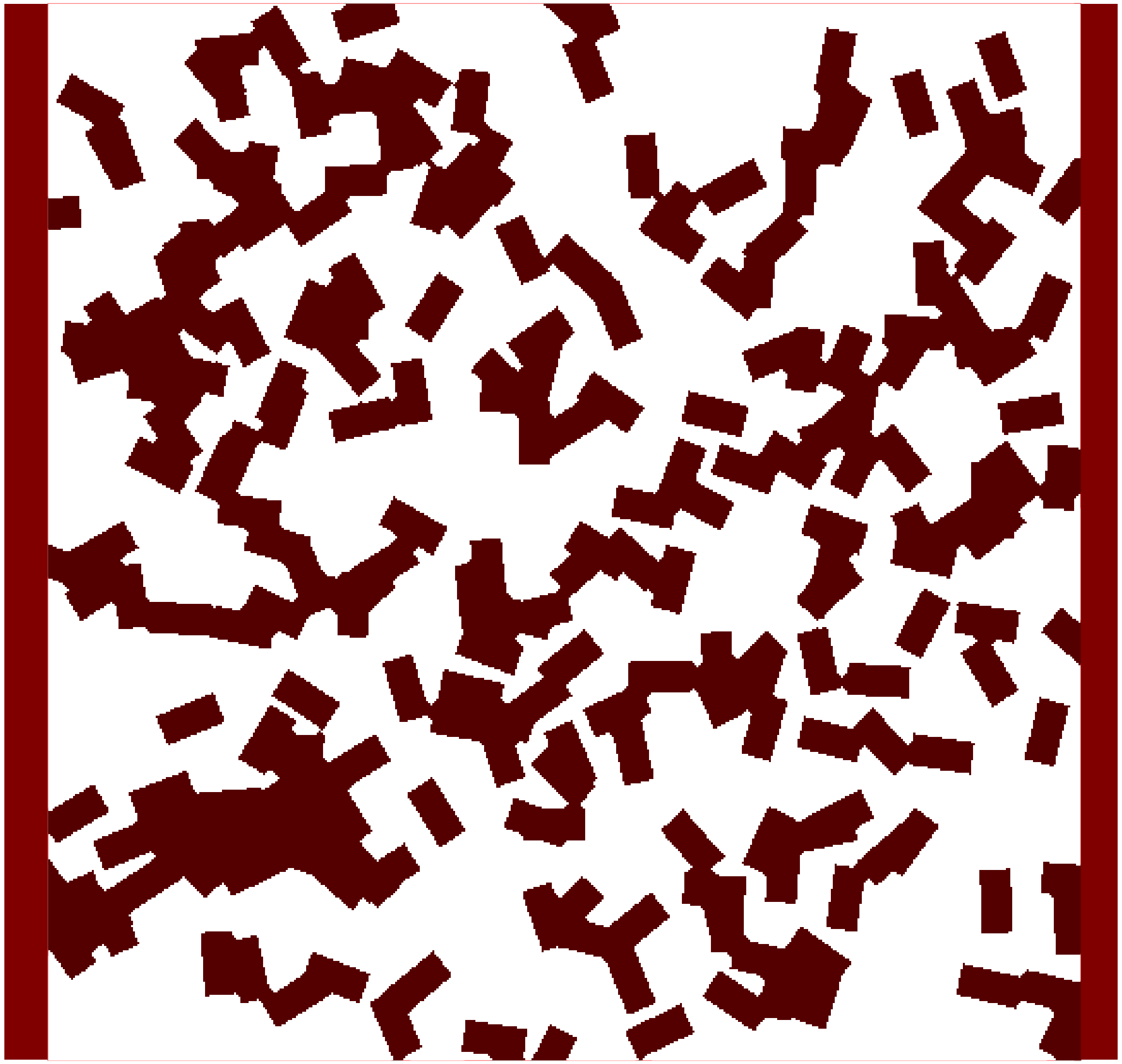
- => Pore size distribution gives saturation at given cap. pressure
- But: connectivity of pores ?

Pore Morphology Method:

- adds connectivity checks to Young-Laplace
- low numerical cost

Drainage I

- Hilpert / Miller 2001
- SatuDict 2010R2
- Guarantees connectivity of NWP to reservoir
- Idea: move in spheres
  - Start: completely wet
  - Start: large radius (i.e. small p_c)
  - Steps: smaller radius (higher p_c)
- No residual water



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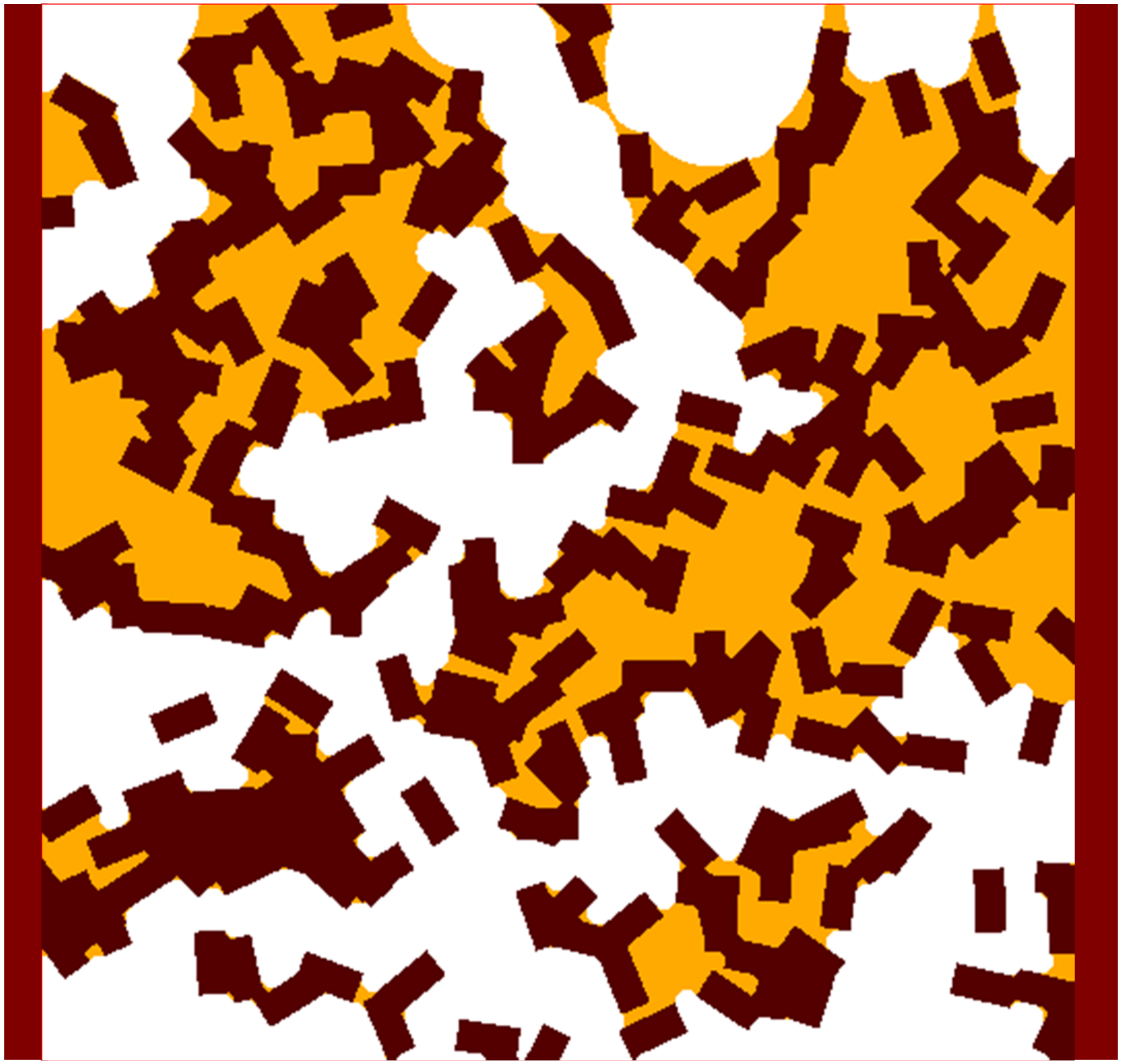
Drainage II

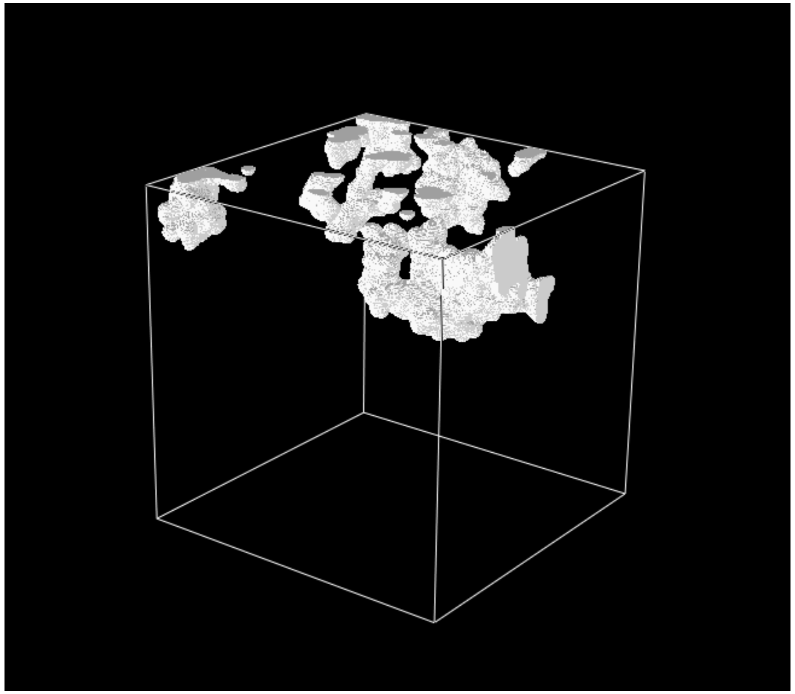
- Ahrenholz et al. 2008
- Additionally: WP must be connected to reservoir
- Residual water (orange)

Non-wetting phase (air) reservoir

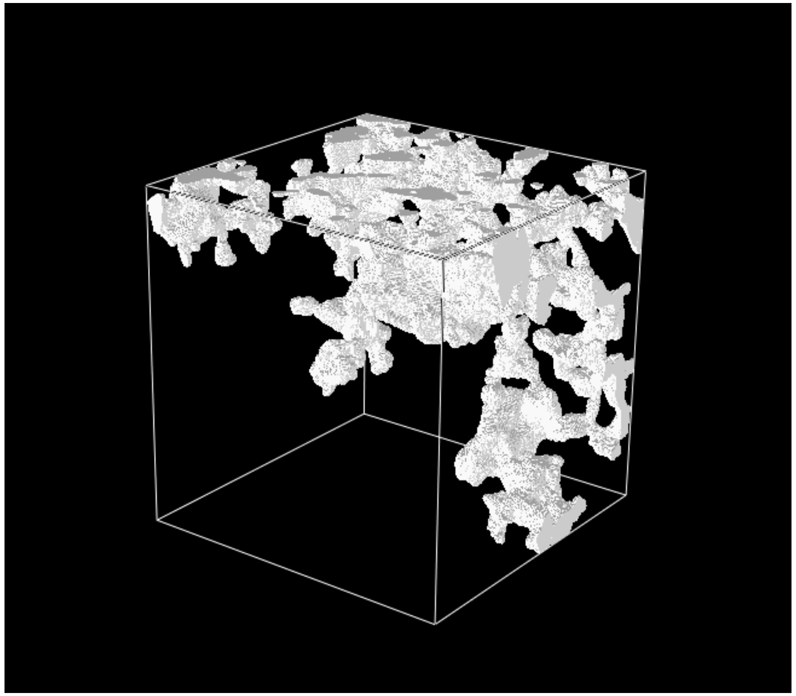


Wetting phase (water) reservoir

Drainage (Sandstone Sample)



Drained pores (r = 14 µm)

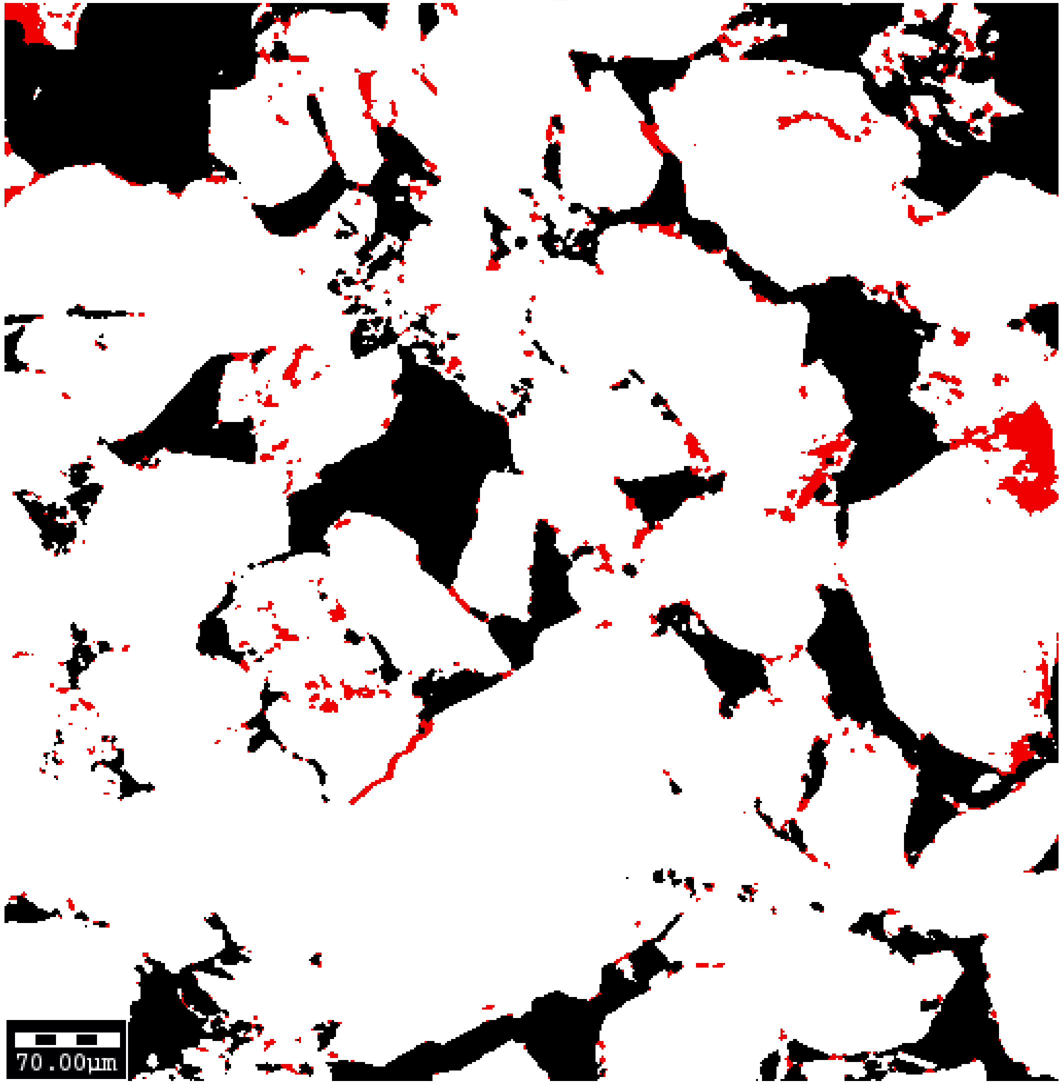


Drained pores (r = 8.4 µm)

Drainage - Sandstone Sample

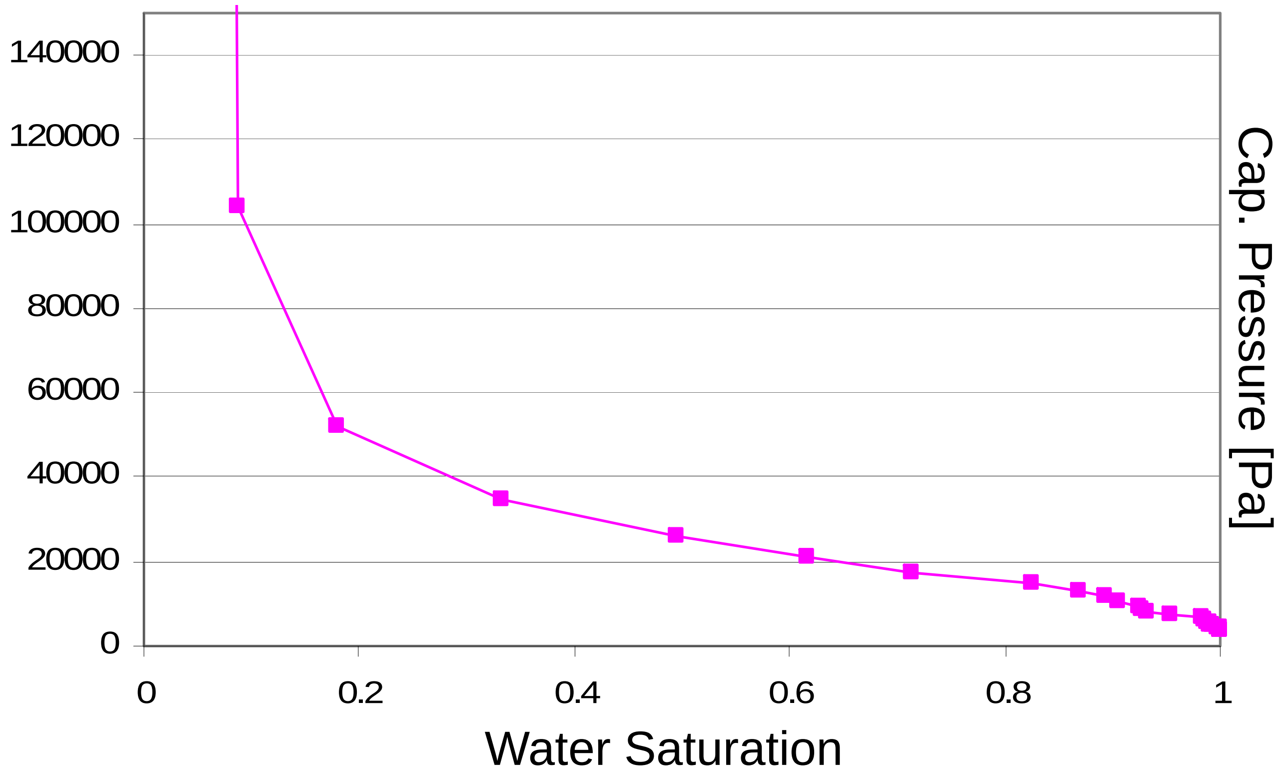
- Slice of the 3D result
- Residual water: 8.6 %

- black: air
- red: residual water
- white: matrix material

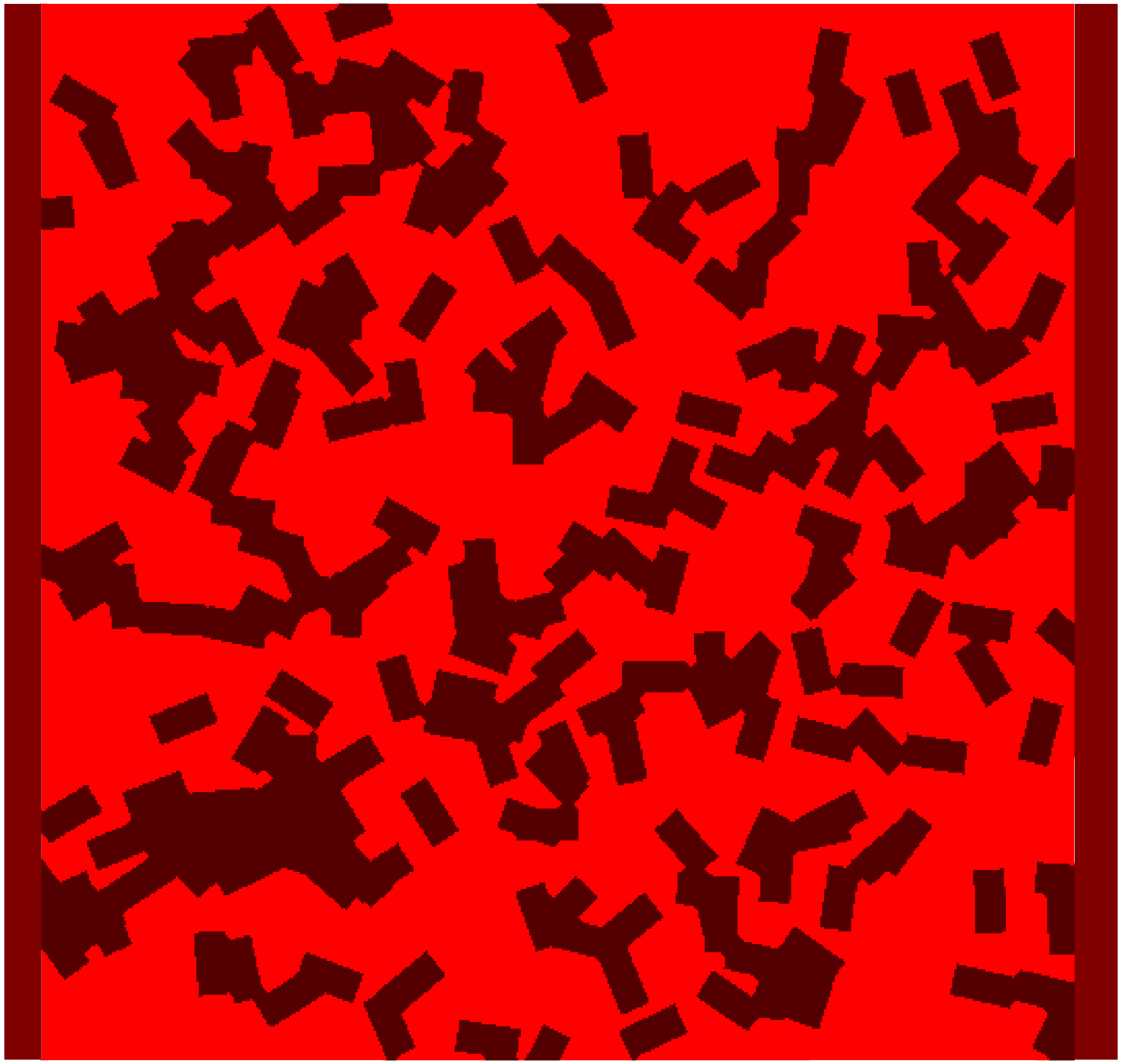


Capillary Pressure Curve (Drainage, Sandstone)

- Drainage II
- contact angle 0°



Imbibition I



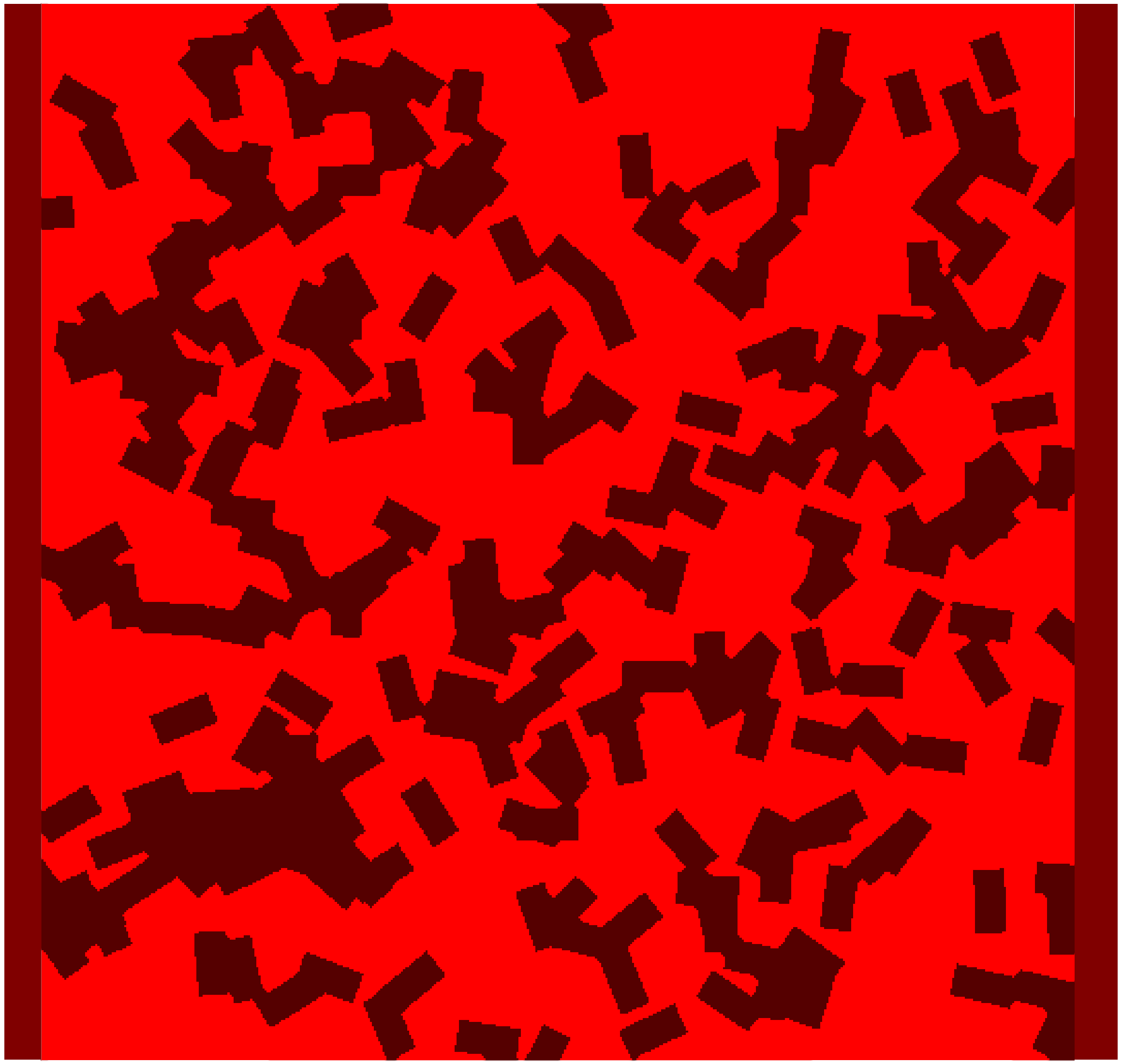
- Hilpert / Miller 2001
- SatuDict 2010R2
- No connectivity checks
- No residual air
  - Start: completely dry
  - Start: small radius (i.e. large p_c)
  - Steps: larger radius (smaller p_c)

Distribution by pore radius (Young-Laplace)

Imbibition II

- Ahrenholz et al. 2008
- WP must be connected to reservoir
- No residual air

Non-wetting phase (air) reservoir

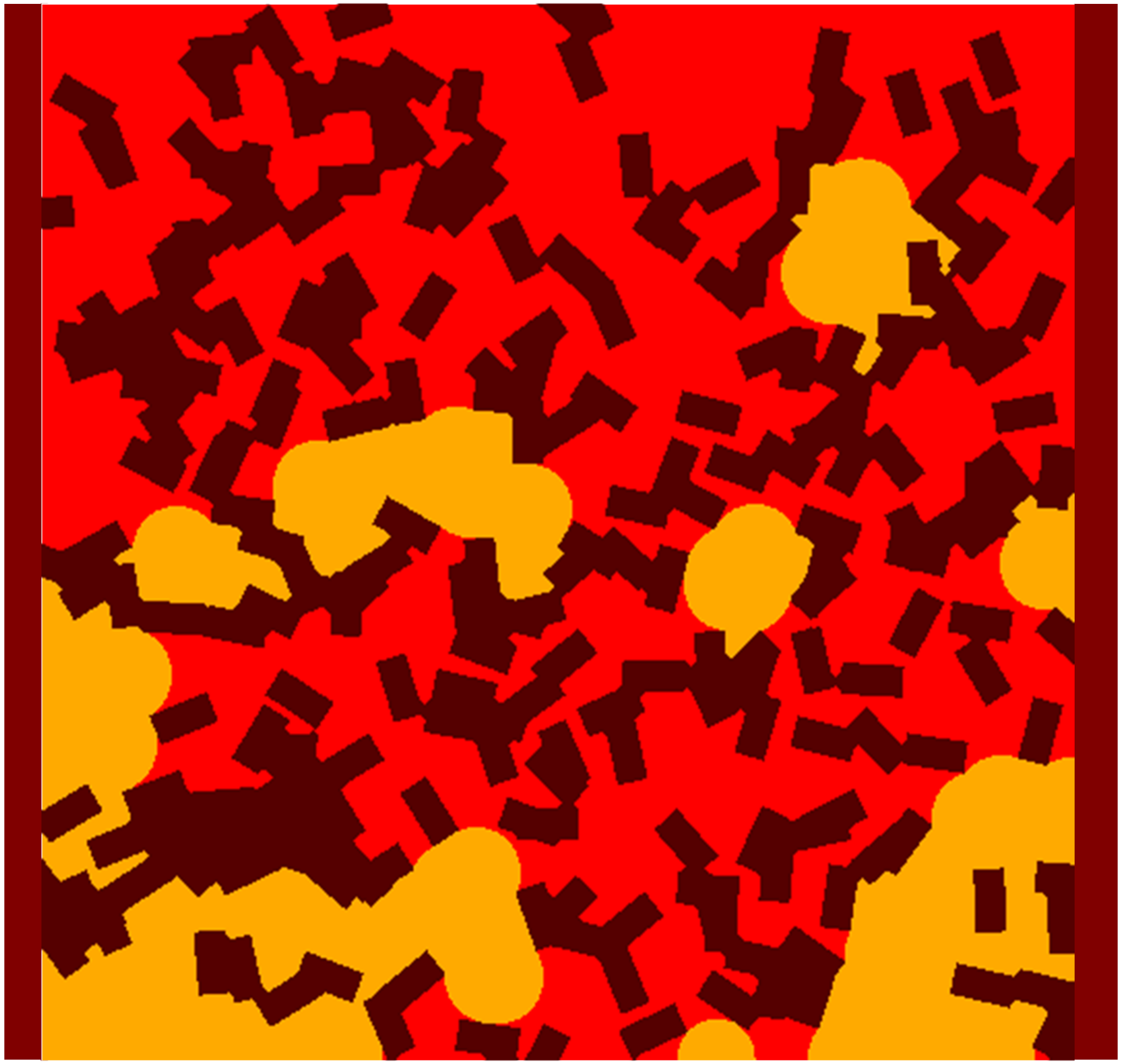


Wetting phase (water) reservoir

Imbibition III

- Ahrenholz et al. 2008
- WP must be connected to reservoir
- NWP must be connected to NWP reservoir
- Residual air (orange)

Non-wetting phase (air) reservoir



Wetting phase (water) reservoir

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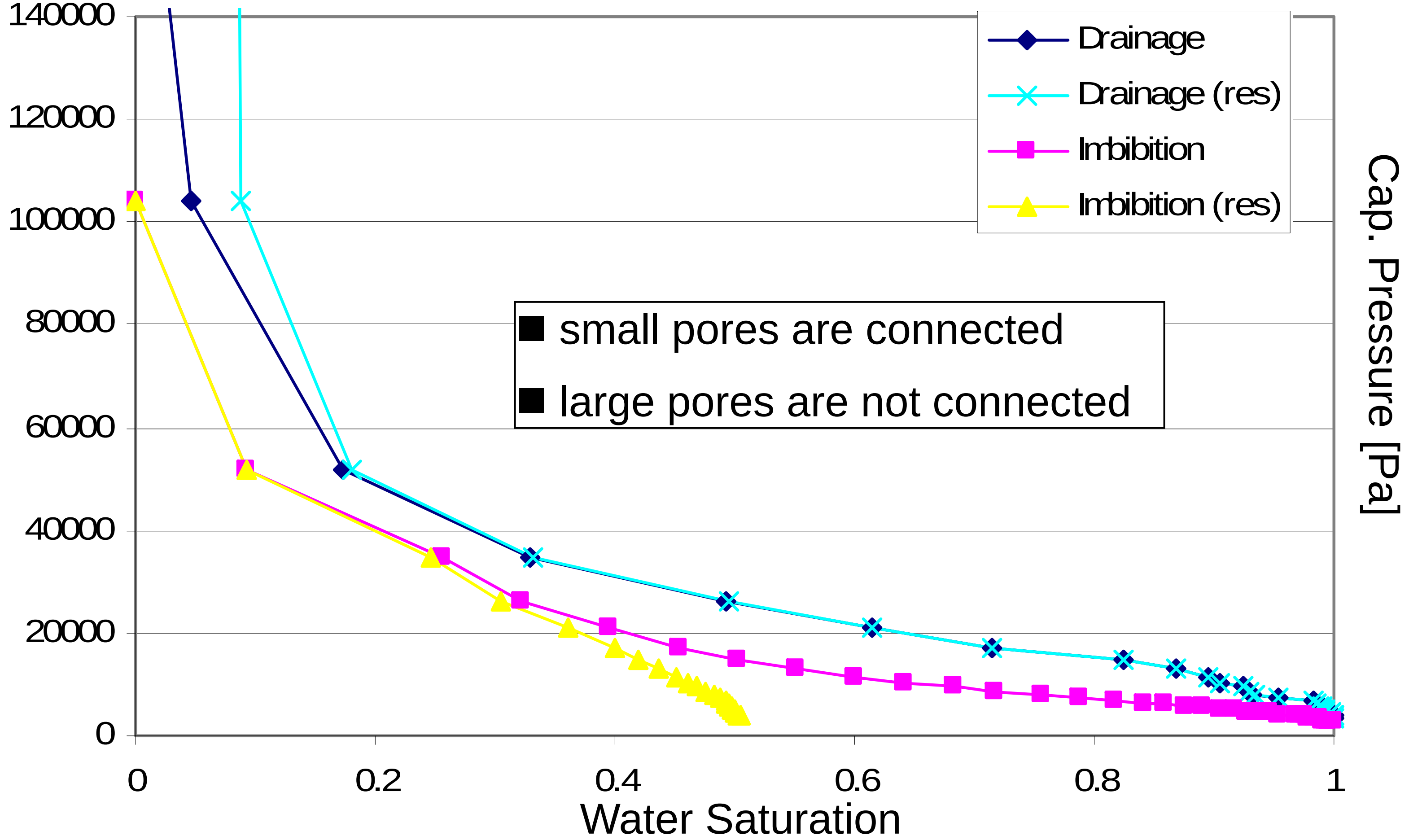
Drainage & Imbibition (Sandstone)

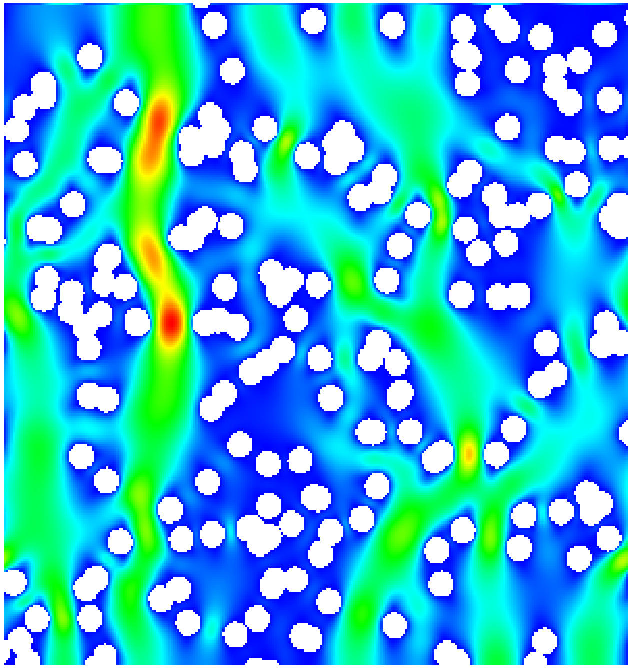


Permeability

Macroscopic description
(homogenized porous media model)

Darcy's law : $u = -\frac{1}{\mu}\kappa \nabla p$

u : average flow velocity
κ : permeability tensor ***unknown***
μ : viscosity
p : pressure



Microscopic description
(pore structure model)

Stokes equation: $-\mu \Delta u + \nabla p = 0$

Boundary conditions: no-slip on surface, pressure drop
κ can be determined from the solution!

Permeability (Sandstone)

FlowDict Result (EJ-Stokes): 0.966 e-12 m^2

Relative Permeability

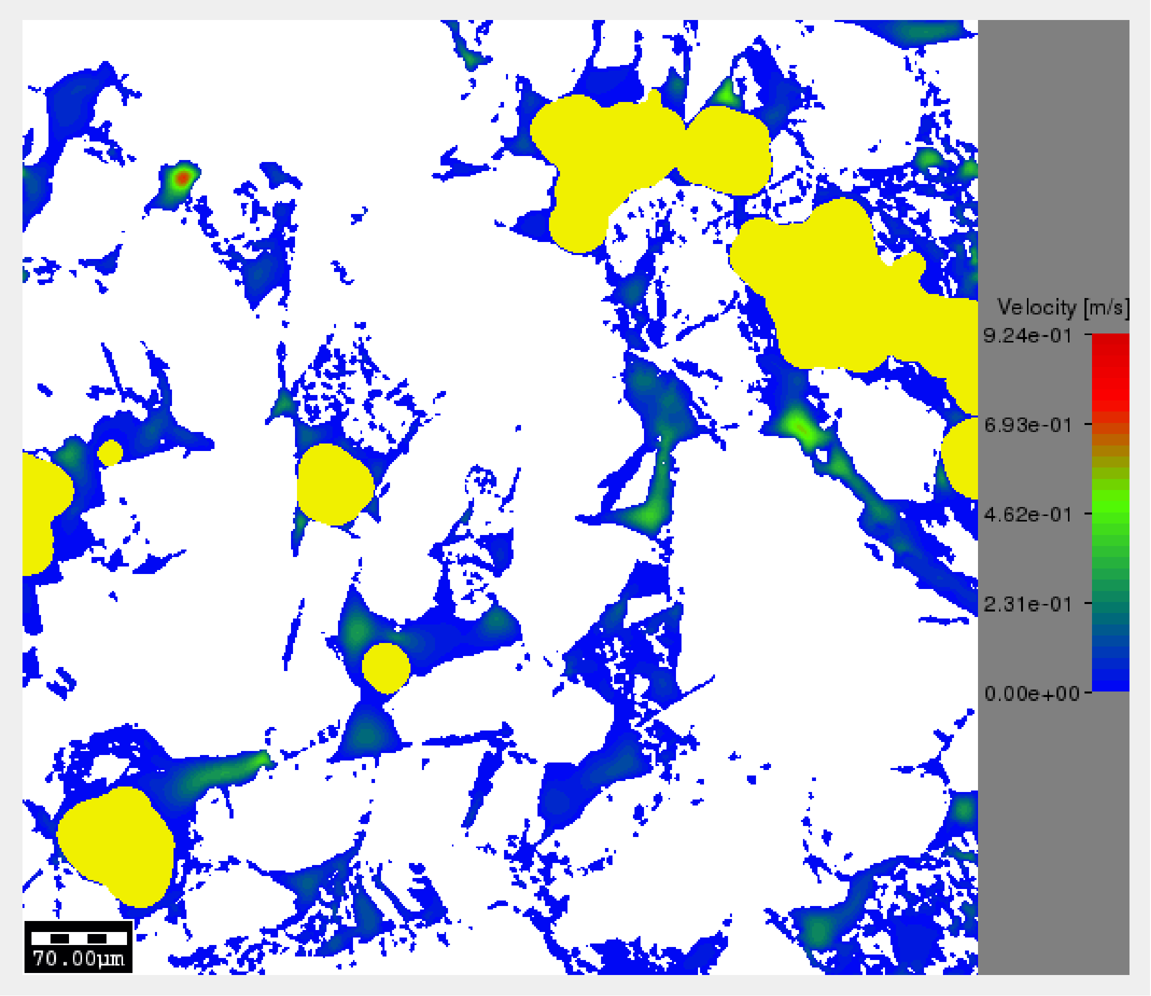
Idea:

- Combine
  - phase distributions from pore morphology
  - single-phase flow

- Advantage:
  - low computational costs
  - stability

Relative Permeability (Sandstone)

- Choose saturation level, choose wetting model
- Use PM to find air distribution (here: yellow)
- Solve Stokes equation in remaining pore space



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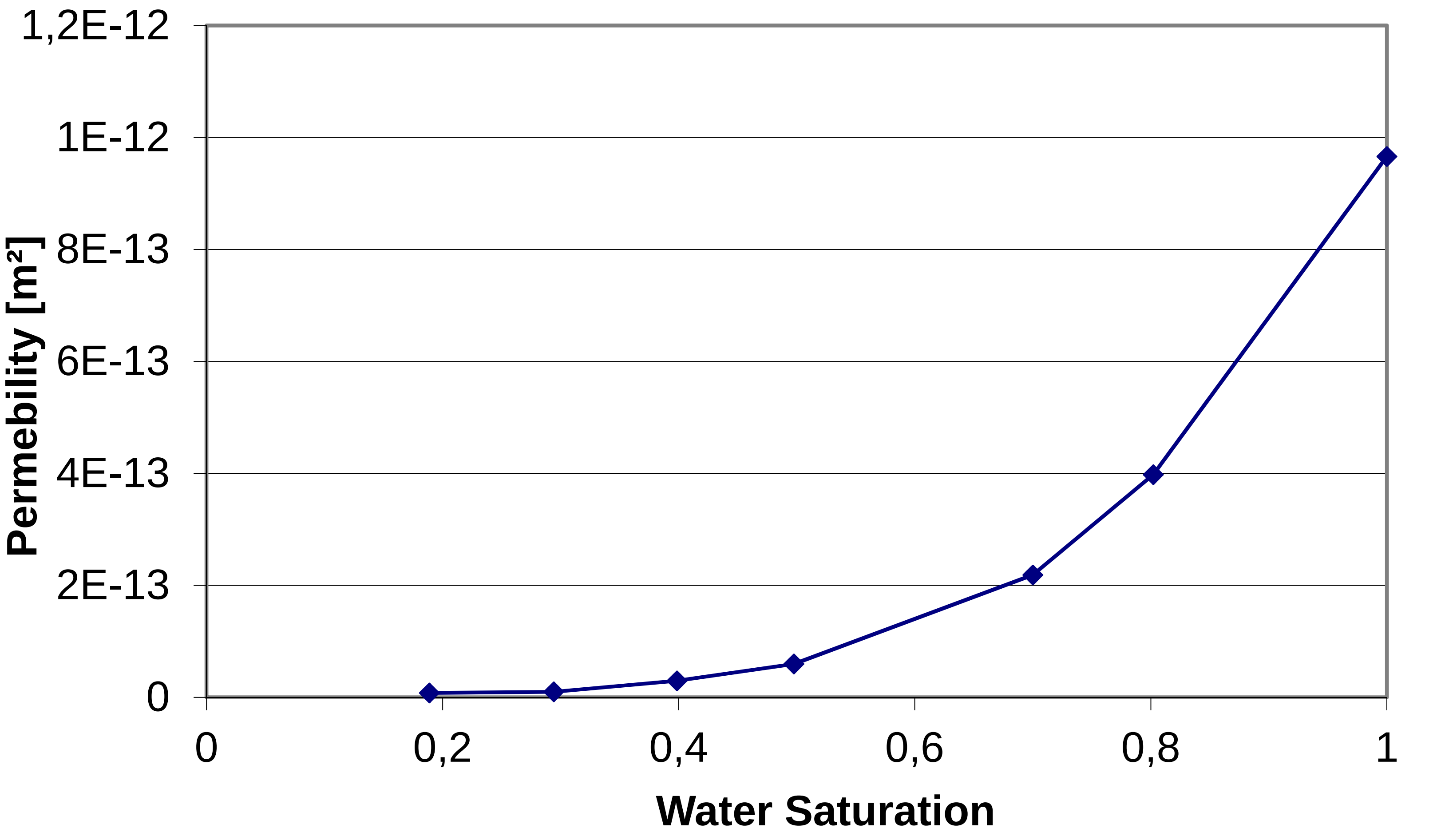
Relative Permeability (Sandstone)



Summary: Case Study

Input:

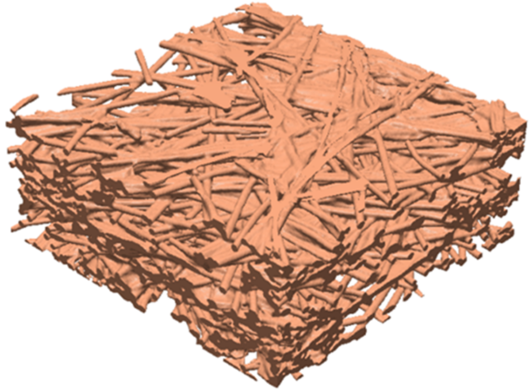
- Tomogram of Palatine Sandstone (Pfälzer Buntsandstein)

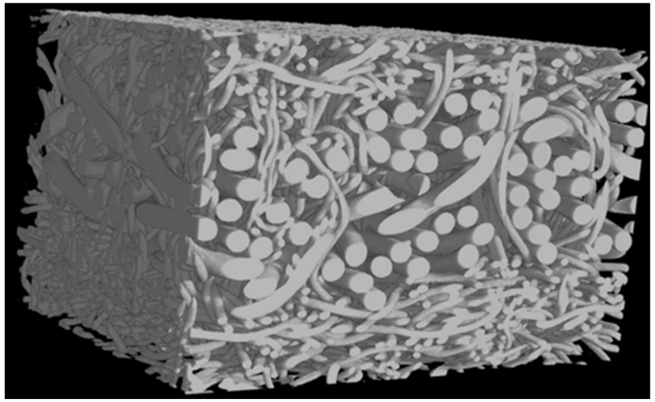
Calculated properties:

- Pore size distribution
- Capillary pressure curve
- Permeability
- Relative permeability

Comments

- Same ideas can be used for diffusivity or conductivity
- Applications:
  - Gas diffusion layer of fuel cells
  - Hygiene products
  - Paper dewatering felts





Thank you !