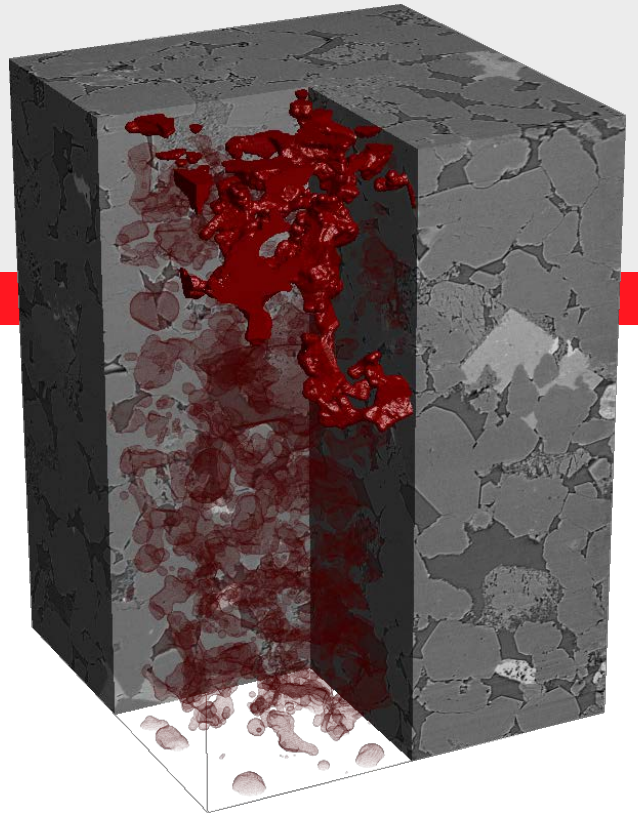
Pore Morphology Method with Hysteresis Effect for Enhanced Oil Recovery Applications



Interpore 05/11/2017, Rotterdam, Netherlands

Dr. Sven Linden

Andreas Wiegmann, PhD

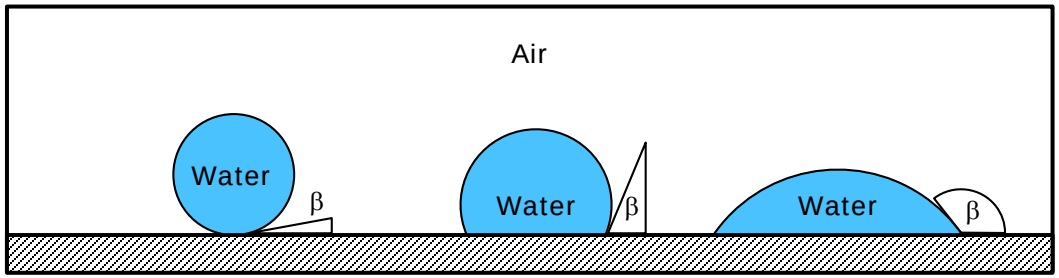
Math2Market GmbH

Math2Market GmbH and its GeoDict software
Some background information

- Math2Market creates & markets software to analyze/design porous & composite materials based on the material's geometric inhomogeneity
- M2Ms software is called GeoDict, the Digital Material Laboratory
- GeoDict works on µCT-based, FIB-SEM-based and intrinsic models - in all cases, the computer representation consists of 3-D images
- M2M was spun off in 2011 from Fraunhofer Institute for Industrial Mathematics
- M2M is based in Kaiserslautern, Germany, and privately owned
- M2M has more than 100 clients from around the world

Two-Phase Systems

- Consider the distribution of two fluids at given static conditions in a porous media
- Two fluids are not mixed but separated by an interface that has a meniscus shape caused by surface tension
  - One fluid wets the surface with a concave shape
  - One fluid has less affinity & is non-wetting with a convex shape



Transition from air-wet (left) to water-wet (right)

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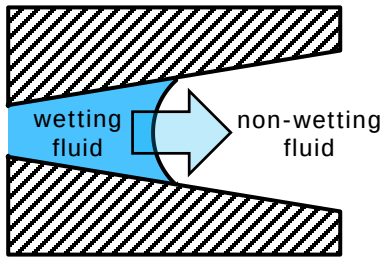
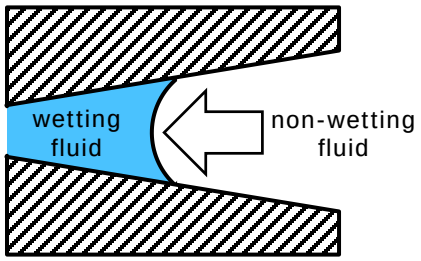
  - One fluid wets the surface with a concave shape
  - One fluid has less affinity & is non-wetting with a convex shape
- For pure (non-)wetting fluid behavior two processes exist
  - Imbibition: **wetting fluid** displaces **non-wetting fluid**
  - Drainage: **non-wetting fluid** displaces **wetting fluid**



Imbibition



Drainage

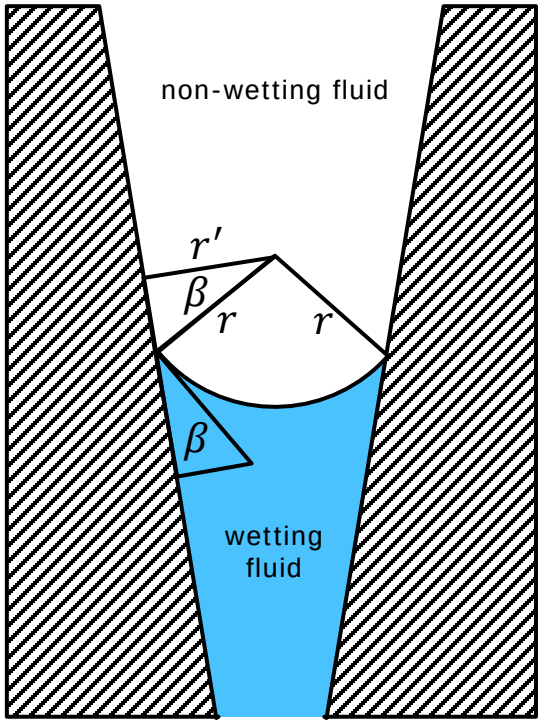
Young Laplace Equation

- For a given pressure difference (capillary pressure) p_c and surface tension γ then mean curvature κ satisfies

$$\begin{aligned} p_c &= \gamma \cdot \kappa \\ &= \gamma \cdot (\kappa_1 + \kappa_2) \\ &= \gamma \cdot \left(\frac{1}{r_1} + \frac{1}{r_2}\right) \end{aligned}$$

- Interface radii $r_{1/2}$ are defined by the capillary pressure
- Interface position is such that the angle of the interface with the cone wall is equal to the contact angle β
- Conical means $r_1 = r_2$ then we can use the pore radius r' which is a function of the position along the cone

$$p_c = \gamma \cdot \frac{2\cos\beta}{r'}$$



capillary pressure + contact angle → pore radius

Pore Morphology Methods ...

... predict the distribution of the two phases inside porous media

Basic Idea

- "Push" spheres into/outside the structure & reduce/increase sphere radii [Hilpert and Miller, 2001]
- Superposition of spheres represent the non-wetting phase
- Perform connectivity checks to consider trapped/residual phases [Ahrenholz et al., 2008]
- Use sphere radii & Young-Laplace to predict the capillary pressure
- Construct different contact angles by using interface radii larger than pore radii [Schulz et al. 2015]

Advantage

- No partial differential equations are solved
- Very low runtime & memory requirements

Assumption

- Quasi-stationary phase distribution
- Cylindrical pores

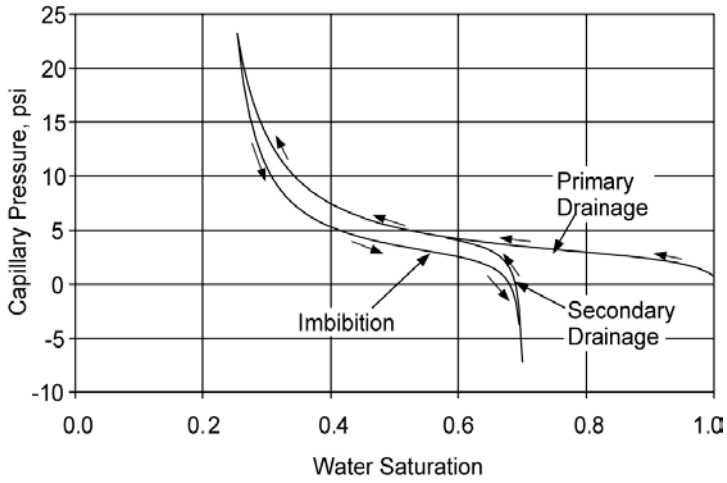
Applications of Two Phase Systems

- Filtration
  - Filter cake washing and drying 
- Electro chemistry
  - Gas and Water distribution in gas diffusion layers 
- Hygiene
  - Air and liquid distribution in diapers 
- Oil and Gas
  - Mercury intrusion capillary pressure (MICP) 
  - Capillary pressure and relative permeability for oil and water systems 

Two-Phase Flows for Enhanced Oil Recovery

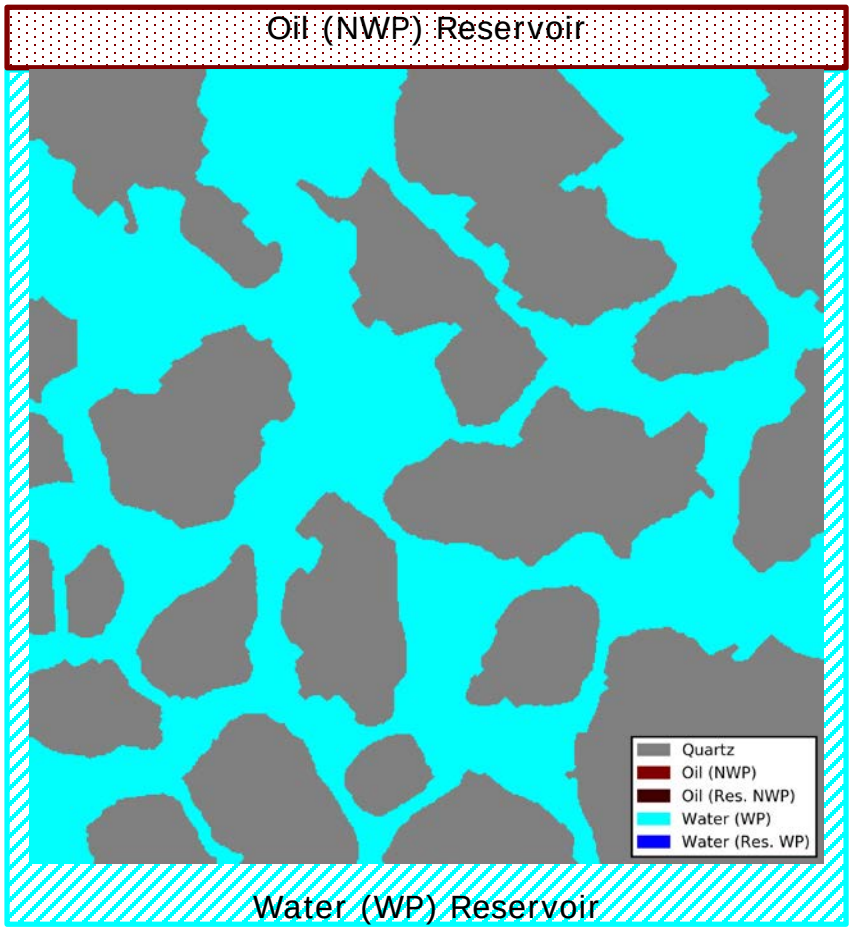
- Two-phase properties of rocks depend on the physical history of the sample
  - Oil that invades a fully water saturated rock leaves a *residual water saturation*
  - If water invades the rock again (waterflooding) then residual water may *reconnect* to invading water phase
  - These *hysteresis* effects have significant influence on the capillary pressure curve and other relative properties
  - Hysteresis effects do not occur in highly porous structures (e.g. gas diffusion layers)

Source: www.petrowiki.org/Capillary_pressure



The original pore morphology method is not able to consider residual WP and residual NWP at the same time

Primary Drainage
Oil displaces Water



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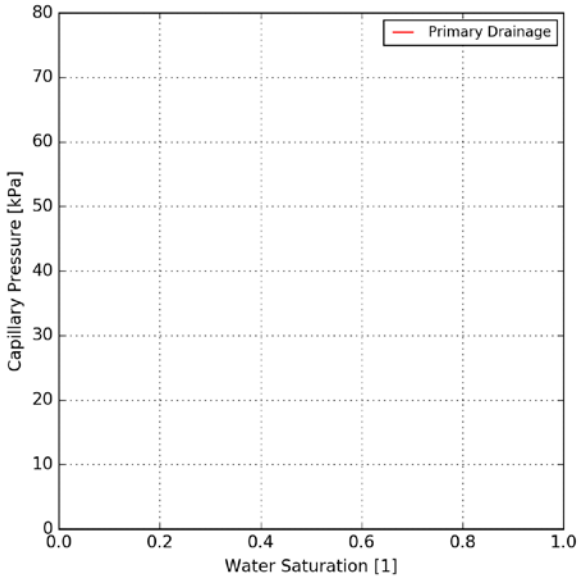

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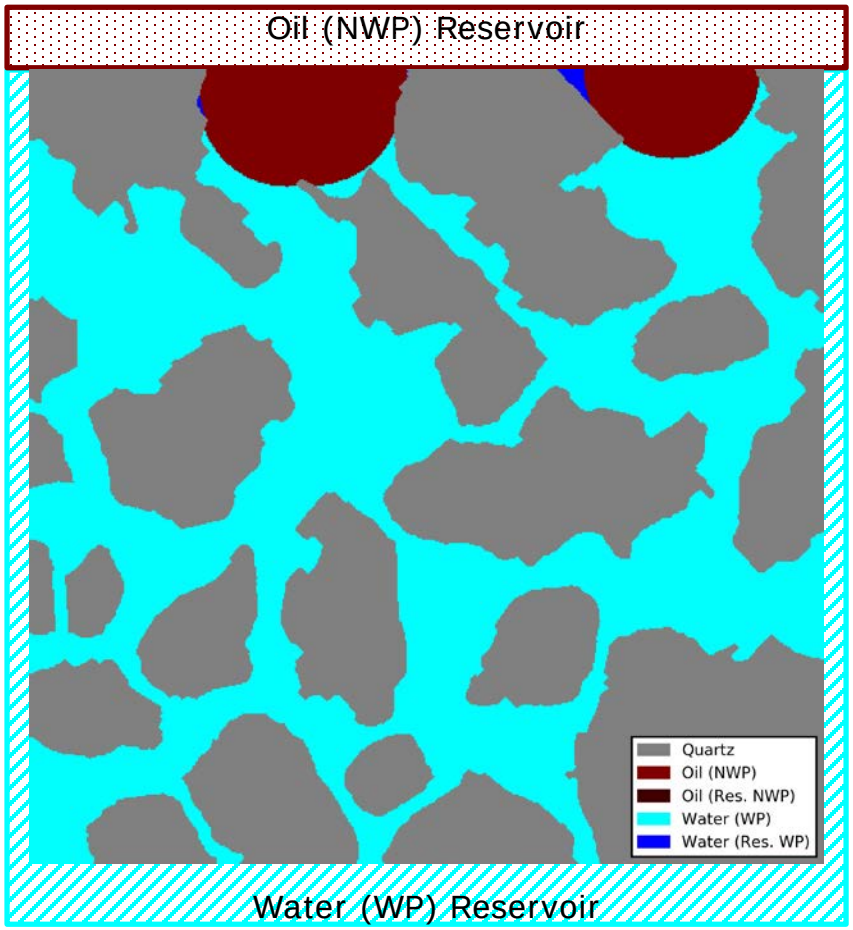

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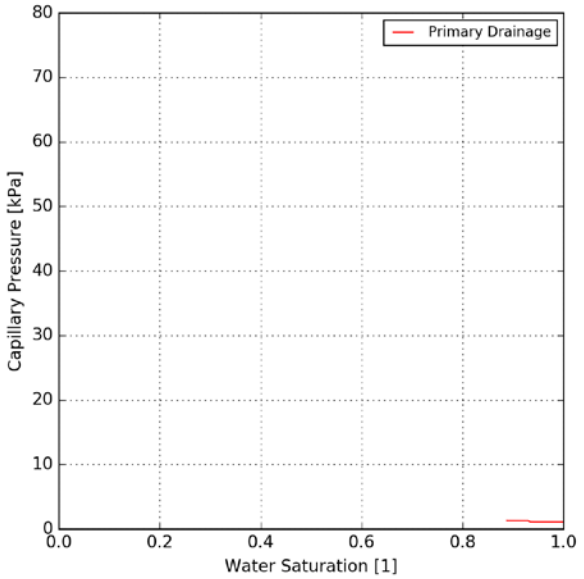

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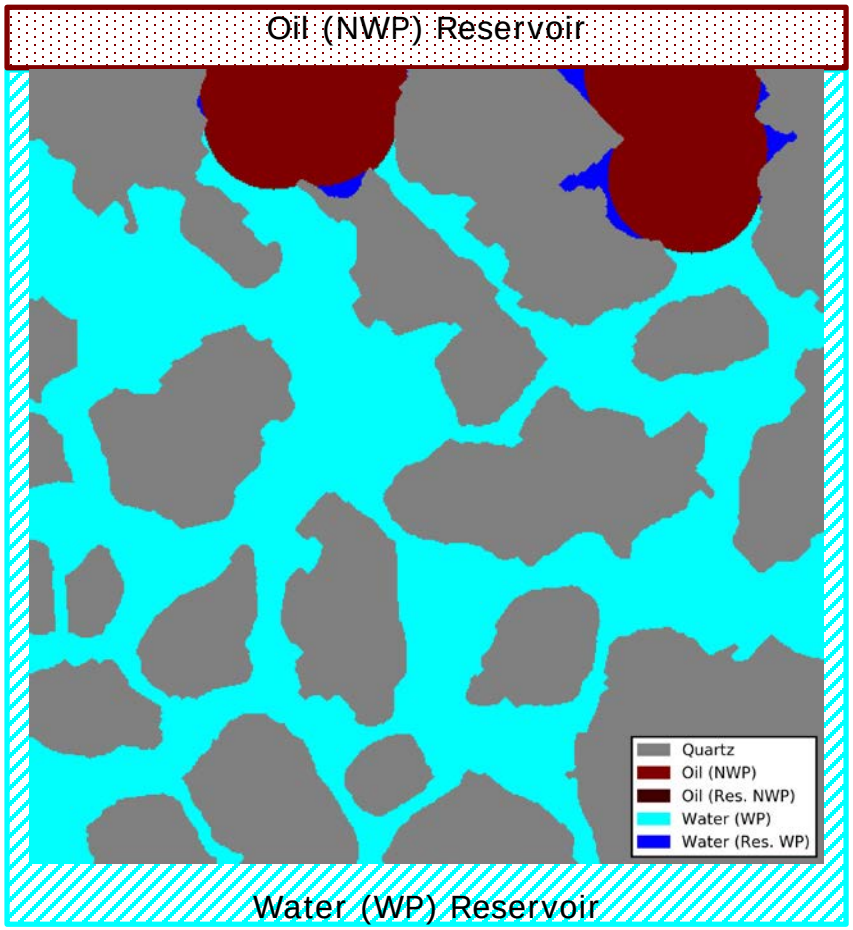

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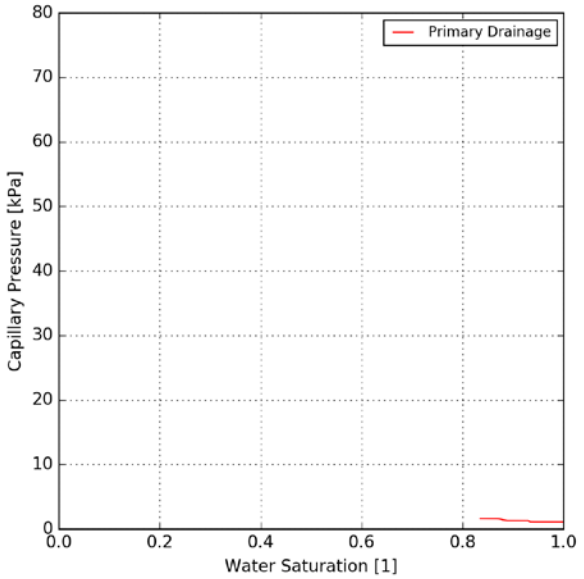

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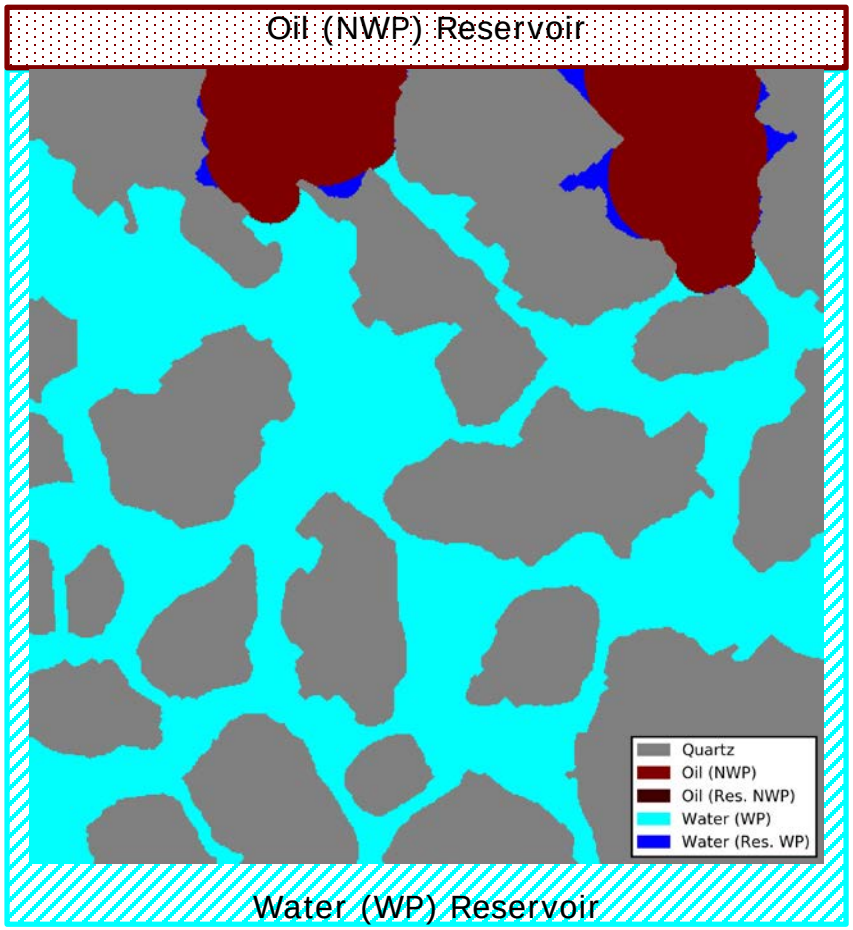

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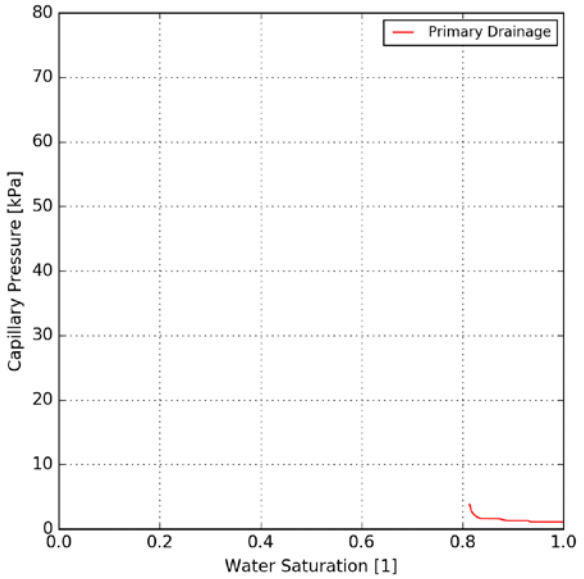

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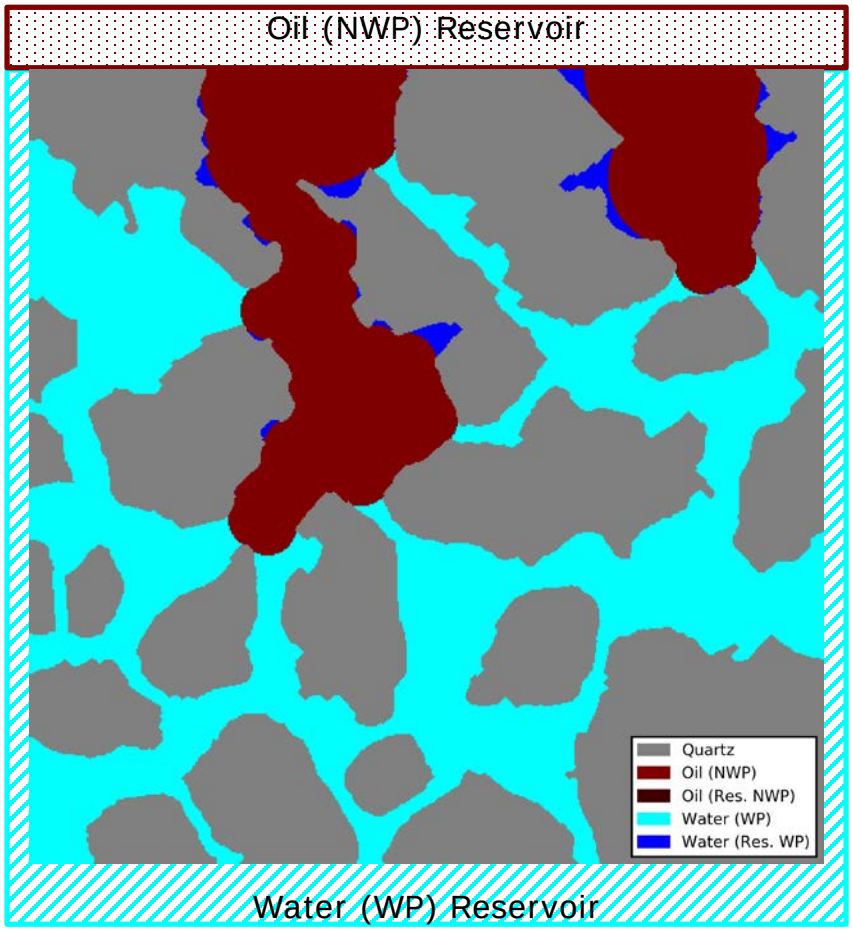

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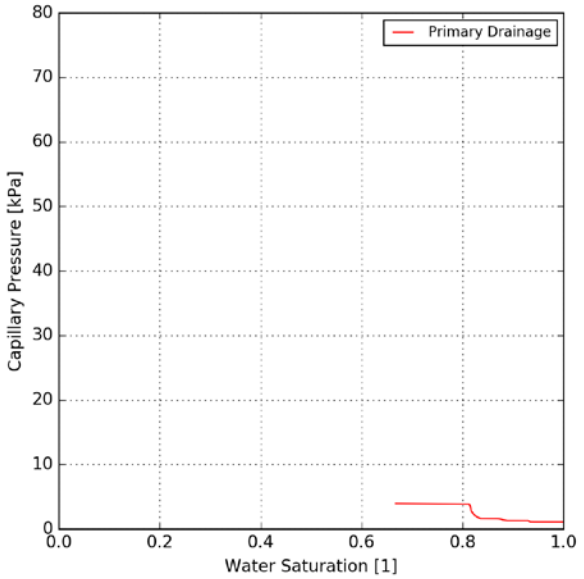

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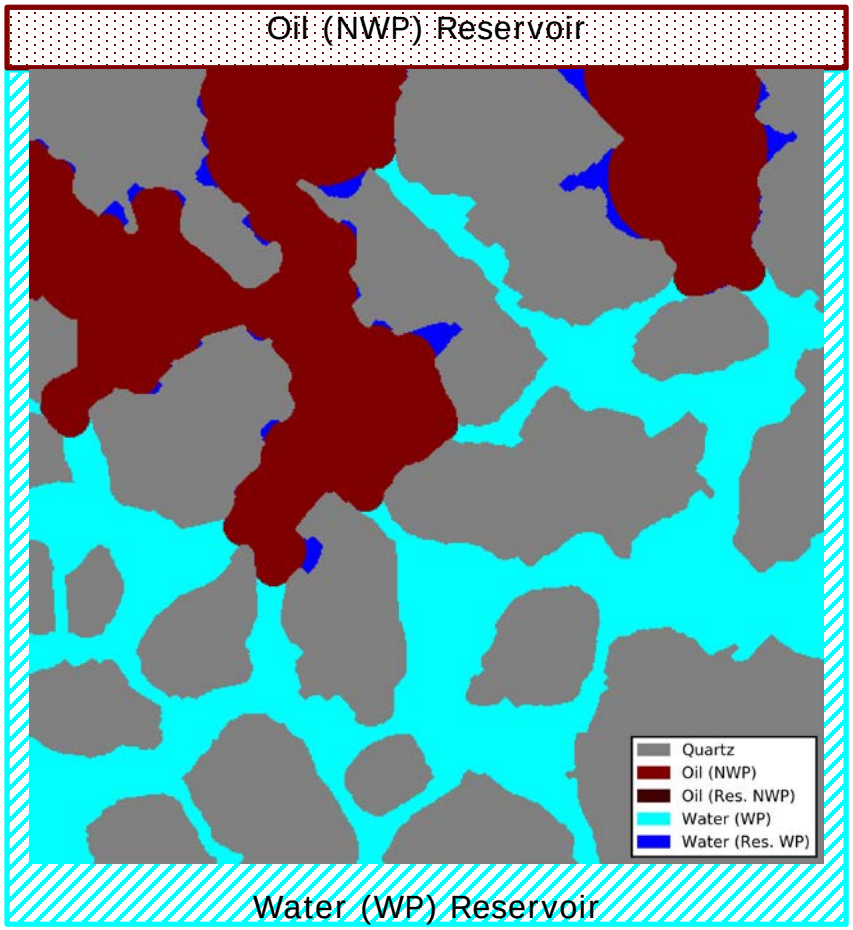

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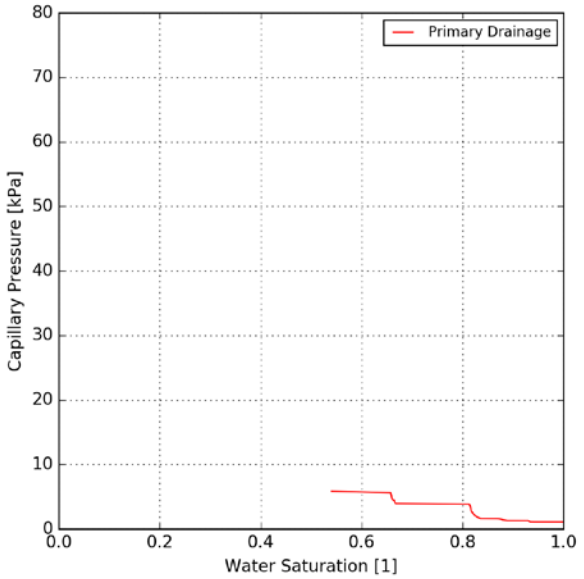

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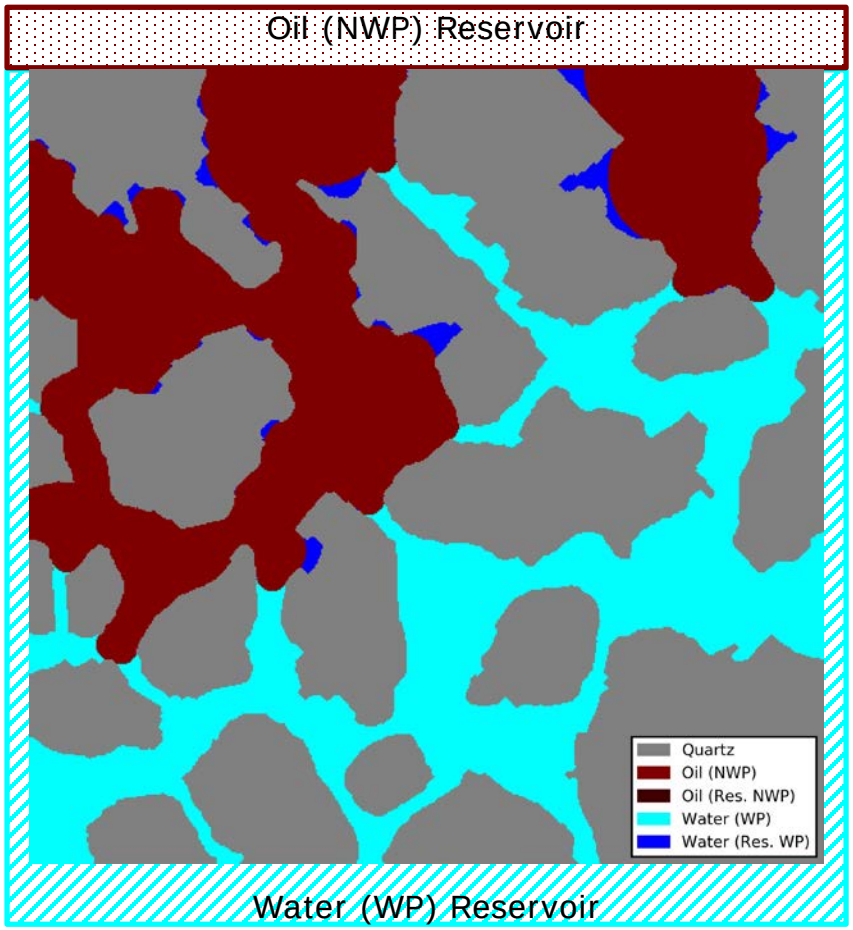

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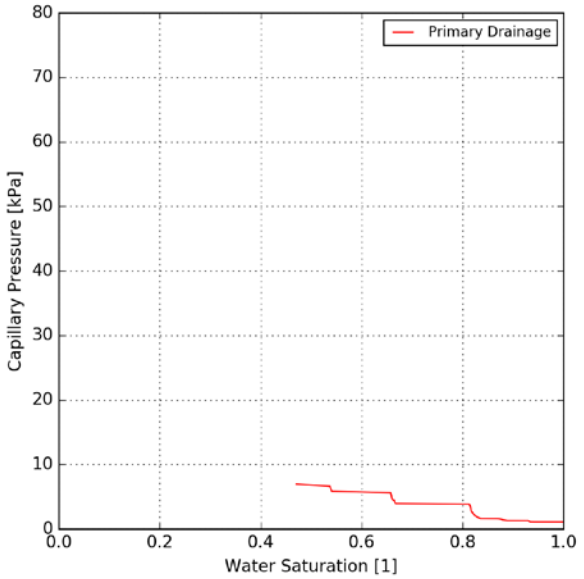

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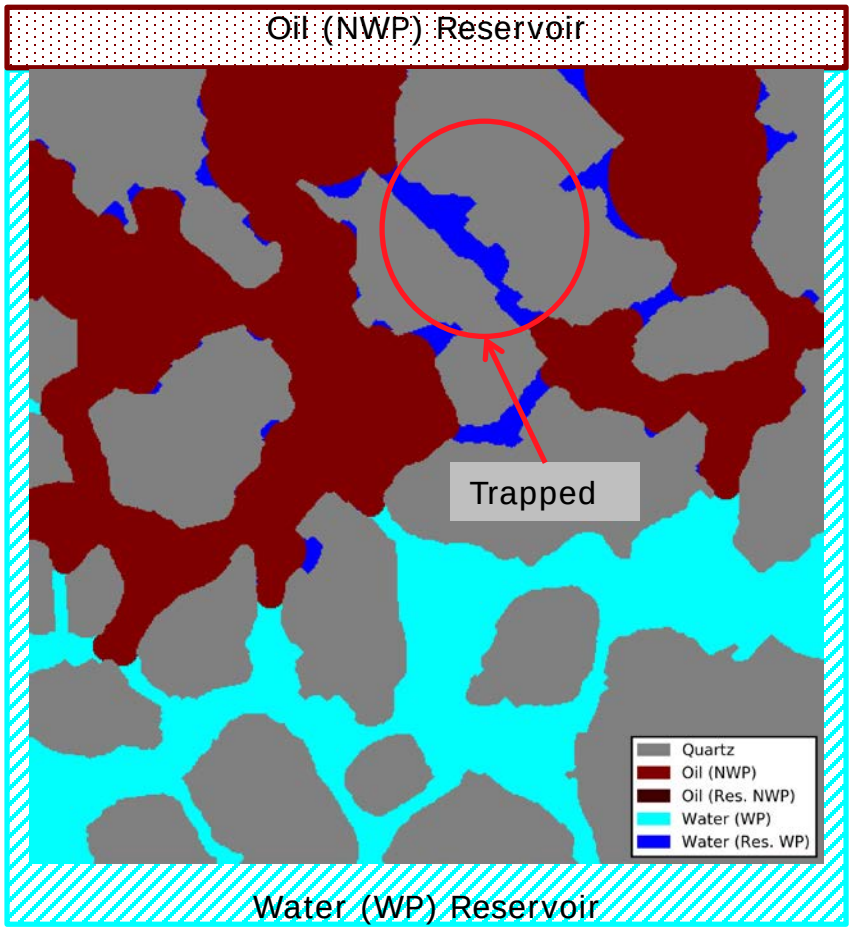

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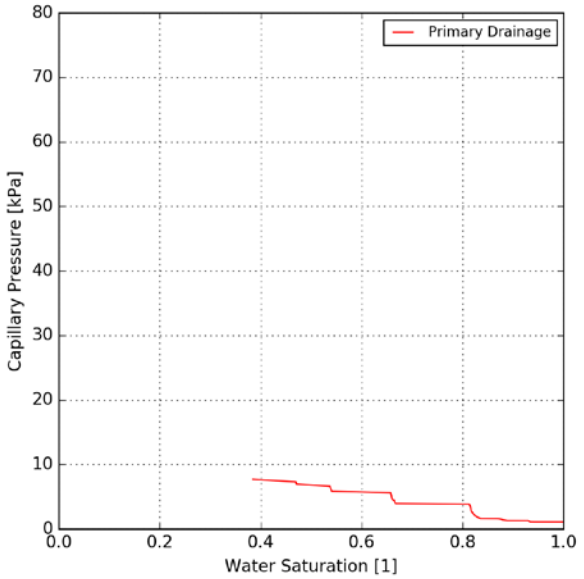

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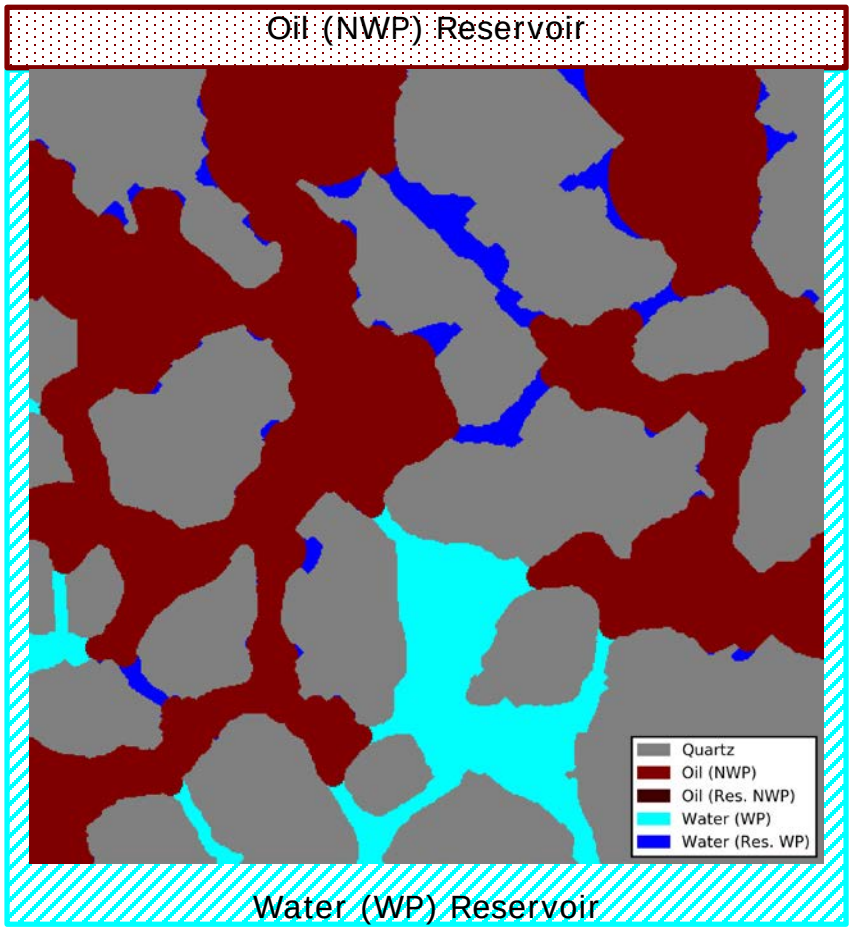

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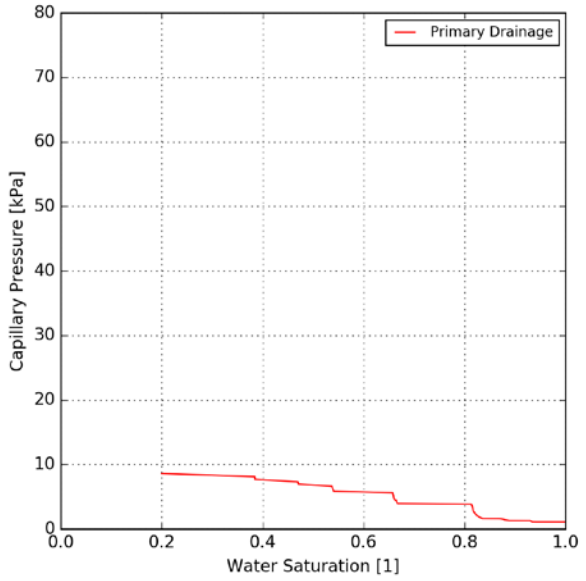

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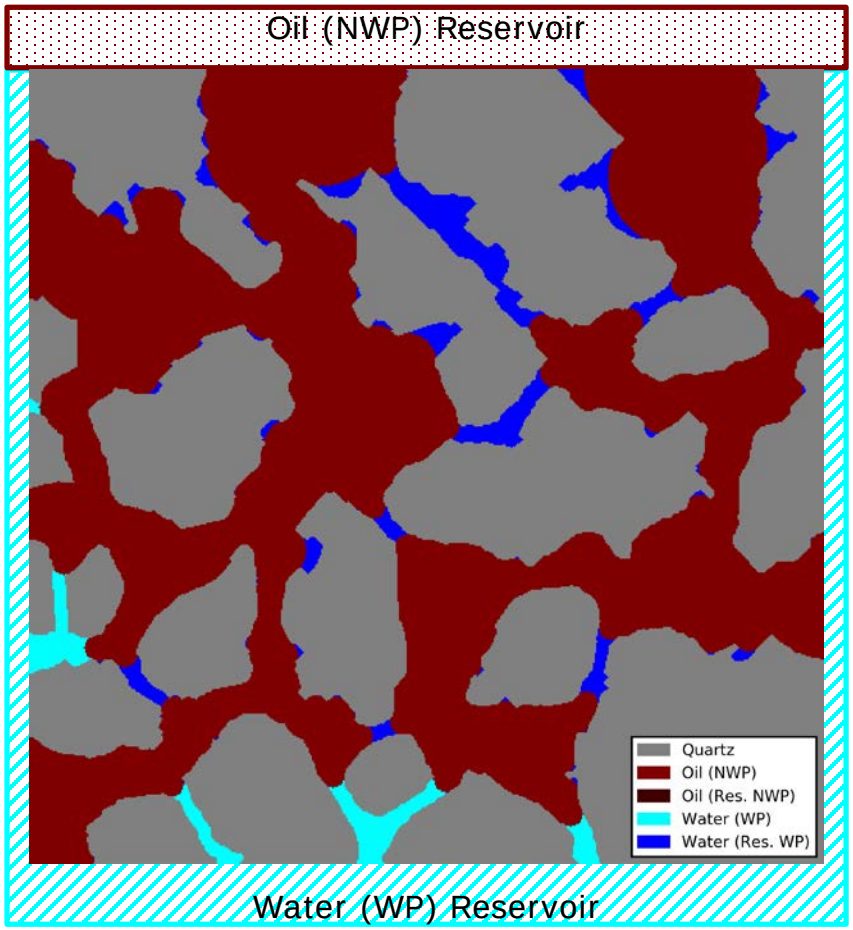

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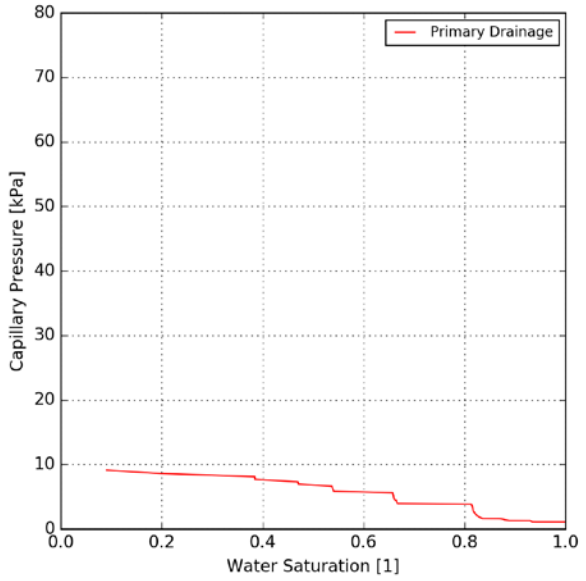

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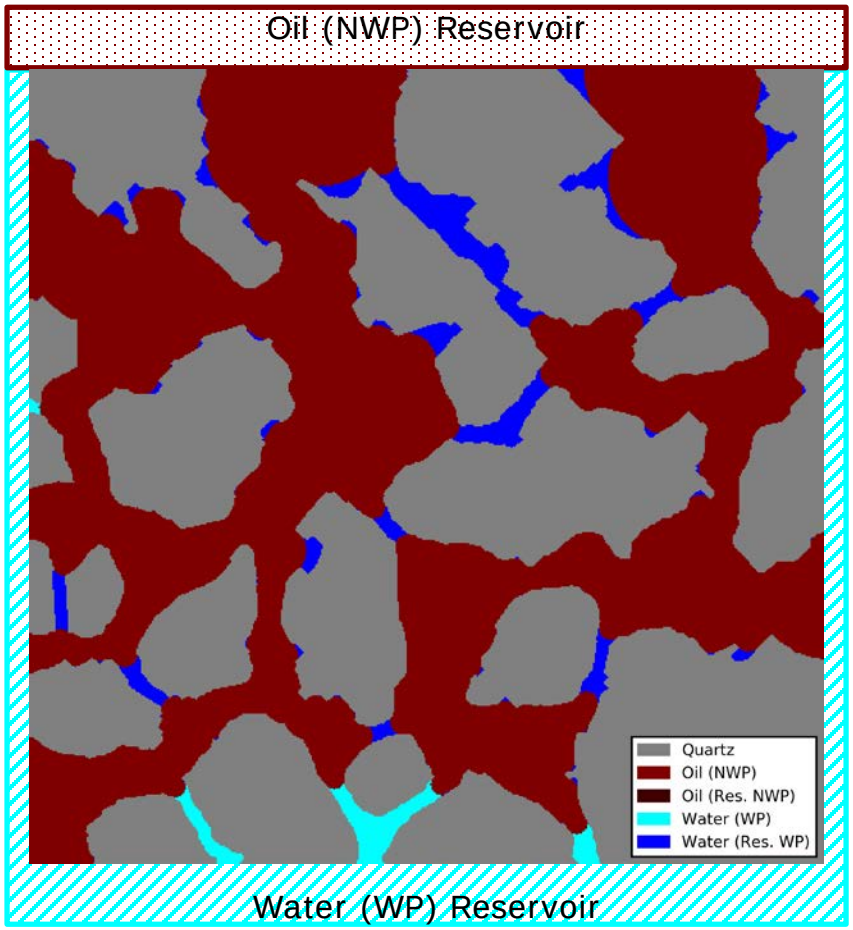

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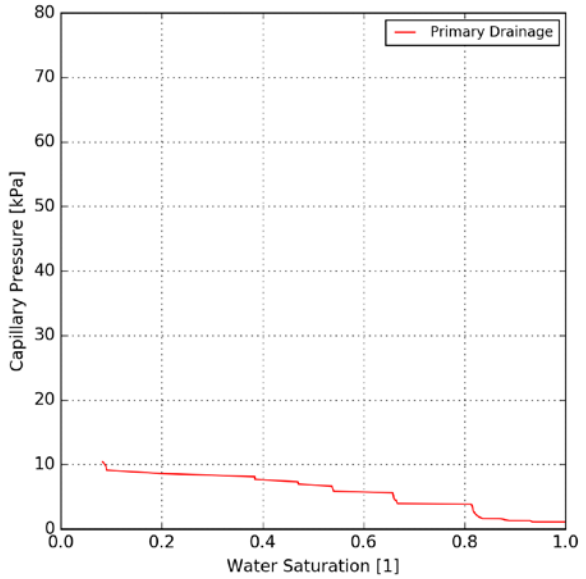

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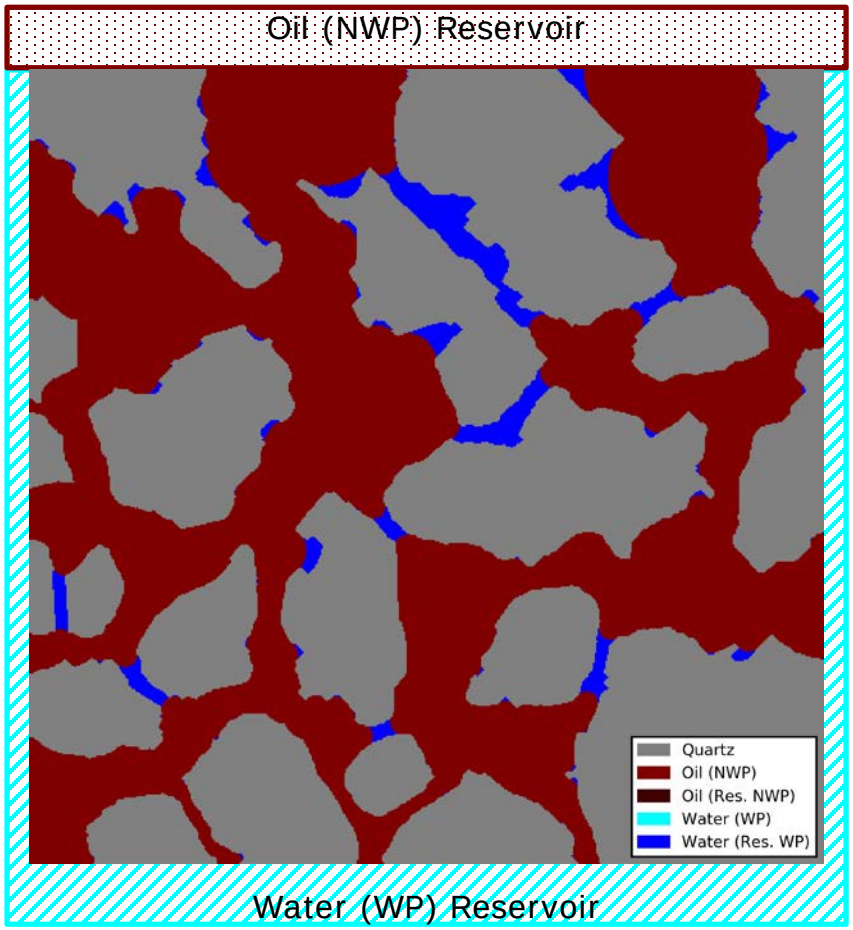

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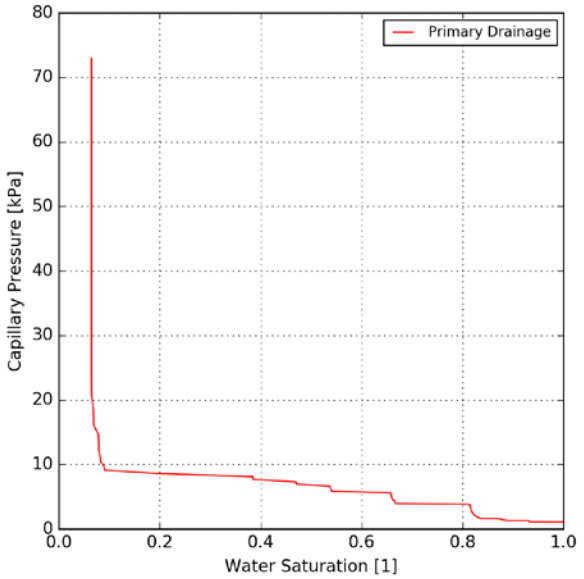
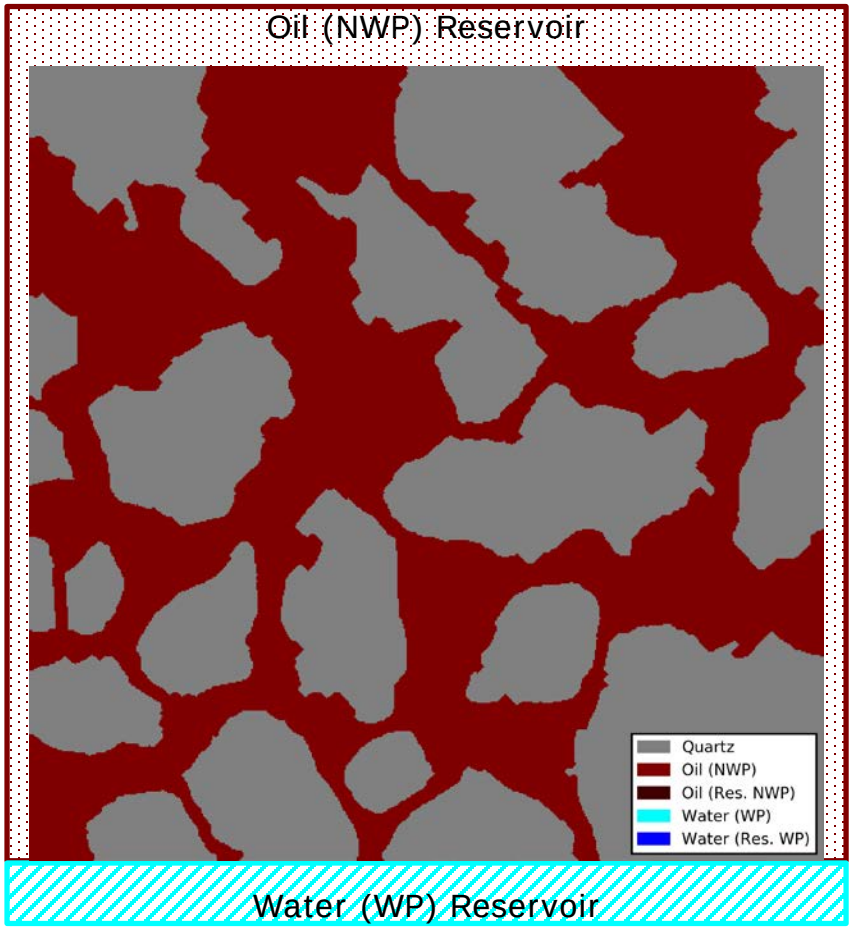


Imbibition (Waterflooding)
Water displaces Oil (Old Method, ignores residual water)



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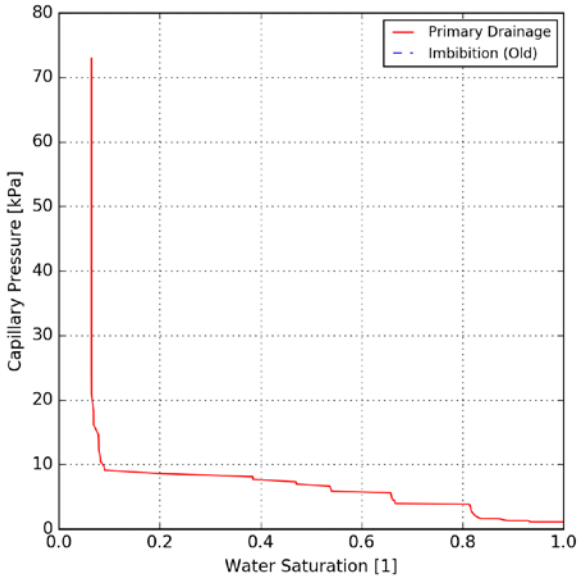

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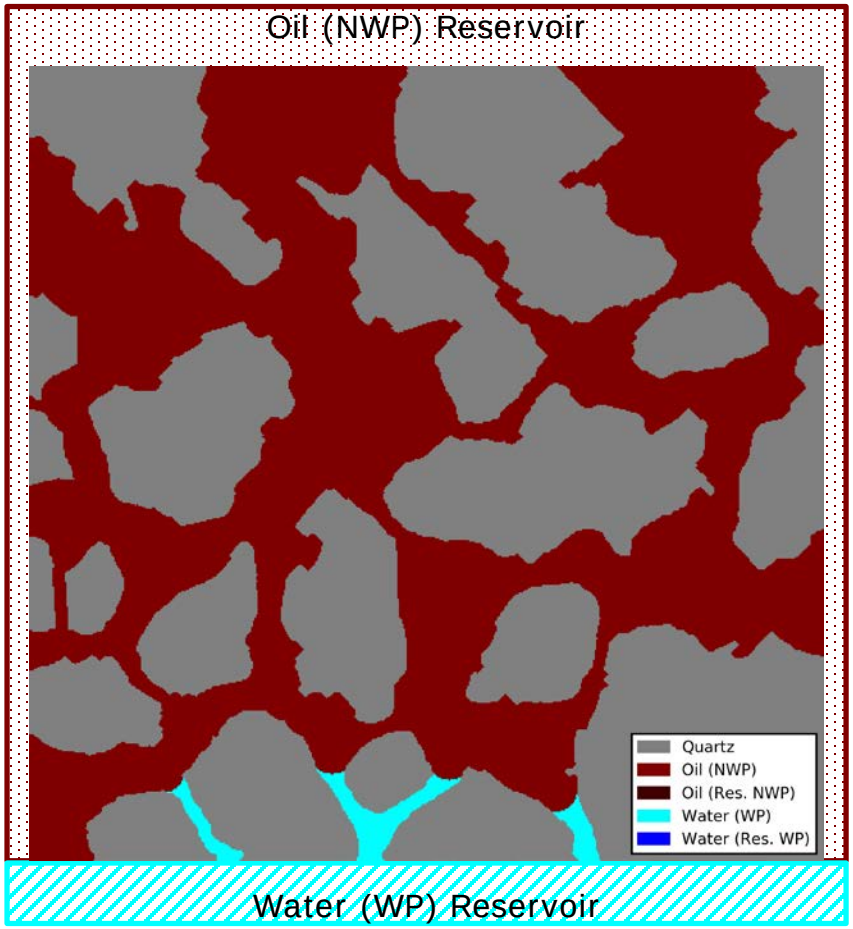

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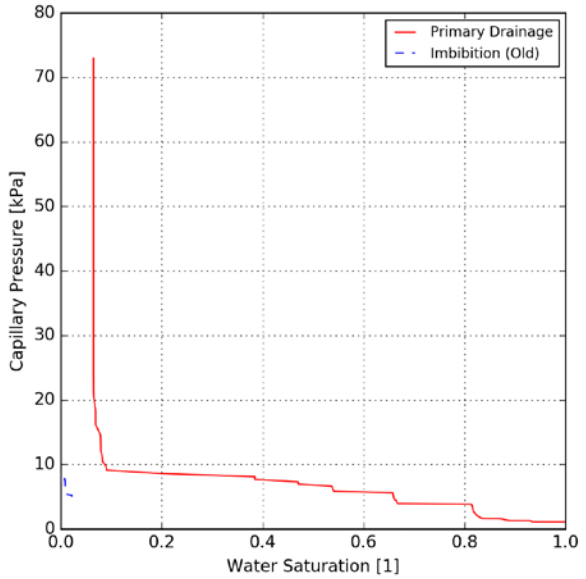

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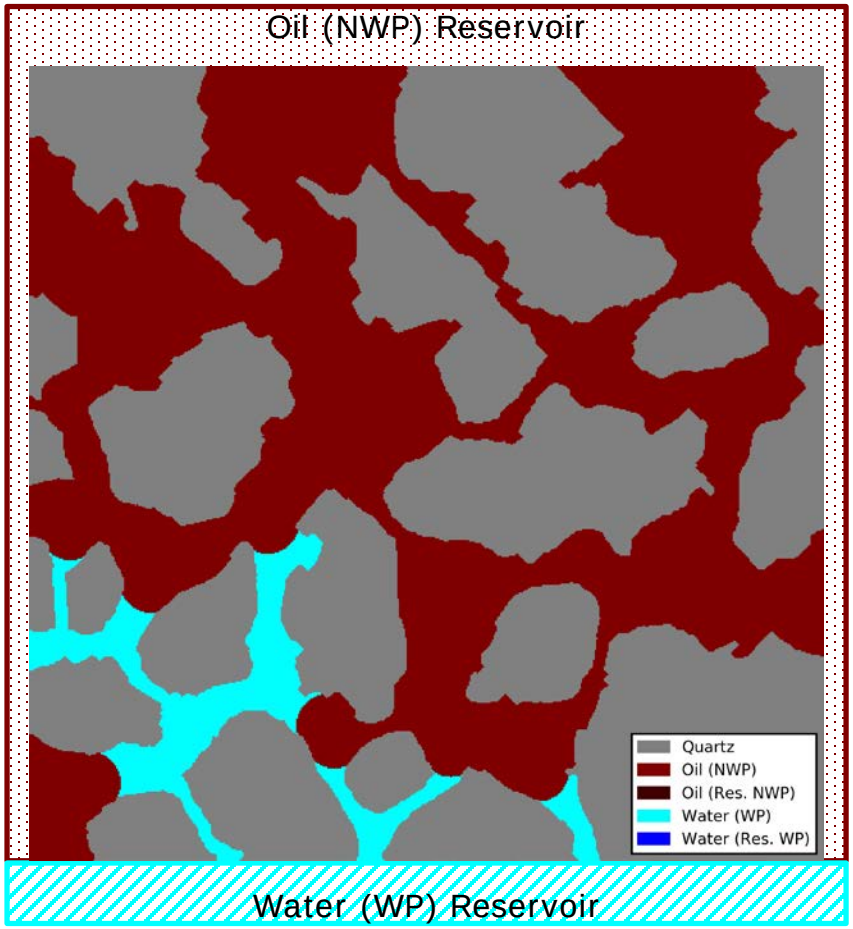

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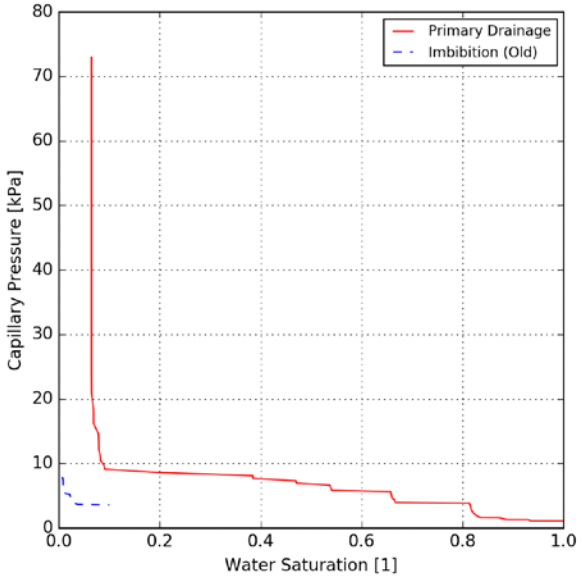

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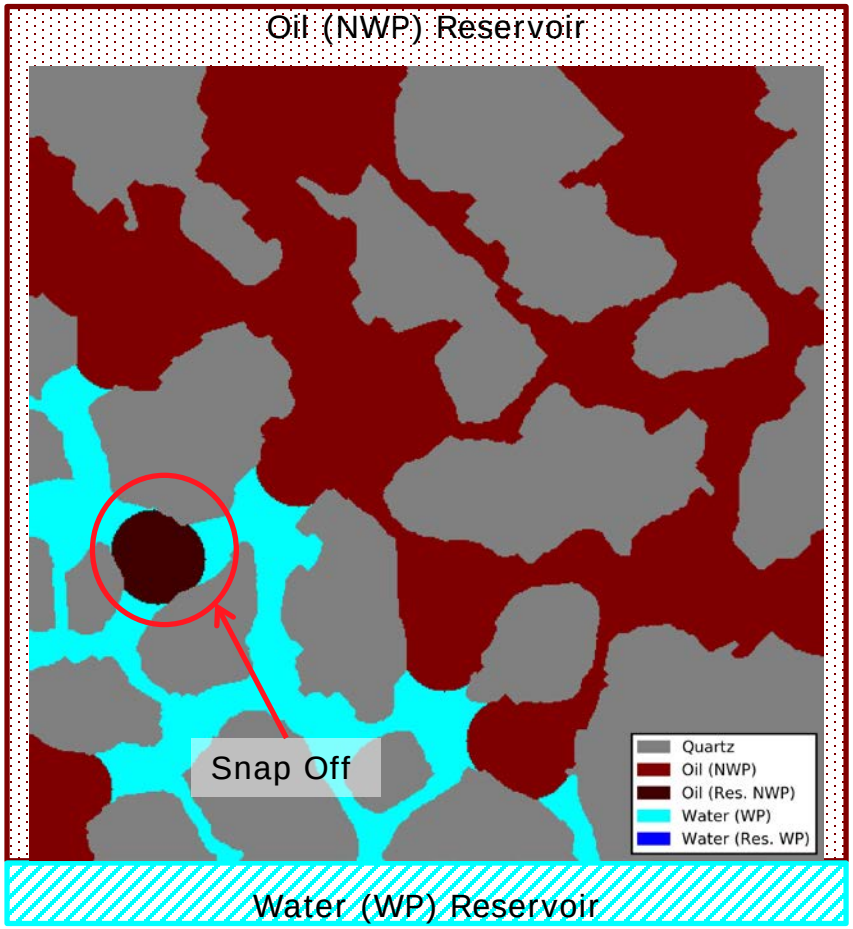

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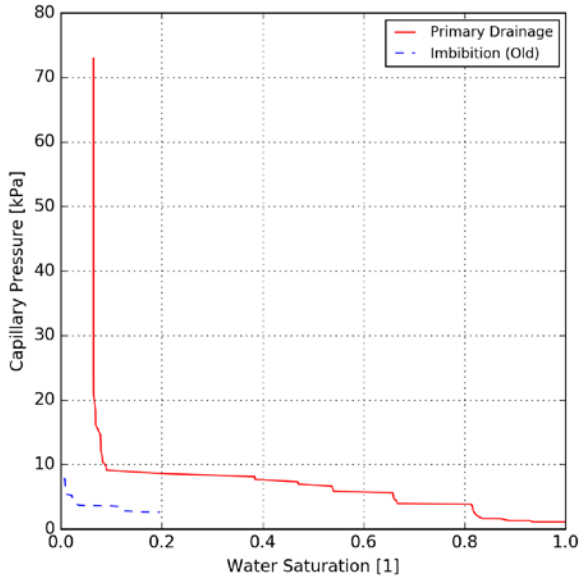

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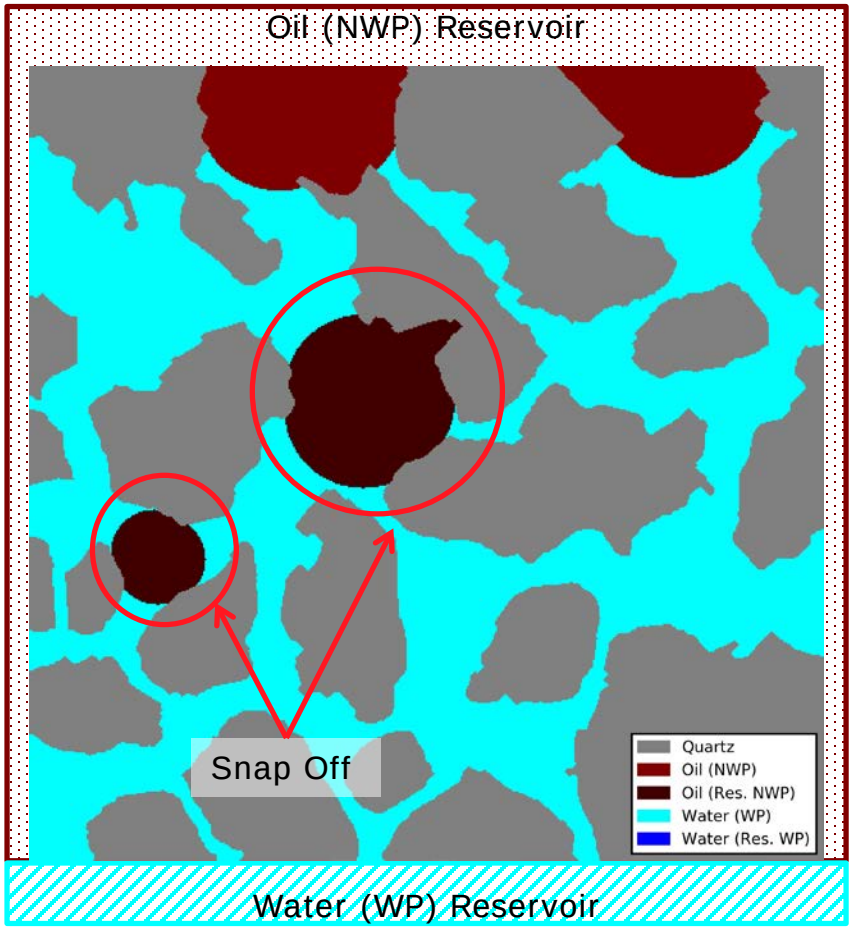

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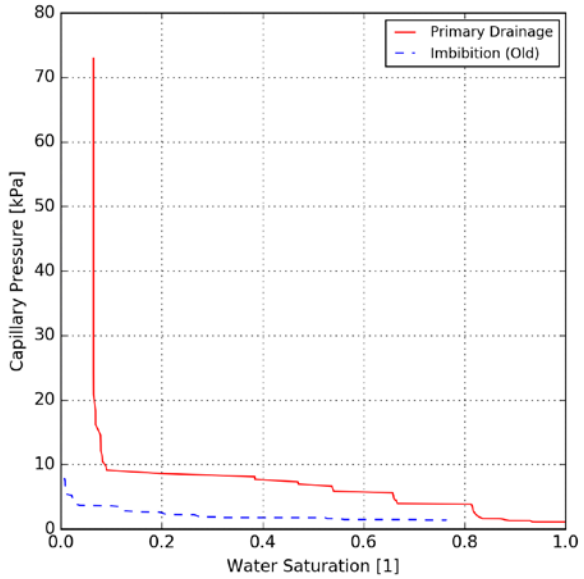
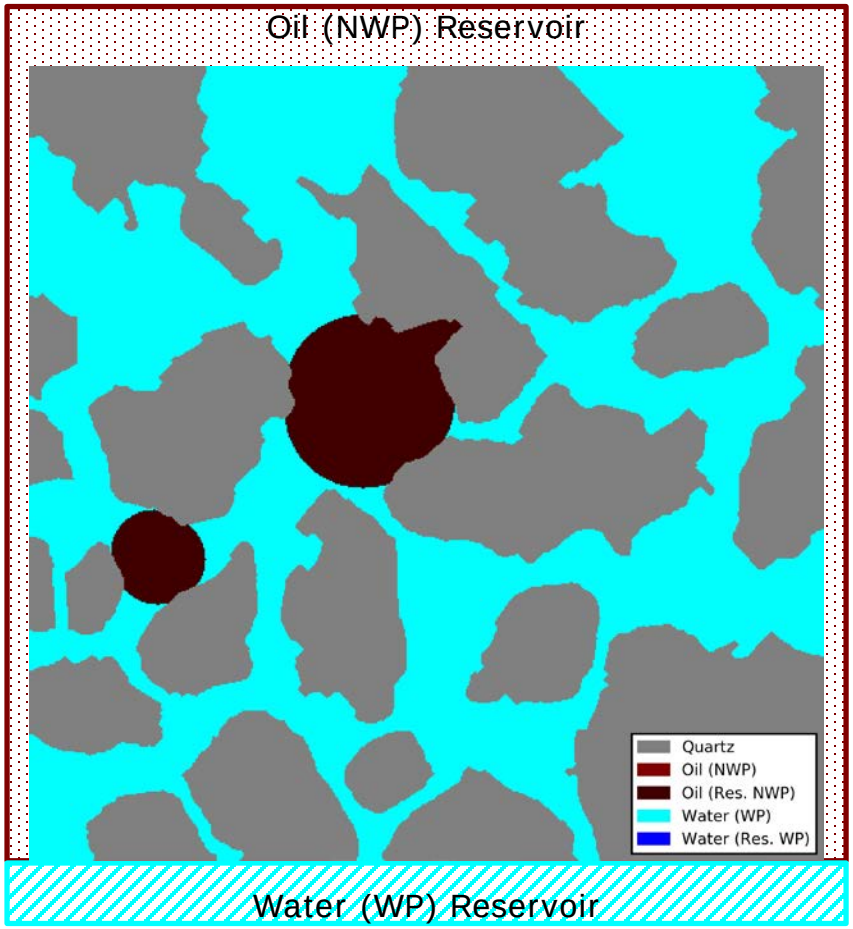


Imbibition (Waterflooding)
Water displaces Oil (Old Method, ignores residual water)



1. Choose radii r_{min}, r_{max} and initial radius $r = r_{min}$
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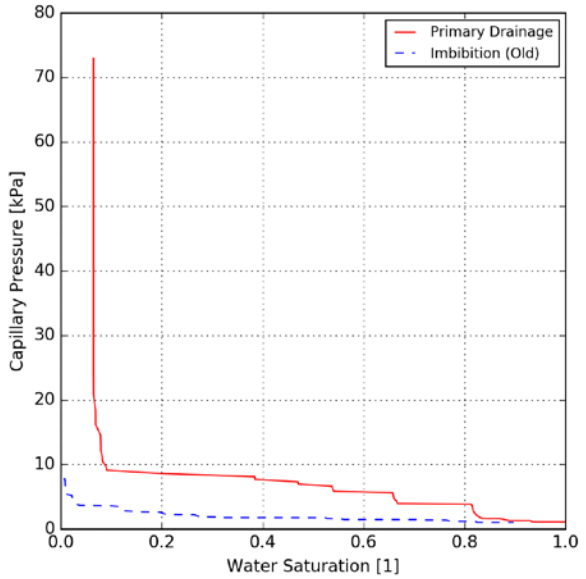
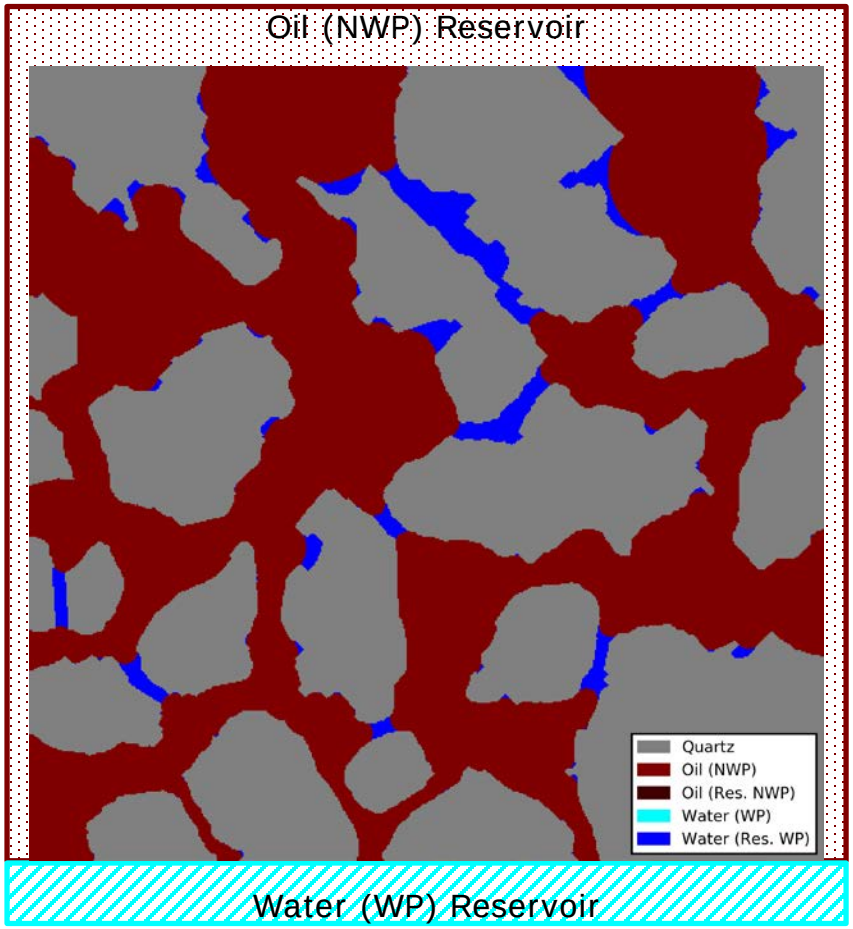


Imbibition (Waterflooding)
Water displaces Oil



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4. *Mark residual WP that is now connected to WP-reservoir as mobile WP*
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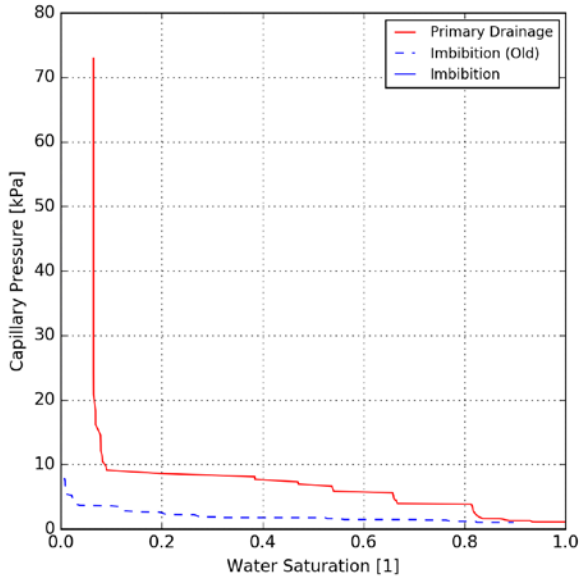
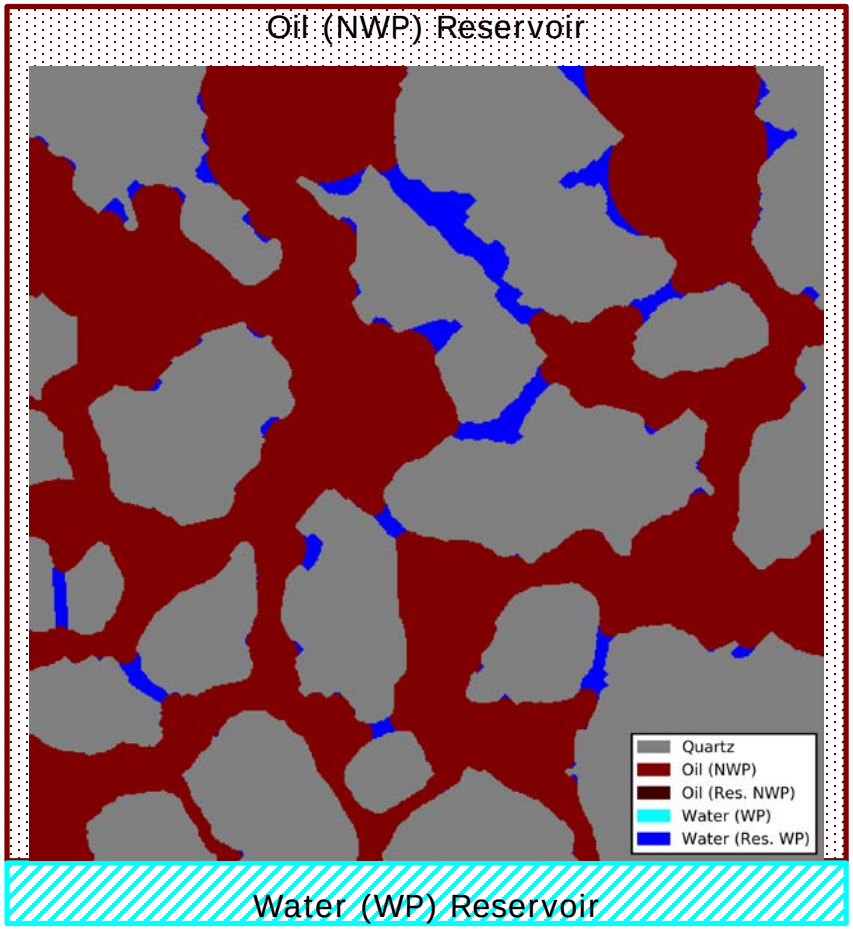


Imbibition (Waterflooding)
Water displaces Oil



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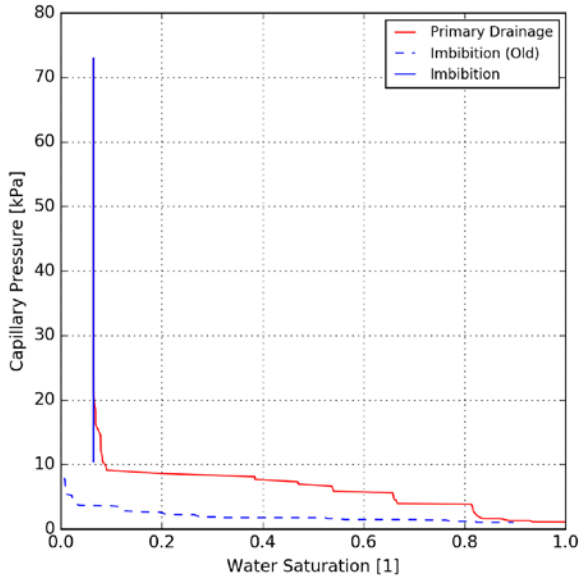
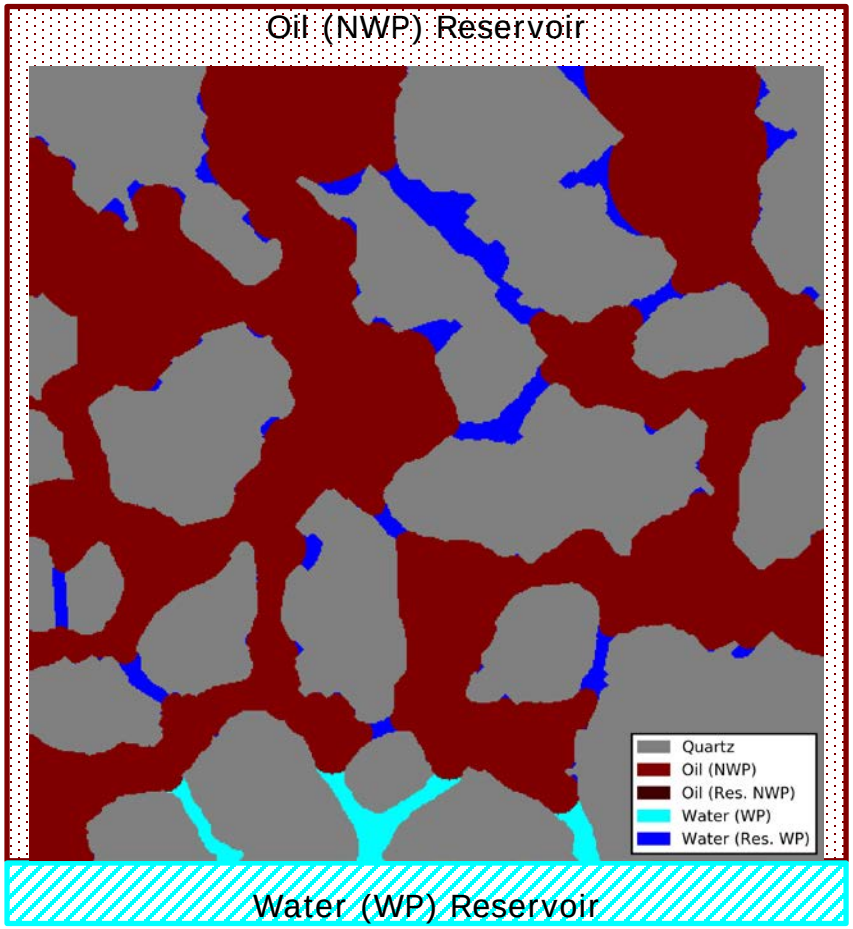


Imbibition (Waterflooding)
Water displaces Oil



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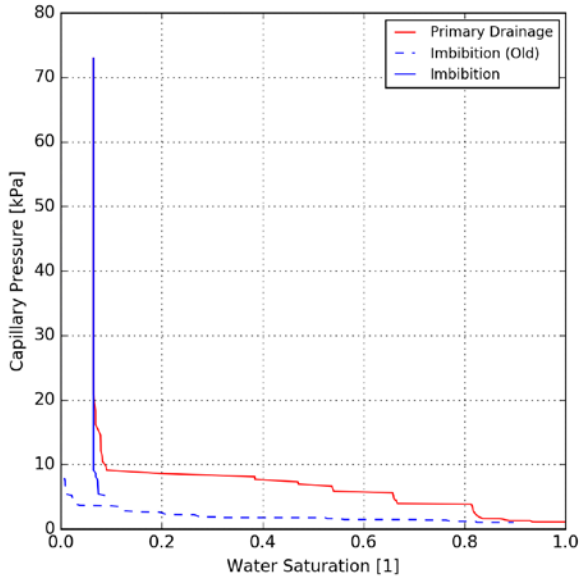
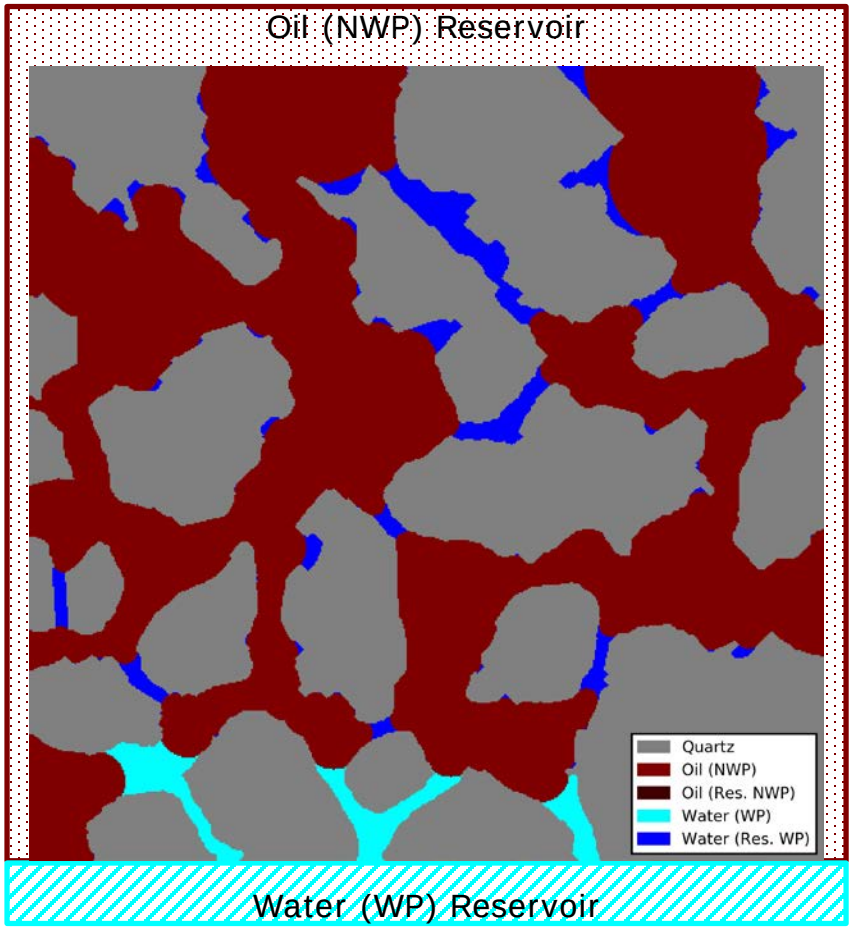


Imbibition (Waterflooding)
Water displaces Oil



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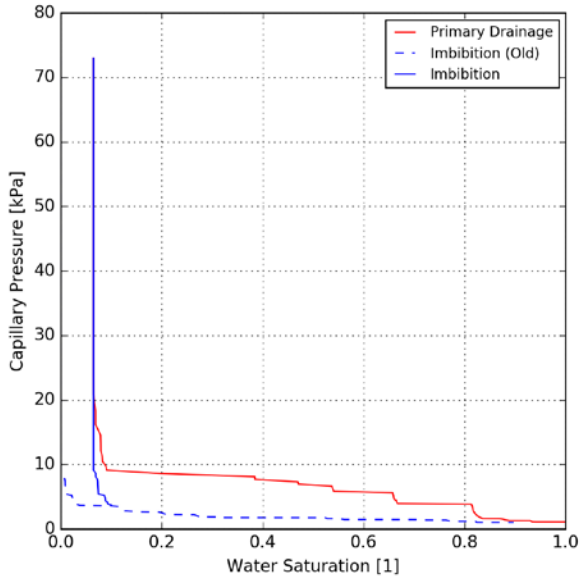
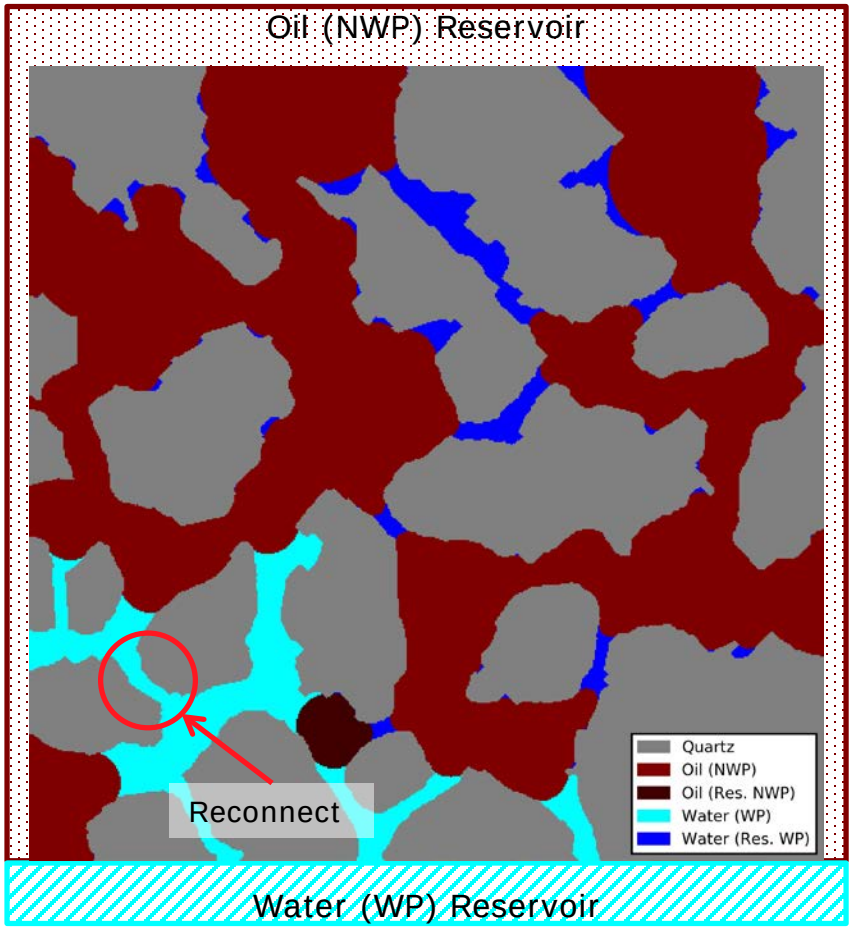


Imbibition (Waterflooding)
Water displaces Oil



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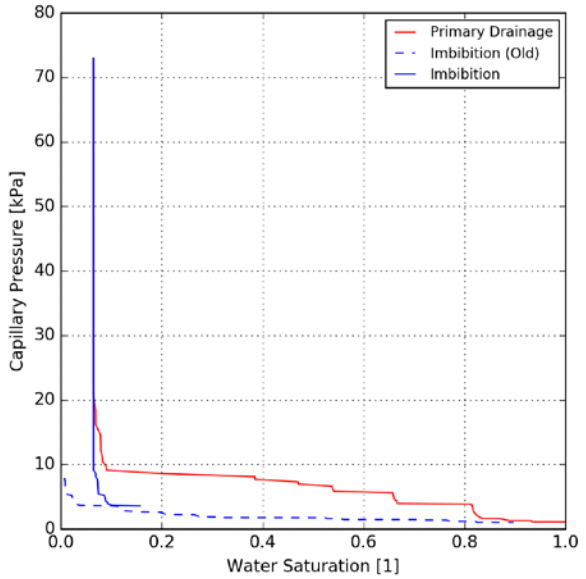
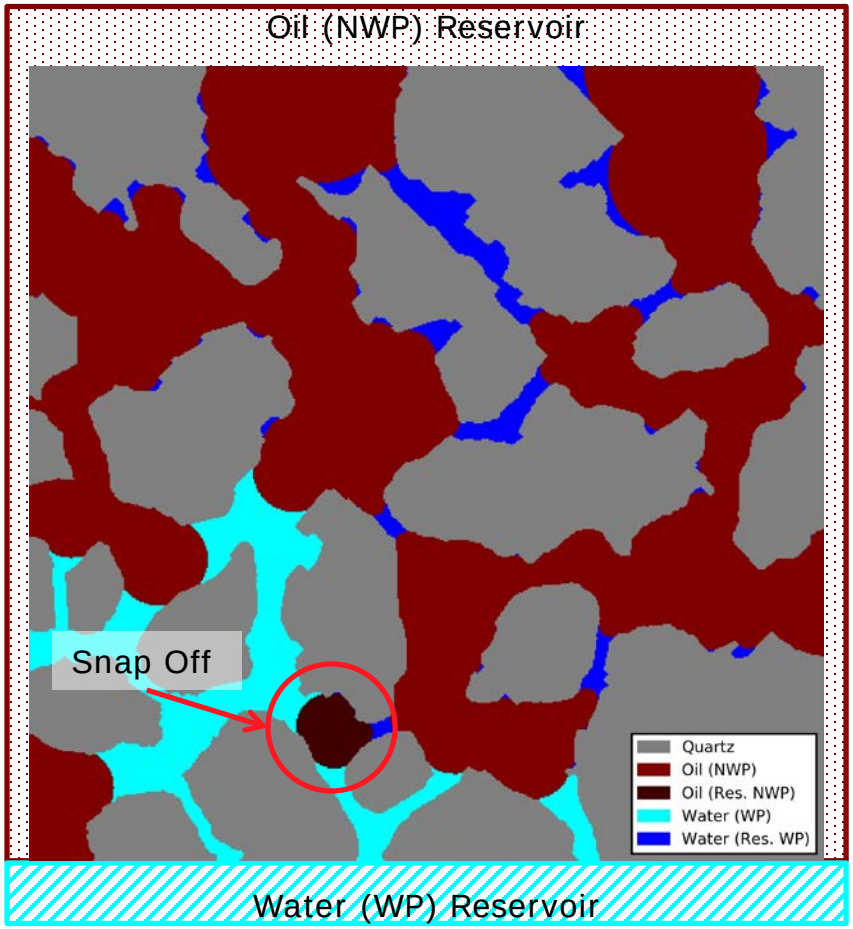


Imbibition (Waterflooding)
Water displaces Oil



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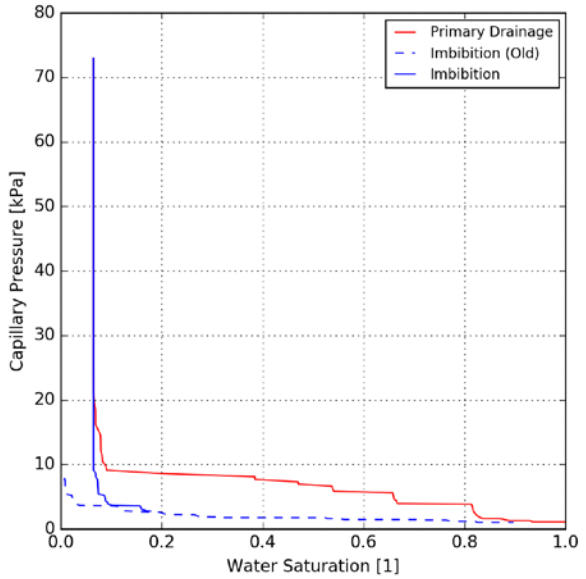

Imbibition (Waterflooding)
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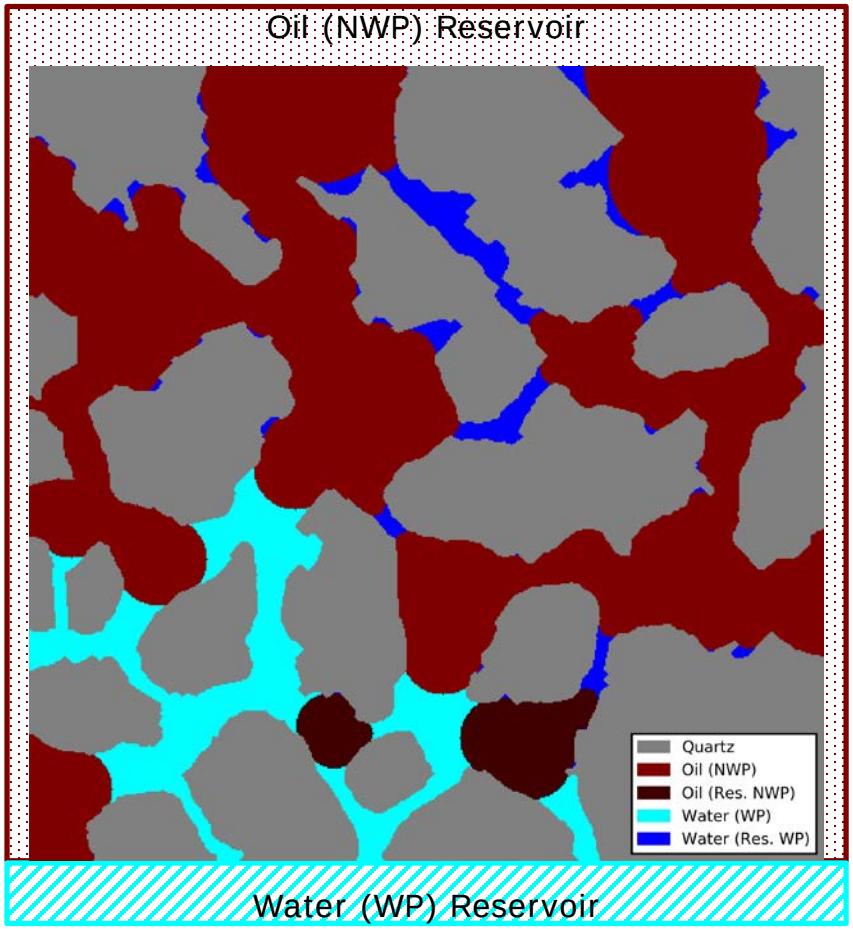

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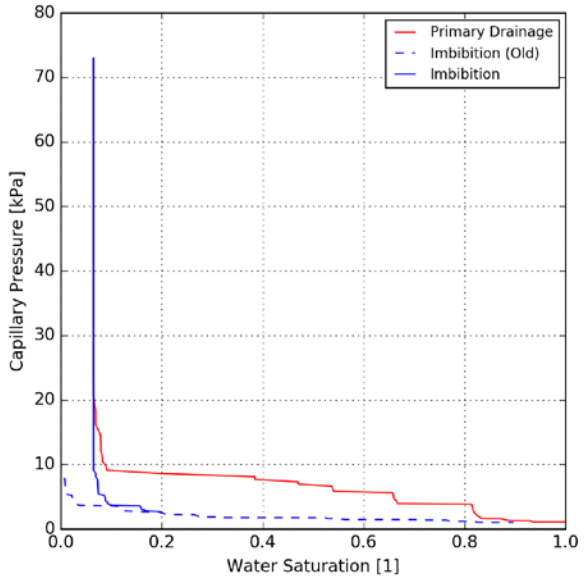

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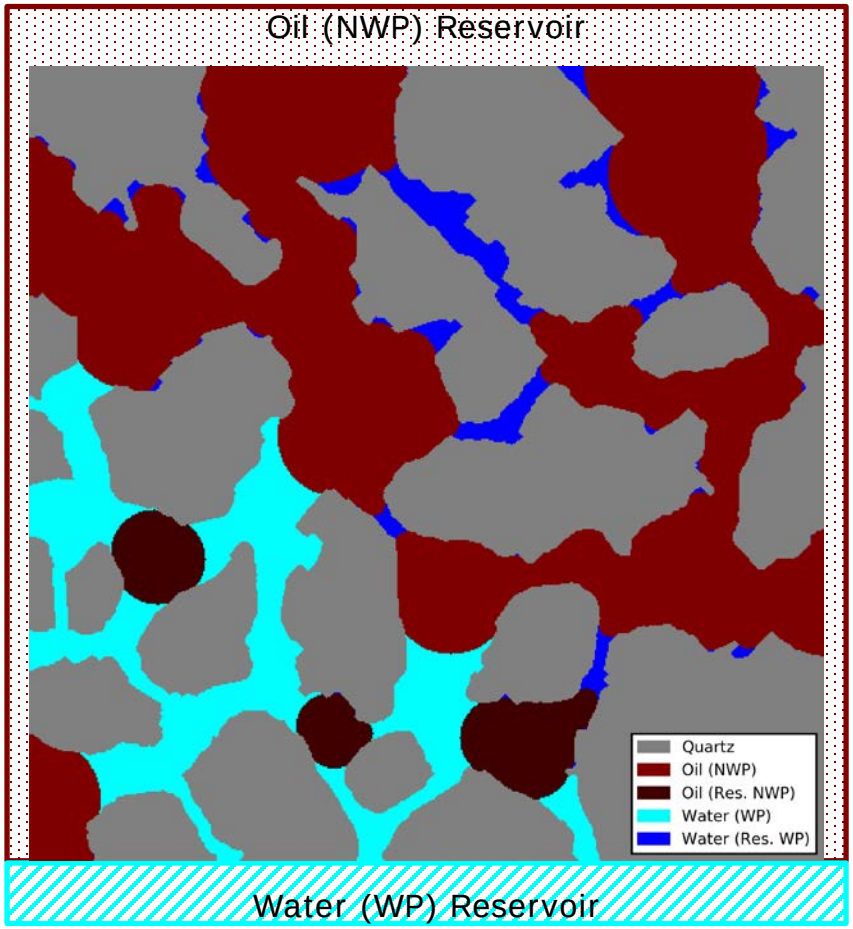

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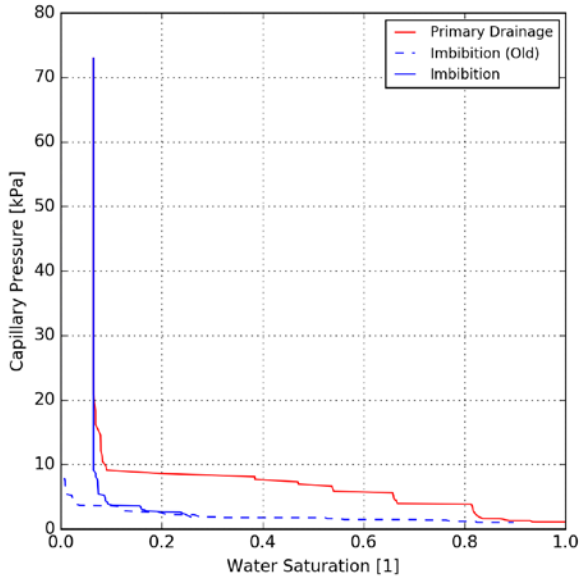

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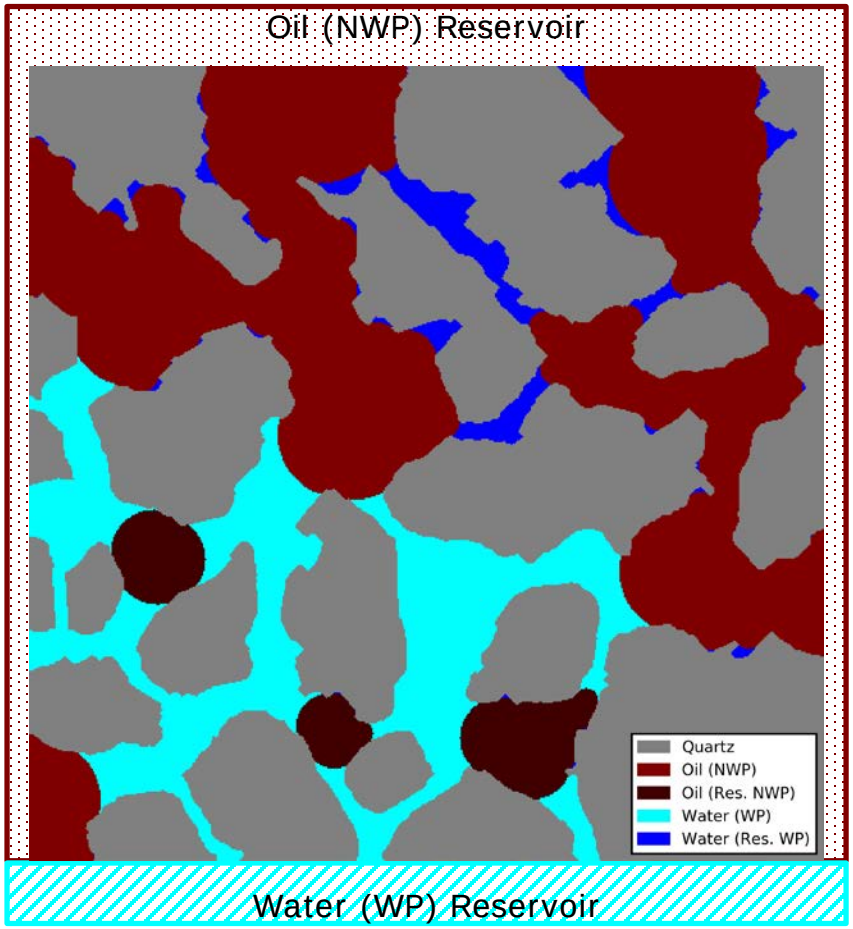

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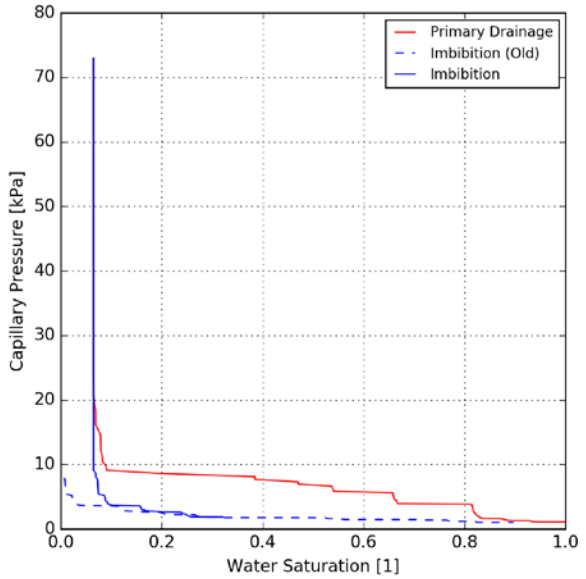
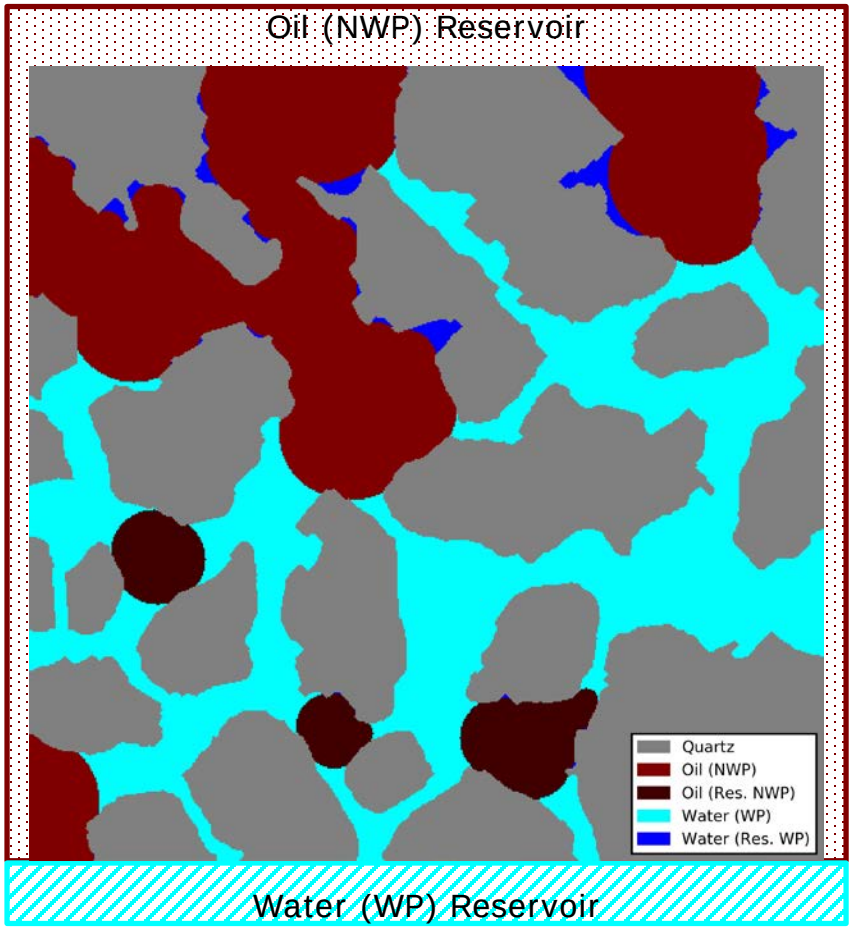


Imbibition (Waterflooding)
Water displaces Oil



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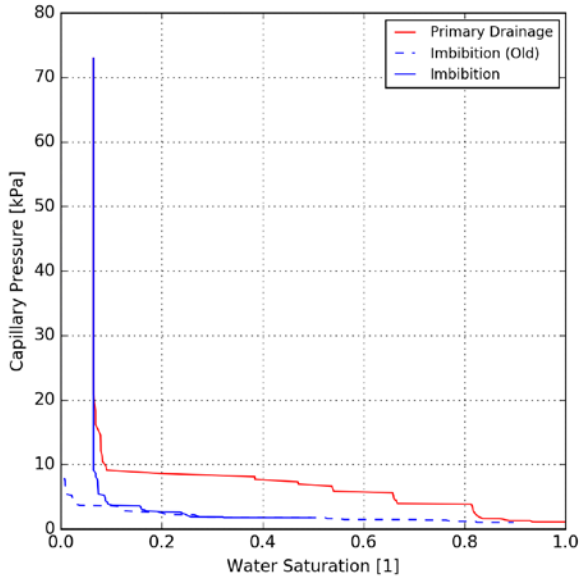

Imbibition (Waterflooding)
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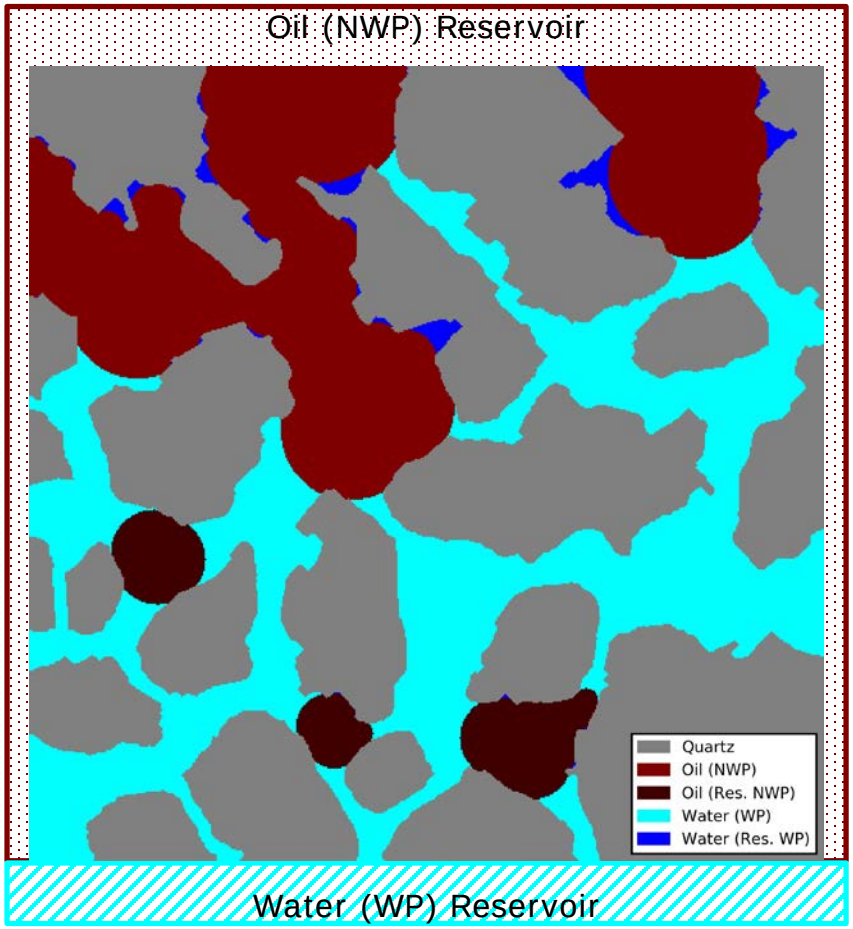

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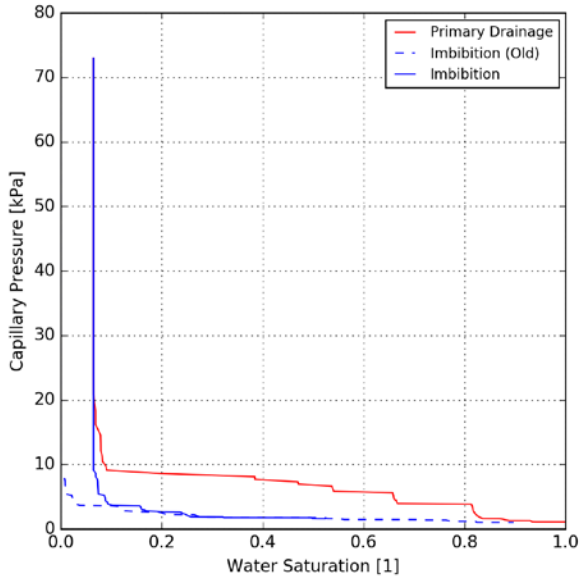

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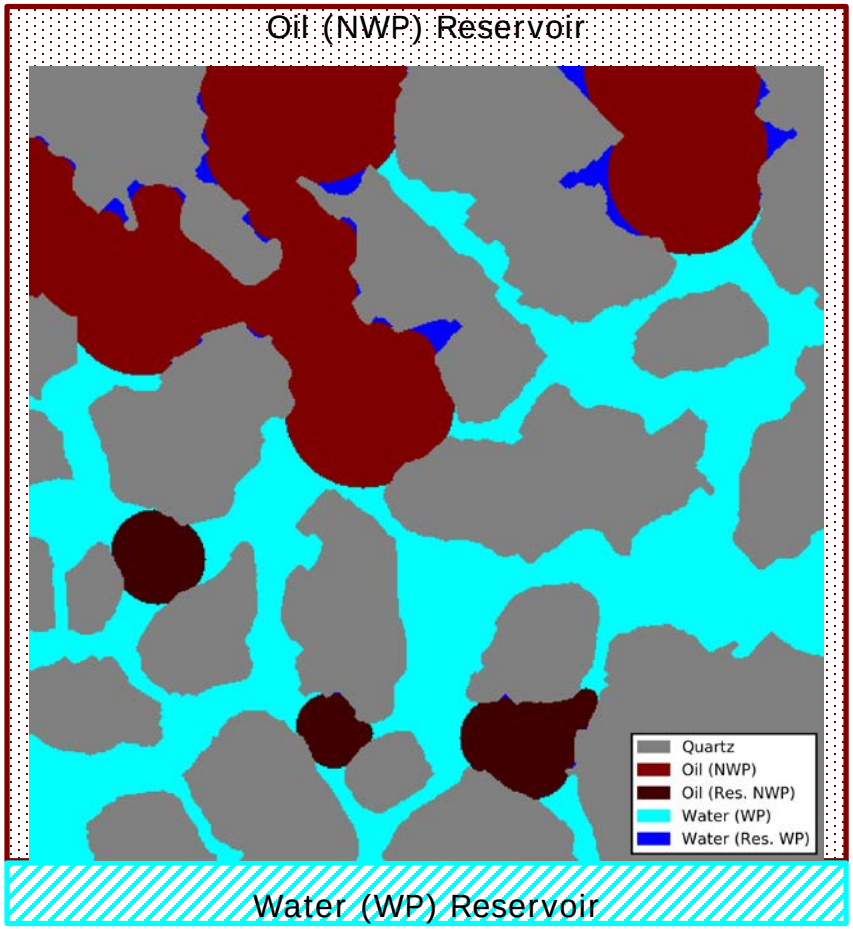

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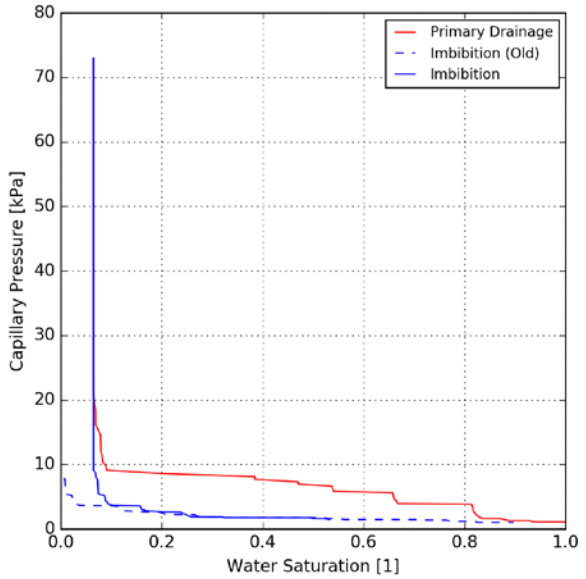

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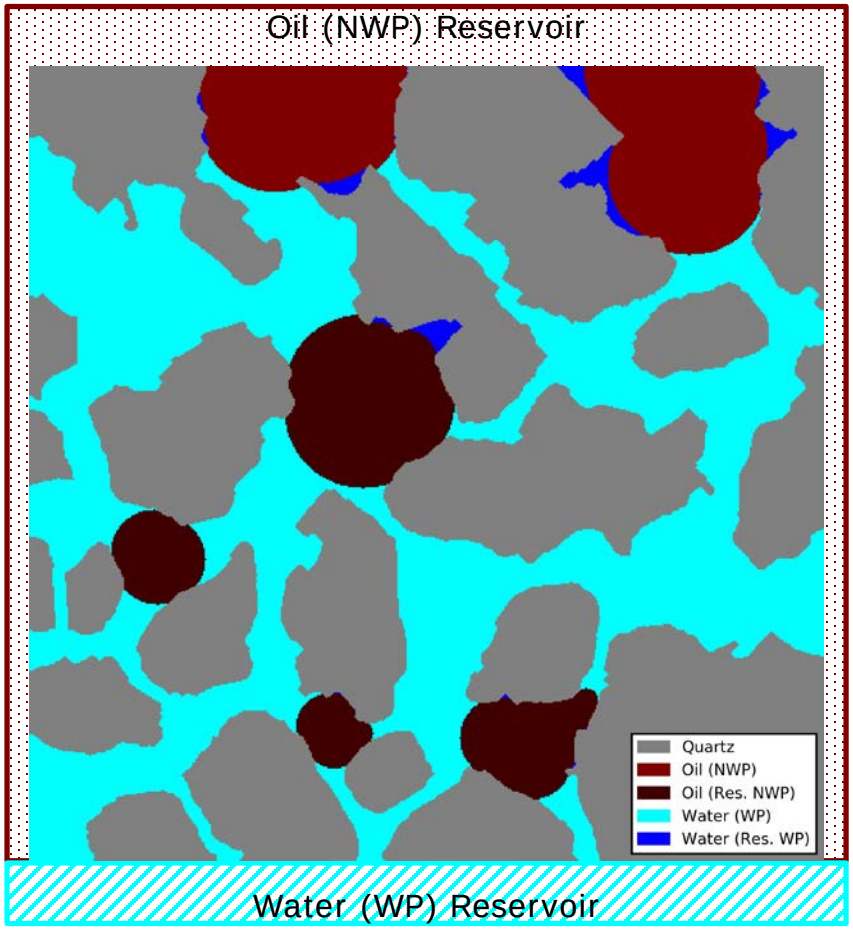
Water displaces Oil



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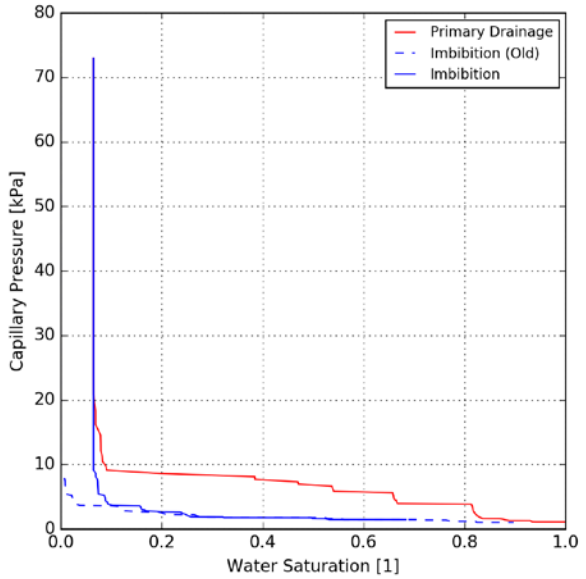

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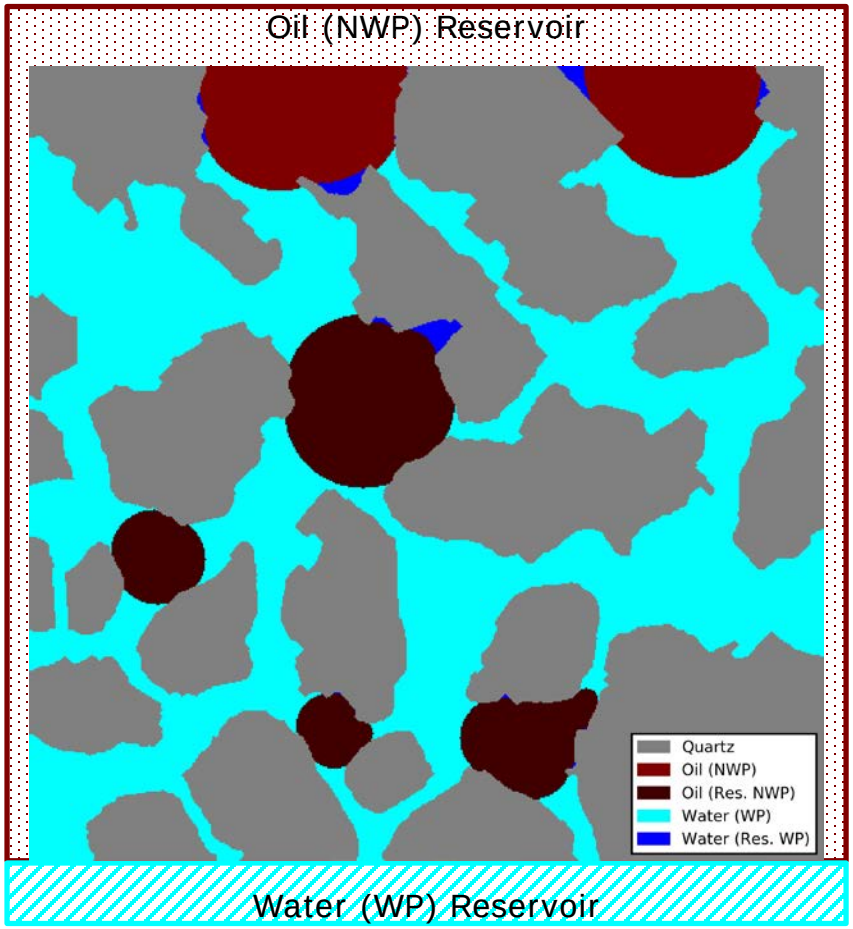
Water displaces Oil



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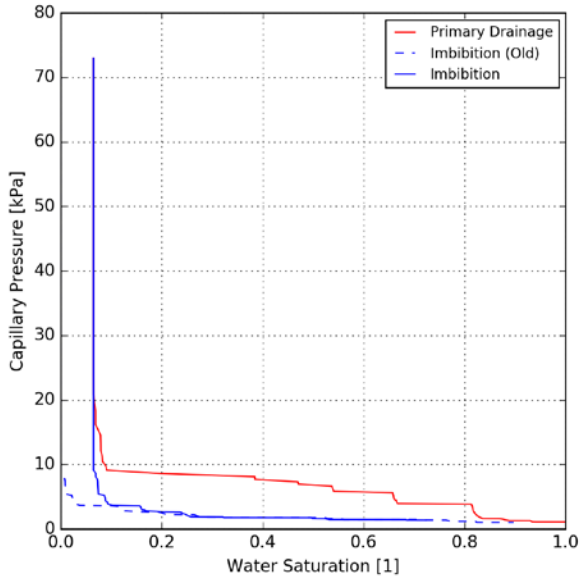

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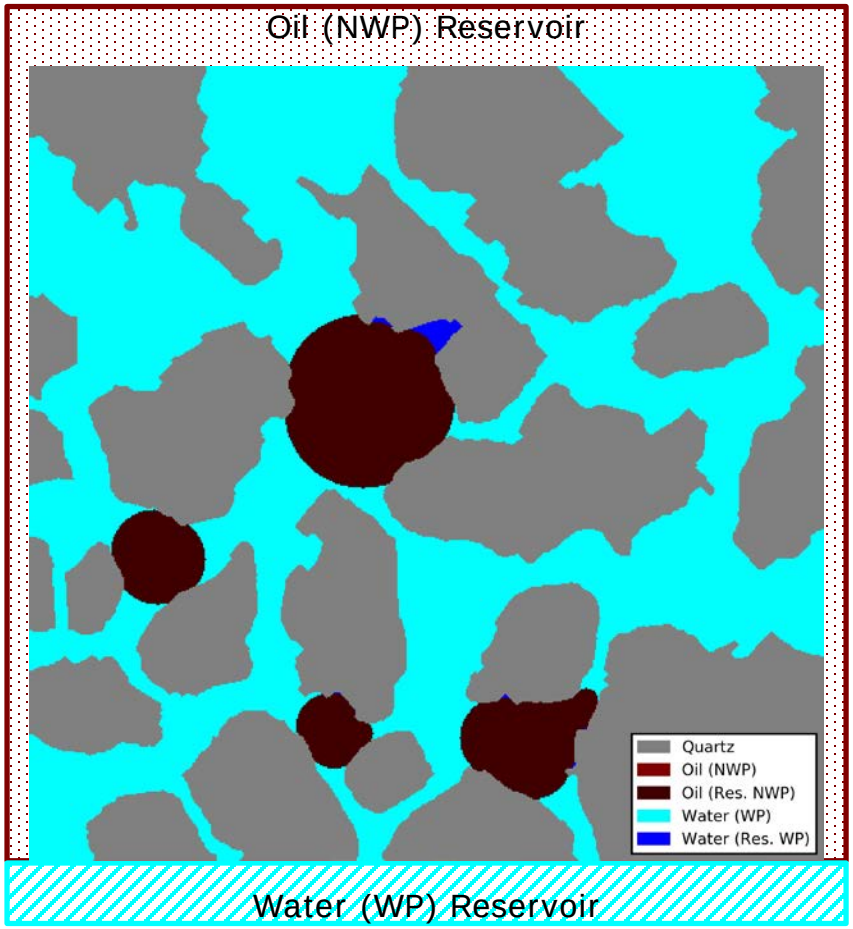
Water displaces Oil



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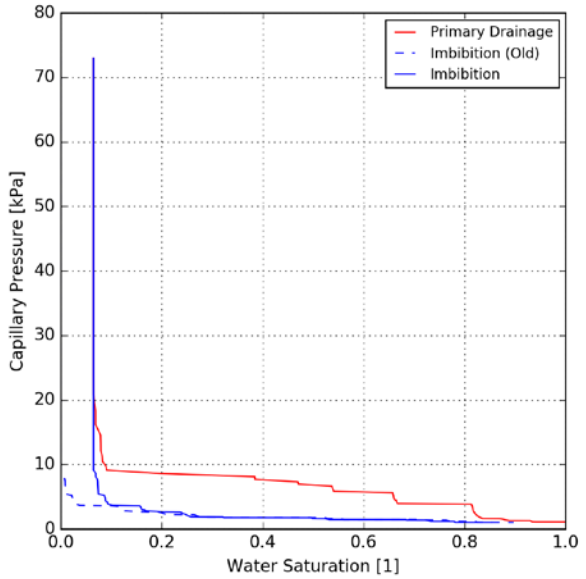
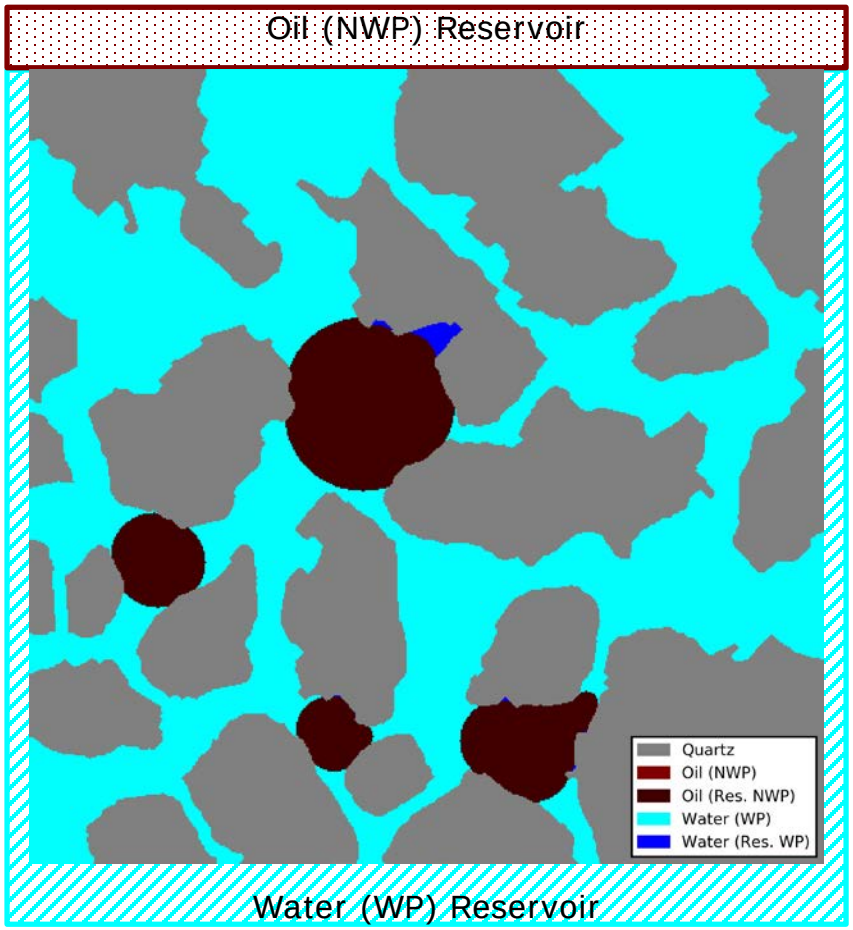


Secondary Drainage
Oil displaces Water



1. Choose radii r_{min}, r_{max} and initial radius $r = r_{max}$
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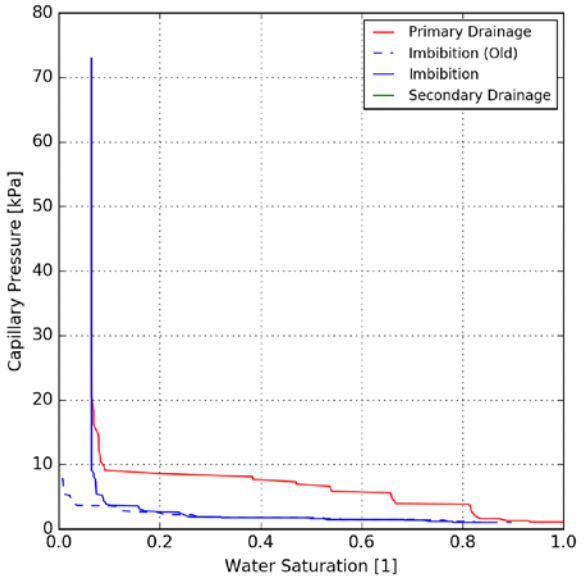
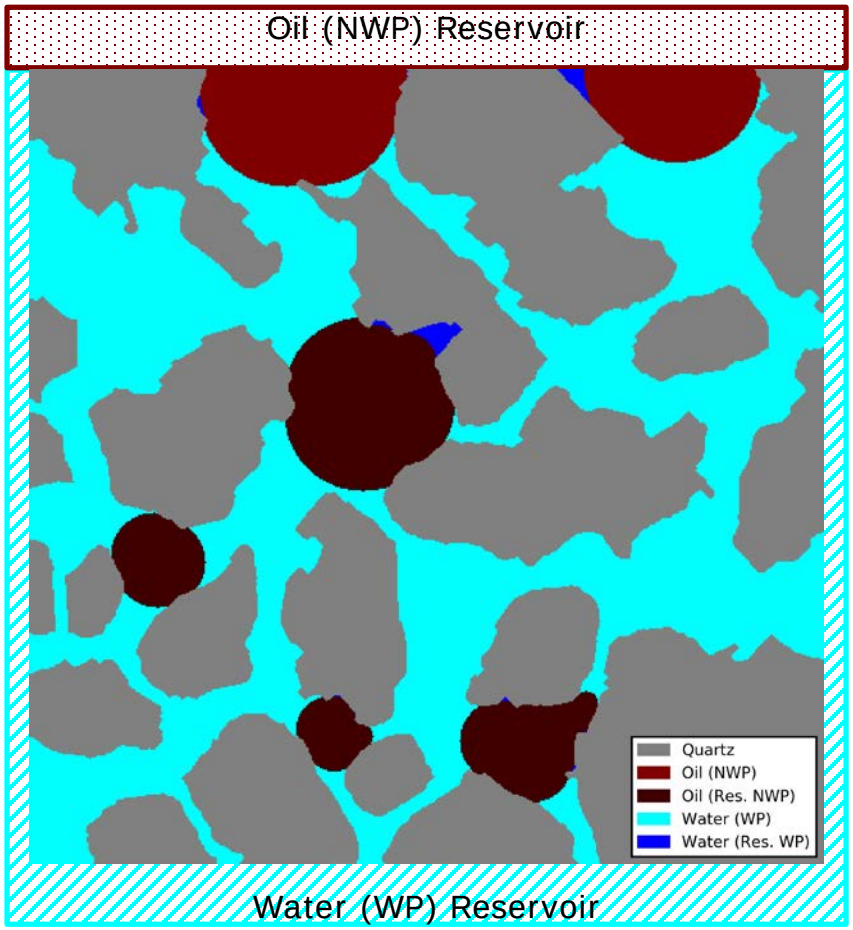


Secondary Drainage
Oil displaces Water



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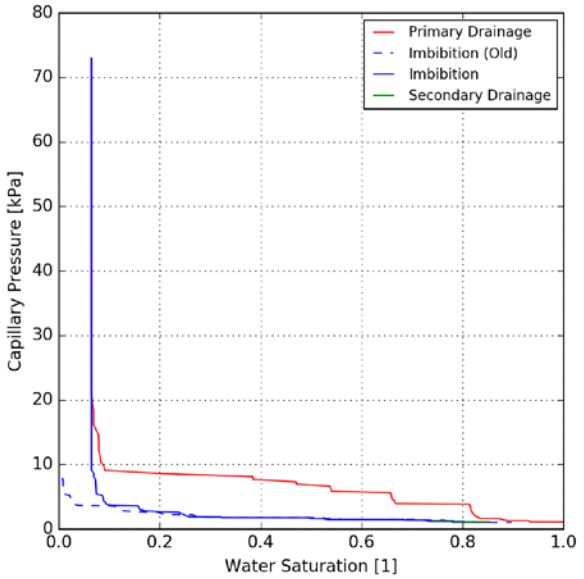
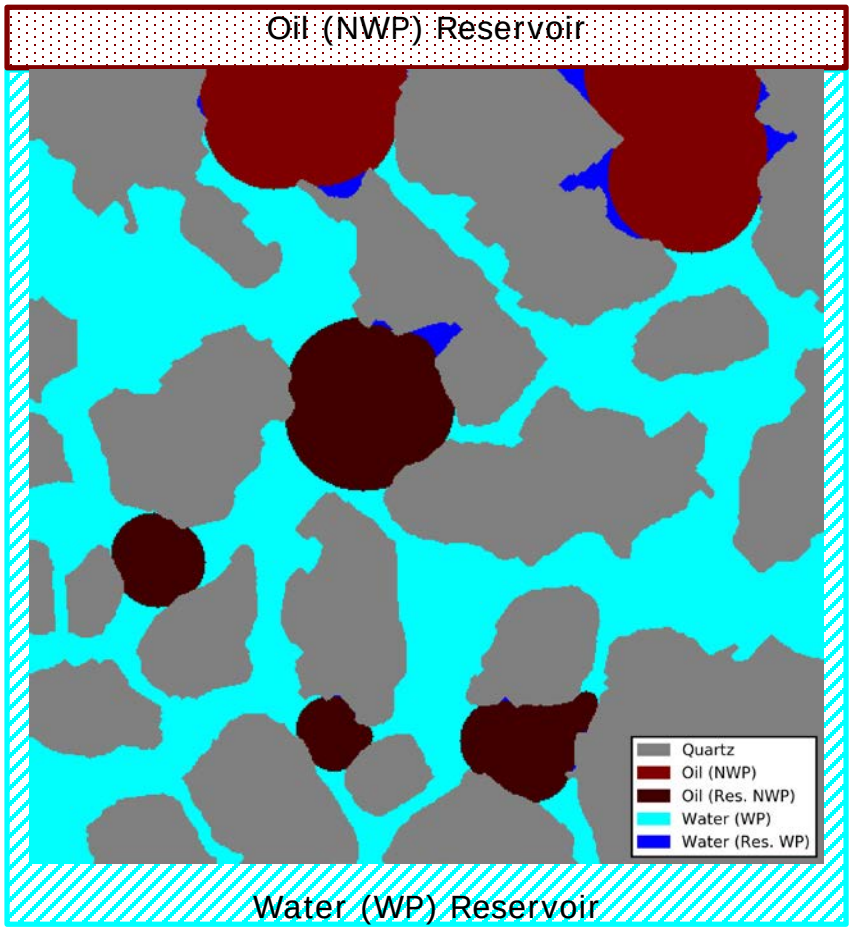


Secondary Drainage
Oil displaces Water



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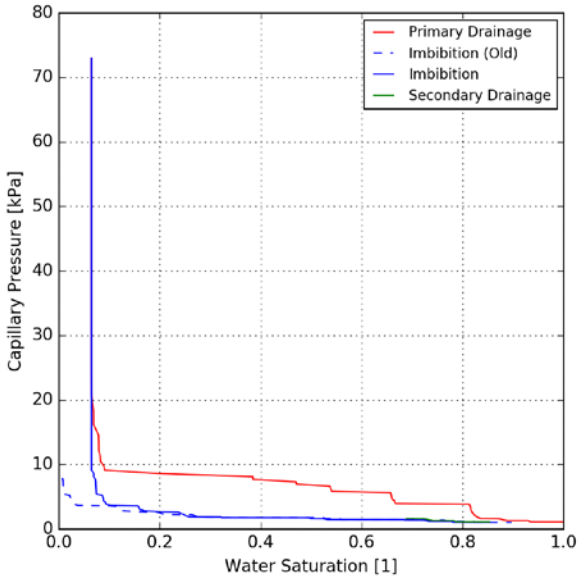
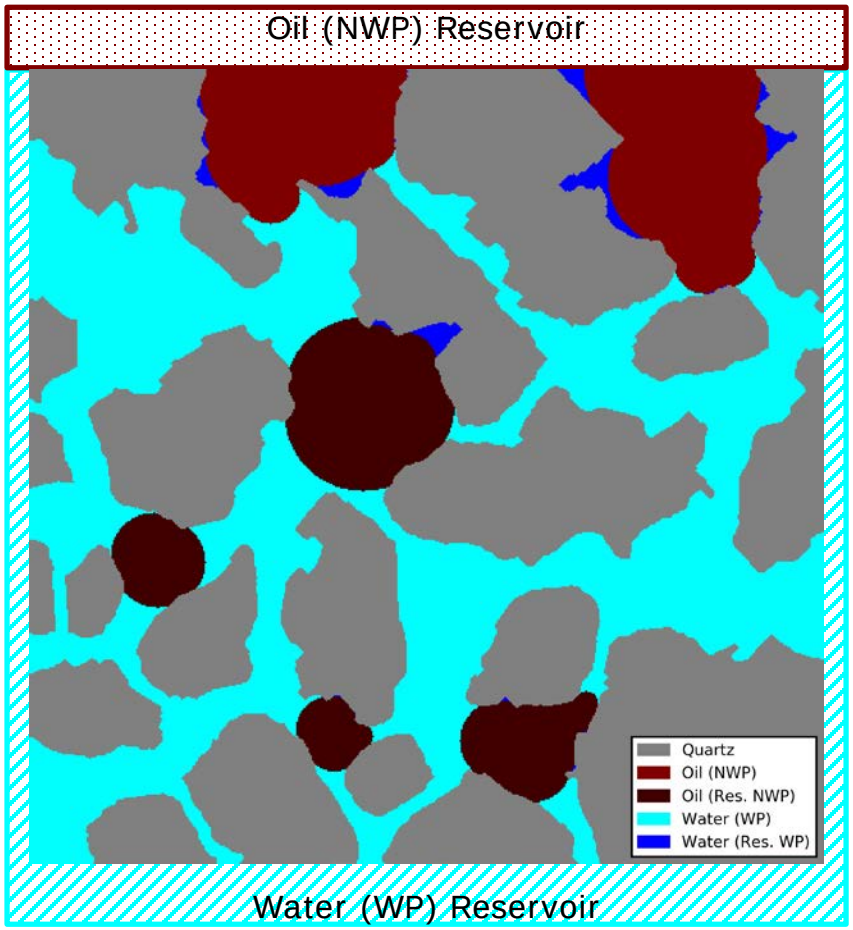


Secondary Drainage
Oil displaces Water



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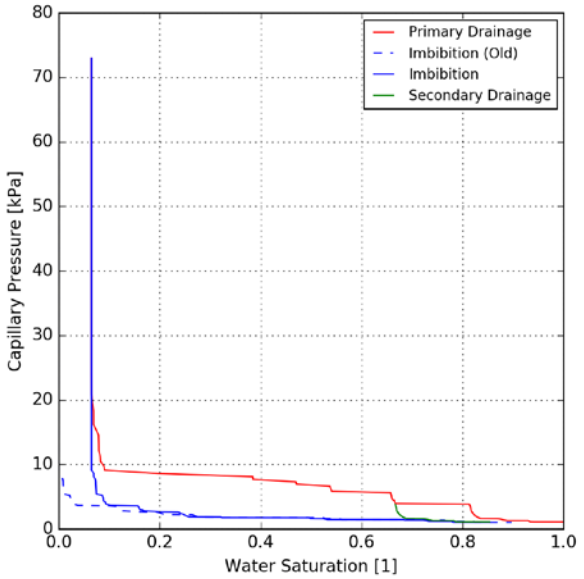
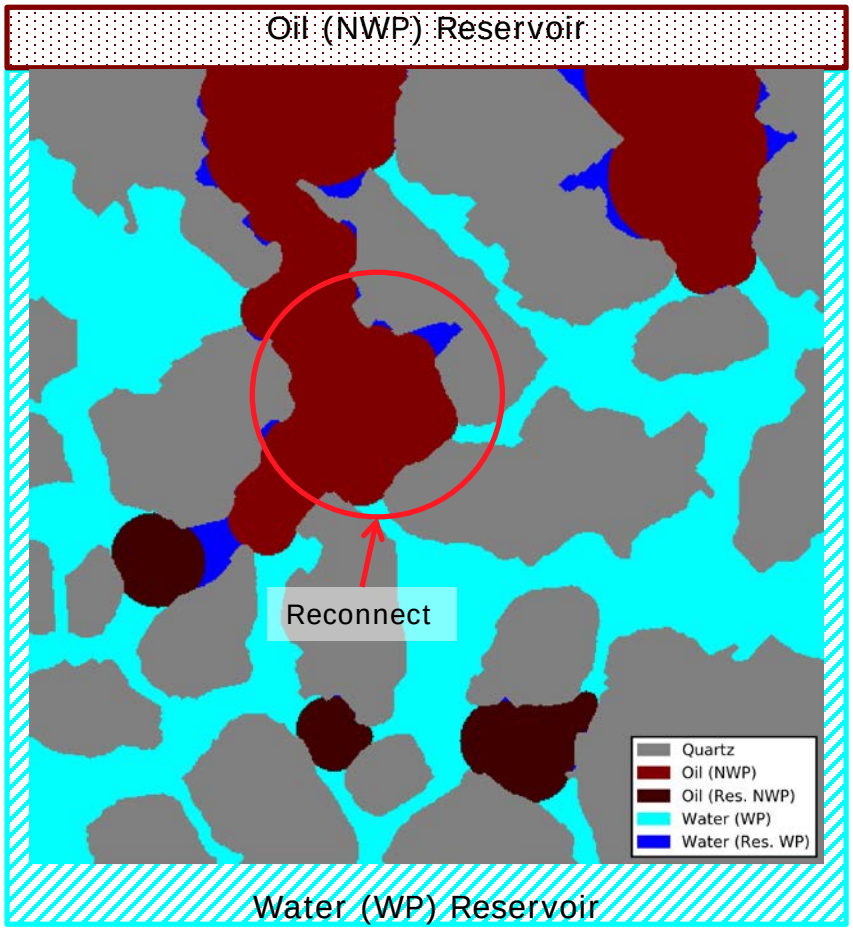


Secondary Drainage
Oil displaces Water



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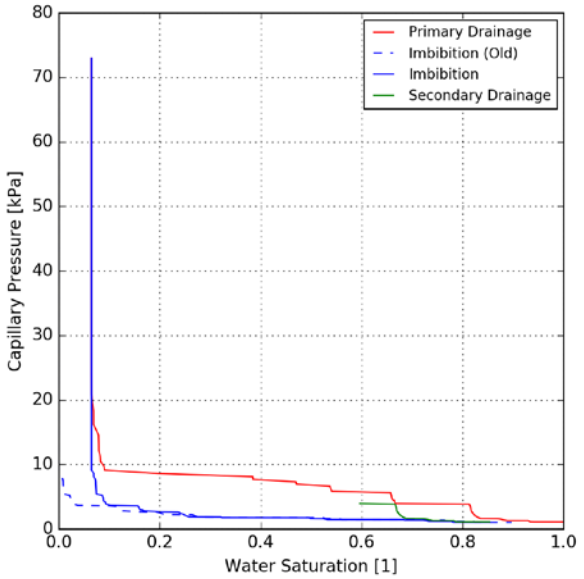

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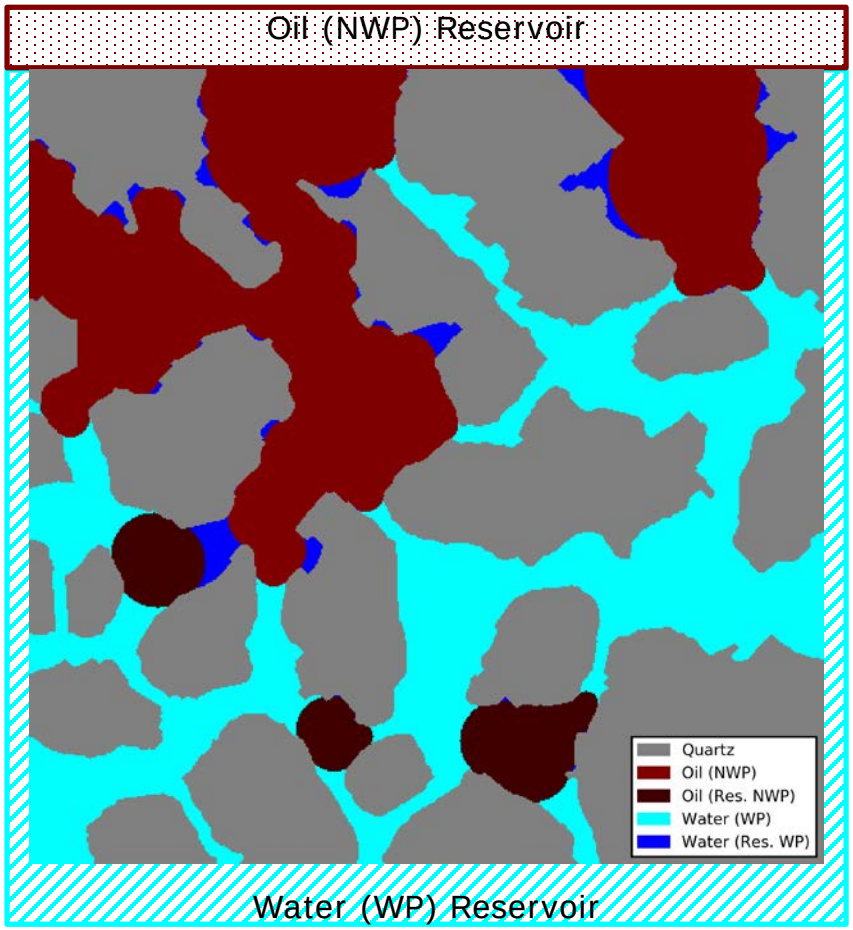

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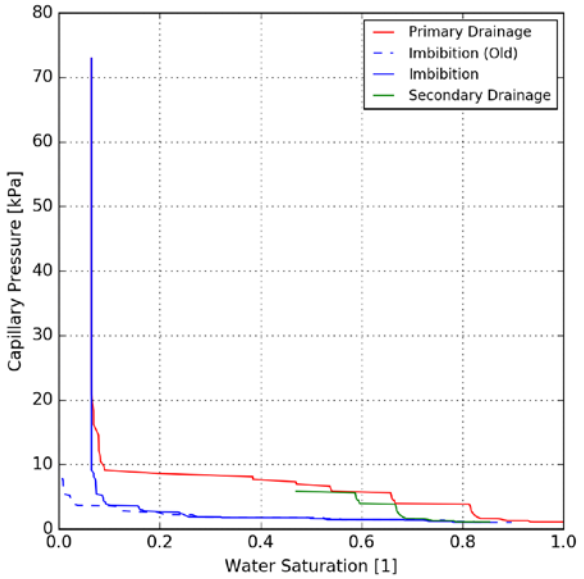

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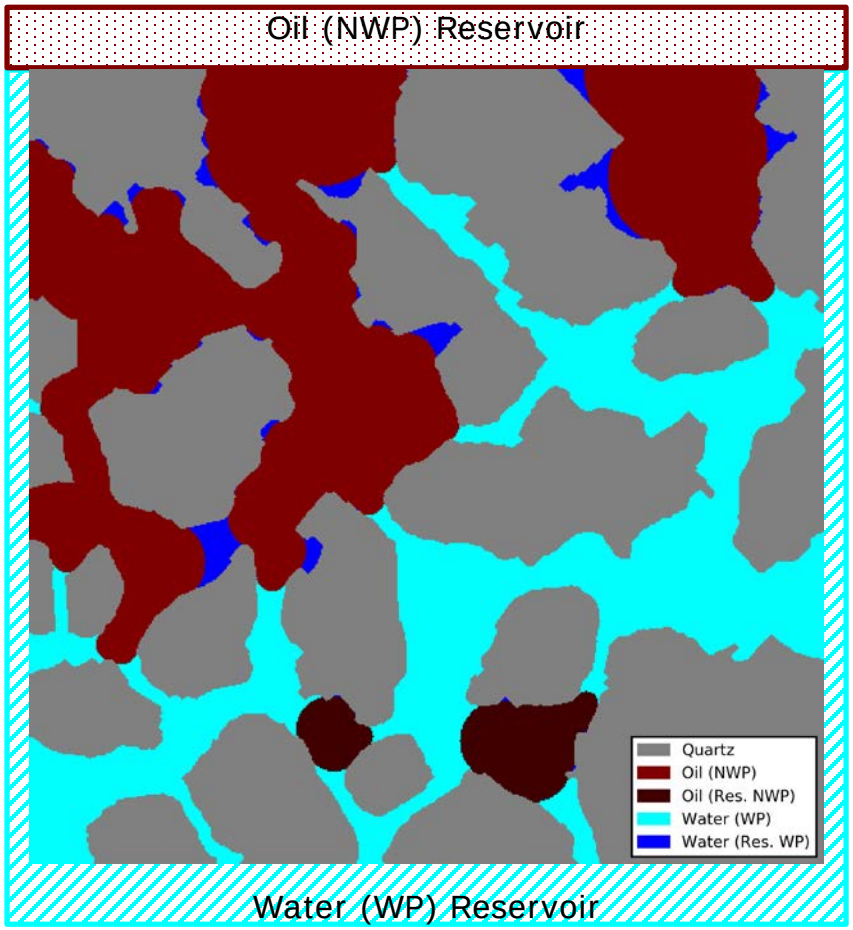

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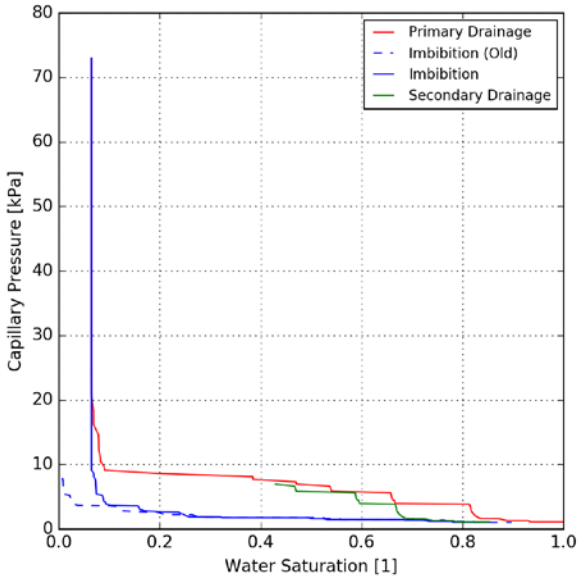

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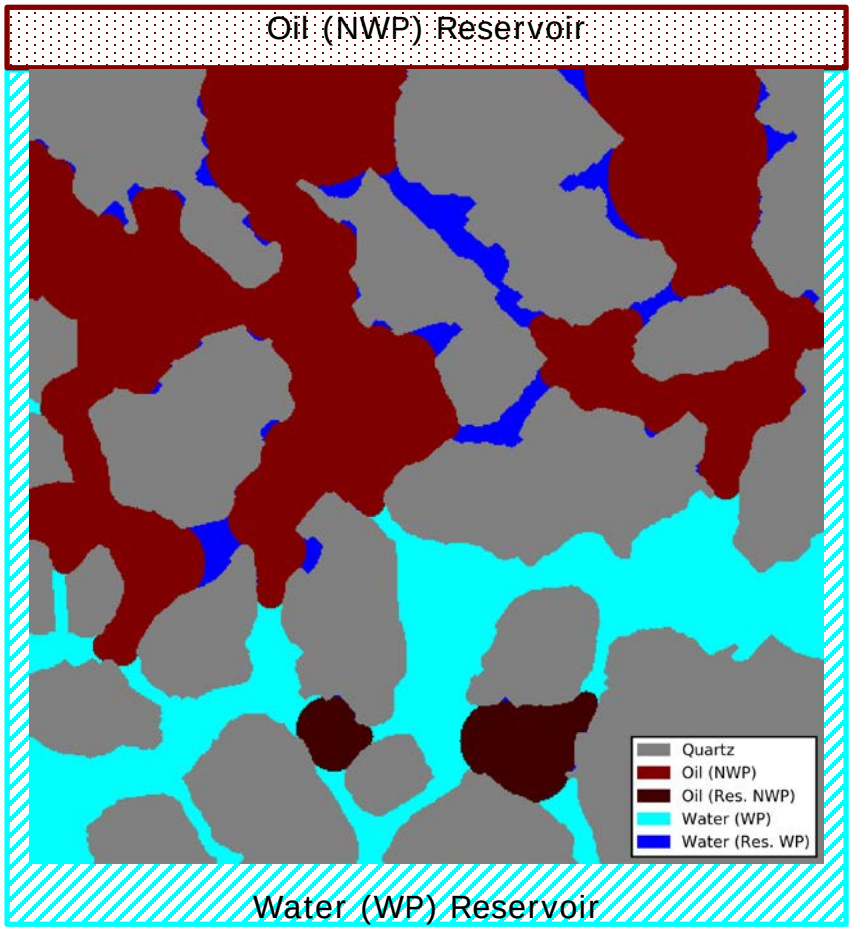

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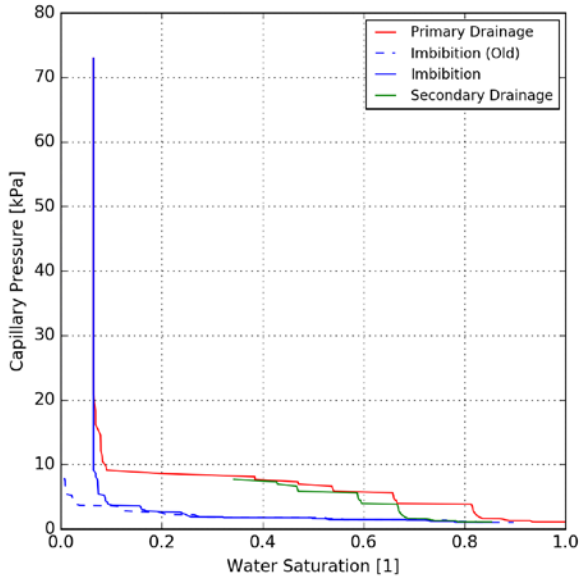

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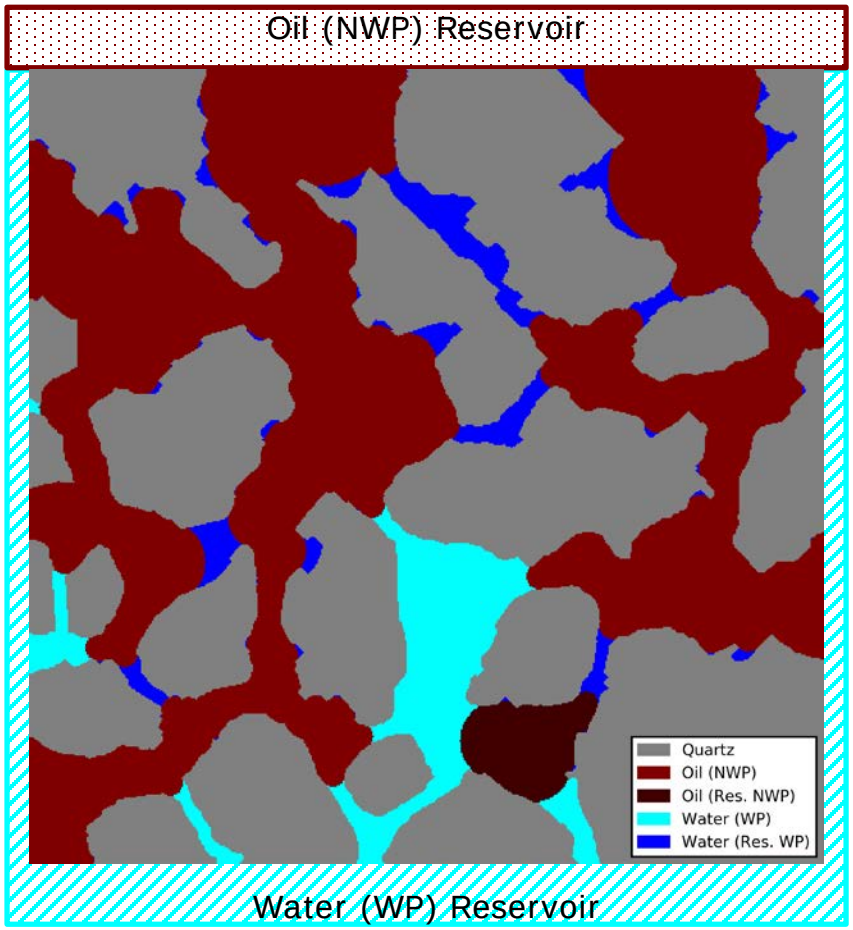

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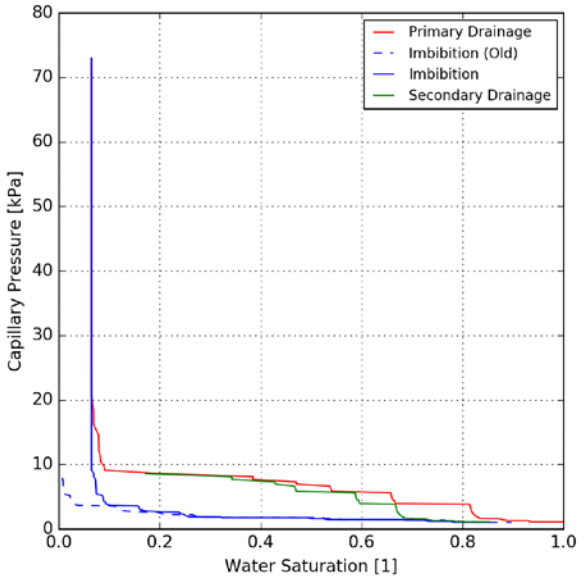

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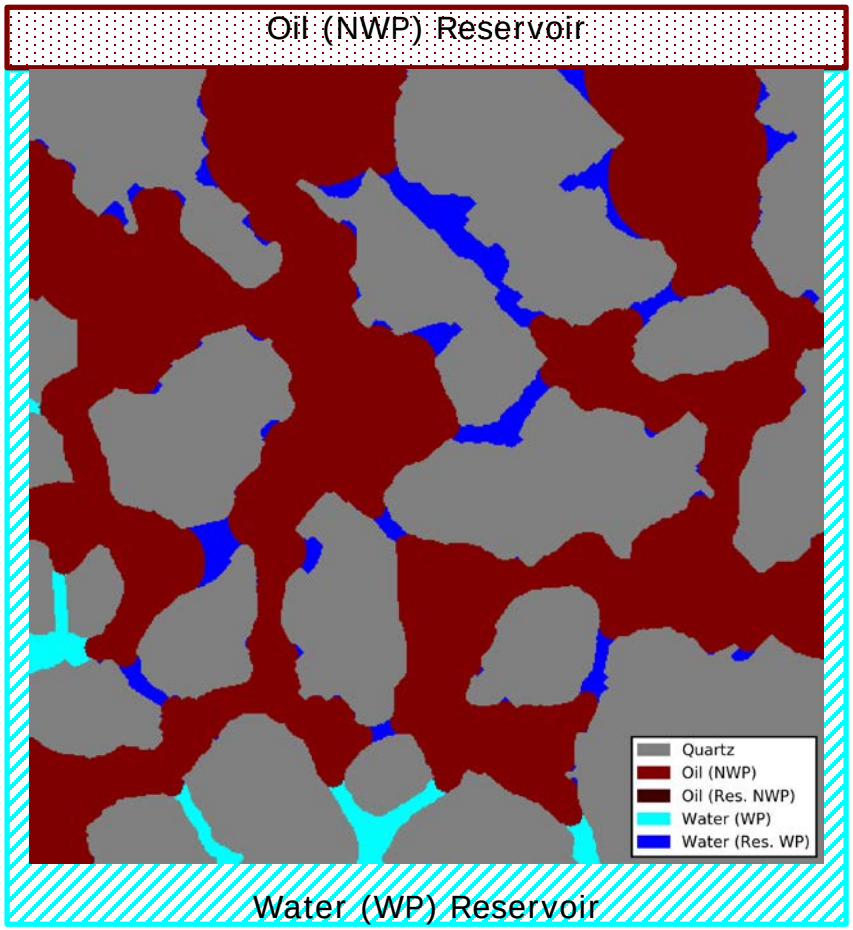

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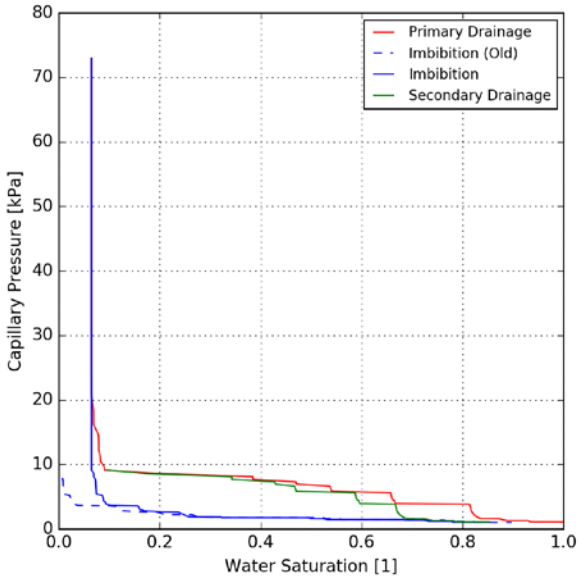

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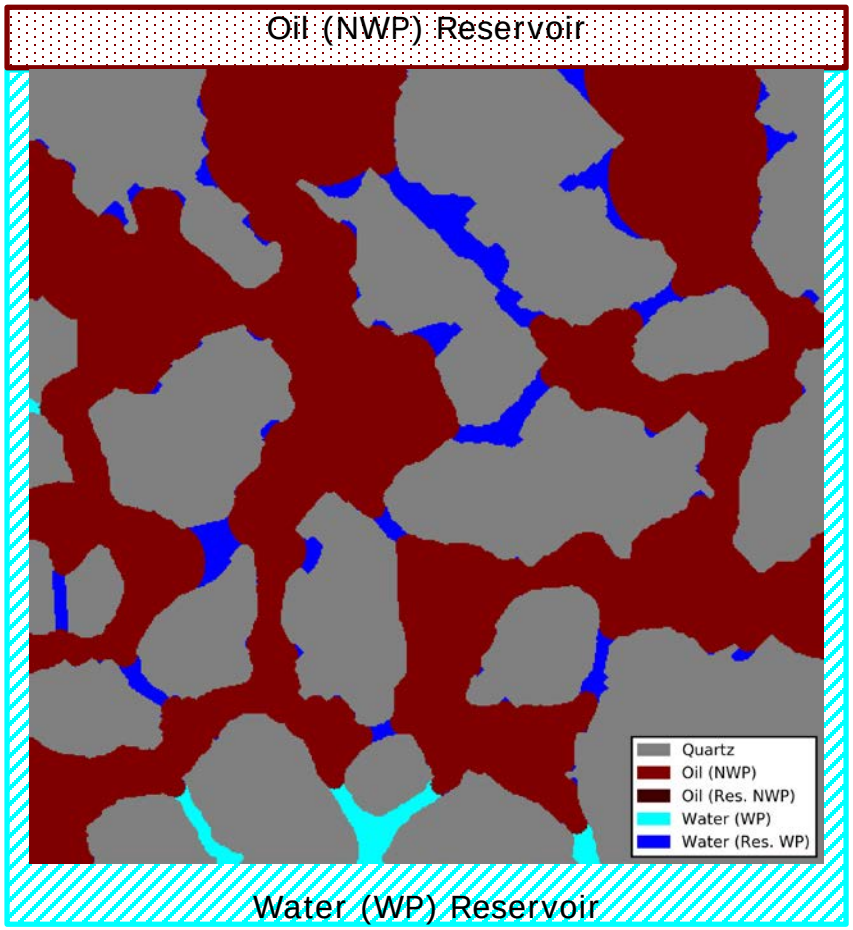

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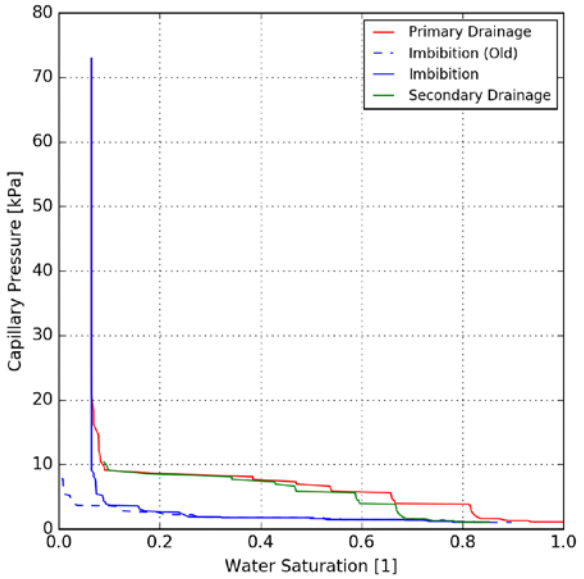

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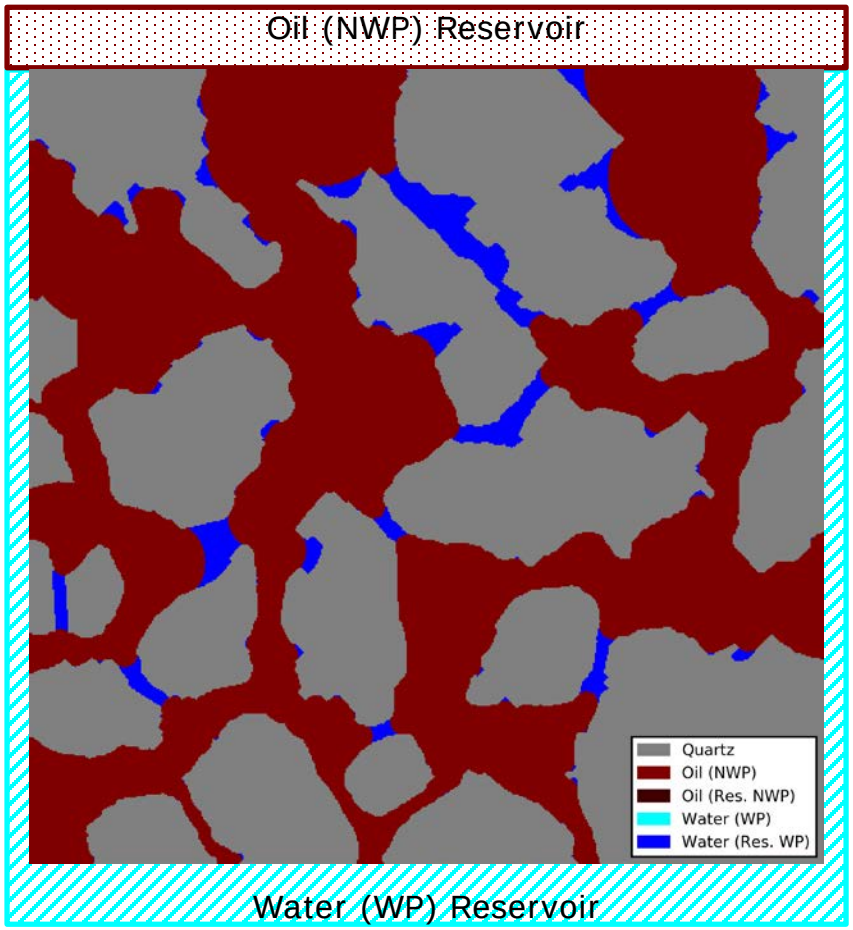

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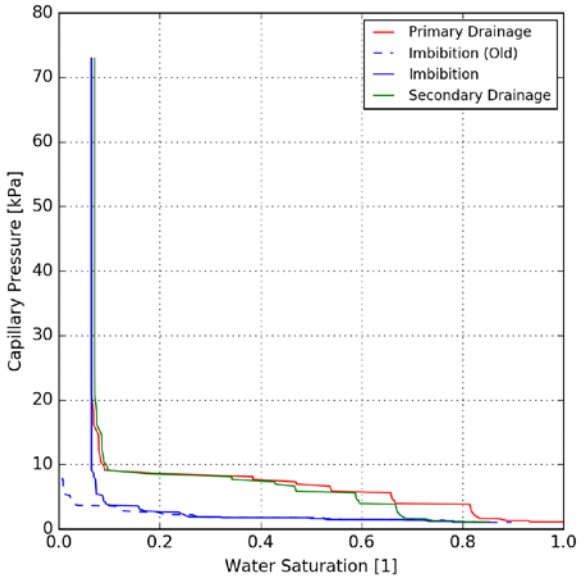


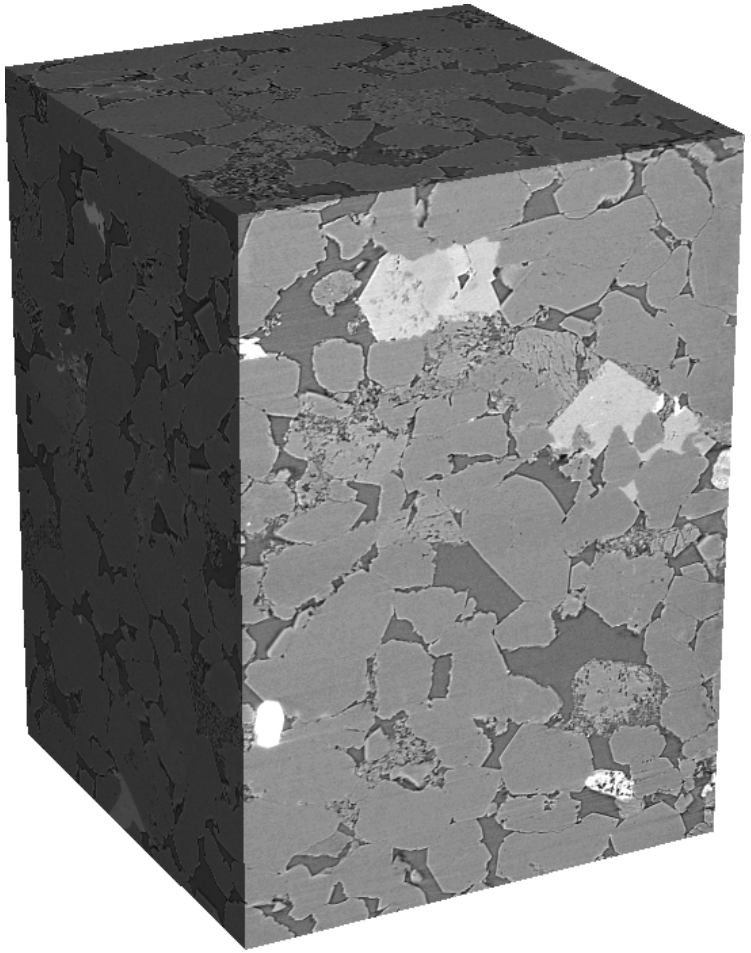
Capillary Pressure for a Berea Sandstone

Structure - Berea Sandstone:

- Size: 720x720x1024
- Voxel length: 0.74 µm
- Porosity: 18.4 %

Simulation Parameters:

- Contact Angle: 30°
- Surface Tension: 0.027 N/m



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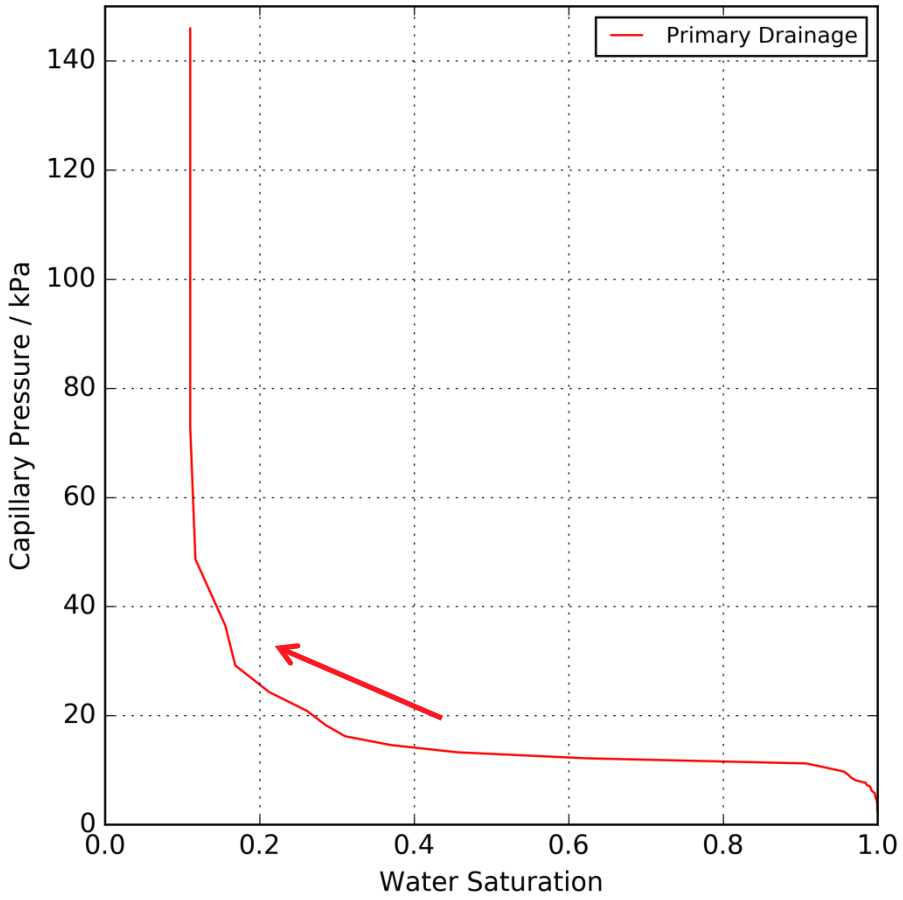
- Irreducible WP: 11%



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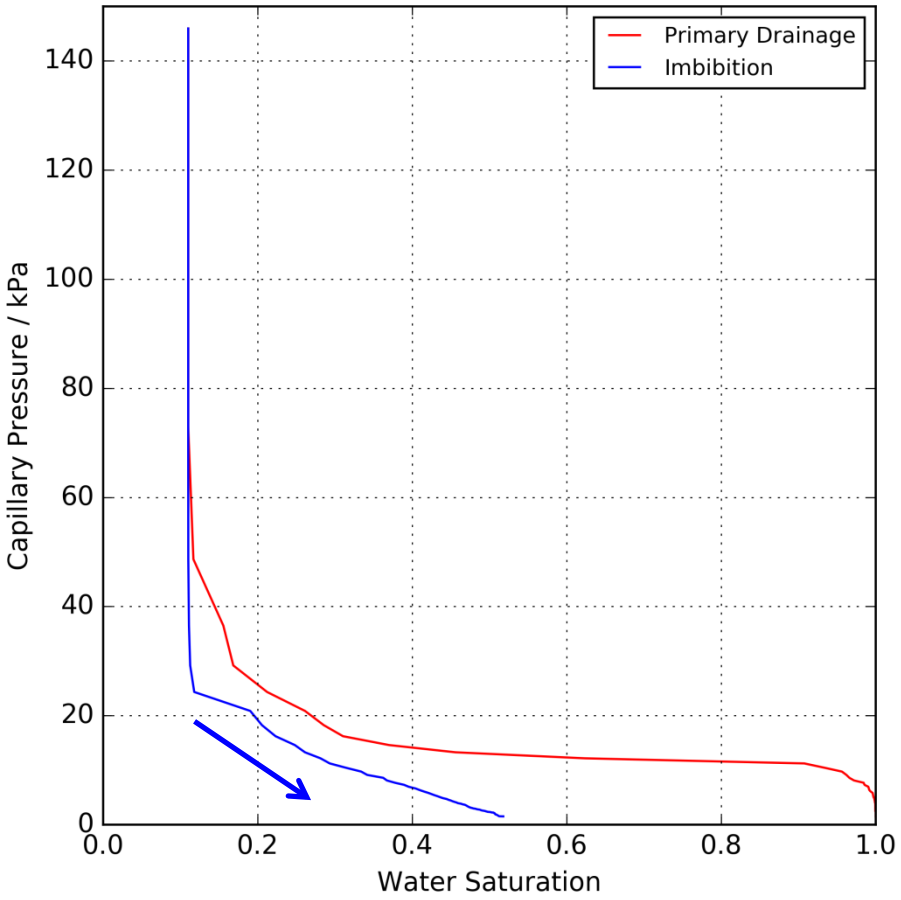
- Irreducible NWP: 51%



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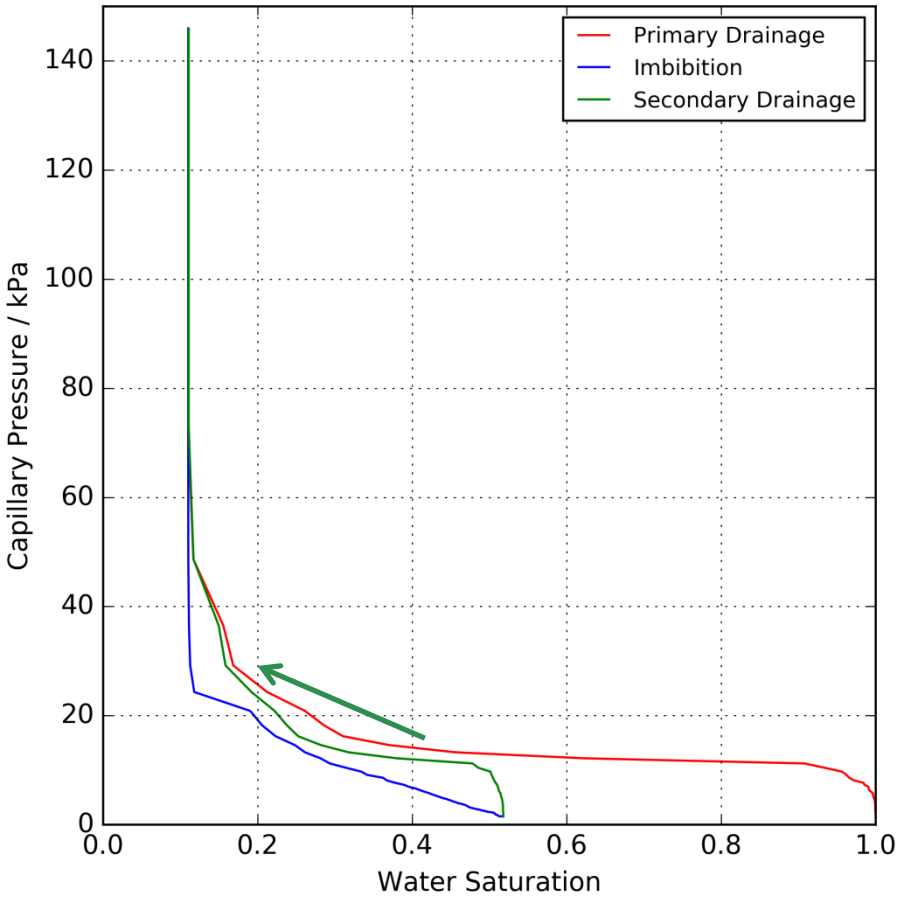
- Irreducible NWP: 51%

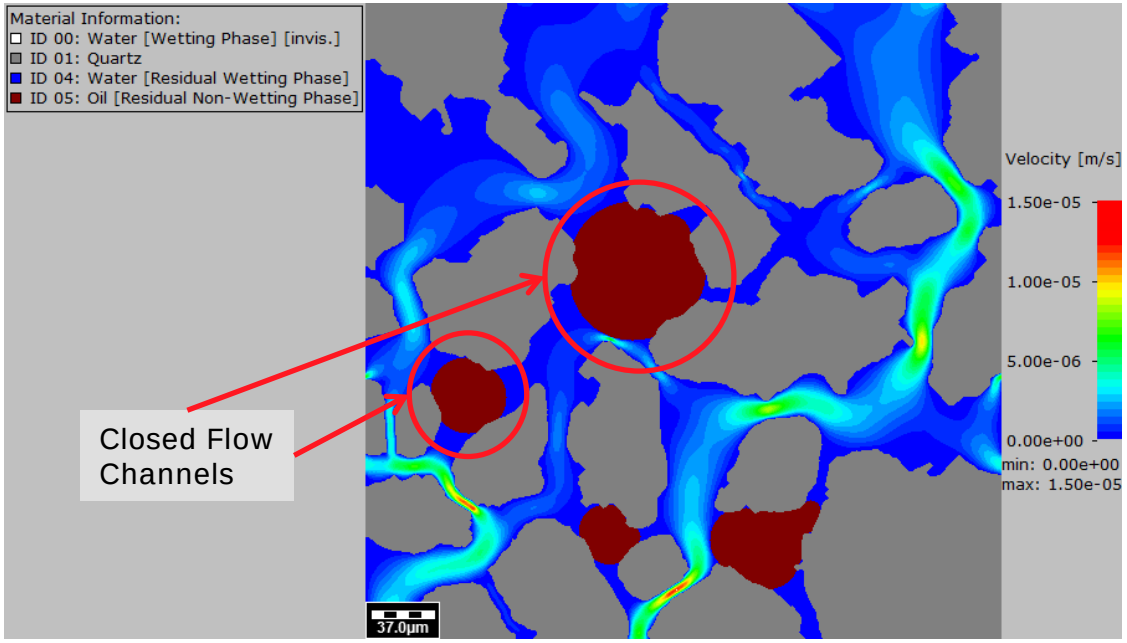
Simulation Performance:

- Memory: 5.2 GB
- Runtime: 6.7 h



Computation of Relative Permeabiliy
Basic Idea

- Find
  - Oil distribution and
  - Water distribution
- Choose
  - Saturation levels and
  - Flow solver parameters
- Solve Stokes equations in
  - Water phase and treat oil phase as solid
  - Oil phase and treat water phase as solid



Stokes flow of water from bottom to top.
Oil droplets close large flow channels.

Relative Permeability for a Berea Sandstone

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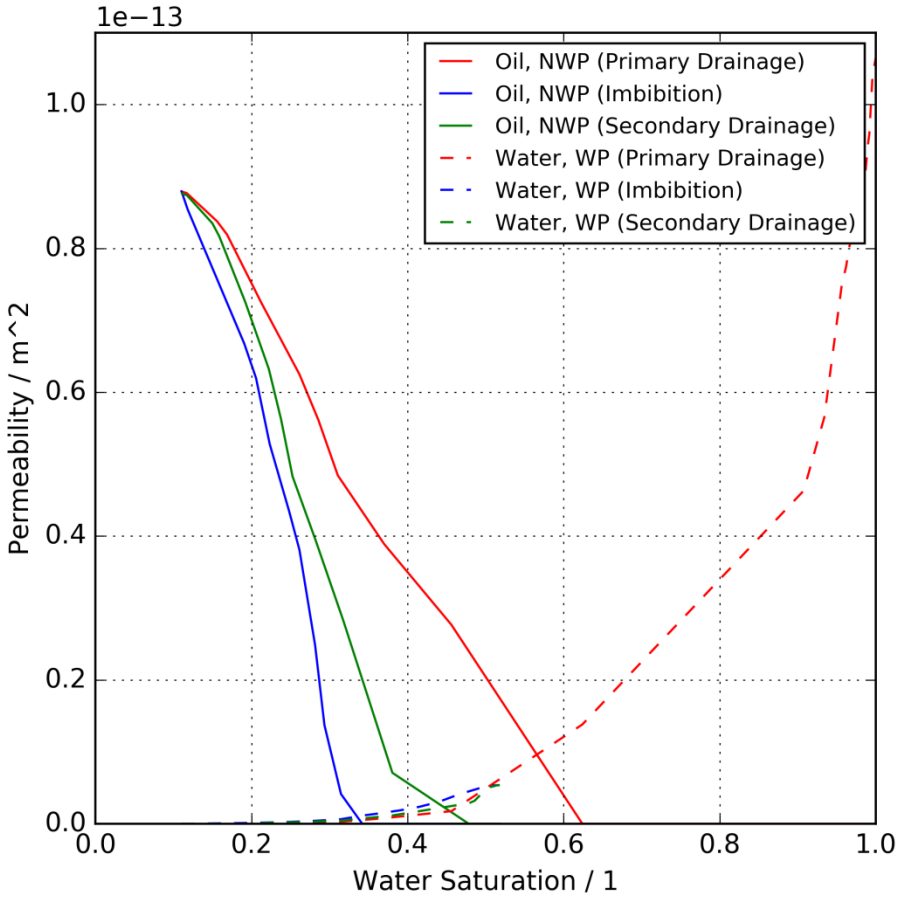

Conclusions & Future Work

Conclusions

- The pore morphology method was extended to consider residual non-wetting and residual wetting phase at the same time
- The approach is able to reproduce the hysteresis effect of capillary pressure for digital rocks

Future Work

- Validation of the approach by comparing simulation results with experiments

Vision

- Compressibility of residual phases
- Mixed wettability

GeoDict

The Digital Material Laboratory

Standard Edition

info@math2market.de
www.geodict.com

Software Design:
Dr. Jürgen Becker, Liping Cheng, PhD,
Dr. Erik Glatt, Dr. Sven Linden,
Dr. Christian Wagner, Dr. Rolf Westerteiger,
Nicolas Harttig, Andreas Grießer,
and Andreas Wiegmann, PhD

Art Design:
Steffen Schwichow

MATH 2 MARKET