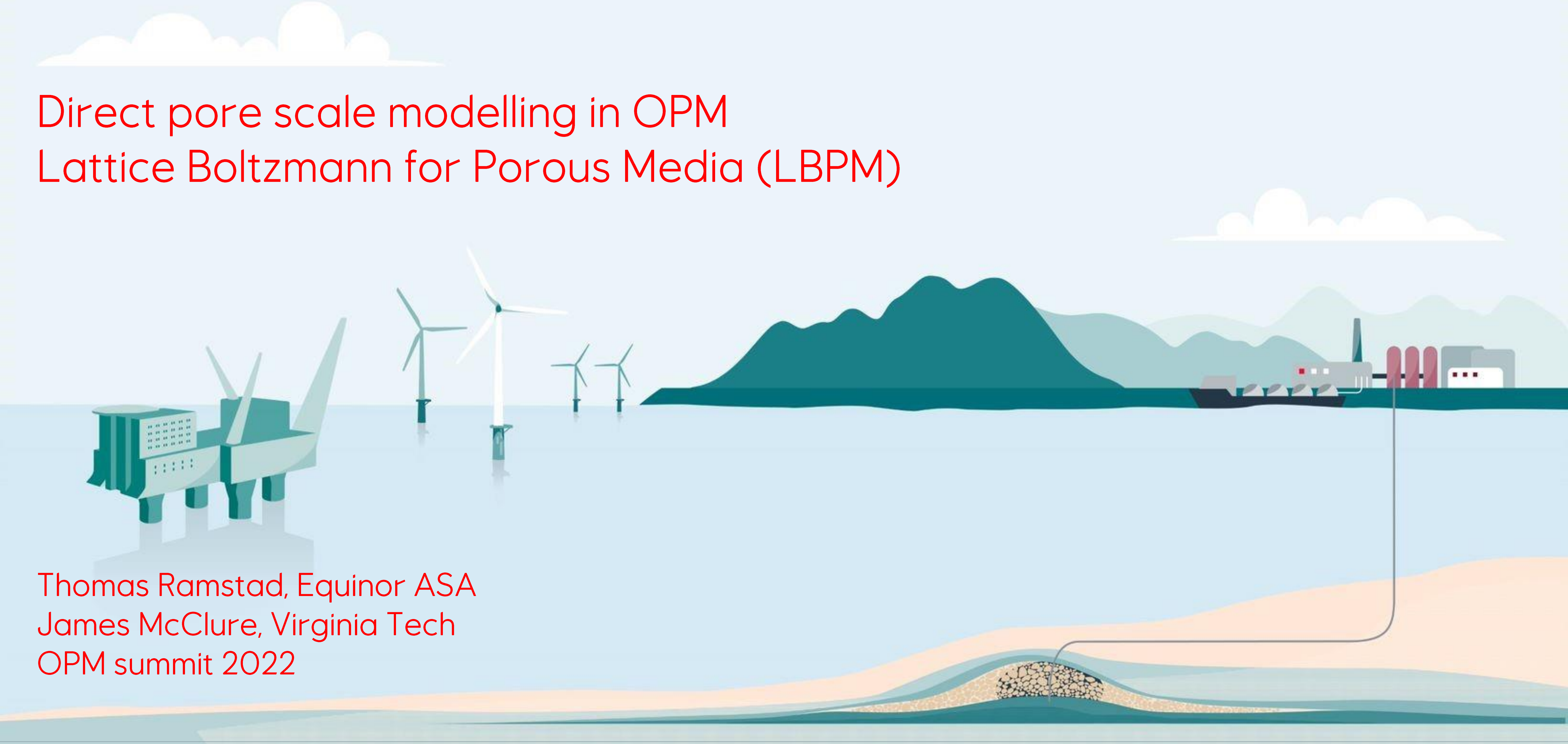
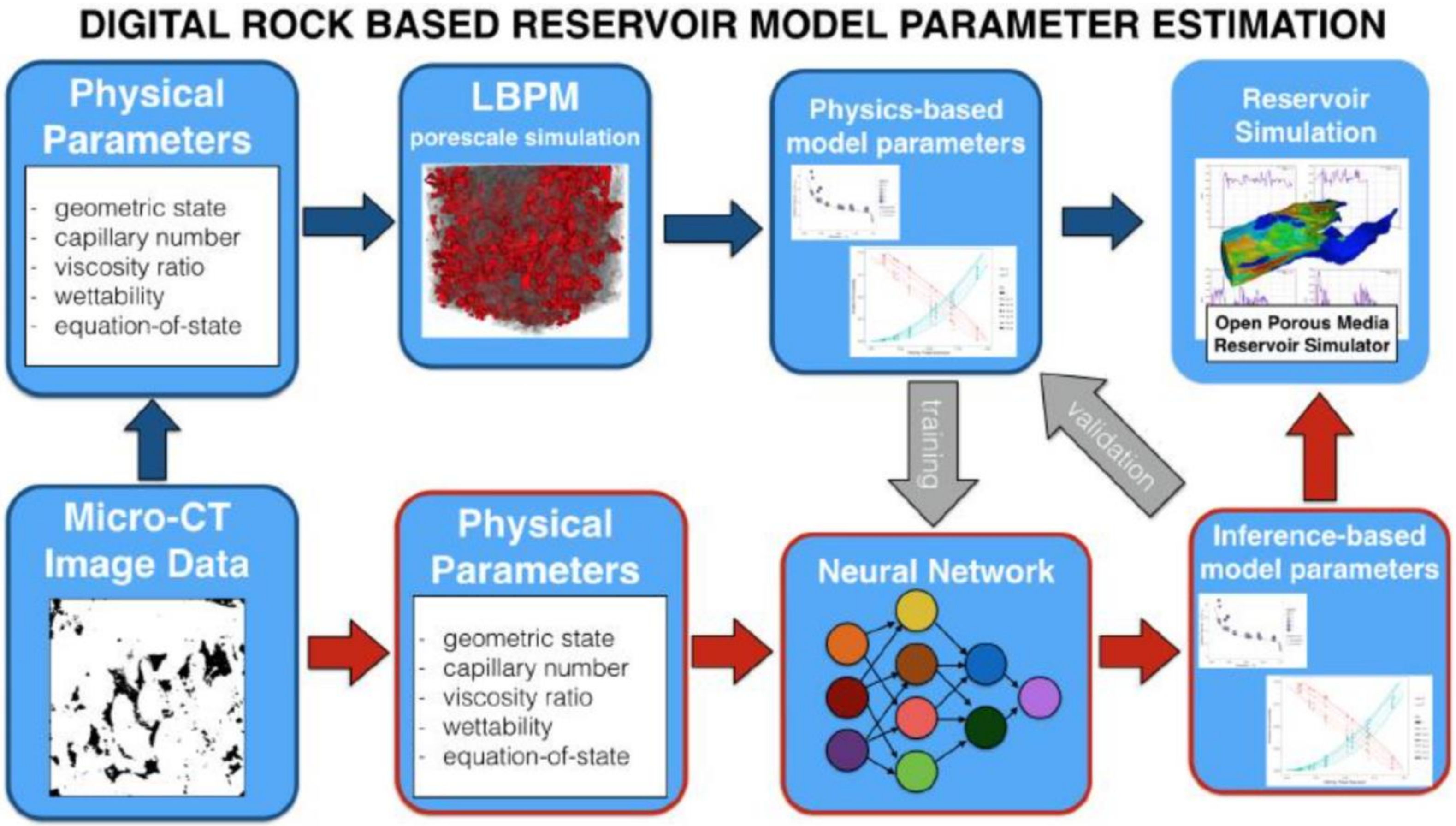
Direct pore scale modelling in OPM
Lattice Boltzmann for Porous Media (LBPM)



Thomas Ramstad, Equinor ASA
James McClure, Virginia Tech
OPM summit 2022

LBPM software package



JE McClure, Z Li, M Berrill and T Ramstad (2021)

Release of LBPM under OPM

- Collaboration Virginia Tech and Equinor
- GPLv-3.0 license
- GPU / CPU runtime environments
- Cmake / ctest
- Stand. Dependencies
    - MPI, HDF5, C++ 14, ….

Source code:
https://github.com/opm/lbpm
Wiki tutorial:
https://github.com/opm/lbpm/wiki

Getting Started with LBPM

- **Source Code**
  - Available from Open Porous Media Initiative
  - https://github.com/opm/lbpm
- **NVIDIA GPU Container Registry**
  - Pre-configured container optimized for NVIDIA GPU
  - LBPM and dependencies already compiled
  - Suitable for cloud systems or HPC
  - https://ngc.nvidia.com/catalog/containers/hpc:lbpm
- **Documentation**
  - Basic documentation with step-by-step examples
  - Installation, Absolute Permeability, Multiphase Flow, Visualization, etc.
  - https://lbpm-sim.org/

- **Collaborators**
  - Thomas Ramstad (Equinor ASA)
  - Zhe Li (Virginia Tech)
  - Steffen Berg (Shell)
  - Mark Berrill (Oak Ridge National Lab)
  - Cheng Chen (NJIT)
  - Ming Fan (Virginia Tech)
  - Alessandro Fanfarillo (AMD)
  - Remco Hartkamp (TU Delft)
  - Tim Mattox (HPE)
  - Johan Padding (TU Delft)
  - Maša Prodanović (University of Texas)
  - Ryan Armstrong (UNSW)

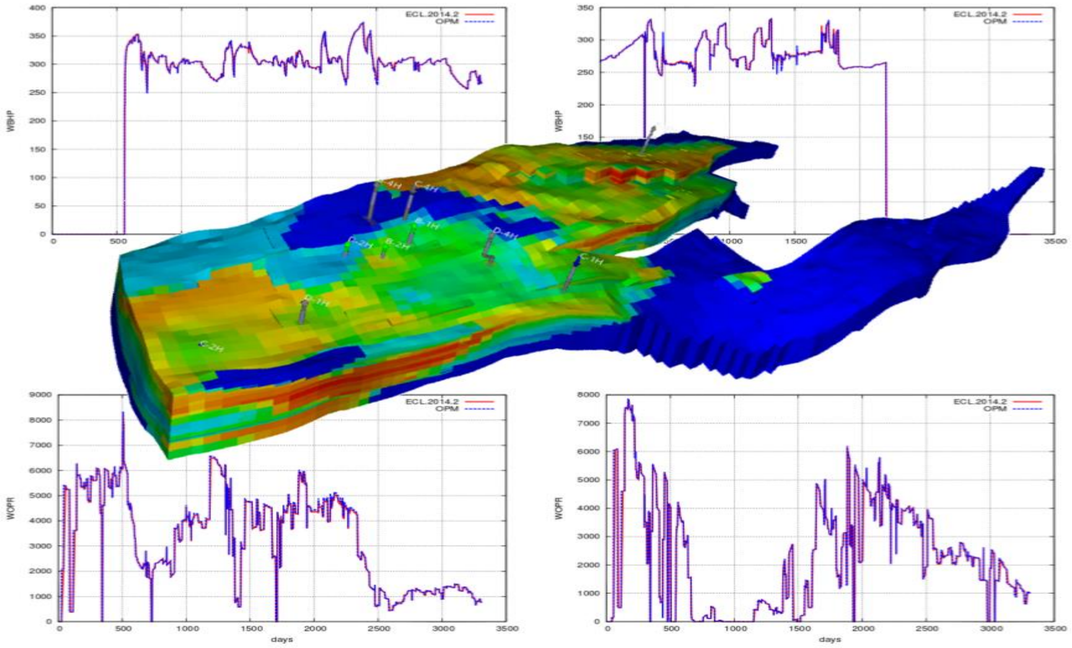
Macroscopic flow functions:
Closing the scale gap

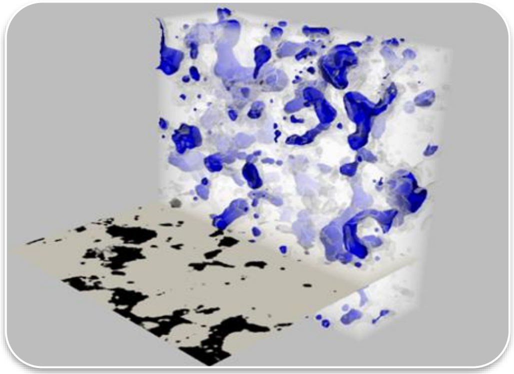
Multiphase
Constitutive
Relationships

$$\mathbf{u_i} = \frac{k_i}{\mu_i}(\rho\mathbf{g} - \nabla p_i)$$

$$k_i^r = \frac{k_i}{K}$$

$$\nabla P_c = \nabla P_i - \nabla P_j$$





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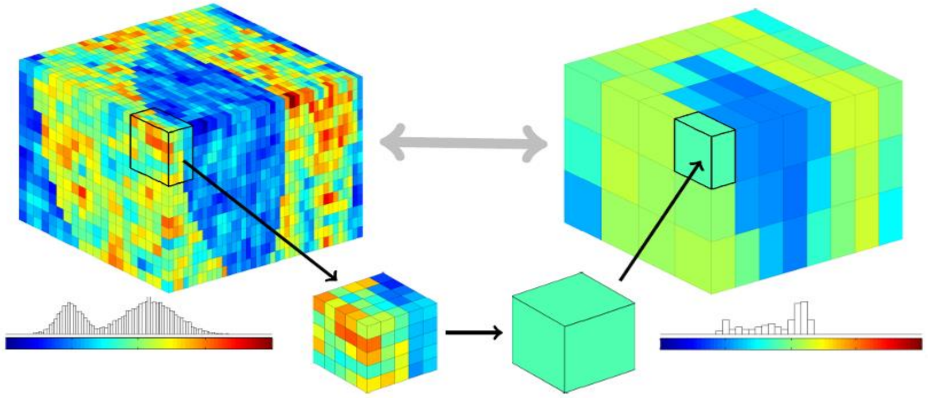
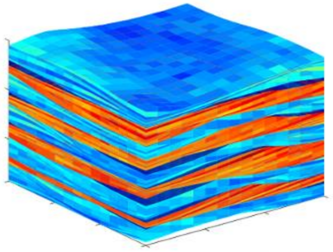
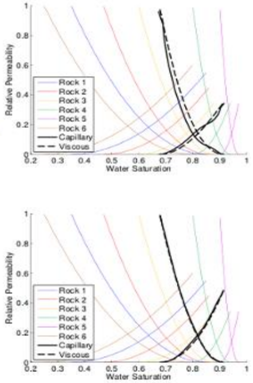
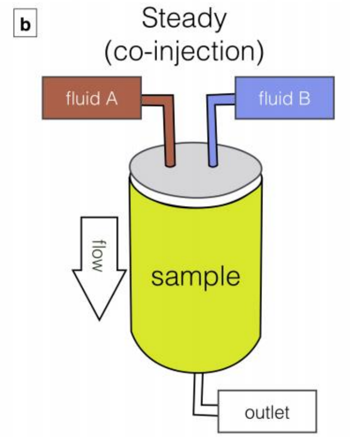


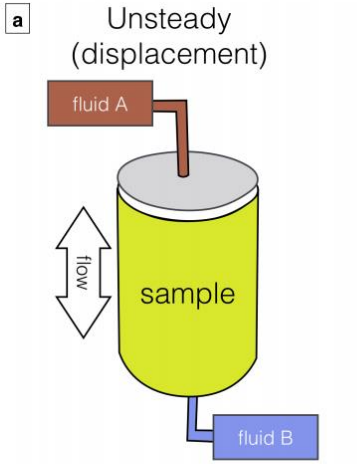




Open

Core analysis (SCAL)





Steady State:

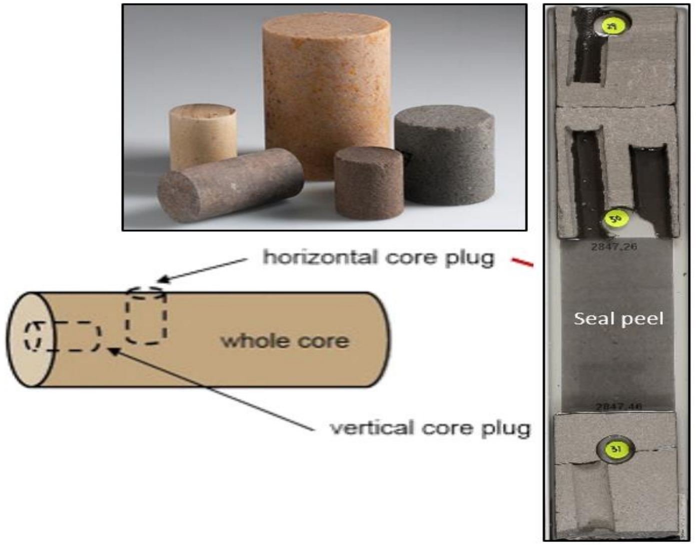
- Defines «entire» shape of the relative permeability curve

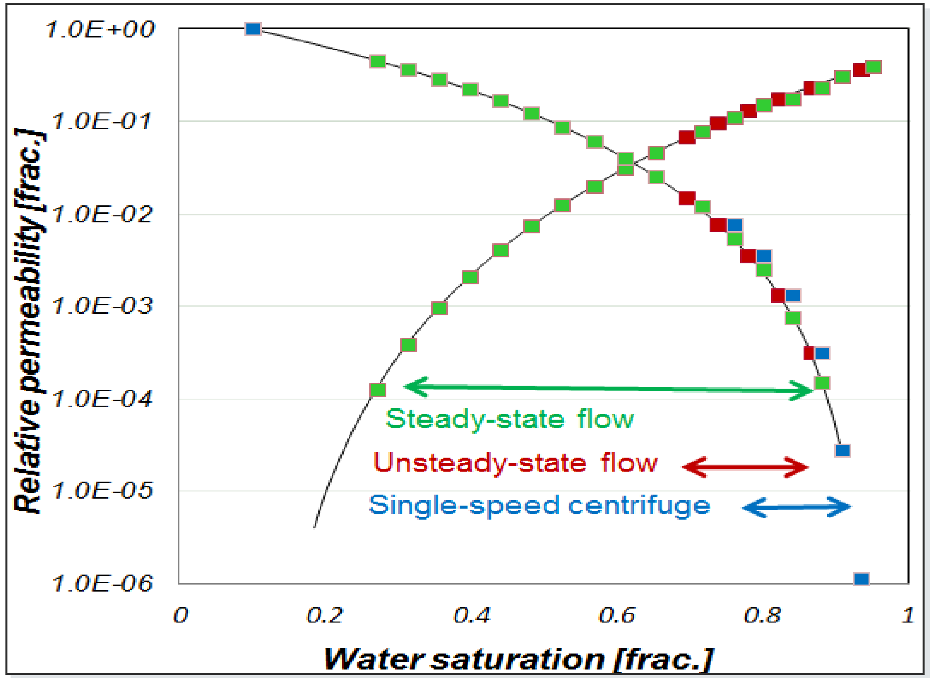
Unsteady State:

- Narrow saturation range with saturation info

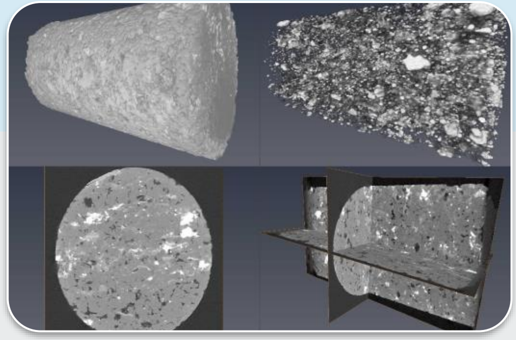
Centrifuge:

- Reliable *end-point saturations*





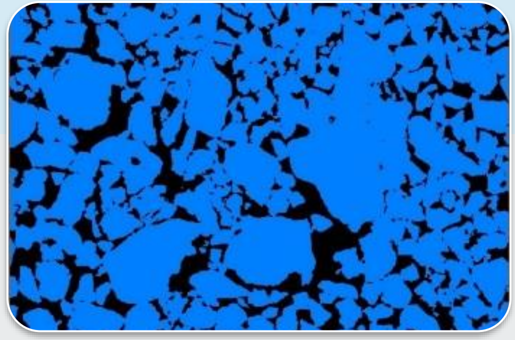
Digital Rock Physics



Preparing small samples from core material

High resolution imaging of core material

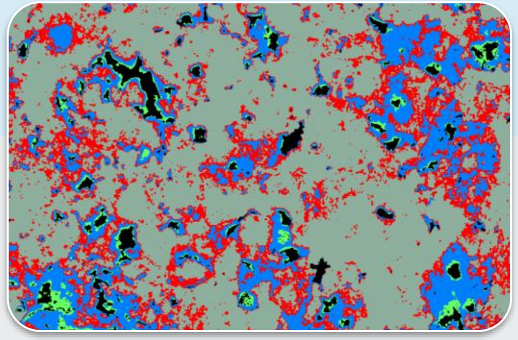
X-ray CT and SEM



Segmentation and image registration

Map pore structures and fluids

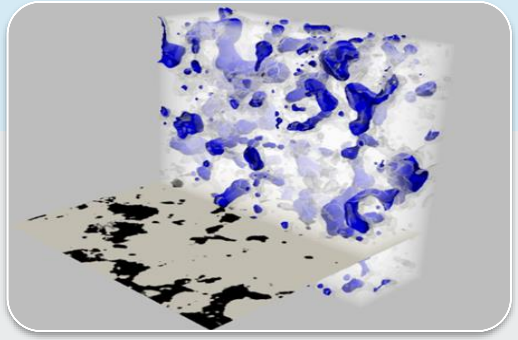
Create porosity maps



Model building including porosity on several scales

Macro and micro porosity

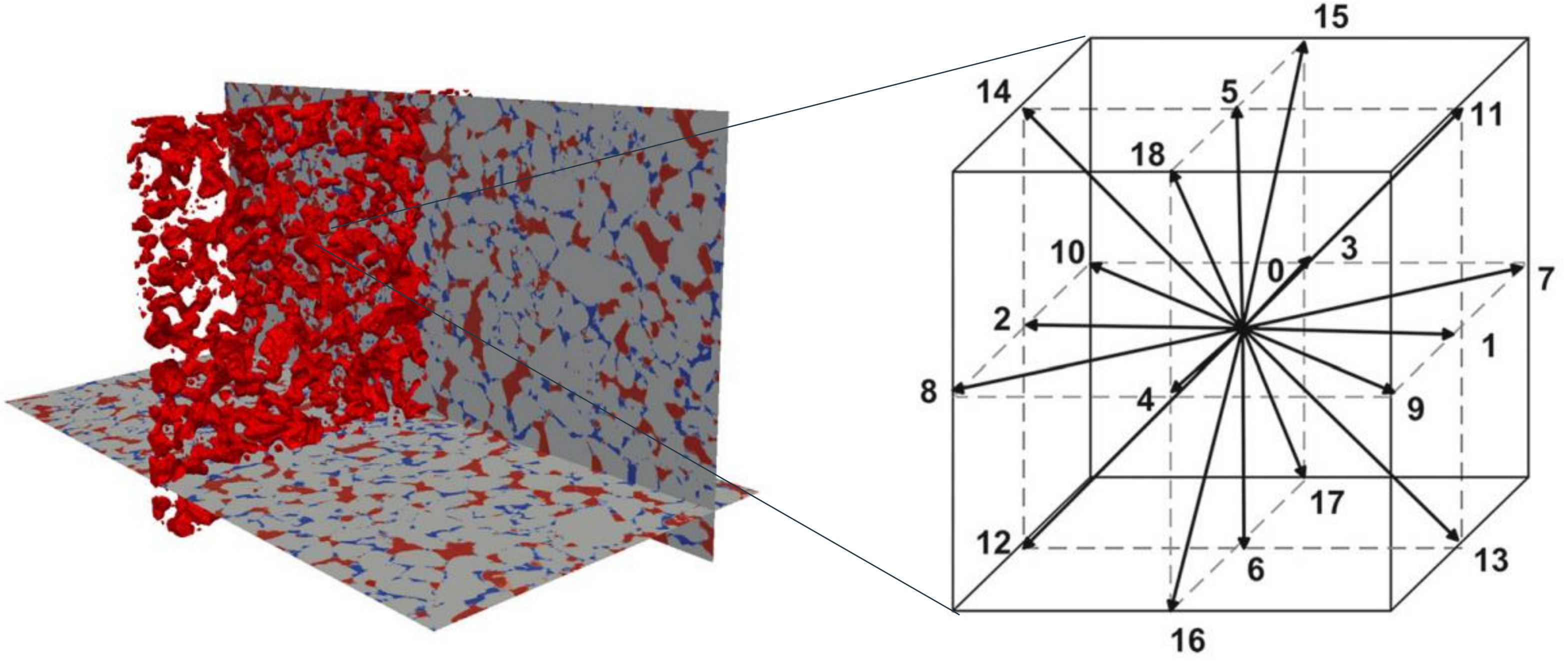
Rocktyping

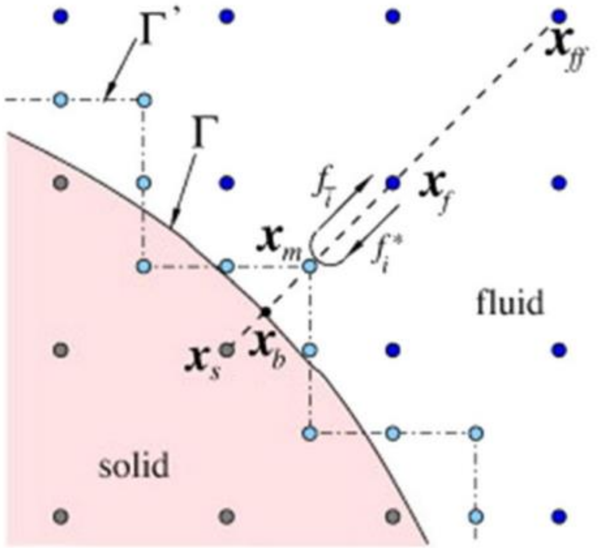


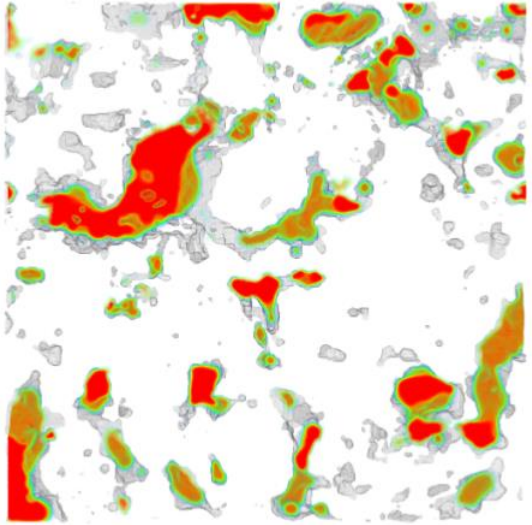
Multiphase flow simulation on digital models

Understanding mechanisms

Sensitivity in flow functions







Lattice Boltzmann Method

- LBM is well established for modelling two-phase flow in porous media
- Well suited for complex boundary conditions
- Discretized velocity space in continuum Boltzmann equation
- Handle fluid interfaces: Local and global effects

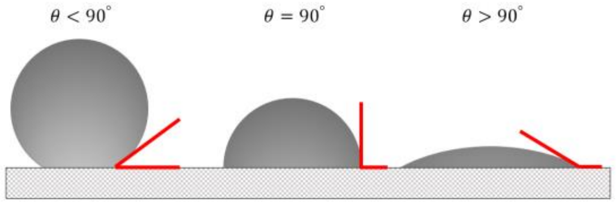
Simulation of pore scale mechanisms

$$\mathrm{Ca} = \frac{\mu_i |\mathbf{u}_i|}{\sigma_{ab}}$$

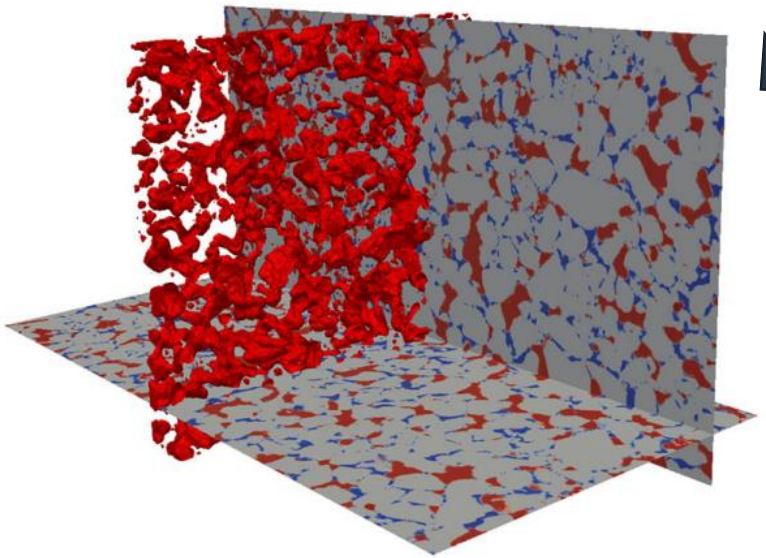
$$\mathrm{M} = \frac{\mu_a}{\mu_b}$$

$$\mathrm{Bo} = \frac{(\rho_a - \rho_b)|\mathbf{g}|D^2}{\sigma_{ab}}$$

Fluid and flow properties

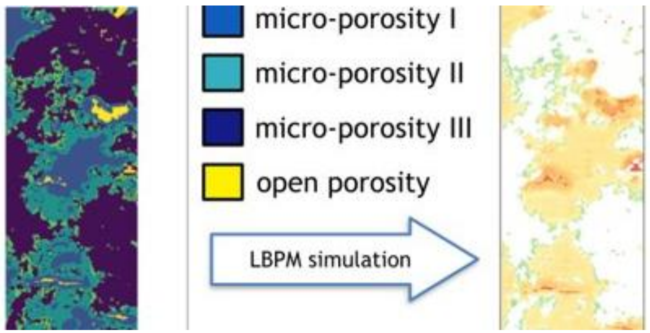


Wettability

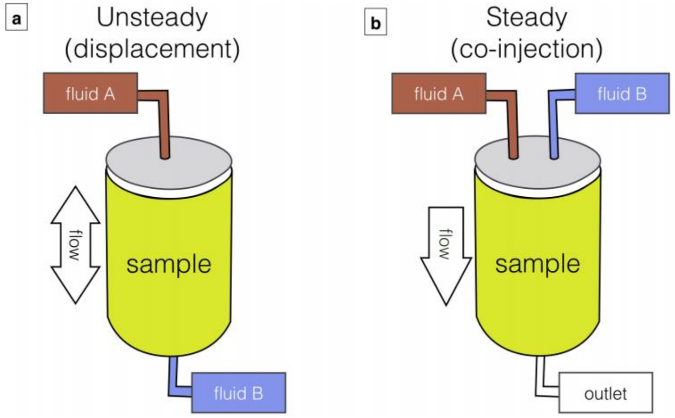


Pore scale flow simulations

JE McClure, Z Li, M Berrill and T Ramstad (2021)

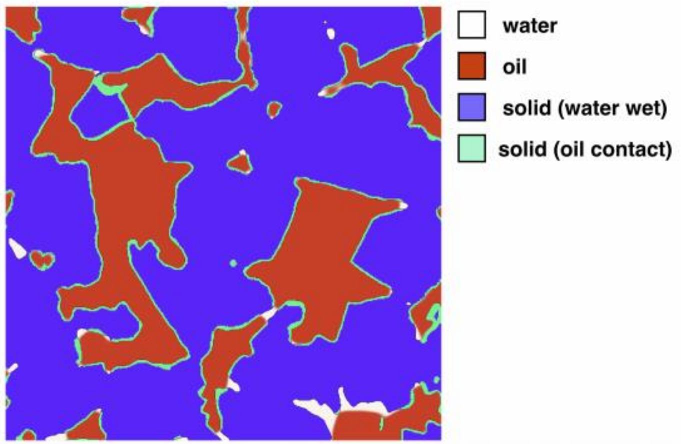


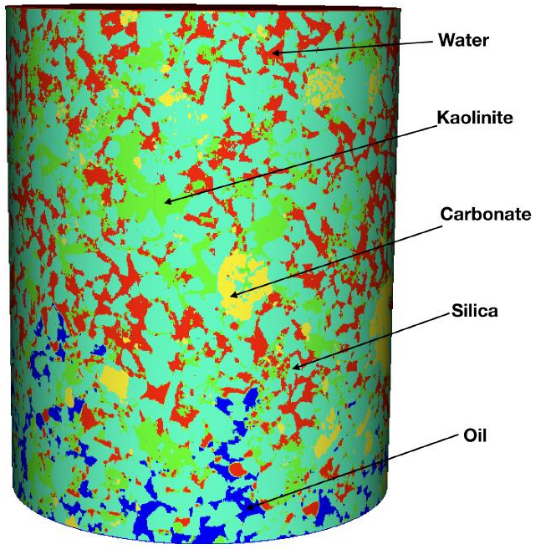
Material properties



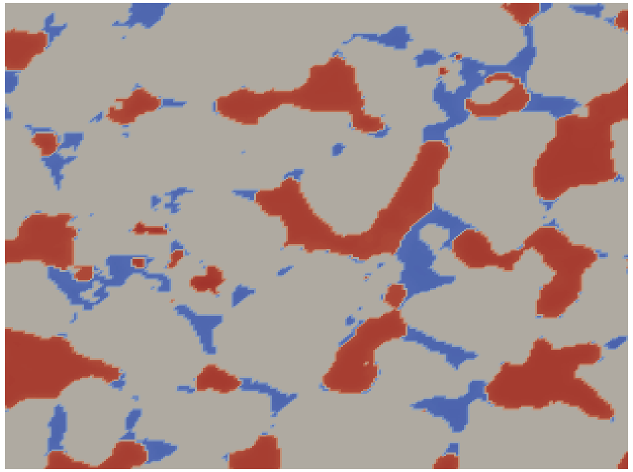
Boundary conditions
SCAL protocols

Wettability maps and spatial wettability

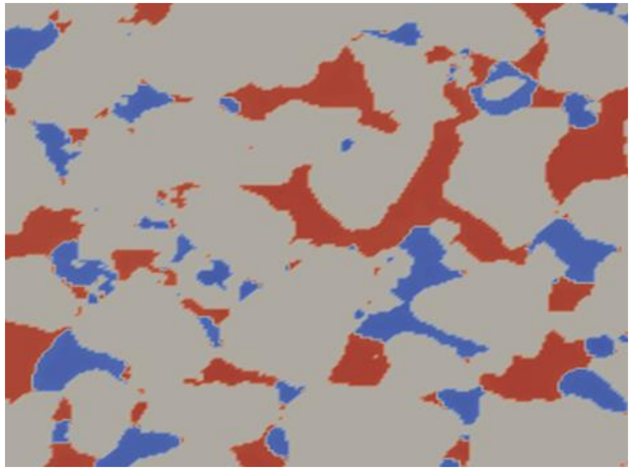




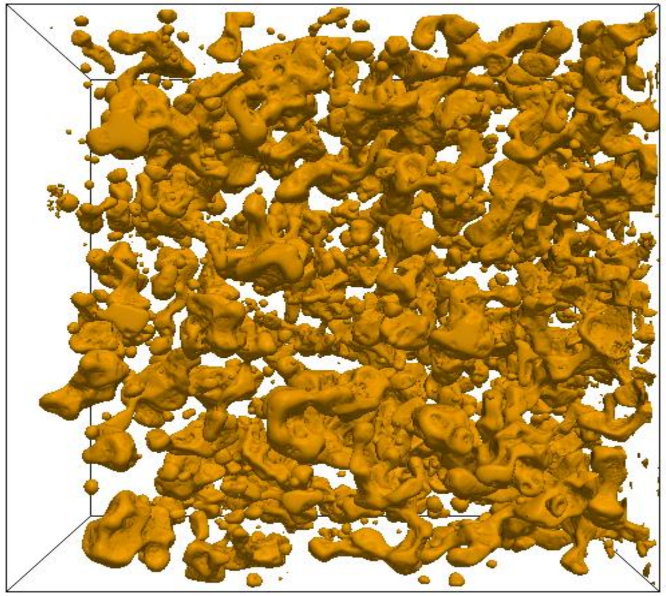
T. Ramstad, A. Kristoffersen, E. Ebeltoft, 2020

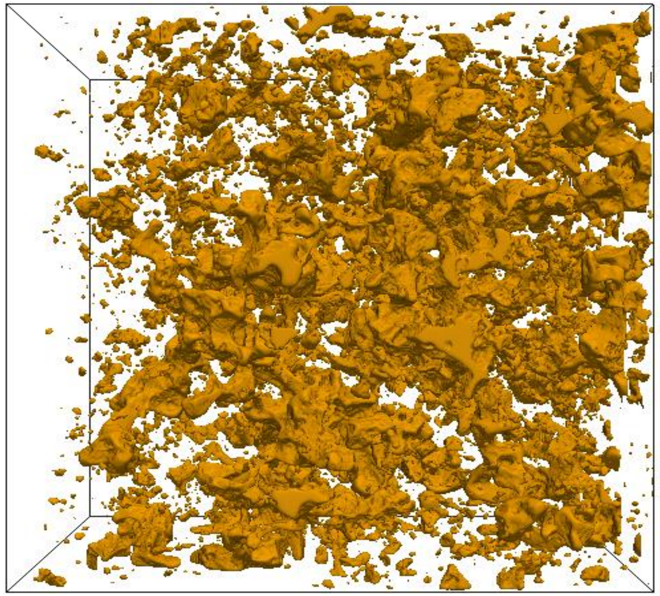


Water wet



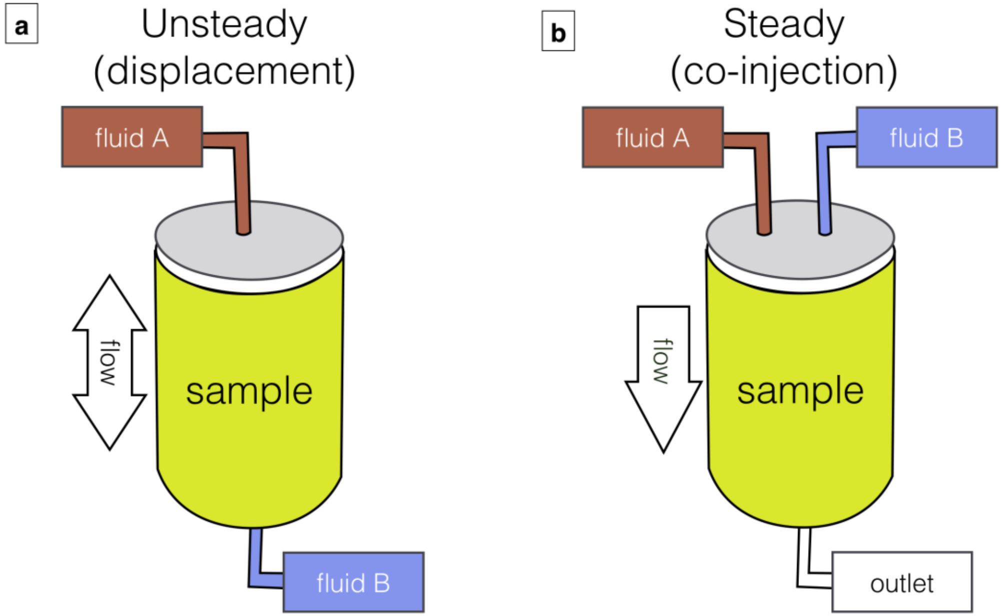
Intermediate wet





SCAL Experimental Protocols

- Established experimental protocols to measure rock properties from SCAL experiments
- Simulations designed as a computational analog of these experiments
- **Unsteady displacement**
  - Fluid injected into sample using a pump
  - Saturation changes due to displacement
- **Steady-state fractional flow**
  - Fluids are co-injected into the sample to cause simultaneous flow of both fluids
  - Goal is to infer steady-state relative permeability (constant saturation)
- **Centrifuge protocol**
  - Fluids mobilized based on centrifugal forces
  - Goal is to infer capillary pressure and endpoint behavior

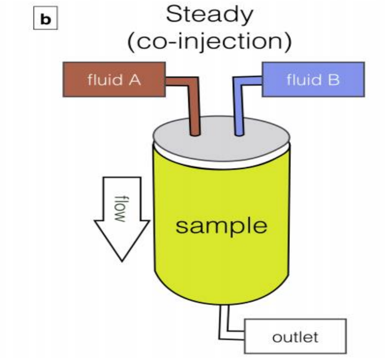


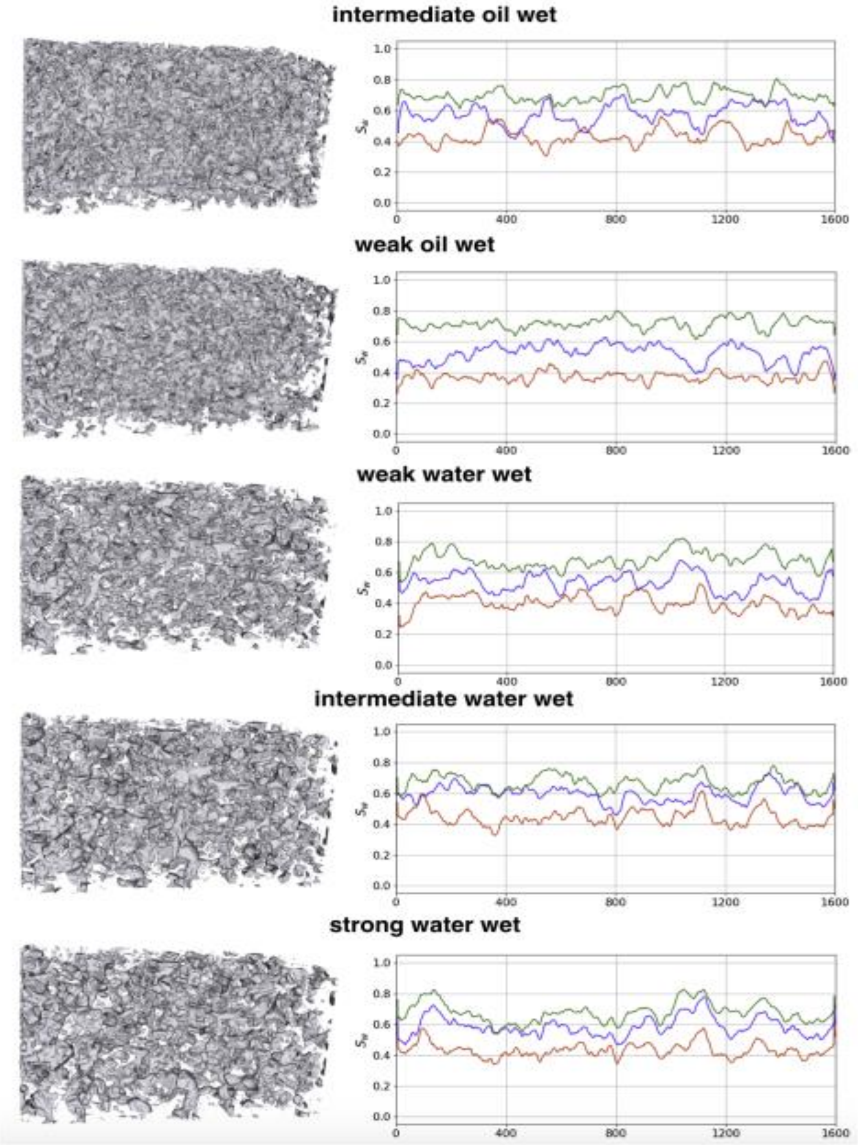
McClure, J.E., Li, Z., Berrill, M. Ramstad, T. The LBPM software package for simulating multiphase flow on digital images of porous rocks. *Comput Geosci* **25,** 871–895 (2021). https://doi.org/10.1007/s10596-020-10028-9

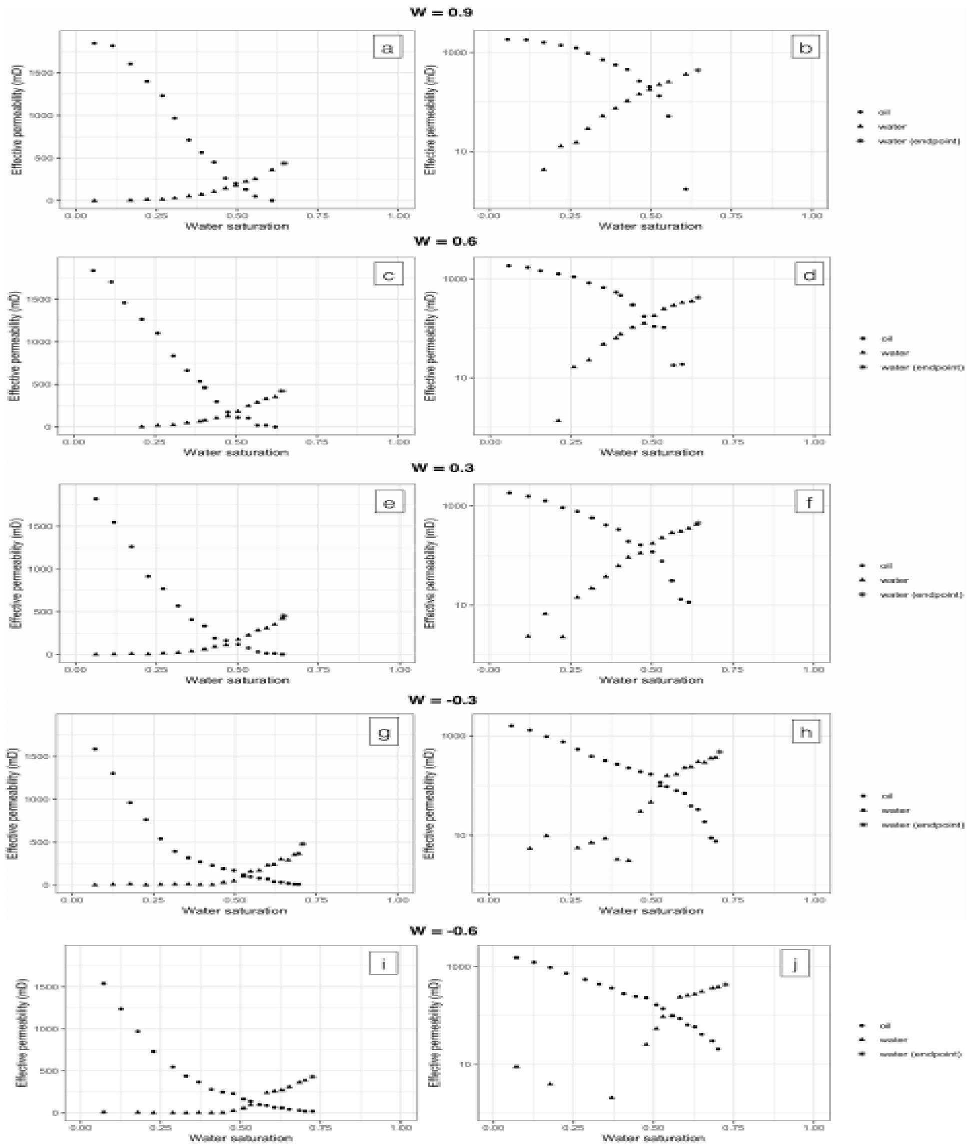
Steady state water flooding

Steady state relative permeability:

- Sensitive to wettability
- Sensitive to flow rate
- Combined with unsteady state end-point simulations



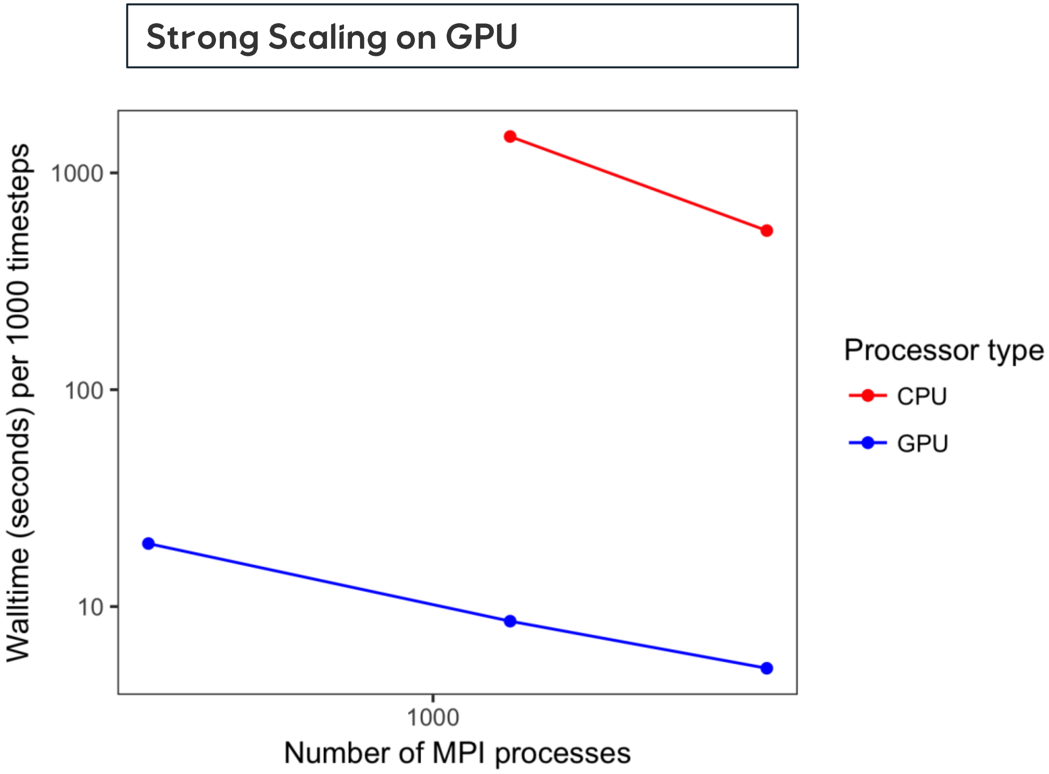




Computational efficiency

- **Efficient computational implementation**
  - Fully parallel (using MPI)
  - Support for multiple architectures
    - CPU implementation (C++)
    - NVIDIA GPU (CUDA)
    - AMD GPU (HIP)

- **Performance on Summit (two-fluid flow)**
  - Summit Node
    - 6 x NVIDIA V100 GPU
    - 2 x IBM Power9 CPU (20 SMC)
    - NVLINK connects GPU within a node
  - CPU comparison is one MPI process per core
  - GPU comparison is one MPI process per GPU



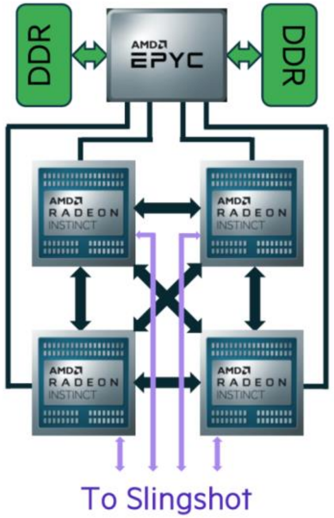
Frontier CAAR program

- **LBPM is one of eight Frontier Center for Accelerated Application Readiness (CAAR) applications across all areas of science**
- Exascale co-design program for the Frontier supercomputer
- Partnership with Oak Ridge Leadership Computing Facility and hadware vendors (AMD and Cray)

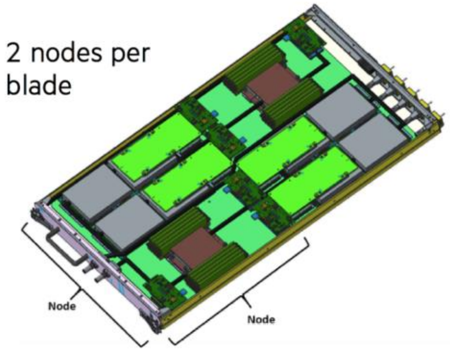
- **Program Goals**
  - 5X performance improvement relative to previous generation (Summit) based on two-phase flow benchmark
    - LBPM currently supports AMD GPU via HIP
  - Advance state-of-the art with respect to scientific simulation capabilities
  - Position the scientific community to next tackle generation of computational problems

https://www.olcf.ornl.gov/frontier/

AMD GPU (ORNL)



Frontier Total:
37,888 Radeon Instinct MI250X GPU



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