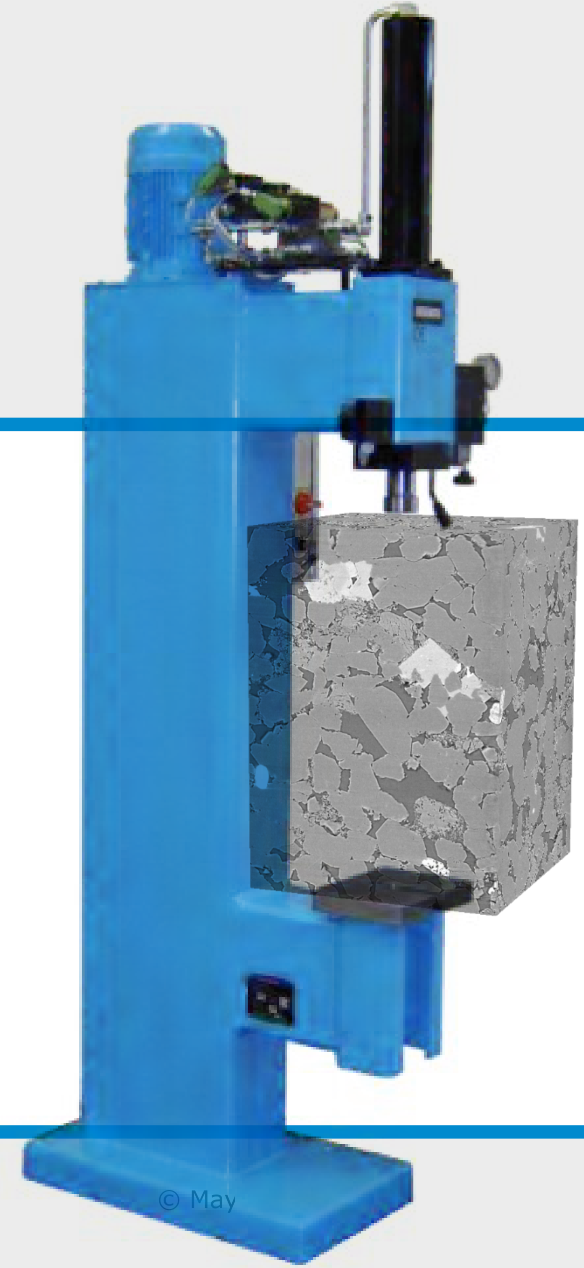
Digital Rock Physics: Digital In-Situ Conditions



ARMA workshop

Digital Rock Physics
Derived Rock Mechanics Properties

June 28th, 2015, San Francisco

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Jens-Oliver Schwarz

Andreas Wiegmann

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Math2Market in a nutshell

Math2Market GmbH, Kaiserslautern, Germany

- M2M's GeoDict Software
  - performs 3d image processing
  - predicts physical rock properties based on CT and SEM images
  - automates workflows and interfaces to MATLAB, EXCEL, Abaqus, Fluent….
- GeoDict Software development since 1998
- Spin off from Fraunhofer Society in September 2011

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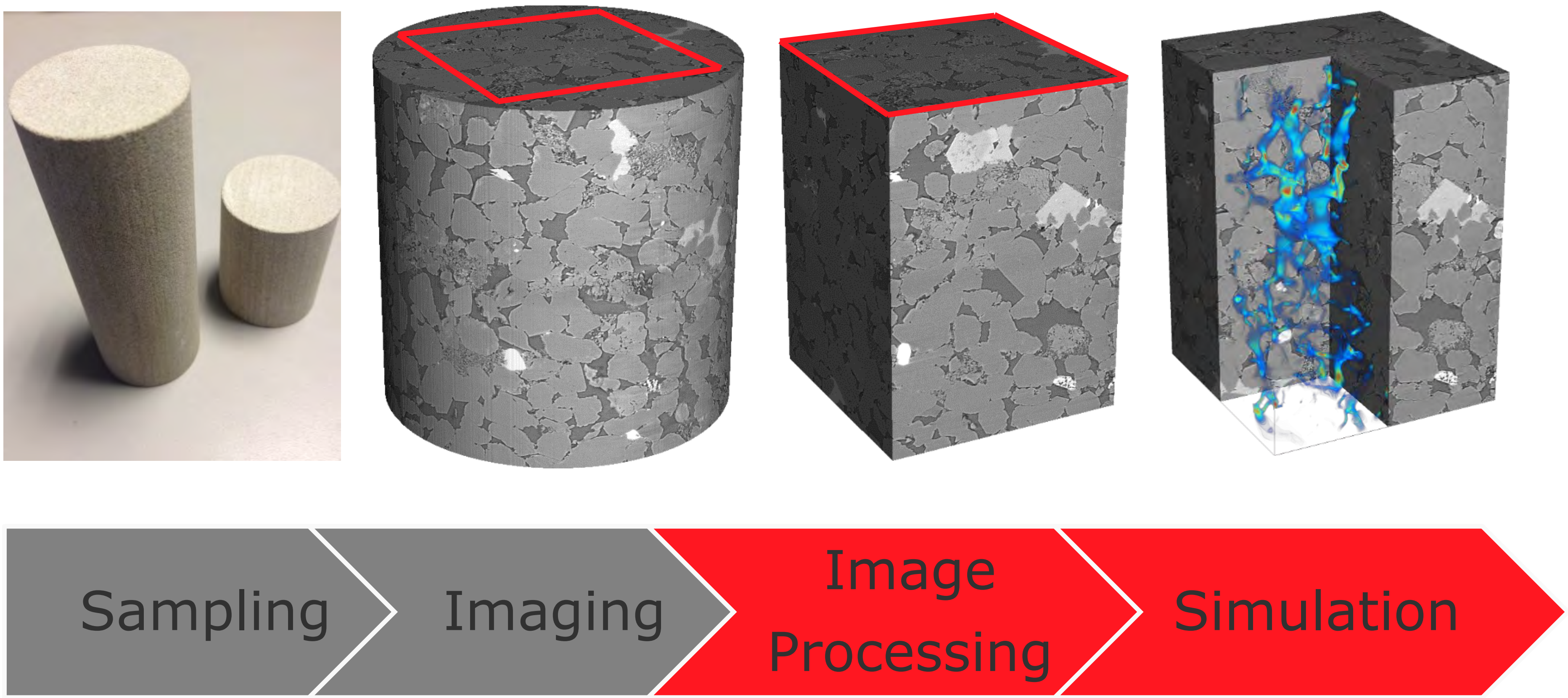
Basic Principle of DRP



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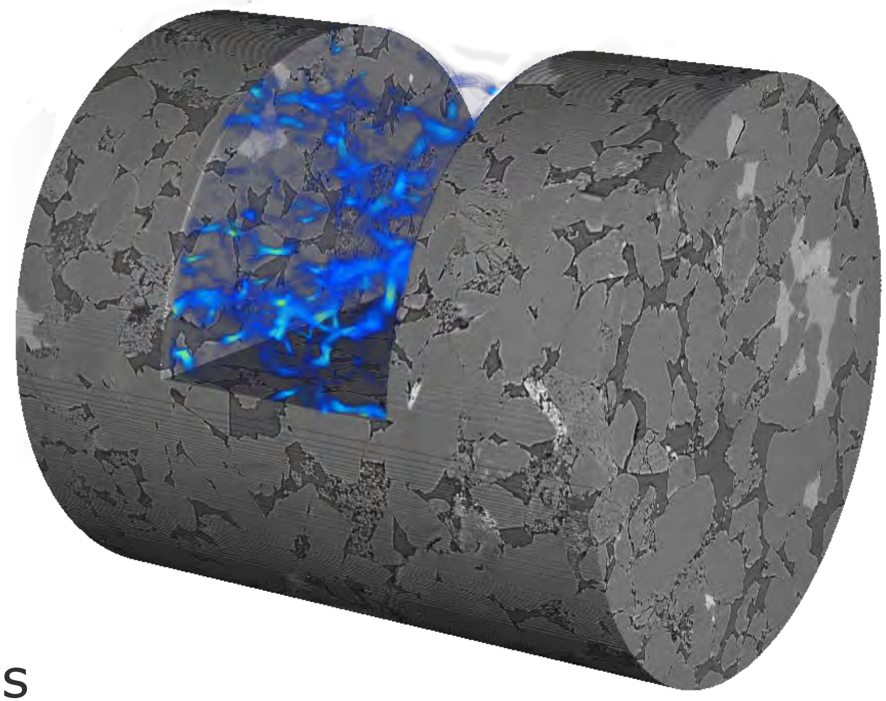
Advantages of DRP

- generates results faster and at lower costs
- requires lower quality of rock material (e.g. cuttings)
- is non-destructive: derives all parameters from one core
- enables sensitivity analysis of parameters via fast solvers
- fosters understanding of processes



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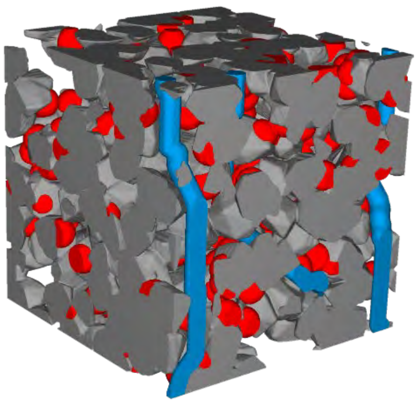
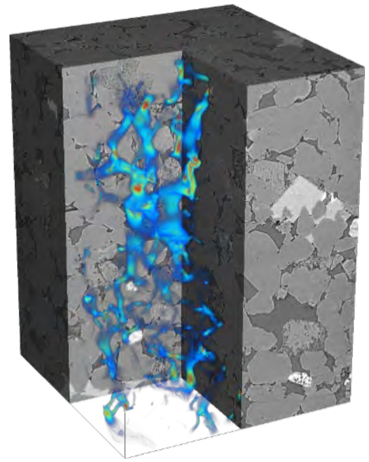
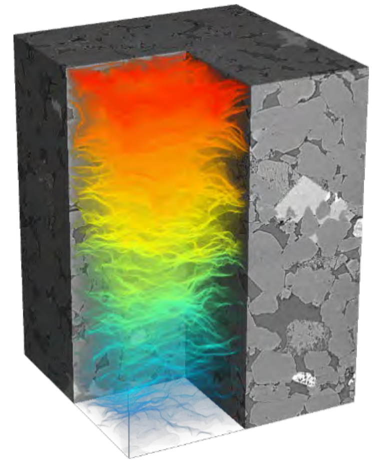
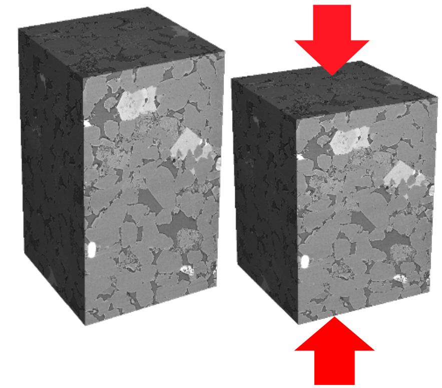
Digital Rock Physics Portfolio

GeoDict









Geometrical parameters	Flow parameters	Electrical Parameters	Mechanical parameters
▪ Porosity	▪ Absolute permeability	▪ Formation factor	▪ Elastic moduli
▪ Pore size distribution	▪ Multi-scale flow	▪ Resistivity index	▪ Stiffness
▪ Percolation	▪ Multi-phase flow	▪ Saturation exponent	▪ In-Situ conditions
▪ Surface area	▪ Relative permeability	▪ Cementation exponent	
▪ Tortuosity	▪ Cap. pressure curve		

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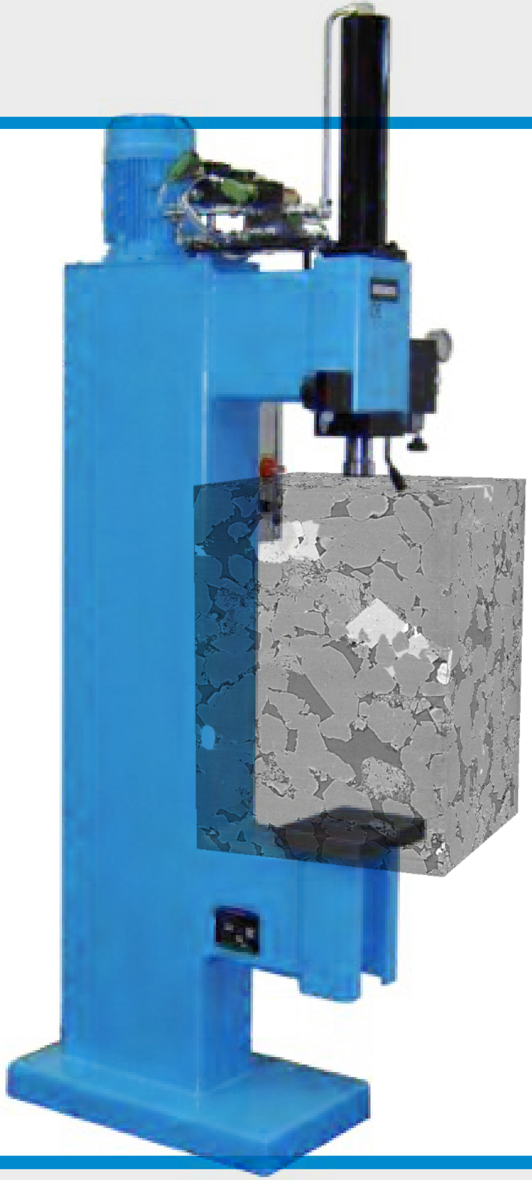
Need for in-situ conditions in DRP

- Rocks in a reservoir are exposed to elevated pressures and temperatures (in-situ conditions)
- Generally in-situ conditions are not maintained during DRP workflows
- Changes in the pressure and temperature conditions
  - impact the properties of fluids: density, viscosity, solubility of phases in the fluid
  - lead to changes in the pore space



Need for in-situ conditions in DRP

Uncompressed image

Compressed image
(3%)

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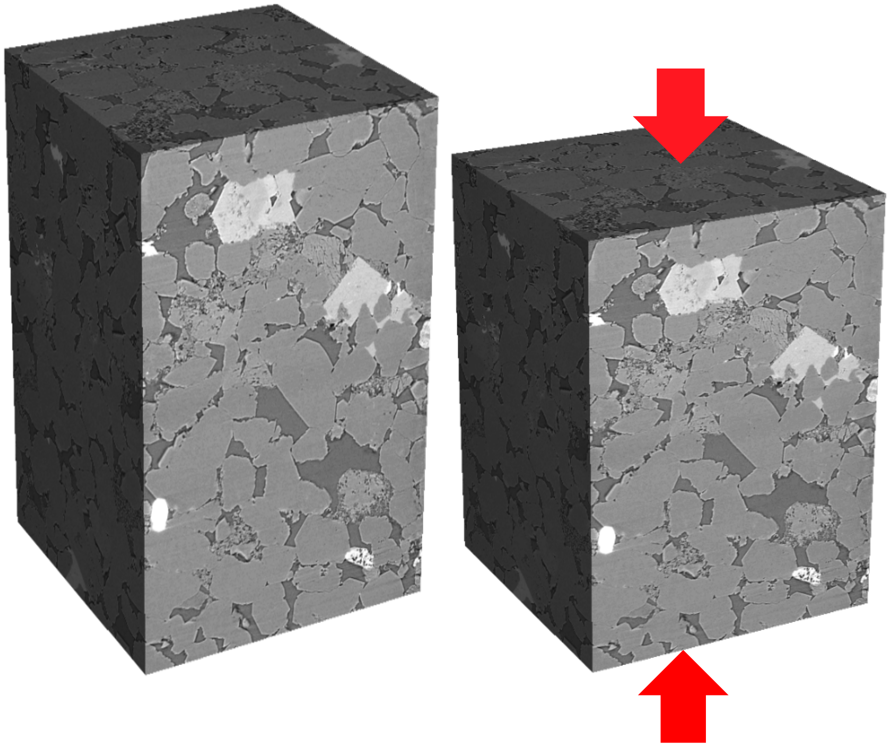
In-Situ DRP techniques

In-Situ imaging

In-Situ modelling



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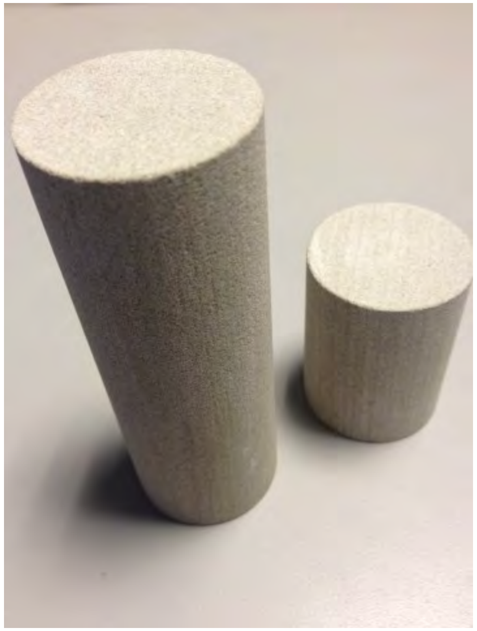
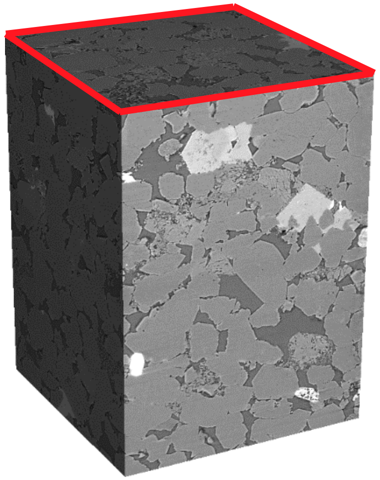
Detailed In-situ DRP workflow
In-situ simulation I



- Cropping
- Noise reduction
- Artifact reduction[1]



Sampling → Imaging → Processing

[1] H. Andrä *et al.*, „Digital rock physics benchmarks—Part I: Imaging and segmentation,“ *Computers & Geosciences*, 2013 (43), pp. 25-32.

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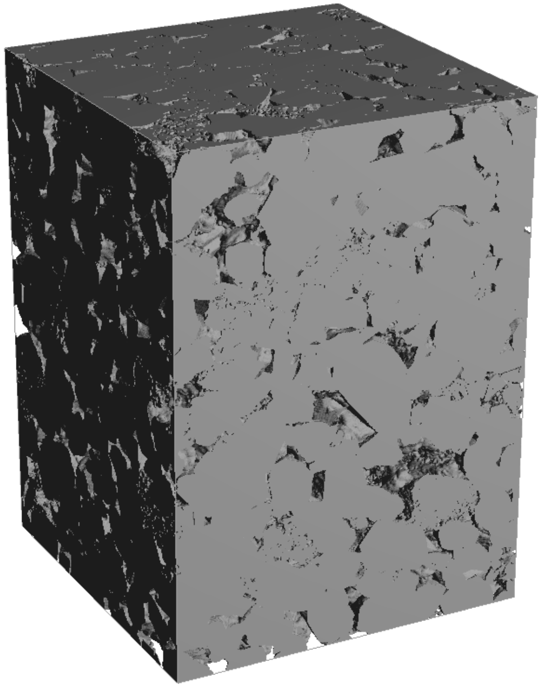
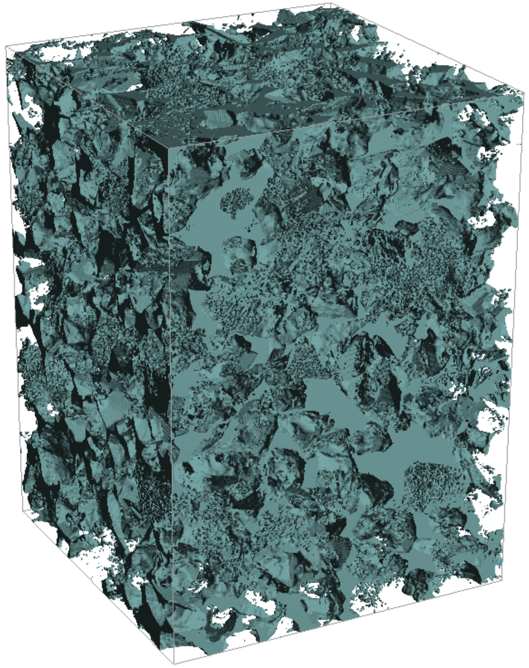
Detailed In-situ DRP workflow
In-situ simulation II

ImportGeo

Solids



Pore space



Segmentation

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[1] H. Andrä *et al*., „Digital rock physics benchmarks—Part I: Imaging and segmentation," *Computers & Geosciences*, 2013 (43), pp. 25-32.

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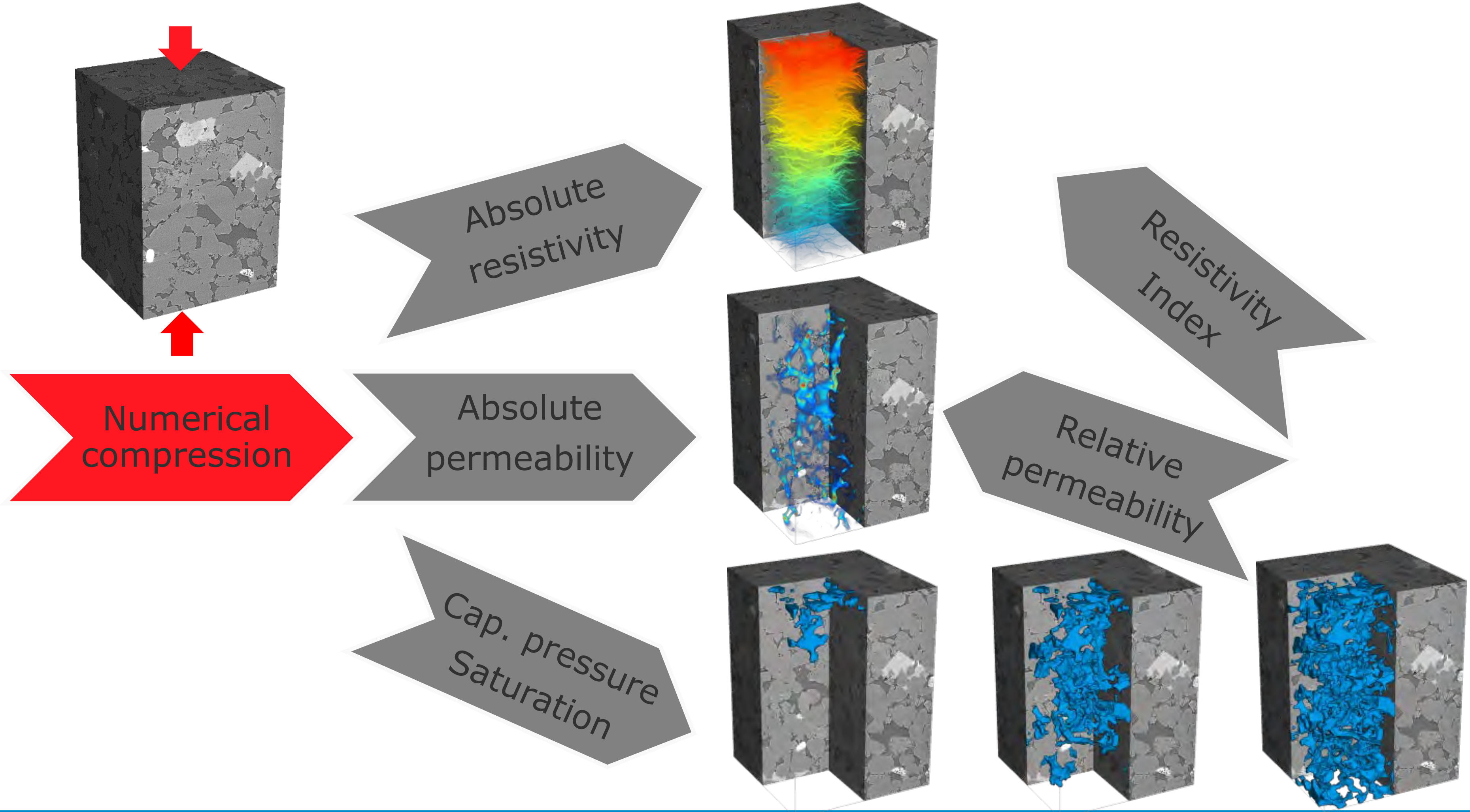
Detailed In-situ DRP Workflow
In-situ simulation III



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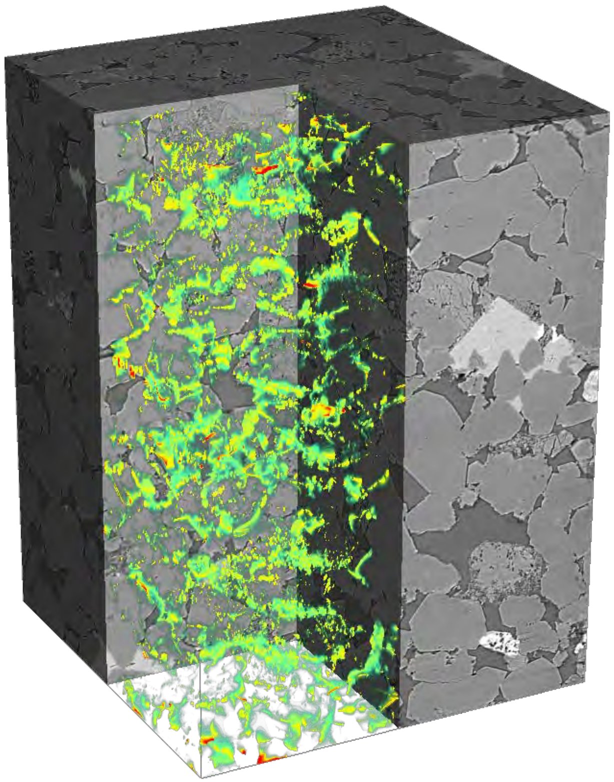
Mechanical Properties

- Two mineral phases
  - Quartz (E = 94.5 GPa, v = 0.074)
  - Void (E = 0 GPa, v = 0)
- FeelMath solver
  - Lippmann-Schwinger formulation for linear / non-linear mechanics
- Elastic properties
  (E = 46.9 GPa, v = 0.108)
- Uniaxial macroscopic stress
  - Periodic boundary conditions
  - Stages [GPa]: 0.12, 0.24, 0.48, 0.71, 0.95, 1.43 (up to 3% compression)


Von-Mises-Stress field

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Lippmann-Schwinger equations for linear elasticity

ElastoDict

Kröner E. Bounds for effective elastic moduli of disordered materials. Journal of the Mechanics and Physics of Solids 1977; 25(2):137 – 155.
Dederichs P H, Zeller R. Variational treatment of the elastic constants of disordered materials. Z. Physik 1973; 259:103 – 116.

Reference stiffness $\mathbb{C}_0$

Strain fluctuation $\varepsilon(\boldsymbol{u}) = \boldsymbol{E} + \varepsilon(\boldsymbol{v})$

Stress polarization $\boldsymbol{\tau} = (\mathbb{C} - \mathbb{C}_0) : \varepsilon(\boldsymbol{u})$

Solution by applying the Green operator

$$\varepsilon(\boldsymbol{v}) + \Gamma_0 * \boldsymbol{\tau} = 0$$

$$\varepsilon(\boldsymbol{u}) + \Gamma_0 * \boldsymbol{\tau} = \boldsymbol{E}$$

Convolution integral $(\Gamma_0 * \boldsymbol{\tau})(x) = \int_\Omega \Gamma_0(y)\boldsymbol{\tau}(x-y)dy$

Integral equation

$$\varepsilon(\boldsymbol{u}) + \Gamma_0 * ((\mathbb{C} - \mathbb{C}_0) : \varepsilon(\boldsymbol{u})) = \boldsymbol{E}$$

$$(I + B_\varepsilon)\varepsilon = \boldsymbol{E}$$

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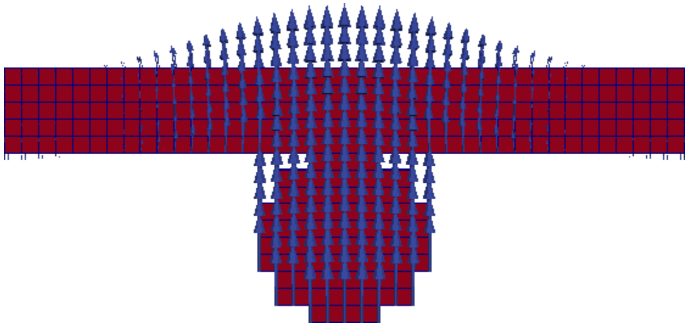
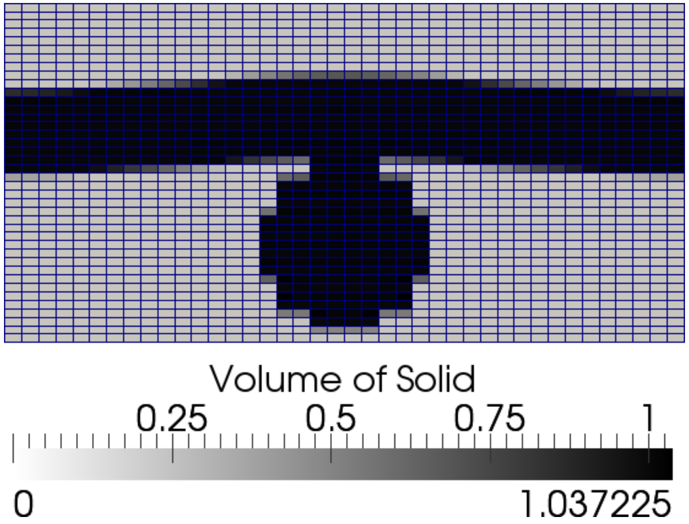
Deformation of 3D Images





- Step 1
  - Solve Lippmann-Schwinger equation
  - Integrate strain field to obtain displacement vector field on the un-deformed geometry
- Step 2
  - Move voxel according to displacement field
  - Cut voxel with deformed mesh

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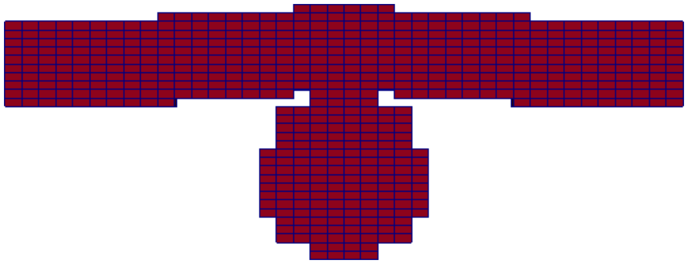
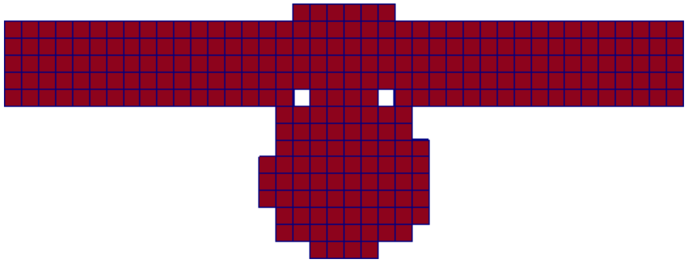
Deformation of 3D Images

ElastoDict



- Step 3
  - Determine optimal threshold
  - Perform segmentation of the grey value image
  - Result: “boxel” image



- Step 4
  - Resample the “boxel” image to obtain a voxel image (with the original resolution)

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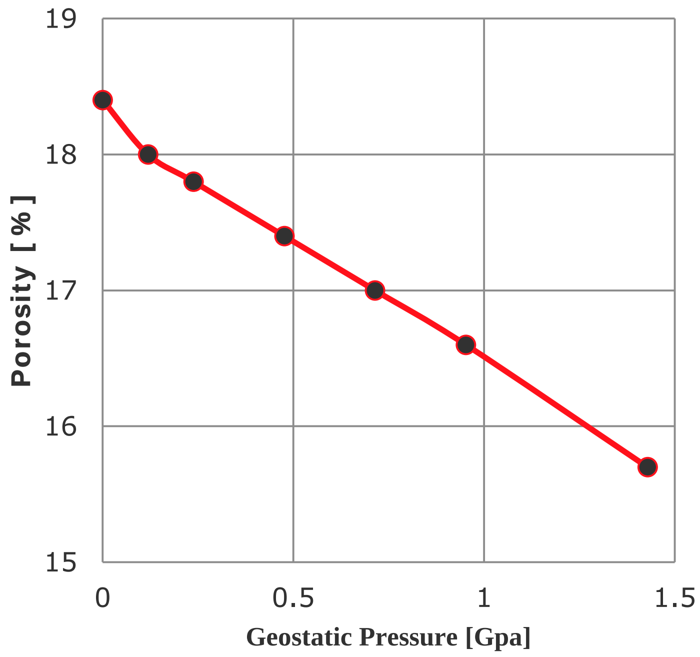
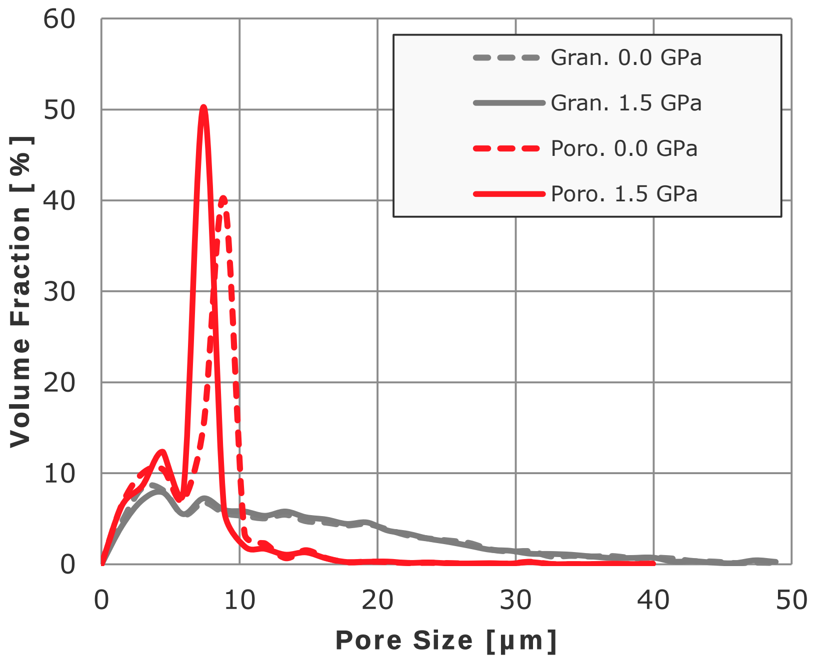
Porosity and Pore Size Distribution

- Porosity: 18.4 changes to 15.7%
- Most frequent pore throat diameter: 8.8 changes to 7.4 µm
- Granulometry and Porosimetry





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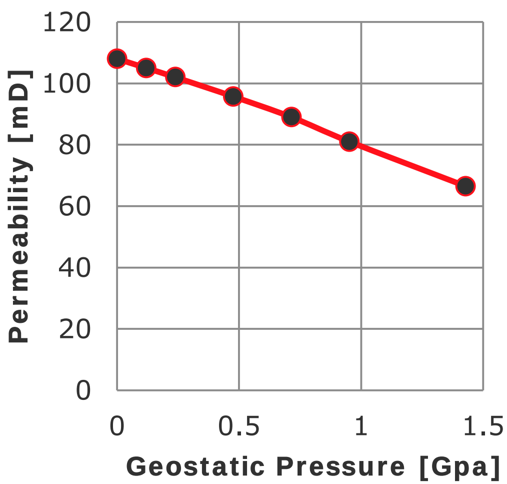
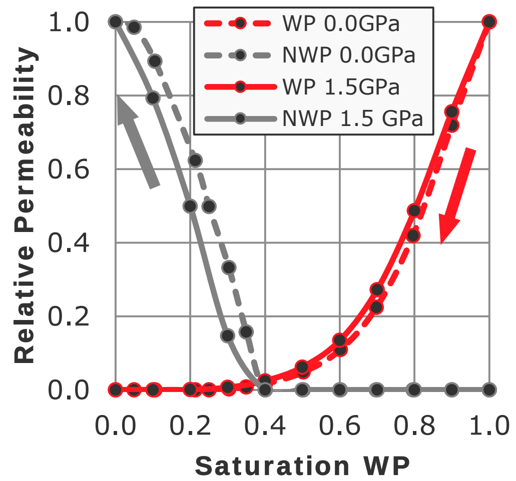
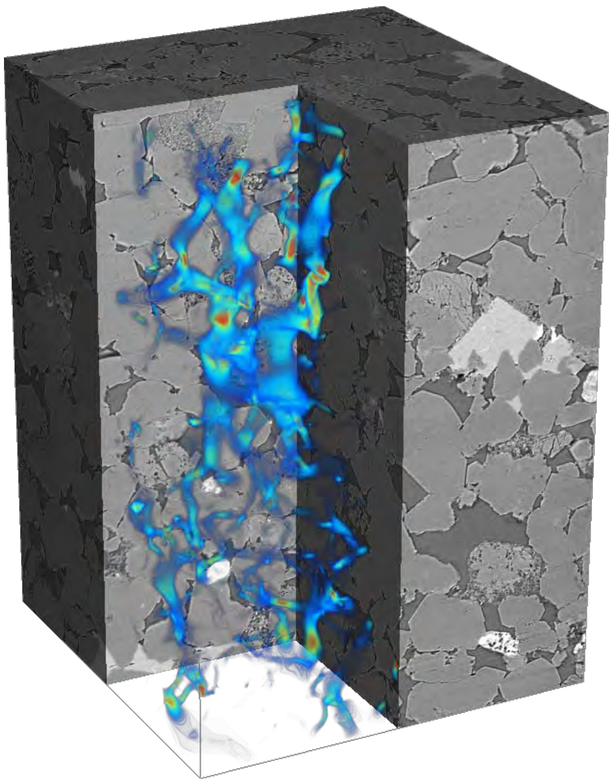
Absolute and Relative Permeability

- Absolute permeability: 108 changes to 66 mD
- Relative permeability
- Two flow solver: LIR-Stokes and SIMPLE-FFT






Velocity field

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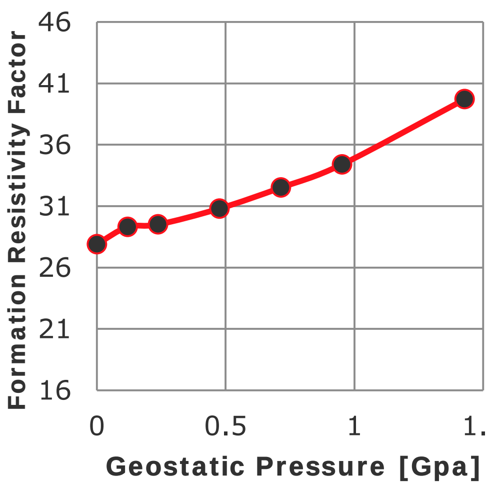
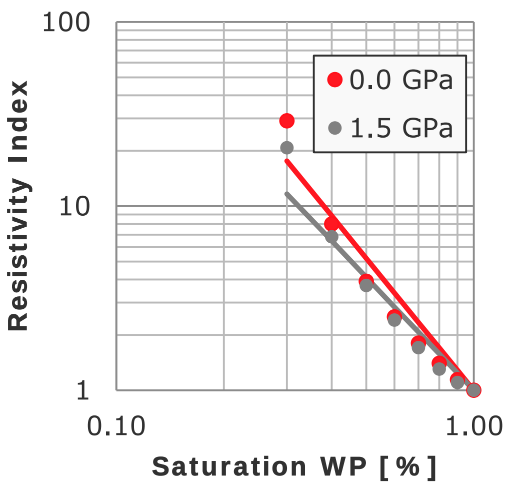
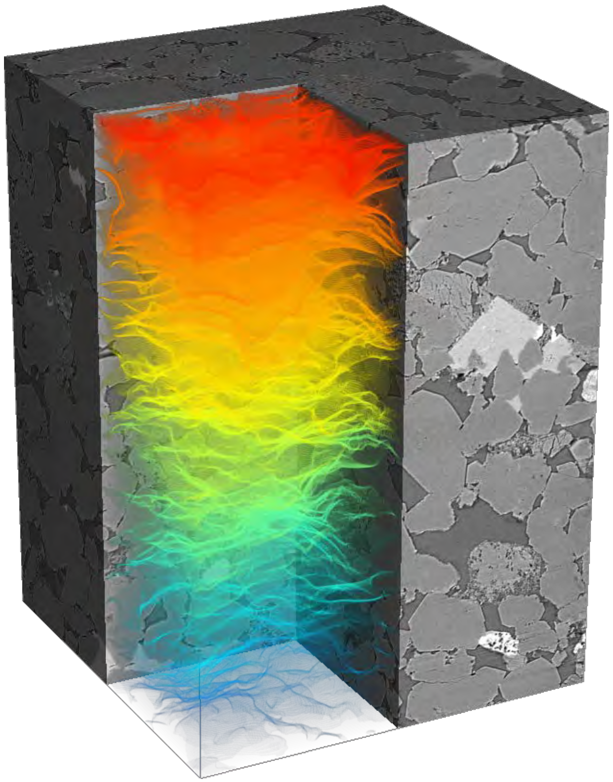
Electrical Conductivity and Resistivity Index

- Electrical Conductivity (Brine 5 S/m): 0.17 S/m
- Formation resistivity factor: 27 changes to 39
- Explicit-Jump immersed interface method







Potential field

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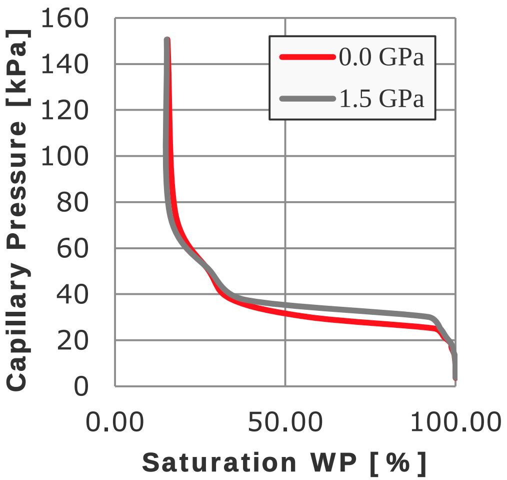
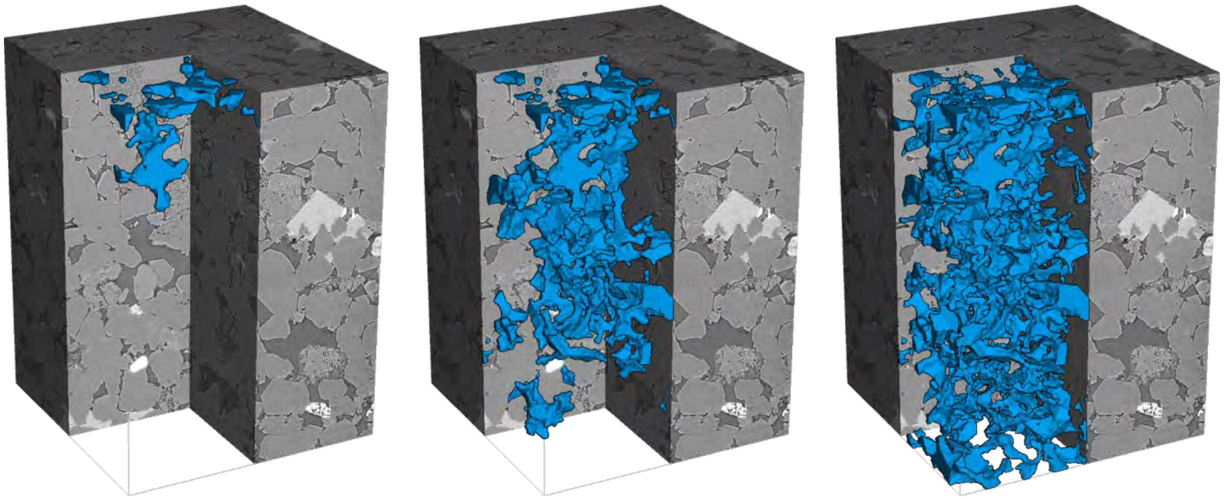
Capillary Pressure

SatuDict

- Irreducible WP saturation: 18%
- Displacement pressure changes from 24 to 29 kPa

- Pore morphology method





Air drains Brine with saturation stages 75%, 50% and 25%

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Solver Performance

- Flow and mechanics are expensive to compute
  - Relative permeability is most expensive
- Efficient solver allow:
  - Property simulations overnight
  - simulations on large data sets ($>2000^3$)
  - sensitivity analysis

Porperty	Flow	Flow	Resistivity	Two phase distribution	Mechanics
Solver	SIMPLE-FFT	LIR Stokes	Explicit Jump	Pore Morphology	FeelMath
Runtime [h]	3.6	3.1	0.6	0.8	8.3
Memory [GB]	42.3	5.4	9.4	5.0	97.1

Runtime and memory requirements per direction for a data set of 720x720x1024 voxels.
Computer with 16 Cores and 128 GB RAM.

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Outlook

- **Evaluation** - comparison of structures generated by:
  - In-situ CT measurements (Zeiss Xradia)
  - Numerical compression of conventional CT scans
- **Improvements** of the workflow e.g. to get realistic pressure:
  - Triaxial compression
  - Segmentation of all present phases
  - Incorporation of special properties for grain-grain contacts in the simulation of deformation
  - Incorporation of poroelasticity

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Conclusions

- In-situ conditions for reservoir rocks are characterized by elevated pressure and temperature conditions
- Influence of temperature can be considered by adjustment of the fluid and mineral phase input parameters
- Pressure changes affect the 3D geometry of the rock and have to be corrected
- Non-consideration of the in-situ pressure can lead to substantial errors in the derived DRP parameters
- Simulation of the in-situ conditions represents an alternative for in-situ measurements

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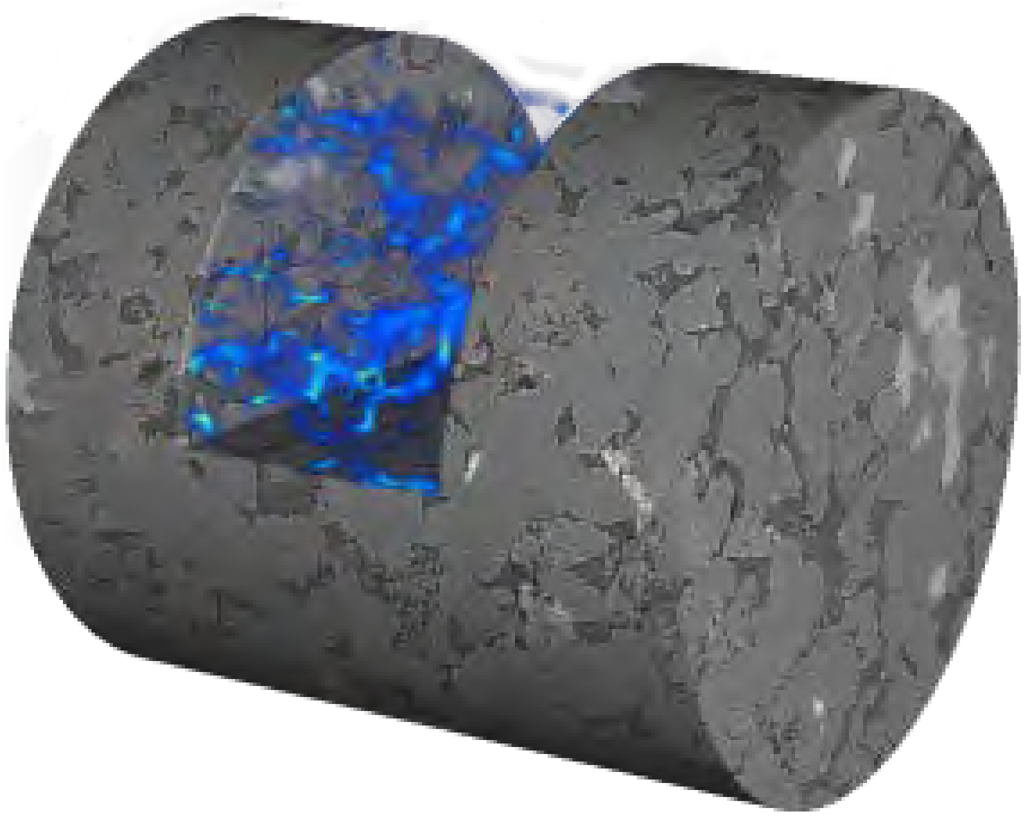
Thank you for your attention!



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