Alert Geomaterials Doctoral School 2025

Microscale geomechanics

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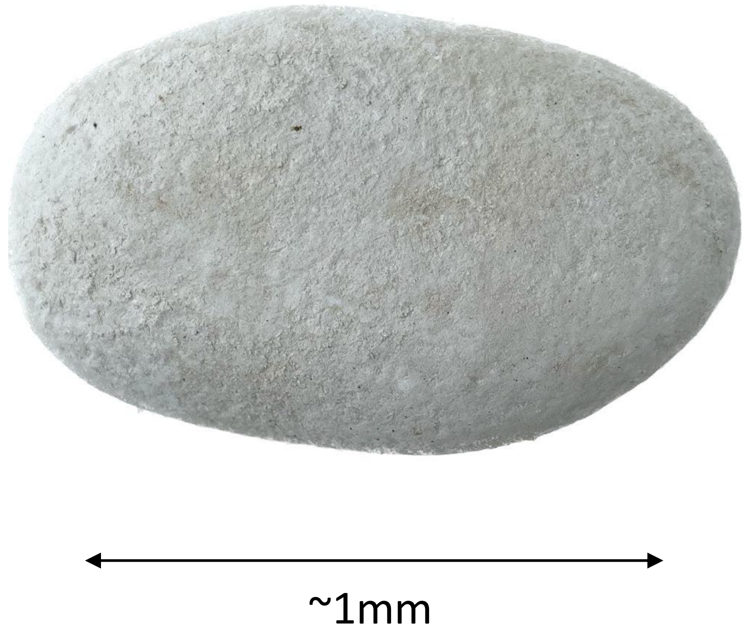
The importance of the microscale for geomechanics

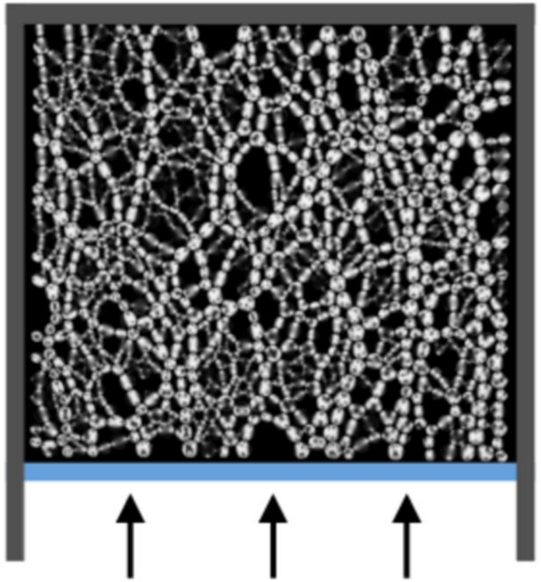
- Scale at which the rock microstructure can be visualised

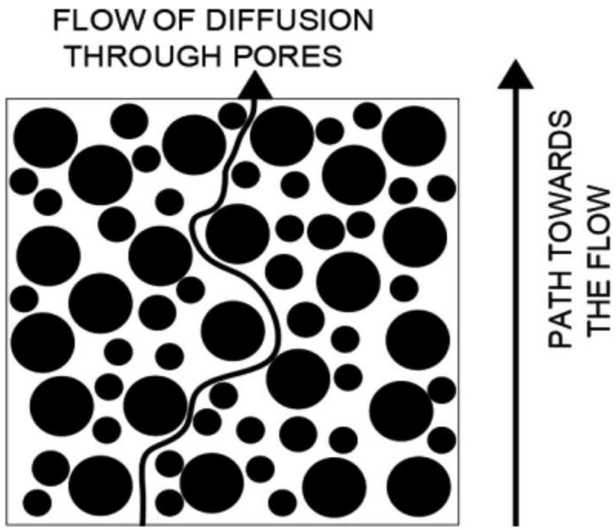


The importance of the microscale for geomechanics

- Uncovering the Structure-Property relationship

➢ Stress: discrete force chains formed at grain contacts
➢ Permeability: tortuosity of pore network
➢ Chemical reactivity: influenced by interfacial area





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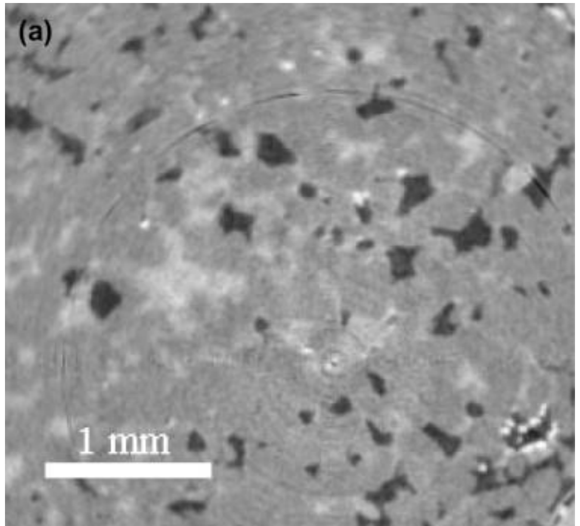
Experimental characterisation

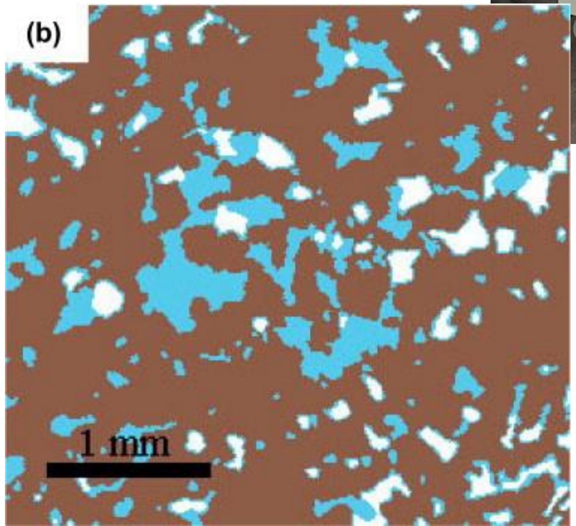
Microscale imaging

- Micro-computed tomography (μCT)

➢ Segmentation to distinguish all phases

➢ Enhanced resolution with synchrotron





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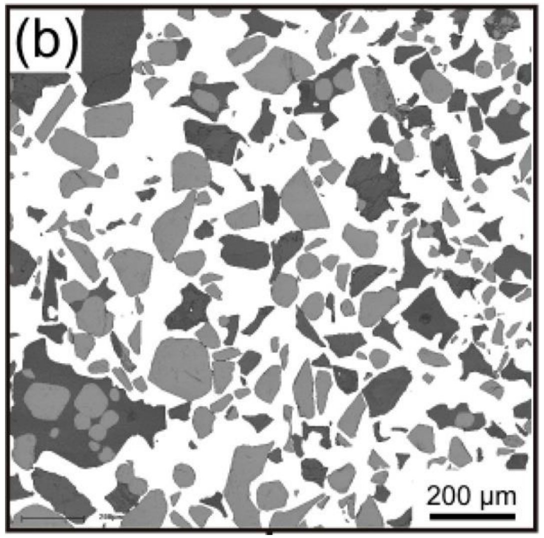
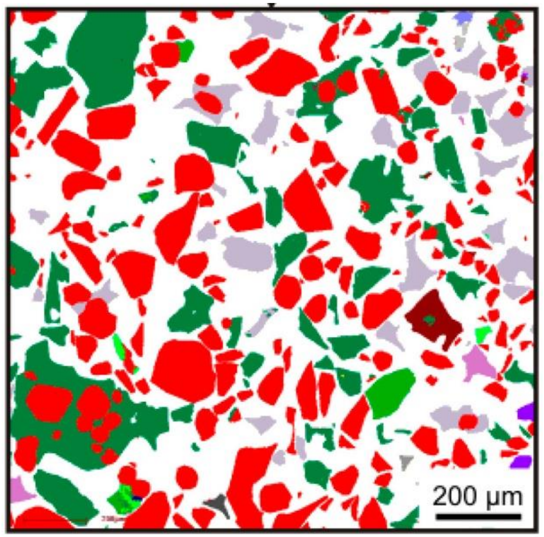
Microscale imaging

- Scanning Electron Microscopy (SEM)

➢High resolution but only surface



➢+mineralogy when coupled with EDS



➢Coupling with µCT for 3D extension

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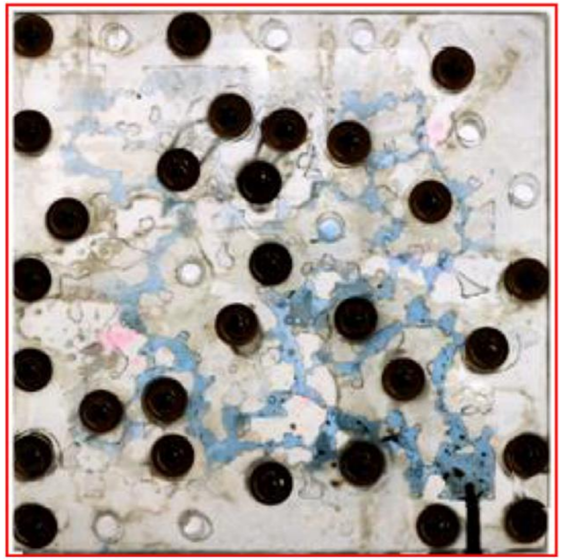
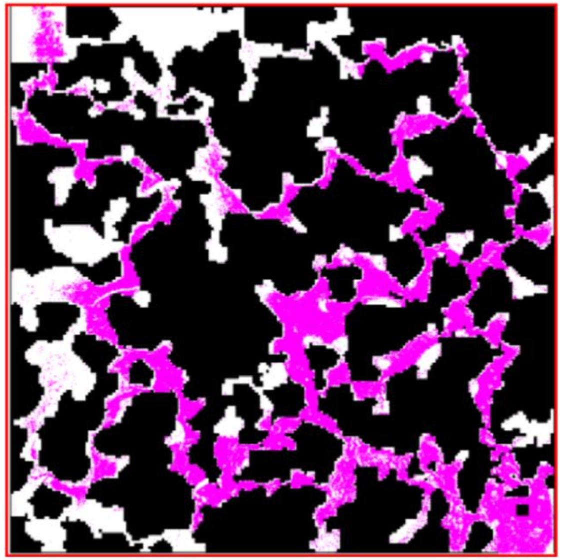
Microscale geomechanics experiments

- Microfluidics

➢ Controlled pore-scale flow mechanisms

➢ Transparency allows direct flow visualisation

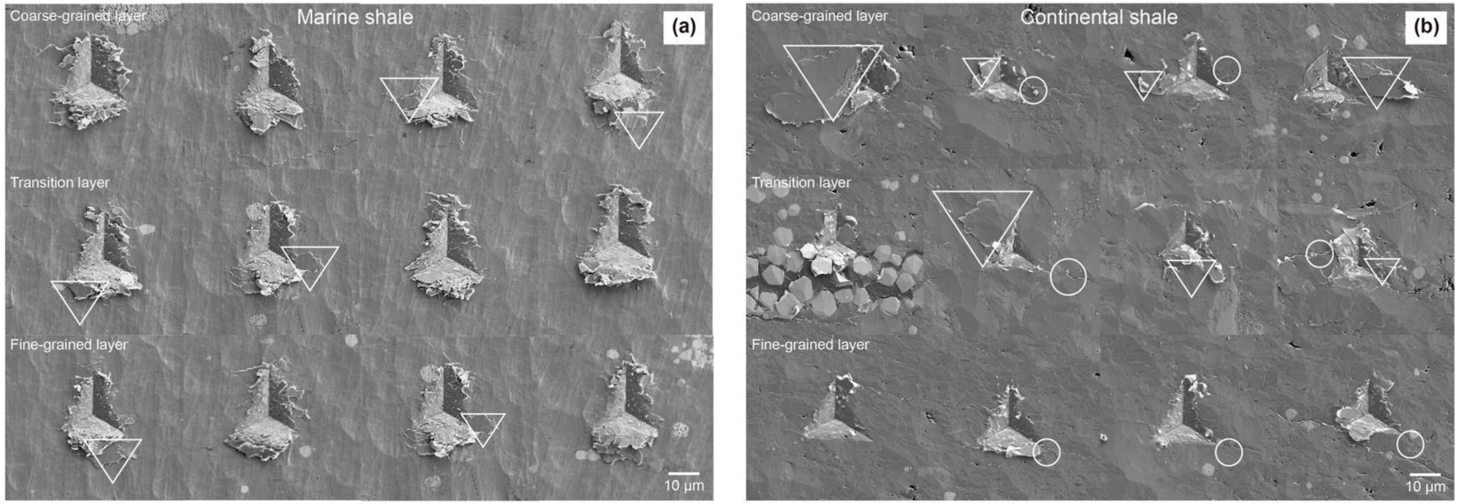




Microscale geomechanics experiments

- Nanoindentation
- Single grain experiments

- ➢ Measurement of local mechanical properties
- ➢ Useful for calibration of numerical models



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Numerical simulation of microscale geomechanics

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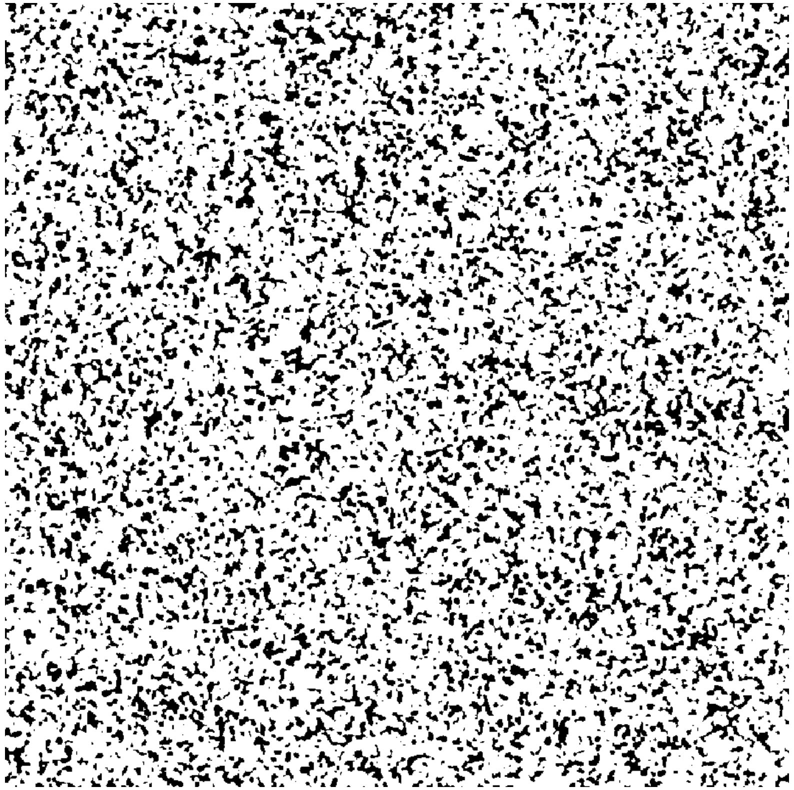
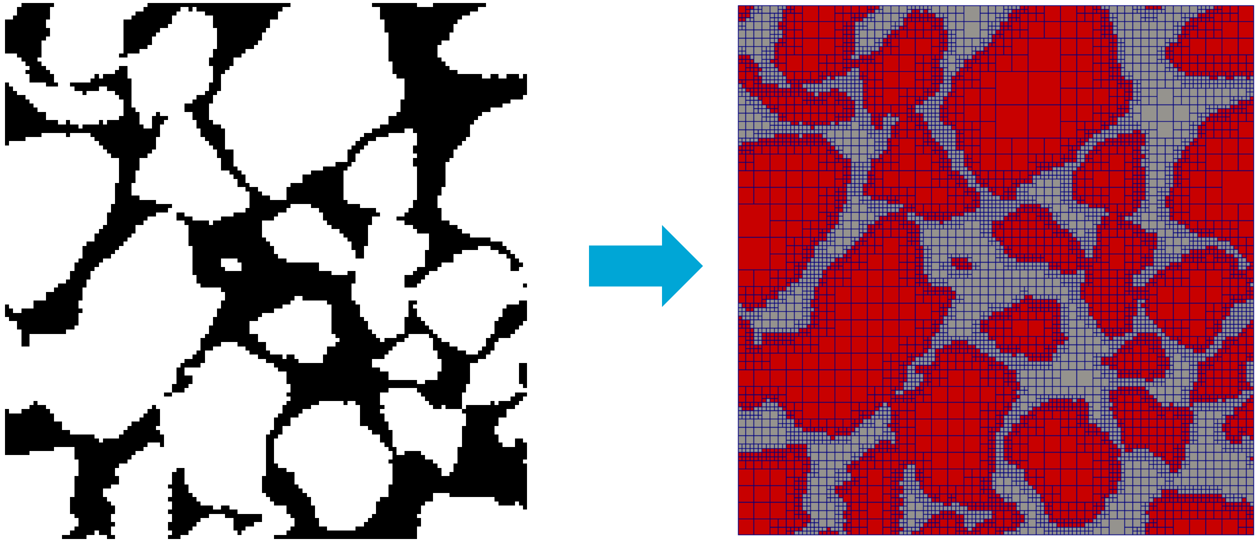
Microstructure generation

1. Idealised models
   - ➢ random packing of particles
   - ➢ Carbonate rocks analogue
2. Synthetic microstructures
   - ➢ For DEM
3. Digital Rocks from µCT-scans





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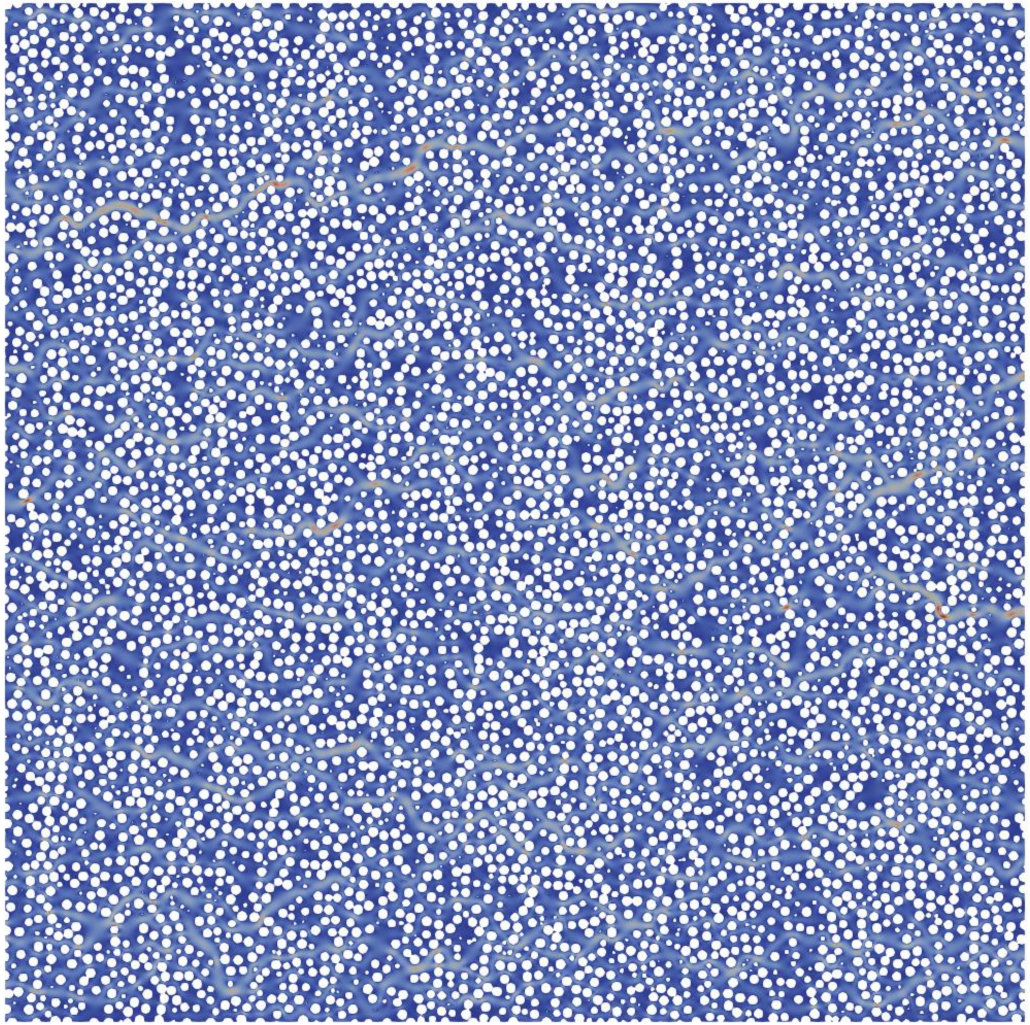
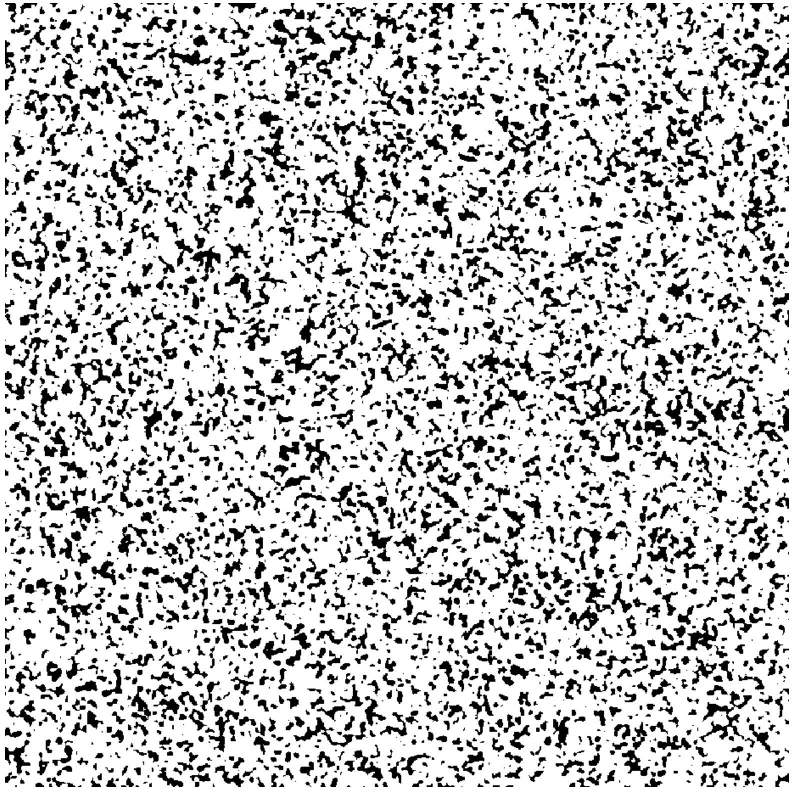
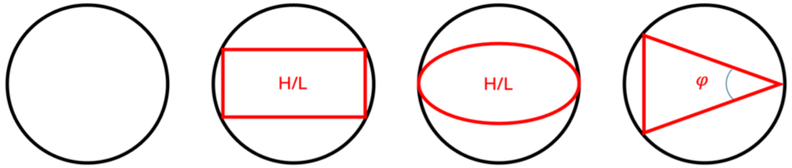
Microstructure generation



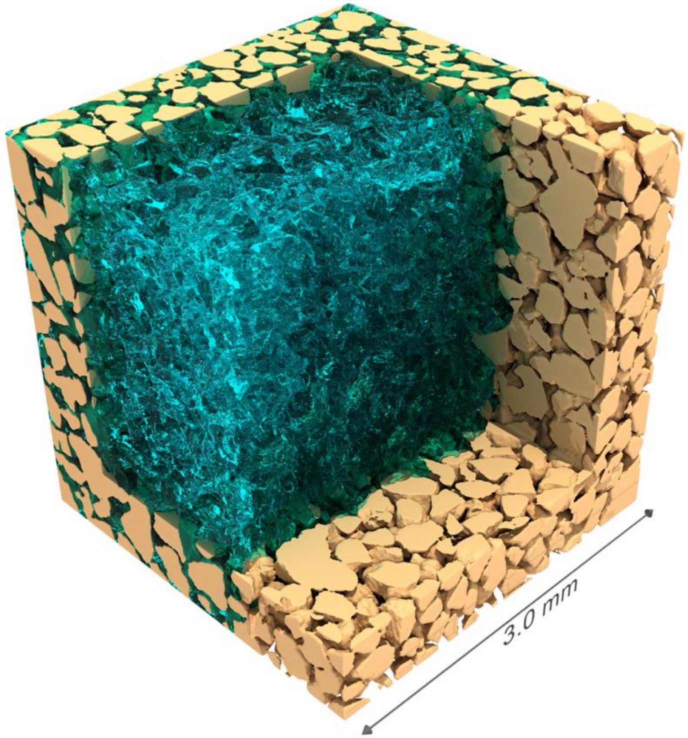




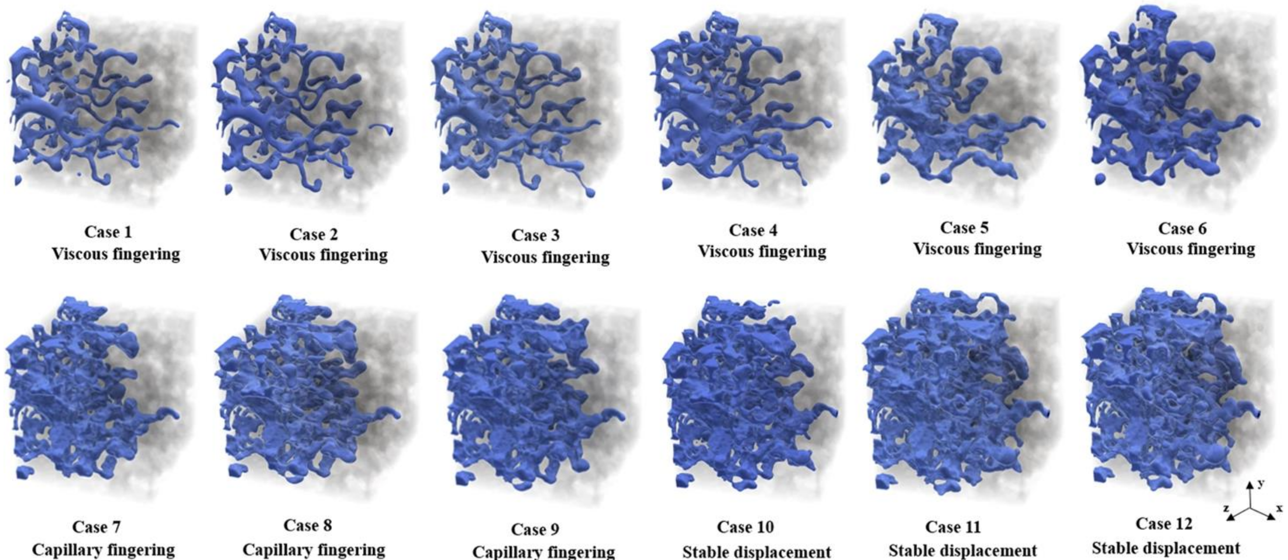
https://github.com/sfzwarts/RockMicro_Minkowskis

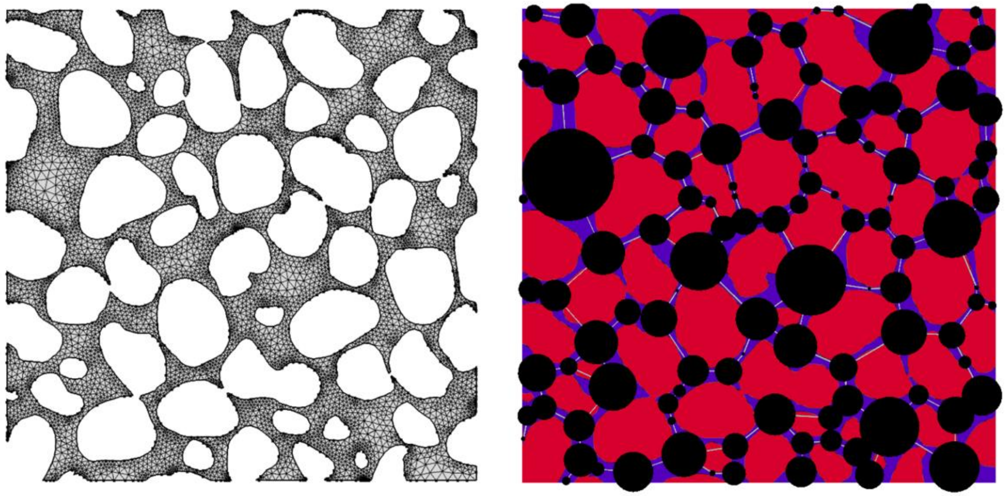
Fluid flow

- Finite Volume/Element Method (FVM/FEM)
- Lattice Boltzmann Method (LBM)
- Pore Network Modelling (PNM)



- Single phase flow → Multiphase flow





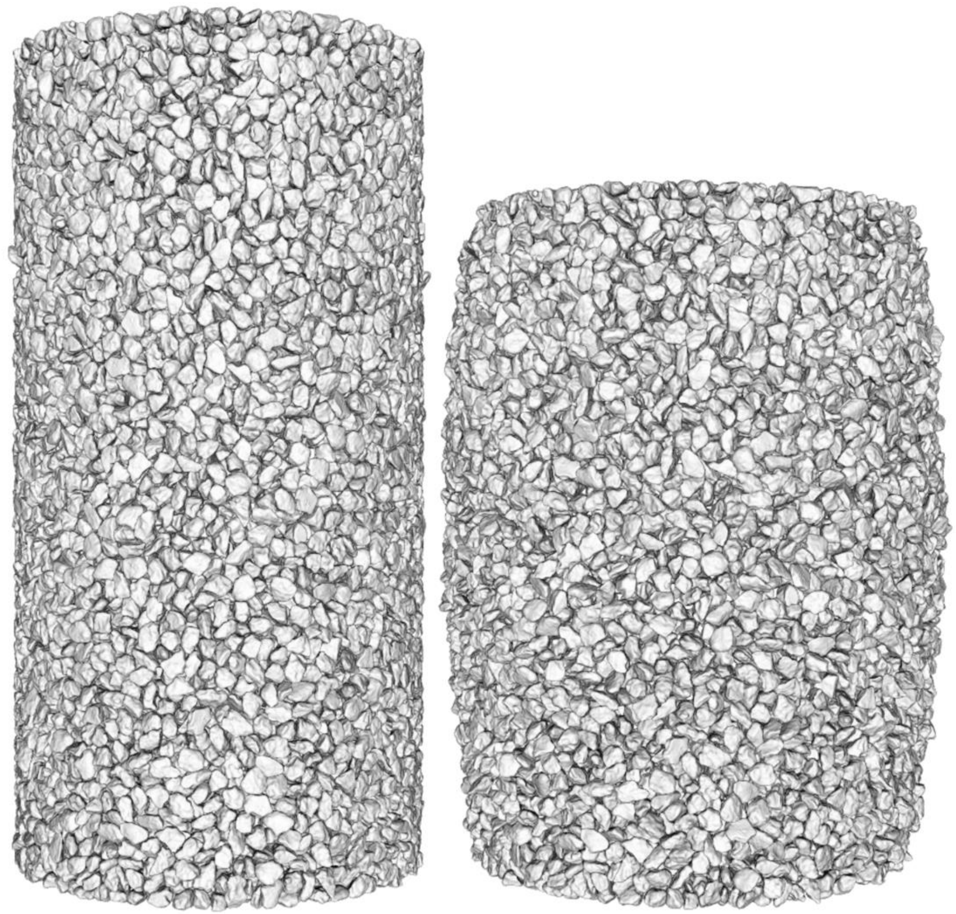
(a) FEM mesh (b) Equivalent PNM

Mechanics

- Discrete Element Method (DEM)
  - ➢Grain interactions through contact laws

- LS-DEM with Level-Set Method
  - ➢Reproduce exact microstructure
  - ➢Perfect digital twin of triaxial experiments

- FEM for non-granular microstructures



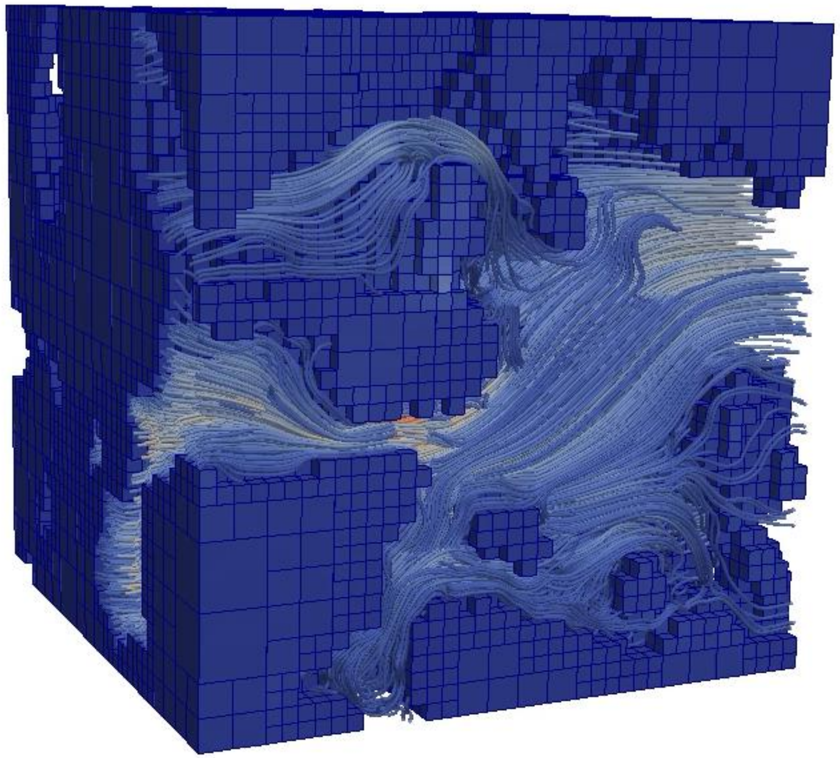
Multiphysics couplings

- Tight coupling like thermal advection

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{q}{\rho c_p} - v \cdot \nabla T$$

- Indirect coupling
  - In the equation of state

- Interface coupling
  - ➢ Fluid-Structure Interaction



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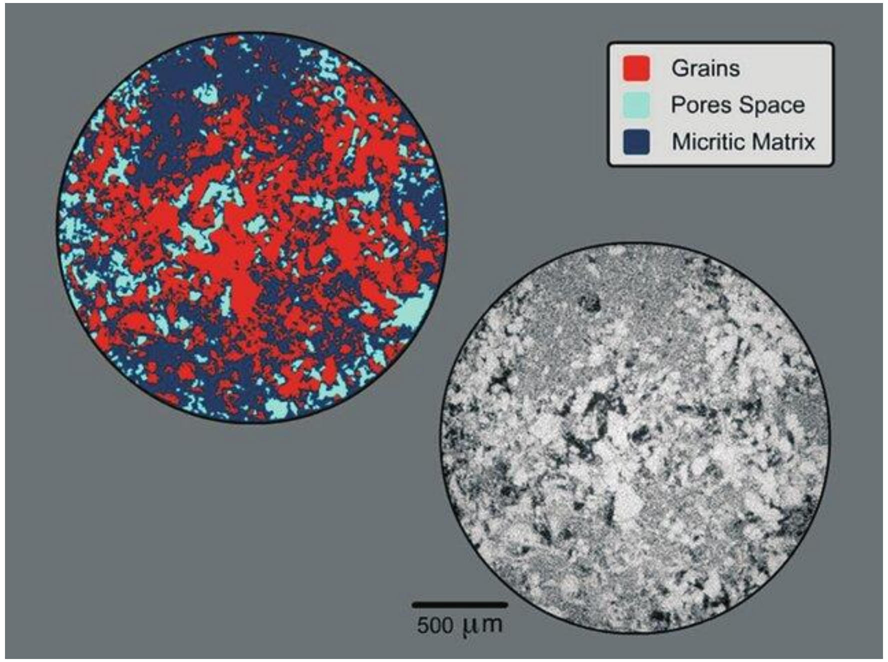
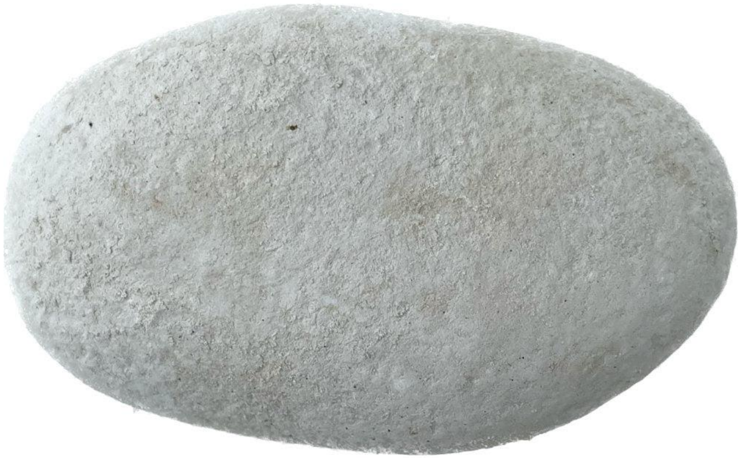
Upscaling principles

Representative Elementary Volume

- Micro-scale: heterogeneous in structure or property distribution
- Past a certain size, statistically homogeneous

➢ REV size

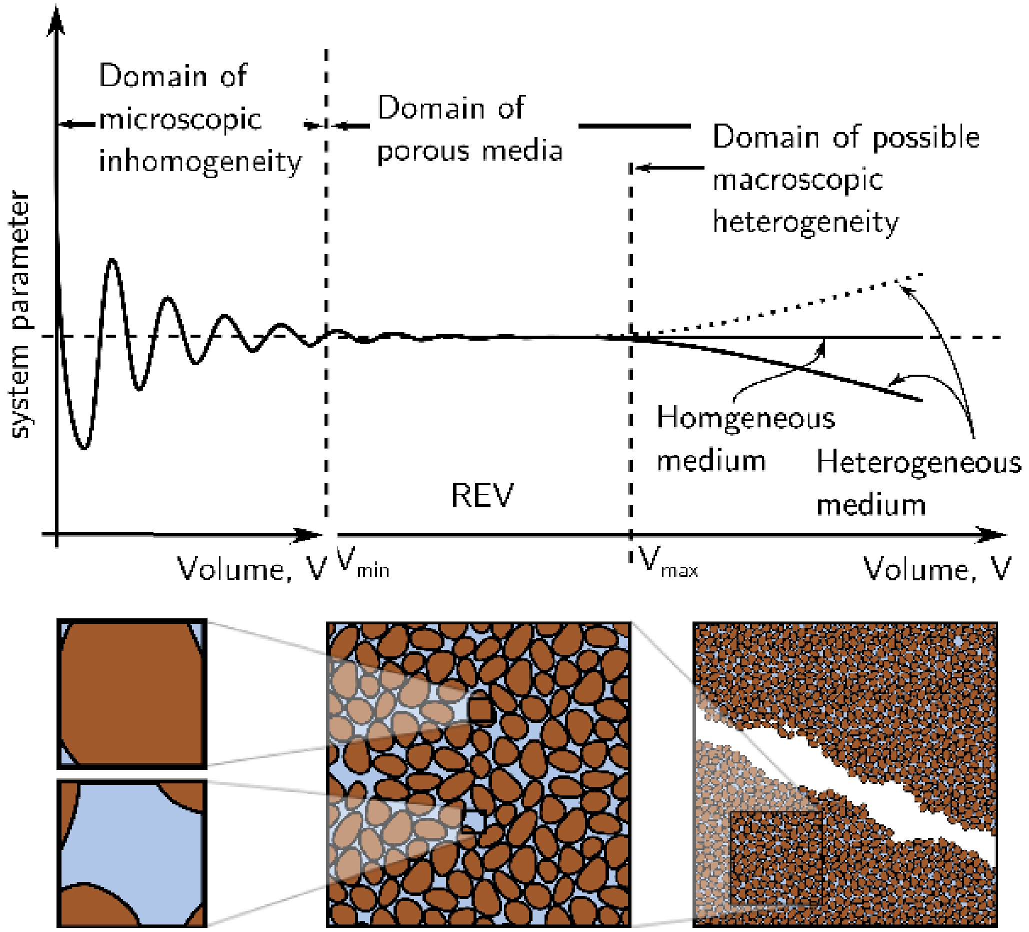




https://doi.org/10.1190/1.3580632

Representative Elementary Volume

- Past REV size → no fluctuation of effective property
- REV stops at higher length scale



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https://api.semanticscholar.org/CorpusID:73544061

Representative Elementary Volume

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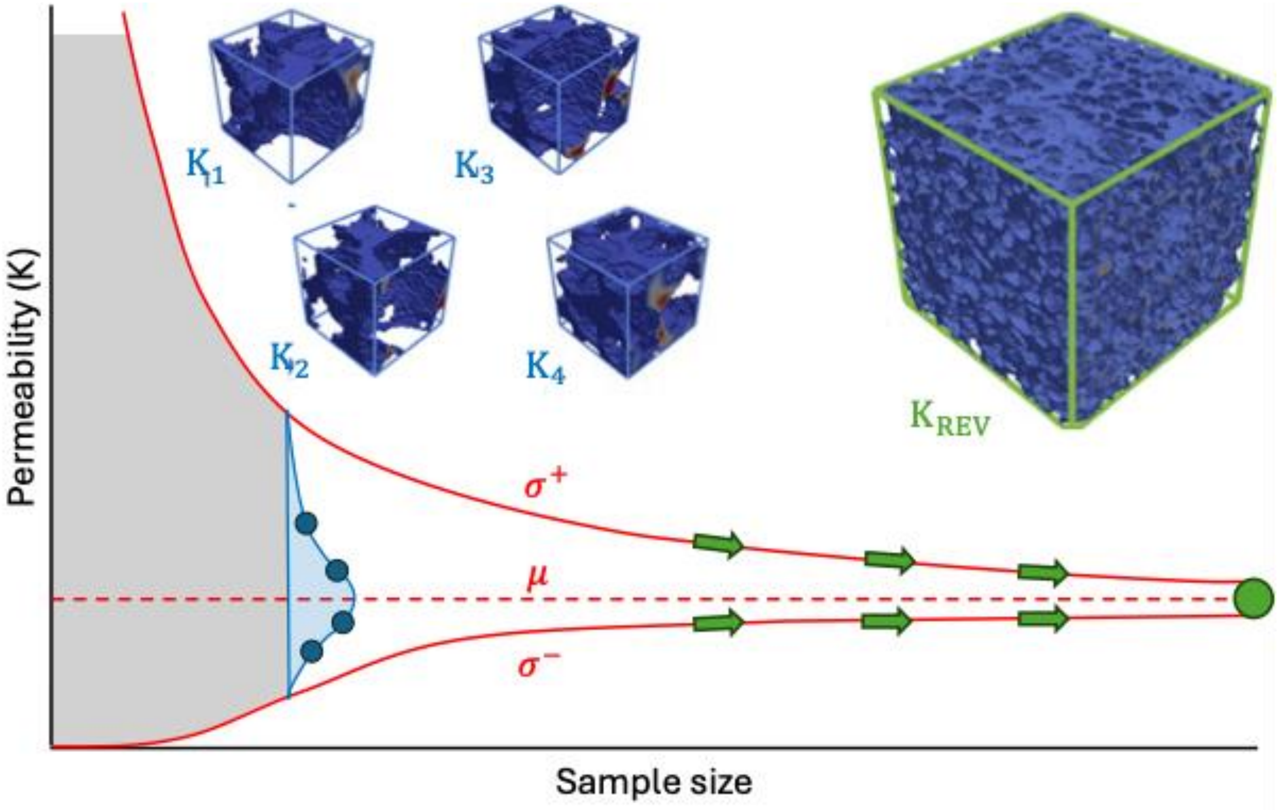

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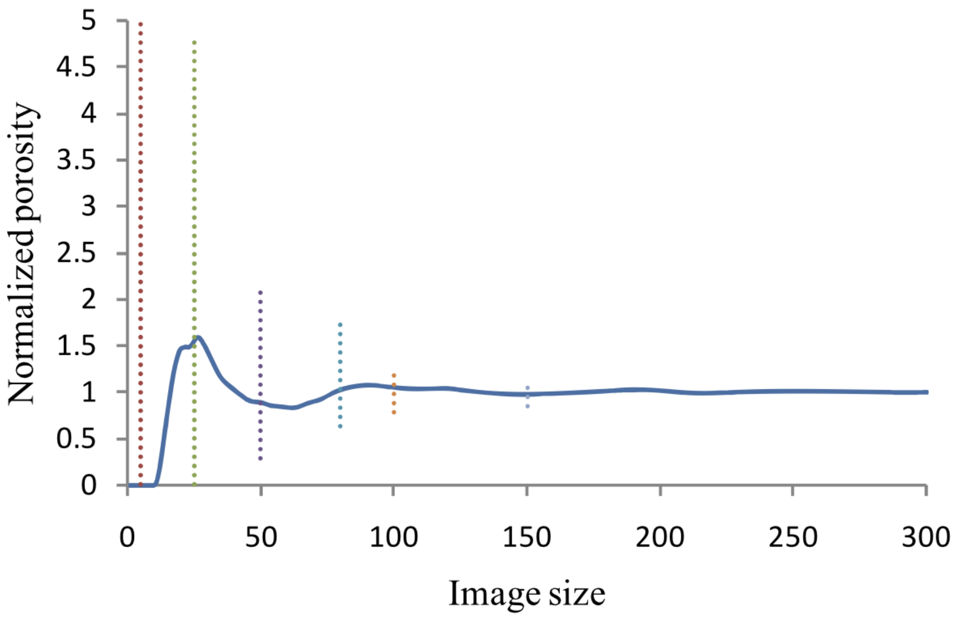
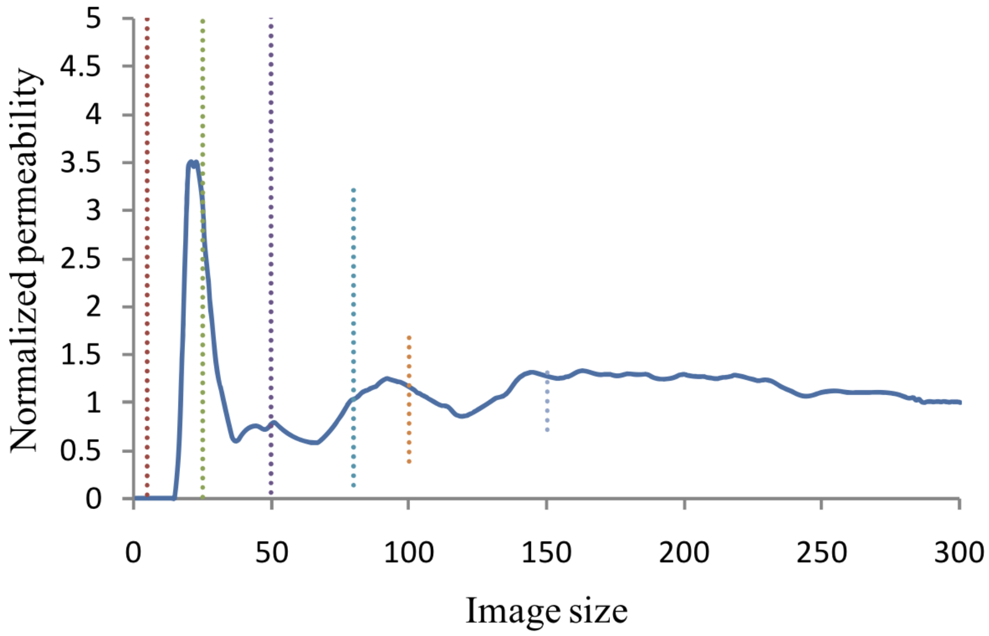
Representative Elementary Volume

- Defined for the property to upscale
- And the length scale considered

Fig. 13 Porosity (**a**), specific surface area (**b**), and permeability (**c**) as a function of image size (measured in number of voxels across each side of a cubic image) for sandstone S1. *Dashed lines* show the variation of properties of all subvolumes of the same size on the image



(a)



(c)

https://doi.org/10.1007/s11004-012-9431-4

Averaging theorem

- Effective quantities obtained by averaging microscopic fields

$$\langle X \rangle = \overline{X} = \frac{1}{V_\Omega} \int_\Omega X \, dV$$

$$X_M = \overline{X_m}$$

- Stems from Hill-Mandel condition which translates thermodynamics principle of conservation of energy across scales

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Averaging theorem

- Microscopic field fluctuates around the averaged value

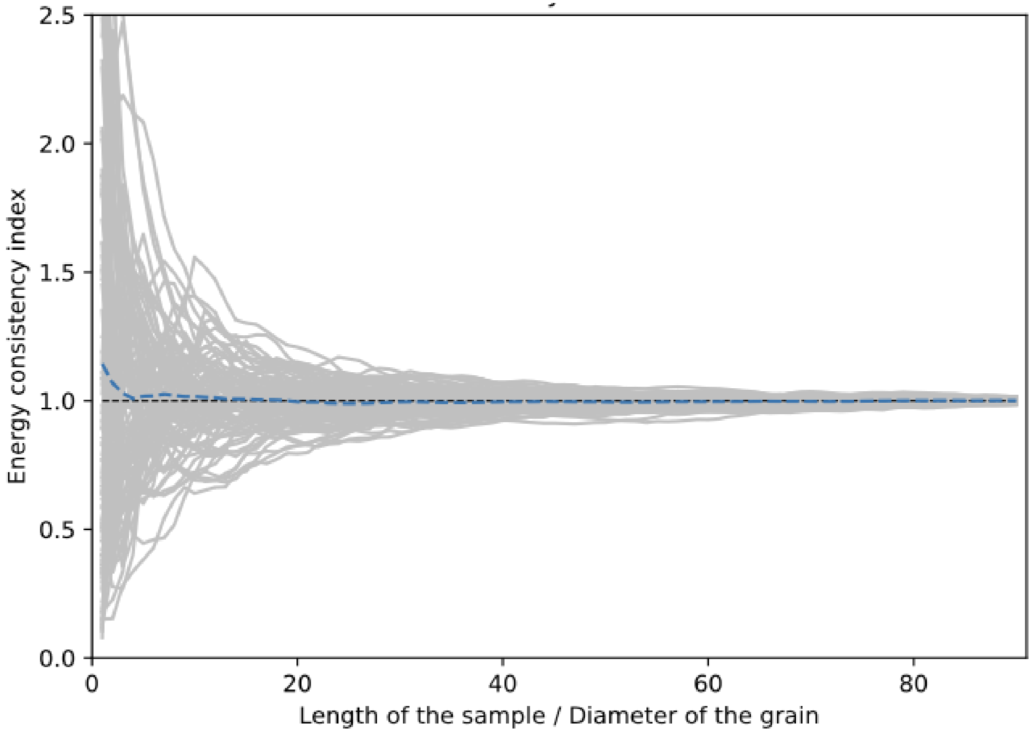
$$X_m = \overline{X_m} + \widetilde{X_m}$$

$$X_M = \overline{X_m}$$

$$X_M = \overline{\overline{X_m} + \widetilde{X_m}} = \overline{X_m} + \cancel{\overline{\widetilde{X_m}}}$$

Fluctuations need to be null

➢ REV needed as computational domain



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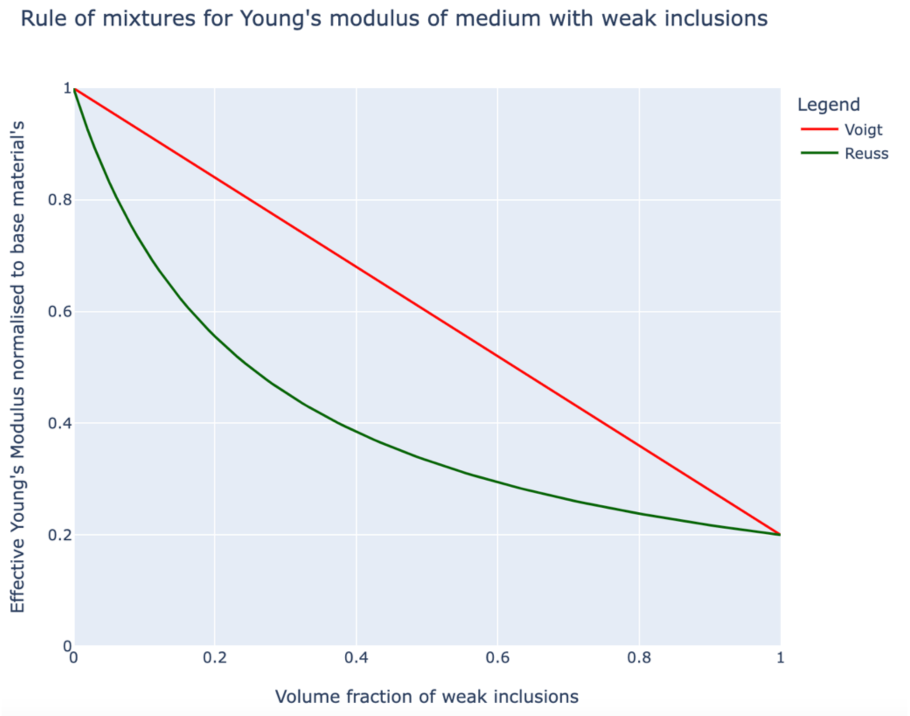
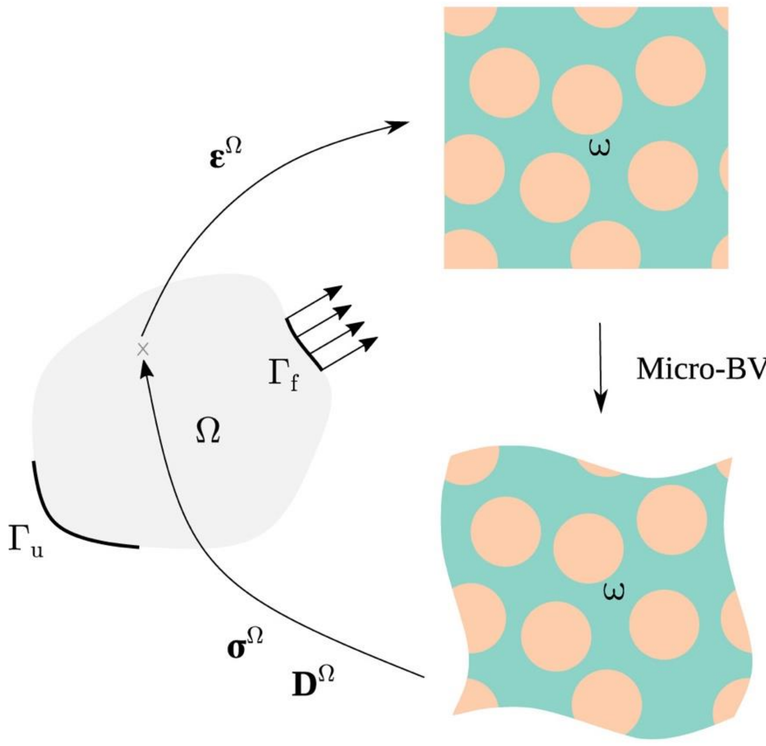
Zwarts, S., & Lesueur, M. (2024). Homogenisation method based on energy conservation and independent of boundary conditions. *Advances in Water Resources*

Upscaling strategies

- Analytical homogenisation models (Voigt, Reuss, Mori-Tanaka…)
- One-off numerical homogenisation
- FE^2 multiscale method





(a) Schematic representation of FE^2

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Maia, M. A., Rocha, I. B., Kerfriden, P., & van der Meer, F. P. (2023). Physically recurrent neural networks for path-dependent heterogeneous materials: Embedding constitutive models in a data-driven surrogate. *Computer Methods in Applied Mechanics and Engineering*, *407*, 115934.

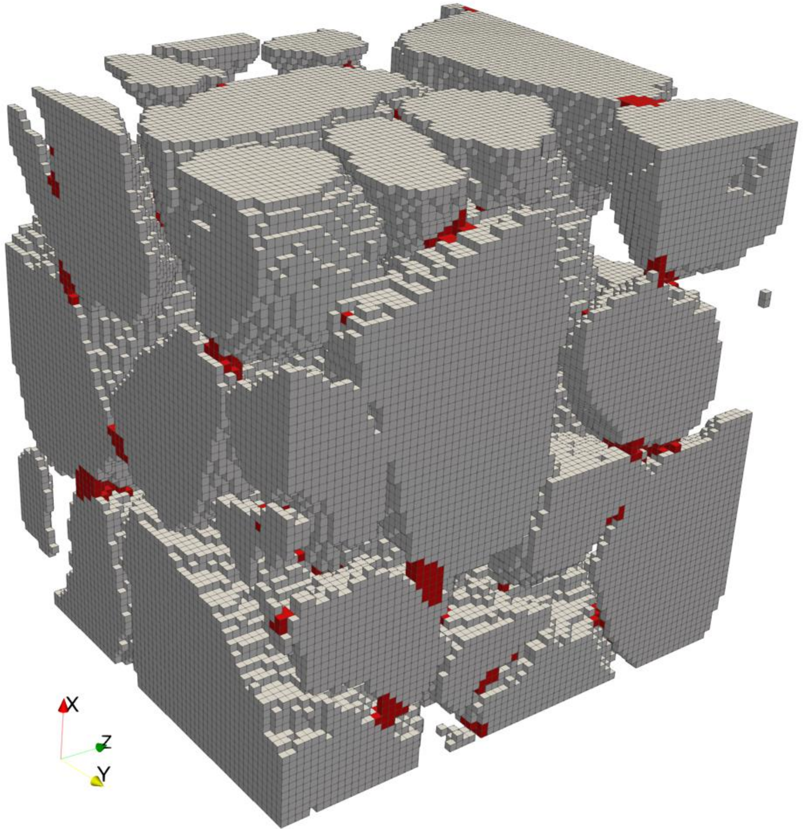
Upscaling example

Example of upscaling the Young’s modulus of a porous material:

1. Macroscopic constitutive law: Hooke’s law

$$\sigma = E \cdot \varepsilon$$

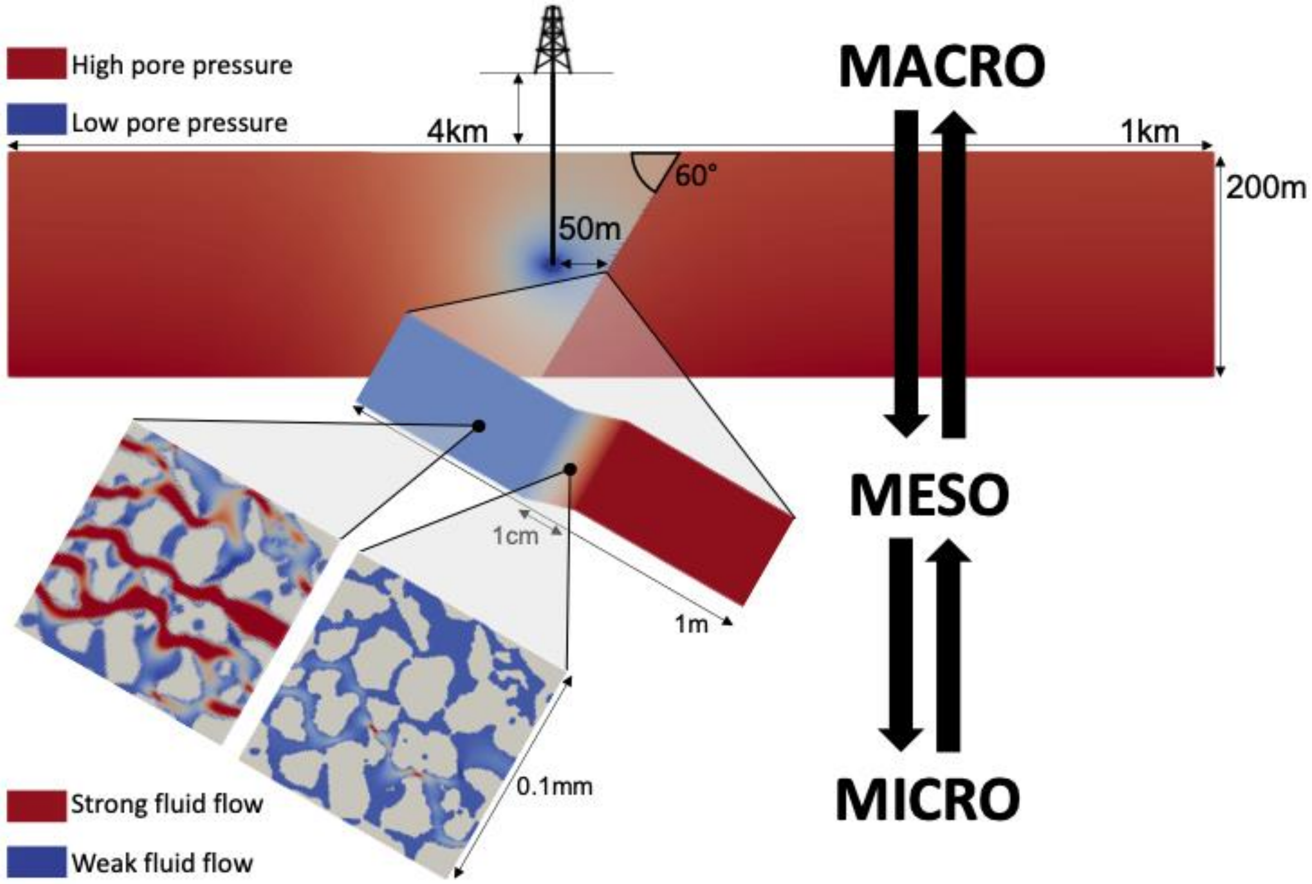
2. Boundary condition of displacement or stress
   - Gives directly the macroscopic value
3. Other variable is averaged from the heterogeneous microscopic field
4. The effective Young’s modulus is calculated from the law



Perspective

Perspective

- Insights into physical processes that govern reservoir-scale behaviour
  - ➢ Predictive models



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Perspective

- Challenge of the complexity of natural systems
  - ➢ Heterogeneous microstructure
  - ➢ Multiphysics subsurface processes

- Additional challenge of stimulation strategies
  - ➢ Cyclic loading
  - ➢ Fracture propagation

- Progress of experiments: in-situ and with increased resolution

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