Determination of hydraulic, mechanical and chemical fracture apertures

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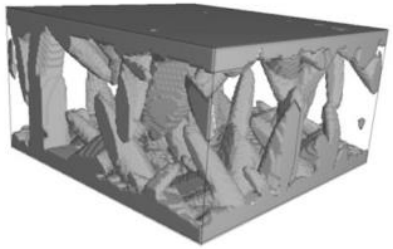
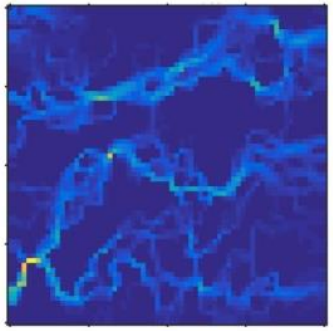
Up- and downscaling: From µm to km-scale

Fractures ↔ Reservoirs

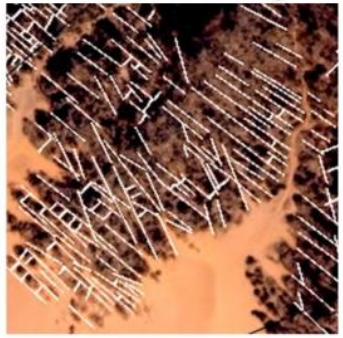
Phase field modelling



Example for flow channeling

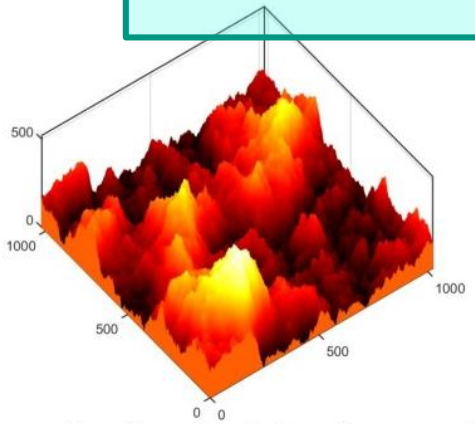


Remote Sensing

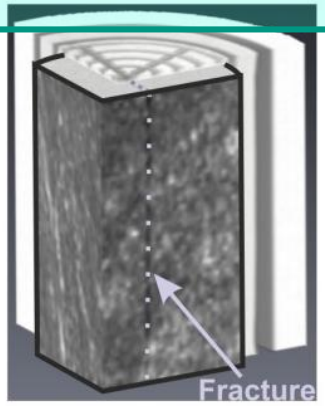


Fluid flow

µm mm cm m km



Random fractal surfaces



X-ray computed tomography

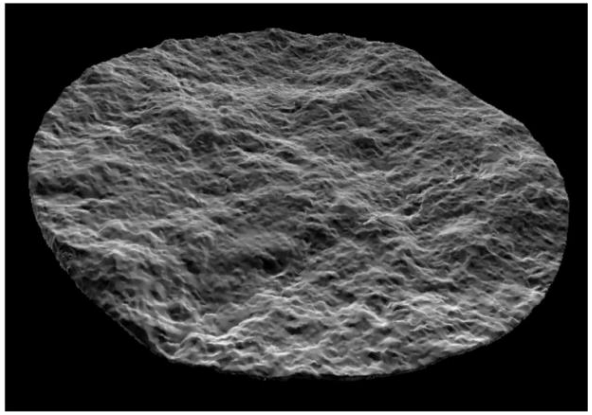
Discrete Fracture Network

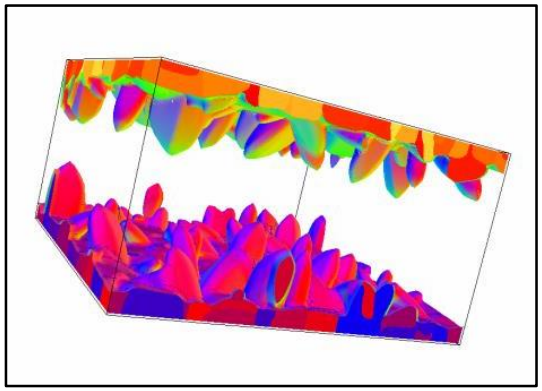
Production rate, Injection rate, Lifetime performance, …

Hydraulic (a_h), mechanical (a_m) and chemical apertures (a_c)

a_h: How to determine hydraulic apertures in the laboratory and the field (µm-m-scale)**?**

a_m: How to simulate fracture closure with increasing stress (mechanical aperture)?





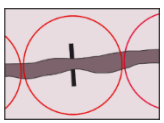
a_c: How does fracture sealing affect fracture flow (chemical aperture)?

How to determine hydraulic apertures (µm-m-scale)?

Four direct and indirect methods

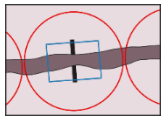
1

TinyPerm 3
(direct)

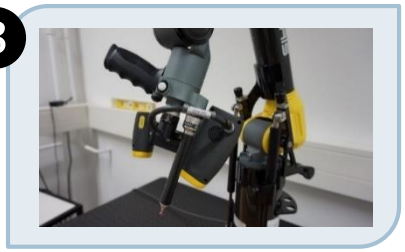


2

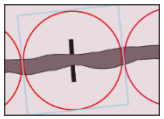
Microscope camera
(indirect)

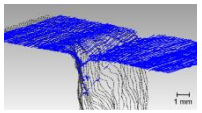


3



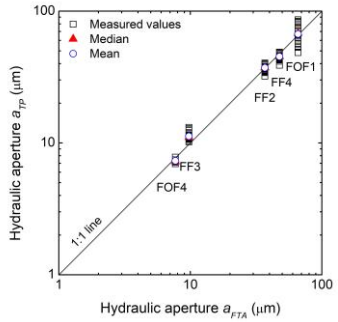
Laser scanner
(indirect)





4

Flow-through*
(direct)



- Application to natural fracture → bedding joints

2 m

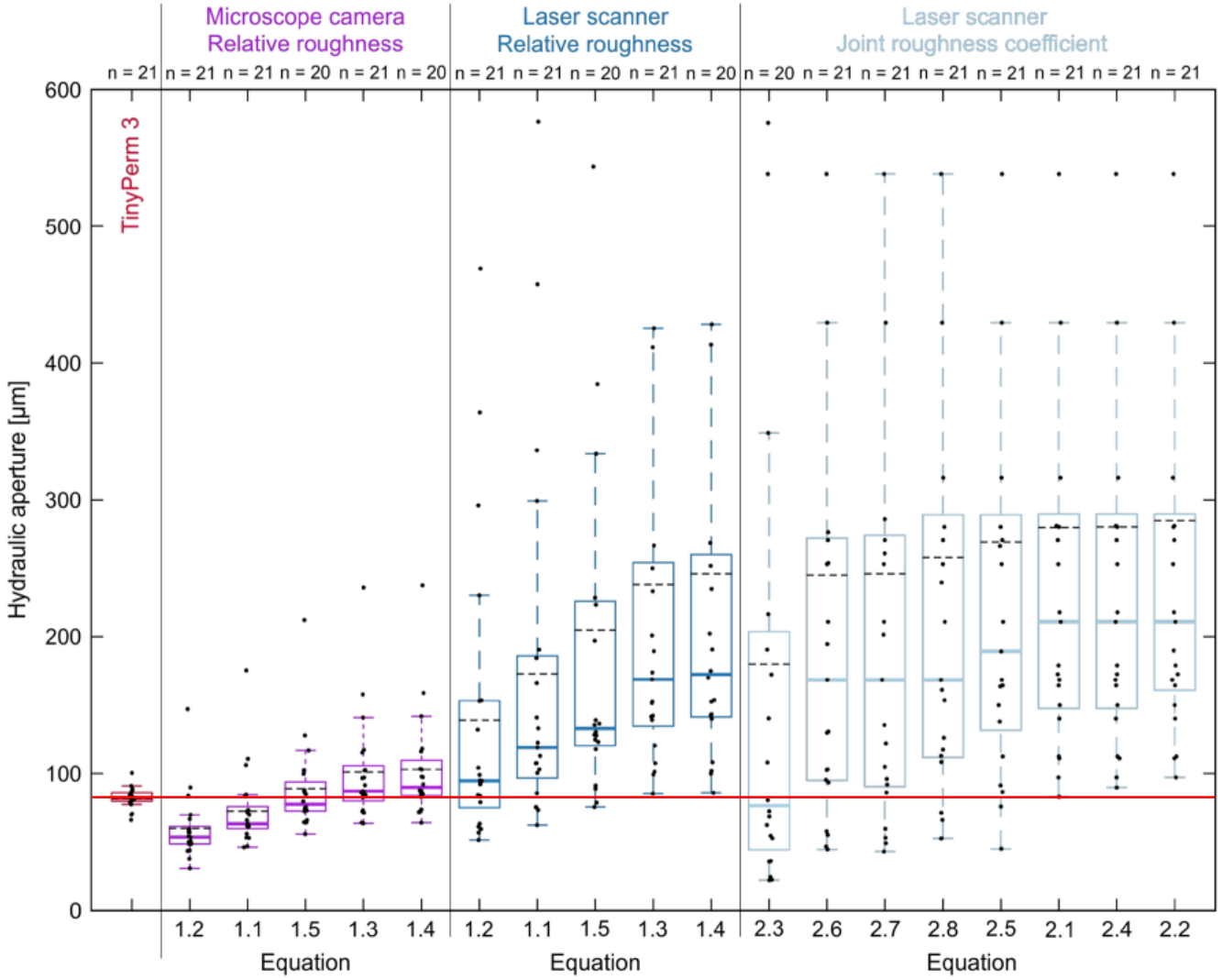
10 cm

a_h a_m a_c

*Cheng, Hale, Milsch, Blum (submitted) *Solid Earth.*

Microscope camera is a good and cheap alternative!

Results of the single bedding joint



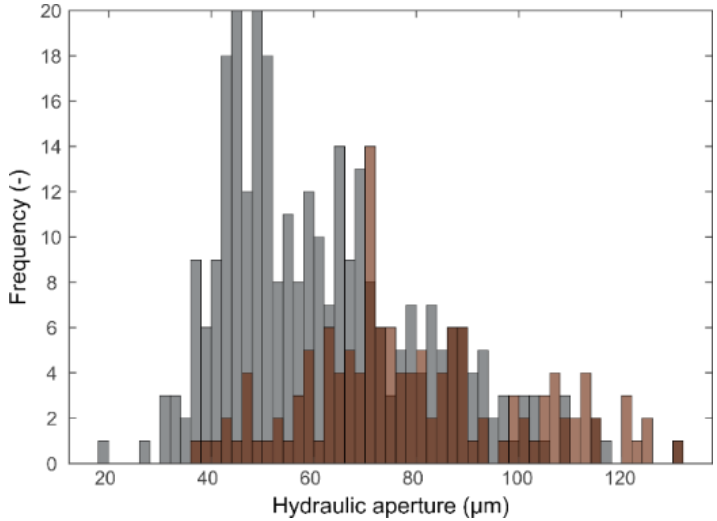
a_h a_m a_c

Hale et al. (2019) *Rock Mech. Rock Eng.*

Air permeameter provides realistic hydraulic apertures!

Field application of the TinyPerm 3

- Repeated accuracy up to **4 µm** (optimal handling)
- Measurements show an anisotropy in hydraulic apertures



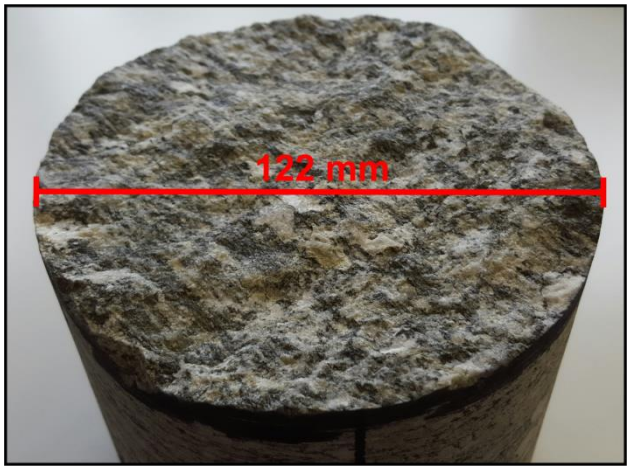
Flechtinger sandstone
(Germany)

a_h (horizontal) = **63 ± 20 µm** (n = 249)

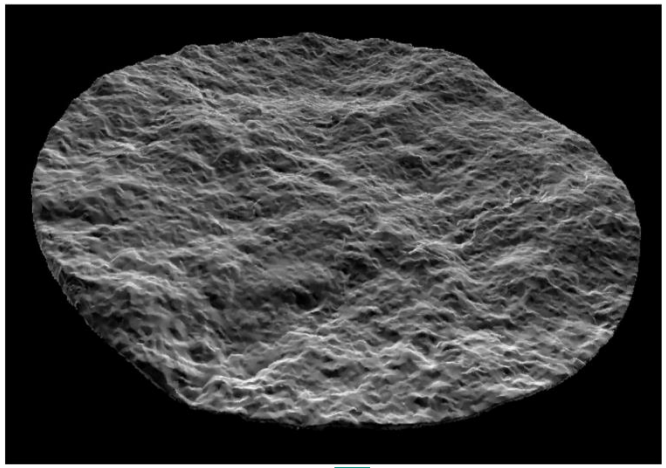
a_h (vertical) = **82 ± 21 µm** (n = 215)

How to simulate fracture closure with increasing stress?

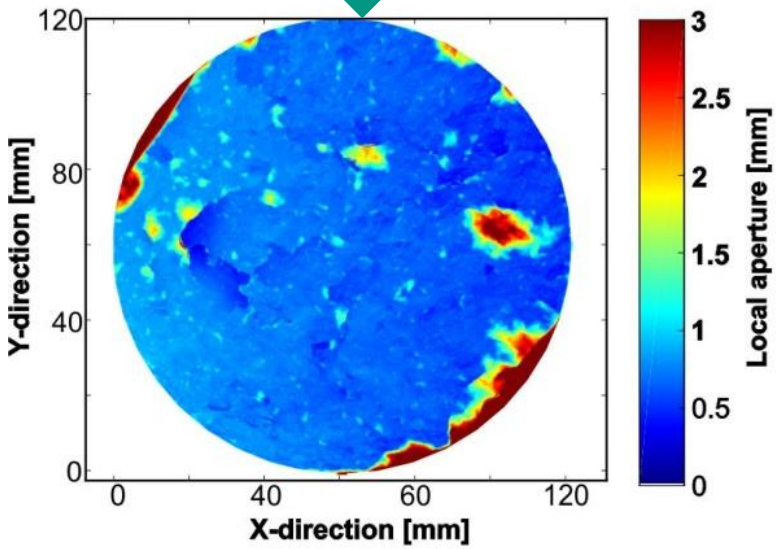
Surface scans → Contact mechanics



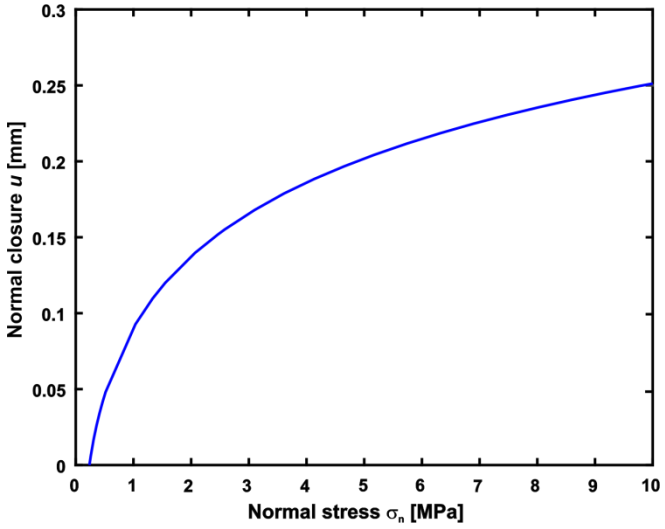
Scan



Match



Model

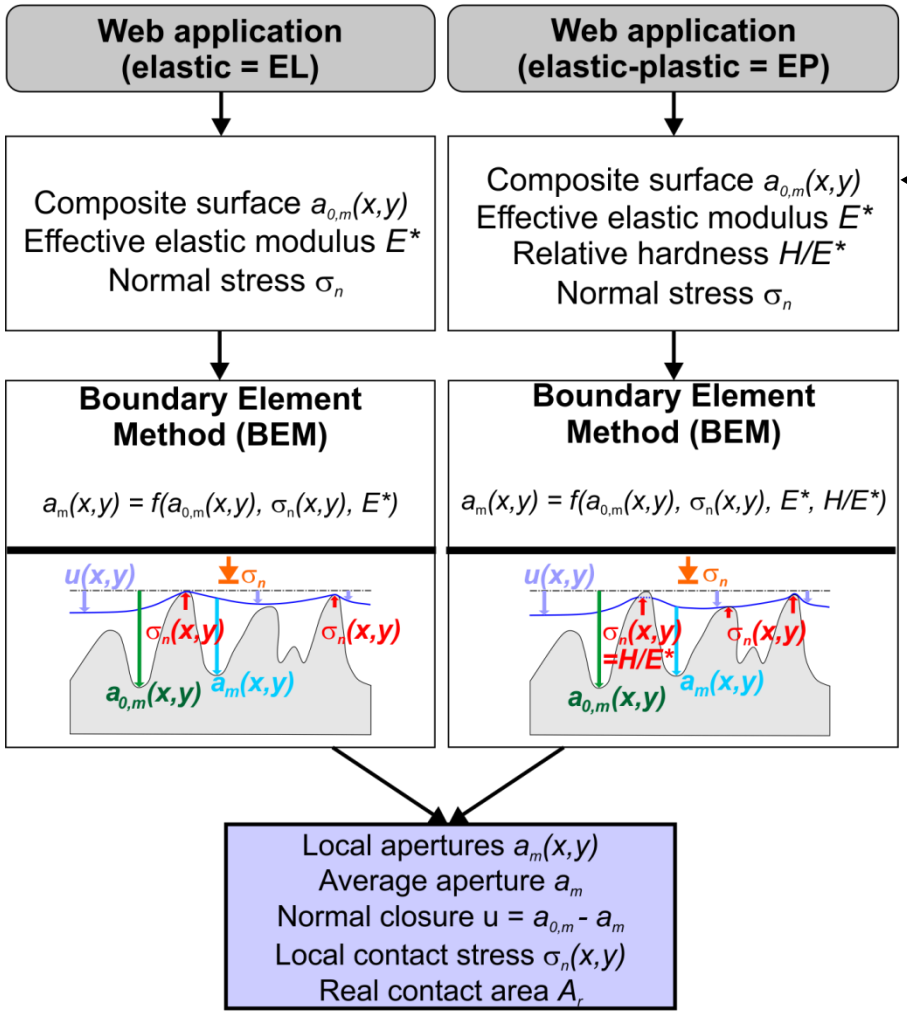


a_h a_m a_c

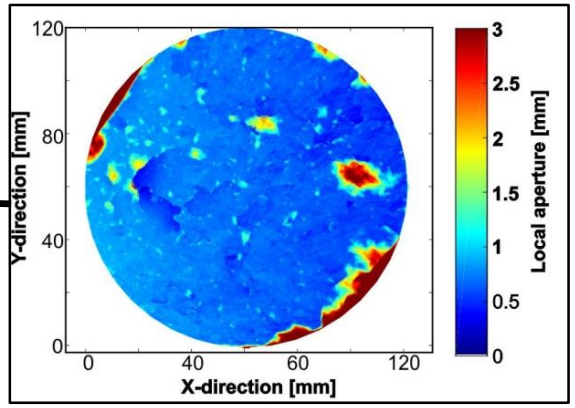
Kling et al. (2018) *Rock Mech. Rock Eng.*

Simulates stress-dependent fracture closure

Contact model → http://contact.engineering/

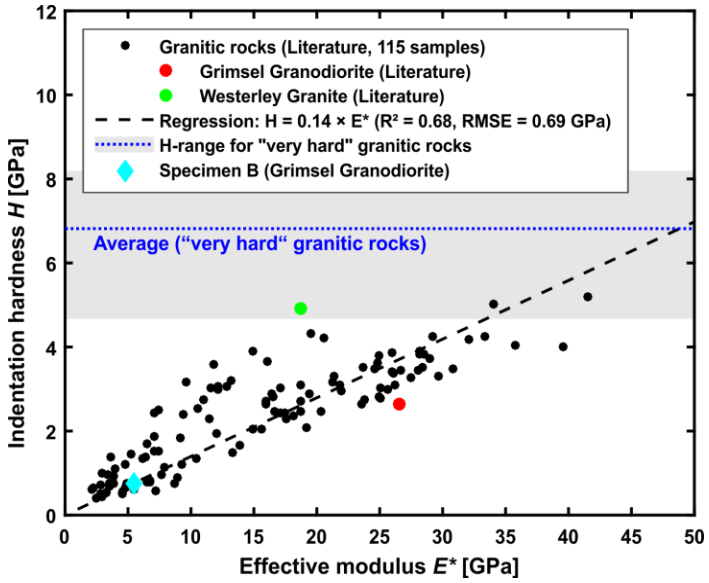


Input



Method

Output

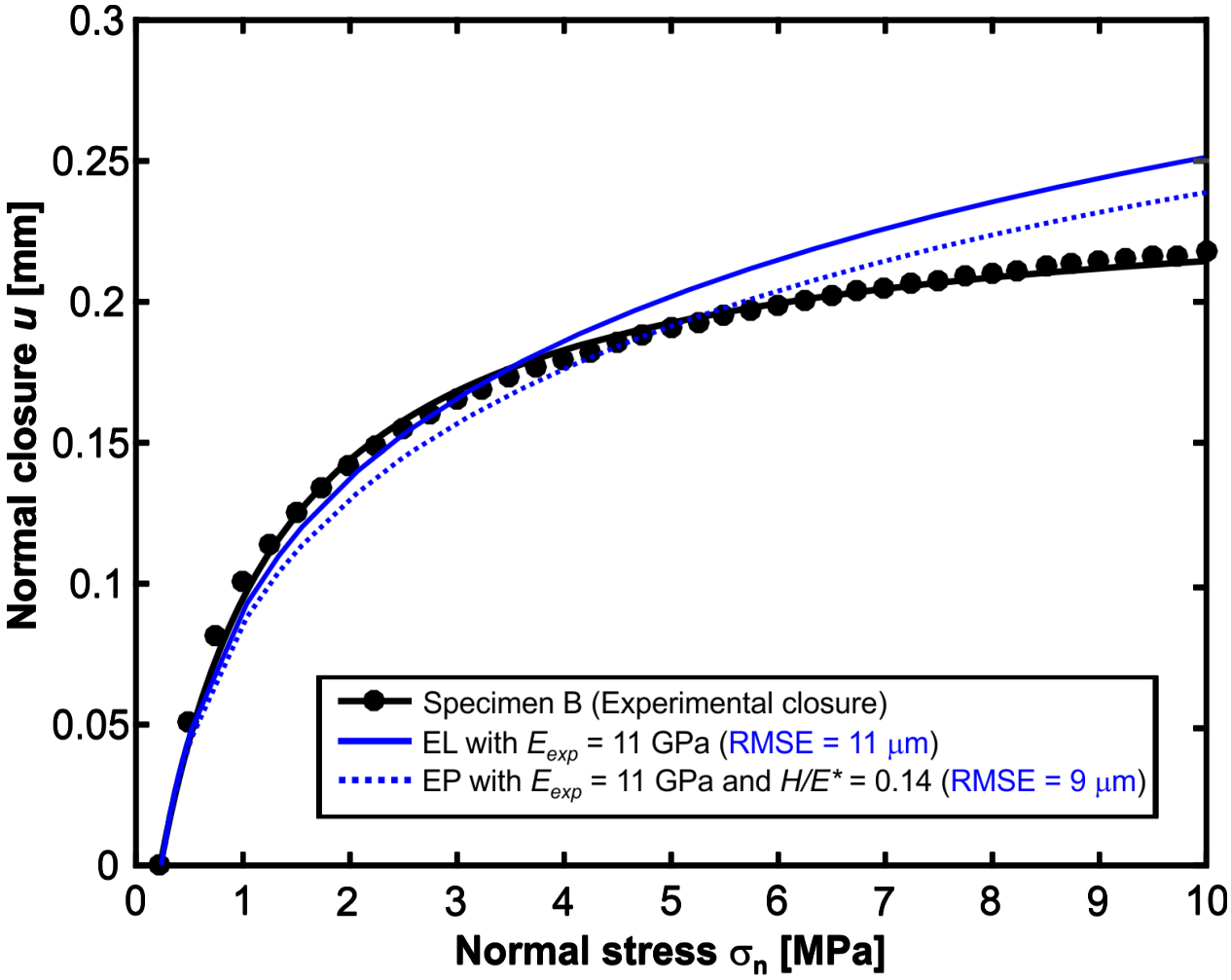


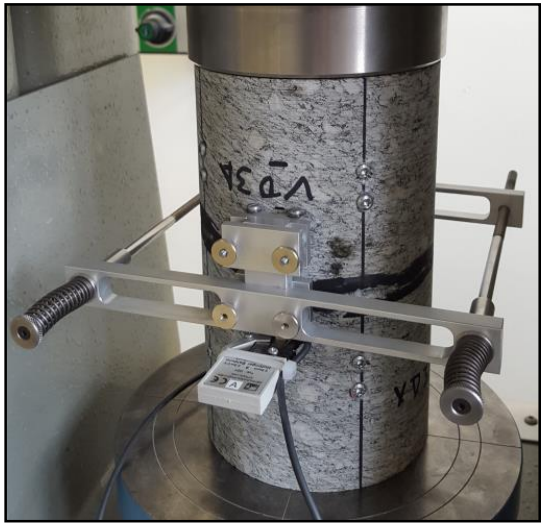
a_h a_m a_c

Kling et al. (2018) *Rock Mech. Rock Eng.*

The elastic-plastic model fits well with experimental results!

Validation of the elastic (EL) and elastic-plastic (EP) models





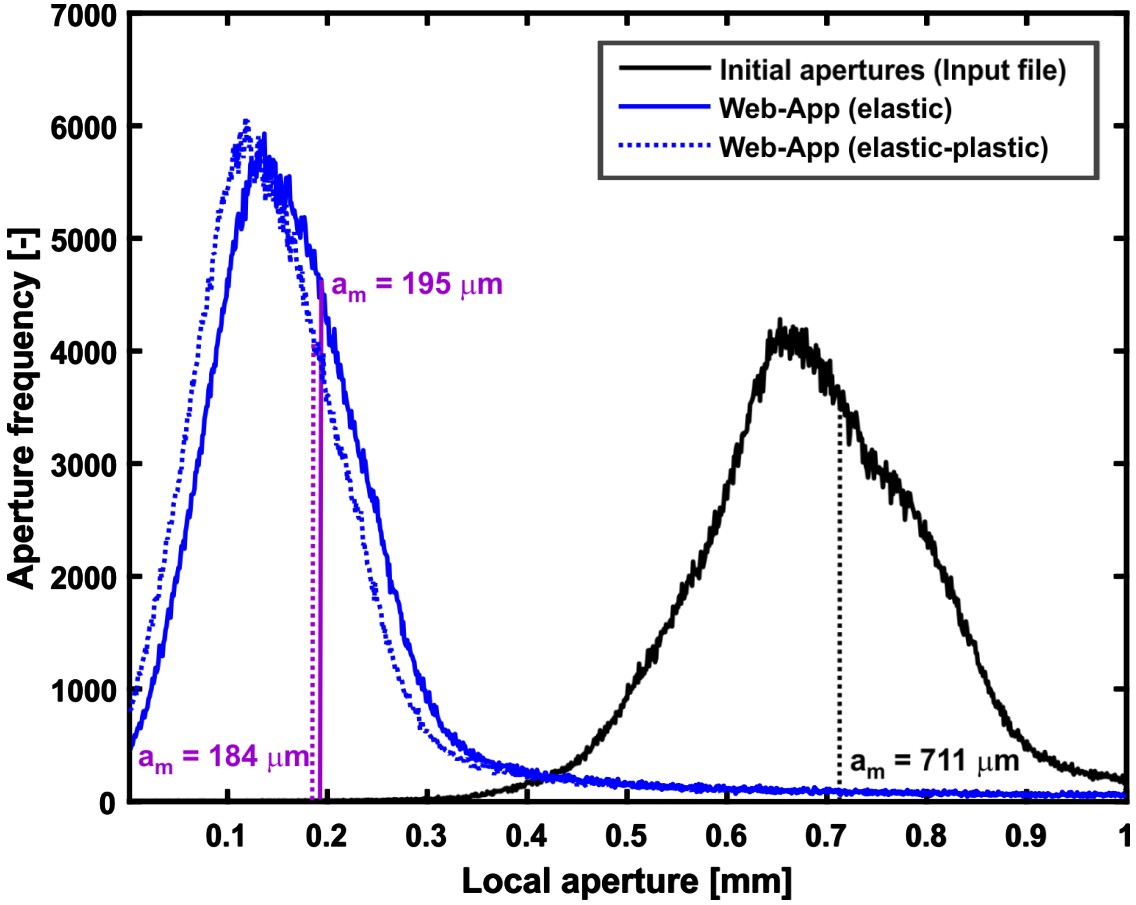
Uniaxial test (ETH Zürich)

a_h a_m a_c

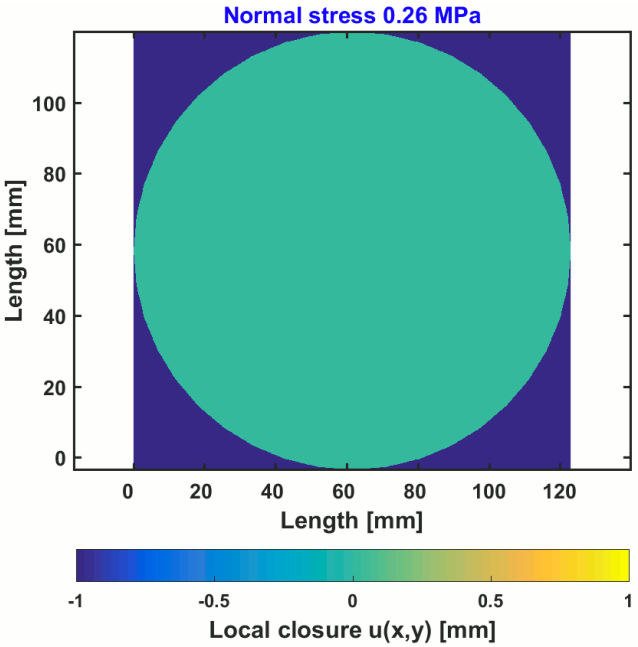
Left: Kling et al. (2018) *Rock Mech. Rock Eng.*
Right: Vogler et al. (2018) J. Geophys. Res.-Sol. Earth

Major local closure occurs along larger apertures

Aperture evolution → σ_n = 10 MPa



Elastic-plastic



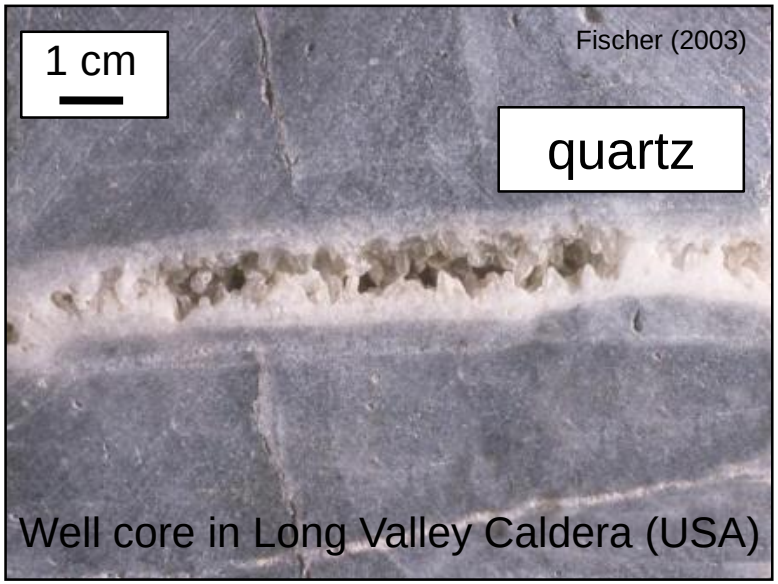
Contact area evolution: Sparse contacts (<2 %) even at high stresses (10 MPa)

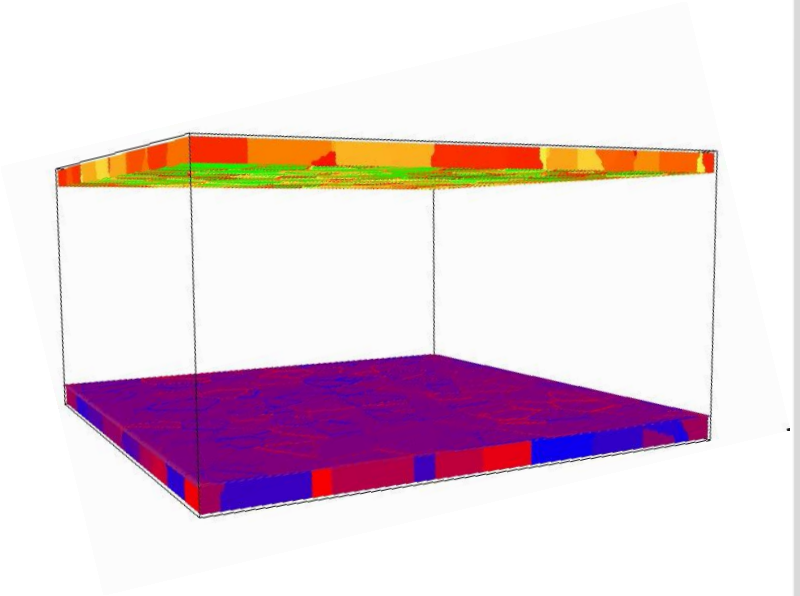
a_h a_m a_c

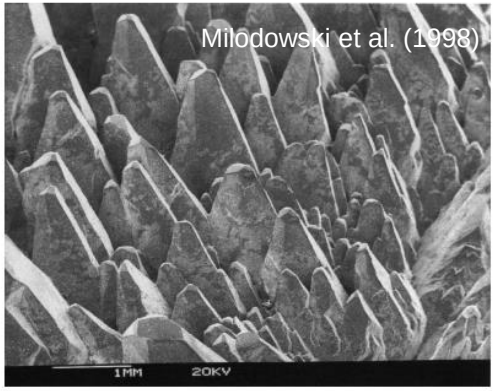
Kling et al. (2018) *Rock Mech. Rock Eng.*

How does fracture sealing affect fluid flow?

Crystal growth in fractures (chemical fractures)







Calcite cyrstal in well # 8 in Sellafield (UK)

- Simulating fracture sealing
- Validation the phase-field method (PFM)
- **Hydrothermal quartz growth**

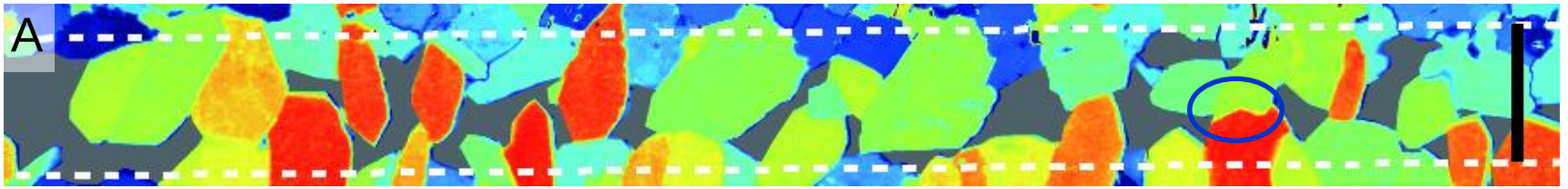
a_h a_m a_c

Left: Fischer (2003) *Dissertation Uni Bochum;*
Right: Wendler et al. (2015) *Geofluids*

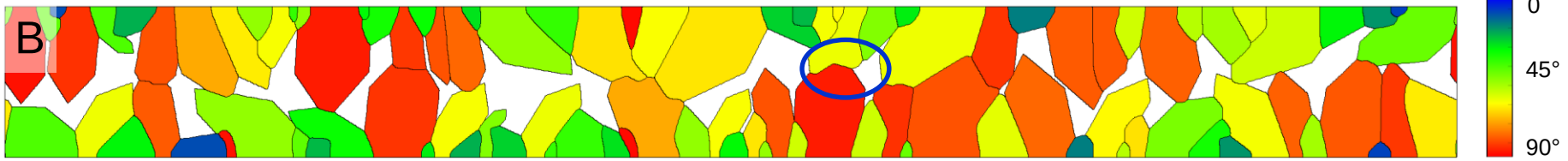
Validation of the phase-field method (PFM)

Wendler et al. (2015) *Geofluids*

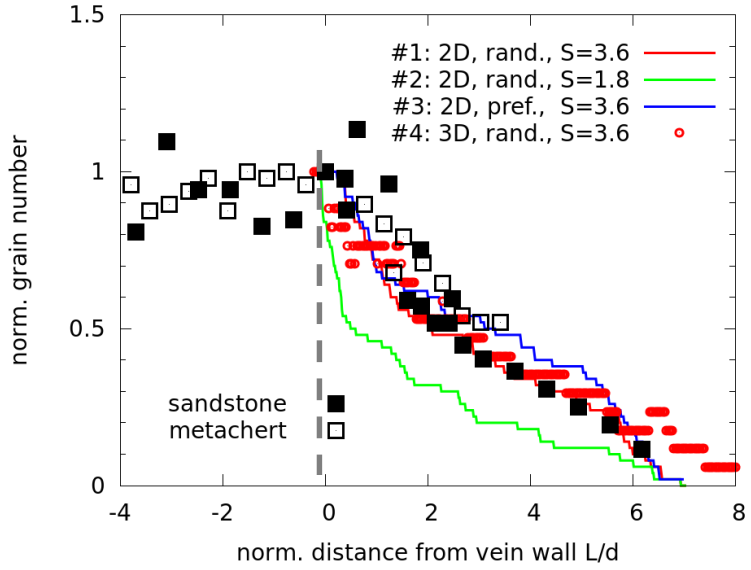
Experiment, Hornblende (metachert), d = 140 µm



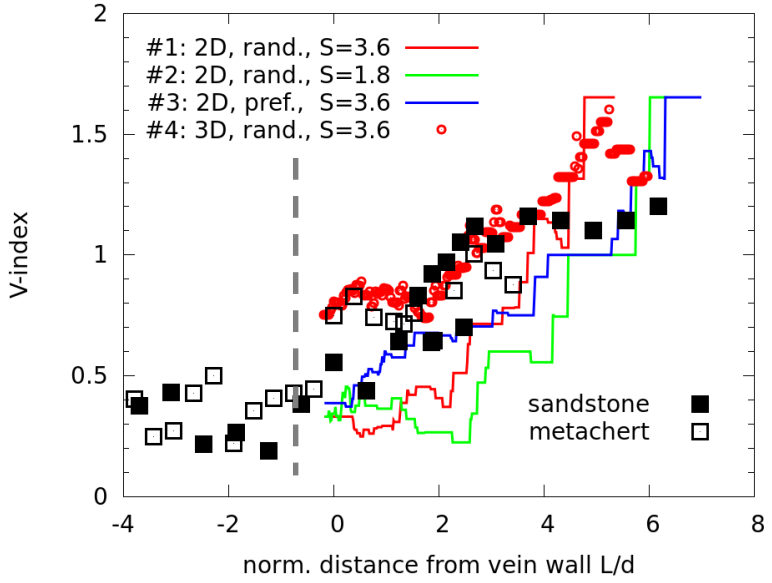
Simulation



Scaled grain number



V-index*

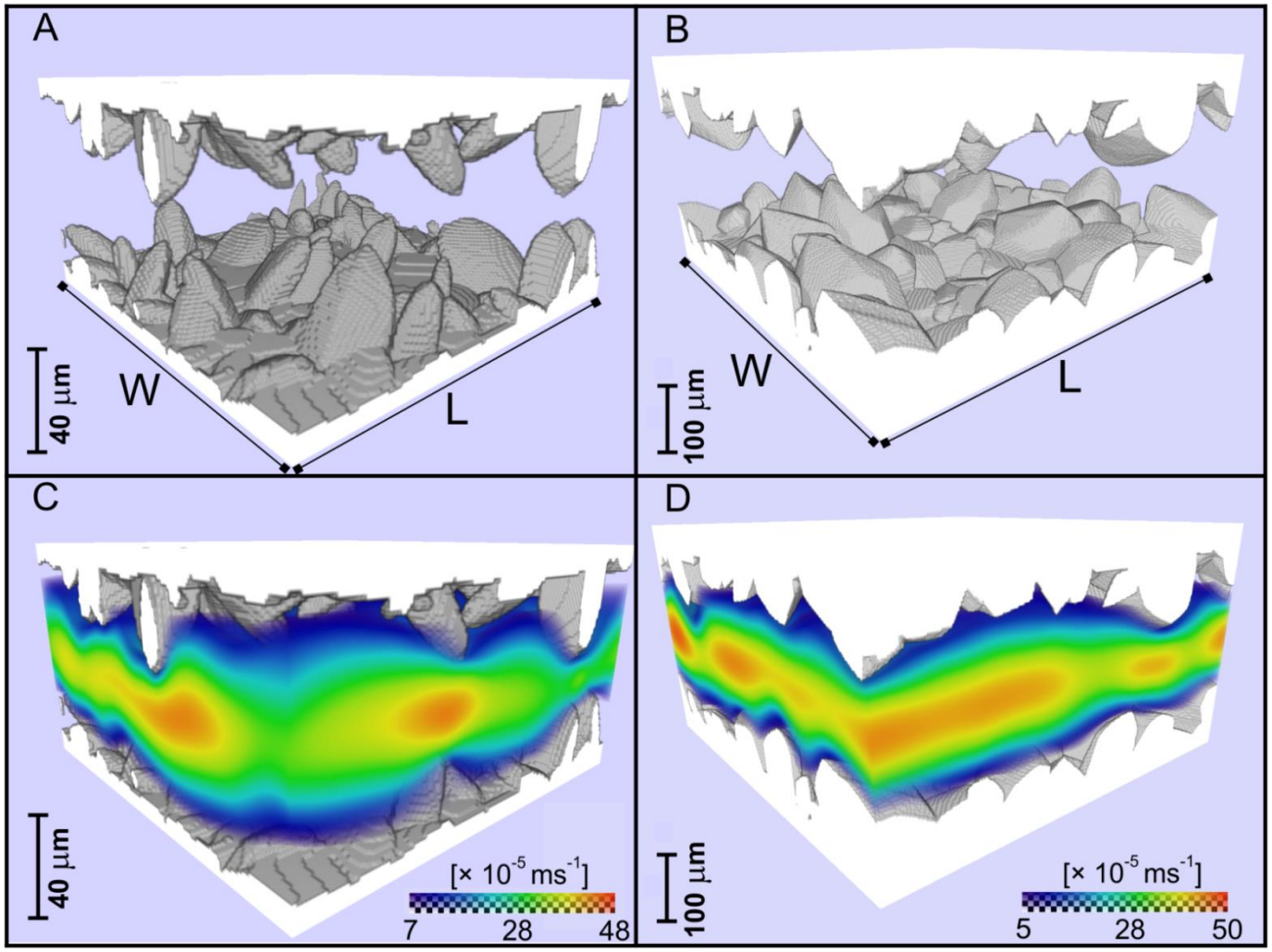


a_h a_m a_c

* V-index quantifies the deviation from random c-axis

Transferring PFMs into flow simulations

Needle and compact quartz growth



Phase-field models (PFM)

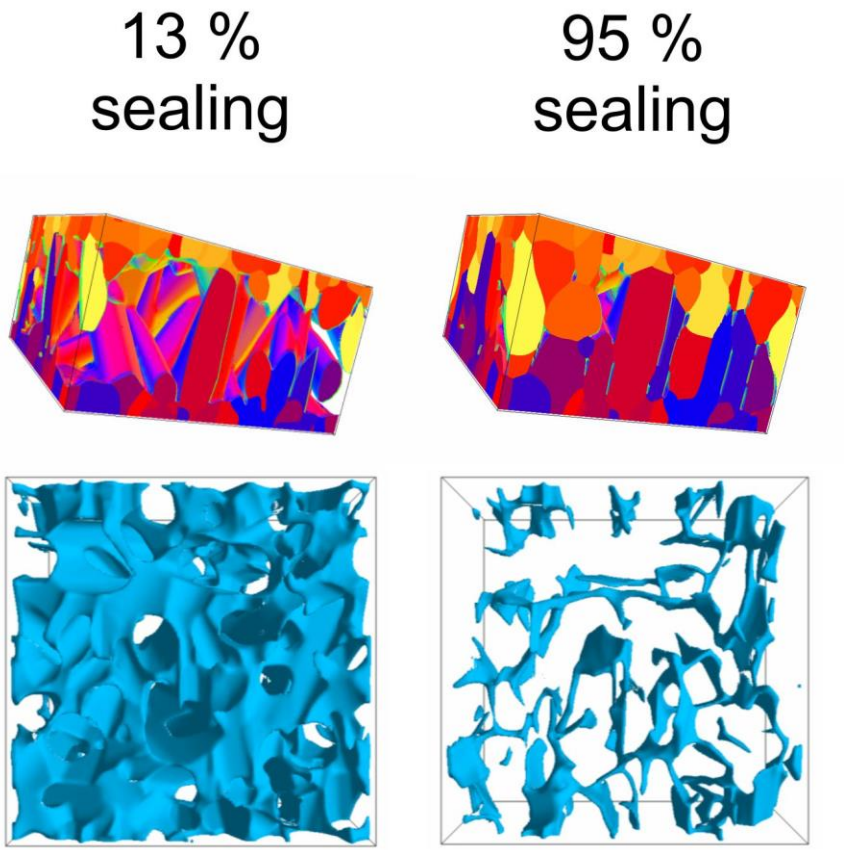
Finite volume method (FVM) solving the Navier-Stokes equation ($Re_{initial} \leq 1$)

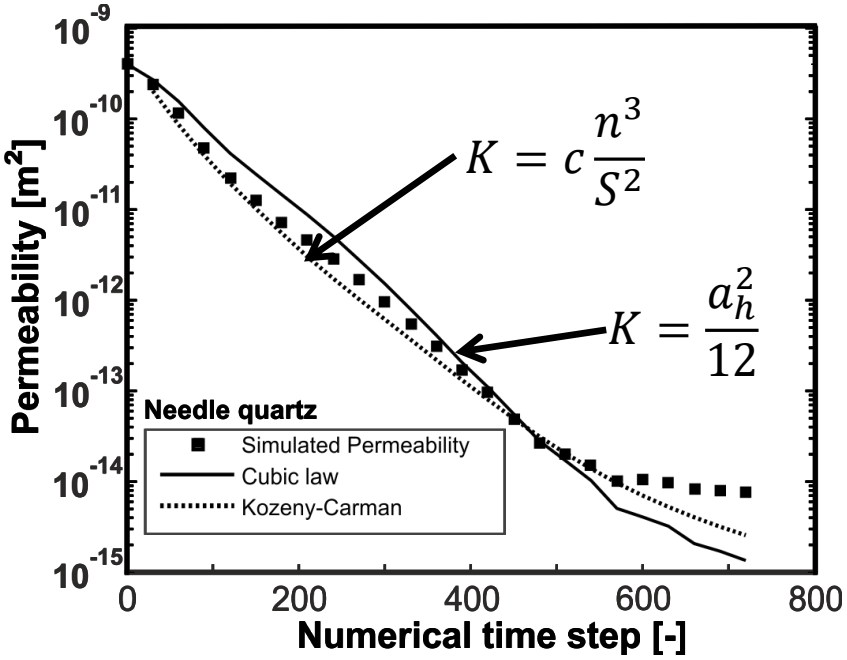
GeoDict

Kling et al. (2017) *Adv. Water Resour.*

Cubic law and Kozeny-Carman equation apply

Flow regime in needle quartz fractures



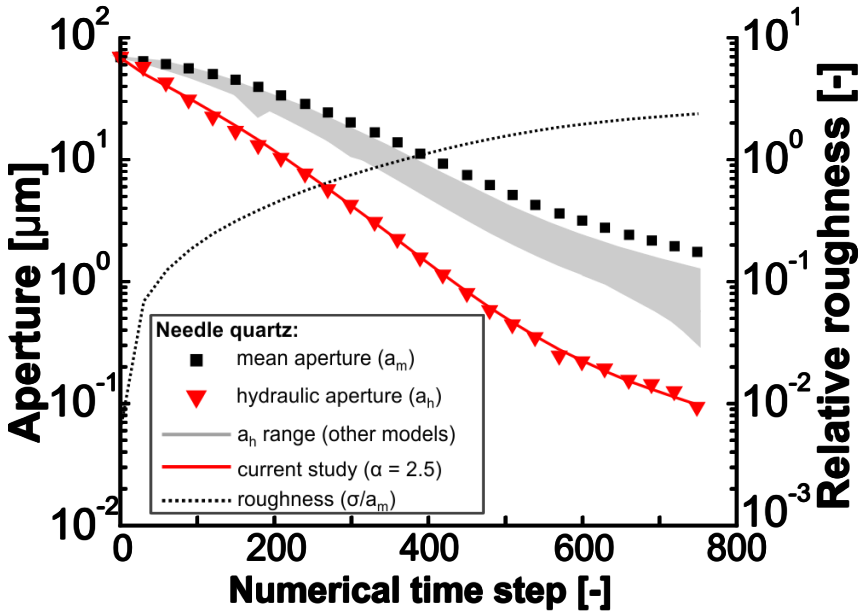


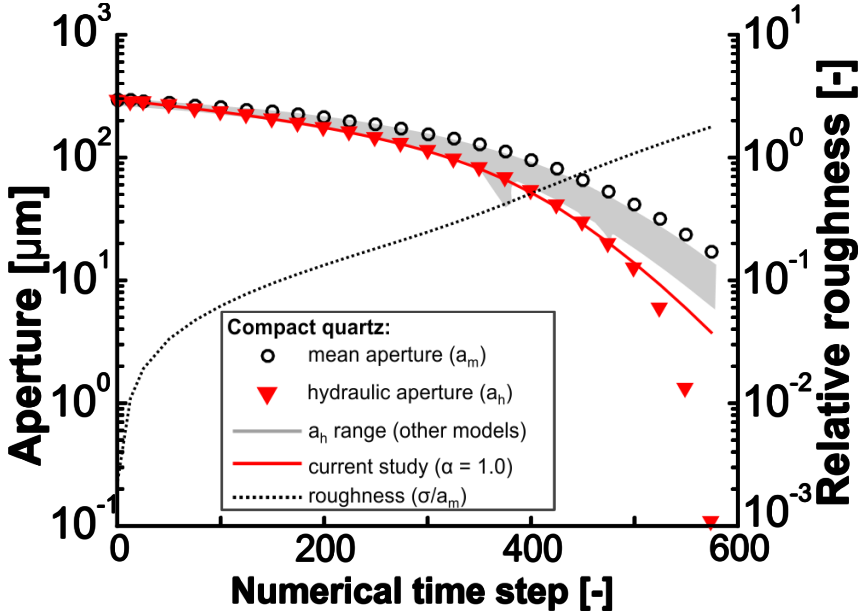
a_h a_m a_c

Kling et al. (2017) *Adv. Water Resour.*

New equation accounting for crystal shapes

Empirical hydraulic apertures





$$a_h = a_c \left(1 + \alpha \frac{\sigma}{a_c}\right)^{-3/2}$$

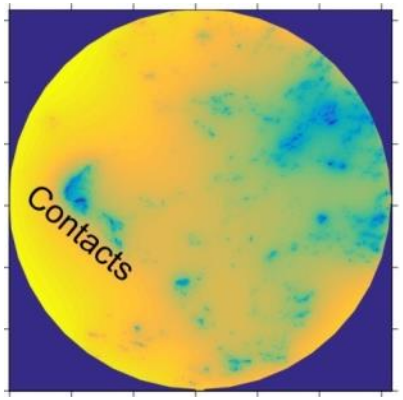
- New equation with a new geometry factor α depending on the crystal shapes

a_h a_m a_c

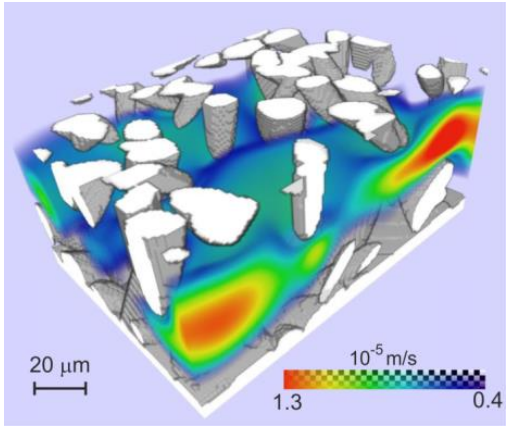
Kling et al. (2017) *Adv. Water Resour.*

Thank you for your attention!

- Air permeameter provides realistic hydraulic apertures
- Microscope camera is a good and cheap alternative



- A contact model is used for normal fracture closure
- Providing also local mechanical apertures



- For sealing fractures hydraulic properties significantly depend on the crystal shape
- A novel equation is derived to estimate hydraulic apertures in sealing fractures

a_h a_m a_c