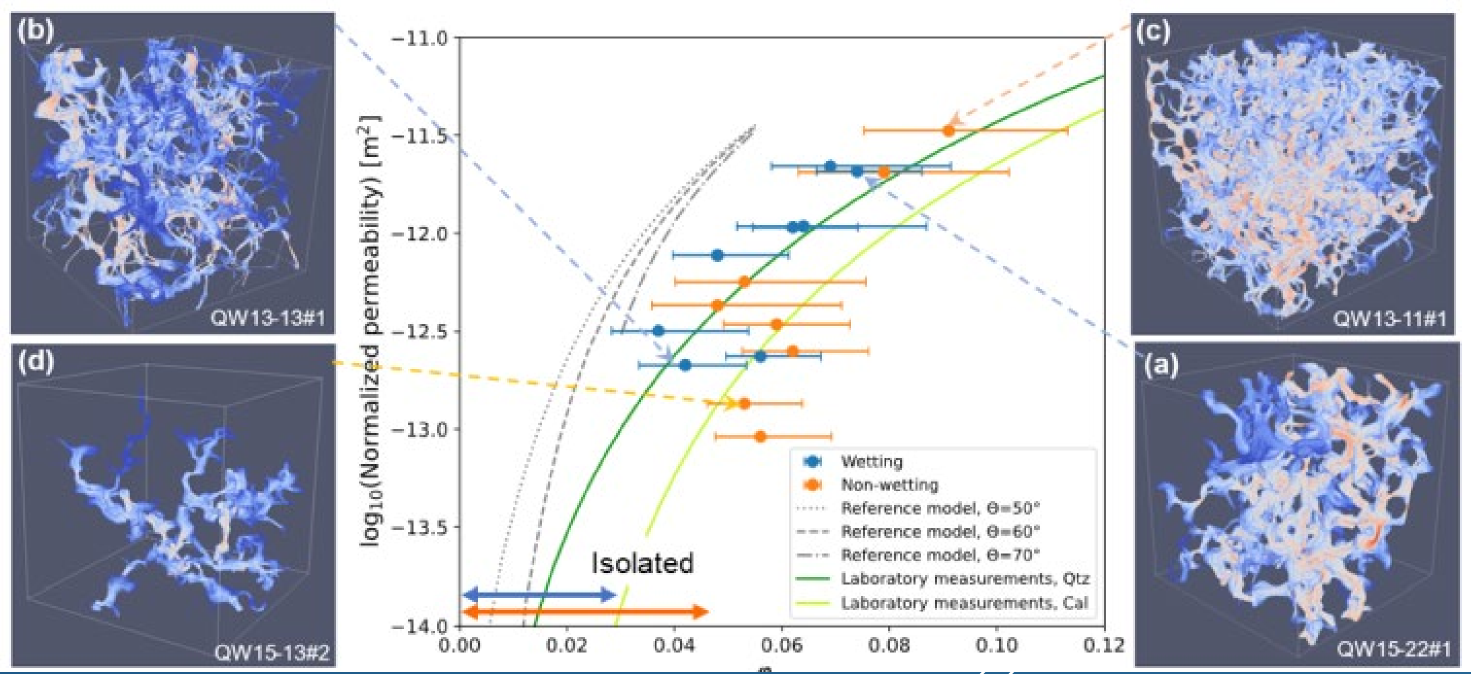
# Fluid segregation and retention in deep-seated rocks near percolation thresholds

Abstract

OA Reference

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# SIGNIFICANCE & OBJECTIVES

- Segregation of geological fluids controls the chemical differentiation and physical properties of the Earth's interior.
  - Dehydration of a subducting slab produces excess pore fluid pressure, a key factor controlling seismic activity within the slab
  - The pore fluids left in the slab contribute to the total amount of water downdragged into the Earth's deep interior.

- Rock-microstructural flamework based on dihedral angle $\theta$
  - $\theta < 60^\circ$: interstitial fluids are connected in an isotropic system; gravity drives fluid segregation and compaction of ductile solid matrix.
  - $\theta > 60^\circ$; fluid ($<$ percolation threshold) can be isolated, escaping gravitational segregation

- Issues to be addressed:
  - How and to what extent are geological fluids retained in deep-seated rocks?

# PREVIOUS STUDIES & STRATEGY OF THIS WORK

- Previous estimates of permeabilities of geological bodies:
  - Hydrological models based on geothermal and metamorphic data (Manning & Ingebritsen 1999; Ingebritsen & Manning 2010)
  - Laboratory measurements of synthetic and natural rocks (Wark & Watson 1998; Katayama+ 2012; Ganzhorn+ 2019)
  - Numerical simulations of network models and experimental products (von Bargen & Waff 1986; Zhu & Hirth 2003; Miller+ 2014; Eberhard+ 2022)
- Quartzite (quartz polycrystalline aggregate)-fluid system:
  - Well-studied semi-analog silicate rocks, moderately anisotropic, textural equilibration (Wark & Watson 1998; Liang+ 2001; Nakamura & Watson, 2001; Yoshino+ 2006; Price+ 2006)
  - Laboratory permeability measurement & indirect interpretation from 2D cross sections
- This study: a digital rock physics approach
  - Direct computation of permeability using the 3D tomographic image
  - To bridge the gap between 3D permeability and 2D cross section
  - Towards a better understanding of how pore microstructures control permeability and isolated fluid fraction of deep-seated rocks

# METHODS

- <u>Quartzite synthesis</u> (Fujita+ 2022)

  Starting materials:

  Qtz powder + Amorphous silica

  Piston-Cylinder *T* = 900˚C, *P* = 1 GPa, *t* = 192 h

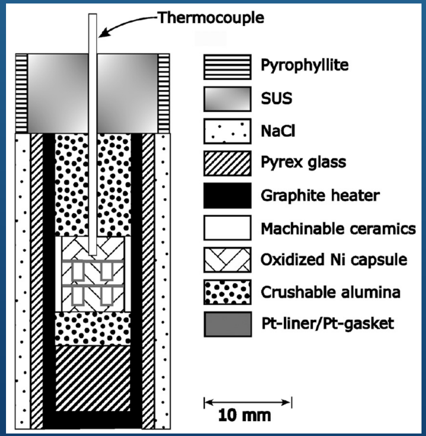
  Added fluid fraction: $\phi_{add}$= 0.025–0.101

  Near-steady-state grain growth

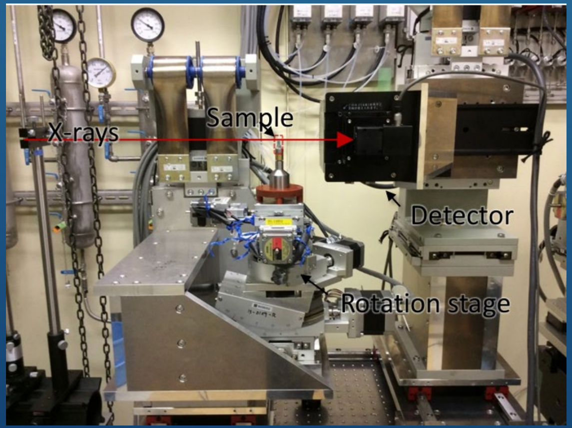
  $X_{CO2}$ =0 (θ = 52˚), 0.28 (61˚), 0.39–0.44(71˚)

  Minimum Energy Fluid Fraction :

  0, 0.035, 0.015 (Park & Yoon 1985; Watson 2015)




P-C cell assembly




X-ray CT @SPring-8

- **<u>SRµCT (Synchrotron X-ray microtomography) Imaging</u>**

  SPring-8 BL20XU (Uesugi+ 2012; Huang+ 2021)

  510 nm edge voxels

  **<u>Microstructure characterization</u>**

  2–6 subvolumes $512^3$ voxels ($261^3$ µm$^3$)

  4.4–6.7 times the mean grain size

  Multi-grain scale (< capsule scale)

  Connected porosity from one side to the opposite

- **<u>Numerical computation</u>**

  Lithospheric and Mantle Evolution Model **(LaMEM)**

  (Kaus+ 2016; Eichheimer+ 2019).

  The computational grid cell = image voxel

  Permeability normalized by grain size to 1 mm

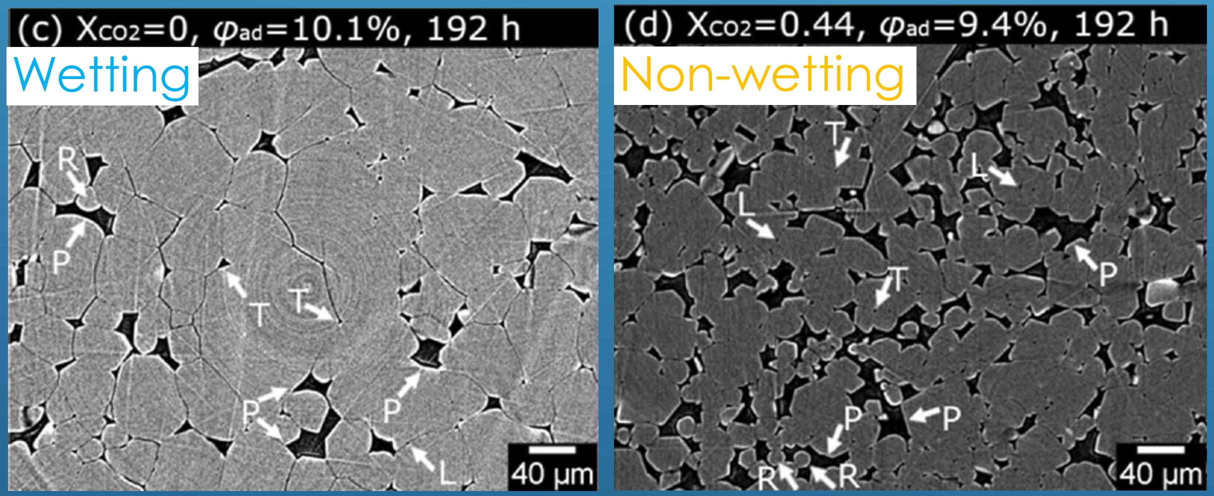
  Mean values of x, y, z directions

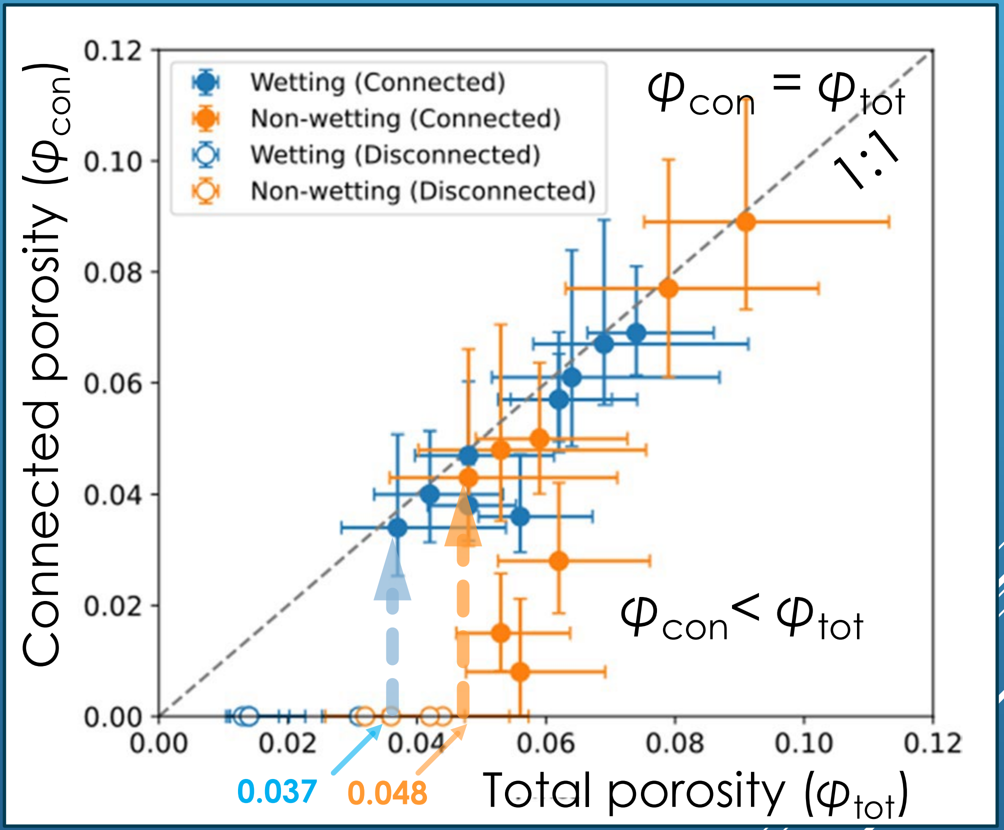
  Reliability tested for pipe flow and sintered

  glass bead media (Eichheimer+ 2019, 2020)

# RESULTS: MICROSTRUCTURE, CONNECTIVITY

SRμCT slice images




- **Fluid geometry**

  Grain-edge **T**ubules

  **L**ens at two grain boundaries
  (more common in high $X_{CO_2}$ samples)

  Large **p**ools surrounded by >4 grains

  **Faced** tubules & pools,

  **Dry triple junctions** even in the wetting sys.
  (Yoshino+ 2006, Price+ 2008)

- $\varphi_{con} < \varphi_{tot}$ at $\varphi_{tot}$ <~0.07 in the non-wetting sys., while maintained pore interconnection
- **Pinch-off thresholds**

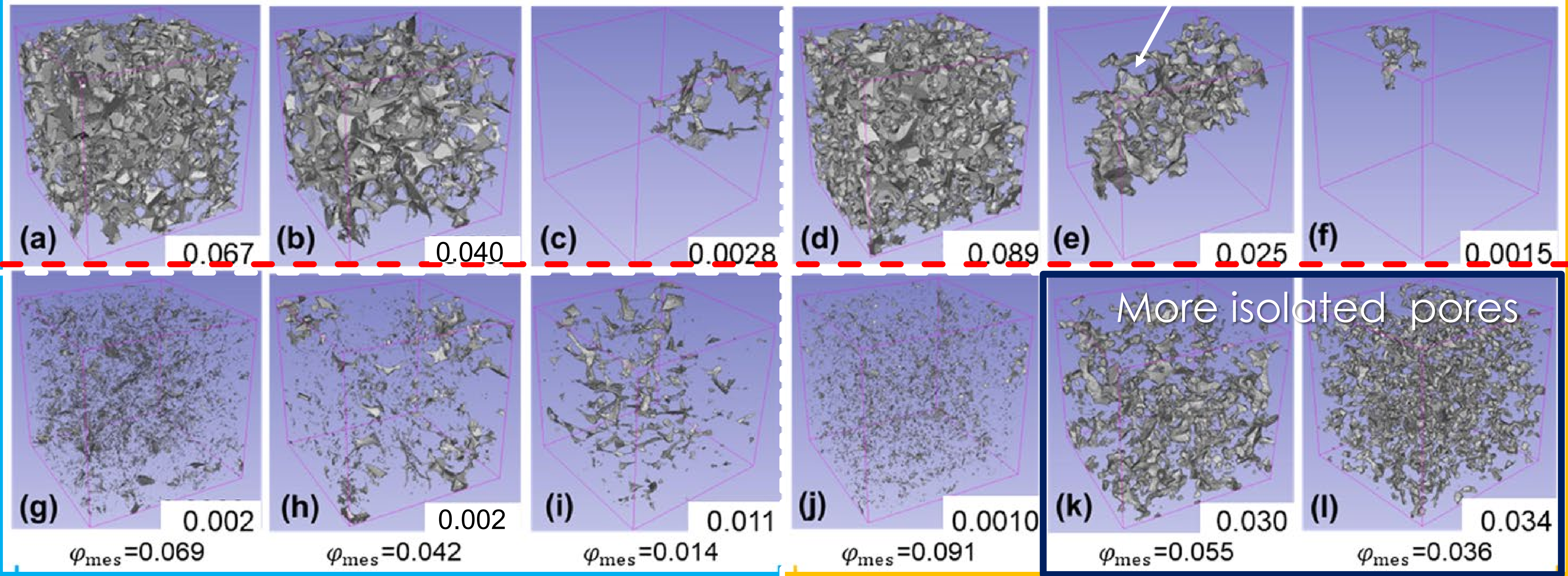
  Wetting: 0.037 > Model (0)

  Non-wetting : 0.048 > Model (0.015–0.035)

# 3D FLUID DISTRIBUTION

The largest interconnected pores

Rounded pores, Thicker tubules




Other remaining pores

Wetting system

Non-wetting system

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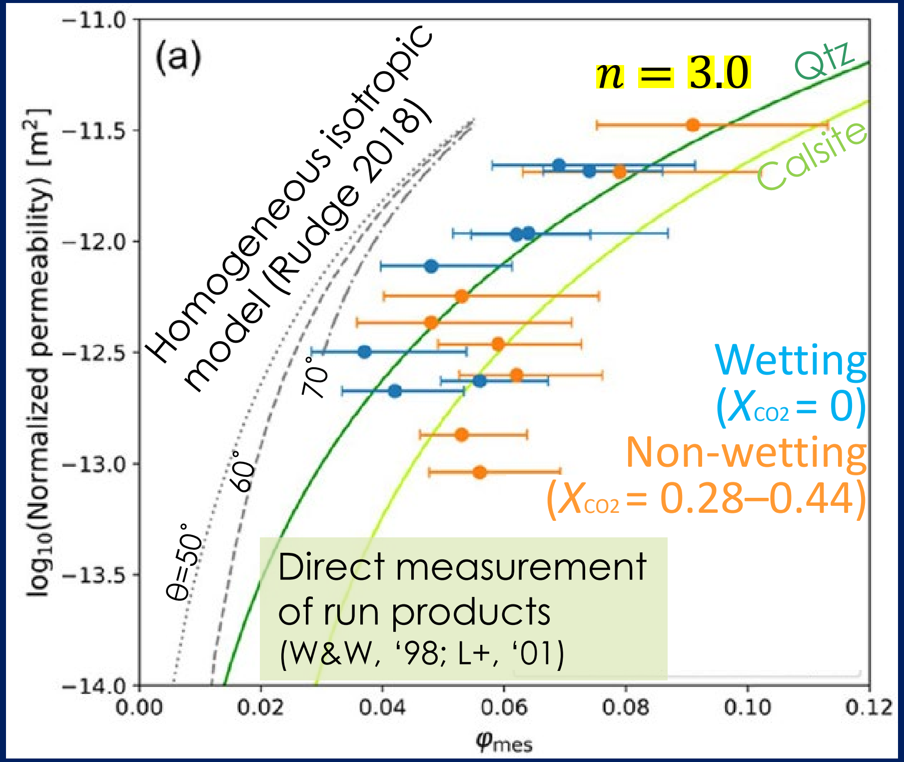
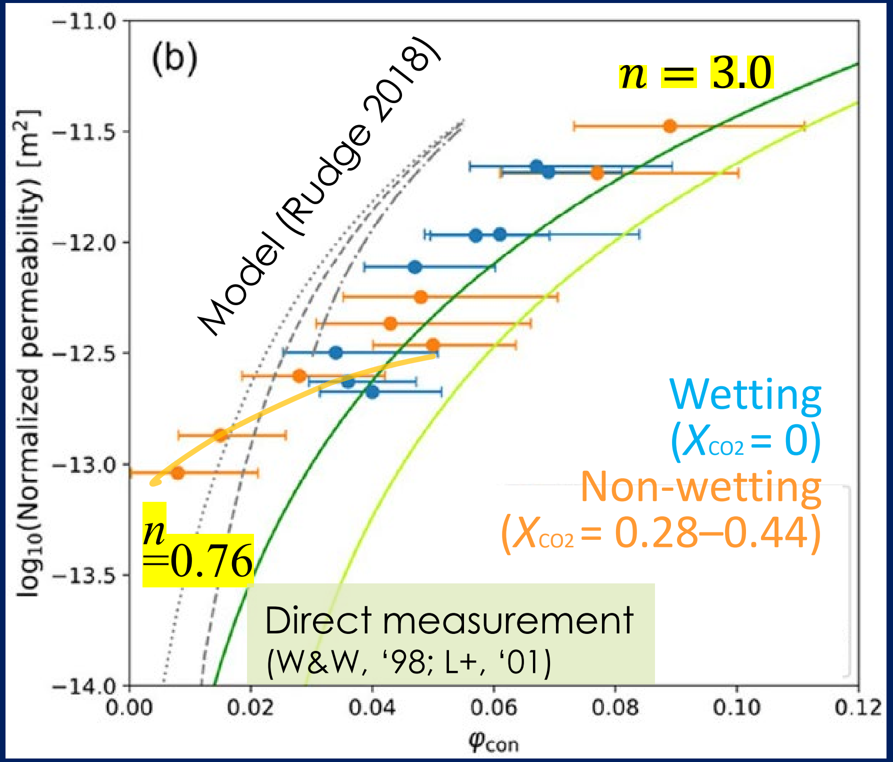
# COMPUTED PERMEABILITIES

Normalized to $d$ =1 mm
Mean values of $k_x$, $k_y$, $k_z$




**Total porosity ($\varphi_{tot}$ )**




**Connected porosity ($\varphi_{con}$ )**

$$k_{abs} = \frac{d^2 \varphi^n}{C}$$

$k_{abs}$: Absolute permeability
$C$: Geometrical factor
$d$: Grain diameter
$\varphi$: Porosity
**$n$: Power law exponent**

- Computed permeabilities were lower than the isotropic model (Rudge '18) by 0.5 order.
- Permeability in the wetting system showed excellent agreement with the directly measured $k$-$\varphi_{tot}$ relation (Wark & Watson '98; Liang+ '01); power law exponent $n$ =3.
- Non-wetting system still maintained interconnection at $\varphi_{tot}$ ~0.05, insensitively to $\varphi_{con}$.

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# FLOW CONCENTRATION AT LOW PORE CONNECTIVITY

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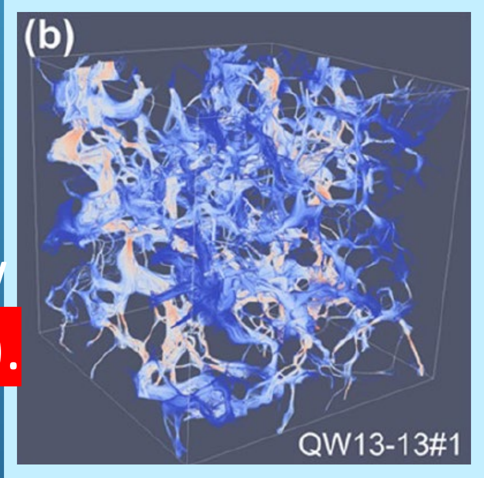
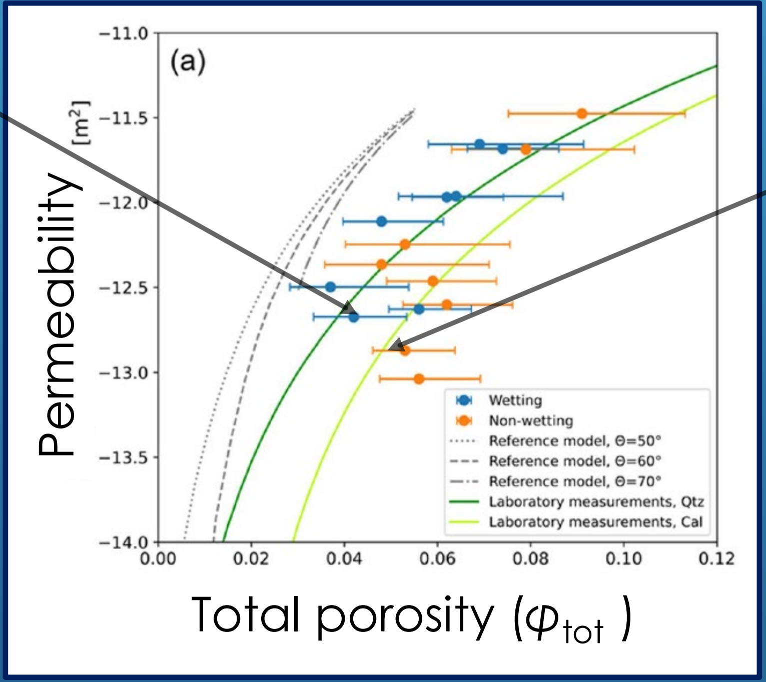
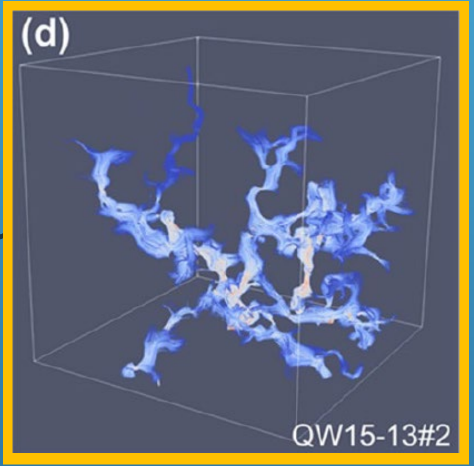
Each channel occupied < 20% of the total flow rate (qi/Q < 0.2).

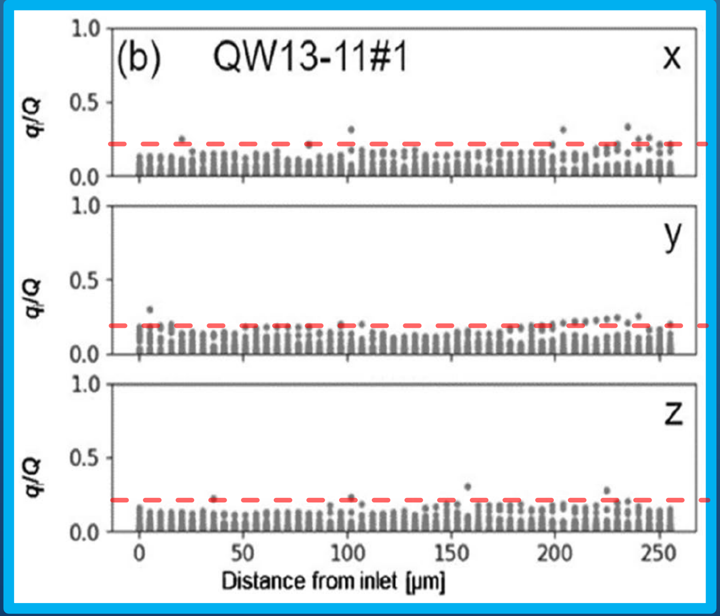


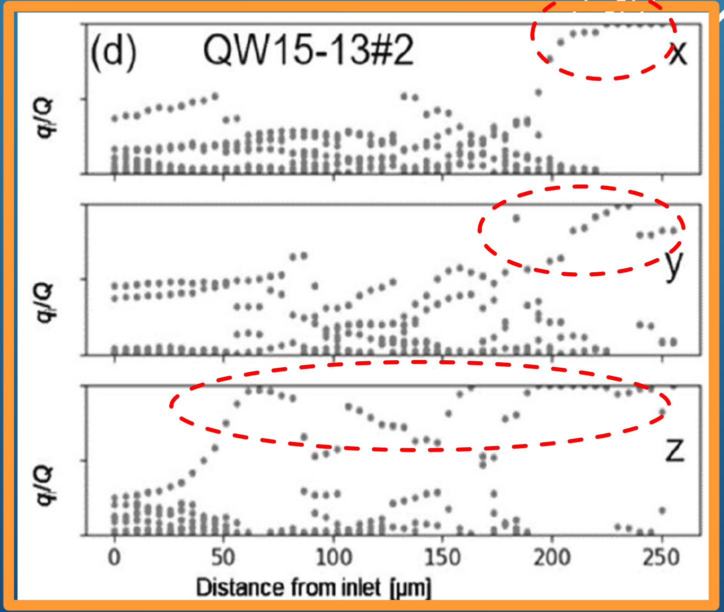




The max qi/Q reached 1, showing flow concentration.

**Wetting sys.**




**Non-wetting**




## qi / Q vs. distance from inlet

$$\left( \frac{\text{Vol. flow rate of each channel in the } i\text{-th cross section}}{\text{total flow rate}} \right)$$

# SUMMARY

- Permeability and pore connectivity of a moderately anisotropic semi-analog rock (quartzite) were computed using SRµCT and LaMEM computations.

- Percolation thresholds, below which pore fluids were isolated, were higher than the theoretical estimations for the isotropic, homogeneous model: the threshold volume fractions were

  0.037 for the wetting system ($\theta$ =52°)

  0.048 for the non-wetting case($\theta$ =61 – 71°)

- A streamline computation in the non-wetting system revealed that with decreasing total porosity, flow focusing into fewer channels maintained the permeability, allowing the effective segregation of the connected fluids, while leaving other pore fluids retained in the rock.

Abstract

OA Reference

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# FUNDING


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JSPS Stockholm Office

GP EES The International Joint Graduate Program in Earth and Environmental Sciences

BGI International Research and Training Group "Deep Earth Volatile Cycles"

科研費 KAKENHI

火山の未来を観る
次世代火山研究・人材育成総合プロジェクト
Integrated Program for Next Generation Volcano Research and Human Resource Development

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# REFERENCES

## Open Access

Fujita *et al.*
*Progress in Earth and Planetary Science* (2024) 11:40
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Progress in Earth and Planetary Science

**RESEARCH ARTICLE** **Open Access**

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# Imaging flow focusing and isolation of aqueous fluids in synthetic quartzite: implications for permeability and retained fluid fraction in deep-seated rocks

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## Companion paper

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# Chemical compaction and fluid segregation in piston cylinder experiments

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ABSTRACT

Fluid segregation is a ubiquitous process in deep-seated rocks, mainly driven by buoyancy and gravitational compaction, which occur in drained systems until permeability decreases and the system become practically undrained. The mechanism and rate of fluid segregation following this stage are poorly constrained, despite the importance of these factors for fluid distribution and the physical and chemical properties in the Earth. To this end, we performed sintering experiments of quartzite, with $H_2O$–$CO_2$ fluids of 1.9%–18.0% added volume fraction using a piston-cylinder apparatus at 900°C under nominally isotropic pressure of 1 GPa. The subsequent chemical redistribution of silica and fluids resulted in capsule-scale fluid segregation (CFS) and the formation of dense quartzite (~0.3%) within 192 h in pure $H_2O$ systems. Comparative experiments showed that dissolution/precipitation was not caused by the temperature gradient. Instead, we considered the fluid pressure difference within the experimental capsule between fluid-rich and fluid-poor domains caused by the different response against small pressure oscillation during experiments. Fluid-rich rock is elastically "soft" (i.e., having larger Skempton's coefficient) compared to fluid-poor rock to increase pore fluid pressure under a compressional stress change. Therefore, more silica dissolves in fluid-rich domains with higher solubility, while it precipitates in fluid-poor domains through diffusive transport, expanding porosity contrast. This chemical compaction in the capsule scale is effective as long as elasticity dominates matrix viscosity because the pressure difference relaxes with time. The calculated relaxation time of quartzite at the experimental condition was comparable to the intervals of the oil pressure addition which produced stress change. A one-dimensional model for porosity evolution showed that time-averaged $SiO_2$ diffusivity during CFS was much larger than the grain boundary diffusivity of tightly sintered quartz aggregates, but was comparable to the diffusivity of $SiO_2$ in aqueous fluid with ~0.1 vol% fluid fraction. During metamorphism where the fluid pressure difference may be maintained for longer duration, the spontaneous silica cementation may play a role for formation of *syn*-metamorphic veins and control of the amount of pore fluids transported to deep Earth.