KG^{2}B, a world-wide inter-laboratory benchmark of low permeability measurement and modelling

Christian David
and the KG^{2}B Team

The KG^{2}B project

Objectives:

An international benchmark for estimating the permeability

- of a selected low permeability material
- by different laboratories (24)
- using different techniques
  (experiments, modelling)

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What's the meaning of KG^{2}B?

~~Комитет государственной безопасности~~

~~*Komitet Gossoudarstvennoi Bezopasnosti*~~

NO

K (permeability) for Grimsel Granodiorite Benchmark

The KG²B team

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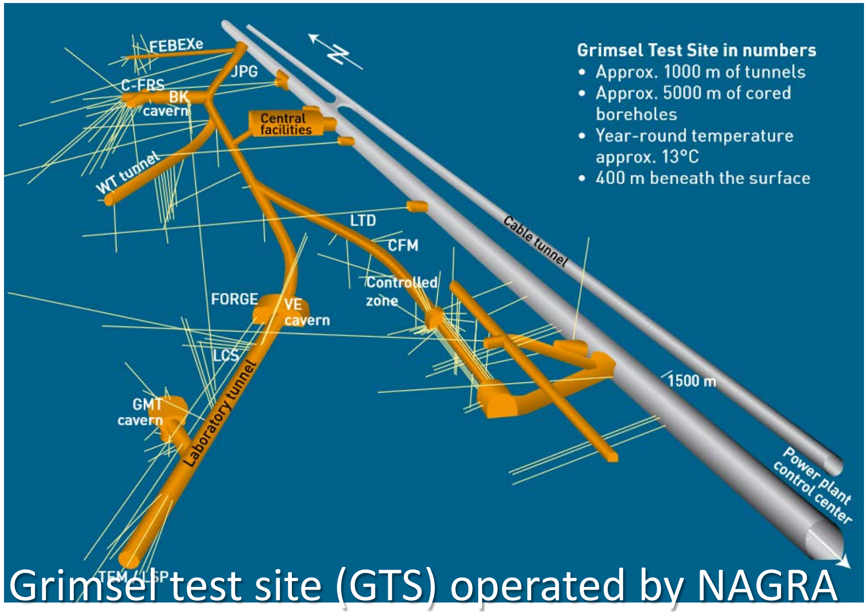
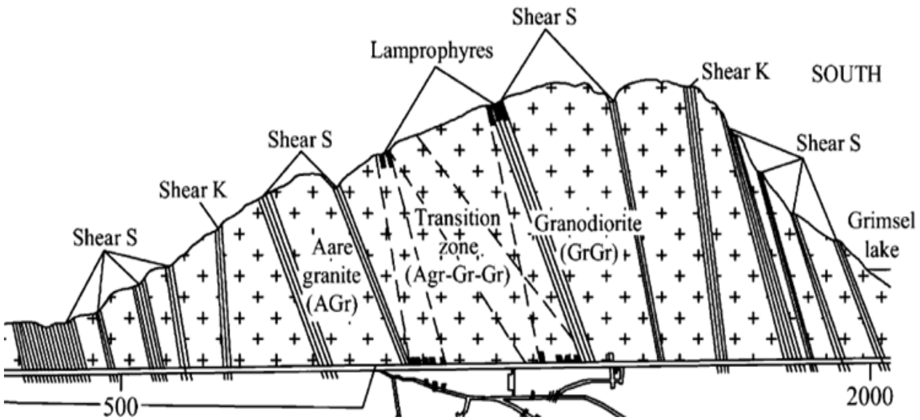
Selected material: the Grimsel granodiorite

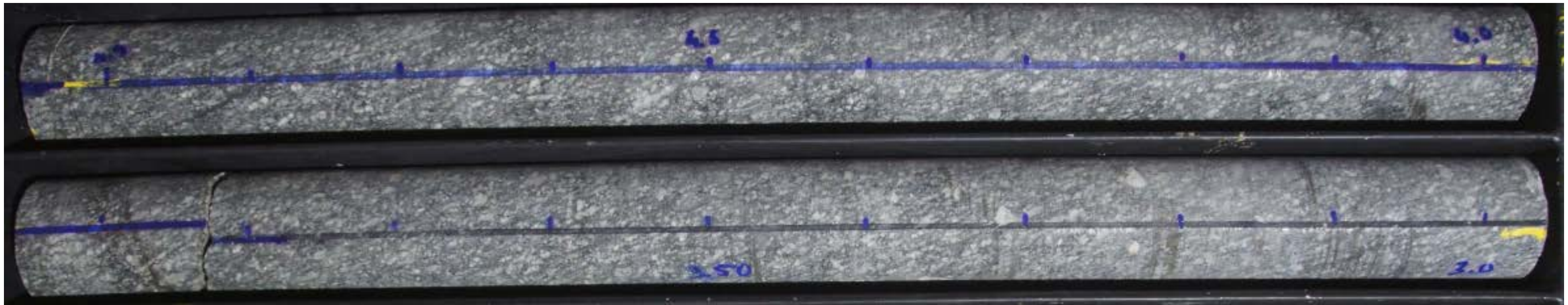


Grimsel test site (GTS) operated by NAGRA



Swiss project for implementing deep geothermal energy in Switzerland: 10 meters deep borehole drilled in a tunnel at GTS

→ Two one-meter-long fresh cores were provided for KG²B



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Selected material: the Grimsel granodiorite

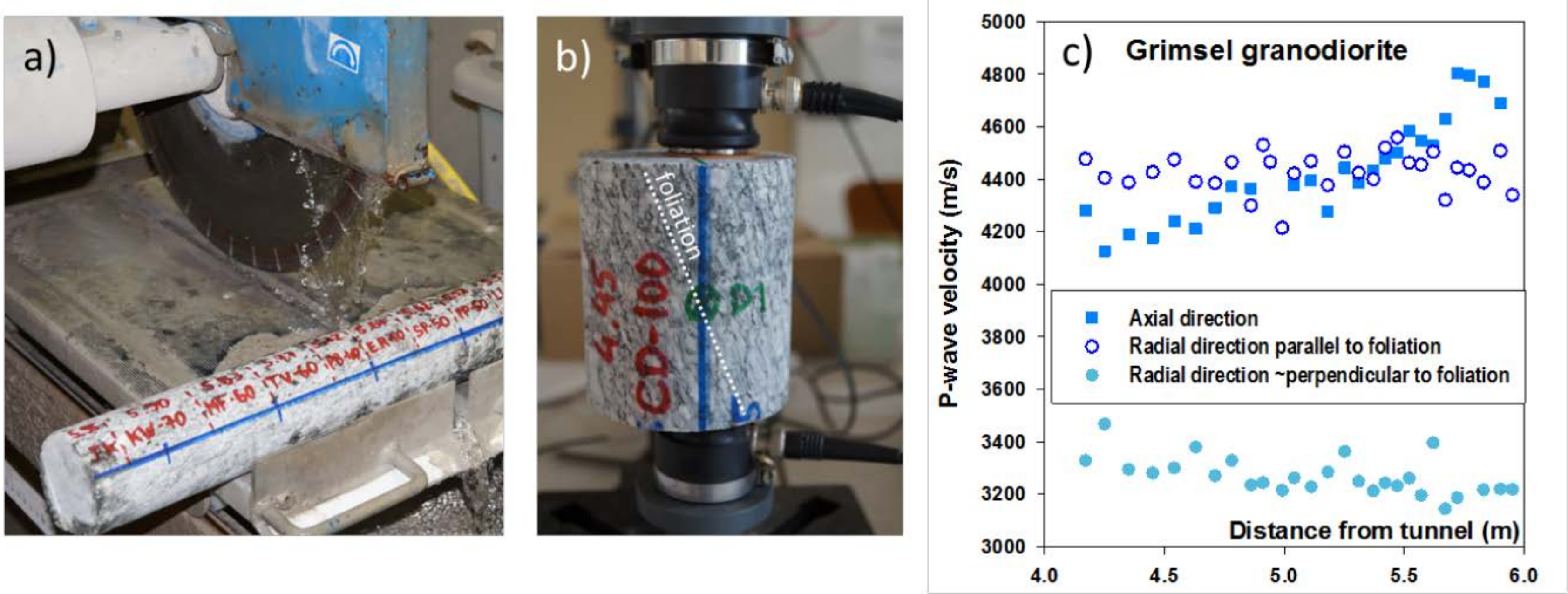

Figure 1. a) Cutting the core into small blocks; b) Measuring the P-wave velocity for quality check; c) P-wave velocity measurements in three orthogonal directions vs. distance from the tunnel.

The sample collection

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Management of the benchmark

Results spreadsheet ***Website: https://labo.u-cergy.fr/~kggb/***

SIZE OF SAMPLE FOR PERM MEASUREMENT :	
PERMEABILITY METHOD :	
PORE FLUID USED :	
SATURATION PROCEDURE :	
CONFINING PRESSURE DURING THE TEST (in MPa) :	
AVERAGE PORE PRESSURE DURING THE TEST (in MPa) :	
PORE PRESSURE DIFFERENCE (in MPa)	
TEMPERATURE :	
DURATION OF MEASUREMENT :	
MEASURED PERMEABILITY (in m²) :	
PRECISION OF MEASUREMENT (in m²) :	
MAIN SOURCES OF ERROR :	
EXTRA MEASUREMENTS DONE :	a)

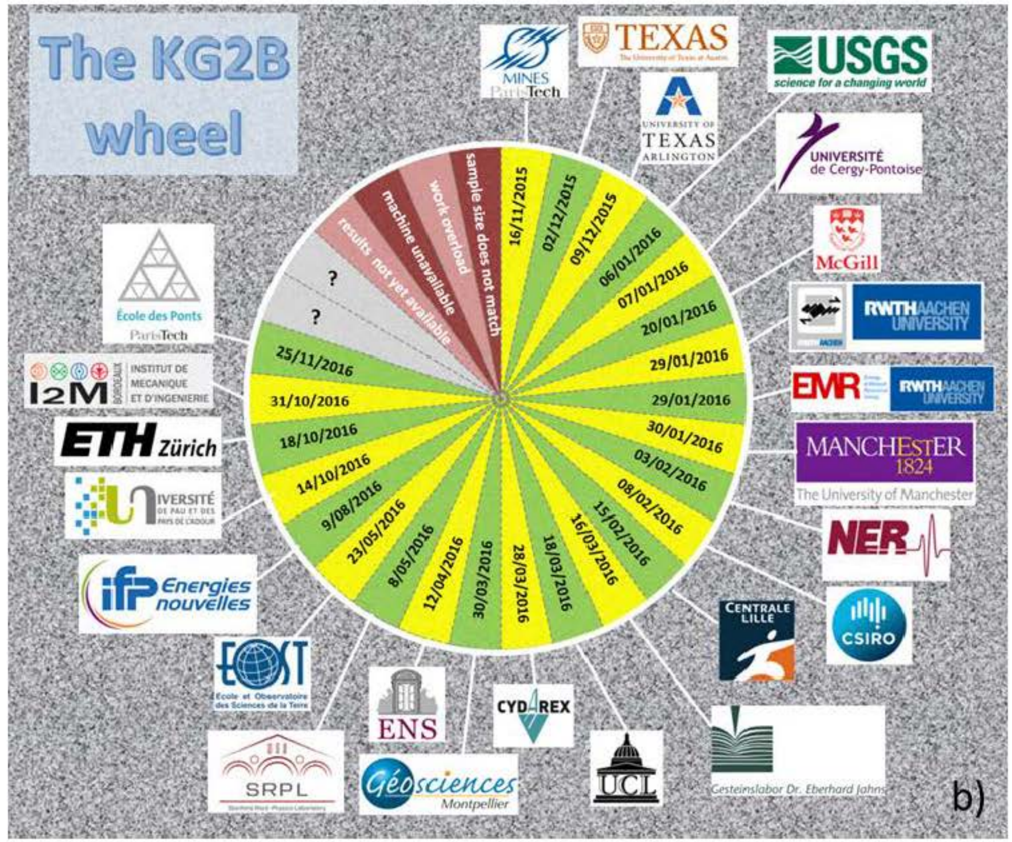

Figure 3. a) Result spreadsheet that each participant was requested to complete; b) The KG²B wheel with updated information on the benchmark progress.

Imposed effective confining pressure : 5 MPa

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Expected outcome of the benchmark

- *Comparison of the results for each method*
- *Comparison of the results from different methods*
- *Influence of experimental conditions (nature of fluid, stress and temperature control, sample size…)*
- *Accuracy of each technique*
- *Suggest « good practice » for low permeability measurements*

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Benchmark « profile »

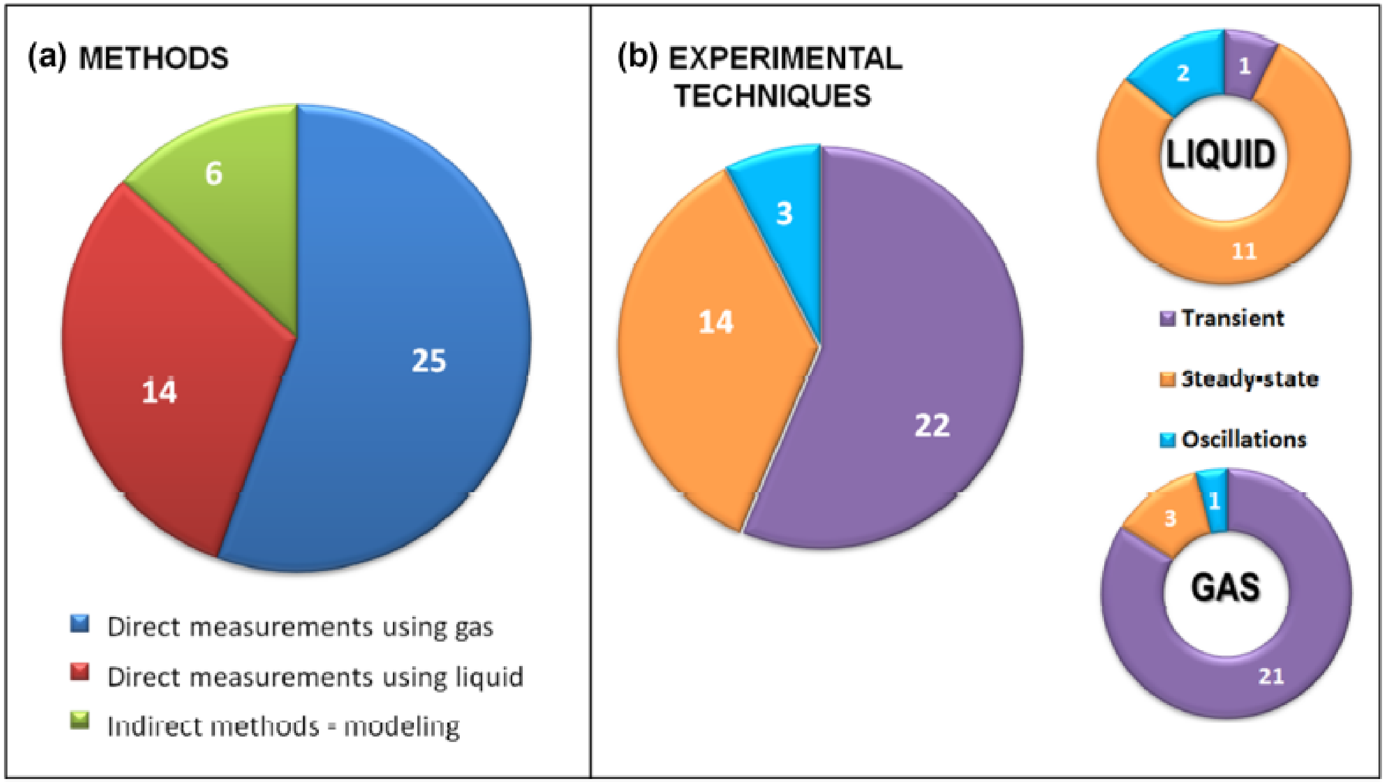

Figure 1. (a) Methods used in the benchmark and (b) techniques used for the experiments, global distribution (left) and distribution by working fluid type (right).

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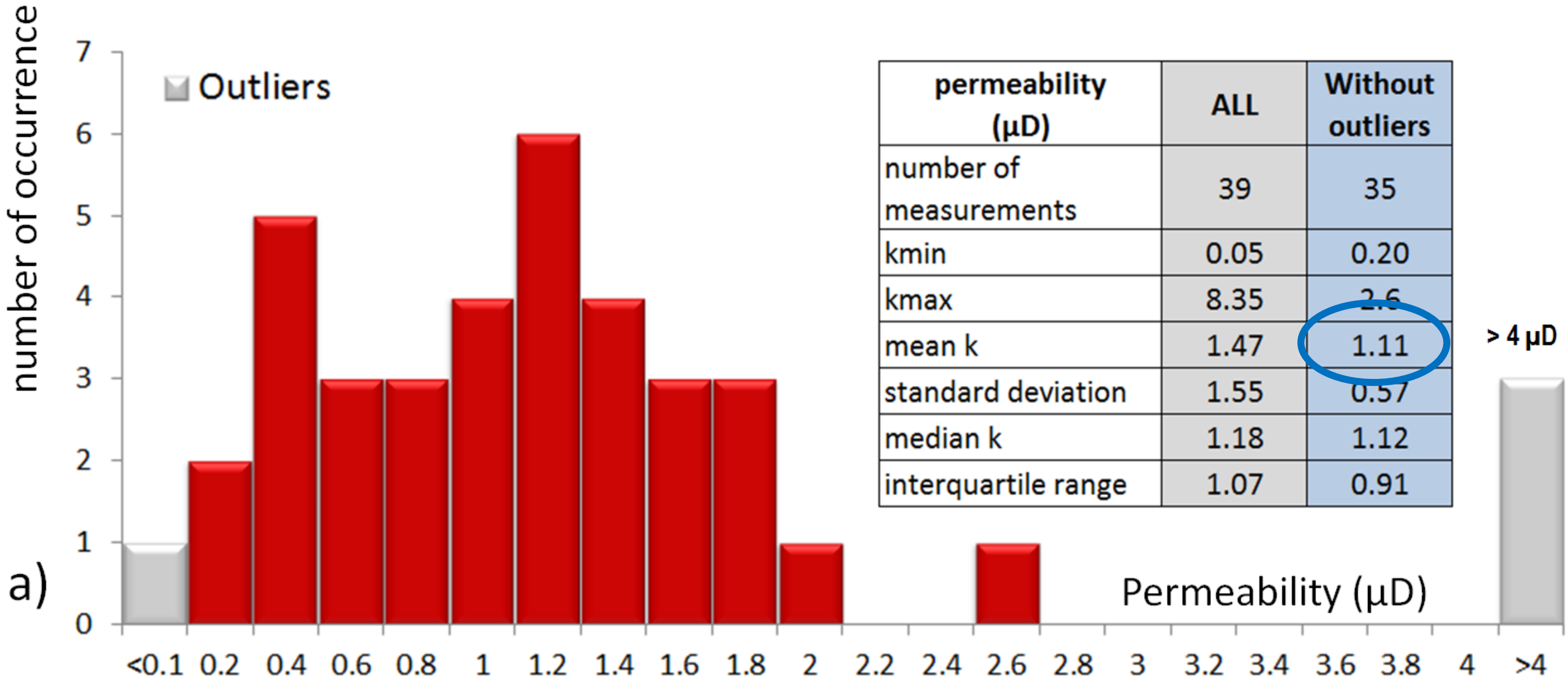
« Bulk » results



permeability (µD)	ALL	Without outliers
number of measurements	39	35
kmin	0.05	0.20
kmax	8.35	2.6
mean k	1.47	1.11
standard deviation	1.55	0.57
median k	1.18	1.12
interquartile range	1.07	0.91

Average permeability: 1.1 µD

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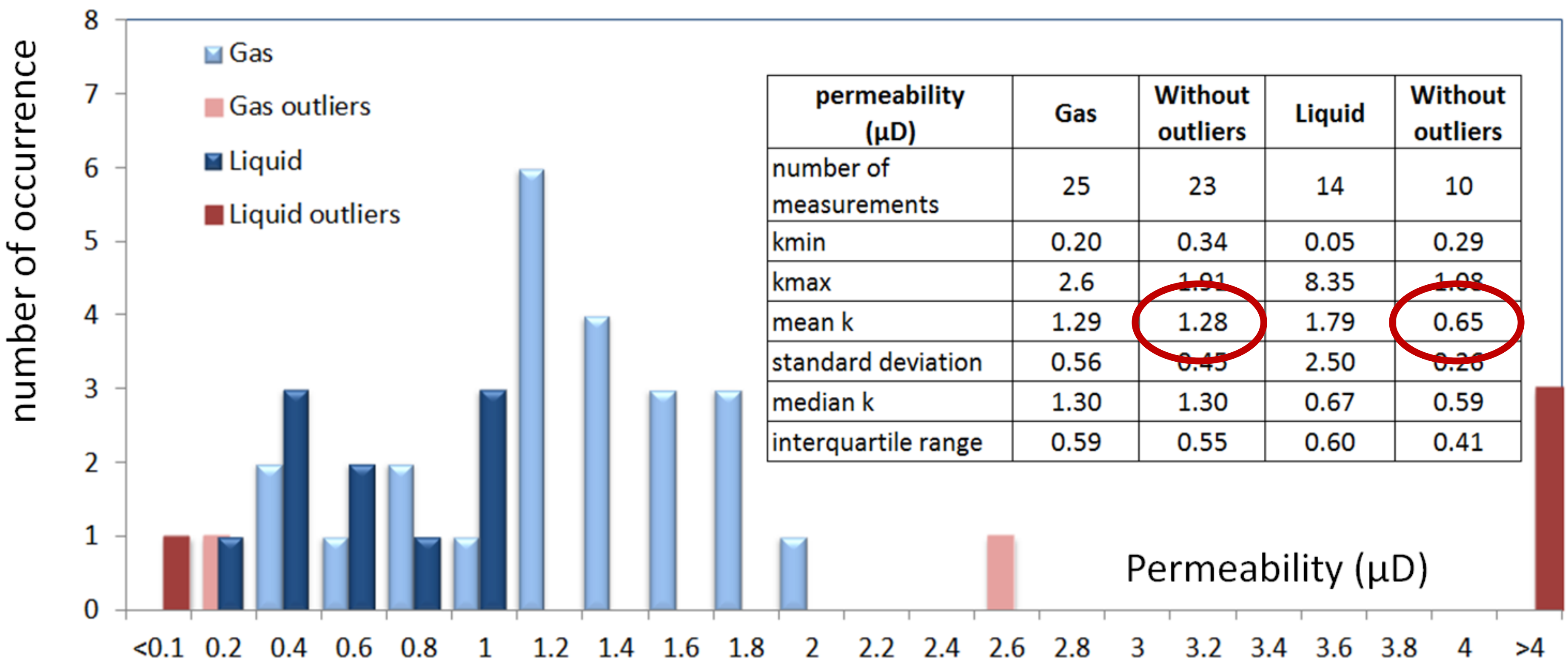
Influence of the pore fluid



permeability (µD)	Gas	Without outliers	Liquid	Without outliers
number of measurements	25	23	14	10
kmin	0.20	0.34	0.05	0.29
kmax	2.6	1.91	8.35	1.08
mean k	1.29	1.28	1.79	0.65
standard deviation	0.56	0.45	2.50	0.26
median k	1.30	1.30	0.67	0.59
interquartile range	0.59	0.55	0.60	0.41

Average Gas permeability ~ 2 x (Average Liquid permeability)

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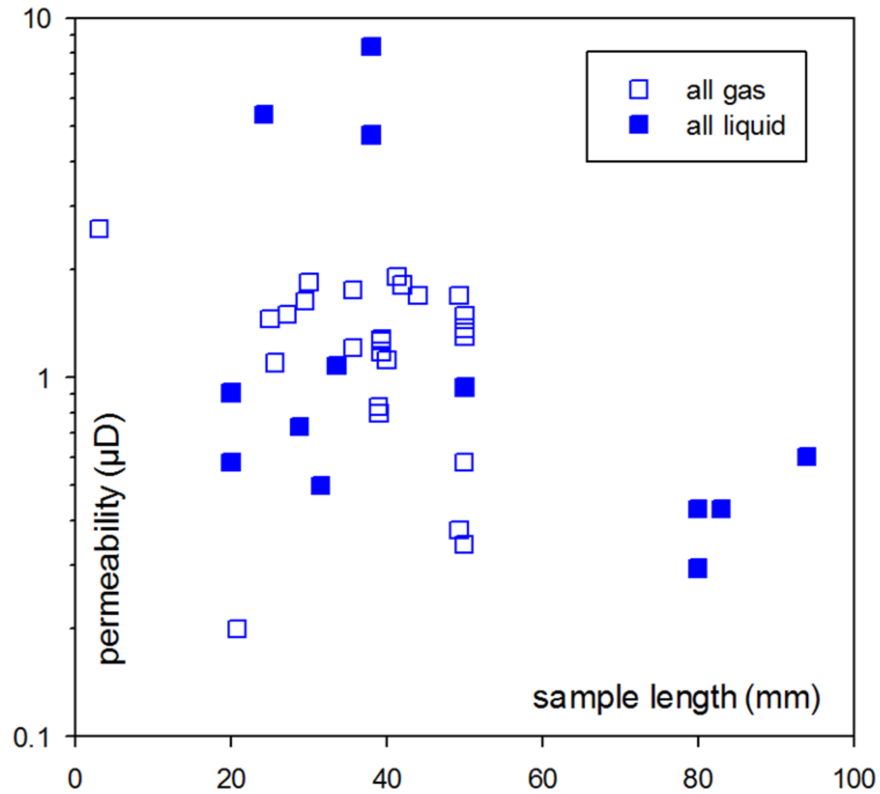
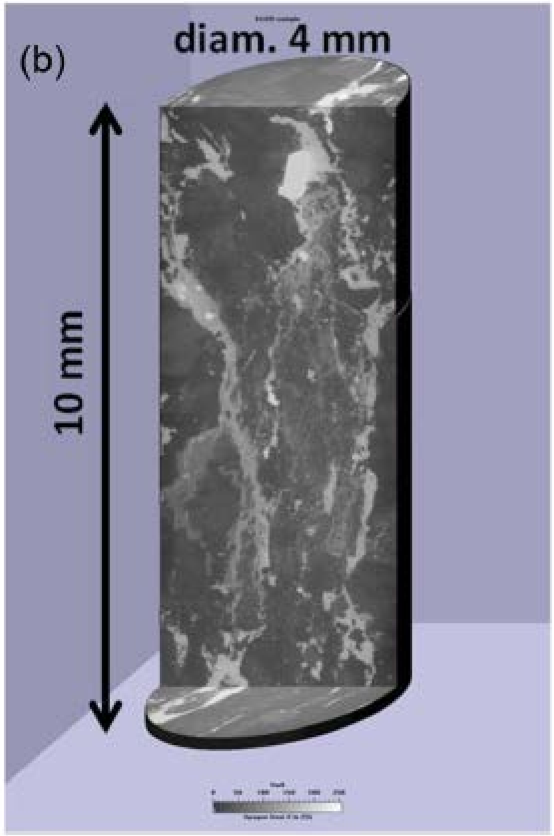
Influence of the sample size

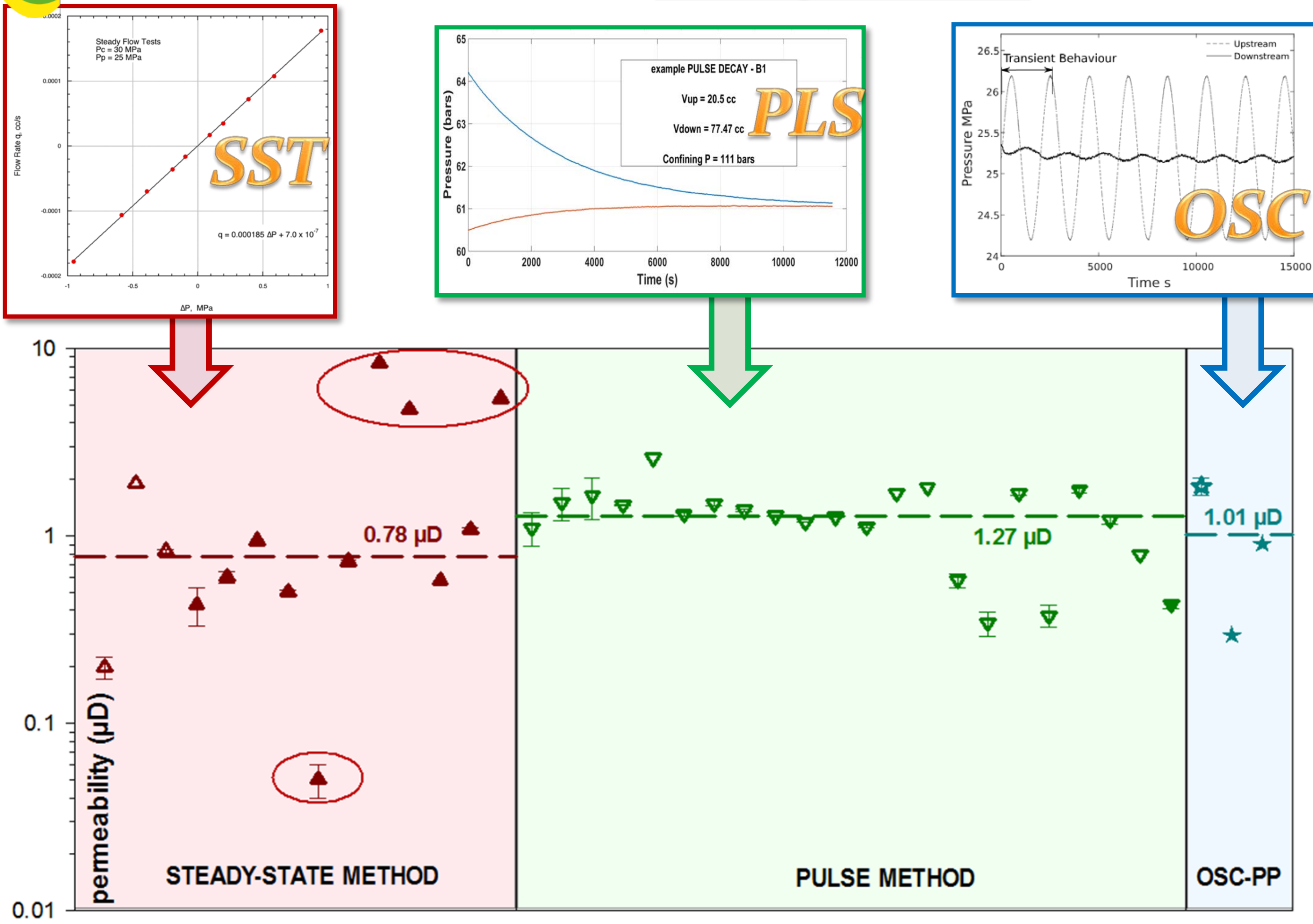




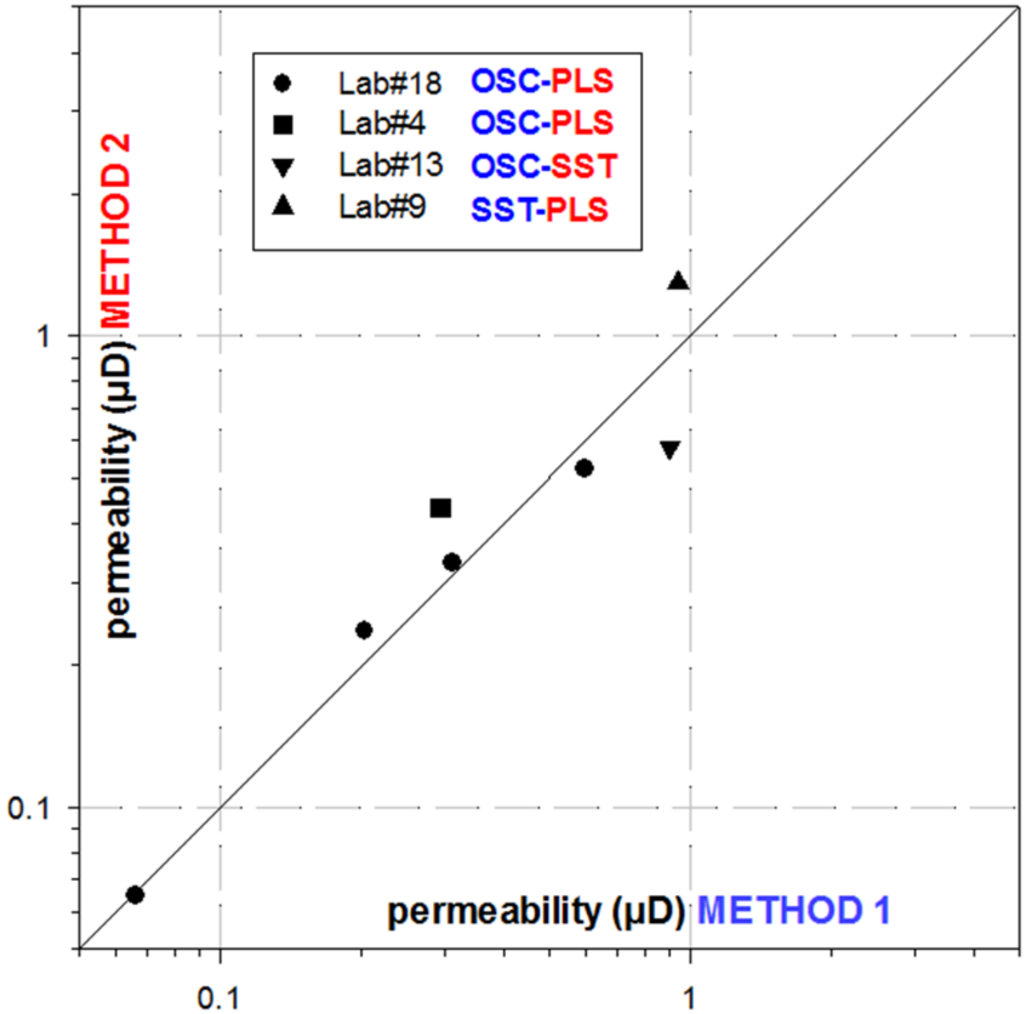
SIZE OF REV?

More scatter for smaller samples

Influence of the testing method



Influence of the testing method



Measurements on:

- the same sample
- with the same fluid
- using different methods

→ the same order is found

$$k_{SST} < k_{OSC} < k_{PLS}$$

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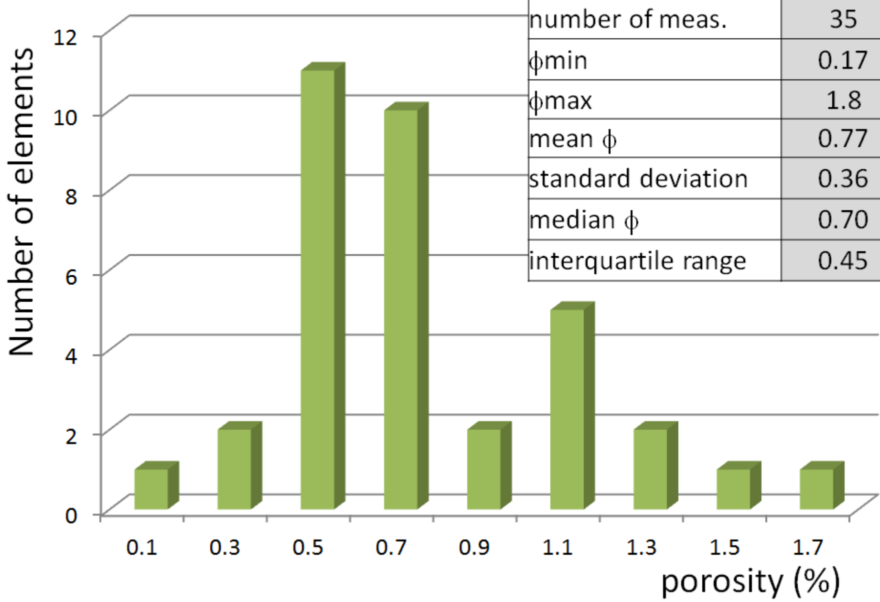
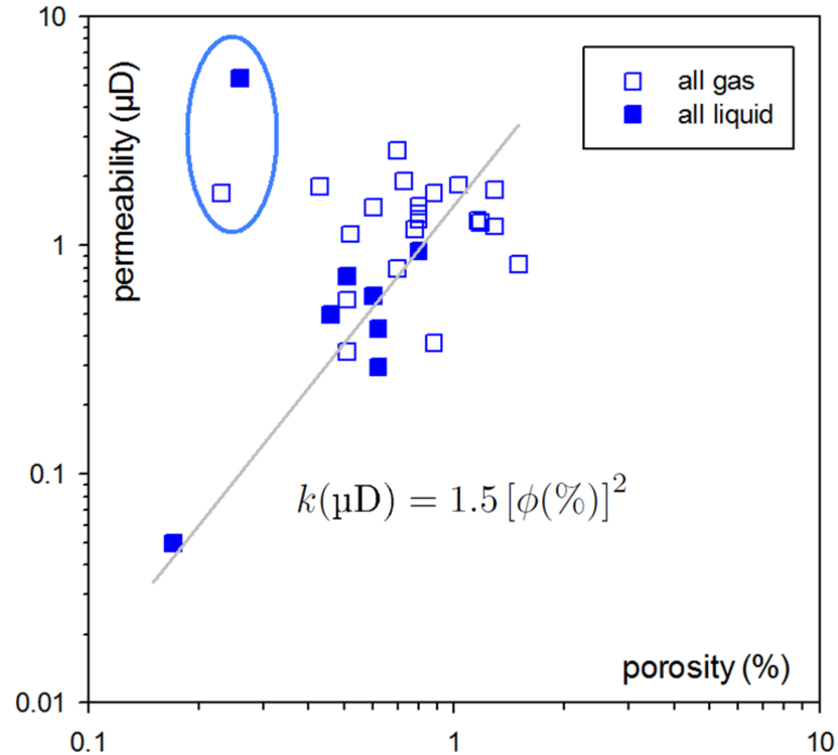
Influence of the porosity



porosity (%)	ALL
number of meas.	35
ϕmin	0.17
ϕmax	1.8
mean ϕ	0.77
standard deviation	0.36
median ϕ	0.70
interquartile range	0.45



porosity variability is not enough to explain permeability variability

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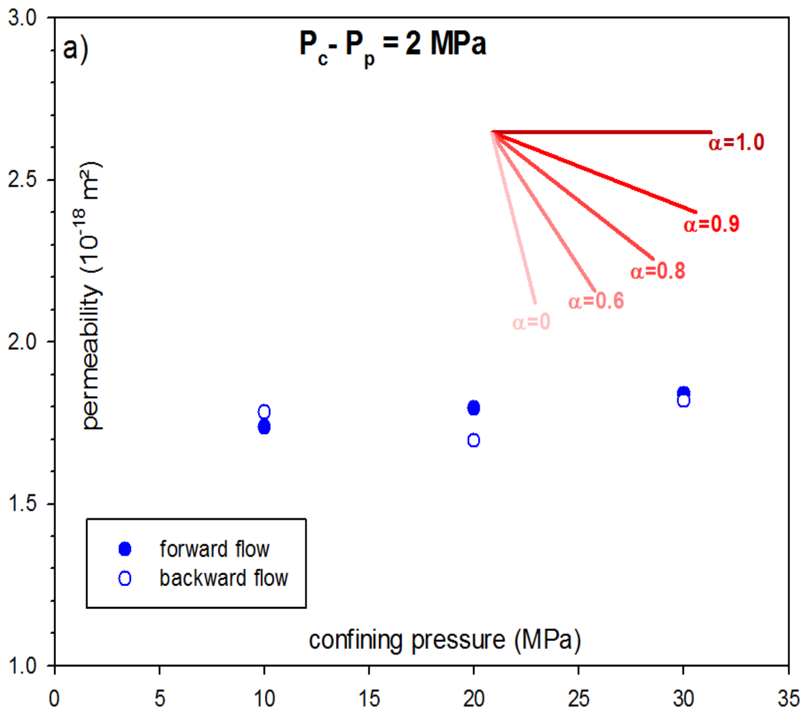
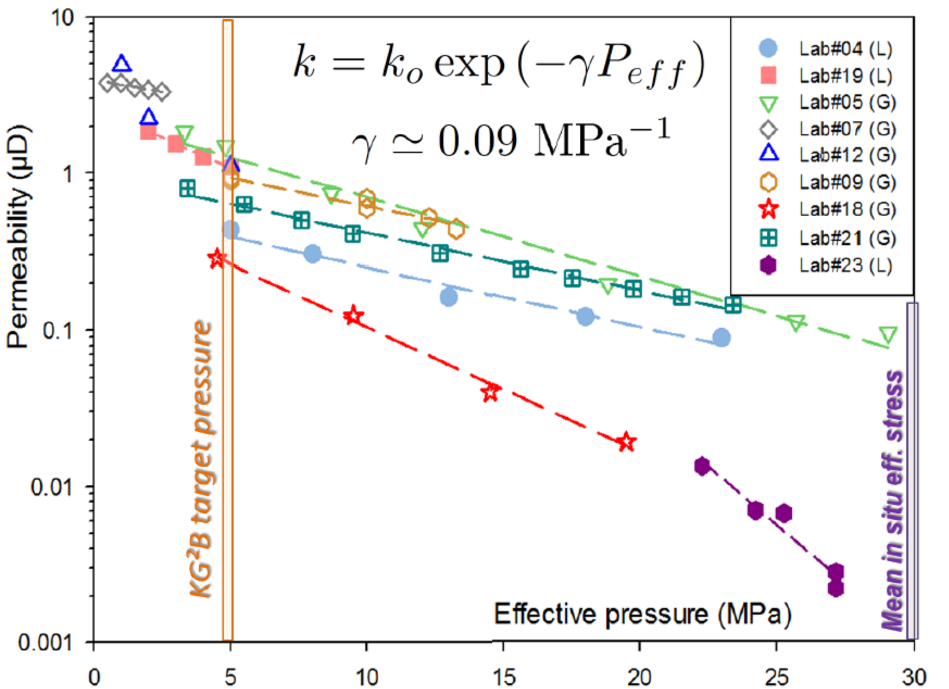
Pressure dependence of permeability

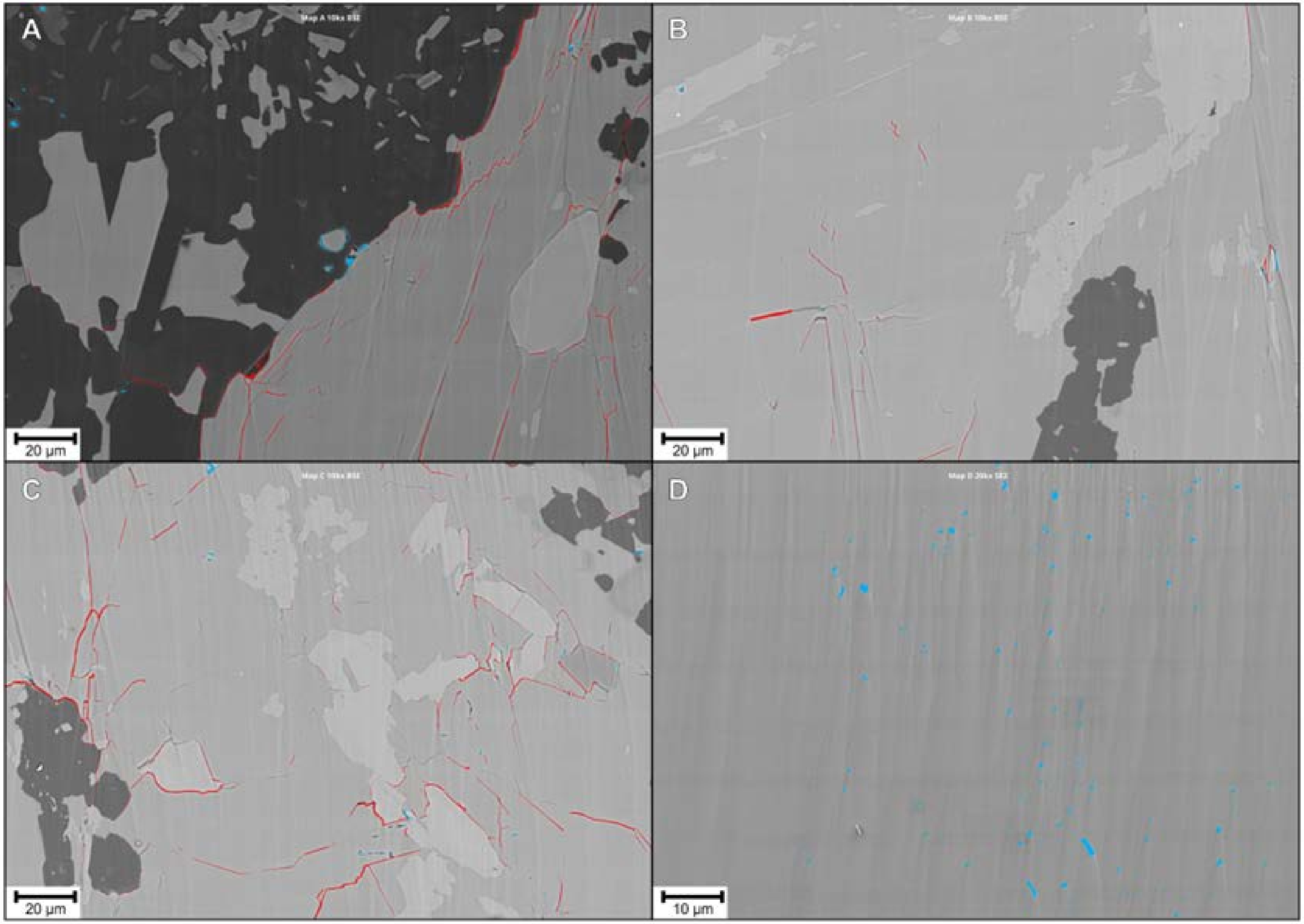




Effective pressure law:
Biot coefficient $\alpha = 1$

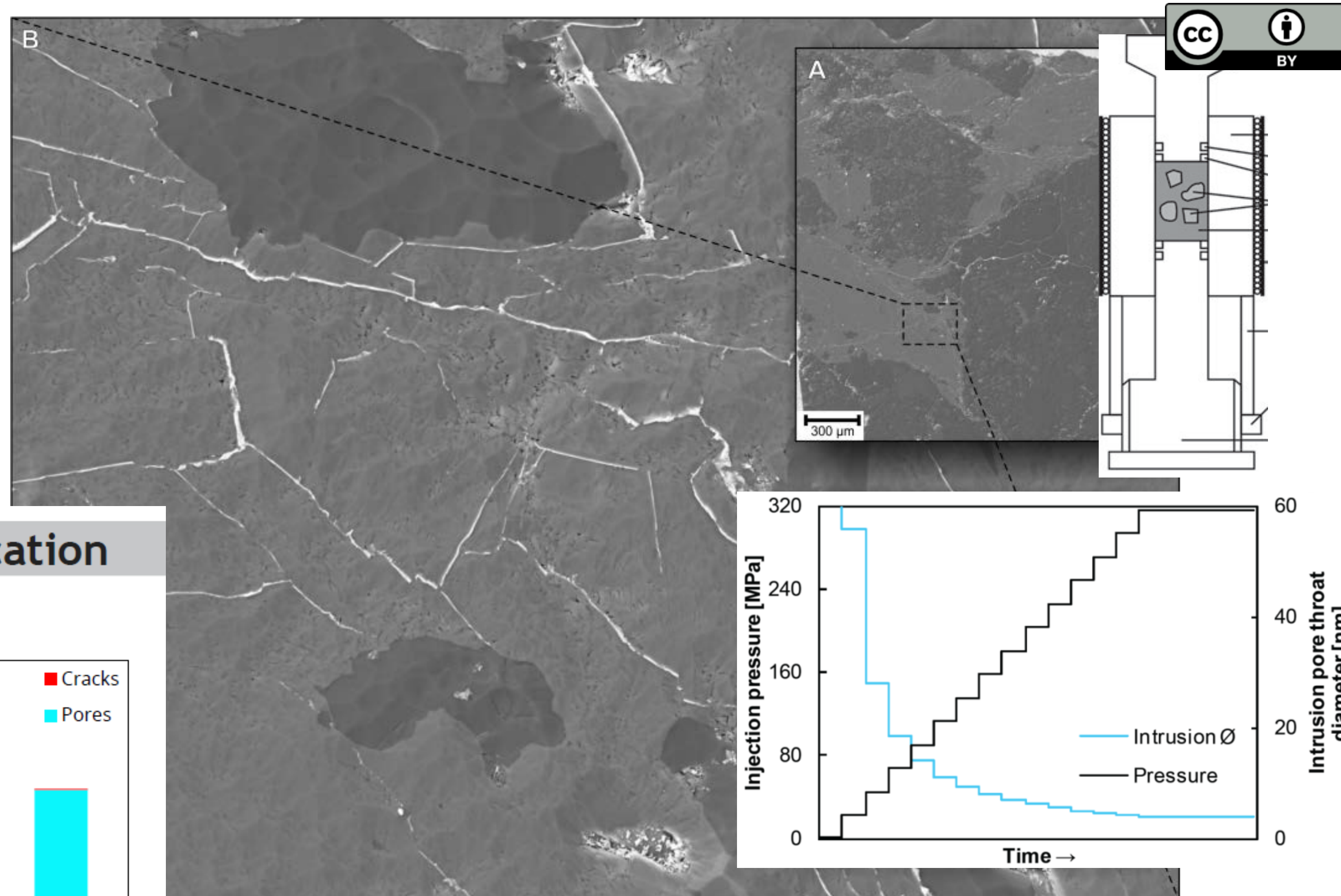
Exponential decrease of permeability with pressure

Microstructure analysis (BIB SEM)

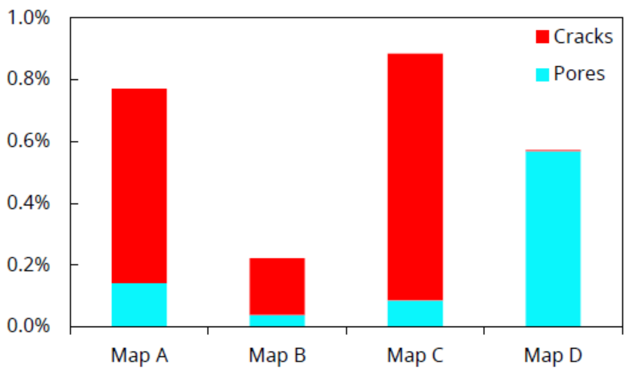


Backscattered Electron image maps with pore space segmentation
Interpreted cracks are in red and pores in cyan

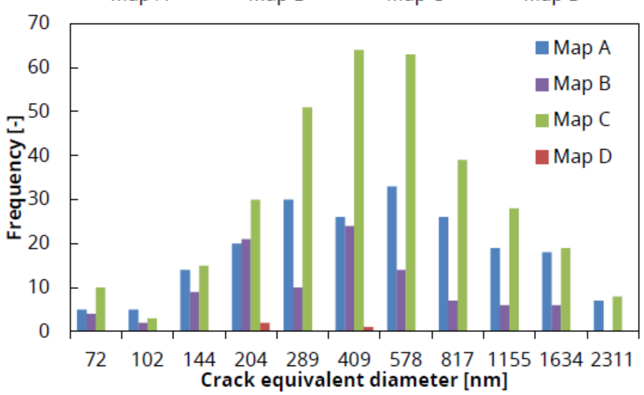
Microstructure analysis



BIB-SEM Pore quantification

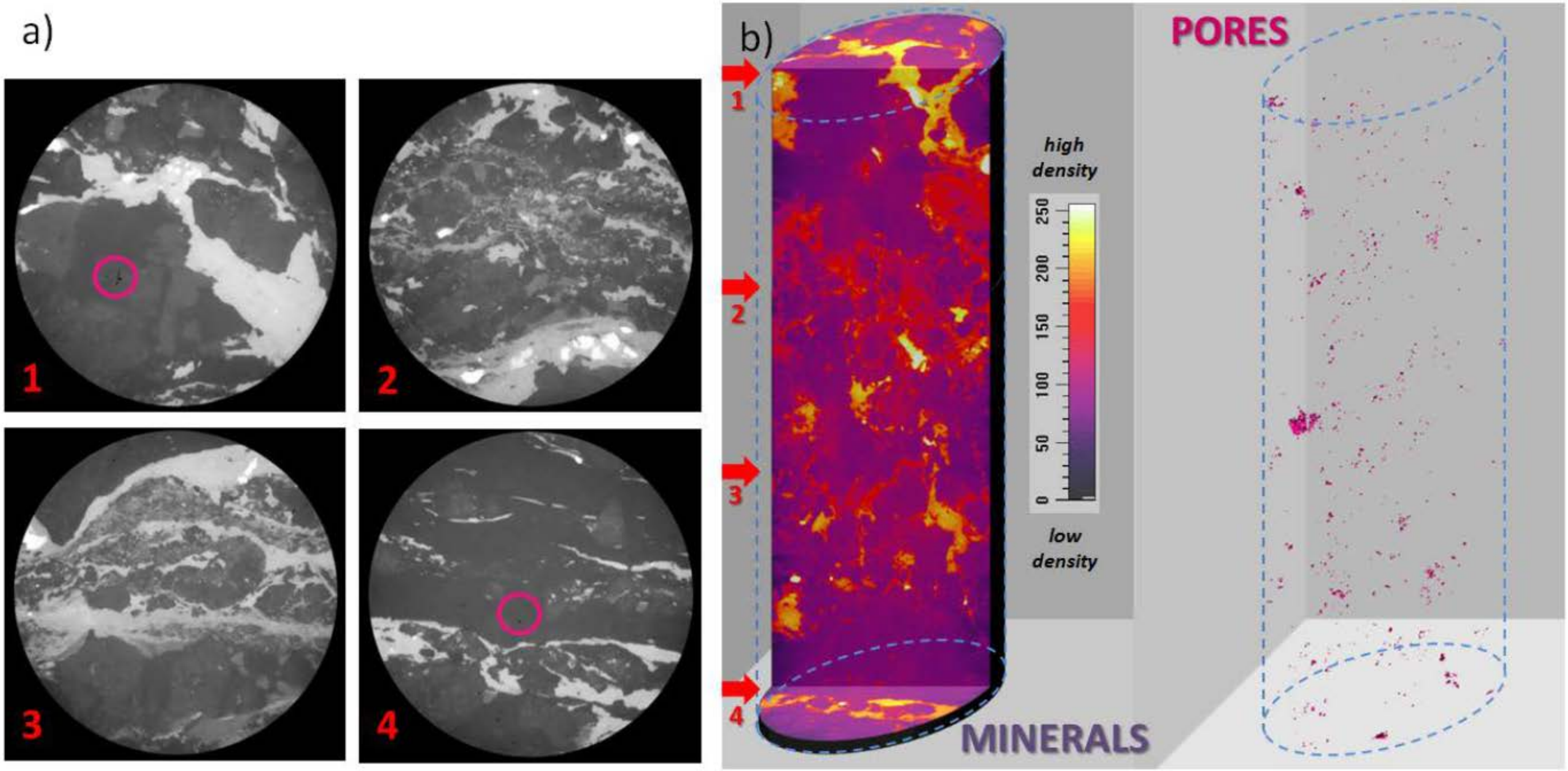


Wood's metal (in white) injection into cracks



Equivalent diameter distribution (in nm) for cracks and pores

Microstructure analysis



X ray microtomography

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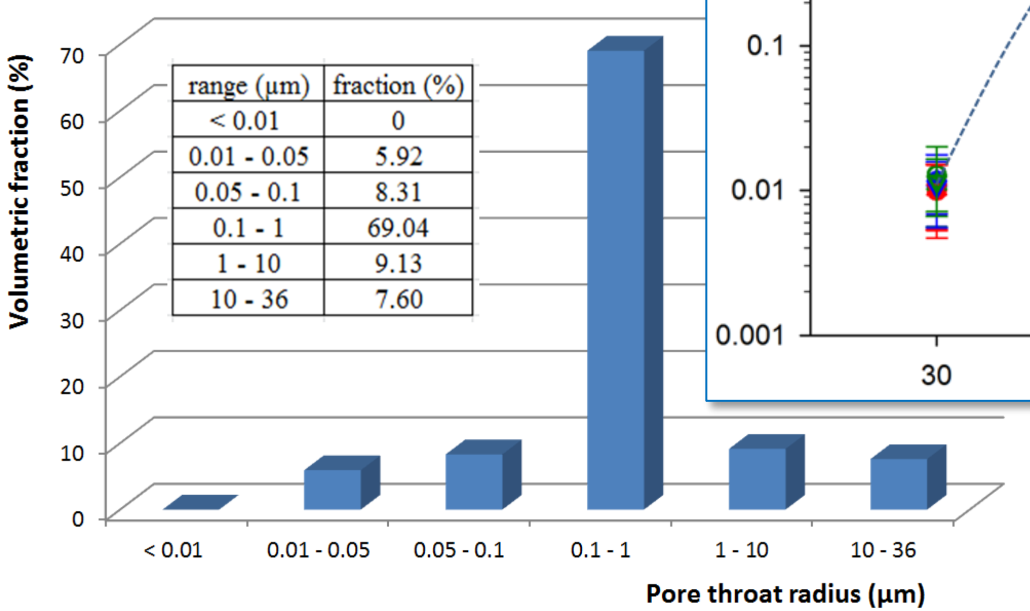
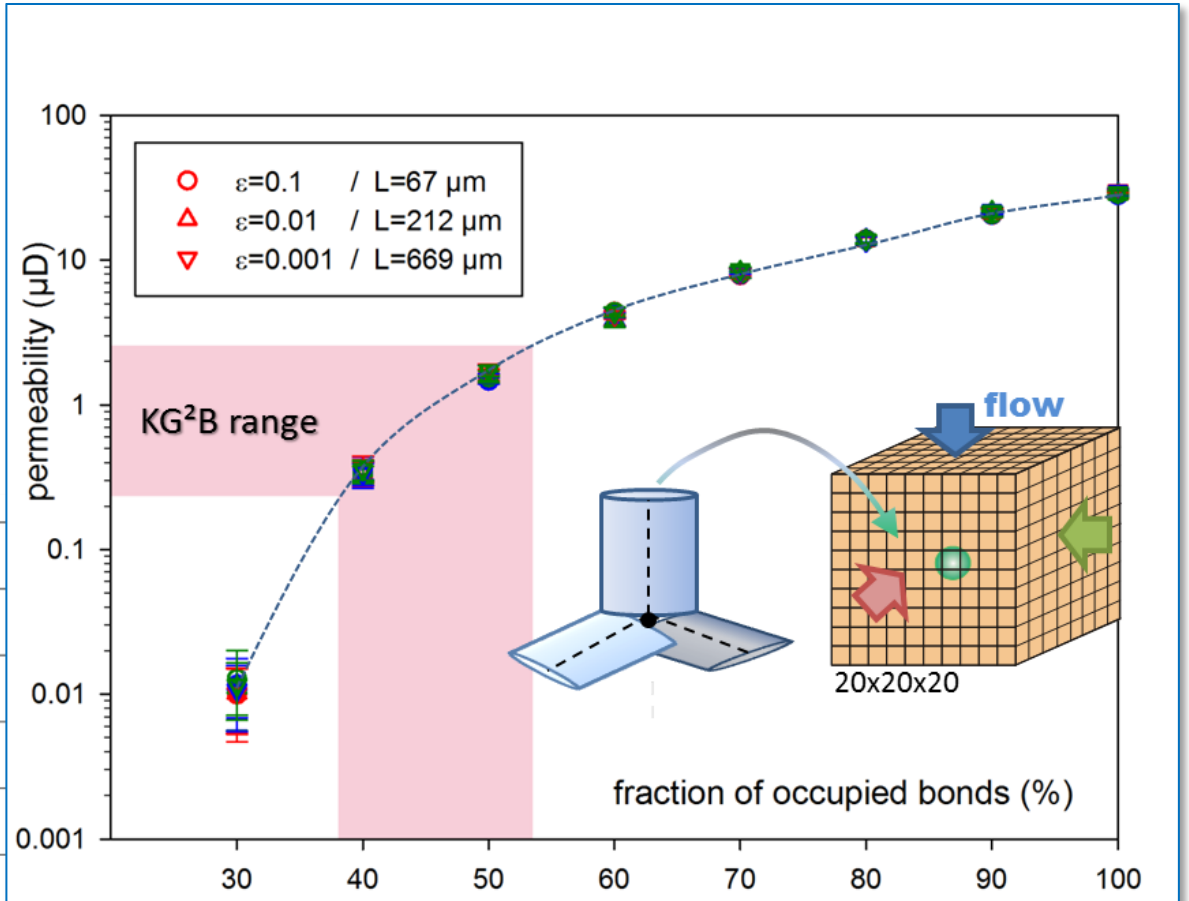
Pore network modelling of permeability

MICP pore throat size distribution



range (µm)	fraction (%)
< 0.01	0
0.01 - 0.05	5.92
0.05 - 0.1	8.31
0.1 - 1	69.04
1 - 10	9.13
10 - 36	7.60



coordination number
Z < 3

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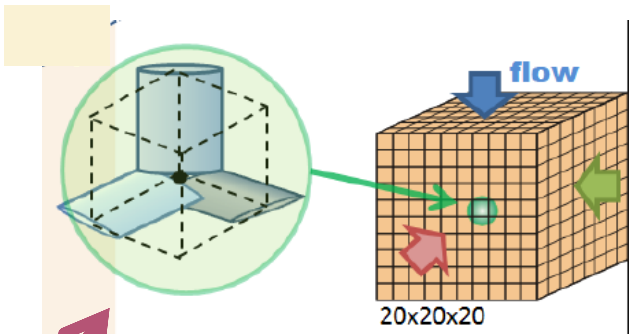
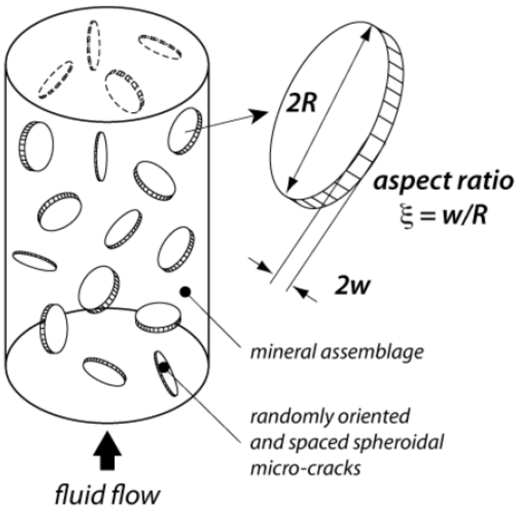
Permeability estimation from modelling

MODEL	DESCRIPTION	INPUT DATA	PERMEABILITY
Statistical model	3D array of orthogonal intersecting cracks	porosity, mean crack aperture	10 μD
Parallel fracture model (Zimmermann et al, 2005)	array of parallel fractures with the same aperture	linear density of fractures, mean aperture	28 μD
Percolation model (Katz & Thompson, 1986)	based on critical crack aperture at percolation	MICP volume vs. pressure data	1.1 μD
Free-fluid model (Coates et al, 1991)	permeability estimation from NMR relaxation time distr.	NMR T2 spectrum, porosity	1.3 - 5 μD
Pore network model (David, 1993)	3D network of pipes with elliptical cross-section	MICP pore size distribution, crack aspect ratio	100% bond: 28 μD 53% bond: 2.5 μD 38% bond: 0.25 μD
Effective medium model (Sarout et al, 2017)	random network of penny-shaped cracks	crack density, porosity, crack aperture	2.5 μD

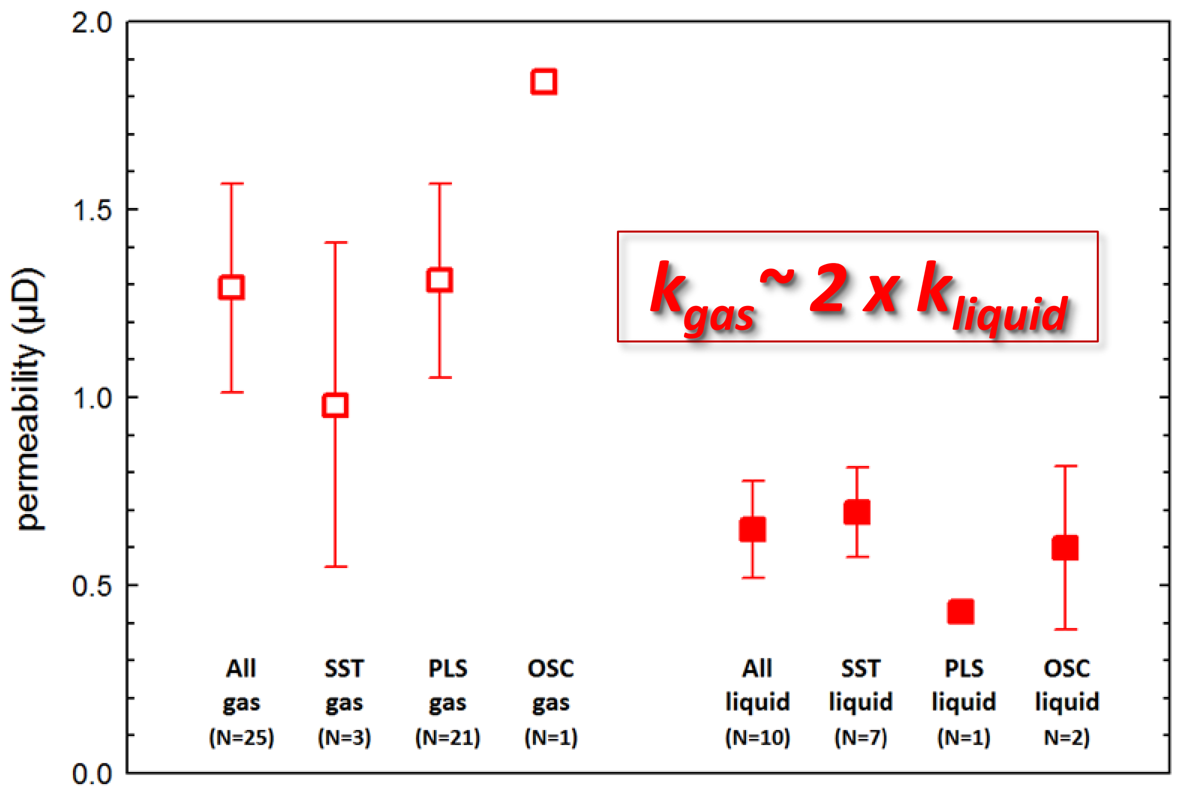


PNM – pore network model



Effective medium model

PUZZLING RESULT



WHY??

Possible explanations

- *k_{liquid} is **underestimated** because of <u>fluid-rock interactions</u>*
- *k_{gas} is **overestimated** because of « <u>insufficient » gas slippage correction</u>*

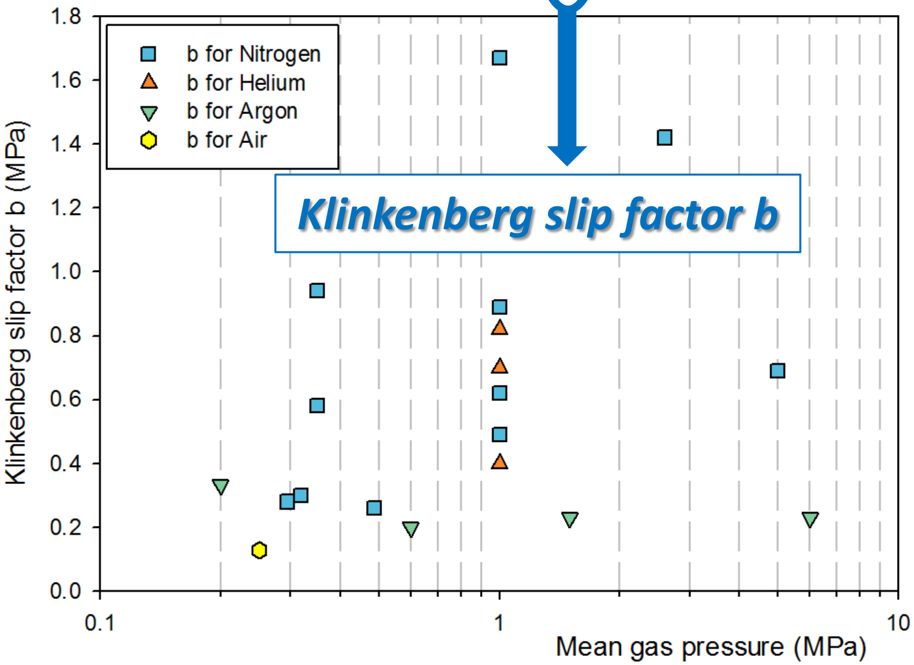
PUZZLING RESULT

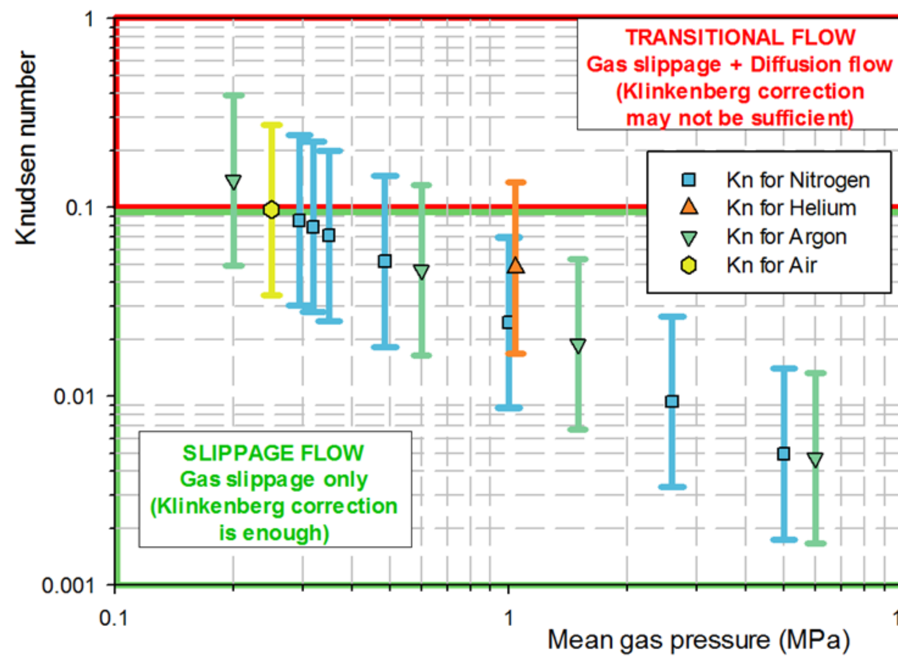
- *Is k_{gas} **overestimated** because of « insufficient » slippage correction?*

$$k_{gas} = k_{\infty}(1 + b/p_m)$$

Knudsen number

$$K_n = b/4p_m$$





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CONCLUSION

- *Collaborative project involving 24 laboratories around the world, measuring or modelling the permeability of a low permeability crystalline rock with different techniques*
- *All the participants did the job very thoroughly, but not always in due time…*
- *Unexpected results on a possible « pore-fluid effect » were found*
- *Contribution to identify « good practice » for low permeability measurements*
- *Cross-checking between different labs when unexpected values were found helped in identifying technical problems in perm measurement*

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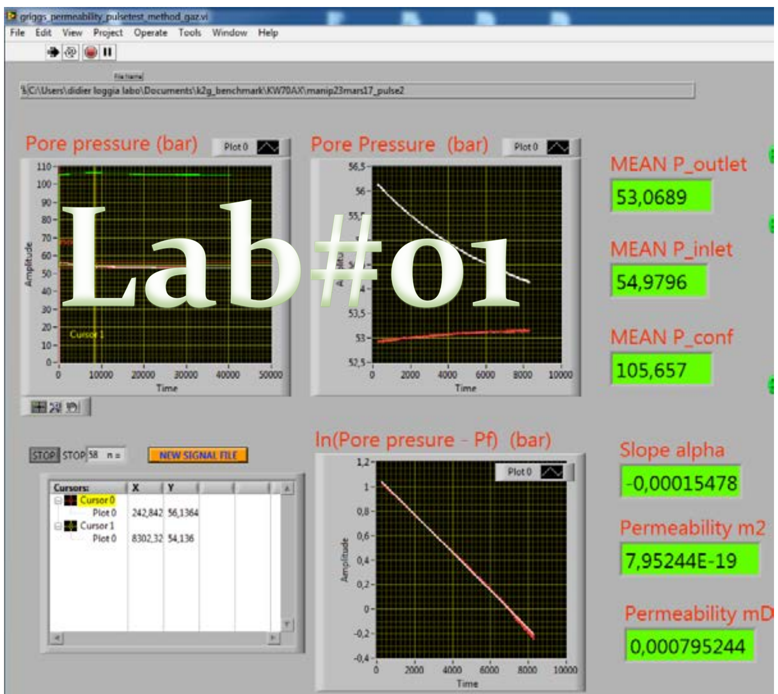
Example of cross-checking

LAB#	LOCATION (m)	SAMPLE LENGTH (mm)	SAMPLE DIAMETER (mm)	FLUID	METHOD	TEMPERATURE (°C)	DURATION	PERM@5_MPa (µD)	
Lab#22	5.9	39	25.4	Argon	PULSE	20 - 24	0.5h per step	34.9	these data are currently been checked because they fall out of the general trend
		38	25.4					35.2	
		38.9	25.4					12.0	

Lab#22

wrong values



Sample was sent to another lab

k=0.79 µD

Lab#22 found the problem (jacket leaks)

Finally KG²B was a

challenging,

exciting,

useful

and fun

thing to do

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GJI Rock and mineral physics, rheology

KG^{2}B, a collaborative benchmarking exercise for estimating the permeability of the Grimsel granodiorite – Part 1: measurements, pressure dependence and pore-fluid effects

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