KG²B, a world-wide inter-laboratory benchmark of low permeability measurement and modelling

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and the KG²B Team

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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 KG²B?

NO

Комитет государственной безопасности
Komitet Gossoudarstvennoi Bezopasnosti

K (permeability) for
Grimsel Granodiorite
Benchmark
The KG2B team

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Selected material: the Grimsel granodiorite

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*

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**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.

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**The sample collection**
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Management of the benchmark

Results spreadsheet

| SIZE OF SAMPLE FOR PERM MEASUREMENT: |     |
| PERMEABILITY METHOD: |     |
| POSE FLUID USED: |     |
| SATURATION PROCEDURE: |     |
| CONFINING PRESSURE DURING THE TEST (in MPa): |     |
| AVERAGE PORE PRESSURE DURING THE TEST (in MPa): |     |
| POSE 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) |

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

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

Average permeability: 1.1 µD
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Influence of the pore fluid

Average Gas permeability \( \sim 2 \times \) (Average Liquid permeability)
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Influence of the sample size

More scatter for smaller samples

SIZE OF REV?
Influence of the testing method

- SST
- PLS
- OSC

Steady Flow Tests
Pc = 10 MPa
Py = 23 MPa

$q = 0.000185 DP + 7.0 \times 10^{-5}$

Pressure (bars)

Time (s)

Confining P = 111 bars

V_sp = 20.5 cc
V_down = 77.47 cc

Transient Behaviour

Pressure MPa

Time s

Transmissibility (μD)

STEADY-STATE METHOD

PULSE METHOD

OSC-PP

0.01

0.1

1

10

0.78 μD

1.27 μD

1.01 μD
Influence of the testing method

Measurements on:

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

→ the same order is found

\[ k_{\text{SST}} < k_{\text{OSC}} < k_{\text{PLS}} \]
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Influence of the porosity

<table>
<thead>
<tr>
<th>porosity (%)</th>
<th>ALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of meas.</td>
<td>35</td>
</tr>
<tr>
<td>$\phi_{\text{min}}$</td>
<td>0.17</td>
</tr>
<tr>
<td>$\phi_{\text{max}}$</td>
<td>1.8</td>
</tr>
<tr>
<td>mean $\phi$</td>
<td>0.77</td>
</tr>
<tr>
<td>standard deviation</td>
<td>0.36</td>
</tr>
<tr>
<td>median $\phi$</td>
<td>0.70</td>
</tr>
<tr>
<td>interquartile range</td>
<td>0.45</td>
</tr>
</tbody>
</table>

$k(\mu D) = 1.5 [\phi(\%)]^2$

porosity variability is not enough to explain permeability variability
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Pressure dependence of permeability

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

$$k = k_0 \exp \left(-\gamma P_{\text{eff}}\right)$$
$$\gamma \approx 0.09 \text{ MPa}^{-1}$$

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

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

<table>
<thead>
<tr>
<th>range (μm)</th>
<th>fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.01</td>
<td>0</td>
</tr>
<tr>
<td>0.01 - 0.05</td>
<td>5.92</td>
</tr>
<tr>
<td>0.05 - 0.1</td>
<td>8.31</td>
</tr>
<tr>
<td>0.1 - 1</td>
<td>69.04</td>
</tr>
<tr>
<td>1 - 10</td>
<td>9.13</td>
</tr>
<tr>
<td>10 - 36</td>
<td>7.60</td>
</tr>
</tbody>
</table>

coordination number $Z < 3$
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Permeability estimation from modelling

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

PNM – pore network model

Effective medium model
PUZZLING RESULT

Possible explanations

- $k_{\text{liquid}}$ is underestimated because of fluid-rock interactions
- $k_{\text{gas}}$ is overestimated because of « insufficient » gas slippage correction
Is $k_{\text{gas}}$ overestimated because of « insufficient » slippage correction?

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

$K_{\text{n}} = b/4p_m$
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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
### Example of cross-checking

<table>
<thead>
<tr>
<th>LAB#</th>
<th>LOCATION (m)</th>
<th>SAMPLE LENGTH (mm)</th>
<th>SAMPLE DIAMETER (mm)</th>
<th>FLUID</th>
<th>METHOD</th>
<th>TEMPERATURE (°C)</th>
<th>DURATION</th>
<th>PERM@5 MPa (μD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab#22</td>
<td>5.9</td>
<td>39</td>
<td>25.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>38</td>
<td>25.4</td>
<td>Action</td>
<td>PULSE</td>
<td>20 - 24</td>
<td>0.5h per step</td>
<td>34.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>38.9</td>
<td>25.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>35.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12.0</td>
</tr>
</tbody>
</table>

These data are currently been checked because they fall out of the general trend.

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**Lab#01**

Sample was sent to another lab

**Lab#22**

Found the problem (jacket leaks)

\[ k = 0.79 \, \mu\text{D} \]
Finally KG²B was a challenging, exciting, useful and fun thing to do
KG²B, a collaborative benchmarking exercise for estimating the permeability of the Grimsel granodiorite – Part 1: measurements, pressure dependence and pore-fluid effects


https://doi:10.1093/gji/ggy304
KG$^2$B, a collaborative benchmarking exercise for estimating the permeability of the Grimsel granodiorite—Part 2: modelling, microstructures and complementary data


https://doi:10.1093/gji/ggy305
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