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Supplement of

Investigation of Percolation-Driven Fluid Transport in Rock Salt under Repository-Relevant Conditions (PeTroS)

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Institut für Gebirgsmechanik GmbH, Leipzig

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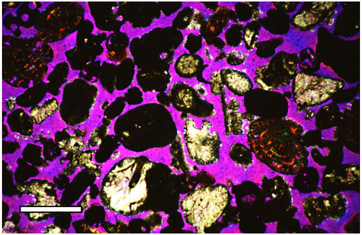
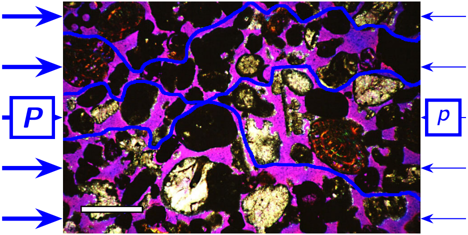
Rock Salt is Impermeable



[limestone, J. Stuby]

Rock Salt is Impermeable



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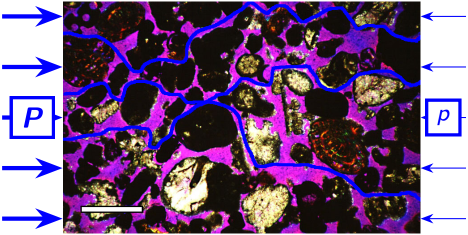

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Recall porous medium:

- ➢ Preexisting connected porosity
- ➢ Darcy's law: flow $\sim \kappa \cdot \Delta P$
- ➢ Permeability κ is material constant

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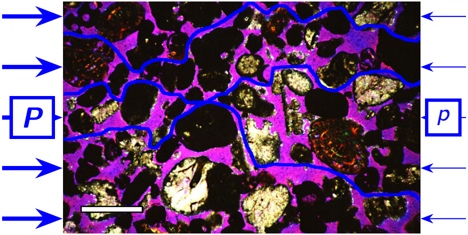

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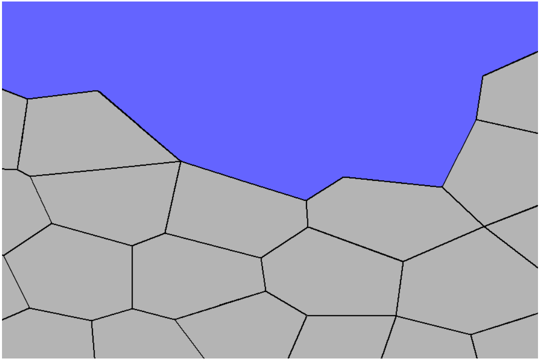

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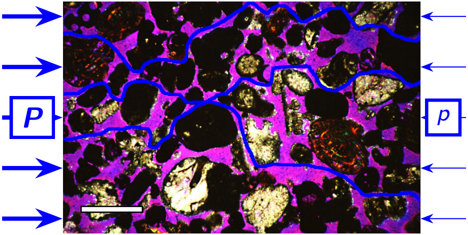

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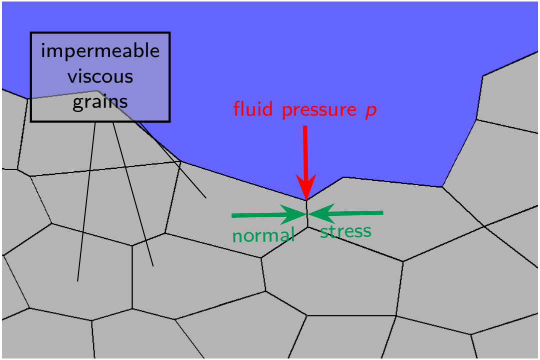

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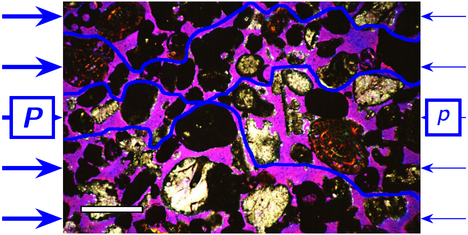

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Recall porous medium:

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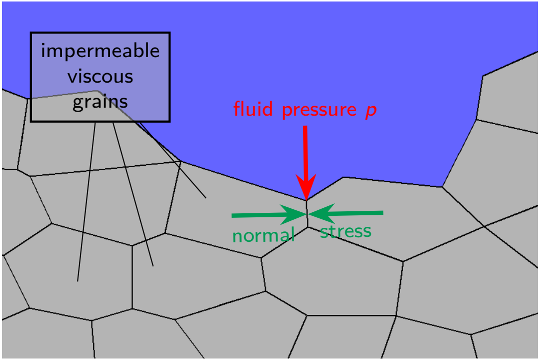
Rock Salt:

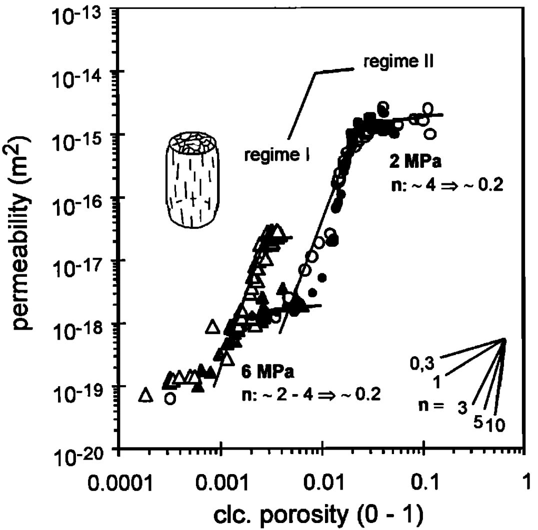
- Polycrystaline viscous material
- No connected pore space
- Darcy's law doesn't apply (or $\kappa = 0$)



Mechanical Damage – Dilatancy Criterion

Stresses exceeding dilatancy boundary or tensile strength

- ⇝ Damage, (micro)fractures, dilatancy
- ⇝ secondary porosity
- ⇝ permeability
- ⇝ mostly in vicinity of openings (EDZ)



[Popp et al. 2001]

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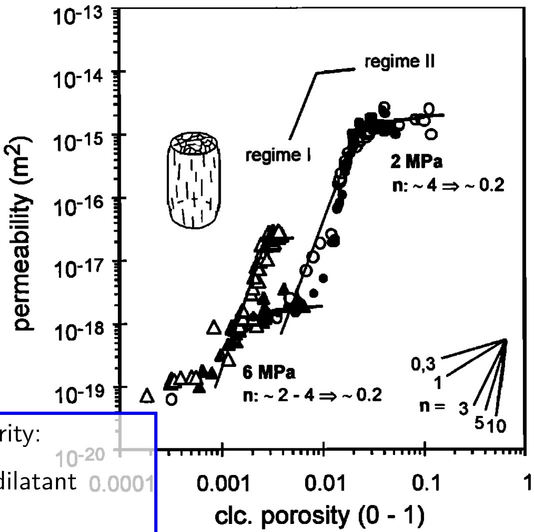

[Popp et al. 2001]

Dilatancy criterion for barrier integrity:

- ➢ require sufficiently thick non-dilatant barrier
- ➢ relevant for drift seals etc.

Pressure-Driven Percolation

- Fluid can open grain boundaries if pressure is high enough
- Possible in undamaged rock salt
- Relevant for geological barriers due to large-scale (thermo-)mechanical stress redistributions

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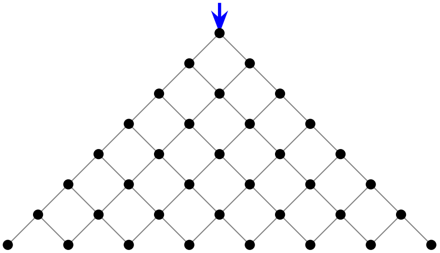

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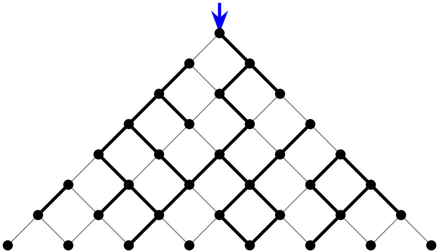

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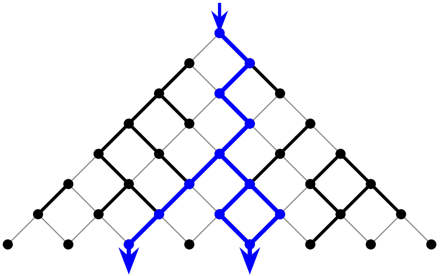

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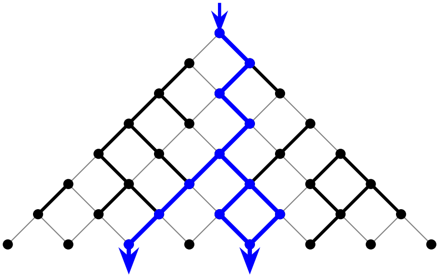

Pressure-driven percolation:

- threshold $p_{\mathrm{fl,crit}} \approx \sigma_{\mathrm{min}}$ in fluid pressure
- directed fluid motion

Pressure-Driven Percolation

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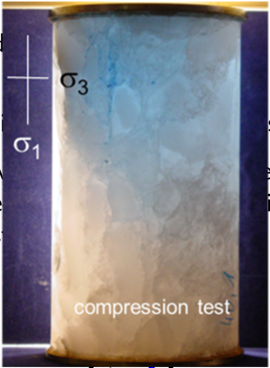
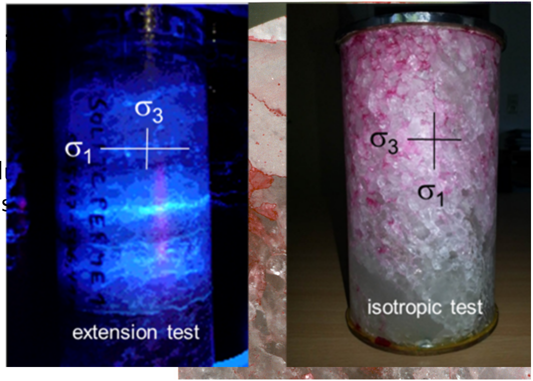
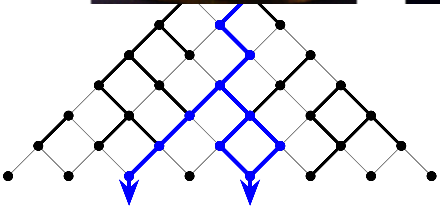
  high
- Possi salt
- Relev ers d
  large ical s
  redis







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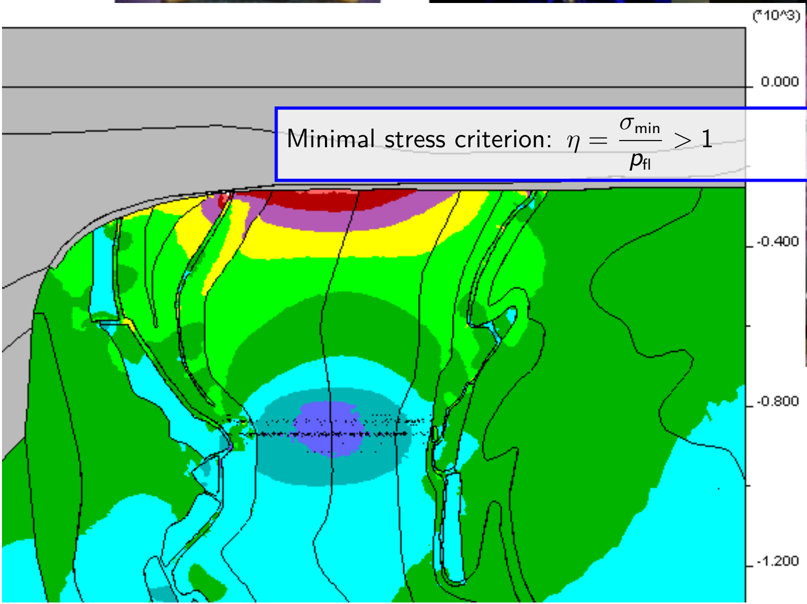


Minimal stress criterion: $\eta = \dfrac{\sigma_{\mathrm{min}}}{p_{\mathrm{fl}}} > 1$

:

in fluid

Hypothetical Mechanisms

p, *T* [Lewis, Holness '96; Ghanbarzadeh et al. '15]

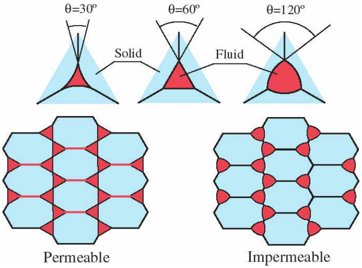
$\rightsquigarrow$ halite-brine dihedral angle

$\rightsquigarrow$ pore network connectivity

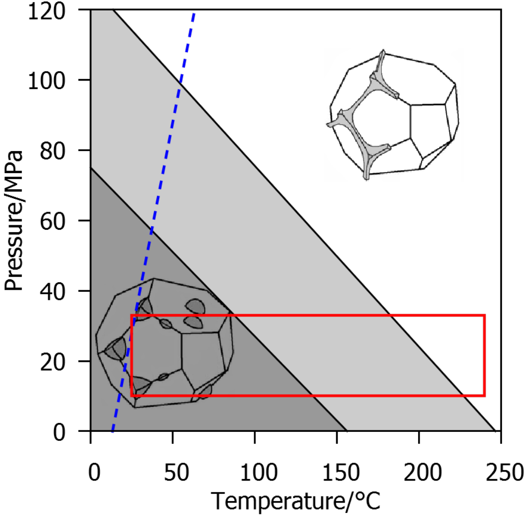
permeable for $\theta < 60°$

" similar to [. . .] sandstones",

"at any porosity"

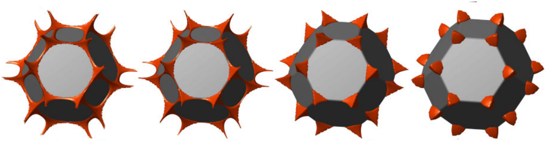


P. Rey



Experimental Basis

- ➢ No measuements of permeability
- ➢ Measurement of dihedral angle in synthetic salt after undrained compaction
- ➢ Fully isotropic: $p_{\text{fl}} = \sigma_{\text{min}} = \sigma_{\text{max}}$
- ⇒ No creep
- ⇒ System exactly at percolation threshold ($\eta = 1$)
- ⇒ Not possible on barrier scale due do different gradients (brine/rock)



Deformation-Driven Percolation

[Ghanbarzadeh et al. '15]

Fluid transport mechanism (dynamic recrystallisation, pressure solution)

- ➢ for dihedral angles $\theta > 60°$ ("‘impermeable"’ region),
- ➢ for stresses $\sigma_{\text{eff}} \gtrsim 1$ MPa,
- ➢ for porosities below 1%,
- ➢ without dilatant damage
- ⇒ practically everywhere, including geological barrier (deviatoric stress due to excavations and waste-generated heat)

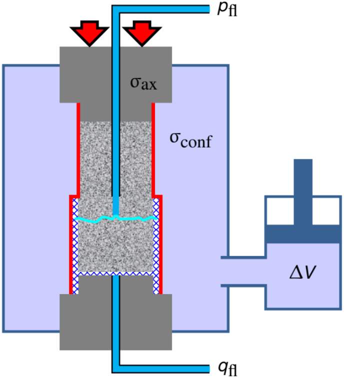
However:

- ➢ Mechanism is vague [Sinn et al. 2018]
- ➢ no estimates of (effective) permeabilities
- ➢ intended to cure mispredictions of *static pore-scale theory*
- ➢ hard to test

And now for. . .

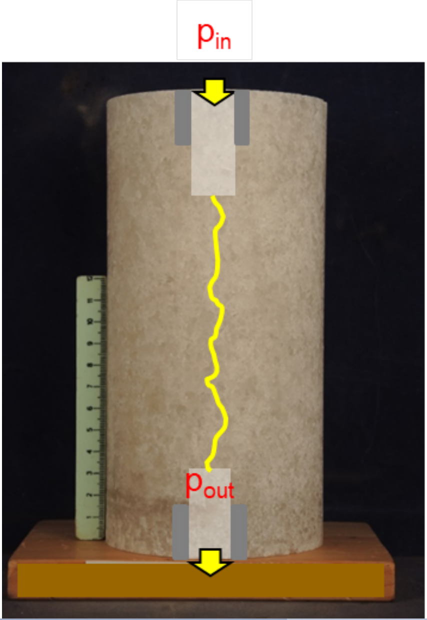
1. Fluid Transport in Rock Salt and Criteria for Integrity
2. Lab Test of Fluid Transport
3. Summary

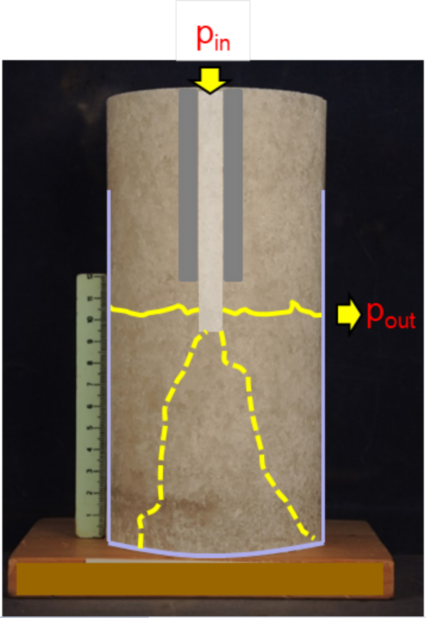
Test Setup



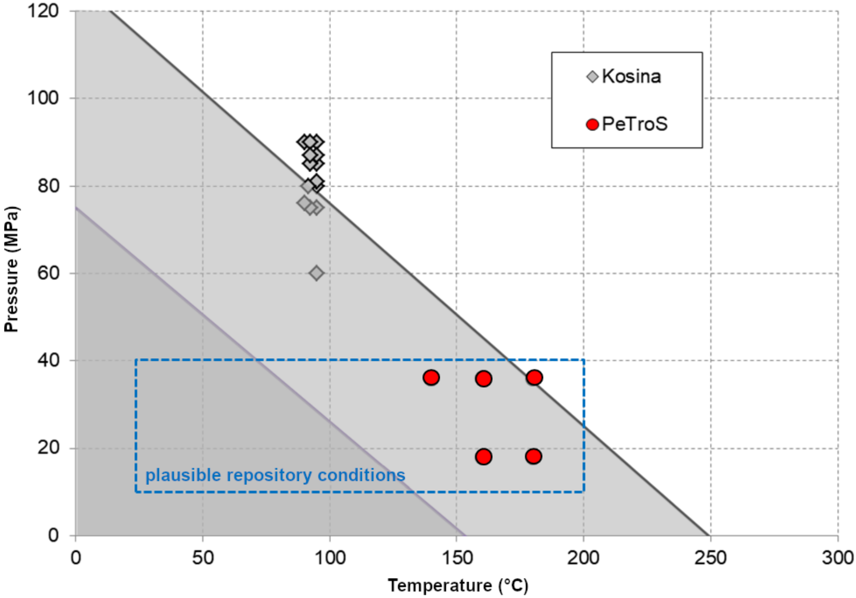
- Permeation in triaxial cell
- Stresses up to 36 MPa
- T up 180 °C
- Rock salt samples, $\varnothing = 100$ mm, $l = 200$ mm

Sample Configuration





Test Matrix



120
100
80
60
40
20
0
Pressure (MPa)
0
50
100
150
200
250
300
Temperature (°C)
Kosina
PeTroS
plausible repository conditions

"Permeability"

- Recall:
  - Undamaged rock salt has essentially zero permeability ...
  - ... but flow possible for $p_{\mathrm{fl}} \geq \sigma_{\mathrm{min}}$
- $\rightsquigarrow$ For quasi-stationary flow, "effective" permeability given by

$$\kappa_{\mathrm{eff}} = q_{\mathrm{out}} \eta \, \frac{p_{\mathrm{out}}}{p_{\mathrm{in}}^2 - p_{\mathrm{out}}^2} \, \frac{1}{\pi h} \ln \frac{R}{r}$$

Note: κ_{eff} depends on current rock stress and fluid pressure
it is not an intrinsic property of the rock salt sample

“Permeability”

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➢ Exception: Preexisting damage from sample collection and preparation

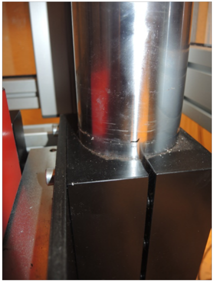
- ➥ Dilatancy in the range 10^{-3}
- ➥ Initial Darcy-type permeability in the range 10^{-21} m^2 to 10^{-20} m^2

Test Procedure

1. Initialisation:
   Heating (8 h)
   Application of (isotropic) stresses
2. Isotropic phase:
   Several stages of fluid pressure below minor principal stress
   Measurement of flow (for nitrogen tests)
3. Fluid breakthrough:
   Axial stress is lowered by (strain-controlled) axial extension
   ($\dot{\epsilon} = 2.5 \times 10^{-7}\ \mathrm{s}^{-1}$ to $\dot{\epsilon} = 2.5 \times 10^{-6}\ \mathrm{s}^{-1}$)
   $\leadsto$ Axial stress ($= \sigma_{\mathrm{min}}$) drops below fluid pressure
   $\leadsto$ pressure-driven percolation, fluid breakthrough
4. After test: Visualisation of flow path by injection of coloured tracer

Experimental Challenges

Schlagartiges Versagen bei hohem Gasdruck mit vollständiger Zerstörung der Probe und Beschädigungen der sensiblen Messtechnik in der Zelle und Schäden am massiven Prüfsystem (Versatz des Querhauptes, Abscheren von Verschraubungen etc.)



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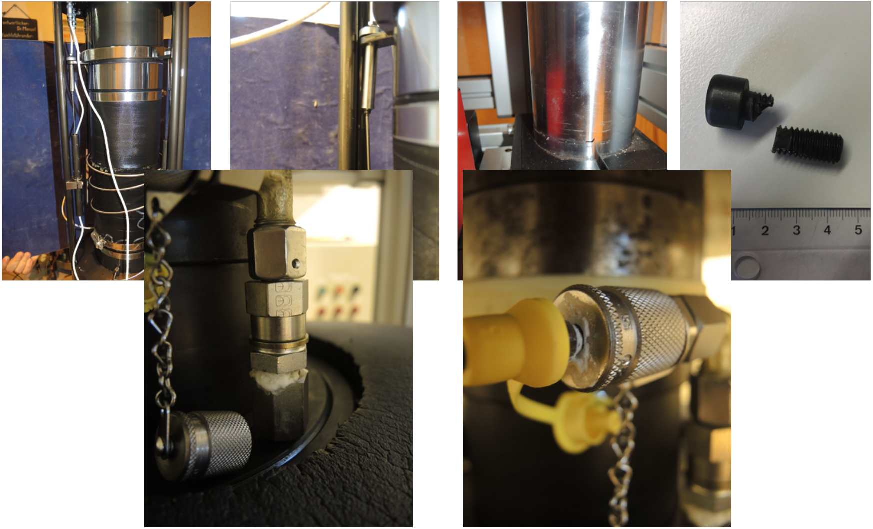
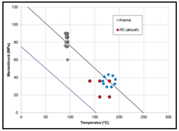
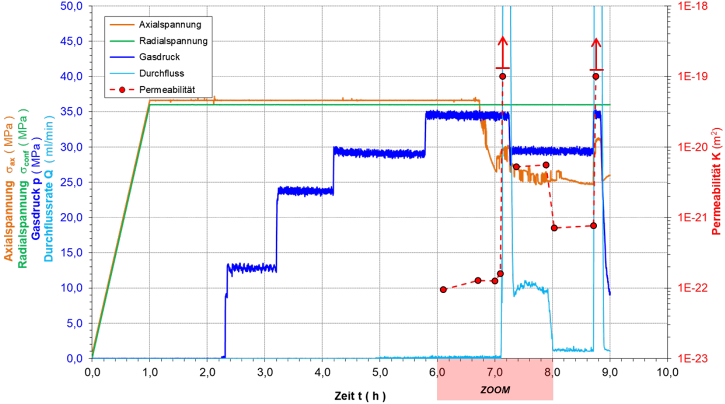
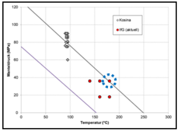




T = 180°C
σ_3 = 36 MPa
Dir. = radial
Medium = Gas



Example: Test 1b (Nitrogen, 180 °C, 36 MPa)



T = 180°C
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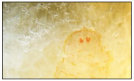
Medium = Gas

Probe ***nach*** Versuch

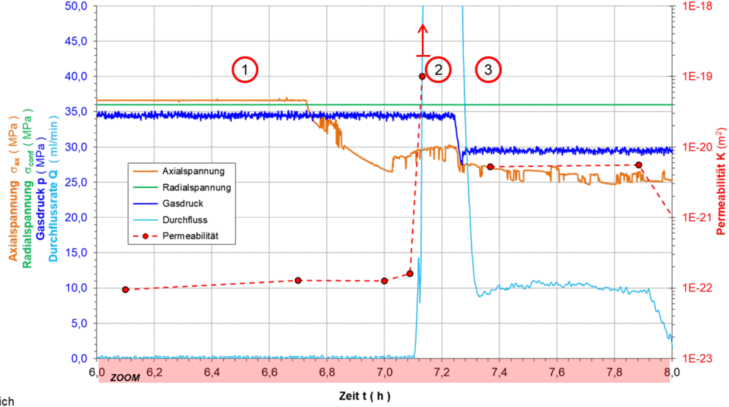


punktueller Austritt
des Markers im oberen Bereich

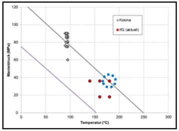
1 isotrope Druckbedingungen ($\sigma_{ax} = \sigma_{conf}$); $p_{in} < \sigma_{ax} = \sigma_{conf}$, nahezu kein Durchfluss

2 Axialspannung in Extension ($\sigma_{ax} = \sigma_{conf}$);); $\sigma_{ax} < p_{in} < \sigma_{conf}$, Durchschlag

3 Axialspannung in Extension ($\sigma_{ax} = \sigma_{conf}$);); Reduzierung Gasdruck, $\sigma_{ax} < p_{in} < \sigma_{conf}$, Rückgang Durchfluss



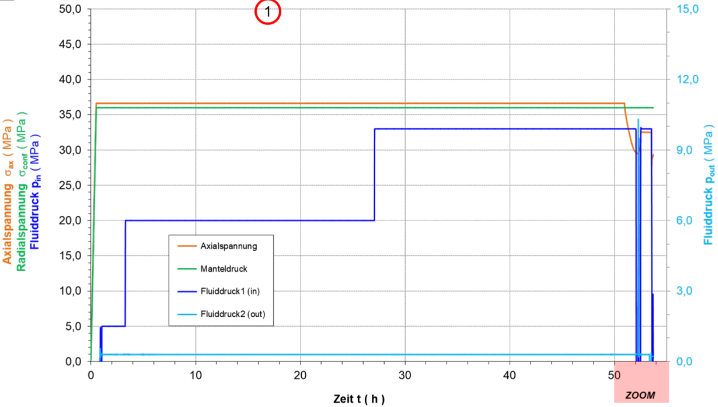
Example: Test 2 (Brine, 180 °C, 36 MPa)



T = 180°C
σ_3 = 36 MPa
Dir. = radial
Medium = Lösung

Probe ***vor*** Versuch

1 isotrope Druckbedingungen ($\sigma_{ax} = \sigma_{conf}$); $p_{in} < \sigma_{ax} = \sigma_{conf}$, kein Fluiddurchfluss



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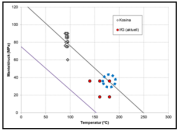


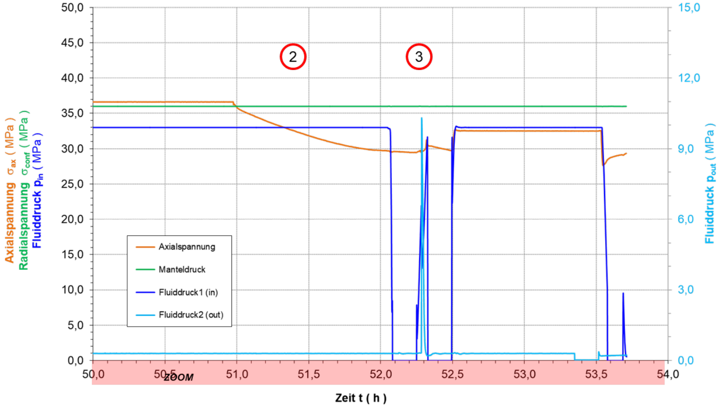
T = 180°C
σ_3 = 36 MPa
Dir. = radial
Medium = Lösung

Probe ***nach*** Versuch

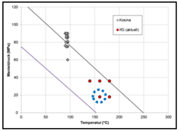
mit punktuellem Austritt des Markers

2 Axialspannung in Extension ($\sigma_{ax} < \sigma_{conf}$); p_{in} konstant, kein Durchfluss

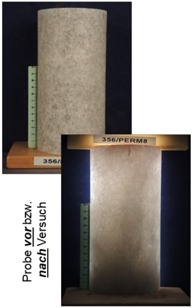
3 Axialspannung in Extension ($\sigma_{ax} < \sigma_{conf}$); p_{in} konstant, Durchfluss



Example: Test 9 (Nitrogen, 160 °C, 18 MPa)



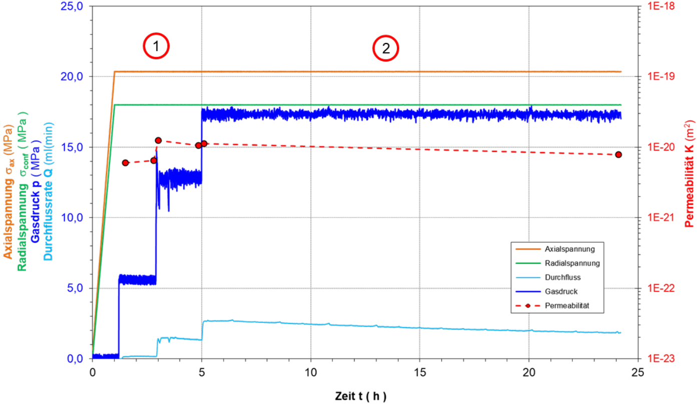
T = 160°C
σ_3 = 18 MPa
Dir. = axial
Medium = Gas



Probe *vor* bzw. ***nach*** Versuch

1 deviatorische Druckbedingungen ($\sigma_{ax} > \sigma_{conf}$); $p_{in} < \sigma_{ax}$, registrierbarer Durchfluss

2 deviatorische Druckbedingungen ($\sigma_{ax} > \sigma_{conf}$); Erhöhung p_{in}, kontinuierlicher Durchfluss



And now for...

Summary

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- Flow is dominant uncertainty
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Summary

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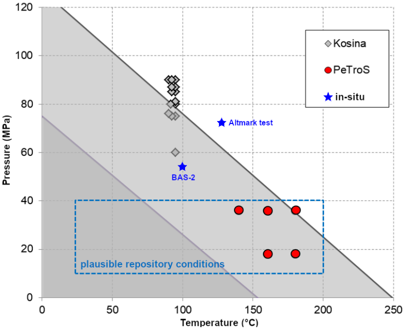
  $\rightsquigarrow$ permeability detection limit $\sim 10^{-22}$ m^2
- Breakthrough for $p_{\text{fl}} > \sigma_{\text{min}}$ at all p-T points
- pressure-driven percolation
- Flow below σ_{min} explained by preexisting damage and sample size:
- consistent with experiments at lower p and T
- flow reduced over time
  $\rightsquigarrow$ Healing of damage under isotropic compression
  $\rightsquigarrow$ no formation of stable connected pore space

Conclusions



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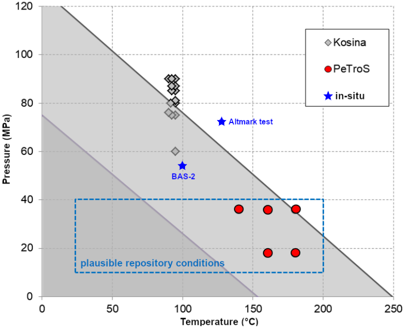

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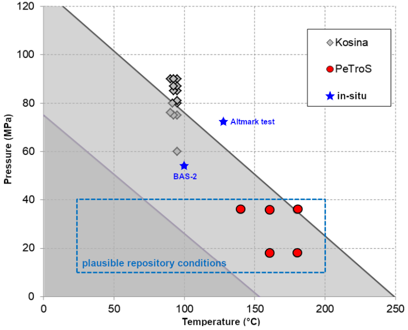

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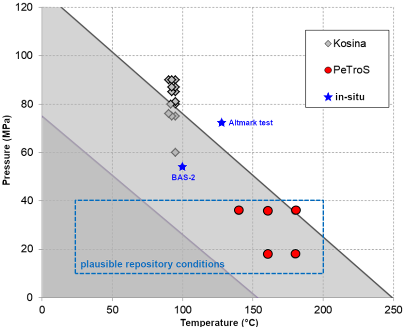
➢ Barrier properties of rock salt persist in the high p-T region

Conclusions



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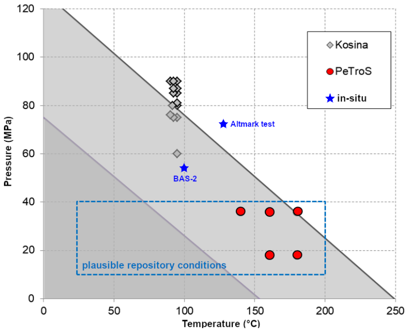

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- Geomechanically, 180 °C are fine

Thank you!

Federal Office
for the Safety of
Nuclear Waste Management

Federal Ministry
for the Environment, Nature Conservation
and Nuclear Safety

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The project and this presentation were done by the IfG; the views expressed here do not necessarily represent the position of BASE or BMU.

PeTroS final report (in German):
`https://download.gsb.bund.de/BFE/Fachdaten/PeTroS_Abschlussbericht.pdf`

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