Interpretation of permeability change due to effective stress with special focus on pore space geometry

Coupling of hydro-mechanical properties of porous media

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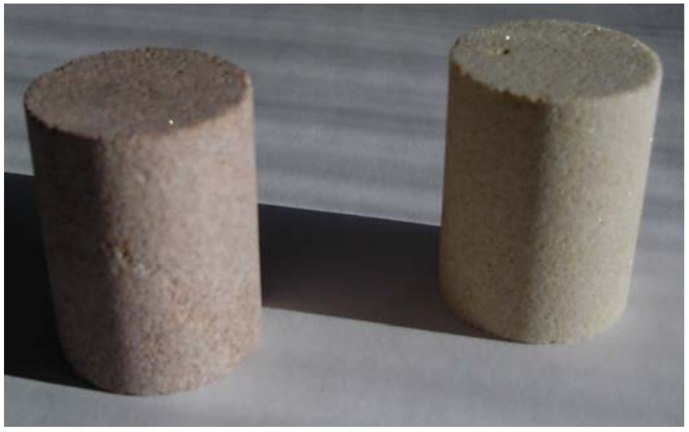
Content of the Presentation

Two different sandstones (Flechtinger and Bentheimer) were investigated:



- Determine the effective pressure ($p_{eff}=p_c-p_p$) dependency of Skempton coefficient B and the permeability k
- Analysing the pore space geometry
- Derive linkages between pore space geometry and transport properties

Skempton Coefficient B Measurement at the Mechanical Test System MTS

Sample dimension:

length: 10cm

diameter: 5cm

Experiment conditions:

fully undrained

pre-conditioned

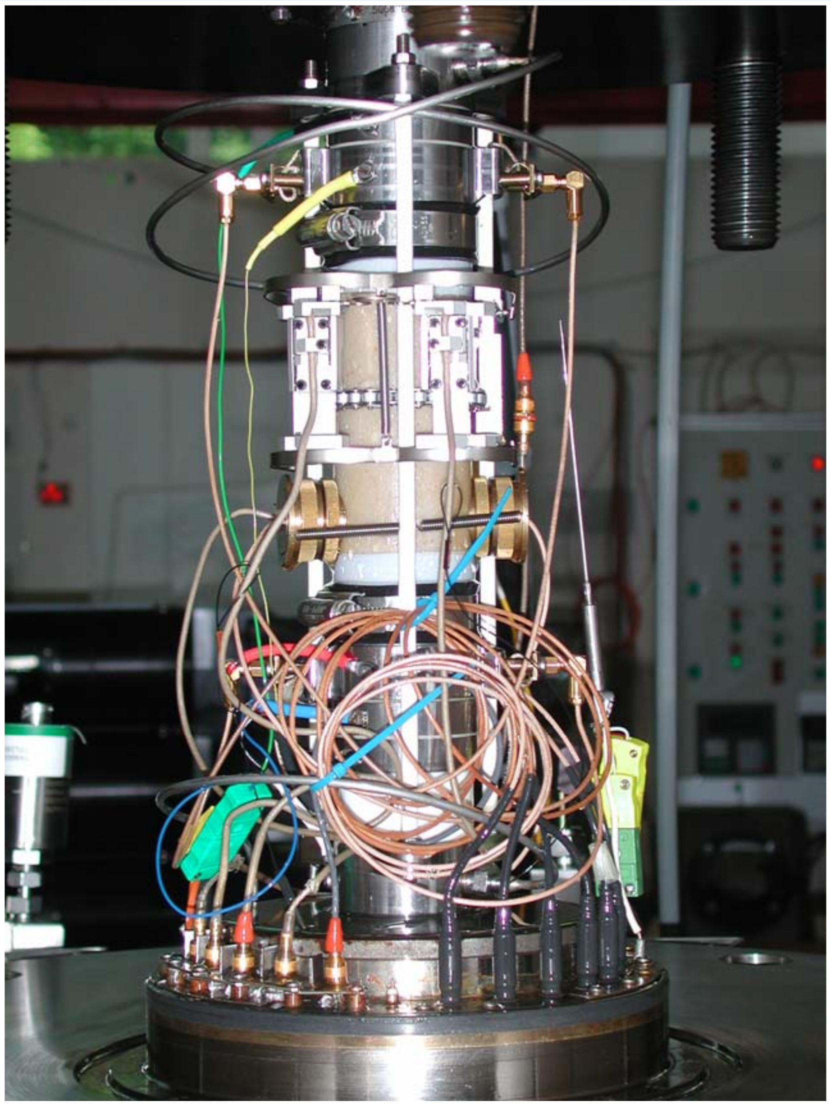
confining pressure range p_c = 5 to 60MPa

Measurement:

pore pressure p_p

Result:

Skempton coefficient $B = \frac{dp_p}{dp_c}$



Permeability Measurement at the High-Temperature-Pressure (HTP) Permeameter

Sample dimension:

length: 4cm
diameter: 3cm
cross sectional area A=7.07cm²

Experiment conditions:

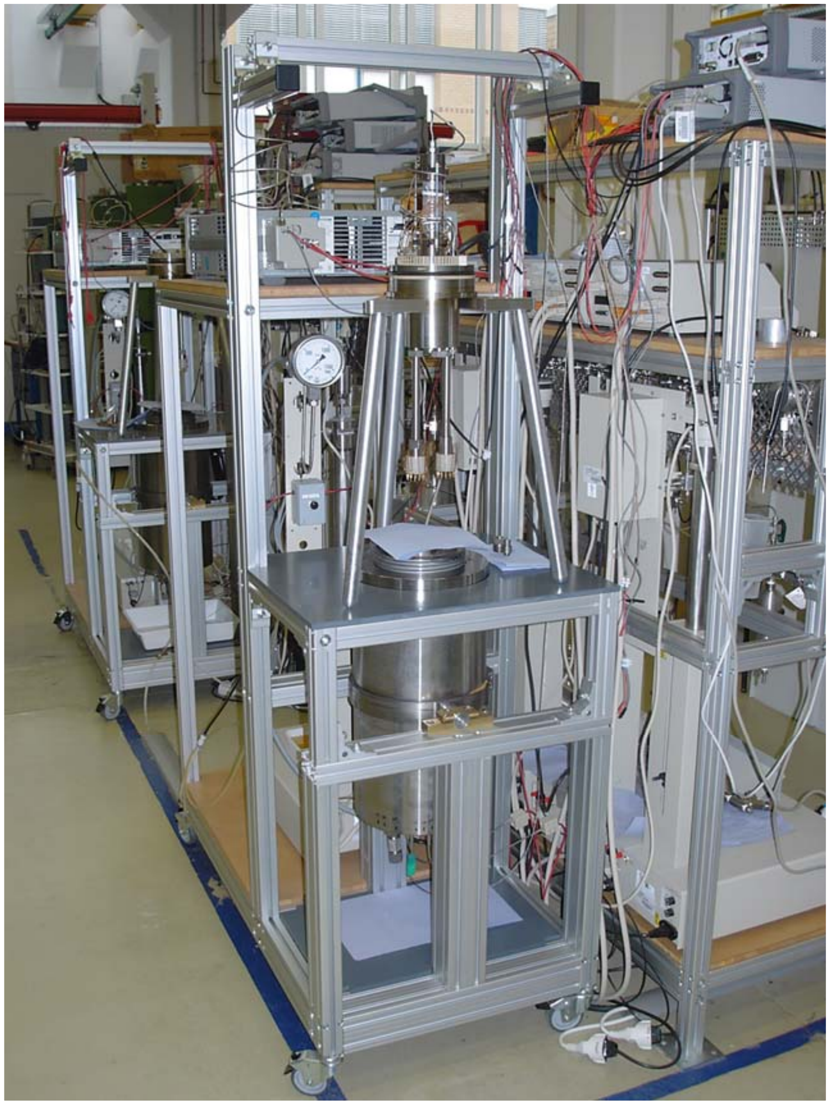
drained
T=40°C
0.1 molar NaCl- brine
confining pressure range p_c = 5 to 47MPa
pore pressure range p_p = 2.5 to 42MPa
flow rate range Q = 0.05 to 30 ml/min

Measurement:

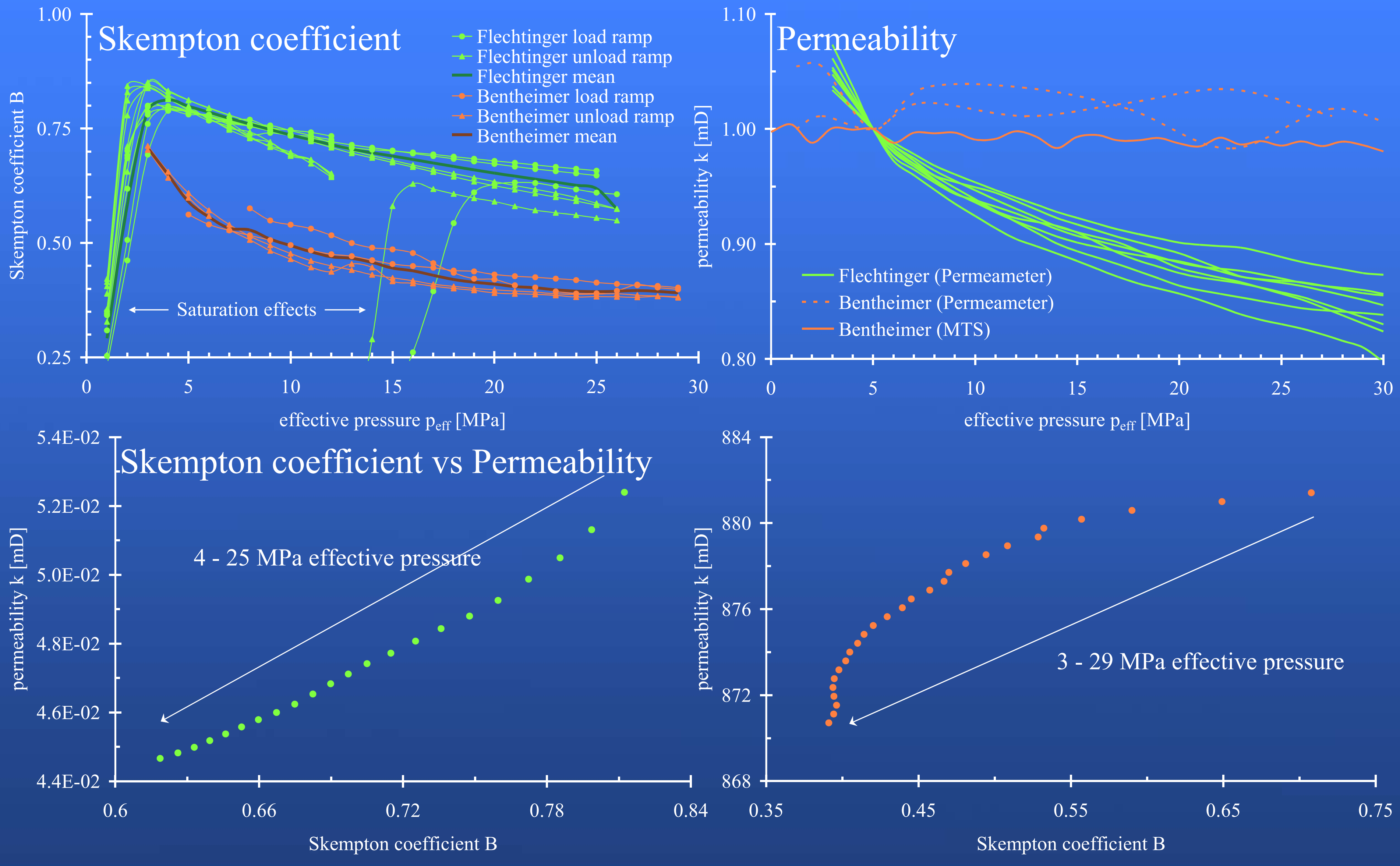
pore pressure gradient grad(p_p)

Result:

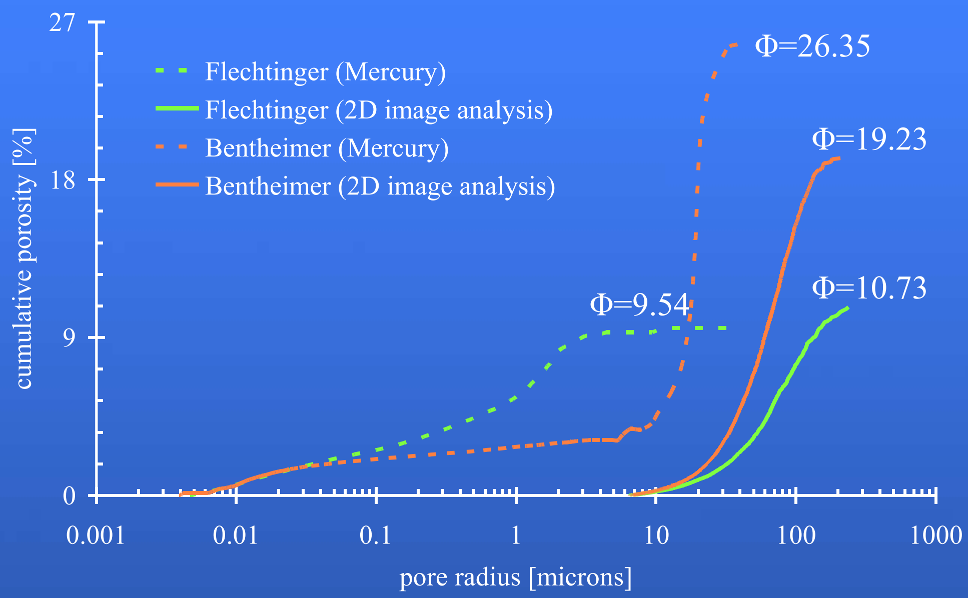
permeability $k = -\frac{Q * \eta}{A * grad(p_p)}$

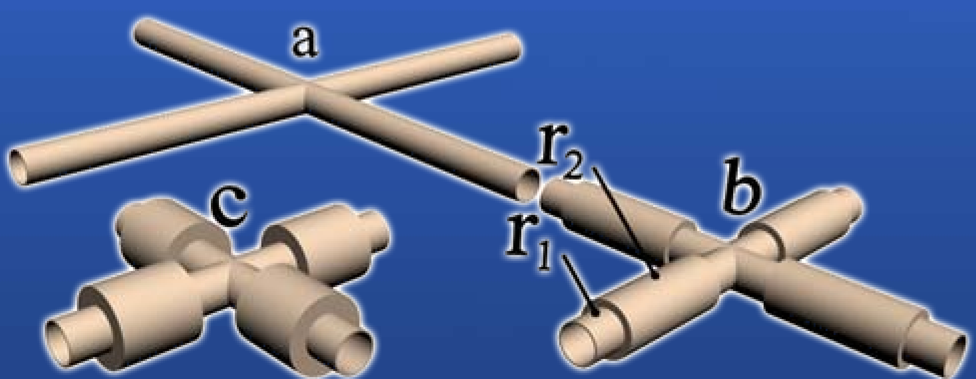


Results of the Laboratory Experiments



Pore Space Analysis
Porosity





Bentheimer:

total porosity: 19.23-26.35

pore radii: 40-110 microns

pore cavity to throat ratio: small

Flechtinger:

total porosity: 9.54-10.73

pore radii: 6.5-200 microns

pore cavity to throat ratio: high

Pore cavity-throat-ratio

- mercury injection assumes cylindrically shaped pores → determined radius is close to pore throat radius
- 2D image analysis directly determines the pore radii

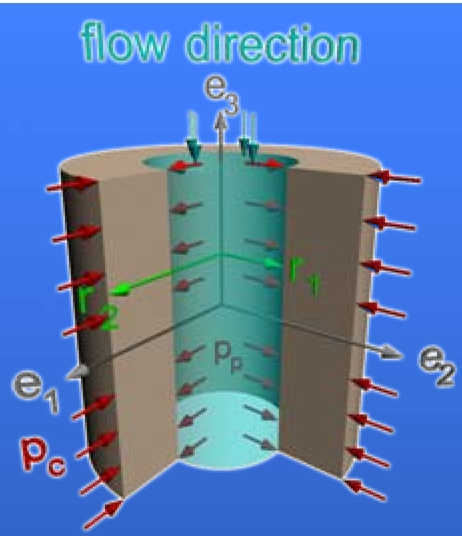
→Gap between Mercury injection and 2D image analysis indicates the pore cavity to throat ratio

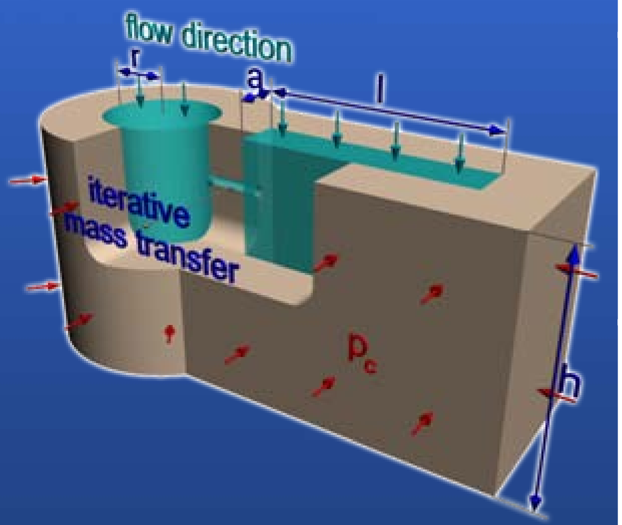
Pore Space Analysis
Pore Model

	Measured pore types		
	2D Image Analysis	Skempton Experiment	Permeability Experiment
Catenary pores	X	X	X
Cul-de-sac pores	X	X	
Closed pores	X		

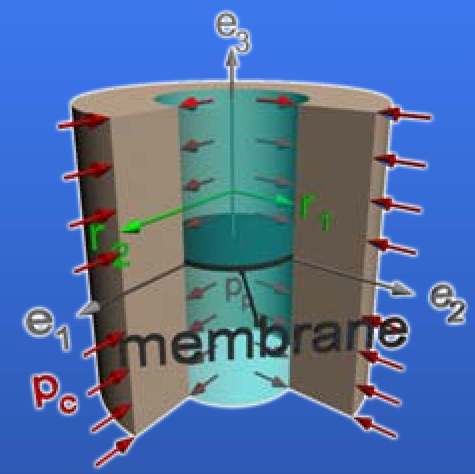
Note: The ratio of Catenary, Cul-de-sac and Closed pores is changing due to effective pressure

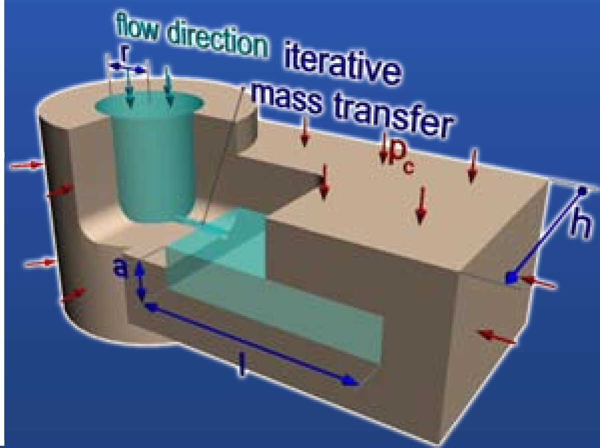
Analytical Examination of Permeability and Skempton Coefficient



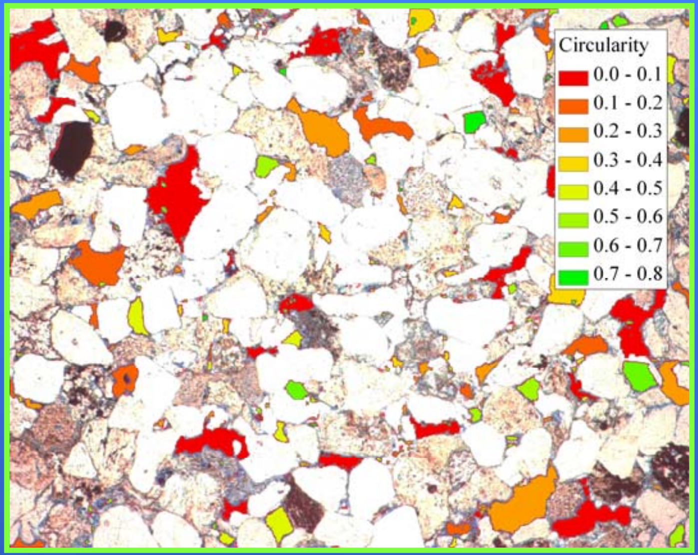


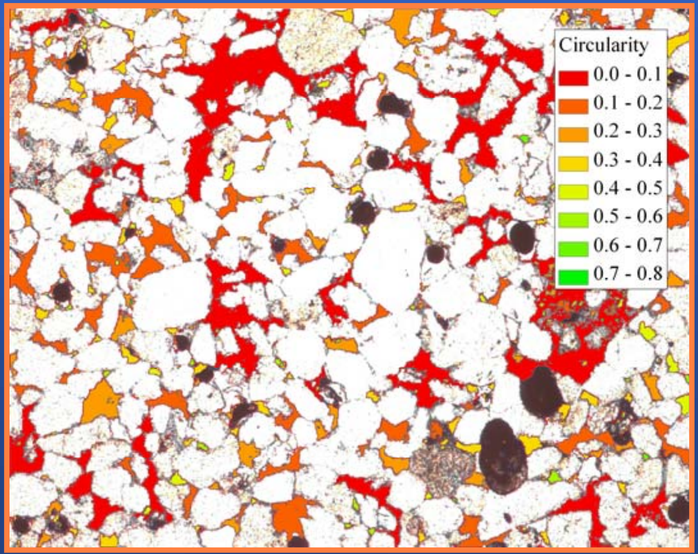
$B(p_{eff}=0MPa)$	0.1373
$k(p_{eff}=0MPa)$ [m²]	7.81E-09
dB/dp_{eff} [1/MPa]	-4.5E-06
dk/dp_{eff} [m²/MPa]	-5.7E-13
$B(p_{eff}=0MPa)$	0.1373
$k(p_{eff}=0MPa)$ [m²]	0
dB/dp_{eff} [1/MPa]	-4.5E-06
dk/dp_{eff} [m²/MPa]	0
$B(p_{eff}=0MPa)$	0.4085
$k(p_{eff}=0MPa)$ [m²]	1.10E-08
dB/dp_{eff} [1/MPa]	-4.5E-05
dk/dp_{eff} [m²/MPa]	-2.3E-12
$B(p_{eff}=0MPa)$	0.4085
$k(p_{eff}=0MPa)$ [m²]	7.81E-09
dB/dp_{eff} [1/MPa]	-4.5E-05
dk/dp_{eff} [m²/MPa]	-5.7E-13





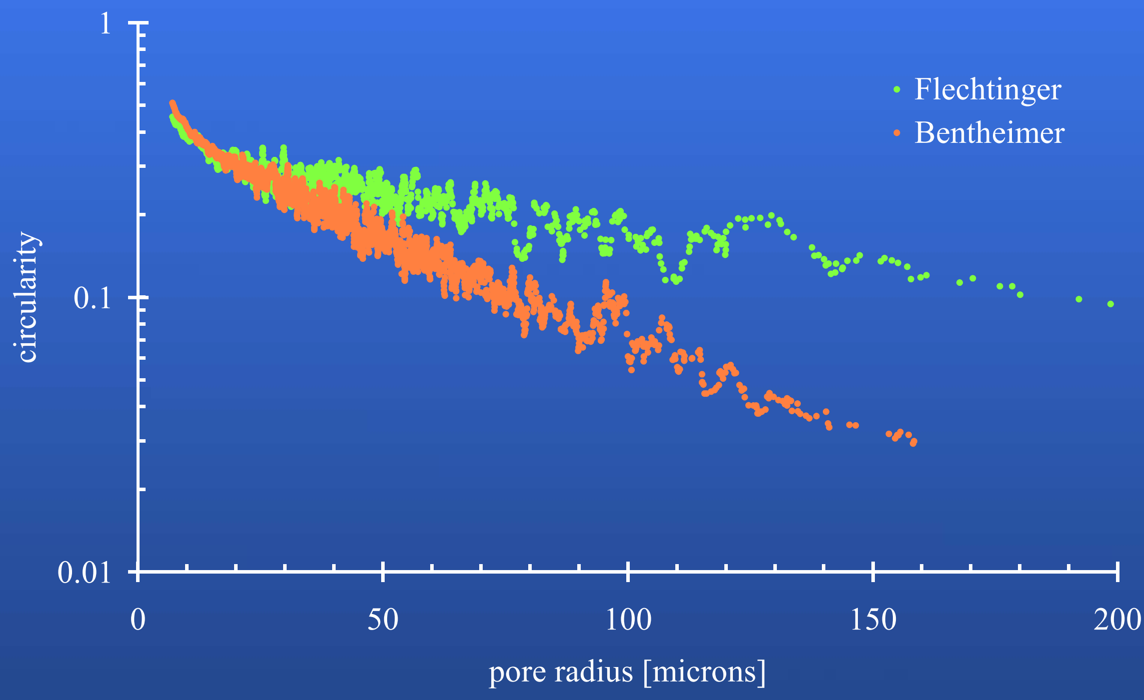
Pore Space Analysis
Circularity



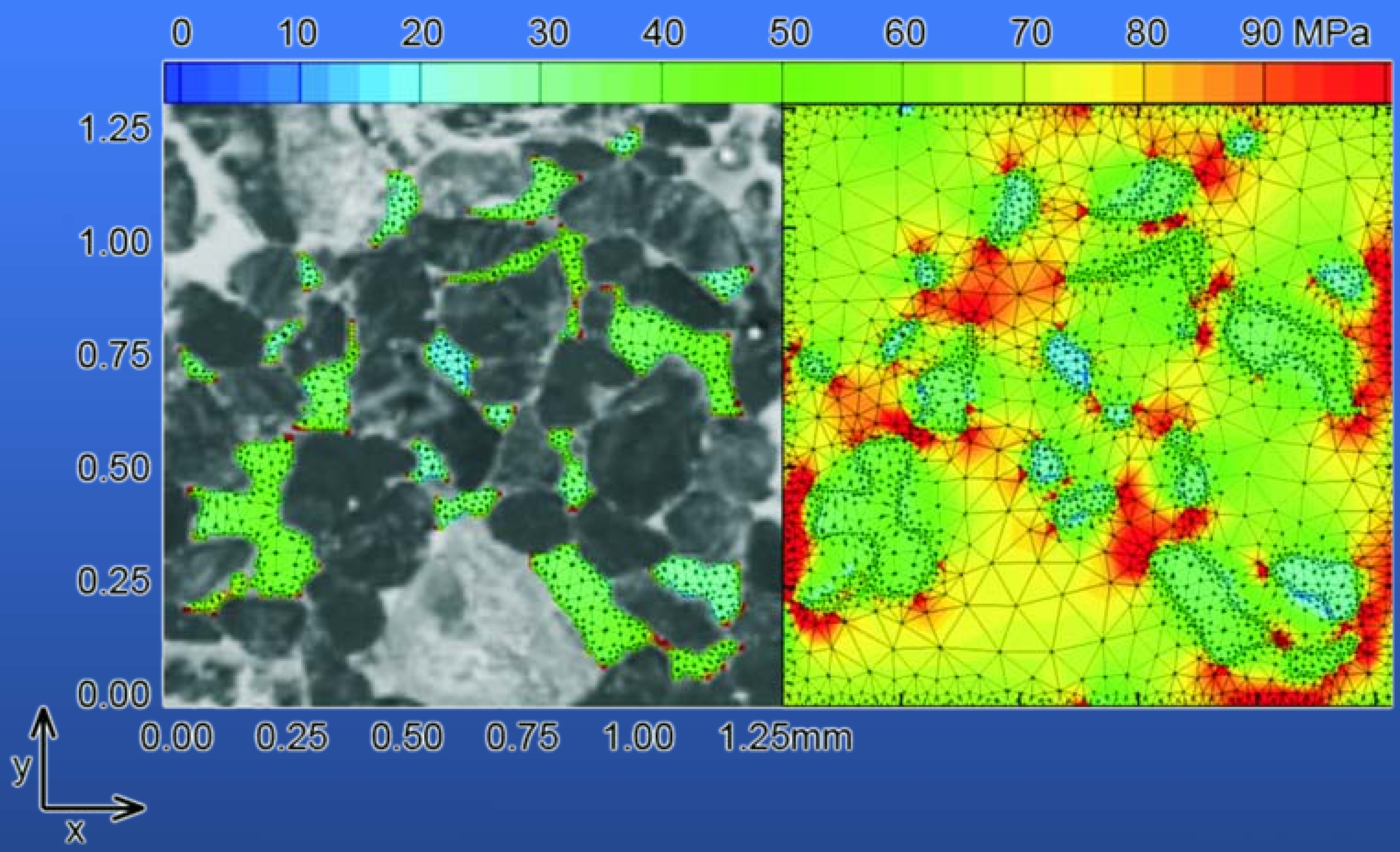


$$C = 4\pi \frac{A_p}{l^2}$$

A_p → pore area
l → perimeter length



Numerical Examination of Skempton Coefficient



Skempton coefficient varies for each single pore from 0.32 to 0.68 dependent on the pore shape

Qualitative Interpretation

Two mechanisms lead to a change in porosity, Skempton coefficient and permeability with changing effective stress:

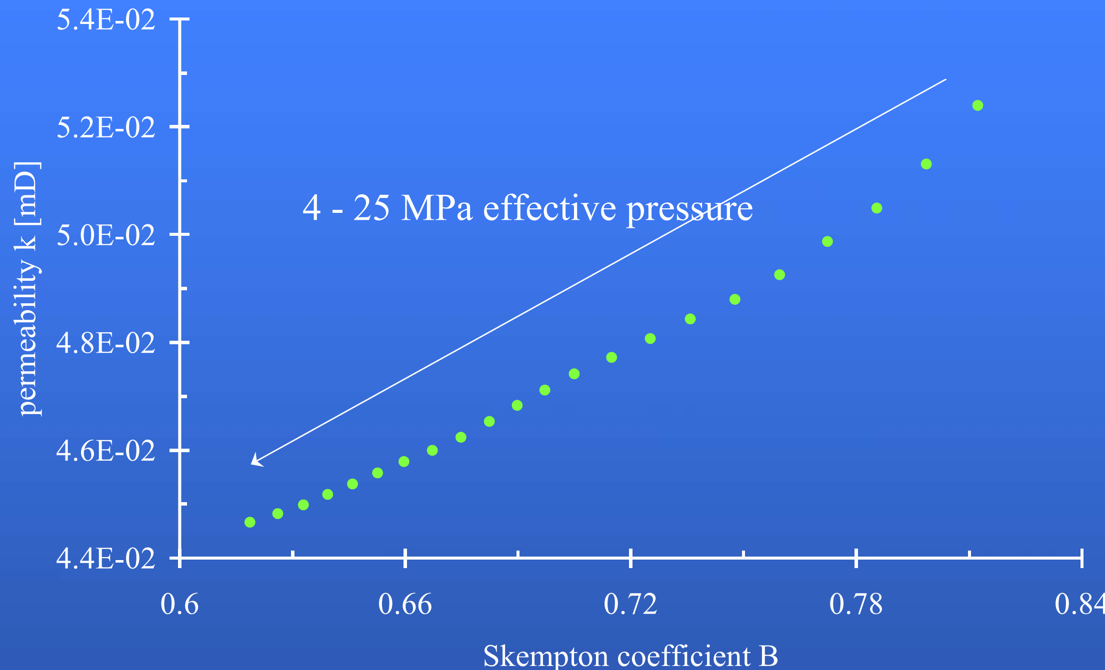
1. A pore separation by closing of pore throats

- Caternary pore → Cul-de-sac pore leads to a decrease of permeability
- Cul-de-sac → Closed pore leads to a decrease of Skempton coefficient
- The separation of pores depends on the pore cavity to throat ratio

2. A poro-elastic deformation of the pore space itself

- poro-elastic deformation affects porosity, Skempton coefficient and permeability
- The change in Skempton coefficient is highest
- Irregularly shaped pores are more susceptible to poro-elastic deformation

Qualitative Interpretation for Flechtinger Sandstone



<u>Observation:</u>

High circularity

High pore cavity-throat-ratio

Continuous decrease of permeability and Skempton coefficient with effective pressure increase

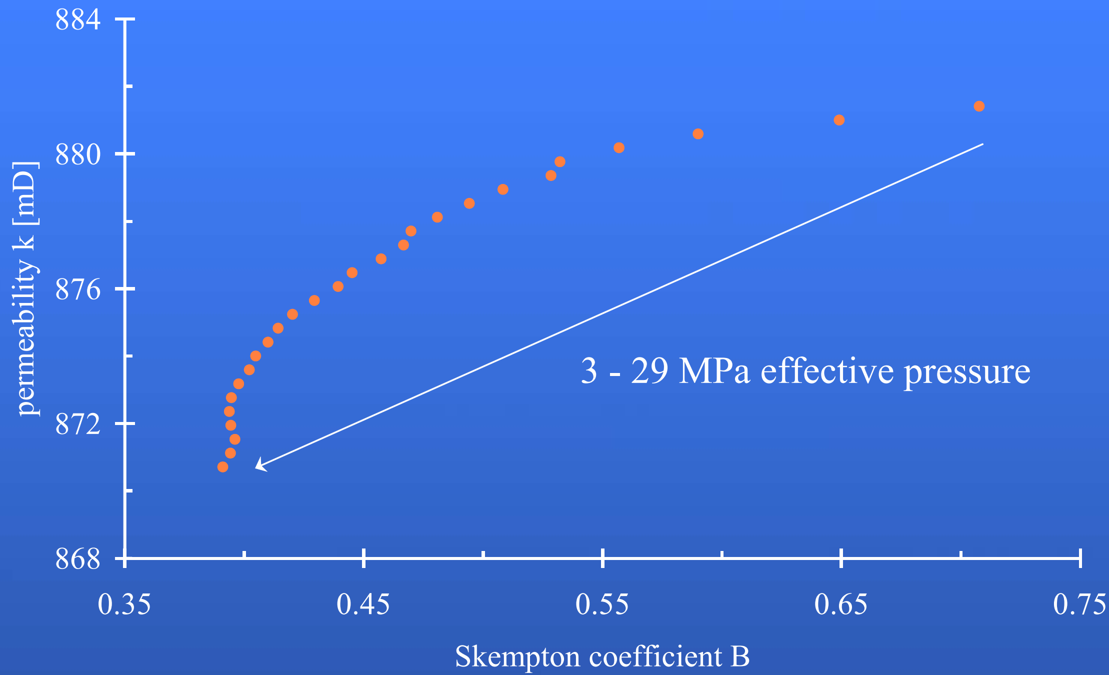
<u>Interpretation:</u>

No change of the pore shape

Separation of pores

Cut-off of flow path leads to a change in permeability and Skempton coefficient

Qualitative Interpretation for Bentheimer Sandstone



Observation:

Low circularity (irregular pore shapes)

Low pore cavity-throat-ratio

High decrease in Skempton coefficient at low effective pressure and no significant change in permeability

Interpretation:

Sensitive for poro-elastic deformation

No separation of pores

High poro-elastic deformation at low effective pressure. After stiffening of the frame work no further change in B and k.

Conclusion and Future Work

Conclusion

- Two types of sandstone (Flechtinger and Bentheimer) were investigated
- Both samples show differences in effective pressure dependencies as expressed by their Skempton coefficient and permeability
- By means of a three pore type model in combination with a heterogeneous pore space geometry change a qualitative interpretation is possible

Future Work

- A quantification of the geometry change will be necessary
- A direct method to measure the geometry change due to effective pressure change must be developed
- Further experiments to validate the results of this work