9th Euroconference on Rock Physics and Geomechanics
Trondheim Norway
17-21 October 2011

The application of fibre optic sensors in laboratory experiments.

Guido Blöcher[1], Thomas Reinsch[1], Harald Milsch[1], Alireza Hassanzadegan[1] & Günter Zimmermann[1]

[1]*Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Potsdam, Germany*

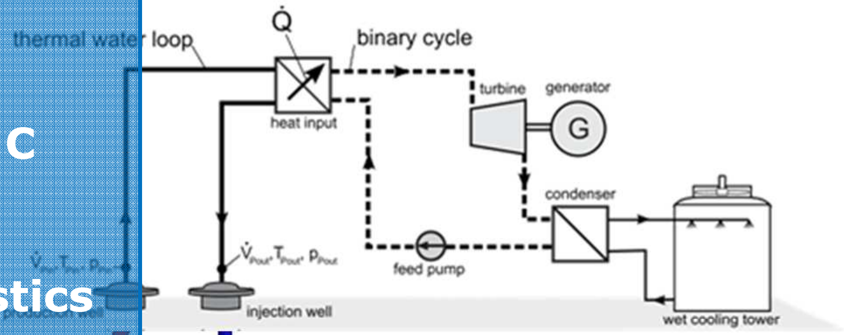
GFZ Helmholtz Centre POTSDAM

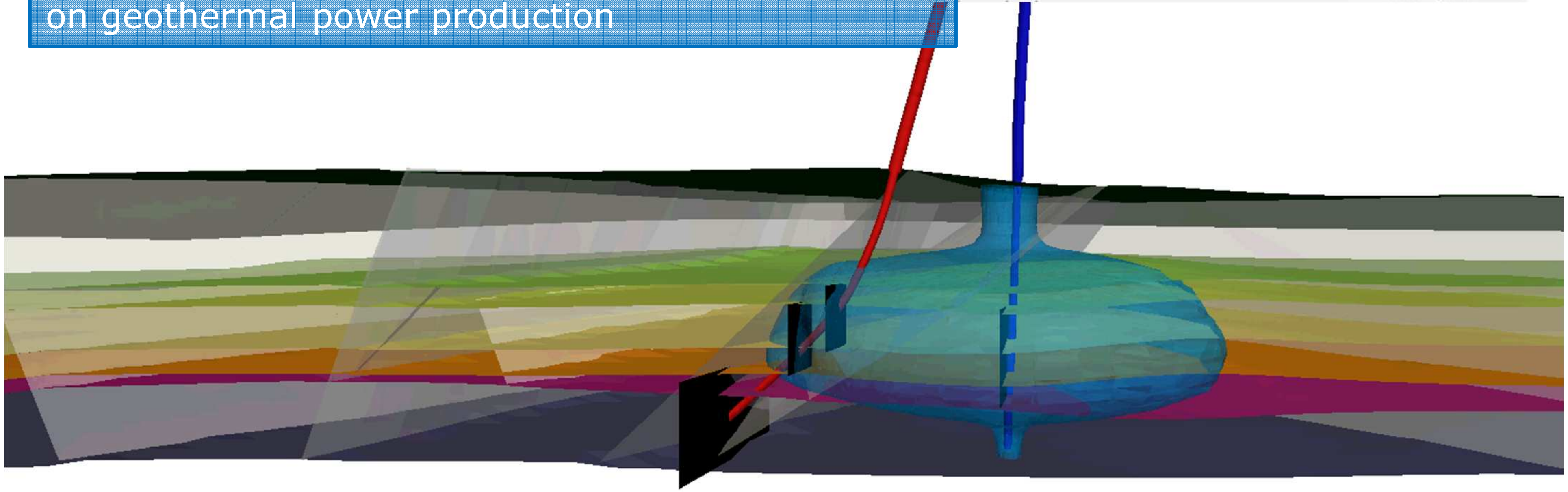
HELMHOLTZ ASSOCIATION

Motivation

- during geothermal power production the temperature and pressure conditions will change
- maximum temperature change **ΔT = 70° C**
- maximum pressure change **Δp = 10 MPa**

→ Impact of **poro-elastics** and **thermo-elastics** on geothermal power production



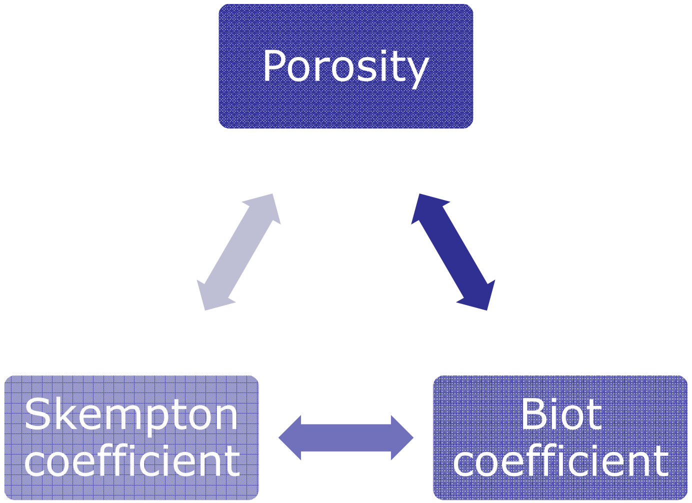


Motivation

- Validating parts of the **theory of poroelasticity**
- Optimisation of **undrained compression** experiments
- Using the techniques of **fibre optic sensors**

Application

- Determination of poro-elastic response of porous media by fibre optic sensors
- Effective pressure dependency of Porosity φ; Biot coefficient α & Skempton coefficient B within mechanical testing system MTS



Porosity

Direct method

$$\phi = \frac{V_p}{V_b} = \frac{V_p^i - dV_p}{V_b^i - dV_b}$$

Mainguy & Longuemare, 2002

Indirect method

$$d\varphi = -\left[\left(1-\varphi^i\right)\beta_b - \beta_s\right] d(p_c - p_p) + \varphi^i(\beta_s - \beta_\varphi)\, dp_p$$

$dp_p = 0$

Ghabezloo, Sulem, Saint-Marc, 2009

Carroll & Katsube, 1983

drained hydrostatic compression jacketed specimen

undrained hydrostatic compression jacketed specimen

hydrostatic compression unjacketed specimen or mixture rule*

*Voigt-Reuss-Hill or Hashin-Shtrikman

α = Biot Coefficient
B = Skempton Coefficient
K_b = Bulk Modulus of the Framework
K_s = Bulk Modulus of Solid Grains
K_f = Bulk Modulus of Pore Fluid
β_b = $1/K_b$ Bulk Compressibility of the Framework
β_s = $1/K_s$ Bulk Compressibility of Solid Grains
β_f = $1/K_f$ Bulk Compressibility of Pore Fluid

V_P = Bulk Volume
V_P = Pore Volume
ϵ_v = Volumetric Strain
ϵ_a = Axial Strain
ϵ_c = Circumferential Strain
p_p = Pore Pressure
p_c = Confining Pressure
φ = Porosity

Biot Coefficient

Direct method

$$\alpha = \frac{dV_p}{V_b \, d\varepsilon_v}$$

Kümpel, 1991

Indirect method

$$\alpha = 1 - \frac{K_b}{K_s}$$

Biot & Willis, 1957
Nur & Byerlee, 1971

drained
hydrostatic compression
jacketed specimen

undrained
hydrostatic compression
jacketed specimen

hydrostatic compression
unjacketed specimen or
mixture rule*

*Voigt-Reuss-Hill or Hashin-Shtrikman

$\boldsymbol{\alpha}$ = Biot Coefficient
$\boldsymbol{B}$ = Skempton Coefficient
$\boldsymbol{K_b}$ = Bulk Modulus of the Framework
$\boldsymbol{K_s}$ = Bulk Modulus of Solid Grains
$\boldsymbol{K_f}$ = Bulk Modulus of Pore Fluid
$\boldsymbol{\beta_b}$ = $1/\boldsymbol{K_b}$ Bulk Compressibility of the Framework
$\boldsymbol{\beta_s}$ = $1/\boldsymbol{K_s}$ Bulk Compressibility of Solid Grains
$\boldsymbol{\beta_f}$ = $1/\boldsymbol{K_f}$ Bulk Compressibility of Pore Fluid

$\boldsymbol{V_p}$ = Bulk Volume
$\boldsymbol{V_p}$ = Pore Volume
$\boldsymbol{\epsilon_v}$ = Volumetric Strain
$\boldsymbol{\epsilon_a}$ = Axial Strain
$\boldsymbol{\epsilon_c}$ = Circumferential Strain
$\boldsymbol{p_p}$ = Pore Pressure
$\boldsymbol{p_c}$ = Confining Pressure
$\boldsymbol{\varphi}$ = Porosity

Skempton Coefficient

Direct method

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

Skempton, 1954

Indirect method

$$B = \frac{\beta_b - \beta_s}{\varphi^i * (\beta_f - \beta_s) + (\beta_b - \beta_s)}$$

Mesri, Adachi, Ullrich, 1976
Jaeger, Cook, Zimmerman, 2007

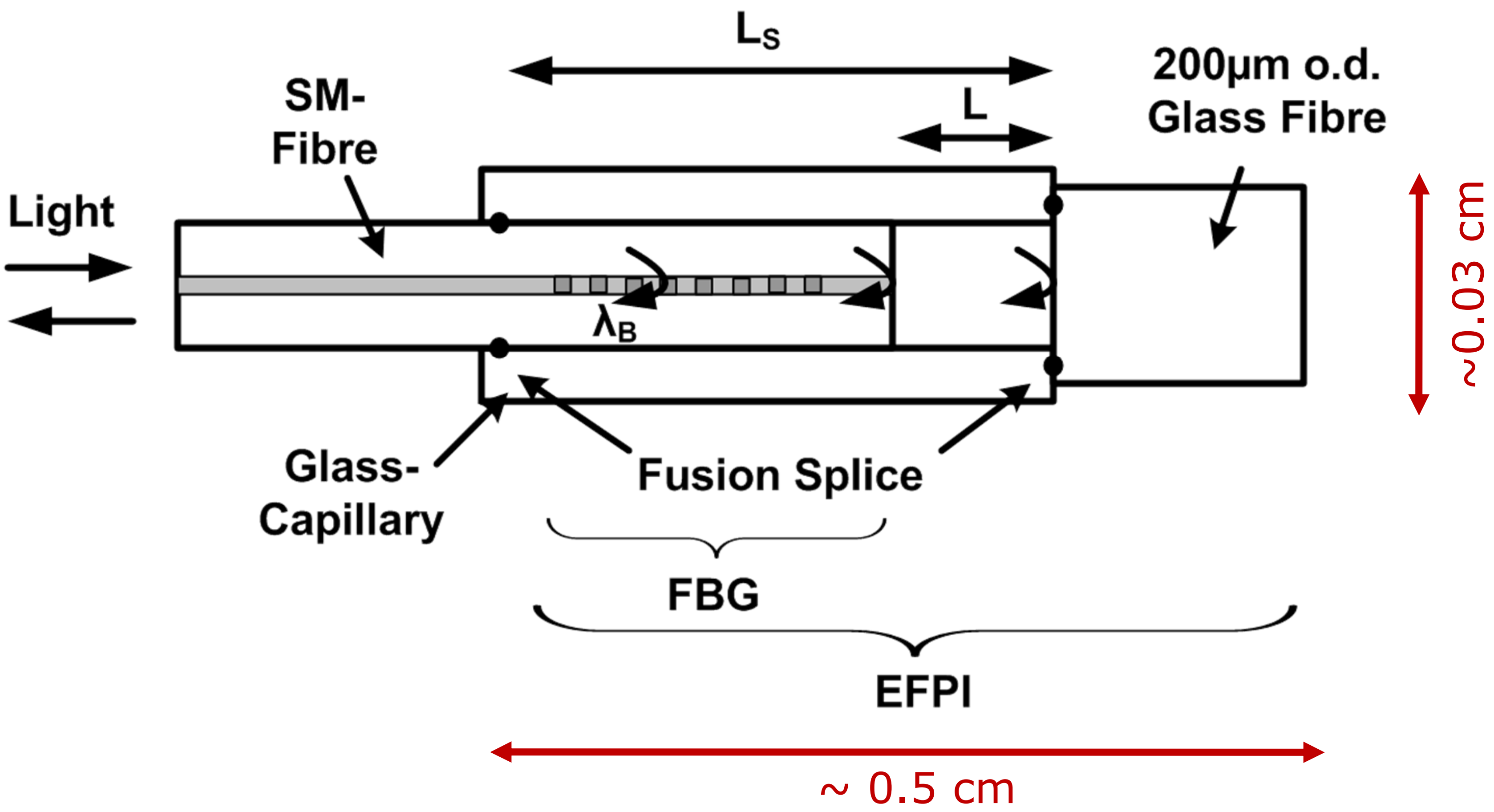
drained hydrostatic compression jacketed specimen	undrained hydrostatic compression jacketed specimen	hydrostatic compression unjacketed specimen or mixture rule*

*Voigt-Reuss-Hill or Hashin-Shtrikman

$\boldsymbol{\alpha}$ = Biot Coefficient
$\boldsymbol{B}$ = Skempton Coefficient
$\boldsymbol{K_b}$ = Bulk Modulus of the Framework
$\boldsymbol{K_s}$ = Bulk Modulus of Solid Grains
$\boldsymbol{K_f}$ = Bulk Modulus of Pore Fluid
$\boldsymbol{\beta_b}$ = $1/\boldsymbol{K_b}$ Bulk Compressibility of the Framework
$\boldsymbol{\beta_s}$ = $1/\boldsymbol{K_s}$ Bulk Compressibility of Solid Grains
$\boldsymbol{\beta_f}$ = $1/\boldsymbol{K_f}$ Bulk Compressibility of Pore Fluid

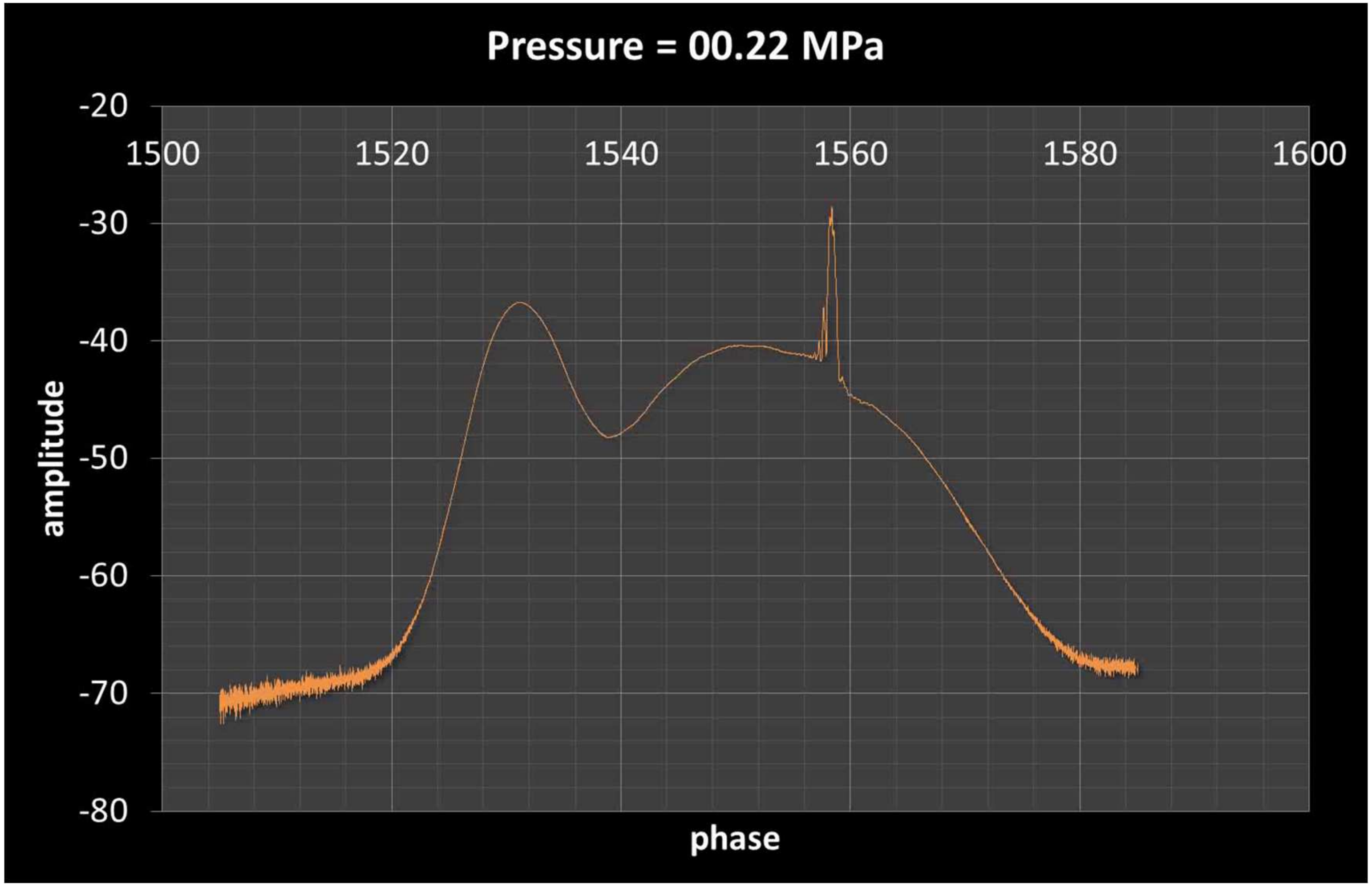
$\boldsymbol{V_p}$ = Bulk Volume
$\boldsymbol{V_p}$ = Pore Volume
$\boldsymbol{\epsilon_v}$ = Volumetric Strain
$\boldsymbol{\epsilon_a}$ = Axial Strain
$\boldsymbol{\epsilon_c}$ = Circumferential Strain
$\boldsymbol{p_p}$ = Pore Pressure
$\boldsymbol{p_c}$ = Confining Pressure
$\boldsymbol{\varphi}$ = Porosity

Sensor

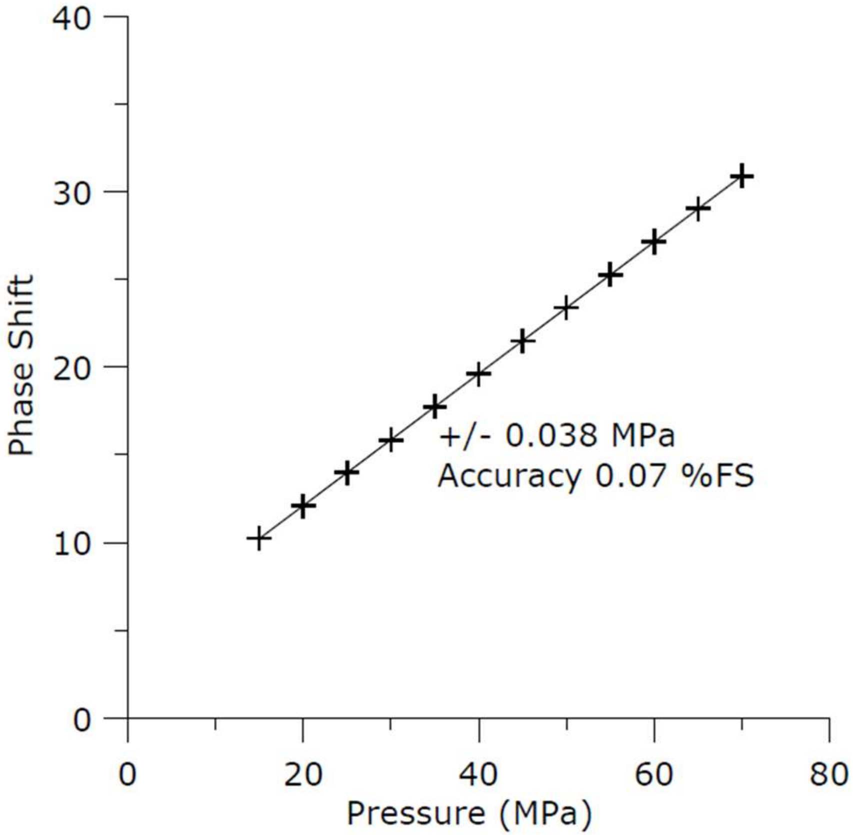


Ls
L
200µm o.d.
Glass Fibre
SM-
Fibre
Light
λB
~0.03 cm
Glass-
Capillary
Fusion Splice
FBG
EFPI
~ 0.5 cm

Fibre Optic Sensor - Calibration



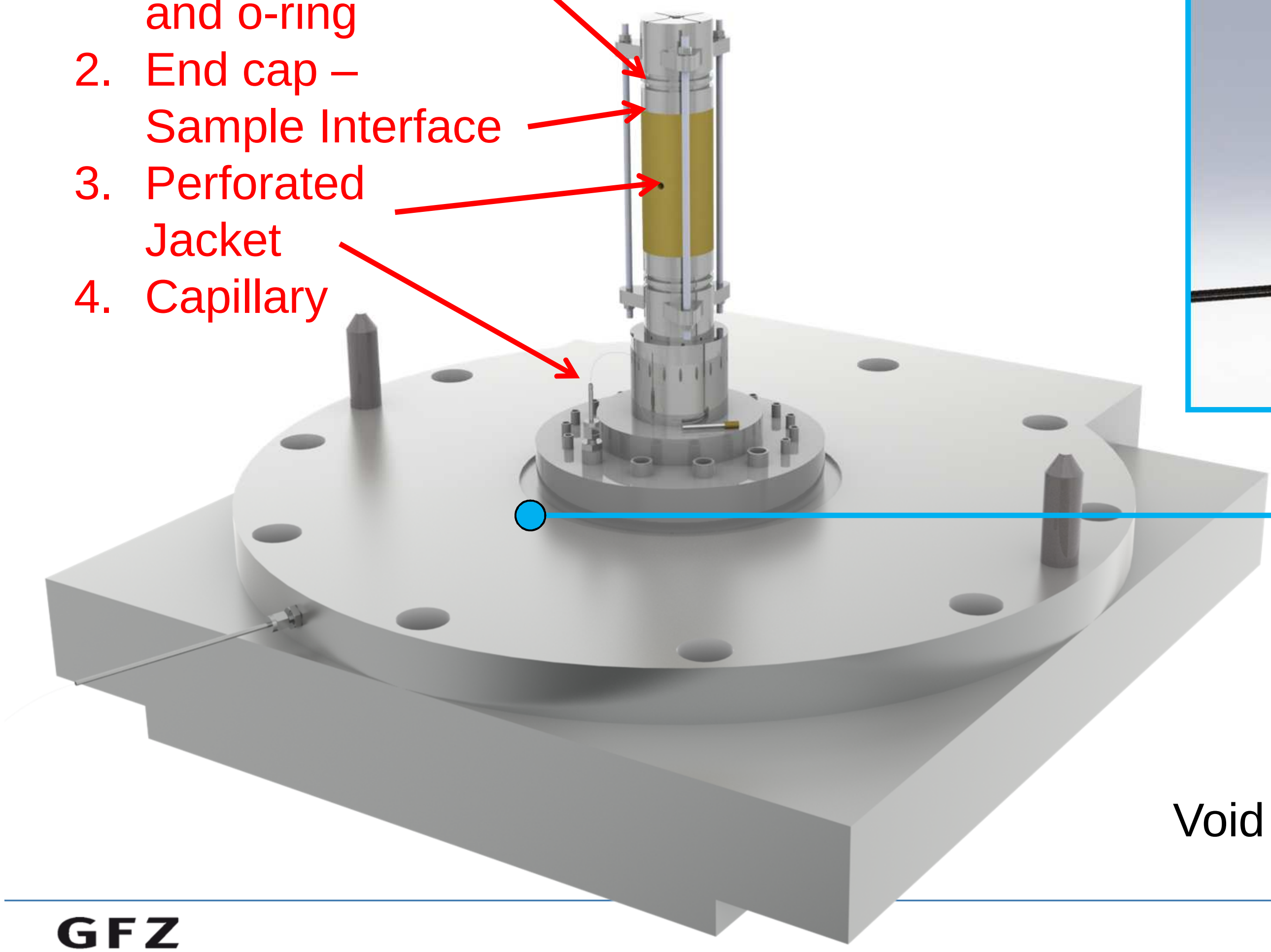
Fibre Optic Sensor - Calibration

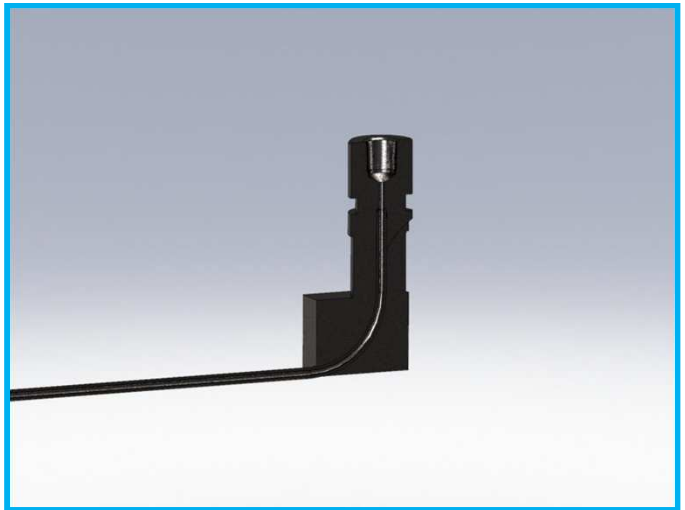


- Pressure
  0-70 MPa +/- 0.5 bar
- Temperature
  Accuracy approx. 0.1° C
- Multiple sensors per sample

Potential leakage & test assembly

1. Between jacket and o-ring
2. End cap – Sample Interface
3. Perforated Jacket
4. Capillary

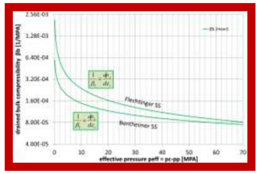




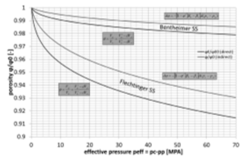
Void Space Fraction < **0.05%**

Results Comparison

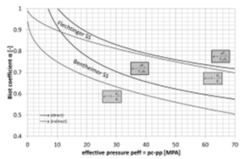
compressibility βb



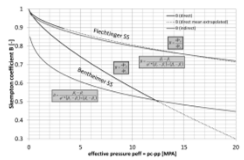
porosity ϕ

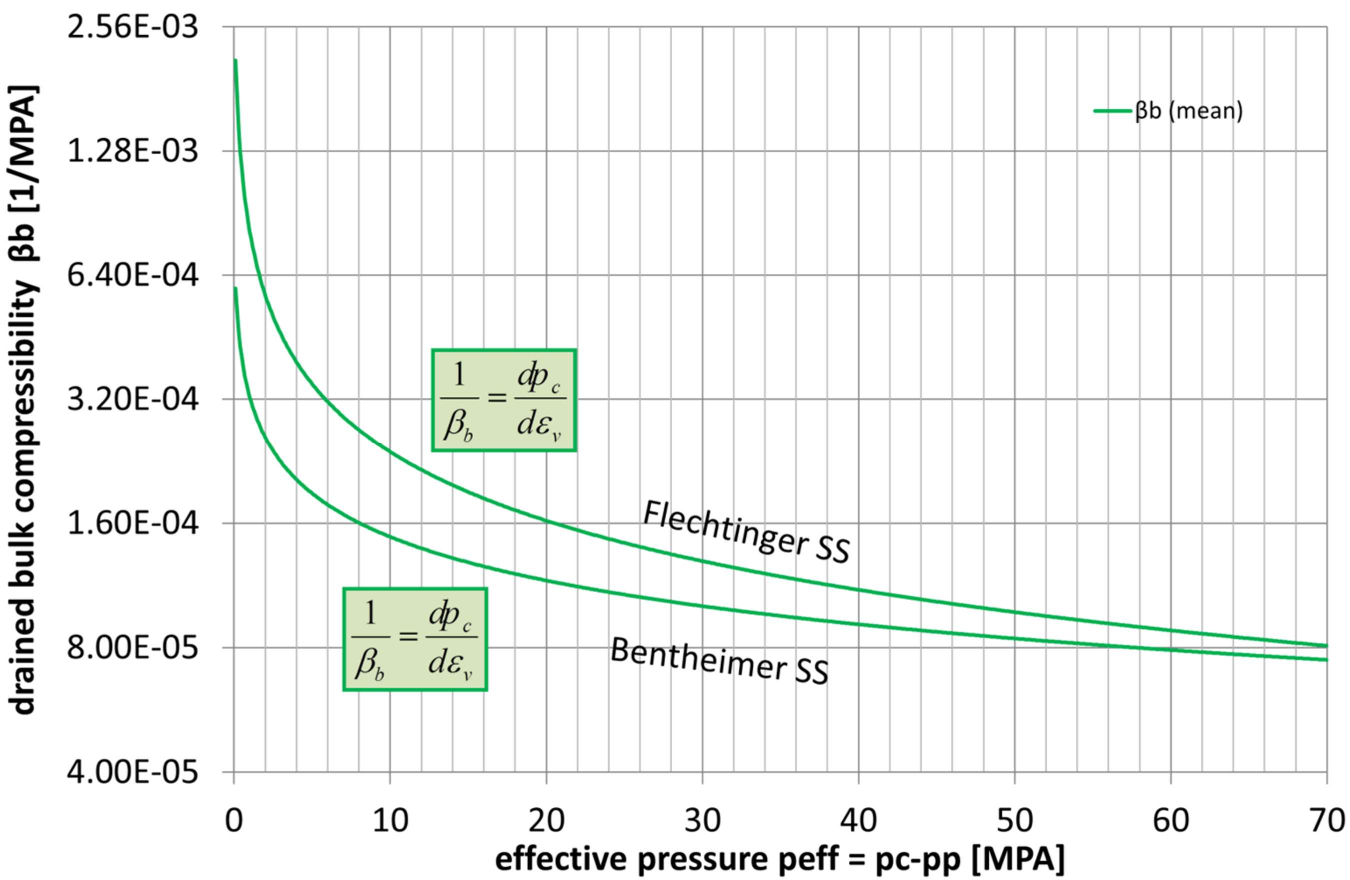


Biot coefficient α



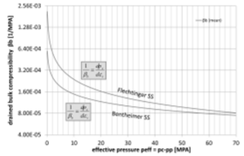
Skempton coefficient B



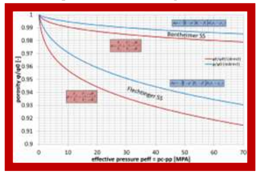


Results Comparison

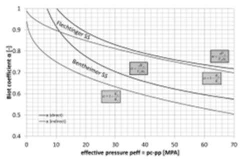
compressibility βb



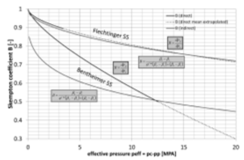
porosity ϕ

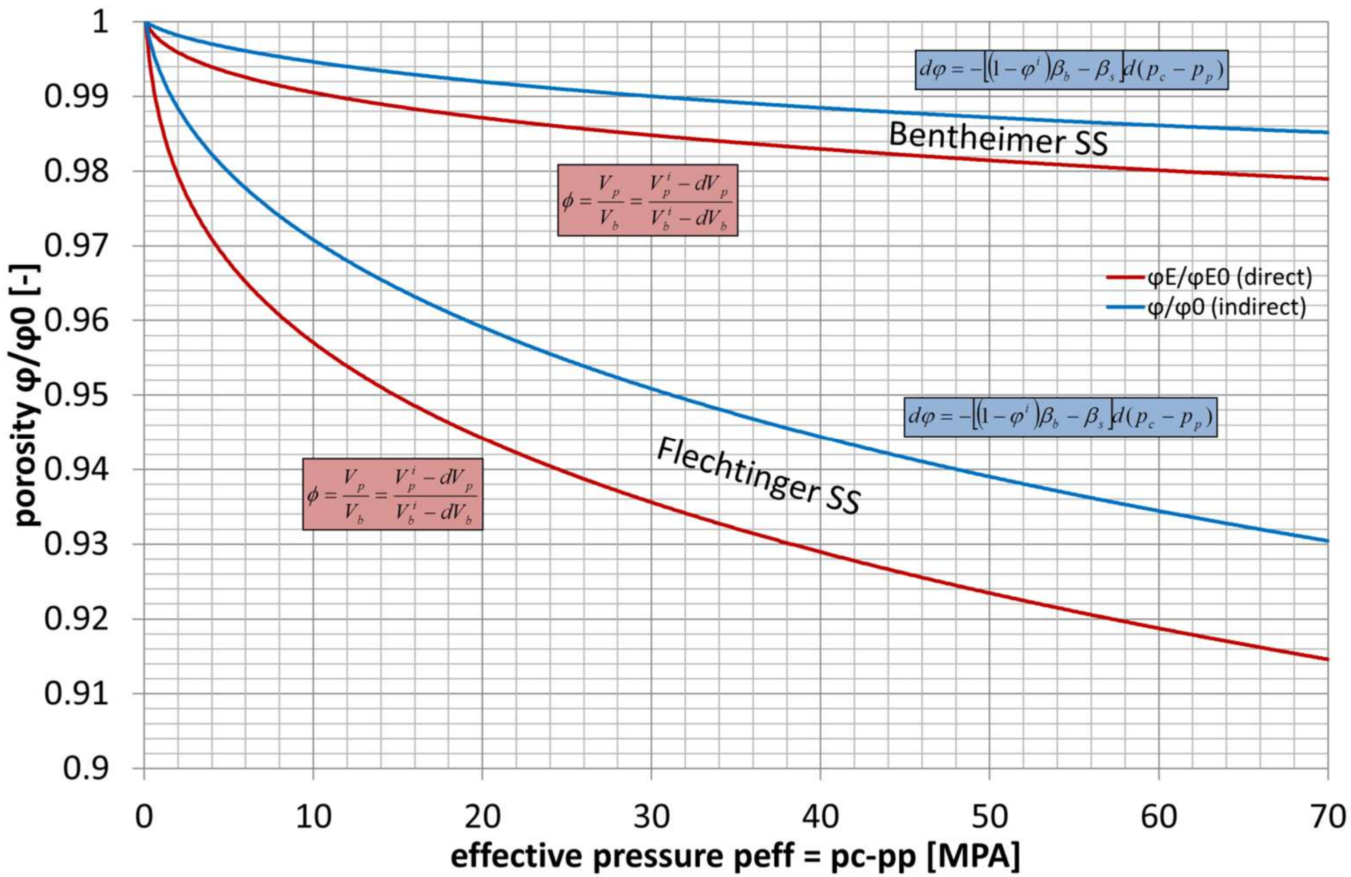


Biot coefficient α



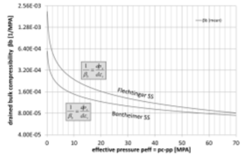
Skempton coefficient B



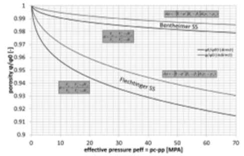


Results Comparison

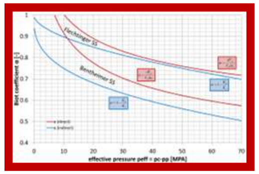
compressibility βb



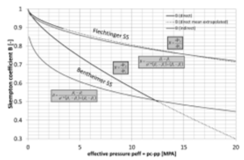
porosity ϕ

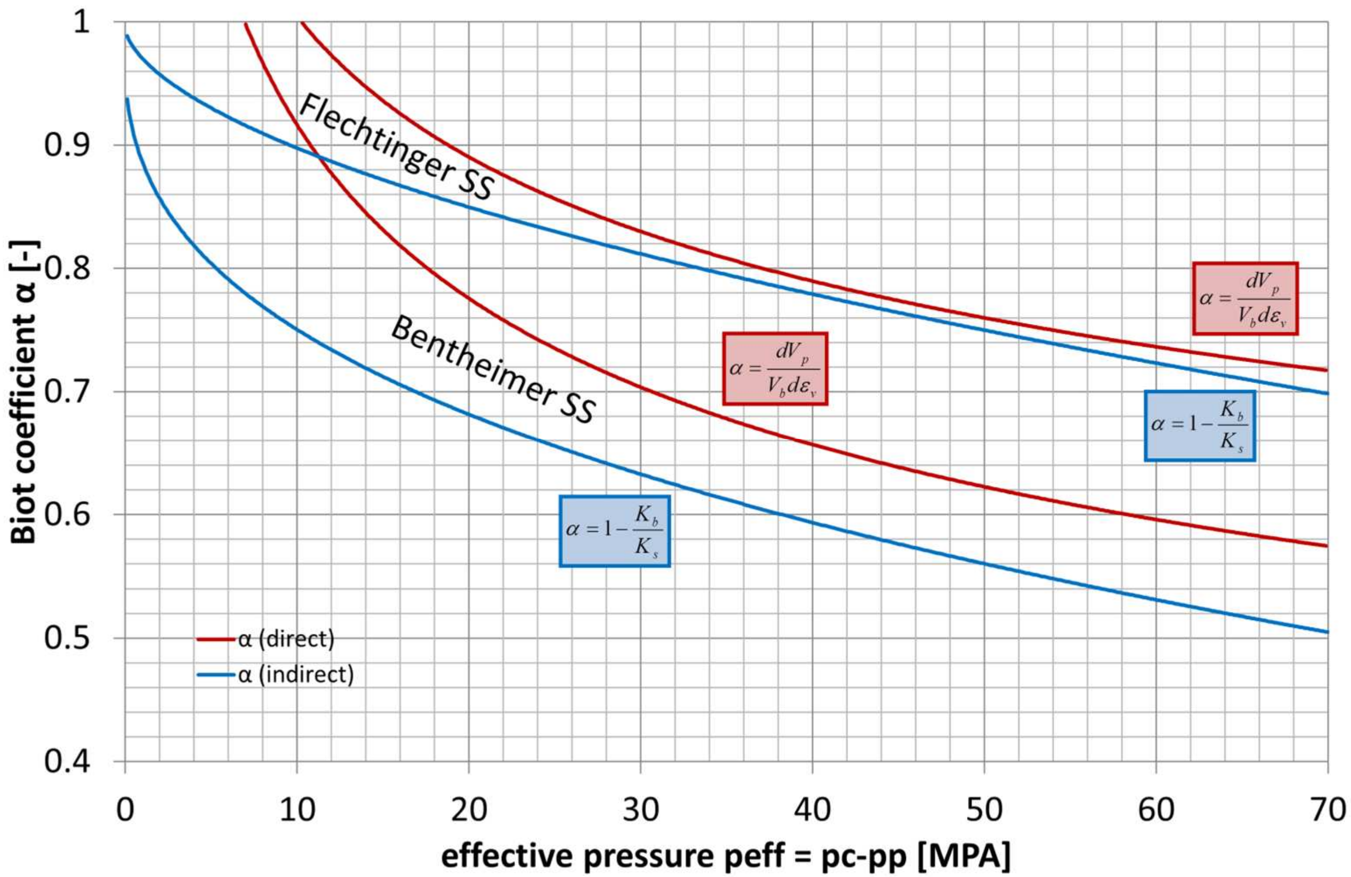


Biot coefficient α



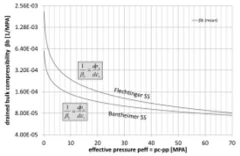
Skempton coefficient B



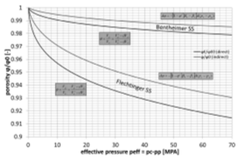


Results Comparison

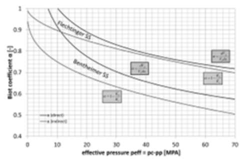
compressibility βb



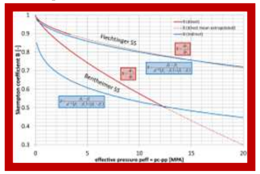
porosity ϕ

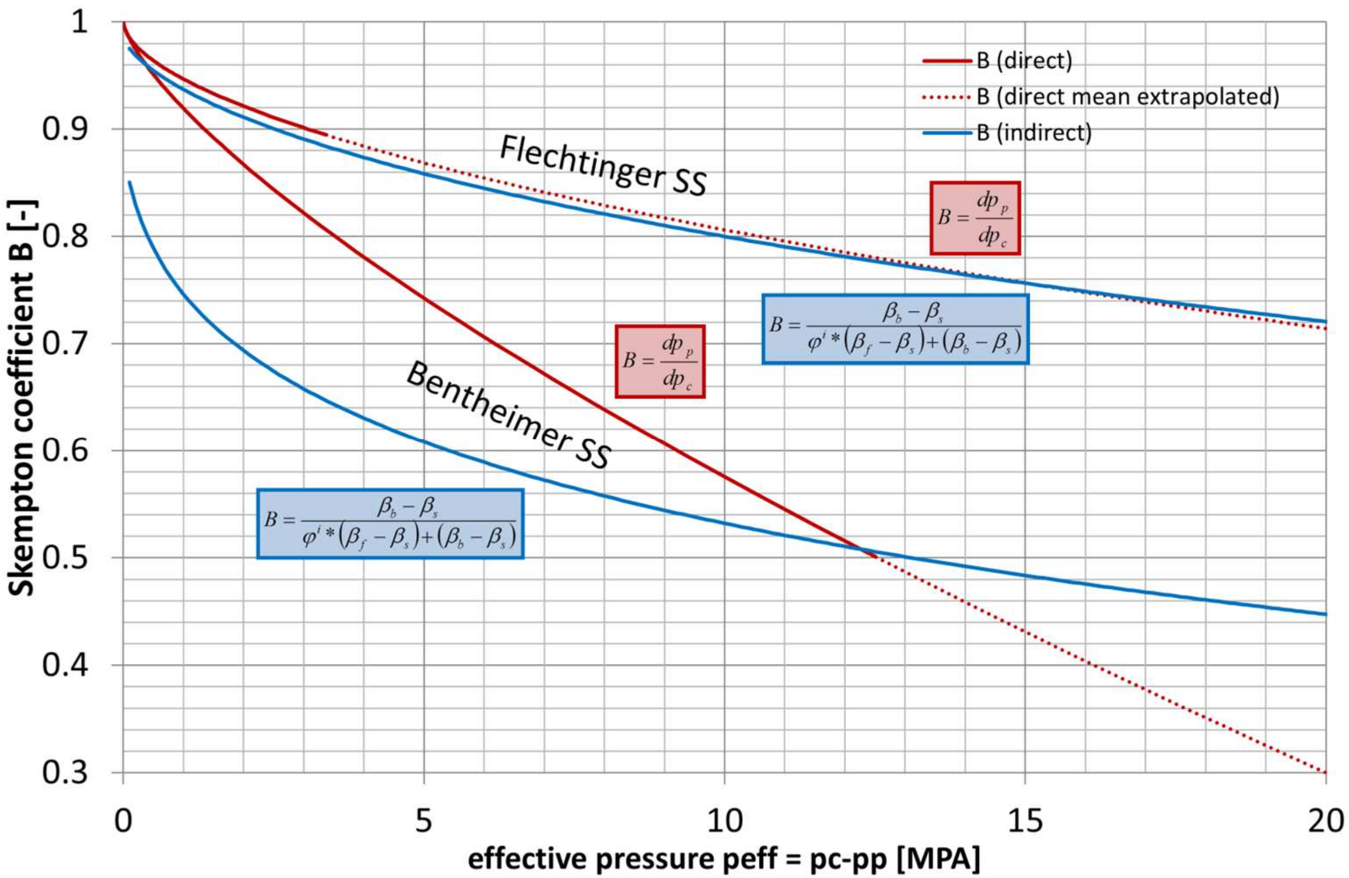


Biot coefficient α

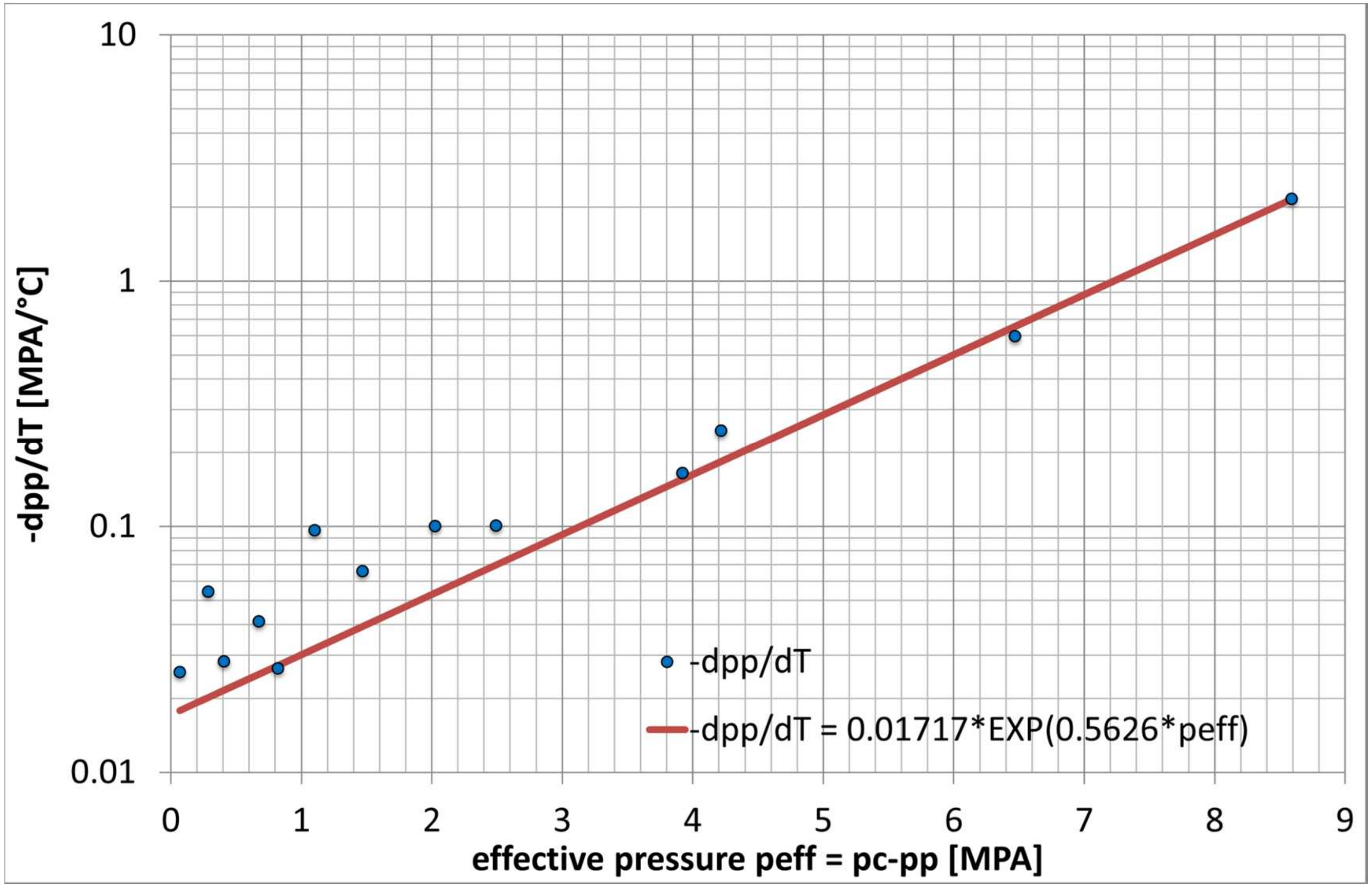


Skempton coefficient B





Results Thermo-elastics



Conclusions

- The poro-elastic behaviour of two different sandstones **Bentheimer SS** & **Flechtinger SS** were investigated by means of fibre optic technique
- Direct and indirect methods for **porosity**, **Biot coefficient** and **Skempton coefficient** measurements were compared
  - Porosity: good agreement
  - Biot coefficient: good agreement at higher effective pressure
  - Skempton coefficient: excellent agreement for Flechtinger SS and poor agreement for Bentheimer SS
- **Fibre optic technique** improves undrained measurement although effective pressure can not be adjusted
- **Temperature effect** are more pronounced at high effective pressure dpp/dT=-0.017EXP(0.56peff)

Future Work

- Improvement of fibre optic technique, e.g. test assembly, data processing, quantity of sensors
- New applications:
  - Pressure distribution along fractures
  - Pressure propagation in shales
- Further investigation of thermo-elastic effects by meassuring T and p simultaneously at the same point

Thanks for your Attention