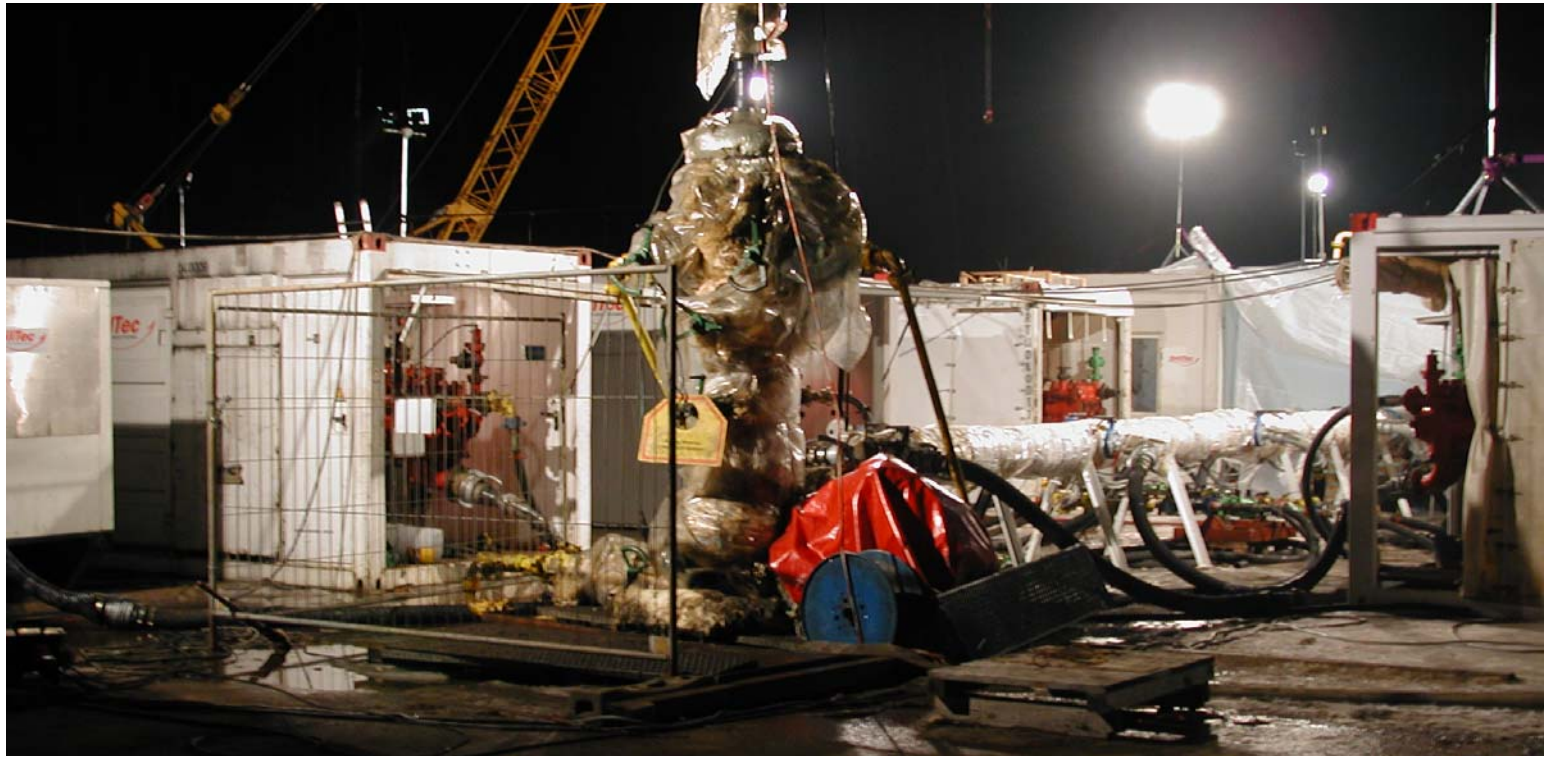
Hydraulic Fracturing and Formation Damage in a Sedimentary Geothermal Reservoir



A. Reinicke, B. Legarth, G. Zimmermann, E. Huenges and G. Dresen

ENGINE – **EN**hanced **G**eothermal **I**nnovative **N**etwork for **E**urope
Workshop 3, "Stimulation of reservoir and microseismicity"
Kartause Ittingen, Zürich, June 29 – July 1, 2006, Switzerland

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The Geothermal in-situ Laboratory Groß Schönebeck 3/90

in-situ laboratory
Groß Schönebeck

In 2002 hydraulic stimulation experiments were conducted in a remediated Rotliegend-well Groß Schönebeck 3/90.

the aim:

Development of technologies to use primary low-productive aquifers for geothermal power generation

objectives:

- **enhance the inflow performance**
- **create new highly conductive flow paths in a porous-permeable rock matrix**
- **maximise potential inflow area**
- **testing the technical feasibility of the fracturing concept**

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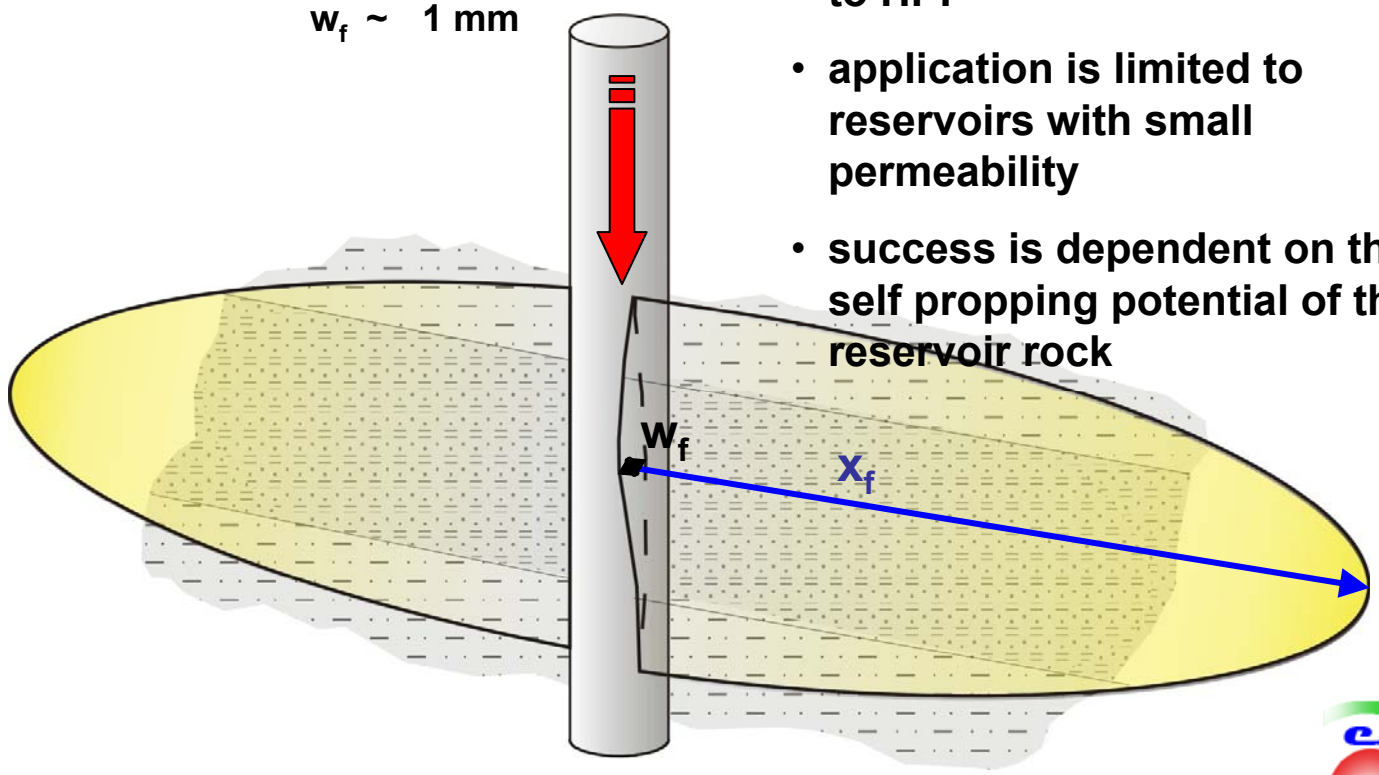
Hydraulic Stimulation Technique: Waterfracs (WF)

low viscous gels:	η	=	10 cP
without proppants or small proppant concentration:	c	=	50 - 200 g/l
long fractures:	x_f	≤	250 m
small width:	w_f	~	1 mm

- connect reservoir regions far from well / maximise inflow area
- reduction in costs compared to HPF
- application is limited to reservoirs with small permeability
- success is dependent on the self propping potential of the reservoir rock



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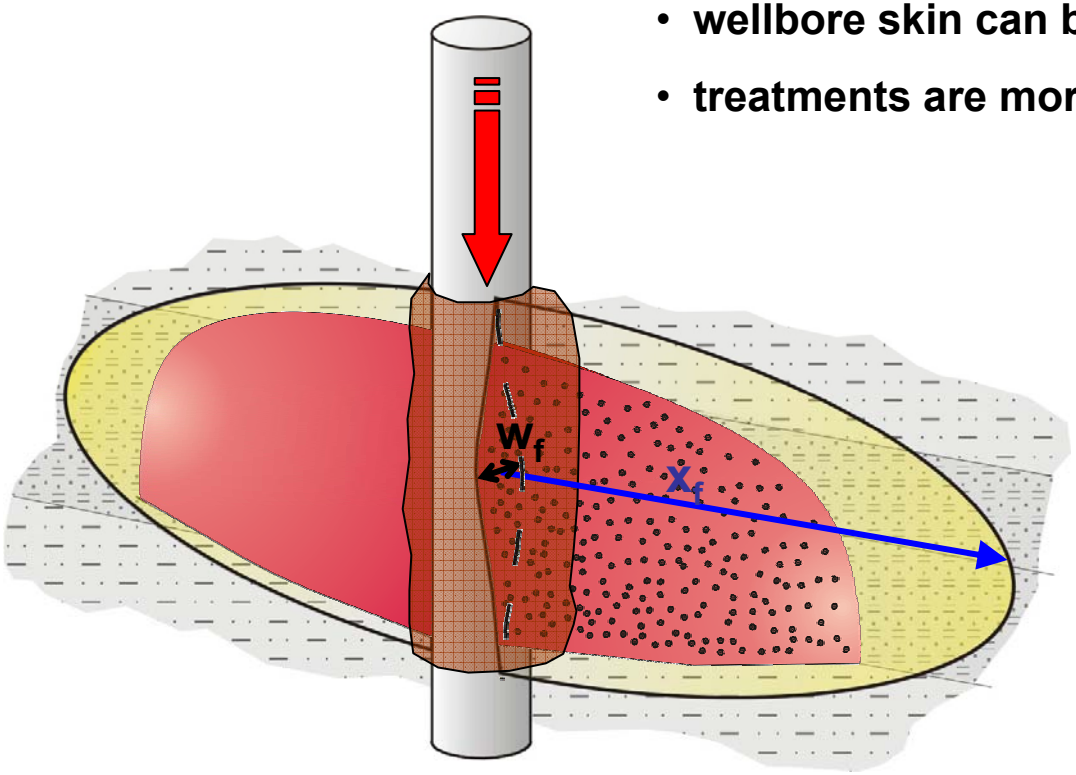
Hydraulic Stimulation Technique: Hydraulic Proppant Fracs (HPF)

high viscous gels:	η	$\geq$	100 cP
high proppant concentration:	c	=	200 - 2000 g/l
shorter fractures:	x_f	$\leq$	150 m
large width:	w_f	=	1 - 25 mm

- wide range of formations (permeabilities) can be treated
- good control of stimulation parameters
- wellbore skin can be bypassed
- treatments are more expensive



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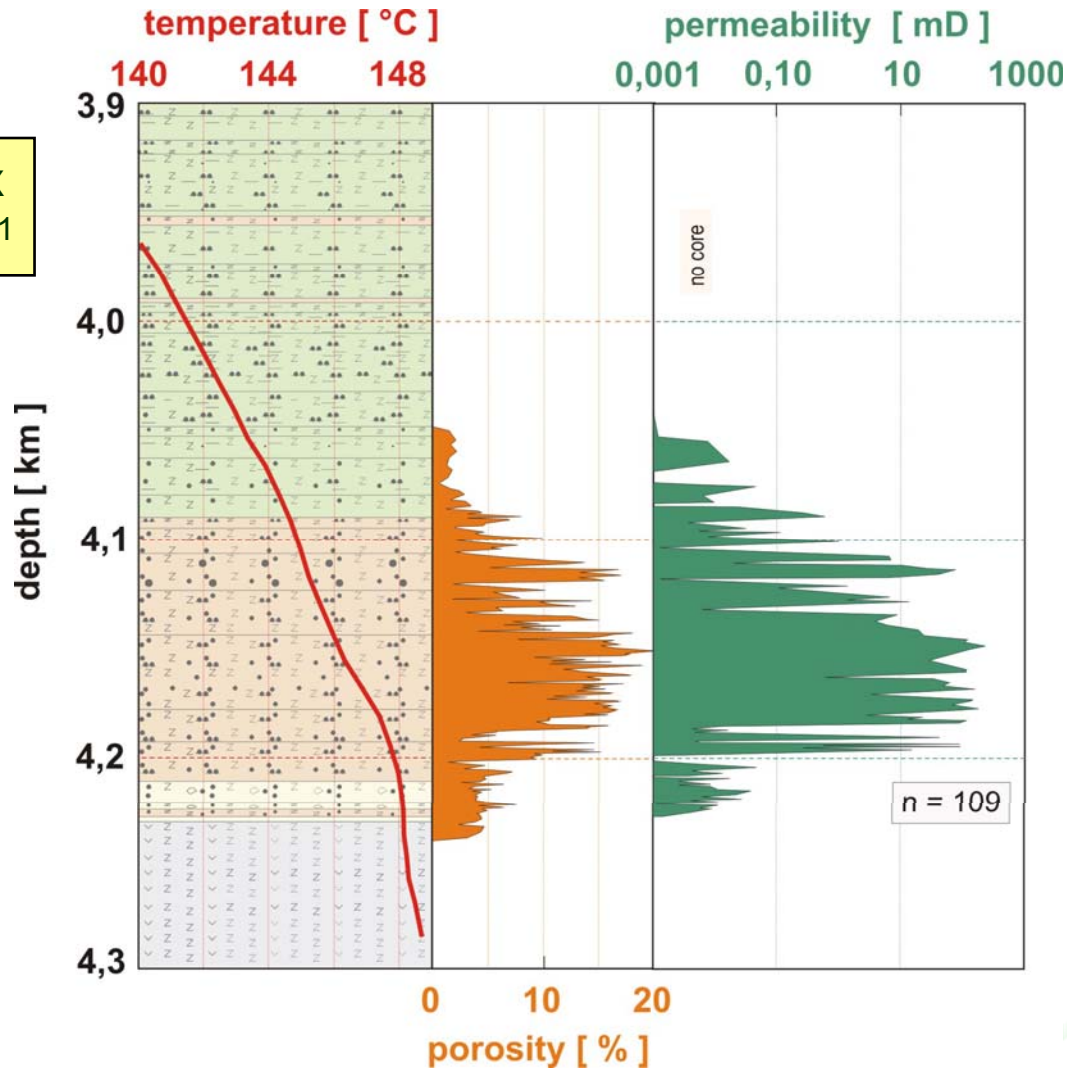
Lithology, Temperature Profile and Petrophysical Reservoir Parameters

initial productivity index
$PI_{prefrac}$: 1.2 $m^3\ h^{-1} MPa^{-1}$

HPF treatments of sandstones to enhance productivity



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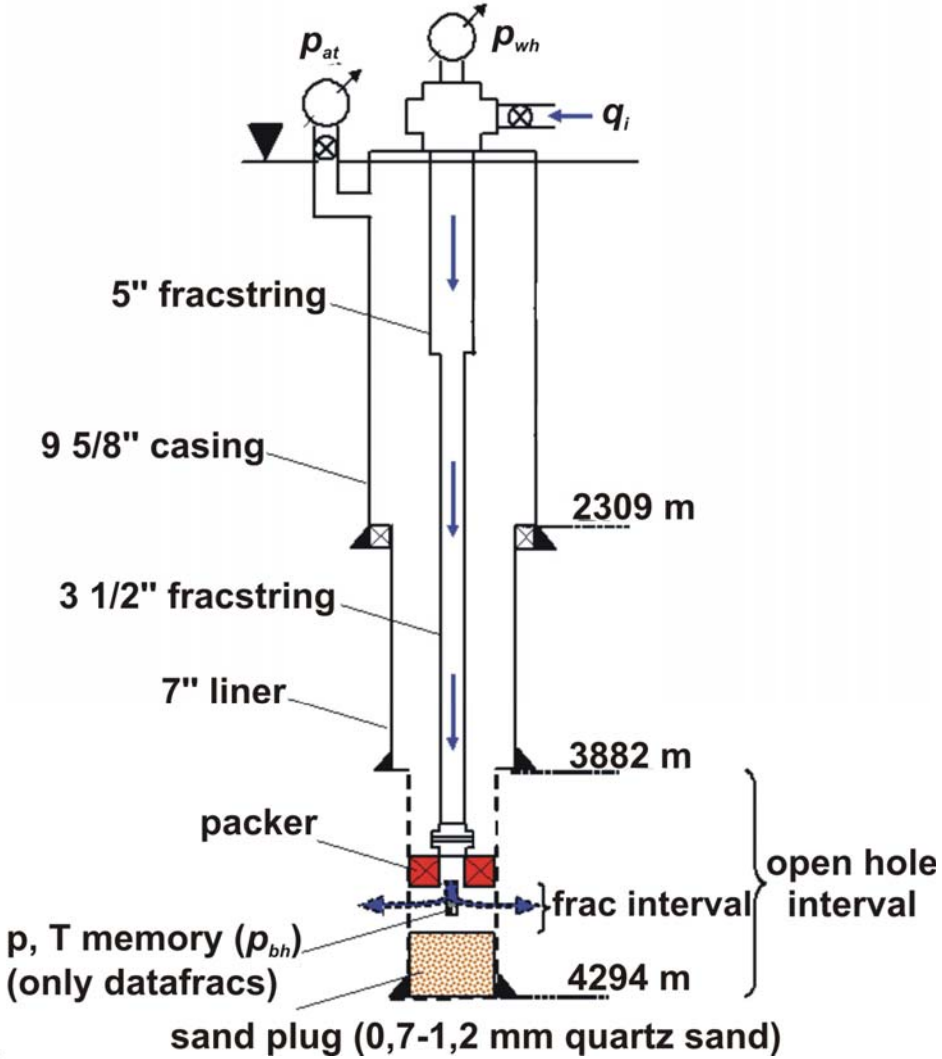
Technical Concept and Chronology of Operations of HPF Treatments in 2002



perforation: 4168 - 4169 m

↓

sand up to 4190 m
packer set. Depth:4130 m

1. lifttest
datafrac 1
T-Log
mainfrac 1 with proppants
2. lifttest

↓

sand up to 4122 m
packer set. Depth:4085 m

datafrac 2
T-Log
mainfrac 2 with proppants

↓

extract sand plug
flowmeter log
casinglift test

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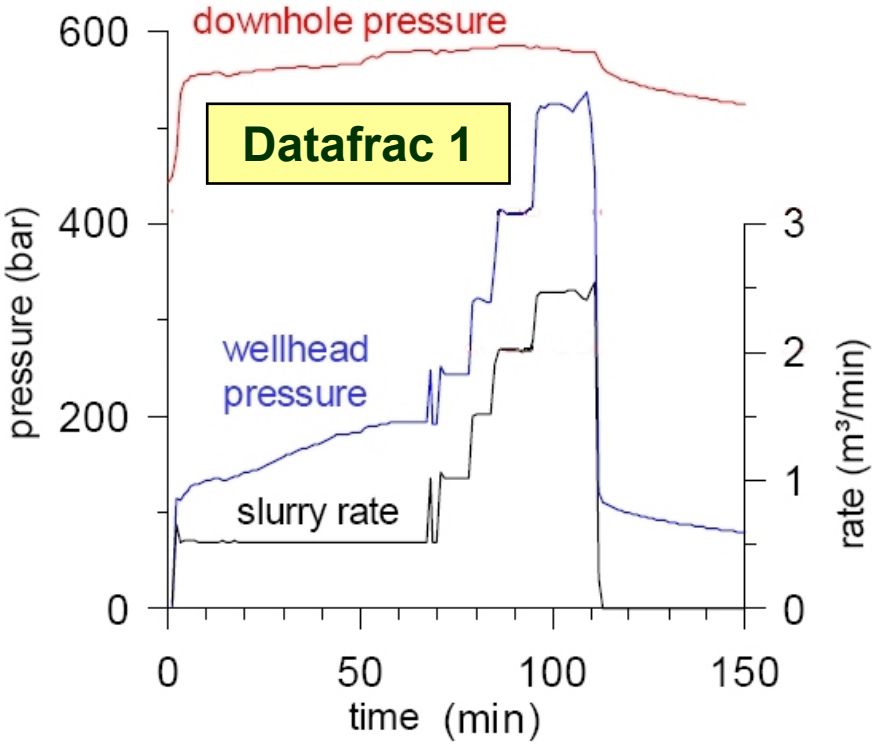
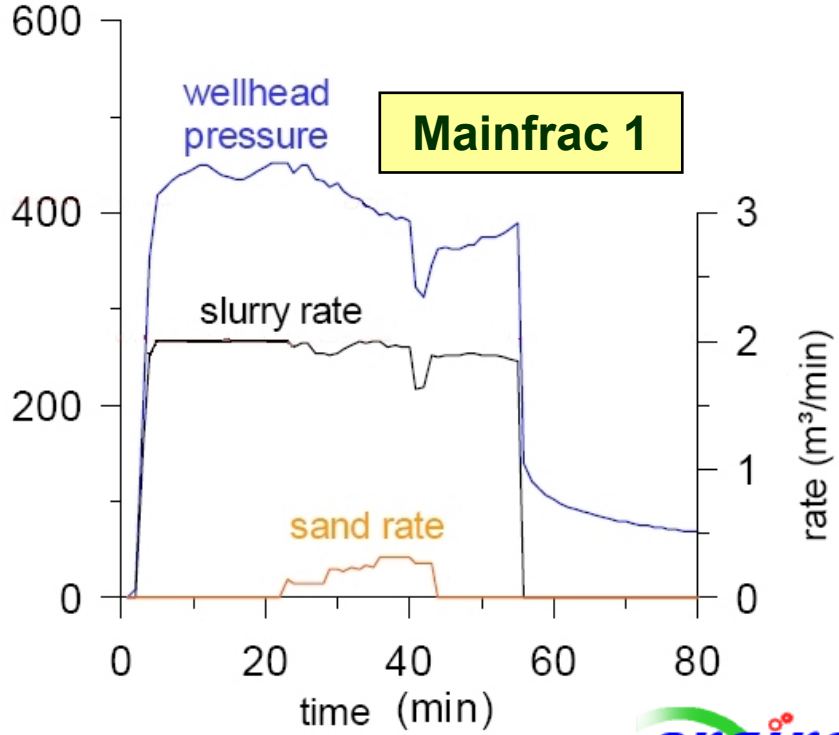
HPF Treatments: Datafrac 1 and Mainfrac 1

Lack of experience with open hole packer treatments at high temperatures

→ less aggressive frac design

- smaller volumes: ~ 100 m^3
- lower proppant concentrations: ~ 280 g/l
- lower pumping rates: ~ 2 m^3/min





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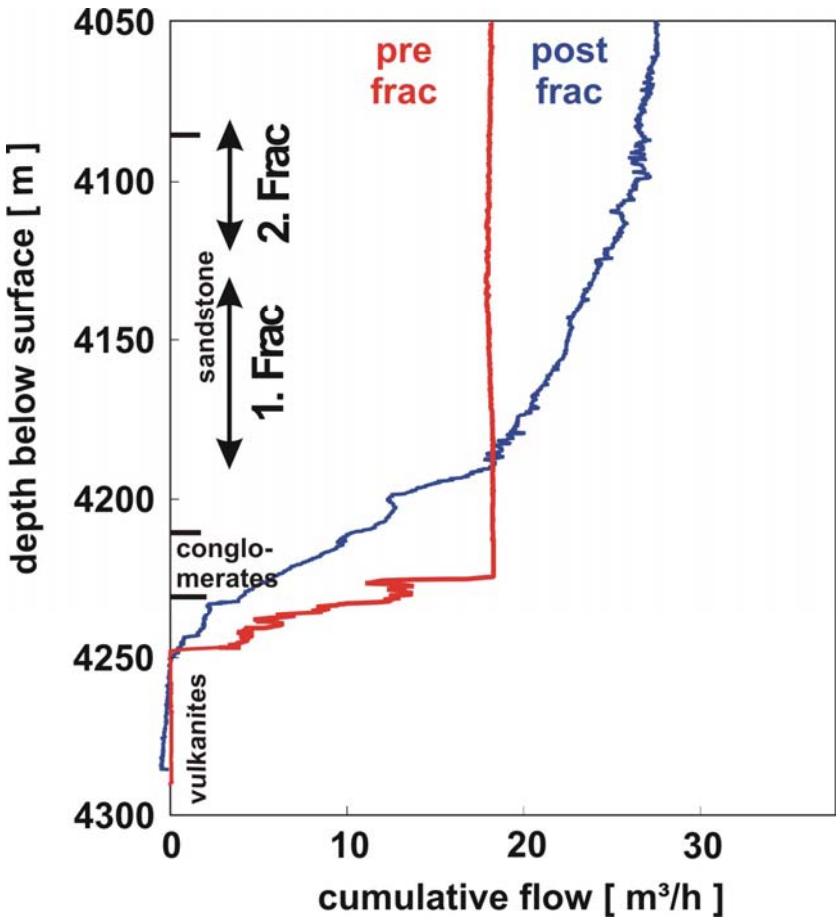
Hydraulic Reservoir Behaviour and Stimulation Effect



significant upward extension of inflow area due to new axial fractures

$PI_{prefrac}$: $1.2\ m^3\ h^{-1} MPa^{-1}$

$PI_{postfrac}$: $2.1\ m^3\ h^{-1} MPa^{-1}$

$PI_{predicted}$: $8.3\ m^3\ h^{-1} MPa^{-1}$ (1)

inflow impairment due to non-Darcy-flow effects and proppant pack damage

(1) Legarth, et al., 2005a

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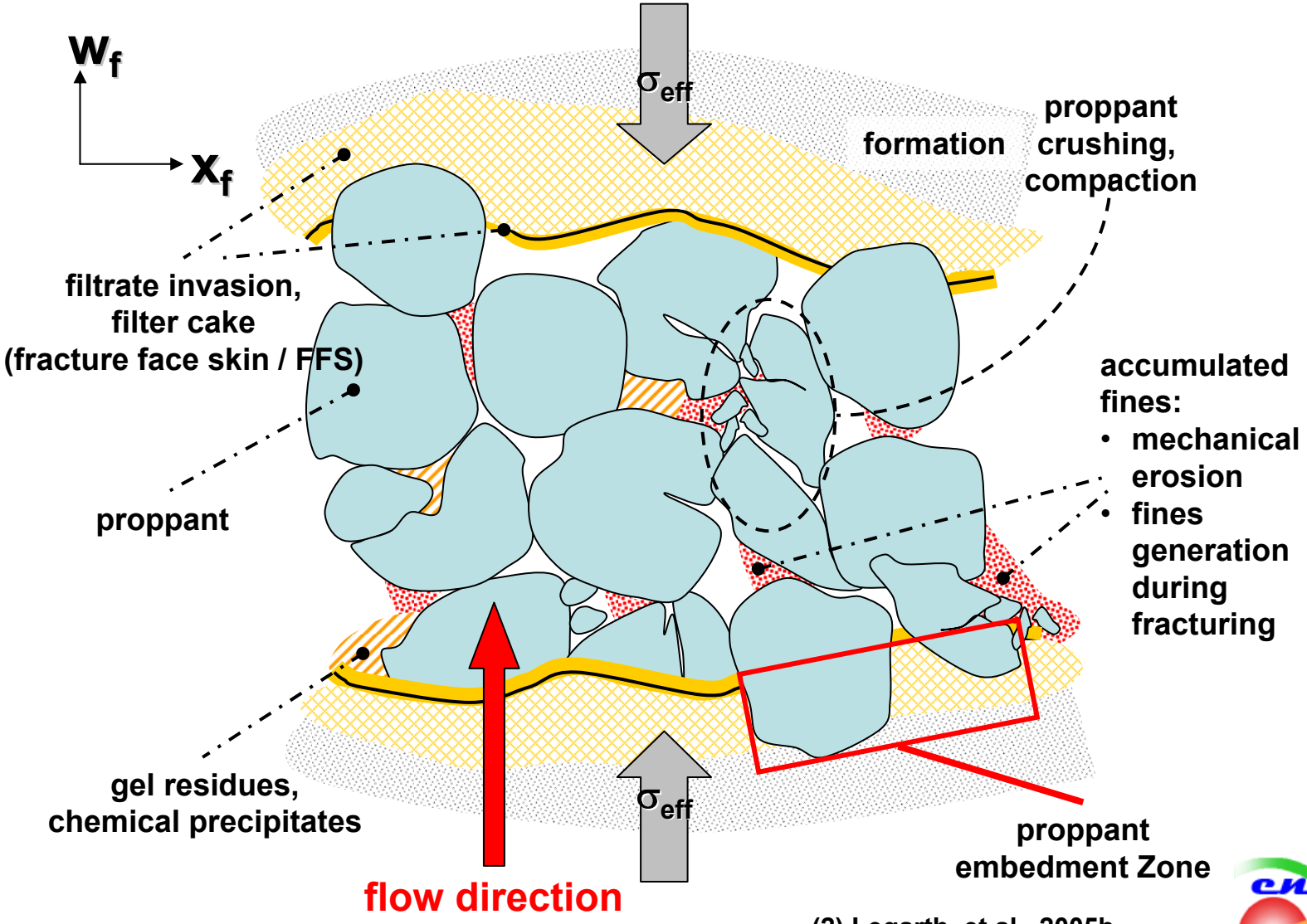
Potential Damage Effects in a Propped Fracture



(2) Legarth, et al., 2005b

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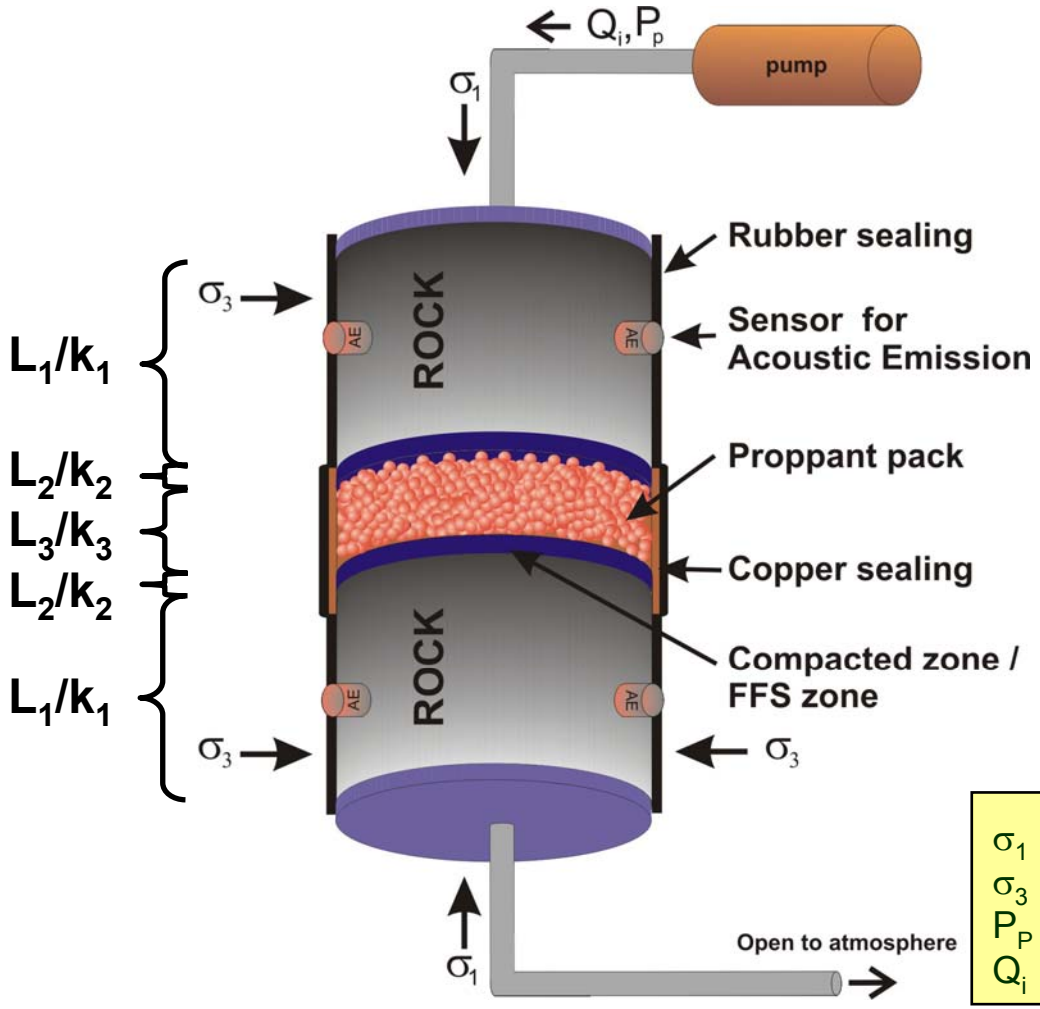
Experimental Setup for Proppant Rock Interaction Testing



$$\Delta P = \frac{Q \cdot \eta}{A}\left[\frac{2 \cdot L_1}{k_1} + \frac{2 \cdot L_2}{k_2} + \frac{L_3}{k_3}\right]$$

A [m²]	area of the sample
η [Pas]	dyn. viscosity
k_1 [m²]	permeability of the rock
k_2 [m²]	permeability of FFS zone
k_3 [m²]	permeability of proppant pack
L_1 [m]	length of one half of the sample
L_2 [m]	extent of FFS zone
L_3 [m]	fracture width
L_t [m]	total length

σ_1	[MPa]	Axial stress
σ_3	[MPa]	Conf. pressure
P_P	[bar]	Pore pressure
Q_i	[ml/min]	Flow rate

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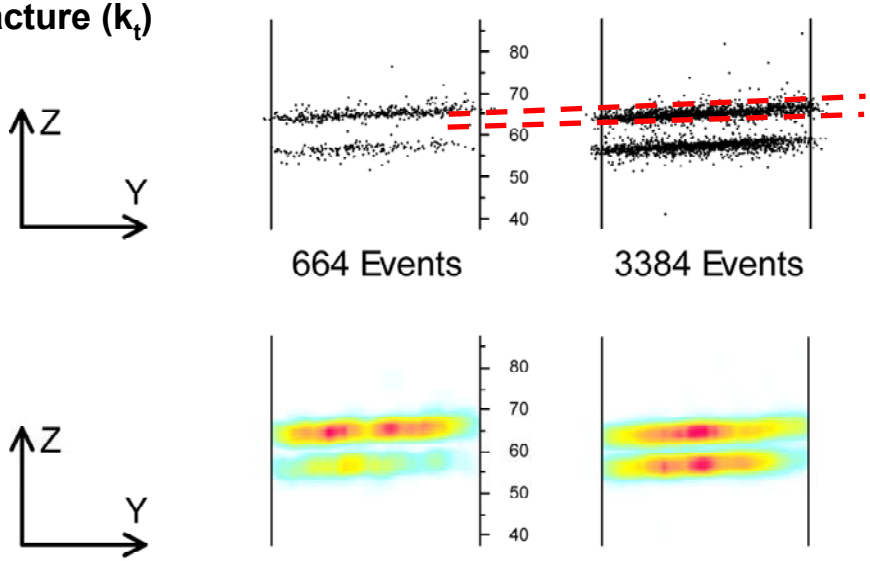
Triaxial Test of a Propped Fracture: Permeability and AE-Activity at Different Stress Levels

Effective Stress	5 MPa	20 MPa
Permeability with propped fracture (k_t)	125 ± 5 mD	116 ± 4 mD



$$k_2 = \frac{k_t k_1 L_2}{L_t(k_1 - k_t) + L_2 k_t}$$

L_2 = 4 mm L_t = 125 mm
k_3 = ∞
(260 D @ 50 MPa eff. stress)

k_2 = 3.7 mD

Rock:	**Bentheim sandstone**	**Porosity: 23%**	**Initial Permeability (k_1): 1250 mD**
Proppants:	**Carbo Lite**	**Mesh: 20/40**	**Concentration: 2lbs/ft²**
Test data:	**Ø = 50 mm**	**σ_3 = 10 MPa**	**Q = 50 ml/min**

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Conclusions

HPF treatment in geothermal research well Groß Schönebeck 3/90

- clear productivity (PI) enhancement achieved
- new axial propped fractures were created

  BUT:
- productivity increase less than expected
- post-job damage (mechanical, non Darcy flow effects)

Proppant rock interaction testing

- Crushing of grains and/or proppants starts at low effective stress (~5 MPa)
- Concentration of AEs at the fracture face
- With increasing effective stress AE activity moves into the proppant pack
- Drastic reduction of sample permeability

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References:

(1) Legarth, B., Huenges, E. and Zimmermann, G., 2005a. *Hydraulic Fracturing in Sedimentary Geothermal Reservoirs: Results and Implications*, Int. Journal of Rock Mech., Vol. 42 p. 1028–1041

(2) Legarth, B., Raab, S., Huenges, E., 2005b. *Mechanical Interactions between proppants and rock and their effect on hydraulic fracture performance*, DGMK-Tagungsbericht 2005-1, Fachbereich Aufsuchung und Gewinnung, 28.-29. April 2005, Celle, Deutschland, pp. 275-288

(3) Cinco-Ley, H., Samaniego-V, F., 1977. *Effect of Wellbore Storage and Damage on the Transient Pressure Behaviour of vertically Fractured Wells*, SPE 6752

(4) Romero, D.J., Valkó, P.P., Economides, M.J., 2003. *Optimization of the Productivity Index and the Fracture Geometry of a Stimulated Well With Fracture Face and Choke Skin*, SPE 81908

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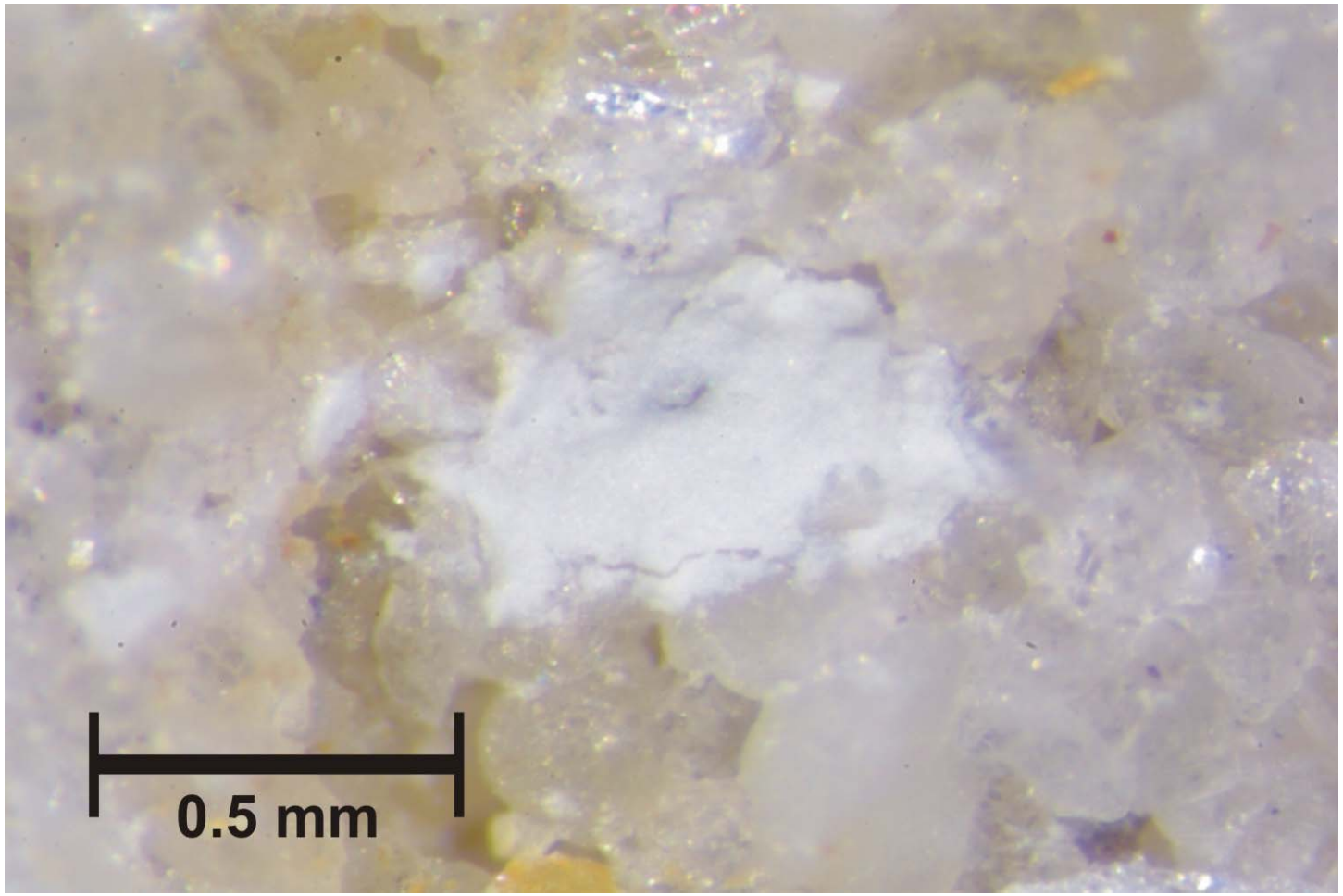
Proppant Imprint (Embedment) into Rock Matrix



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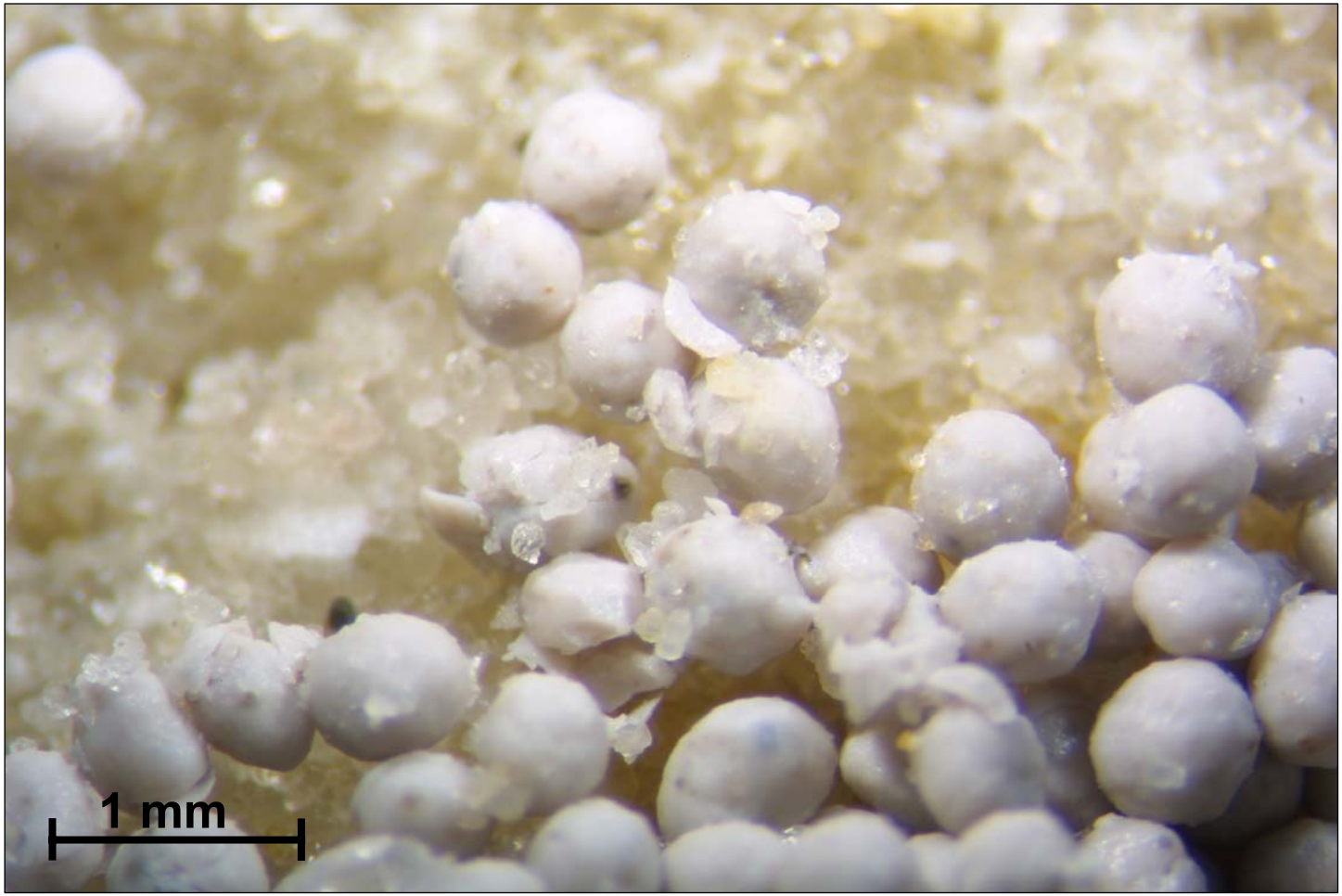
Triaxial Test of a Propped Fracture
Crushed Proppants and Fines



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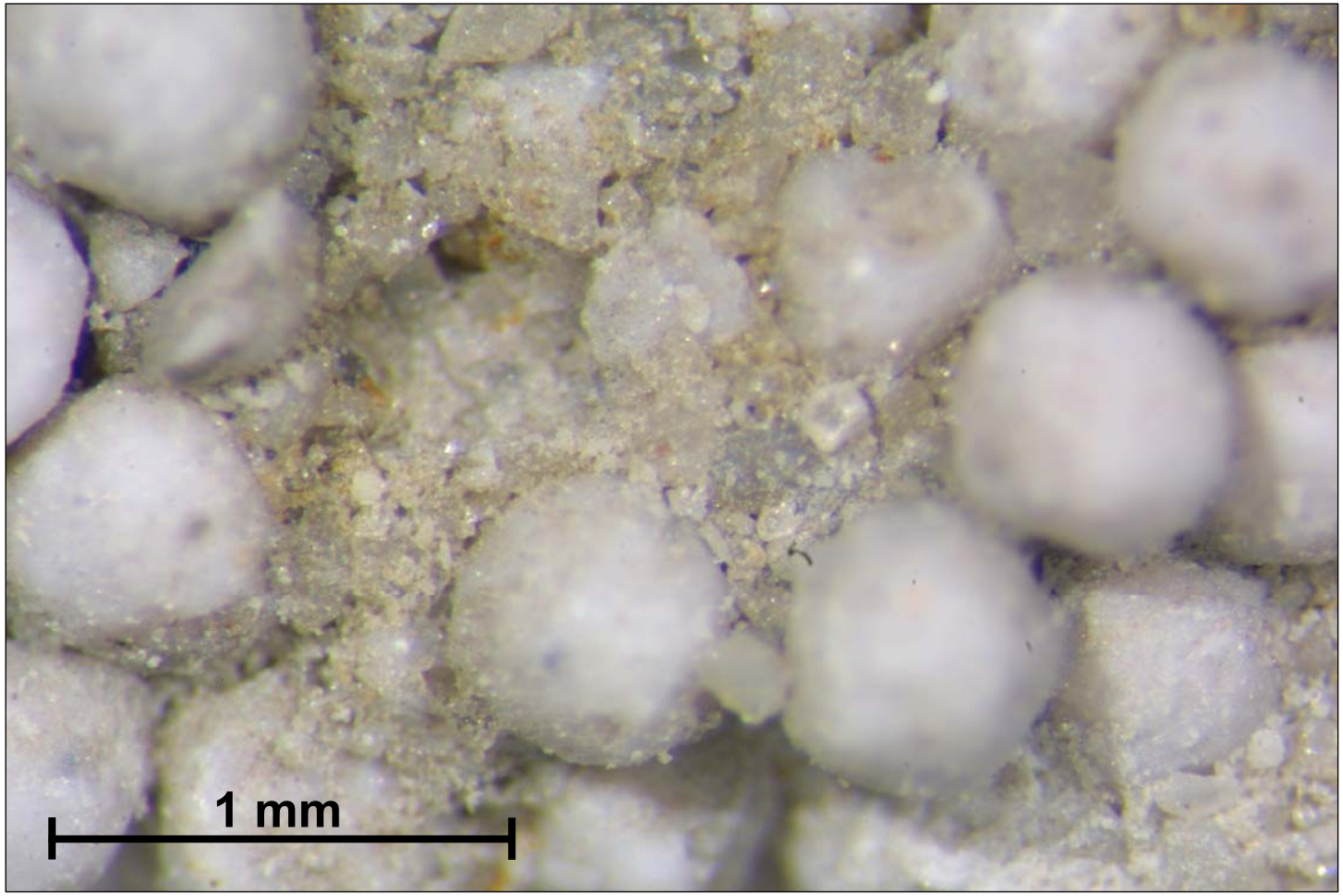
Lab Testing: Picture of crushed Proppants and Fines



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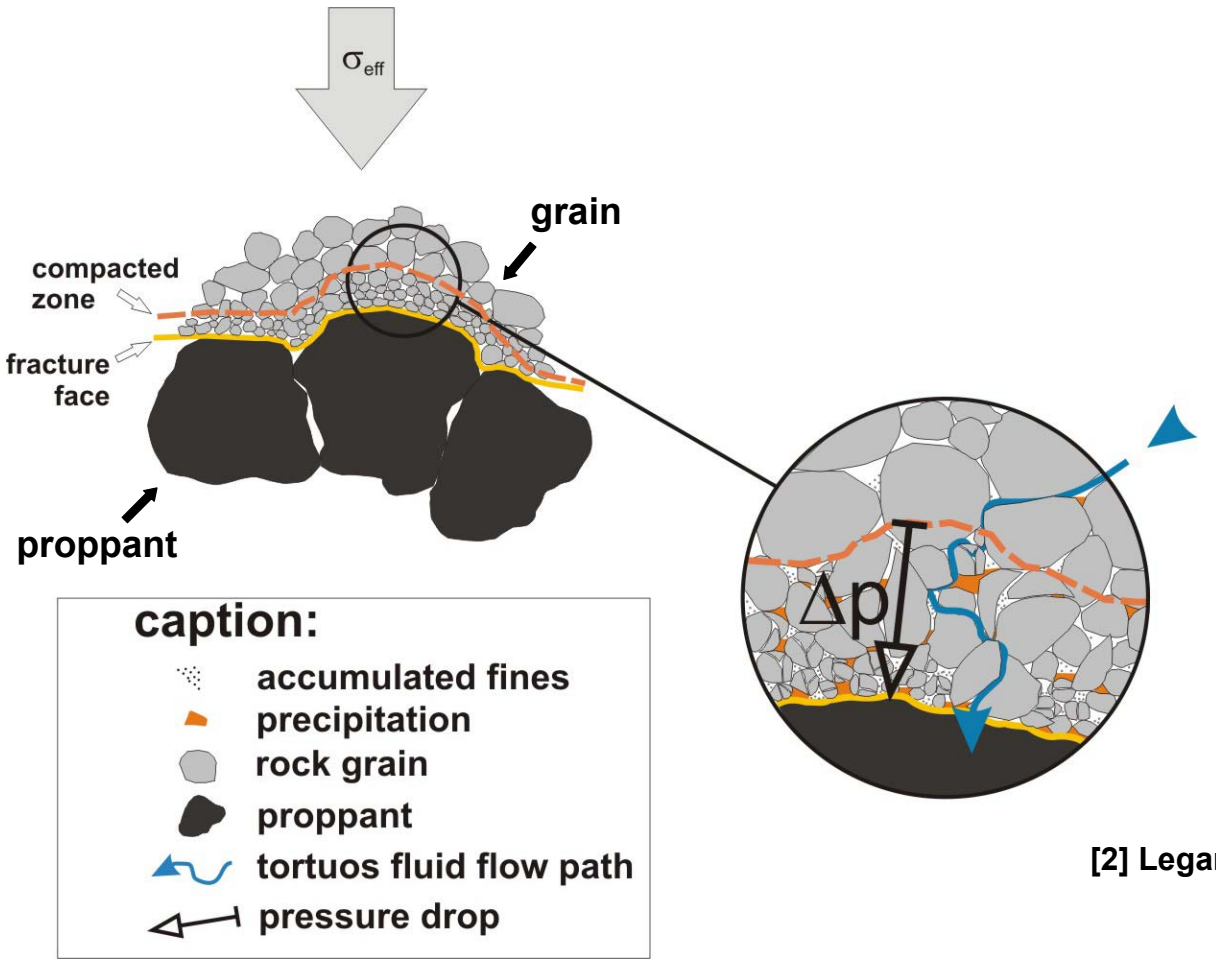
Mechanical Induced FFS



[2] Legarth, et al., 2005

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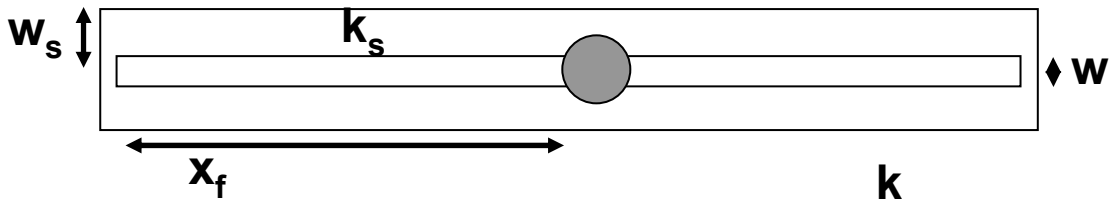
Fracture Face Skin (FFS)



$$s_{ff} = \frac{\pi \cdot w_s}{2 \cdot x_f}\left(\frac{k}{k_s} - 1\right)$$

Eq. 1) Fracture Face Skin-factor [1]

s_{ff} [-]	Fracture Face Skin-factor
w [m]	Fracture width
w_s [m]	Skin zone depth
k [m²]	Reservoir permeability
k_s [m²]	Skin zone permeability
x_f [m]	Fracture half length

[1] Cinco-Ley, et al., 1977

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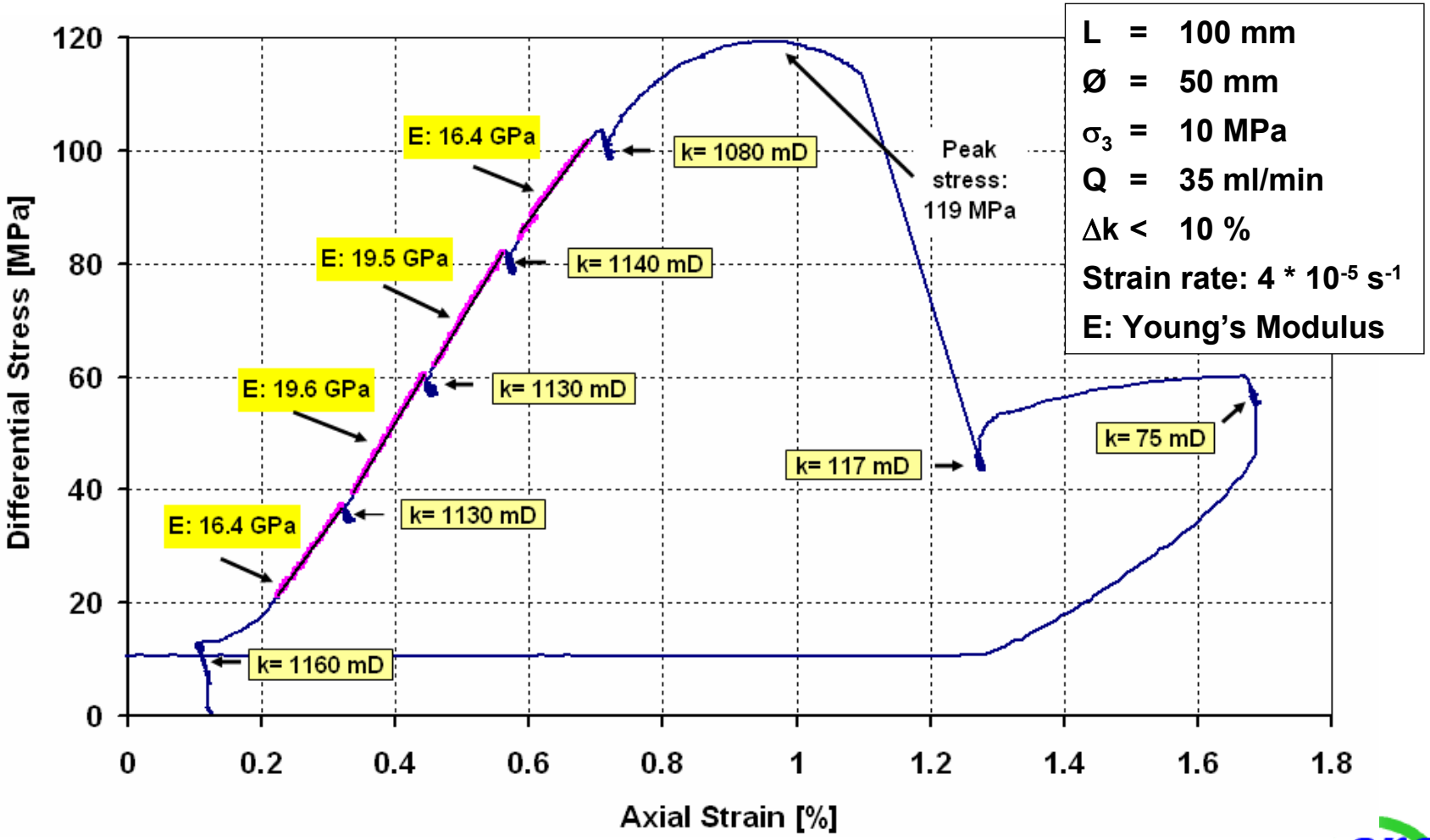
Triaxal Test on Bentheim Sandstone



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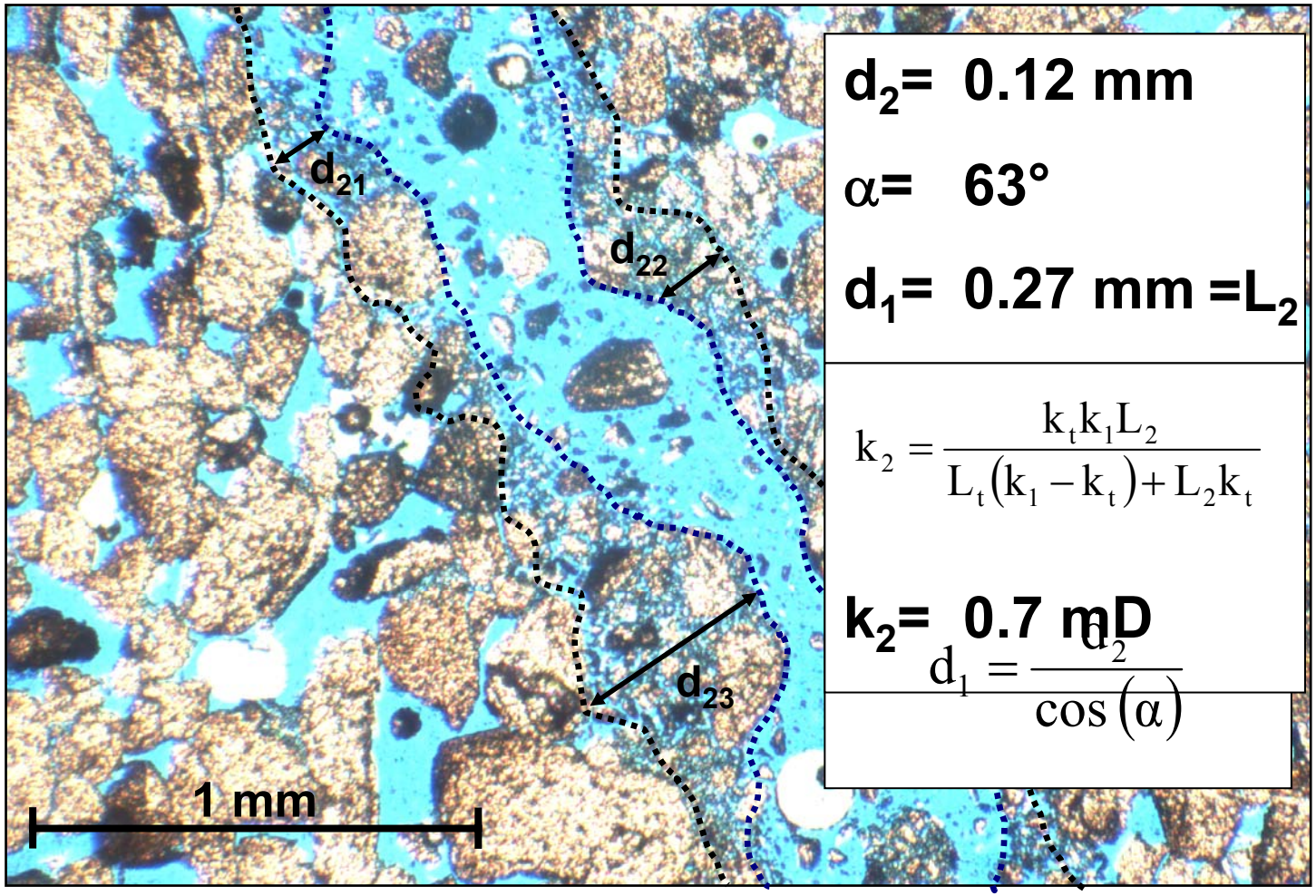
Micrograph of the Created Shear Fracture / Permeability of Damaged Zone



d_2= 0.12 mm

α= 63°

d_1= 0.27 mm =L_2

$$k_2 = \frac{k_t k_1 L_2}{L_t(k_1 - k_t) + L_2 k_t}$$

k_2= 0.7 mD

$$d_1 = \frac{d_2}{\cos(\alpha)}$$

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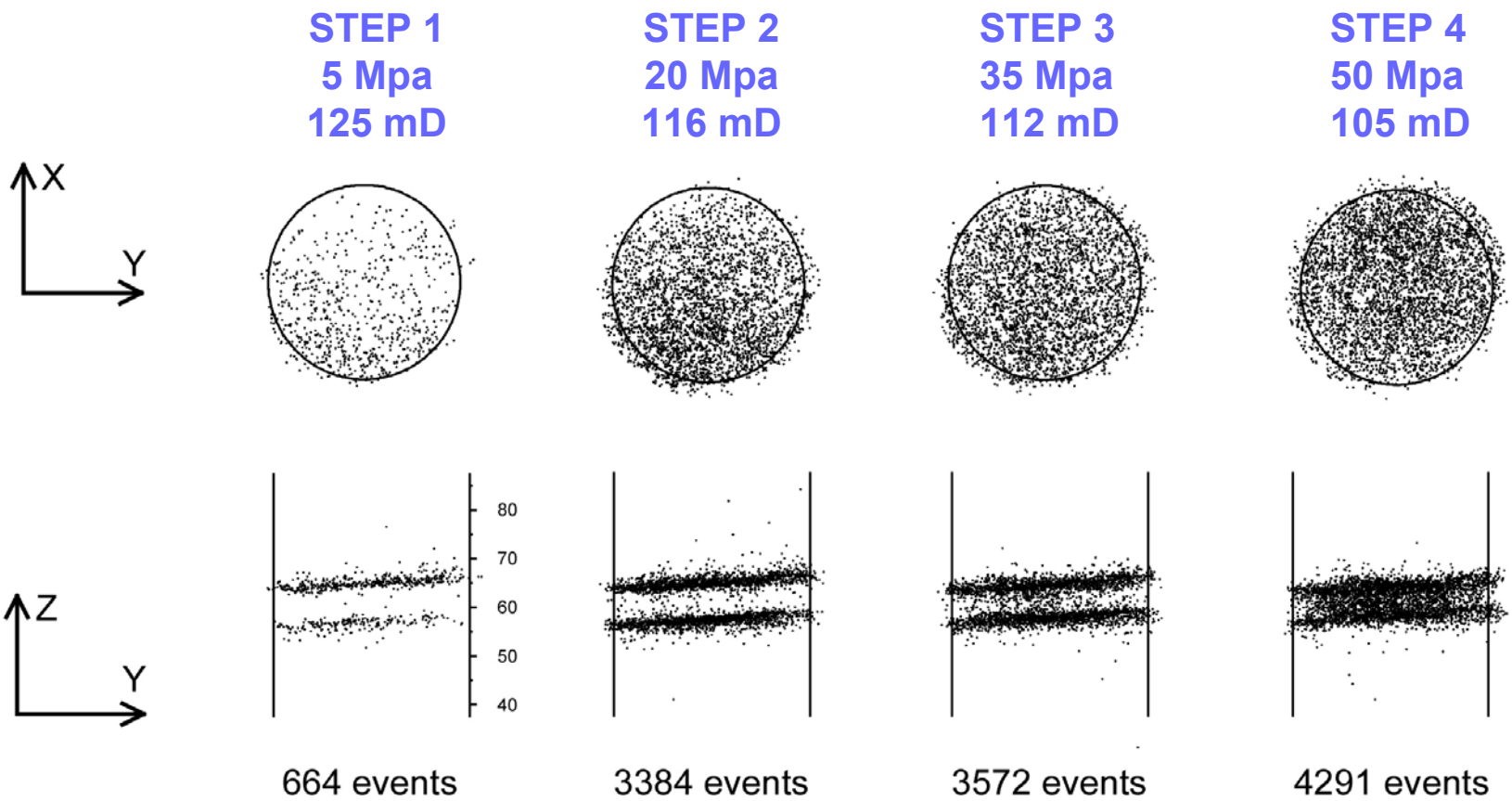
Lab Testing: AE-Activity



Resolution < 2 mm / Amplitude > 3 V

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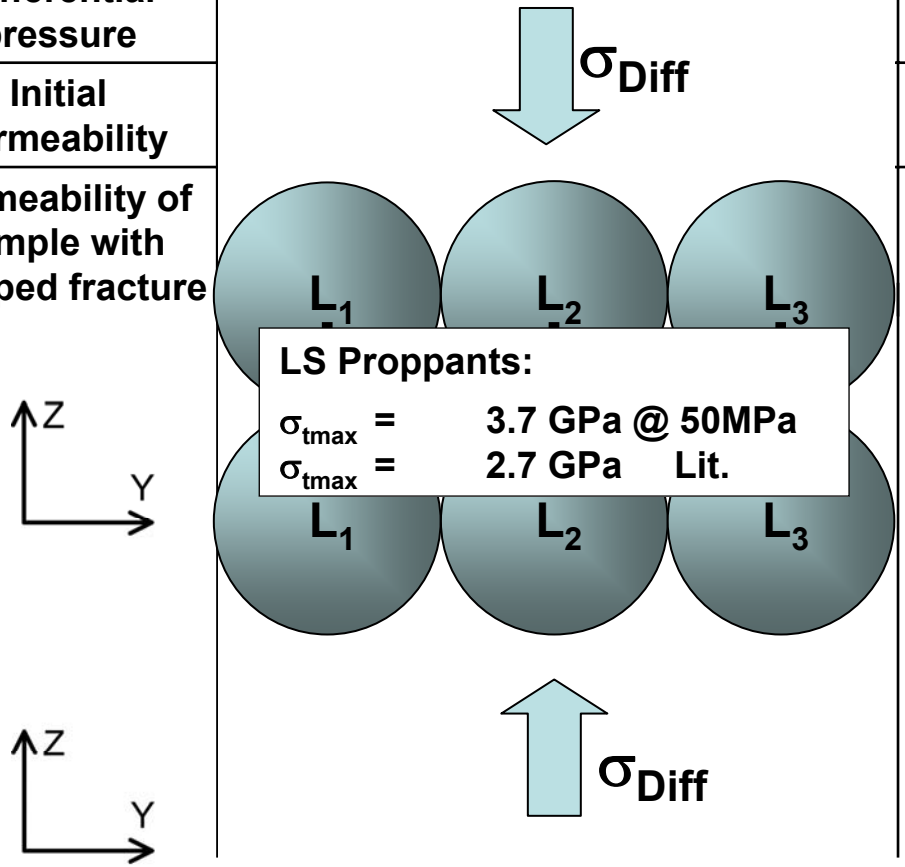
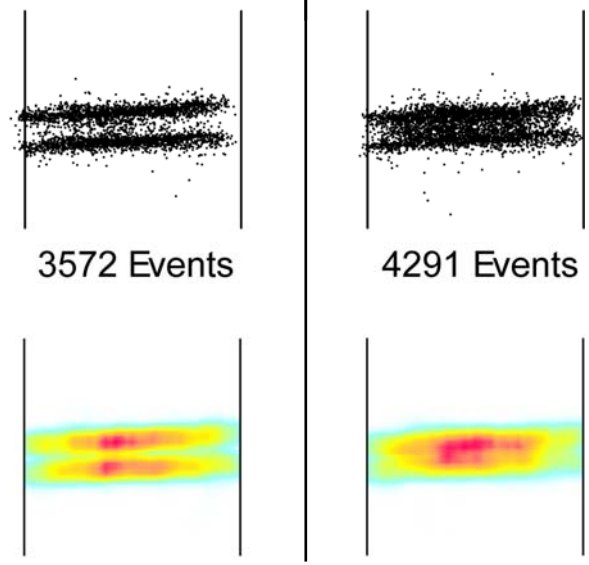
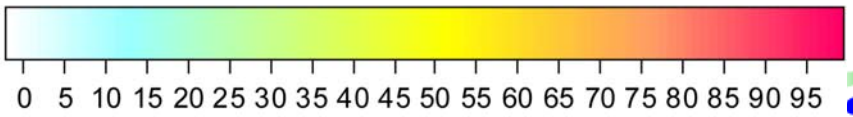
Triaxial Test of a Propped Fracture

Differential pressure	35 MPa	50 MPa
Initial permeability	1270±30 mD	1310±120 mD
Permeability of sample with propped fracture	112±4 mD	105±3 mD





Normalised AE-Activity [%]



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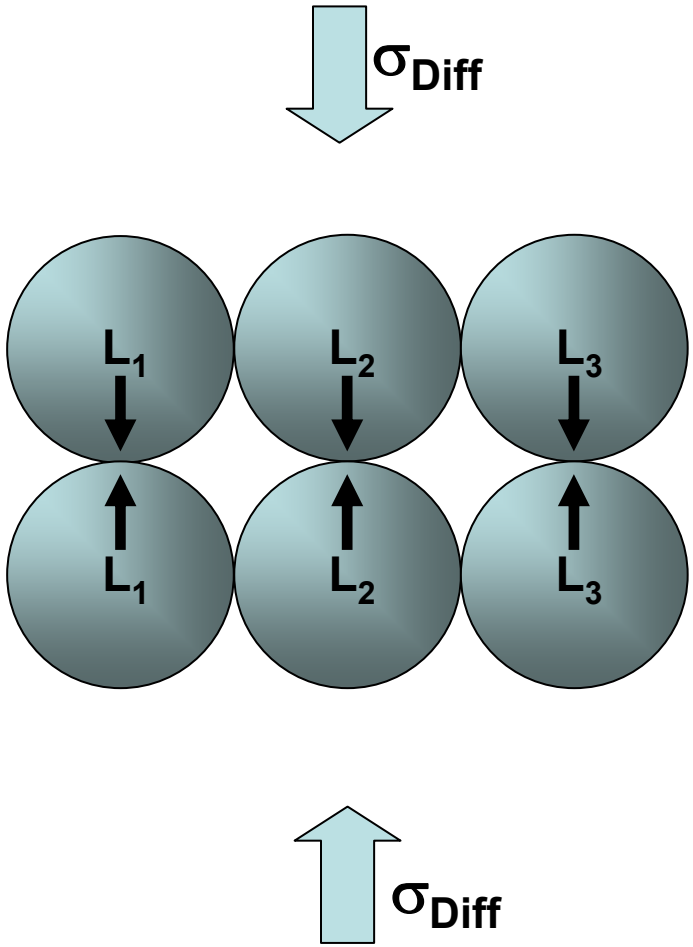
Hertzien Contact of Proppants



$$a_P = \sqrt[3]{\frac{3 \cdot (1-\nu^2) \cdot R_P \cdot F_i}{4 \cdot E}}$$

Eq. 4) Contact radius

$$\sigma_{tmax} = \frac{(1-2\nu) \cdot F_i}{2\Pi \cdot a_P^2}$$

Eq. 5) Maximum tensile stress

LS Proppants:

E (Al_2O_3): 380 GPa

ν (Al_2O_3): 0.23

a_P[m]	contact radius
σ_{tmax} [GPa]	maximum tensile stress
ν [1]	Poisson ratio
R_P [m]	proppant radius
E [GPa]	Young's modulus
F_i [kN]	load on single proppant

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Experimental Procedure for Proppant Testing

1) Triaxial test with intact sample

→ Determination of Young's Modulus and initial permeability

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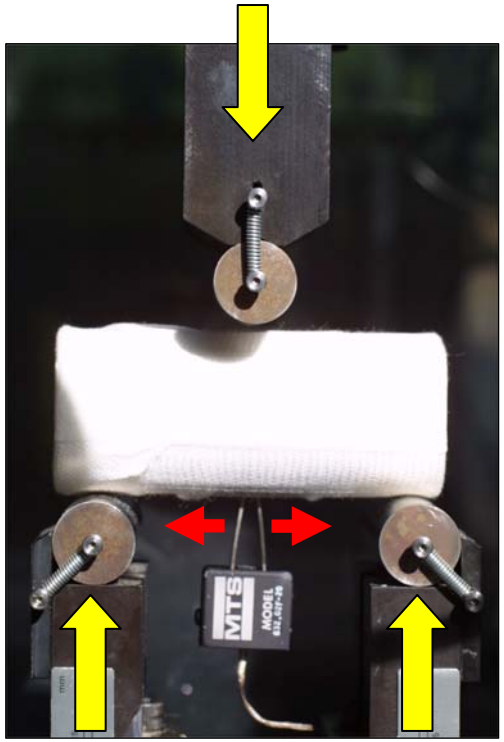
Experimental Procedure for Proppant Testing

1) Triaxial test with intact sample

→ Determination of Young's Modulus and initial permeability

2) Tensile fracture via 3-Point-Bending-Test

→ Generation of a naturally rough fracture face



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Experimental Procedure for Proppant Testing

1) Triaxial test with intact sample

→ Determination of Young's Modulus and initial permeability

2) Tensile fracture via 3-Point-Bending-Test

→ Generation of a naturally rough fracture face

Triaxial test with fractured sample (small axial load)

→ Determination of permeability of fractured sample

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Experimental Procedure for Proppant Testing

1) Triaxial test with intact sample

   → Determination of Young's Modulus and initial permeability

2) Tensile fracture via 3-Point-Bending-Test

   → Generation of a naturally rough fracture face

   Triaxial test with fractured sample (small axial load)

   → Determination of permeability of fractured sample

3) Opening the fracture, filling with proppants, closing fracture aligned

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Experimental Procedure for Proppant Testing

a) Triaxial test with intact sample

→ Determination of Young's Modulus and initial permeability

b) Tensile fracture via 3-Point-Bending-Test

→ Generation of a naturally rough fracture face

Triaxial test with fractured sample (small axial load)

→ Determination of permeability of fractured sample

c) Opening the fracture, filling with proppants, closing fracture aligned

Triaxial test with propped fracture within range of elasticity

→ Determination of fracture stiffness, fracture width, permeability and AE-activity

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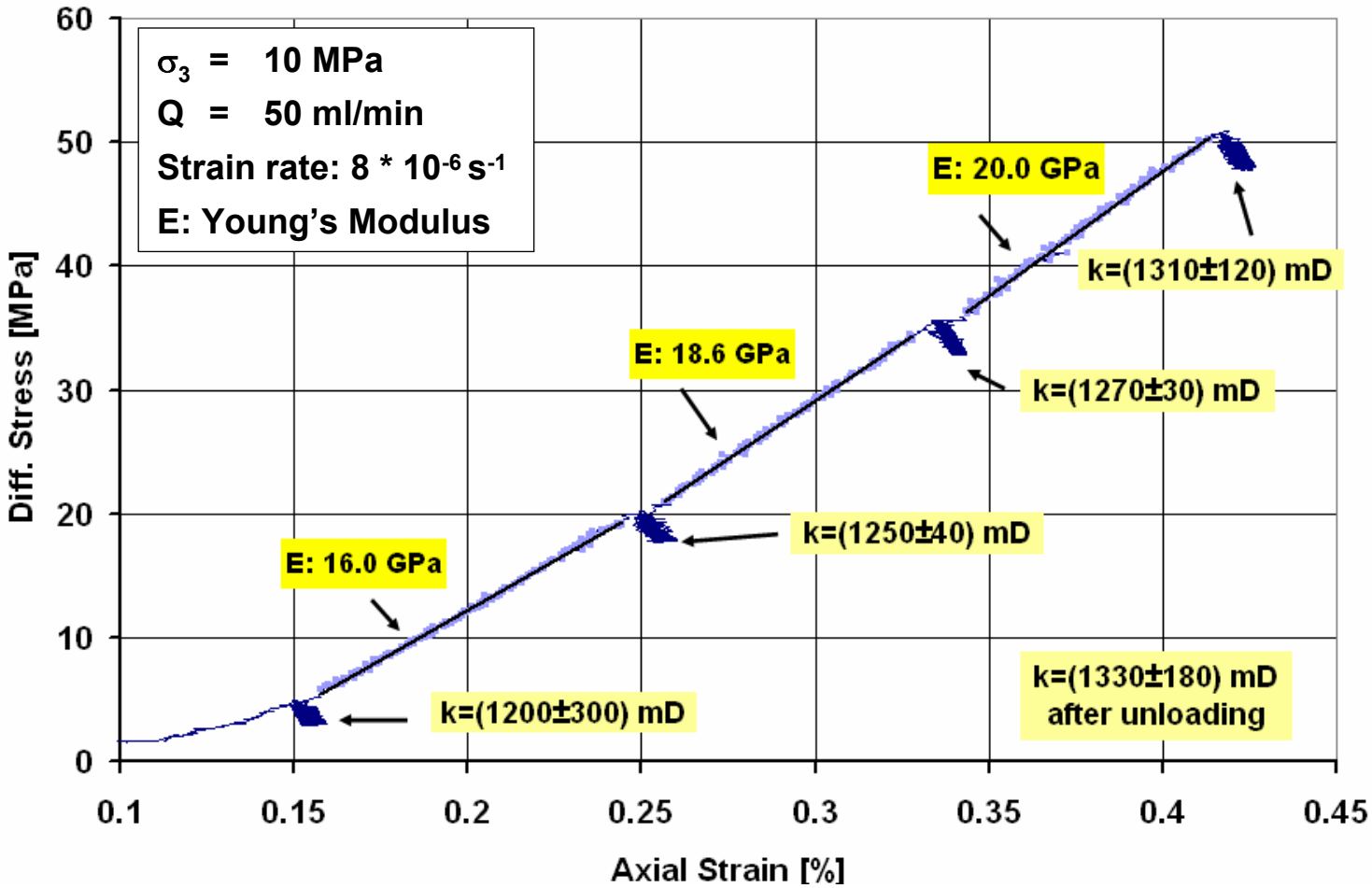
Lab Testing: Step 1) Initial Loading of the Sample



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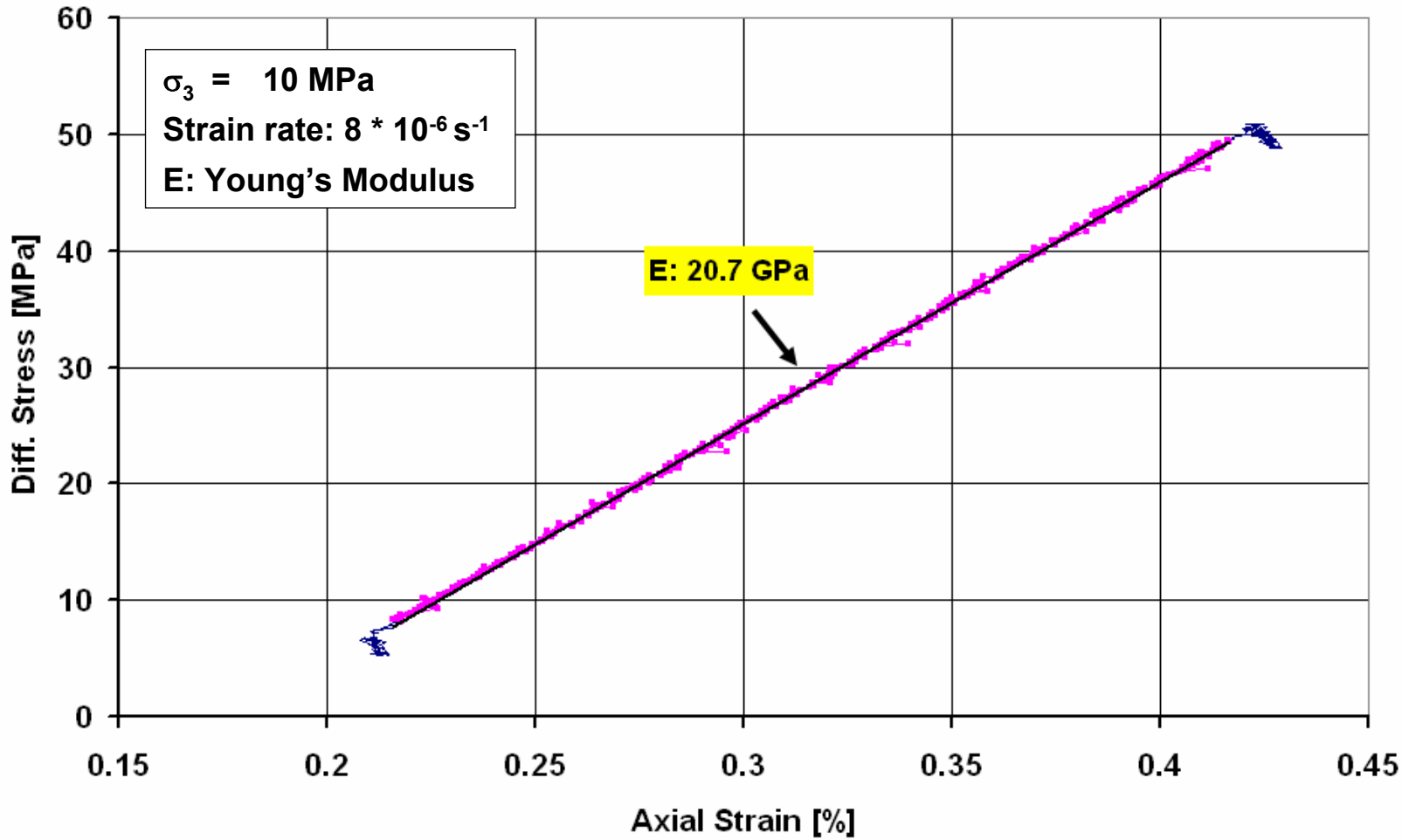
Lab Testing: Step 1) 2nd Loading Cycle



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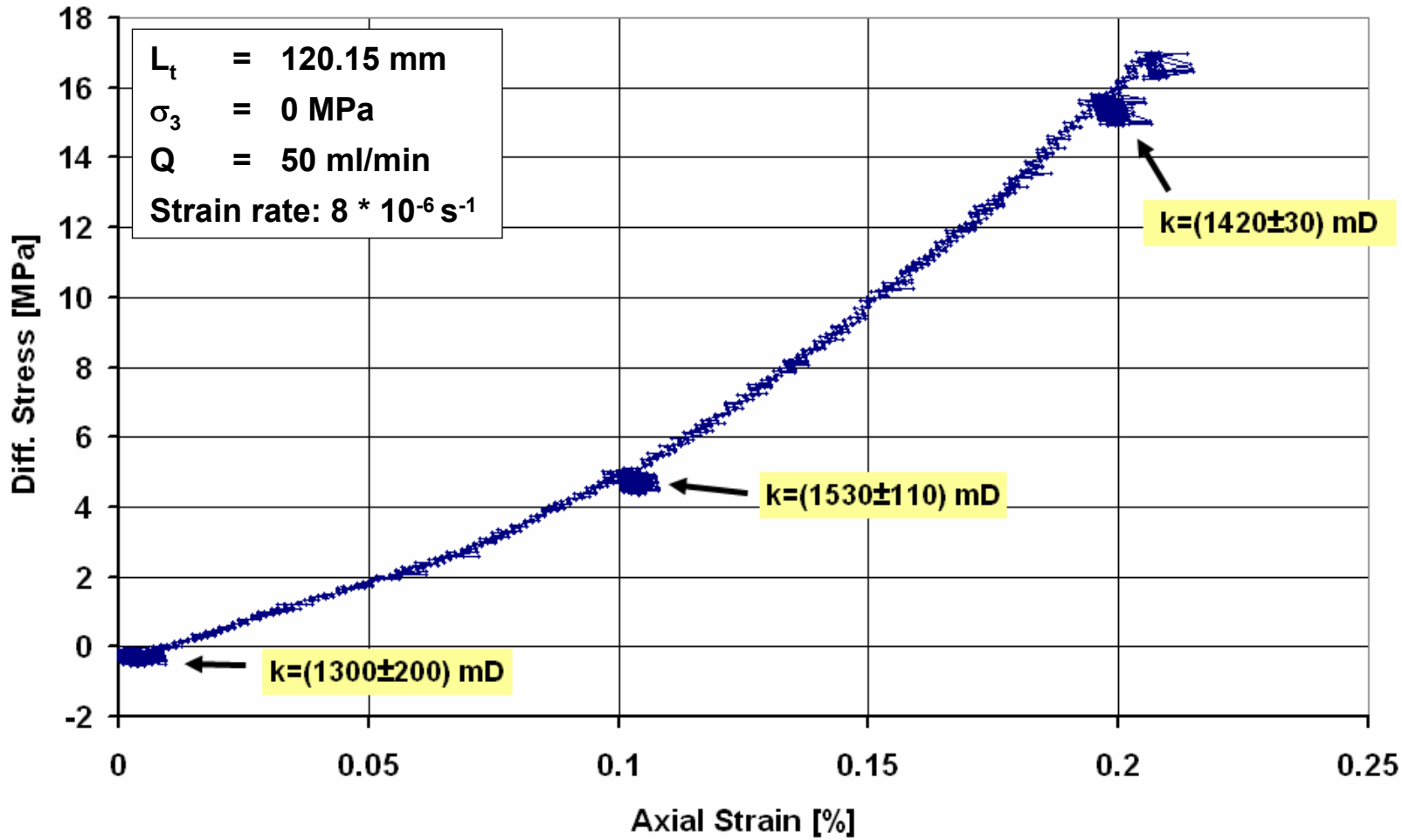
Lab Testing: Step 2) Reloading of the Sample with Fracture



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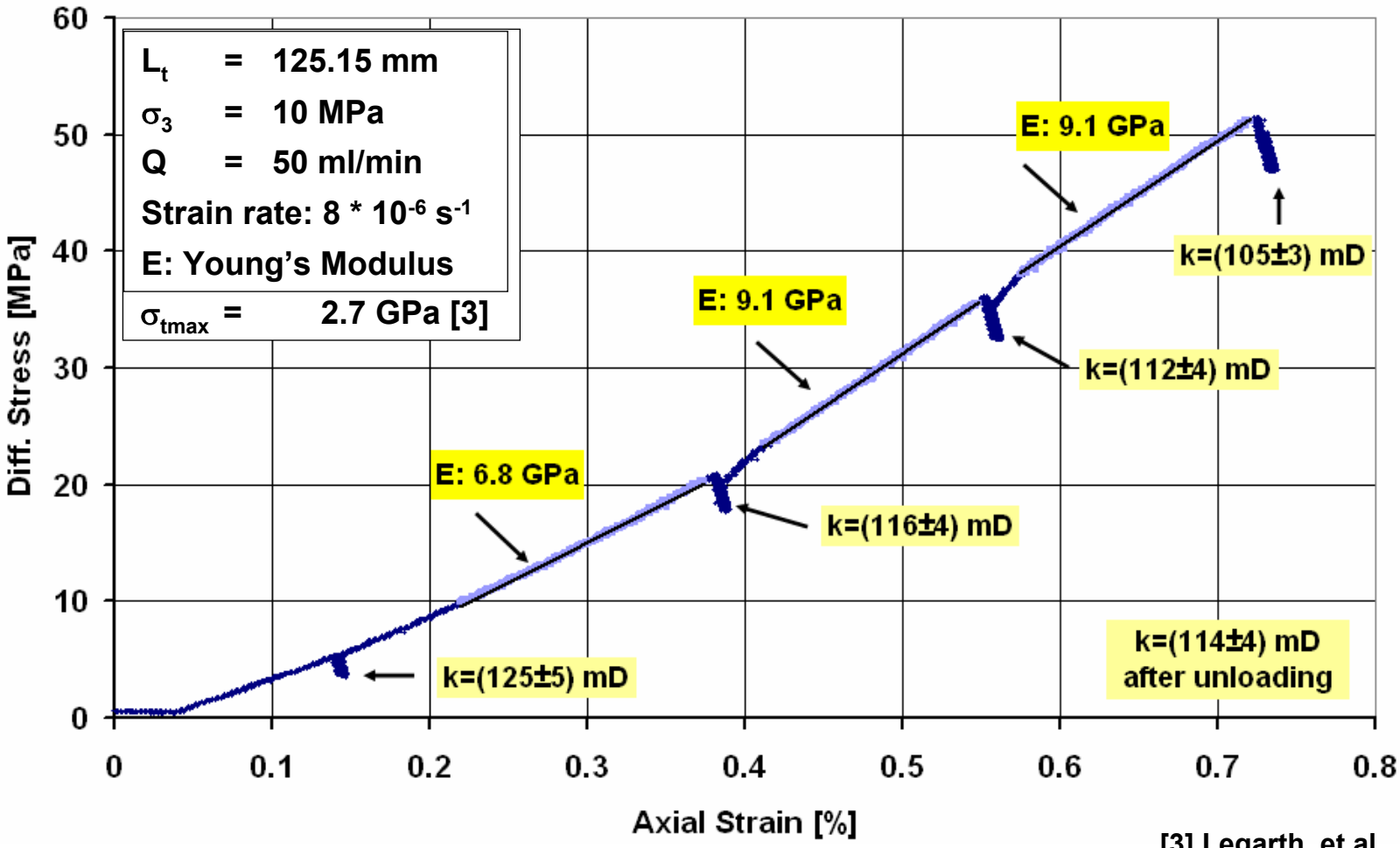
Lab Testing: Step 3) Reloading of the Sample with Proppant Filled Fracture



[3] Legarth, et al., 2005

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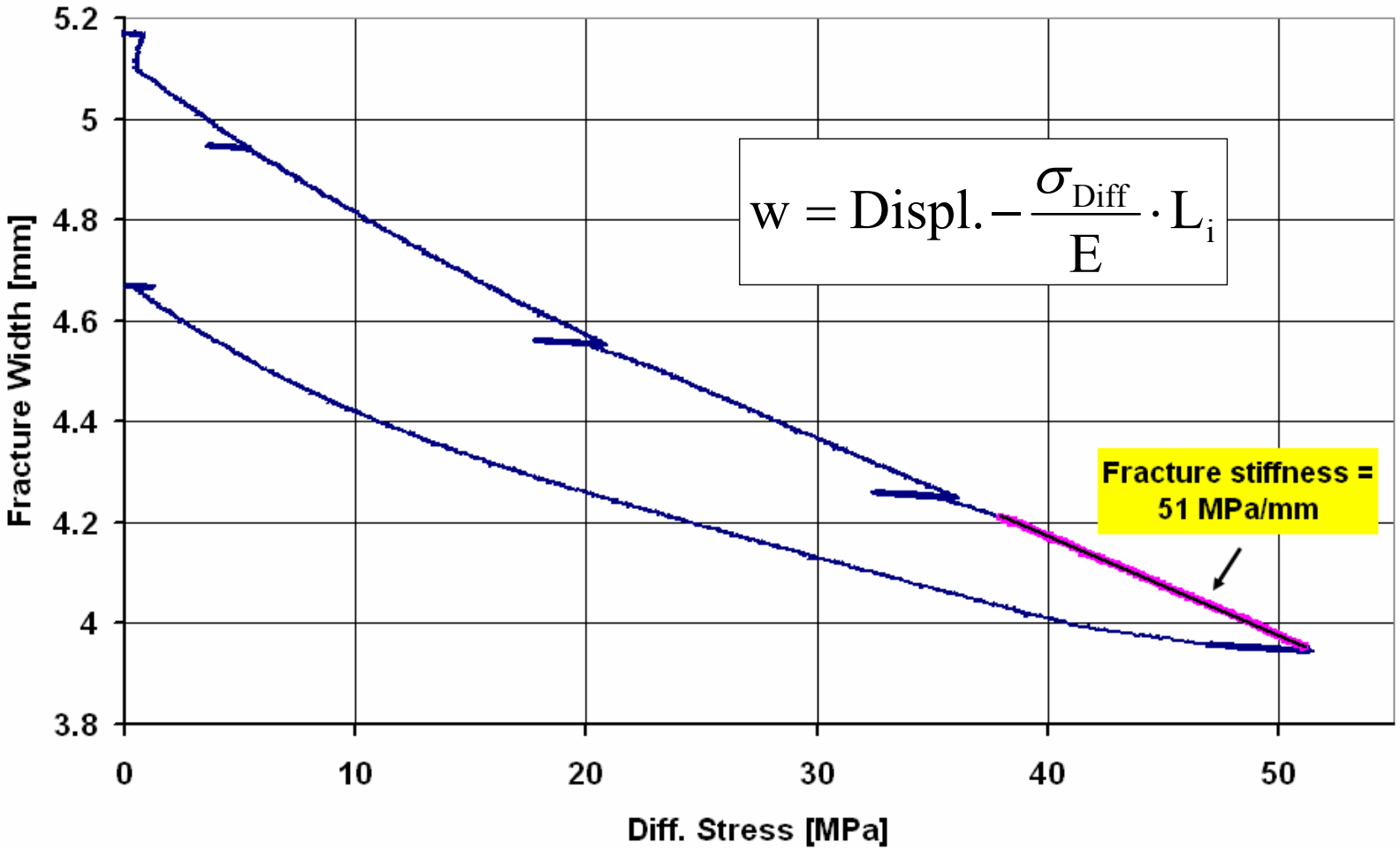
Lab Testing: Calculated Fracture Width vs. Closure Stress



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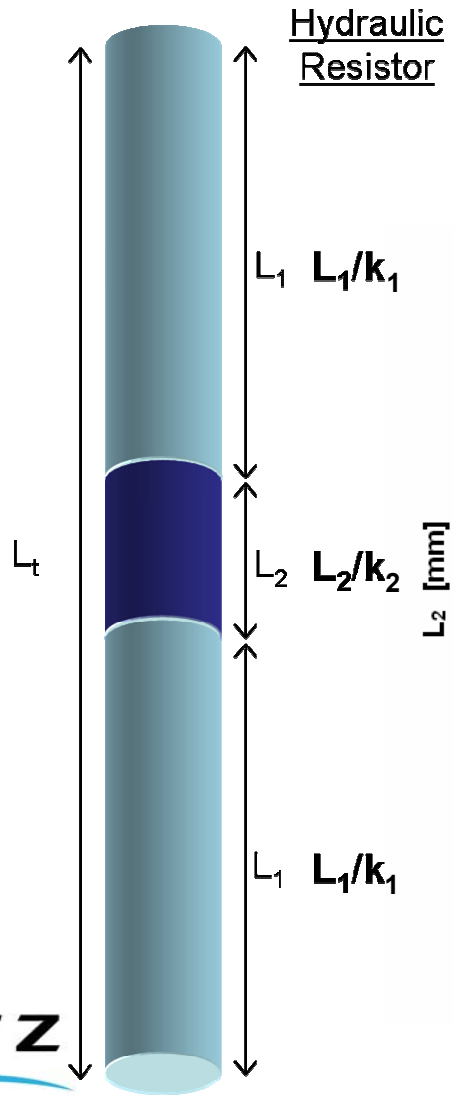
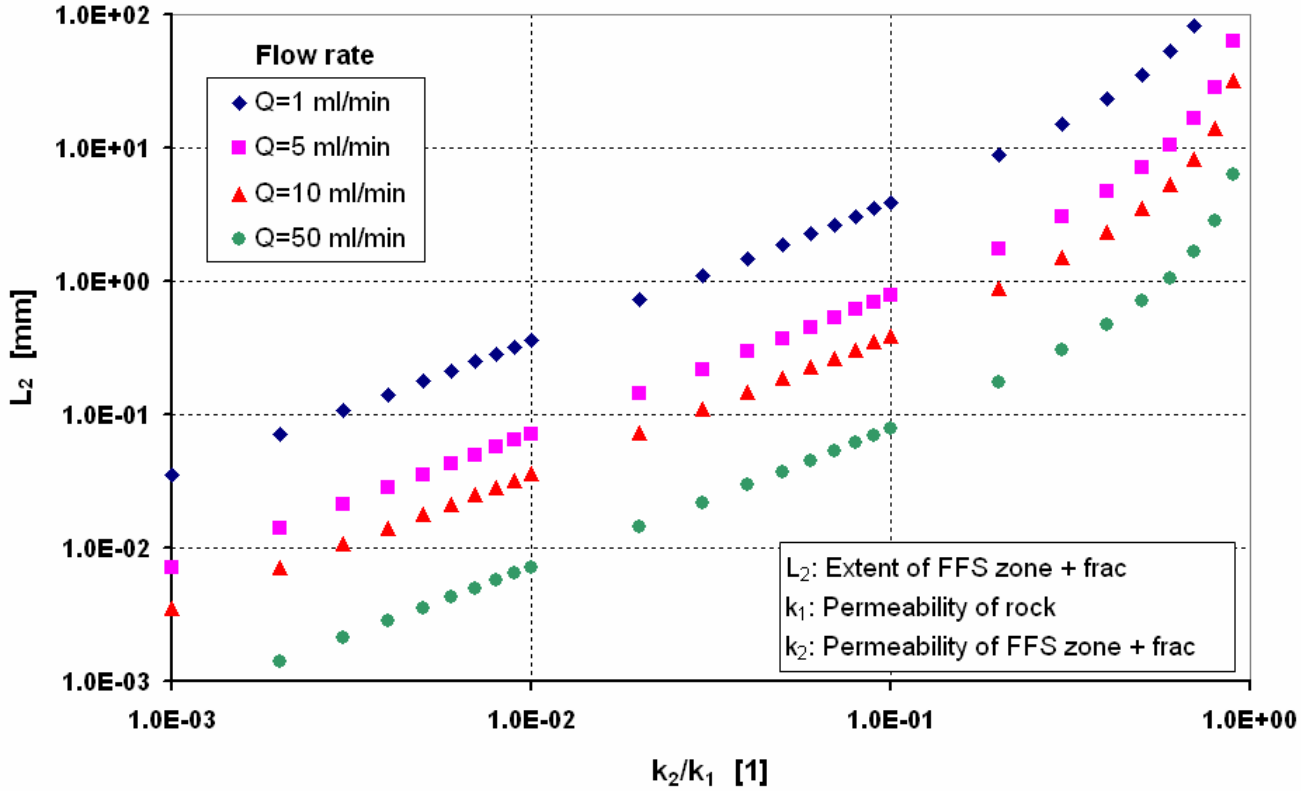
Conceptual Model: Minimum Detectable Depth of a FFS Zone



$$L_2 = \frac{\Delta\Delta P \cdot A}{Q \cdot \eta}\left[\frac{k_1 \cdot k_2}{k_1 - k_2}\right]$$

Eq. 4) Minimum depth of the hydraulic resistor L_2/k_2 for a given $\Delta\Delta P$

$\Delta\Delta P$: Pressure transducer resolution



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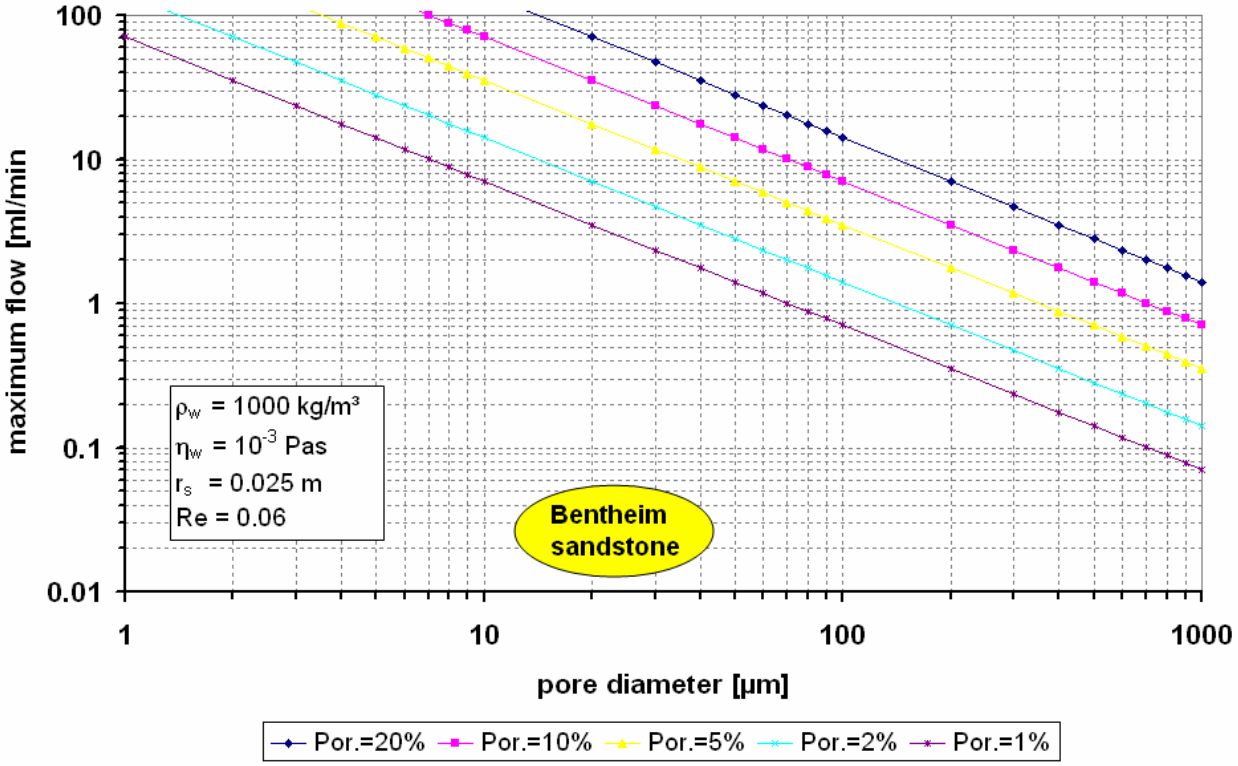
Maximum flow rate for a Reynolds Number = 0.06

$$Q = \frac{Re \cdot \pi \cdot r_s^2 \cdot \eta \cdot \Phi}{\rho \cdot d}$$

Eq. 5) Flow rate as a function of the Reynolds number (for flow in a porous media)

Q [m³/s]	flow rate	Φ [1]	porosity
Re [1]	Reynolds number	ρ [kg/m³]	density
r_s [m]	sample diameter	d [m]	characteristic length
η [Pas]	dyn. viskosity		



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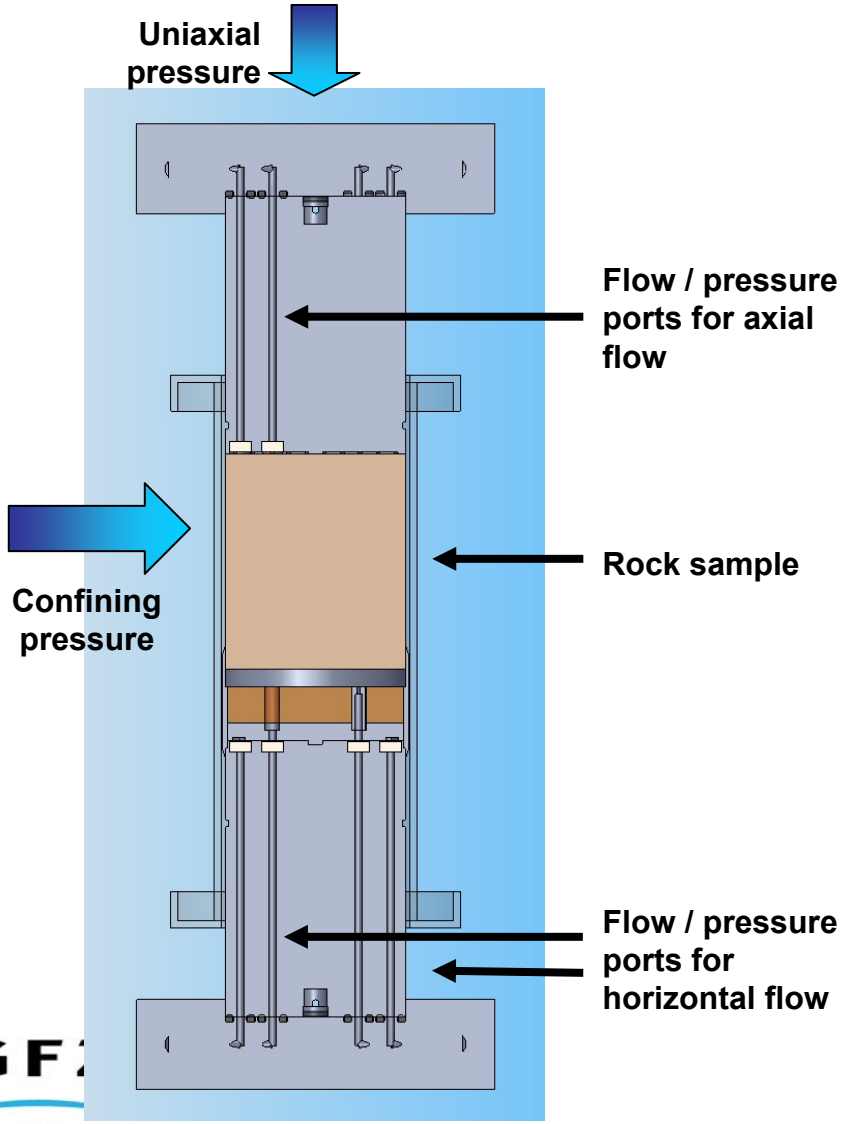
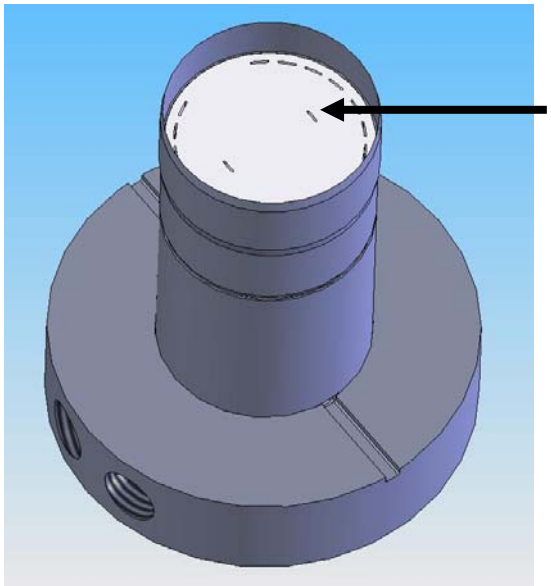
The new Set-Up





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