Hydraulic Fracturing and Formation Damage in a Sedimentary Geothermal Reservoir

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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
Hydraulic Stimulation Technique: Waterfracs (WF)

- 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

- Low viscous gels: $\eta = 10 \text{ cP}$
- Without proppants or small proppant concentration: $c = 50 - 200 \text{ g/l}$
- Long fractures: $x_f \leq 250 \text{ m}$
- Small width: $w_f \sim 1 \text{ mm}$
Hydraulic Stimulation Technique: Hydraulic Proppant Fracs (HPF)

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

- wide range of formations (permeabilities) can be treated
- good control of stimulation parameters
- wellbore skin can be bypassed
- treatments are more expensive
Lithology, Temperature Profile and Petrophysical Reservoir Parameters

Initial productivity index $P_{I_{\text{prefrac}}}$: 1.2 m$^3$ h$^{-1}$MPa$^{-1}$

HPF treatments of sandstones to enhance productivity
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. Lift test
  - Datafrac 1
  - T-Log
  - Mainfrac 1 with proppants
  - 2. Lift test

- 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
Lack of experience with open hole packer treatments at high temperatures

- less aggressive frac design
  - smaller volumes: ~ 100 m³
  - lower proppant concentrations: ~ 280 g/l
  - lower pumping rates: ~ 2 m³/min
Hydraulic Reservoir Behaviour and Stimulation Effect

significant upward extension of inflow area due to new axial fractures

\[ P_{I_{\text{prefrac}}} = 1.2 \, \text{m}^3 \, \text{h}^{-1} \, \text{MPa}^{-1} \]
\[ P_{I_{\text{postfrac}}} = 2.1 \, \text{m}^3 \, \text{h}^{-1} \, \text{MPa}^{-1} \]
\[ P_{I_{\text{predicted}}} = 8.3 \, \text{m}^3 \, \text{h}^{-1} \, \text{MPa}^{-1} \] (1)

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

(1) Legarth, et al., 2005a
Potential Damage Effects in a Propped Fracture

- filtrate invasion, filter cake (fracture face skin / FFS)
- gel residues, chemical precipitates
- accumulated fines:
  - mechanical erosion
  - fines generation during fracturing
- formation crushing, compaction
- proppant embedment Zone

(2) Legarth, et al., 2005b
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
- \( \eta \) [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

\( \sigma_1 \) [MPa]: Axial stress
\( \sigma_3 \) [MPa]: Conf. pressure
\( P_P \) [bar]: Pore pressure
\( Q_i \) [ml/min]: Flow rate
Triaxial Test of a Propped Fracture: Permeability and AE-Activity at Different Stress Levels

**Effective Stress**

<table>
<thead>
<tr>
<th>Stress</th>
<th>Permeability with propped fracture (kₙ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 MPa</td>
<td>125 ± 5 mD</td>
</tr>
<tr>
<td>20 MPa</td>
<td>116 ± 4 mD</td>
</tr>
</tbody>
</table>

**Equation**

\[ k_2 = \frac{k_1L_2}{L_t(k_1 - k_0) + L_2k_1} \]

- L₂ = 4 mm  
- Lₜ = 125 mm  
- k₃ = \infty  
- (260 D @ 50 MPa eff. stress)

\[ k_2 = 3.7 \text{ mD} \]

**Details**

- Rock: Bentheim sandstone  
- Porosity: 23%  
- Initial Permeability (k₁): 1250 mD
- Proppants: Carbo Lite  
- Mesh: 20/40  
- Concentration: 2lbs/ft²  
- Test data: Ø = 50 mm  
- \( \sigma_3 = 10 \text{ MPa} \)  
- Q = 50 ml/min
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
References:


Proppant Imprint (Embedment) into Rock Matrix

0.5 mm
Triaxial Test of a Propped Fracture
Crushed Proppants and Fines

1 mm
Lab Testing: Picture of crushed Proppants and Fines
Mechanical Induced FFS

[2] Legarth, et al., 2005

caption:
- accumulated fines
- precipitation
- rock grain
- proppant
- tortuous fluid flow path
- pressure drop

\( \sigma_{\text{eff}} \)

compacted zone

fracture face

grain

proppant

\( \Delta p \)
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

Triaxial Test on Bentheim Sandstone

- L = 100 mm
- Ø = 50 mm
- $\sigma_3 = 10$ MPa
- Q = 35 ml/min
- $\Delta k < 10\%$
- Strain rate: $4 \times 10^{-5}$ s$^{-1}$
- E: Young’s Modulus
Micrograph of the Created Shear Fracture / Permeability of Damaged Zone

\[ d_2 = 0.12 \text{ mm} \]
\[ \alpha = 63^\circ \]
\[ d_1 = 0.27 \text{ mm} = L_2 \]

\[ k_2 = \frac{k_1 k_1 L_2}{L_1 (k_1 - k_t) + L_2 k_t} \]

\[ k_2 = 0.7 \text{ mD} \]

\[ d_1 = \frac{d_2}{\cos (\alpha)} \]
Lab Testing: AE-Activity

STEP 1
5 Mpa
125 mD

STEP 2
20 Mpa
116 mD

STEP 3
35 Mpa
112 mD

STEP 4
50 Mpa
105 mD

Resolution < 2 mm / Amplitude > 3 V
Triaxial Test of a Propped Fracture

Differential pressure

Initial permeability

Permeability of sample with propped fracture

\[ \sigma_{\text{Diff}} \]

L1 L2 L3

LS Proppants:
\[ \sigma_{\text{tmax}} = 3.7 \text{ GPa} @ 50 \text{MPa} \]
\[ \sigma_{\text{tmax}} = 2.7 \text{ GPa} \quad \text{Lit.} \]

<table>
<thead>
<tr>
<th>35 MPa</th>
<th>50 MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1270±30 mD</td>
<td>1310±120 mD</td>
</tr>
<tr>
<td>112±4 mD</td>
<td>105±3 mD</td>
</tr>
</tbody>
</table>

Normalised AE-Activity [%]

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**Hertzian Contact of Proppants**

\[ a_p = \frac{3 \cdot (1 - \nu^2) \cdot R_p \cdot F_i}{4 \cdot E} \]

Eq. 4) Contact radius

\[ \sigma_{\text{tmax}} = \frac{(1 - 2\nu) \cdot F_i}{2\pi \cdot a_p^2} \]

Eq. 5) Maximum tensile stress

**LS Proppants:**
- \( E (Al_2O_3): 380 \text{ GPa} \)
- \( \nu (Al_2O_3): 0.23 \)

Legend:
- \( a_p [\text{m}] \) contact radius
- \( \sigma_{\text{tmax}} [\text{GPa}] \) maximum tensile stress
- \( \nu [1] \) Poisson ratio
- \( R_p [\text{m}] \) proppant radius
- \( E [\text{GPa}] \) Young’s modulus
- \( F_i [\text{kN}] \) load on single proppant
Experimental Procedure for Proppant Testing

1) Triaxial test with intact sample
   ➔ Determination of Young’s Modulus and initial permeability
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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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1) Triaxial test with intact sample
   → Determination of Young’s Modulus and initial permeability

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   → Generation of a naturally rough fracture face
   Triaxial test with fractured sample (small axial load)
   → Determination of permeability of fractured sample
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
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
Lab Testing: Step 1) Initial Loading of the Sample

\[ \sigma_3 = 10 \text{ MPa} \]
\[ Q = 50 \text{ ml/min} \]

Strain rate: \(8 \times 10^{-6} \text{ s}^{-1}\)

E: Young’s Modulus

![Graph showing stress-strain relationship with values and annotations for Young's Modulus and permeability values.]
Lab Testing: Step 1) 2nd Loading Cycle

- \( \sigma_3 = 10 \text{ MPa} \)
- Strain rate: \( 8 \times 10^{-6} \text{ s}^{-1} \)
- \( E: \) Young’s Modulus

Graph showing the relationship between differential stress (MPa) and axial strain (%). The line indicates a linear relationship with a slope indicating an elastic modulus of approximately 20.7 GPa.
Lab Testing: Step 2) Reloading of the Sample with Fracture

- $L_t = 120.15\, \text{mm}$
- $\sigma_3 = 0\, \text{MPa}$
- $Q = 50\, \text{ml/min}$
- Strain rate: $8 \times 10^{-6}\, \text{s}^{-1}$

Graph showing the relationship between differential stress and axial strain with key points indicating permeability values:

- $k = 1300 \pm 200\, \text{mD}$
- $k = 1530 \pm 110\, \text{mD}$
- $k = 1420 \pm 30\, \text{mD}$
Lab Testing: Step 3) Reloading of the Sample with Proppant Filled Fracture

\[ \sigma_{t_{\text{max}}} = 2.7 \text{ GPa} \]  
\[ L_t = 125.15 \text{ mm} \]  
\[ \sigma_3 = 10 \text{ MPa} \]  
\[ Q = 50 \text{ ml/min} \]  
\[ \text{Strain rate: } 8 \times 10^{-6} \text{ s}^{-1} \]  
\[ E: \text{Young's Modulus} \]  
\[ k = (105 \pm 3) \text{ mD} \]  
\[ k = (112 \pm 4) \text{ mD} \]  
\[ k = (116 \pm 4) \text{ mD} \]  
\[ k = (125 \pm 5) \text{ mD} \]  
\[ k = (114 \pm 4) \text{ mD after unloading} \]  

[3] Legarth, et al., 2005
Lab Testing: Calculated Fracture Width vs. Closure Stress

\[ w = \text{Displ.} - \frac{\sigma_{\text{Diff}}}{E} \cdot L_i \]
Eq. 4) Minimum depth of the hydraulic resistor $L_2/k_2$ for a given $\Delta\Delta P$

$\Delta\Delta P$: Pressure transducer resolution
Maximum flow rate for a Reynolds Number = 0.06

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

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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>m³/s</td>
<td>flow rate</td>
</tr>
<tr>
<td>Re</td>
<td>[1]</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>ρ</td>
<td>[kg/m³]</td>
<td>density</td>
</tr>
<tr>
<td>r_s</td>
<td>[m]</td>
<td>sample diameter</td>
</tr>
<tr>
<td>η</td>
<td>[Pas]</td>
<td>dyn. viscosity</td>
</tr>
<tr>
<td>Φ</td>
<td>[1]</td>
<td>porosity</td>
</tr>
<tr>
<td>d</td>
<td>[m]</td>
<td>characteristic length</td>
</tr>
</tbody>
</table>

\[ \rho_w = 1000 \text{ kg/m}^3 \]
\[ \eta_w = 10^{-3} \text{ Pas} \]
\[ r_s = 0.025 \text{ m} \]
\[ \text{Re} = 0.06 \]

Bentheim sandstone

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The new Set-Up

Uniaxial pressure

Confining pressure

Flow / pressure ports for axial flow

Rock sample

Flow / pressure ports for horizontal flow

Small slots of 0.4 mm for in- and outflow ports