MeSy® Stress measurements

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GEothermie2020

HYDRAULIC FRACTURING STRESS MEASUREMENTS IN BOREHOLE GEo-2

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Content

Appendix

Abbreviations

F	:	frac-cycle
g	:	gravitational acceleration
P	:	measured injection pressure
p	:	pulse test
P_c	:	breakdown pressure (fracture initiation)
P_{clo}	:	closure pressure
P_{hyd}	:	hydrostatic pressure
$P_{jacking}$	:	jacking pressure
P_p	:	pore pressure
P_{prop}	:	propagation pressure
P_r	:	refrac pressure (fracture re-opening)
P_{si}	:	shut-in pressure
Q	:	injection flow-rate
RF	:	refrac-cycle
S_h	:	minimum horizontal principal stress
S_H	:	maximum horizontal principal stress
S_v	:	vertical principal stress
SR	:	step-rate test
T	:	in - situ hydraulic tensile strength
z	:	measured depth
ρ	:	rock density
ρ_{water}	:	water density

1. Introduction

As part of the present geological and hydrological site investigation for the GEothermie2020 Project in Geneva/Switzerland, Solexperts AG was awarded to carry out hydraulic fracturing stress measurements in the vertical borehole GEo-2 of 1455 m depth, besides comprehensive hydraulic tests. Main objective of the hydraulic fracturing tests was to determine the magnitude and the orientation of the in-situ stress. In summary, a total of 8 hydraulic-fracturing tests was conducted during 15.-20.07.2020. For fracture orientation determination, BHTV-logging was conducted prior and after hydraulic fracturing. The present Final Report contains the characteristic hydrofrac pressure values on the basis of a detailed analysis of the digital test records, a discussion of the fracture orientation data as well as the estimation of the in-situ stresses.

2. Borehole Characteristics

Borehole GEo-02 is located at Chemin des Cornaches, 1233 Lully, Geneve, Switzerland (N 46°9'40", E 6°4'9"). The location of the borehole site is shown in a satellite view in Figure 2.1. Available technical data of borehole GEo-2 are summarized in Table 2.1. Drilling of borehole GEo-02 was completed at a final depth of 1455.5 m and an open-hole section of 6-½ inch / 165 mm diameter. The uppermost 807 m were protected with a 7-5/8 inch casing.

The borehole penetrates sedimentary rocks of the Quaternary (0-38 m, average density 2.4 g/cm^3), Molasse (38-630 m, 2.55 g/cm^3), Siderolith (630-769.9 m, 2.5 g/cm^3), Cretaceous (769.9-996 m, 2.66 g/cm^3) and Jurassic (996-1455 m, 2.66 g/cm^3). Thus, the vertical stress S_v due to the weight of the overburden rock can be estimated to 37 MPa at the bottom of the borehole at 1455 m.

Figure 2.1	Location of Borehole PAL-1

Table 2.1	Technical Borehole Data
location	Chemin des Cornaches, 1233 Lully, Geneve, Switzerland
borehole	GEo-2
national coordinates	X: 2494219 Y: 1113094
geographical coordinates	N 46°9'40" E 6°4'9"
altitude (a.m.s.l.), m	410.85
borehole depth, m	1455.5
casing depth, m	807
open-hole diameter	165 mm (6-½ inch)
borehole fluid	plymer mud
drilling contractor	Hydroforage, Virieu-le-Grand, France

3. Hydraulic Fracturing / Hydraulic Injection Techniques for in-situ Stress Determination

3.1 Principle of Hydraulic Fracturing / Hydraulic Injection Tests

In rock mechanics the term hydraulic fracturing is used for fluid injection operations into sealed - off borehole intervals to induce and propagate hydraulic fractures in the rock mass. The pressure data during hydraulic fracturing can be used to determine the stress regime in the rock mass. Although this technique was well known as a stimulation technique for oil - and gas wells since the late 1940's, first hydraulic fracturing stress measurements were performed at an underground test site in northern Minnesota in 1968. Since then, hydraulic fracturing has been used world - wide in numerous shallow to deep boreholes to measure in - situ stresses at depth.

The classical hydrofrac analysis is based on the Kirsch solution for the stress distribution around a circular hole in a homogeneous, isotropic, elastic material subjected to far-field compressive stresses. In case of a vertical borehole, the Kirsch solutions are used in the Hubbert and Willis formula (1957) for the critical pressure P_c at the moment of fracture initiation:

$$P_c = 3 \cdot S_h - S_H + T - P_P \quad (3.1)$$

where S_h and S_H are the horizontal far-field principal stresses, T is the in-situ hydraulic tensile strength of the rock, and P_p is the pore pressure in the rock mass. It is assumed that the overburden stress is a principal stress, the rock is homogeneous, isotropic and initially impermeable, and that the induced fracture is oriented perpendicular to the minimum horizontal principal stress S_h. The last assumption yields

$$S_h = P_{si} \quad (3.2)$$

where P_{si} is the shut-in pressure to merely keep the fracture open after the pressurizing system is shut-in. Using this linear elastic approach, the principal stresses can be expressed by the relations:

$$S_h = P_{si} \quad (3.3)$$

$$S_H = 3 \cdot P_{si} - P_r - P_p$$

$$S_v = \rho \cdot g \cdot z$$

$$P_r = P_c - T$$

Thus, the stress analysis only requires knowledge on the rock mass density ρ, the determination of characteristic pressure values, the shut-in pressure P_{si} and fracture re-opening pressure P_r at depth z where the fracture is induced, and information on the pore pressure. The azimuths of the induced vertical fractures correspond to the orientation of S_H.

Considering the simple and idealistic assumptions used in the Hubbert and Willis approach, the determination of stresses by these equations may sometimes be questioned. This, in particular, applies to the assumptions on rock mass isotropy and the pore pressure.

In addition, the rock at depth is always characterized by the presence of pre - existing (micro -) fractures or weakness planes with different orientations with respect to the orientation of the principal stresses. By fluid injection into a sealed - off borehole interval containing such a fracture, it will open as soon as the fluid pressure exceeds the normal stress S_n acting across the (arbitrarily oriented) fracture plane. In this case the shut - in pressure P_{si} to keep the fracture open after the pressurizing system is shut - in is equal to the normal stress S_n. Solutions to compute the in - situ stress - field from the values of observed normal stresses by using inversion techniques were presented by Cornet (1986) or Baumgärtner and Rummel (1989). This requires that at least 5 values of S_n at various depths on fractures with different orientation are available. The procedures are known as HTPF - method (hydraulic testing of pre - existing fractures) or as P_{si} - method in the literature. The inversion solutions are attractive since no assumptions on the pore pressure are necessary for deriving the principal stresses.

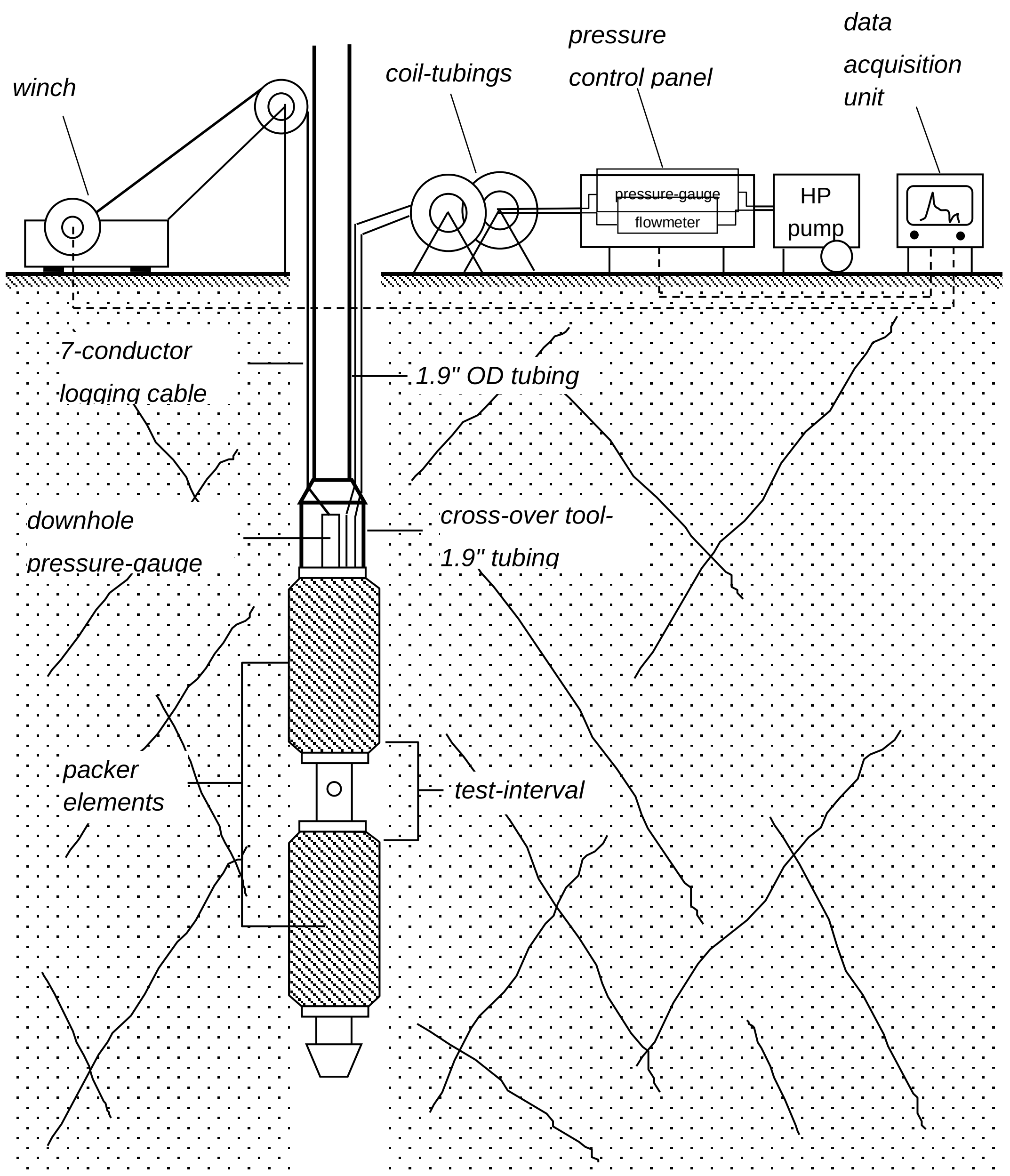
3.2 Hydraulic Fracturing Test Equipment

Due to concerns caused by the expected artesian conditions of borehole GEo-2, the hydraulic fracturing stress measurements were carried out using a combination of conventional (tubing conveyed) and the MeSy® wireline conveyed hydrofrac technique. In detail, the straddle packer tool was connected to a 1.9 inch diameter tubing string which was only used as tool carrier. For packer and interval pressurization, two thin coil-tubings (OD: 8 mm, ID: 6 mm) were clamped on the tubing string. In addition, a seven conductor borehole logging cable was attached to the string for downhole pressure monitoring (Fig. 3.1). The use of a work string maximizes the pull-out force for tool recovery. The thin coil tubing of the wireline system contributes a stiff hydraulic system allowing controlled fracture growth. In combination with the downhole pressure recording device, a maximum resolution is achieved with respect to determination of the characteristic pressure values.

For the case of the hydraulic fracturing experiments in the 6-½ inch / 165 mm diameter open-hole borehole section, the MeSy® straddle packer assembly PERFRAC-140 equipped with Kevlar-reinforced packer elements (IPI, type DuraFRAC OD: 5.5 inch) was used. The sealing length of each packer element was about 1.2 m, the length of the test interval between the two packers was about 1 m.

For pressurization of both, the packer elements and the test interval, an electric driven three-plunger pump (SPECK, type HP 400 / 2 - 10) with a maximum working pressure of 40 MPa and a maximum injection rate of 10 lpm was used. The injection fluid was water.

Figure 3.1	**Schematic view of the testing system**

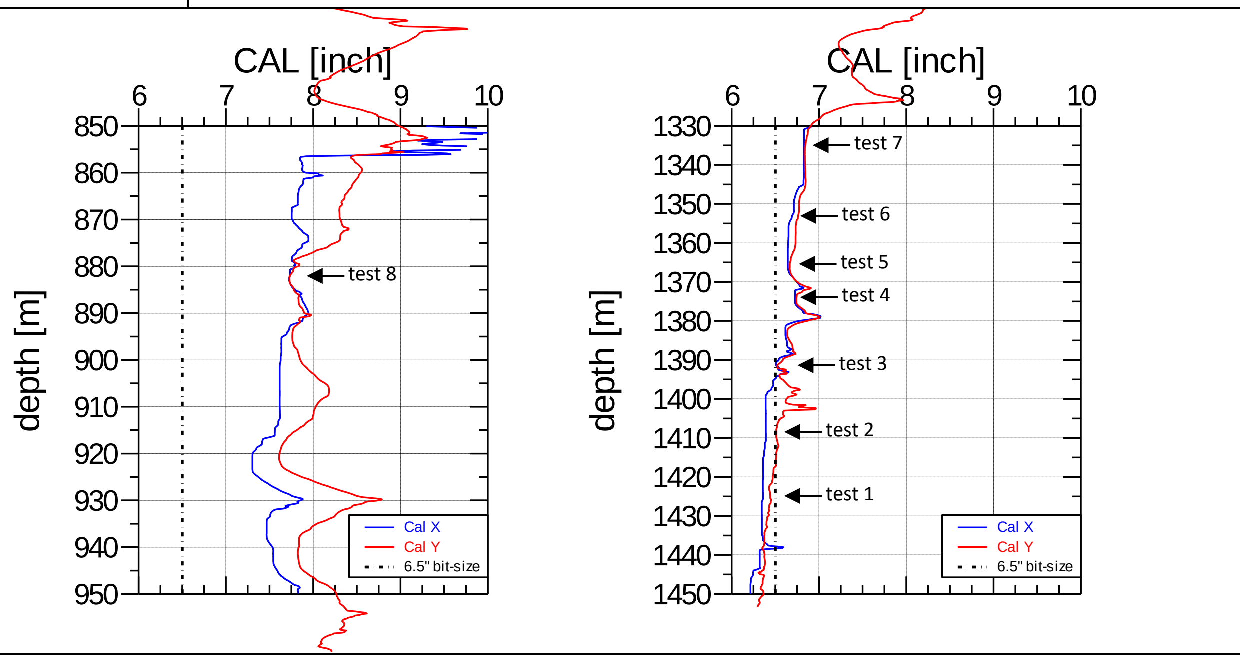


Packer and interval pressure were measured uphole and downhole with high precision electric pressure transducers (KELLER, type PAA-33X, 0 - 40 MPa), the injection flow-rate was recorded with a turbine-type flowmeter (RCI, type QPT-01, 0-10 lpm). The values were recorded by a digital data acquisition system (Solexperts SCI-A, 16 channels, 16 bit resolution, sampling rate: 5 Hz). As part of the quality assurance, the pressure transducers and the flow meter were calibrated prior to in-situ testing. In general, the pressure transducers were tested against a reference load cell. The flow meter was examined by mass determination per unit of time with a precise balance. The calibrations were continuously checked during the execution of the field tests.

3.3 Test Program and Testing Procedure

Originally, a total of eight hydraulic fracturing tests was planned within the entire open-hole borehole section below 807 m depth. However, the caliper-log measured after completion of drilling showed that most of the open-hole borehole section is significantly enlarged and not suitable for inflation of packers at high pressure. Only within the bottom borehole section below 1330 m depth, the borehole was in gauge which allows pressurization of the packers up to 30 MPa (Fig. 3.2). Thus, seven test sections between 1335 m and 1424 m depth were selected for the tests, which also showed a pre-frac BHTV-image of sufficient quality. In addition, one test section within the Cretaceous rocks at 883 m was selected although the borehole diameter of about 7-¾ inch only allows packer pressurization up to 20 MPa.

Figure 3.2	**Caliper-log borehole GEo-2**



The in - situ tests in borehole GEo-2 were carried out during 15.-20.07.2020. A summary of the major activities during the in - situ test phase is given in Table 3.1 (details were already given in the Activity Report dated 05.08.2020). Following the hydraulic fracturing tests, a post-frac acoustic televiewer (BHTV) log was conducted.

The hydrofrac tests were conducted in close agreement with the recommendations of the ISRM standard (Haimson and Cornet, 2003). A typical test record illustrating the test procedure is shown in Figure 3.3 for the test at 1409.0 m. Each test consisted of the following injection cycles after inflating the packer elements to a differential (above hydrostatic) pressure of about 10 MPa:

- rapid pressurization of the test interval to a differential pressure of about 1 - 2 MPa and subsequent monitoring of the pressure decline for several minutes (P - test in Fig. 3.3)
- release of the interval pressure and recovery of fluid volume
- pressurization of the test interval with an injection rate of about 1-2 lpm until a drop in interval pressure occurs or a constant injection pressure is reached (F - cycle in Fig. 3.3); termination of injection and shut-in for about 3 minutes
- release of the interval pressure and recovery of fluid volume including short interruption of the back-flow to observe the pressure-response as proof of fracture initiation and fluid injection into the fracture (Fig. 3.3)
- re - pressurization of the test interval with injection rates of 1 to 3 lpm (increasing order) until constant injection pressure is reached (RF - cycle in Fig. 3.3); termination of injection and shut-in for about 3 minutes
- release of the interval pressure and recovery of fluid volume including short interruption of the back-flow to observe the pressure-response
- several repetitions of the refrac - cycles until shut-in pressures are reproduced
- stepwise increase of the injection flow-rate and observation of the corresponding injection pressure (SR - cycle in Fig. 3.3)
- release of the interval pressure and recovery of fluid volume including short interruption of the back-flow to observe the pressure-response
- packer deflation and movement to the next test section

Figure 3.3	Downhole injection and packer pressure and surface flow-rate record of the hydrofrac test at 1409.0 m

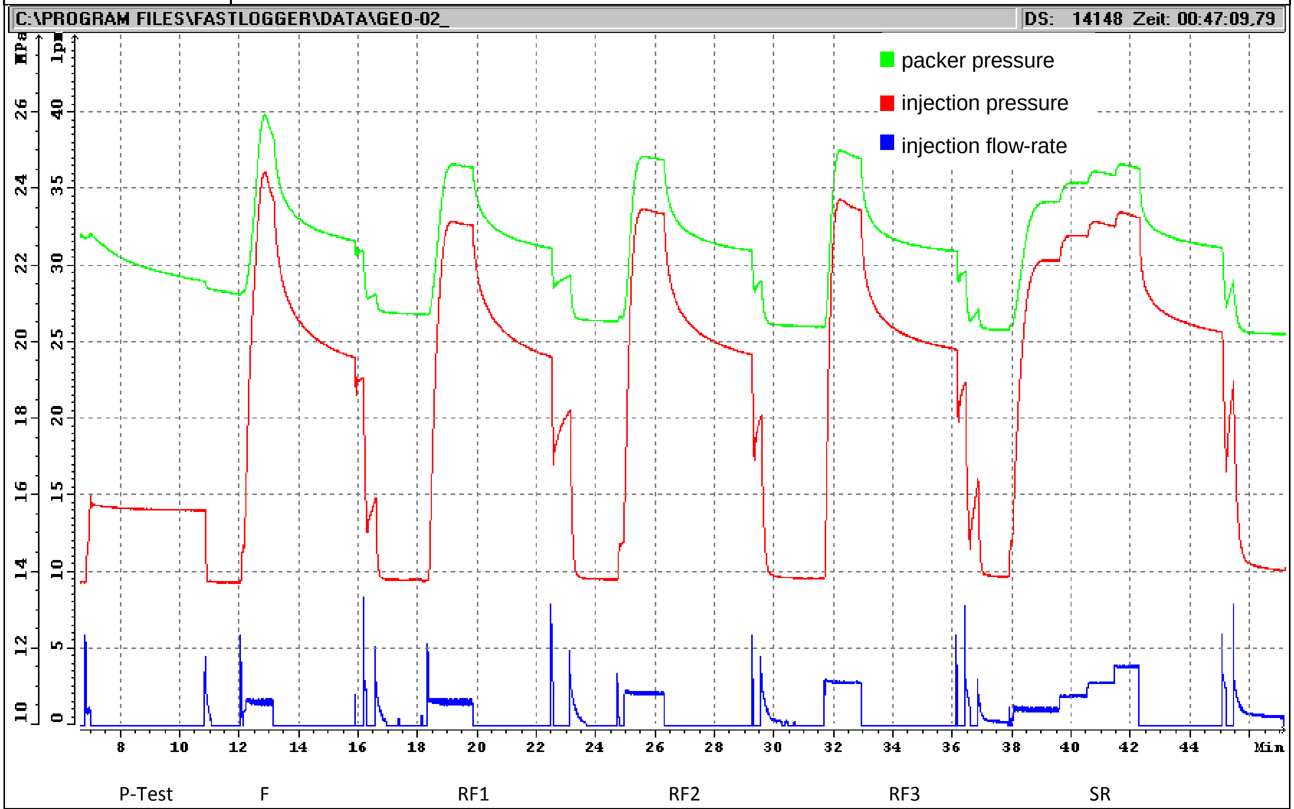


Table 3.1	Test operation summary
Date	**Activity**
13.+14.07.2020	Mobilization of Solexperts GmbH personnel to Geneve
15.07.2020	Preparation of test equipment, run in hole (RIH) to 120 m[1]
16.07.2020	RIH to 1150 m
17.07.2020	RIH to 1424.0 m, conduction of hydrofrac-tests at 1424.0 m, 1409.0 m, 1391.0 m, 1374.0 m, 1366.0 m, 1353.0 m, and 1335.0 m, pull upward to 1000 m
18.07.2020	Pull upward to 883 m, conduction of hydrofrac-test at 883.0 m.
20.07.2020	Pull out of hole, disassembly and loading of equipment
21.07.2020	Demobilization of Solexperts GmbH personnel and equipment

[1] depth is related to the center of the 1 m long test section

4. Analysis of Hydraulic Fracturing Measurements and Results

4.1 Data Analysis

The stress determination from the in - situ hydrofrac / hydraulic injection tests generally requires the following test data:

- breakdown pressures P_c (fracture initiation)
- refrac pressures P_r (fracture re - opening)
- shut - in pressures P_{si}
- determination of the spatial orientation of induced or stimulated fractures

The pressure values breakdown pressure P_c, refrac or re - opening pressure P_r, shut - in pressure P_{si} are identified by the following analysis procedure:

- The breakdown pressure P_c is defined as the maximum pressure observed during the frac - cycle (first pressurization). P_c is determined from a detailed pressure P vs. time t plot.
- The determination of the refrac pressure P_r is based on the analysis of the stiffness (dP/dV) during the pressurization of the test interval. Fracture opening is correlated with a significant deviation of the stiffness from linearity.
- The shut - in pressure P_{si}, which corresponds to the acting stress across the fracture plane, marks the transition from a rapid linear pressure drop (observed immediately after shut - in) to the beginning of diffusion dominated slowly pressure decrease. The transition can be determined by the tangent to the linear pressure decrease in a detailed P vs. time t plot. As upper and lower bound estimations, the propagation pressure P_{prop} at pump stop (Q = 0) and the fracture closure pressure P_{clo} are determined. The closure pressure P_{clo} is derived from plot of pressure vs. square-root of time-difference since shut-in, assuming that the deviation from linearity marks the closure of the fracture.

  The jacking pressure $P_{jacking}$ as an additional estimation of the minimum principle stress is derived from the step rate tests using the quasi steady state P - Q data pairs determined from a detailed pressure P and flow - rate Q vs. time t - plot. In most cases, the shut - in pressure is close or equal to the jacking pressure.

4.2 Characteristic Hydrofrac Pressure Data

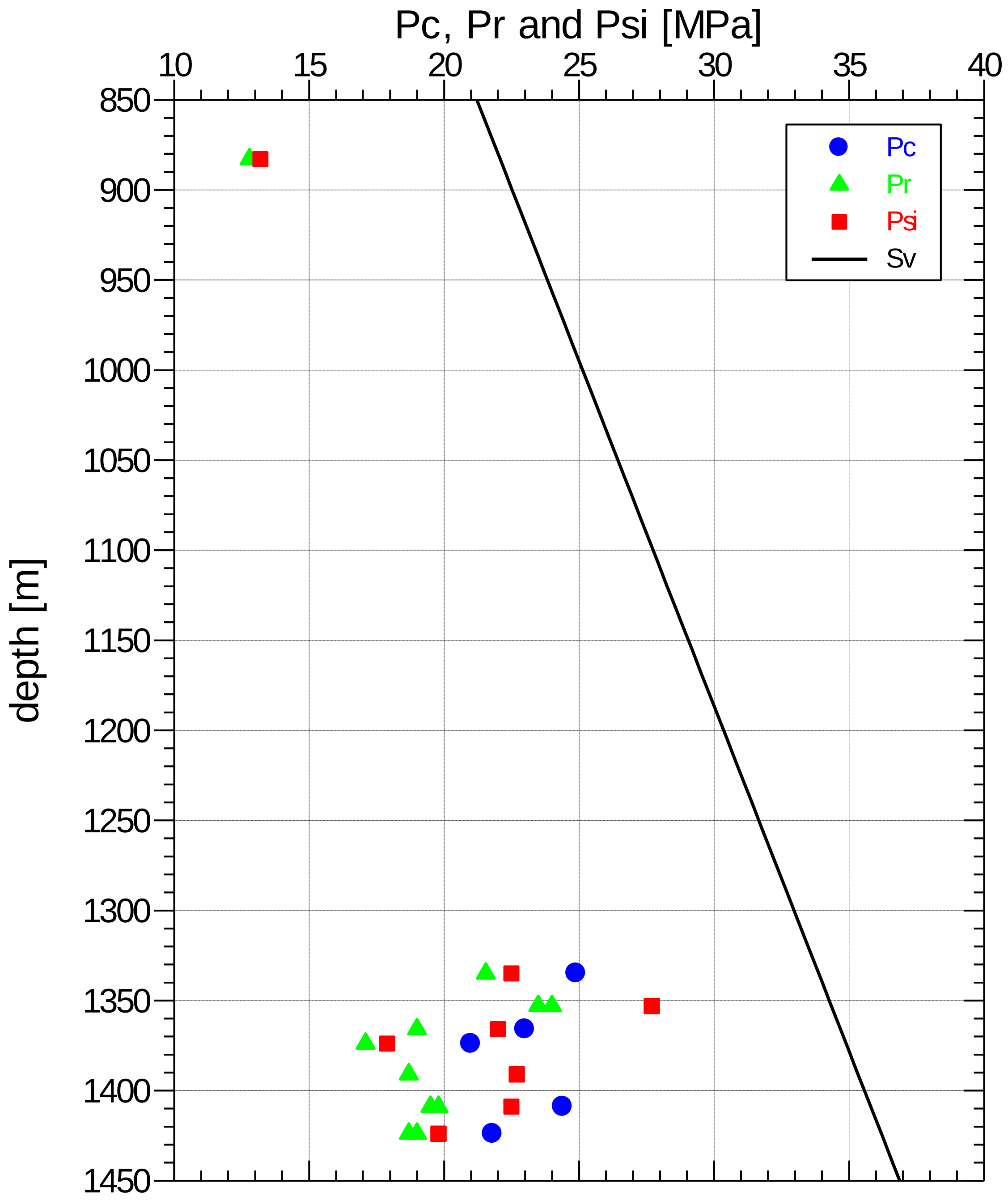
A total of 8 hydrofrac / hydraulic injection tests was conducted in borehole GEo-2 at 883.0 m and between 1335.0 m - 1424.0 m. Overview - plots of the test records together with remarks concerning the test conduction and the data analysis are given in Appendix A. The derived characteristic hydrofrac pressure data (breakdown pressure P_c at fracture initiation, fracture re-opening pressure P_r, shut-in pressure P_{si}, and the resulting in - situ tensile strength $T = P_c - P_r$) are summarized in Table 4.1 and are shown graphically in Figure 4.1. The pressure data are listed as downhole values.

Of the 8 tests, the 5 tests at 1335.0 m, 1366.0 m, 1374.0 m, 1409.0 and 1424.0 m are characterized by (weak) fracture initiation events with low breakdown pressure values ranging from 21.0 MPa to 24.9 MPa. In the remaining 3 test sections at 883.0 m, 1353.0 m and 1391.0 m pre - existing fractures without distinct pressure peaks were stimulated. The refrac-pressure values vary between 12.8 MPa at 883.0 m and 23.5-24.0 MPa at 1353.0 m, the corresponding in-situ hydraulic tensile strength T between 2.8-3.1 MPa and 4.6-4.9 MPa with a mean value of $T = 3.8 \pm 0.7$ MPa. The tests yield rather distinct and reliable shut-in pressure values which scatter significantly between 1335.0 m and 1424.0 m depth between 17.9 MPa to 27.7 MPa, besides the value of 13.2 MPa at 883.0 m depth. As shown in Figure 4.3, the characteristic hydrofrac pressure values are considerable lower than the calculated vertical stress S_v due to the weight of the overburden rock mass. The low shut-in pressure indicates the initiation or stimulation of non-horizontal fractures.

Table 4.1	Result of hydraulic fracturing tests in borehole GEo-2 (P_c: breakdown-pressure, P_r: refrac-pressure, T: hydraulic tensile strength, P_{si}: shut-in pressure).				
test no.	depth [m]	P_c [MPa]	P_r [MPa]	T [MPa]	P_{si} [MPa]
8	883.0	-	12.8	-	13.2
7	1335.0	24.9	21.55	3.35	22.5
6	1353.0	-	23.5 - 24.0 <23.75>	-	27.7
5	1366.0	23.0	19.0	4.0	22.0
4	1374.0	21.0	17.1	3.9	17.9
3	1391.0	-	18.7	-	22.7
2	1409.0	24.4	19.5 - 19.8 <19.65>	4.6 - 4.9 <4.75>	22.5
1	1424.0	21.8	18.7 - 19.0 <18.85>	2.8 - 3.1 <2.95>	19.8

<> mean value

Figure 4.1	Breakdown - pressure P_c, refrac-pressure P_r and shut-in pressure P_{si} in bore-hole GEo-2 in relation to the vertical stress S_v



4.3 Fracture Orientation Data

For determination of the orientation of the induced fractures, a post-frac acoustic televiewer (BHTV) log was run on 22.07.2020. Comparative plots of the logs before and after hydraulic fracturing testing are presented in Appendix B. Note that the logs show depth differences of about 1 m, which partly complicates the comparison. Furthermore, the post-frac log reached only 1401 m and therefore provided no information from the two deepest test sections at 1409.0 m and 1424.0 m. **For the remaining test sections, none hydraulically induced fractures could be detected**. Apparently, the resolution of the BHTV-tool and the quality of the images was not sufficient to detect the (sometimes hairfine) fracture traces.

4.4 Stress Estimation

Due to the lack of fracture orientation data, the stress estimation could be carried out only on the basis of the Hubbert and Willis (1957) concept, although the scatter of the shut-in pressure data between 1335.0 m and 1424.0 m depth indicate that fractures with different spatial orientation were possibly induced or stimulated. The maximum horizontal stress S_H was calculated assuming the hydrostatic pore pressure conditions ($P_p = \rho_{water} \cdot g \cdot z$) . The results are listed in Table 4.2 and are graphically shown in Figure 4.2 in comparison to the vertical stress S_v. Neglecting the high pressure data at 1353.0 m depth, the horizontal stresses may be estimated from the following mean stress - gradients S_h/z and S_H/z (Fig. 4.3):

$$S_h/z \text{ [MPa/m]} = 0.015 \pm 0.001$$
$$S_H/z \text{ [MPa/m]} = 0.022 \pm 0.003$$

where z is depth (in meters). The vertical principal stress S_v was calculated within the Cretaceous and Jurassic borehole section below 769.9 m by using a mean rock mass density of 2.66 g/cm^3:

$$S_v \text{ [MPa]} = 19.1 + 0.0261 \cdot (z \text{ [m]} - 769.9)$$

Table 4.3	Result of stress evaluation using the Hubbert and Willis (1957) approach for borehole GEo-2.					
depth [m]	P_{hyd} [MPa]	S_v [MPa]	S_h [MPa]	S_h/z [MPa/m]	S_H [MPa]	S_H/z [MPa/m]
883.0	8.7	22.1	13.2	0.015	18.1	0.0205
1335.0	13.1	33.9	22.5	0.017	32.85	0.025
1353.0	13.3	34.3	(27.7)	(0.020)	(45.8-46.3) (<46.05>)	(0.034)
1366.0	13.4	34.7	22.0	0.016	33.6	0.025
1374.0	13.5	34.9	17.9	0.013	23.1	0.017
1391.0	13.65	35.3	22.7	0.016	35.75	0.026
1409.0	13.8	35.8	22.5	0.016	33.9-34.2 <34.05>	0.024
1424.0	14.0	36.2	19.8	0.014	26.4-26.7 <26.55>	0.019

<> mean value () negelcted for averaging

Figure 4.2	Principal stresses for borehole GEo-2.

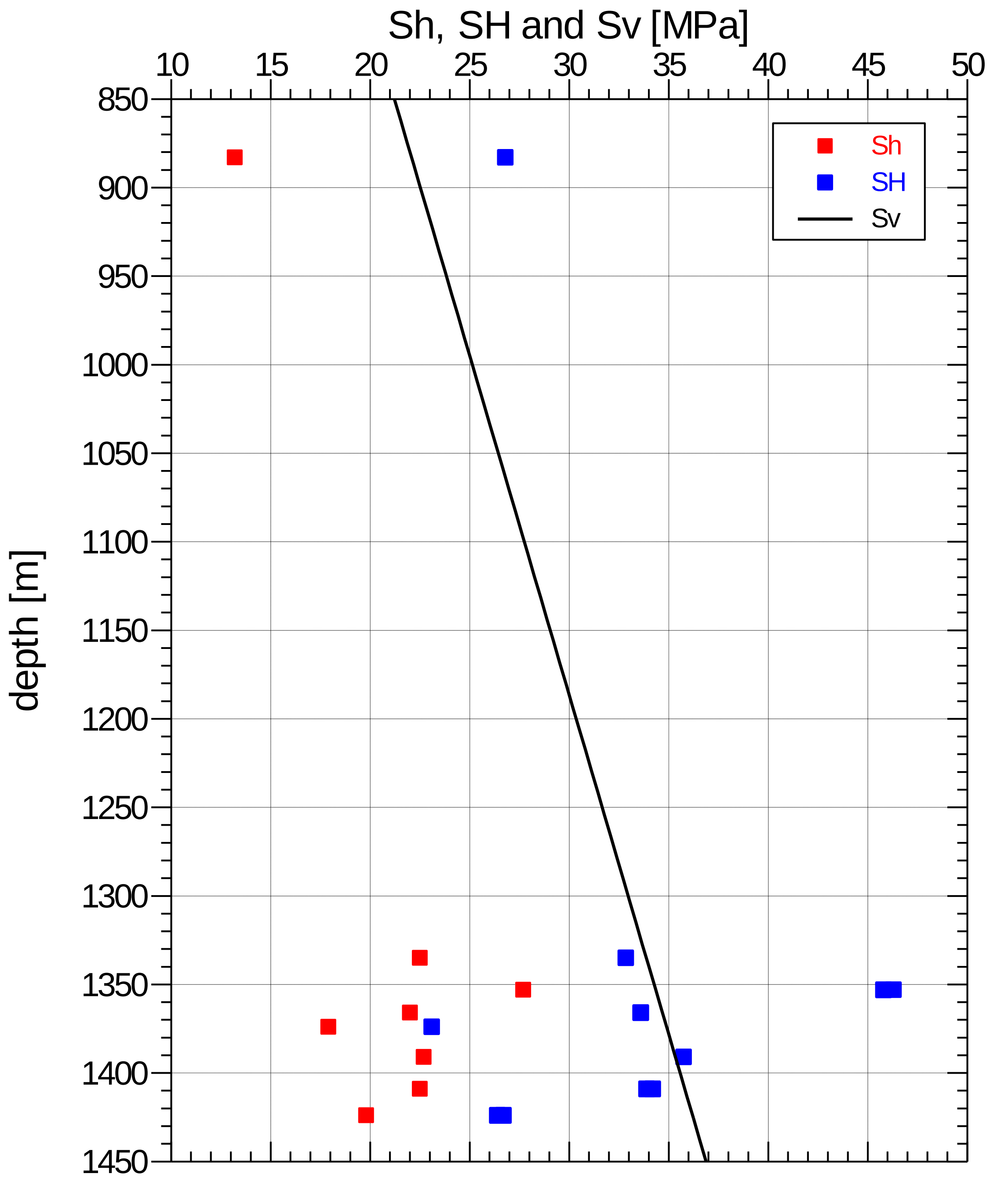
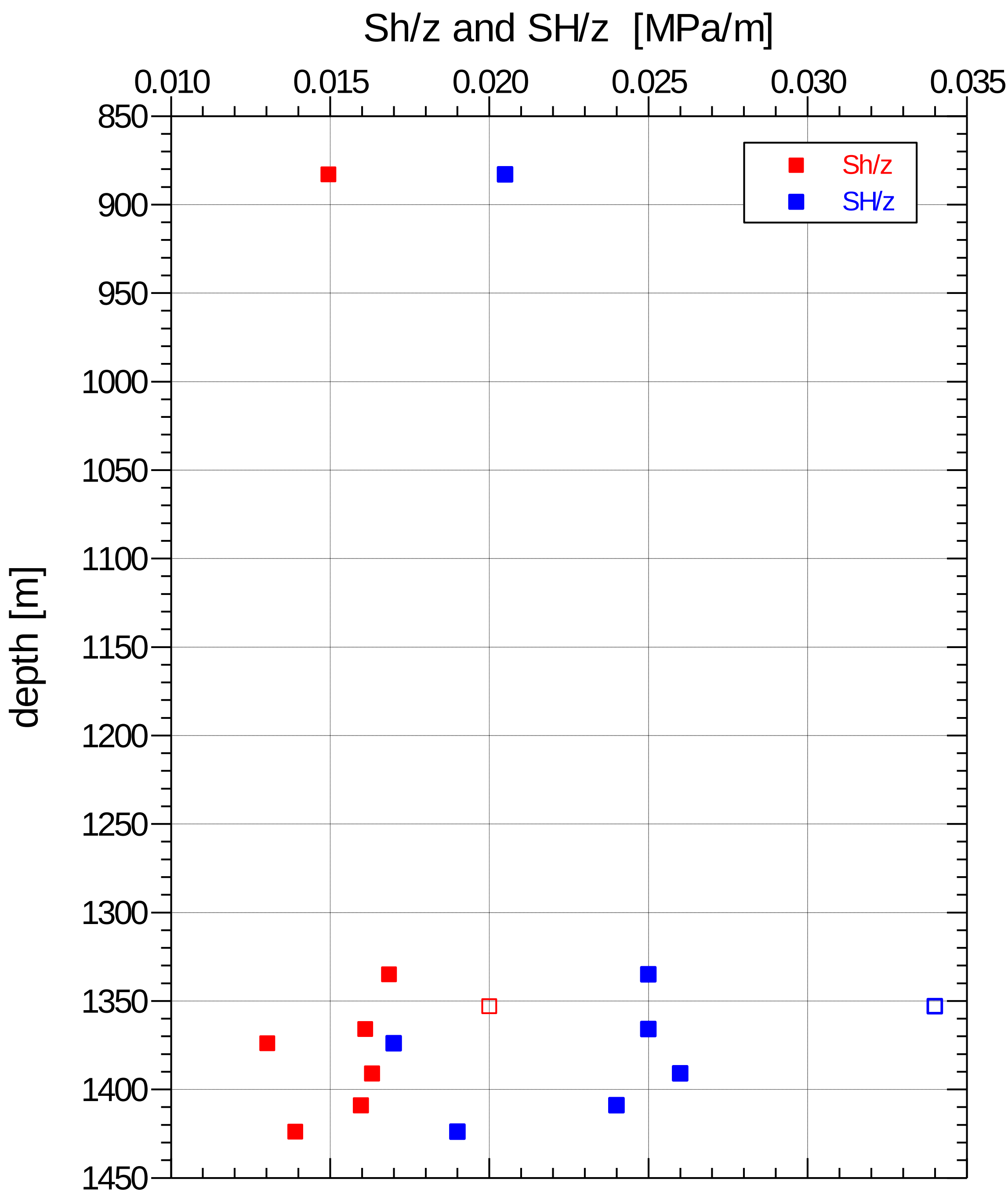


Figure 4.3	Horizontal stress gradients S_h/z and S_H/z for borehole GEo-2.



5. References

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Hubbert, M. K. and D. K. Willis (1957). Mechanics of Hydraulic Fracturing. Trans AIME; 210: 153-163.

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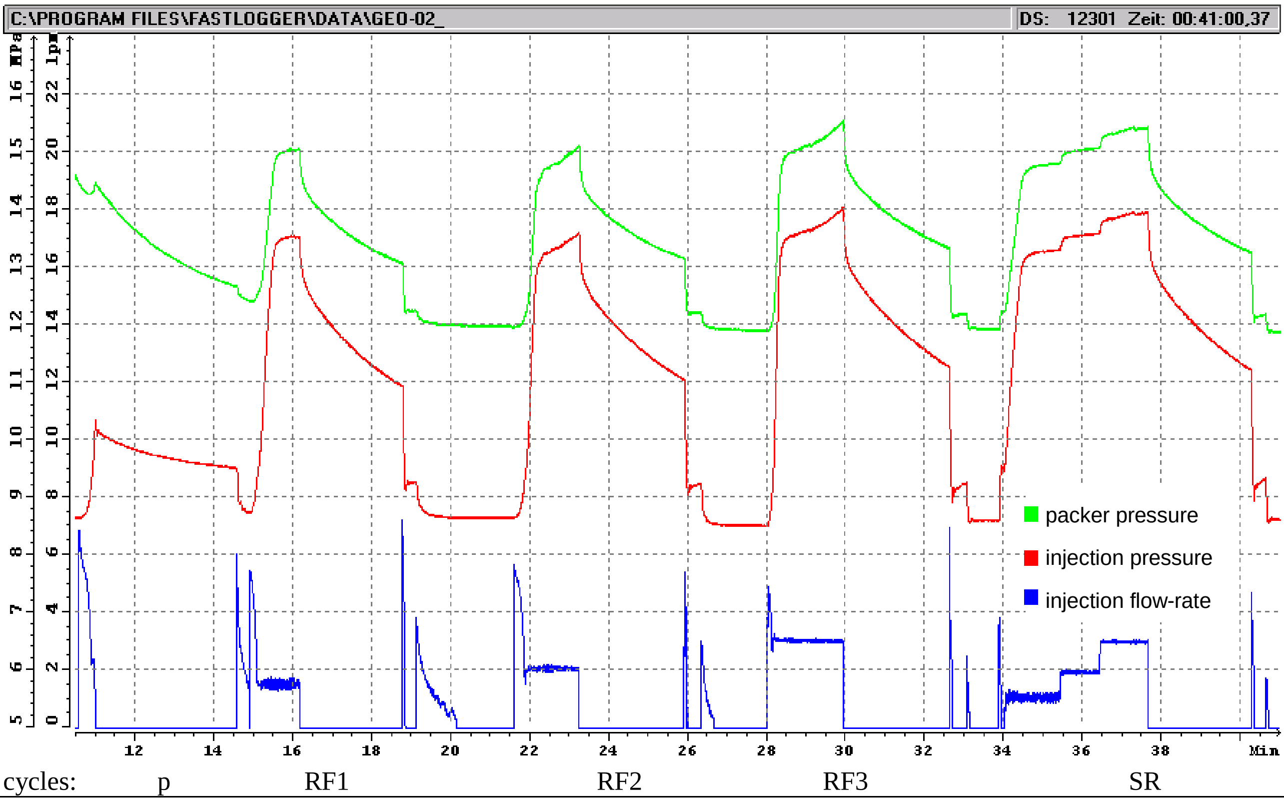
APPENDIX A

Analysis of the Hydraulic Fracturing Tests

Test No. 8 at 883.0 m



Analysis:

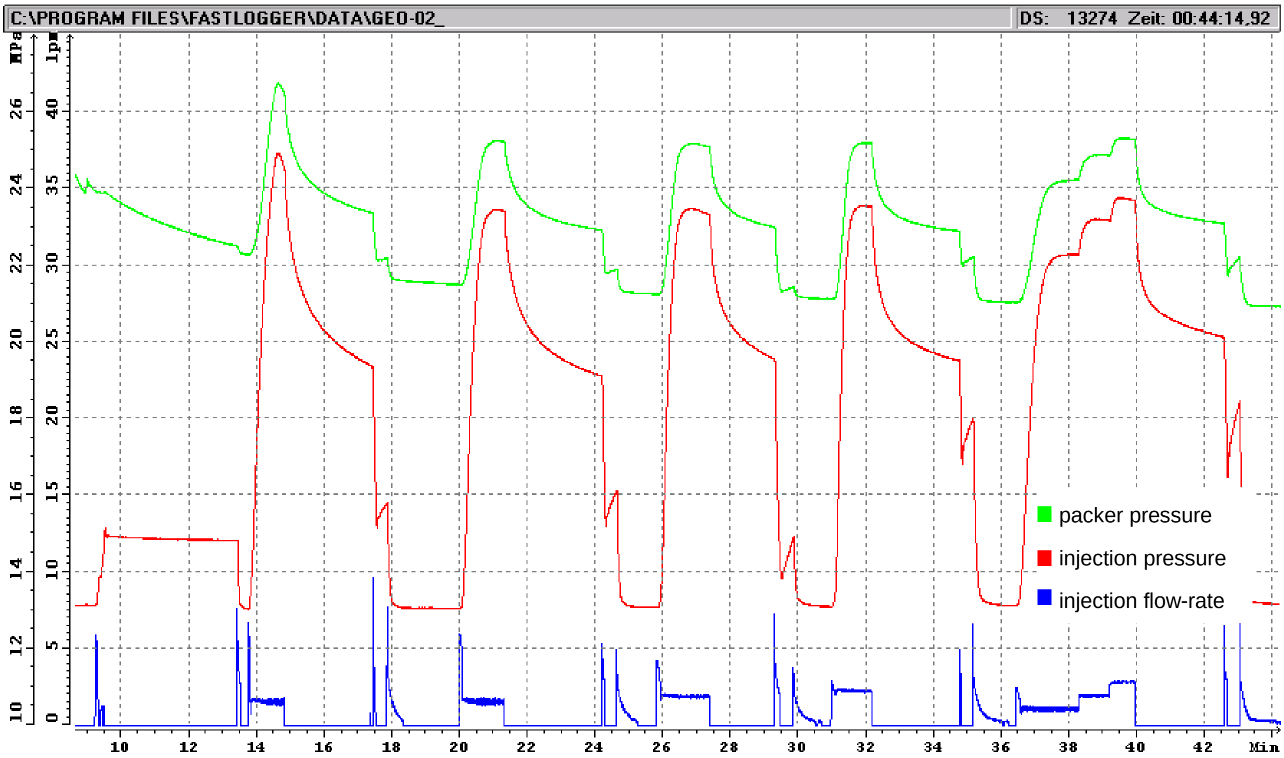
p-test	dP [MPa]	-0.61	dt [sec]	207

cycle	Q [lpm]	V_{in} [l]	V_{out} [l]	P_c [MPa]	P_r [MPa]	P_{prop} [MPa]	P_{si} [MPa]	P_{clo} [MPa]	P (SR) [MPa]
RF1	1.6	2.3	1.6	-	**12.8**	13.5	13.1	12.8	
RF2	2.1	4.1	0.7		12.4	13.6	**13.2**	12.8	
RF3	3.0	5.1	0.4		12.7	14.0	13.2-13.4	13.2	
SR	1.1 1.9 3.0	7.2	0.3				13.3	13.1	13.28 13.55 13.94
total		18.7	3.0				$P_{jacking}$		13.3

Remark:

The initial injection cycle indicates the stimulation of a pre-existing fracture (no breakdown-event). Distinct refrac- and shut-in pressures as well as pressure response during interruption of the venting phases observed.

Test No. 7 at 1335.0 m



cycles: p F RF1 RF2 RF3 RF4

Analysis:

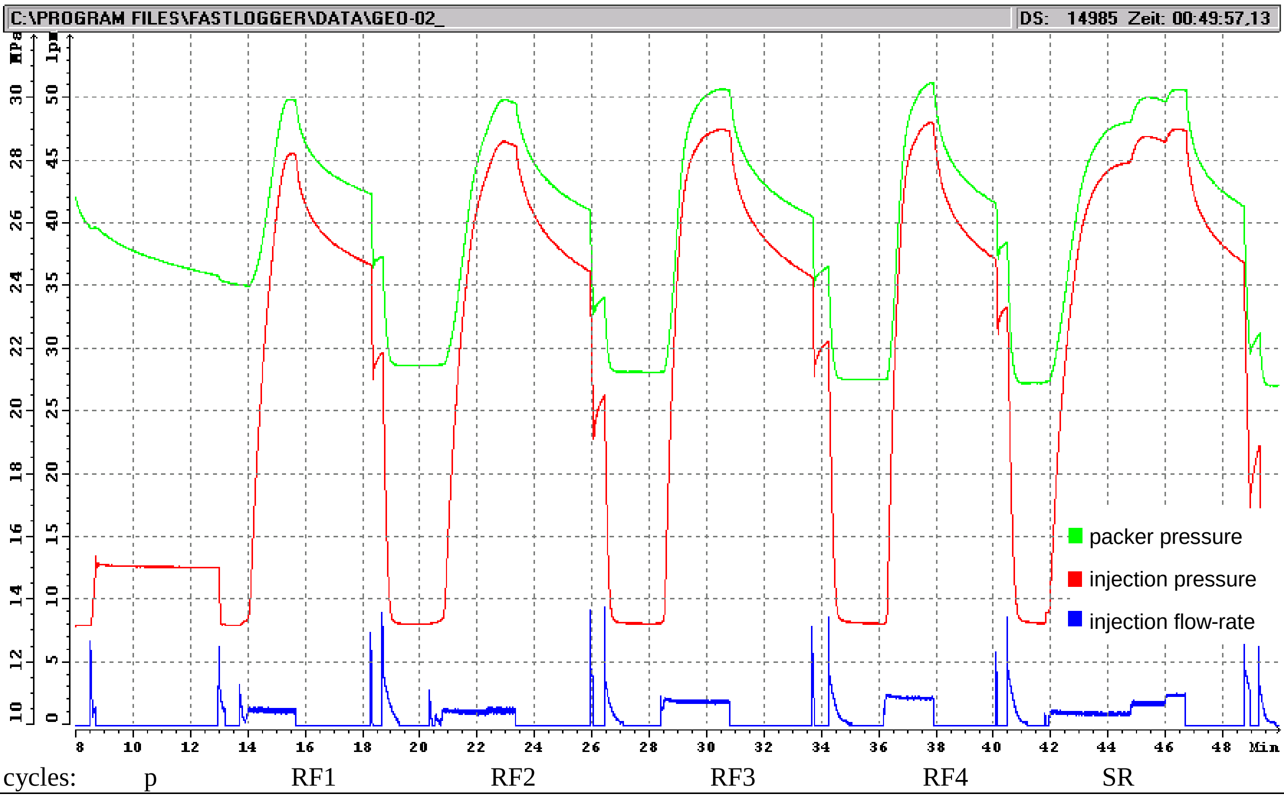
p-test	dP [MPa]	-0.12	dt [sec]	222

cycle	Q [lpm]	V_{in} [l]	V_{out} [l]	P_c [MPa]	P_r [MPa]	P_{prop} [MPa]	P_{si} [MPa]	P_{clo} [MPa]	P (SR) [MPa]
F	1.6	2.0	1.0	**24.9**		24.5	23.7	22.0	
RF1	1.6	2.4	1.0		**21.55**	23.4	22.6	21.3	
RF2	1.9	3.2	1.1		21.4	23.3	**22.5**	21.3	
RF3	2.3	2.7	1.1		21.3	23.5	**22.5**	21.3	
SR	1.0 1.9 2.8	6.0	1.1				**22.5**	21.5	22.25 23.15 23.66
total		16.3	5.3				$P_{jacking}$		22.25

Remark:

The initial injection cycle indicates the initiation of a fracture with a distinct breakdown-event. Distinct refrac- and shut-in pressures as well as good pressure response during interruption of the venting phases observed.

Test No. 6 at 1353.0 m



Analysis:

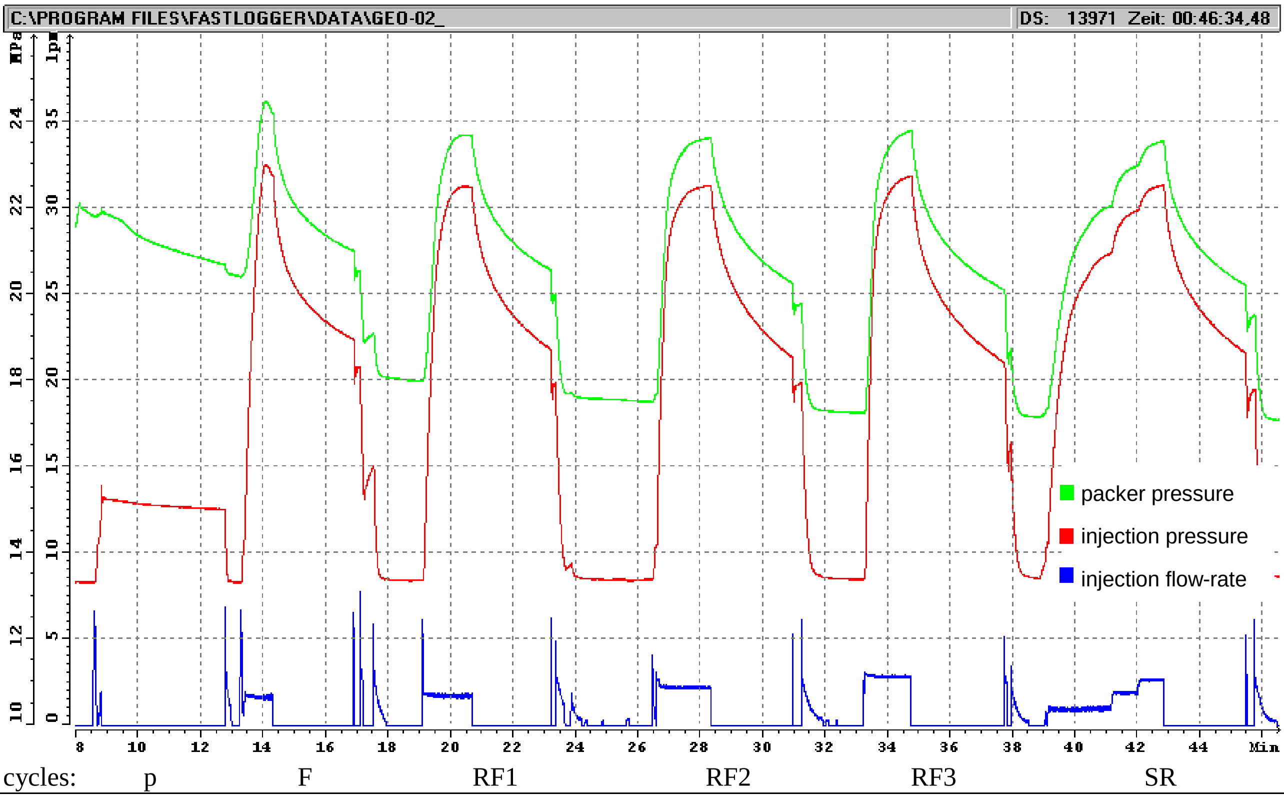
p-test	dP [MPa]	-0.1	dt [sec]	248

cycle	Q [lpm]	V_{in} [l]	V_{out} [l]	P_c [MPa]	P_r [MPa]	P_{prop} [MPa]	P_{si} [MPa]	P_{clo} [MPa]	P (SR) [MPa]
RF1	1.2	2.3	1.4	-	**23.7**	28.15	**27.7**	26.8	
RF2	1.2	3.0	1.4		23.3	28.4	28.0	26.3	
RF3	1.9	4.6	1.3		**23.5-24.0**	28.9	28.3	26.5	
RF4	2.2	3.8	1.3		23.4	29.15	28.4	26.7	
SR	1.0 1.8 2.4	6.6	1.4			28.9	28.2	26.5	27.90 28.56 28.91
total		20.3	6.8				$P_{jacking}$		27.9

Remark:

The initial injection cycle indicates the stimulation of a pre-existing fracture (no breakdown-event). Distinct refrac- and shut-in pressures observed which slightly increased during the successive injection cycles. Good pressure response during interruption of the venting phases observed.

Test No. 5 at 1366.0 m



Analysis:

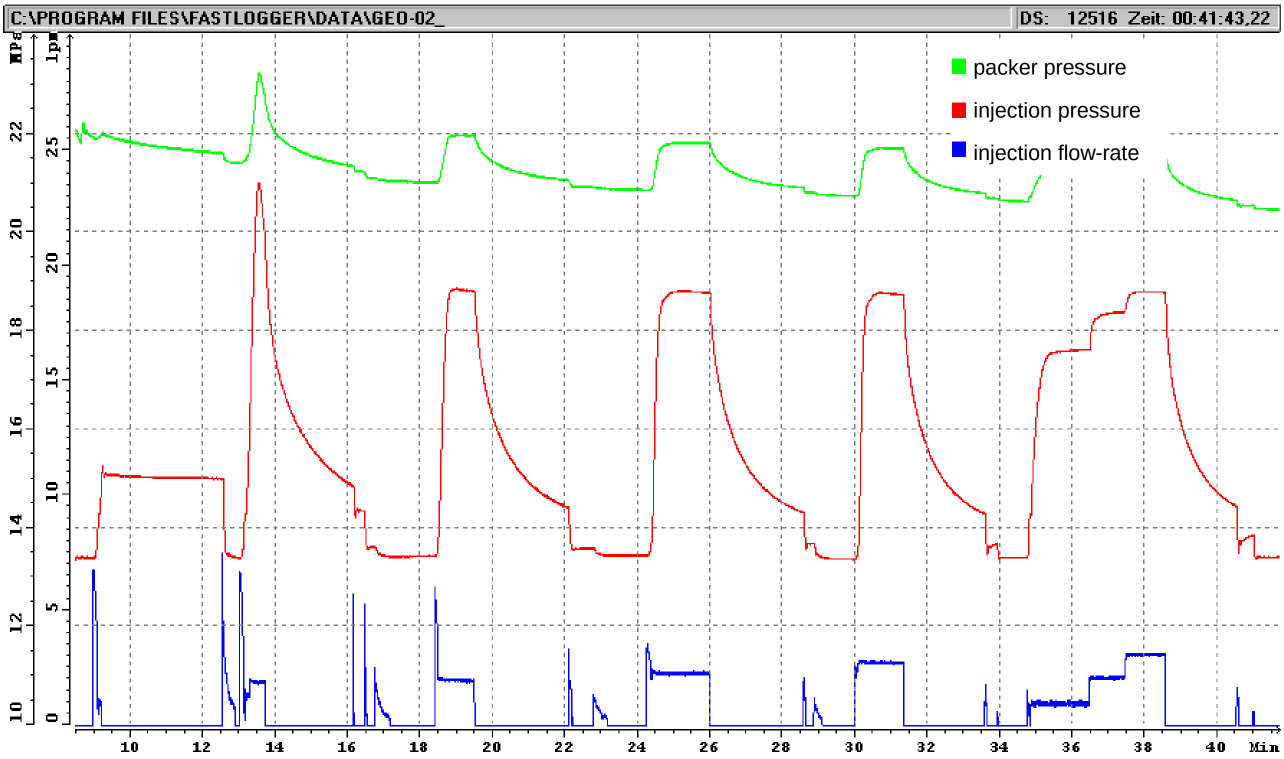
p-test	dP [MPa]	-0.26	dt [sec]	226

cycle	Q [lpm]	V_{in} [l]	V_{out} [l]	P_c [MPa]	P_r [MPa]	P_{prop} [MPa]	P_{si} [MPa]	P_{clo} [MPa]	P (SR) [MPa]
F	1.7	2.0	0.9	**23.0**		22.7	22.1	21.0	
RF1	1.7	3.0	1.0		**19.0**	22.4	**22.0**	20.5	
RF2	2.2	4.2	1.0		**19.0**	22.5	**22.0**	20.5	
RF3	2.9	4.4	0.8		**19.0**	22.7	22.1	20.8	
SR	1.0 1.9 2.7	5.7	0.8				**22.0**	20.3	20.91 21.90 22.48
total		19.3	4.5				$P_{jacking}$		20.9

Remark:

The initial injection cycle indicates the initiation of a fracture with a weak breakdown-event. Distinct refrac- and shut-in pressures as well as good pressure response during interruption of the venting phases observed.

Test No. 4 at 1374.0 m



cycles: p F RF1 RF2 RF3 SR

Analysis:

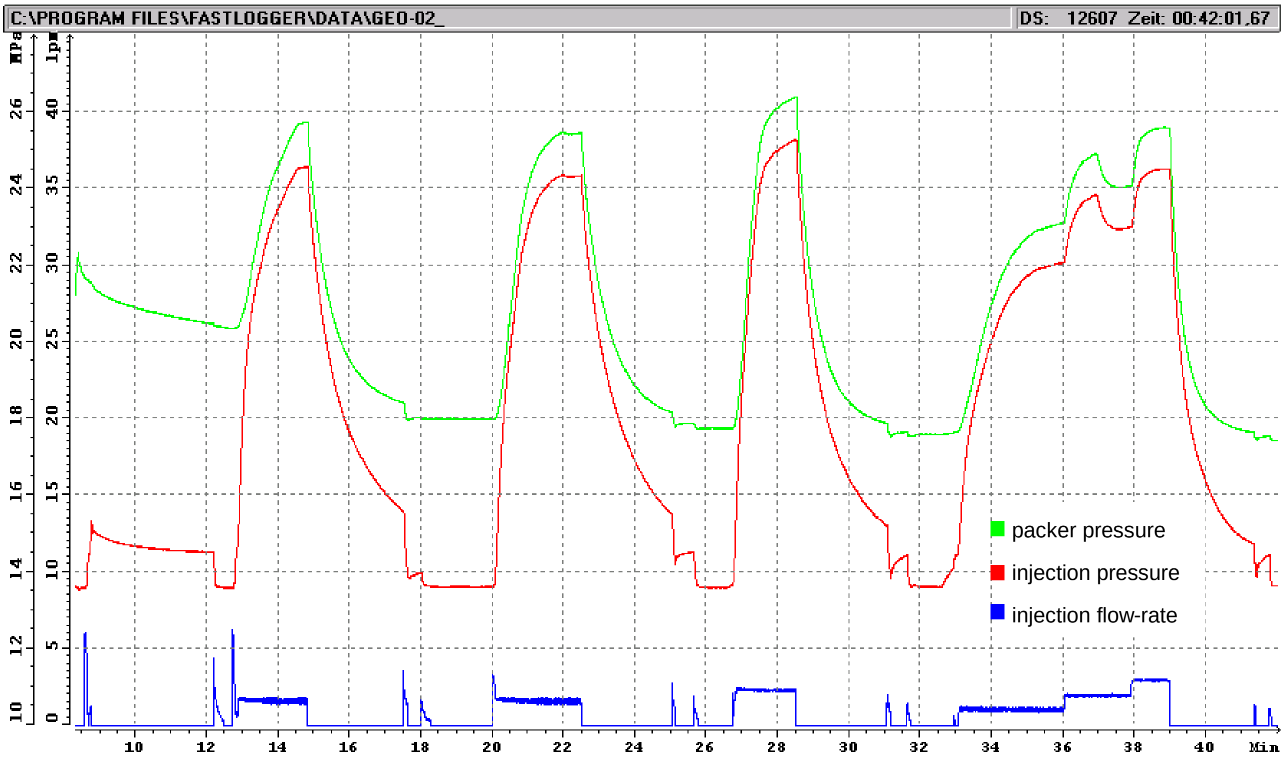
p-test	dP [MPa]	-0.1	dt [sec]	191

cycle	Q [lpm]	V_{in} [l]	V_{out} [l]	P_c [MPa]	P_r [MPa]	P_{prop} [MPa]	P_{si} [MPa]	P_{clo} [MPa]	P (SR) [MPa]
F	1.9	1.5	0.6	**21.0**		20.0	19.0	17.9	
RF1	2.0	2.5	0.5		**17.1**	18.8	18.1	16.5	
RF2	2.3	4.0	0.2		16.75	18.75	18.0	16.0	
RF3	2.7	3.6	0.1		17.0	18.7	**17.9**	16.0	
SR	1.0 2.1 3.1	7.0	0.1				**17.9**	16.0	17.60 18.36 18.75
total		18.65	1.5				$P_{jacking}$		17.7

Remark:

The initial injection cycle indicates the initiation of a fracture with a distinct breakdown-event. Distinct refrac- and shut-in pressures as well as small pressure response during interruption of the venting phases observed.

Test No. 3 at 1391.0 m



cycles: p RF1 RF2 RF3 SR

Analysis:

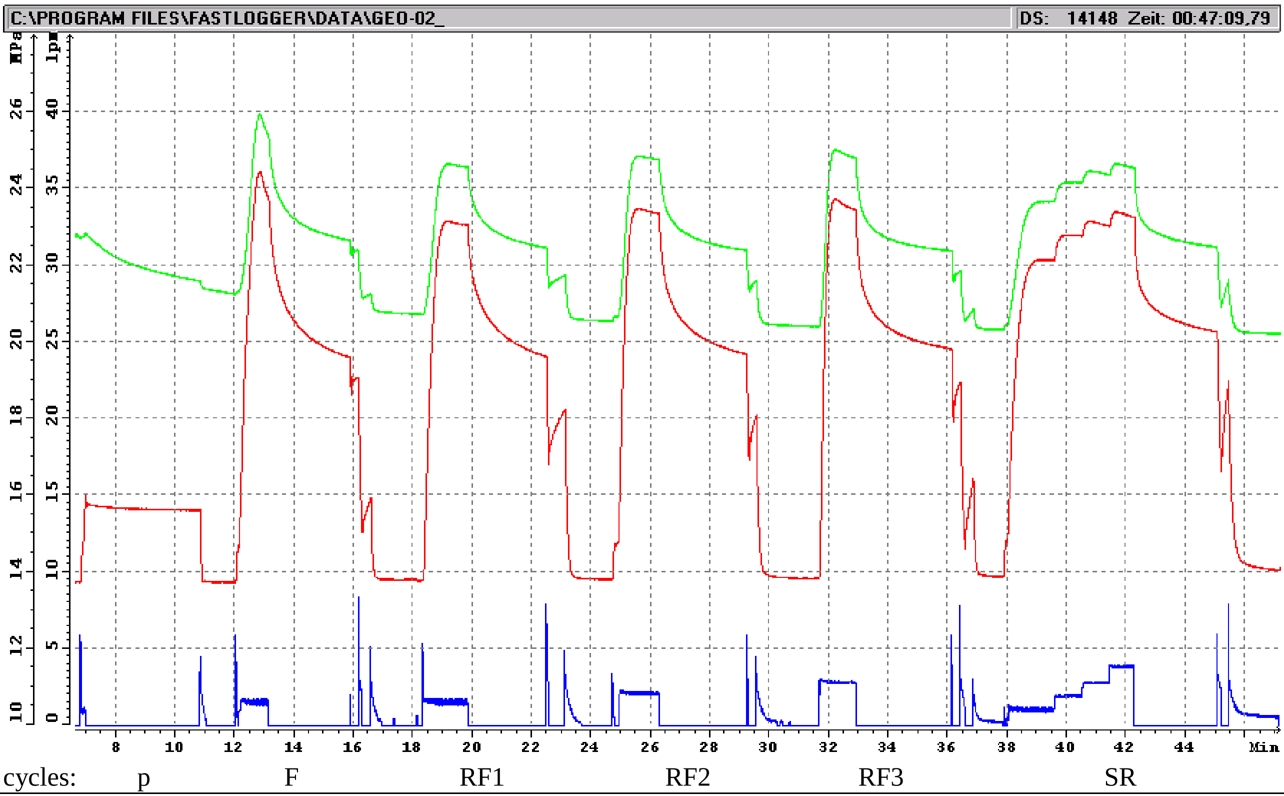
p-test	dP [MPa]	-0.55	dt [sec]	200

cycle	Q [lpm]	V_{in} [l]	V_{out} [l]	P_c [MPa]	P_r [MPa]	P_{prop} [MPa]	P_{si} [MPa]	P_{clo} [MPa]	P (SR) [MPa]
RF1	1.7	3.6	0.4	-	**18.7**	24.55	**22.7**	19.0	
RF2	1.6	4.1	0.2		17.1	24.3	22.8	19.0	
RF3	2.3	4.0	0.2		18.1	25.2	**22.7**	19.0	
SR	1.0 2.0 3.0	10.0	0.1			24.5	22.6	18.5	22.05 22.96 24.46
total		21.7	0.9				$P_{jacking}$		22.05- 23.0

Remark:

The initial injection cycle indicates the stimulation of a pre-existing fracture (no breakdown-event). Refrac- and shut-in pressures are difficult to identify. Small pressure response during interruption of the venting phases observed.

Test No. 2 at 1409.0 m



Analysis:

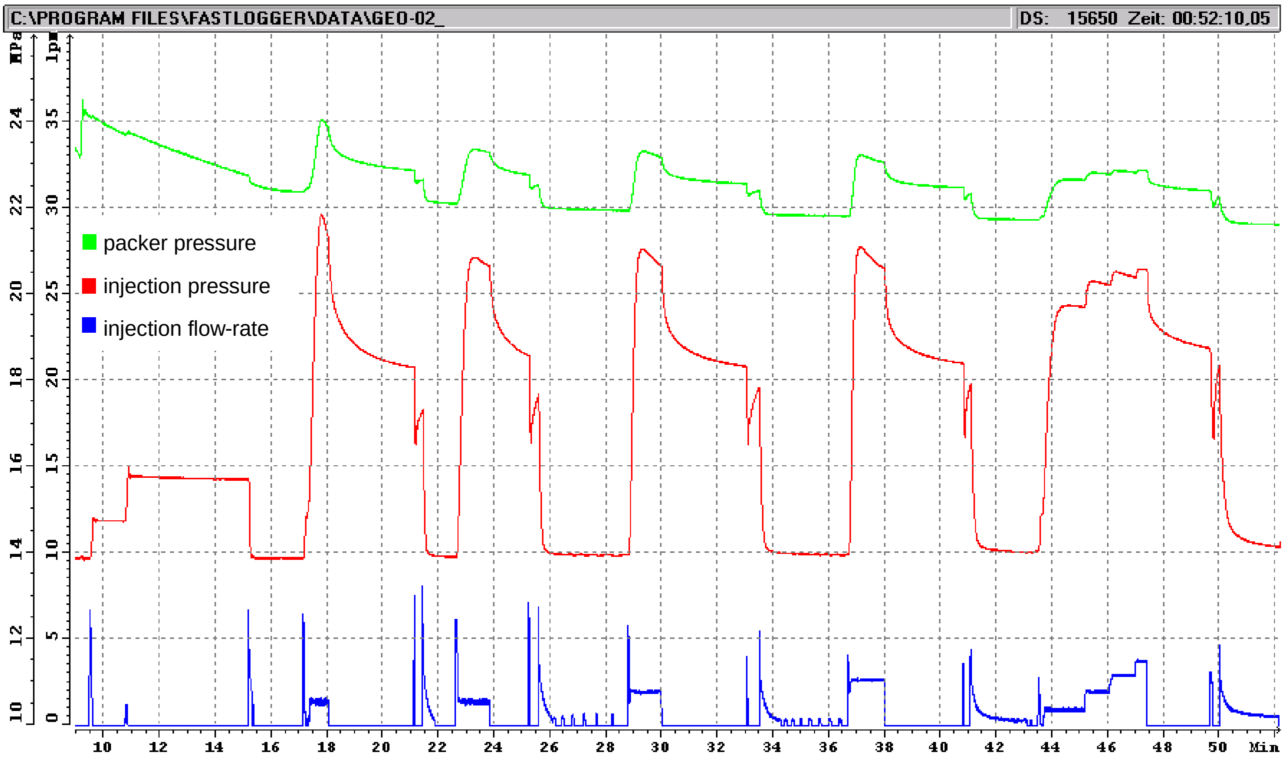
p-test	**dP [MPa]**	-0.14	**dt [sec]**	221

cycle	**Q [lpm]**	**V_{in} [l]**	**V_{out} [l]**	**P_c [MPa]**	**P_r [MPa]**	**P_{prop} [MPa]**	**P_{si} [MPa]**	**P_{clo} [MPa]**	**P (SR) [MPa]**
F	1.6	1.8	0.8	**24.4**		23.7	23.0	22.0	
RF1	1.6	2.5	0.8		**19.5**	23.0	22.5	21.4	
RF2	2.1	3.1	0.9		**19.8**	23.3	22.55	21.5	
RF3	2.9	3.5	1.0		19.2	23.4	**22.5**	21.5	
SR	1.1 2.0 2.8 3.1	9.2	1.9				22.2	21.8	22.11 22.74 22.99 23.21
total		20.1	5.4				$P_{jacking}$		22.6

Remark:

The initial injection cycle indicates the initiation of a fracture with a distinct breakdown-event. Distinct refrac- and shut-in pressures as well as good pressure response during interruption of the venting phases observed.

Test No. 1 at 1424.0 m



cycles: p F RF1 RF2 RF3 SR

Analysis:

p-test	dP [MPa]	-0.07	dt [sec]	249

cycle	Q [lpm]	V_{in} [l]	V_{out} [l]	P_c [MPa]	P_r [MPa]	P_{prop} [MPa]	P_{si} [MPa]	P_{clo} [MPa]	P (SR) [MPa]
F	1.4	1.4	0.8	**21.8**		21.3	20.6	19.9	
RF1	1.4	2.0	1.1		**18.7**	20.6	20.2	19.5	
RF2	1.9	2.6	1.1		18.9	20.6	19.9	19.5	
RF3	2.7	3.6	1.4		**19.0**	20.55	**19.8**	19.5	
SR	0.9 1.9 2.9 3.7	7.4	2.1				**19.8**	19.5	19.66 20.19 20.36 20.54
total		17.0	6.5				$P_{jacking}$		19.9

Remark:

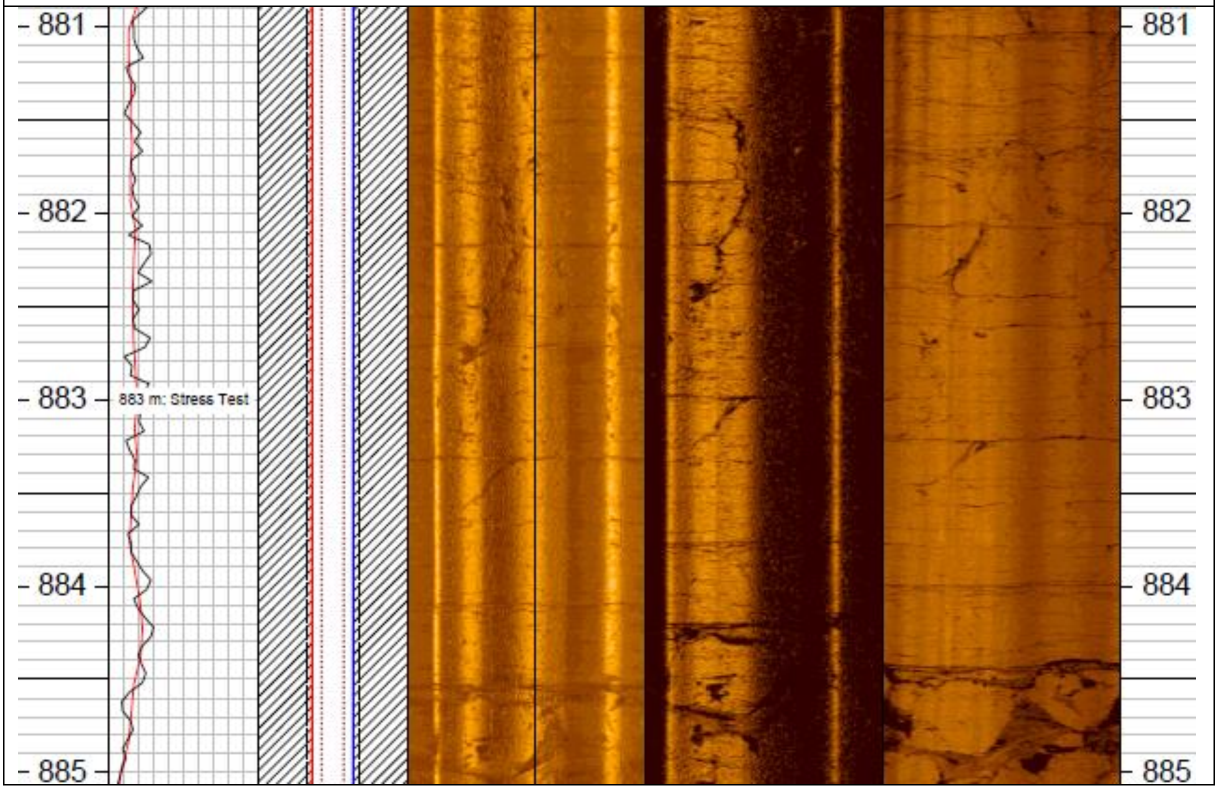
The initial injection cycle indicates the initiation of a fracture with a distinct breakdown-event. Distinct refrac- and shut-in pressures as well as good pressure response during interruption of the venting phases observed.

APPENDIX B

BHTV - Logs before and after Hydraulic Fracturing Testing

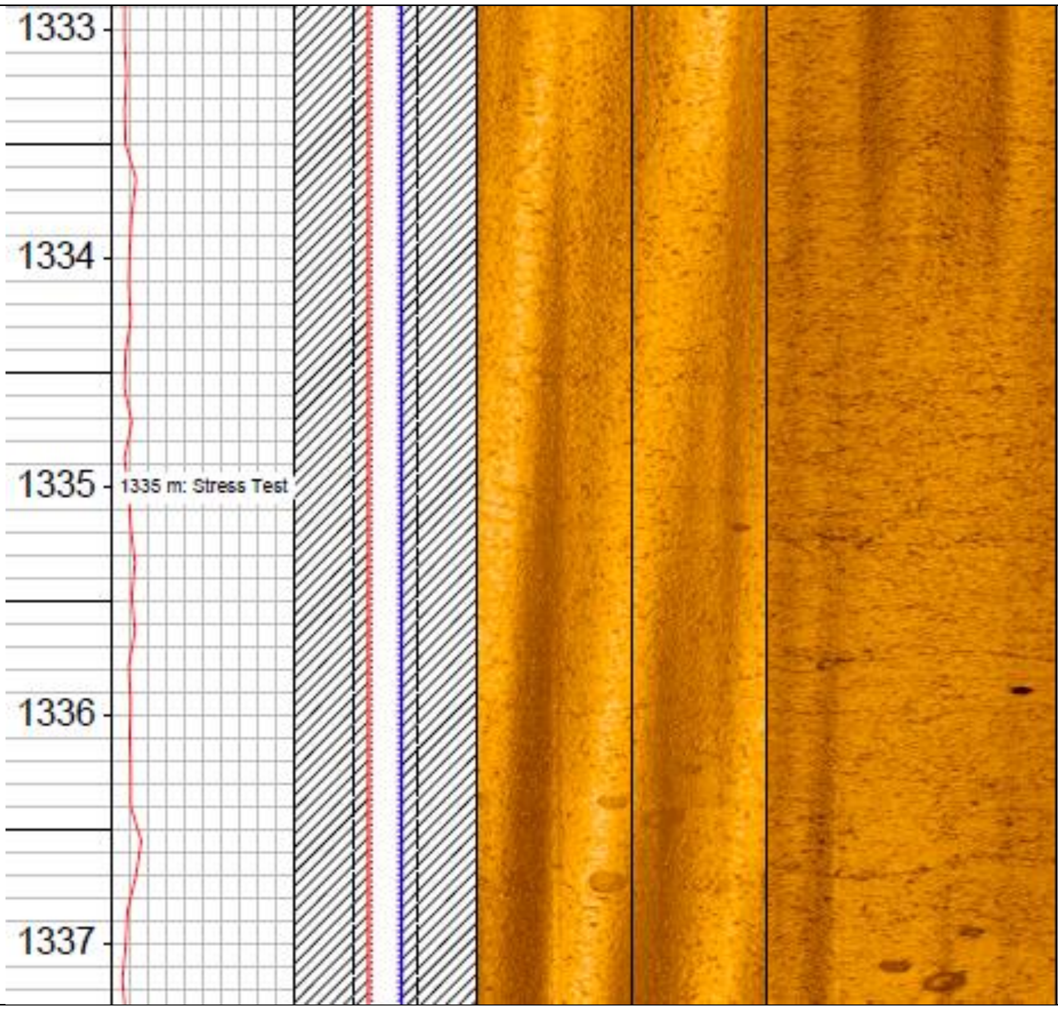
Test No. 8 at 883.0 m

left image: post-frac BHTV (22.07.2020), middle and right image: pre-frac BHTV (29.06.2020 and 15.05.2020)



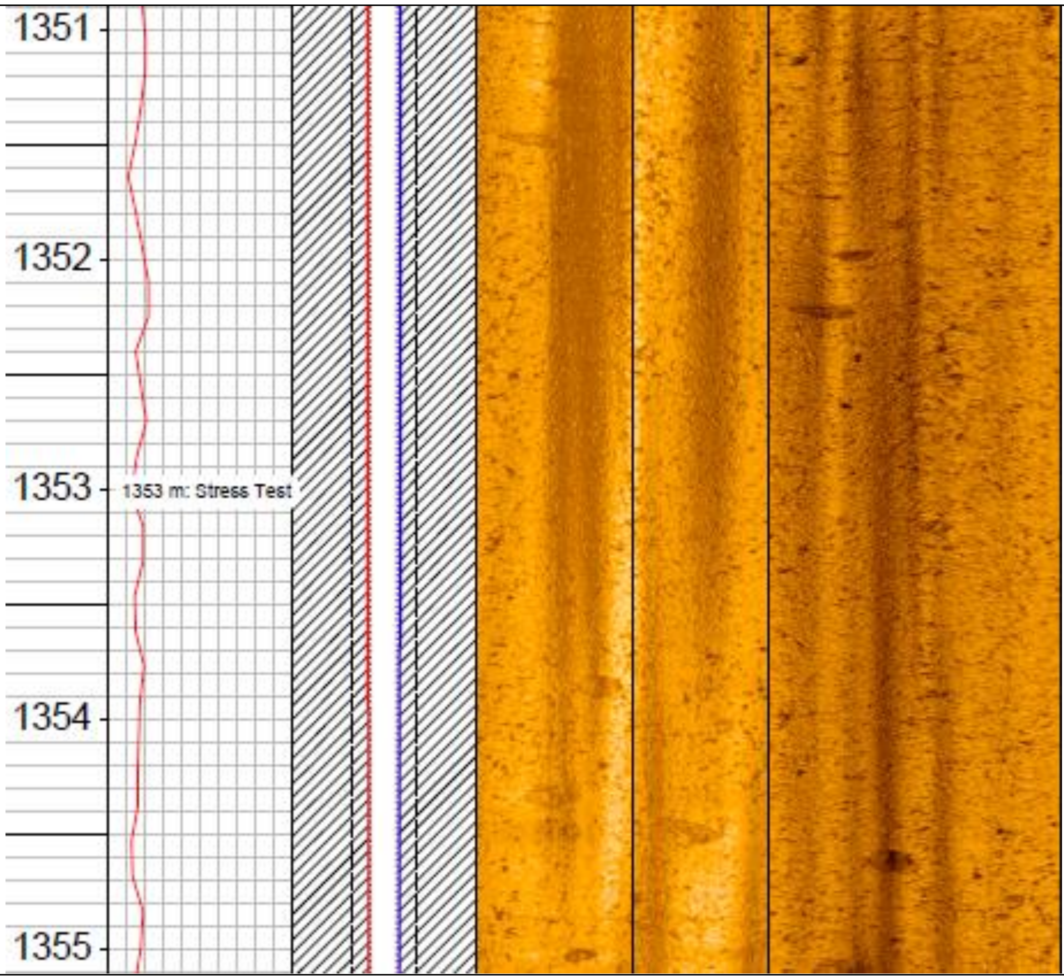
Test No. 7 at 1335.0 m

left image: post-frac BHTV (22.07.2020), right image: pre-frac BHTV (29.06.2020)



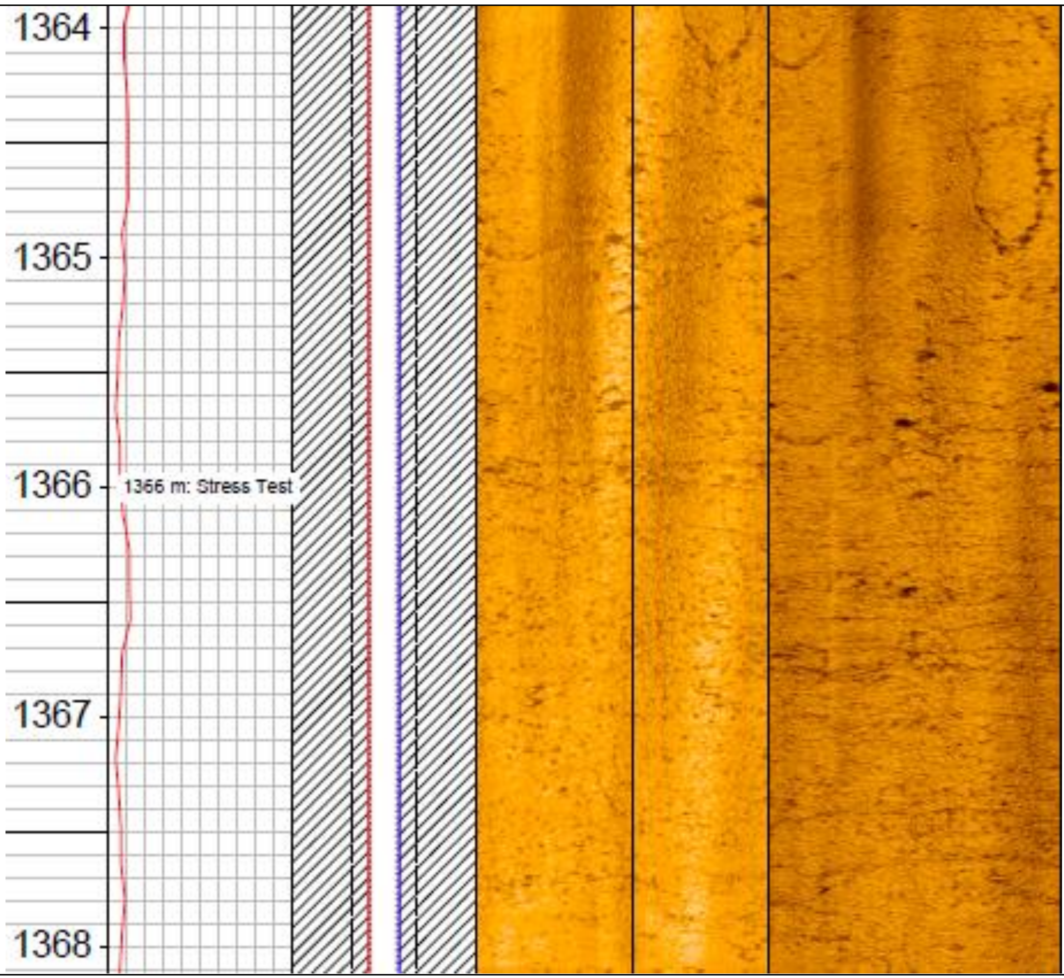
Test No. 6 at 1353.0 m

left image: post-frac BHTV (22.07.2020), right image: pre-frac BHTV (29.06.2020)



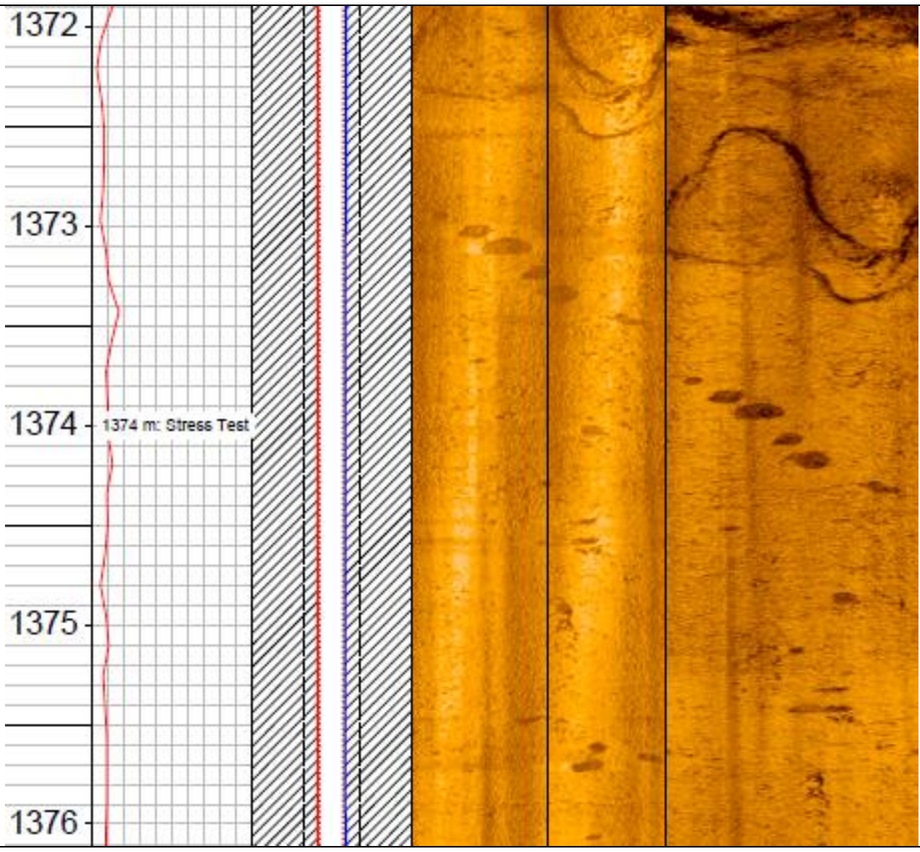
Test No. 5 at 1366.0 m

left image: post-frac BHTV (22.07.2020), right image: pre-frac BHTV (29.06.2020)



Test No. 4 at 1374.0 m

left image: post-frac BHTV (22.07.2020), right image: pre-frac BHTV (29.06.2020)



Test No. 3 at 1391.0 m

left image: post-frac BHTV (22.07.2020), right image: pre-frac BHTV (29.06.2020)