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ENIGMA Project – GPR monitoring of fractures at Äspö HRL

Results of field investigations in TAS04

Peter Andersson

Johanna Ragvald

SVENSK KÄRNBRÄNSLEHANTERING AB

SWEDISH NUCLEAR FUEL
AND WASTE MANAGEMENT CO

Box 3091, SE-169 03 Solna
Phone +46 8 459 84 00
skb.se

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Results of field investigations in TAS04

Peter Andersson, Johanna Ragvald
Geosigma AB

Abstract

The aim of the project was to obtain information of fracture connectivity and tracer pathways in the upper eight metres below tunnel TAS04 at Äspö HRL, as a preparation for measurements with Ground Penetrating Radar (GPR). The field investigations were divided into four steps:

Phase 1 – Drilling

Phase 2 – Characterization; optical televiewer (OPTV), core log analysis and hydraulic injection tests

Phase 3 – Pre-tests (tracer tests) and set-up for the GPR-measurements

Phase 4 – GPR-measurements combined with tracer tests

Three vertical boreholes were drilled to about 9.5 m depth in the floor of TAS04. During drilling of borehole 2 and 3 pressure was measured in the already drilled borehole. Pressure responses from drilling showed connections between all three boreholes.

The boreholes were characterized geologically with core log analysis and logged with optical televiewer (OPTV). Hydraulic characterization of the boreholes was performed by injection and outflow tests with constant pressure in 1-m sections of the boreholes. In total five of the measured sections had a transmissivity higher than the measurement limit; three succeeding 1-m sections in Bh1 and one 1-m section in each of Bh2 and Bh3. These results were consistent with the pressure responses from drilling and the geological characterisation.

Based on the results from the borehole characterisation, a pre-test with the tracer Amino G Acid was planned and performed. Tracer labelled water was injected in Bh2 and water was withdrawn from Bh1. Both injection and withdrawal were done in packed off sections chosen from the results from the hydraulic tests. First tracer breakthrough occurred after about 5 hours and the concentration in the pumped water reached at maximum 9 % of the injection concentration.

Two more tracer tests were then performed, at the same time as measurements with GPR equipment. Deionized water was used for injection to achieve an electrical conductivity contrast to the ambient water, for the GPR measurements, and the water was also labelled with Uranine (test #1) and Uranine + Rhodamine WT (test #2). Test #1 was performed with the same setup as pre-test and the results were consistent. Test #2 was performed between Bh2 and Bh3 (injection in Bh2 and withdrawal in Bh3) and the results showed a slower and possibly lower tracer breakthrough than test #1.

Sammanfattning

Syftet med denna undersökning var att ta fram information om sprickors konnektivitet och flödesvägar i de åtta översta metrarna under tunnel TAS04 i Äspö HRL. Undersökningarna gjordes som en förberedelse och underlag till mätningar med markradar (GPR). Fältundersökningarna gjordes i 4 steg:

Fas 1 – Borrning

Fas 2 – Karakterisering med optisk televiewer (OPTV), kärnloggning och hydrauliska injektionstester

Fas 3 – För-tester (spårförsök) och förberedelser för markradarmätningar

Fas 4 – Markradarmätningar kombinerat med spårförsök

Tre vertikala kärnborrhål borrades till ett djup av ca 9,5 m från botten av TAS04. Under borrningen av hål 2 och 3 registrerades tryckförändringarna i det första hålet vilket visade att de tre hålen var konnekterade.

Borrhålen karakteriserades geologiskt med kärnloggning och optisk televiewer (OPTV). Hydraulisk karakterisering av borrhålen gjordes med injektions- och utflödestester med konstant tryck i 1m-sektioner. Totalt fem av de mätta sektionerna hade en transmissivitet överstigande mätgränsen, tre intilliggande sektioner i borrhål 1 och en sektion var i borrhål 2 och 3. Dessa resultat överensstämde väl med uppmätta tryckresponser från borrningen och den geologiska karakteriseringen.

Baserat på resultaten från den inledande karakteriseringen utfördes ett för-test med spårämnet Amino G Acid. Spårämnesmärkt vatten injicerades i borrhål 2 och vatten flödades ur borrhål 1. Injicering och vattenuttag gjordes i borrhålssektioner som avmanschetterats i utvalda sektioner baserade på resultaten från de hydrauliska testerna. Första genombrott av spårämne registrerades efter ca 5 timmar och koncentrationen i det utflödande vattnet nådde maximalt 9 % av den injicerade koncentrationen.

Ytterligare två spårförsök genomfördes samtidigt med markradarmätningarna. Avjonat vatten användes i dessa försök i syfte att uppnå en kontrast i elektrisk ledningsförmåga till det omgivande salta vattnet i tunneln. Vattnet märktes också med spårämnet Uranin (test #1) och Uranin + Rhodamin WT (test #2). Test #1 utfördes i samma geometri som förtestet och uppvisade liknade resultat. Test #2 utfördes genom injicering i borrhål 2 och uttag i borrhål 3 och resultaten visade en långsammare transport och en lägre recovery.

Contents

1 Introduction

The identification of water conducting fractures in the subsurface is critical for evaluating potential contaminant transport pathways from deep disposal sites. One approach is to develop Discrete Fracture Network (DFN) models from field mapping (boreholes and outcrops) and hydraulic experiments. As a part of the ENIGMA ITN project (European training Network for in situ imaGing of dynaMic processes in heterogeneous subsurfAce environments) work is planned to demonstrate the ability of the GPR method to identify open fractures in formations of very low overall permeability that are targeted to store canisters containing spent nuclear fuel and to provide results improving the predictive capacity of stochastic DFN models by conditioning to geophysical data at scales from a few to tens of meters.

This report describes the initial characterisation of the experimental site located tunnel niche TAS04 at about 410 m depth in the Äspö HRL, see Figure 1-1. TAS04 has earlier been used for investigations of the excavation damaged zone (EDZ) and further information about geology, fracturing, mineralogy, etc, can be found in Ericsson et al. (2015).

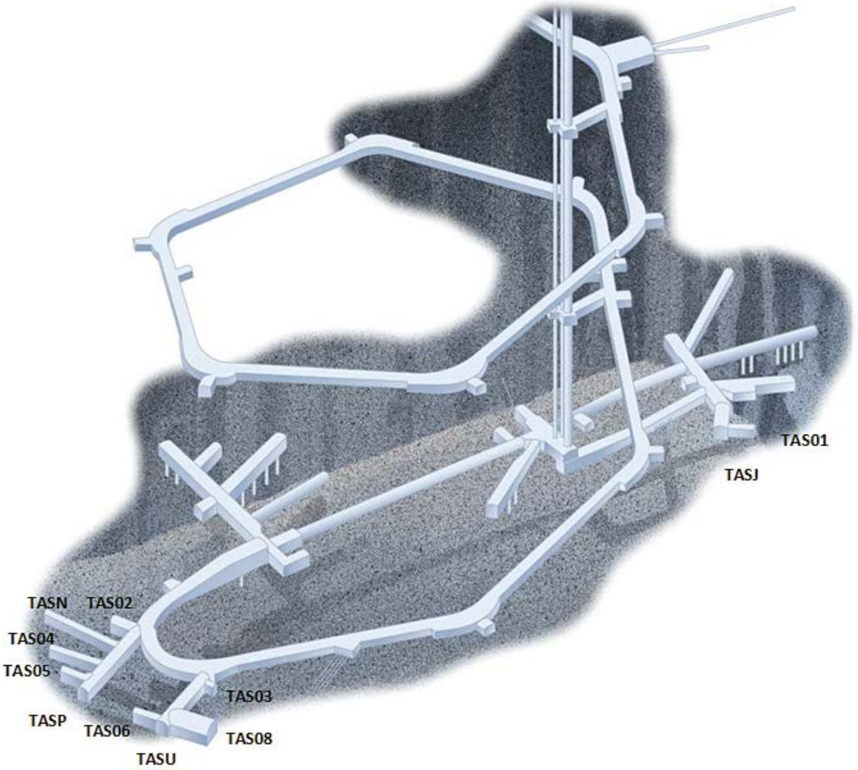

Figure 1-1. *Overview of the Äspö HRL. Tunnel niche TAS04 is located at 410 m depth in the lower left corner.*

2 Aim and scope

The aim of these experiments is to obtain geometrically constrained information about fracture connectivity and tracer pathways in the upper 8 m below TAS04 at Äspö HRL. These data will be used within a PhD project of the ENIGMA-ITN to build discrete fracture network (DFN) models that are conditioned to geological data, borehole data, static 3-D ground penetrating radar (GPR) information and tracer-monitored GPR-data (present project).

The experimental work at Äspö is divided in four phases:

Phase 1 – Drilling

Phase 2 – Characterization; OPTV, core log analysis and hydraulic injection tests

Phase 3 – Pre-tests (tracer tests) and set-up for the GPR-measurements

Phase 4 – GPR-measurements combined with tracer tests

3 Work performed

3.1 Phase 1 – Drilling

Three vertical boreholes, diameter 76 mm, 9.5 m deep and placed 4.3 m apart were drilled in the floor of the tunnel niche TAS04 at about 410 m depth in the Äspö HRL, see Table 3-1 and Figure 3-1 for basic information and Appendix 1 for drilling records. The boreholes are called Bh1, Bh2 and Bh3 in the following text.

Table 3-1. Borehole coordinates and depths (referring to the top of the borehole in Äspö 96 coordinate system).

Borehole ID	Drilling depth	Borehole diameter	NORTHING	EASTING	ELEVATION
K04018G02 (Bh1)	9.65 m	0.076 m	7351.702	2429.105	−409.553
K04022G02 (Bh2)	9.55 m	0.076 m	7348.499	2431.800	−409.508
K04026G02 (Bh3)	9.50 m	0.076 m	7346.502	2434.310	−409.451

During drilling of the boreholes, formation water was used from borehole HD0025A having a similar ionic composition as the formation water at the site. However, for Bh1, water from borehole KA2598A was used by mistake. After drilling of Bh1, water was therefore pumped out of the hole and replaced with water from HD0025A. No tracer was added to the drilling water to avoid interference with tracers used in the experiment.

Pressure in the already drilled boreholes was measured during the drilling of the subsequent holes by installing mechanical packers at 1 m depth in the already drilled hole/holes, see Section 4.1.

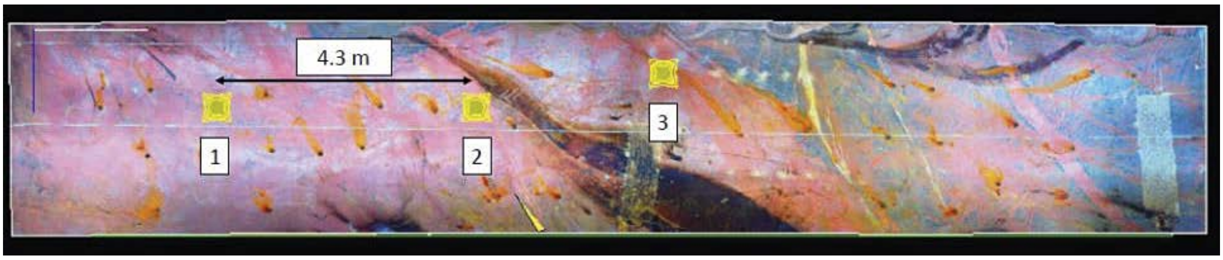

Figure 3-1. Location of Bh1, Bh2 and Bh3 projected on the tunnel floor of TAS04.

3.2 Phase 2A – Basic characterisation, OPTV and Core log analysis

Optical Televiewer (OPTV) measurements were performed to determine fracture orientation and dip, and to give some indications of aperture. The OPTV also serves as a basis for the core log analysis, including mineralogy. The detailed analysis was made with the Boremap system developed by SKB. Data from the detailed analysis is not included in this report but has been stored in the SKB database SICADA.

Based on results from the injection tests (Phase 2B below), and pressure response during drilling, a special study was made on OPTV images from the flowing sections of the three boreholes, see Section 4.4 below.

3.3 Phase 2B – Basic characterisation, Injection tests

The transmissivity of the rock was measured with injection and outflow tests in the three boreholes in packed-off intervals of 1 m with the HWIC (High pressure Water Injection Controller), see Figure 3-2. HWIC is an equipment for hydraulic testing, developed by Geosigma for SKB, for testing in tunnel boreholes down to 500 m depth. It includes pumping system, regulation system, flow meters, pressure transducer and data logger. The equipment can automatically control injection and flow tests with either constant pressure or constant flow in the range of 2 mL/min up to 90 L/min.

Figure 3-2. *High pressure Water Injection Controller (HWIC).*

Due to the very low transmissivity of the rock in combination with the high ambient pressures in the boreholes (about 2 000 kPa), outflow tests were considered to give more reliable results than injection tests. The reason being that injection pressures in the order of 4 000 kPa were needed to exceed the lower measurement limit of the HWIC (2 mL/min) which could create uplift of the rock.

Outflow tests were performed in 1 m packed-off sections in the interval 1–8 meters below the tunnel floor, in each borehole. A single packer was also placed at 1 m depth in the two non-active boreholes while doing outflow tests in the active borehole and pressure responses were measured in the interval from 1 m to the bottom of the hole. Following the outflow tests, stationary and transient evaluations of the tests were executed. The down-hole equipment is shown in Figure 3-3.

Figure 3-3. *Installation of a double-packer for hydraulic tests.*

3.4 Steady-state evaluation

Hydraulic transmissivity from the injection tests was estimated in accordance with Moye's formula (Moye 1967):

$$T_M = \frac{Q_p \cdot \rho_w \cdot g}{dP_p} \cdot C_M$$

Where

$$C_M = \frac{1 + \ln\left(\frac{L_w}{2r_w}\right)}{2\pi}$$

T_M = hydraulic transmissivity ($m^2 s^{-1}$)

Q_p = flow rate at the end of the flow period ($m^3 s^{-1}$)

ρ_w = density of water ($kg\ m^{-3}$)

g = acceleration of gravity ($m\ s^{-2}$)

C_M = geometrical shape factor (-)

dP_p = injection pressure $P_p - P_i$ (Pa)

r_w = borehole radius (m)

L_w = section length (m)

Moye's formula is based on the assumption that steady-state is reached at the end of the flow period. For practical reasons the flow period is set to about 15 minutes, which normally is sufficient for attaining pseudo-stationary flow conditions.

3.5 Transient evaluation

Transient evaluation was performed using the software AQTESOLV for the 5 sections with flow over the measurement limit. In four sections data were best fitted with the Hurst-Clark-Brauer solution (Hurst et al. 1969) for a constant head test with a confined aquifer, see Figure 3-4. The fifth section was best fitted with the Hantush solution for a leaky confined aquifer, see Figure 3-5.

Since the estimated skin factor is strongly correlated to the storativity, storativity was calculated using an empirical regression relationship between storativity and transmissivity (Rhén et al. 1997):

$S = 0.0007 \cdot T^{0.5}$

S = storativity (-)

T = transmissivity (m^2/s)

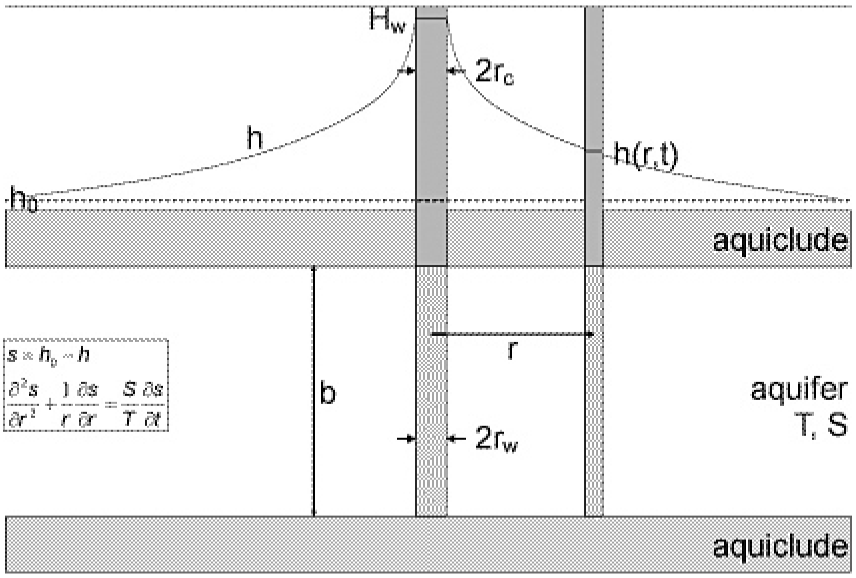

Figure 3-4. *The Hurst-Clark-Brauer solution (illustration from AQTESOLV Software).*

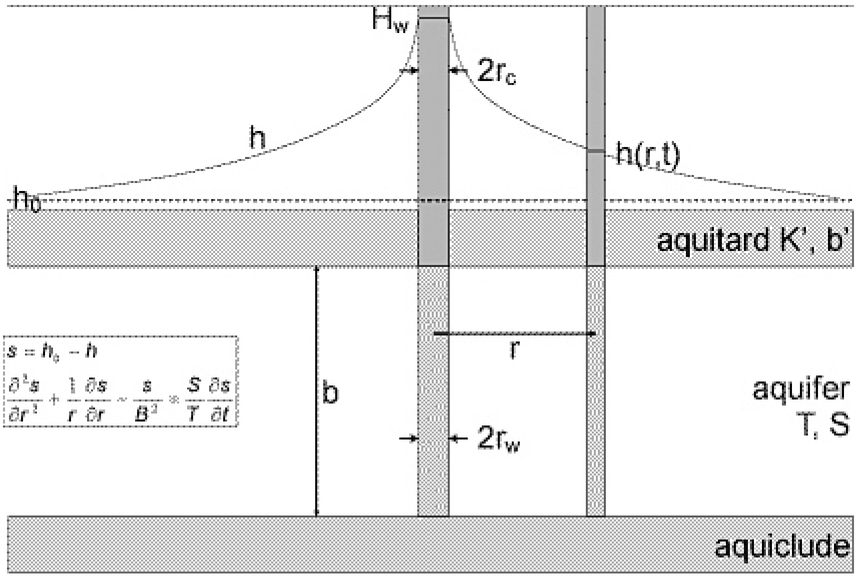

Figure 3-5. *The Hantush solution (illustration from AQTESOLV Software).*

3.6 Phase 3 – Pre-test tracer test

Based on the results of geological mapping, hydraulic tests and responses during drilling, a tracer test was performed between Bh2 and Bh1 to test the travel time, connectivity and possible recovery of tracer in the flow path between the holes. The fluorescent dye Amino G Acid was used as tracer.

Bh2 was packed-off in a 0.5 m interval covering the flowing fractures in the interval 3.2–3.7 m depth and Bh1 was packed off in the interval 3.0–6.0 m. In Bh1, volume reducers were installed to reduce volume and delay in the borehole volume, see Figure 3-6. Pressure transducers were also installed for measuring pressures below the lower packers in both boreholes.

The pre-test was initiated on October 23rd , 2018, using the HWIC for injection. However, due to very low flow rate, high pressure and limited volume of water, the risk of overheating the equipment became too big and the test was stopped after 60 minutes. The injection was then re-started the next day with another equipment, called EDZ-equipment (mainly developed for injection tests in short boreholes in the excavation damaged zone (EDZ)).

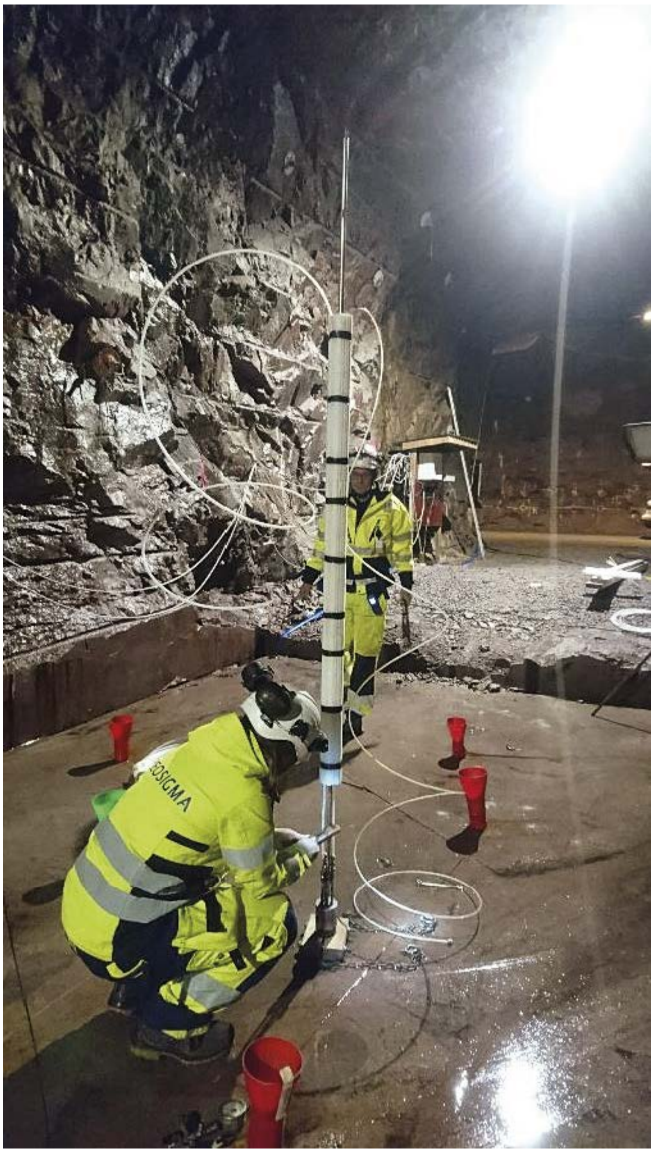

Figure 3-6. *Installation of double-packer with volume reducers for tracer tests in Bh1.*

The EDZ-equipment consists of a data collection and control system which is mounted on a carriage. The system is connected to the packers via hydraulic tubes. The measurement principle is based on that a pressure tank with water is pressurized with a pre-determined pressure using nitrogen gas. The water flow is measured with an accurate mass flow meter. Flow rates can be measured in two different flow directions, but the pressure regulation works only for injection tests. The pressure in the borehole section was measured for test 1 and test 2 using a pressure sensor connected with a tube to the same tube as water was injected with, see Figure 3-7. For pre-test, only pressure in pressure bottle was measured, but when the valve from the pressure bottle to the section is opened the pressure in the pressure bottle and section is the same.

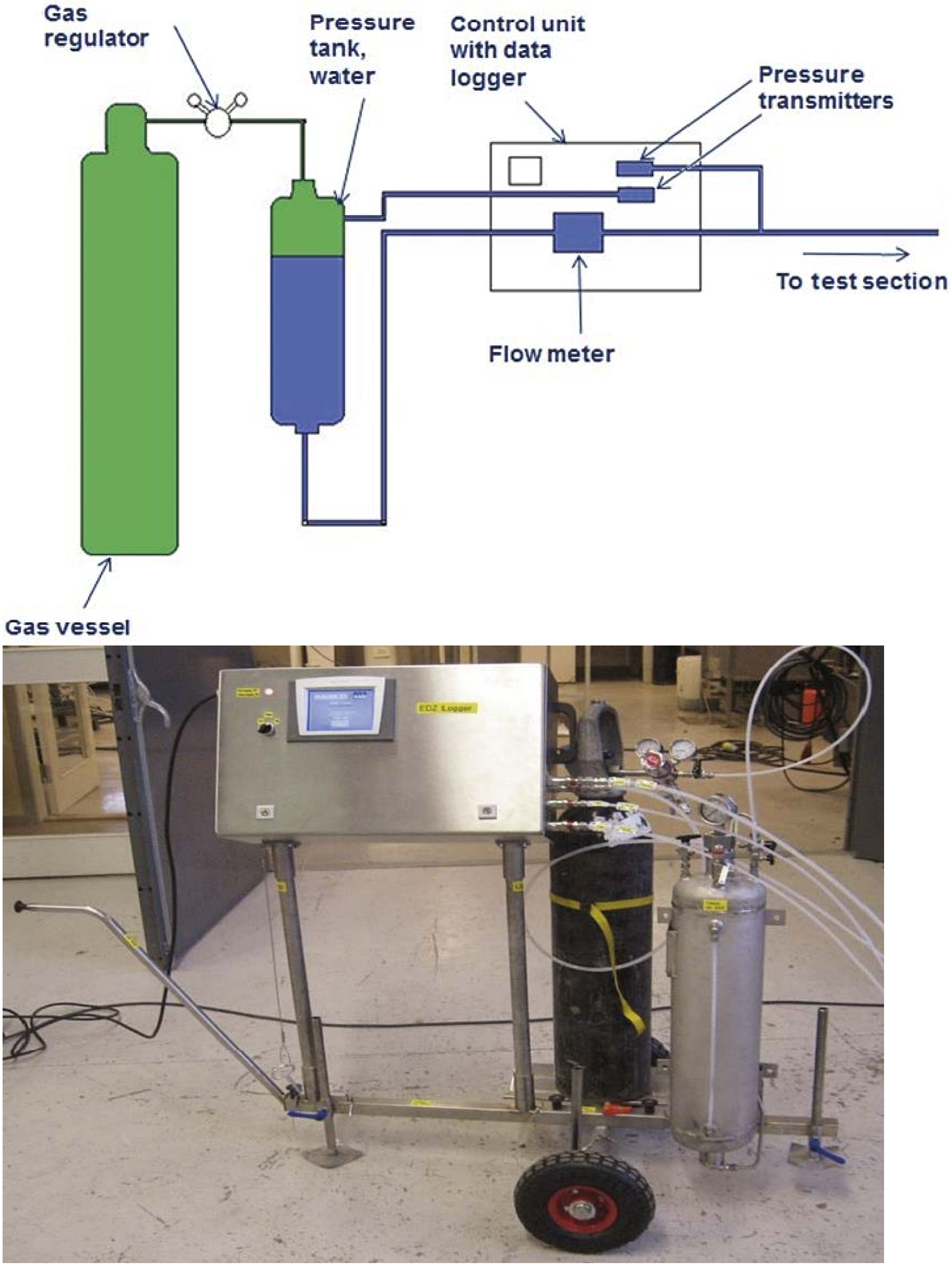

Figure 3-7. Equipment for injection of water/tracer.

Tracer sampling was done by opening the sampling borehole section completely to the atmosphere, i.e. lowering the ambient pressure with about 1 475 kPa.

Flow and electric conductivity (EC) of the water from the sampling hole was measured continuously with a flow meter and EC-sensor connected to a data logger, see Figure 3-8.

Samples were retrieved with constant flow by a peristaltic pump into 19 mL test tubes, see Figure 3-9. Sampling times were altered between 10–60 minutes during the tests. Tracer analyses were made at Geosigma by means of fluorometry.

Figure 3-8. *Equipment for measurements of EC and flow and data logger.*

Figure 3-9. *Sampling equipment, sampling changer and peristaltic pump.*

3.7 Phase 4 – Tracer tests #1 and #2

Based on the results from the pre-tests, two more tracer tests were performed in conjunction with GPR measurements using the same equipment and methodology as described in Section 3.6. Deionized water was used for injection to achieve an electrical conductivity contrast for the GPR measurements.

In total three tracer tests were performed in unequal dipole geometry using the only section with flow above measurement limit in Bh2 as source. Test geometry and tracers used are given in Table 3-2 below. A log of all events (injection start-stop, tracer injections, etc) are given in Appendix 2.

Table 3-2. Summary of tracer tests performed.

Test	Injection section	Pumping section	Tracer used
Pre-test	Bh2 (3.2–3.7 m)	Bh1 (3–6 m)	Amino G Acid
Test #1	Bh2 (3.2–3.7 m)	Bh1 (3–6 m)	Uranine in deionized water
Test #2	Bh2 (3.2–3.7 m)	Bh3 (4–5 m)	Uranine + Rhodamine WT in deionized water

4 Results

4.1 Pressure measurements during drilling

Pressure responses were detected in Bh1 both during drilling of Bh2 and Bh3, and in Bh2 during drilling of Bh3, see Figure 4-1 and Figure 4-2. This indicates that all three boreholes are hydraulically connected.

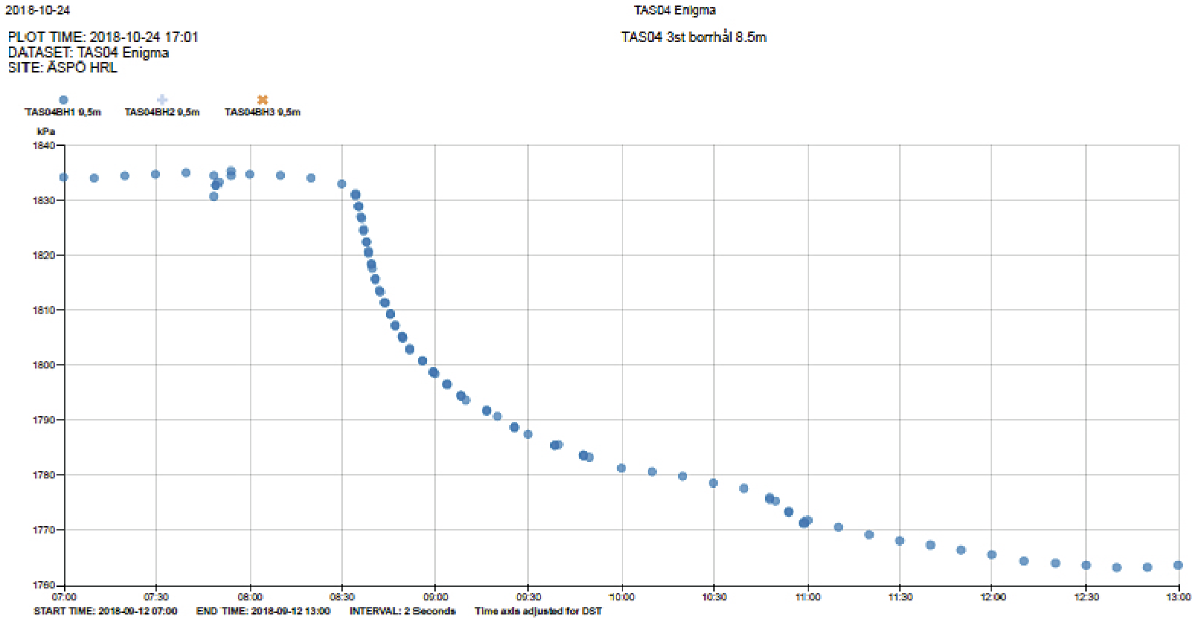

Figure 4-1. *Pressure response in Bh1 during drilling of Bh2. A clear response can be seen at about 8:35 corresponding to a drilling depth of about 3.3 m in Bh2.*

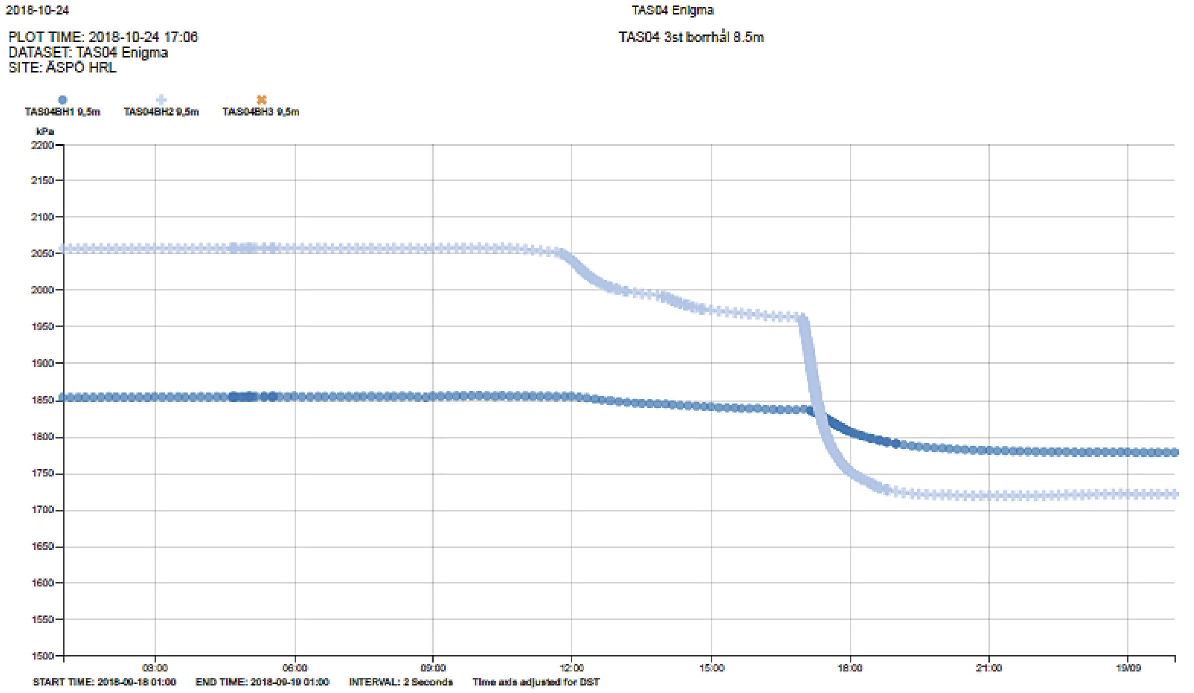

Figure 4-2. *Pressure response in Bh1 and Bh2 during drilling of Bh3. A clear response can be seen in both holes at about 17:00 corresponding to a drilling depth of about 4.9 m in Bh3.*

After drilling was finished, all three holes were packed off and pressure build-up was measured, see Figure 4-3. As expected, pressures are lower closer to the main tunnel (Bh1).

4.2 Geological mapping

The geological mapping shows relatively homogeneous rock with all three boreholes having only one and same reddish rock type, Ävrö granodiorite, Figure 4-4. In total 17, 13 and 11 fractures were mapped in Bh1, Bh2 and Bh3, respectively. Dominating fracture fillings are chlorite and calcite, and some minor parts of quartz, pyrite and hematite. A special study of the water conducting sections, made in advance of the Boremap mapping, is presented in Section 4.4.

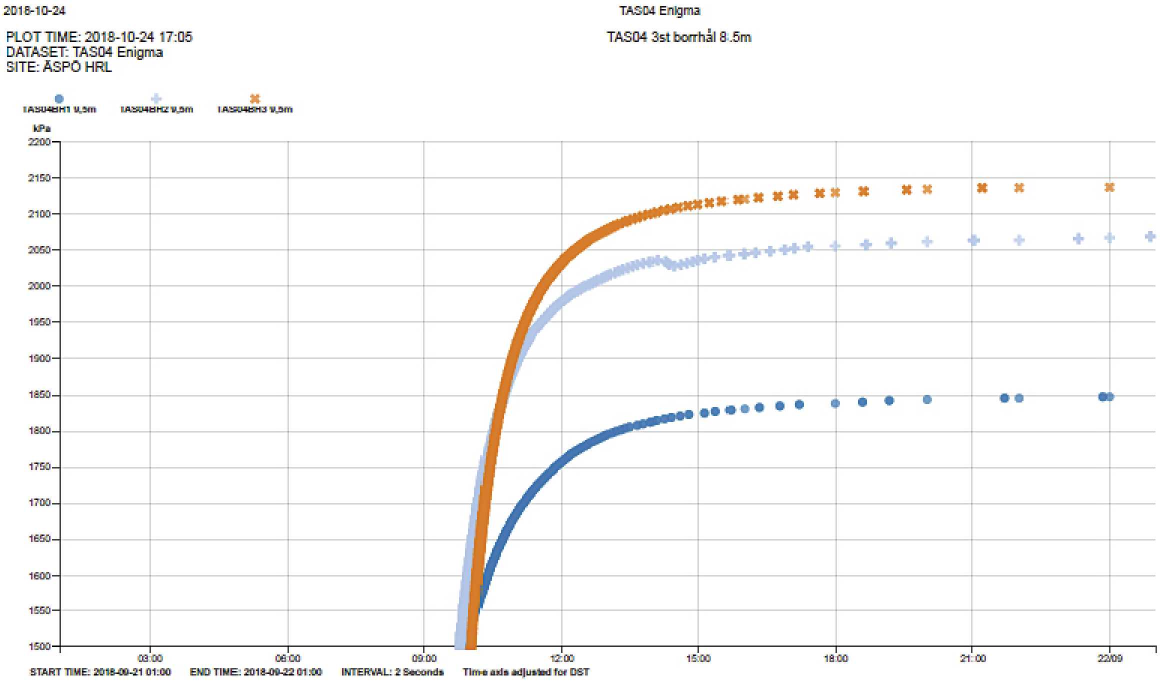

Figure 4-3. *Pressure build-up in Bh1, Bh2 and Bh3 after drilling.*

Figure 4-4. *Core box photo showing the core from Bh2 and the Ävrö granodiorite with two subparallel fractures at 3.5 – 3.7 m, see also Figure 4-5.*

4.3 Hydraulic parameters

The outflow tests showed a very low transmissive rock at the site. In total, only five 1-m sections of the 21 tested gave flow rates above the measurement limit, see Table 4-1. Specific capacity and Moye transmissivity are in the order of 10^{-9} to 10^{-10} m^2/s. Diagrams of flow and pressure during the tests are presented in Appendix 3.

Transient evaluation was possible to perform for all five sections with flow above detection limit (see Table 4-1), but the values for the section in Bh2 are uncertain. In four of the sections, the confined aquifer solution fitted the data best, while in the fifth (section 5–6 m in Bh1) a leaky aquifer solution gave the best fit to the data. Log-log plots and matched curves are presented in Appendix 4. The log-log diagrams from the transient evaluations can be used to determine flow regimes in the section. The interpreted flow regimes in the measured sections are of different types, see Table 4-1. Pseudo-radial flow (PRF) indicates a fracture plane and pseudo-spherical flow (PSF) a 3-dimentional fracture network and no flow boundary (NFB) that the fracture ends.

Table 4-1. Results of hydraulic tests. Negative injection pressures imply outflow measurement.

Borehole	Secup (m)	Seclow (m)	Injection pressure, P_{inj} (kPa)	Final flow rate, Qp (L/min)	Specific capacity, Q/s (m^2/s)	Transmissivity Moye, T_M (m^2/s)	Transmissivity transient evaluation, T_T (m^2/s)	Flow regime
Bh1	1	2	200	*)				
Bh1	2	3	510	*)				
Bh1	3	4	−1427	−0.0033	3.8E−10	2.2E−10	4.0E−10	PRF → NFB?
Bh1	4	5	−1086	−0.0073	1.1E−09	6.3E−10	1.3E−9	PRF
Bh1	5	6	−1080	−0.0065	9.8E−10	5.6E−10	5.7E−10	PSF
Bh1	6	7	−1449	*)				
Bh1	7	8	−1376	*)				
Bh2	1	2	656	*)				
Bh2	2	3	493	*)				
Bh2	2	3	−1875	*)				
Bh2	3	4	401	*)				
Bh2	3	4	−1589	−0.0038	3.9E−10	2.2E−10	1.2E−10	?
Bh2	4	5	400	*)				
Bh2	5	6	401	*)				
Bh2	5	6	−1979	*)				
Bh2	5	6	290	*)				
Bh2	6	7	−1600	*)				
Bh2	6	7	400	*)				
Bh2	7	8	−1979	*)				
Bh2	7	8	401	*)				
Bh3	1	2	175	*)				
Bh3	2	3	−833	*)				
Bh3	3	4	191	*)				
Bh3	4	5	−1300	−0.0097	1.2E−09	7.0E−10	8.1E−10	PRF
Bh3	5	6	−1600	*)				
Bh3	6	7	−1659	*)				
Bh3	7	8	−1300	*)				

*) Below measurement limit.

4.4 Fracture geometry from OPTV

A special study was made of the fracturing in the five water conducting sections found during hydraulic testing. Strike and dips of the possible water conducting fractures discussed below have been corrected to Boremap mapping results.

The mapping, presented in Figure 4-5 to Figure 4-7 below, shows a set of three subparallel subhorizontal fractures in the interval 3.2 – 3.7 m in Bh2. The fractures have orientations 128/42 (strike/dip), 125/37 and 119/44.

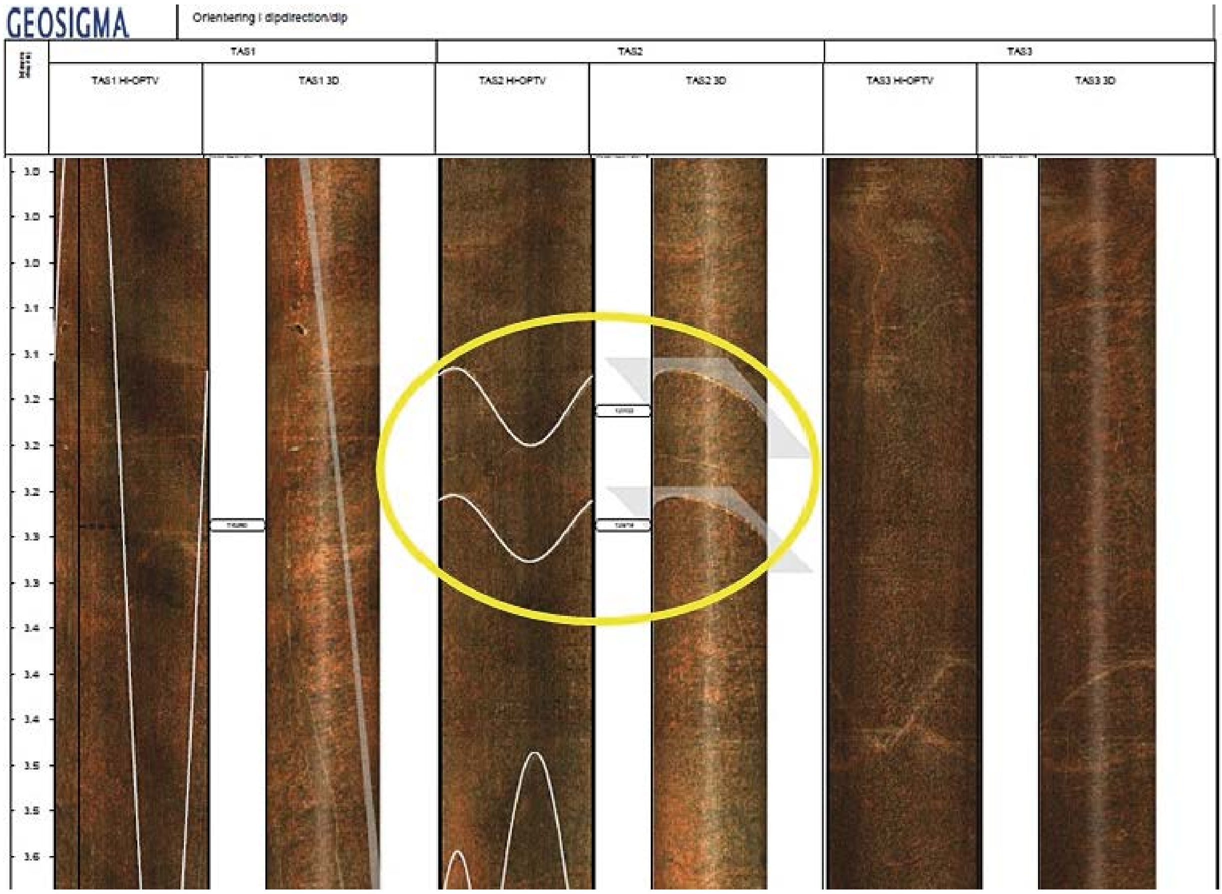

Figure 4-5. OPTV images of Bh1, 2 and 3, interval 3.0 – 3.7 m. The subhorizontal fracture set in Bh2 is marked with a yellow ring.

A similar set of three subhorizontal fractures can also be seen in Bh1 at 3.6 – 4.1 m depth having orientations 69/21, 104/33 and 104/30.

There are also some more steeply dipping fractures that may be water conducting and connected to Bh3 at 4–5 m where only steeper fractures are found having dips of between 62–77 degrees. The drilling response indicates that fractures around 4.9 m depth are connected to Bh2, see also Figure 4-2.

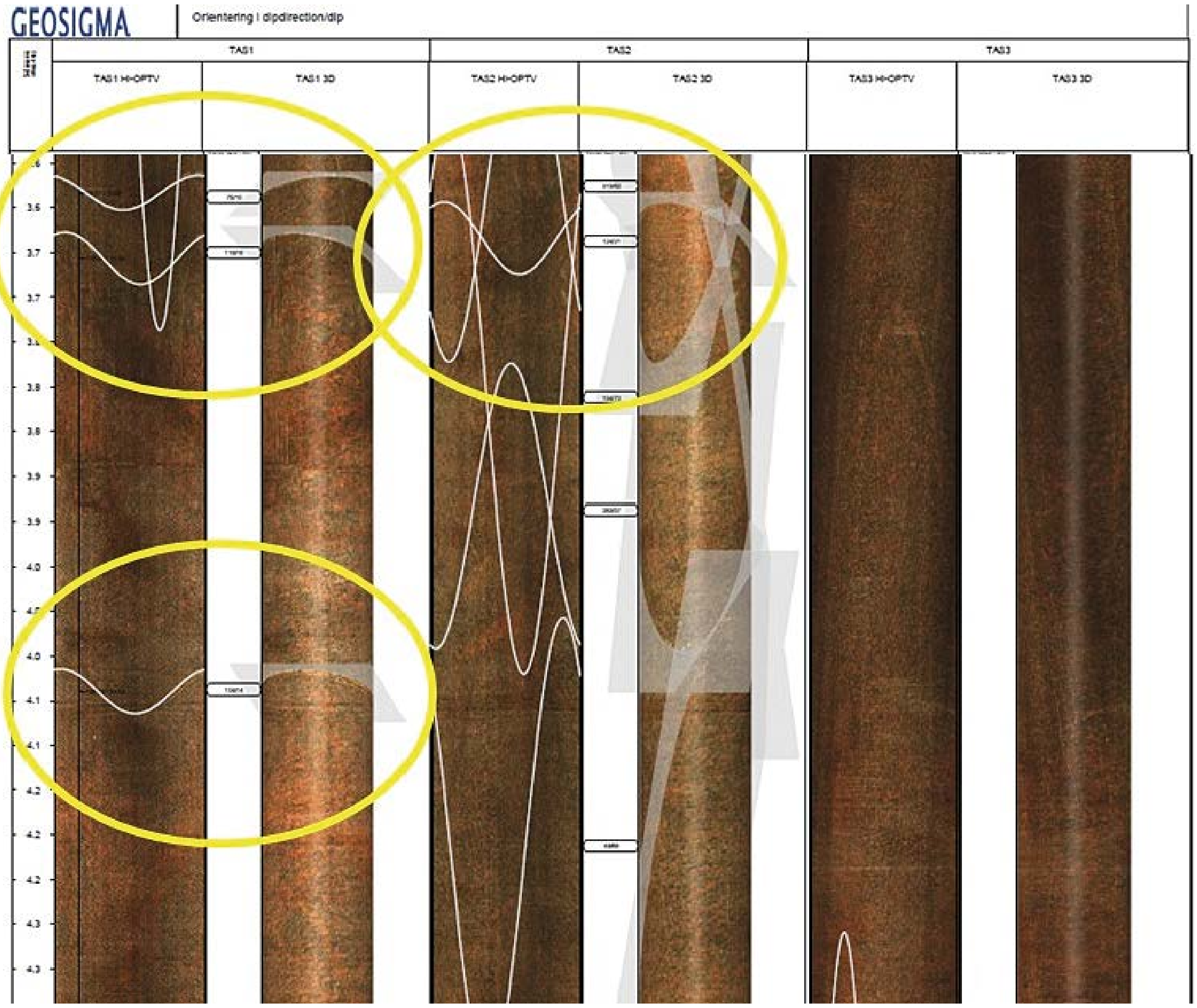

Figure 4-6. OPTV images of Bh1, Bh2 and Bh3, interval 3.7 – 4.4 m. The subhorizontal fracture set in Bh1 and Bh2 is marked with a yellow ring.

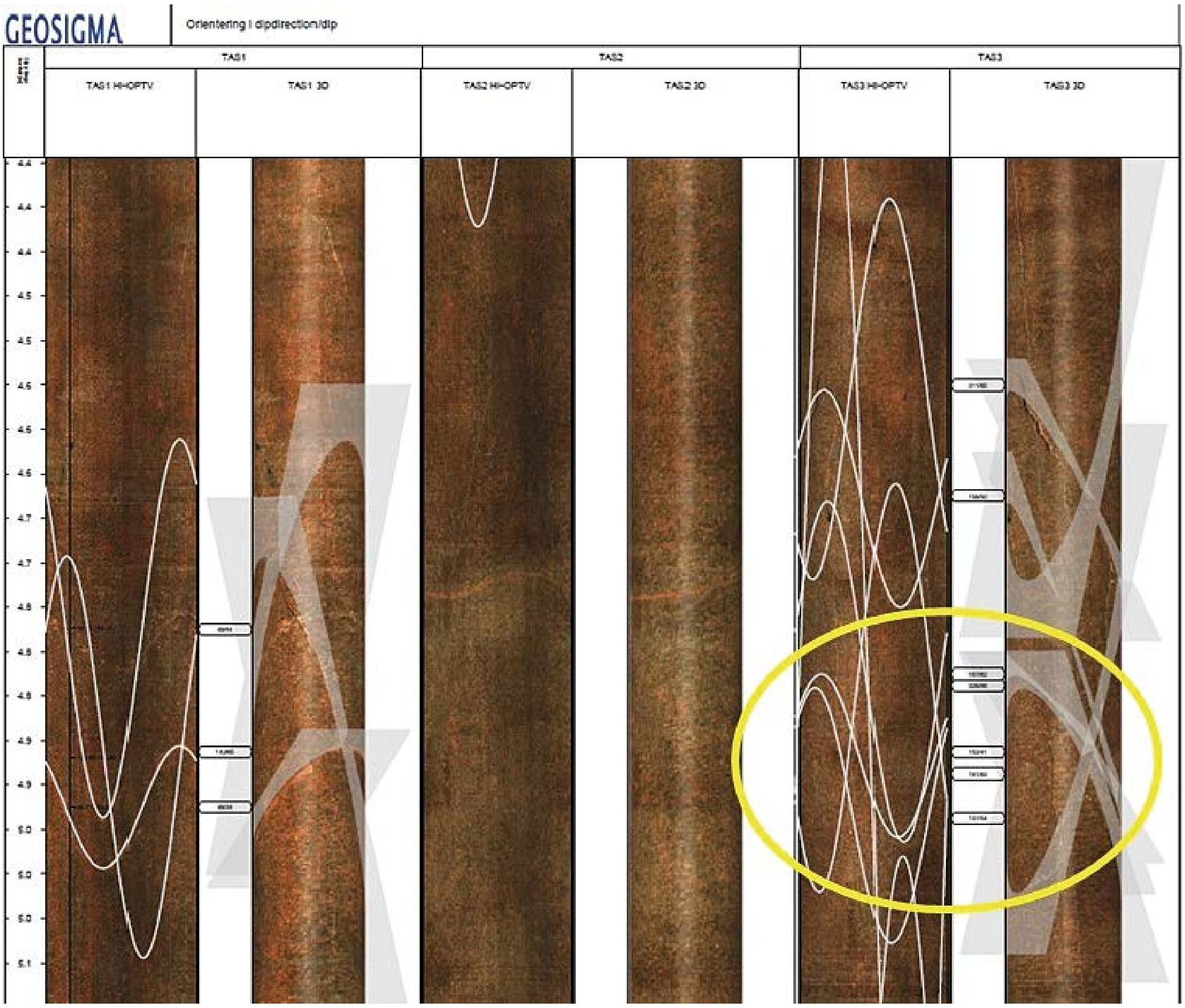

Figure 4-7. OPTV images of Bh1, Bh2 and Bh3, interval 4.4–5.1 m. The fracture set giving response during drilling in Bh1 and Bh2 is marked with a yellow ring.

4.5 Tracer tests

4.5.1 Pressure measurements during tracer tests

Figure 4-8 shows a plot of the pressures (absolute pressures including air pressure) in all three boreholes before, during and after tracer tests. On October 22nd the test sections in Bh1 and Bh2 are installed and pressure is measured in the packed-off intervals until October 23rd, which explains the lowered pressures during that time.

In Bh3 clear responses of the activities in the other boreholes can be observed. The pressure in Bh3 decreases when sections in the other holes are opened and increases during injection in Bh2. A summary of flows and pressures during the pre-test and main tests are presented in Sections 4.5.2 to 4.5.4.

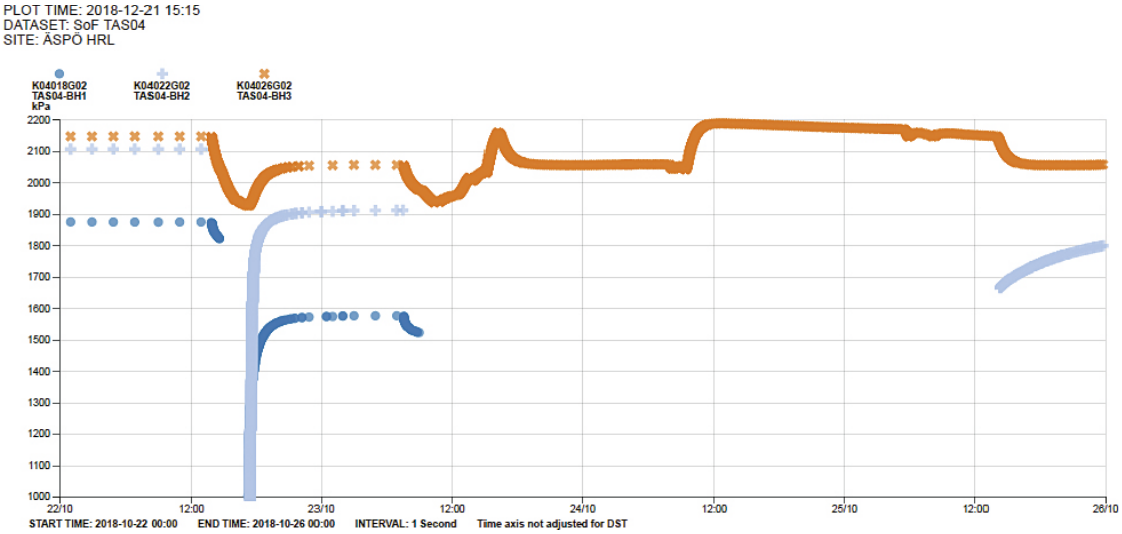

***Figure 4-8.** Pressures (absolute pressures) during installation of packers and pre-tests in Bh1–3.*

4.5.2 Pre-test tracer test

The pre-test was initiated on October 23rd using the HWIC for injection, but due to equipment problem the test had to be stopped after only 60 minutes. After changing the equipment (cf. Section 3.6) the test was re-started on October 24th. Pressure was set to about 4 000 kPa, implying an overpressure of about 2 500 kPa compared to the ambient pressure. Flow and pressure in the injection hole (Bh2) are shown in Figure 4-9.

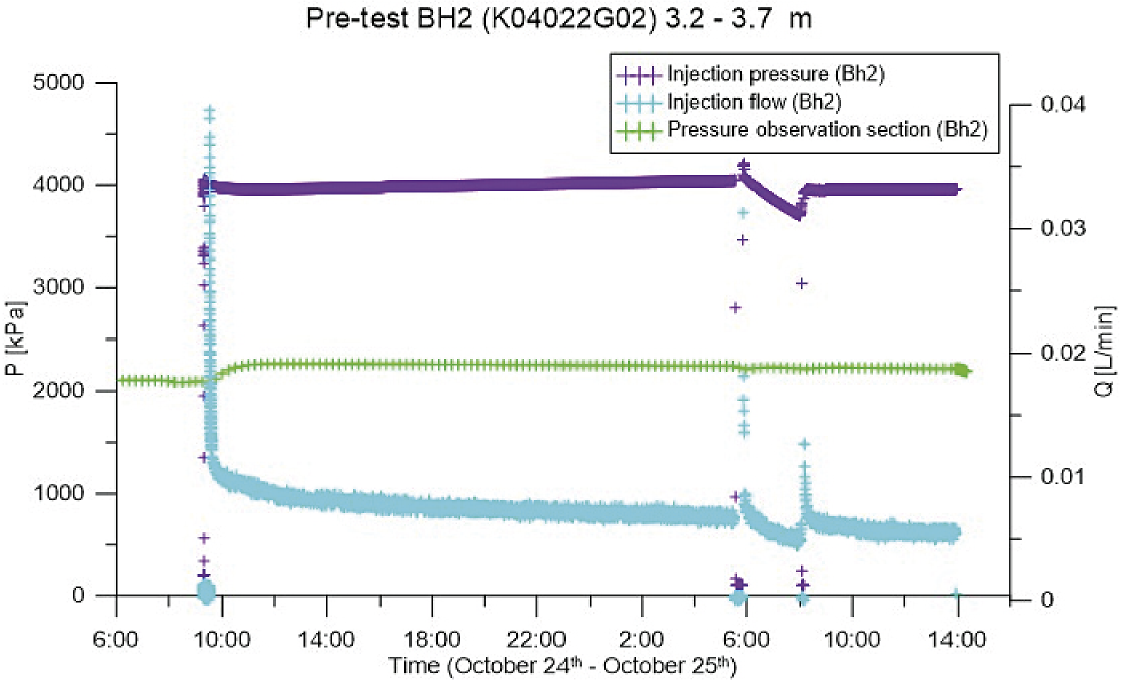

***Figure 4-9.** Injection pressure (purple) and flow rate (blue) in Bh2 during Pre-test. The green symbols show pressure in the section below 4.2 m in Bh2.*

Figure 4-10 shows the tracer breakthrough of Amino G Acid and electrical conductivity in the pumped water from Bh1. The breakthrough coincides with a simultaneous sinking of EC due to a somewhat lower EC in the injection water (from borehole HD0025A) than in the formation water. Flow rate was continuously logged but values turned out to be below measurement limit. Manual measurements were however also made showing a steady outflow of 20 ml/min from Bh1.

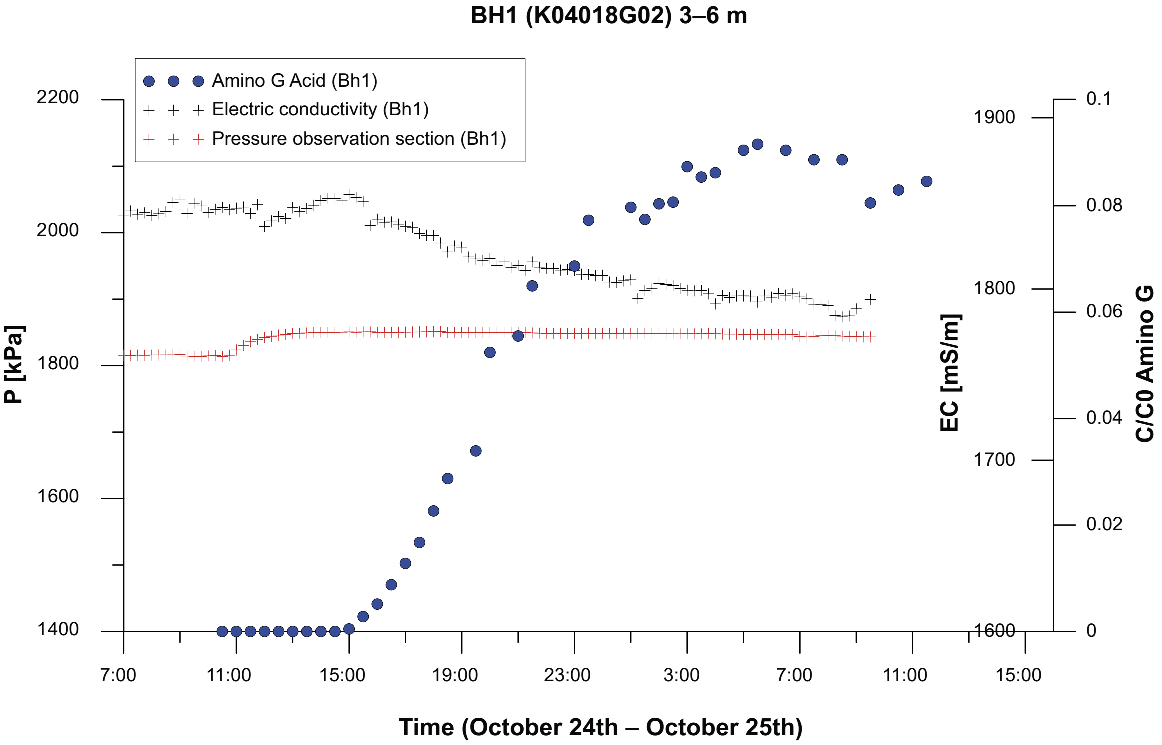

Figure 4-10. *Tracer breakthrough (blue), EC (black) in outflow from the pumping section (3–6 m) and pressure in the section below pumping section (7.0 m to bottom) (red), all in Bh1.*

4.5.3 Tracer test #1

Tracer test #1 was initiated on November 6th. Pressure was set to about 4 000 kPa, (implying an overpressure of about 2 000 kPa compared to the ambient pressure) and was then increased to about 5 000 kPa (implying an overpressure of about 3 000 kPa). Flow and pressure in the injection hole (Bh2) are shown in Figure 4-11.

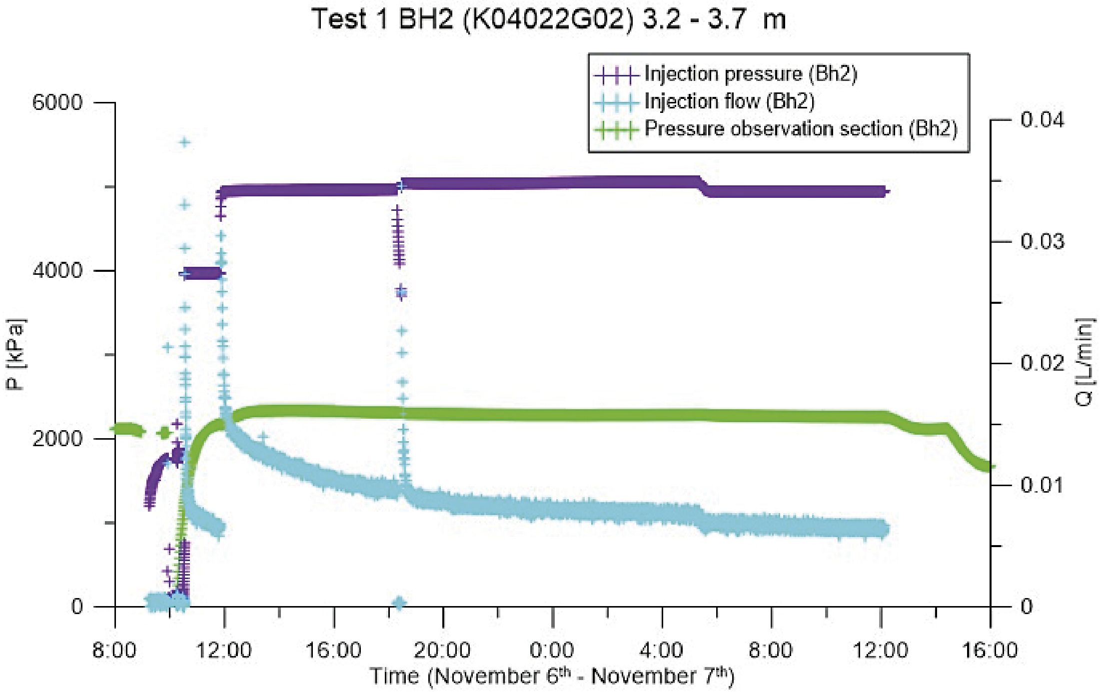

Figure 4-11. *Injection pressure (purple) and flow rate (blue) in Bh2 during test #1. The green symbols show pressure in the section below injection section (4.2 m to bottom) in Bh2.*

Figure 4-12 shows the tracer breakthrough of Uranine and electric conductivity (EC) in the pumped water from Bh1. The breakthrough coincides with a simultaneous sinking of EC due to a much lower EC in the injection water (deionized water) than in the formation water. Flow rate was continuously logged but values turned out to be below measurement limit. Manual measurements were however also made showing a steady outflow of around 20 ml/min from Bh1.

Injection in Bh2 was going on until 12:07, November 7th. At 12:20 the outflow tube from Bh1 was closed causing a pressure build-up in the outflow section in Bh1 (Figure 4-13) and also a pressure increase in the observation section in Bh1 (see Figure 4-12).

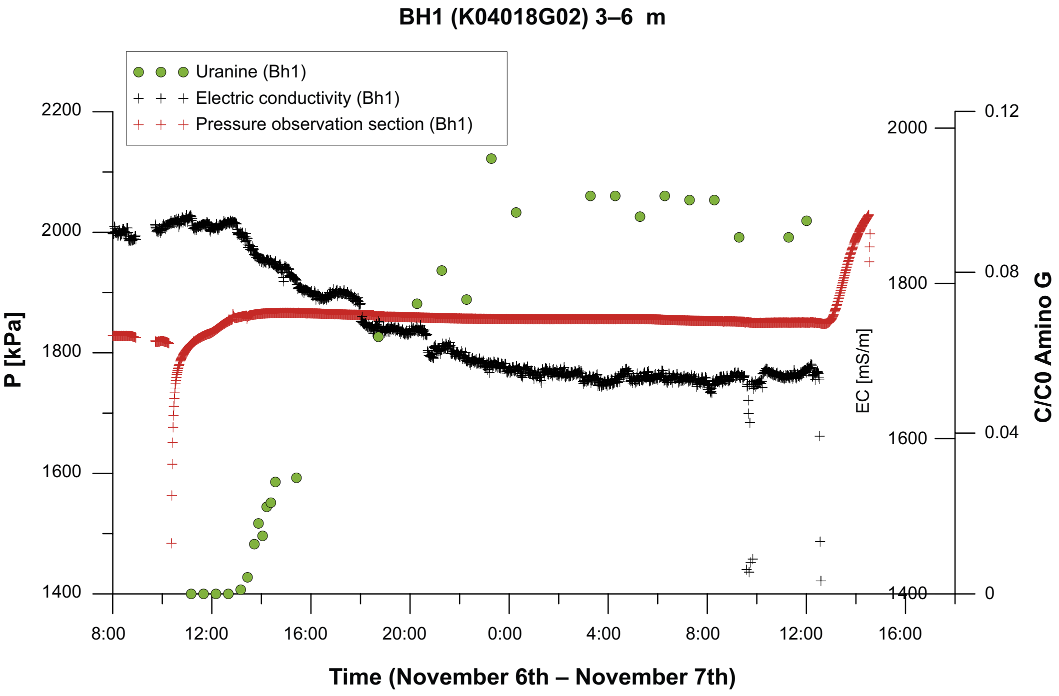

***Figure 4-12.** Tracer breakthrough (green), EC (black) in outflow from the pumping section (3–6 m) and pressure in the section below pumping section (7.0 m to bottom) (red), all in Bh1.*

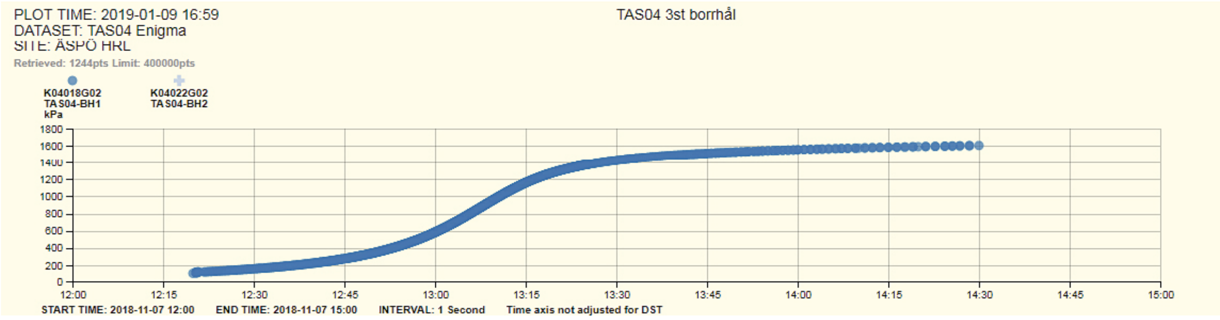

***Figure 4-13.** Pressure build-up in outflow section in Bh1 after closing of outflow tube.*

4.5.4 Tracer test #2

Tracer test #2 was initiated on November 8th. Pressure was set to about 5 000 kPa, (implying an over-pressure of about 3 000 kPa compared to the ambient pressure). Flow and pressure in the injection hole (Bh2) are shown in Figure 4-14.

Figure 4-15 shows the tracer breakthrough of Rhodamine WT and EC of the pumped water from Bh3. The breakthrough coincides with a simultaneous sinking of EC due to a much lower EC in the injection water (deionized water) than in the formation water. Flow rate was continuously logged but values turned out to be below measurement limit. Manual measurements were however also made showing a steady outflow of around 18 ml/min from Bh3.

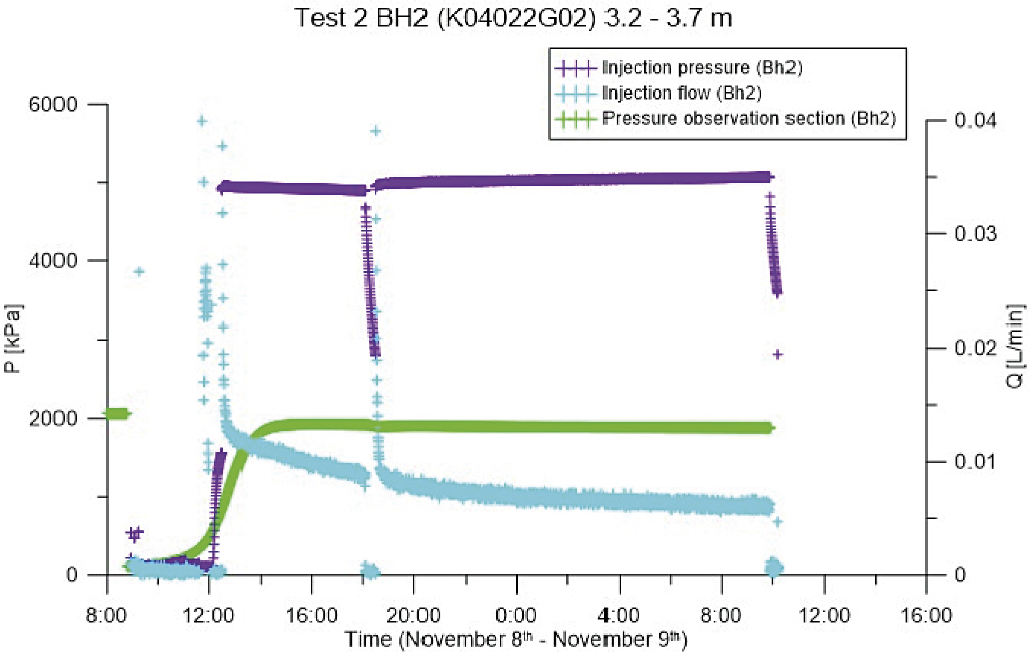

Figure 4-14. Injection pressure (purple) and flow rate (blue) in Bh2 during pre-test. The green symbols show pressure in the section below injection section (4.2 m to bottom) in Bh2.

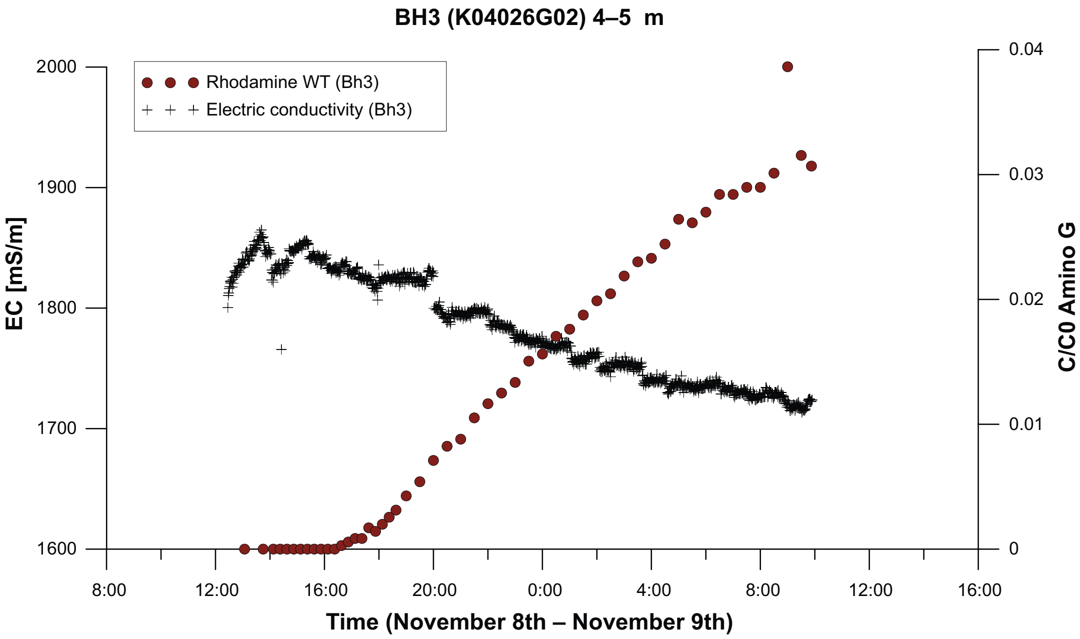

Figure 4-15. Tracer breakthrough (red), EC (black) in the pumped section in Bh3 (4–5 m).

4.5.5 Tracer breakthrough curves

In Figure 4-16 the complete breakthrough curves are shown for all tests. For the pre-test it also includes the recovery phase, but for tests #1 and #2 sampling was stopped soon after injection stop.

Pre-test and test #1 were performed with the same set-up, between the same borehole sections (injection in Bh2, pumping in Bh1), but with different tracers. The curves have very good agreement except that the response from test #1 was a bit earlier. The reason for this is that the borehole was pre-filled with tracer-marked water before injection started in this test, while in the pre-test the tracer labelled water first had to be transported down the hole before moving into the fracture. The plateau in the curve for pre-test at about 34–38 hours is most likely an effect of gas bubbles blocking the sampling tube.

In test #2 water was also injected in Bh2 but pumped from Bh3. This means that the transport of tracer was against the natural pressure gradient which can be one of the reasons that the tracer breakthrough was much slower and possibly more diluted by ambient water. There were also no horizontal fractures found in Bh3 which means that the fractures in Bh3 are not directly connected to Bh2. It is likely that also the total recovery of tracer is lower in test #2 than in the other tests. It is however difficult to assess as only a small portion of the breakthrough curve in Bh 3 was collected before ending the test.

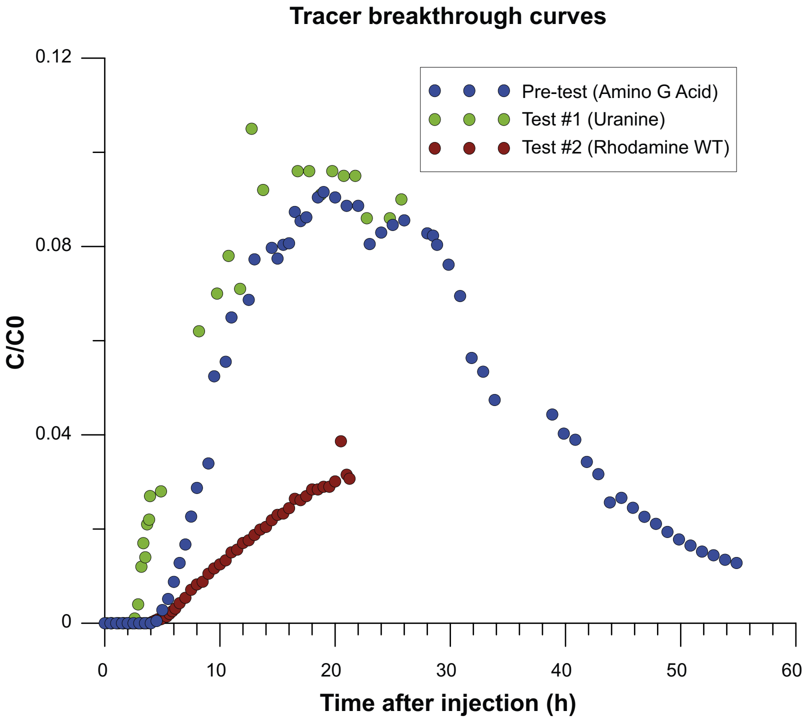

Figure 4-16. *Tracer breakthrough in Bh1 during the pre-test and test #1 and tracer breakthrough in Bh3 during test #2.*

5 Conclusions

The characterization of the rock volume below the tunnel floor of TAS04 was done with a combination of drilling, rock mapping, optical televiewer, hydraulic tests and tracer tests. This combination of methods was shown to effectively locate and characterize low transmissive flowing fractures and to give a firm ground for doing detailed GPR measurements in later stages of the project. Some aspects of the methods that may be mentioned as particularly valuable was:

- The pressure measurements in previously drilled holes during drilling of the next ones. This gave an early indication that connected fractures existed in the targeted rock volume.
- The combination of OPTV, rock mapping and hydraulic injection tests was shown to be a good strategy to identify and quantify geometric and hydraulic properties of low-transmissive fractures.
- The use of tracer tests to confirm connectivity and to compare (at least qualitatively) different pathways in terms of transport properties.

The combination of low transmissivity, $T < 10^{-9}$ m^2/s, and high ambient pressures (about 2 000 kPa), made it difficult to perform hydraulic injection tests as very high injection pressures are needed with the risk of creating rock uplift and thereby also increased transmissivity, or even opening new pathways to the tunnel. Thus, in such environments, outflow tests are preferable. However, when injecting deionized water for the GPR measurement, high injection pressures had to be applied to achieve a good and fast enough spreading of the water and tracer solution along the fracture planes. The preliminary analysis indicates an increased flow, compared to the pre-test, during the first 10–12 hours of injection which could indicate rock uplift and/or opening of flow paths (increase of the fracture aperture).

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Hurst W, Clark J D, Brauer E B, 1969. The skin effect in producing wells. Journal of Petroleum Technology 21, 1483–1489.

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Rhen I (ed), Gustafson G, Stanfors R, Wikberg P, 1997. Äspö HRL – Geoscientific evaluation 1997/5. Models based on site characterization 1986–1995. SKB TR 97-06, Svensk Kärnbränslehantering AB.

Appendix 1

Drilling records

Bh1 (K04018G02)

Idcode	Start date	Stop date	Secup	Seclow
Bh1	2018-09-03 16:00	2018-09-03 17:30	0.00	0.80
Bh1	2018-09-04 08:30	2018-09-04 09:30	0.80	1.20
Bh1	2018-09-04 10:00	2018-09-04 11:00	1.20	1.80
Bh1	2018-09-04 11:30	2018-09-04 12:10	1.80	2.35
Bh1	2018-09-04 13:30	2018-09-04 14:45	2.35	3.40
Bh1	2018-09-05 11:30	2018-09-05 12:45	3.40	4.70
Bh1	2018-09-05 14:20	2018-09-05 15:00	4.70	5.20
Bh1	2018-09-05 15:00	2018-09-05 15:20	5.20	5.70
Bh1	2018-09-10 08:45	2018-09-10 09:15	5.70	6.20
Bh1	2018-09-10 09:19	2018-09-10 09:30	6.20	6.70
Bh1	2018-09-10 11:10	2018-09-10 11:30	6.70	7.20
Bh1	2018-09-10 11:30	2018-09-10 11:49	7.20	7.60
Bh1	2018-09-10 13:20	2018-09-10 13:35	7.60	8.10
Bh1	2018-09-10 13:35	2018-09-10 14:00	8.10	8.60
Bh1	2018-09-10 14:45	2018-09-10 15:05	8.60	9.10
Bh1	2018-09-10 15:05	2018-09-10 15:15	9.10	9.20
Bh1	2018-09-11 08:30	2018-09-11 08:40	9.20	9.65

Bh2 (K04022G02)

Idcode	Start date	Stop date	Secup	Seclow
Bh2	2018-09-11 15:00	2018-09-11 15:18	0.00	0.50
Bh2	2018-09-11 15:24	2018-09-11 15:35	0.50	0.63
Bh2	2018-09-11 16:03	2018-09-11 16:13	0.63	0.97
Bh2	2018-09-11 16:30	2018-09-11 16:46	0.97	1.47
Bh2	2018-09-11 17:05	2018-09-11 17:35	1.47	1.89
Bh2	2018-09-11 18:13	2018-09-11 18:27	1.89	2.39
Bh2	2018-09-11 18:27	2018-09-11 18:37	2.39	2.70
Bh2	2018-09-12 08:15	2018-09-12 08:31	2.70	3.20
Bh2	2018-09-12 08:31	2018-09-12 08:40	3.20	3.55
Bh2	2018-09-12 10:32	2018-09-12 10:45	3.55	4.05
Bh2	2018-09-12 10:45	2018-09-12 10:49	4.05	4.20
Bh2	2018-09-12 11:35	2018-09-12 11:48	4.20	4.70
Bh2	2018-09-12 11:48	2018-09-12 11:53	4.70	4.82
Bh2	2018-09-12 13:30	2018-09-12 13:45	4.82	5.32
Bh2	2018-09-12 13:45	2018-09-12 13:58	5.32	5.46
Bh2	2018-09-12 14:30	2018-09-12 14:52	5.46	5.96
Bh2	2018-09-12 15:30	2018-09-12 15:47	5.96	6.46
Bh2	2018-09-12 15:47	2018-09-12 15:56	6.46	6.63
Bh2	2018-09-12 16:52	2018-09-12 17:06	6.63	7.13
Bh2	2018-09-12 17:06	2018-09-12 17:20	7.13	7.54
Bh2	2018-09-12 18:00	2018-09-12 18:13	7.54	8.04
Bh2	2018-09-12 18:13	2018-09-12 18:25	8.04	8.29
Bh2	2018-09-13 08:08	2018-09-13 08:21	8.29	8.79
Bh2	2018-09-13 08:21	2018-09-13 08:30	8.79	9.07
Bh2	2018-09-13 10:35	2018-09-13 10:50	9.07	9.55

Bh3 (K04026G02)

Idcode	Start date	Stop date	Secup	Seclow
Bh3	2018-09-17 14:28	2018-09-17 14:43	0.00	0.50
Bh3	2018-09-17 14:43	2018-09-17 14:49	0.50	0.65
Bh3	2018-09-18 09:12	2018-09-18 09:32	0.65	1.15
Bh3	2018-09-18 10:30	2018-09-18 10:42	1.15	1.42
Bh3	2018-09-18 11:35	2018-09-18 11:49	1.42	1.92
Bh3	2018-09-18 11:49	2018-09-18 12:02	1.92	2.18
Bh3	2018-09-18 13:32	2018-09-18 13:52	2.18	2.68
Bh3	2018-09-18 13:52	2018-09-18 14:04	2.68	2.90
Bh3	2018-09-18 14:43	2018-09-18 15:06	2.90	3.40
Bh3	2018-09-18 15:38	2018-09-18 15:50	3.40	3.90
Bh3	2018-09-18 15:50	2018-09-18 16:00	3.90	4.40
Bh3	2018-09-18 16:48	2018-09-18 17:03	4.40	4.90
Bh3	2018-09-18 17:03	2018-09-18 17:15	4.90	5.21
Bh3	2018-09-18 17:55	2018-09-18 18:08	5.21	5.71
Bh3	2018-09-18 18:08	2018-09-18 18:17	5.71	5.92
Bh3	2018-09-19 08:20	2018-09-19 08:35	5.92	6.42
Bh3	2018-09-19 08:35	2018-09-19 08:55	6.42	6.86
Bh3	2018-09-19 10:38	2018-09-19 10:50	6.86	7.36
Bh3	2018-09-19 10:50	2018-09-19 11:04	7.36	7.85
Bh3	2018-09-19 13:48	2018-09-19 14:02	7.85	8.35
Bh3	2018-09-19 14:02	2018-09-19 14:10	8.35	8.58
Bh3	2018-09-19 15:43	2018-09-19 16:02	8.58	9.07
Bh3	2018-09-19 17:37	2018-09-19 18:01	9.07	9.50

Appendix 2

Log of events tracer tests

Pre-test

Time (GMT+1)	Event
2018-10-22 13:55	Single packer in Bh2 is opened (Pressure measurement in HMS-system disconnected)
2018-10-22 14:42	Single packer in Bh1 is opened (Pressure measurement in HMS-system disconnected)
2018-10-22 16:00	Packers in Bh2 expanded (injection section: 3.2 – 3.7 m)
2018-10-22 17:00	Packers in Bh1 expanded (outflow section: 3–6 m)
2018-10-22 17:15	Pressure measurement in HMS-system connected to both boreholes (injection section and outflow section)
2018-10-23 07:32	Pressure measurement in HMS-system disconnected from Bh2
2018-10-23 08:08	Pressure measurement in HMS-system disconnected from Bh1
2018-10-23 15:00	Sampling started
2018-10-23 15:10	Injection started (Bh2 → Bh1)
2018-10-23 16:10	Injection stopped (Bh2 → Bh1)
2018-10-24 09:30	Injection started (Bh2 → Bh1)
2018-10-25 05:32	Injection stopped (Bh2 → Bh1) to refill injection bottle
2018-10-25 05:52	Injection restarted (Bh2 → Bh1)
2018-10-25 08:03	Injection stopped (Bh2 → Bh1) to refill injection bottle
2018-10-25 08:08	Injection restarted (Bh2 → Bh1)
2018-10-25 13:55	Injection stopped
2018-10-27 14:05	Pressure in injection bottle is decreased to 16 bar
2018-10-27 14:06	Open valve from pressure bottle to injection section in Bh2 (to measure pressure in section)
2018-10-25 14:15	Pressure measurement in HMS-system connected to injection section in Bh2

Test #1 and test #2

Time (GMT+1)	Event
2018-11-05 afternoon	Samples from pre-test are collected Uranine is added to big tank
2018-11-05 16:38	Pressure measurement in HMS-system disconnected from injection section in Bh2
2018-11-06 08:38	Removal of bubbles in tubing from injection section in Bh2 (flow out)
2018-11-06 08:56	Stop logging (outflow, EC, Pressure observation sections (why?)
2018-11-06 09:10	Injection section connected to pressure transducer in EDZ-equipment (section closed, pressure build up)
2018-11-06 09:43	Start logging (outflow, EC, Pressure observation sections
2018-11-06 09:54	Packers in Bh2 deflated
2018-11-06 09:54	Tubings and borehole is filled with tracer (EC is checked above packers in Bh2)
2018-10-06 10:15	Packers in Bh2 expanded
2018-11-06 10:15	Observation section (under lower packer) in both Bh1 and Bh2 is opened shortly to evacuate pressure increase due to packer expansion
2018-11-06 10:20	Injection section in Bh2 opened shortly to evacuate pressure increase due to packer expansion
2018-11-06 10:32	Start injection (Bh2 → Bh1)
2018-11-06 10:35	Start sampling
2018-11-06 11:51	Increase of injection pressure
2018-11-06 18:18	Stop injection to refill injection tank
2018-11-06 18:28	Restart injection (Bh2 → Bh1)
2018-11-07 12:07	Stop injection
2018-11-07 12:20	Pressure measurement in HMS-system connected to outflow section in Bh1 (section is closed)
2018-11-07 12:23	Start outflow from Bh2
2018-11-07 12:23	Outflow from Bh2 is connected to flow meter, EC-meter and sampling
	Flow meter is disconnected due to low flow
2018-11-07 14:22	Single packer in Bh3 is opened (Pressure measurement in HMS-system disconnected)
2018-11-07 14:35	Packers in Bh1 is deflated
2018-11-07 15:07	Bh1 is filled with water
2018-11-07 15:22	Single packer in Bh1 is closed and pressure measurement in HMS-system is connected
2018-11-07 16:37	Packers in Bh3 are expanded
2018-11-07 16:43	Observation section (under lower packer) Bh3 closed (but measurement of pressure doesn't work)
2018-11-07 16:50	Pressure measurement in HMS-system connected to outflow section in Bh3 (section is closed)
2018-11-07 17:00	Tracer Rhodamine is added to injection tank
2018-11-08 08:47	Packers in Bh2 deflated
	Water in Bh2 is removed with nitrogen gas
	Tubings and borehole is filled with tracer
2018-11-08 c 09:30	Packers in Bh2 expanded
2018-11-08 09:28	Observation section (under lower packer) Bh2 closed
2018-11-08 09:30	Pressure in both in measuring section and observation section is Bh2 increase slowly (probably because of air in tubings and borehole)
2018-11-08 11:38	Tubing from injection section in Bh2 opened to remove gas bubbles
2018-11-08 12:10	Tubing from injection section in Bh2 closed (pressure build up)
2018-11-08 12:18	Outlet from BH3 is opened
2018-11-08 12:30	Start injection Bh2 → Bh3
2018-11-08 18:06	Stop injection to refill injection tank and change gas bottle
2018-11-08 18:30	Restart injection (Bh2 → Bh3)
2018-11-09 09:53	Stop injection Bh2 → Bh3

Appendix 3

Pressure and flow, injection and outflow tests

BH 1 – K04018G02

Pressure during the whole testing period

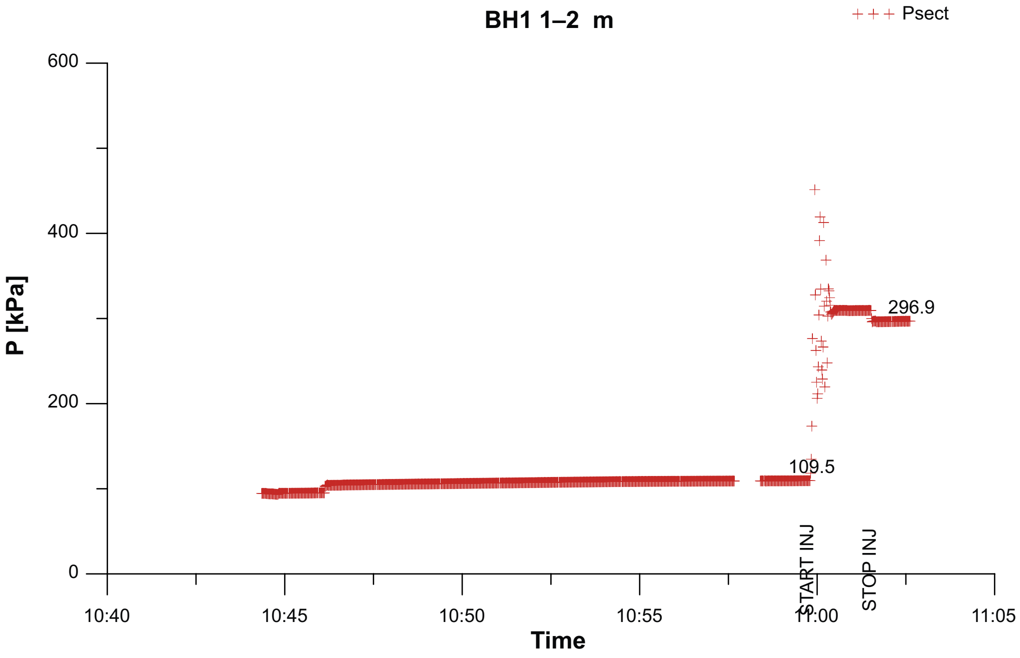


Figure A3-1. *Pressure during pressure build up, flow period (injection) and recovery period for section 1–2 m.*

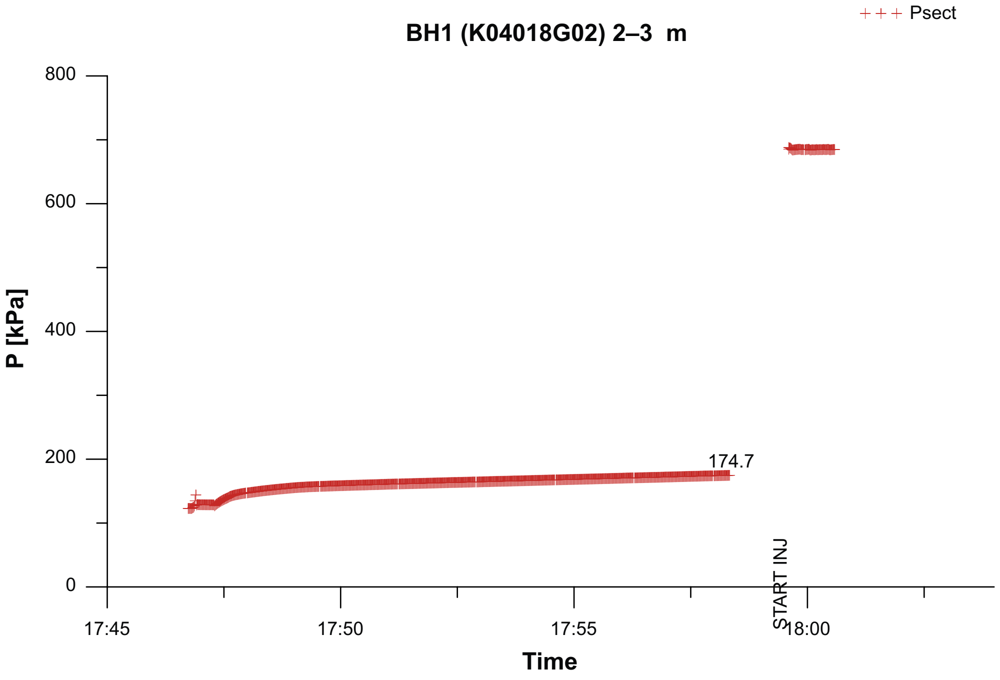


Figure A3-2. *Pressure during pressure build up, flow period (injection) for section 2–3 m.*

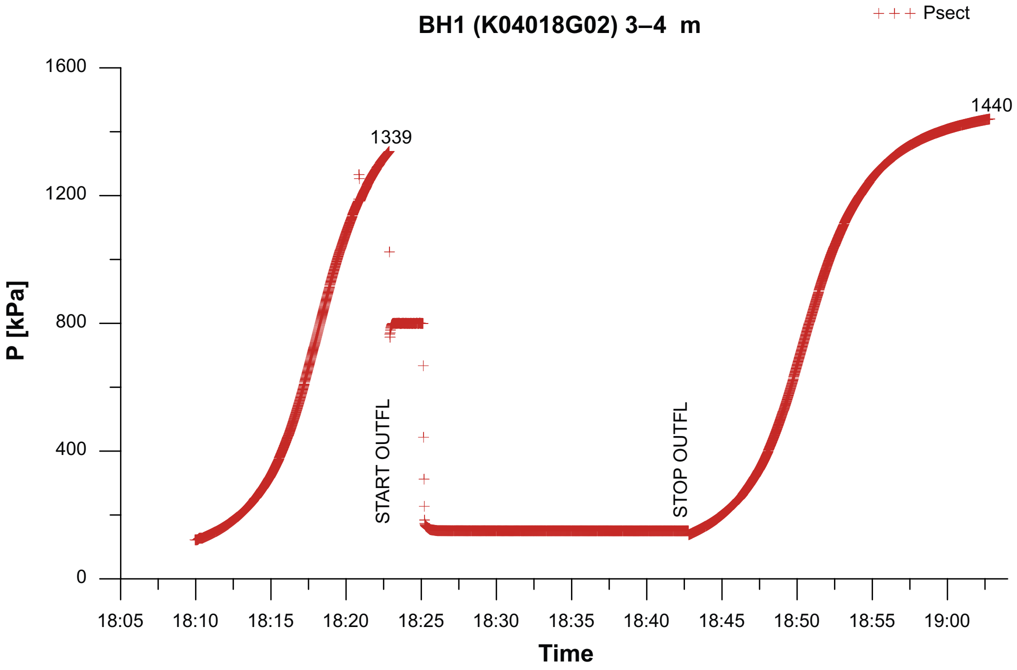
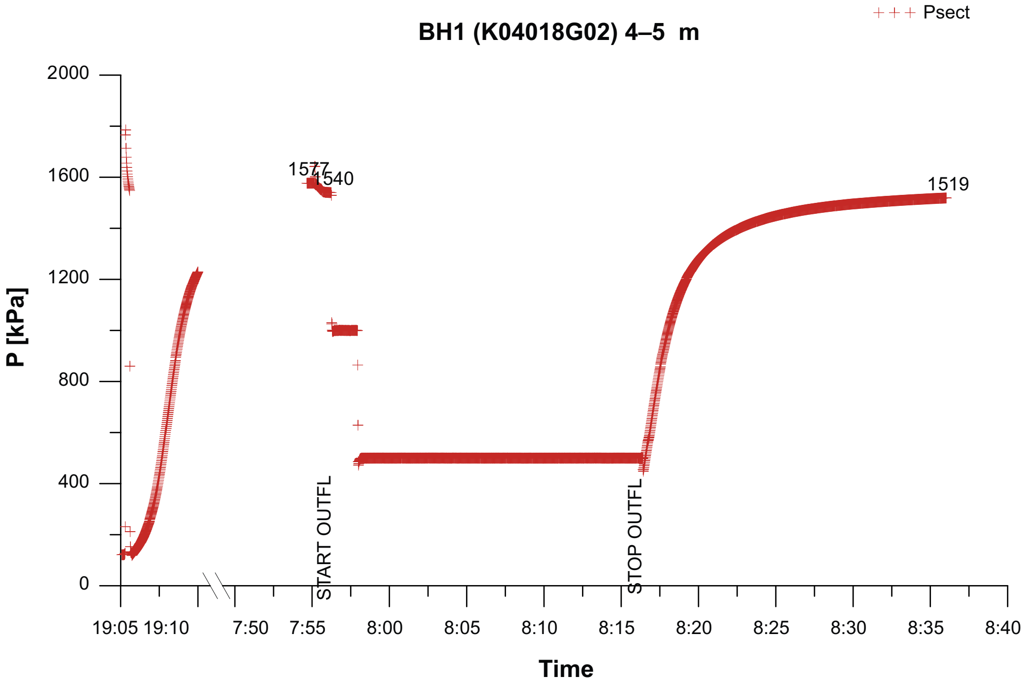


Figure A3-3. *Pressure during pressure build up, flow period (outflow) and recovery period for section 3–4 m.*



Figur A3-4. *Pressure during pressure build up, flow period (outflow) and recovery period for section 4–5 m.*

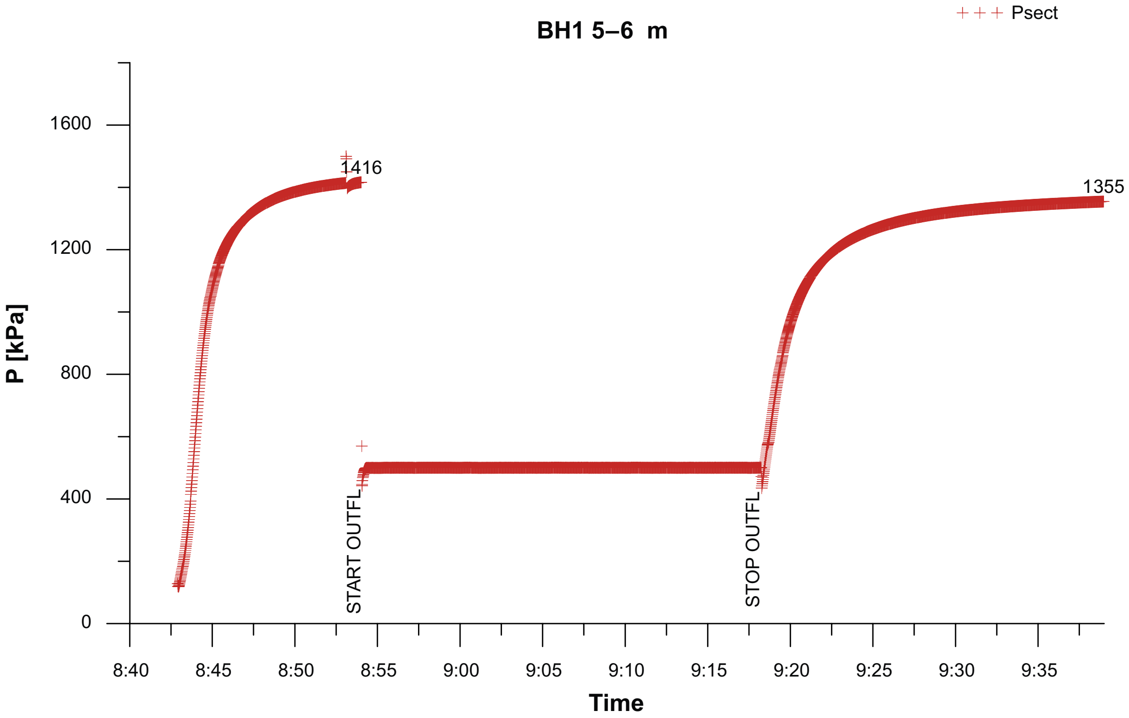


***Figure A3-5.** Pressure during pressure build up, flow period (outflow) and recovery for section 5–6 m.*

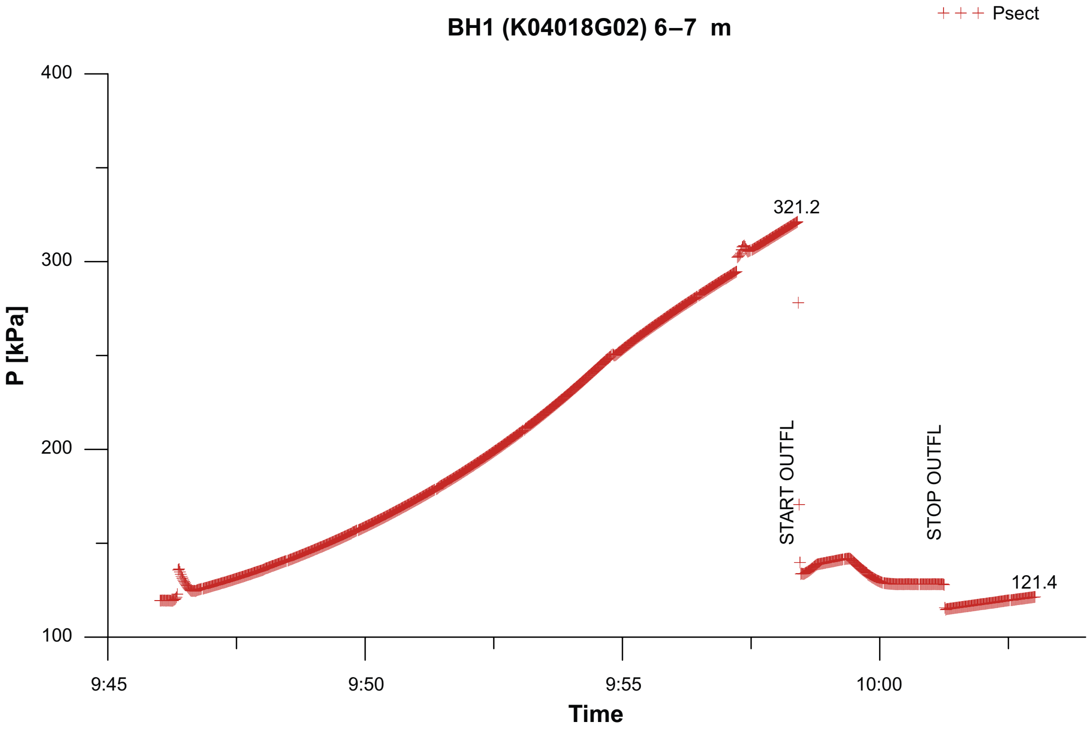


***Figure A3-6.** Pressure during pressure build up, flow period (outflow) and short recovery for section 6–7 m.*

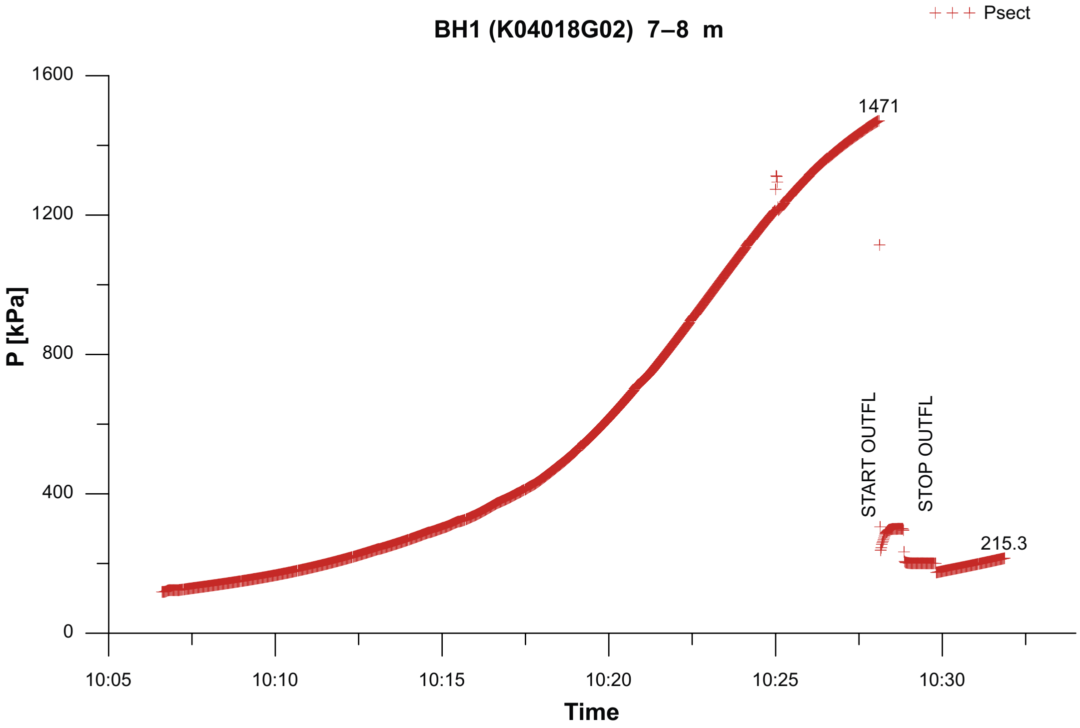


Figure A3-7. *Pressure during pressure build up, flow period (outflow) and short recovery for section 7–8 m.*

Pressure and flow during the flow period and recovery period for sections with flow over measurement limit

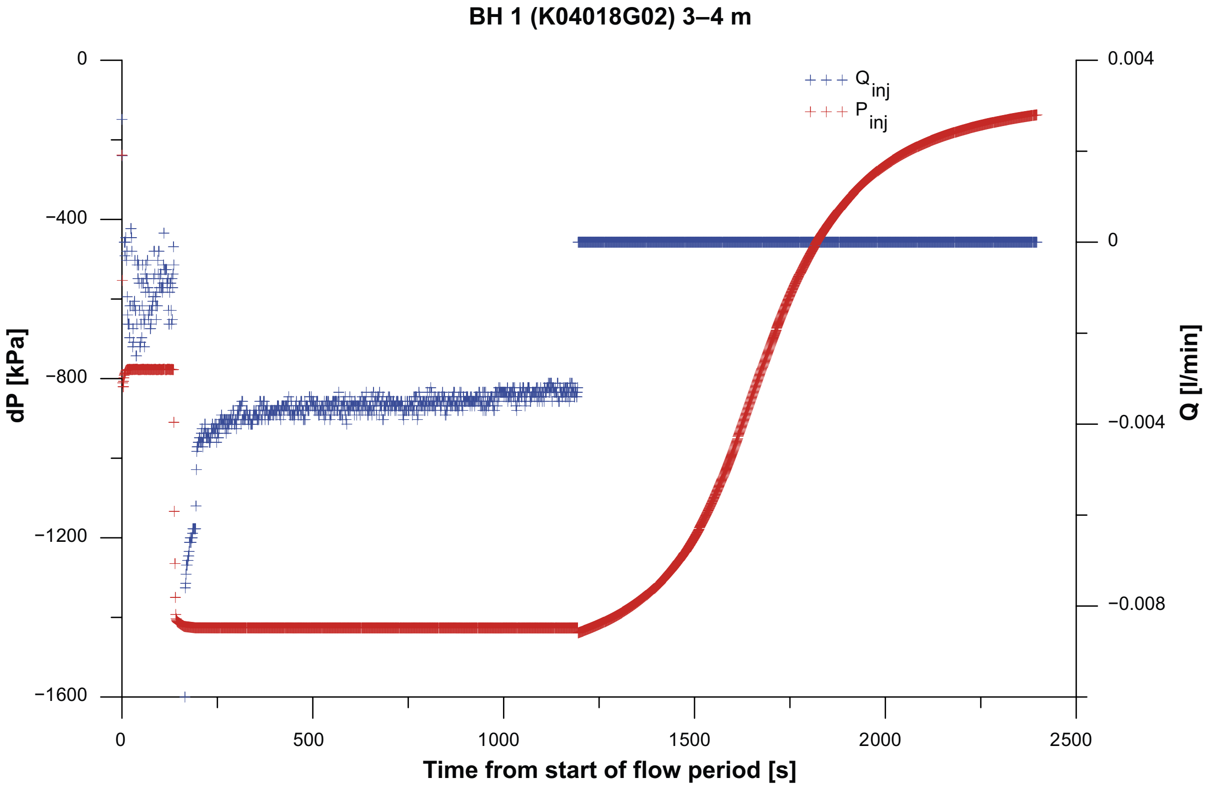


Figure A3-8. *Flow and pressure change in section 3–4 m during outflow test and recovery. The target value for pressure was lowered after c 150 s to increase the flow above measurement limit.*

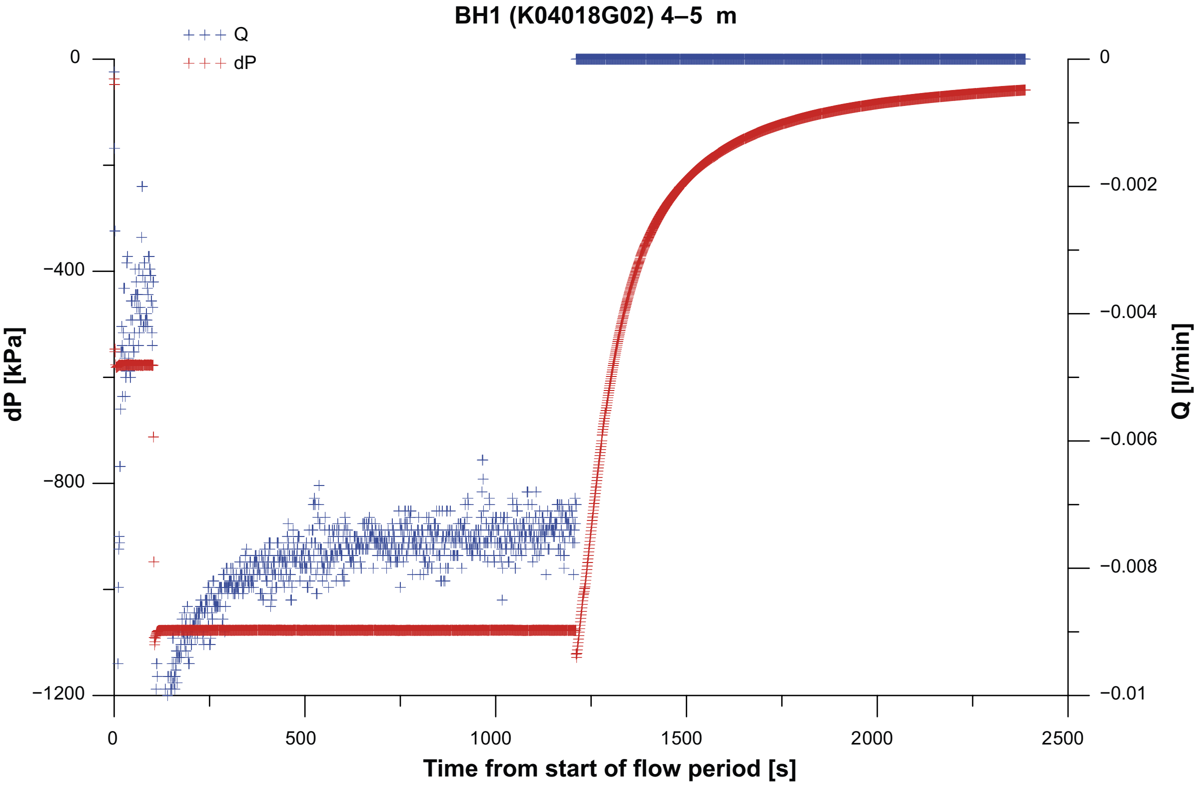


Figure A3-9. *Flow and pressure change in section 4–5 m during outflow test and recovery. The target value for pressure was lowered after c 100 s to increase the flow above measurement limit.*

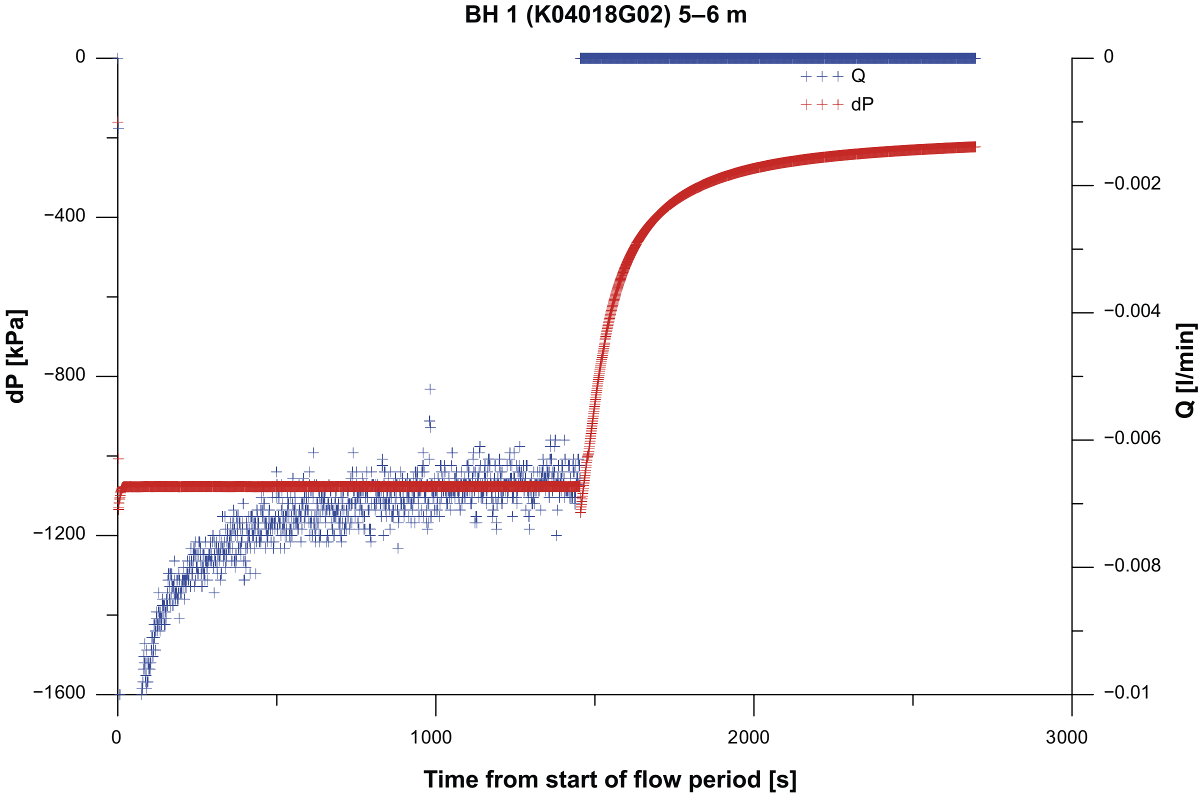


Figure A3-10. *Flow and pressure change in section 6–7 m during outflow test and recovery.*

BH 2 – K04022G02

Pressure during the whole testing period

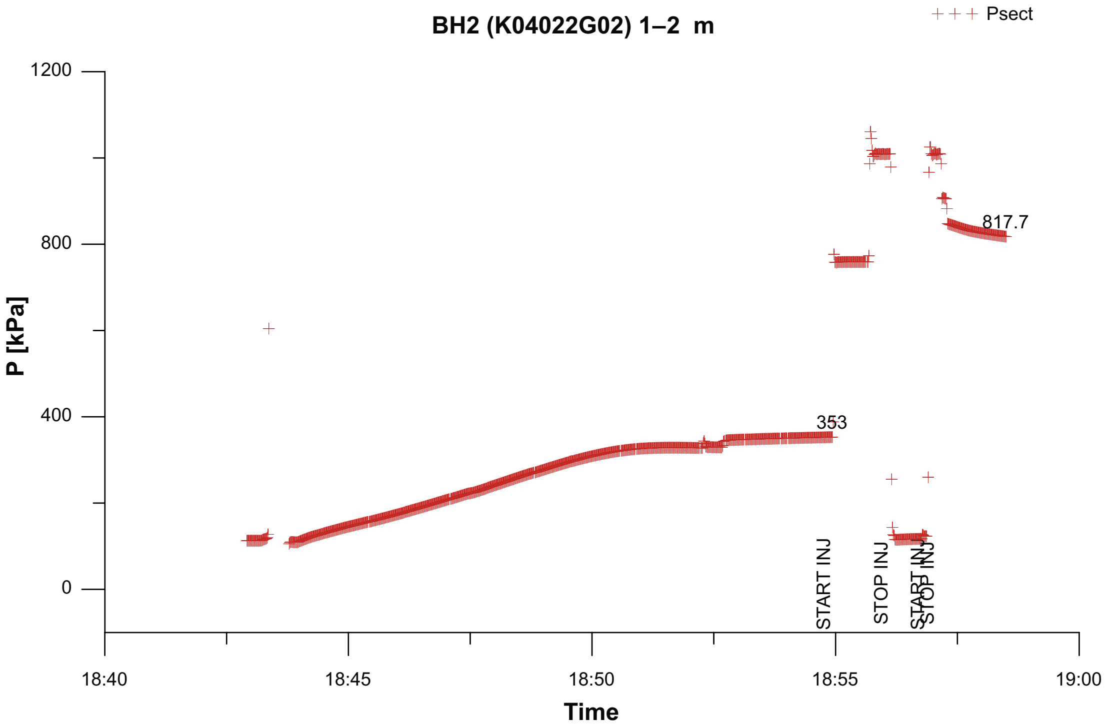


Figure A3-11. *Pressure during pressure build up, flow period (injection) and short recovery for section 1–2 m.*

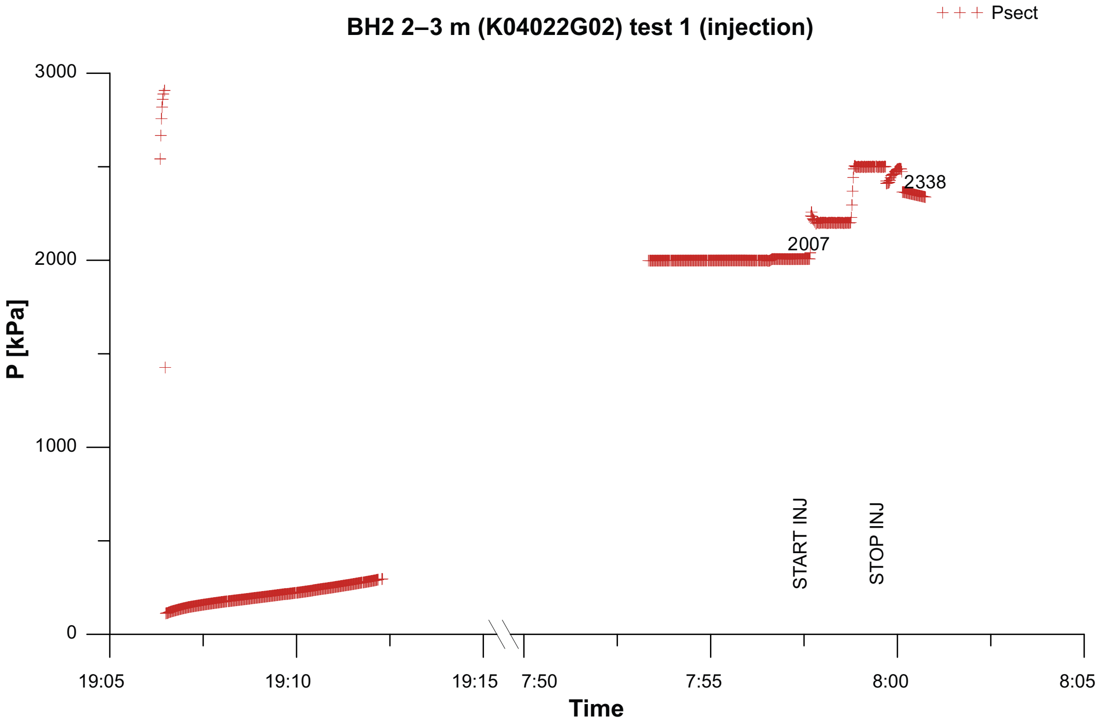


Figure A3-12. *Pressure during pressure build up, flow period (injection) for section 2–3 m.*

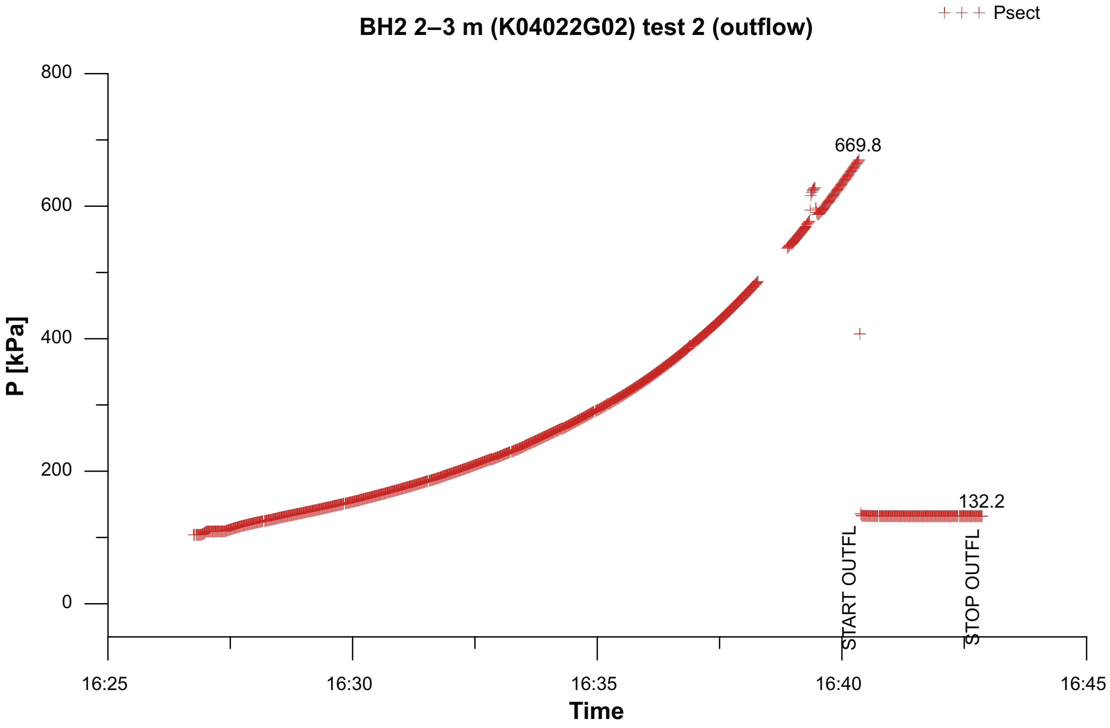


Figure A3-13. *Pressure during pressure build up, flow period (outflow) for section 2–3 m.*

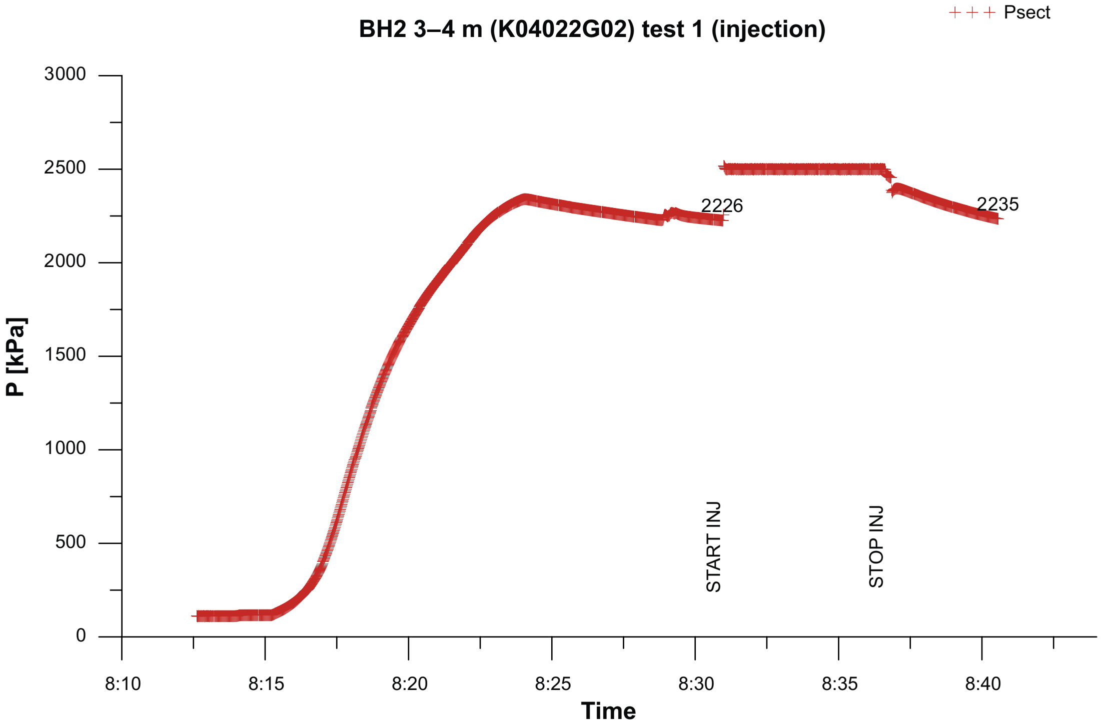


Figure A3-14. *Pressure during pressure build up, flow period (injection) and short recovery for section 3–4 m.*

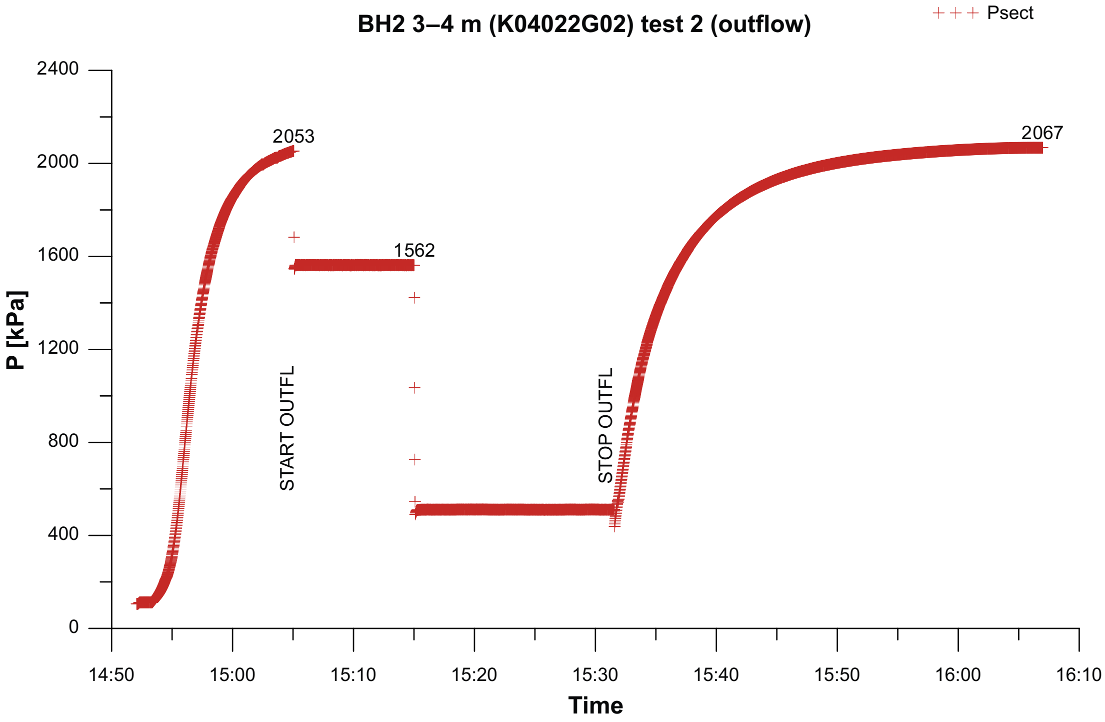


Figure A3-15. Pressure during pressure build up, flow period (outflow) and recovery for section 3–4 m.

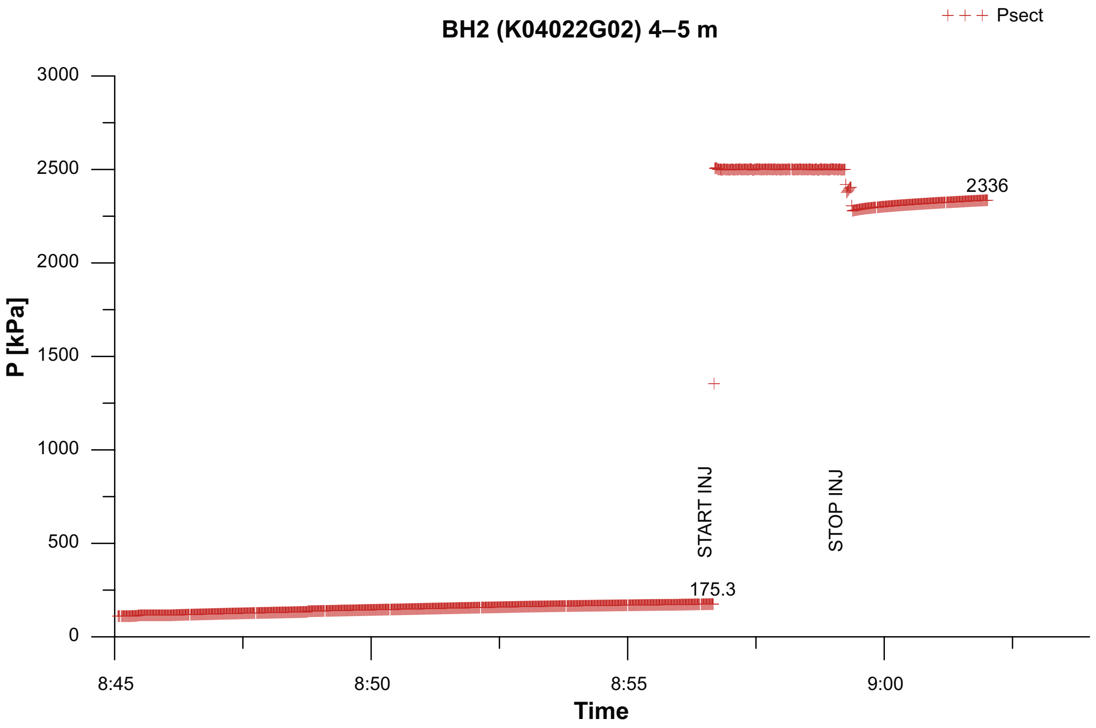


Figure A3-16. Pressure during pressure build up, flow period (injection) and short recovery for section 4–5 m.

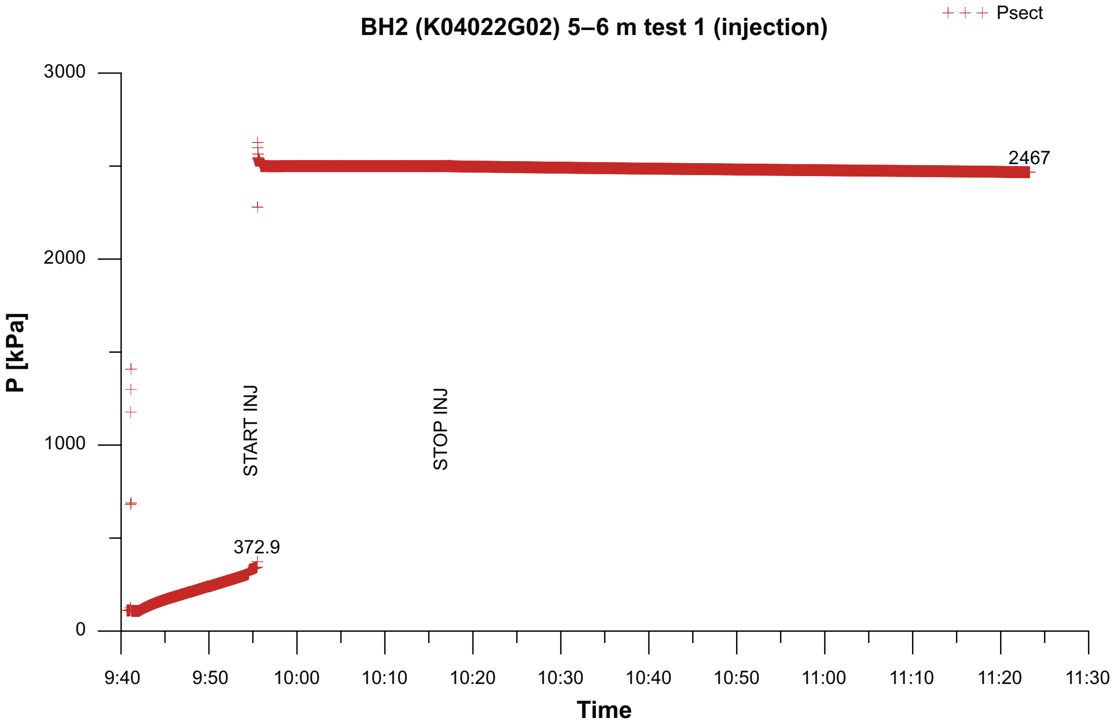


Figure A3-17. Pressure during pressure build up, flow period (injection) and recovery for section 5–6 m.

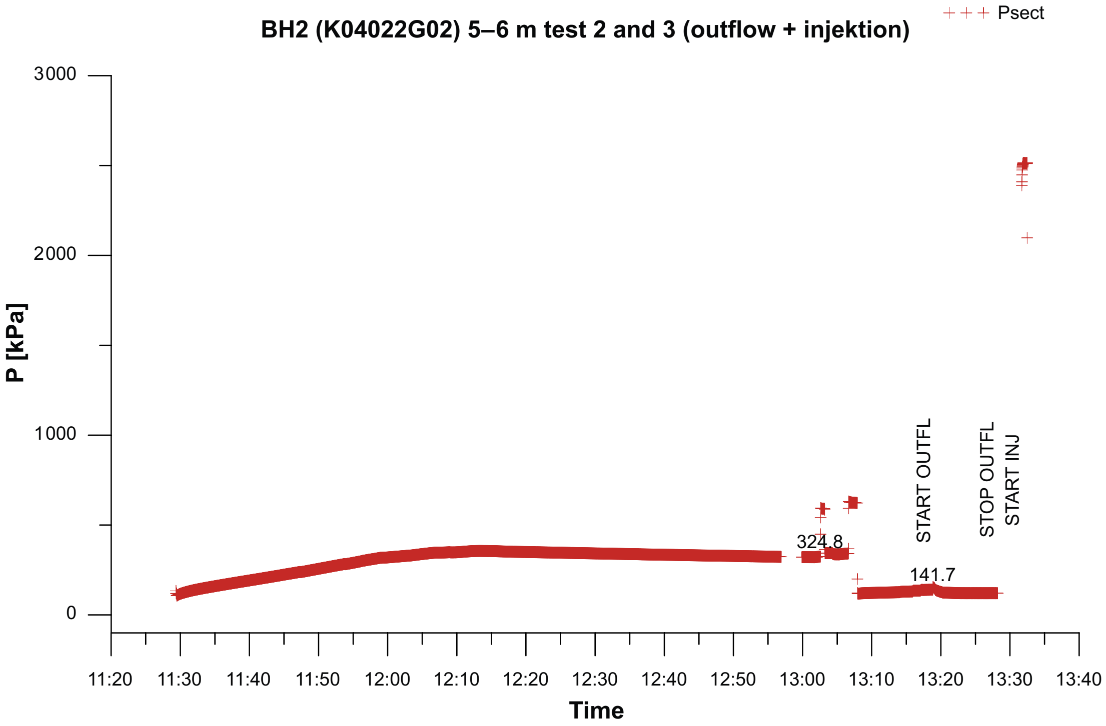


Figure A3-18. Pressure during pressure build up, flow period (outflow + injection) for section 5–6 m.

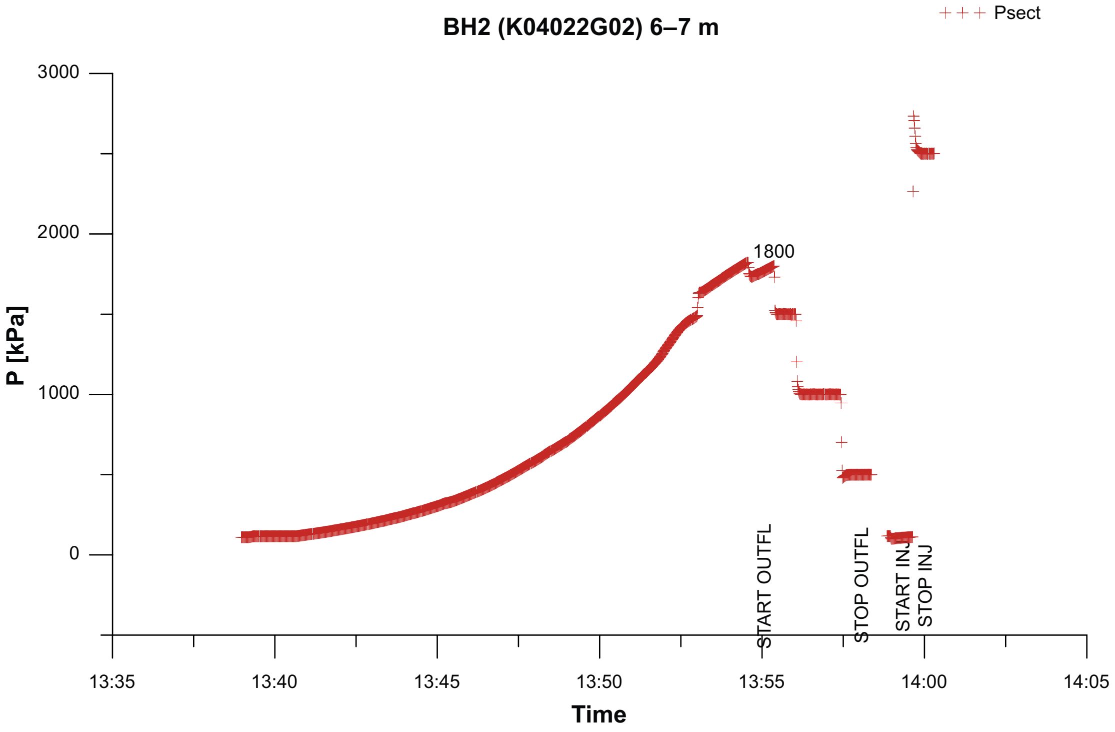


Figure A3-19. *Pressure during pressure build up, flow period (outflow + injection) for section 6–7 m.*

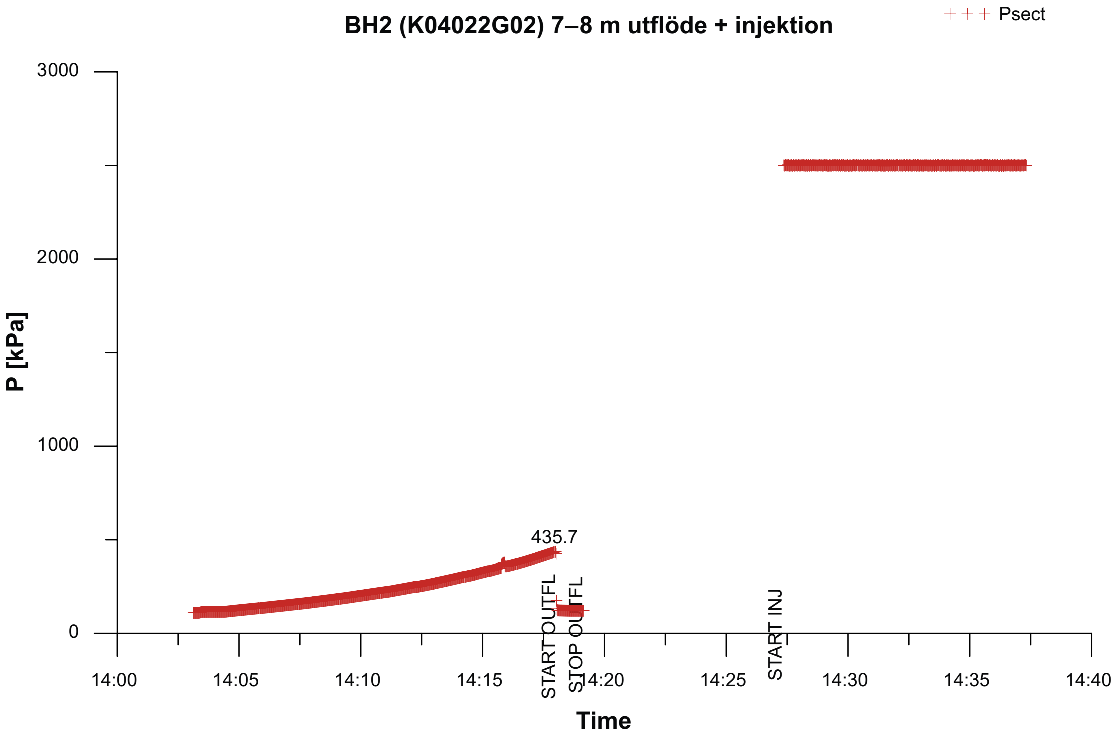


Figure A3-20. *Pressure during pressure build up, flow period (outflow + injection) for section 7–8 m.*

Pressure and flow during the flow period and recovery period

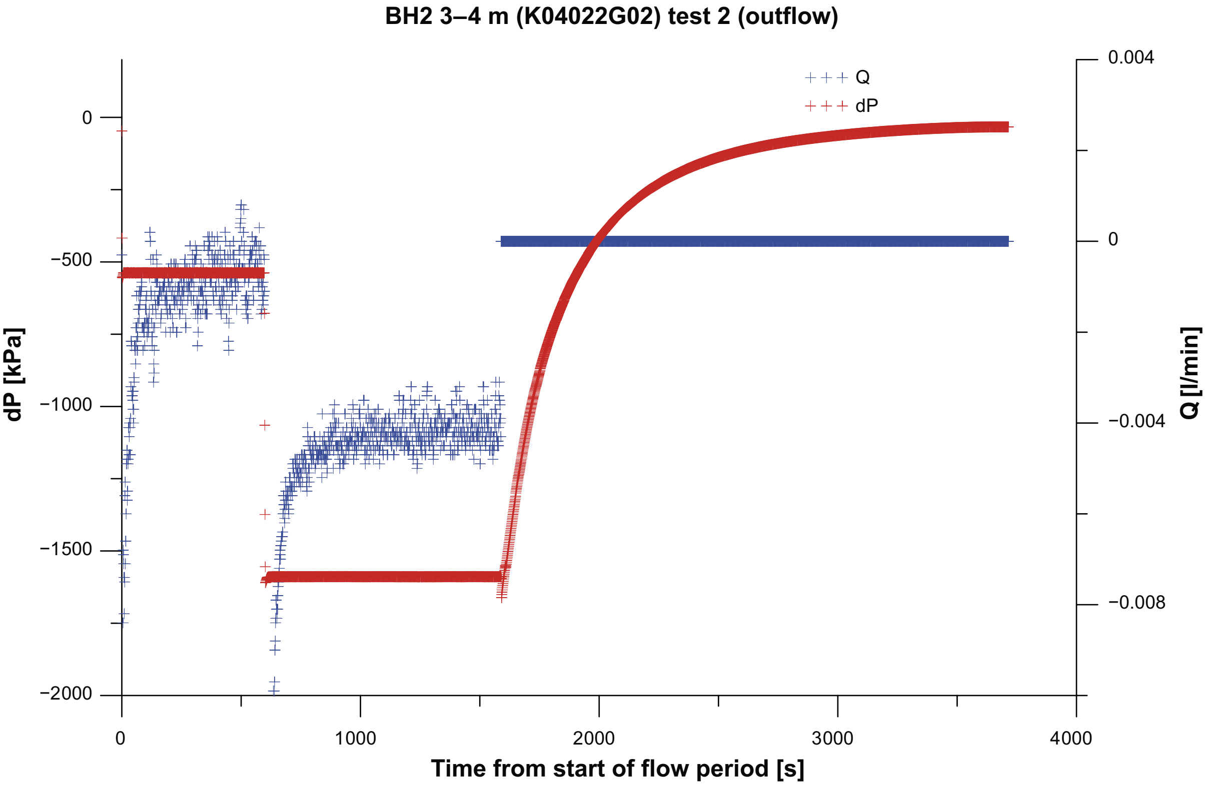


Figure A3-21. *Flow and pressure change in section 3–4 m during outflow test and recovery. The target value for pressure was lowered after c 600 s to increase the flow above measurement limit.*

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Pressure during the whole testing period

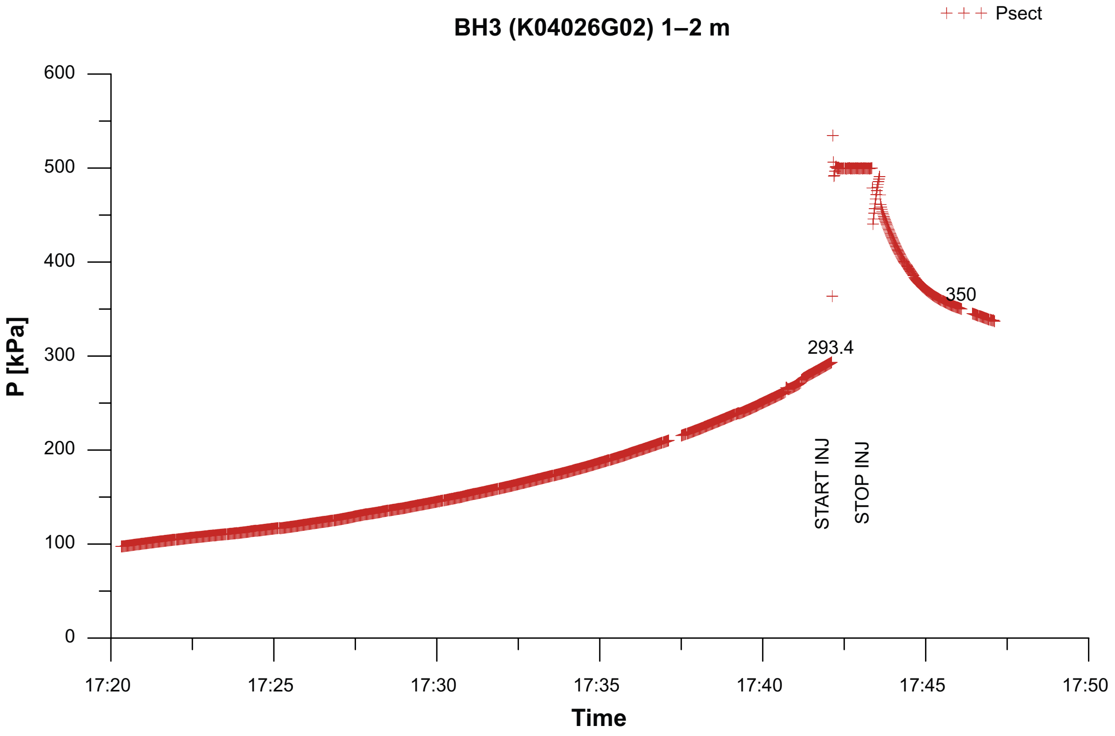

Figure A3-22. *Pressure during pressure build up, flow period (injection) and short recovery for section 1–2 m.*

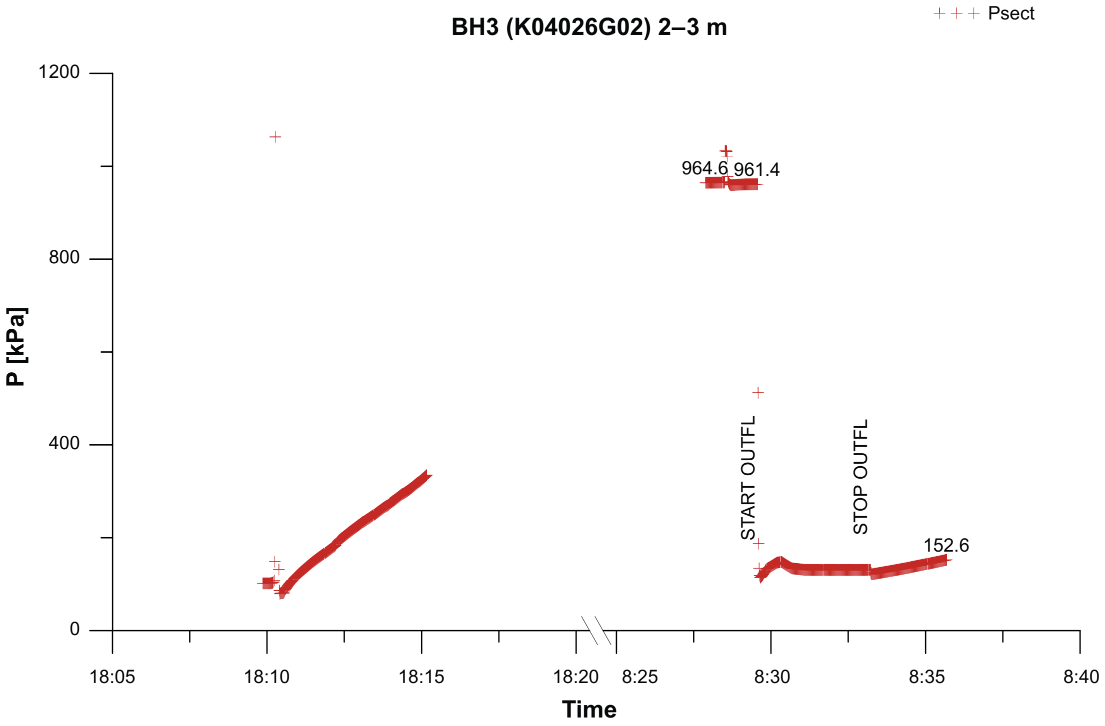

Figure A3-23. *Pressure during pressure build up, flow period (ouflow) and short recovery for section 2–3 m.*

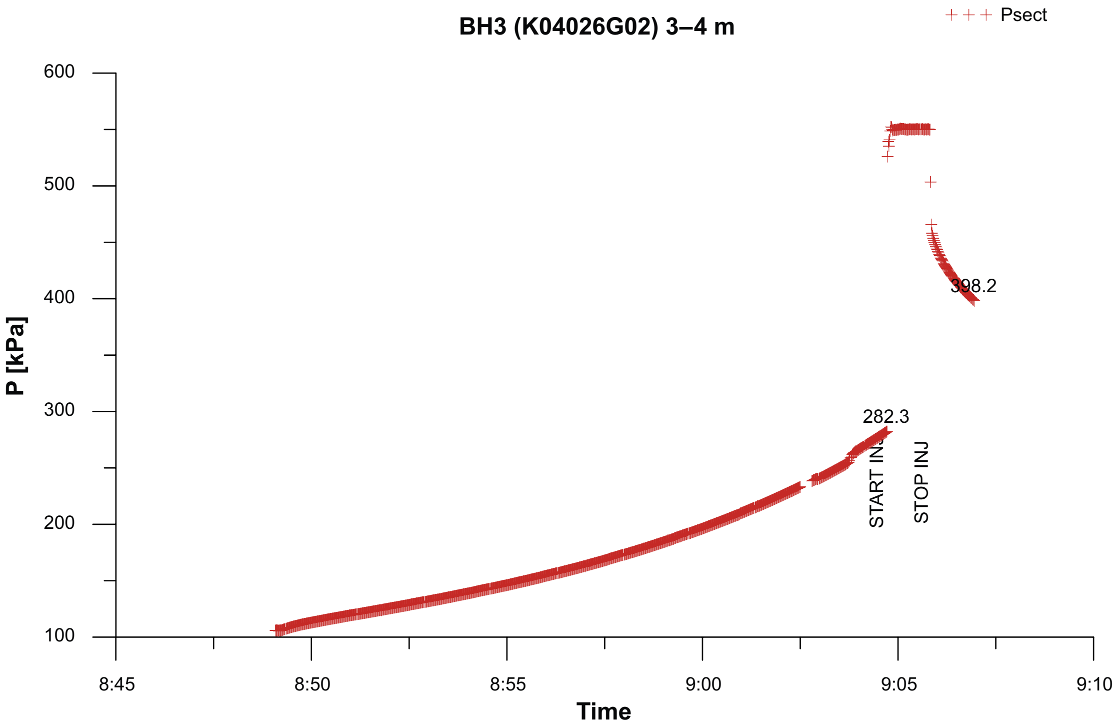

Figure A3-24. *Pressure during pressure build up, flow period (injection) and short recovery for section 3–4 m.*

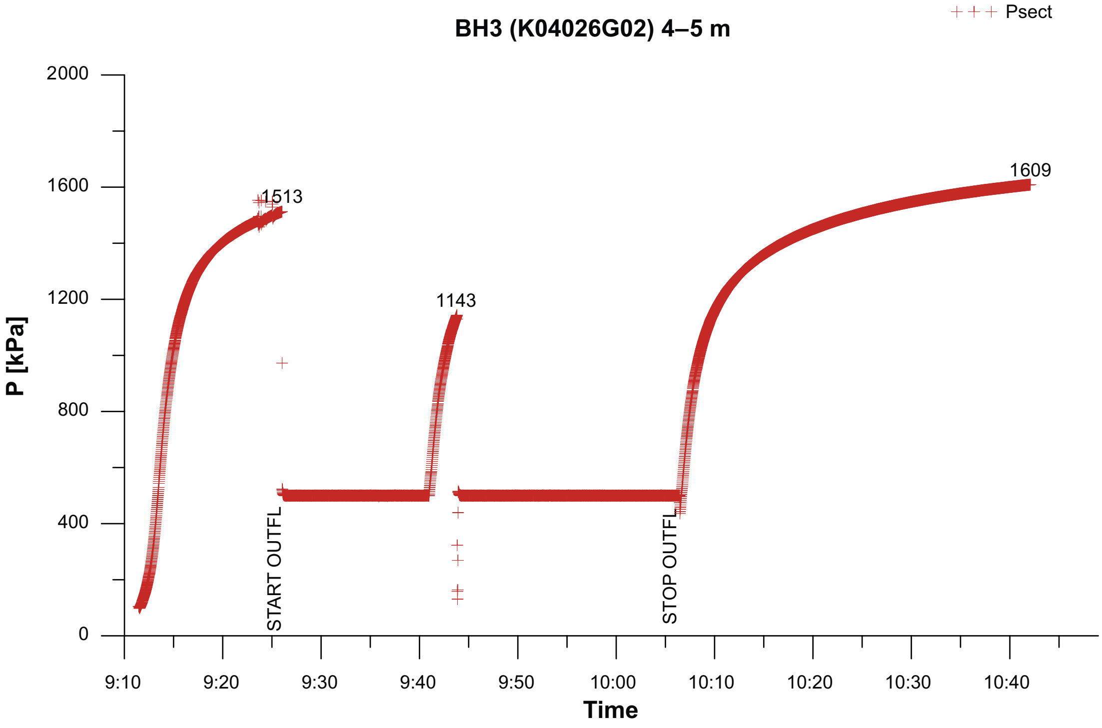

Figure A3-25. *Pressure during pressure build up, flow period (outflow) and recovery for section 4–5 m. Test was accidently stopped and restarted after c 15 min.*

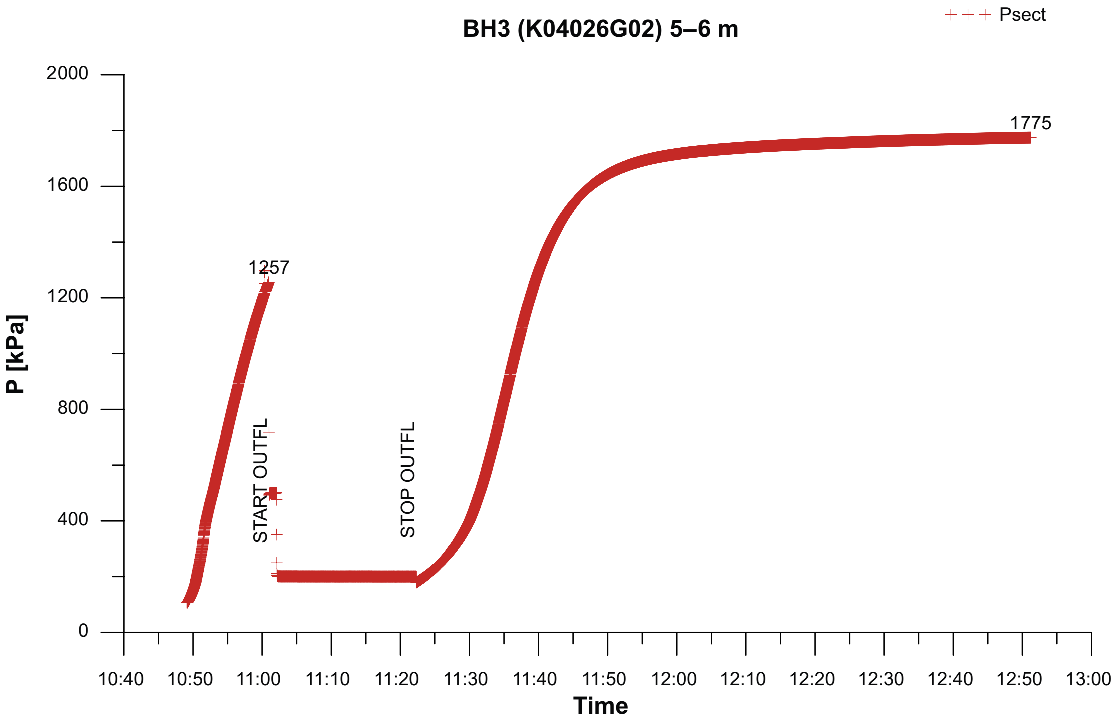

***Figure A3-26.** Pressure during pressure build up, flow period (outflow) and recovery for section 5–6 m.*

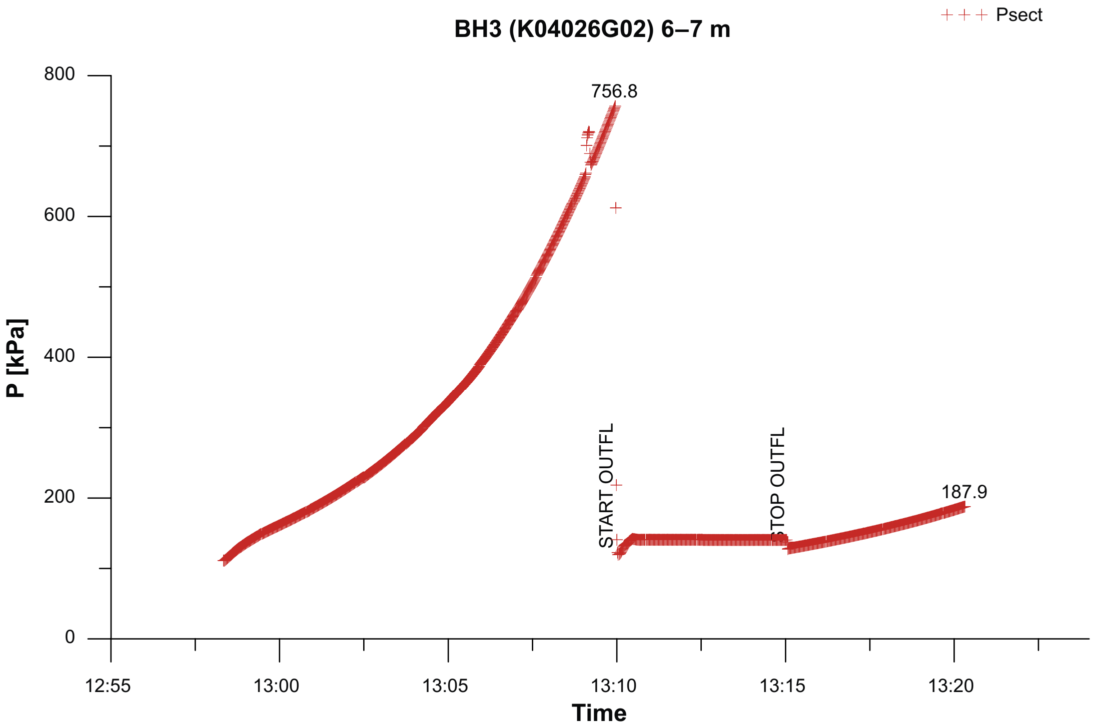

***Figure A3-27.** Pressure during pressure build up, flow period (outflow) and short recovery for section 6–7 m.*

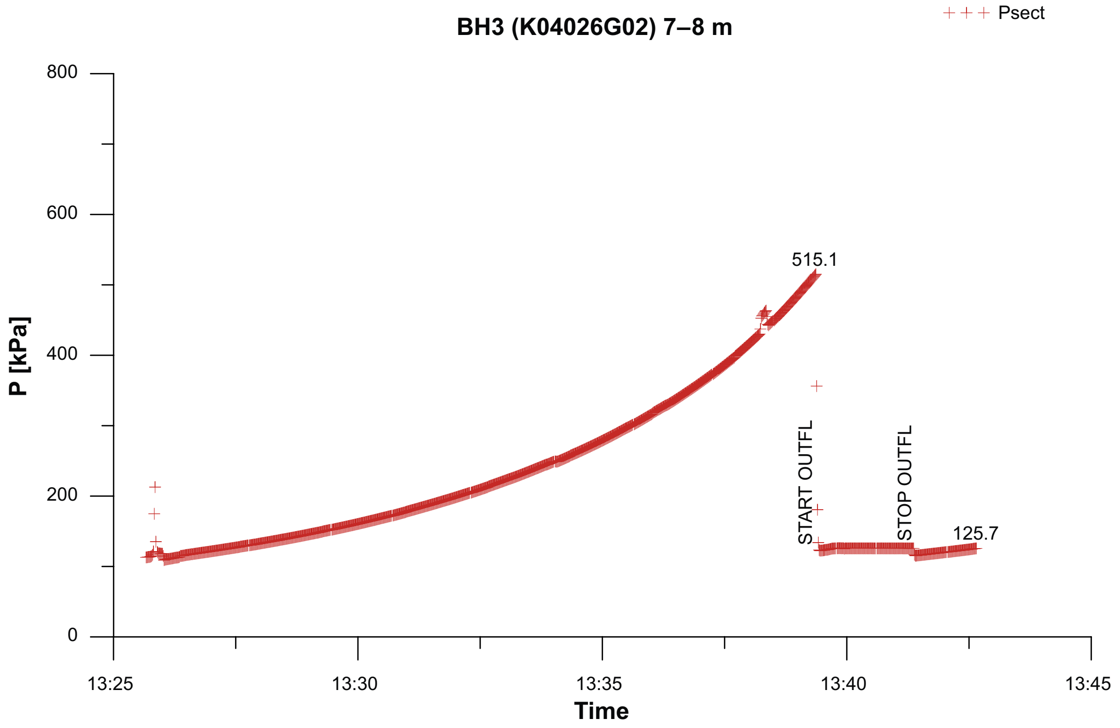

Figure A3-28. *Pressure during pressure build up, flow period (outflow) and short recovery for section 7–8 m.*

Pressure and flow during the flow period and recovery period

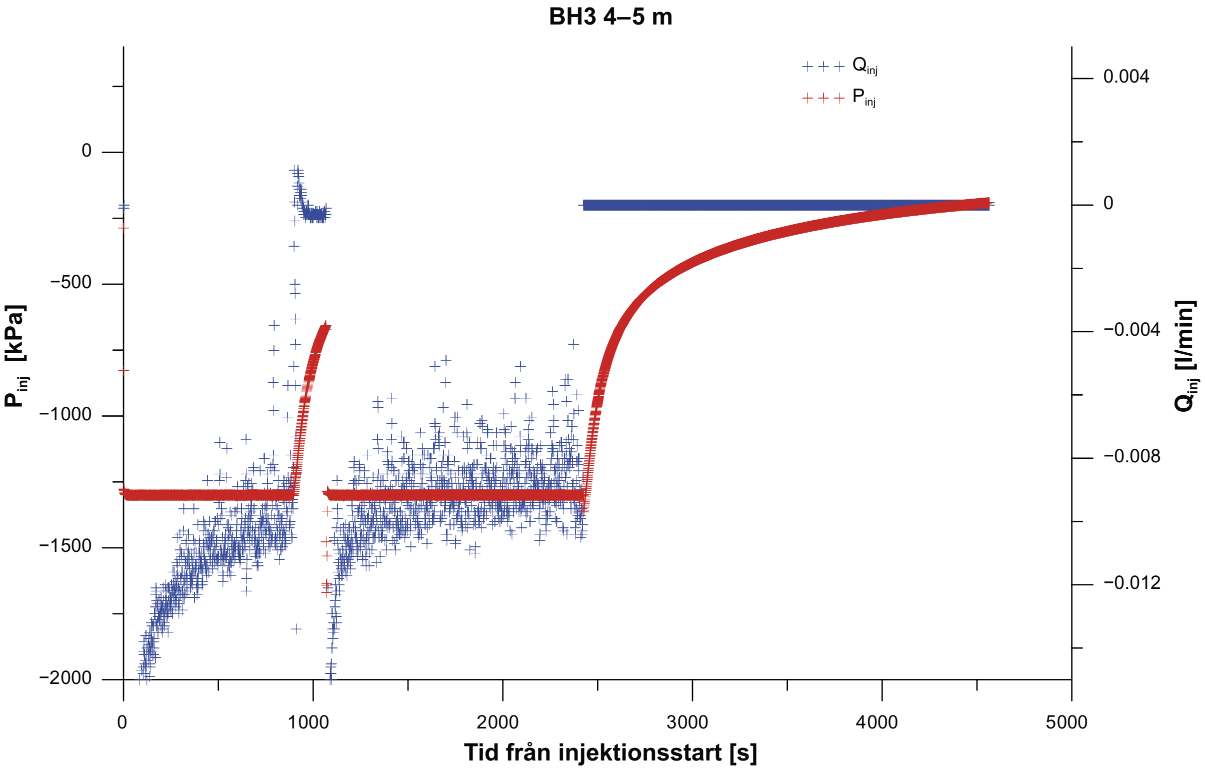

Figure A3-29. *Flow and pressure change in section 3–4 m during outflow test and recovery. Test was accidently stopped and restarted after c 15 min.*

Appendix 4

Transient evaluations

Transient evaluations of outflow tests in BH1 (K04018G02)

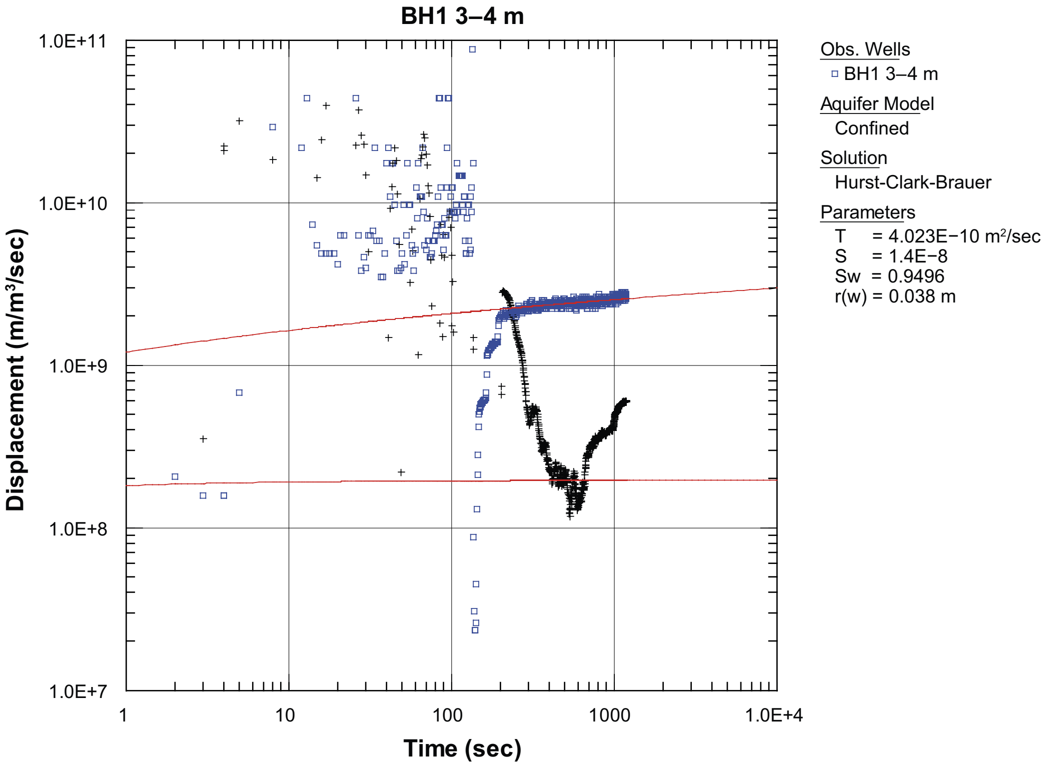

Figure A4-1. *Transient evaluation of outflow test in BH1, section 3–4 m. Pseudo-radial flow regime, followed by possible now-flow-boundary.*

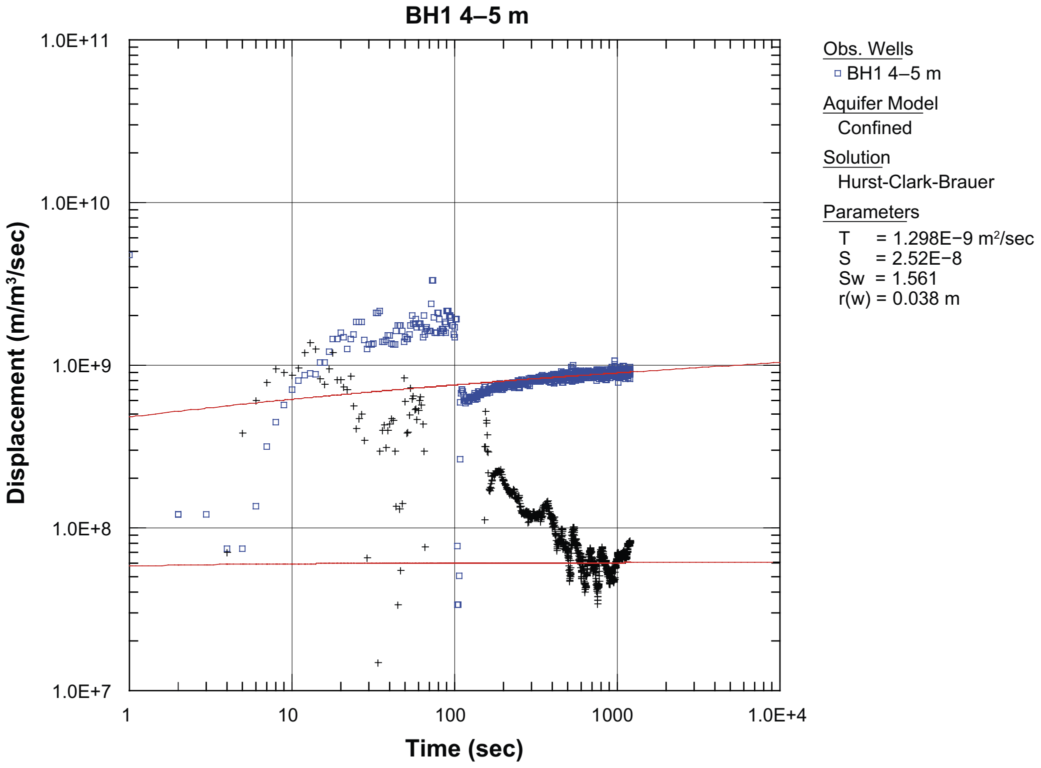

***Figure A4-2.** Transient evaluation of outflow test in BH1, section 4–5 m. Pseudo-radial flow regime.*

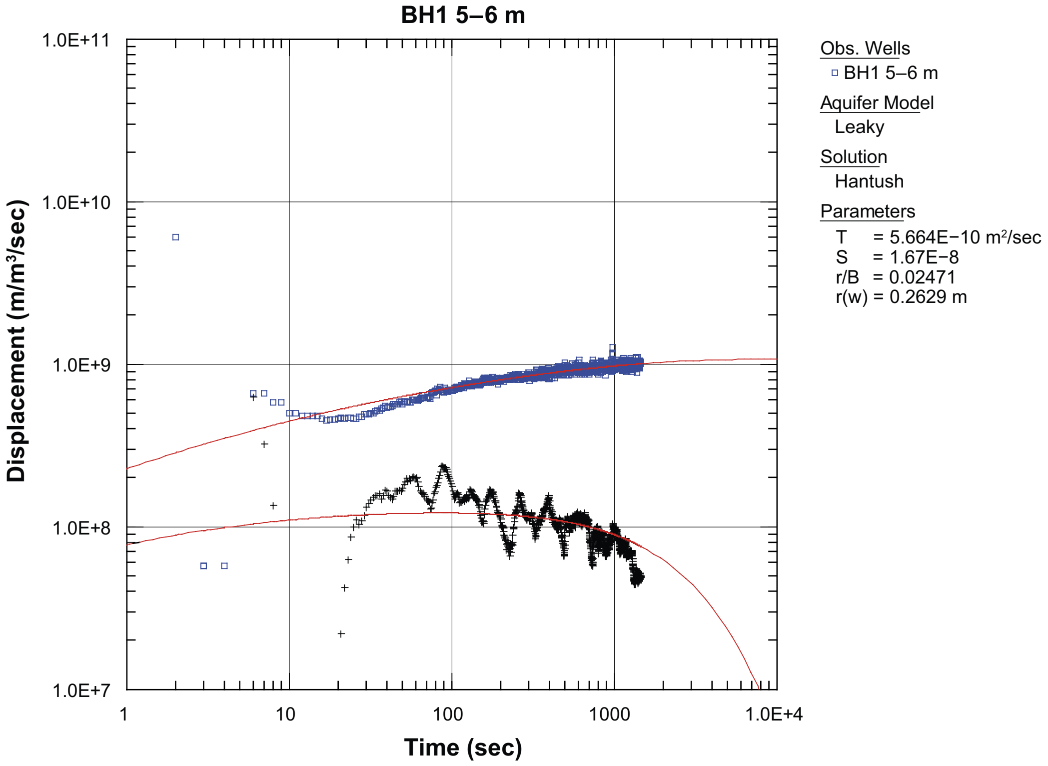

***Figure A4-3.** Transient evaluation of outflow test in BH1, section 5–6 m. Pseudo-spherical flow regime.*

Transient evaluations of outflow tests in BH2 (K04022G02)

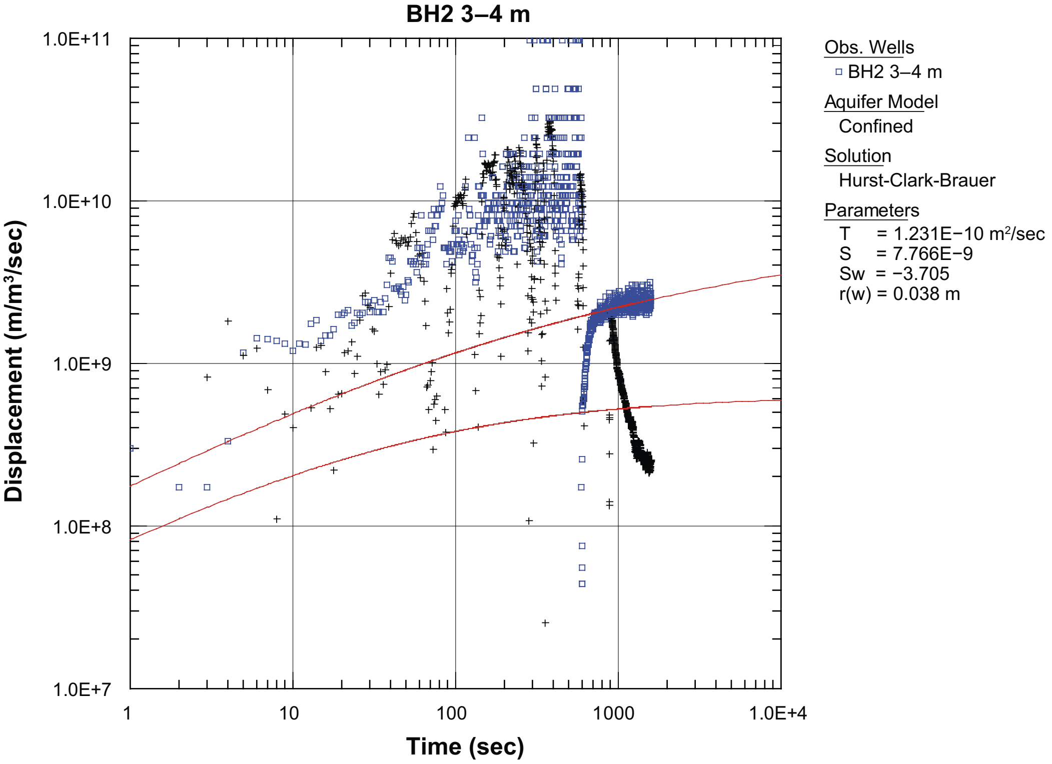

Figure A4-4. *Transient evaluation of outflow test in BH2, section 3–4 m. Uncertain evaluation.*

Transient evaluations of outflow tests in BH3 (K04026G02)

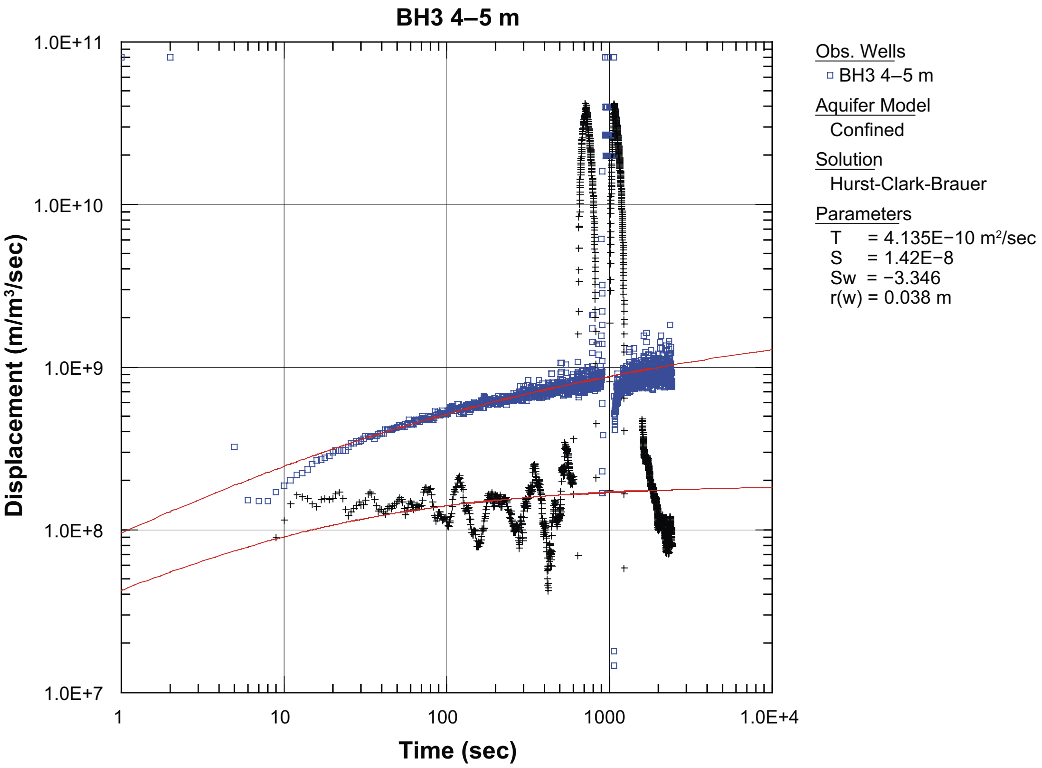

Figure A4-5. *Transient evaluation of outflow test in BH3, section 4–5 m. Test was accidently stopped and restarted after c 15 min. Pseudo-radial flow regime.*

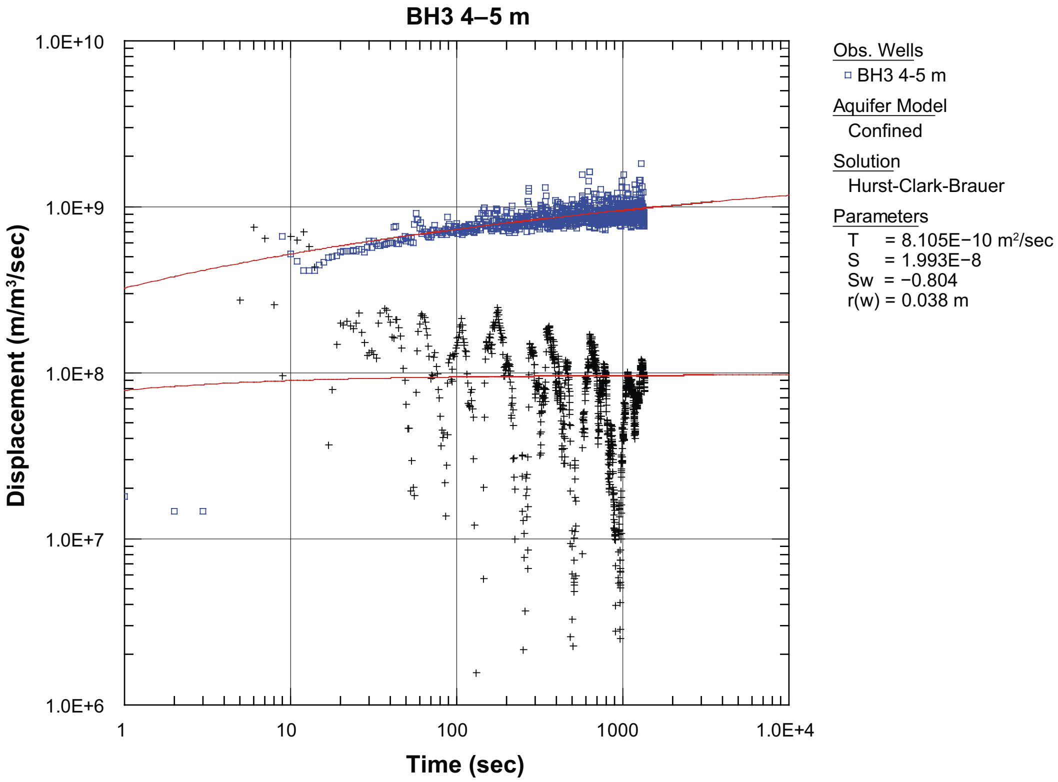

Figure A4-6. *Transient evaluation of outflow test in BH3, section 4–5 m, only the part after restart. Pseudo-radial flow regime.*

Arkitektkopia AB, Bromma, 2021

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