P-05-145

Forsmark site investigation

Single-hole injection tests in borehole KFM02A, re-measurements after hydraulic fracturing

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May 2005

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ISSN 1651-4416
SKB P-05-145

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Keywords: Forsmark, Hydrogeology, Hydraulic tests, Injection tests, Single-hole tests, Hydraulic parameters, Transmissivity, Hydraulic conductivity, Hydraulic fracturing, AP PF 400-04-73.

Abstract

The borehole KFM02A, which is the second core-drilled borehole within the site investigations in the Forsmark area, is of SKB chemistry type. It is designed as a so called telescopic borehole, with an enlarged diameter in the upper approximately 100 m, which enables installation of certain bulky borehole equipment. The borehole is sub-vertical, about 1,000 m deep and cased to a depth of about 100 m. The borehole diameter is about 77 mm in the interval 100–1,000 m.

This report presents injection tests performed in October 2004 using the pipe string system PSS3 in borehole KFM02A and the test results. Injection tests have previously been performed in KFM02A during March 2004.

Injection tests were performed in selected sections as a re-measure after hydraulic fracturing. The main aim of re-measurements in KFM02A was to examine if the hydraulic fracturing resulted in any detectable changes in transmissivity in the vicinity of the borehole. Hydraulic parameters such as transmissivity, dominating flow regime and possible outer hydraulic boundaries were determined using analysis methods for stationary as well as transient conditions.

For all tests conducted previous to hydraulic fracturing in the selected test sections the injection period was interrupted due to no detectable flow. During the re-measurements a flow rate above the measurement limit was registrated in all sections with an estimated increase in transmissivity from c.75 to 600 percent.

Sammanfattning

Borrhål KFM02A, som var det andra kärnborrhålet i platsundersökningarna i Forsmarksområdet, är av SKB kemityp. Det är utfört som ett så kallat teleskopborrhål för att göra det möjligt att installera viss skrymmande borrhålsutrustning i de övre, ca 100 m med större diameter än resten av borrhålet. Borrhålet är subvertikalt, ca 1 000 m djupt och försett med foderrör till ca 100 m djup. Borrhålsdiametern är ca 77 mm i intervallet 100–1 000 m.

Föreliggande rapport beskriver genomförda injektionstester under oktober 2004 med rörgångssystemet PSS3 i borrhål KFM02A samt resultaten från desamma. Injektionstester har tidigare utförts i KFM02A under mars 2004

Injektionstester utfördes i utvalda sektioner som om-mätning efter hydraulisk spräckning. Huvudsyftet med om-mätningarna i KFM02A var att undersöka om den hydrauliska spräckningen lämnar några detekterbara förändringar med avseende på transmissivitet i borrhålets närhet. Hydrauliska parametrar såsom transmissivitet, dominerande flödesregim och eventuella yttre hydrauliska randvillkor bestämdes med hjälp av analysmetoder för såväl stationära som transienta förhållanden.

För samtliga test utförda före hydraulisk spräckning i de utvalda sektionerna avbröts injektionsfasen på grund av att inget flöde kunde detekteras. Vid ommätning, efter hydraulisk spräckning registrerades ett flöde över systemets mätgräns i samtliga sektioner med en uppskattad ökning av transmissivitet mellan 75 och 600 procent.

Contents

1 Introduction

The injection tests in borehole KFM02A at Forsmark, Sweden, were carried out in October 2004 by Geosigma AB. The borehole KFM02A was the second deep cored borehole within the on-going site investigation in the Forsmark area. The borehole is a so called telescopic borehole. This borehole design permits installation of certain bulky borehole equipment in the upper c. 100 m where the diameter is larger than in the rest of the borehole. The borehole is sub-vertical, c.1,000 m deep and cased to c. 100 m depth. The borehole diameter is c. 77 mm in the interval 102.00–1,002.44 m. The location of the borehole is shown in Figure 1-1.

Hydraulic fracturing (HF) and hydraulic testing of pre-existing fractures (HTPF) has previously been carried out in KFM02A. Re-measurements with PSS have been conducted in a selected number of sections, Table 4-2. The selected sections have prior to the hydraulic fracturing been measured with PSS /1/ and the transmissivities, for all sections, were then found to be below the measurement limit with the PSS.

This document reports the results obtained from the injection tests in selected sections performed after hydraulic fracturing in borehole KFM02A. The activity is performed within the Forsmark site investigation. The work was carried out in compliance with the SKB internal controlling documents, presented in Table 1-1. Data and results were delivered to the SKB site characterization database SICADA.

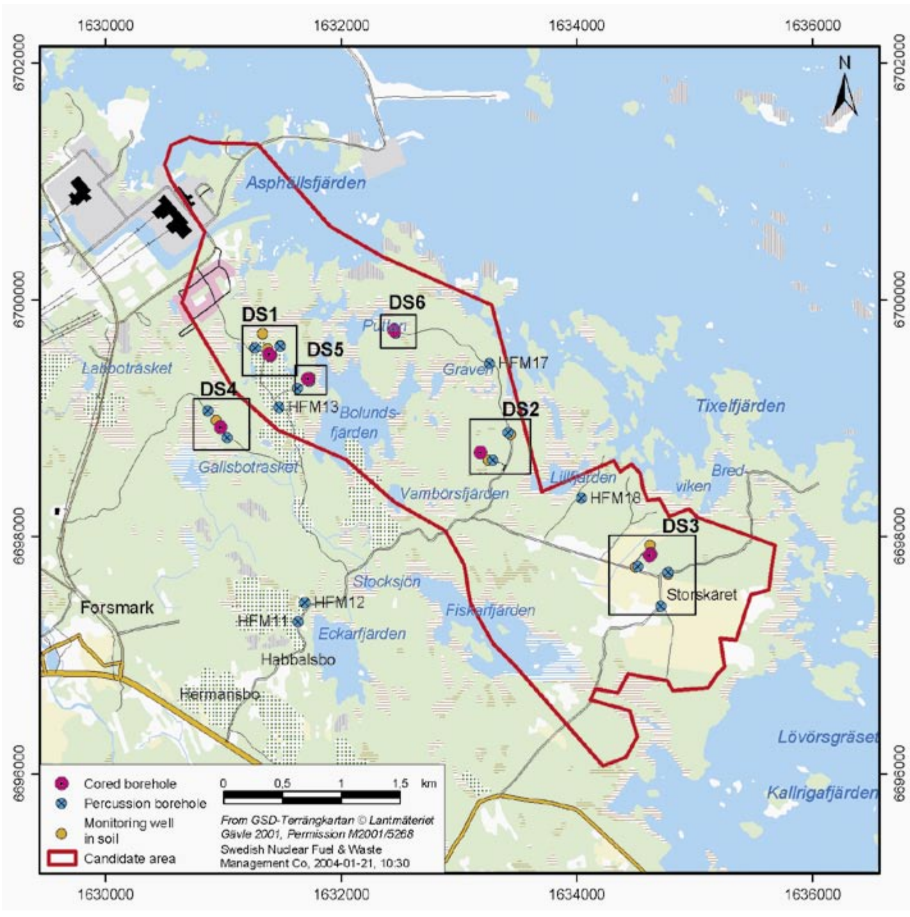


Figure 1-1. The investigation area at Forsmark including the candidate area selected for more detailed investigations. Borehole KFM02A is situated at drill site DS2.

Table 1-1. SKB internal controlling documents for the performance of the activity.

Activity Plan	Number	Version
Hydraulic injection tests in borehole KFM02A with PSS3, re-measurements after hydraulic fracturing	AP PF 400-04-73	1.0
Method descriptions	**Number**	**Version**
Mätsystembeskrivning (MSB) – Allmän del. Pipe String System (PSS3).	SKB MD 345.100	1.0
Mätsystembeskrivning för: Kalibrering, PSS3.	SKB MD 345.122	1.0
Mätsystembeskrivning för: Skötsel, service, serviceprotokoll, PSS3.	SKB MD 345.124	1.0
Metodbeskrivning för hydrauliska injektionstester	SKB MD 323.001	1.0
Instruktion för analys av injektions- och enhålspumptester	SKB MD 320.004	1.0

2 Objectives

The main aim of re-measurements, using injection tests, in KFM02A was to examine if the hydraulic fracturing caused any detectable changes in transmissivity in the vicinity of the borehole. The primary parameter to be determined was hydraulic transmissivity from which hydraulic conductivity can be derived. Other hydraulic parameters of interest were flow regimes and outer hydraulic boundaries. These parameters were analysed using transient evaluation on the test responses during the injection- and recovery periods.

A comparison with the results of the previously performed injection tests in KFM02A was included in the activity to verify changes in the hydraulic conductivity due to the hydraulic fracturing.

3 Scope

3.1 Borehole data

Technical data of the tested borehole are shown in Table 3-1 and in Appendix 4. The reference point of the boreholes is defined as the centre of top of casing (ToC), given as “Elevation” in the table below. The Swedish National coordinate system (RT90) is used for the horizontal coordinates together with RHB70 for the elevation. “Northing” and “Easting” refer to the top of the boreholes.

Table 3-1. Technical data of borehole KFM02A (printout from SKB database, SICADA).

Borehole length(m):	1,002.440				
Drilling Period(s):	**From Date**	**To Date**	**Secup (m)**	**Seclow (m)**	**Drilling Type**
	2002-11-20	2002-11-26	0.000	100.400	Percussion drilling
	2003-01-08	2003-03-12	100.420	1,002.440	Core drilling
Starting point coordinate:	**Length (m)**	**Northing (m)**	**Easting (m)**	**Elevation**	**Coord System**
	0.000	6698712.501	1633182.863	7.353	RT90-RHB70
Angles:	**Length (m)**	**Bearing**	**Inclination (– = down)**		
	0.000	275.764	–85.385		
Borehole diameter:	**Secup (m)**	**Seclow (m)**	**Hole Diam (m)**		
	0.000	2.390	0.440		
	2.390	11.800	0.358		
	11.800	100.400	0.251		
	100.420	102.000	0.086		
	102.000	1,002.440	0.077		
Core diameter:	**Secup (m)**	**Seclow (m)**	**Core Diam (m)**		
	100.420	102.000	0.072		
	102.000	1,002.440	0.051		
Casing diameter:	**Secup (m)**	**Seclow (m)**	**Case In (m)**	**Case Out (m)**	
	0.000	100.140	0.200	0.280	
	0.100	11.800	0.265	0.273	

3.2 Tests performed

The injection tests in borehole KFM02A, performed according to Activity Plan AP PF 400-04-73, see Table 1-1, are listed in Table 3-2. The injection tests were carried out with the Pipe String System (PSS3). The test procedure, together with the equipment, is described in the measurement system description for PSS (SKB MD 345.100-01) and in the corresponding method descriptions for hydraulic injection tests (SKB MD 323.001, Table 1-1).

The test were performed in selected test sections in order to compare results from tests conducted before and after the hydraulic fracturing. Hence the upper and lower limits for the test sections were in accordance with the upper and lower limits of the test sections during the previous injection tests made in KFM02A /1/.

Table 3-2. Single-hole injection tests performed in borehole KFM02A.

Borehole	Test section		Section length	Test type[1)]	Test no	Test start date, time	Test stop date, time
Bh ID	secup	seclow		(1–6)		YYYYMMDD hh:mm	YYYYMMDD hh:mm
KFM02A	146	151	5	3	1	20041019 10:08	20041019 12:57
KFM02A	211	216	5	3	1	20041019 13:47	20041019 15:16
KFM02A	471	476	5	3	1	20041019 17:25	20041019 18:39
KFM02A	516	521	5	3	1	20041019 19:08	20041019 20:23
KFM02A	551	556	5	3	1	20041020 08:46	20041020 10:01

[1)] 3: Injection test

3.3 Equipment checks

The PSS3 equipment was fully serviced, according to SKB internal controlling documents (SKB MD 345.124, service and SKB MD 345.122, calibration), in February 2004. Some service and calibration was also made in April 2004.

Functioning checks of the equipment were performed during the installation of the PSS equipment at the test site. In order to check the function of the pressure sensors, the air pressure was recorded and found to be as expected. While lowering, the sensors showed good agreement with the total head of water (p/ρg). Simple functioning checks of down-hole sensors were done at every change of test section interval. Checks were also made continuously while lowering the pipe string along the borehole.

4 Description of equipment

4.1 Overview

4.1.1 Measurement container

All of the equipment needed to perform the injection tests is located in a steel container (Figure 4-1). The container is divided into two compartments; a data-room and workshop. The container is placed on pallets in order to obtain a suitable working level in relation to the borehole casing.

The hoisting rig is of a hydraulic chain-feed type. The jaws, holding the pipe string, are opened hydraulically and closed mechanically by springs. The rig is equipped with a load transmitter and the load limit may be adjusted. The maximum load is 22 kN.

The packers and the test valve are operated hydraulically by water filled pressure vessels. Expansion and release of packers, as well as opening and closing of the test valve, is done using magnetic valves controlled by the software in the data acquisition system.

The injection system consists of a tank, a pump and a flow metre. The injection flow rate may be manually or automatically controlled. At small flow rates, a water filled pressure vessel connected to a nitrogen gas regulator is used instead of the pump.

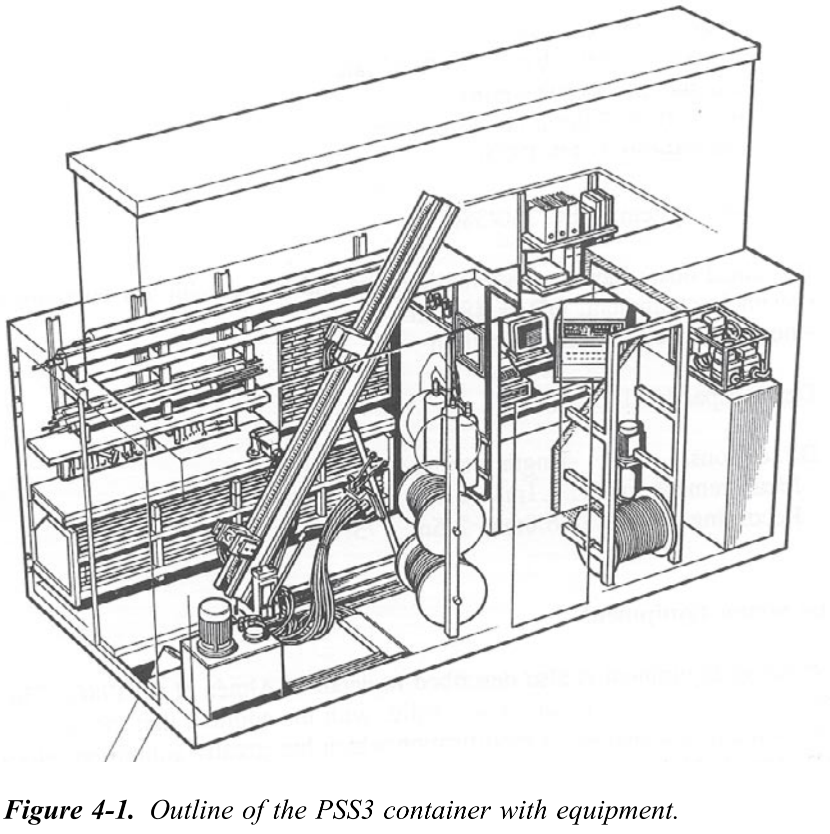


Figure 4-1. Outline of the PSS3 container with equipment.

4.1.2 Down-hole equipment

A schematic drawing of the down-hole equipment is shown in Figure 4-2. The pipe string consists of aluminium pipes of 3 m length, connected by stainless steel taps sealed with double o-rings. Pressure is measured above (Pa), within (P) and below (Pb) the test section, which is isolated by two packers. The groundwater temperature in the test section is also measured. The hydraulic connection between the pipe string and the test section can be closed or opened by a test valve operated by the measurement system.

At the lower end of the borehole equipment, a level indicator (caliper type) gives a signal as the reference depth marks along the borehole are passed.

The length of the test section may be varied (5, 20 or 100 metres).

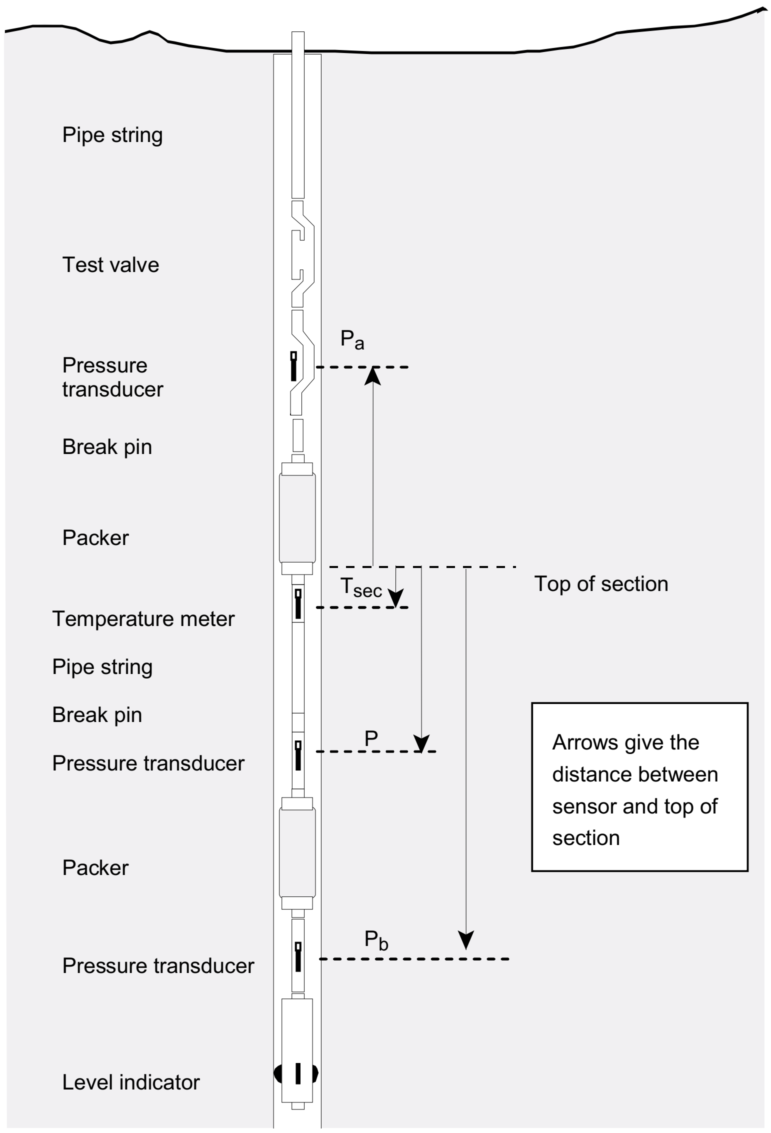


Figure 4-2. *Schematic drawing of the down-hole equipment in the PSS3 system.*

4.2 Measurement sensors

Technical data for the measurement sensors in the PSS system together with corresponding data of the system are shown in Table 4-1.

The sensor positions are fixed relative to the top of the test section. In Table 4-2, the position of the sensors is given with top of test section as reference (Figure 4-2).

Table 4-1. Technical data for sensors together with estimated data for the PSS system (based on current experience).

Technical specification Parameter		Unit	Sensor	PSS	Comments
Absolute pressure	Output signal	mA	4–20		
	Meas. range	MPa	0–13.5		
	Resolution	kPa	< 1.0		
	Accuracy[1)]	% F.S	0.1		
Differential pressure, 200 kPa	Accuracy	kPa		< ± 5	Estimated value
Temperature	Output signal	mA	4–20		
	Meas. range	°C	0–32		
	Resolution	°C	< 0.01		
	Accuracy	°C	± 0.1		
Flow Qbig	Output signal	mA	4–20		
	Meas. range	m^3/s	$1.67 \cdot 10^{-5}$–$1.67 \cdot 10^{-3}$		
	Resolution	m^3/s	$6.7 \cdot 10^{-8}$		
	Accuracy[2)]	% O.R	0.15–0.3	0.2–1	The specific accuracy is depending on actual flow
Flow Qsmall	Output signal	mA	4–20		
	Meas. range	m^3/s	$1.67 \cdot 10^{-8}$–$1.67 \cdot 10^{-5}$		
	Resolution	m^3/s	$6.7 \cdot 10^{-10}$		
	Accuracy[2)]	% O.R	0.4–10	0.4–20	The specific accuracy is depending on actual flow

[1)] 0.1 % of Full Scale. Includes hysteresis, linearity and repeatability.

2) Maximum error in % of actual reading (% o.r.). The higher numbers correspond to the lower flow.

Table 4-2. Position of sensors in the borehole and displacement volume of equipment in the test section.

Parameter	Length of test section (m)
	5
Equipment displacement volume in test section [1)]	4
Total volume of test section [2)]	23
Position for sensor Pa, pressure above test section, (m above secup) [3)]	1.89
Position for sensor P, pressure in test section, (m above secup) [3)]	–0.98
Position for sensor Pb, pressure below test section, (m above secup) [3)]	–6.99

[1)] Displacement volume in test section due to pipe string, signal cable and packer ends (in litres).

2) Total volume of test section (V = section length*π*d2/4).

3) Position of sensor relative top of test section. A negative value indicates a position below top of test section, (secup).

4.3 Data acquisition system

The data acquisition system in the PSS equipment contains a standard office PC connected to an I/O-unit (Datascan 7320). Using the Orchestrator software, pumping and injection tests are monitored and borehole sensor data are collected. In addition to the borehole parametres, packer and atmospheric pressure, container air temperature and water temperature are logged. Test evaluation may be performed on-site after a conducted test. An external display enables monitoring of test parameters.

The data acquisition system may be used to start and stop the automatic control system (computer and servo motors). These are connected as shown in Figure 4-3. The control system monitors the flow regulator and uses differential pressure across the regulating valve together with pressure in test section as input signals.

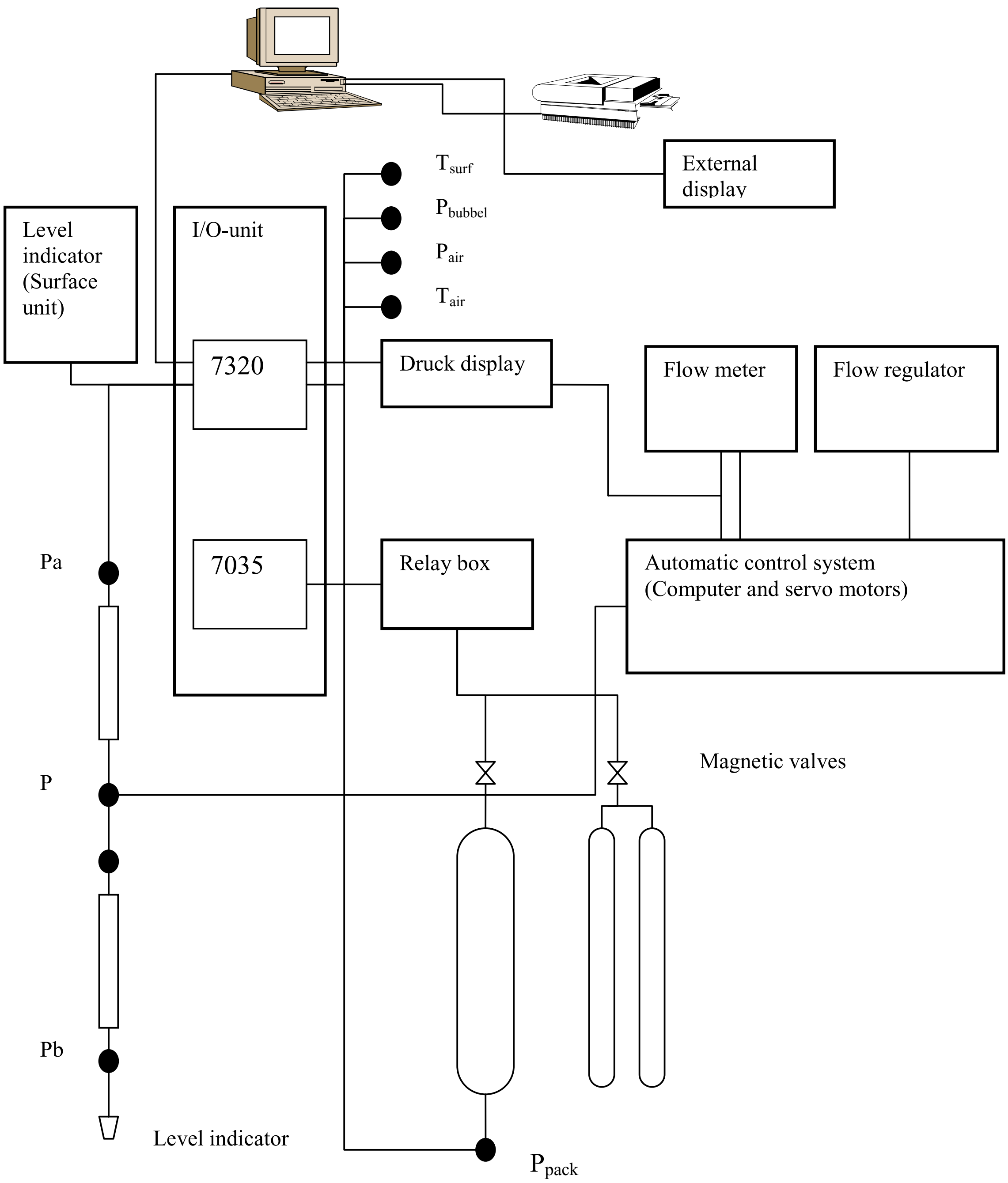


Figure 4-3. *Schematic drawing of the data acquisition system and the automatic control system in PSS.*

5 Execution

5.1 Preparation

5.1.1 Calibration

All sensors included in PSS are calibrated at the Geosigma engineering service station in Uppsala. Calibration is generally performed prior to each measurement campaign. Results from calibration, e.g. calibration constants, of sensors are kept in a document folder in PSS. If a sensor is replaced at the test site, calibration constants are altered as well. If a new, un-calibrated, sensor is to be used, calibration may be performed afterwards and data re-calculated.

5.1.2 Functioning checks

Equipment functioning checks were performed during the establishment of PSS at the test site. Simple function checks of down-hole sensors were done at every change of test section length, as well as while lowering the pipe string along the borehole.

5.2 Test performance

5.2.1 Test principle

The injection tests in KFM02A after hydraulic fracturing were carried out while maintaining a constant head of c. 200 kPa in the test section. Before start of the injection period, approximately steady-state pressure conditions prevailed in the test section. After the injection period, the pressure recovery was measured.

5.2.2 Test procedure

Generally, the tests were performed according to the Activity Plan AP PF 400-04-73. Exceptions to this are presented in section 5.5.

A test cycle includes the following phases: 1) Transfer of down-hole equipment to the next section, 2) Packer inflation, 3) Pressure stabilisation, 4) Injection, 5) Pressure recovery and 6) Packer deflation. The estimated times for the various phases are presented in Table 5-1.

Table 5-1. Packer inflation times, pressure stabilisation times and test times used for the injection tests in KFM02A.

Test section length (m)	Packer inflation time (min)	Time for pressure stabilisation (min)	Injection period (min)	Recovery period (min)	Total time/test (min)[1)]
5	25	5	20	20	70

[1)] Exclusive of trip times in the borehole

5.2.3 Test strategy

Hydraulic fracturing (HF) and hydraulic testing of pre-existing fractures (HTPF) has previously been performed in KFM02A /2/. The latter test type was applied to both vertical (-v) and horiszontal (-h) fractures as well as on fractures of intermediate dip. Re-measurements with PSS have been conducted in a selected number of sections, Table 4-2. The selected sections have prior to the hydraulic fracturing been measured with PSS /1/ and the transmissivities, for all sections, were then found to be below the measurement limit of the PSS.

Table 5-2. Selected test sections in KFM02A for re-measurements with PSS.

Section (m)	Hydraulic fracturing (test type)
146–151	HTPF-h (149.28–149.88)
211–216	HTPF-h (214.0–214.6)
471–476	HTPF-v (472.73–473.33)
516–521	HTPF-v (519.92–520.52)
551–556	HF (552.9–553.5 and 551.3–551.9)

5.3 Data handling

With the PSS system, primary data are handled using the Orchestrator software (Version 2.3.8). During a test, data are continuously logged in *.odl-files. After the test is finished, a report file (*.ht2) with space separated data is generated. The *.ht2-file (mio-format) contains logged parameters as well as test-specific information, such as calibration constants and background data. The parameters are presented as percentage of sensor measurement range and not in engineering units. The report file in ASCII-format is the raw data file delivered to the data base SICADA.

The *.ht2-files are automatically named with borehole id, top of test section and date and time of test start (as for example __KFM02A_0211.00_200410191347.ht2. The name differs slightly from the convention stated in Instructions for analysis of injection and single-borehole pump test, SKB MD 320.004 (SKB internal document).

Using the IPPLOT software (Version 2.0), the *.ht2-files are converted to parameter files suitable for plotting using the code SKB-plot and analysis with the AQTESOLV software.

A file description table is presented in Appendix 1.

5.4 Analysis and interpretation

5.4.1 Single-hole injection tests

As discussed in section 5.2.1, the injection tests in KFM02A were performed as transient constant head tests followed by a pressure recovery period. The routine data processing of the measured data was done according to the Instruction for analysis of injection and single-hole pumping tests (SKB MD 320.004, see Table 1-1). From the injection period, the (reciprocal) flow rate versus time was plotted in log-log and lin-log diagrams together with the corresponding derivative. From the recovery period, the pressure and pressure change were plotted versus Agarwal equivalent time in lin-log and log-log diagrams, respectively, together with the corresponding derivatives.

Initially, a qualitative evaluation of actual flow regimes, e.g. wellbore storage (WBS), pseudo-radial flow regime (PRF), pseudo-spherical flow regime (PSF) and pseudo-stationary flow regime (PSS), respectively, was performed. In addition, indications of outer boundary conditions during the tests were identified. The qualitative evaluation was mainly made from the log-log diagrams of the responses during the flow and recovery periods. In particular, time intervals with pseudo-radial flow, reflected by a constant (horizontal) derivative in the test diagrams, were identified. Apparent no-flow (NFB) and constant head boundaries (CHB) or equivalent boundary conditions of fractures are reflected by an increase/decrease of the derivative. In addition, a preliminary steady-state analysis of transmissivity according to Moye's formula (denoted T_M) was made for the injection period for all tests.

From the results of the qualitative evaluation, appropriate interpretation methods for the quantitative evaluation of the tests were selected. When possible, transient analysis was made on both the flow and recovery periods of the tests.

The transient analysis was performed using a special version of the test analysis software AQTESOLV, which enables both visual and automatic type curve matching. The quantitative transient evaluation is generally carried out as an iterative process of manual type curve matching and automatic matching. For the injection period, a model presented by Hurst, Clark and Brauer (1969) /3/ was applied for estimating transmissivity and skin factor. The storativity was set to a fixed value of 10^{-6}, according to the instruction SKB MD 320.004 (Table 1-1). The model uses the effective wellbore radius concept to account for non-zero skin factors.

For tests showing pseudo-spherical (leaky) flow during the injection period, a model by Hantush (1959) /4/ for constant head tests was used for the evaluation. In this model, the skin factor is not separated explicitly but can be calculated from the simulated (effective) borehole radius according to Equation (5-3) below. In addition, the apparent leakage coefficient K'/b' can be calculated from the simulated value on the leakage factor r/B. The corresponding model for constant flow rate tests, Hantush (1955) /5/, was used by the evaluation of the recovery period for tests showing pseudo-spherical-, possibly transitioning to pseudo-stationary flow, during this period. The Hantush' model allows calculation of the skin factor from Equation (5-1) together with the wellbore storage coefficient according to Equation (5-5).

$$\zeta = \ln(r_w/r_{wf}) \qquad (5\text{-}1)$$

ζ = skin factor

r_w = borehole radius (m)

r_{wf} = effective borehole radius

For evaluating transient recovery data, the Dougherty-Babu (1984) /6/ model was applied. This model also uses the effective wellbore radius concept to account for non-zero skin factors. The wellbore storage is treated as the water level change in a fictive stand pipe connected to the section. The wellbore storage can be calculated from the fictive radius of this pipe, denoted casing radius in AQTESOLV, see below. The nomenclature used in AQTESOLV is listed in Appendix 3. The model was used to estimate values of transmissivity, skin factor and the wellbore storage coefficient (represented by the fictive casing radius r (c)), cf Equation 5-2.

The different transient estimates of transmissivity, in general from the pseudo-radial flow regimes during flow and recovery period, respectively, were compared and examined. One of these was chosen as the best representative value of transient transmissivity of the formation adjacent to the test section. This value is denoted T_T. In all cases where a transient evaluation of the recovery period was possible, the transient estimates of transmissivity from the injection period were considered more representative than those from the recovery period.

Finally, a representative value of transmissivity of the section, T_R, was chosen from T_T and T_M. Whenever the flow rate by the end of the injection period (Q_p) was not defined, and thus neither T_T nor T_M could be estimated, the most representative value of transmissivity for the test section was considered to be the estimated lower measurement limit for Q/s (i.e. T_R = Q/s-measl-L).

An estimated value of the borehole storage coefficient, C, based on actual borehole geometrical data and assumed fluid properties is shown in Table 5-3. The net water volume in the test section, V_w, has in Table 5-3 been calculated by subtracting the volume of equipment in the test section (pipes and thin hoses) from the total volume of the test section. For an isolated test section, the wellbore storage coefficient, C, may be calculated as /7/:

$$C = V_w \cdot c_w = L_w \cdot \pi \cdot r_w^2 \cdot c_w \qquad (5\text{-}2)$$

V_w = water volume in test section (m^3)

r_w = nominal borehole radius (m)

L_w = section length (m)

c_w = compressibility of water (Pa^{-1})

When appropriate, estimation of the actual borehole storage coefficient C in the test sections was also made from the recovery period, based on the early borehole response with 1:1 slope in the log-log diagrams. The coefficient C was calculated only for tests with a well-defined line of slope 1:1 in the beginning of the recovery period.The latter values may be compared with the net values of C based on geometry (Table 5-3).

Furthermore, when using the model by Dougherty-Babu (1984), a fictive casing radius, r(c), is obtained from the parameter estimation. This value can then be used for calculating C as /7/:

$$C = \frac{\pi \cdot r(c)^2}{\rho \cdot g} \qquad (5\text{-}3)$$

Although this calculation was not done regularly and the results are not presented in this report, the calculations corresponded in most cases well to the value of C obtained from the line of slope 1:1 in the beginning of the recovery period.

Table 5-3. Calculated net values of the wellbore storage coefficient C for injection tests based on the actual geometrical properties of the borehole and equipment configuration in the test section.

Borehole	r_w (m)	L_w (m)	Volume of test section (m^3)	Volume of equipment insection (m^3)	V_w (m^3)	C (m^3/Pa)
KFM02A	0.0385	5	0.023	0.004	0.020	$9.1 \cdot 10^{-12}$

The estimated values of C from the tests may differ from the net value in Table 5-3 based on geometry. For example, the effective compressibility for an isolated test section may sometimes be higher than the water compressibility due to e.g. packer compliance, resulting in increased C-values.

5.4.2 Measurement limit for flow rate and specific flow rate

The estimated standard lower measurement limit for the flow rate for injection tests with PSS is c. 1 mL/min ($1.7 \cdot 10^{-8}$ m^3/s). However, if the flow rate for a test was close to, or below, the standard lower measurement limit, a test-specific estimate of the lower measurement limit was used. The test-specific lower limit was based on the measurement noise before and after the injection period. The decisive factor for the varying lower measurement limit is not identified but it might be of both technical and hydraulic character.

The lower measurement limit for transmissivity is defined in terms of the specific flow rate (Q/s). The minimum specific flow rate corresponds to the estimated lower measurement limit for the flow rate together with the actual injection pressure during the test, see Table 5-4. The intention during this test campaign was to use a standard injection pressure of 200 kPa (20 m water column). A higher injection pressure is often a result of the test section being of low hydraulic conductivity. A low injection pressure is often a result of either the test section being highly conductive or the test section being of low conductivity. The latter might cause the pressure in the section to increase due to packer expansion before injection start. The injection pressure for the test considered in this report ranged from 223 kPa to 234 kPa, i.e. no large deviations from the standard injection pressure of 200 kPa.

Whenever a final flow rate (Q_p) can not be defined (i.e. not clearly above the measurement noise level before and after the injection period), the estimated lower measurement limit for specific flow rate is based on the estimated lower measurement limit for the specific test and a standard injection pressure of 200 kPa.

The lower measurement limits for the flow rate corresponds to different values of steady-state transmissivity, T_M, depending on the section lengths used in the factor C in Moye's formula, as described in the Instruction for analysis of injection and single-hole pumping tests (SKB MD 320.004, Table 1-1), see Table 5-4.

Table 5-4. Estimated lower measurement limit for specific capacity (Q/s) and steady-state transmissivity for different injection pressures, measurement scales and estimated lower measurement limits for flow rate for the injection tests in borehole KFM02A.

Borehole	r_w (m)	L_w (m)	Q-measl-L(m^3/s)	Injection pressure (kPa)	Q/s-measl-L(m^2/s)	Factor C in Moye's formula	T_M-measl-L (m^2/s)
KFM02A	0.0385	5	1.7E–08	100	1.6E–09	0.82	1.3E–09
KFM02A	0.0385	5	1.7E–08	200	8.2E–10	0.82	6.7E–10
KFM02A	0.0385	5	1.7E–08	300	5.5E–10	0.82	4.5E–10
KFM02A	0.0385	5	1.2E–08	100	1.1E–09	0.82	9.4E–10
KFM02A	0.0385	5	1.2E–08	200	5.7E–10	0.82	4.7E–10
KFM02A	0.0385	5	1.2E–08	300	3.8E–10	0.82	3.1E–10
KFM02A	0.0385	5	5.0E–09	100	4.9E–10	0.82	4.0E–10
KFM02A	0.0385	5	5.0E–09	200	2.5E–10	0.82	2.0E–10
KFM02A	0.0385	5	5.0E–09	300	1.6E–10	0.82	1.3E–10

The practical upper measurement limit for the PSS system is estimated at a flow rate of c. 30 L/min ($5 \cdot 10^{-4}$ m^3/s) and an injection pressure of c. 1 m. Thus, the upper measurement limit for the specific flow rate is $5 \cdot 10^{-4}$ m^2/s. However, the practical upper measurement limit may vary, depending on e.g. depth of the test section (friction losses in the pipe string).

5.5 Nonconformities

The test program in KFM02A was carried out according to the Activity Plan (AP PF 400-04-73) with the following exceptions:

- Due to a shortcut in the down-hole cable, the temperature sensor in the test section was not in use.
- The pressure registration below the test section, Pb, was affected by rapid changes in the signal intensity from the pressure sensor in the test section, Psec. See section 6.2.3 for a more detailed problem description.

6 Results

6.1 Nomenclature and symbols

The nomenclature and symbols used for the results of the injection tests in KFM02A are in accordance with the Instruction for analysis of injection and single-hole pumping tests (SKB MD 320.004). Additional symbols used are explained in the text and in Appendix 5. Symbols used by the AQTESOLV software are explained in Appendix 3.

6.2 Routine evaluation of the single-hole injection tests

6.2.1 General test data

General test data with selected pressure and flow data from all tests are listed in Appendix 2.1 and 2.2, respectively.

6.2.2 Length corrections

The down-hole equipment is supplied with a level indicator located c. 3 m below the lower packer in the test section, see Figure 4-2. The level indicator transmits a signal each time a reference mark in the borehole is passed. In KFM02A, reference marks were milled in the borehole wall at every 50 m (with a few exceptions).

During the injection tests in KFM02A with the PSS presented in this report, length reference marks were detected as presented in Table 6-1.

At each mark, the length scale for the injection tests was adjusted according to the reported length to the reference mark. The difference between two consecutive measurements over a 100 m borehole interval was 0.04 m or less in all cases. Since the length scale was adjusted in the field every time a reference mark was passed, and since the difference between consecutive marks was small, it was not found worthwhile to make any further adjustments after the measurements, e.g. by linear interpolation between reference marks.

Table 6-1. Detected reference marks during the injection tests in KFM02A.

Borehole length (m)	Detected during the injection tests in 5 m sections
110	yes
150	yes
200	yes
250	yes
304.5	yes
350	yes
400	–
450	yes
506	yes
550	yes

6.2.3 General results

The main aim of re-measurements, using injection tests, in KFM02A was to examine if hydraulic fracturing produced any detectable changes in transmissivity in originally unfractured rock and in fractures of very low conductivity. The test results clearly indicate that there is a detectable increase in hydraulic conductivity in the selected test sections after hydraulic fracturing has been performed. A quantitative comparison is presented in section 6.3.

A summary of the results of the routine evaluation of the injection tests in KFM02A is presented, test by test, in Table 6-2. Selected test diagrams are presented in Appendix 3. In general, one linear diagram showing the entire test sequence together with lin-log and log-log diagrams from the injection and recovery periods, respectively, are presented. The quantitative analysis was performed from such diagrams using the AQTESOLV software.

The dominating transient flow regimes during the injection and recovery periods, respectively, as interpreted from the qualitative test evaluation, are listed in Table 6-2 and further commented in section 6.2.4.

In the quantitative evaluation, the steady-state transmissivity (T_M) was calculated by Moye's formula. Transient evaluation was performed for all tests but one. Transient evaluation was performed on the injection period in four out of five tests and on the recovery period in three out of five tests. See Table 6-2 for a complete compilation of the evaluated parameters.

The value judged as the most reliable from the transient evaluation of the tests was selected as T_T. The associated value for the skin factor is listed in Table 6-2. The transmissivity calculated from the injection period is considered as the most reliable transient analysis for the injection tests in all test sections. In addition, the transient evaluation of transmissivity from the injection period was in all cases also judged to be the most representative estimate of transmissivity, T_R.The approximate start and stop times used for the transient evaluation are also listed in Table 6-2. For those tests where transient evaluation was not possible or not considered representative, T_M was chosen as the representative transmissivity value, T_R.

The results of the routine evaluation of the injection tests in borehole KFM02A are also compiled in appropriate tables in Appendix 5, to be stored in the SICADA database.

For the evaluation of the test data, no corrections of the measured flow rate and absolute pressure data (e.g. due to barometric pressure variations or tidal fluctuations) have been made. For short-time single-hole tests, such corrections are generally not needed, unless very small pressure changes are applied. No subtraction of the barometric pressure from the measured absolute pressure has been made, since the length of the test periods are short relative to the time scale for barometric pressure changes. In addition, pressure differences rather than the pressure magnitudes are used by the evaluation.

A malfunction in the signal transmission from the pressure transmitter in the test section was discovered in connection to the assembly of the borehole equipment. Since time was a critical factor during these measurements and temperature registration in the test section is of minor importance for injection tests, the temperature sensor in the test section, Tsec, was sacrificed in favour of a pressure transmitter. Hence no temperature data from the test section are available from any of the reported tests.

Table 6-2. Summary of the routine evaluation of the single-hole injection tests in borehole KFM02A.

Secup (m)	Seclow (m)	Test start YYYYMMDD hh:mm	b (m)	Flow regime [1)] injection	recovery	Q/s-measl-L (m^2/s)	Q/s (m^2/s)	Q_p (m3/s)	T_M (m^2/s)	T_f (m^2/s)	T_s (m^2/s)	T_T (m^2/s)	T_R (m^2/s)	ξ (–)	t_1 (s)	t_2 (s)	C (m^3/Pa)
146.00	151.00	20041019 10:08	5	PRF->NFB	WBS->NFB	8.2E–10	1.01E–9	2.200E	8.28E–10	7.10E–10	9.46E–10	7.10E–10	7.10E–10	–1.0	20	80	2.24E–11
211.00	216.00	20041019 13:47	5	(PRF)	WBS->(PRF)	8.2E–10	1.49E–9	3.372E	1.23E–09	4.96E–10	4.20E–10	4.96E–10	4.96E–10	–1.6	–	–	1.72E–11
471.00	476.00	20041019 17:25	5	PRF->PSF	WBS->PSF	8.2E–10	4.17E–9	9.489E	3.43E–09	1.49E–09	2.39E–09	1.49E–09	1.49E–09	–1.2	10	60	1.93E–11
516.00	521.00	20041019 19:08	5	PSF	WBS->?	8.2E–10	1.63E–9	3.404E	1.35E–09	4.96E–10	–	4.96E–10	4.96E–10	–1.0	–	–	2.95E–11
551.00	556.00	20041020 08:46	5	NFB	WBS	2.5E–10	4.48E–10	8.987E	3.69E–10	–	–	–	3.69E–10	–	–	–	4.58E–11

[1)] The acronyms in the column "Flow regime" are as follow: wellbore storage (WBS), pseudo-linear flow (PLF), pseudo-radial flow (PRF), pseudo-spherical flow (PSF), pseudo-stationary flow (PSS) and apparent no-flow boundary (NFB). The flow regime definitions are further discussed in section 6.2.5 below

The pressure registration below the test section, Pb, was affected by rapid changes in the signal intensity from the pressure sensor in the test section, Psec. In addition pressure data below the test section was scattered, see linear plots in Appendix 3.2. This effect was distinct in the uppermost test section and less pronounced as the test section was moved downwards in the borehole. Normal sensor accuracy reported in section 4.2 are not valid for pressure data below the test section, Pb. Since these problems disappeared after the measurements, unreliable data from the pressure transmitter, Pb, are interpreted to be due to water penetration in one of the underwater contacts.

Considering distances to sourrounding boreholes, test times and the low conductivity characteristics of the selected test sections, any possible activities in the sourrounding boreholes are assumed to be negligible to test data.

In Figure 6-1, a comparison between calculated transmissivities in the test sections from steady-state evaluation (T_M) and transmissivity values from the transient evaluation (T_T) is shown. The standard lower measurement limit of transmissivity in 5 m sections for a flow rate of 1 mL/min and an injection pressure of 200 kPa is indicated in the figure.

The wellbore storage coefficient, C, was calculated from the straight line with a unit slope in the log-log diagrams from the recovery period, see Table 6-2. Calculation of wellbore storage coefficient was possible for all tests. The values of C presented in Table 6-2 may be compared with the net value of C (based on geometry) in Table 5-2.

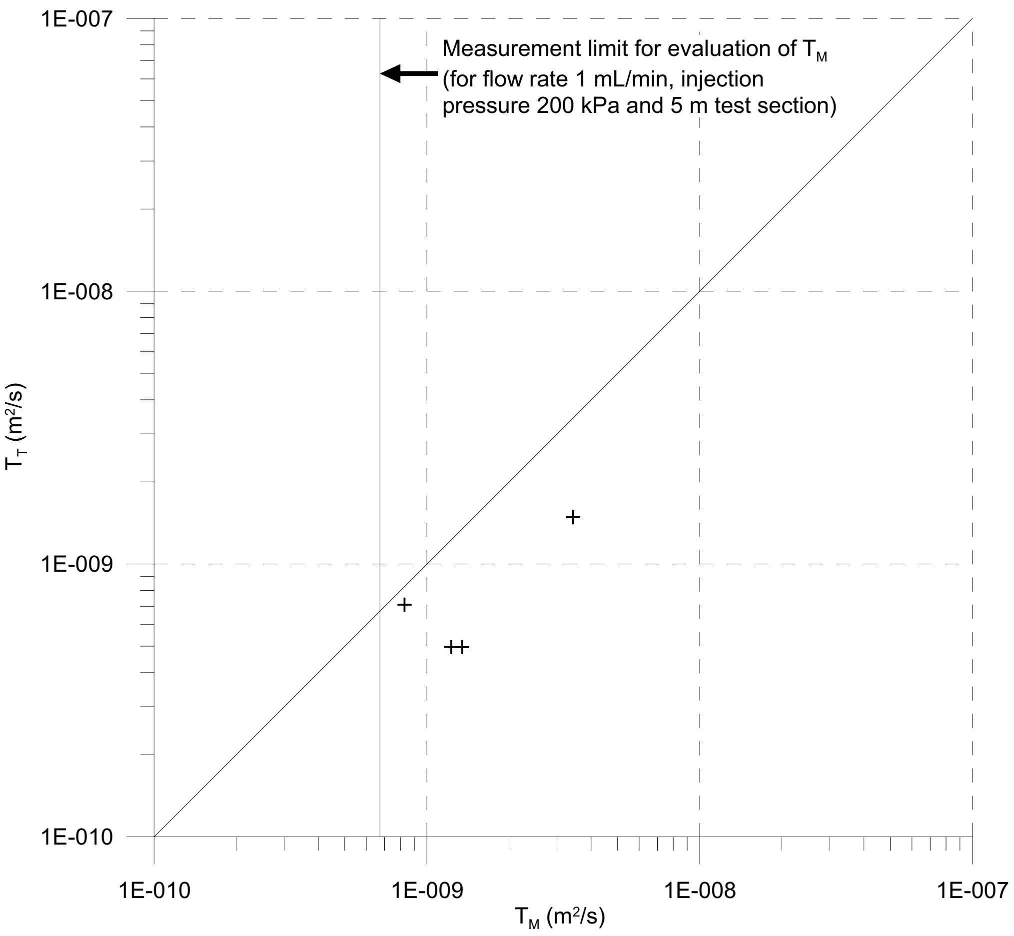


***Figure 6-1.** Estimated transmissivities in test sections from steady-state (T_M) and transient (T_T) evaluation.*

Table 6-2 shows that calculated C values from the tests there is, in general, good agreement between the calculated C values from the tests and those listed in Table 5-3, although the calculated values from the tests tend to be slightly higher. This is expected and mainly explained by elasticity in the borehole equipment.

6.2.4 Comments on the tests

Short comments on each test follow below. Flow regimes and hydraulic boundaries are in the text referred to as:

WBS = Wellbore storage

PRF = Pseudo-radial flow regime

PLF = Pseudo-linear flow regime

PSF = Pseudo-spherical flow regime

PSS = Pseudo-stationary flow regime

NFB = No-flow boundary

As discussed in section 5.4, the flow regimes were mainly interpreted from the log-log plots of flow rate and pressure together with the corresponding derivatives. WBS is identified as a straight line of unit slope. PRF corresponds to a visible period of a horizontal derivative. PLF may at the beginning of the tests be reflected by a straight line of slope 0.5 or less in the log-log diagrams, both for the measured variable (flow rate or pressure) and the derivative. A true PSF is reflected by a straight line with a slope of –0.5 for the derivative. However, other slopes may indicate transitions to PSF or PSS. The latter flow regime corresponds to almost stationary conditions with a derivative approaching zero. Due to the limited resolution of the flow metre and pressure sensor, the derivative may at some times erroneously indicate a horizontal line by the end of periods with PSS.

146–151 m

During the injection period a PRF is indicated from c. 20 s to 80 s. After c. 80 s to the end of the injection period an apparent NFB appears. WBS is dominating the recovery period up to c. 50 s. After c. 50 s to the end of the recovery period an apparent NFB is shown during both injection- and recovery period an apparent NFB is indicated which supports the interpreted flow regime and that this is characteristic of the rock formation and fractures.

211–216 m

By the end of the injection period an approximate PRF was approached. The first c. 50 s of the recovery period was dominated by WBS followed by a transition phase towards a possible PRF.

471–476 m

Indication of a PRF between 10 s and 60 s during the injection period followed by a PSF. Evaluation with leaky aquifer model (Hantush) shows good type curve fit and supports the presence of a flow regime of higher dimension (the same derivative characteristics as an equivalent leaky aquifer). The recovery period is dominated by WBS the first 20 s followed by a transition to a possible PSF after c. 300 s. Only an approximate transient evaluation was possible on the recovery period due to no distinctly developed PRF.

516–521 m

A PSF is indicated during the injection period after c. 10 s. The recovery period is dominated by WBS up to c. 90 s where a transition is indicated. No PRF developed during the recovery period.

551–556 m

An apparent NFB is indicated during the injection period. WBS is dominating throughtout the recovery period. No unique transient evaluation can be made on either the flow- or the recovery period.

6.2.5 Flow regimes

The low conductivity character of the sections selected for re-measurements does affect the flow regime interpretation. Since flow is close to the measurement limit of the PSS in all sections the (reciprocal) flow data and in particular the flow data derivative tend to be scattered, complicating the flow regime interpretation for the injection period. However PRF has been indicated in three out of the four tests where transient evaluation was possible.

The recovery period for low conductivity test sections are, in general, always dominated by WBS. WBS has been indicated during the first part of the recovery period for all of the tested sections.

The other flow regimes indicated, besides the ones mentioned above, are PSF and NFB.

It should be noted that the interpretation of flow regimes is only tentative and based on visual inspection of the data curves.

6.3 Comparison with results from previous injection tests in KFM02A

Injection tests conducted previous to hydraulic fracturing in the selected test sections were all below the measurement limit of the PSS. The injection period was interrupted for all test sections after c. 5 minutes due to no detectable flow. During the recovery periods pressure was rising in all sections. This phenomenon can be observed in test sections with a very low conductivity due to the fact that the packers continue to expand throughout the test. Linear diagrams of test data from injection tests conducted previous to the hydraulic fracturing is presented in Appendix 3.1.

During the re-measurements, after hydraulic fracturing had been conducted, a flow rate above the measurement limit was observed in all sections. An estimate of the percentage increase in flow rate at the end of the injection period, Qp, and in representative transmissivity value, T_R, is presented for each test in Table 6-3. Note that test conducted before the hydraulic fracturing were all below the measurement limit. Transmissivity and flow rate presented in Table 6-3 for the test conducted prior to the hydraulic fracturing are therefore considered to be rough estimates. The estimated values are based on knowledge of the magnitude of flow produced by packer expansion and the fact that an increase in pressure was observed in all sections during recovery period.

Table 6-3. Observed effects of hydraulic fracturing on approximate steady-state flow and evaluated transmissivity.

Secup (m)	Seclow (m)	Q_p (m3/s) [1]			T_R (m^2/s)		
		Before hydraulic fracturing	After hydraulic fracturing	Percentage increase	Before hydraulic fracturing	After hydraulic fracturing	Percentage increase
146.00	151.00	<5.0E–9	2.200E–8	>340	<2.1E–10	7.10E–10	>238
211.00	216.00	<5.0E–9	3.372E–8	>574	<2.1E–10	4.96E–10	>136
471.00	476.00	<5.0E–9	9.489E–8	>1,798	<2.1E–10	1.49E–09	>610
516.00	521.00	<5.0E–9	3.404E–8	>581	<2.1E–10	4.96E–10	>136
551.00	556.00	<5.0E–9	8.987E–9	>80	<2.1E–10	3.69E–10	>76

[1] Maximum deviation from standard injection pressure is 26 kPa. Observed final flow in the test sections are not normalized to the standard injection pressure of 200 kPa.

7 References

/1/ **Källgården J, Ludvigson J-E, Jönsson J, 2004.** Single-hole injection tests in borehole KFM02A. Forsmark site investigation, SKB P-reports – Report series from the site investigation 04-100. SKB P-04-100, Svensk Kärnbränslehantering AB.

/2/ **Klee G, Rummel F, 2004.** Rock stress measurements with hydraulic fracturing and hydraulic testing of pre-existing fractures in borehole KFM01A, KFM01B, KFM02A and KFM04A. Results of in-situ tests. Forsmark site investigation. SKB P-04-311, Svensk Kärnbränslehantering AB.

/3/ **Hurst W, Clark J D, Brauer E B, 1969.** The skin effect in producing wells. J. Pet. Tech. Nov.1969, pp.1,483–1,489.

/4/ **Hantush M S, 1959.** Nonsteady flow to flow wells in leaky aquifers, Journal of Geophysical Research, vol. 64, no. 5, pp. 1,043–1,052.

/5/ **Hantush, M S and C E Jacob, 1955.** Non-steady radial flow in an infinite leaky aquifer, Am. Geophys. Union Trans. vol. 36, pp. 95–100.

/6/ **Dougherty D E, Babu D K, 1984.** Flow to a partially penetrating well in a double-porosity reservoir. Water Resour. Res. 20 (8), 1,116–1,122.

/7/ **Almén K-E, Andersson J-E, Carlsson L, Hansson K, Larsson N-Å, 1986.** Hydraulic testing in crystalline rock. A comparative study of single-hole test methods. Technical Report 86-27, Svensk Kärnbränslehantering AB.

Appendix 1

File description table

Bh id	Testsection		Test type	Test no	Test start Date, time	Test stop Date, time	Data files of raw and primary data	Parameters in file	Comments
idcode	(m)	(m)	(1–6)*		YYYYMMDD hh:mm	YYYYMMDD hh:mm	__Borehole id_secup_date and time of test start		
KFM02A	146.00	151.00	3	1	20041019 10:08	20041019 12:57	__KFM02A_0146.00_200410191008.ht2	P,Q,Te	
KFM02A	211.00	216.00	3	1	20041019 13:47	20041019 15:16	__KFM02A_0211.00_200410191347.ht2	P,Q,Te	
KFM02A	471.00	476.00	3	1	20041019 17:25	20041019 18:39	__KFM02A_0471.00_200410191725.ht2	P,Q,Te	
KFM02A	516.00	521.00	3	1	20041019 19:08	20041019 20:23	__KFM02A_0516.00_200410191908.ht2	P,Q,Te	
KFM02A	551.00	556.00	3	1	20041020 08:46	20041020 10:01	__KFM02A_0551.00_200410200846.ht2	P,Q,Te	

[1)] Test type 3 equals to injection test

Appendix 2.1

General test data

Borehole:	KFM02A
Testtype:	CHir (Constant Head injection and recovery)
Field crew:	K. Gokall-Norman, T. Svensson, C. Hjerne and R. Nordqvist
General comment:	

Test section secup (m)	**Test section seclow (m)**	**Test start YYYYMMDD hh:mm**	**Start of flow period YYYYMMDD hh:mm:ss**	**Stop of flow period YYYYMMDD hh:mm:ss**	**Test stop YYYYMMDD hh:mm**	**Total flow time t_p (min)**	**Total recovery time t_F (min)**
146.00	151.00	20041019 10:08	20041019 11:17:41	20041019 11:38:03	20041019 12:57	1,222	4,445
211.00	216.00	20041019 13:47	20041019 14:33:33	20041019 14:53:55	20041019 15:16	1,222	1,203
471.00	476.00	20041019 17:25	20041019 17:57:12	20041019 18:17:34	20041019 18:39	1,222	1,210
516.00	521.00	20041019 19:08	20041019 19:41:19	20041019 20:01:42	20041019 20:23	1,223	1,211
551.00	556.00	20041020 08:46	20041020 09:19:04	20041020 09:39:26	20041020 10:01	1,222	1,221

Appendix 2.2

Pressure and flow data

Summary of pressure and flow data for all tests in KFM02A.

Test section secup (m)	seclow (m)	Pressure p_i (kPa)	p_p (kPa)	p_F (kPa)	Flow Q_p (m^3/s)	Q_m (m^3/s)	V_p (m^3)
146.00	151.00	1,488.67	1,703.34	1,555.74	2.200E–08	3.56E–08	4.35E–05
211.00	216.00	2,121.39	2,343.05	2,163.09	3.372E–08	4.69E–08	5.73E–05
471.00	476.00	4,689.05	4,912.34	4,693.98	9.489E–08	1.05E–07	1.29E–04
516.00	521.00	5,153.20	5,357.57	5,162.52	3.404E–08	3.83E–08	4.68E–05
551.00	556.00	5,510.36	5,707.27	5,650.27	8.987E–09	2.71E–08	3.31E–05

p_i Pressure in test section before start of flow period.

p_p Pressure in test section before stop of flow period.

p_F Pressure in test section at the end of recovery period.

Q_p Flow rate just before stop of flow period.

Q_m Mean (arithmetic) flow rate during flow period.

V_p Total volume injected during the flow period.

Appendix 3.1

Test diagrams – Injection tests conducted previous to hydraulic fracturing

In the following pages diagrams are presented for all test sections from test conducted in March 2004, previous to the hydraulic fracturing. A linear diagram of pressure and flow rate is presented for each test.

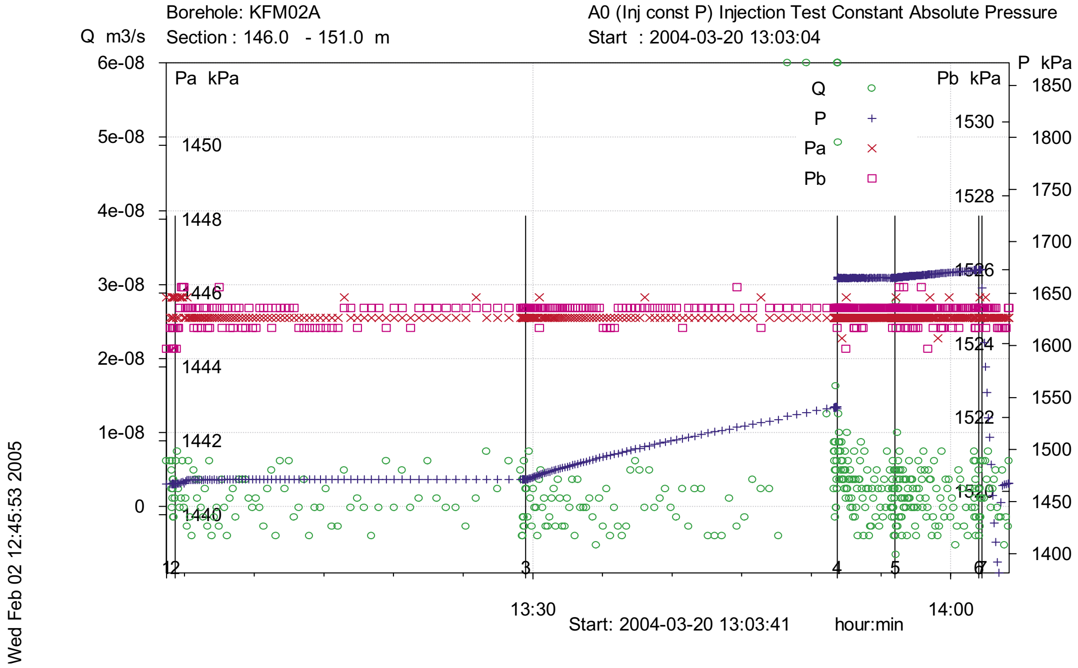


Figure A3-1. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the injection test conducted previous to hydraulic fracturing in section 146.0–151.0 m in borehole KFM02A.*

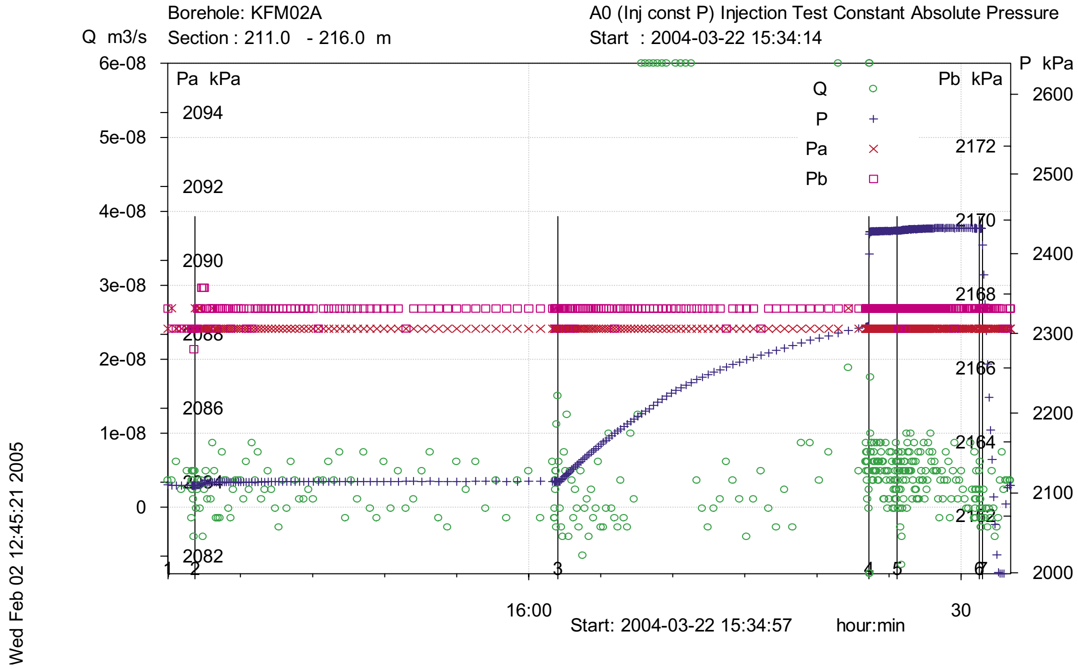


Figure A3-2. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the injection test conducted previous to hydraulic fracturing in section 211.0–216.0 m in borehole KFM02A.*

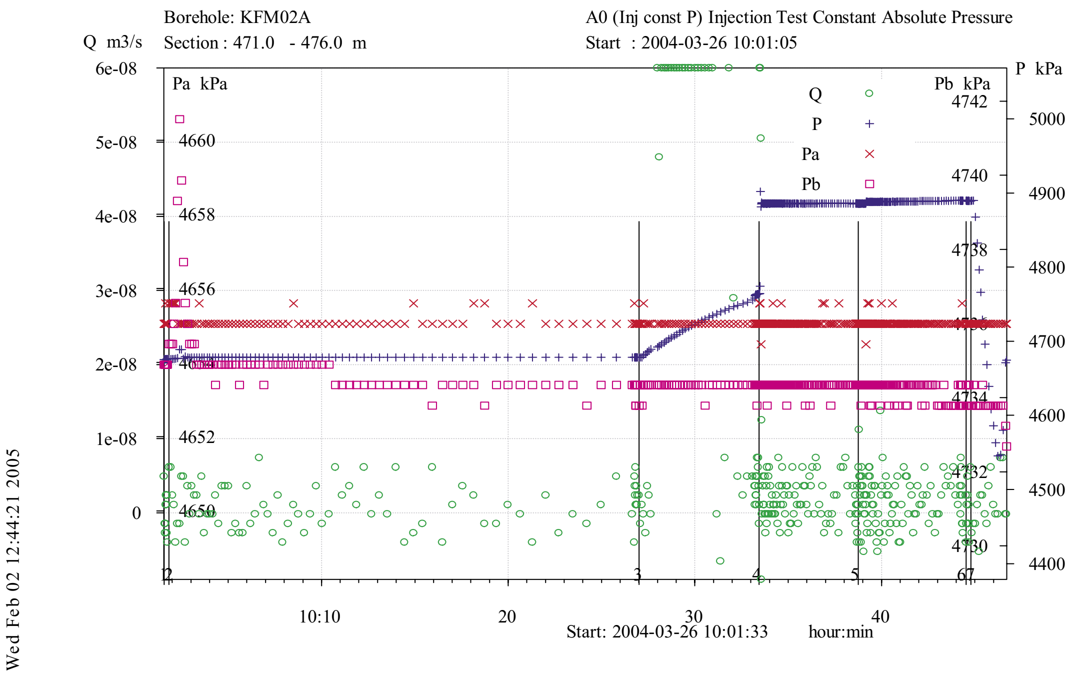


Figure A3-3. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the injection test conducted previous to hydraulic fracturing in section 471.0–476.0 m in borehole KFM02A.*

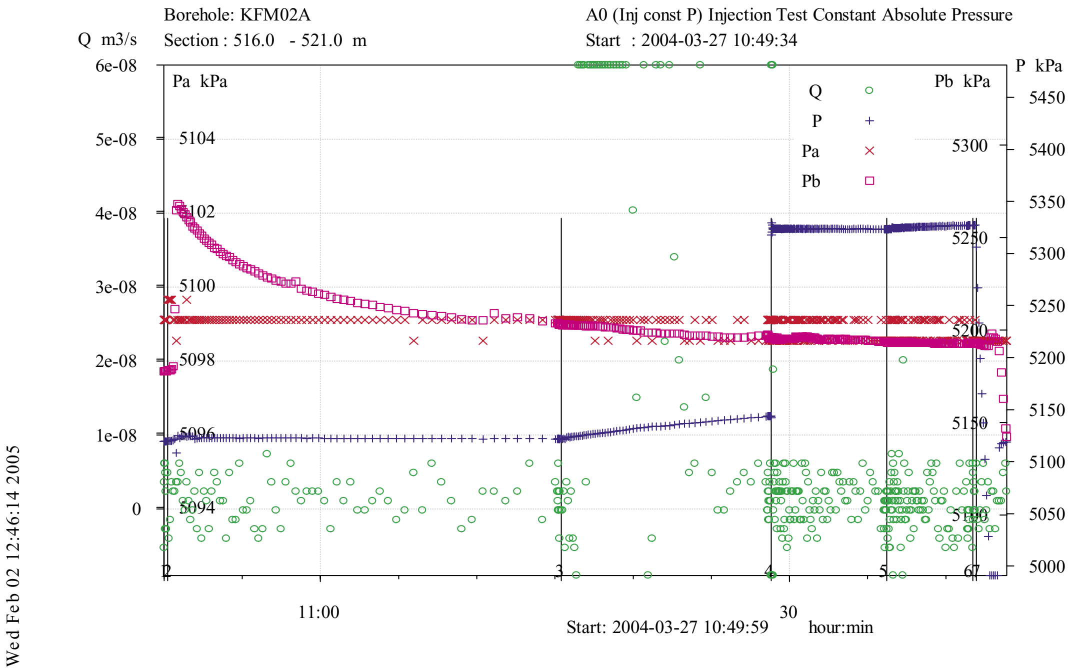


Figure A3-4. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the injection test conducted previous to hydraulic fracturing in section 516.0–521.0 m in borehole KFM02A.*

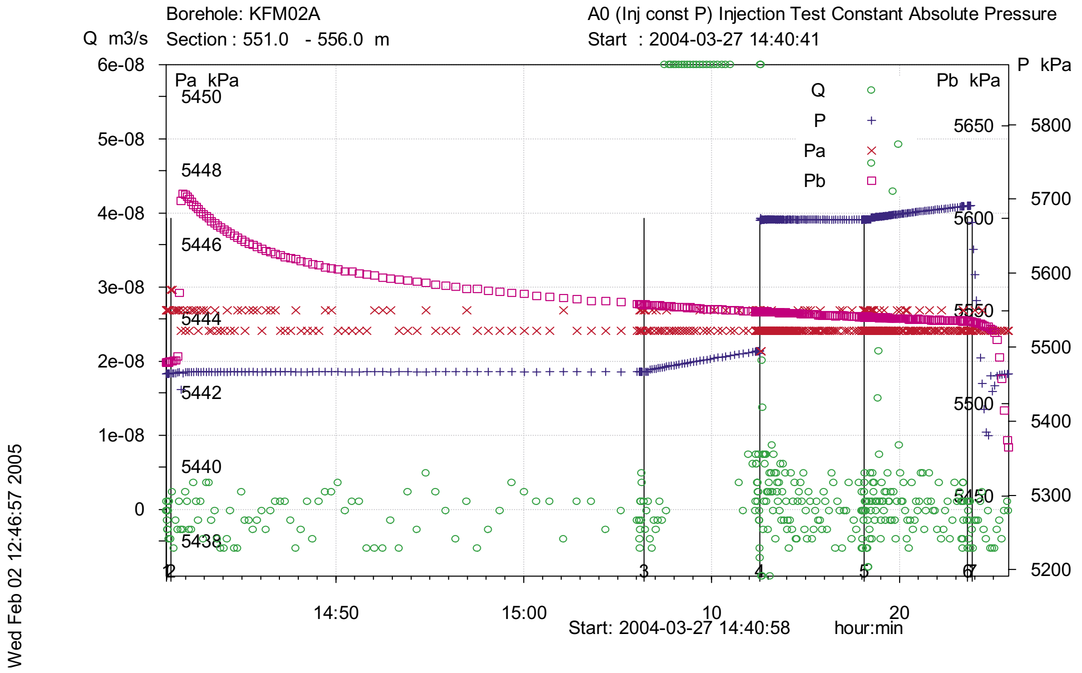


Figure A3-5. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the injection test conducted previous to hydraulic fracturing in section 551.0–556.0 m in borehole KFM02A.*

Appendix 3.2

Test diagrams – Injection tests, re-measurements

In the following pages diagrams are presented for all test sections. A linear diagram of pressure and flow rate is shown for each test. In addition lin-log and log-log diagrams are presented, from the injection and recovery period respectively.

Nomenclature for Aqtesolv:

T	= transmissivity (m^2/s)
S	= storativity (–)
K_Z/K_r	= ratio of hydraulic conductivities in the vertical and radial direction (set to 1)
Sw	= skin factor
r(w)	= borehole radius (m)
r(c)	= effective casing radius (m)

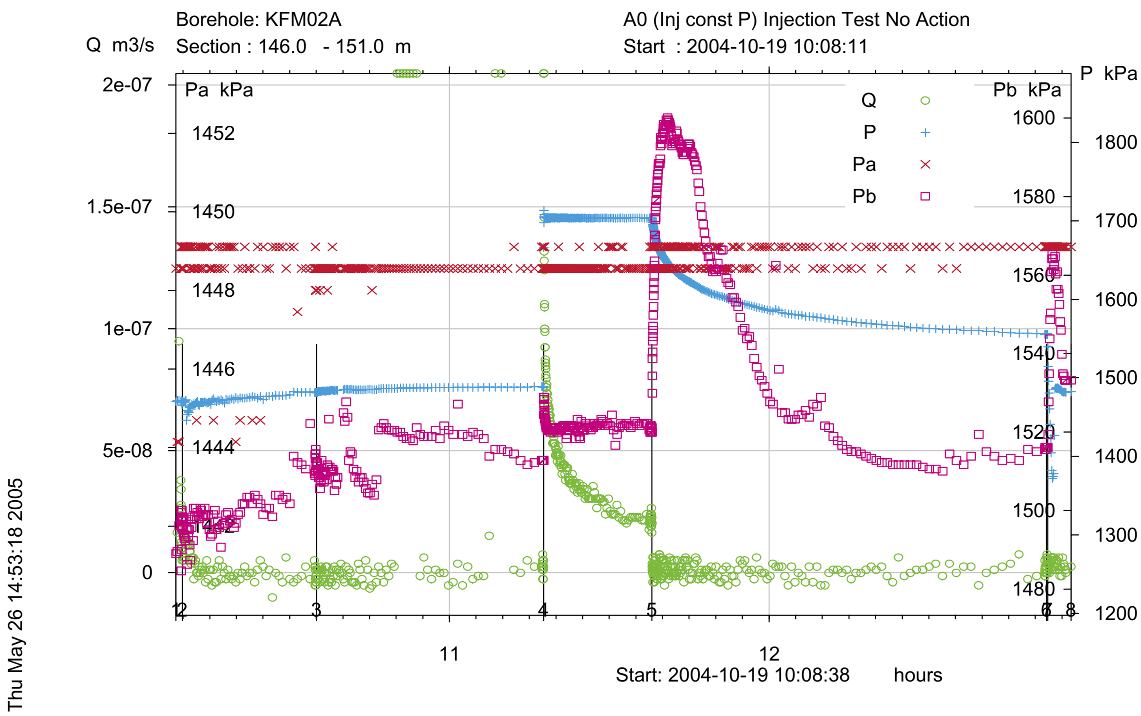


Figure A3-6. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the injection test in section 146.0–151.0 m in borehole KFM02A.*

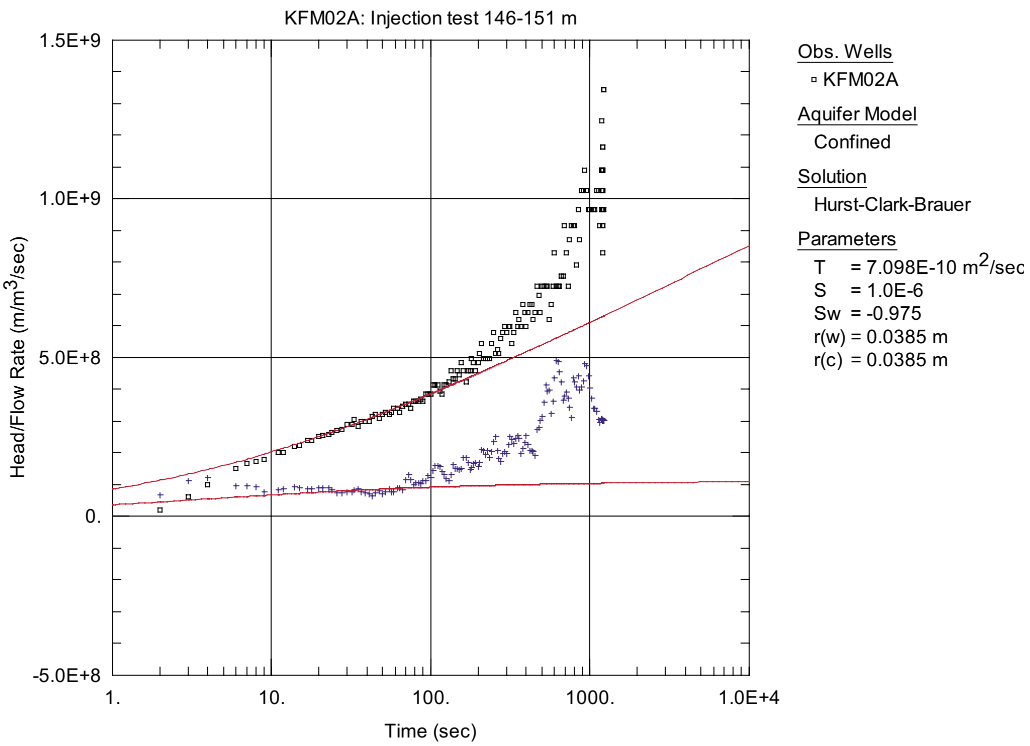


Figure A3-7. Lin-log plot of head/flow rate (□) and derivative (+) versus time, from the injection test in section 146.0–151.0 m in borehole KFM02A.

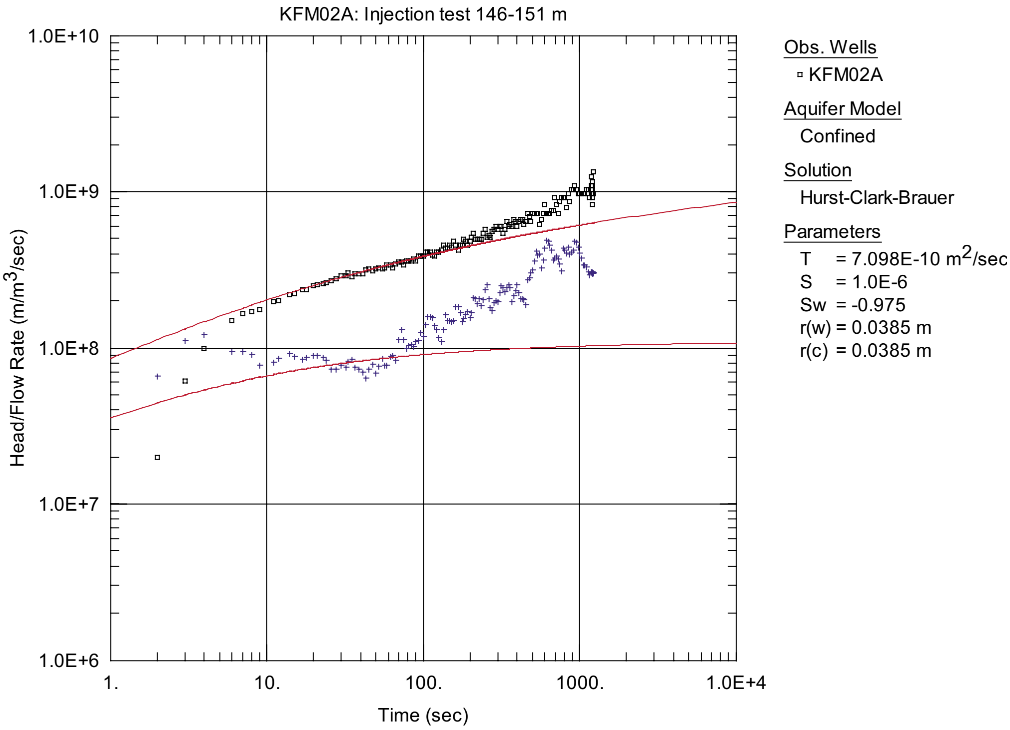


Figure A3-8. *Log-log plot of head/flow rate (□) and derivative (+) versus time, from the injection test in section 146.0–151.0 m in borehole KFM02A.*

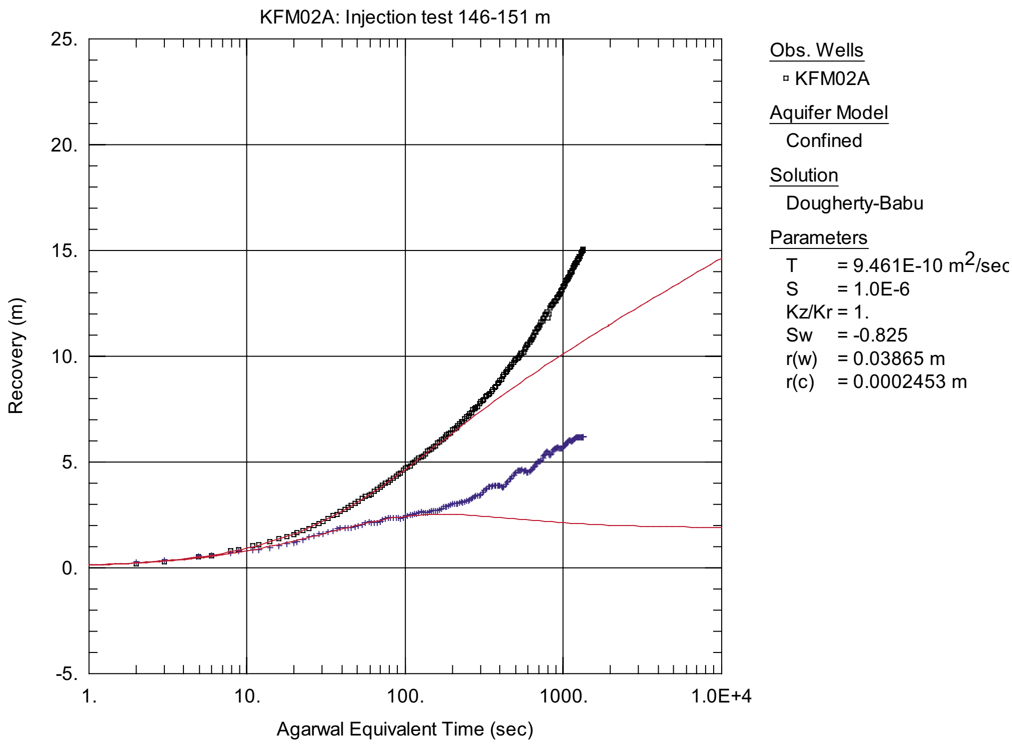


Figure A3-9. *Lin-log plot of recovery (□) and derivative (+) versus equivalent time, from the injection test in section 146.0–151.0 m in borehole KFM02A.*

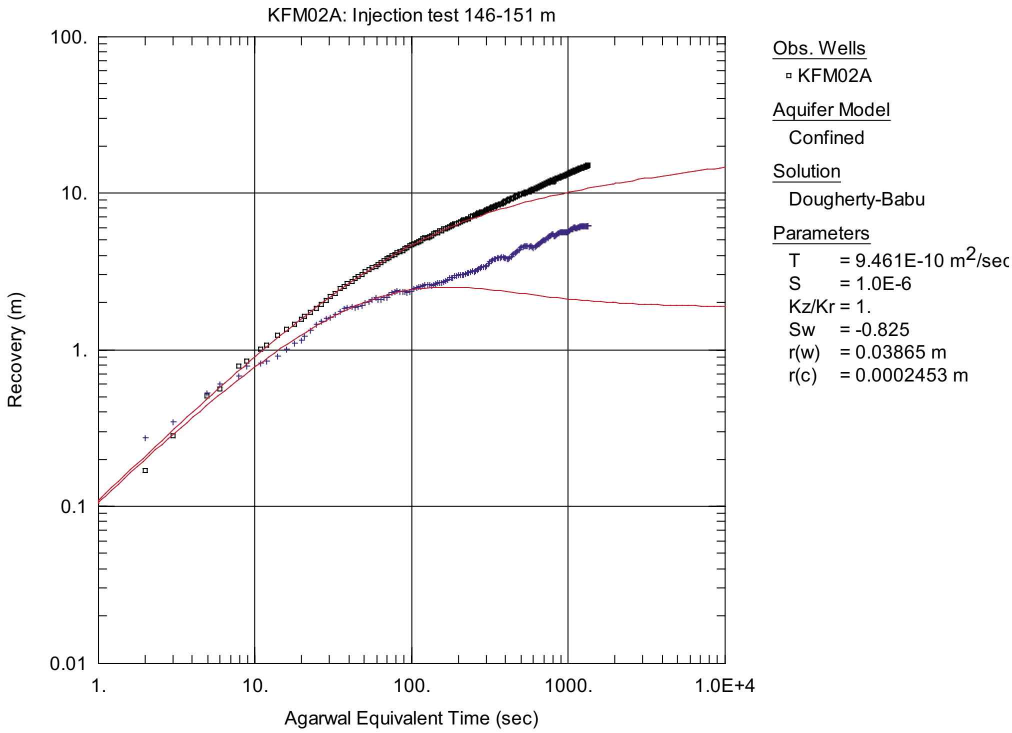


Figure A3-10. *Log-log plot of recovery (□) and derivative (+) versus equivalent time, from the injection test in section 146.0–151.0 m in borehole KFM02A.*

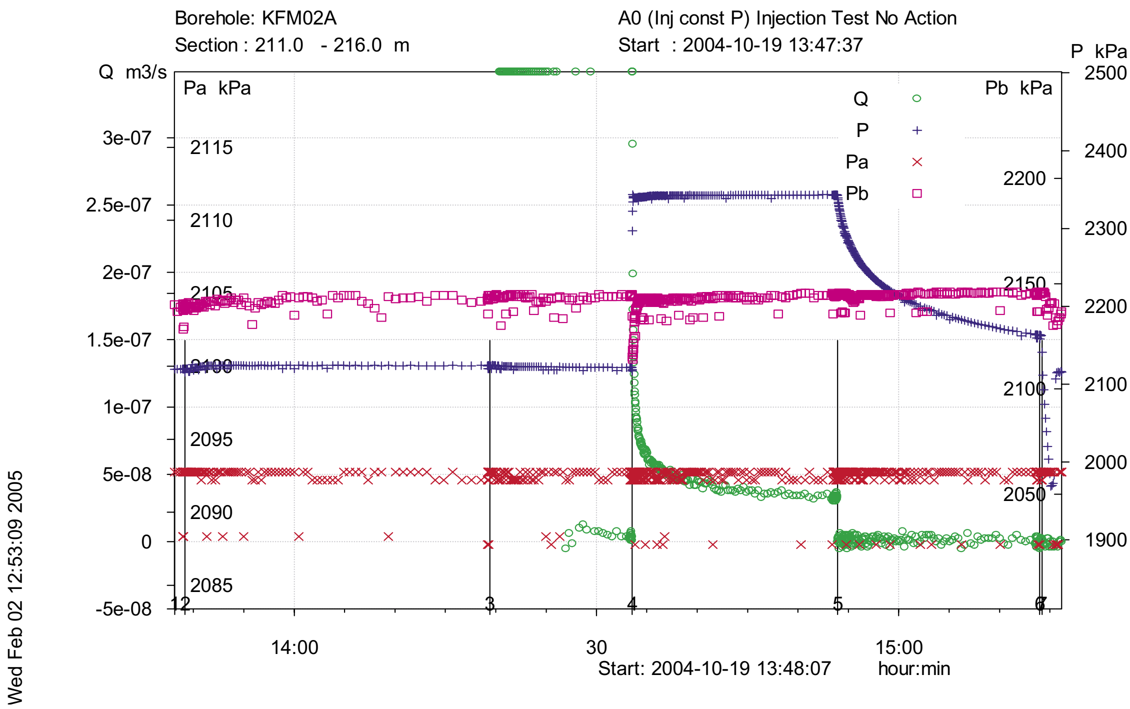


Figure A3-11. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the injection test in section 211.0–216.0 m in borehole KFM02A.*

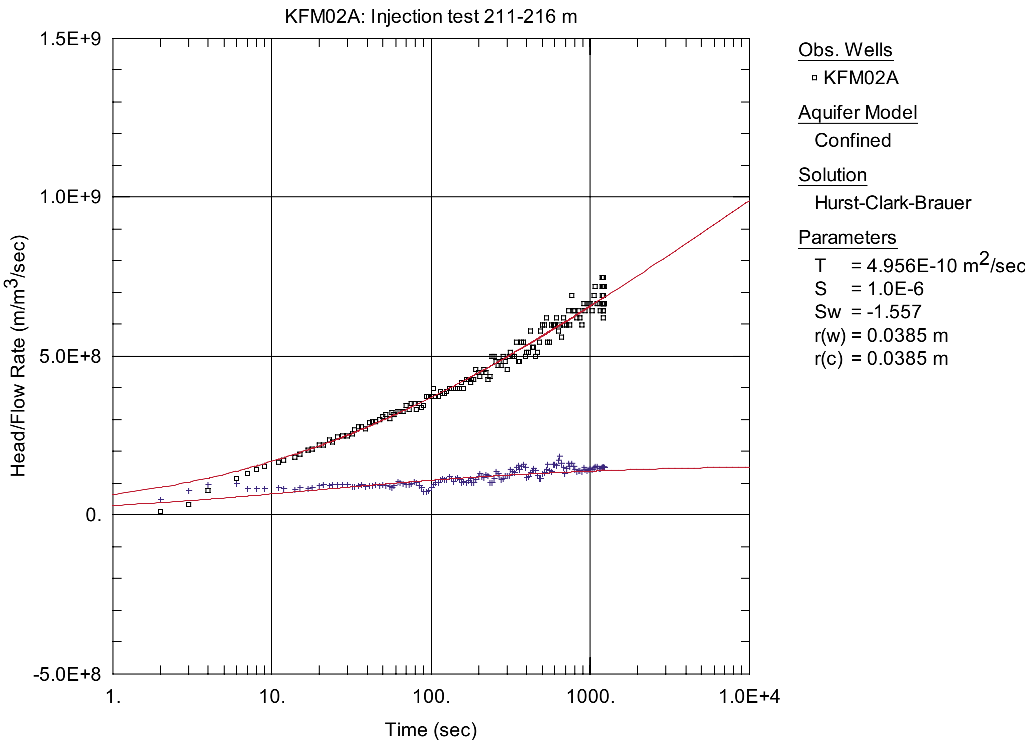


Figure A3-12. *Lin-log plot of head/flow rate (□) and derivative (+) versus time, from the injection test in section 211.0–216.0 m in borehole KFM02A.*

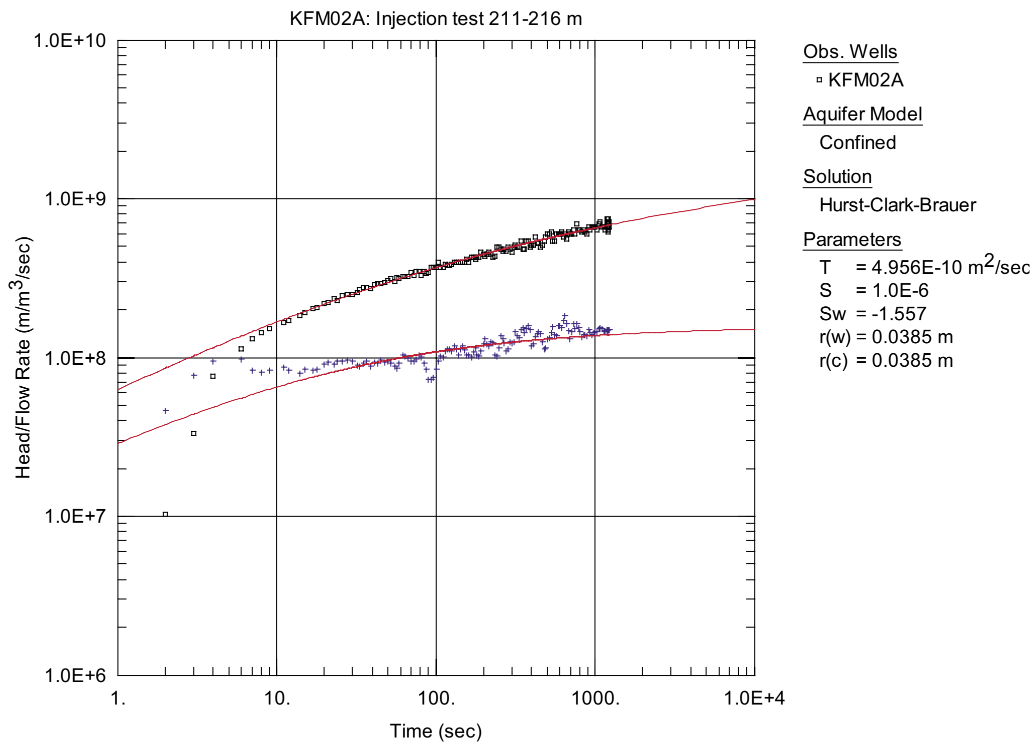


Figure A3-13. *Log-log plot of head/flow rate (□) and derivative (+) versus time, from the injection test in section 211.0–216.0 m in borehole KFM02A.*

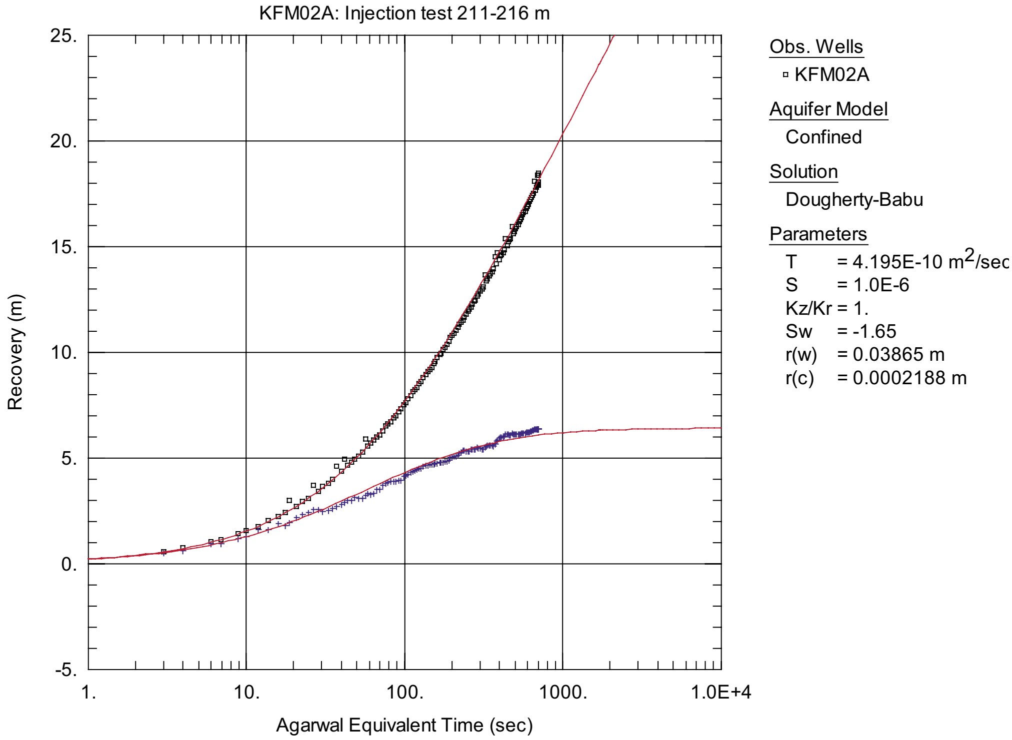


Figure A3-14. *Lin-log plot of recovery (□) and derivative (+) versus equivalent time, from the injection test in section 211.0–216.0 m in borehole KFM02A.*

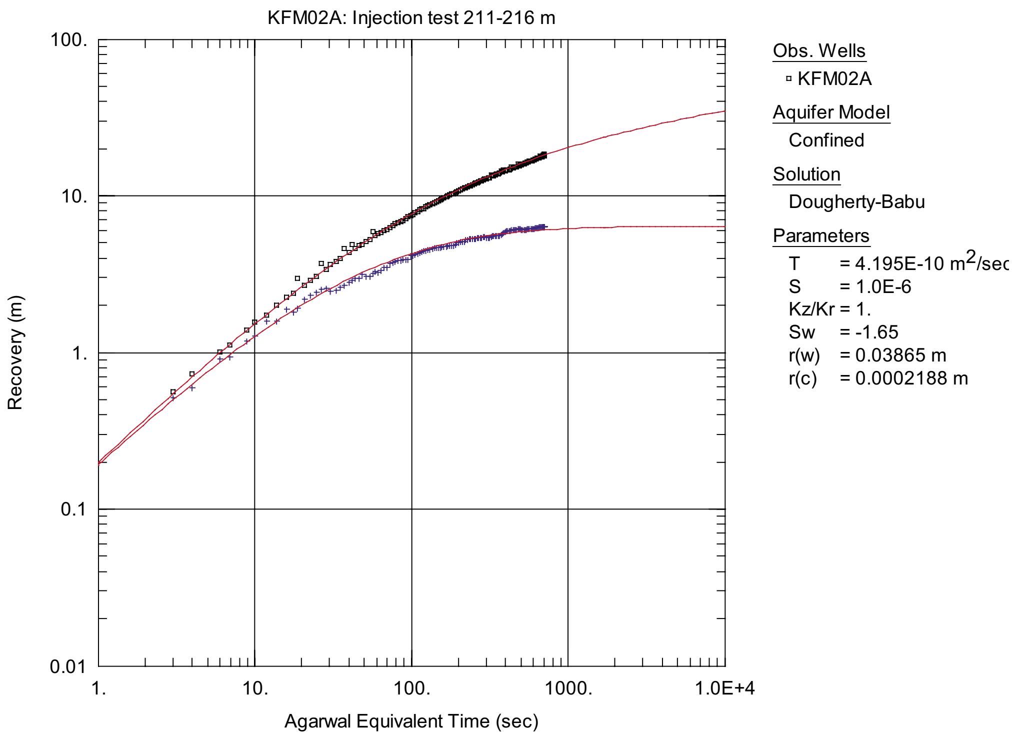


Figure A3-15. *Log-log plot of recovery (□) and derivative (+) versus equivalent time, from the injection test in section 211.0–216.0 m in borehole KFM02A.*

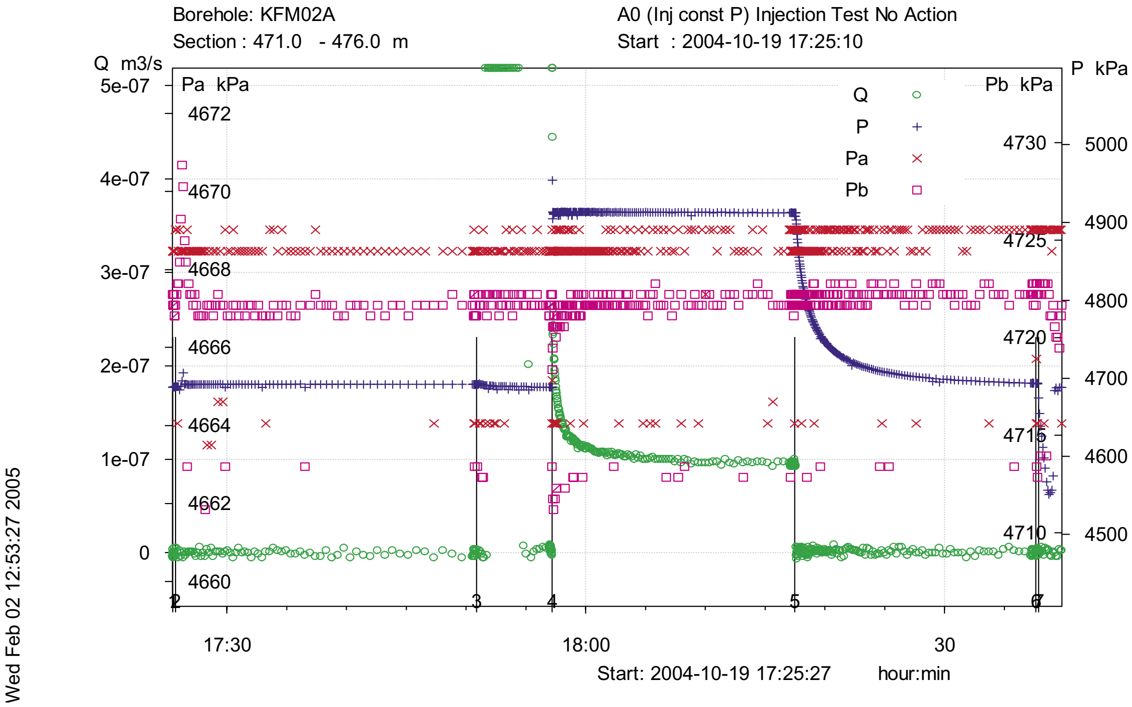


Figure A3-16. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the injection test in section 471.0–476.0 m in borehole KFM02A.*

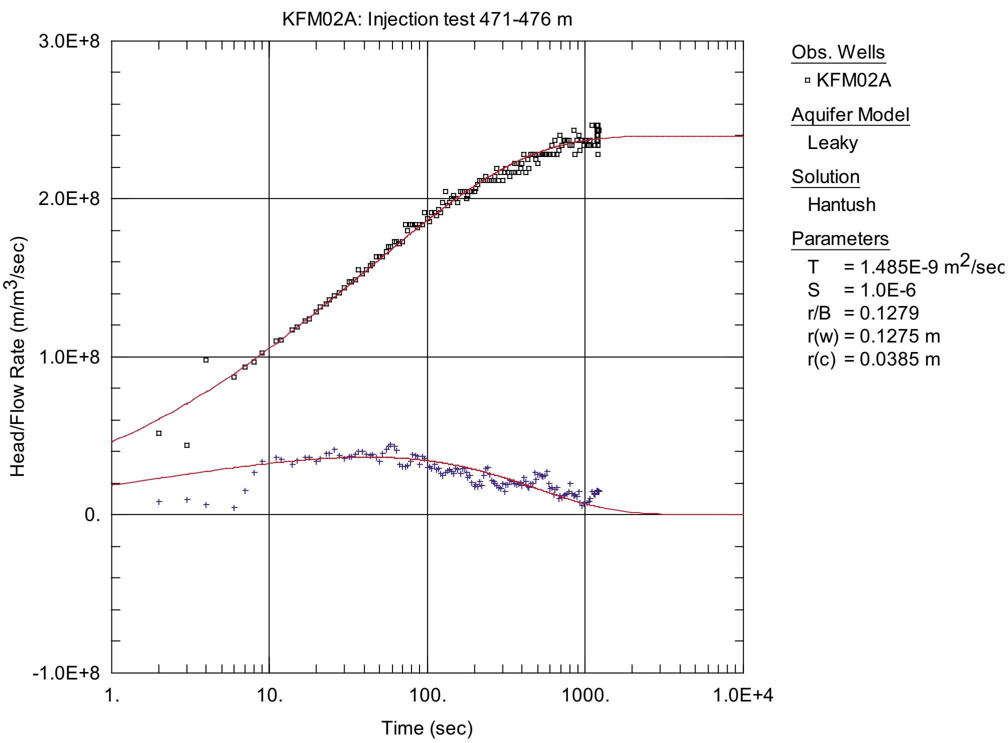


Figure A3-17. *Lin-log plot of head/flow rate (□) and derivative (+) versus time, from the injection test in section 471.0–476.0 m in borehole KFM02A.*

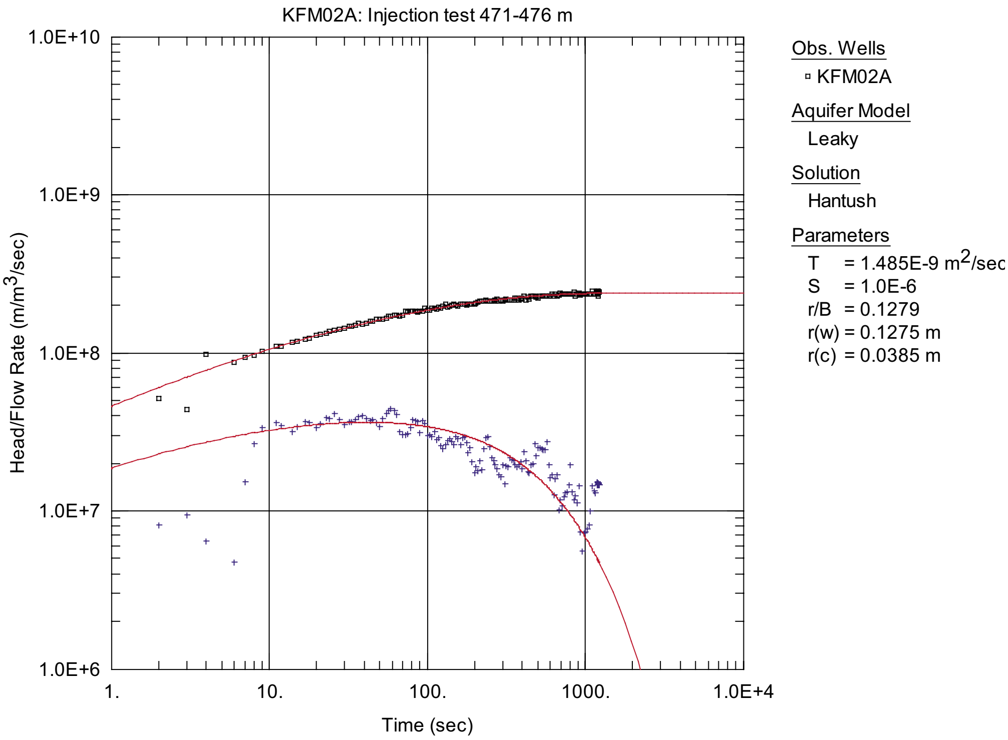


Figure A3-18. *Log-log plot of head/flow rate (□) and derivative (+) versus time, from the injection test in section 471.0–476.0 m in borehole KFM02A.*

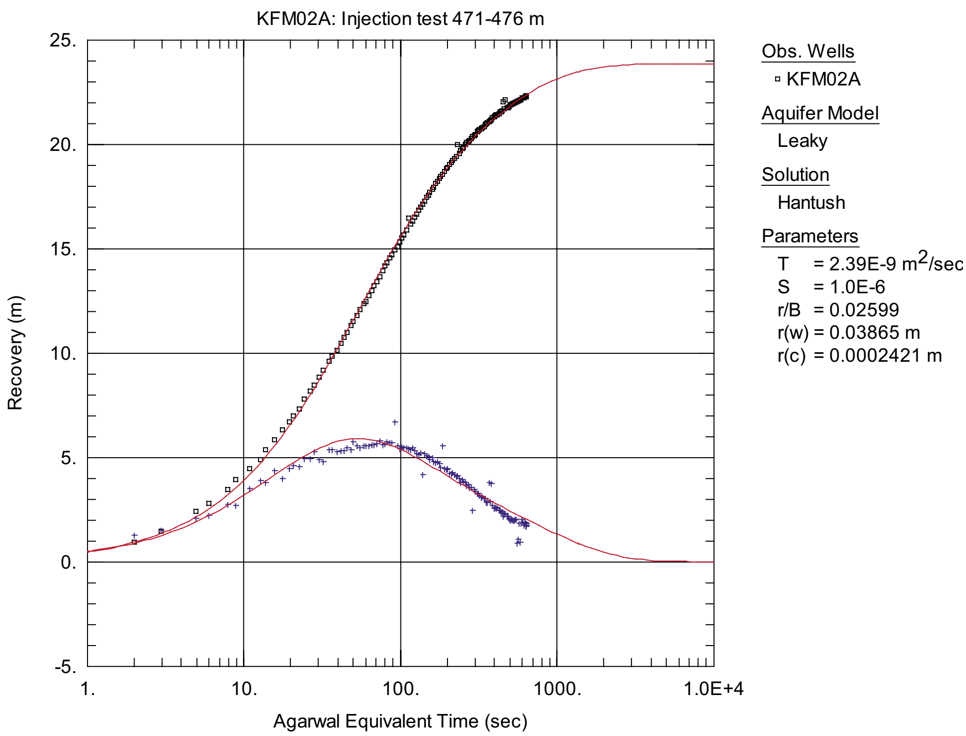


Figure A3-19. *Lin-log plot of recovery (□) and derivative (+) versus equivalent time, from the injection test in section 471.0–476.0 m in borehole KFM02A.*

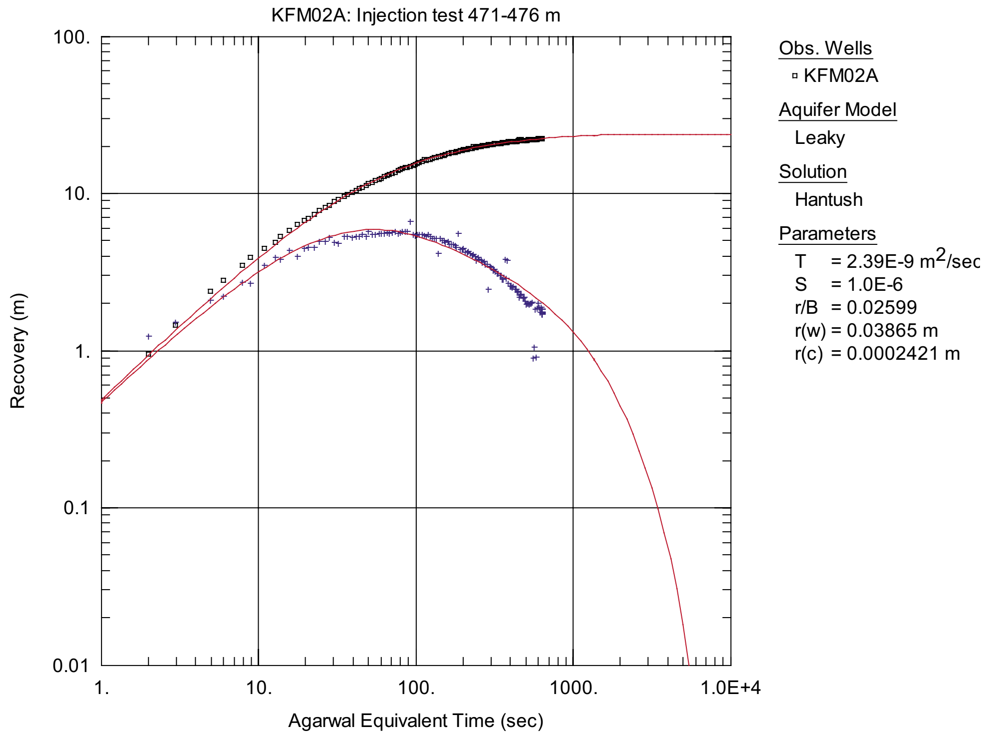


Figure A3-20. *Log-log plot of recovery (□) and derivative (+) versus equivalent time, from the injection test in section 471.0–476.0 m in borehole KFM02A.*

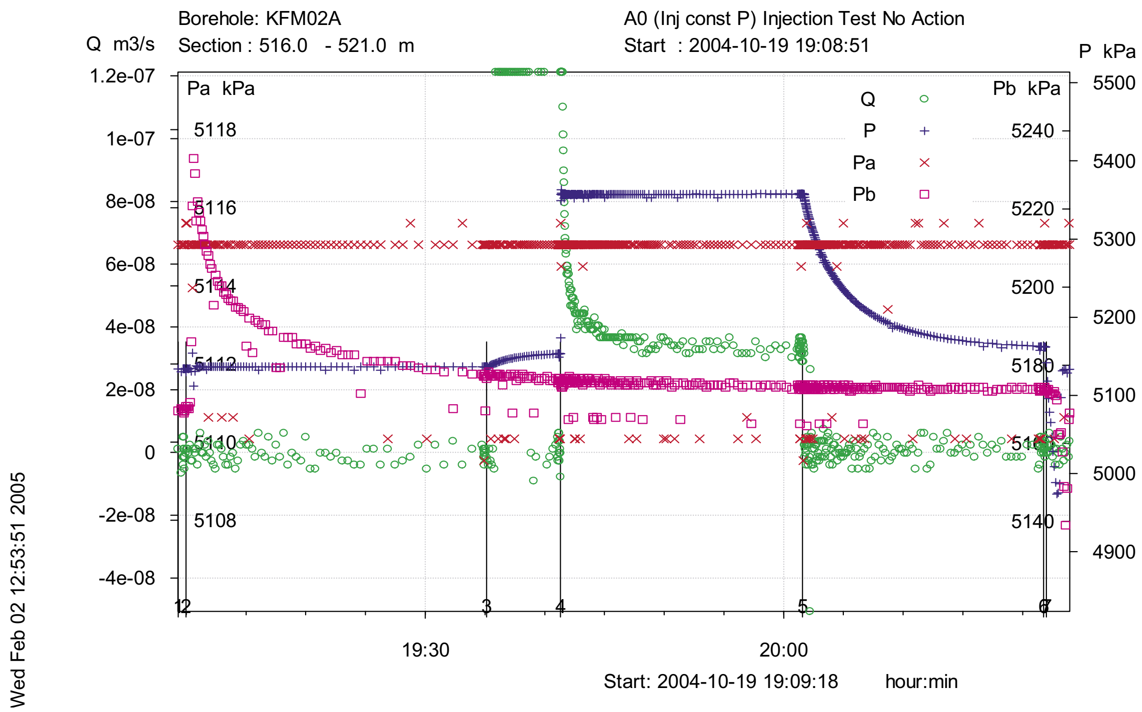


Figure A3-21. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the injection test in section 516.0–521.0 m in borehole KFM02A.*

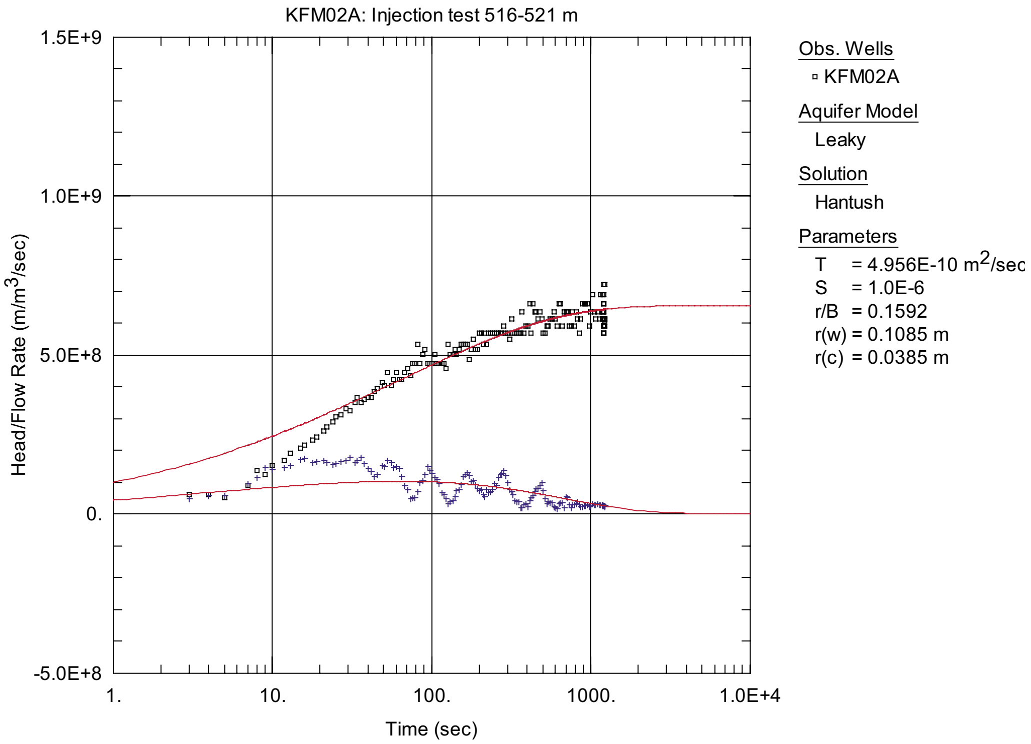


Figure A3-22. *Lin-log plot of head/flow rate (□) and derivative (+) versus time, from the injection test in section 516.0–521.0 m in borehole KFM02A.*

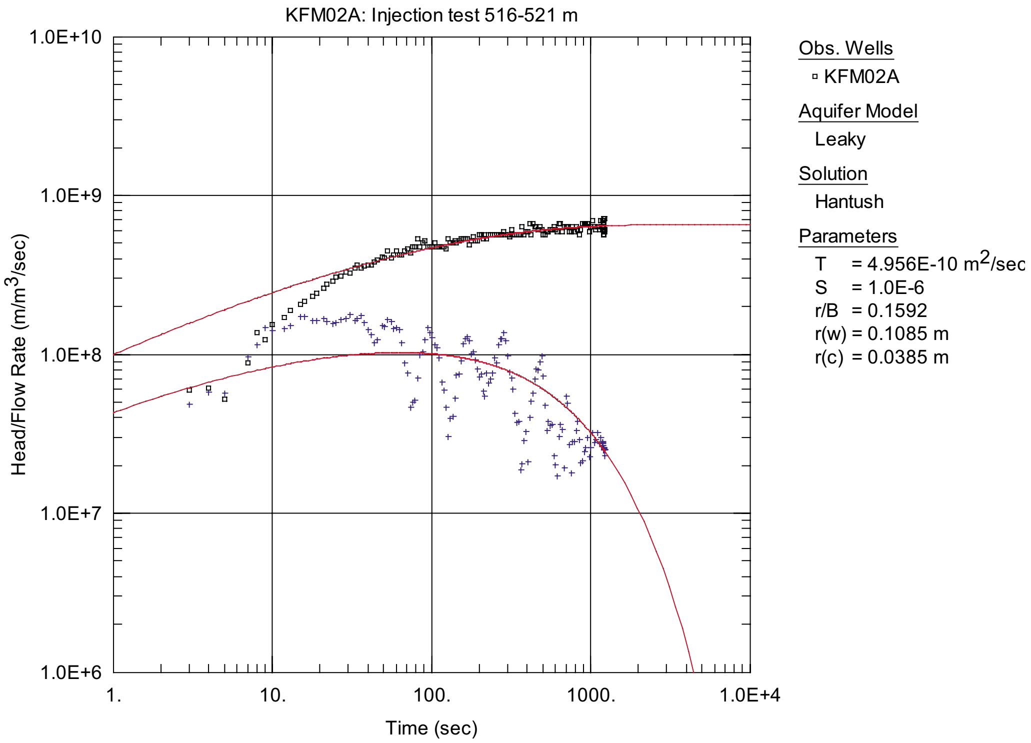


Figure A3-2-23. *Log-log plot of head/flow rate (□) and derivative (+) versus time, from the injection test in section 516.0–521.0 m in borehole KFM02A.*

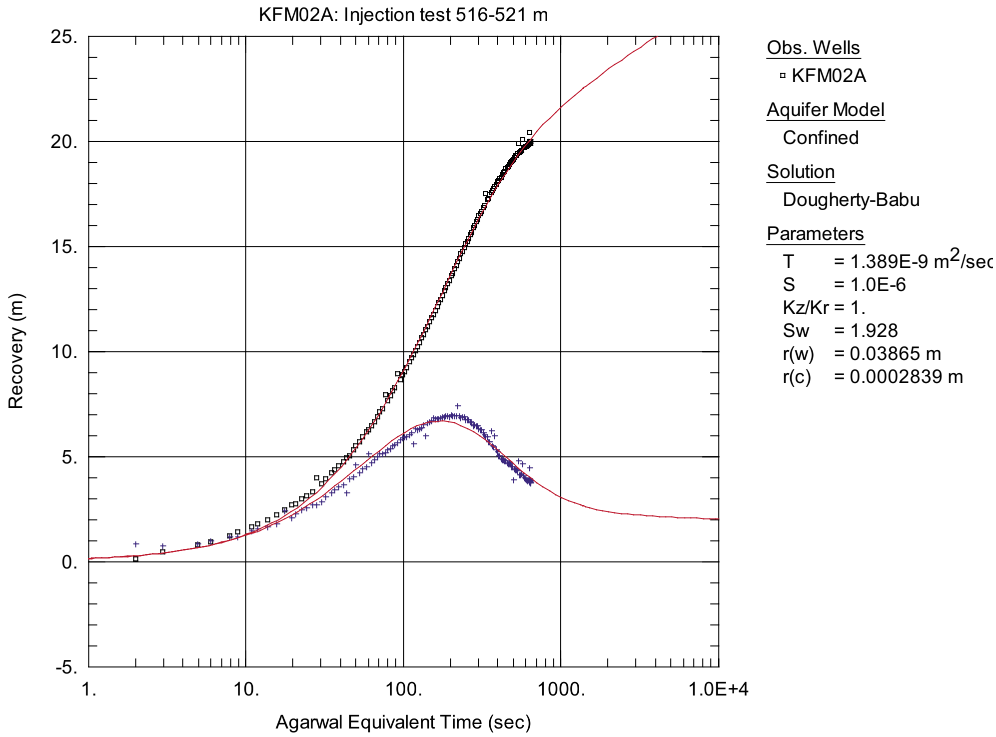


Figure A3-24. *Lin-log plot of recovery (□) and derivative (+) versus equivalent time, from the injection test in section 516.0–521.0 m in borehole KFM02A.*

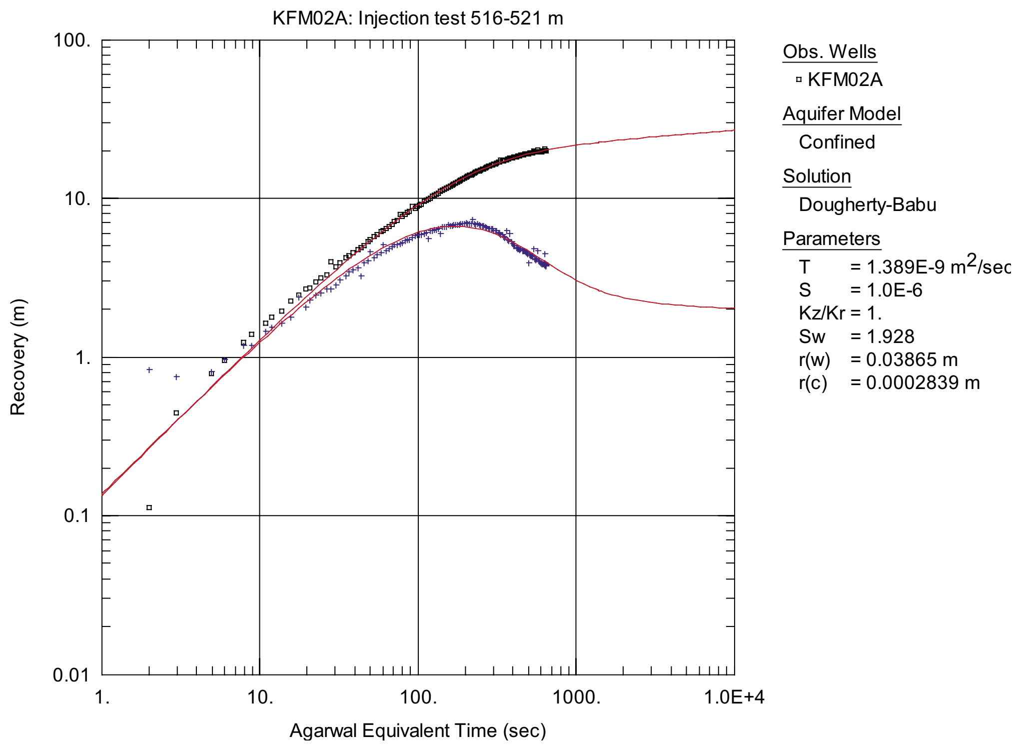


Figure A3-2-25. *Log-log plot of recovery (□) and derivative (+) versus equivalent time, from the injection test in section 516.0–521.0 m in borehole KFM02A.*

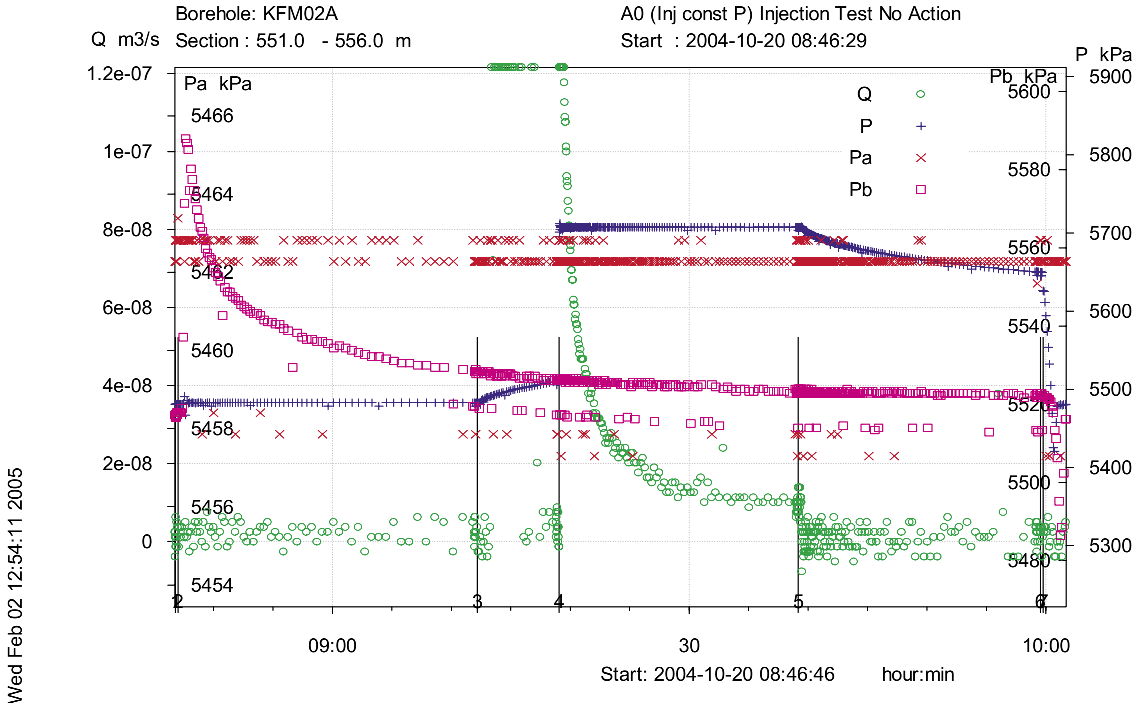


Figure A3-26. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the injection test in section 551.0–556.0 m in borehole KFM02A.*

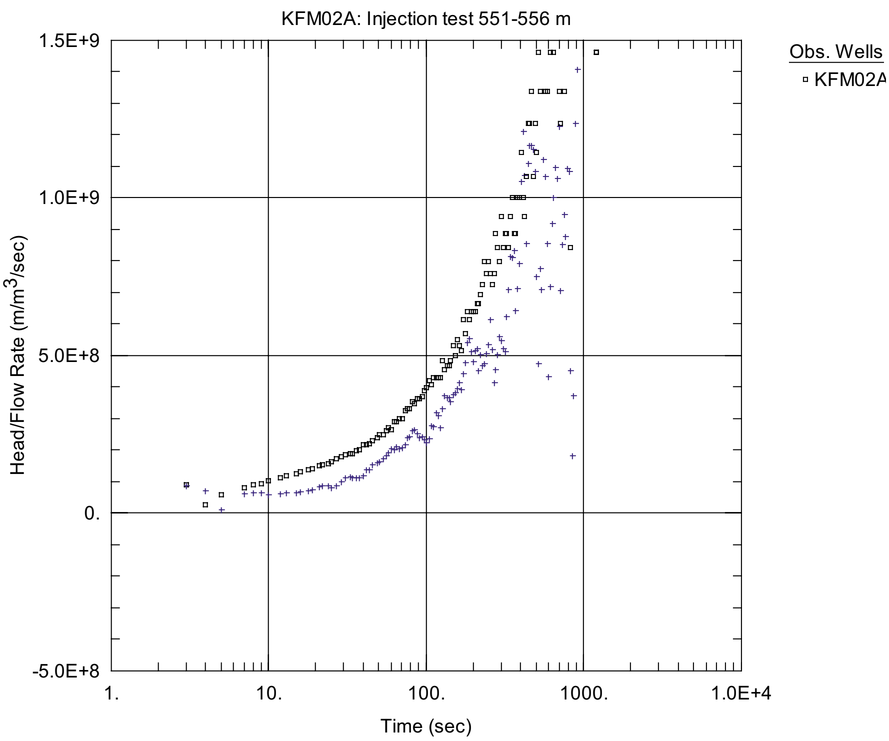


Figure A3-27. *Lin-log plot of head/flow rate (□) and derivative (+) versus time, from the injection test in section 551.0–556.0 m in borehole KFM02A.*

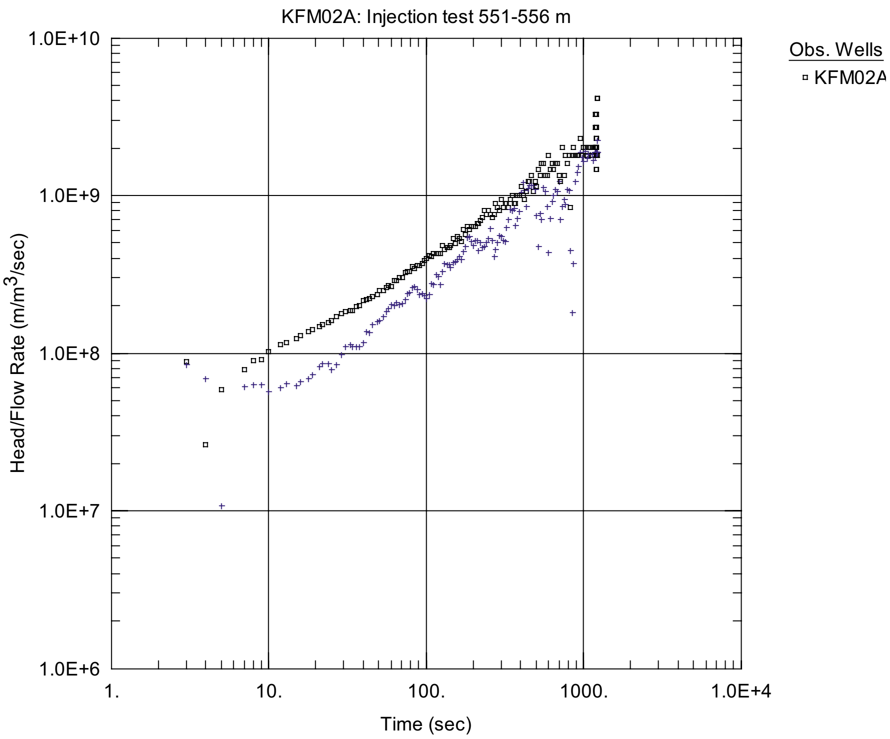


Figure A3-28. *Log-log plot of head/flow rate (□) and derivative (+) versus time, from the injection test in section 551.0–556.0 m in borehole KFM02A.*

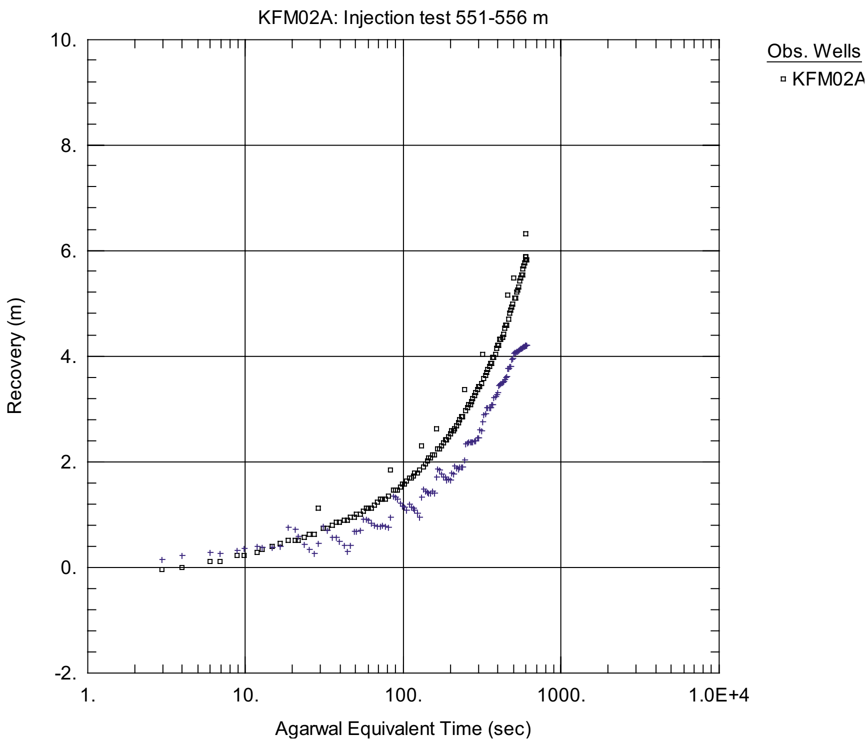


Figure A3-29. *Lin-log plot of recovery (□) and derivative (+) versus equivalent time, from the injection test in section 551.0–556.0 m in borehole KFM02A.*

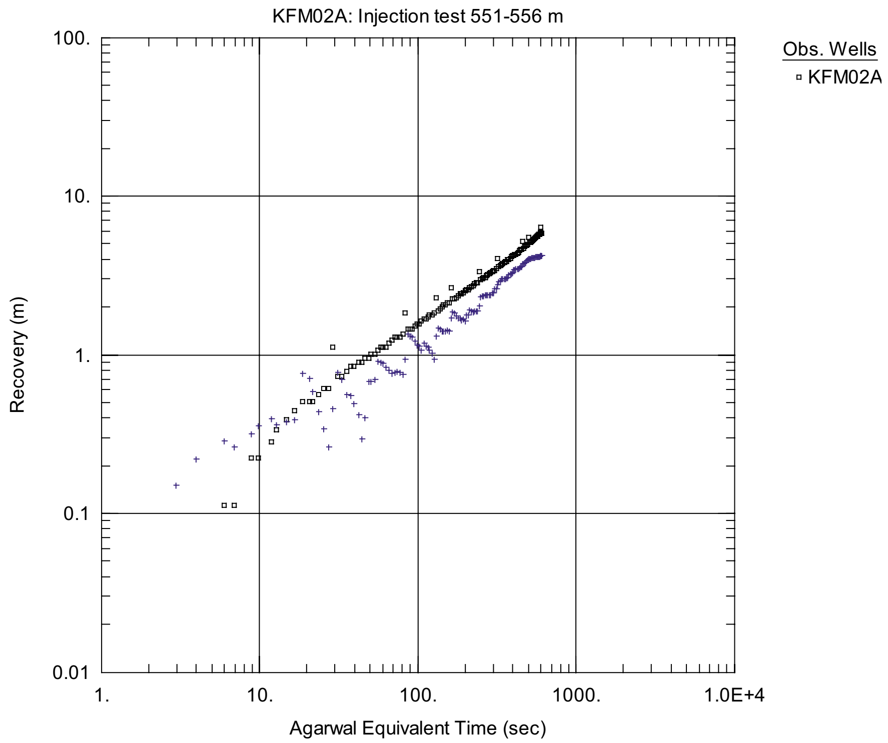
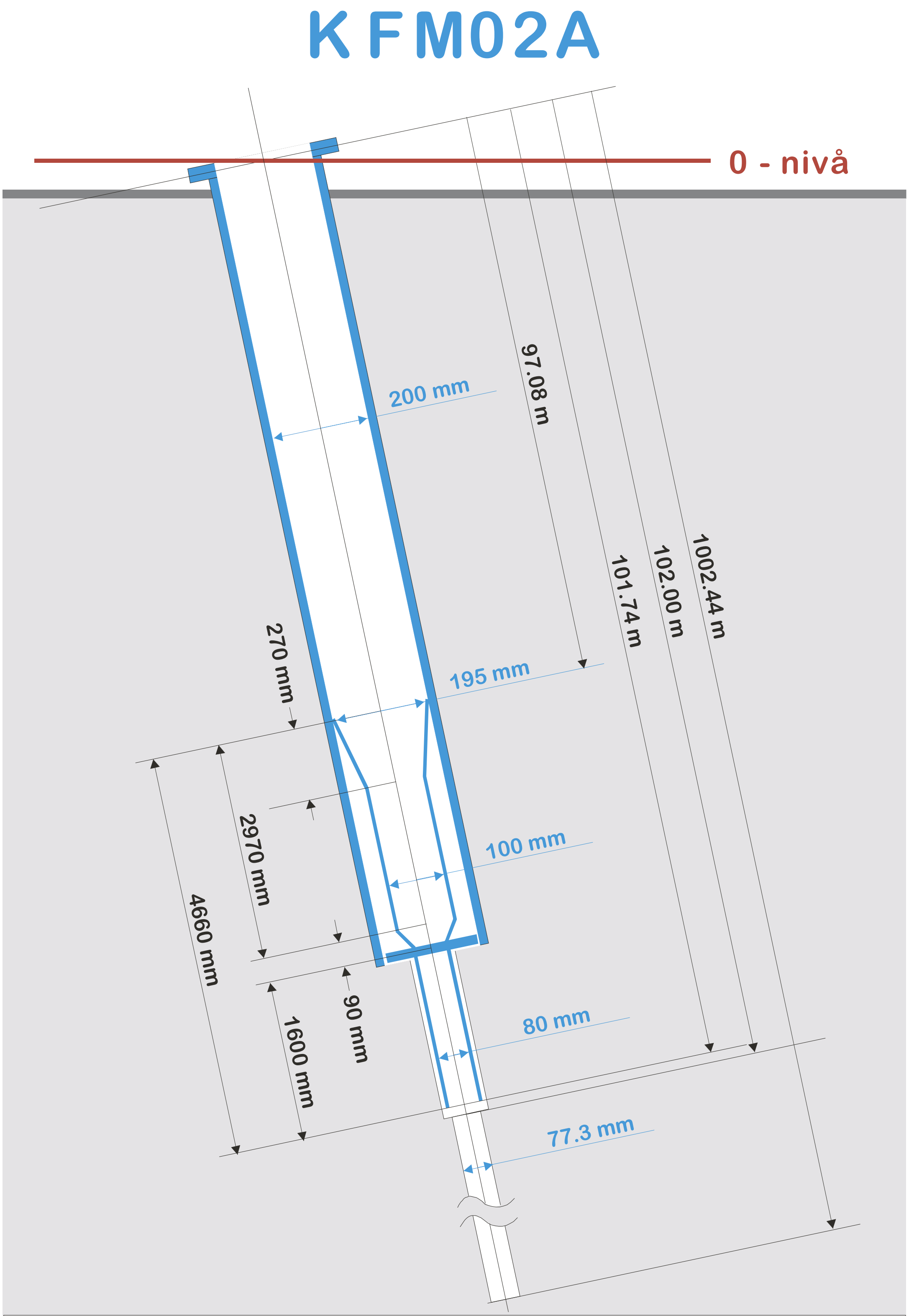


Figure A3-30. *Log-log plot of recovery (□) and derivative (+) versus equivalent time, from the injection test in section 551.0–556.0 m in borehole KFM02A.*

Borehole technical data



Drilling period
Drilling start date: 2002-11-20
Drilling stop date: 2003-03-26

Drilling reference point
Northing: 6698712.51 (m), RT90 2,5 gon V 0:-15
Easting: 1633182.86 (m), RT90 2,5 gon V 0:-15
Elevation: 7.353 (m), RHB 70

Appendix 5

Sicada tables

Nomenclature plu_s_hole_test_d.

Column	Datatype	Unit	Column Description	Alt. Symbol
site	CHAR		Investigation site name	
activity_type	CHAR		Activity type code	
start_date	DATE		Date (yymmdd hh:mm:ss)	
stop_date	DATE		Date (yymmdd hh:mm:ss)	
project	CHAR		Project code	
idcode	CHAR		Object or borehole identification code	
secup	FLOAT	m	Upper section limit (m)	
seclow	FLOAT	m	Lower section limit (m)	
section_no	INTEGER	number	Section number	
test_type	CHAR		Test type code (1–7), see table description	
formation_type	CHAR		1: Rock, 2: Soil (superficial deposits)	
start_flow_period	DATE	yyyymmdd	Date & time of pumping/injection start (YYYY-MM-DD hh:mm:ss)	
stop_flow_period	DATE	yyyymmdd	Date & time of pumping/injection stop (YYYY-MM-DD hh:mm:ss)	
flow_rate_end_qp	FLOAT	m**3/s	Flow rate at the end of the flowing period	
value_type_qp	CHAR		0:true value,–1<lower meas.limit1:>upper meas.limit	
mean_flow_rate_qm	FLOAT	m**3/s	Arithmetic mean flow rate during flow period	
q_measl__l	FLOAT	m**3/s	Estimated lower measurement limit of flow rate	Q-measl-L
q_measl__u	FLOAT	m**3/s	Estimated upper measurement limit of flow rate	Q-measl-U
tot_volume_vp	FLOAT	m**3	Total volume of pumped(positive) or injected(negative) water	
dur_flow_phase_tp	FLOAT	s	Duration of the flowing period of the test	
dur_rec_phase_tf	FLOAT	s	Duration of the recovery period of the test	
initial_head_hi	FLOAT	m	Hydraulic head in test section at start of the flow period	
head_at_flow_end_hp	FLOAT	m	Hydraulic head in test section at stop of the flow period.	
final_head_hf	FLOAT	m	Hydraulic head in test section at stop of recovery period.	
initial_press_pi	FLOAT	kPa	Groundwater pressure in test section at start of flow period	
press_at_flow_end_pp	FLOAT	kPa	Groundwater pressure in test section at stop of flow period.	
final_press_pf	FLOAT	kPa	Ground water pressure at the end of the recovery period.	
fluid_temp_tew	FLOAT	oC	Measured section fluid temperature, see table description	
fluid_elcond_ecw	FLOAT	mS/m	Measured section fluid el. conductivity,see table descr.	
fluid_salinity_tdsw	FLOAT	mg/l	Total salinity of section fluid based on EC,see table descr.	
fluid_salinity_tdswm	FLOAT	mg/l	Tot. section fluid salinity based on water sampling,see...	
reference	CHAR		SKB report No for reports describing data and evaluation	
comments	VARCHAR		Short comment to data	
error_flag	CHAR		If error_flag = “*” then an error occured and an error	
in_use	CHAR		If in_use = “*” then the activity has been selected as	
sign	CHAR		Signature for QA data accknowledge (QA - OK)	
lp	FLOAT	m	Hydraulic point of application	

Nomenclature plu_s_hole_test_ed1.

Column	Datatype	Unit	Column Description	Alt. Symbol
site	CHAR		Investigation site name	
activity_type	CHAR		Activity type code	
start_date	DATE		Date (yymmdd hh:mm:ss)	
stop_date	DATE		Date (yymmdd hh:mm:ss)	
project	CHAR		Project code	
idcode	CHAR		Object or borehole identification code	
secup	FLOAT	m	Upper section limit (m)	
seclow	FLOAT	m	Lower section limit (m)	
section_no	INTEGER	number	Section number	
test_type	CHAR		Test type code (1–7), see table description!	
formation_type	CHAR		Formation type code. 1: Rock, 2: Soil (superficial deposits)	
lp	FLOAT	m	Hydraulic point of application for test section, see descr.	
seclen_class	FLOAT	m	Planned ordinary test interval during test campaign.	
spec_capacity_q_s	FLOAT	m**2/s	Specific capacity (Q/s) of test section, see table descript.	Q/s
value_type_q_s	CHAR		0:true value,–1:Q/s<lower meas.limit,1:Q/s>upper meas.limit	
transmissivity_tq	FLOAT	m**2/s	Tranmissivity based on Q/s, see table description	
value_type_tq	CHAR		0:true value,–1:TQ<lower meas.limit,1:TQ>upper meas.limit.	
bc_tq	CHAR		Best choice code. 1 means TQ is best choice of T, else 0	
transmissivity_moye	FLOAT	m**2/s	Transmissivity,TM, based on Moye (1967)	T_M
bc_tm	CHAR		Best choice code. 1 means Tmoye is best choice of T, else 0	
value_type_tm	CHAR		0:true value,–1:TM<lower meas.limit,1:TM>upper meas.limit.	
hydr_cond_moye	FLOAT	m/s	K_M: Hydraulic conductivity based on Moye (1967)	K_M
formation_width_b	FLOAT	m	b:Aquifer thickness repr. for T(generally b = Lw) ,see descr.	b
width_of_channel_b	FLOAT	m	B:Inferred width of formation for evaluated TB	
tb	FLOAT	m**3/s	TB:Flow capacity in 1D formation of T & width B, see descr.	
l_measl_tb	FLOAT	m**3/s	Estimated lower meas. limit for evaluated TB,see description	
u_measl_tb	FLOAT	m**3/s	Estimated upper meas. limit of evaluated TB,see description	
sb	FLOAT	m	SB:S = storativity,B = width of formation,1D model,see descript.	
assumed_sb	FLOAT	m	SB* : Assumed SB,S = storativity,B = width of formation,see...	
leakage_factor_lf	FLOAT	m	Lf:1D model for evaluation of Leakage factor	
transmissivity_tt	FLOAT	m**2/s	TT:Transmissivity of formation, 2D radial flow model,see...	T_T
value_type_tt	CHAR		0:true value,–1:TT<lower meas.limit,1:TT>upper meas.limit,	
bc_tt	CHAR		Best choice code. 1 means TT is best choice of T, else 0	
l_measl_q_s	FLOAT	m**2/s	Estimated lower meas. limit for evaluated TT,see table descr	Q/s-measl-L
u_measl_q_s	FLOAT	m**2/s	Estimated upper meas. limit for evaluated TT,see description	Q/s-measl-U
storativity_s	FLOAT		S:Storativity of formation based on 2D rad flow,see descr.	
assumed_s	FLOAT		Assumed Storativity,2D model evaluation,see table descr.	
leakage_coeff	FLOAT	1/s	K'/b':2D rad flow model evaluation of leakage coeff,see desc	
hydr_cond_ksf	FLOAT	m/s	Ksf:3D model evaluation of hydraulic conductivity,see desc.	
value_type_ksf	CHAR		0:true value,–1:Ksf<lower meas.limit,1:Ksf>upper meas.limit,	
l_measl_ksf	FLOAT	m/s	Estimated lower meas.limit for evaluated Ksf,see table desc.	
u_measl_ksf	FLOAT	m/s	Estimated upper meas.limit for evaluated Ksf,see table descr	
spec_storage_ssf	FLOAT	1/m	Ssf:Specific storage,3D model evaluation,see table descr.	
assumed_ssf	FLOAT	1/m	Ssf*:Assumed Spec.storage,3D model evaluation,see table des.	
c	FLOAT	m**3/pa	C: Wellbore storage coefficient; flow or recovery period	C
cd	FLOAT		CD: Dimensionless wellbore storage coefficient	

Column	Datatype	Unit	Column Description	Alt. Symbol
skin	FLOAT		Skin factor;best estimate of flow/recovery period,see descr.	ξ
dt1	FLOAT	s	Estimated start time of evaluation, see table description	dt_1
dt2	FLOAT	s	Estimated stop time of evaluation. see table description	dt_2
t1	FLOAT	s	Start time for evaluated parameter from start flow period	
t2	FLOAT	s	Stop time for evaluated parameter from start of flow period	
dte1	FLOAT	s	Start time for evaluated parameter from start of recovery	
dte2	FLOAT	s	Stop time for evaluated parameter from start of recovery	
p_horner	FLOAT	kPa	p*:Horner extrapolated pressure, see table description	
transmissivity_t_nlr	FLOAT	m**2/s	T_NLR Transmissivity based on None Linear Regression...	
storativity_s_nlr	FLOAT		S_NLR = storativity based on None Linear Regression,see..	
value_type_t_nlr	CHAR		0:true value,–1:T_NLR<lower meas.limit,1:>upper meas.limit	
bc_t_nlr	CHAR		Best choice code. 1 means T_NLR is best choice of T, else 0	
c_nlr	FLOAT	m**3/pa	Wellbore storage coefficient, based on NLR, see descr.	
cd_nlr	FLOAT		Dimensionless wellbore storage constant, see table descrip.	
skin_nlr	FLOAT		Skin factor based on Non Linear Regression,see desc.	
transmissivity_t_grf	FLOAT	m**2/s	T_GRF:Transmissivity based on Genelized Radial Flow,see...	
value_type_t_grf	CHAR		0:true value,–1:T_GRF<lower meas.limit,1:>upper meas.limit	
bc_t_grf	CHAR		Best choice code. 1 means T_GRF is best choice of T, else 0	
storativity_s_grf	FLOAT		S_GRF:Storativity based on Generalized Radial Flow, see des.	
flow_dim_grf	FLOAT		Inferred flow dimesion based on Generalized Rad. Flow model	
comment	VARCHAR	no_unit	Short comment to the evaluated parameters	
error_flag	CHAR		If error_flag = “*” then an error occured and an error	
in_use	CHAR		If in_use = “*” then the activity has been selected as	
sign	CHAR		Signature for QA data accknowledge (QA - OK)	

Nomenclature plu_s_hole_test_obs.

Column	Datatype	Unit	Column Description
site	CHAR		Investigation site name
activity_type	CHAR		Activity type code
idcode	CHAR		Object or borehole identification code
start_date	DATE		Date (yymmdd hh:mm:ss)
secup	FLOAT	m	Upper section limit (m)
seclow	FLOAT	m	Lower section limit (m)
obs_secup	FLOAT	m	Upper limit of observation section
obs_seclow	FLOAT	m	Lower limit of observation section
pi_above	FLOAT	kPa	Groundwater pressure above test section,start of flow period
pp_above	FLOAT	kPa	Groundwater pressure above test section,at stop flow period
pf_above	FLOAT	kPa	Groundwater pressure above test section at stop recovery per
pi_below	FLOAT	kPa	Groundwater pressure below test section at start flow period
pp_below	FLOAT	kPa	Groundwater pressure below test section at stop flow period
pf_below	FLOAT	kPa	Groundwater pressure below test section at stop recovery per
comments	VARCHAR		Comment text row (unformatted text)

KFM02A plu_s_hole_test_d. Left. (This result table to SICADA includes more columns which are empty, these columns are not presented here.)

idcode	start_date	stop_date	secup	seclow	test_ type	formation_ type	start_flow_period	stop_flow_period	flow_rate_ end_qp	value_ type qp	mean_flow_ rate_qm
KFM02A	2004-10-19 10:08	2004-10-19 12:57	146.00	151.00	3	1	2004-10-19 11:17:41	2004-10-19 11:38:03	2.20E–08	0	3.56E–08
KFM02A	2004-10-19 13:47	2004-10-19 15:16	211.00	216.00	3	1	2004-10-19 14:33:33	2004-10-19 14:53:55	3.37E–08	0	4.69E–08
KFM02A	2004-10-19 17:25	2004-10-19 18:39	471.00	476.00	3	1	2004-10-19 17:57:12	2004-10-19 18:17:34	9.49E–08	0	1.05E–07
KFM02A	2004-10-19 19:08	2004-10-19 20:23	516.00	521.00	3	1	2004-10-19 19:41:19	2004-10-19 20:01:42	3.40E–08	0	3.83E–08
KFM02A	2004-10-20 08:46	2004-10-20 10:01	551.00	556.00	3	1	2004-10-20 09:19:04	2004-10-20 09:39:26	8.99E–09	0	2.71E–08

KFM02A plu_s_hole_test_d. Right. (This result table to SICADA includes more columns which are empty, these columns are not presented here.)

idcode	secup	seclow	q_measl__l	q_measl__u	tot_volume_ vp	dur_flow_ phase_tp	dur_rec_ phase_tf	initial_ press_pi	press_at_ flow_end_pp	final_press_ pf	fluid_ temp_tew	reference	comments
KFM02A	146.00	151.00	1.67E–08	1.0000E–03	4.35E–05	1,222	4,445	1,488.67	1,703.34	1,555.74			No Tew avaliable
KFM02A	211.00	216.00	1.67E–08	1.0000E–03	5.73E–05	1,222	1,203	2,121.39	2,343.05	2,163.09			No Tew avaliable
KFM02A	471.00	476.00	1.67E–08	1.0000E–03	1.29E–04	1,222	1,210	4,689.05	4,912.34	4,693.98			No Tew avaliable
KFM02A	516.00	521.00	1.67E–08	1.0000E–03	4.68E–05	1,223	1,211	5,153.2	5,357.57	5,162.52			No Tew avaliable
KFM02A	551.00	556.00	5.00E–09	1.0000E–03	3.31E–05	1,222	1,221	5,510.36	5,707.27	5,650.27			No Tew avaliable

KFM02A plu_s_hole_test_ed1. Left. (This result table to SICADA includes more columns which are empty, these columns are not presented here.)

idcode	start_date	stop_date	secup	seclow	test_ type	formation_ type	spec_ capacity_q_s	value_ type_q_s	transmissivity_ moye	bc_ tm	value_ type_tm	hydr_cond_ moye	formation_ width_b
KFM02A	2004-10-19 10:08	2004-10-19 12:57	146.00	151.00	3	1	1.01E–09	0	8.28E–10	0	0	1.66E–10	5.00
KFM02A	2004-10-19 13:47	2004-10-19 15:16	211.00	216.00	3	1	1.49E–09	0	1.23E–09	0	0	2.46E–10	5.00
KFM02A	2004-10-19 17:25	2004-10-19 18:39	471.00	476.00	3	1	4.17E–09	0	3.43E–09	0	0	6.87E–10	5.00
KFM02A	2004-10-19 19:08	2004-10-19 20:23	516.00	521.00	3	1	1.63E–09	0	1.35E–09	0	0	2.69E–10	5.00
KFM02A	2004-10-20 08:46	2004-10-20 10:01	551.00	556.00	3	1	4.48E–10	0	3.69E–10	1	0	7.38E–11	5.00

KFM02A plu_s_hole_test_ed1. Right. (This result table to SICADA includes more columns which are empty, these columns are not presented here.)

idcode	secup	seclow	transmissivity_tt	value_type_tt	bc_tt	l_measl_q_s	u_measl_q_s	assumed_s	c	skin	t1	t2	dte1	dte2	comment
KFM02A	146.00	151.00	7.10E–10	0	1	7.62E–10	5.00E–04	1.00E–06	2.24E–11	–9.75E–01	20.00	80.00			
KFM02A	211.00	216.00	4.96E–10	0	1	7.38E–10	5.00E–04	1.00E–06	1.72E–11	–1.56E+00	–	–			
KFM02A	471.00	476.00	1.49E–09	0	1	7.32E–10	5.00E–04	1.00E–06	1.93E–11	–1.20E+00	10.00	60.00			
KFM02A	516.00	521.00	4.96E–10	0	1	8.00E–10	5.00E–04	1.00E–06	2.95E–11	–1.04E+00	–	–			
KFM02A	551.00	556.00	–	0	0	2.49E–10	5.00E–04	1.00E–06	4.58E–11	–	–	–			

KFM02A plu_s_hole_test_obs. (This result table to SICADA includes more columns which are empty, these columns are not presented here.)

idcode	start_date	stop_date	secup	seclow	obs_secup	obs_seclow	pi_above	pp_above	pf_above	pi_below	pp_below	pf_below	comments
KFM02A	2004-10-19 10:08	2004-10-19 12:57	146.00	151.00	100.14	145.00	1,448.69	1,448.69	1,449.11				
KFM02A	2004-10-19 10:08	2004-10-19 12:57	146.00	151.00	152.00	1,002.44				1,512.78	1,520.52	1,515.55	
KFM02A	2004-10-19 13:47	2004-10-19 15:16	211.00	216.00	100.14	210.00	2,092.62	2,092.76	2,087.79				
KFM02A	2004-10-19 13:47	2004-10-19 15:16	211.00	216.00	217.00	1,002.44				2,142.19	2,144.54	2,136.67	
KFM02A	2004-10-19 17:25	2004-10-19 18:39	471.00	476.00	100.14	470.00	4,666.67	4,668.74	4,669.02				
KFM02A	2004-10-19 17:25	2004-10-19 18:39	471.00	476.00	477.00	1,002.44				4,720.02	4,721.67	4,721.67	
KFM02A	2004-10-19 19:08	2004-10-19 20:23	516.00	521.00	100.14	515.00	5,113.81	5,115.05	5,115.05				
KFM02A	2004-10-19 19:08	2004-10-19 20:23	516.00	521.00	522.00	1,002.44				5,176.20	5,174.27	5,173.31	
KFM02A	2004-10-20 08:46	2004-10-20 10:01	551.00	556.00	100.14	550.00	5,462.55	5,460.06	5,462.27				
KFM02A	2004-10-20 08:46	2004-10-20 10:01	551.00	556.00	557.00	1,002.44				5,526.10	5,523.34	5,512.86	