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Single-hole injection tests and pressure pulse tests in borehole KFM07B

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January 2006

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Abstract

Borehole KFM07B is a 300 m long core-drilled borehole within the site investigation area in Forsmark. The borehole is inclined c 54 degrees from the horizontal plane. This borehole has been injected with cement down to about 209 m, except in a section between c 66 and 70 m along the borehole. The borehole diameter is approximately 76 mm.

This report presents injection tests and pressure pulse tests performed using the pipe string system PSS3 in borehole KFM07B and the test results. Pressure pulse tests were performed instead of injection tests in sections where the flow rate was assumed to be below or close to the measurement limit for injection tests.

The main aim of the injection tests and pressure pulse tests in KFM07B was to characterize the hydraulic conditions of the rock adjacent to the borehole on a 5 m measurement scale. Hydraulic parameters such as transmissivity and hydraulic conductivity together with the dominating flow regime and possible outer hydraulic boundaries were determined using analysis methods for stationary as well as transient conditions.

Six of the tests in KFM07B were performed as injection tests and in four of those, the transient evaluation was chosen as representative. The evaluation was done from the injection period in two of those tests and from the recovery period in the remaining two tests. In two of the injection tests a period with pseudo-radial flow could be identified. The PRF was, however, chosen for evaluation only in one of those cases. The pressure pulse tests were evaluated using a stationary evaluation method. For 2 out of 8 pressure pulse tests a transient evaluation was also possible, however the values from the transient evaluation were not regarded as representative.

No highly conductive sections were found in KFM07B. The highest transmissivity was detected in section 234–239 m, at 4.3×10^{-8} m^2/s.

The injection tests provide a database for statistical analysis of the hydraulic conductivity distribution along the borehole. Basic statistical parameters are presented in this report.

Sammanfattning

Borrhål KFM07B är ett ca 300 m långt, lutande kärnborrhål, som borrats inom ramen för platsundersökningarna i Forsmarksområdet. Lutningen på borrhålet är ca 54 grader från horisontalplanet. Detta borrhål har injekterats med cement ner till ca 209 m, förutom i ett avsnitt mellan ca 66 och 70 m längs borrhålet. Borrhålets innerdiameter är ca 76 mm.

Denna rapport beskriver genomförda injektionstester och pulstester med rörgångssystemet PSS3 i borrhål KFM07B samt resultaten från desamma. Pulstester genomfördes i stället för injektionstester i några sektioner där flödet befarades hamna under mätgränsen för injektionstester.

Huvudsyftet med injektionstesterna och pulstesterna var att karaktärisera de hydrauliska förhållandena av berget i anslutning till borrhålet i 5 m mätskala. Hydrauliska parametrar såsom transmissivitet och hydraulisk konduktivitet tillsammans med dominerande flödesregim och eventuella yttre hydrauliska randvillkor, bestämdes med hjälp av analysmetoder för såväl stationära som transienta förhållanden.

Sex av testerna i KFM07B utfördes som injektionstester och i fyra av dessa ansågs den transienta utvärderingen som mest representativ. Utvärderingen utfördes på injektionsperioden i två av dessa tester och på återhämtningen i de övriga två testerna. I två av injektionstesterna kunde en viss period med pseudoradiellt flöde identifieras. Perioden med PRF valdes dock för utvärdering endast i ett av dessa fall. Pulstesterna utvärderades med en stationär metod. Transient utvärdering var också möjlig för 2 av 8 pulstester, men värdena från den transienta utvärderingen ansågs inte vara representativa.

Inga högkonduktiva sektioner återfanns i KFM07B. Den högsta transmissiviteten i borrhålet, $4,3 \times 10^{-8}$ m^2/s, registrerades i sektionen 234–239 m.

Resultaten från injektionstesterna utgör en databas för statistisk analys av den hydrauliska konduktivitetens fördelning längs borrhålet. Viss statistisk analys har utförts inom ramen för denna aktivitet och grundläggande statistiska parametrar presenteras i rapporten.

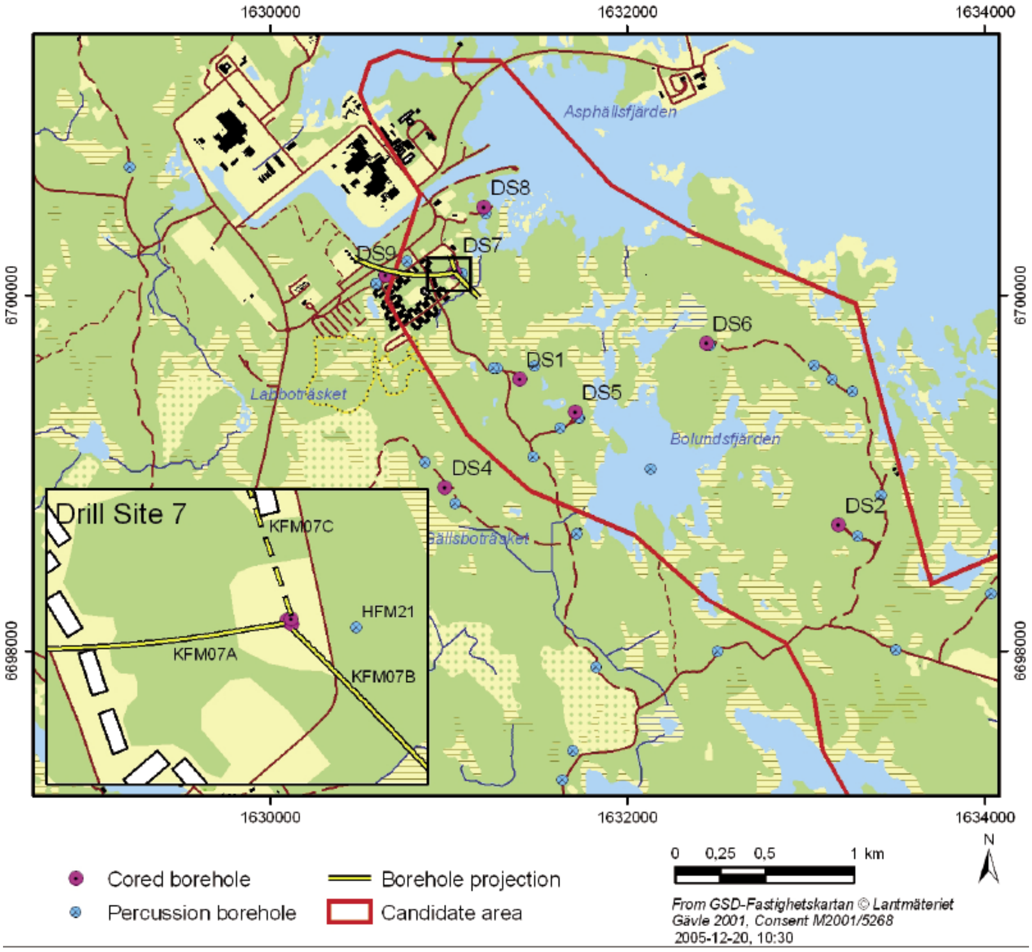
Contents

Appendix on CD

1 Introduction

Injection tests and pressure pulse tests were carried out in borehole KFM07B at Forsmark, Sweden, during January 2006 by GEOSIGMA AB. The borehole KFM07B is a core-drilled borehole within the on-going site investigation in the Forsmark area. It is c 300 m long, inclined c 54 degrees from the horizontal and cased to c 65 m depth. This borehole has been injected with cement below the casing down to about 209 m, except in a section between the casing and 70 m along the borehole. The borehole diameter is approximately 76 mm. The location of the borehole is shown in Figure 1-1.

This document reports the results obtained from hydraulic tests in borehole KFM07B. Primarily injection tests were performed. However, in sections for which a flow rate below or close to the measurement limit for injection tests was expected, pressure pulse tests were carried out instead. 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, where they are traceable by the activity plan number.



From GSD-Fastighetskartan © Lantmäteriet
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Figure 1-1. *The investigation area at Forsmark including part of the candidate area selected for more detailed investigations. Borehole KFM07B is situated at drill site 7 (DS7).*

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

Activity Plans	**Number**	**Version**
Hydraulic injection tests in borehole KFM07B with PSS3	AP PF 400-05-049	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
Instruktion för rengöring av borrhålsutrustning och viss markbaserad utrustning	SKB MD 600.004	1.0

2 Objectives

The main aim of the injection- and pressure pulse tests in borehole KFM07B was to characterize the hydraulic properties of the rock adjacent to the borehole on a 5 m measurement scale. 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 flow- and recovery periods.

The results of the injection tests provide a database which can be used for statistical analyses of the hydraulic conductivity distribution along the borehole. Basic statistical analyses are presented in this report.

3 Scope

3.1 Borehole

Technical data of the tested borehole are shown in Tables 3-1 and in Appendix 4. The reference point of the borehole 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 KFM07B (printout from SKB database, SICADA).

Borehole length (m):	298.930				
Drilling Period(s):	**From Date**	**To Date**	**Secup (m)**	**Seclow (m)**	**Drilling Type**
	2005-05-31	2005-10-18	0.000	298.930	Core drilling
Starting point coordinate:	**Length (m)**	**Northing (m)**	**Easting (m)**	**Elevation**	**Coord System**
	0.000	6700123.622	1631036.833	3.363	RT90-RHB70
Angles:	**Length (m)**	**Bearing**	**Inclination (– = down)**		
	0.000	134.346	–53.713		
Borehole diameter:	**Secup (m)**	**Seclow (m)**	**Hole Diam (m)**		
	0.000	5.180	0.116		
	5.180	65.690	0.096		
	65.690	298.930	0.076		
Core diameter:	**Secup (m)**	**Seclow (m)**	**Core Diam (m)**		
	5.180	65.690	0.063		
	65.690	298.930	0.051		
Casing diameter:	**Secup (m)**	**Seclow (m)**	**Case In (m)**	**Case Out (m)/ In (m)**	
	0.000	65.290	0.077	0.090/0.076	

3.2 Tests performed

The injection tests and pressure pulse tests in borehole KFM07B, performed according to Activity Plan AP PF 400-05-049, are listed in Table 3-2. The injection- and pressure pulse tests were carried out with the Pipe String System (PSS3). The test procedure and the equipment is described in the measurement system description for PSS (SKB MD 345.100) and in the corresponding method descriptions for hydraulic injection tests (SKB MD 323.001), see Table 1-1.

On at least one occasion the test was not performed as intended because the time required for achieving a constant head in the test section was judged to be too long, or equipment malfunctions caused pressure and/or flow rate disturbances. Whenever such disturbances were expected to affect data evaluation, the test was repeated. Test number (Test no in Table 3-2) refers to the number of tests performed in the actual section. For evaluation, only data from the last test in each section were used.

Table 3-2. Single-hole injection tests and pressure pulse tests performed in borehole KFM07B.

Bore hole bh id	Test section secup	 seclow	Section length	Test type[1)] (1–6)	Test no	Test start date, time YYYYMMDD hh:mm	Test stop date, time YYYYMMDD hh:mm
KFM07B	209.00	214.00	5.00	3	1	20060123 09:22	20060123 10:14
KFM07B	214.00	219.00	5.00	4B	1	20060123 10:28	20060123 12:12
KFM07B	219.00	224.00	5.00	3	1	20060123 12:51	20060123 13:33
KFM07B	224.00	229.00	5.00	3	1	20060123 13:46	20060123 15:05
KFM07B	229.00	234.00	5.00	3	2	20060125 16:17	20060125 17:33
KFM07B	234.00	239.00	5.00	3	1	20060123 16:46	20060123 18:02
KFM07B	239.00	244.00	5.00	3	1	20060124 06:46	20060124 08:31
KFM07B	244.00	249.00	5.00	4B	1	20060124 08:47	20060124 10:03
KFM07B	249.00	254.00	5.00	4B	1	20060124 10:19	20060124 12:23
KFM07B	254.00	259.00	5.00	4B	1	20060124 12:34	20060124 14:27
KFM07B	259.00	264.00	5.00	4B	1	20060124 14:36	20060125 09:09
KFM07B	264.00	269.00	5.00	4B	1	20060125 09:22	20060125 10:44
KFM07B	269.00	274.00	5.00	4B	1	20060125 11:00	20060125 12:41
KFM07B	274.00	279.00	5.00	4B	1	20060125 12:59	20060125 14:19

[1)] 3: Injection test, 4B: Pressure pulse test.

Pressure pulse tests were performed instead of injection tests in sections where the transmissivity was expected to be below or near the measurement limit for injection tests. It may be appropriate to perform a pressure pulse test when the flow rate at the end of the injection period is less than c 1.5 mL/min. To decide whether an injection test or a pressure pulse test should be carried out in a particular section, a so called diagnostic test was conducted during the packer inflation period. The diagnostic test involves closing the test valve after 5 minutes of packer inflation and observing the pressure in the test section during the following 5 minutes. A pressure pulse test was made if the pressure increase after 5 minutes exceeded c 20 kPa. Otherwise an injection test was carried out. A pressure pulse test is performed similar to an injection test, the differences being a longer time for packer inflation, a shorter injection (pulse) time and a longer recovery period, see Table 5-1a and Table 5-1b.

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 December 2005.

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). The temperature sensor displayed expected values in both air and water.

Ordinarily, simple functioning checks of down-hole sensors are done at every change of test section interval. For this commission only the 5 m test section was used though, and consequently only one check was performed. 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 a 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 pressure vessels filled with an ethanol mixture. 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 meter. 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.

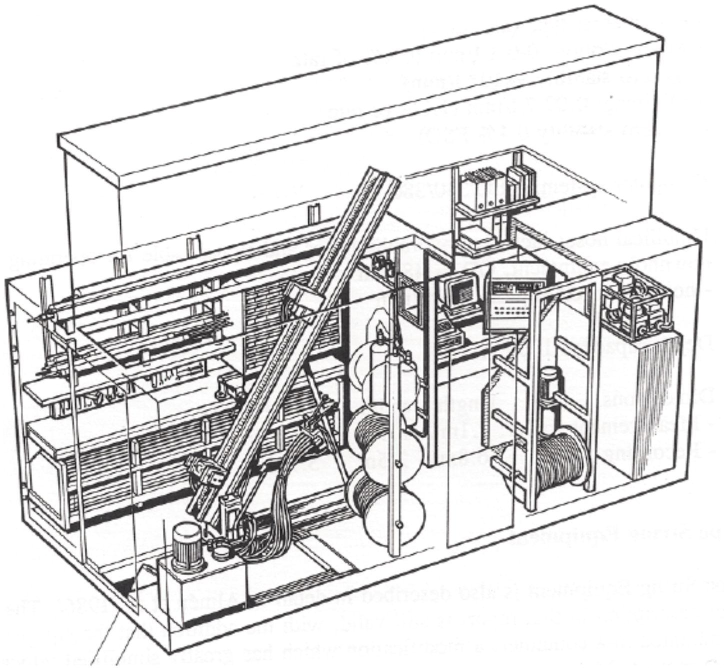

Figure 4-1. *Outline of the PSS3 container with equipment.*

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 (P_a), within (P) and below (P_b) 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 (calliper 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 m).

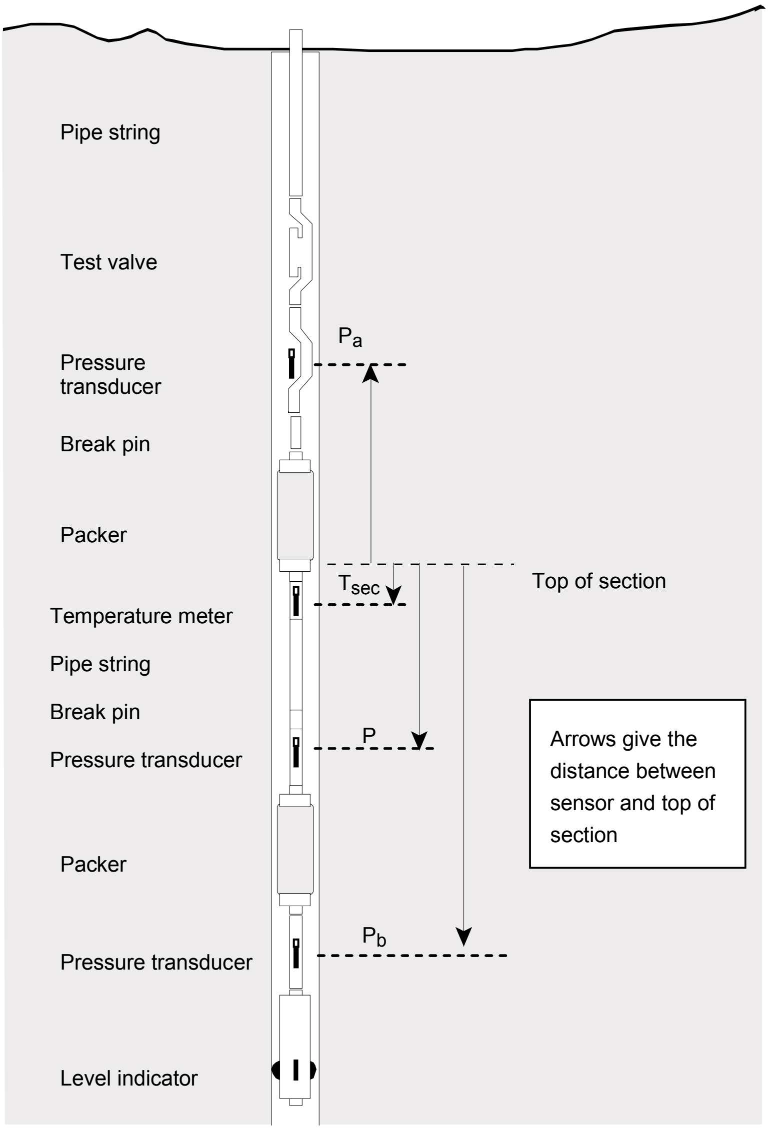

Figure 4-2. Schematic drawing of the down-hole equipment in the PSS3 system.

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 sensors are components of the PSS system. The accuracy of the PSS system may also be affected by the I/O-unit, cf Figure 4-3, and the calibration of the system.

The sensor positions are fixed relative to the top of the test section. In Table 4-2, the position of the sensors as well as displacement volume of equipment are given with top of test section as reference where applicable (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		
	Accuracy1)	% 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	1.67×10^{-5}–1.67×10^{-3}		The specific accuracy is depending on actual flow
	Resolution	m^3/s	6.7×10^{-8}		
	Accuracy2)	% O.R	0.15–0.3	< 1%	
Flow Qsmall	Output signal	mA	4–20		
	Meas. range	m^3/s	1.67×10^{-8}–1.67×10^{-5}		The specific accuracy is depending on actual flow
	Resolution	m^3/s	6.7×10^{-10}		
	Accuracy3)	% O.R	0.1–0.4	0.5–20	

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

2) Maximum error in % of actual reading (% o.r.).

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

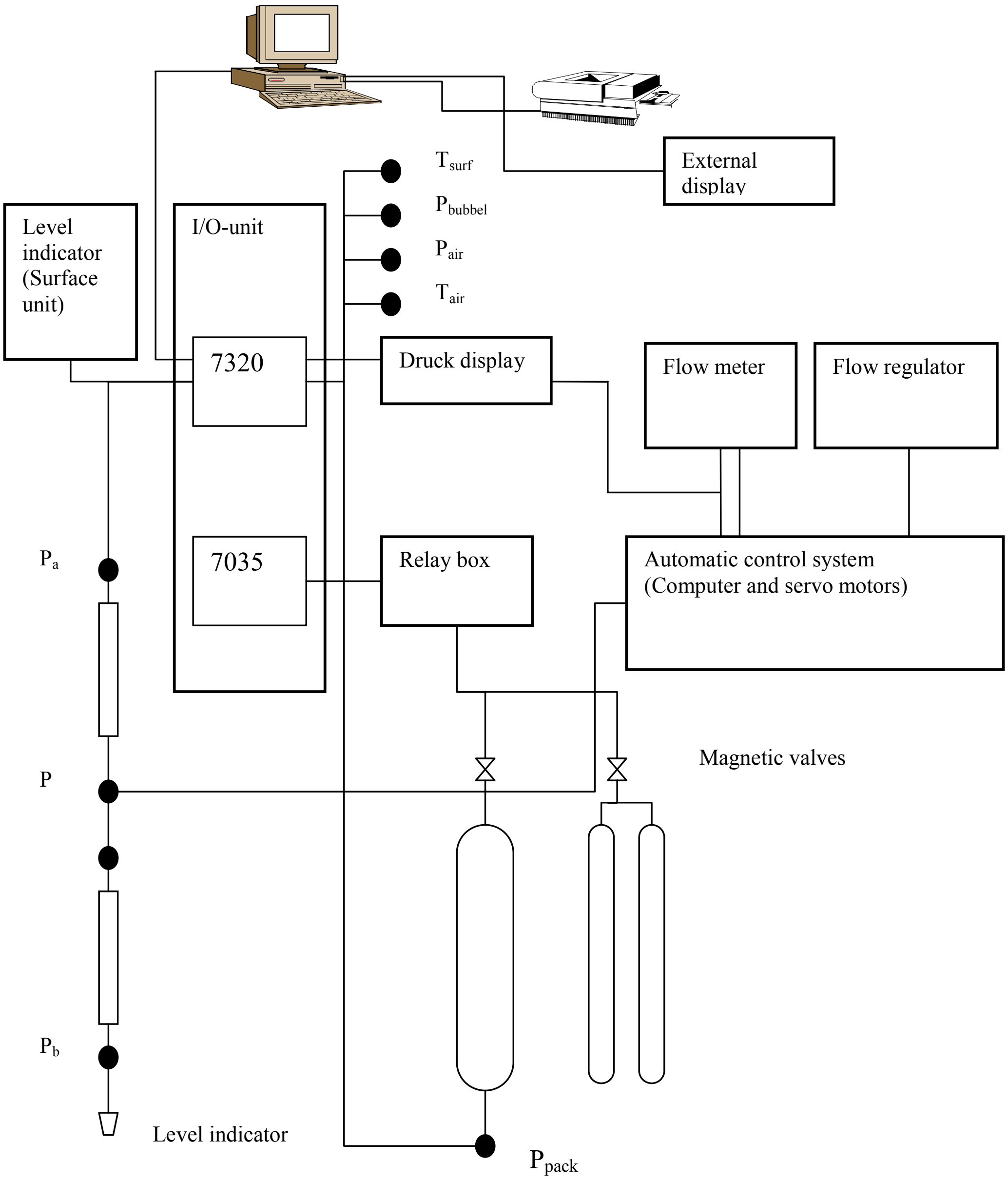

Figure 4-3. *Schematic drawing of the data acquisition system and the automatic control system in PSS.*

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 (L)	(m)
Equipment displacement volume in test section 1)	3.6	
Total volume of test section 2)	23	
Position for sensor P_a, pressure above test section, (m above secup) 3)		1.88
Position for sensor P, pressure in test section, (m above secup) 3)		–4.12
Position for sensor T_{sec}, Temperature in test section, (m above secup) 3)		–0.96
Position for sensor P_b, pressure below test section, (m above secup) 3)		–7.00

1) Displacement volume in test section due to pipe string, signal cable, sensors and packer ends (in litre).

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

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 parameters, 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.

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 while lowering the pipe string along the borehole.

5.1.3 Cleaning of equipment

Cleaning of the borehole equipment was performed according to the cleaning instruction (SKB MD 600.004, see Table 1-1), level 1.

5.2 Test performance

5.2.1 Test principle

Two kinds of test were performed in KFM07B, injection tests and pressure pulse tests. The injection tests in KFM07B were carried out while maintaining a constant head of generally 200 kPa (c 20 m water column) 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.

Pressure pulse tests were carried out instead of injection tests in some low-conductive sections, where the flow rate was expected to be close to or below the measurement limit for injection tests. The pressure pulse tests in KFM07B were performed by introducing a pressure pulse to the isolated test section. The pulse was accomplished by applying a pressure of c 200 kPa to the pipe string above the test section and then opening the test valve. After 2 minutes the valve was closed and the pressure recovery in the test section was measured.

Pressure pulse tests showing a continuing pressure increase due to packer expansion after the pulse (during the recovery period) were interrupted after c 10 minutes and no transient evaluation was made. A steady-state evaluation was however performed.

5.2.2 Test procedure

Generally, the tests were performed according to the Activity Plan AP PF 400-05-049. Exceptions to this are presented in Section 5.5.

A test cycle of a standard injection test 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.

When the transmissivity in a section was expected to be low, a diagnostic test was conducted to decide whether to perform a pressure pulse test or an injection test. A test cycle in these cases includes the following events: 1) Transfer of down-hole equipment to the next section, 2) Packer inflation, 3) Closing of test valve after five minutes, 4) Observing the pressure during the following five minutes, 5) Deciding which type of test to conduct, 6) Opening of test valve, 7) Continuing packer inflation, 8) Pressure stabilisation, 9) Injection or pulse, 10) Pressure recovery and 11) Packer deflation. The test phases are the same regardless if a pressure pulse test or an injection test is decided to be performed, but the duration of the different phases differs according to Tables 5-1a and 5-1b. The diagnostic test is included in the given durations.

The criterion used to decide which test to perform was that a pressure pulse test was made if the pressure increased 20 kPa or more during test phase 4 above. Otherwise an injection test was carried out.

Table 5-1a. Packer inflation times, pressure stabilisation times and test times used for the injection tests in KFM07B. Including the diagnostic test.

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.

Table 5-1b. Packer inflation times, pressure stabilisation times and test times used for the pressure pulse tests in KFM07B. Including the diagnostic test.

Test section length (m)	Packer inflation time (min)	Time for pressure stabilisation (min)	Pulse period (min)	Recovery period (min)	Total time/test (min)[1]
5	40	20	2	40	102

[1] Exclusive of trip times in the borehole.

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 __KFM07B_0209.00_200601180900.ht2). The name differs slightly from the convention stated in Instructions for analysis of injection and single-borehole pump test, SKB MD 320.004.

Using the IPPLOT software (Version 3.0), the *.ht2-files are converted to parameter files suitable for plotting applying the code SKB-plot and analysis with the AQTESOLV software.

A backup of data files was created on a regular basis by CD-storage and by sending the files to the Geosigma office in Uppsala by a file transfer protocol. A file description table is presented in Appendix 1.

5.4 Analysis and interpretation

5.4.1 General

As described in Section 5.2.1, the injection tests in KFM07B were performed as transient constant head tests followed by a pressure recovery period. 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 was plotted versus Agarwal equivalent time in lin-log and log-log diagrams, respectively, together with the corresponding derivative. 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).

For pressure pulse tests the standard transient evaluation is performed in a lin-log diagram showing the normalized recovery H/H_0 versus elapsed recovery time together with the corresponding derivative. The recovery is generally normalized with respect to H_0, which is the initial pressure in the borehole section before the packers are expanded. In addition, a stationary evaluation method, accounting for the packer generated flow, was used for evaluation of the pressure pulse tests, see Section 5.4.4.

For 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 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.

5.4.2 Measurement limit for flow rate and specific flow rate

The estimated standard lower measurement limit for flow rate for injection tests with PSS is c 1 mL/min (1.7×10^{-8} m^3/s). However, if the flow rate for a test is close to, or below, the standard lower measurement limit, a test-specific estimate of the lower measurement limit of flow rate can be made. The test-specific lower limit is based on the measurement noise level of the flow rate before and after the injection period. The decisive factor for the varying lower measurement limit is not unambiguously identified, but it might be of both technical and hydraulic character. Since pressure pulse tests were conducted in sections with a possible low transmissivity, only two of the injection tests in KFM07B had a flow rate below or close to the standard lower measurement limit. Hence, these tests were the only ones where a test specific estimate of the lower measurement limit for the flow rate was made.

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 of the flow rate together with the actual injection pressure during the test. The intention during this test campaign was to use a standard injection pressure of 200 kPa (20 m water column). However, for most test sections in KFM07B, the actual injection pressure deviated somewhat from the intended 200 kPa, and in two cases the difference was considerable. The injection pressure exceeded 300 kPa for one test, and for another test the injection pressure was below 100 kPa. A low injection pressure is often the result of a test section of low conductivity due to a pressure increase, caused by packer expansion, before the injection start. A highly conductive section may also result in a low injection pressure due to limited flow capacity of PSS. Since the flow rate was only below the standard lower measurement limit for injection tests on two occasions in KFM07B, it was only necessary to calculate a test specific lower measurement limit for the specific flow rate for those tests.

The lower measurement limit for flow rate corresponds to different values of the steady-state transmissivity, T_M, depending on the section length used in the factor C_M in Moye's formula (Equation 5-2), as described in the Instruction for analysis of injection and single-hole pumping tests (SKB MD 320.004). Only 5 m section lengths were used in borehole KFM07B. The standard lower measurement limit for flow rate of 1 mL/min (1.7×10^{-8} m^3/s) together with the value of C_M ($C_{M,\,5m}$=0.82) for a five metres test section results in the lower measurement limits for steady-state transmissivity (T_M) of 1.4×10^{-9} m^2/s, 7.0×10^{-10} m^2/s and 4.7×10^{-10} m^2/s for injection pressures 100 kPa, 200 kPa and 300 kPa respectively.

To define the lower measurement limit of transmissivity for pressure pulse tests with the PSS, further consideration of the packer generated flow is necessary. Since the packers generate a small, but not negligible, flow throughout the test period, the estimated transmissivities from the transient evaluation of pressure pulse tests will be underestimated in low-transmissivity sections because no correction is normally made for the packer generated flow. In the stationary evaluation, the packer generated flow is taken into account (see Section 5.4.4 for a further discussion). Among other potential problems, the stationary evaluation has an inherent risk of overestimating the transmissivity, since the tests have a limited duration and true stationary conditions, in fact, never prevail. In addition, the uncertainty and variations in the assumed packer generated flow from test to test is being ignored.

The selected, most representative transmissivity from the pressure pulse tests corresponds to the calculated transmissivity from either the transient evaluation or the stationary evaluation. However, no transmissivity values lower than 5×10^{-11} m^2/s are reported. The latter value is considered as the practical lower measurement limit of transmissivity from pressure pulse tests considering the effects of packer compliance. Due to the increased uncertainty of estimated transmissivities from pressure pulse tests, all these values are assigned Value type –1 in the SICADA database, i.e. below the measurement limit.

The practical upper measurement limit of hydraulic transmissivity for the PSS system is estimated from a flow rate of c 30 L/min (5×10^{-4} m^3/s) and an injection pressure of c 1 m. Thus, the upper measurement limit for specific flow rate is 5×10^{-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).

5.4.3 Qualitative analysis

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 for the injection tests. In addition, indications of outer boundary conditions during the tests were identified. The qualitative evaluation was mainly interpreted from the log-log plots of flow rate and pressure together with the corresponding derivatives. No flow regimes were identified for the pressure pulse tests.

In particular, time intervals with pseudo-radial flow, reflected by a constant (horizontal) derivative in the test diagrams, were identified. Pseudo-linear flow may, at the beginning of the test, be reflected by a straight line of slope 0.5 or less in log-log diagrams, both for the measured variable (flow rate or pressure) and the derivative. A true spherical flow regime is reflected by a straight line with a slope of –0.5 for the derivative. However, other slopes may indicate transitions to pseudo-spherical (leaky) or pseudo-stationary flow. The latter flow regime corresponds to almost stationary conditions with a derivative approaching zero.

The interpreted flow regimes can also be described in terms of the distance from the borehole:

- **Inner zone:** Representing very early responses that may represent the fracture properties close to the borehole which may possibly be affected by turbulent head losses. These properties are generally reflected by the skin factor.
- **Middle zone:** Representing the first response from which it is considered possible to evaluate the hydraulic properties of the formation close to the borehole.
- **Outer zone:** Representing the response at late times of hydraulic feature(s) connected to the hydraulic feature for the middle zone. Sometimes it is possible to deduce the possible character of the actual feature or boundary and evaluate the hydraulic properties of the features.

Due to the limited resolution of, in particular, the pressure sensor, the derivative may some times erroneously indicate a false horizontal line by the end of recovery periods with pseudo-stationary flow. Apparent no-flow (NFB) and constant head boundaries (CHB), or equivalent boundary conditions of fractures, are reflected by an increase/decrease of the derivative, respectively.

5.4.4 Quantitative analysis

Injection tests

A preliminary steady-state analysis of transmissivity according to Moye's formula (denoted T_M) was made for the injection period for all injection tests in conjunction with the qualitative analysis according to the following equation:

$$T_M = \frac{Q_p \cdot \rho_w \cdot g}{dp_p} \cdot C_M \qquad (5\text{-}1)$$

$$C_M = \frac{1 + \ln\left(\frac{L_w}{2r_w}\right)}{2\pi} \qquad (5\text{-}2)$$

Q_p = flow rate by the end of the flow period (m^3/s)

ρ_w = density of water (kg/m^3)

g = acceleration of gravity (m/s^2)

C_M= geometrical shape factor (–)

dp_p = $p_p - p_i$ (Pa)

r_w = borehole radius (m)

L_w = section length (m)

From the results of the qualitative evaluation, appropriate interpretation models for the quantitative evaluation of the tests were selected. When possible, transient analysis was made on both the injection and recovery periods of the injection 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 based on the Jacob and Lohman (1952) solution /1/ was applied for estimating the transmissivity and skin factor for an assumed value on the storativity when a certain period with pseudo-radial flow could be identified. The model is based on the effective wellbore radius concept to account for non-zero (negative) skin factors according to Hurst, Clark and Brauer (1969) /2/.

In borehole KFM07B, the storativity was calculated using an empirical regression relationship between storativity and transmissivity, see Equation 5-3 (Rhén et al. 1997) /3/. Firstly, the transmissivity and skin factor was obtained by type curve matching on the data curve using a fixed storativity value of 10^{-6}, according to the instruction SKB MD 320.004. From the transmissivity value obtained, the storativity was then calculated according to Equation 5-3 and the type curve matching was repeated.

$$S=0.0007\times T^{0.5} \tag{5-3}$$

S=storativity (–)

T=transmissivity (m^2/s)

In most cases the change of storativity did not significantly alter the calculated transmissivity by the new type curve matching. Instead, the estimated skin factor, which is strongly correlated to the storativity using the effective borehole radius concept, was altered correspondingly.

For transient analysis of the recovery period, a model presented by Dougherty-Babu (1984) /4/ was used when a certain period with pseudo-radial flow could be identified. In this model, a variety of transient solutions for flow in fractured porous media is available, accounting for e g wellbore storage and skin effects, double porosity etc. The solution for wellbore storage and skin effects is analogous to the corresponding solution presented in Earlougher (1977) /5/ based on the effective wellbore radius concept to account for non-zero (negative) skin factors. However, for tests in isolated test sections, wellbore storage is represented by a radius of a fictive standpipe (denoted fictive casing radius, r(c)) connected to the test section, cf Equation 5-6. This concept is equivalent to calculating the wellbore storage coefficient C from the compressibility in an isolated test section according to Equation 5-5.

When a certain period with pseudo-radial flow could be identified, the model by Dougherty-Babu (1984) was used to estimate the transmissivity and skin factor from the recovery period. The storativity was calculated using Equation 5-3 in the same way as described above for the transient analysis of the injection period. In addition, the wellbore storage coefficient was estimated, both from the simulated value on the fictive casing radius r(c) and, when applicable, from the slope of 1:1 in the log-log recovery plots.

For tests characterized by pseudo-spherical (leaky) flow or pseudo-stationary flow during the injection period, a model by Hantush (1959) /6/ for constant head tests was adopted for the evaluation. In this model, the skin factor is not separated but can be calculated from the simulated effective borehole radius according to Equation 5-4. In addition, the leakage coefficient K'/b' can be calculated from the simulated leakage factor r/B. The corresponding model for constant flow rate tests, (Hantush 1955) /7/, was applied for evaluation of the recovery period for tests showing pseudo-spherical- or pseudo-stationary flow during this period. This model also allows calculation of the wellbore storage coefficient according to Equation 5-6.

$$\zeta = \ln(r_w/r_{wf}) \qquad (5\text{-}4)$$

ζ = skin factor

r_w = borehole radius (m)

r_{wf} = effective borehole radius (m)

When a test indicates a fracture response (a slope of 0.5 or less in a log-log plot), models for single fractures are used for the transient analysis as a complement to the standard models. The models by Ozkan-Raghavan (1991a) /8/ and (1991b) /9/ for a vertical fracture were employed. In these cases, the test section length was used to convert K and S_s to T and S, respectively, after analysis by fracture models. The quotient K_x/K_y of the hydraulic conductivity in the x and the y-direction, respectively, was assumed to be 1.0 (one). Type curve matching provided values of K_x and L_f, where L_f is the theoretical fracture length.

The different transient estimates of transmissivity from the injection and recovery period, respectively, were then compared and examined. One of these was chosen as the best representative value of the transient transmissivity of the formation adjacent to the test section. This value is denoted T_T. In cases with more than one pseudo-radial flow regime during the injection or recovery period, the first one is in most cases assumed as the most representative for the hydraulic conditions in the rock close to the tested section.

Finally, a representative value of transmissivity of the test section, T_R, was chosen from T_T and T_M. The latter transmissivity is to be chosen whenever a transient evaluation of the test data is not possible or not being judged as reliable. If the flow rate by the end of an injection period (Q_p) is too low to be defined, and thus neither T_T nor T_M can be estimated, the representative transmissivity for the test section is considered to be less than T_M based on the estimated lower measurement limit for Q/s (i.e. $T_R < T_M$=Q/s-measl-L×C_M).

The estimated value of the borehole storage coefficient, C, based on actual borehole geometrical data and assumed fluid properties for a 5 m section is shown in Table 5-2 together with the estimated effective C_{eff} from laboratory experiments /10/. The net water volume in the test section, V_w, has in Table 5-2 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 demonstrated by Almén et al, (1986) /11/:

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

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}).

Table 5-2. Calculated net values of C, based on the actual geometrical properties of the borehole and equipment configuration in the test section (C_{net}) together with the effective wellbore storage coefficient (C_{eff}) for injection- and pressure pulse tests from laboratory experiments /10/.

r_w (m)	L_w (m)	Volume of test section (m^3)	Volume of equipment in section (m^3)	V_w (m^3)	C_{net} (m^3/Pa)	C_{eff} (m^3/Pa)
0.0382	5	0.0229	0.004	0.0189	8.7×10^{-12}	1.6×10^{-11}

When appropriate, estimation of the actual borehole storage coefficient C in the test sections was 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. In the most conductive sections, this period occurred during very short periods at early test times. The latter values may be compared with the net value of C based on geometry and the value of C_{eff} based on laboratory experiments, (Table 5-2).

Furthermore, when using the model by Dougherty-Babu (1984), a fictive casing radius, r(c), is obtained from the parameter estimation of the recovery period. This value can then be used for calculating C as /11/:

$$C = \frac{\pi \cdot r(c)^2}{\rho \cdot g} \tag{5-6}$$

Although this calculation is not done regularly and the results are not presented in this report, the calculations correspond, in the one case that they were performed in KFM07B, well to the value of C obtained from the line of slope 1:1 in the beginning of the recovery period.

The estimated values of C from the tests may differ from the net values in Table 5-2 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.

The radius of influence at a certain time may be estimated from Jacob's approximation of the Theis' well function, Cooper and Jacob (1946) /12/:

$$r_i = \sqrt{\frac{2.25Tt}{S}} \tag{5-7}$$

T = Representative transmissivity from the test (m^2/s).

S = Storativity estimated from Equation 5-3.

r_i = Radius of influence (m).

t = Time after start of injection (s).

If a certain time interval of pseudo-radial flow (PRF) can be identified from t_1 to t_2 during the injection period, the radius of influence is estimated using time t_2 in Equation 5-7. If no interval of PRF can be identified, the actual total injection time t_p is used. The radius of influence can be used to estimate the length of the hydraulic feature(s) tested.

Furthermore, an r_i-index (–1, 0 or 1) is defined to characterize the hydraulic conditions at the end of the test. The r_i-index is defined as shown below.

- r_i-index = 0: The transient response indicates that the size of the hydraulic feature tested is greater than the radius of influence based on the actual test time (t_2=t_p), i.e. the PRF is continuing at stop of the test. This fact is reflected by a flat derivative at the end of the injection period.
- r_i-index = 1: The transient response indicates that the hydraulic feature tested is connected to a hydraulic feature with lower transmissivity or an apparent no-flow boundary (NFB). This fact is reflected by an increase of the derivative. The size of the hydraulic feature tested is estimated as the radius of influence based on t_2, provided that a PRF can be identified.
- r_i-index = –1: The transient response indicates that the hydraulic feature tested is connected to a hydraulic feature with higher transmissivity or an apparent constant head boundary (CHB). This fact is reflected by a decrease of the derivative. The size of the hydraulic feature tested is estimated as the radius of influence based on t_2, if a PRF can be identified.

Pressure pulse tests

By the evaluation of the pressure pulse tests both a transient and a stationary evaluation were made. A model described by Dougherty and Babu (1984) /4/ was used for transient evaluation of the pressure pulse tests performed. The normalized recovery H/H_0 was plotted versus elapsed time during the recovery period in a lin-log diagram. In this analysis, the actual head change, H, was not corrected for effects of packer generated flow.

As for the injection tests, the effective borehole radius concept, Equation (5-4), was applied for calculating the skin factor as well as the concept of a fictive standpipe connected to the test section representing wellbore storage according to Equation (5-6). The value of C_{eff} (see Table 5-2) used to calculate the radius of the fictive standpipe, r(c), is derived from laboratory experiments /10/. The transmissivity and skin factor were estimated for a certain value of storativity and wellbore storage coefficient (represented by the radius of the fictive standpipe) from type curve matching. The storativity was calculated from Equation (5-3) as for the injection tests.

Whenever the transmissivity in the section was so low that the packer generated flow caused a pressure increase after the pulse, the test was interrupted and no transient evaluation was made. Since the packers are still slowly expanding, even after the time allowed for packer expansion and pressure stabilization (60 minutes), a small flow is generated throughout the tests by the packers. For such low-conductive sections this flow is not negligible, which leads to an underestimation of the transmissivities. Efforts have been made to make corrections for the packer generated flow by different methods (e.g. by correcting H) before performing transient evaluation by standard methods for pressure pulse tests, but none of them gave satisfactory results. Instead, a stationary method was developed for evaluation of pressure pulse tests.

The stationary method used to evaluate the pressure pulse tests should be regarded as a simple tool to estimate transmissivities below the standard measurement limit of the PSS system /10/. This method is described below and is in this report referred to as the stationary evaluation method. Firstly, some assumptions have to be made when estimating the packer generated flow:

- The test section which exhibited the highest pressure increase due to packer generated flow (packer compliance) in conjunction with pressure pulse tests performed with PSS at Forsmark so far, can be regarded as virtually impermeable, i.e. the flow rate into the formation is much less than the flow rate generated by the packers. The highest pressure increase so far (107.1 Pa/s) was observed during the pressure pulse test in section 244–249 m in KFM07B.
- The average flow rate generated by the packers in this section can be calculated according to Equation (5-8) based on the corresponding pressure increase (dp_{packer}) in this section during the first time interval (dt) of the recovery period after the application of the pressure pulse due to packer compliance. By this calculation, the estimated effective borehole storage coefficient (C_{eff}) for the actual test section length from the laboratory tests /10/ is used. The value of C_{eff} for a 5 m test section is presented in Table 5-2.
- The estimated effective borehole coefficient (C_{eff}) from laboratory tests is assumed to also be valid for field tests.

$$Q_{ave\ (packer)} = C_{eff} \frac{dp_{packer}}{dt} \tag{5-8}$$

$Q_{ave\ (packer)}$ = Average packer generated flow during the time interval dt (m^3/s).

C_{eff} = Effective borehole storage coefficient of test section (m^3/Pa).

dp_{packer}/dt = Rate of pressure increase during first phase of the recovery period due to packer compliance in a virtually impermeable test section (Pa/s).

By the estimation of transmissivity some additional assumptions are made:

- The packer-generated flow rate is assumed to be identical in all test sections (independent of the section length) and equal to the estimated flow in the selected virtually impermeable section mentioned above. However, there are some indications from field tests that this assumption may not always be correct (the flow may vary from test to test).
- The pressure pulse is applied at the same time after start of packer sealing for all tests. This assumption also includes the impermeable section which was used to estimate the packer generated flow rate.

The average flow rate into the formation during the first phase of the recovery period of a pressure pulse test may be calculated based on the estimated packer-generated flow rate (from Equation (5-8)) and the actual change of borehole storage (water and packers) in the test section according to Equation (5-9). The change of borehole storage in the test section (dV/dt) is calculated from the observed pressure change (dp) during a certain period (dt) of the first phase of the recovery period (e.g. 10 min) and the estimated effective borehole storage coefficient (C_{eff}) for the actual section length from laboratory tests according to Equation (5-10).

$$Q_{ave\ (formation)} = Q_{ave\ (packer)} + dV/dt \tag{5-9}$$

$Q_{ave\ (formation)}$ = Average flow rate into the formation during time interval dt (m^3/s).

$Q_{ave\ (packer)}$ = Average packer generated flow rate (m^3/s).

dV/dt = Change of borehole storage in test section (m^3/s).

$$dV/dt = C_{eff}\,\frac{dp}{dt} \qquad (5\text{-}10)$$

dp/dt = Rate of pressure change during the initial phase of the recovery period (Pa/s).

The packer generated flow is thus calculated from the virtually impermeable section KFM07B: 244–249 m and is assumed to be the same for all tested sections in KFM07B. The change of borehole storage, dV/dt, however, is calculated individually for each test to give the test-specific average flow rate into the formation, $Q_{ave\ (formation)}$. For the borehole storage, the sign convention is that a *decreasing* pressure during the selected 10 minute interval results in a *positive* dp/dt and an *increasing* pressure results in a *negative* dp/dt.

Finally, the transmissivity is estimated by a stationary evaluation according to Equation (5-11), based on the estimated average flow rate into the formation and the applied head difference dh_p during the pulse period. If the head difference during the first phase of the recovery period is significantly different from dh_p and/or varies during this period, an average value on dh_p may be used in Equation (5-11).

$$T_{ss,\ pulse} = Q_{ave\ (formation)} / dh_p \qquad (5\text{-}11)$$

$T_{ss,\ pulse}$ = Estimated stationary transmissivity from pressure pulse test (m^2/s)

dh_p = Applied head difference during the pulse period or actual head difference during the first phase of the recovery period (m)

The method gives a possibility to roughly estimate the transmissivity in very low-conductive sections (also when the pressure is still increasing during the recovery period).

5.5 Nonconformities

The test program in KFM07B was carried out according to the Activity Plan AP PF 400-05-049 with the following exceptions:

- The tecalan hose connected to P_{bubbel}, the transducer measuring the ground water level, could not be put into position in the borehole before testing. This was due to the small diameter of the upper part of the borehole which made it impossible to get it down to the groundwater table.
- The packers were expanded progressively and the nominal expansion pressure could not be reached for section 249.0–254.0 m or any of the sections below that position. This was because the pressure below the test section rose too much due to packer compliance. This makes the effects from the packer compliance even more unpredictable.
- Because the packers had to be expanded manually, see above, the actual packer expansion times may differ slightly from test to test.
- Not all planned injection tests were performed. This was because the rapidly increasing pressure below the test section when expanding the packers made it very difficult to expand the packers enough. Additionally, calculations showed that the total transmissivity in the remaining part of the borehole would not exceed the lower measurement limit for the equipment. The planned last four tests were therefore not performed.

6 Results

6.1 Nomenclature and symbols

The nomenclature and symbols used for the results of the injection tests in KFM07B are in accordance with the Instruction for analysis of injection and single-hole pumping tests (SKB MD 320.004). Additional symbols 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 and selected pressure and flow data from all tests are listed in Appendix 2.1 and 2.2, respectively.

Some unexplained pressure disturbances were registered above the test section during all of the tests. The pressure above the test section started to decrease in connection with the packer expansion in all but one test where the opposite, a pressure increase, was detected. The pressure stabilized a few minutes after the start of the packer expansion at a new level, differing from the level before packer expansion by c 3–5 kPa. This is not believed to have affected any of the tests since the pressure in the test section was always stable before the start of the injection. Drilling of KFM01D and pumping in HFM01 as well as rinse pumping in KFM01C are activities that may have affected the pressure in KFM07B even though no evident signs of that have been discovered.

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. The reference marks are used to make length corrections, i.e. to adjust the length scale for the injection tests according to the reference marks. In KFM07B, four reference marks, at 100, 150, 200 and 250 m along the borehole, have been milled into the borehole wall.

During the injection tests in KFM07B with the PSS, all length reference marks were detected. At each mark, the length scale for the injection tests was adjusted according to the reported length to the reference mark.

The largest difference between the reported and measured lengths at the reference marks during the injection tests was 0.16 m, which occurred at the 250 m reference mark. The difference between two consecutive measurements 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 because 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.

6.2.3 General results

A summary of the results of the routine evaluation of the injection tests and pressure pulse tests is presented, test by test, in Table 6-1 and Table 6-2 respectively. Figure 6-2 shows the most representative transmissivity values from both injection- and pressure pulse tests in KFM07B. 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 are presented for the injection tests. The quantitative analysis was performed from such diagrams using the AQTESOLV software. For each pressure pulse test one linear diagram showing the entire test sequence together with a lin-log diagram displaying the normalized recovery H/H_0 plotted versus elapsed time is presented. From pressure pulse tests that were interrupted during the recovery period because of increasing pressure, only the linear diagram is presented. The results of the routine evaluation of the tests in borehole KFM07B are also compiled in appropriate tables in Appendix 5 to be stored in the SICADA database.

The last four tests that were planned in the deepest part of KFM07B were never executed. This was because that part of the borehole was so tight that it made normal expansion of the packers impossible. An approximate calculation using numbers from the packer compliance calculations discussed in Section 5.4.4, produced results that showed that the total transmissivity of the remaining borehole would be clearly below the measurement limit.

Injection tests

For the injection tests, transient evaluation was conducted, whenever possible, both on the injection and recovery periods (T_f and T_s, respectively) according to the methods described in Section 5.4.4. The steady-state transmissivity (T_M) was calculated by Moye's formula according to Equation 5-1. The quantitative analysis was performed using the AQTESOLV software.

The dominating transient flow regimes during the injection and recovery periods, as interpreted from the qualitative test evaluation, are listed in Table 6-1 and are further commented on in Section 6.2.4. Pseudo-radial flow was not reached during the recovery period in any of the tests. On the other hand, during the injection period, a certain time interval with pseudo-radial flow could, in two out of four tests with a definable Q_p, be identified. Standard methods for single-hole tests with wellbore storage and skin effects were generally used for the routine evaluation of the tests. The approximate start and stop times of the pseudo-radial flow regime used for the transient evaluation are also listed in Table 6-1.

The transmissivity judged as the most reliable from the transient evaluation of the flow- and recovery periods of the tests was selected as T_T. The associated value of the skin factor is listed in Table 6-1. Equally many representative values of transmissivity, T_R, have been chosen from the injection period as from the recovery period in KFM07B.

For those tests where transient evaluation is not possible or not considered representative, T_M is to be chosen as the representative transmissivity value, T_R. In KFM07B, T_M was never chosen as the most representative value in tests with a definable Q_p. If Q_p is below the actual test-specific measurement limit, the representative transmissivity value is assumed to be less than the estimated T_M, based on Q/s-measl-L, see Section 5.4.2 and 5.4.4

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

Table 6-1. Summary of the routine evaluation of the single-hole injection tests in borehole KFM07B.

Secup	Seclow	Test start	b	Flow regime 1)		T_M	T_f	T_s	T_T	T_R	ξ	t_1	t_2	dte_1	dte_2	C	r_i	r_i-index
(m)	(m)	YYYYMMDD hh:mm	(m)	injection	Reco-very	(m^2/s)	(m^2/s)	(m^2/s)	(m^2/s)	(m^2/s)	(–)	(s)	(s)	(s)	(s)	(m^3/Pa)	(m)	(–)
209.00	214.00	20060123 09:22	5.00			1.65E–10				1.65E–10								
219.00	224.00	20060123 12:51	5.00			1.65E–10				1.65E–10								
224.00	229.00	20060123 13:46	5.00	PSF	PSF	5.88E–09	2.98E–09	4.24E–09	2.98E–09	2.98E–09	–2.62						14.61	0
229.00	234.00	20060125 16:17	5.00	PRF1- > PRF2	WBS- > PSF- > PSS	1.36E–09	2.21E–09	1.83E–09	2.21E–09	2.21E–09	0.64	10	100			1.79E–11	3.89	1
234.00	239.00	20060123 16:46	5.00	PRF1- > PRF2	(WBS)- > PSS	3.57E–08	1.12E–07	4.27E–08	4.27E–08	4.27E–08	5.41	500	1,200				28.33	–1
239.00	244.00	20060124 06:46	5.00	PLF- > NFB	PLF	7.09E–10		4.37E–10	4.37E–10	4.37E–10	–4.64						9.02	0

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 5.4.3 above.

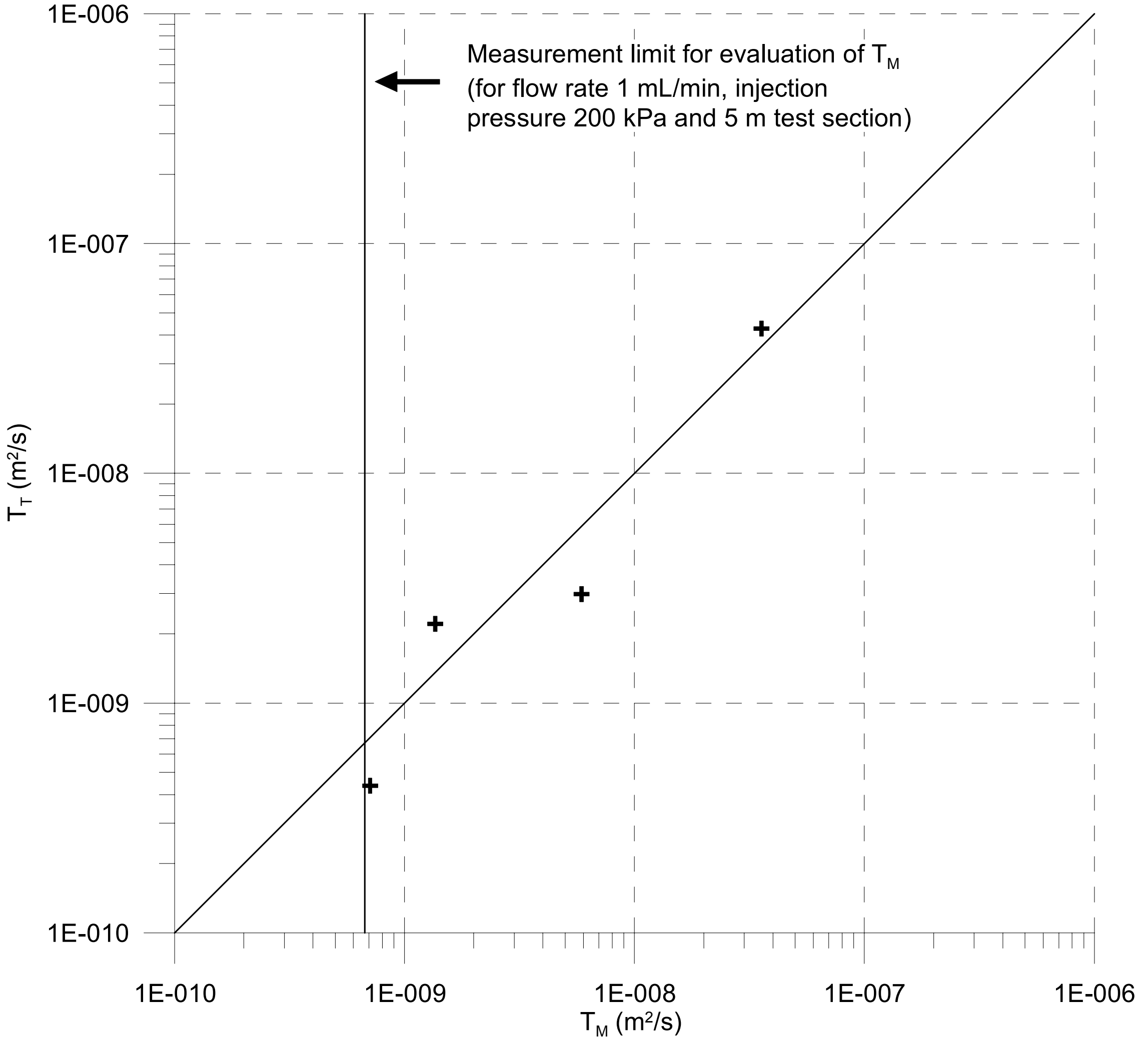

Figure 6-1. *Estimated transmissivities in 5 m sections from steady-state (T_M) and transient (T_T) evaluation for the injection tests in KFM07B.*

The wellbore storage coefficient, C, was calculated from the straight line with a unit slope in the log-log diagrams from the recovery period in KFM07B, see Table 6-1. The coefficient C was only calculated for tests with a well-defined line of unit slope in the beginning of the recovery period, which during this campaign only happened in one section. In the more conductive sections, this period occurred during very short intervals at very early times and is not visible in the diagrams. In sections with a very low transmissivity, the estimates of C may be uncertain due to difficulties in defining an accurate time for the start of the recovery period. Furthermore, the resolution of the pressure sensors causes the recovery to be quite scattered in sections of low transmissivity. The values of C presented in Table 6-1 may be compared with the net values of C, C_{net} (based on geometry) and the value of C obtained from laboratory experiments, C_{eff} /10/, both found in Table 5-2.

As mentioned above, there was only one test with a well-defined line of unit slope for which it was possible to calculate C. Table 6-1 shows that the calculated value from the test is slightly higher than C_{net} presented in Table 5-2. However, when the calculated value is compared to the value C_{eff} obtained from laboratory experiments, the agreement is better, although the calculated value is still slightly higher. This is an expected result which has been observed also in other boreholes.

Pressure pulse tests

Transient evaluation was performed for the pressure pulse tests, together with the stationary evaluation described in Section 5.4.4, except for the tests that were interrupted because the pressure increased after the pulse. For these tests only the stationary method was applied.

In Table 6-2 the results from the transient evaluation ($T_{T,\ pulse}$) and from the stationary evaluation ($T_{ss,\ pulse}$) are presented together with the selected, most representative estimate of transmissivity, $T_{R,\ pulse}$.

For all of the pulse tests the stationary evaluation was considered as the most representative. This is, for a majority of the tests, due to the fact that the packers strongly affect the section, resulting in an underestimation of the transmissivities by the transient evaluation. The transmissivity value reported for the individual pulse test is also chosen as the lower measurement limit for the specific test section. However, no values lower than 5.0×10^{-11} m^2/s are regarded to be representative, entailing that the results from the individual pulse tests only represent the upper limit of transmissivity for that section. This also means that all values will be reported to SICADA as on, or below, measurement limit, indicated by value type –1, cf Appendix 5.

For the two pressure pulse tests where a transient evaluation was possible, the value from the transient evaluation was much lower than the value from the stationary evaluation due to packer compliance. In fact, the values from the transient evaluations were even smaller than the transmissivities in the sections showing a pressure increase after the pulse which, however, is not likely. Hence the larger transmissivity value, from the stationary evaluation was chosen.

The method used to estimate the stationary transmissivity presupposes that section 244.0–249.0 m is virtually impermeable, and therefore no evaluation can be made for this section. The transmissivity is considered to be less than 5.0×10^{-11} m^2/s.

In total, five sections have an estimated transmissivity lower than 5.0×10^{-11} m^2/s, all of these being the ones where the pressure still increases after the pulse.

No standard tests were performed in KFM07B below 279.0 m due to difficulties in expanding the packers. Calculations of transmissivity for section 279.0–298.9 m using similar methods as used for the pressure pulse tests were however done. The results showed that the total transmissivity in the remaining part of the borehole was below the measurement limit. This result is included in Table 6-2 and Figure 6-2 below as well as reported to SICADA.

Table 6-2. Summary of the routine evaluation of the single-hole pressure pulse tests in borehole KFM07B.

Secup (m)	Seclow (m)	Test start YYYYMMDD hh:mm	b (m)	$T_{ss,\ pulse}$ (m^2/s)	$T_{T,\ pulse}$ (m^2/s)	ξ (–)	$T_{meas.\ limit}$ (m^2/s)	$T_{R,\ pulse}$ (m)
214.00	219.00	20060123 10:28	5.00	6.28E–11			6.28E–11	6.28E–11
244.00	249.00	20060124 08:47	5.00	0.00E+00			5.00E–11	5.00E–11
249.00	254.00	20060124 10:19	5.00	4.68E–11			5.00E–11	5.00E–11
254.00	259.00	20060124 12:34	5.00	7.36E–11	8.00E–12	10.00	7.36E–11	7.36E–11
259.00	264.00	20060124 14:36	5.00	1.12E–10	3.15E–12	–3.53	1.12E–10	1.12E–10
264.00	269.00	20060125 09:22	5.00	1.78E–11			5.00E–11	5.00E–11
269.00	274.00	20060125 11:00	5.00	5.18E–11			5.18E–11	5.18E–11
274.00	279.00	20060125 12:59	5.00	1.51E–11			5.00E–11	5.00E–11
280.00	298.9	20060125 12:59	18.90	1.23E–12			5.00E–11	5.00E–11

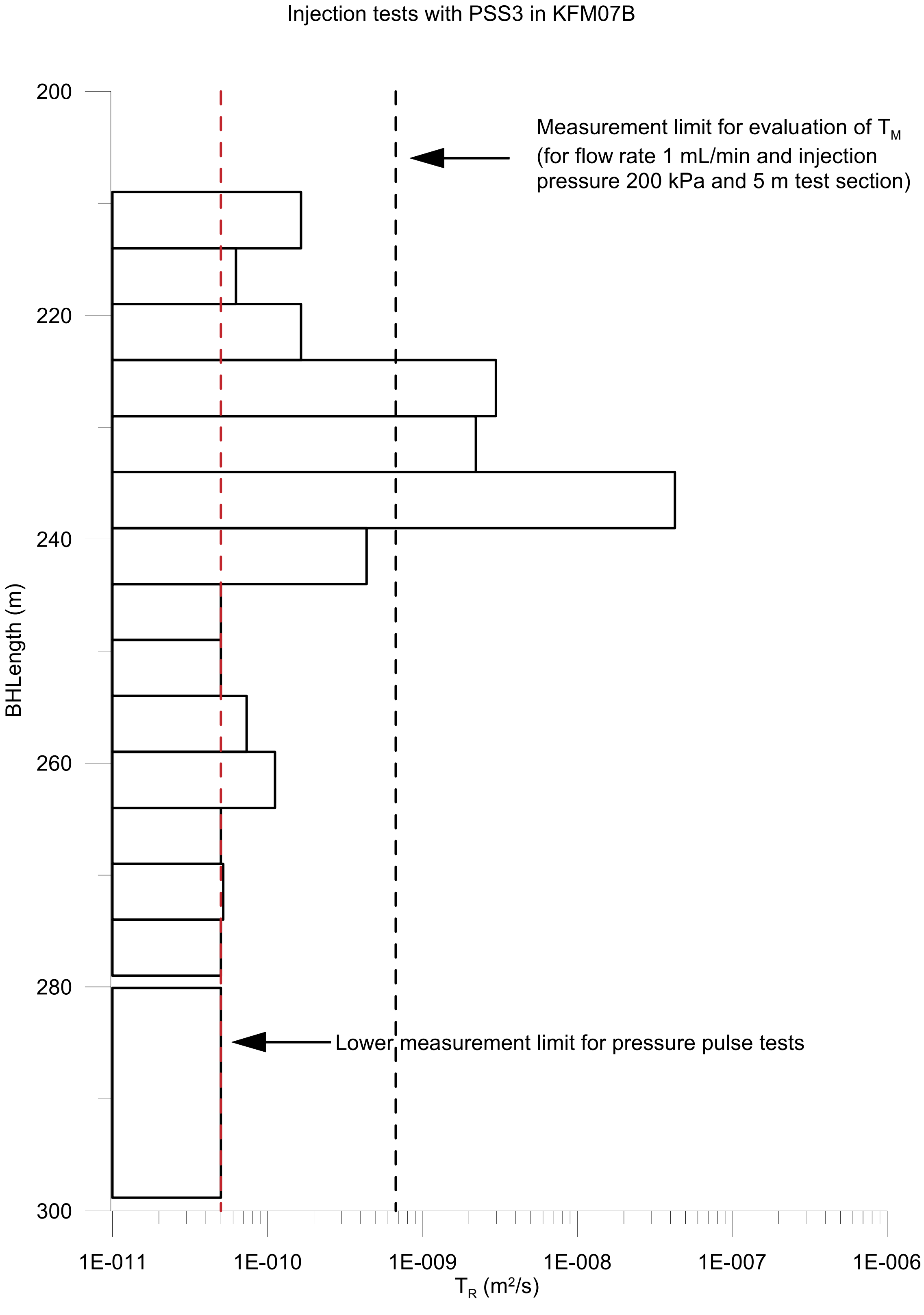

Figure 6-2. *Estimated best representative transmissivity values (T_R and $T_{R,\ pulse}$) from both injection tests and pressure pulse tests for sections of 5 m length in borehole KFM07B as well as the value of transmissivity from the single packer test below 280 m. The estimated transmissivity value for the lower standard measurement limit from stationary evaluation of injection tests (T_M-measl-L) is also shown together with the lower measurement limit for pressure pulse tests.*

6.2.4 Comments on the tests

Short comments on each test follow below. Flow regimes and hydraulic boundaries, as discussed in Section 5.4.3, 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
CHB = Constant-head boundary

209.0–214.0 m

The test section has a very low transmissivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. The injection time was therefore shortened. As a result T_M, based on Q/s-measl-L, was considered to be the most representative transmissivity value for this section.

214.0–219.0 m (Pressure pulse test)

The test was performed as a pulse test. Following the pulse, only a pressure increase was registered, indicating that the section is of such low transmissivity that the packer expansion is influencing the pressure in the test section throughout the test period. Since the pressure increases, the test vas terminated after 10 minutes of recovery and no transient evaluation was made.

219.0–224.0 m

The test section has a very low transmissivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. The injection time was therefore shortened. As a result T_M, based on Q/s-measl-L, was considered to be the most representative transmissivity value for this section.

224.0–229.0 m

During the injection period a PSF is dominating. The recovery period only shows signs of a transition period into a PSF which then lasts throughout the recovery period. The pressure is almost completely recovered after c 300 s of the recovery period.

229.0–234.0 m

The injection period displays an early PRF, beginning after c 10 s and lasting until approximately 100 s, when another PRF with a slightly lower transmissivity starts. The second PRF lasts throughout the injection period. The pressure in the test section recovers very rapidly and is almost fully recovered after c 600 s. The recovery shows signs of WBS transitioning to PSF and PSS by the end of the period with rapidly decreasing derivative approaching zero. Transient evaluation was made using the Hantush' model on the recovery period. The latter evaluation gives consistent results with the injection period.

234.0–239.0 m

The injection period is dominated by an apparent PRF or possibly two separate PRFs where the second period of PRF starts c 500 s into, and lasts until the end of the flow period. Evaluation using a model for radial flow produces very high skin values. During the recovery period the pressure decreases very quickly and is approximately fully recovered after c 100 s, after which only a PSS is present. A short period of WBS and a transition period precede the PSS. Due to the high skin factor from the injection period, the evaluated transmissivity from the recovery period was chosen as the best representative transmissivity value for this section. The choice is supported by the stationary evaluation which provides similar results.

239.0–244.0 m

The injection period indicates a PLF transitioning to an apparent NFB by the end of the flow period. No unambiguous transient evaluation is possible on this period. The recovery period is dominated by a PLF. The pressure below the test section is strongly affected by the packer expansion, indicating that the borehole interval below the lower packer is of low transmissivity.

244.0–249.0 m (Pressure pulse test)

The pressure increase after the pulse is large, indicating a very low transmissivity. Since the pressure increases the test vas terminated after 10 minutes of recovery and no transient evaluation was made. The pressure increase after the pulse was the largest measured so far, hence this section is regarded as completely tight, i.e. the flow rate into the formation is much less than the flow rate generated by the packers. This means that no evaluation can be made of the transmissivity in this section which therefore is considered to be lower than the measurement limit of 5.0×10^{-11} m^2/s. The pressure increase was rapid both after the first and the second closing of the test valve. When expanding the packers the pressure in the section below the test section rises and slowly recovers during the rest of the tests. This indicates a rather low transmissivity also below the tested section.

249.0–254.0 m (Pressure pulse test)

The pressure increases after the pulse, indicating a very low transmissivity. Since the pressure increases the test vas terminated after 10 minutes of recovery and no transient evaluation was made. The transmissivity in this section is lower than the measurement limit of 5.0×10^{-11} m^2/s. When the test valve was closed for the first time, the pressure increase in the section was larger than after the second closing. The pressure in the section below the test section increases a lot when the packers are expanded, again pointing out that transmissivity is low in the section below the test section. The packer expansion had to be performed progressively and the nominal expansion pressure could not be reached due to the increasing pressure in the section below the test section.

254.0–259.0 m (Pressure pulse test)

The recovery from this pulse test shows a very small but visible decrease in the pressure. H_0 is calculated as $P_p – P_0$. The transient evaluation using the Dougherty-Babu model did not result in any good fit, and the T-value from the stationary evaluation of the test is therefore chosen as the most representative. The expansion of the packers caused an increased pressure in the section below the test section. Pressure in the section above however decreased after the expansion of the packer. The packer expansion had to be performed progressively and the nominal expansion pressure could not be reached due to the increasing pressure in the section below the test section.

259.0–264.0 m (Pressure pulse test)

Recovery from this pulse test shows a rather large recovery of the pressure. Since the pressure increase after the second closing of the test valve is not so large, the head is calculated as P_p–P_i. The Babu model resulted in a good fit, but the T-value from this evaluation is lower than values from sections with increasing pressure after the pulse, which is not likely. Therefore the transmissivity obtained from the stationary evaluation is regarded as representative for this section. The packer expansion had to be performed progressively and the nominal expansion pressure could not be reached due to the increasing pressure in the section below the test section.

264.0–269.0 m (Pressure pulse test)

The pressure increases after the pulse, indicating a very low transmissivity. Since the pressure increases the test vas terminated after 10 minutes of recovery and no transient evaluation was made. When the test valve was closed for the first time the pressure increase in the section was larger than after the second closing. The transmissivity in this section is lower than the measurement limit of 5.0×10^{-11} m^2/s. The pressure in the section below the test section increases a lot when the packers are expanded, again pointing out that transmissivity is low in the section below this section. The packer expansion had to be conducted progressively and the nominal expansion pressure could not be reached due to the increasing pressure in the section below the test section.

269.0–274.0 m (Pressure pulse test)

The pressure increases after the pulse, indicating a very low transmissivity. Since the pressure increases the test vas terminated after 10 minutes of recovery and no transient evaluation was made. The transmissivity in this section is lower than the measurement limit of 5.0×10^{-11} m^2/s. When the test valve was closed for the first time, the pressure increase in the section was larger than after the second closing. The pressure in the section below increases a lot when the packers are expanded, and recovers very slowly during the rest of the test, again pointing out that transmissivity is low in the section below this section. The packer expansion had to be performed progressively and the nominal expansion pressure could not be reached due to the increasing pressure in the section below the test section.

274.0–279.0 m (Pressure pulse test)

The pressure increases after the pulse, indicating a very low transmissivity. Since the pressure increases the test vas terminated after 10 minutes of recovery and no transient evaluation was made. The transmissivity in this section is lower than the measurement limit of 5.0×10^{-11} m^2/s. When the test valve was closed for the first time, the pressure increase in the section was larger than after the second closing. The pressure in the section below the test section increases a lot when the packers are expanded, and shows almost no recovery during the rest of the test, pointing out that the transmissivity is very low in the deepest parts of the borehole. The packer expansion had to be performed progressively and the nominal expansion pressure could not be reached due to the increasing pressure in the section below the test section.

280.0–298.9 m (Pressure pulse test below single packer)

Evaluation of the pressure increase below test section 274.0–279.0 m caused by packer compliance was performed by methods corresponding to those used for ordinary pressure pulse tests but adjusted for the flow induced by a single packer. The results show that the total remaining transmissivity in the lower parts of the borehole (below 280 m) is considerably lower than the measurement limit at 5.0×10^{-11} m^2/s. No further tests were made below test position 274.0–279.0 m.

6.2.5 Flow regimes

A summary of the frequency of identified flow regimes is presented in Table 6-3, which shows all identified flow regimes during the tests. For example, a pseudo-radial flow regime (PRF) transitioning to a pseudo-spherical flow regime (PSF) will contribute to one observation of PRF and one observation of PSF. The numbers within brackets denote the number of tests where the actual flow regime is the only one present.

It should be noted that the interpretation of flow regimes is only tentative and only based on visual inspection of the data curves. It should also be observed that there might be some pseudo-linear flow regime during the beginning of an injection period that is missed due to the fact that a certain time is required for achieving a constant pressure, which may mask the initial flow regime.

No flow regimes have been identified for the pressure pulse tests; hence Table 6-3 is only valid for the injection tests.

Table 6-3 shows that a certain period of pseudo-radial flow could be identified from the injection period in two of the four tests that had a definable Q_p. The PRF was also the most common flow regime for the injection period. During the recovery period, an even distribution of flow regimes was detected, except for the PRF and the NFB which were never observed.

Table 6-3. Interpreted flow regimes during the injection tests in KFM07B.

Borehole	Section length (m)	Number of injection tests[1)]	Number of tests with definable Qp	Injection period					Recovery period					
				PLF	PRF	PSF	PSS	NFB	WBS	PLF	PRF	PSF	PSS	NFB
KFM07B	5	6	4	1(0)	2(2)	1(1)	0(0)	1(0)	2(0)	1(1)	0(0)	2(1)	2(0)	0(0)

1) Only the injection tests are included in this table.

6.3 Basic statistics of hydraulic conductivity distributions

Some basic statistical parameters were calculated for the hydraulic conductivity distributions from the tests in borehole KFM07B. The hydraulic conductivity is obtained by dividing the transmissivity by the section length, in this case T_R/L_w. The basic statistical parameters were derived for the hydraulic conductivity considered most representative ($K_R=T_R/L_w$), including all tests, both injection- and pressure pulse tests. In the statistical analysis, the logarithm (base 10) of K_R was used. Selected results are shown in Table 6-4.

Section 244.0–249.0 m borehole length, was the tightest section measured during the testing in KFM07B. It was also the tightest section measured so far with pressure pulse tests in Forsmark. Therefore it is considered, by definition, to be completely non-conductive. Still, it is included in the statistical calculations that Table 6-4 is based on, and the practical measurement limit for pulse tests is us used for this section, cf Table 6-2.

Table 6-4. Basic statistical parameters for the hydraulic conductivity considered most representative (K_R) in borehole KFM07B. L_w=section length, m=arithmetic mean, s=standard deviation.

Borehole	Parameter	Unit	Lw=5 m
KFM07B	Measured borehole interval	m	209.0–279.0
KFM07B	Total number of tests	–	14
KFM07B	No. of pulse tests	–	8
KFM07B	m (Log10(KR))	Log10(m/s)	–10.36
KFM07B	s (Log10(KR))	–	0.89

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Forsmark site investigation

Single-hole injection tests and pressure pulse tests in borehole KFM07B

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Keywords: Forsmark, Hydrogeology, Hydraulic tests, Injection tests, Pressure pulse tests, Single-hole tests, Hydraulic parameters, Transmissivity, Hydraulic conductivity, AP PF 400-05-049.

Abstract

Borehole KFM07B is a 300 m long core-drilled borehole within the site investigation area in Forsmark. The borehole is inclined c 54 degrees from the horizontal plane. This borehole has been injected with cement down to about 209 m, except in a section between c 66 and 70 m along the borehole. The borehole diameter is approximately 76 mm.

This report presents injection tests and pressure pulse tests performed using the pipe string system PSS3 in borehole KFM07B and the test results. Pressure pulse tests were performed instead of injection tests in sections where the flow rate was assumed to be below or close to the measurement limit for injection tests.

The main aim of the injection tests and pressure pulse tests in KFM07B was to characterize the hydraulic conditions of the rock adjacent to the borehole on a 5 m measurement scale. Hydraulic parameters such as transmissivity and hydraulic conductivity together with the dominating flow regime and possible outer hydraulic boundaries were determined using analysis methods for stationary as well as transient conditions.

Six of the tests in KFM07B were performed as injection tests and in four of those, the transient evaluation was chosen as representative. The evaluation was done from the injection period in two of those tests and from the recovery period in the remaining two tests. In two of the injection tests a period with pseudo-radial flow could be identified. The PRF was, however, chosen for evaluation only in one of those cases. The pressure pulse tests were evaluated using a stationary evaluation method. For 2 out of 8 pressure pulse tests a transient evaluation was also possible, however the values from the transient evaluation were not regarded as representative.

No highly conductive sections were found in KFM07B. The highest transmissivity was detected in section 234–239 m, at 4.3×10^{-8} m^2/s.

The injection tests provide a database for statistical analysis of the hydraulic conductivity distribution along the borehole. Basic statistical parameters are presented in this report.

Sammanfattning

Borrhål KFM07B är ett ca 300 m långt, lutande kärnborrhål, som borrats inom ramen för platsundersökningarna i Forsmarksområdet. Lutningen på borrhålet är ca 54 grader från horisontalplanet. Detta borrhål har injekterats med cement ner till ca 209 m, förutom i ett avsnitt mellan ca 66 och 70 m längs borrhålet. Borrhålets innerdiameter är ca 76 mm.

Denna rapport beskriver genomförda injektionstester och pulstester med rörgångssystemet PSS3 i borrhål KFM07B samt resultaten från desamma. Pulstester genomfördes i stället för injektionstester i några sektioner där flödet befarades hamna under mätgränsen för injektionstester.

Huvudsyftet med injektionstesterna och pulstesterna var att karaktärisera de hydrauliska förhållandena av berget i anslutning till borrhålet i 5 m mätskala. Hydrauliska parametrar såsom transmissivitet och hydraulisk konduktivitet tillsammans med dominerande flödesregim och eventuella yttre hydrauliska randvillkor, bestämdes med hjälp av analysmetoder för såväl stationära som transienta förhållanden.

Sex av testerna i KFM07B utfördes som injektionstester och i fyra av dessa ansågs den transienta utvärderingen som mest representativ. Utvärderingen utfördes på injektionsperioden i två av dessa tester och på återhämtningen i de övriga två testerna. I två av injektionstesterna kunde en viss period med pseudoradiellt flöde identifieras. Perioden med PRF valdes dock för utvärdering endast i ett av dessa fall. Pulstesterna utvärderades med en stationär metod. Transient utvärdering var också möjlig för 2 av 8 pulstester, men värdena från den transienta utvärderingen ansågs inte vara representativa.

Inga högkonduktiva sektioner återfanns i KFM07B. Den högsta transmissiviteten i borrhålet, $4{,}3 \times 10^{-8}$ m^2/s, registrerades i sektionen 234–239 m.

Resultaten från injektionstesterna utgör en databas för statistisk analys av den hydrauliska konduktivitetens fördelning längs borrhålet. Viss statistisk analys har utförts inom ramen för denna aktivitet och grundläggande statistiska parametrar presenteras i rapporten.

Contents

Appendix on CD

1 Introduction

Injection tests and pressure pulse tests were carried out in borehole KFM07B at Forsmark, Sweden, during January 2006 by GEOSIGMA AB. The borehole KFM07B is a core-drilled borehole within the on-going site investigation in the Forsmark area. It is c 300 m long, inclined c 54 degrees from the horizontal and cased to c 65 m depth. This borehole has been injected with cement below the casing down to about 209 m, except in a section between the casing and 70 m along the borehole. The borehole diameter is approximately 76 mm. The location of the borehole is shown in Figure 1-1.

This document reports the results obtained from hydraulic tests in borehole KFM07B. Primarily injection tests were performed. However, in sections for which a flow rate below or close to the measurement limit for injection tests was expected, pressure pulse tests were carried out instead. 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, where they are traceable by the activity plan number.

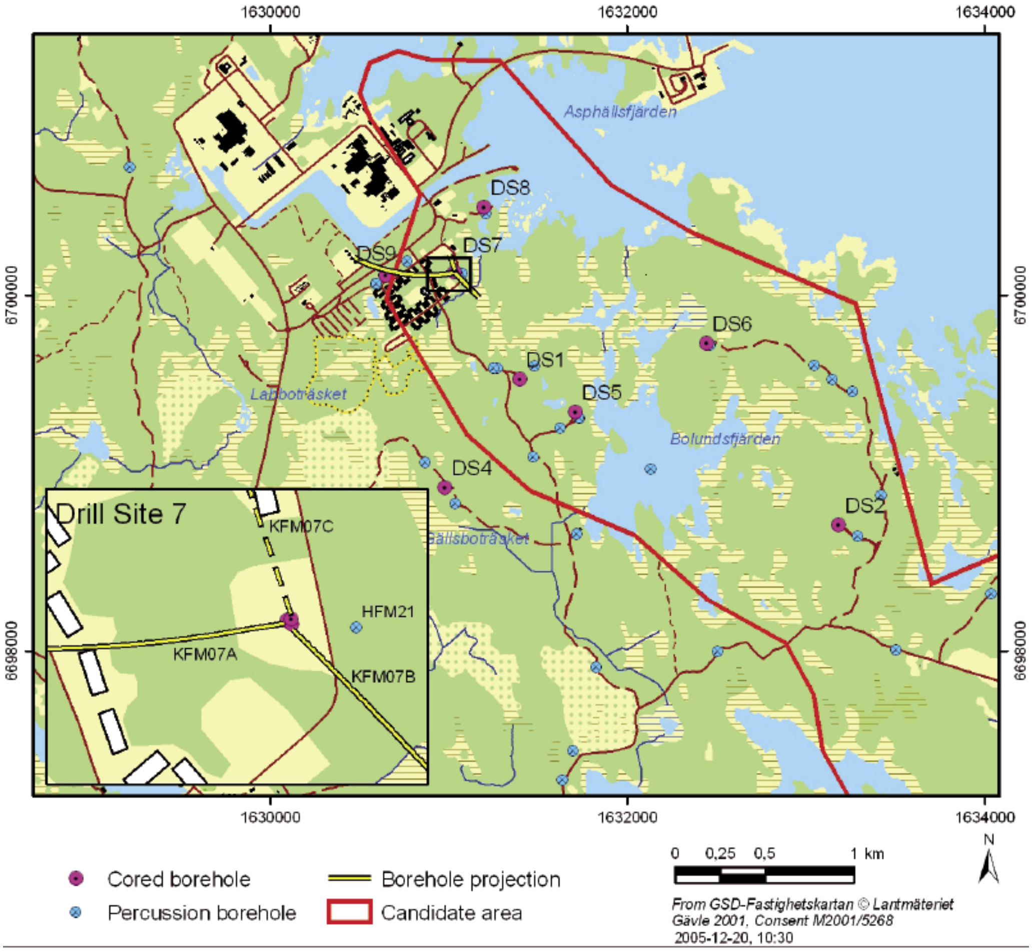

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***Figure 1-1.** The investigation area at Forsmark including part of the candidate area selected for more detailed investigations. Borehole KFM07B is situated at drill site 7 (DS7).*

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

Activity Plans	**Number**	**Version**
Hydraulic injection tests in borehole KFM07B with PSS3	AP PF 400-05-049	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
Instruktion för rengöring av borrhålsutrustning och viss markbaserad utrustning	SKB MD 600.004	1.0

2 Objectives

The main aim of the injection- and pressure pulse tests in borehole KFM07B was to characterize the hydraulic properties of the rock adjacent to the borehole on a 5 m measurement scale. 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 flow- and recovery periods.

The results of the injection tests provide a database which can be used for statistical analyses of the hydraulic conductivity distribution along the borehole. Basic statistical analyses are presented in this report.

3 Scope

3.1 Borehole

Technical data of the tested borehole are shown in Tables 3-1 and in Appendix 4. The reference point of the borehole 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 KFM07B (printout from SKB database, SICADA).

Borehole length (m):	298.930				
Drilling Period(s):	**From Date**	**To Date**	**Secup (m)**	**Seclow (m)**	**Drilling Type**
	2005-05-31	2005-10-18	0.000	298.930	Core drilling
Starting point coordinate:	**Length (m)**	**Northing (m)**	**Easting (m)**	**Elevation**	**Coord System**
	0.000	6700123.622	1631036.833	3.363	RT90-RHB70
Angles:	**Length (m)**	**Bearing**	**Inclination (– = down)**		
	0.000	134.346	–53.713		
Borehole diameter:	**Secup (m)**	**Seclow (m)**	**Hole Diam (m)**		
	0.000	5.180	0.116		
	5.180	65.690	0.096		
	65.690	298.930	0.076		
Core diameter:	**Secup (m)**	**Seclow (m)**	**Core Diam (m)**		
	5.180	65.690	0.063		
	65.690	298.930	0.051		
Casing diameter:	**Secup (m)**	**Seclow (m)**	**Case In (m)**	**Case Out (m)/ In (m)**	
	0.000	65.290	0.077	0.090/0.076	

3.2 Tests performed

The injection tests and pressure pulse tests in borehole KFM07B, performed according to Activity Plan AP PF 400-05-049, are listed in Table 3-2. The injection- and pressure pulse tests were carried out with the Pipe String System (PSS3). The test procedure and the equipment is described in the measurement system description for PSS (SKB MD 345.100) and in the corresponding method descriptions for hydraulic injection tests (SKB MD 323.001), see Table 1-1.

On at least one occasion the test was not performed as intended because the time required for achieving a constant head in the test section was judged to be too long, or equipment malfunctions caused pressure and/or flow rate disturbances. Whenever such disturbances were expected to affect data evaluation, the test was repeated. Test number (Test no in Table 3-2) refers to the number of tests performed in the actual section. For evaluation, only data from the last test in each section were used.

Table 3-2. Single-hole injection tests and pressure pulse tests performed in borehole KFM07B.

Bore hole bh id	Test section secup	 seclow	Section length	Test type[1)] (1–6)	Test no	Test start date, time YYYYMMDD hh:mm	Test stop date, time YYYYMMDD hh:mm
KFM07B	209.00	214.00	5.00	3	1	20060123 09:22	20060123 10:14
KFM07B	214.00	219.00	5.00	4B	1	20060123 10:28	20060123 12:12
KFM07B	219.00	224.00	5.00	3	1	20060123 12:51	20060123 13:33
KFM07B	224.00	229.00	5.00	3	1	20060123 13:46	20060123 15:05
KFM07B	229.00	234.00	5.00	3	2	20060125 16:17	20060125 17:33
KFM07B	234.00	239.00	5.00	3	1	20060123 16:46	20060123 18:02
KFM07B	239.00	244.00	5.00	3	1	20060124 06:46	20060124 08:31
KFM07B	244.00	249.00	5.00	4B	1	20060124 08:47	20060124 10:03
KFM07B	249.00	254.00	5.00	4B	1	20060124 10:19	20060124 12:23
KFM07B	254.00	259.00	5.00	4B	1	20060124 12:34	20060124 14:27
KFM07B	259.00	264.00	5.00	4B	1	20060124 14:36	20060125 09:09
KFM07B	264.00	269.00	5.00	4B	1	20060125 09:22	20060125 10:44
KFM07B	269.00	274.00	5.00	4B	1	20060125 11:00	20060125 12:41
KFM07B	274.00	279.00	5.00	4B	1	20060125 12:59	20060125 14:19

[1)] 3: Injection test, 4B: Pressure pulse test.

Pressure pulse tests were performed instead of injection tests in sections where the transmissivity was expected to be below or near the measurement limit for injection tests. It may be appropriate to perform a pressure pulse test when the flow rate at the end of the injection period is less than c 1.5 mL/min. To decide whether an injection test or a pressure pulse test should be carried out in a particular section, a so called diagnostic test was conducted during the packer inflation period. The diagnostic test involves closing the test valve after 5 minutes of packer inflation and observing the pressure in the test section during the following 5 minutes. A pressure pulse test was made if the pressure increase after 5 minutes exceeded c 20 kPa. Otherwise an injection test was carried out. A pressure pulse test is performed similar to an injection test, the differences being a longer time for packer inflation, a shorter injection (pulse) time and a longer recovery period, see Table 5-1a and Table 5-1b.

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 December 2005.

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). The temperature sensor displayed expected values in both air and water.

Ordinarily, simple functioning checks of down-hole sensors are done at every change of test section interval. For this commission only the 5 m test section was used though, and consequently only one check was performed. 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 a 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 pressure vessels filled with an ethanol mixture. 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 meter. 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.

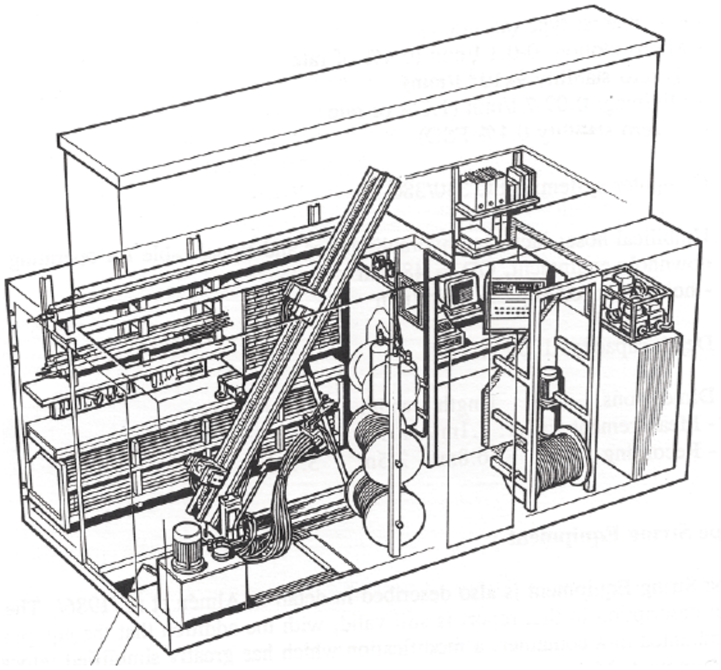

Figure 4-1. *Outline of the PSS3 container with equipment.*

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 (P_a), within (P) and below (P_b) 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 (calliper 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 m).

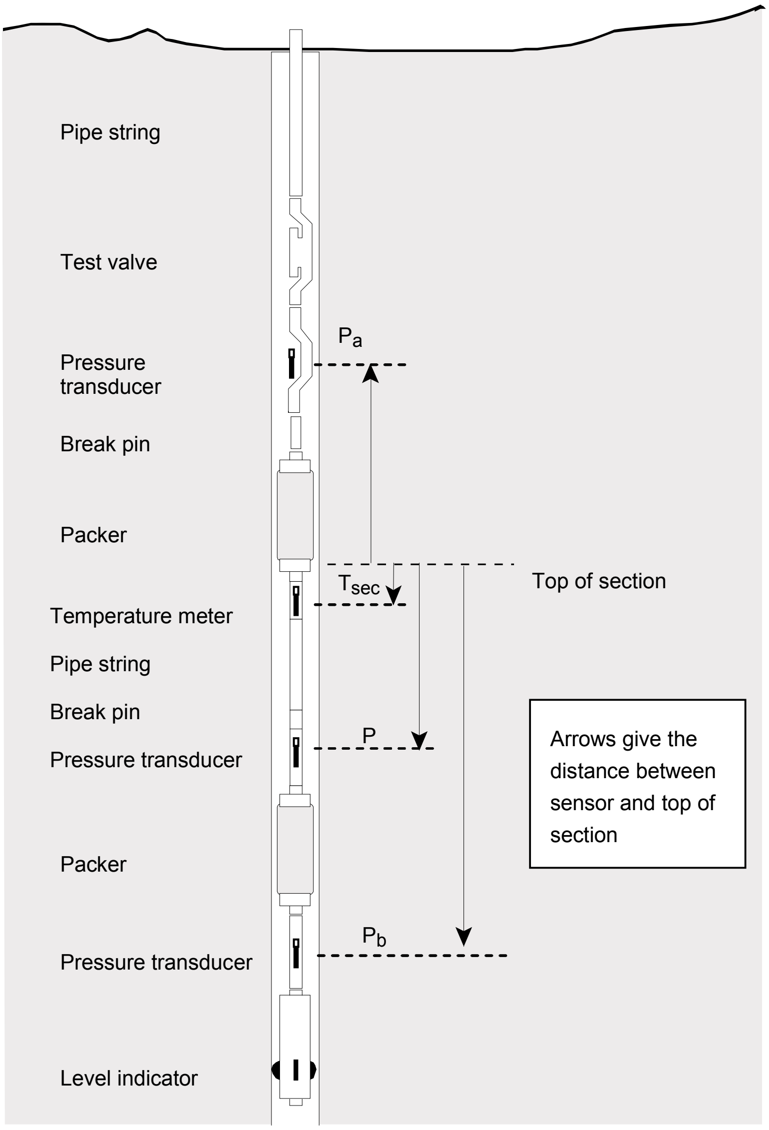

Figure 4-2. Schematic drawing of the down-hole equipment in the PSS3 system.

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 sensors are components of the PSS system. The accuracy of the PSS system may also be affected by the I/O-unit, cf Figure 4-3, and the calibration of the system.

The sensor positions are fixed relative to the top of the test section. In Table 4-2, the position of the sensors as well as displacement volume of equipment are given with top of test section as reference where applicable (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		
	Accuracy1)	% 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	1.67×10^{-5}–1.67×10^{-3}		The specific accuracy is depending on actual flow
	Resolution	m^3/s	6.7×10^{-8}		
	Accuracy2)	% O.R	0.15–0.3	< 1%	
Flow Qsmall	Output signal	mA	4–20		
	Meas. range	m^3/s	1.67×10^{-8}–1.67×10^{-5}		The specific accuracy is depending on actual flow
	Resolution	m^3/s	6.7×10^{-10}		
	Accuracy3)	% O.R	0.1–0.4	0.5–20	

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

2) Maximum error in % of actual reading (% o.r.).

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

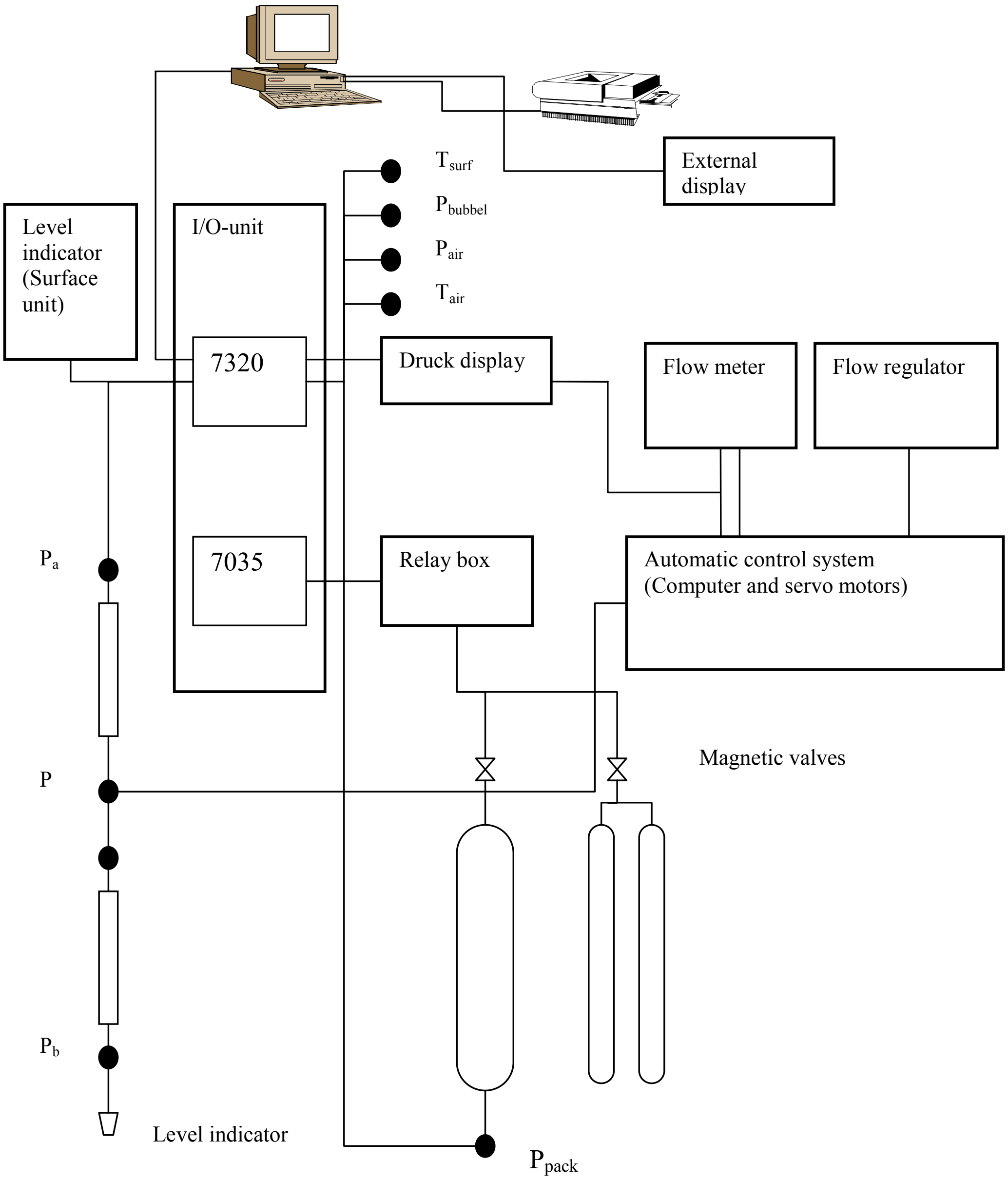

Figure 4-3. *Schematic drawing of the data acquisition system and the automatic control system in PSS.*

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	
	(L)	**(m)**
Equipment displacement volume in test section 1)	3.6	
Total volume of test section 2)	23	
Position for sensor P_a, pressure above test section, (m above secup) 3)		1.88
Position for sensor P, pressure in test section, (m above secup) 3)		–4.12
Position for sensor T_{sec}, Temperature in test section, (m above secup) 3)		–0.96
Position for sensor P_b, pressure below test section, (m above secup) 3)		–7.00

1) Displacement volume in test section due to pipe string, signal cable, sensors and packer ends (in litre).

2) Total volume of test section (V= section length*π*d^2/4) (in litre).

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 parameters, 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.

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 while lowering the pipe string along the borehole.

5.1.3 Cleaning of equipment

Cleaning of the borehole equipment was performed according to the cleaning instruction (SKB MD 600.004, see Table 1-1), level 1.

5.2 Test performance

5.2.1 Test principle

Two kinds of test were performed in KFM07B, injection tests and pressure pulse tests. The injection tests in KFM07B were carried out while maintaining a constant head of generally 200 kPa (c 20 m water column) 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.

Pressure pulse tests were carried out instead of injection tests in some low-conductive sections, where the flow rate was expected to be close to or below the measurement limit for injection tests. The pressure pulse tests in KFM07B were performed by introducing a pressure pulse to the isolated test section. The pulse was accomplished by applying a pressure of c 200 kPa to the pipe string above the test section and then opening the test valve. After 2 minutes the valve was closed and the pressure recovery in the test section was measured.

Pressure pulse tests showing a continuing pressure increase due to packer expansion after the pulse (during the recovery period) were interrupted after c 10 minutes and no transient evaluation was made. A steady-state evaluation was however performed.

5.2.2 Test procedure

Generally, the tests were performed according to the Activity Plan AP PF 400-05-049. Exceptions to this are presented in Section 5.5.

A test cycle of a standard injection test 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.

When the transmissivity in a section was expected to be low, a diagnostic test was conducted to decide whether to perform a pressure pulse test or an injection test. A test cycle in these cases includes the following events: 1) Transfer of down-hole equipment to the next section, 2) Packer inflation, 3) Closing of test valve after five minutes, 4) Observing the pressure during the following five minutes, 5) Deciding which type of test to conduct, 6) Opening of test valve, 7) Continuing packer inflation, 8) Pressure stabilisation, 9) Injection or pulse, 10) Pressure recovery and 11) Packer deflation. The test phases are the same regardless if a pressure pulse test or an injection test is decided to be performed, but the duration of the different phases differs according to Tables 5-1a and 5-1b. The diagnostic test is included in the given durations.

The criterion used to decide which test to perform was that a pressure pulse test was made if the pressure increased 20 kPa or more during test phase 4 above. Otherwise an injection test was carried out.

Table 5-1a. Packer inflation times, pressure stabilisation times and test times used for the injection tests in KFM07B. Including the diagnostic test.

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.

Table 5-1b. Packer inflation times, pressure stabilisation times and test times used for the pressure pulse tests in KFM07B. Including the diagnostic test.

Test section length (m)	Packer inflation time (min)	Time for pressure stabilisation (min)	Pulse period (min)	Recovery period (min)	Total time/test (min)[1]
5	40	20	2	40	102

[1] Exclusive of trip times in the borehole.

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 __KFM07B_0209.00_200601180900.ht2). The name differs slightly from the convention stated in Instructions for analysis of injection and single-borehole pump test, SKB MD 320.004.

Using the IPPLOT software (Version 3.0), the *.ht2-files are converted to parameter files suitable for plotting applying the code SKB-plot and analysis with the AQTESOLV software.

A backup of data files was created on a regular basis by CD-storage and by sending the files to the Geosigma office in Uppsala by a file transfer protocol. A file description table is presented in Appendix 1.

5.4 Analysis and interpretation

5.4.1 General

As described in Section 5.2.1, the injection tests in KFM07B were performed as transient constant head tests followed by a pressure recovery period. 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 was plotted versus Agarwal equivalent time in lin-log and log-log diagrams, respectively, together with the corresponding derivative. 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).

For pressure pulse tests the standard transient evaluation is performed in a lin-log diagram showing the normalized recovery H/H_0 versus elapsed recovery time together with the corresponding derivative. The recovery is generally normalized with respect to H_0, which is the initial pressure in the borehole section before the packers are expanded. In addition, a stationary evaluation method, accounting for the packer generated flow, was used for evaluation of the pressure pulse tests, see Section 5.4.4.

For 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 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.

5.4.2 Measurement limit for flow rate and specific flow rate

The estimated standard lower measurement limit for flow rate for injection tests with PSS is c 1 mL/min (1.7×10^{-8} m^3/s). However, if the flow rate for a test is close to, or below, the standard lower measurement limit, a test-specific estimate of the lower measurement limit of flow rate can be made. The test-specific lower limit is based on the measurement noise level of the flow rate before and after the injection period. The decisive factor for the varying lower measurement limit is not unambiguously identified, but it might be of both technical and hydraulic character. Since pressure pulse tests were conducted in sections with a possible low transmissivity, only two of the injection tests in KFM07B had a flow rate below or close to the standard lower measurement limit. Hence, these tests were the only ones where a test specific estimate of the lower measurement limit for the flow rate was made.

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 of the flow rate together with the actual injection pressure during the test. The intention during this test campaign was to use a standard injection pressure of 200 kPa (20 m water column). However, for most test sections in KFM07B, the actual injection pressure deviated somewhat from the intended 200 kPa, and in two cases the difference was considerable. The injection pressure exceeded 300 kPa for one test, and for another test the injection pressure was below 100 kPa. A low injection pressure is often the result of a test section of low conductivity due to a pressure increase, caused by packer expansion, before the injection start. A highly conductive section may also result in a low injection pressure due to limited flow capacity of PSS. Since the flow rate was only below the standard lower measurement limit for injection tests on two occasions in KFM07B, it was only necessary to calculate a test specific lower measurement limit for the specific flow rate for those tests.

The lower measurement limit for flow rate corresponds to different values of the steady-state transmissivity, T_M, depending on the section length used in the factor C_M in Moye's formula (Equation 5-2), as described in the Instruction for analysis of injection and single-hole pumping tests (SKB MD 320.004). Only 5 m section lengths were used in borehole KFM07B. The standard lower measurement limit for flow rate of 1 mL/min (1.7×10^{-8} m^3/s) together with the value of C_M ($C_{M,\,5m}$=0.82) for a five metres test section results in the lower measurement limits for steady-state transmissivity (T_M) of 1.4×10^{-9} m^2/s, 7.0×10^{-10} m^2/s and 4.7×10^{-10} m^2/s for injection pressures 100 kPa, 200 kPa and 300 kPa respectively.

To define the lower measurement limit of transmissivity for pressure pulse tests with the PSS, further consideration of the packer generated flow is necessary. Since the packers generate a small, but not negligible, flow throughout the test period, the estimated transmissivities from the transient evaluation of pressure pulse tests will be underestimated in low-transmissivity sections because no correction is normally made for the packer generated flow. In the stationary evaluation, the packer generated flow is taken into account (see Section 5.4.4 for a further discussion). Among other potential problems, the stationary evaluation has an inherent risk of overestimating the transmissivity, since the tests have a limited duration and true stationary conditions, in fact, never prevail. In addition, the uncertainty and variations in the assumed packer generated flow from test to test is being ignored.

The selected, most representative transmissivity from the pressure pulse tests corresponds to the calculated transmissivity from either the transient evaluation or the stationary evaluation. However, no transmissivity values lower than 5×10^{-11} m^2/s are reported. The latter value is considered as the practical lower measurement limit of transmissivity from pressure pulse tests considering the effects of packer compliance. Due to the increased uncertainty of estimated transmissivities from pressure pulse tests, all these values are assigned Value type –1 in the SICADA database, i.e. below the measurement limit.

The practical upper measurement limit of hydraulic transmissivity for the PSS system is estimated from a flow rate of c 30 L/min (5×10^{-4} m^3/s) and an injection pressure of c 1 m. Thus, the upper measurement limit for specific flow rate is 5×10^{-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).

5.4.3 Qualitative analysis

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 for the injection tests. In addition, indications of outer boundary conditions during the tests were identified. The qualitative evaluation was mainly interpreted from the log-log plots of flow rate and pressure together with the corresponding derivatives. No flow regimes were identified for the pressure pulse tests.

In particular, time intervals with pseudo-radial flow, reflected by a constant (horizontal) derivative in the test diagrams, were identified. Pseudo-linear flow may, at the beginning of the test, be reflected by a straight line of slope 0.5 or less in log-log diagrams, both for the measured variable (flow rate or pressure) and the derivative. A true spherical flow regime is reflected by a straight line with a slope of –0.5 for the derivative. However, other slopes may indicate transitions to pseudo-spherical (leaky) or pseudo-stationary flow. The latter flow regime corresponds to almost stationary conditions with a derivative approaching zero.

The interpreted flow regimes can also be described in terms of the distance from the borehole:

- **Inner zone:** Representing very early responses that may represent the fracture properties close to the borehole which may possibly be affected by turbulent head losses. These properties are generally reflected by the skin factor.
- **Middle zone:** Representing the first response from which it is considered possible to evaluate the hydraulic properties of the formation close to the borehole.
- **Outer zone:** Representing the response at late times of hydraulic feature(s) connected to the hydraulic feature for the middle zone. Sometimes it is possible to deduce the possible character of the actual feature or boundary and evaluate the hydraulic properties of the features.

Due to the limited resolution of, in particular, the pressure sensor, the derivative may some times erroneously indicate a false horizontal line by the end of recovery periods with pseudo-stationary flow. Apparent no-flow (NFB) and constant head boundaries (CHB), or equivalent boundary conditions of fractures, are reflected by an increase/decrease of the derivative, respectively.

5.4.4 Quantitative analysis

Injection tests

A preliminary steady-state analysis of transmissivity according to Moye's formula (denoted T_M) was made for the injection period for all injection tests in conjunction with the qualitative analysis according to the following equation:

$$T_M = \frac{Q_p \cdot \rho_w \cdot g}{dp_p} \cdot C_M \qquad (5\text{-}1)$$

$$C_M = \frac{1 + \ln\left(\frac{L_w}{2r_w}\right)}{2\pi} \qquad (5\text{-}2)$$

Q_p = flow rate by the end of the flow period (m^3/s)

ρ_w = density of water (kg/m^3)

g = acceleration of gravity (m/s^2)

C_M= geometrical shape factor (–)

dp_p = $p_p - p_i$ (Pa)

r_w = borehole radius (m)

L_w = section length (m)

From the results of the qualitative evaluation, appropriate interpretation models for the quantitative evaluation of the tests were selected. When possible, transient analysis was made on both the injection and recovery periods of the injection 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 based on the Jacob and Lohman (1952) solution /1/ was applied for estimating the transmissivity and skin factor for an assumed value on the storativity when a certain period with pseudo-radial flow could be identified. The model is based on the effective wellbore radius concept to account for non-zero (negative) skin factors according to Hurst, Clark and Brauer (1969) /2/.

In borehole KFM07B, the storativity was calculated using an empirical regression relationship between storativity and transmissivity, see Equation 5-3 (Rhén et al. 1997) /3/. Firstly, the transmissivity and skin factor was obtained by type curve matching on the data curve using a fixed storativity value of 10^{-6}, according to the instruction SKB MD 320.004. From the transmissivity value obtained, the storativity was then calculated according to Equation 5-3 and the type curve matching was repeated.

$$S=0.0007\times T^{0.5} \tag{5-3}$$

S=storativity (–)

T=transmissivity (m^2/s)

In most cases the change of storativity did not significantly alter the calculated transmissivity by the new type curve matching. Instead, the estimated skin factor, which is strongly correlated to the storativity using the effective borehole radius concept, was altered correspondingly.

For transient analysis of the recovery period, a model presented by Dougherty-Babu (1984) /4/ was used when a certain period with pseudo-radial flow could be identified. In this model, a variety of transient solutions for flow in fractured porous media is available, accounting for e g wellbore storage and skin effects, double porosity etc. The solution for wellbore storage and skin effects is analogous to the corresponding solution presented in Earlougher (1977) /5/ based on the effective wellbore radius concept to account for non-zero (negative) skin factors. However, for tests in isolated test sections, wellbore storage is represented by a radius of a fictive standpipe (denoted fictive casing radius, r(c)) connected to the test section, cf Equation 5-6. This concept is equivalent to calculating the wellbore storage coefficient C from the compressibility in an isolated test section according to Equation 5-5.

When a certain period with pseudo-radial flow could be identified, the model by Dougherty-Babu (1984) was used to estimate the transmissivity and skin factor from the recovery period. The storativity was calculated using Equation 5-3 in the same way as described above for the transient analysis of the injection period. In addition, the wellbore storage coefficient was estimated, both from the simulated value on the fictive casing radius r(c) and, when applicable, from the slope of 1:1 in the log-log recovery plots.

For tests characterized by pseudo-spherical (leaky) flow or pseudo-stationary flow during the injection period, a model by Hantush (1959) /6/ for constant head tests was adopted for the evaluation. In this model, the skin factor is not separated but can be calculated from the simulated effective borehole radius according to Equation 5-4. In addition, the leakage coefficient K'/b' can be calculated from the simulated leakage factor r/B. The corresponding model for constant flow rate tests, (Hantush 1955) /7/, was applied for evaluation of the recovery period for tests showing pseudo-spherical- or pseudo-stationary flow during this period. This model also allows calculation of the wellbore storage coefficient according to Equation 5-6.

$$\zeta = ln(r_w/r_{wf}) \qquad (5\text{-}4)$$

ζ = skin factor

r_w = borehole radius (m)

r_{wf} = effective borehole radius (m)

When a test indicates a fracture response (a slope of 0.5 or less in a log-log plot), models for single fractures are used for the transient analysis as a complement to the standard models. The models by Ozkan-Raghavan (1991a) /8/ and (1991b) /9/ for a vertical fracture were employed. In these cases, the test section length was used to convert K and S_s to T and S, respectively, after analysis by fracture models. The quotient K_x/K_y of the hydraulic conductivity in the x and the y-direction, respectively, was assumed to be 1.0 (one). Type curve matching provided values of K_x and L_f, where L_f is the theoretical fracture length.

The different transient estimates of transmissivity from the injection and recovery period, respectively, were then compared and examined. One of these was chosen as the best representative value of the transient transmissivity of the formation adjacent to the test section. This value is denoted T_T. In cases with more than one pseudo-radial flow regime during the injection or recovery period, the first one is in most cases assumed as the most representative for the hydraulic conditions in the rock close to the tested section.

Finally, a representative value of transmissivity of the test section, T_R, was chosen from T_T and T_M. The latter transmissivity is to be chosen whenever a transient evaluation of the test data is not possible or not being judged as reliable. If the flow rate by the end of an injection period (Q_p) is too low to be defined, and thus neither T_T nor T_M can be estimated, the representative transmissivity for the test section is considered to be less than T_M based on the estimated lower measurement limit for Q/s (i.e. $T_R < T_M$=Q/s-measl-L×C_M).

The estimated value of the borehole storage coefficient, C, based on actual borehole geometrical data and assumed fluid properties for a 5 m section is shown in Table 5-2 together with the estimated effective C_{eff} from laboratory experiments /10/. The net water volume in the test section, V_w, has in Table 5-2 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 demonstrated by Almén et al, (1986) /11/:

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

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}).

Table 5-2. Calculated net values of C, based on the actual geometrical properties of the borehole and equipment configuration in the test section (C_{net}) together with the effective wellbore storage coefficient (C_{eff}) for injection- and pressure pulse tests from laboratory experiments /10/.

r_w (m)	L_w (m)	Volume of test section (m^3)	Volume of equipment in section (m^3)	V_w (m^3)	C_{net} (m^3/Pa)	C_{eff} (m^3/Pa)
0.0382	5	0.0229	0.004	0.0189	8.7×10^{-12}	1.6×10^{-11}

When appropriate, estimation of the actual borehole storage coefficient C in the test sections was 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. In the most conductive sections, this period occurred during very short periods at early test times. The latter values may be compared with the net value of C based on geometry and the value of C_{eff} based on laboratory experiments, (Table 5-2).

Furthermore, when using the model by Dougherty-Babu (1984), a fictive casing radius, r(c), is obtained from the parameter estimation of the recovery period. This value can then be used for calculating C as /11/:

$$C = \frac{\pi \cdot r(c)^2}{\rho \cdot g} \qquad (5\text{-}6)$$

Although this calculation is not done regularly and the results are not presented in this report, the calculations correspond, in the one case that they were performed in KFM07B, well to the value of C obtained from the line of slope 1:1 in the beginning of the recovery period.

The estimated values of C from the tests may differ from the net values in Table 5-2 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.

The radius of influence at a certain time may be estimated from Jacob's approximation of the Theis' well function, Cooper and Jacob (1946) /12/:

$$r_i = \sqrt{\frac{2.25Tt}{S}} \qquad (5\text{-}7)$$

T = Representative transmissivity from the test (m^2/s).

S = Storativity estimated from Equation 5-3.

r_i = Radius of influence (m).

t = Time after start of injection (s).

If a certain time interval of pseudo-radial flow (PRF) can be identified from t_1 to t_2 during the injection period, the radius of influence is estimated using time t_2 in Equation 5-7. If no interval of PRF can be identified, the actual total injection time t_p is used. The radius of influence can be used to estimate the length of the hydraulic feature(s) tested.

Furthermore, an r_i-index (–1, 0 or 1) is defined to characterize the hydraulic conditions at the end of the test. The r_i-index is defined as shown below.

- r_i-index = 0: The transient response indicates that the size of the hydraulic feature tested is greater than the radius of influence based on the actual test time (t_2=t_p), i.e. the PRF is continuing at stop of the test. This fact is reflected by a flat derivative at the end of the injection period.
- r_i-index = 1: The transient response indicates that the hydraulic feature tested is connected to a hydraulic feature with lower transmissivity or an apparent no-flow boundary (NFB). This fact is reflected by an increase of the derivative. The size of the hydraulic feature tested is estimated as the radius of influence based on t_2, provided that a PRF can be identified.
- r_i-index = –1: The transient response indicates that the hydraulic feature tested is connected to a hydraulic feature with higher transmissivity or an apparent constant head boundary (CHB). This fact is reflected by a decrease of the derivative. The size of the hydraulic feature tested is estimated as the radius of influence based on t_2, if a PRF can be identified.

Pressure pulse tests

By the evaluation of the pressure pulse tests both a transient and a stationary evaluation were made. A model described by Dougherty and Babu (1984) /4/ was used for transient evaluation of the pressure pulse tests performed. The normalized recovery H/H_0 was plotted versus elapsed time during the recovery period in a lin-log diagram. In this analysis, the actual head change, H, was not corrected for effects of packer generated flow.

As for the injection tests, the effective borehole radius concept, Equation (5-4), was applied for calculating the skin factor as well as the concept of a fictive standpipe connected to the test section representing wellbore storage according to Equation (5-6). The value of C_{eff} (see Table 5-2) used to calculate the radius of the fictive standpipe, r(c), is derived from laboratory experiments /10/. The transmissivity and skin factor were estimated for a certain value of storativity and wellbore storage coefficient (represented by the radius of the fictive standpipe) from type curve matching. The storativity was calculated from Equation (5-3) as for the injection tests.

Whenever the transmissivity in the section was so low that the packer generated flow caused a pressure increase after the pulse, the test was interrupted and no transient evaluation was made. Since the packers are still slowly expanding, even after the time allowed for packer expansion and pressure stabilization (60 minutes), a small flow is generated throughout the tests by the packers. For such low-conductive sections this flow is not negligible, which leads to an underestimation of the transmissivities. Efforts have been made to make corrections for the packer generated flow by different methods (e.g. by correcting H) before performing transient evaluation by standard methods for pressure pulse tests, but none of them gave satisfactory results. Instead, a stationary method was developed for evaluation of pressure pulse tests.

The stationary method used to evaluate the pressure pulse tests should be regarded as a simple tool to estimate transmissivities below the standard measurement limit of the PSS system /10/. This method is described below and is in this report referred to as the stationary evaluation method. Firstly, some assumptions have to be made when estimating the packer generated flow:

- The test section which exhibited the highest pressure increase due to packer generated flow (packer compliance) in conjunction with pressure pulse tests performed with PSS at Forsmark so far, can be regarded as virtually impermeable, i.e. the flow rate into the formation is much less than the flow rate generated by the packers. The highest pressure increase so far (107.1 Pa/s) was observed during the pressure pulse test in section 244–249 m in KFM07B.
- The average flow rate generated by the packers in this section can be calculated according to Equation (5-8) based on the corresponding pressure increase (dp_{packer}) in this section during the first time interval (dt) of the recovery period after the application of the pressure pulse due to packer compliance. By this calculation, the estimated effective borehole storage coefficient (C_{eff}) for the actual test section length from the laboratory tests /10/ is used. The value of C_{eff} for a 5 m test section is presented in Table 5-2.
- The estimated effective borehole coefficient (C_{eff}) from laboratory tests is assumed to also be valid for field tests.

$$Q_{ave\ (packer)} = C_{eff} \frac{dp_{packer}}{dt} \tag{5-8}$$

$Q_{ave\ (packer)}$ = Average packer generated flow during the time interval dt (m^3/s).

C_{eff} = Effective borehole storage coefficient of test section (m^3/Pa).

dp_{packer}/dt = Rate of pressure increase during first phase of the recovery period due to packer compliance in a virtually impermeable test section (Pa/s).

By the estimation of transmissivity some additional assumptions are made:

- The packer-generated flow rate is assumed to be identical in all test sections (independent of the section length) and equal to the estimated flow in the selected virtually impermeable section mentioned above. However, there are some indications from field tests that this assumption may not always be correct (the flow may vary from test to test).
- The pressure pulse is applied at the same time after start of packer sealing for all tests. This assumption also includes the impermeable section which was used to estimate the packer generated flow rate.

The average flow rate into the formation during the first phase of the recovery period of a pressure pulse test may be calculated based on the estimated packer-generated flow rate (from Equation (5-8)) and the actual change of borehole storage (water and packers) in the test section according to Equation (5-9). The change of borehole storage in the test section (dV/dt) is calculated from the observed pressure change (dp) during a certain period (dt) of the first phase of the recovery period (e.g. 10 min) and the estimated effective borehole storage coefficient (C_{eff}) for the actual section length from laboratory tests according to Equation (5-10).

$$Q_{ave\ (formation)} = Q_{ave\ (packer)} + dV/dt \tag{5-9}$$

$Q_{ave\ (formation)}$ = Average flow rate into the formation during time interval dt (m^3/s).

$Q_{ave\ (packer)}$ = Average packer generated flow rate (m^3/s).

dV/dt = Change of borehole storage in test section (m^3/s).

$$dV/dt = C_{eff}\,\frac{dp}{dt} \qquad (5\text{-}10)$$

dp/dt = Rate of pressure change during the initial phase of the recovery period (Pa/s).

The packer generated flow is thus calculated from the virtually impermeable section KFM07B: 244–249 m and is assumed to be the same for all tested sections in KFM07B. The change of borehole storage, dV/dt, however, is calculated individually for each test to give the test-specific average flow rate into the formation, $Q_{ave\ (formation)}$. For the borehole storage, the sign convention is that a *decreasing* pressure during the selected 10 minute interval results in a *positive* dp/dt and an *increasing* pressure results in a *negative* dp/dt.

Finally, the transmissivity is estimated by a stationary evaluation according to Equation (5-11), based on the estimated average flow rate into the formation and the applied head difference dh_p during the pulse period. If the head difference during the first phase of the recovery period is significantly different from dh_p and/or varies during this period, an average value on dh_p may be used in Equation (5-11).

$$T_{ss,\ pulse} = Q_{ave\ (formation)} / dh_p \qquad (5\text{-}11)$$

$T_{ss,\ pulse}$ = Estimated stationary transmissivity from pressure pulse test (m^2/s)

dh_p = Applied head difference during the pulse period or actual head difference during the first phase of the recovery period (m)

The method gives a possibility to roughly estimate the transmissivity in very low-conductive sections (also when the pressure is still increasing during the recovery period).

5.5 Nonconformities

The test program in KFM07B was carried out according to the Activity Plan AP PF 400-05-049 with the following exceptions:

- The tecalan hose connected to P_{bubbel}, the transducer measuring the ground water level, could not be put into position in the borehole before testing. This was due to the small diameter of the upper part of the borehole which made it impossible to get it down to the groundwater table.
- The packers were expanded progressively and the nominal expansion pressure could not be reached for section 249.0–254.0 m or any of the sections below that position. This was because the pressure below the test section rose too much due to packer compliance. This makes the effects from the packer compliance even more unpredictable.
- Because the packers had to be expanded manually, see above, the actual packer expansion times may differ slightly from test to test.
- Not all planned injection tests were performed. This was because the rapidly increasing pressure below the test section when expanding the packers made it very difficult to expand the packers enough. Additionally, calculations showed that the total transmissivity in the remaining part of the borehole would not exceed the lower measurement limit for the equipment. The planned last four tests were therefore not performed.

6 Results

6.1 Nomenclature and symbols

The nomenclature and symbols used for the results of the injection tests in KFM07B are in accordance with the Instruction for analysis of injection and single-hole pumping tests (SKB MD 320.004). Additional symbols 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 and selected pressure and flow data from all tests are listed in Appendix 2.1 and 2.2, respectively.

Some unexplained pressure disturbances were registered above the test section during all of the tests. The pressure above the test section started to decrease in connection with the packer expansion in all but one test where the opposite, a pressure increase, was detected. The pressure stabilized a few minutes after the start of the packer expansion at a new level, differing from the level before packer expansion by c 3–5 kPa. This is not believed to have affected any of the tests since the pressure in the test section was always stable before the start of the injection. Drilling of KFM01D and pumping in HFM01 as well as rinse pumping in KFM01C are activities that may have affected the pressure in KFM07B even though no evident signs of that have been discovered.

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. The reference marks are used to make length corrections, i.e. to adjust the length scale for the injection tests according to the reference marks. In KFM07B, four reference marks, at 100, 150, 200 and 250 m along the borehole, have been milled into the borehole wall.

During the injection tests in KFM07B with the PSS, all length reference marks were detected. At each mark, the length scale for the injection tests was adjusted according to the reported length to the reference mark.

The largest difference between the reported and measured lengths at the reference marks during the injection tests was 0.16 m, which occurred at the 250 m reference mark. The difference between two consecutive measurements 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 because 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.

6.2.3 General results

A summary of the results of the routine evaluation of the injection tests and pressure pulse tests is presented, test by test, in Table 6-1 and Table 6-2 respectively. Figure 6-2 shows the most representative transmissivity values from both injection- and pressure pulse tests in KFM07B. 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 are presented for the injection tests. The quantitative analysis was performed from such diagrams using the AQTESOLV software. For each pressure pulse test one linear diagram showing the entire test sequence together with a lin-log diagram displaying the normalized recovery H/H_0 plotted versus elapsed time is presented. From pressure pulse tests that were interrupted during the recovery period because of increasing pressure, only the linear diagram is presented. The results of the routine evaluation of the tests in borehole KFM07B are also compiled in appropriate tables in Appendix 5 to be stored in the SICADA database.

The last four tests that were planned in the deepest part of KFM07B were never executed. This was because that part of the borehole was so tight that it made normal expansion of the packers impossible. An approximate calculation using numbers from the packer compliance calculations discussed in Section 5.4.4, produced results that showed that the total transmissivity of the remaining borehole would be clearly below the measurement limit.

Injection tests

For the injection tests, transient evaluation was conducted, whenever possible, both on the injection and recovery periods (T_f and T_s, respectively) according to the methods described in Section 5.4.4. The steady-state transmissivity (T_M) was calculated by Moye's formula according to Equation 5-1. The quantitative analysis was performed using the AQTESOLV software.

The dominating transient flow regimes during the injection and recovery periods, as interpreted from the qualitative test evaluation, are listed in Table 6-1 and are further commented on in Section 6.2.4. Pseudo-radial flow was not reached during the recovery period in any of the tests. On the other hand, during the injection period, a certain time interval with pseudo-radial flow could, in two out of four tests with a definable Q_p, be identified. Standard methods for single-hole tests with wellbore storage and skin effects were generally used for the routine evaluation of the tests. The approximate start and stop times of the pseudo-radial flow regime used for the transient evaluation are also listed in Table 6-1.

The transmissivity judged as the most reliable from the transient evaluation of the flow- and recovery periods of the tests was selected as T_T. The associated value of the skin factor is listed in Table 6-1. Equally many representative values of transmissivity, $T_{R,}$ have been chosen from the injection period as from the recovery period in KFM07B.

For those tests where transient evaluation is not possible or not considered representative, T_M is to be chosen as the representative transmissivity value, T_R. In KFM07B, T_M was never chosen as the most representative value in tests with a definable Q_p. If Q_p is below the actual test-specific measurement limit, the representative transmissivity value is assumed to be less than the estimated T_M, based on Q/s-measl-L, see Section 5.4.2 and 5.4.4

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

Table 6-1. Summary of the routine evaluation of the single-hole injection tests in borehole KFM07B.

Secup (m)	Seclow (m)	Test start YYYYMMDD hh:mm	b (m)	Flow regime 1) injection	Recovery	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)	dte_1 (s)	dte_2 (s)	C (m^3/Pa)	r_i (m)	r_i-index (–)
209.00	214.00	20060123 09:22	5.00			1.65E–10				1.65E–10								
219.00	224.00	20060123 12:51	5.00			1.65E–10				1.65E–10								
224.00	229.00	20060123 13:46	5.00	PSF	PSF	5.88E–09	2.98E–09	4.24E–09	2.98E–09	2.98E–09	–2.62						14.61	0
229.00	234.00	20060125 16:17	5.00	PRF1- > PRF2	WBS- > PSF- > PSS	1.36E–09	2.21E–09	1.83E–09	2.21E–09	2.21E–09	0.64	10	100			1.79E–11	3.89	1
234.00	239.00	20060123 16:46	5.00	PRF1- > PRF2	(WBS)- > PSS	3.57E–08	1.12E–07	4.27E–08	4.27E–08	4.27E–08	5.41	500	1,200				28.33	–1
239.00	244.00	20060124 06:46	5.00	PLF- > NFB	PLF	7.09E–10		4.37E–10	4.37E–10	4.37E–10	–4.64						9.02	0

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 5.4.3 above.

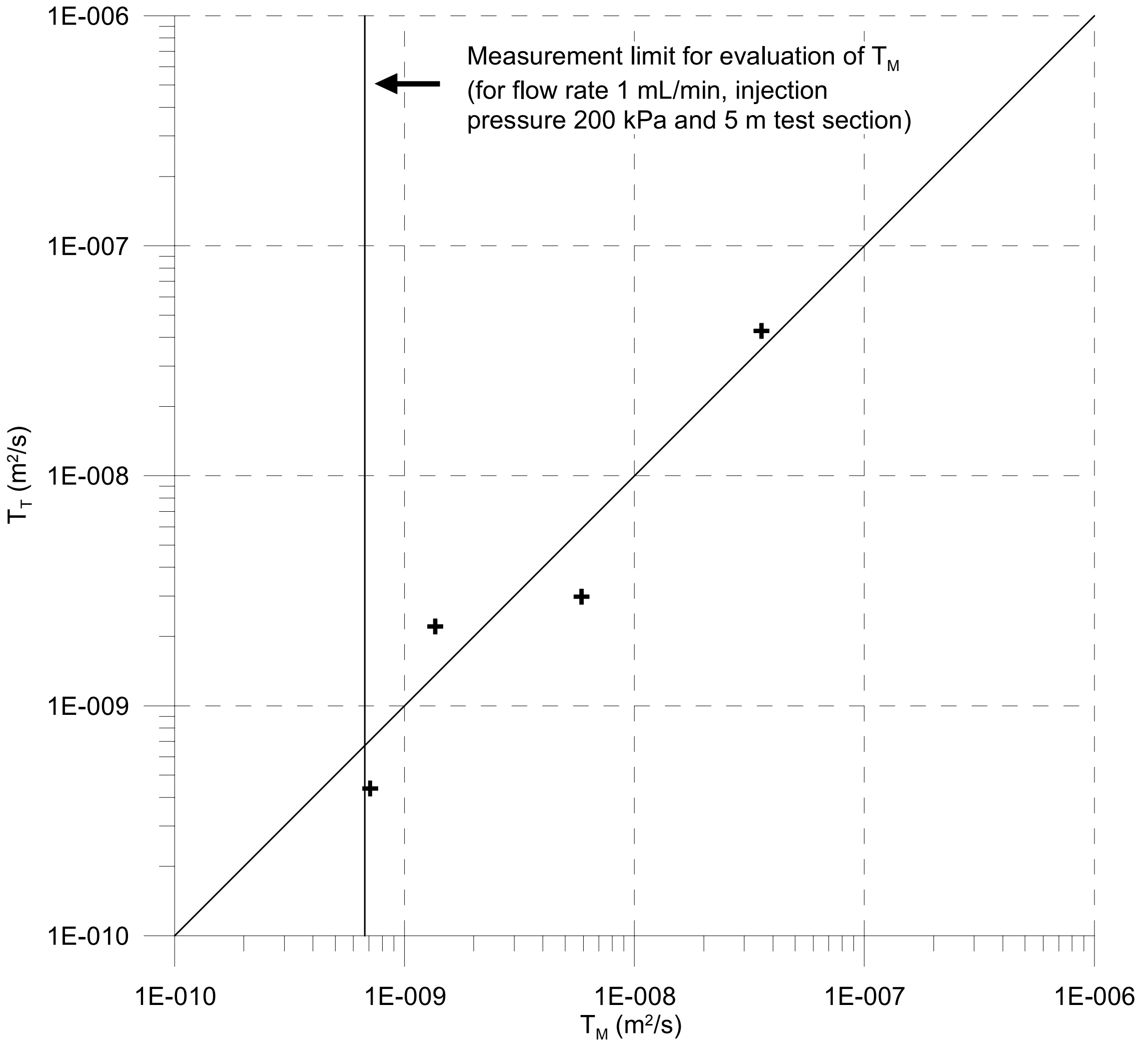

Figure 6-1. *Estimated transmissivities in 5 m sections from steady-state (T_M) and transient (T_T) evaluation for the injection tests in KFM07B.*

The wellbore storage coefficient, C, was calculated from the straight line with a unit slope in the log-log diagrams from the recovery period in KFM07B, see Table 6-1. The coefficient C was only calculated for tests with a well-defined line of unit slope in the beginning of the recovery period, which during this campaign only happened in one section. In the more conductive sections, this period occurred during very short intervals at very early times and is not visible in the diagrams. In sections with a very low transmissivity, the estimates of C may be uncertain due to difficulties in defining an accurate time for the start of the recovery period. Furthermore, the resolution of the pressure sensors causes the recovery to be quite scattered in sections of low transmissivity. The values of C presented in Table 6-1 may be compared with the net values of C, C_{net} (based on geometry) and the value of C obtained from laboratory experiments, C_{eff} /10/, both found in Table 5-2.

As mentioned above, there was only one test with a well-defined line of unit slope for which it was possible to calculate C. Table 6-1 shows that the calculated value from the test is slightly higher than C_{net} presented in Table 5-2. However, when the calculated value is compared to the value C_{eff} obtained from laboratory experiments, the agreement is better, although the calculated value is still slightly higher. This is an expected result which has been observed also in other boreholes.

Pressure pulse tests

Transient evaluation was performed for the pressure pulse tests, together with the stationary evaluation described in Section 5.4.4, except for the tests that were interrupted because the pressure increased after the pulse. For these tests only the stationary method was applied.

In Table 6-2 the results from the transient evaluation ($T_{T, pulse}$) and from the stationary evaluation ($T_{ss, pulse}$) are presented together with the selected, most representative estimate of transmissivity, $T_{R, pulse}$.

For all of the pulse tests the stationary evaluation was considered as the most representative. This is, for a majority of the tests, due to the fact that the packers strongly affect the section, resulting in an underestimation of the transmissivities by the transient evaluation. The transmissivity value reported for the individual pulse test is also chosen as the lower measurement limit for the specific test section. However, no values lower than 5.0×10^{-11} m^2/s are regarded to be representative, entailing that the results from the individual pulse tests only represent the upper limit of transmissivity for that section. This also means that all values will be reported to SICADA as on, or below, measurement limit, indicated by value type –1, cf Appendix 5.

For the two pressure pulse tests where a transient evaluation was possible, the value from the transient evaluation was much lower than the value from the stationary evaluation due to packer compliance. In fact, the values from the transient evaluations were even smaller than the transmissivities in the sections showing a pressure increase after the pulse which, however, is not likely. Hence the larger transmissivity value, from the stationary evaluation was chosen.

The method used to estimate the stationary transmissivity presupposes that section 244.0–249.0 m is virtually impermeable, and therefore no evaluation can be made for this section. The transmissivity is considered to be less than 5.0×10^{-11} m^2/s.

In total, five sections have an estimated transmissivity lower than 5.0×10^{-11} m^2/s, all of these being the ones where the pressure still increases after the pulse.

No standard tests were performed in KFM07B below 279.0 m due to difficulties in expanding the packers. Calculations of transmissivity for section 279.0–298.9 m using similar methods as used for the pressure pulse tests were however done. The results showed that the total transmissivity in the remaining part of the borehole was below the measurement limit. This result is included in Table 6-2 and Figure 6-2 below as well as reported to SICADA.

Table 6-2. Summary of the routine evaluation of the single-hole pressure pulse tests in borehole KFM07B.

Secup (m)	Seclow (m)	Test start YYYYMMDD hh:mm	b (m)	$T_{ss, pulse}$ (m^2/s)	$T_{T, pulse}$ (m^2/s)	ξ (–)	$T_{meas. limit}$ (m^2/s)	$T_{R, pulse}$ (m)
214.00	219.00	20060123 10:28	5.00	6.28E–11			6.28E–11	6.28E–11
244.00	249.00	20060124 08:47	5.00	0.00E+00			5.00E–11	5.00E–11
249.00	254.00	20060124 10:19	5.00	4.68E–11			5.00E–11	5.00E–11
254.00	259.00	20060124 12:34	5.00	7.36E–11	8.00E–12	10.00	7.36E–11	7.36E–11
259.00	264.00	20060124 14:36	5.00	1.12E–10	3.15E–12	–3.53	1.12E–10	1.12E–10
264.00	269.00	20060125 09:22	5.00	1.78E–11			5.00E–11	5.00E–11
269.00	274.00	20060125 11:00	5.00	5.18E–11			5.18E–11	5.18E–11
274.00	279.00	20060125 12:59	5.00	1.51E–11			5.00E–11	5.00E–11
280.00	298.9	20060125 12:59	18.90	1.23E–12			5.00E–11	5.00E–11

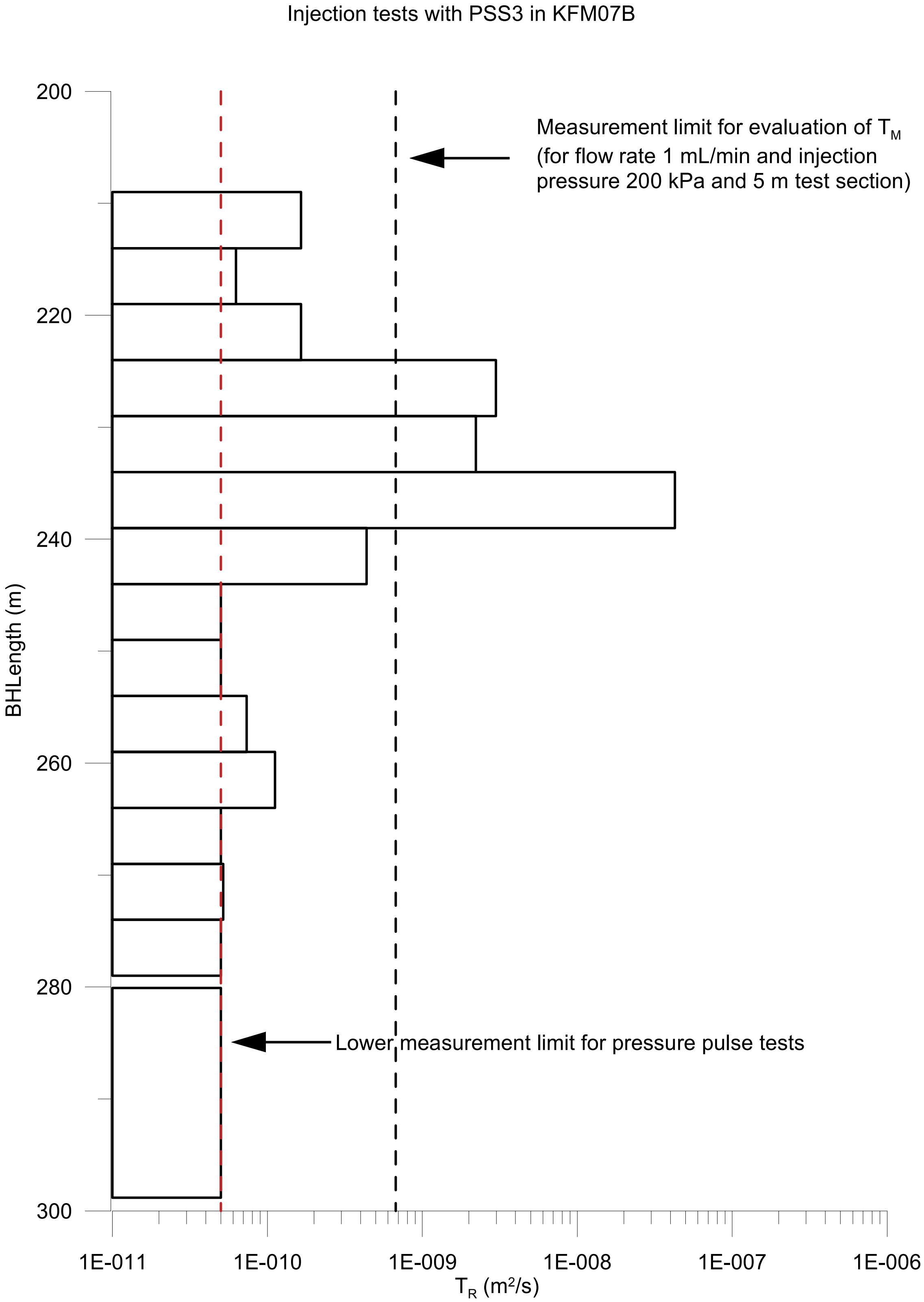

Figure 6-2. *Estimated best representative transmissivity values (T_R and $T_{R,\ pulse}$) from both injection tests and pressure pulse tests for sections of 5 m length in borehole KFM07B as well as the value of transmissivity from the single packer test below 280 m. The estimated transmissivity value for the lower standard measurement limit from stationary evaluation of injection tests (T_M-measl-L) is also shown together with the lower measurement limit for pressure pulse tests.*

6.2.4 Comments on the tests

Short comments on each test follow below. Flow regimes and hydraulic boundaries, as discussed in Section 5.4.3, 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
CHB = Constant-head boundary

209.0–214.0 m

The test section has a very low transmissivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. The injection time was therefore shortened. As a result T_M, based on Q/s-measl-L, was considered to be the most representative transmissivity value for this section.

214.0–219.0 m (Pressure pulse test)

The test was performed as a pulse test. Following the pulse, only a pressure increase was registered, indicating that the section is of such low transmissivity that the packer expansion is influencing the pressure in the test section throughout the test period. Since the pressure increases, the test vas terminated after 10 minutes of recovery and no transient evaluation was made.

219.0–224.0 m

The test section has a very low transmissivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. The injection time was therefore shortened. As a result T_M, based on Q/s-measl-L, was considered to be the most representative transmissivity value for this section.

224.0–229.0 m

During the injection period a PSF is dominating. The recovery period only shows signs of a transition period into a PSF which then lasts throughout the recovery period. The pressure is almost completely recovered after c 300 s of the recovery period.

229.0–234.0 m

The injection period displays an early PRF, beginning after c 10 s and lasting until approximately 100 s, when another PRF with a slightly lower transmissivity starts. The second PRF lasts throughout the injection period. The pressure in the test section recovers very rapidly and is almost fully recovered after c 600 s. The recovery shows signs of WBS transitioning to PSF and PSS by the end of the period with rapidly decreasing derivative approaching zero. Transient evaluation was made using the Hantush' model on the recovery period. The latter evaluation gives consistent results with the injection period.

234.0–239.0 m

The injection period is dominated by an apparent PRF or possibly two separate PRFs where the second period of PRF starts c 500 s into, and lasts until the end of the flow period. Evaluation using a model for radial flow produces very high skin values. During the recovery period the pressure decreases very quickly and is approximately fully recovered after c 100 s, after which only a PSS is present. A short period of WBS and a transition period precede the PSS. Due to the high skin factor from the injection period, the evaluated transmissivity from the recovery period was chosen as the best representative transmissivity value for this section. The choice is supported by the stationary evaluation which provides similar results.

239.0–244.0 m

The injection period indicates a PLF transitioning to an apparent NFB by the end of the flow period. No unambiguous transient evaluation is possible on this period. The recovery period is dominated by a PLF. The pressure below the test section is strongly affected by the packer expansion, indicating that the borehole interval below the lower packer is of low transmissivity.

244.0–249.0 m (Pressure pulse test)

The pressure increase after the pulse is large, indicating a very low transmissivity. Since the pressure increases the test vas terminated after 10 minutes of recovery and no transient evaluation was made. The pressure increase after the pulse was the largest measured so far, hence this section is regarded as completely tight, i.e. the flow rate into the formation is much less than the flow rate generated by the packers. This means that no evaluation can be made of the transmissivity in this section which therefore is considered to be lower than the measurement limit of 5.0×10^{-11} m^2/s. The pressure increase was rapid both after the first and the second closing of the test valve. When expanding the packers the pressure in the section below the test section rises and slowly recovers during the rest of the tests. This indicates a rather low transmissivity also below the tested section.

249.0–254.0 m (Pressure pulse test)

The pressure increases after the pulse, indicating a very low transmissivity. Since the pressure increases the test vas terminated after 10 minutes of recovery and no transient evaluation was made. The transmissivity in this section is lower than the measurement limit of 5.0×10^{-11} m^2/s. When the test valve was closed for the first time, the pressure increase in the section was larger than after the second closing. The pressure in the section below the test section increases a lot when the packers are expanded, again pointing out that transmissivity is low in the section below the test section. The packer expansion had to be performed progressively and the nominal expansion pressure could not be reached due to the increasing pressure in the section below the test section.

254.0–259.0 m (Pressure pulse test)

The recovery from this pulse test shows a very small but visible decrease in the pressure. H_0 is calculated as P_p–P_0. The transient evaluation using the Dougherty-Babu model did not result in any good fit, and the T-value from the stationary evaluation of the test is therefore chosen as the most representative. The expansion of the packers caused an increased pressure in the section below the test section. Pressure in the section above however decreased after the expansion of the packer. The packer expansion had to be performed progressively and the nominal expansion pressure could not be reached due to the increasing pressure in the section below the test section.

259.0–264.0 m (Pressure pulse test)

Recovery from this pulse test shows a rather large recovery of the pressure. Since the pressure increase after the second closing of the test valve is not so large, the head is calculated as P_p–P_i. The Babu model resulted in a good fit, but the T-value from this evaluation is lower than values from sections with increasing pressure after the pulse, which is not likely. Therefore the transmissivity obtained from the stationary evaluation is regarded as representative for this section. The packer expansion had to be performed progressively and the nominal expansion pressure could not be reached due to the increasing pressure in the section below the test section.

264.0–269.0 m (Pressure pulse test)

The pressure increases after the pulse, indicating a very low transmissivity. Since the pressure increases the test vas terminated after 10 minutes of recovery and no transient evaluation was made. When the test valve was closed for the first time the pressure increase in the section was larger than after the second closing. The transmissivity in this section is lower than the measurement limit of 5.0×10^{-11} m^2/s. The pressure in the section below the test section increases a lot when the packers are expanded, again pointing out that transmissivity is low in the section below this section. The packer expansion had to be conducted progressively and the nominal expansion pressure could not be reached due to the increasing pressure in the section below the test section.

269.0–274.0 m (Pressure pulse test)

The pressure increases after the pulse, indicating a very low transmissivity. Since the pressure increases the test vas terminated after 10 minutes of recovery and no transient evaluation was made. The transmissivity in this section is lower than the measurement limit of 5.0×10^{-11} m^2/s. When the test valve was closed for the first time, the pressure increase in the section was larger than after the second closing. The pressure in the section below increases a lot when the packers are expanded, and recovers very slowly during the rest of the test, again pointing out that transmissivity is low in the section below this section. The packer expansion had to be performed progressively and the nominal expansion pressure could not be reached due to the increasing pressure in the section below the test section.

274.0–279.0 m (Pressure pulse test)

The pressure increases after the pulse, indicating a very low transmissivity. Since the pressure increases the test vas terminated after 10 minutes of recovery and no transient evaluation was made. The transmissivity in this section is lower than the measurement limit of 5.0×10^{-11} m^2/s. When the test valve was closed for the first time, the pressure increase in the section was larger than after the second closing. The pressure in the section below the test section increases a lot when the packers are expanded, and shows almost no recovery during the rest of the test, pointing out that the transmissivity is very low in the deepest parts of the borehole. The packer expansion had to be performed progressively and the nominal expansion pressure could not be reached due to the increasing pressure in the section below the test section.

280.0–298.9 m (Pressure pulse test below single packer)

Evaluation of the pressure increase below test section 274.0–279.0 m caused by packer compliance was performed by methods corresponding to those used for ordinary pressure pulse tests but adjusted for the flow induced by a single packer. The results show that the total remaining transmissivity in the lower parts of the borehole (below 280 m) is considerably lower than the measurement limit at 5.0×10^{-11} m^2/s. No further tests were made below test position 274.0–279.0 m.

6.2.5 Flow regimes

A summary of the frequency of identified flow regimes is presented in Table 6-3, which shows all identified flow regimes during the tests. For example, a pseudo-radial flow regime (PRF) transitioning to a pseudo-spherical flow regime (PSF) will contribute to one observation of PRF and one observation of PSF. The numbers within brackets denote the number of tests where the actual flow regime is the only one present.

It should be noted that the interpretation of flow regimes is only tentative and only based on visual inspection of the data curves. It should also be observed that there might be some pseudo-linear flow regime during the beginning of an injection period that is missed due to the fact that a certain time is required for achieving a constant pressure, which may mask the initial flow regime.

No flow regimes have been identified for the pressure pulse tests; hence Table 6-3 is only valid for the injection tests.

Table 6-3 shows that a certain period of pseudo-radial flow could be identified from the injection period in two of the four tests that had a definable Q_p. The PRF was also the most common flow regime for the injection period. During the recovery period, an even distribution of flow regimes was detected, except for the PRF and the NFB which were never observed.

Table 6-3. Interpreted flow regimes during the injection tests in KFM07B.

Borehole	Section length (m)	Number of injection tests[1)]	Number of tests with definable Qp	Injection period					Recovery period					
				PLF	PRF	PSF	PSS	NFB	WBS	PLF	PRF	PSF	PSS	NFB
KFM07B	5	6	4	1(0)	2(2)	1(1)	0(0)	1(0)	2(0)	1(1)	0(0)	2(1)	2(0)	0(0)

[1)] Only the injection tests are included in this table.

6.3 Basic statistics of hydraulic conductivity distributions

Some basic statistical parameters were calculated for the hydraulic conductivity distributions from the tests in borehole KFM07B. The hydraulic conductivity is obtained by dividing the transmissivity by the section length, in this case T_R/L_w. The basic statistical parameters were derived for the hydraulic conductivity considered most representative ($K_R=T_R/L_w$), including all tests, both injection- and pressure pulse tests. In the statistical analysis, the logarithm (base 10) of K_R was used. Selected results are shown in Table 6-4.

Section 244.0–249.0 m borehole length, was the tightest section measured during the testing in KFM07B. It was also the tightest section measured so far with pressure pulse tests in Forsmark. Therefore it is considered, by definition, to be completely non-conductive. Still, it is included in the statistical calculations that Table 6-4 is based on, and the practical measurement limit for pulse tests is us used for this section, cf Table 6-2.

Table 6-4. Basic statistical parameters for the hydraulic conductivity considered most representative (K_R) in borehole KFM07B. L_w=section length, m=arithmetic mean, s=standard deviation.

Borehole	Parameter	Unit	Lw=5 m
KFM07B	Measured borehole interval	m	209.0–279.0
KFM07B	Total number of tests	–	14
KFM07B	No. of pulse tests	–	8
KFM07B	m (Log10(KR))	Log10(m/s)	–10.36
KFM07B	s (Log10(KR))	–	0.89

7 References

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/11/ **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.

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Appendix 1. File description table

Bh id	Test section		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)[1]		YYYYMMDD hh:mm	YYYYMMDD hh:mm	__Borehole id_secup_date and time of test start		
KFM07B	209.0	214.0	3	1	20060123 09:22	20060123 10:14	__KFM07B_0209.00_200601230922.ht2	P, Q, Te	
KFM07B	214.0	219.0	4B	1	20060123 10:28	20060123 12:12	__KFM07B_0214.00_200601231028.ht2	P, Q, Te	
KFM07B	219.0	224.0	3	1	20060123 12:51	20060123 13:33	__KFM07B_0219.00_200601231251.ht2	P, Q, Te	
KFM07B	224.0	229.0	3	1	20060123 13:46	20060123 15:05	__KFM07B_0224.00_200601231346.ht2	P, Q, Te	
KFM07B	229.0	234.0	3	1	20060123 15:16	20060123 16:33	__KFM07B_0229.00_200601231516.ht2	P, Q, Te	
KFM07B	229.0	234.0	3	2	20060125 16:17	20060125 17:33	__KFM07B_0229.00_200601251617.ht2	P, Q, Te	
KFM07B	234.0	239.0	3	1	20060123 16:46	20060123 18:02	__KFM07B_0234.00_200601231646.ht2	P, Q, Te	
KFM07B	239.0	244.0	3	1	20060124 06:46	20060124 08:31	__KFM07B_0239.00_200601240646.ht2	P, Q, Te	
KFM07B	244.0	249.0	4B	1	20060124 08:47	20060124 10:02	__KFM07B_0244.00_200601240847.ht2	P, Q, Te	
KFM07B	249.0	254.0	4B	1	20060124 10:19	20060124 12:23	__KFM07B_0249.00_200601241019.ht2	P, Q, Te	
KFM07B	254.0	259.0	4B	1	20060124 12:34	20060124 14:27	__KFM07B_0254.00_200601241234.ht2	P, Q, Te	
KFM07B	259.0	264.0	4B	1	20060124 14:36	20060125 09:09	__KFM07B_0259.00_200601241436.ht2	P, Q, Te	
KFM07B	264.0	269.0	4B	1	20060125 09:22	20060125 10:44	__KFM07B_0264.00_200601250922.ht2	P, Q, Te	
KFM07B	269.0	274.0	4B	1	20060125 11:00	20060125 12:41	__KFM07B_0269.00_200601251100.ht2	P, Q, Te	
KFM07B	274.0	279.0	4B	1	20060125 12:59	20060125 14:19	__KFM07B_0274.00_200601251259.ht2	P, Q, Te	

[1] 3: Injection test, 4B pulse test

Appendix 2.1. General test data

Borehole:	KFM07B
Testtype:	CHir (Constant Head injection and recovery)
Field crew:	C. Hjerne, K. Gokall-Norman, J Harrström, T. Svensson, E Gustavsson
General comment:	

Test section secup	**Test section seclow**	**Test start**	**Start of flow period**	**Stop of flow period**	**Test stop**	**Total flow time t_p**	**Total recovery time t_F**
(m)	(m)	YYYYMMDD hh:mm	YYYYMMDD hh:mm:ss	YYYYMMDD hh:mm:ss	YYYYMMDD hh:mm	(min)	(min)
209.00	214.00	20060123 09:22	20060123 10:03:24	20060123 10:06:47	20060123 10:14	3	5
214.00	219.00	20060123 10:28	20060123 11:28:06	20060123 11:30:11	20060123 12:12	2	40
219.00	224.00	20060123 12:51	20060123 13:24:27	20060123 13:26:23	20060123 13:33	2	5
224.00	229.00	20060123 13:46	20060123 14:22:51	20060123 14:43:08	20060123 15:05	20	20
229.00	234.00	20060125 16:17	20060125 16:51:11	20060125 17:11:29	20060125 17:33	20	20
234.00	239.00	20060123 16:46	20060123 17:20:15	20060123 17:40:31	20060123 18:02	20	20
239.00	244.00	20060124 06:46	20060124 07:48:50	20060124 08:09:07	20060124 08:31	20	20
244.00	249.00	20060124 08:47	20060124 09:47:01	20060124 09:49:07	20060124 10:02	2	12
249.00	254.00	20060124 10:19	20060124 12:08:38	20060124 12:10:43	20060124 12:23	2	10
254.00	259.00	20060124 12:34	20060124 13:43:12	20060124 13:45:17	20060124 14:27	2	40
259.00	264.00	20060124 14:36	20060125 08:24:36	20060125 08:27:05	20060125 09:09	2	40
264.00	269.00	20060125 09:22	20060125 10:29:29	20060125 10:31:52	20060125 10:44	2	10
269.00	274.00	20060125 11:00	20060125 12:26:57	20060125 12:29:03	20060125 12:41	2	10
274.00	279.00	20060125 12:59	20060125 14:05:17	20060125 14:07:23	20060125 14:19	2	10

Appendix 2.2 Pressure and flow data

Summary of pressure and flow data for all tests in KFM07B

Test section		**Pressure**			**Flow**		
secup	**seclow**	**p_i**	**p_p**	**p_F**	**Q_p**[1)]	**Q_m**[1)]	**V_p**[1)]
(m)	(m)	(kPa)	(kPa)	(kPa)	(m^3/s)	(m^3/s)	(m^3)
209.00	214.00	1760.92	1962.55	1962.55	-	-	-
214.00	219.00	1822.70	2020.94	2052.79	-	-	-
219.00	224.00	1840.20	2064.13	2059.35	-	-	-
224.00	229.00	1854.28	2167.35	1855.93	2.28E-07	2.59E-07	3.15E-04
229.00	234.00	1895.16	2121.69	1896.39	3.81E-08	5.11E-08	6.24E-05
234.00	239.00	1934.25	2171.60	1934.11	1.05E-06	1.08E-06	1.32E-03
239.00	244.00	1978.41	2215.50	2126.60	2.08E-08	5.43E-08	6.60E-05
244.00	249.00	2180.06	2243.36	2315.81	-	-	-
249.00	254.00	2128.52	2287.38	2309.25	-	-	-
254.00	259.00	2220.12	2328.39	2313.63	-	-	-
259.00	264.00	2141.37	2359.02	2306.52	-	-	-
264.00	269.00	2273.56	2397.83	2446.51	-	-	-
269.00	274.00	2270.97	2440.49	2459.08	-	-	-
274.00	279.00	2402.63	2481.50	2532.35	-	-	-

[1)] No value indicates that the test is performed as a pressure pulse test and the parameters could not be calculated due to low and uncertain flow rates. Alternatively the test was performed as an injection test with a flow below measurement limit (measurement limit is unique for each test but nominally 1.67 E-8 m3/s).

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. Test diagrams – Injection- and Pressure Pulse Tests

In the following pages diagrams are presented for all test sections. A linear diagram of pressure and flow rate is presented for each test. For most injection tests lin-log and log-log diagrams are presented, from injection and recovery period respectively. For two of the pressure pulse tests the linear diagram is presented together with a lin-log diagram.

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)
C = well loss constant (set to 0)
r/B = leakage factor (-)

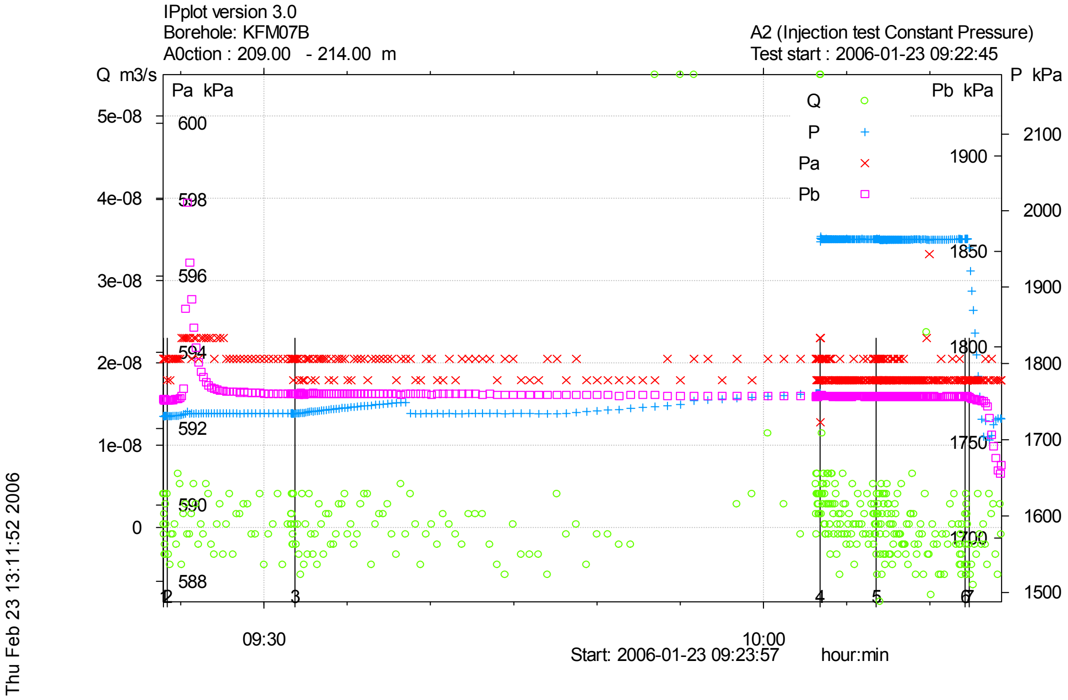


Figure A3-1. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the injection test in section 209.0-214.0 m in borehole KFM07B.*

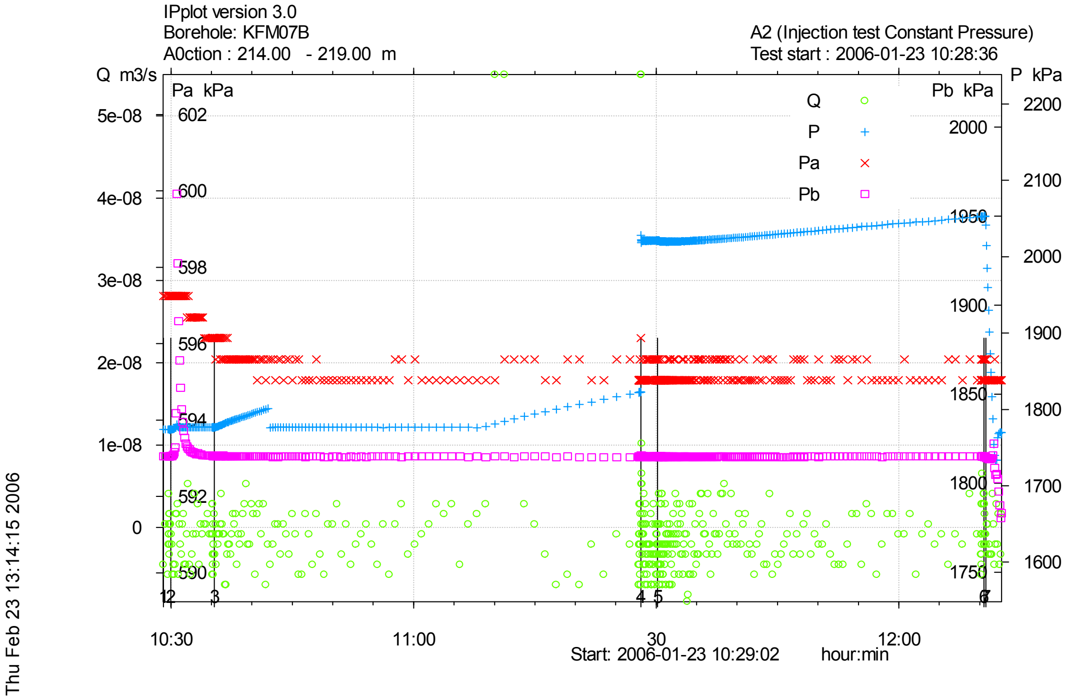


Figure A3-2. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the pressure pulse test in section 214.0-219.0 m in borehole KFM07B.*

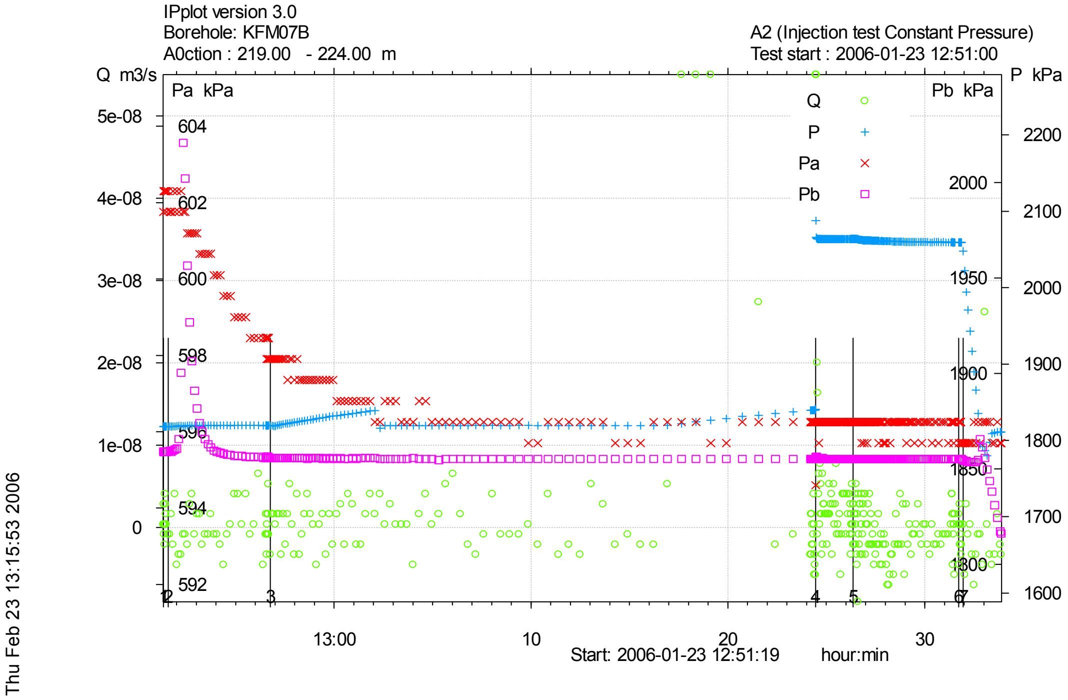


Figure A3-3. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the injection test in section 219.0-224.0 m in borehole KFM07B.*

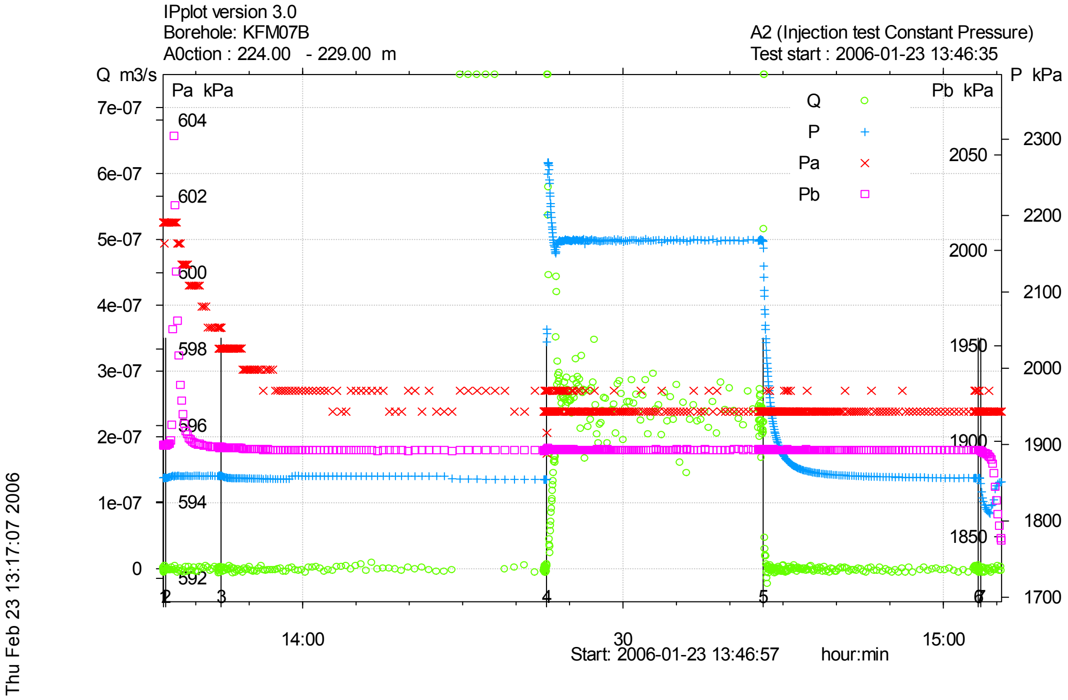


Figure A3-4. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the injection test in section 224.0-229.0 m in borehole KFM07B.*

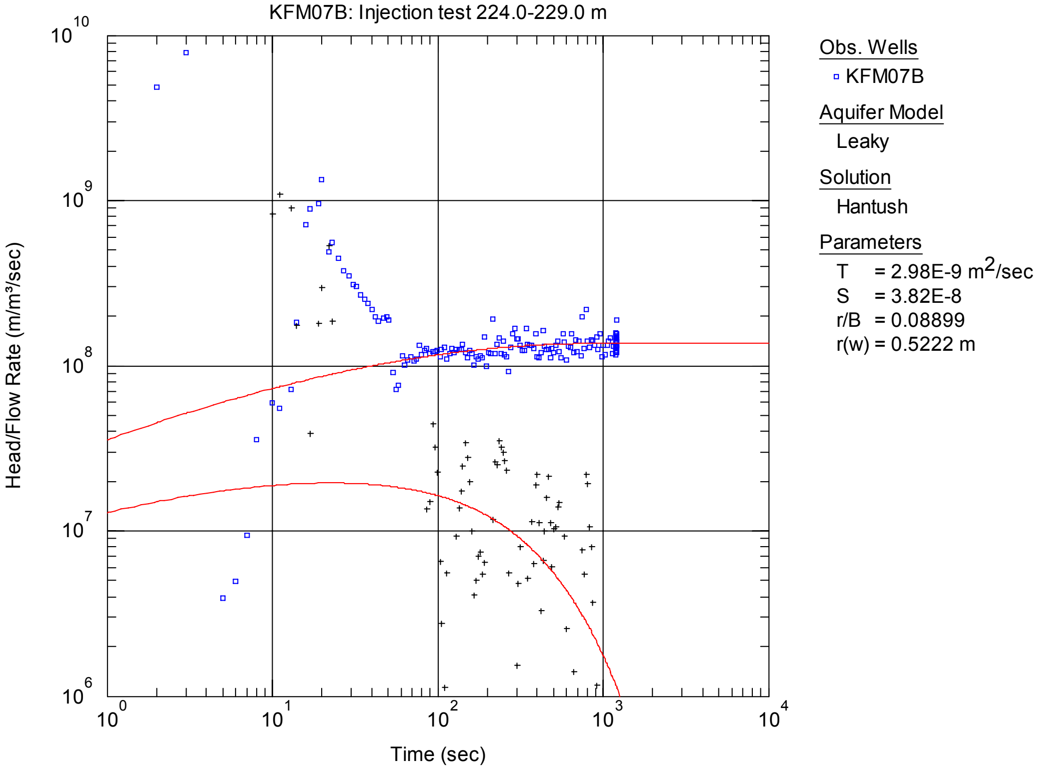


Figure A3-5. *Log-log plot of head/flow rate (□) and derivative (+) versus time, from the injection test in section 224.0-229.0 m in KFM07B.*

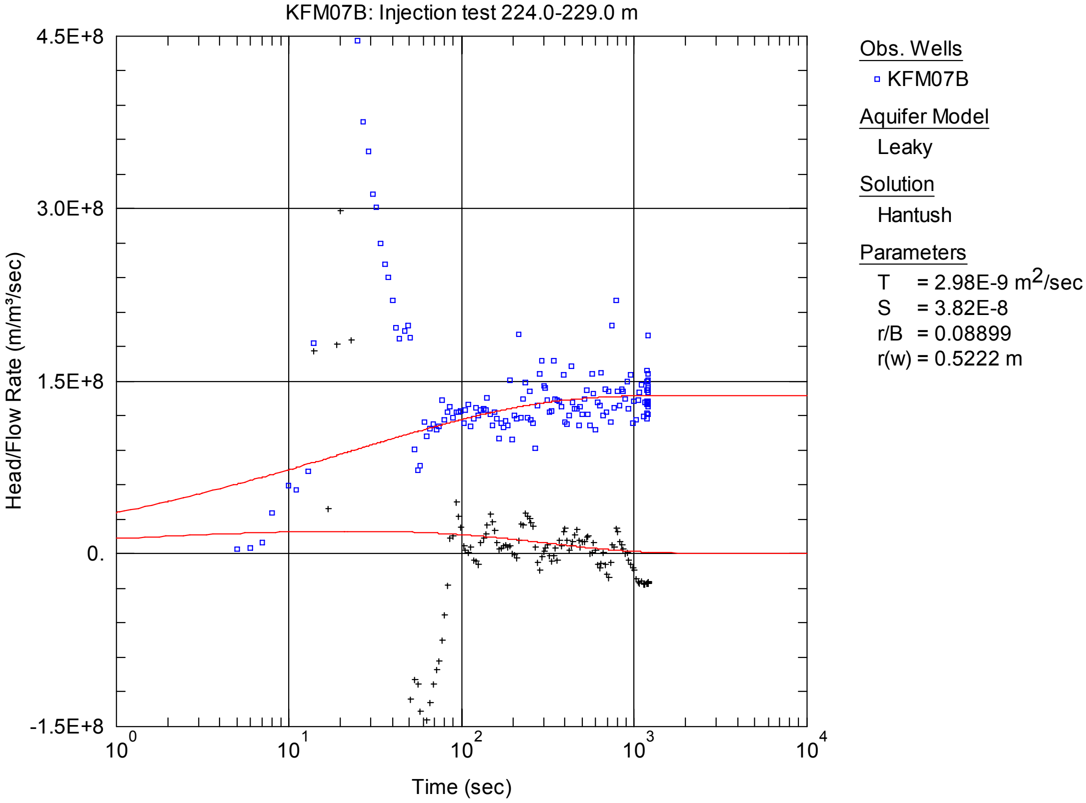


Figure A3-6. *Lin-log plot of head/flow rate (□) and derivative (+) versus time, from the injection test in section 224.0-229.0 m in KFM07B.*

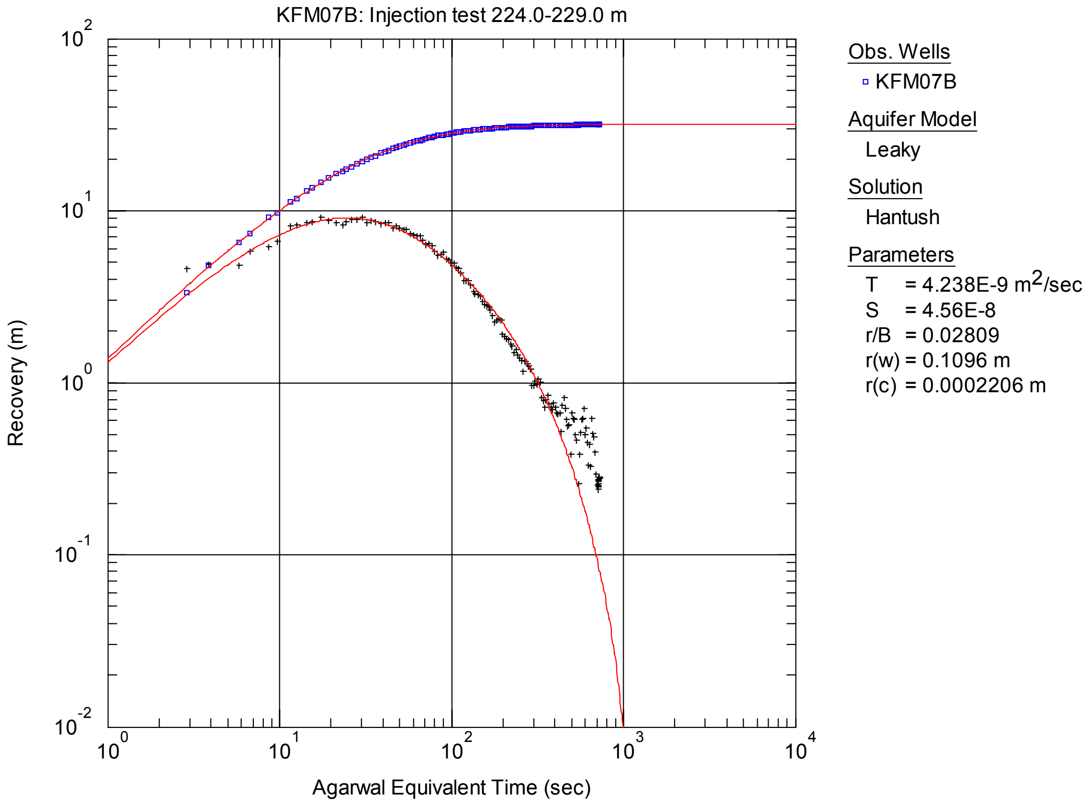


Figure A3-7. *Log-log plot of recovery (□) and derivative (+) versus equivalent time, from the injection test in section 224.0-229.0 m in KFM07B.*

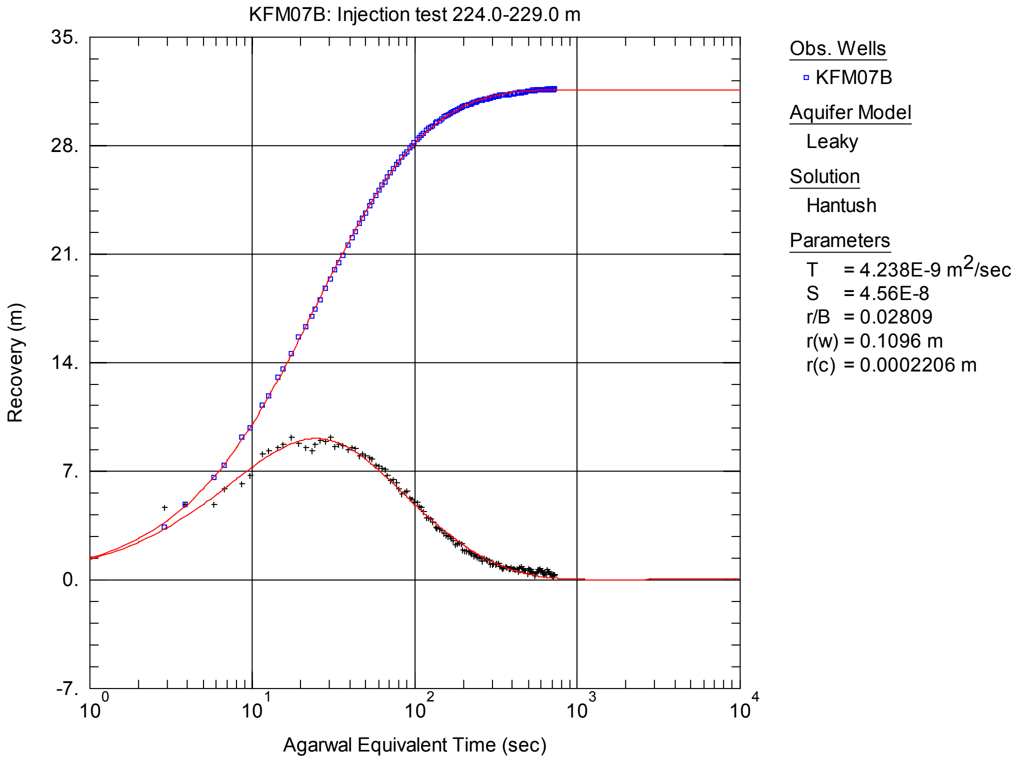


Figure A3-8. *Lin-log plot of recovery (□) and derivative (+) versus equivalent time, from the injection test in section 224.0-229.0 m in KFM07B.*

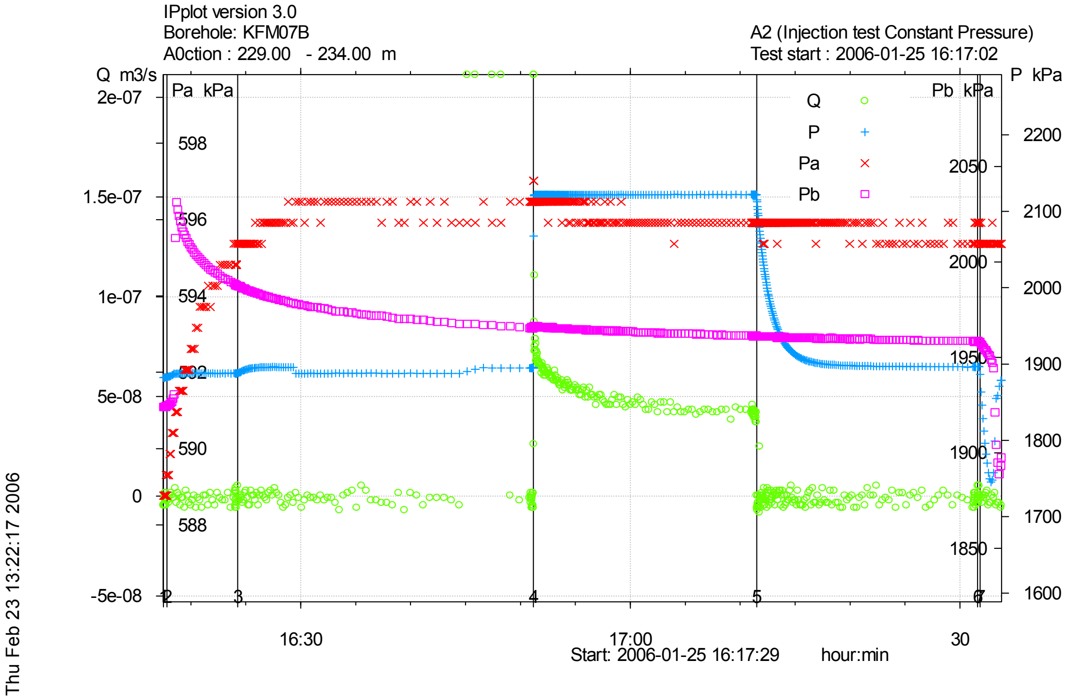


Figure A3-9. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the injection test in section 229.0-234.0 m in borehole KFM07B.*

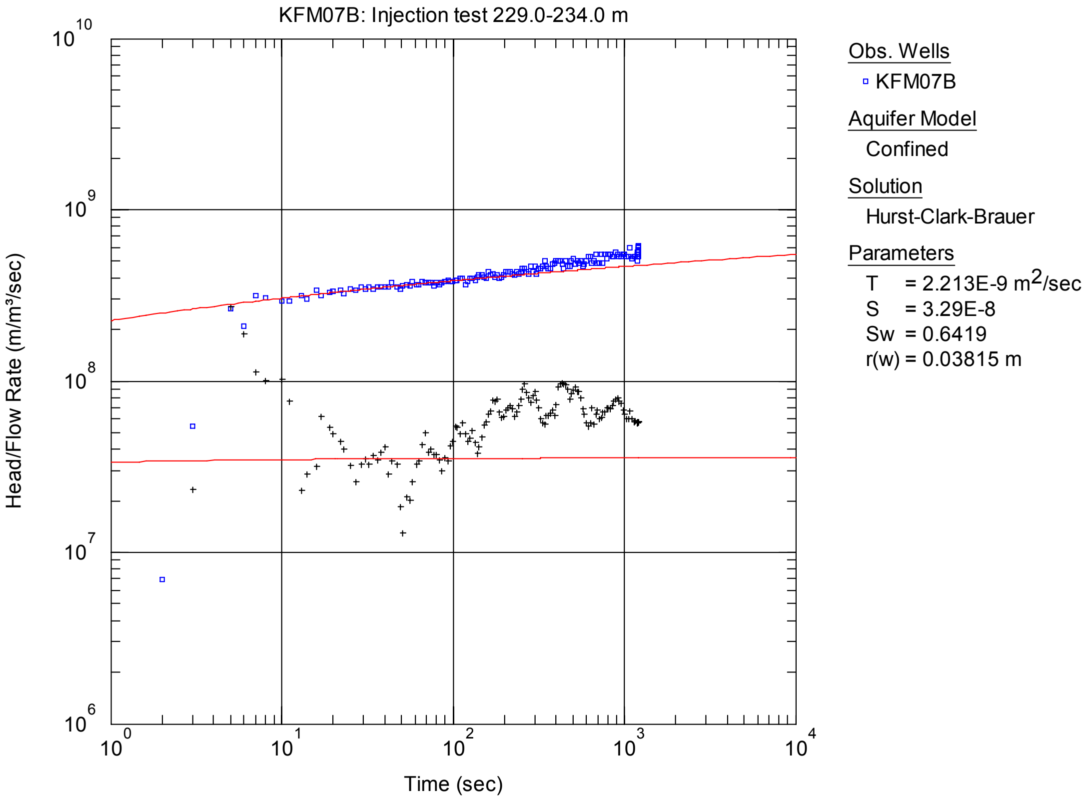


Figure A3-10. *Log-log plot of head/flow rate (□) and derivative (+) versus time, from the injection test in section 229.0-234.0 m in KFM07B.*

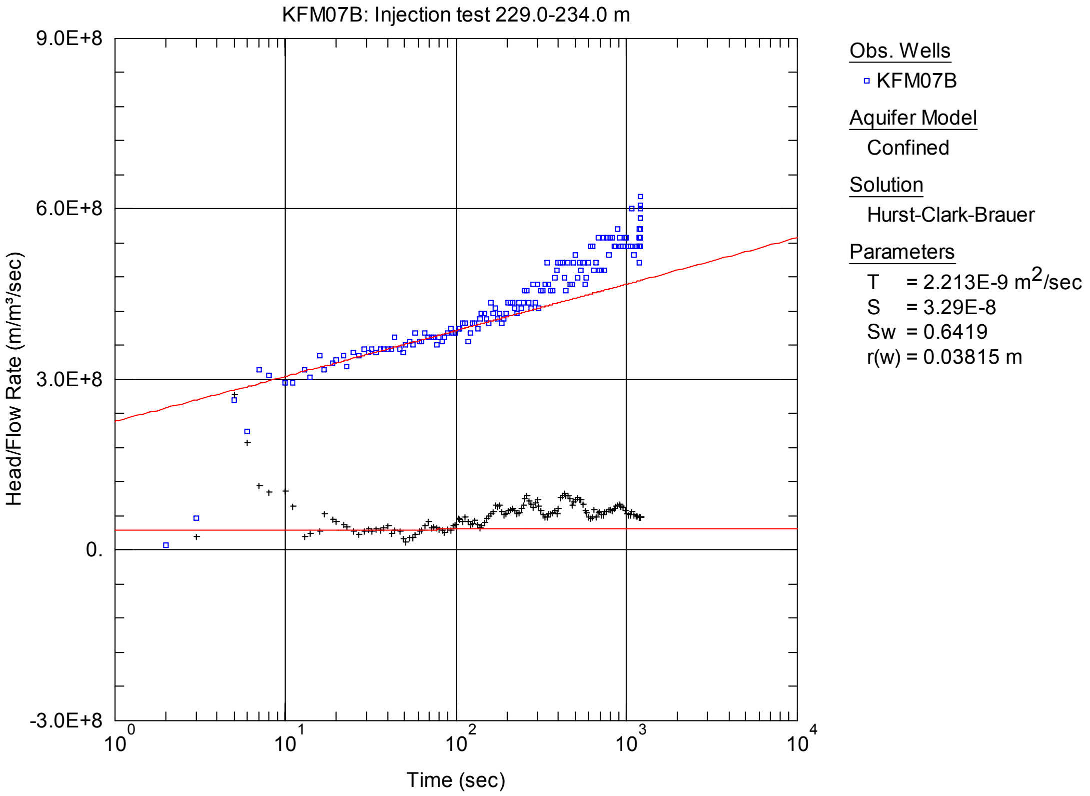


Figure A3-11. *Lin-log plot of head/flow rate (□) and derivative (+) versus time, from the injection test in section 229.0-234.0 m in KFM07B.*

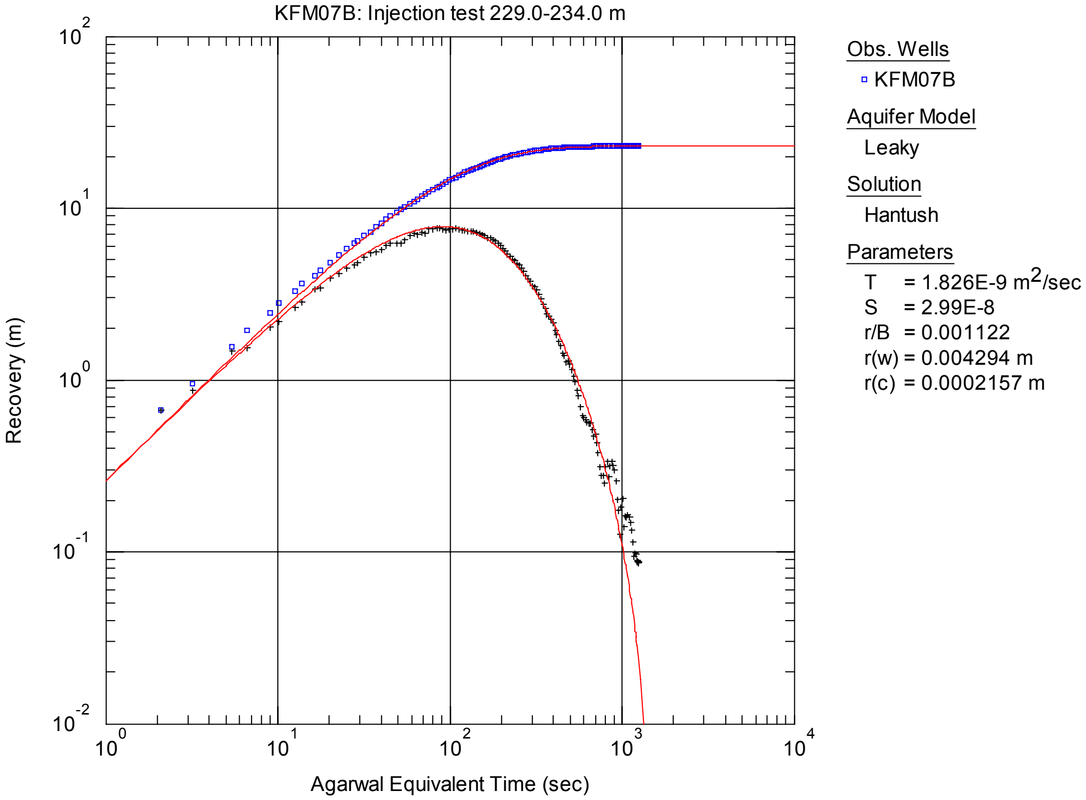


Figure A3-12. *Log-log plot of recovery (□) and derivative (+) versus equivalent time, from the injection test in section 229.0-234.0 m in KFM07B.*

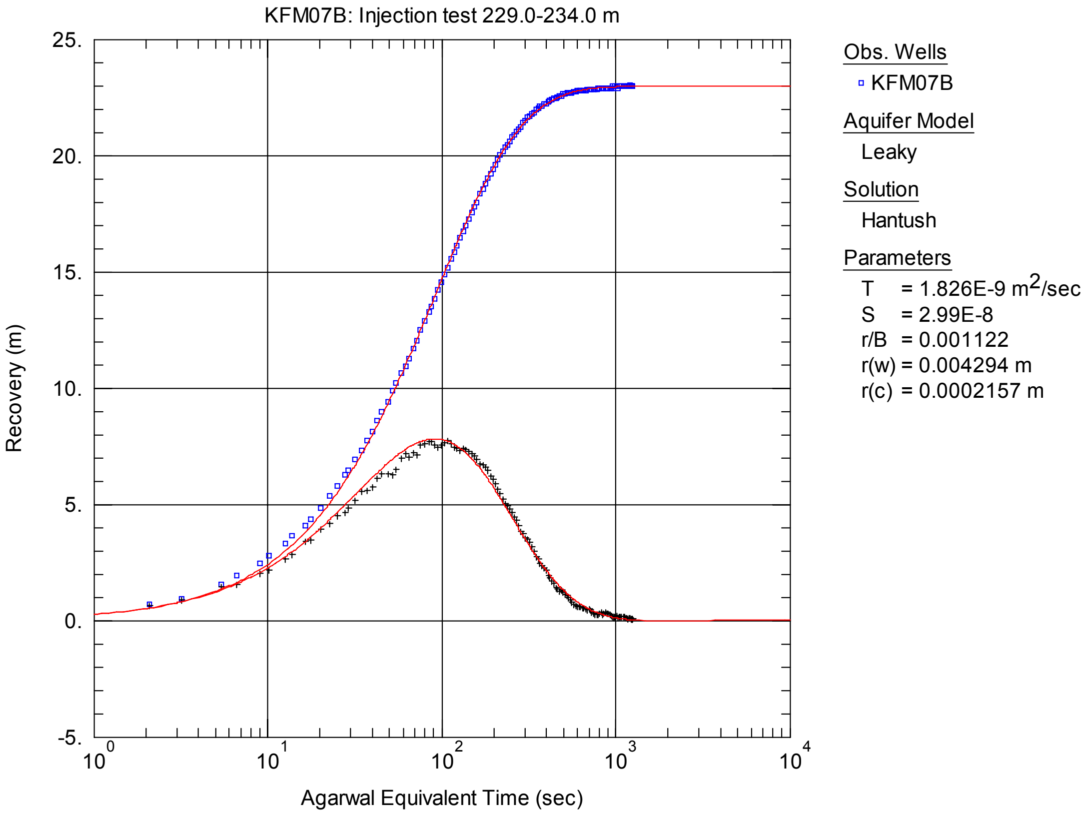


__Figure A3-13.__ Lin-log plot of recovery (□) and derivative (+) versus equivalent time, from the injection test in section 229.0-234.0 m in KFM07B.

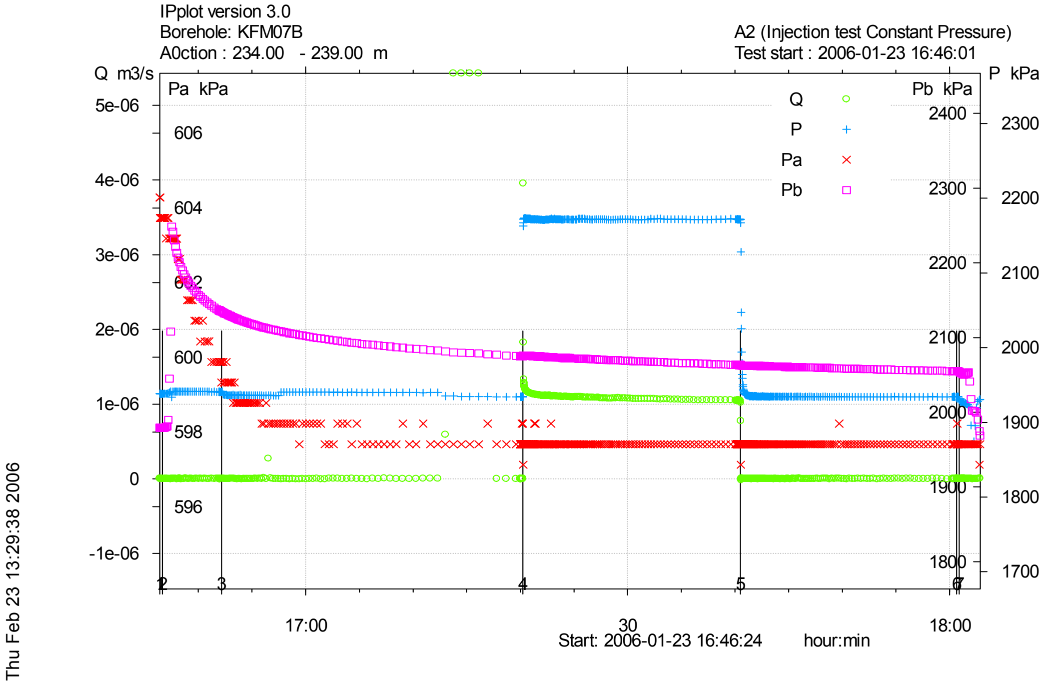


__Figure A3-14.__ Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the injection test in section 234.0-239.0 m in borehole KFM07B.

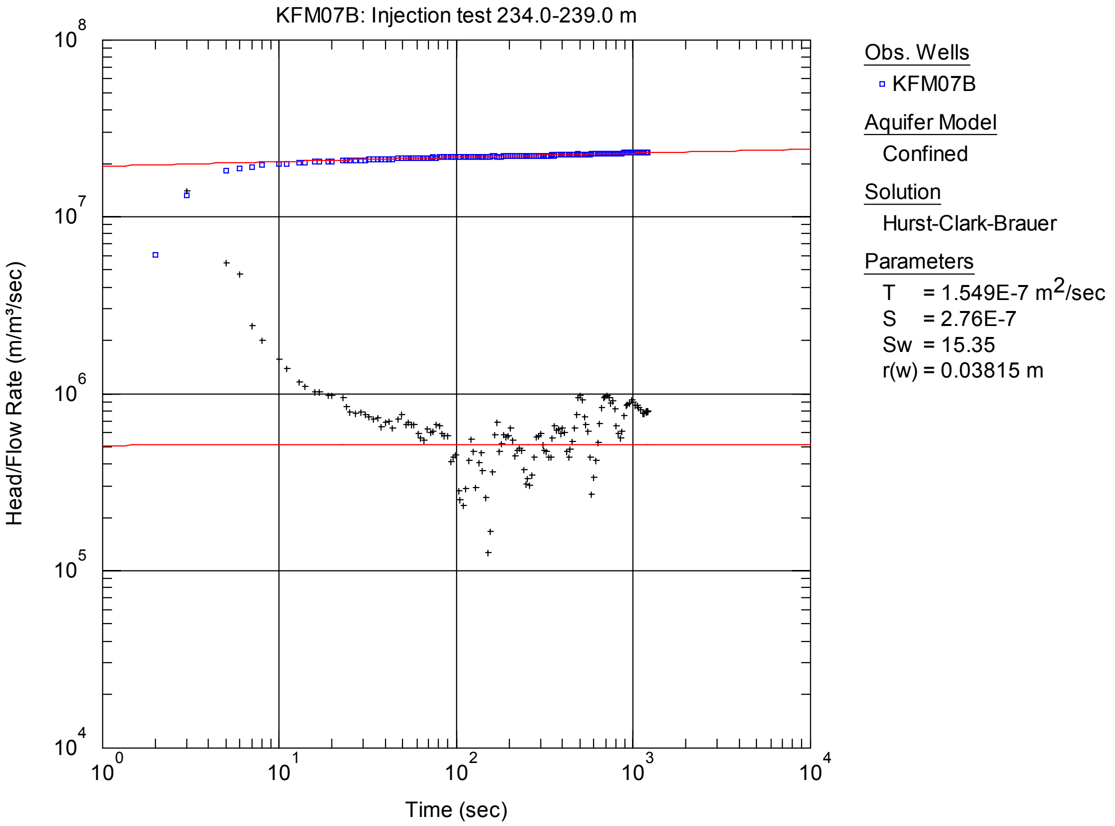


Figure A3-15. *Log-log plot of head/flow rate (□) and derivative (+) versus time, from the injection test in section 234.0-239.0 m in KFM07B.*

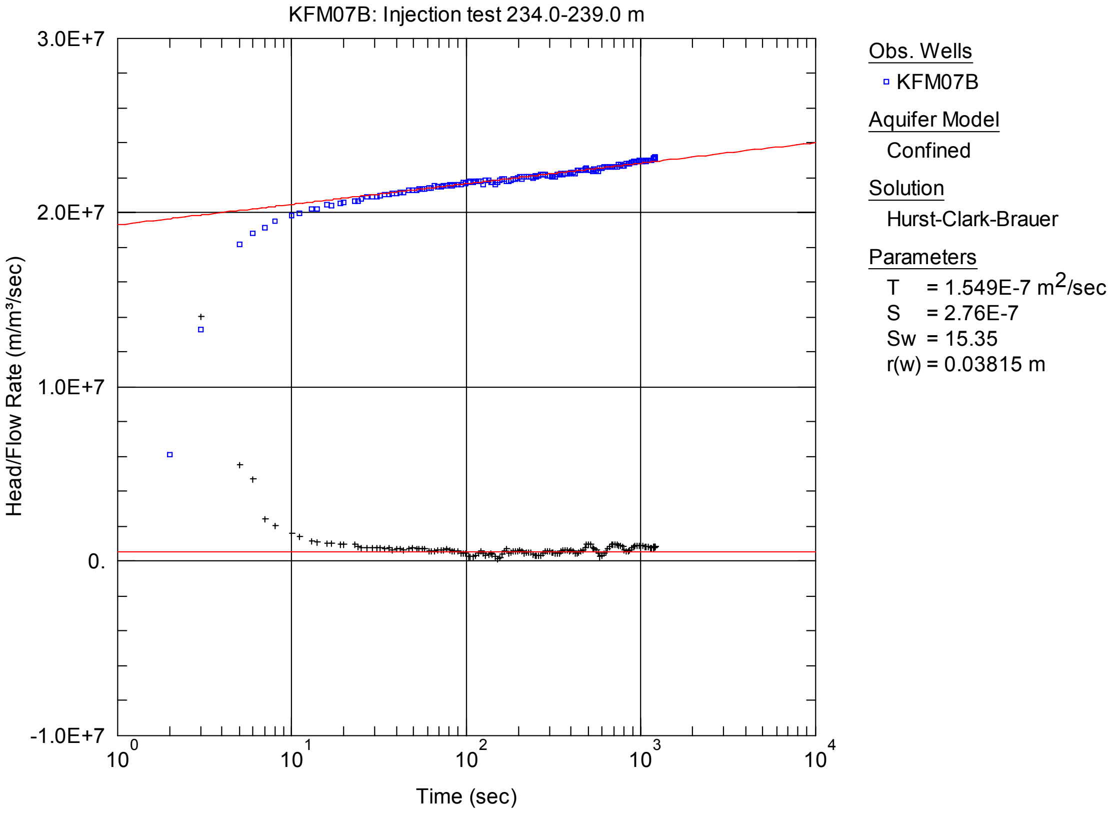


Figure A3-16. *Lin-log plot of head/flow rate (□) and derivative (+) versus time, from the injection test in section 234.0-239.0 m in KFM07B.*

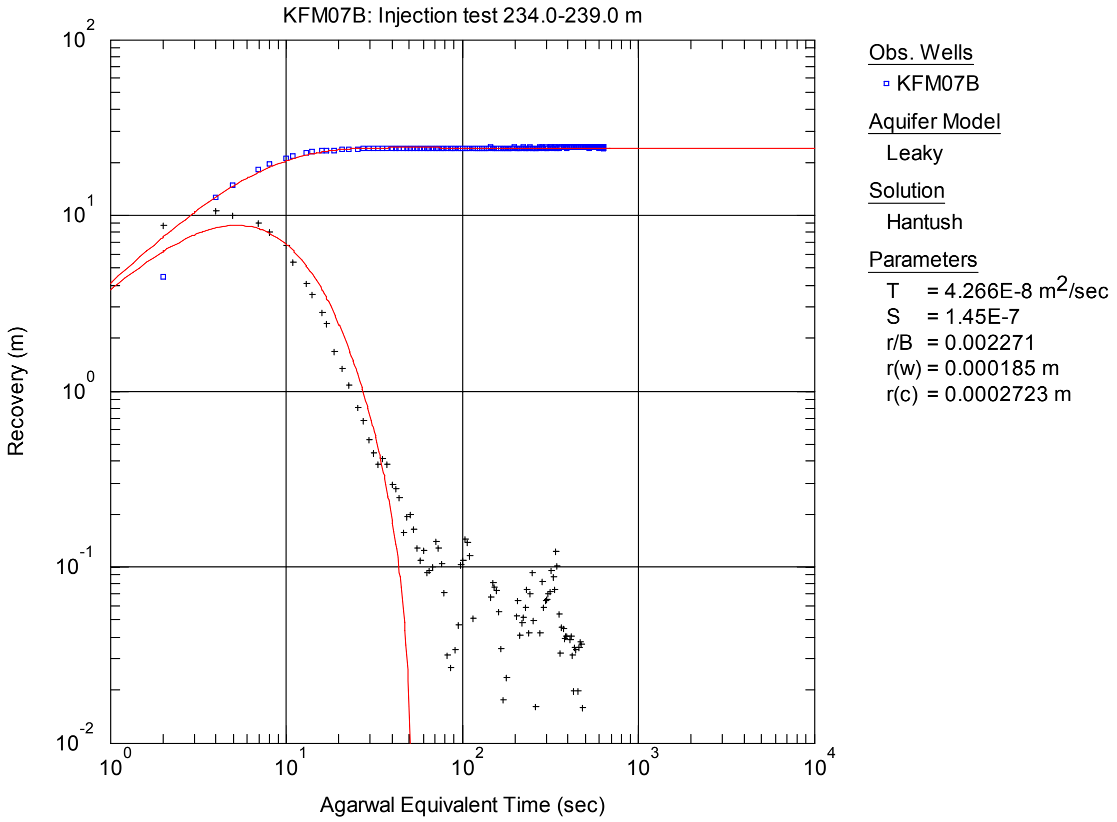


Figure A3-17. *Log-log plot of recovery (□) and derivative (+) versus equivalent time, from the injection test in section 234.0-239.0 m in KFM07B.*

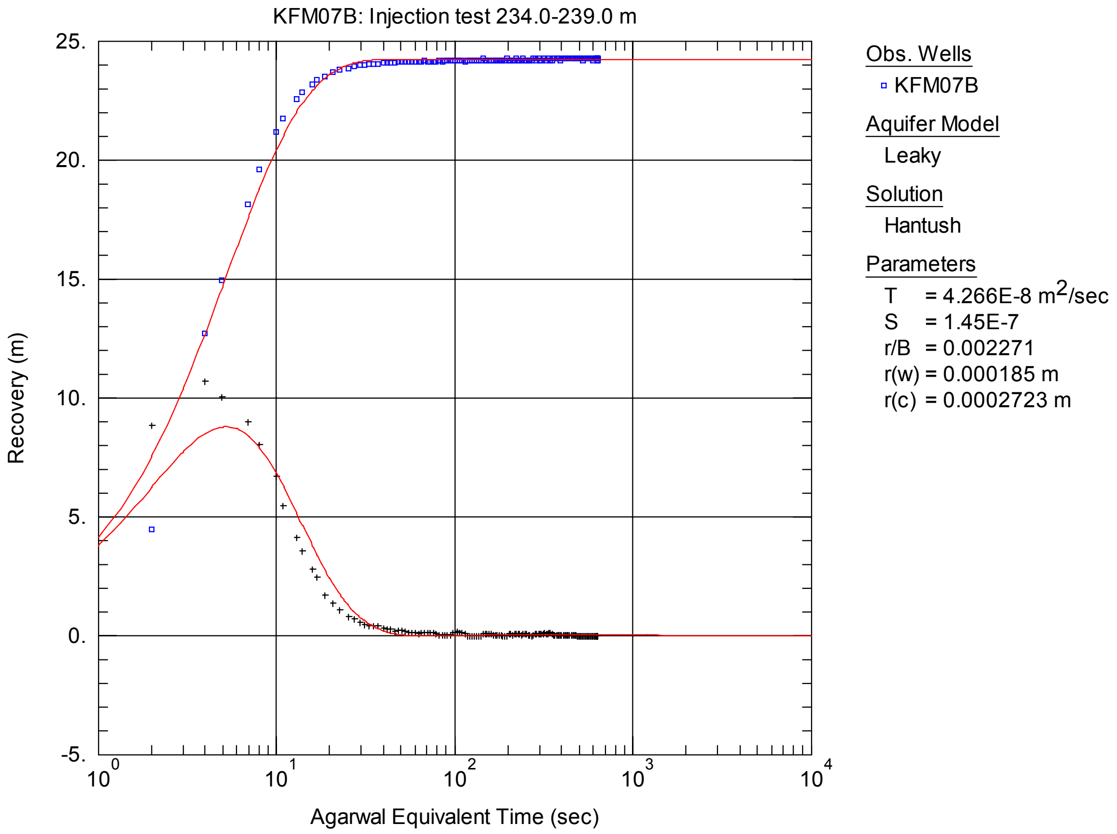


Figure A3-18. *Lin-log plot of recovery (□) and derivative (+) versus equivalent time, from the injection test in section 234.0-239.0 m in KFM07B.*

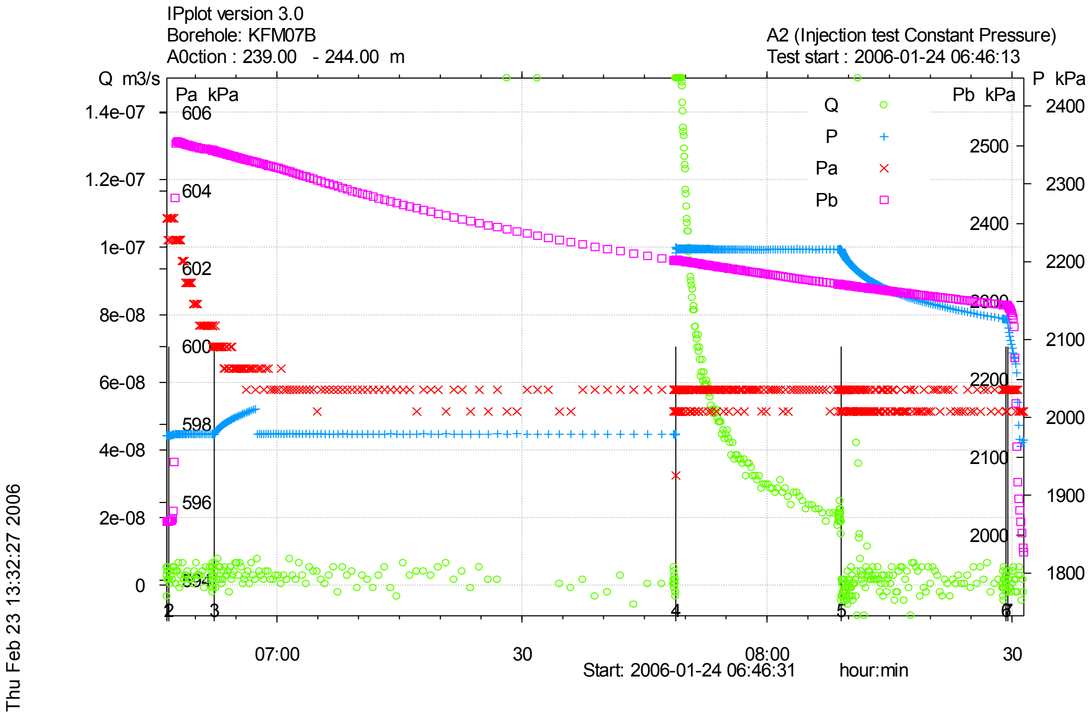


Figure A3-19. Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the injection test in section 239.0-244.0 m in borehole KFM07B.

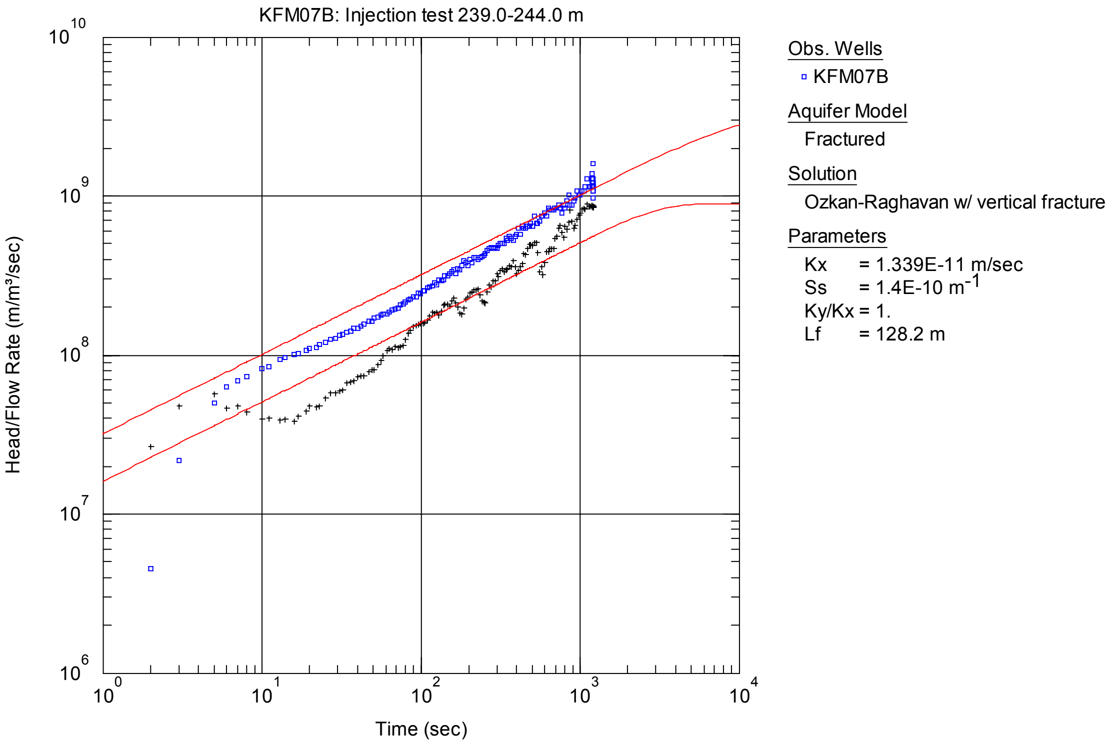


Figure A3-20. Log-log plot of head/flow rate (□) and derivative (+) versus time, from the injection test in section 239.0-244.0 m in KFM07B. It should be emphasised that this evaluation from the injection period was not used.

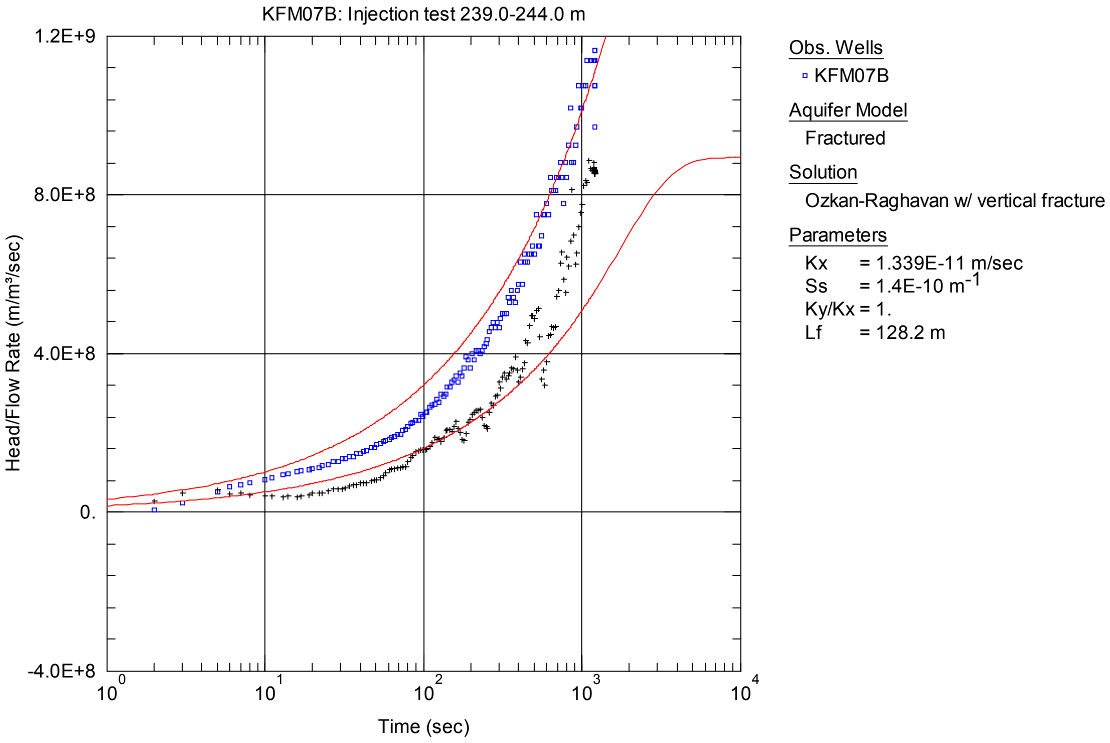


Figure A3-21. *Lin-log plot of head/flow rate (□) and derivative (+) versus time, from the injection test in section 239.0-244.0 m in KFM07B. It should be emphasised that this evaluation from the injection period was not used.*

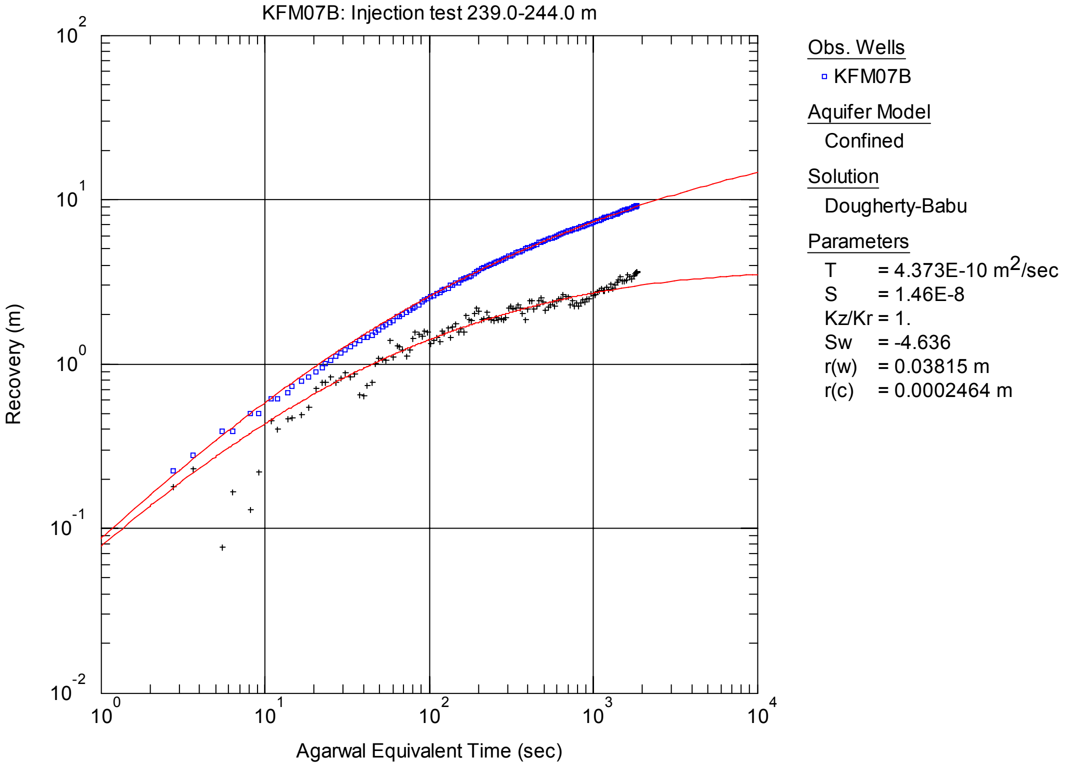


Figure A3-22. *Log-log plot of recovery (□) and derivative (+) versus equivalent time, from the injection test in section 239.0-244.0 m in KFM07B. Plot showing fit using the Dougherty-Babu model for pseudo radial flow.*

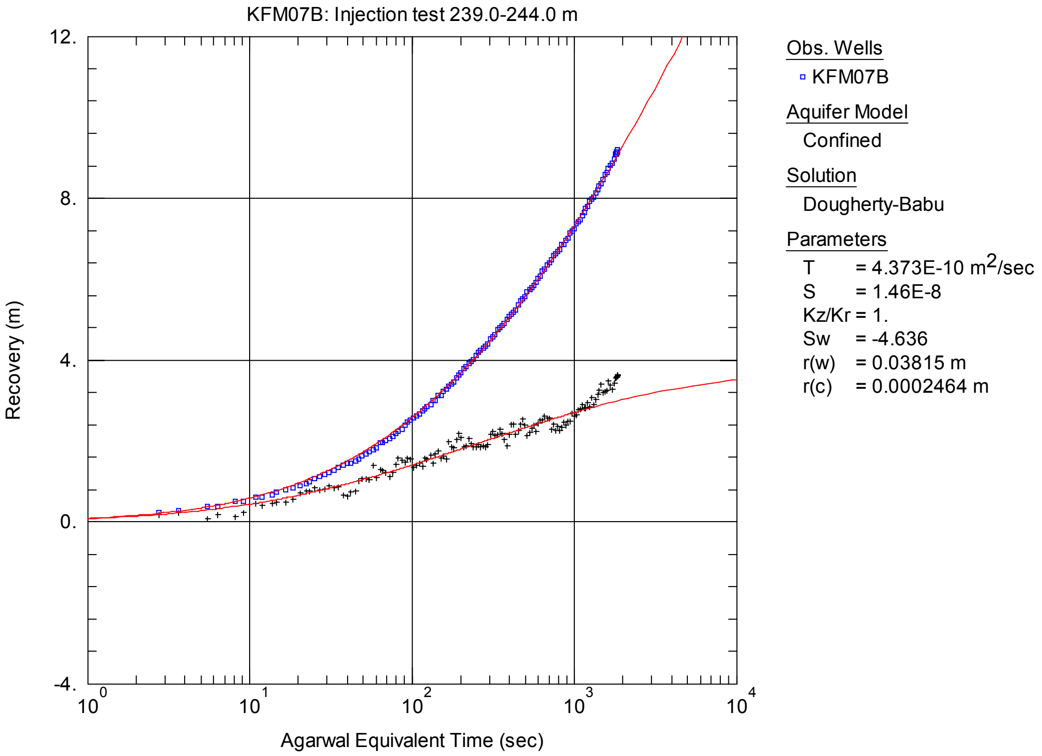


Figure A3-23. *Lin-log plot of recovery (□) and derivative (+) versus equivalent time, from the injection test in section 239.0-244.0 m in KFM07B. Plot showing fit using the Dougherty-Babu model for pseudo radial flow.*

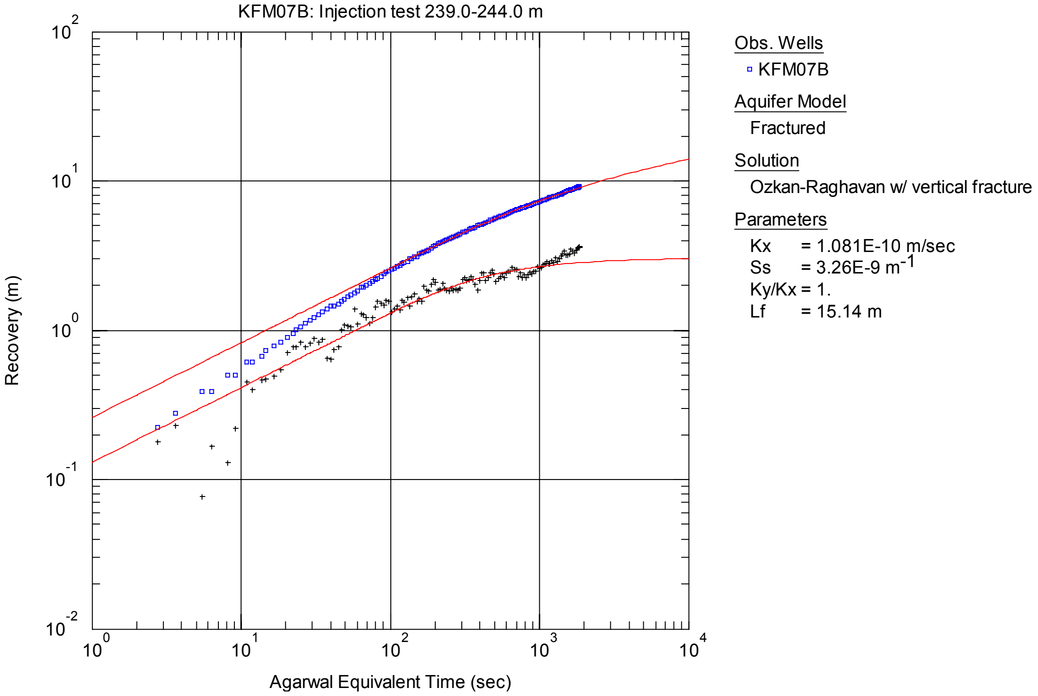


Figure A3-24. *Log-log plot of recovery (□) and derivative (+) versus equivalent time, from the injection test in section 239.0-244.0 m in KFM07B. Plot showing fit when using a model for linear flow.*

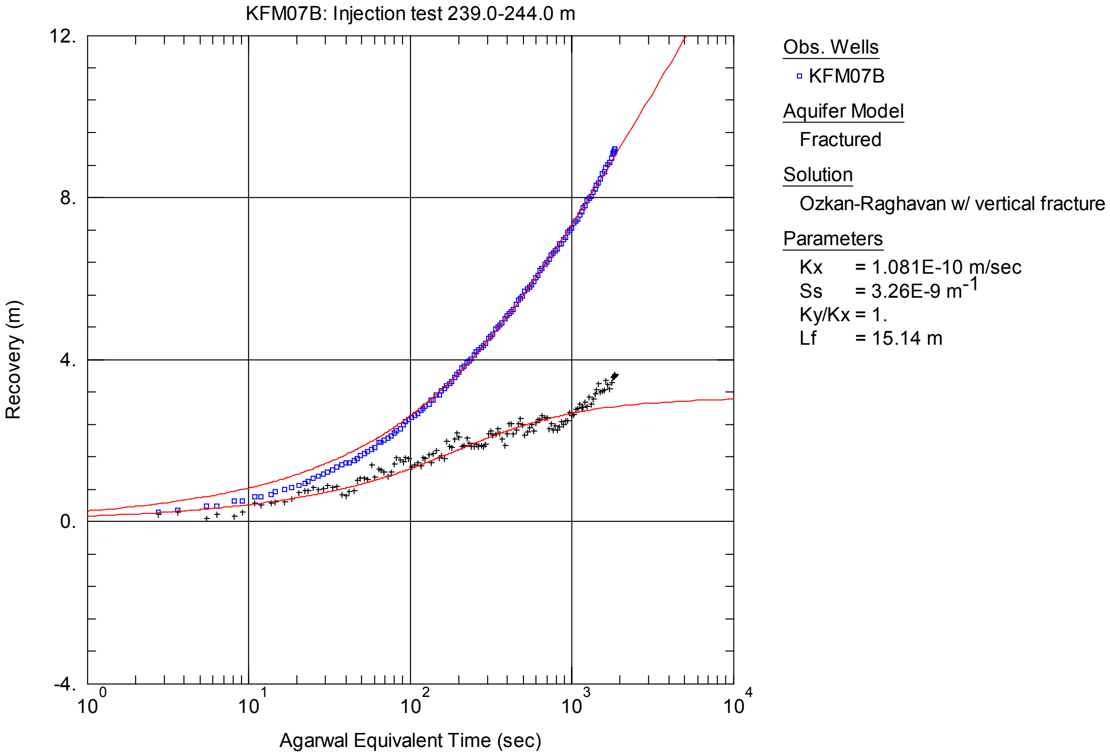


__Figure A3-25.__ Lin-log plot of recovery (□) and derivative (+) versus equivalent time, from the injection test in section 239.0-244.0 m in KFM07B. Plot showing fit when using a model for linear flow.

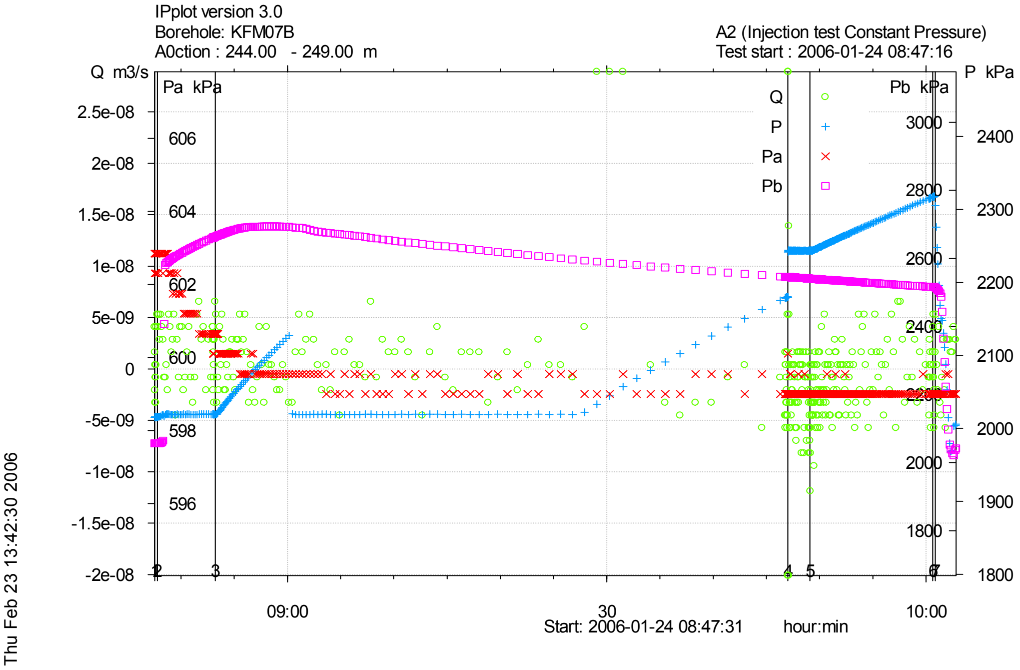


__Figure A3-26.__ Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the pressure pulse test in section 244.0-249.0 m in borehole KFM07B.

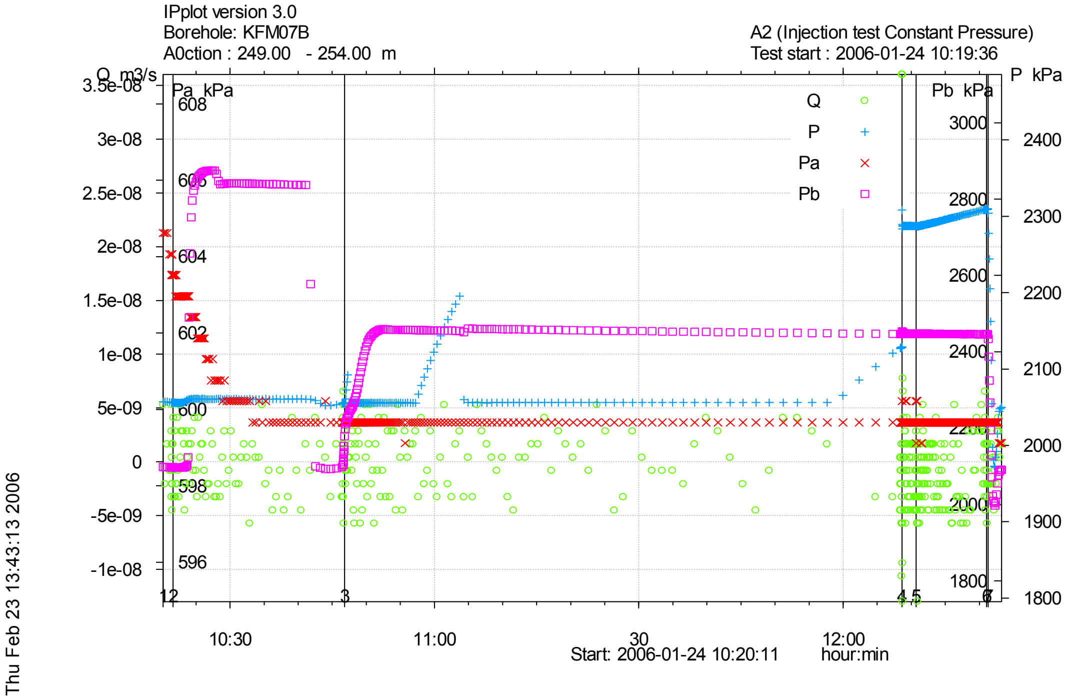


Figure A3-27. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the pressure pulse test in section 249.0-254.0 m in borehole KFM07B.*

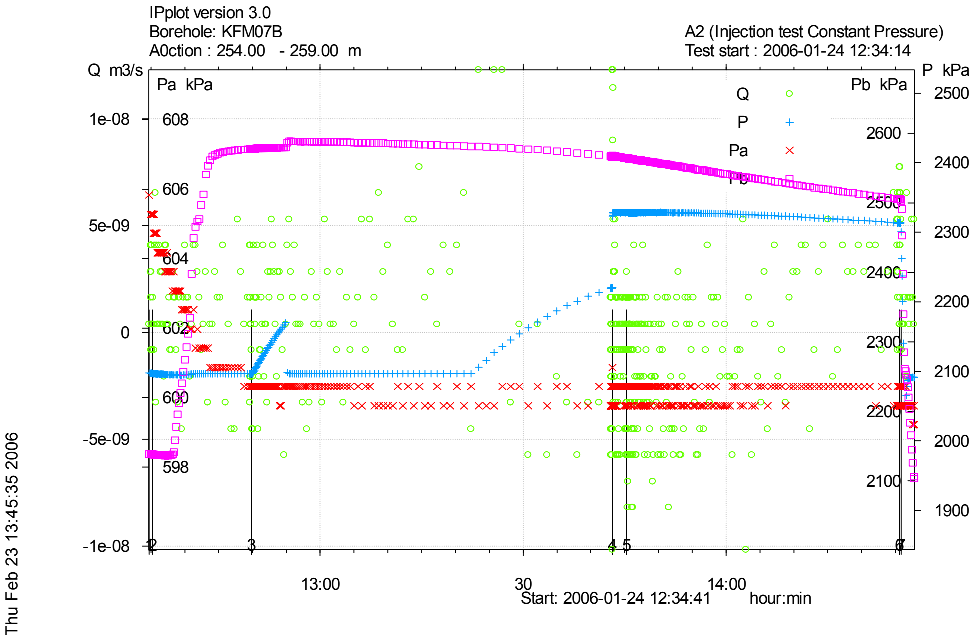


Figure A3-28. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the pressure pulse test in section 254.0-259.0 m in borehole KFM07B.*

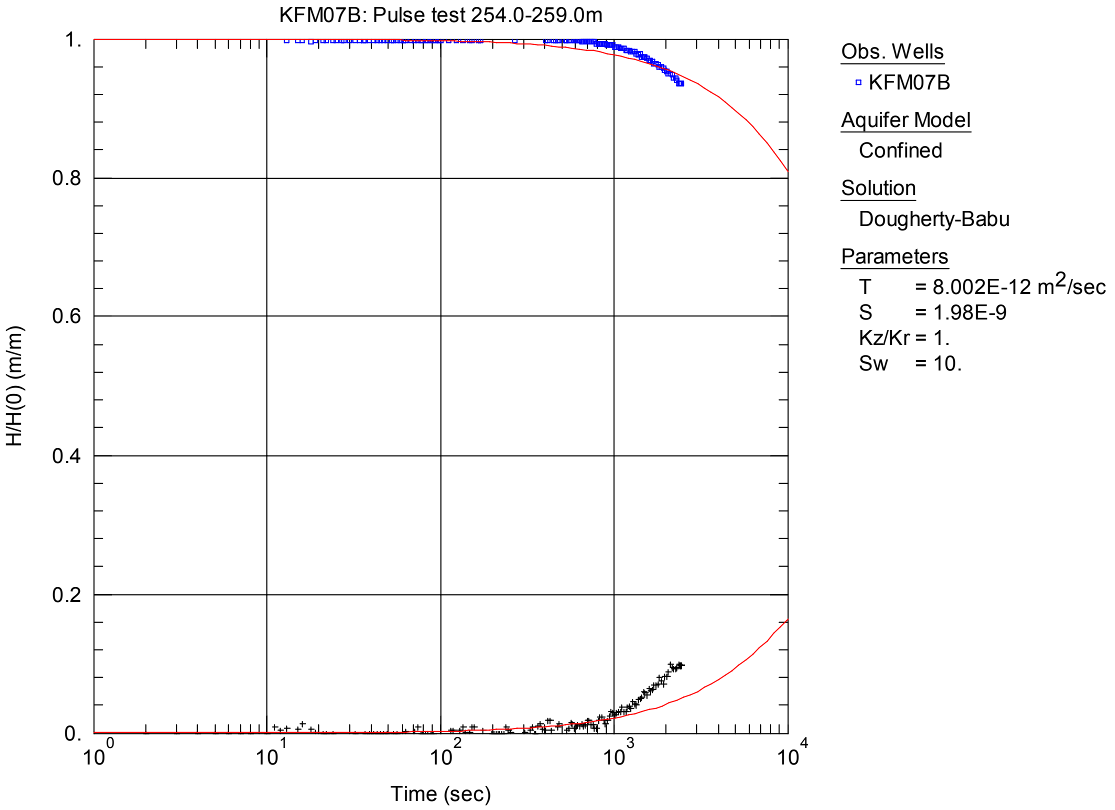


Figure A3-29. *Lin-log plot of normalized head (□) and derivative (+) versus time, from the pressure pulse test in section 254.0-259.0 m in KFM07B.*

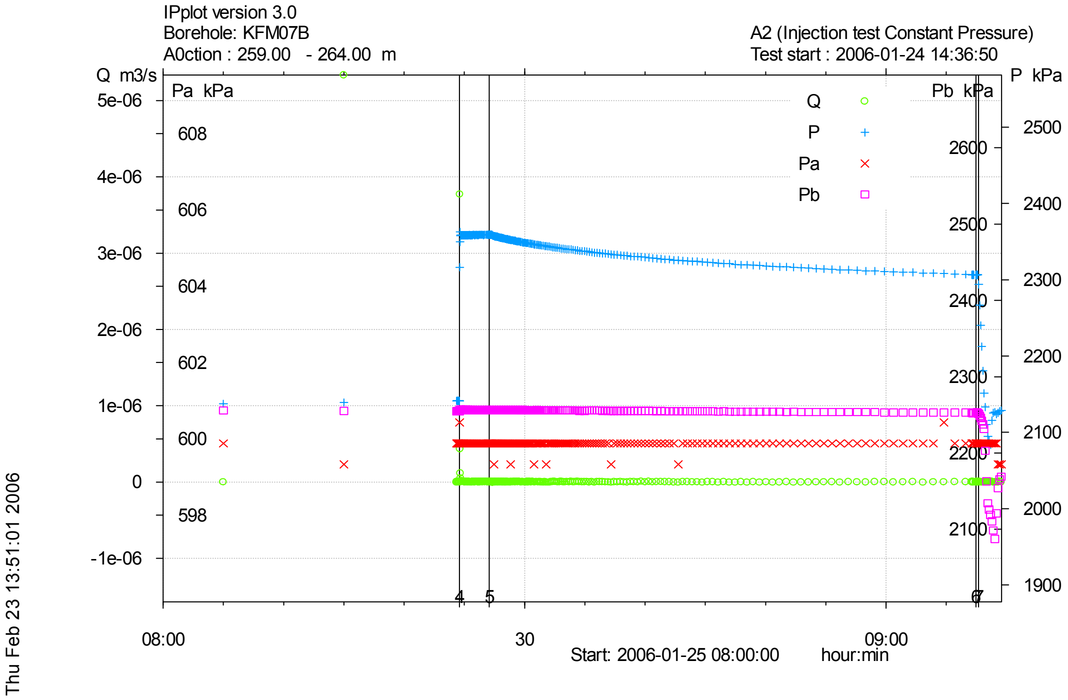


Figure A3-30. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the pressure pulse test in section 259.0-264.0 m in borehole KFM07B.*

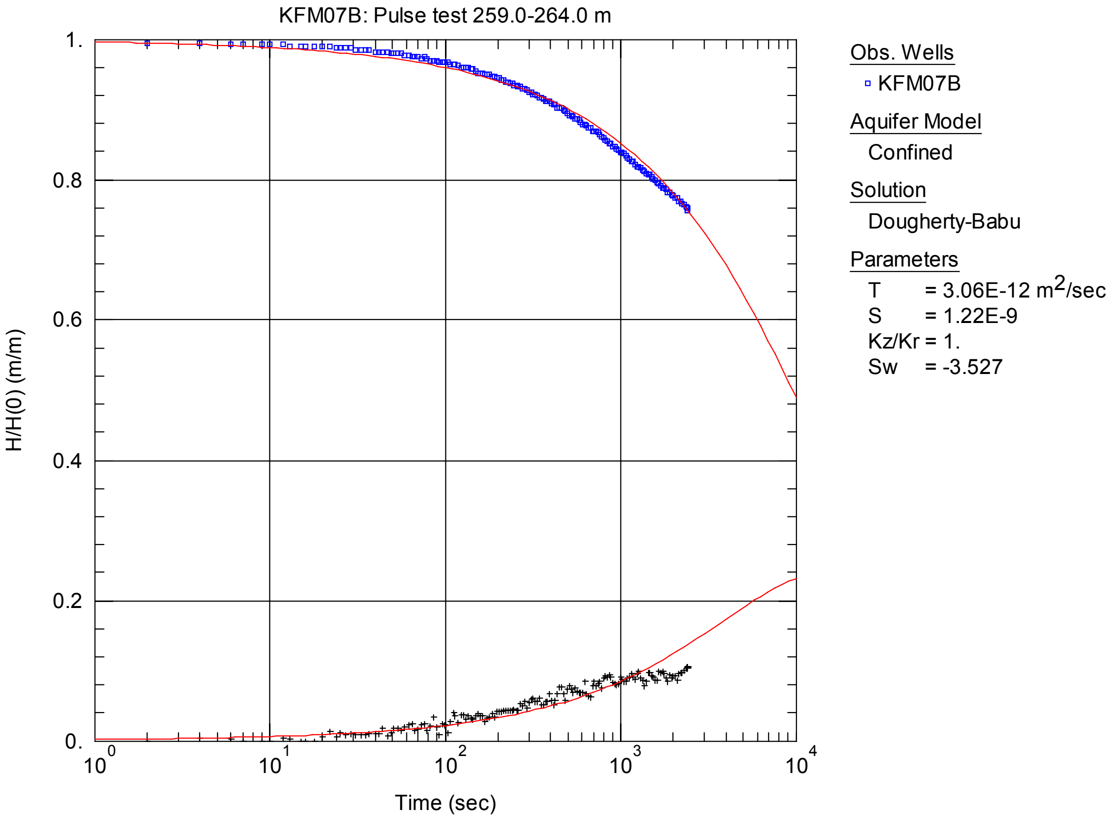


Figure A3-31. *Lin-log plot of normalized head (□) and derivative (+) versus time, from the pressure pulse test in section 259.0-264.0 m in KFM07B.*

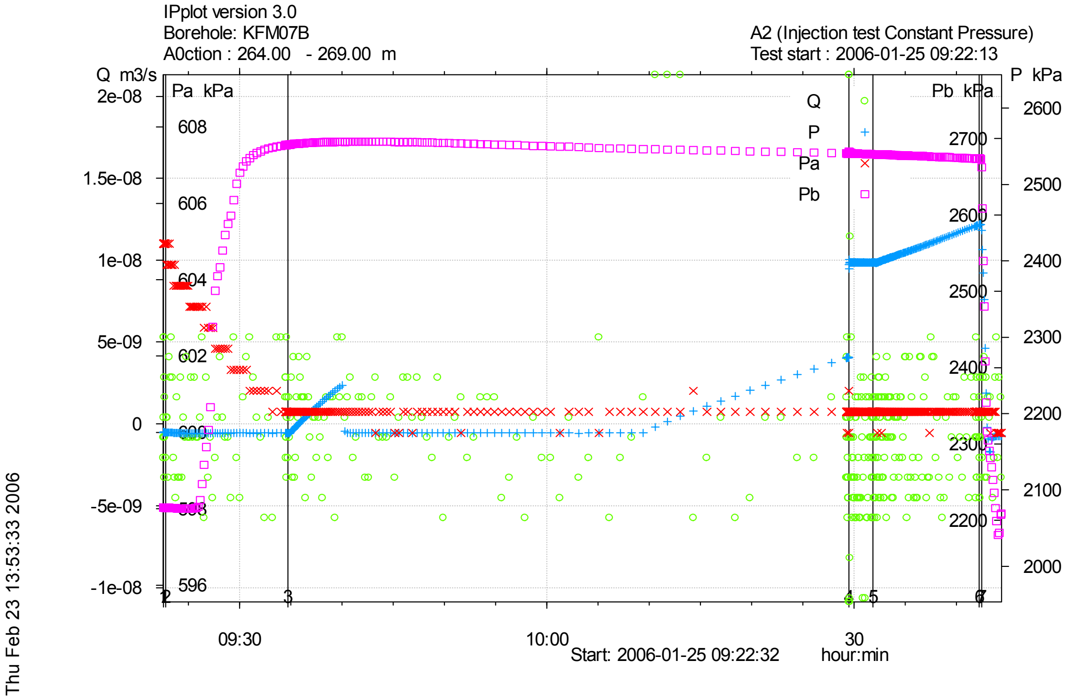


Figure A3-32. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the pressure pulse test in section 264.0-269.0 m in borehole KFM07B.*

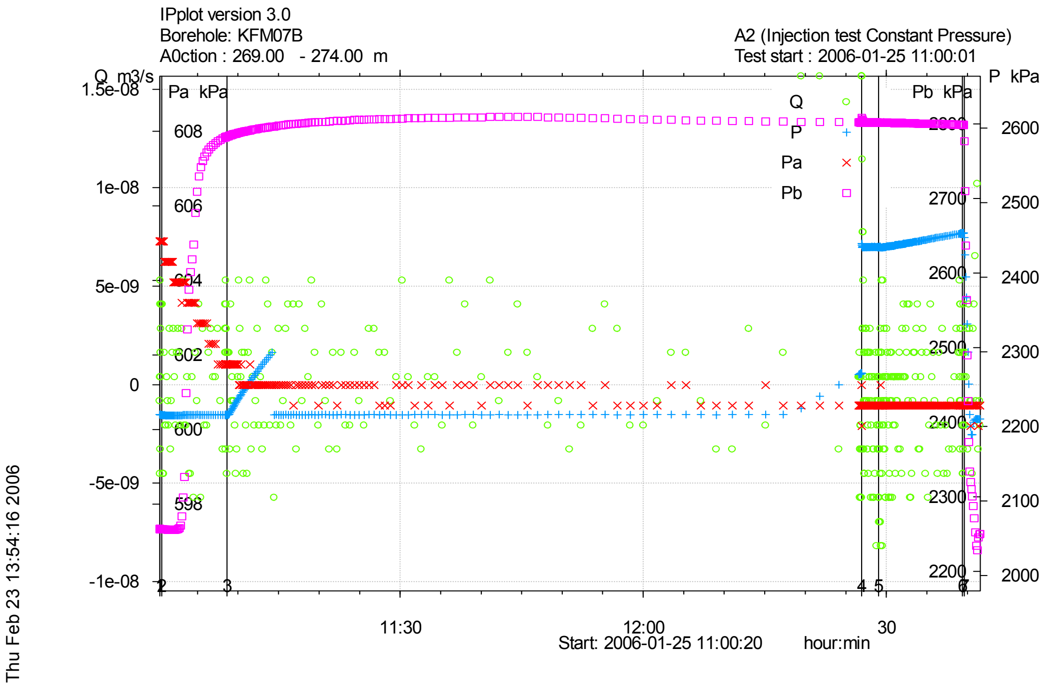


Figure A3-33. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the pressure pulse test in section 269.0-274.0 m in borehole KFM07B.*

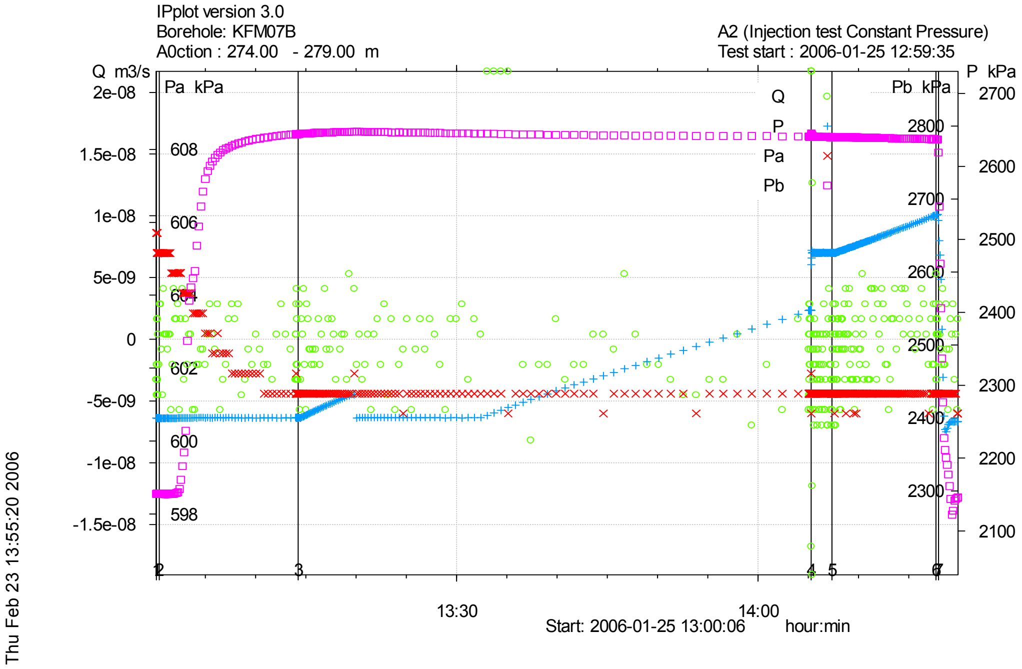
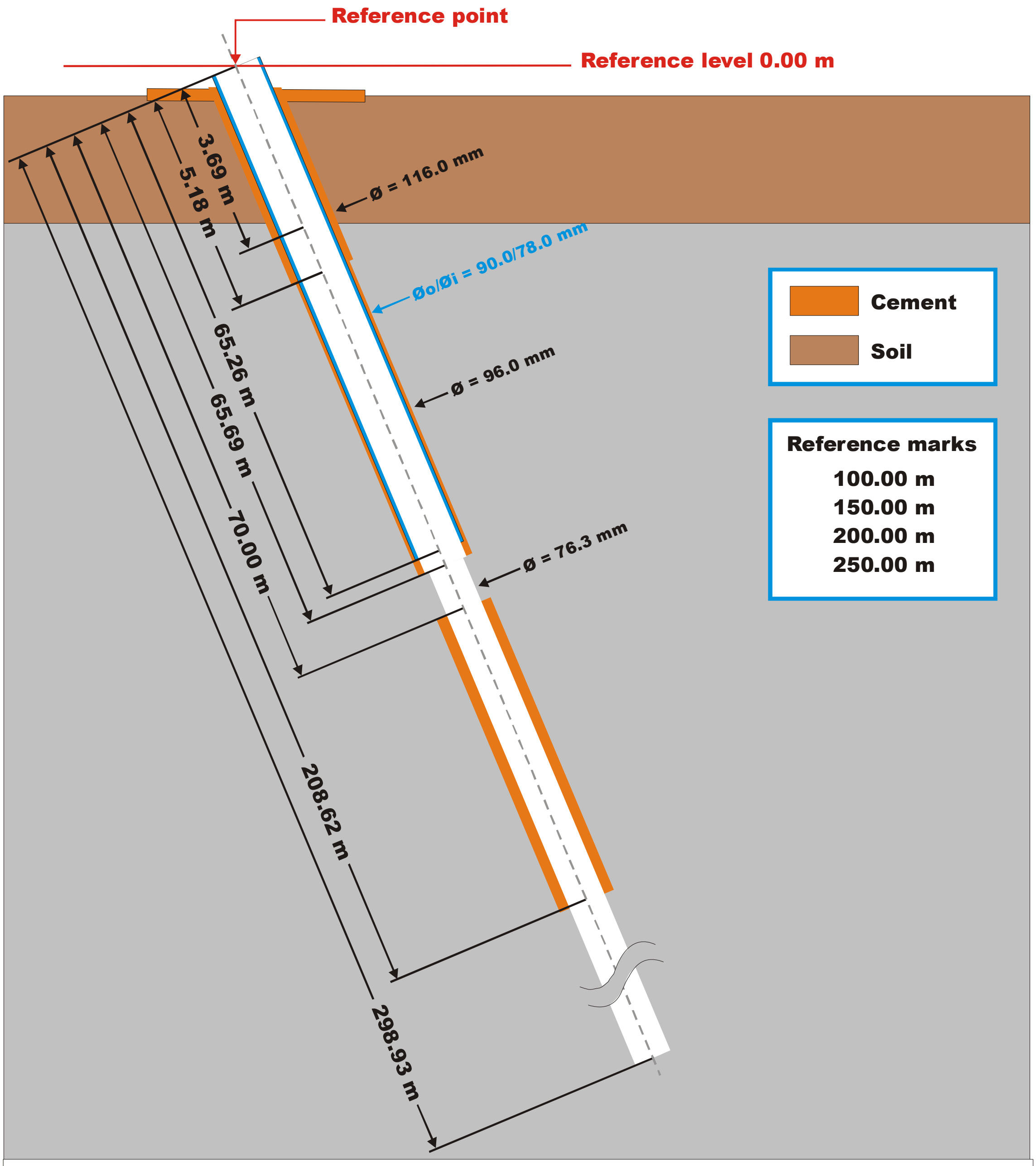


Figure A3-34. *Linear plot of flow rate (Q), pressure (P), pressure above section (Pa) and pressure below section (Pb) versus time from the pressure pulse test in section 274.0-279.0 m in borehole KFM07B.*

Appendix 4. Borehole technical data

Technical data

Borehole KFM07B



Drilling reference point

Northing: 6700123.62 (m), RT90 2,5 gon V 0:-15
Easting: 1631036.83 (m), RT90 2,5 gon V 0:-15
Elevation: 3.36 (m), RHB 70

Orientation

Bearing: 134.35°
Inclination: -53.71°

Drilling period

Drilling start date: 2005-05-30
Drilling stop date: 2005-10-18

2005-11-17 rev 2

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 or injected 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	

Column	Datatype	Unit	Column Description	Alt. Symbol
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.	
bc_s	FLOAT		Best choice of S (Storativity) ,see descr.	
ri	FLOAT	m	Radius of influence	
ri_index	CHAR		ri index=index of radius of influence :-1,0 or 1, see 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	
skin	FLOAT		Skin factor;best estimate of flow/recovery period,see descr.	ξ
dt1	FLOAT	s	Estimated start time of evaluation, see table description	
dt2	FLOAT	s	Estimated stop time of evaluation. see table description	
t1	FLOAT	s	Start time for evaluated parameter from start flow period	t_1
t2	FLOAT	s	Stop time for evaluated parameter from start of flow period	t_2
dte1	FLOAT	s	Start time for evaluated parameter from start of recovery	dte_1
dte2	FLOAT	s	Stop time for evaluated parameter from start of recovery	dte_2
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..	

Column	Datatype	Unit	Column Description	Alt. Symbol
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)

Nomenclature plu_pulse_test_ed

Column	Datatype	Unit	Column Description
site	CHAR		Investigation site name
idcode	CHAR		Object or borehole identification code
secup	FLOAT	m	
seclow	FLOAT	m	Lower section limit (m)
start_date	DATE		Date (yymmdd hh:mm:ss)
stop_date	DATE		Date (yymmdd hh:mm:ss)
activity_type	CHAR		Activity type code
test_type	CHAR		Type of test, one of 7, see table description
formation_type	CHAR		1: Rock, 2: Soil (superficial deposits)
start_flow_period	DATE		Date and time of flow phase start (YYYYMMDD hhmmss)
dur_flow_phase_tp	FLOAT	s	Time for the flowing phase of the test (tp)
dur_rec_phase_tf	FLOAT	s	Time for the recovery phase of the test (tF)
initial_head_h0	FLOAT	m	Initial formation hydraulic head, see table description
initial_displacem_dh0	FLOAT	m	Initial displacement of hydraulic head,see table description
displacem_dh0_p	FLOAT	m	Initial displacement of slugtest,see table description
displacem_dh0_f	FLOAT	m	Initial displacement of bailtest,see table description
head_at_flow_end_hp	FLOAT	m	Hydraulic head at end of flow phase,see table description
final_head_hf	FLOAT	m	Hydraulic head at the end of the recovery,see table descr.
initial_press_pi	FLOAT	kPa	Initial formation pressure
initial_press_diff_dp0	FLOAT	kPa	Initial pressure change from pi at time dt=0,pulse test
press_change_dp0_p	FLOAT	kPa	Initial pressure change;pulse test-measured
press_at_flow_end_pp	FLOAT	kPa	Final pressure at the end of the flowing period
final_press_pf	FLOAT	kPa	Final pressure at the end of the recovery period
formation_width_b	FLOAT	m	b:Interpreted formation thickness repr. for evaluated T,see
transmissivity_ts	FLOAT	m**2/s	Ts: Transmissivity based on slugtest, see table description
value_type_ts	CHAR		0:true value,-1:Ts<lower meas.limit,1:Ts>upper meas.limit
bc_ts	CHAR		Best choice code.1 means Ts is best choice of transm.,else 0
transmissivity_tp	FLOAT	m**2/s	TP: Transmissivity based on pulse test, see table descript.
value_type_tp	CHAR		0:true value,-1:Tp<lower meas.limit,1:Tp>upper meas.limit
bc_tp	CHAR		Best choice code.1 means Tp is best choice of transm.,else 0
l_meas_limit_t	FLOAT	m**2	Estimated lower measurement limit for Ts orTp,see descript.
u_meas_limit_t	FLOAT	m**2	Estimated upper measurement limit for Ts & Tp, see descript.
storativity_s	FLOAT		S= Storativity, see table description
assumed_s	FLOAT		S*=assumed storativity, see table description
skin	FLOAT		Skin factor
assumed_skin	FLOAT		Asumed skin factor
c	FLOAT	m**3/pa	Well bore storage coefficient
fluid_temp_tew	FLOAT	oC	Fluid temperature in the test section, see table description
fluid_elcond_ecw	FLOAT	mS/m	Fluid electric conductivity in test section,see table descri
fluid_salinity_tdsw	FLOAT	mg/l	Total salinity of the test section fluid (EC), see descr.
fluid_salinity_tdswm	FLOAT	mg/l	Total salinity of the test section fluid (samples),see descr
dt1	FLOAT	s	Estimated start time of evaluation, see table description
dt2	FLOAT	s	Estimated stop time of evaluation, see table description
reference	CHAR		SKB report No for reports describing data and evaluation
comments	CHAR		Short comment to evaluated parameters

KFM07B 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
KFM07B	20060123 09:22	20060123 10:14	209.00	214.00	3	1	20060123 10:03:24	20060123 10:06:47	0.00E+00	-1	
KFM07B	20060123 12:51	20060123 13:33	219.00	224.00	3	1	20060123 13:24:27	20060123 13:26:23	0.00E+00	-1	
KFM07B	20060123 13:46	20060123 15:05	224.00	229.00	3	1	20060123 14:22:51	20060123 14:43:08	2.28E-07	0	2.59E-07
KFM07B	20060125 16:17	20060125 17:33	229.00	234.00	3	1	20060125 16:51:11	20060125 17:11:29	3.81E-08	0	5.11E-08
KFM07B	20060123 16:46	20060123 18:02	234.00	239.00	3	1	20060123 17:20:15	20060123 17:40:31	1.05E-06	0	1.08E-06
KFM07B	20060124 06:46	20060124 08:31	239.00	244.00	3	1	20060124 07:48:50	20060124 08:09:07	2.08E-08	0	5.43E-08

KFM07B 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
KFM07B	209.00	214.00	4.0E-09	1.0E-03		203	321	1760.92	1962.55	1962.55	7.85
KFM07B	219.00	224.00	4.0E-09	1.0E-03		116	321	1840.20	2064.13	2059.35	7.92
KFM07B	224.00	229.00	1.7E-08	1.0E-03	3.15E-04	1217	1209	1854.28	2167.35	1855.93	7.96
KFM07B	229.00	234.00	1.7E-08	1.0E-03	6.24E-05	1218	1206	1895.16	2121.69	1896.39	8.01
KFM07B	234.00	239.00	1.7E-08	1.0E-03	1.32E-03	1216	1209	1934.25	2171.60	1934.11	8.04
KFM07B	239.00	244.00	1.7E-08	1.0E-03	6.60E-05	1217	1211	1978.41	2215.50	2126.60	8.08

KFM07B 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
KFM07B	20060123 09:22	20060123 10:14	209.00	214.00	3	1	2.00E-10	-1	1.65E-10	0	-1	3.30E-11	5.00
KFM07B	20060123 12:51	20060123 13:33	219.00	224.00	3	1	2.00E-10	-1	1.65E-10	0	-1	3.30E-11	5.00
KFM07B	20060123 13:46	20060123 15:05	224.00	229.00	3	1	7.13E-09	0	5.88E-09	0	0	1.18E-09	5.00
KFM07B	20060125 16:17	20060125 17:33	229.00	234.00	3	1	1.65E-09	0	1.36E-09	0	0	2.72E-10	5.00
KFM07B	20060123 16:46	20060123 18:02	234.00	239.00	3	1	4.32E-08	0	3.57E-08	0	0	7.13E-09	5.00
KFM07B	20060124 06:46	20060124 08:31	239.00	244.00	3	1	8.59E-10	0	7.09E-10	0	0	1.42E-10	5.00

KFM07B 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	bc_s	ri	ri_index	c	skin	t1	t2	dte1	dte2
KFM07B	209.00	214.00	-	-1	0	2.0E-10	5.0E-04	-	-	-	-						
KFM07B	219.00	224.00	-	-1	0	2.0E-10	5.0E-04	-	-	-	-						
KFM07B	224.00	229.00	2.98E-09	0	1	5.2E-10	5.0E-04	3.82E-08	3.82E-08	14.61	0		-2.62				
KFM07B	229.00	234.00	2.21E-09	0	1	7.2E-10	5.0E-04	3.29E-08	3.29E-08	3.89	1	1.79E-11	0.64	10	100		
KFM07B	234.00	239.00	4.27E-08	0	1	6.9E-10	5.0E-04	1.45E-07	1.45E-07	28.33	-1		5.41				
KFM07B	239.00	244.00	4.37E-10	0	1	6.9E-10	5.0E-04	1.46E-08	1.46E-08	9.02	0		-4.64				

KFM07B 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
KFM07B	20060123 09:22	20060123 10:14	209.00	214.00	65.69	208.00	593.68	593.69	593.27				
KFM07B	20060123 09:22	20060123 10:14	209.00	214.00	215.00	298.93				1774.36	1774.08	1773.81	
KFM07B	20060123 10:28	20060123 12:12	214.00	219.00	65.69	213.00	595.04	595.04	595.04				
KFM07B	20060123 10:28	20060123 12:12	214.00	219.00	220.00	298.93				1815.07	1814.94	1815.07	
KFM07B	20060123 12:51	20060123 13:33	219.00	224.00	65.69	218.00	596.25	596.25	596.25				
KFM07B	20060123 12:51	20060123 13:33	219.00	224.00	225.00	298.93				1855.24	1855.24	1855.24	
KFM07B	20060123 13:46	20060123 15:05	224.00	229.00	65.69	223.00	596.50	596.36	596.36				
KFM07B	20060123 13:46	20060123 15:05	224.00	229.00	230.00	298.93				1895.40	1895.82	1895.40	
KFM07B	20060125 16:17	20060125 17:33	229.00	234.00	65.69	228.00	596.61	595.92	595.92				
KFM07B	20060125 16:17	20060125 17:33	229.00	234.00	235.00	298.93				1965.28	1961.15	1958.13	
KFM07B	20060123 16:46	20060123 18:02	234.00	239.00	65.69	233.00	597.81	597.68	597.68				
KFM07B	20060123 16:46	20060123 18:02	234.00	239.00	240.00	298.93				2074.77	2063.22	2054.97	
KFM07B	20060124 06:46	20060124 08:31	239.00	244.00	65.69	238.00	598.75	598.75	598.89				
KFM07B	20060124 06:46	20060124 08:31	239.00	244.00	245.00	298.93				2352.64	2321.82	2295.97	
KFM07B	20060124 08:47	20060124 10:02	244.00	249.00	65.69	243.00	599.27	599.00	599.00				
KFM07B	20060124 08:47	20060124 10:02	244.00	249.00	250.00	298.93				2545.21	2540.81	2516.59	
KFM07B	20060124 10:19	20060124 12:23	249.00	254.00	65.69	248.00	599.80	599.80	599.66				
KFM07B	20060124 10:19	20060124 12:23	249.00	254.00	255.00	298.93				2446.71	2447.27	2446.17	
KFM07B	20060124 12:34	20060124 14:27	254.00	259.00	65.69	253.00	600.32	600.32	599.76				
KFM07B	20060124 12:34	20060124 14:27	254.00	259.00	260.00	298.93				2566.39	2564.32	2505.04	
KFM07B	20060124 14:36	20060125 09:09	259.00	264.00	65.69	258.00	600.02	599.88	599.88				
KFM07B	20060124 14:36	20060125 09:09	259.00	264.00	265.00	298.93				2254.69	2256.34	2252.49	
KFM07B	20060125 09:22	20060125 10:44	264.00	269.00	65.69	263.00	600.68	600.54	600.54				
KFM07B	20060125 09:22	20060125 10:44	264.00	269.00	270.00	298.93				2680.15	2679.47	2673.40	
KFM07B	20060125 11:00	20060125 12:41	269.00	274.00	65.69	268.00	600.78	600.65	600.65				
KFM07B	20060125 11:00	20060125 12:41	269.00	274.00	275.00	298.93				2801.74	2801.61	2798.86	
KFM07B	20060125 12:59	20060125 14:19	274.00	279.00	65.69	273.00	601.44	601.30	601.30				
KFM07B	20060125 12:59	20060125 14:19	274.00	279.00	280.00	298.93				2785.37	2784.96	2781.80	

KFM07B plu_pulse test_ed. 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	dur_flow_phase_tp	dur_rec_phase_tf	initial_press_pi	press_change_dp0_p	press_at_flow_end_pp
KFM07B	2006-01-23 10:28	2006-01-23 12:12	214.00	219.00	4B	1	2006-01-23 11:28	125.00	2421.00	1822.70	198.24	2020.94
KFM07B	2006-01-24 08:47	2006-01-24 10:02	244.00	249.00	4B	1	2006-01-24 09:47	126.00	692.00	2180.06	63.30	2243.36
KFM07B	2006-01-24 10:19	2006-01-24 12:23	249.00	254.00	4B	1	2006-01-24 12:08	125.00	622.00	2128.52	158.86	2287.38
KFM07B	2006-01-24 12:34	2006-01-24 14:27	254.00	259.00	4B	1	2006-01-24 13:43	125.00	2421.00	2220.12	108.27	2328.39
KFM07B	2006-01-24 14:36	2006-01-25 09:09	259.00	264.00	4B	1	2006-01-25 08:24	149.00	2423.00	2141.37	217.65	2359.02
KFM07B	2006-01-25 09:22	2006-01-25 10:44	264.00	269.00	4B	1	2006-01-25 10:29	143.00	622.00	2273.56	124.27	2397.83
KFM07B	2006-01-25 11:00	2006-01-25 12:41	269.00	274.00	4B	1	2006-01-25 12:26	126.00	622.00	2270.97	169.52	2440.49
KFM07B	2006-01-25 12:59	2006-01-25 14:19	274.00	279.00	4B	1	2006-01-25 14:05	126.00	621.00	2402.63	78.87	2481.50
KFM07B	2006-01-25 12:59	2006-01-25 14:19	280.00	298.90	4B	1						

KFM07B plu_pulse test_ed. Right (This result table to SICADA includes more columns which are empty, these columns are not presented here.)

idcode	secup	seclow	final_press_pf	formation_width_b	transmissivity_tp	value_type_tp	bc_tp	l_meas_limit_t	assumed_s	skin	fluid_temp_tew
KFM07B	214.00	219.00	2052.79	5.00	6.28E-11	-1	1	6.28E-11	5.55E-09		7.88
KFM07B	244.00	249.00	2315.81	5.00	5.00E-11	-1	1	5.00E-11	4.95E-09		8.12
KFM07B	249.00	254.00	2309.25	5.00	5.00E-11	-1	1	5.00E-11	4.95E-09		8.16
KFM07B	254.00	259.00	2313.63	5.00	7.36E-11	-1	1	7.36E-11	6.00E-09		8.20
KFM07B	259.00	264.00	2306.52	5.00	1.12E-10	-1	1	1.12E-10	7.42E-09		8.24
KFM07B	264.00	269.00	2446.51	5.00	5.00E-11	-1	1	5.00E-11	4.95E-09		8.28
KFM07B	269.00	274.00	2459.08	5.00	5.18E-11	-1	1	5.18E-11	5.04E-09		8.31
KFM07B	274.00	279.00	2532.35	5.00	5.00E-11	-1	1	5.00E-11	4.95E-09		8.34
KFM07B	280.00	298.90		18.90	5.00E-11	-1	1	5.00E-11			