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Forsmark site investigation

Single-hole injection tests and pressure pulse tests in borehole KFM08A

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October 2006

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Abstract

Borehole KFM08A is a deep core-drilled borehole within the site investigations in the Forsmark area. The borehole is about 1,000 m long and it is cased and grouted to about 100 m. The inclination of the borehole is c 60° from the horizontal plane at the surface and decreasing strongly along the borehole so that it is only c 36° at 1,000 m. The borehole diameter is about 77 mm in the interval c 102–1,001 m.

This report presents injection tests and pressure pulse tests performed using the pipe string system PSS3 in borehole KFM08A 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 and pressure pulse tests in KFM08A was to characterize the hydraulic conditions of the rock adjacent to the borehole on different measurement scales (100 m, 20 m and 5 m). Hydraulic parameters such as transmissivity and hydraulic conductivity were determined using analysis methods for stationary as well as transient conditions together with the dominating flow regime and possible outer hydraulic boundaries. In addition, a comparison with the results of previously performed difference flow logging in KFM08A was made.

The injection tests gave consistent results on the different measurement scales regarding transmissivity. For more than half of the tests, some period with pseudo-radial flow could be identified making a relatively straight-forward transient evaluation possible. The pressure pulse tests were evaluated using a stationary evaluation method. For 4 out of 36 pressure pulse tests transient evaluation was also possible. The sections 184–199 m, 274–279 m and 684–689 m contribute most to the total transmissivity in KFM08A.

The agreement between the injection tests and the previous difference flow logging in KFM08A was somewhat poorer than for earlier measured boreholes in the Forsmark area. The injection test results generally showed higher estimated transmissivity values than the results from the difference flow logging.

The injection and pressure pulse tests provide a database for statistical analysis of the hydraulic conductivity distribution along the borehole on the different measurement scales. Basic statistical parameters are presented in this report.

Sammanfattning

Borrhål KFM08A är ett djupt kärnborrhål borrat inom ramen för platsundersökningarna i Forsmarksområdet. Borrhålet är ca 1 000 m långt och det är försett med foderrör samt har injekterats till ca 100 m. Borrhålets lutning är ca 60° från horisontalplanet vid ytan och minskar kraftigt längs borrhålet så att lutningen bara är ca 36° vid 1 000 m. Borrhålsdiametern är ca 77 mm i intervallet ca 102–1,001 m.

Denna rapport beskriver genomförda injektionstester och pulstester med rörgångssystemet PSS3 i borrhål KFM08A samt resultaten från desamma. Pulstester genomfördes i stället för injektionstester i några sektioner där flödet befarades hamna under mätgränsen för injektionstester.

Huvudsyftet med injektionstesterna var att karaktärisera de hydrauliska förhållandena i berget i anslutning till borrhålet i olika mätskalor (100 m, 20 m och 5 m). 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. En jämförelse med resultaten av den tidigare utförda differensflödesloggningen i KFM08A gjordes också.

Injektionstesterna gav samstämmiga resultat för de olika mätskalorna beträffande transmissivitet. Under drygt hälften av testen kunde en viss period med pseudoradiellt flöde identifieras vilket möjliggjorde en standardmässig transient utvärdering. Pulstesterna utvärderades med en stationär metod. Transient utvärdering var också möjlig för fyra av 36 pulstester. Sektionerna 184–199 m, 274–279 m och 684–689 m bidrar mest till den totala transmissiviteten i KFM08A.

Samstämmigheten mellan resultaten från injektionstesterna och den tidigare utförda differensflödesloggningen i KFM08A var något sämre än den varit för borrhål som tidigare undersökts i Forsmark. Injektionstesternas resultat visade generellt på högre transmissiviteter än vad resultaten från differensflödesloggningen visade.

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

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1 Introduction

Injection and pressure pulse tests were carried out in borehole KFM08A at Forsmark, Sweden, in May–June, 2006, by Geosigma AB. Borehole KFM08A is a deep, cored borehole within the on-going site investigation in the Forsmark area. The location of the borehole is shown in Figure 1-1. The borehole is about 1,000 m long, cased and grouted to c 100 m and at the groung surface inclined c 60° from the horizontal plane. Deviation measurements have revealed that the borehole is bending upwards versus depth, entailing that the lowermost parts are inclined only c 36°. The borehole is designed as a so called telescopic borehole, with an enlarged diameter in the upper approximately 100 m, below that the borehole diameter is c 77.3 mm.

In KFM08A, difference flow logging was previously performed during May 2005. According to the results of this investigation, 41 flowing fractures were detected and the most high-transmissive fractures were found at 189.8 m, 190.5 m, 275.2 m and 687.0 m. Below 687 m, no flowing fractures were identified, Rouhiainen and Sokolnicki (2005) /1/.

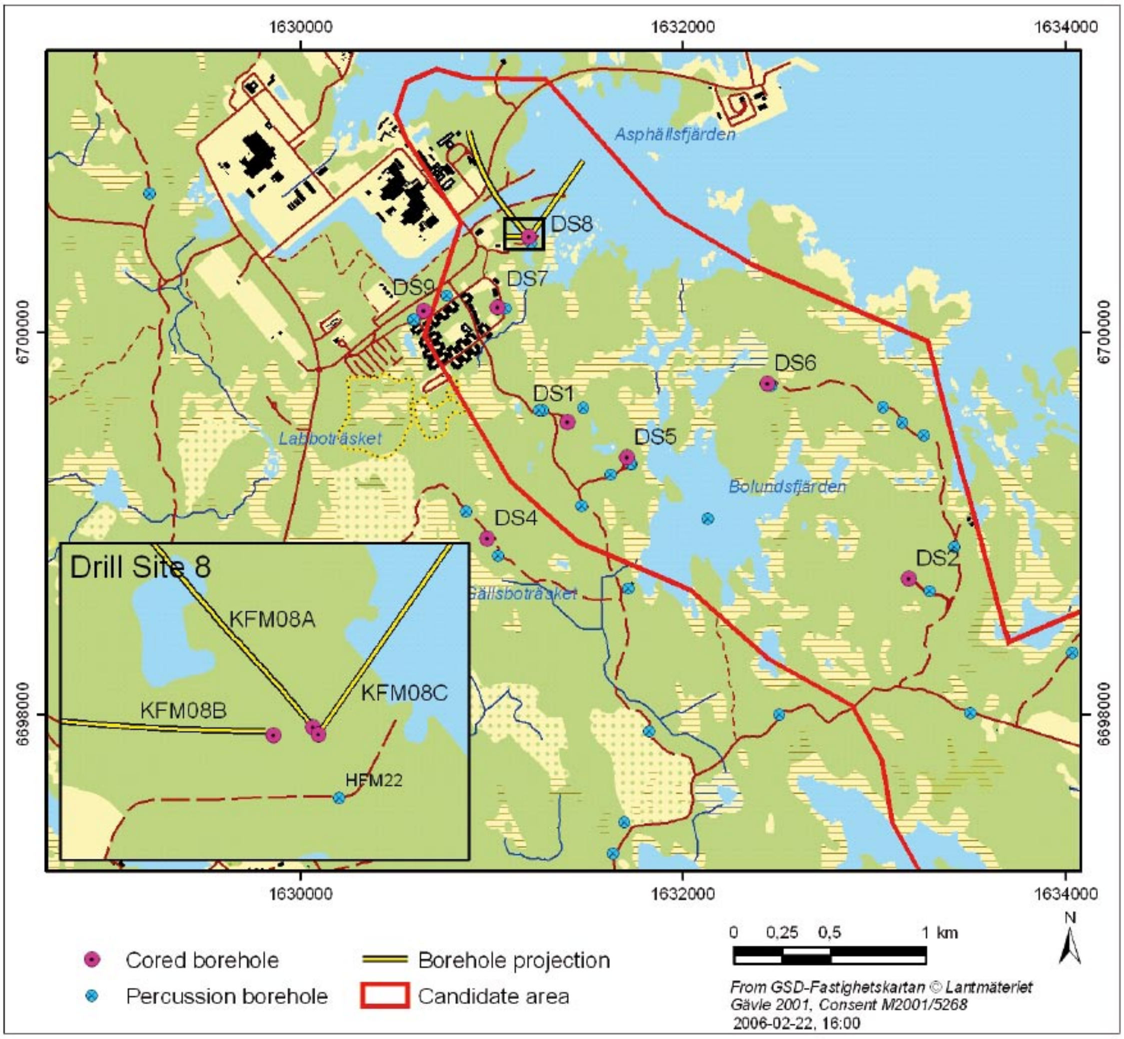

Figure 1-1. *The investigation area at Forsmark including the candidate area selected for more detailed investigations. Borehole KFM08A is situated at drill site DS8.*

This document reports the results obtained from the injection tests and pressure pulse tests in borehole KFM08A. In some 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 of injection tests. 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.

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

Activity plans	**Number**	**Version**
Hydraulic injection tests in borehole KFM08A with PSS3	AP PF 400-05-032	1.0
Method documents	**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, service-protokoll, PSS3	SKB MD 345.124	1.0
Metodbeskrivning för hydrauliska injektionstester	SKB MD 323.001	1.0
Instruktion för analys av injektions- och enhålspump-tester	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 KFM08A was to characterize the hydraulic properties of the rock adjacent to the borehole on different measurement scales (100 m, 20 m and 5 m). The primary parameter to be determined was hydraulic transmissivity from which hydraulic conductivity can be derived. The results of the injection tests provide a database which can be used for statistical analyses of the hydraulic conductivity distribution along the borehole on different measurement scales. Basic statistical analyses are presented in this report.

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.

A comparison with the results of the previously performed difference flow logging in KFM08A was also included in the activity, as a check of the plausibility of the test results. Further, the combined analysis of the injection tests and the difference flow logging provides a more comprehensive understanding of the hydraulic conditions of boreholes KFM08A.

3 Scope

3.1 Borehole data

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

3.2 Tests performed

The injection tests and pressure pulse tests in borehole KFM08A, performed according to Activity Plan AP PF 400-05-032 (see Table 1-1), 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 are 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, Table 1-1).

Table 3-1. Pertinent technical data of borehole KFM08A (printout from SKB database, SICADA).

Borehole length (m):	1,001.190				
Drilling period(s):	**From date**	**To date**	**Secup (m)**	**Seclow (m)**	**Drilling type**
	2004-09-13	2004-09-27	0.000	100.450	Percussion drilling
	2005-01-25	2005-01-25	97.140	100.550	Core drilling
	2005-01-25	2005-03-31	100.550	1,001.190	Core drilling
Starting point coordinate:	**Length (m)**	**Northing (m)**	**Easting (m)**	**Elevation**	**Coord system**
	0.000	6700494.492	1631197.060	2.487	RT90-RHB70
	3.000	6700495.626	1631196.141	–0.134	RT90-RHB70
Angles:	**Length (m)**	**Bearing**	**Inclination (– = down)**		**Coord system**
	0.000	321.000	–60.887		RT90-RHB70
Borehole diameter:	**Secup (m)**	**Seclow (m)**	**Hole diam (m)**		
	0.000	9.140	0.343		
	9.140	97.140	0.249		
	97.140	102.400	0.086		
	102.400	1,001.190	0.077		
Core diameter:	**Secup (m)**	**Seclow (m)**	**Core Diam (m)**		
	100.550	1,001.190	0.051		
Casing diameter:	**Secup (m)**	**Seclow (m)**	**Case in (m)**	**Case out (m)**	
	0.000	100.150	0.200	0.208	
	0.230	9.140	0.310	0.323	
	100.150	100.200	0.170	0.208	

Some of the tests were not performed as intended because the time required for achieving a constant head in the test section was judged to be too long or, in other cases, 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.

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 for the 5 m sections. For the 20 m sections the limit was 4 kPa and for the 100 m sections the limit was 1 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 5-1.

The upper and lower packer positions for the injection test sections were as close as possible to the section limits used during the previous difference flow logging in 5 m sections in KFM08A Rouhiainen and Sokolnicki (2005) /1/. However, after the length calibration of the difference flow logging measurements in KFM08A, it turned out that a short distance was omitted between the sections. In addition, some of the injection test sections were shifted intentionally from the section limits used during the difference flow logging in order to avoid cavities in the borehole. Therefore, the section limits used for the injection tests and difference flow logging respectively differed with a maximum of 1.82 m along the borehole. However, among the test sections which have results above the measurement limit the section limits are not deviating more than 1.51 m.

3.3 Equipment checks

The PSS3 equipment was serviced, according to SKB internal controlling documents (SKB MD 345.124, service, and SKB MD 345.122, calibration), in January 2006.

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 the water.

Simple functioning checks of down-hole sensors were done at every change of test section interval. Checks were also made continuously while lowering the pipe string along the borehole.

Table 3-2. Single-hole injection tests and pressure pulse tests performed in borehole KFM08A.

Borehole 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
KFM08A	104.00	204.00	100.00	3	1	2006-05-22 07:47	2006-05-22 09:37:58
KFM08A	204.00	304.00	100.00	3	1	2006-05-22 11:04	2006-05-22 13:25:59
KFM08A	304.00	404.00	100.00	3	2	2006-05-30 08:36	2006-05-30 10:26:55
KFM08A	404.00	504.00	100.00	3	1	2006-05-23 07:04	2006-05-23 08:54:07
KFM08A	504.00	604.00	100.00	3	1	2006-05-23 10:16	2006-05-23 12:11:00

Borehole	Test section		Section length	Test type[1)]	Test no	Test start date, time	Test stop date, time
Bh ID	secup	seclow		(1–6)		YYYYMMDD hh:mm	YYYYMMDD hh:mm
KFM08A	604.00	704.00	100.00	3	1	2006-05-23 13:50	2006-05-23 15:40:08
KFM08A	704.00	804.00	100.00	3	2	2006-05-29 15:52	2006-05-29 17:39:32
KFM08A	804.00	904.00	100.00	3	1	2006-05-24 08:58	2006-05-24 10:06:35
KFM08A	889.00	989.00	100.00	3	1	2006-05-29 08:09	2006-05-29 10:07:10
KFM08A	104.00	124.00	20.00	3	1	2006-05-31 13:59	2006-05-31 15:27:23
KFM08A	124.00	144.00	20.00	3	1	2006-05-31 15:43	2006-05-31 17:01:35
KFM08A	144.00	164.00	20.00	3	1	2006-06-01 08:32	2006-06-01 09:48:20
KFM08A	164.00	184.00	20.00	3	1	2006-06-01 10:06	2006-06-01 11:24:17
KFM08A	184.00	204.00	20.00	3	2	2006-06-13 21:23	2006-06-13 22:37:09
KFM08A	204.00	224.00	20.00	3	1	2006-06-01 14:04	2006-06-01 15:19:48
KFM08A	224.00	244.00	20.00	3	1	2006-06-01 15:35	2006-06-01 16:50:51
KFM08A	244.00	264.00	20.00	3	1	2006-06-02 08:04	2006-06-02 09:19:54
KFM08A	264.00	284.00	20.00	3	1	2006-06-02 09:41	2006-06-02 10:55:53
KFM08A	284.00	304.00	20.00	3	1	2006-06-02 11:16	2006-06-02 13:25:23
KFM08A	404.00	424.00	20.00	3	1	2006-06-02 14:36	2006-06-02 15:51:49
KFM08A	424.00	444.00	20.00	4B	1	2006-06-02 16:07	2006-06-02 17:50:37
KFM08A	444.00	464.00	20.00	3	1	2006-06-07 09:03	2006-06-07 10:39:53
KFM08A	464.00	484.00	20.00	3	1	2006-06-07 10:58	2006-06-07 12:24:33
KFM08A	484.00	504.00	20.00	4B	1	2006-06-07 13:32	2006-06-07 15:16:10
KFM08A	604.00	624.00	20.00	4B	1	2006-06-07 17:01	2006-06-08 09:05:06
KFM08A	624.00	644.00	20.00	4B	1	2006-06-08 09:27	2006-06-08 10:43:32
KFM08A	644.00	664.00	20.00	4B	1	2006-06-08 11:21	2006-06-08 13:11:02
KFM08A	664.00	684.00	20.00	4B	1	2006-06-08 13:33	2006-06-08 14:49:52
KFM08A	684.00	704.00	20.00	3	2	2006-06-13 16:28	2006-06-13 17:55:54
KFM08A	704.00	724.00	20.00	4B	1	2006-06-09 08:07	2006-06-09 09:23:52
KFM08A	724.00	744.00	20.00	4B	1	2006-06-09 09:46	2006-06-09 11:02:29
KFM08A	744.00	764.00	20.00	4B	1	2006-06-09 12:24	2006-06-09 13:41:18
KFM08A	764.00	784.00	20.00	4B	1	2006-06-12 08:15	2006-06-12 10:12:28
KFM08A	784.00	804.00	20.00	3	1	2006-06-12 10:54	2006-06-12 13:20:43
KFM08A	904.00	924.00	20.00	4B	1	2006-06-12 14:54	2006-06-12 16:40:51
KFM08A	924.00	944.00	20.00	4B	1	2006-06-13 05:50	2006-06-13 07:45:00
KFM08A	944.00	964.00	20.00	4B	1	2006-06-13 08:12	2006-06-13 10:01:26
KFM08A	964.00	984.00	20.00	4B	1	2006-06-13 10:29	2006-06-13 11:43:45
KFM08A	104.00	109.00	5.00	3	1	2006-06-28 22:50	2006-06-29 09:04:30
KFM08A	109.00	114.00	5.00	3	1	2006-06-28 21:24	2006-06-28 22:37:52
KFM08A	114.00	119.00	5.00	3	1	2006-06-28 19:56	2006-06-28 21:11:01
KFM08A	119.00	124.00	5.00	3	1	2006-06-28 15:24	2006-06-28 16:43:18
KFM08A	124.00	129.00	5.00	3	1	2006-06-28 13:45	2006-06-28 15:07:51
KFM08A	129.00	134.00	5.00	3	1	2006-06-28 11:03	2006-06-28 13:25:51
KFM08A	134.00	139.00	5.00	3	1	2006-06-28 09:27	2006-06-28 10:49:41
KFM08A	139.00	144.00	5.00	4B	1	2006-06-28 07:55	2006-06-28 09:11:27
KFM08A	144.00	149.00	5.00	3	1	2006-06-28 06:10	2006-06-28 07:33:13
KFM08A	149.00	154.00	5.00	3	1	2006-06-27 22:00	2006-06-27 23:15:39
KFM08A	154.00	159.00	5.00	3	1	2006-06-27 20:54	2006-06-27 21:49:09
KFM08A	159.00	164.00	5.00	4B	1	2006-06-27 18:58	2006-06-27 20:43:09
KFM08A	164.00	169.00	5.00	3	1	2006-06-15 13:30	2006-06-15 15:19:54
KFM08A	169.00	174.00	5.00	3	1	2006-06-15 15:57	2006-06-15 17:20:14

Borehole	Test section		Section length	Test type[1)]	Test no	Test start date, time	Test stop date, time
Bh ID	secup	seclow		(1–6)		YYYYMMDD hh:mm	YYYYMMDD hh:mm
KFM08A	174.00	179.00	5.00	3	1	2006-06-16 08:56	2006-06-16 10:12:29
KFM08A	179.00	184.00	5.00	3	1	2006-06-16 10:23	2006-06-16 11:40:18
KFM08A	184.00	189.00	5.00	3	1	2006-06-27 17:23	2006-06-27 18:36:51
KFM08A	189.00	194.00	5.00	3	1	2006-06-27 15:49	2006-06-27 17:03:34
KFM08A	194.00	199.00	5.00	3	2	2006-06-28 17:56	2006-06-28 19:10:55
KFM08A	199.00	204.00	5.00	3	1	2006-06-27 12:33	2006-06-27 13:55:59
KFM08A	204.00	209.00	5.00	3	2	2006-06-27 10:12	2006-06-27 11:31:52
KFM08A	209.00	214.00	5.00	3	1	2006-06-16 14:11	2006-06-16 15:34:08
KFM08A	214.00	219.00	5.00	3	1	2006-06-16 15:47	2006-06-16 17:03:00
KFM08A	219.00	224.00	5.00	3	1	2006-06-19 06:08	2006-06-19 07:22:38
KFM08A	224.00	229.00	5.00	4B	1	2006-06-19 07:32	2006-06-19 09:18:40
KFM08A	229.00	234.00	5.00	4B	1	2006-06-19 09:29	2006-06-19 11:13:44
KFM08A	234.00	239.00	5.00	3	1	2006-06-19 11:53	2006-06-19 12:33:14
KFM08A	239.00	244.00	5.00	3	1	2006-06-19 12:43	2006-06-19 14:02:58
KFM08A	244.00	249.00	5.00	3	1	2006-06-27 08:21	2006-06-27 09:43:51
KFM08A	249.00	254.00	5.00	4B	1	2006-06-27 06:24	2006-06-27 08:07:58
KFM08A	254.00	259.00	5.00	4B	1	2006-06-26 22:23	2006-06-26 23:50:06
KFM08A	259.00	264.00	5.00	3	1	2006-06-26 20:56	2006-06-26 22:13:32
KFM08A	264.00	269.00	5.00	3	1	2006-06-26 19:08	2006-06-26 20:40:07
KFM08A	269.00	274.00	5.00	3	1	2006-06-26 17:41	2006-06-26 18:58:34
KFM08A	274.00	279.00	5.00	3	1	2006-06-26 16:07	2006-06-26 17:29:08
KFM08A	279.00	284.00	5.00	4B	1	2006-06-26 14:07	2006-06-26 15:52:07
KFM08A	284.00	289.00	5.00	4B	1	2006-06-19 14:33	2006-06-19 16:01:27
KFM08A	289.00	294.00	5.00	4B	1	2006-06-19 16:21	2006-06-19 18:05:07
KFM08A	294.00	299.00	5.00	3	1	2006-06-19 18:29	2006-06-19 19:50:16
KFM08A	299.00	304.00	5.00	3	1	2006-06-19 20:06	2006-06-19 21:26:20
KFM08A	404.00	409.00	5.00	4B	1	2006-06-19 22:45	2006-06-20 00:29:13
KFM08A	409.00	414.00	5.00	3	1	2006-06-20 08:16	2006-06-20 09:40:45
KFM08A	414.00	419.00	5.00	4B	1	2006-06-20 09:54	2006-06-20 11:03:16
KFM08A	419.00	424.00	5.00	4B	1	2006-06-20 12:11	2006-06-20 13:27:05
KFM08A	444.00	449.00	5.00	4B	1	2006-06-20 13:58	2006-06-20 15:14:32
KFM08A	449.00	454.00	5.00	3	1	2006-06-20 15:28	2006-06-20 16:49:51
KFM08A	454.00	459.00	5.00	3	1	2006-06-21 06:06	2006-06-21 07:20:41
KFM08A	459.00	464.00	5.00	3	1	2006-06-21 07:29	2006-06-21 08:44:12
KFM08A	464.00	469.00	5.00	4B	1	2006-06-21 08:53	2006-06-21 10:10:04
KFM08A	469.00	474.00	5.00	4B	1	2006-06-21 10:18	2006-06-21 12:03:05
KFM08A	474.00	479.00	5.00	4B	1	2006-06-21 12:17	2006-06-21 13:28:09
KFM08A	479.00	484.00	5.00	3	1	2006-06-21 13:37	2006-06-21 14:51:54
KFM08A	684.00	689.00	5.00	3	1	2006-06-21 16:59	2006-06-21 18:23:09
KFM08A	689.00	694.00	5.00	4B	1	2006-06-21 18:39	2006-06-21 20:23:53
KFM08A	694.00	699.00	5.00	4B	1	2006-06-21 20:49	2006-06-21 21:59:10
KFM08A	699.00	704.00	5.00	4B	1	2006-06-21 22:19	2006-06-21 23:23:36
KFM08A	784.00	789.00	5.00	4B	1	2006-06-22 10:49	2006-06-22 13:14:56
KFM08A	789.00	794.00	5.00	4B	1	2006-06-22 13:34	2006-06-22 15:18:52
KFM08A	794.00	799.00	5.00	3	1	2006-06-22 15:40	2006-06-22 17:01:46
KFM08A	799.00	804.00	5.00	4B	1	2006-06-26 06:13	2006-06-26 07:56:58

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

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 water filled pressure vessels. Expansion and release of packers, as well as opening and closing of the test valve, are obtained 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.

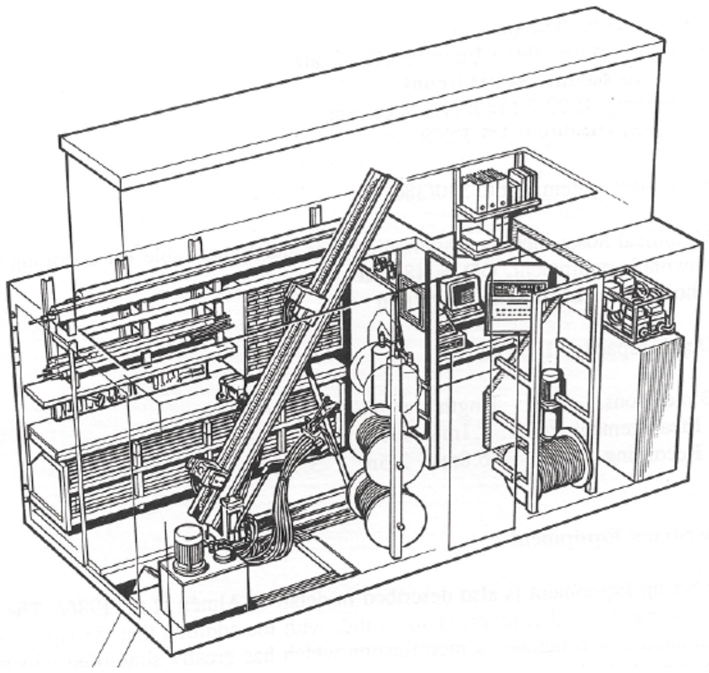

Figure 4-1. *Outline of the PSS3 container with associated equipment.*

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).

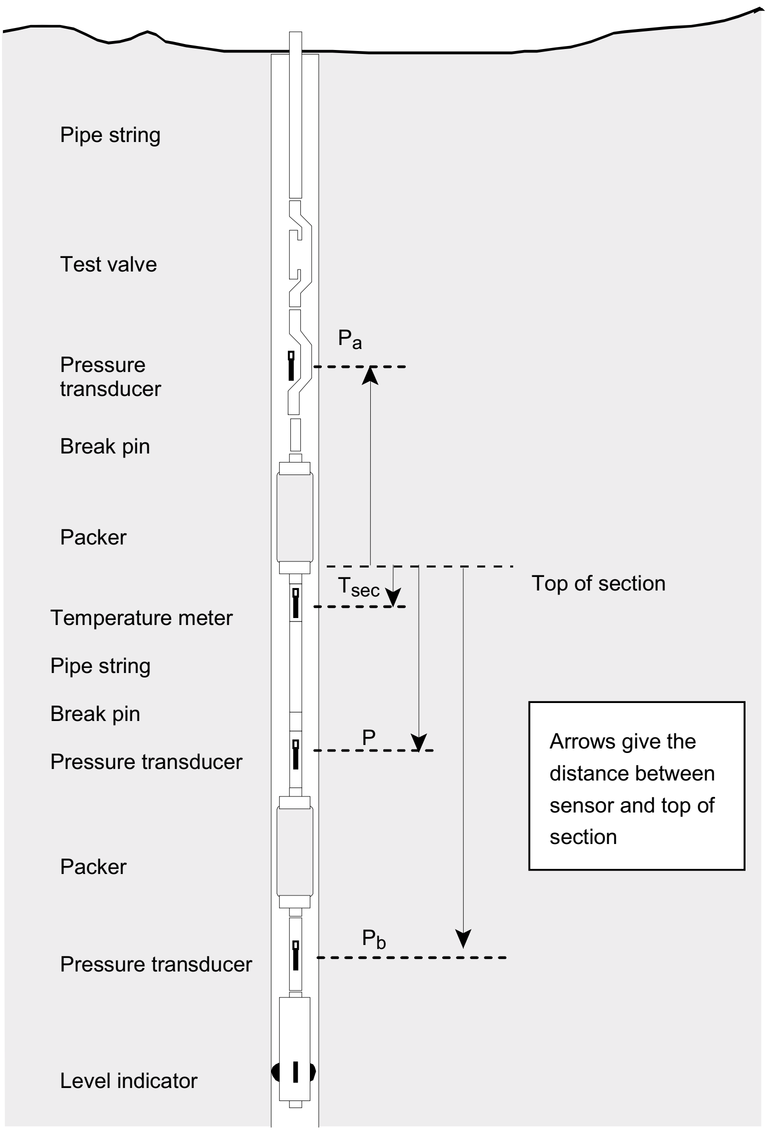

Figure 4-2. *Schematic drawing of the down-hole equipment in the PSS3 system.*

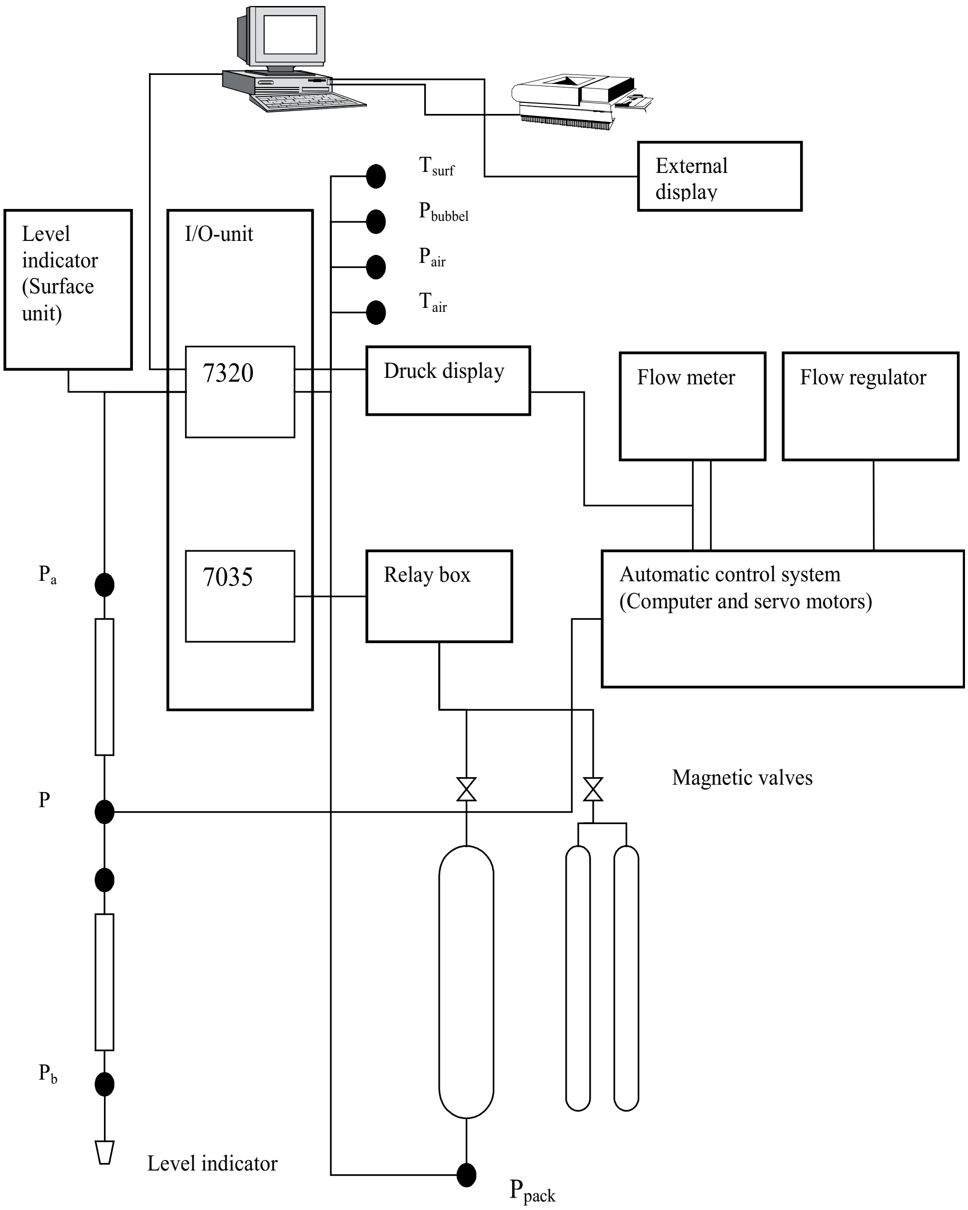

Figure 4-3. *Schematic drawing of the data acquisition system and the automatic control system in PSS.*

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 is given with top of test section as reference (Figure 4-2).

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

Technical specification Parameter		Unit	Sensor	PSS	Comments
Absolute pressure	Output signal	mA	4–20		
	Meas. range	MPa	0–13.5		
	Resolution	kPa	< 1.0		
	Accuracy[1)]	% F.S	0.1		
Differential pressure, 200 kPa	Accuracy	kPa		< ± 5	Estimated value
Temperature	Output signal	mA	4–20		
	Meas. range	°C	0–32		
	Resolution	°C	< 0.01		
	Accuracy	°C	± 0.1		
Flow Qbig	Output signal	mA	4–20		
	Meas. range	m^3/s	$1.67 \cdot 10^{-5}$–$1.67 \cdot 10^{-3}$		The specific accuracy is depending on actual flow
	Resolution	m^3/s	$6.7 \cdot 10^{-8}$		
	Accuracy[2)]	% O.R	0.15–0.3	< 1.5	
Flow Qsmall	Output signal	mA	4–20		
	Meas. range	m^3/s	$1.67 \cdot 10^{-8}$–$1.67 \cdot 10^{-5}$		The specific accuracy is depending on actual flow
	Resolution	m^3/s	$6.7 \cdot 10^{-10}$		
	Accuracy[3)]	% 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.

Table 4-2. Position of sensors in the borehole and displacement volume of equipment in the test section in borehole KFM08A.

Parameter	Length of test section (m) 5 (L)	5 (m)	20 (L)	20 (m)	100 (L)	100 (m)
Equipment displacement volume in test section [1)]	3.6		13.0		61.0	
Total volume of test section [2)]	23.5		93.9		469.3	
Position for sensor Pa, pressure above test section, (m above secup) [3)]		1.89		1.88		1.90
Position for sensor P, pressure in test section, (m above secup) [3)]		–4.12		–19.13		–99.12
Position for sensor Tsec, temperature in test section, (m above secup) [3)]		–0.98		–0.98		–0.99
Position for sensor Pb, pressure below test section, (m above secup) [3)]		–7.02		–22.02		–102.02

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

[2)] Total volume of test section (V = section length·π·d^2/4) (in litres).

[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 at least every year. Results from calibration, e.g. calibration constants, of sensors are kept in a document folder in PSS. If a sensor is replaced at the test site, calibration constants are altered as well. If a new, un-calibrated, sensor is to be used, calibration may be performed afterwards and data re-calculated.

5.1.2 Functioning checks

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

5.1.3 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 KFM08A, injection tests and pressure pulse tests. The injection and pressure pulse tests in KFM08A were carried out while maintaining a constant head of generally 200 kPa (20 m) 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 KFM08A 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.

For injection tests the injection phase was interrupted if the injection flow was clearly below the measurement limit. Thereafter, the recovery was measured for at least 5 minutes to verify the low conductivity of the section.

5.2.2 Test procedure

Generally, the tests were performed according to the Activity Plan AP PF 400-05-032. 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 Table 5-1. The diagnostic test is included in the given durations. Regarding the packer inflation times and actual injection and recovery times for injection tests, slightly different procedures were used for the tests in 100 m sections compared to the tests in 20 m and 5 m sections in accordance with AP PF 400-05-032.

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 for the 5 m sections. For the 20 m sections the limit was 4 kPa and for the 100 m sections the limit was 1 kPa. If the pressure increased less than the limit, an injection test was carried out.

5.2.3 Test strategy

Firstly, tests in 100 m sections were performed within the interval 104.0–989.0 m. The limits of the test sections were, as far as possible, the same as were used by the difference flow logging, to facilitate comparison of the results.

Secondly, the 100 m sections with a definable flow rate were measured in five successive injection tests using 20 m section length. Tests in 20 m sections were carried out within nearly the same interval as the 100 m sections (104.0–984.0 m).

Thirdly, tests with 5 m section length were conducted in the 20 m sections which had a definable flow rate.

Since the results of the tests in 100 m sections have a strong effect on the continued test program (i.e. whether a 100 m section would be measured with shorter sections as well), it was particularly important to ensure accurate results of these tests, including sections close to the lower measurement limit.

The total number of injection tests was thus dependent on the results of the previous tests.

Table 5-1. Packer inflation times, pressure stabilisation times and test times used for the injection tests pressure pulse tests in KFM08A. 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)]
100[2)]	30	15	30	30	105
20[2)]	25	5	20	20	70
5[2)]	25	5	20	20	70
5, 20, 100[3)]	40	20	2	40	102

[1)] Exclusive of trip times in the borehole.

[2)] Injection tests.

[3)] Pressure pulse tests.

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 __KFM08A_0104.00_200605220747.ht2). The name differs slightly from the convention stated in Instruction for analysis of injection and single-hole pumping tests, SKB MD 320.004.

Using the IPPLOT software (Version 3.0), the *.ht2-files are converted to parameter files suitable for plotting using 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 KFM08A 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 also 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. No subtraction of the barometric pressure from the measured absolute pressure has been made, since the length of the test periods are short relative to the time scale for barometric pressure changes. In addition, pressure differences rather than the pressure magnitudes are used by the evaluation.

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 ($1.7 \cdot 10^{-8}$ m^3/s). However, if the flow rate for a test was close to, or below, the standard lower measurement limit, a test-specific estimate of the lower measurement limit of flow rate was made. The test-specific lower limit was 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 identified, but it might be of both technical and hydraulic character.

The lower measurement limit for transmissivity is defined in terms of the specific flow rate (Q/s). The minimum specific flow rate corresponds to the estimated lower measurement limit of the flow rate together with the actual injection pressure during the test, see Table 5-2. The intention during this test campaign was to use a standard injection pressure of 200 kPa (20 m water column). Still, the injection pressure can be considerably different (see Section 6.2.3). An apparently 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.

Whenever the final flow rate (Q_p) was not defined (i.e. not clearly above the measurement noise before and after the injection period), the estimated lower measurement limit for specific flow rate was based on the estimated lower measurement limit for flow rate for the specific test and a standard injection pressure of 200 kPa. This is done in order to avoid excessively high, apparent estimates of the specific flow rate for these low conductivity sections, which would have resulted if the actual pressure difference at start of injection had been used as injection pressure.

Table 5-2. Estimated lower measurement limit for specific flow rate and steady-state transmissivity for different injection pressures, measurement scales and estimated lower measurement limits for flow rate for the injection tests in borehole KFM08A.

rw (m)	Lw (m)	Q-measl-L (m^3/s)	Injection pressure (kPa)	Q/s-measl-L (m^2/s)	Factor CM in Moye's formula	TM-measl-L (m^2/s)
0.03865	100	1.7E–08	100	1.6E–09	1.30	2.1E–09
0.03865	100	1.7E–08	200	8.2E–10	1.30	1.1E–09
0.03865	100	1.7E–08	300	5.5E–10	1.30	7.1E–10
0.03865	100	1.2E–08	100	1.1E–09	1.30	1.5E–09
0.03865	100	1.2E–08	200	5.7E–10	1.30	7.4E–10
0.03865	100	1.2E–08	300	3.8E–10	1.30	5.0E–10
0.03865	100	5.0E–09	100	4.9E–10	1.30	6.4E–10
0.03865	100	5.0E–09	200	2.5E–10	1.30	3.2E–10
0.03865	100	5.0E–09	300	1.6E–10	1.30	2.1E–10
0.03865	20	1.7E–08	100	1.6E–09	1.04	1.7E–09
0.03865	20	1.7E–08	200	8.2E–10	1.04	8.5E–10
0.03865	20	1.7E–08	300	5.5E–10	1.04	5.7E–10
0.03865	20	1.2E–08	100	1.1E–09	1.04	1.2E–09
0.03865	20	1.2E–08	200	5.7E–10	1.04	6.0E–10
0.03865	20	1.2E–08	300	3.8E–10	1.04	4.0E–10
0.03865	20	5.0E–09	100	4.9E–10	1.04	5.1E–10
0.03865	20	5.0E–09	200	2.5E–10	1.04	2.6E–10
0.03865	20	5.0E–09	300	1.6E–10	1.04	1.7E–10
0.03865	5	1.7E–08	100	1.6E–09	0.82	1.3E–09
0.03865	5	1.7E–08	200	8.2E–10	0.82	6.7E–10
0.03865	5	1.7E–08	300	5.5E–10	0.82	4.5E–10
0.03865	5	1.2E–08	100	1.1E–09	0.82	9.4E–10
0.03865	5	1.2E–08	200	5.7E–10	0.82	4.7E–10
0.03865	5	1.2E–08	300	3.8E–10	0.82	3.1E–10
0.03865	5	5.0E–09	100	4.9E–10	0.82	4.0E–10
0.03865	5	5.0E–09	200	2.5E–10	0.82	2.0E–10
0.03865	5	5.0E–09	300	1.6E–10	0.82	1.3E–10

The lower measurement limits for the flow rate correspond to different values of steady-state transmissivity, T_M, depending on the section lengths used in the factor C_M in Moye's formula, as described in the Instruction for analysis of injection and single-hole pumping tests (SKB MD 320.004), see Table 5-2.

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 $5 \cdot 10^{-11}$ 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 at a flow rate of c 30 L/min ($5 \cdot 10^{-4}$ m^3/s) and an injection pressure of c 1 m. Thus, the upper measurement limit for the specific flow rate is $5 \cdot 10^{-4}$ m^2/s. However, the practical upper measurement limit may vary, depending on e.g. depth of the test section (friction losses in the pipe string).

5.4.3 Qualitative analysis

Initially, a qualitative evaluation of actual flow regimes, e.g. wellbore storage (WBS), pseudo-linear flow regime (PLF), pseudo-radial flow regime (PRF), pseudo-spherical flow regime (PSF) and pseudo-stationary flow regime (PSS), respectively, was performed. In addition, indications of outer boundary conditions during the tests were identified. The qualitative evaluation was mainly 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 structure(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.

Due to the limited resolution of the flow meter and pressure sensor, the derivative may some times indicate a false horizontal line by the end of 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 tests in conjunction with the qualitative analysis according to the following equations:

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

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

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 = injection pressure $p_p - p_i$ (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 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 /2/ 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) /3/.

In borehole KFM08A, the storativity was calculated using an empirical regression relationship between storativity and transmissivity, see Equation 5-3 (Rhén et al. 1997) /4/. Firstly, the transmissivity and skin factor were 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. 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.

S	$= 0.0007 \cdot T^{0.5}$	(5-3)
S	= storativity (–)	
T	= transmissivity (m^2/s)	

For transient analysis of the recovery period, a model presented by Dougherty-Babu (1984) /5/ 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) /6/ 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. 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 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) /7/ 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. This model also allows calculation of the wellbore storage coefficient according to Equation 5-6. 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) /8/, was applied for evaluation of the recovery period for tests showing pseudo-spherical- or pseudo-stationary flow during this period.

ζ	$= ln(r_w/r_{wf})$	(5-4)
ζ	= skin factor	
r_w	= borehole radius (m)	
r_{wf}	= effective borehole radius	

Some tests showed fracture responses (a slope of 0.5 or less in a log-log plot). A model for single fractures was then used for the transient analysis as a complement to the standard models. The model by Ozkan-Raghavan (1991a) /9/ and (1991b) /10/ for a vertical fracture was employed. In this case, 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).

Estimated values of the borehole storage coefficient, C, based on actual borehole geometrical data and assumed fluid properties are shown in Table 5-3 together with the estimated effective C_{eff} from laboratory experiments /12/. The net water volume in the test section, V_w, has in Table 5-3 been calculated by subtracting the volume of equipment in the test section (pipes and thin hoses) from the total volume of the test section. For an isolated test section, the wellbore storage coefficient, C, may be calculated as by Almén et al. (1986) /11/:

$$C = V_w \cdot c_w = L_w \cdot \pi \cdot r_w^2 \cdot c_w \tag{5-5}$$

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})

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 values of C based on geometry and the value of C_{eff} based on laboratory experiments /12/, (Table 5-3).

Furthermore, when using the model by Dougherty-Babu (1984) /5/ or Hantush (1955) /8/, 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 by Almén et al. (1986) /11/:

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

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

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

Table 5-3. 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 tests from laboratory experiments /12.

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)
0.03865	100	0.469	0.061	0.408	$1.9 \cdot 10^{-10}$	$1.9 \cdot 10^{-10}$
0.03865	20	0.094	0.013	0.081	$3.7 \cdot 10^{-11}$	$4.3 \cdot 10^{-11}$
0.03865	5	0.023	0.004	0.019	$9.0 \cdot 10^{-12}$	$1.6 \cdot 10^{-11}$

The radius of influence at a certain time may be estimated from Jacob's approximation of the Theis' well function, Cooper and Jacob (1946) /13/:

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

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) from t_1 to t_2 can be identified during the test, 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 flow time t_p is used. The radius of influence can be used to deduce the length of the hydraulic feature(s) tested.

Furthermore, an r_i-index (–1, 0 or 1) is defined to characterize the hydraulic conditions by the end of the test. The r_i-index is defined as shown below. It is assumed that a certain time interval of PRF can be identified between t_1 and t_2 during the test.

- 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 this time.
- 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 barrier 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.
- 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 certain time interval of PRF cannot be identified during the test, the r_i-indices –1 and 1 are defined as above. In such cases the radius of influence is estimated using the flow time t_p in Equation 5-7.

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) /5/ 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 used 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 /12/. 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 after 10 minutes 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 /12/. 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 (317.59 Pa/s) was observed during the pressure pulse test in section 699.0–704.0 m in KFM08A.
- 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 /12/ is used. The value of C_{eff} for different test section lengths are 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 (m³/s)

C_{eff} = Effective borehole storage coefficient of the virtually impermeable test section (m³/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)

$$dV/dt = C_{eff} \frac{dp}{dt} \tag{5-10}$$

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 KFM08A: 699.0–704.0 m and is assumed to be the same for all tested sections in KFM08A. 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.

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

$T_{ss,\ pulse}$ = 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 KFM08A was carried out according to the Activity Plan AP PF 400-05-032 with the following exceptions:

- The packers were expanded progressively and the nominal expansion pressure could not be reached for some sections in the deeper parts of the borehole borehole due to increasing pressure below the test section. This fact makes the effects from packer compliance even more unpredictable. Hence, the actual packer expansion times and the time before the prognostic test may differ slightly from test to test.
- The two deepest 100 m sections; section 804.0–904.0 m and section 889.0–989.0 m, were partly overlapping because of the actual length of the borehole.
- There were three possible candidates for pressure pulse tests in the 100 m test sections but they were all performed as injection tests because of uncertainties of the actual limit during the prognostic tests.
- Due to flow sensitive measurements (difference flow measurements in KFM08C) in the area during a period of time, a few highly conductive 5 m sections in the upper part of the borehole were measured on the way up in the borehole instead of on the way down.

6 Results

6.1 Nomenclature and symbols

The nomenclature and symbols used for the results of the injection tests in KFM08A 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.

During some tests in KFM08A pumping and flushing was performed in KFM07C. This fact may have showed in some tests as scattered pressure data. This has been commented on when observed but has not affected the results.

6.2.2 Length corrections

The down-hole equipment is supplied with a level indicator located c 3 m below the lower packer in the test section, see Figure 4-2. The level indicator transmits a signal each time a reference mark in the borehole is passed. In KFM08A, reference marks were milled into the borehole wall at approximately every 50 m.

During the injection tests in KFM08A with the PSS, length reference marks were detected as presented in Table 6-1. As seen from Table 6-1, all of the length marks of the borehole 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 0.31 m, at the 950 m reference mark. The difference between two consecutive measurements over a 50 m borehole interval was 0.06 m or less in all cases. A comparison of the measurements performed with different section lengths results in a maximum difference of 0.03 m.

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 6-2 and Table 6-3 respectively. Figure 6-2 shows the most representative transmissivity values from both injection- and pressure pulse tests in KFM08A.

Table 6-1. Detected reference marks during the injection tests in KFM08A.

Borehole length (m)	Detected during the injection tests in 100 m sections	Detected during the injection tests in 20 m sections	Detected during the injection tests in 5 m sections
151.0	Yes	Yes	Yes
200.0	Yes	Yes	Yes
250.0	Yes	Yes	Yes
299.8	Yes	Yes	Yes
350.0	Yes	Yes	Yes
400.0	Yes	Yes	Yes
450.0	Yes	Yes	Yes
500.0	Yes	Yes	Yes
552.0	Yes	Yes	Yes
600.0	Yes	Yes	Yes
650.0	Yes	Yes	Yes
700.0	Yes	Yes	Yes
750.0	Yes	Yes	Yes
800.0	Yes	Yes	Yes
850.0	Yes	Yes	
900.0	Yes	Yes	
950.0	Yes	Yes	
981.0	Yes	Yes	

Selected test diagrams are presented in Appendix 3. In general, one linear diagram showing the entire test sequence together with lin-log and log-log diagrams from the injection and recovery periods, respectively, are presented for the injection tests. The quantitative analysis was performed from such diagrams using the AQTESOLV software. From injection tests with a flow rate below the estimated lower measurement limit for the specific test, only the linear diagram is presented. 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 KFM08A are also compiled in appropriate tables in Appendix 5 to be stored in the SICADA database.

Injection tests

For the injection tests, transient evaluation was conducted, whenever possible, both on the injection and recovery periods (e.g. transmissivity 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. Transient evaluation was performed for all tests for which a significant final flow rate, Q_p, could be identified, see Section 5.4.2. The quantitative analysis was conducted 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 6-2 and further commented on in Section 6.2.4. 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, see Table 6-2.

For 30 out of 59 tests with a definable final flow rate in KFM08A, the transient evaluation of the injection period was considered to give the most representative transient transmissivity value. The corresponding number for the recovery period was 21. Several of the responses during the recovery period were strongly influenced by wellbore storage effects. On the other hand, during the injection period a certain time interval with pseudo-radial flow could often be identified. Consequently, standard methods for single-hole tests with wellbore storage and skin effects were commonly 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 6-2.

For tests where transient evaluation was not possible or not considered representative, T_M was chosen as the representative transmissivity value, T_R. In 12 out of 59 tests with a definable final flow rate in KFM08A the steady-state transmissivity, T_M, was chosen as the most representative value. This number is unusually high, partly because of frequently occurring apparent no flow boundaries during both the injection and the recovery period. If the final flow rate Q_p was below the actual test-specific measurement limit, the representative transmissivity value was assumed to be less than the estimated T_M, based on Q/s-measl-L.

The estimated standard lower measurement limit for flow rate for injection tests with PSS is c 1 mL/min ($1.7 \cdot 10^{-8}$ m^3/s). However, for approximately 35% of the injection tests in KFM08A, the lower measurement limit was close to, or below, the standard lower measurement limit. Hence a test-specific estimate of the lower measurement limit of flow rate was made which ranged from $4.1 \cdot 10^{-9}$ m^3/s to $7.4 \cdot 10^{-9}$ m^3/s. The lower measurement limit for transmissivity is defined in terms of the specific flow rate (Q/s), and the overall estimated test specific lower measurement limit for the specific flow rate in KFM08A ranged from $1.7 \cdot 10^{-10}$ m^2/s to $3.4 \cdot 10^{-10}$ m^2/s (see Section 5.4.2).

For a few tests, a type curve fit is displayed in the diagrams in Appendix 3 despite the fact that the estimated parameters from the fit are judged as ambiguous or non-representative and not included in the result tables in SICADA. For these tests, the type curve fit is presented as an example, e.g. to illustrate that an assumption of pseudo-radial flow regime is not justified for the test and some other flow regime is dominating or, alternatively, to show one possible fit in the case of unambiguous evaluation. For example, for test responses showing only wellbore storage and tests approaching a pseudo-stationary flow, no unambiguous transient evaluation is possible.

Some of the tests in KFM08A showed unusual responses, both during the injection- and recovery period, possibly representing flow in conductive fractures of limited extension or with varying apertures. During the injection period of these tests the flow rate decreased rapidly during the entire period indicating apparent no-flow boundaries (NFB), but the final flow rate was still rather high in many tests. No unambiguous transient evaluation of the injection period was possible for these tests. After stop of the injection, the pressure recovered very slowly and only to a limited extent during the recovery period. One possible explanation to these responses is flow in a rather high-conductive fracture close to the borehole with decreasing aperture away from the borehole or other geometrical restrictions of the fracture. Some other tests show initial pseudo-radial flow transitioning to flow in an apparent no-flow boundary, followed by slow and limited pressure recovery after the stop of the injection.

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. The agreement between the two populations is in general considered as good. Steady-state analysis of transmissivity according to Moye's formula (denoted T_M) may slightly overestimate the transmissivity if steady-state conditions do not prevail in the borehole. This fact is likely to be the main explanation to the predominance of points below the 1:1 curve since steady-state conditions are normally not attained during the injection period. In addition, skin effects (both positive and negative) may cause discrepancies between transient and steady-state evaluation. For low values of transmissivity, discrepancies in transmissivity may also occur due to the definition of the lower measurement limit in transient and steady-state evaluation, respectively.

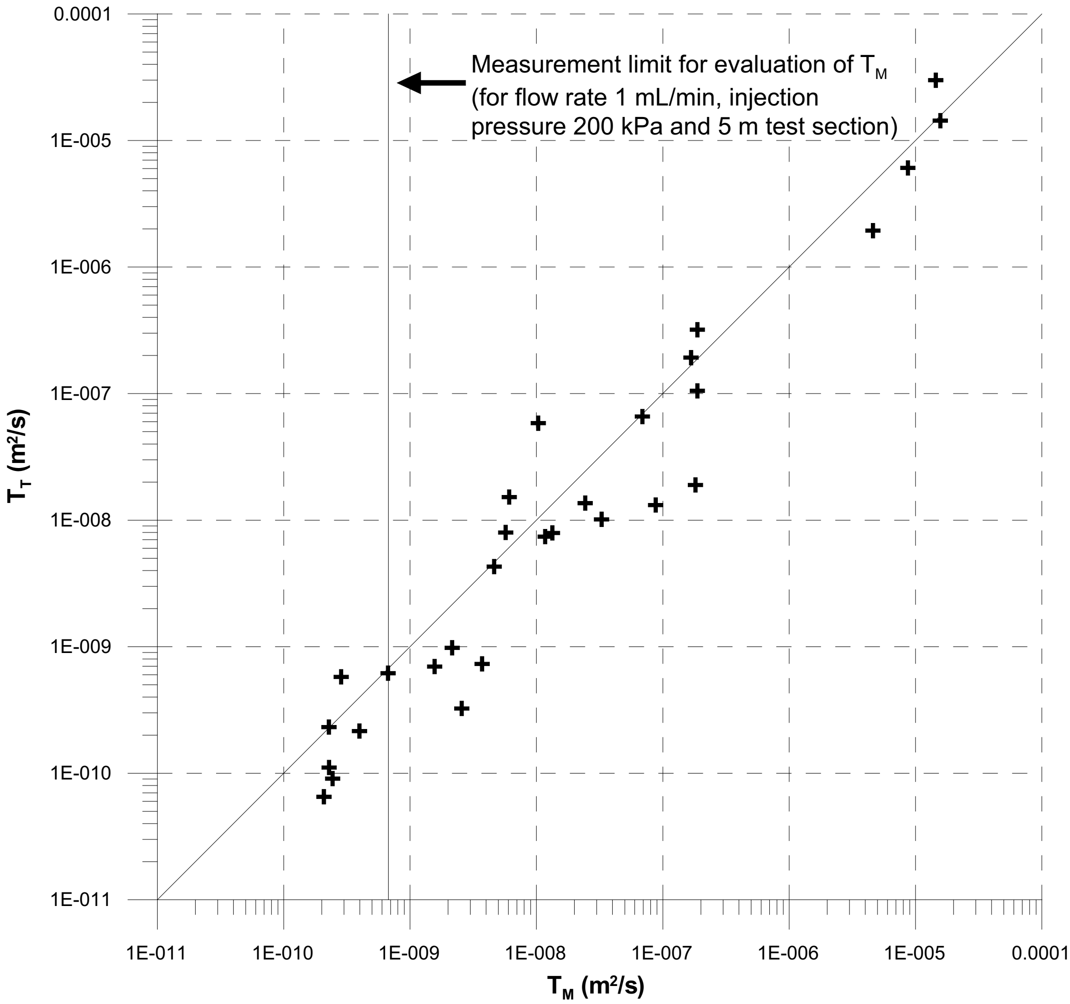

Figure 6-1. *Estimated transmissivities in 5 m sections from steady-state (T_M) and transient (T_T) evaluation for the injection tests in KFM08A.*

In the latter evaluation the measurement limit is based on the test-specific flow rate while in transient evaluation, the transmissivity is based on the change of the (inverse) flow rate during the injection period.

In cases where apparent no-flow boundaries appear at the end of the injection period and transient evaluation is performed on the early part of the data curve, the steady-state transmissivity T_M may be low in comparison with the transient estimate of transmissivity. In this case, two different zones of the bedrock are measured during the early and late parts of the injection period, respectively.

The lower standard measurement limit of steady-state 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. However, for some test sections in KFM08A, the actual injection pressure was considerably different, as previously denoted in Section 5.4.2. The highest injection pressure during the tests in KFM08A was 286 kPa, and for eight of the tests the injection pressure was below 100 kPa in the transient evaluation.

The wellbore storage coefficient, C, was calculated from the straight line with a unit slope in the log-log diagrams from the recovery period, see Table 6-2. The coefficient C was only calculated for tests with a well-defined line of unit slope in the beginning of the recovery period. In the most 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 6-2 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} /12/, both found in Table 5-3.

The number of injection tests with a well-defined line of unit slope from which it was possible to calculate C was 3 out of 8 tests with a definable Q_p, when using the 100 m test section. The corresponding numbers for the 20 m tests were 6 out of 15, and for the 5 m tests; 5 out of 36. Table 6-2 shows that there is, in general, a relatively good agreement between the calculated C-values from the tests and those listed in Table 5-3, although the calculated values from the tests tend to be slightly higher. The higher C-values observed in the tests may partly be explained by the compressibility contribution of the rock formation and water in good hydraulic connection (i.e. open fractures or cavities) with the section.

When constructing 95% confidence intervals (using a t-distribution) from calculated values of C from the tests, the values of C_{net} and C_{eff} listed in Table 5-3 are within these confidence intervals except for C_{net} for the 5 m section which is lower then the confidence interval. The wellbore storage coefficient was also calculated from the simulation of the recovery responses in AQTESOLV based on the estimated radius of the fictive standpipe, r(c), to the test section according to Equation 5-6.

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 used.

In Table 6-3 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 most of the pulse tests the stationary evaluation was considered as the most representative. This is, for a majority of the tests, because 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 $5.0 \cdot 10^{-11}$ m^2/s are regarded to be representative.

In many cases where a transient evaluation appeared 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. In these cases the larger transmissivity value from the stationary evaluation was chosen.

Section 699.0–704.0 m in KFM08A had the highest rate of pressure increase during the first part of the recovery period measures in the Forsmark boreholes and is therefore considered, by definition, to be a virtually impermeable test section. The method used to estimate the stationary transmissivity presupposes that section 699.0–704.0 m is virtually impermeable, and therefore no evaluation can be made for this section. The transmissivity is considered to be less than $5.0 \cdot 10^{-11}$ m^2/s. In total, this is the only pressure pulse test that has an estimated transmissivity lower than $5.0 \cdot 10^{-11}$ m^2/s.

Table 6-2. Summary of the routine evaluation of the single-hole injection tests in borehole KFM08A.

Secup (m)	Seclow (m)	Test start YYYY-MM-DD hh:mm	b (m)	Flow regime [1)] injection	Recovery	T_M (m²/s)	T_f (m²/s)	T_s (m²/s)	T_T (m²/s)	T_R [2)] (m²/s)	ξ (–)	t_1 (s)	t_2 (s)	dte_1 (s)	dte_2 (s)	C (m³/Pa)	r_i (m)	r_i-index (–)
104.00	204.00	2006-05-22 07:47	100.0	PLF	PLF	2.10E–05	1.97E–06	6.28E–06	6.28E–06	6.28E–06							120.83	1
204.00	304.00	2006-05-22 11:04	100.0	PRF-> PSF	PRF1-> PRF2	1.28E–05	9.33E–06	1.90E–05	9.33E–06	9.33E–06	–2.06	100	1,000	200	1,000		99.09	–1
304.00	404.00	2006-05-30 08:36	100.0	PRF-> PSF	WBS->	7.65E–10	7.34E–11	1.01E–10	1.01E–10	1.01E–10	–5.90	100	1,000			2.69E–10	7.67	1
404.00	504.00	2006-05-23 07:04	100.0	PRF-> (NFB)	(PLF)-> PRF-> (NFB)	5.38E–07	1.37E–07	2.58E–07	1.37E–07	1.37E–07	–5.38	30	200	60	300		15.42	1
504.00	604.00	2006-05-23 10:16	100.0	PLF	PLF->	6.08E–10				6.08E–10							12.07	–
604.00	704.00	2006-05-23 13:50	100.0	PRF-> NFB	PRF-> (NFB)	1.98E–05				1.98E–05							161.04	–
704.00	804.00	2006-05-29 15:52	100.0	PLF/PRF	WBS->	2.80E–09	6.78E–10	6.50E–10	6.78E–10	6.78E–10	–4.12	50	1,800			2.68E–10	12.27	0
804.00	904.00	2006-05-24 08:58	100.0	–	–	< 3.21E–10				< 3.21E–10							–	–
889.00	989.00	2006-05-29 08:09	100.0	PSF	WBS->	3.70E–09	7.70E–10	3.88E–10	7.70E–10	7.70E–10	–3.93					4.59E–10	12.74	–1
104.00	124.00	2006-05-31 13:59	20.0	NFB	PLF->	1.41E–07		1.77E–07	1.77E–07	1.77E–07							40.33	1
124.00	144.00	2006-05-31 15:43	20.0	NFB	PLF/PRF-> NFB	3.39E–07		1.30E–06	1.30E–06	3.39E–07	–6.04						47.72	1
144.00	164.00	2006-06-01 08:32	20.0	PLF/PRF-> NFB	PRF-> NFB	1.58E–07	1.09E–07	1.03E–06	1.09E–07	1.09E–07	–6.02	50	100	10	300		10.31	1
164.00	184.00	2006-06-01 10:06	20.0	PRF-> NFB	WBS-> PRF-> NFB	1.39E–08	7.87E–09	1.34E–08	7.87E–09	7.87E–09	–3.17	100	300	200	500	1.18E–10	9.25	1
184.00	204.00	2006-06-13 21:23	20.0	PLF	PLF	1.86E–05		7.50E–06	7.50E–06	7.50E–06							103.03	1
204.00	224.00	2006-06-01 14:04	20.0	PRF-> (NFB)	WBS-> (PRF)	1.46E–08	7.80E–09	6.56E–09	7.80E–09	7.80E–09	–5.03	120	1,000			4.41E–10	16.85	1
224.00	244.00	2006-06-01 15:35	20.0	PRF-> PSF	WBS-> PSF-> (NFB)	1.52E–08	8.60E–09	6.70E–09	8.60E–09	8.60E–09	–2.17					6.08E–11	19.04	–1
244.00	264.00	2006-06-02 08:04	20.0	PLF/PRF	PRF1-> (PRF2)	2.34E–07	9.67E–08	1.34E–07	9.67E–08	9.67E–08	–4.36	100	600	20	250	7.84E–10	24.49	0
264.00	284.00	2006-06-02 09:41	20.0	PSF-> NFB	PLF-> PSF> NFB	1.07E–05	3.48E–06	2.96E–06	2.96E–06	2.96E–06	–4.81						81.96	1
284.00	304.00	2006-06-02 11:16	20.0	PRF	WBS->	2.50E–09	1.03E–09	1.04E–09	1.03E–09	1.03E–09	–3.16	200	1,200			4.65E–11	11.13	0
404.00	424.00	2006-06-02 14:36	20.0	PLF	PLF	1.11E–07	1.23E–08	2.47E–08	1.23E–08	1.23E–08	–6.38						20.74	1
444.00	464.00	2006-06-07 09:03	20.0	PLF-> NFB	PLF-> PRF	9.28E–08	1.49E–08	7.45E–08	7.45E–08	7.45E–08	–4.46			60	1,200		32.45	0
464.00	484.00	2006-06-07 10:58	20.0	PRF1-> PRF2	PSF-> NFB	2.44E–07	3.34E–07	4.62E–07	3.34E–07	3.34E–07	1.32	20	300				23.60	0
684.00	704.00	2006-06-13 16:28	20.0	(PRF)-> NFB	PRF-> NFB	1.91E–05	1.51E–05	3.35E–05	3.35E–05	1.91E–05	–1.81			10	80		130.33	1
784.00	804.00	2006-06-12 10:54	20.0	PLF/PRF	WBS-> (PRF)	2.48E–09	5.38E–10	1.37E–09	1.37E–09	1.37E–09	–2.76	300	1,200	450	1,000	4.97E–11	10.91	0
104.00	109.00	2006-06-28 22:50	5.0	PRF	WBS-> (PRF)	1.34E–08	3.35E–09	7.93E–09	7.93E–09	7.93E–09	–4.62	300	1,200				18.51	–1
109.00	114.00	2006-06-28 21:24	5.0	NFB?	PLF	8.76E–08	4.42E–08	5.11E–08		8.76E–08							34.08	–
114.00	119.00	2006-06-28 19:56	5.0	NFB	PLF-> NFB	1.98E–08				1.98E–08							23.54	–
119.00	124.00	2006-06-28 15:24	5.0	PRF	PLF->	2.44E–10	9.07E–11	5.04E–10	9.07E–11	9.07E–11	–4.06	200	1,200				6.06	0
124.00	129.00	2006-06-28 13:45	5.0	NFB	PLF-> (PRF)	3.11E–09				3.11E–09							14.80	–
129.00	134.00	2006-06-28 11:03	5.0	PLF	PLF	1.81E–07	1.90E–08		1.90E–08	1.90E–08	–6.89						23.28	1
134.00	139.00	2006-06-28 09:27	5.0	NFB	PLF-> (PRF)	1.29E–07				1.29E–07							37.63	–

Secup (m)	Seclow (m)	Test start YYYY-MM-DD 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 [2] (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 (–)
144.00	149.00	2006-06-28 06:10	5.0	NFB	PRF-> NFB	1.07E–07				1.07E–07							35.87	–
149.00	154.00	2006-06-27 22:00	5.0	NFB	WBS-> PRF	1.03E–08		5.83E–08	5.83E–08	5.83E–08	1.53			550	1,200		30.48	0
154.00	159.00	2006-06-27 20:54	5.0	–	–	< 1.53E–10				< 1.53E–10							–	–
164.00	169.00	2006-06-15 13:30	5.0	PRF-> NFB	PRF	4.63E–09	4.30E–09	7.89E–09	4.30E–09	4.30E–09	–3.17	40	100	300	1,200		4.59	1
169.00	174.00	2006-06-15 15:57	5.0	PRF-> (PSS)	WBS->	3.98E–10	2.15E–10	2.45E–10	2.15E–10	2.15E–10	–1.58	10	100			1.84E–11	2.17	–1
174.00	179.00	2006-06-16 08:56	5.0	PRF1-> PRF2	(WBS)-> PRF-> NFB	6.09E–09	1.52E–08	1.08E–08	1.52E–08	1.52E–08	4.48	30	200	70	200		8.91	1
179.00	184.00	2006-06-16 10:23	5.0	(PRF)-> NFB	WBS-> PRF-> NFB	2.85E–10	8.79E–10	5.78E–10	5.78E–10	5.78E–10	–3.05	10	80	60	1,000		8.79	1
184.00	189.00	2006-06-27 17:23	5.0	PRF	WBS-> (PRF)	4.61E–06	1.94E–06	5.92E–06	1.94E–06	1.94E–06	–5.63	200	1,200				73.30	1
189.00	194.00	2006-06-27 15:49	5.0	PLF	PRF-> NFB	1.57E–05		1.43E–05	1.43E–05	1.43E–05	–5.13			30	200		49.32	1
194.00	199.00	2006-06-28 17:56	5.0	PLF/NFB?	PLF	4.79E–06				4.79E–06							92.37	–
199.00	204.00	2006-06-27 12:33	5.0	(PSF)-> PSS	PSF	1.67E–07		1.93E–07	1.93E–07	1.93E–07	0.19						41.14	–1
204.00	209.00	2006-06-27 10:12	5.0	PRF/PLF-> (NFB)	WBS->	1.56E–09	6.96E–10		6.96E–10	6.96E–10	–3.75	30	700				7.71	1
209.00	214.00	2006-06-16 14:11	5.0	PRF-> NFB	PLF-> NFB	2.43E–08	1.36E–08	1.07E–08	1.36E–08	1.36E–08	–3.84	200	1,000				19.38	1
214.00	219.00	2006-06-16 15:47	5.0	PLF> (PRF)	PLF	3.72E–09	7.32E–10		7.32E–10	7.32E–10							10.30	0
219.00	224.00	2006-06-19 06:08	5.0	PRF-> NFB	PLF-> PRF-> NFB	2.28E–10	2.32E–10	1.48E–09	2.32E–10	2.32E–10	–4.61	30	200	100	1,000		3.13	1
234.00	239.00	2006-06-19 11:53	5.0	–	–	< 1.94E–10				< 1.94E–10							–	–
239.00	244.00	2006-06-19 12:43	5.0	PRF?	PRF-> PSF	1.17E–08	2.92E–08	6.03E–09	6.03E–09	6.03E–09	–2.11	150	1,200	5	40		3.16	–1
244.00	249.00	2006-06-27 08:21	5.0	PLF/PRF	PLF/PRF	1.88E–07	1.05E–07	1.42E–07	1.05E–07	1.05E–07	–4.15	50	1,200				35.36	1
259.00	264.00	2006-06-26 20:56	5.0	NFB?	PLF	4.15E–09				4.15E–09							15.92	–
264.00	269.00	2006-06-26 19:08	5.0	PLF?-> PRF	PLF->	2.56E–09	3.25E–10		3.25E–10	3.25E–10	–5.61	500	1,200				8.34	0
269.00	274.00	2006-06-26 17:41	5.0	PLF-> PSF	PLF-> (PSF)	3.28E–08	1.01E–08	8.49E–09	1.01E–08	1.01E–08							19.84	–1
274.00	279.00	2006-06-26 16:07	5.0	PRF-> NFB	PRF1-> PRF2	8.70E–06	1.78E–05	6.07E–06	6.07E–06	6.07E–06	–3.72	200	500	20	60		21.80	–1
294.00	299.00	2006-06-19 18:29	5.0	PLF	WBS->	2.08E–10		6.53E–11	6.53E–11	2.08E–10	–4.23					1.29E–11	7.52	1
299.00	304.00	2006-06-19 20:06	5.0	PRF	WBS-> PRF	2.29E–10	7.80E–11	1.11E–10	1.11E–10	1.11E–10	–3.14	20	1,200	700	1,200	1.63E–11	6.38	0
409.00	414.00	2006-06-20 08:16	5.0	PLF-> PRF	PLF	8.78E–08	1.32E–08		1.32E–08	1.32E–08	–6.30	700	1,200				21.05	0
449.00	454.00	2006-06-20 15:28	5.0	NFB	PLF-> PRF	6.90E–08		6.58E–08	6.58E–08	6.58E–08	–4.47			100	1,300		32.74	0
454.00	459.00	2006-06-21 06:06	5.0	PRF1-> (PRF2)	WBS-> PRF-> NFB	6.70E–10	6.18E–10	5.69E–10	6.18E–10	6.18E–10	–2.80	10	100	100	400	2.19E–11	2.83	1
459.00	464.00	2006-06-21 07:29	5.0	(PRF)-> NFB	PRF-> NFB	5.71E–09	5.89E–09	7.99E–09	7.99E–09	7.99E–09	–2.94	10	50	10	200		7.58	1
479.00	484.00	2006-06-21 13:37	5.0	PRF-> NFB	NFB	1.88E–07	3.20E–07		3.20E–07	3.20E–07	1.23	30	200				19.07	1
684.00	689.00	2006-06-21 16:59	5.0	PRF-> NFB	PRF-> NFB	1.45E–05	1.04E–05	2.99E–05	2.99E–05	2.99E–05	–1.49	200	400	10	100		41.93	1
794.00	799.00	2006-06-22 15:40	5.0	(PRF1)-> PRF2	WBS-> PRF-> (NFB)	2.15E–09	9.81E–10	2.71E–09	9.81E–10	9.81E–10	–3.56	100	1,200	100	400	2.10E–11	10.99	1

[1] The acronyms in the column "Flow regime" are as follows: 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.

[2] For the tests where Q_p was not detected, T_R was assumed to be less than T_M based on the estimated Q/s-measl-L

Table 6-3. Summary of the routine evaluation of the single-hole pressure pulse tests in borehole KFM08A.

Secup (m)	Seclow (m)	Test start YYYYMMDD hh:mm	b (m)	Tss, pulse (m^2/s)	TT, pulse (m^2/s)	ξ (–)	Tmeas. limit (m^2/s)	TR, pulse (m)
424.00	444.00	20060602 16:07	20.00	6.58E–10	–	–	6.58E–10	6.58E–10
484.00	504.00	20060607 13:32	20.00	5.88E–10	–	–	5.88E–10	5.88E–10
604.00	624.00	20060607 17:01	20.00	3.94E–10	–	–	3.94E–10	3.94E–10
624.00	644.00	20060608 09:27	20.00	2.22E–10	–	–	2.22E–10	2.22E–10
644.00	664.00	20060608 11:21	20.00	1.80E–10	–	–	1.80E–10	1.80E–10
664.00	684.00	20060608 13:33	20.00	1.92E–10	–	–	1.92E–10	1.92E–10
704.00	724.00	20060609 08:07	20.00	1.54E–10	–	–	1.54E–10	1.54E–10
724.00	744.00	20060609 09:46	20.00	2.14E–10	–	–	2.14E–10	2.14E–10
744.00	764.00	20060609 12:24	20.00	2.50E–10	–	–	2.50E–10	2.50E–10
764.00	784.00	20060612 08:15	20.00	3.51E–10	–	–	3.51E–10	3.51E–10
904.00	924.00	20060612 14:54	20.00	3.50E–10	–	–	3.50E–10	3.50E–10
924.00	944.00	20060613 05:50	20.00	1.21E–09	4.40E–10	–2.34	4.40E–10	4.40E–10
944.00	964.00	20060613 08:12	20.00	2.39E–10	–	–	2.39E–10	2.39E–10
964.00	984.00	20060613 10:29	20.00	1.90E–10	–	–	1.90E–10	1.90E–10
139.00	144.00	20060628 07:55	5.00	1.35E–10	–	–	1.35E–10	1.35E–10
159.00	164.00	20060627 18:58	5.00	3.13E–10	–	–	3.13E–10	3.13E–10
224.00	229.00	20060619 07:32	5.00	7.15E–10	3.14E–10	–0.88	3.14E–10	3.14E–10
229.00	234.00	20060619 09:29	5.00	5.90E–10	–	–	5.90E–10	5.90E–10
249.00	254.00	20060627 06:24	5.00	2.79E–10	–	–	2.79E–10	2.79E–10
254.00	259.00	20060626 22:23	5.00	4.58E–10	–	–	4.58E–10	4.58E–10
279.00	284.00	20060626 14:07	5.00	3.46E–10	–	–	3.46E–10	3.46E–10
284.00	289.00	20060619 14:33	5.00	8.28E–10	6.74E–10	–1.01	6.74E–10	6.74E–10
289.00	294.00	20060619 16:21	5.00	6.18E–10	4.42E–10	2.21	4.42E–10	4.42E–10
404.00	409.00	20060619 22:45	5.00	2.48E–10	–	–	2.48E–10	2.48E–10
414.00	419.00	20060620 09:54	5.00	8.56E–11	–	–	8.56E–11	8.56E–11
419.00	424.00	20060620 12:11	5.00	1.54E–10	–	–	1.54E–10	1.54E–10
444.00	449.00	20060620 13:58	5.00	1.38E–10	–	–	1.38E–10	1.38E–10
464.00	469.00	20060621 08:53	5.00	1.64E–10	–	–	1.64E–10	1.64E–10
469.00	474.00	20060621 10:18	5.00	2.14E–10	–	–	2.14E–10	2.14E–10
474.00	479.00	20060621 12:17	5.00	1.75E–10	–	–	1.75E–10	1.75E–10
689.00	694.00	20060621 18:39	5.00	4.06E–10	–	–	4.06E–10	4.06E–10
694.00	699.00	20060621 20:49	5.00	5.51E–11	–	–	5.51E–11	5.51E–11
699.00	704.00	20060621 22:19	5.00	0.00E+00	–	–	5.00E–11	5.00E–11
784.00	789.00	20060622 10:49	5.00	3.94E–10	–	–	3.94E–10	3.94E–10
789.00	794.00	20060622 13:34	5.00	3.10E–10	–	–	3.10E–10	3.10E–10
799.00	804.00	20060626 06:13	5.00	3.88E–10	–	–	3.88E–10	3.88E–10

6.2.4 Comments on the tests

Short comments on each test follow below. Tests were performed within the interval 104.0–989.0 m in KFM08A. 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

104–204 m

Both the injection- and recovery period is dominated by a PLF. The transient evaluation of the injection period is regarded as somewhat uncertain. The pressure only recovered c 3 m of the applied injection pressure of c 65 kPa, possibly indicating a flow feature of limited extension or alternatively, the presence of flow restrictions away from the borehole. Hence the transient evaluation of the recovery period with the Ozkan-Raghavan model also is regarded as uncertain for this section. The transient evaluation from the recovery period was selected as the representative for the section. At the start of the injection period, the pressure in the section above dropped instantaneously. This may be an effect of the equipment and not a true feature of the rock formation. Since the measurement noise with a zero flow was centred slightly below zero, the flow data was manually elevated by $4 \cdot 10^{-9}$ m^3/s. This fact had, however, a very small effect on the evaluation since the flow rate is rather high.

204–304 m

A PRF is indicated between c 120 s and 900 s during the injection period followed by a rapid decrease in the derivative which may suggest a transition to a PSF. The recovery period indicates two separate periods of PRF, one early period between 20 and 70 s, and a later, longer period from 200 to 1,000 s. Transient evaluations of the injection period and the later PRF period of the recovery give rather consistent results. The transient evaluation from the injection period was selected as the representative for the section. Since the measurement noise with a zero flow was centred slightly below zero, the flow rate measurement limit as well as the flow data was manually elevated by $4 \cdot 10^{-9}$ m^3/s. This fact had, however, a very small effect on the evaluation since the flow rate is rather high.

304–404 m

Although data are scattered the injection period indicates a PRF followed by a PSF after c 1,000 s. The recovery period displays a WBS and a transition period. Although no PRF was developed during the recovery period, the Hurst-Clark-Brauer model for the injection period and the Dougherty-Babu model for the recovery period give consistent results. The transient evaluation from the recovery period was selected as the representative for the section. Since the measurement noise with a zero flow was centred slightly below zero, the flow rate measurement limit as well as the flow data were manually elevated by $3 \cdot 10^{-9}$ m^3/s.

404–504 m

The injection period indicates a PRF followed by a possible, but rather weak, apparent NFB. The recovery period demonstrates an initial, rather short PLF followed by a PRF between 60 and 300 s. After c 300 s, indications of a possible, apparent NFB are seen. However, just as during the injection, the apparent NFB is rather weak. The transient evaluation from the injection period was selected as the representative for the section. There was a change of test valve after c 1,020 s of the injection period which resulted in a temporarily increased pressure. The pressure in the section below the test section was quite scattered for unknown reasons.

504–604 m

Due to a drift in the gas pressure regulator, the pressure in the test section increased by c 2 kPa during the injection period. As a result, the reciprocal flow rate was disturbed throughout the injection period. The pressure drift caused an increasing trend in the derivative that may not be representative for the rock formation. Still, with consideration taken to the pressure drift, a PLF is interpreted as the dominating flow regime during the injection period. During the recovery period a possible PLF occurs. The pressure only recovered c 1.5 m during the recovery period indicating a very tight section. No unambiguous transient evaluation could be made on either the injection period or the recovery period. Hence, the steady-state transmissivity TM from the injection period is regarded as the most representative for the section. Examples of possible transient evaluations are shown for the injection period as well as the recovery period.

604–704 m

Both the injection- and recovery period are displaying a possible, early PRF transitioning to an apparent NFB. Alternatively, a PLF may be interpreted during the entire period. The pressure only recovered c 7 m of the applied injection pressure of c 11 m, possibly indicating a flow feature of limited extension or alternatively, the presence of flow restrictions away from the borehole. The Hurst-Clark-Brauer model for the injection period and the Dougherty-Babu model for the recovery period based on the assumed PRF give consistent results. However, the transient evaluations on both periods are considered as uncertain and probably non-representative due to the presence of the apparent NFB. Hence, the steady-state transmissivity TM from the injection period is regarded as the most representative for the section. Examples of transient evaluations based on the early PRF are shown for the injection period as well as the recovery period.

704–804 m

The injection period indicates an intermediate flow regime between a PLF and a PRF approaching a true PRF. Transient evaluation with a PRF-model and a single fracture model gave consistent results. In addition, transient evaluation from the injection and recovery period gives consistent estimates of transmissivity. The recovery period begins with a WBS followed by a transition period at the end of the period. The transient evaluation from the injection period was selected as the representative for the section.

804–904 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. Hence, in accordance with AP PF 400-05-032, the injection time was shortened. As a result TM, based on Q/s-measl-L, was considered to be the most representative transmissivity value for this section. Since the measurement noise with a zero flow was centred slightly below zero, the flow rate measurement limit was manually elevated $2.47 \cdot 10^{-9}$ m^3/s.

889–989 m

A PSF is indicated during the injection period. The recovery period begins with WBS followed by a transition period. The transient evaluation of the injection- and recovery period results in similar transmissivities. The transient evaluation from the injection period was selected as the representative for the section.

104–124 m

Although an automatic change of flow range interval (valves) disturbs the flow rate after c 330 s during the injection period there are strong indications of an apparent NFB throughout this period, possibly corresponding to a flow feature of limited extension or decreasing aperture away from the borehole. On the other hand, the recovery period demonstrates a PLF and a transition period. The responses during the injection and recovery period are thus not consistent. The pressure only recovered c 40 kPa of the applied injection pressure of c 225 kPa, possibly indicating a flow feature of limited extension or alternatively, the presence of flow restrictions away from the borehole. Transient evaluations on the recovery period with models for PRF and single fracture model give consistent results. Although the transient evaluation of the recovery period is uncertain it is considered as the representative transmissivity of the section because of the apparent NFB during the injection period.

124–144 m

Although an automatic change of flow range interval (valves) disturbs the flow rate after c 800 s during the injection period there are strong indications of an apparent NFB throughout this period, possibly corresponding to a flow feature of limited extension or decreasing aperture away from the borehole. On the other hand, the recovery period demonstrates a PLF/PRF transitioning to an apparent NFB. The responses during the injection and recovery period are not consistent. The pressure only recovered c 35 kPa of the applied injection pressure of c 220 kPa, possibly indicating a flow feature of limited extension or alternatively, the presence of flow restrictions away from the borehole. Transient evaluations on the recovery period with models for PRF and single fracture model give consistent results but the results are considered as uncertain due to the apparent NFB by the end. Thus, the steady-state transmissivity TM from the injection period is considered as the representative transmissivity of the section.

144–164 m

An automatic change of flow range interval (valves) causes a disturbance in the flow after c 260 s during the injection period. Still, the injection period indicates a PLF/PRF transitioning to an apparent NFB by the end. During the recovery period a PRF is assumed between 10 and 300 s transitioning to an apparent NFB by the end. The transient evaluation of the recovery period results in a higher T-value in comparison to the injection period and also TM. Transient evaluation with the Hurst-Clark-Brauer model on the first part of the injection period is considered as the most representative transmissivity value for the section.

164–184 m

A PRF is indicated during the beginning of the injection period transitioning to an apparent NFB after c 300 s. The initial phase of the recovery period displays WBS transitioning to a possible PRF which is interrupted by an apparent NFB lasting until the end of the recovery period. Since the measurement noise with a zero flow was centred slightly below zero, the flow rate measurement limit as well as the flow data was manually elevated $2.5 \cdot 10{-}9$ m^3/s. The transient evaluation from the injection period was selected as the representative for the section.

184–204 m

Due to the high flow rate in the section, the time to achieve a constant injection pressure was unusually long; still, both the injection- and recovery period is dominated by a PLF. The high transmissivity of the section also made it impossible to achieve an injection pressure close to 20 m. The transient evaluation for the injection period is considered as uncertain. Hence, the transient evaluation of the recovery period is considered as the most representative for this section, despite of the incomplete recovery (c 20 kPa) of the applied injection head of c 40 kPa.

204–224 m

During the injection period a PRF is indicated between c 120 and 1,000 s followed by a transition into a possible apparent NFB by the end. The recovery period indicates WBS transitioning to an approximate PRF after c 500 s which continues for the rest of the recovery period. The transient evaluations from the injection and recovery period are consistent. The transient evaluation from the injection period was selected as the representative for the section.

224–244 m

Although the flow rate derivative is rather scattered, a PRF identified after c 100 s with a transition to a PSF is dominating the injection period. The recovery period initially shows WBS transitioning into a PSF. After approximately 500 s an apparent NFB is weakly indicated but considered as uncertain. Transient evaluation using the Hantush-model for pseudo-spherical flow was made for both the injection and recovery period. The transient evaluation from the injection period was selected as the representative for the section.

244–264 m

The injection period indicates an intermediate between a PRF and a PLF. The single fracture model by Ozkan-Raghavan supports the estimated transmissivity value from the Hurst-Clark-Brauer model for PRF. During the recovery period a first PRF is observed between 20 s and 250 s after which time a second PRF is weakly indicated between c 300 s until 800s. The transient evaluation from the injection period was selected as the representative for the section.

264–284 m

The injection period starts with an increase in the derivative followed by a rapid drop interpreted as a PSF. After c 300 s a transition into an apparent NFB is indicated. The recovery period starts with a PLF transitioning to a PSF. After c 250 s an apparent NFB is indicated. The transient evaluation of the injection period is uncertain; hence the recovery period is regarded to provide the best estimate of the transmissivity on the tested section.

284–304 m

The flow rate is low, close to the measurement limit and hence the data, especially the flow derivative, is quite scattered. In addition, the change from pump to pressure vessel introduces a pressure disturbance. Despite these facts a PRF is assumed to dominate the injection period between c 200 s throughout the period. Only WBS followed by a transition period is observed during the recovery period. The transient evaluation from the injection and recovery period is consistent. The transient evaluation from the injection period was selected as the representative for the section.

404–424 m

During the injection period a PLF is dominating during the entire period. The recovery period is also indicating an apparent PLF. The transient evaluation from the injection and recovery period is consistent. The transient evaluation from the injection period was selected as the representative for the section.

424–444 m (Pressure pulse test)

The period of measured recovery displayed a decreasing pressure. The transient evaluation provides an apparently good curve fitting, but results in an unrealistic transmissivity value probably because of packer compliance. Hence, the transmissivity from the stationary evaluation is regarded as most representative for this section.

444–464 m

During the beginning of the injection period a PLF was observed transitioning to an apparent NFB by the end. A PLF is also indicated in the beginning of the recovery period transitioning to a PRF after c 60 s. The transient evaluation from the recovery period was selected as the representative for the section.

484–504 m (Pressure pulse test)

The period of measured recovery displayed a decreasing pressure. No unambiguous transient evaluation was possible for this test. Hence, the transmissivity from the stationary evaluation is regarded as most representative for this section. During the 40 min recovery period the pressure recovered c 45 kPa out of the applied head change of c 140 kPa.

604–624 m (Pressure pulse test)

The period of measured recovery displayed a decreasing pressure. The transient evaluation provides an apparently good curve fitting, but results in an unrealistic transmissivity value probably because of packer compliance. Hence, the transmissivity from the stationary evaluation is regarded as most representative for this section. During the 40 min recovery period the pressure only recovered c 20 kPa out of the applied head change of c 140 kPa indicating a low transmissivity.

624–644 m (Pressure pulse test)

The period of measured recovery only showed a pressure increase indicating that the section is of such low transmissivity that packer compliance affects the pressure throughout the period. Hence, in accordance with Appendix 3 in the Quality plan the recovery time was shortened. No transient evaluation was possible and the stationary evaluation was considered to give the most representative transmissivity value for this section.

644–664 m (Pressure pulse test)

The period of measured recovery only showed a pressure increase indicating that the section is of such low transmissivity that packer compliance affects the pressure throughout the period. Hence, in accordance with Appendix 3 in the Quality plan the recovery time was shortened. No transient evaluation was possible and the stationary evaluation was considered to give the most representative transmissivity value for this section.

664–684 m (Pressure pulse test)

The period of measured recovery only showed a pressure increase indicating that the section is of such low transmissivity that packer compliance affects the pressure throughout the period. Hence, in accordance with Appendix 3 in the Quality plan the recovery time was shortened. No transient evaluation was possible and the stationary evaluation was considered to give the most representative transmissivity value for this section.

684–704 m

The injection period indicates a short approximate PRF between c 100–200 s followed by an apparent NFB throughout the period. The recovery period also displays a short PRF transitioning to an apparent NFB. Only approximate transient evaluations are possible on both the injection as well as the recovery period. Hence, the stationary transmissivity is considered to give the most representative transmissivity value for this section.

704–724 m (Pressure pulse test)

The period of measured recovery only showed a pressure increase indicating that the section is of such low transmissivity that packer compliance affects the pressure throughout the period. Hence, in accordance with Appendix 3 in the Quality plan the recovery time was shortened. No transient evaluation was possible and the stationary evaluation was considered to give the most representative transmissivity value for this section.

724–744 m (Pressure pulse test)

The period of measured recovery only showed a pressure increase indicating that the section is of such low transmissivity that packer compliance affects the pressure throughout the period. Hence, in accordance with Appendix 3 in the Quality plan the recovery time was shortened. No transient evaluation was possible and the stationary evaluation was considered to give the most representative transmissivity value for this section.

744–764 m (Pressure pulse test)

The period of measured recovery only showed a pressure increase indicating that the section is of such low transmissivity that packer compliance affects the pressure throughout the period. Hence, in accordance with Appendix 3 in the Quality plan the recovery time was shortened. No transient evaluation was possible and the stationary evaluation was considered to give the most representative transmissivity value for this section.

764–784 m (Pressure pulse test)

The period of measured recovery displayed a decreasing pressure. The transient evaluation provides an apparently good curve fitting, but results in an unrealistic transmissivity value probably because of packer compliance. Hence, the transmissivity from the stationary evaluation is regarded as most representative for this section.

784–804 m

During the injection period an inadvertently closed valve lead to a decreasing injection pressure throughout the injection period. The total pressure decrease was approximately 4 kPa. This fact is likely to cause a slight underestimation of the evaluated transmissivity from the injection period as well as an uncertain tendency towards linear flow. This assumption is supported by the transient evaluation from the recovery period which results in a slightly larger value of transmissivity. During the injection period an intermediate between a PLF and a PRF is indicated whereas the recovery shows an initial WBS which then transitions into an approximate PRF. The transient evaluation from the recovery period is chosen as the most representative for this section.

904–924 m (Pressure pulse test)

The period of measured recovery displayed a decreasing pressure. The transient evaluation provides an apparently good curve fitting, but results in an unrealistic transmissivity value probably because of packer compliance. Hence, the transmissivity from the stationary evaluation is regarded as most representative for this section.

924–944 m (Pressure pulse test)

The period of measured recovery displayed a decreasing pressure and a steady-state evaluation as well as a transient evaluation were possible. The test does not seem to be strongly affected by packer compliance, and also the curve fitting is good. The stationary evaluation and the transient evaluation give consistent results and the transient evaluation is considered to provide the most representative transmissivity value for this section.

944–964 m

The test was performed as a pressure pulse test. The period of measured recovery displayed a very weak pressure decrease followed by an equally weak pressure increase. This indicates that the section is of such low transmissivity that packer expansion affects the pressure throughout the period. Hence, no transient evaluation was possible and the steady-state evaluation was considered to give the representative transmissivity value for this section.

964–984 m (Pressure pulse test)

The period of measured recovery only showed a pressure increase indicating that the section is of such low transmissivity that packer compliance affects the pressure throughout the period. Hence, in accordance with Appendix 3 in the Quality plan the recovery time was shortened. No transient evaluation was possible and the stationary evaluation was considered to give the most representative transmissivity value for this section.

104–109 m

The time to achieve constant pressure in the section during the injection period is rather long since the flow is rapidly decreasing in the beginning. Throughout the rest of the injection period the flow rate data are scattered due to that the automatic pressure regulation valve was working near one of its end positions. After c 300 s a PRF is indicated. In the beginning of the recovery period WBS is indicated transitioning to an approximate PRF throughout the recovery period. The transient evaluation from the recovery period gives consistent T-values with the evaluation from the injection period. The transient evaluation from the recovery period is considered to give the most representative transmissivity value for this section.

109–114 m

The time to achieve constant pressure in the section during the injection period is rather long since the flow is rapidly decreasing in the beginning. After c 600 s an apparent PRF is observed lasting until about 1,000 s when the flow slightly decreases. However, the PRF is considered as very uncertain and an apparent NFB is assumed to dominate the entire injection period. During the recovery period a PLF is dominating throughout the period. The pressure recovery was only c 50 kPa which might indicate a flow feature of limited extension, i.e. decreasing fracture aperture away from the borehole. The transient evaluations from both the injection and recovery period are considered as uncertain. Thus, the steady-state evaluation from the injection period is considered as the most representative for this section.

114–119 m

The time to reach a constant pressure in the test section is increased due to changes between the pump and pressure vessel as well as an automatic change of pressure regulation valve. This fact also contributed to the scattered flow rate data. The injection period show strong signs of an apparent NFB throughout the period. The recovery period indicates a PLF transitioning to an apparent NFB. No unambiguous transient evaluation can be made from the injection period. An approximate transient evaluation was made on the recovery period but this evaluation is considered as uncertain due to the low total recovery achieved (c 15 kPa) of the applied injection head of c 210 kPa in this section. This fact might indicate a flow feature of limited extension, i.e. decreasing fracture aperture away from the borehole. The steady-state transmissivity TM was chosen as the representative transmissivity for the test section. The transient evaluation shown on the recovery period is shown as an example only.

119–124 m

The flow rate is low, close to the measurement limit and hence the data, especially the flow derivative, is quite scattered. Still, the injection period is assumed to be dominated by a PRF from c 200 s and throughout the period. The recovery periods indicate a PLF and a transition period to some other flow regime. The Hurst-Clark-Brauer model for the injection period and the Dougherty-Babu model for the recovery period as well as the stationary evaluation give fairly consistent results.

124–129 m

During the injection period, it was difficult to obtain a constant pressure in the test section due to changes between the pump and pressure vessel and two automatic changes of pressure regulation valve. From c 60–900 s the actual pressure regulation valve was working near one of its end positions. Although this fact contributed to the scattering of the flow rate data, is not considered to significantly affect the analysis of the test. A strong apparent NFB is indicated during the entire injection period and thus, no unambiguous transient evaluation can be made on the injection period. The total recovery in the test section is only c 16 kPa, indicating a flow feature of limited extension, i.e. decreasing fracture aperture away from the borehole. It is possible to obtain a good fit to the recovery period using the Dougherty-Babu model. However, the calculated Agarwal equivalent time is very large and the reliability of the transient recovery evaluation may be questioned. Hence, TM was considered to be the most representative transmissivity value for this section.

129–134 m

Both the injection and recovery periods are dominated by a PLF that lasts to the end of each period. It is possible to obtain a good fit for both periods; however, it was not possible to obtain an unambiguous evaluation for the recovery period. On the other hand, transient evaluations using the Hurst-Clark-Brauer model and the Ozkan-Raghavan model give consistent results for the injection period.

134–139 m

The injection period displays an increasing derivative which implies an apparent NFB from c 150 s and throughout this period. The recovery period is indicating a PLF with a transition into a possible PRF by the end. No unambiguous transient evaluation can be made from the injection period. An approximate transient evaluation was made on the recovery period but this evaluation is considered as uncertain due to the low total recovery achieved (c 1 m) of the applied injection head of c 130 kPa in this rather high-transmissive section. This fact might indicate a flow feature of limited extension, i.e. decreasing fracture aperture away from the borehole. The steady-state transmissivity TM was chosen as the representative transmissivity for the test section. The transient evaluations shown on the injection and recovery period respectively are shown as examples only.

139–144 m (Pressure pulse test)

The period of measured recovery only showed a pressure increase indicating that the section is of such low transmissivity that packer compliance affects the pressure throughout the period. Hence, in accordance with Appendix 3 in the Quality plan the recovery time was shortened. No transient evaluation was possible and the stationary evaluation was considered to give the most representative transmissivity value for this section.

144–149 m

The entire injection period is dominated by an apparent NFB. The recovery period is indicating a possible PRF with a transition into an apparent NFB after c 100 s. No unambiguous transient evaluation can be made from the injection period. An approximate transient evaluation was made on the recovery period but this evaluation is considered as uncertain due to the low total recovery achieved (c 35 kPa) of the applied injection head of c 200 kPa in this rather high-transmissive section. This fact might indicate a flow feature of limited extension, i.e. decreasing fracture aperture away from the borehole. The steady-state transmissivity TM was chosen as the representative transmissivity for the test section. The transient evaluation shown on the recovery period is an example only.

149–154 m

The injection period displays an increasing derivate after c 150 s indicating an apparent NFB. The recovery period shows initial WBS with a transition into a PRF after c 550 s. No unambiguous transient evaluation can be made from the injection period. The transient evaluation from the recovery period is considered to provide the most representative value of transmissivity for this section. The transient evaluation shown on the injection period is shown as an example only. Since the measurement noise with a zero flow was centred slightly below zero, the flow rate measurement limit was manually elevated $3.95 \cdot 10^{-9}$ m^3/s.

154–159 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. Hence, in accordance with AP PF 400-05-032, the injection time was shortened. As a result TM, based on Q/s-measl-L, was considered to be the most representative transmissivity value for this section. Since the measurement noise with a zero flow was centred slightly below zero, the flow rate measurement limit was manually elevated $4 \cdot 10^{-9}$ m^3/s.

159–164 m (Pressure pulse test)

The period of measured recovery displayed a decreasing pressure. The transient evaluation provides an apparently good curve fitting, but results in an unrealistic transmissivity value probably because of packer compliance. Hence, the transmissivity from the stationary evaluation is regarded as most representative for this section.

164–169 m

The injection period shows a short and early PRF followed by a NFB. The recovery period is dominated by a PRF preceded by WBS. At the end of the recovery period the derivative is seemingly increasing which would indicate an apparent NFB. However, this is probably an artefact of the measurement noise and the derivative filter and not a true characteristic of the tested rock formation. Since the measurement noise with a zero flow was centred slightly below zero, the flow rate measurement limit as well as the flow data was manually elevated $3.75 \cdot 10^{-9}$ m^3/s. The scattered pressure in the test section may depend on an ongoing activity in borehole KFM07C.

169–174 m

The flow rate is low, close to the measurement limit and hence the data, especially the flow derivative, is quite scattered. The injection period indicates a possible PRF, however, the extent of the flow regime is rather difficult to evaluate. After c 100 s the flow rate stabilizes which may indicate a transition a PSS. The recovery period is dominated by a WBS and a transition period to some other flow regime. Even though the PRF during the injection period is rather uncertain and no flow regime was developed during the recovery, the Hurst-Clark-Brauer model for the injection period and the Dougherty-Babu model for the recovery period give consistent and realistic results. Since the measurement noise with a zero flow was centred slightly below zero, the flow rate measurement limit as well as the flow data was manually elevated $3.75 \cdot 10^{-9}$ m^3/s.

174–179 m

The injection period indicates two separate periods of PRF where the first has a higher skin factor and transmissivity than the second. The recovery period displays a short period of WBS followed by a PRF and later an apparent NFB. The Hurst-Clark-Brauer model for the first PRF period during the injection and the Dougherty-Babu model for the recovery period give consistent results.

179–184 m

The flow rate is low, close to the measurement limit and hence the data, especially the flow derivative, is quite scattered. The injection period indicates an initial PRF with a transition into an apparent NFB. During the recovery period WBS with a transition into a PRF and subsequently an apparent NFB was identified. As the flow derivate during the injection period was scattered the transmissivity from the recovery period was considered most representative. Since the measurement noise with a zero flow was centred slightly below zero, the flow rate measurement limit as well as the flow data was manually elevated $1.48 \cdot 10^{-9}$ m^3/s.

184–189 m

Due to a poor regulation of the injection pressure the time to achieve a stable injection pressure was unusually long for this test and the flow derivate during the entire injection period was not stable. Hence the interpretation of a flow regime for the injection period was rather difficult but a possible PRF is indicated. The recovery period indicated initial WBS with a transition into a possible PRF by the end. The transient evaluation from the injection period is considered as most representative for the section. The pressure in the section below the test section increased c 3.7 kPa during the injection period. Since transmissivity in the section below is higher than the transmissivity in the section 184.0–189.0, this relatively small pressure interference has probably resulted in an overestimation of the transmissivity.

189–194 m

Due to a poor initial regulation the time to achieve a stable injection pressure was unusually long for this test. Still, the injection period clearly indicates a PLF from c 400 s and throughout the period. The recovery shows a short PRF followed by a transition to an apparent NFB. The Dougherty-Babu model for the recovery period and the transient evaluation give consistent results while the Hurst-Clark-Brauer and the Ozkan-Raghavan model give type curve fits of are of lesser quality. Hence, the transient evaluation from the recovery period is regarded as the most representative. The pressure in the section above the test section increased c 1 m during the injection period and the pressure in the section below increased c 11 kPa. Since transmissivity in the sections below is of the same magnitude or slightly higher than in the section 189.0–194.0, this relatively high pressure interference may have resulted in an overestimation of the transmissivity in this section. The pressure interference with the section above should not have a major impact of the test performed in the section.

194–199 m

The time to reach a constant pressure in the test section was extended since the initial flow rate was very high after which it was decreasing rapidly. Hence, the evaluation of the injection period is rather difficult. The rapidly decreasing flow rate would suggest of flow regime of rather small dimension, i.e. a PLF or possibly NFB. The recovery period only displays a PLF.

No unambiguous transient evaluation is possible of any of the periods, hence TM is considered as the best estimate of transmissivity in the test section. The pressure in the section above the test section increased c 9.7 kPa during the injection period. Since transmissivity in the section above is higher than the transmissivity in the section 194.0–199.0 m, this pressure interference may have resulted in an overestimation of the transmissivity in this section.

199–204 m

The flow rate stabilizes rather quickly and even increases towards the end of the injection period. Hence, the greater part of the injection period is considered to be dominated by PSS. It is possible to interpret a short PSF preceding the PSS. However, no unambiguous transient evaluation of the injection period is possible. The recovery period is clearly dominated by a PSF throughout the period and the Hantush model give rather satisfying results. An example of analysis of the injection period is shown in the appendix assuming the same transmissivity as estimated from the recovery period.

204–209 m

The injection period indicates an intermediate between PLF and PRF from c 30 s to 700 s. After 700 s the derivative increases which is interpreted as an apparent NFB. The recovery only displays WBS and a transition to some other flow regime and no unambiguous transient evaluation of the period with a good fit is possible. Since the measurement noise with a zero flow was centred slightly below zero, the flow rate measurement limit as well as the flow data was manually elevated $3.95 \cdot 10^{-9}$ m^3/s.

209–214 m

Due to a drift in the gas pressure regulator the flow rate in the test section was affected and made the data from the injection period unstable. Still a PRF is indicated between c 200 and 1,000 s transitioning to an apparent NFB by the end of the injection period. The recovery period indicates an initial PLF transitioning to an apparent NFB after c 200 s. The Hurst-Clark-Brauer model assuming PRF for the injection period and a single fracture model for the recovery period give consistent results, hence the drift in the gas pressure regulator may not have affected the results significantly. The total recovery achieved was c 13 m of the applied injection head of c 20 m in this section which might indicate a flow feature of limited extension, i.e. decreasing fracture aperture away from the borehole. The transient evaluation from the injection period is considered as most representative for the section.

214–219 m

The injection period indicates a PLF transitioning towards a possible PRF. During the recovery period a PLF is dominating. No unambiguous transient evaluation was possible of the recovery period since the PLF do not display sufficient character. Hence, the transient evaluation from the injection period is considered most representative. The total recovery achieved was c 90 kPa of the applied injection head of c 200 kPa in this section which might indicate a flow feature of limited extension, i.e. decreasing fracture aperture away from the borehole.

219–224 m

The injection period indicates a PRF with a transition into an apparent NFB. During the recovery period a PLF with a transition into a possible PRF and then an apparent NFB is identified. The total recovery in this section, with rather high transmissivity, is only c 30 kPa, indicating a flow feature of limited extension, i.e. decreasing fracture aperture away from the borehole. The transient evaluation from the injection period was chosen as the representative for the section.

224–229 m (Pressure pulse test)

The period of measured recovery displayed a decreasing pressure and a steady-state evaluation as well as a transient evaluation was possible. The test does not seem to be strongly affected by packer compliance, and also the curve fitting is good. The stationary evaluation and the transient evaluation give consistent results and the transient evaluation is considered to give the most representative transmissivity value for this section.

229–234 m

"The period of measured recovery displayed a decreasing pressure. The transient evaluation does not converge when the whole period is used for curve fitting, but a manual fitting on the beginning of the recovery period is possible, providing a value of transmissivity in the same order of magnitude as the stationary evaluation. Since the transient evaluation is not unambiguous, the stationary evaluation has to be considered to provide the best estimate of T for the section. The pressure recovery displays an unusual behaviour; after c 26 minutes of recovery the pressure suddenly drops faster. This probably depends on a sudden small change in the properties of rock formation.

234–239 m

During the prognostic test the pressure increased c 10 kPa. According to Appendix 3 in the Quality plan an injection test was supposed to be performed if the pressure increase was less than 20 kPa, otherwise a pressure pulse test was supposed to be carried out. Still the test section had a very low transmissivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-05-032, the injection time was shortened. As a result TM, based on Q/s-measl-L, was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low transmissivity that packer expansion affects the pressure throughout the period.

239–244 m

During the injection period a possible PRF is indicated but is considered as uncertain. The recovery period indicates a PRF with a transition into a PSF. The transient evaluation on the recovery period was chosen as the most representative for the test section.

244–249 m

During both the injection and recovery period an intermediate flow regime PLF/PRF with a slightly increasing derivative is observed. Transient evaluation with models for PRF and PLF, respectively give similar results. Furthermore, the Hurst-Clark-Brauer PRF-model for the injection period and the Dougherty-Babu PRF-model for the recovery period give consistent results. Transient evaluation of the injection period was considered to give the most representative transmissivity value for this section.

249–254 m (Pressure pulse test)

The period of measured recovery displayed a decreasing pressure. No unambiguous transient evaluation was possible for this test. Hence, the transmissivity from the stationary evaluation is regarded as most representative for this section. The pressure recovers very slowly, and after c 18 minutes of recovery the pressure starts to increase slowly, indicating the transmissivity is so low that the packer expansion still affects the section. During the 40 min recovery period the pressure recovered only c 20 kPa out of the applied head change of c 220 kPa, also indicating a very low transmissivity.

254–259 m (Pressure pulse test)

The period of measured recovery displayed a decreasing pressure. The transient evaluation does not converge when the whole period is used for curve fitting, but a manual fitting on the beginning of the recovery period is possible, providing a value of transmissivity in the same order of magnitude as the stationary evaluation. Since the transient evaluation is not unambiguous, the stationary evaluation has to be considered to provide the best estimate of T for the section. The pressure decreases fast during the early part of the recovery period.

259–264 m

The flow rate is low, close to the measurement limit and hence the data, especially the flow derivative, is quite scattered. There was also a change in regulation valves after c 10 min into the test, making the pressure a bit unstable for a short while. Due to the scattered data it is difficult to evaluate the injection period. However, it seems like the injection period is dominated by a NFB which makes a transient evaluation of the period impossible. The recovery clearly shows a PLF throughout the period and no unambiguous transient evaluation is possible. Since no unambiguous transient evaluations were possible of either the injection or the recovery period, TM was considered to be the most representative transmissivity value for this section.

264–269 m

The injection pressure was rather unstable during this test and the transient evaluation is somewhat difficult to interpret. Still, the injection period seems to be dominated by a PRF from at least 500 s and throughout the period. It is possibly preceded by a PLF. The recovery period only displays a PLF and a possible short transition period to some other flow regime. Transient evaluations using the Hurst-Clark-Brauer model and the Ozkan-Raghavan model give consistent results for the injection period, while no unambiguous transient evaluation of the recovery period is possible.

269–274 m

The initial phase of both the injection and recovery period was dominated by a PLF. After c 200 s of the injection period and after c 400 s of the recovery period, the derivative decreases which may indicate a PSF. However, the Hantush model (assuming PSF) did not give any unambiguous evaluations of neither period. On the other hand, the Ozkan-Raghavan model gave consistent results for both periods. The injection pressure during this test was rather unstable but it did not affect the transient evaluations of the test. The transient evaluation of the injection period was chosen as the representative for the section.

274–279 m

Due to a malfunction in the test equipment the injection started about 80 seconds after the test valve had opened, but since the section had such large transmissivity this was not considered to affect the results of the test. A PRF may be interpreted from c 200 s to 500 s but it is rather uncertain due too the unstable injection pressure the first couple of minutes but still a PRF. From c 500 s and throughout the injection period, an apparent NFB seems to dominate. The recovery period displays two separate periods with rather different skin factors. Since there are uncertainties about the flow regime during the injection period, the transient evaluation of the early PRF during the recovery period was considered to give the most representative transmissivity value for this section.

279–284 m (Pressure pulse test)

The period of measured recovery displayed a decreasing pressure. The transient evaluation provides an apparently good curve fitting, but results in an unrealistic transmissivity value probably because of packer compliance. Hence, the transmissivity from the stationary evaluation is regarded as most representative for this section.

284–289 m (Pressure pulse test)

The period of measured recovery displayed a decreasing pressure and a steady-state evaluation as well as a transient evaluation was possible. The test does not seem to be strongly affected by packer compliance, and also the curve fitting is good. The stationary evaluation and the transient evaluation give consistent results and the transient evaluation is considered to give the most representative transmissivity value for this section. The applied pressure of c 220 kPa water column recovers almost completely.

289–294 m (Pressure pulse test)

The period of measured recovery displayed a decreasing pressure and a steady-state evaluation as well as a transient evaluation was possible. The test does not seem to be strongly affected by packer compliance, and also the curve fitting is good. The stationary evaluation and the transient evaluation give consistent results and the transient evaluation is considered to give the most representative transmissivity value for this section. The applied pressure of c 220 kPa water column recovers almost completely.

294–299 m

The flow rate is low, close to the measurement limit and hence the data, especially the flow derivative, is quite scattered. During the injection period a PLF indicated. However, no unambiguous transient evaluation can be made on the injection period. The recovery period only demonstrates a WBS and a transition to some other flow regime. It is possible to get a good fit with the Dougherty-Babu model during the recovery period. However, since the flow regime during the recovery period is not well developed, the transient evaluation is regarded to provide the best estimate of transmissivity. Since the measurement noise with a zero flow was centred slightly below zero, the flow rate measurement limit as well as the flow data was manually elevated $8.56 \cdot 10^{-10}$ m^3/s.

299–304 m

The flow rate is low, close to the measurement limit and hence the data, especially the flow derivative, is quite scattered. Still, the injection period is assumed to be dominated by a PRF. The recovery period demonstrates a WBS transitioning to a PRF. As the flow derivate during the injection period is very scattered and the recovery period displays a good type curve fit, the transient evaluation from the recovery period is considered most representative. Since the measurement noise with a zero flow was centred slightly below zero, the flow rate measurement limit as well as the flow data was manually elevated $1.48 \cdot 10^{-9}$ m^3/s.

404–409 m (Pressure pulse test)

The period of measured recovery displayed a decreasing pressure. No unambiguous transient evaluation was possible for this test. Hence, the transmissivity from the stationary evaluation is regarded as most representative for this section. The pressure recovers very slowly. During the 40 min recovery period the pressure recovered only c 20 kPa out of the applied head change of c 220 kPa, also indicating a very low transmissivity.

409–414 m

The injection period indicates a PLF transitioning to a PRF after c 700 s. The recovery only displays a PLF. Transient evaluations using the Hurst-Clark-Brauer model and the Ozkan-Raghavan model give consistent results for the injection period. An unambiguous transient evaluation of the recovery period is not possible.

414–419 m (Pressure pulse test)

The period of measured recovery only showed a pressure increase indicating that the section is of such low transmissivity that packer compliance affects the pressure throughout the period. Hence, in accordance with Appendix 3 in the Quality plan the recovery time was shortened. No transient evaluation was possible and the stationary evaluation was considered to give the most representative transmissivity value for this section.

419–424 m (Pressure pulse test)

The period of measured recovery only showed a pressure increase indicating that the section is of such low transmissivity that packer compliance affects the pressure throughout the period. Hence, in accordance with Appendix 3 in the Quality plan the recovery time was shortened. No transient evaluation was possible and the stationary evaluation was considered to give the most representative transmissivity value for this section. Unfortunately, the change of test phases was not correctly performed. The consequence was that the scanning interval was much lower than usual during the pulse and following recovery.

444–449 m (Pressure pulse test)

The period of measured recovery only showed a pressure increase indicating that the section is of such low transmissivity that packer compliance affects the pressure throughout the period. Hence, in accordance with Appendix 3 in the Quality plan the recovery time was shortened. No transient evaluation was possible and the stationary evaluation was considered to give the most representative transmissivity value for this section.

449–454 m

The injection period only indicates an apparent NFB and no unambiguous transient evaluation of the injection period is possible. On the other hand, the recovery displays a clear PRF from c 100 s, preceded by a PLF. A transient evaluation using the Dougherty-Babu model for the recovery period and the steady-state evaluation give consistent results.

454–459 m

Both the injection and recovery period displays an early PRF followed by an increasing derivative. The injection period also indicates a later PRF while the recovery does not display any such flow regime. The Hurst-Clark-Brauer model for the injection period and the Dougherty-Babu model for the recovery period give very similar results for the early PRF. Since the measurement noise with a zero flow was centred slightly below zero, the flow rate measurement limit as well as the flow data were manually elevated $2 \cdot 10^{-9}$ m^3/s.

459–464 m

Both the injection and recovery period demonstrates a short PRF followed by an apparent NFB. Transient evaluation of both periods with a PRF model gives similar results. The transient evaluation of the recovery period is regarded as the most representative for the section since the PRF is clearer during the recovery than during the injection period. Still, the transient evaluation of the injection period supports the recovery evaluation.

464–469 m (Pressure pulse test)

The period of measured recovery only showed a pressure increase indicating that the section is of such low transmissivity that packer compliance affects the pressure throughout the period. Hence, in accordance with Appendix 3 in the Quality plan the recovery time was shortened. No transient evaluation was possible and the stationary evaluation was considered to give the most representative transmissivity value for this section.

469–474 m (Pressure pulse test)

The period of measured recovery only showed a pressure increase indicating that the section is of such low transmissivity that packer compliance affects the pressure throughout the period. Hence, in accordance with Appendix 3 in the Quality plan the recovery time was shortened. No transient evaluation was possible and the stationary evaluation was considered to give the most representative transmissivity value for this section.

474–479 m (Pressure pulse test)

The period of measured recovery only showed a pressure increase indicating that the section is of such low transmissivity that packer compliance affects the pressure throughout the period. Hence, in accordance with Appendix 3 in the Quality plan the recovery time was shortened. No transient evaluation was possible and the stationary evaluation was considered to give the most representative transmissivity value for this section.

479–484 m

The injection period indicates a PRF with a transition into a NFB. The recovery only displays an apparent NFB and no transient evaluation of the period is possible.

684–689 m

Both the injection and recovery periods indicate a PRF transitioning to an apparent NFB. However, the PRF during the injection period is rather short and considered as uncertain. Hence, the transient evaluation from the recovery period is regarded as the most representative.

689–694 m (Pressure pulse test)

The period of measured recovery displayed a decreasing pressure. The transient evaluation provides an apparently good curve fitting, but results in an unrealistic transmissivity value probably because of packer compliance. Hence, the transmissivity from the stationary evaluation is regarded as most representative for this section.

694–699 m (Pressure pulse test)

The period of measured recovery only showed a pressure increase indicating that the section is of such low transmissivity that packer compliance affects the pressure throughout the period. Hence, in accordance with Appendix 3 in the Quality plan the recovery time was shortened. No transient evaluation was possible and the stationary evaluation was considered to give the most representative transmissivity value for this section.

699–704 m (Pressure pulse test)

The period of measured recovery only showed a pressure increase indicating that the section is of such low transmissivity that packer compliance affects the pressure throughout the period. Hence, in accordance with Appendix 3 in the Quality plan the recovery time was shortened.

No transient evaluation was possible and the stationary evaluation was considered to give the most representative transmissivity value for this section.

784–789 m (Pressure pulse test)

The period of measured recovery displayed a decreasing pressure. No unambiguous transient evaluation was possible for this test. Hence, the transmissivity from the stationary evaluation is regarded as most representative for this section.

789–794 m (Pressure pulse test)

The period of measured recovery displayed a decreasing pressure. No unambiguous transient evaluation was possible for this test. Hence, the transmissivity from the stationary evaluation is regarded as most representative for this section. The pressure recovery is very slow during the last 20 minutes. The pressure recovered only c 40 kPa from the applied head change of c 210 kPa applied.

794–799 m

The injection period seems to display two separate periods of PRF. However, the first PRF is considered as uncertain. A second approximate PRF starts at c 100 s and is assumed to continue throughout the period although there are some variations of the flow rate curve. The recovery indicates initial WBS followed by a short PRF. By the end there are weak indications of an apparent NFB. The transient evaluation on the injection period is selected as the most representative for the test section.

799–804 m (Pressure pulse test)

The period of measured recovery displayed a decreasing pressure. No unambiguous transient evaluation was possible for this test. Hence, the transmissivity from the stationary evaluation is regarded as most representative for this section. In total the pressure recovered only c 30 kPa from the applied head change of c 210 kPa applied. Almost all the pressure recovery takes place during the first 10 minutes of the recovery period. Possibly, this result in an overestimation of the transmissivity since the evaluation is made on these first 10 minutes.

6.2.5 Flow regimes

A summary of the frequency of identified flow regimes on different scales is presented in Table 6-4, 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 parenthesis 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 just based on visual inspection of the data curves. It should also be observed that the number of tests with a pseudo-linear flow regime during the beginning of the injection period may be underestimated due to the fact that a certain time is required for achieving a constant pressure, which fact may mask the initial flow regime.

No flow regimes have been identified for the pressure pulse tests; hence Table 6-4 is only valid for the injection tests.

Table 6-4. Interpreted flow regimes during the injection tests in KFM08A.

Section length (m)	Number of tests	Borehole interval (m)	Number of tests with definable Qp	Injection period					Recovery period					
				PLF	PRF	PSF	PSS	NFB	WBS	PLF	PRF	PSF	PSS	NFB
5	38	104–804	36	10(3)	22(8)	2(0)	2(0)	18(8)	11(3)	16(8)	20(2)	3(1)	0(0)	12(1)
20	15	104–984	15	6(2)	9(2)	2(0)	0(0)	8(2)	5(1)	6(3)	8(1)	3(0)	0(0)	7(0)
100	9	104–989	8	3(2)	5(0)	3(1)	0(0)	2(0)	3(3)	3(2)	3(1)	0(0)	0(0)	2(0)

Table 6-4 shows that a certain period of pseudo-radial flow could be identified from the injection period in c 61% of the tests with a definable final flow rate for KFM08A. This percentage is higher for the tests in 100 m sections compared to the tests in 20 m and 5 m. For the recovery period, the corresponding result is c 56%. It should be observed that the measured borehole intervals with 5 m, 20 m and 100 m sections are slightly different in KFM08A, see Table 6-4. Noticeable is also that apparent NFB occurs rather often compared to previously measured boreholes in Forsmark, e.g. KFM03A /14/, KFM04A /15/ and KFM06A /16/.

For c 53% of the tests in the borehole, more than one flow regime could be identified. The most common transitions in KFM08A during the injection and recovery period were from PRF to NFB. During the injection period transitions from PRF1 to PRF2 and from PRF to PSF were also quite common. During the recovery period transitions from WBS to PRF and PLF to PRF appeared rather frequently as well.

6.3 Comparison of transmissivity values on different test scales

The transmissivity values as considered the most representative, T_R, from the injection and pressure pulse tests in KFM08A in the tested sections of 100 m, 20 m and 5 m length, respectively, are shown in Figure 6-2. This figure demonstrates a good agreement between results obtained from tests on different scales in KFM08A. A consistency check of the transmissivity values on the different scales was made by summation of calculated values from smaller scales (20 m and 5 m) and comparing with the estimated values in longer sections (100 m and 20 m). The total transmissivity of KFM08A is dominated by the intervals between 184.0–199.0 m, 274.0–279.0 m and 684.0–689.0 m.

In Table 6-5, estimated transmissivity values in 100 m and 20 m test sections in KFM08A according to steady-state (T_M) and most representative evaluation (T_R) are listed together with summed transmissivities in 20 m and 5 m sections over the corresponding 100 m and 20 m sections. Also, the corresponding sum of transmissivity values from the difference flow logging in 5 m sections is shown. When the transmissivity values are below the measurement limit (Q_p could not be defined), the most representative transmissivity value, T_R, was considered to be less than T_M, based on Q/s-measl-L, for the test section. The measurement limit values are included in the summed values in Table 6-5. This leads to overestimated values of the summed transmissivities.

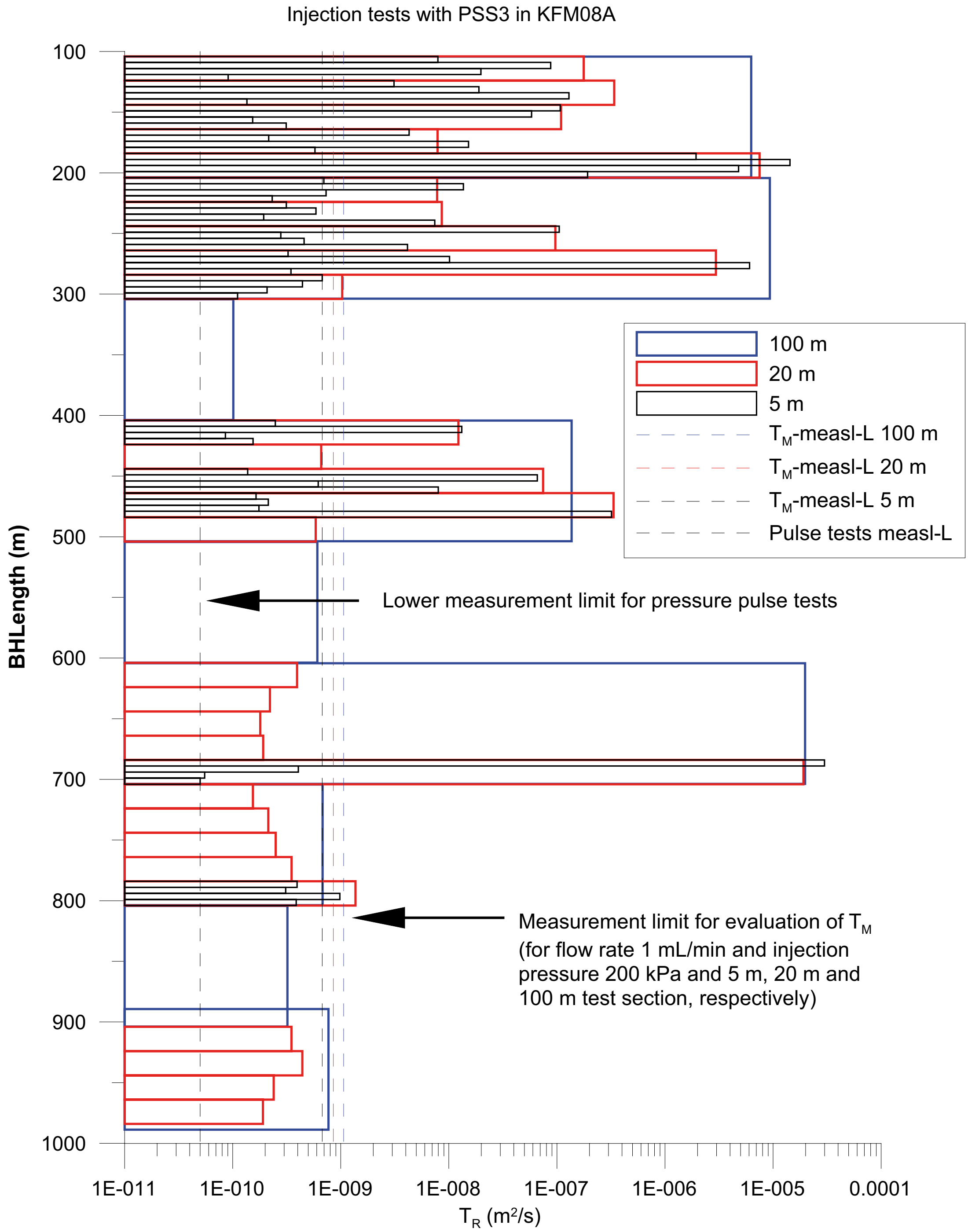

Figure 6-2. *Estimated best representative transmissivity values (T_R and $T_{R, pulse}$) from both injection tests and pressure pulse tests for sections of 100 m, 20 m and 5 m length in borehole KFM08A. Estimated transmissivity values for the lower standard measurement limit from stationary evaluation (T_M-measl-L) for different test section lengths are also shown together with the practical lower measurement limit for pressure pulse tests.*

Table 6-5. Estimated transmissivity values in 100 m and 20 m test sections together with summed up transmissivity values in 20 m and 5 m sections in the corresponding borehole intervals from the injection and pressure pulse tests in KFM08A. In addition, the corresponding sum of transmissivity values from the difference flow logging in 5 m sections is shown.

Borehole Idcode	Secup inj/pulse (m)	Seclow inj/pulse (m)	L_w (m)	T_M inj. tests (m^2/ s)	T_R inj/pulse (m^2/s)	SUM T_M (20 m) inj. tests (m^2/s)	SUM T_R (20 m) inj/pulse (m^2/s)	SUM T_M (5 m) inj. tests (m^2/s)	SUM T_R (5 m) inj/pulse (m^2/s)	Secup diff-flow log (m)	Seclow diff-flow log (m)	SUM-T_D (5 m) diff-flow log (m^2/s)
KFM08A	104.00	204.00	100.00	2.10E–05	6.28E–06	1.92E–05	8.13E–06	2.58E–05	2.17E–05	104.63	204.81	4.40E–06
KFM08A	204.00	304.00	100.00	1.28E–05	9.33E–06	1.10E–05	3.08E–06	8.97E–06	6.22E–06	204.81	304.97	1.56E–06
KFM08A	304.00	404.00	100.00	7.65E–10	1.01E–10	n.m. 20 m	n.m. 20 m	n.m. 5 m	n.m. 5 m	304.98	405.13	1.69E–08
KFM08A	404.00	504.00	100.00	5.38E–07	1.37E–07	4.48E–07	4.22E–07	3.51E–07	4.09E–07	405.14	505.21	1.13E–07
KFM08A	504.00	604.00	100.00	6.08E–10	6.08E–10	n.m. 20 m	n.m. 20 m	n.m. 5 m	n.m. 5 m	505.22	605.38	1.68E–08
KFM08A	604.00	704.00	100.00	1.98E–05	1.98E–05	1.91E–05	1.91E–05	1.45E–05	2.99E–05	605.39	705.58	1.93E–06
KFM08A	704.00	804.00	100.00	2.80E–09	6.78E–10	2.48E–09	2.34E–09	2.15E–09	2.07E–09	705.58	805.68	1.68E–08
KFM08A	804.00	904.00	100.00	< 3.21E–10[1)]	< 3.21E–10[1)]	n.m. 20 m	n.m. 20 m	n.m. 5 m	n.m. 5 m	805.68	905.82	1.67E–08
KFM08A	889.00	989.00	100.00	3.70E–09[1)]	7.70E–10[1)]	n.m. 20 m	1.22E–09[2)]	n.m. 5 m	n.m. 5 m	890.80	915.83	1.65E–09
KFM08A	104.00	124.00	20.00	1.41E–07	1.77E–07			1.21E–07	1.15E–07	104.63	124.66	1.16E–08
KFM08A	124.00	144.00	20.00	3.39E–07	3.39E–07			3.14E–07	1.52E–07	124.67	144.70	2.87E–08
KFM08A	144.00	164.00	20.00	1.58E–07	1.09E–07			1.18E–07	1.66E–07	144.71	164.73	6.53E–09
KFM08A	164.00	184.00	20.00	1.39E–08	7.87E–09			1.14E–08	2.03E–08	164.74	184.77	3.40E–09
KFM08A	184.00	204.00	20.00	1.86E–05	7.50E–06			2.53E–05	2.12E–05	184.78	204.81	4.35E–06
KFM08A	204.00	224.00	20.00	1.46E–08	7.80E–09			2.98E–08	1.53E–08	204.81	224.84	3.21E–09
KFM08A	224.00	244.00	20.00	1.52E–08	8.60E–09			1.19E–08	7.13E–09	224.85	244.88	2.97E–09
KFM08A	244.00	264.00	20.00	2.34E–07	9.67E–08			1.92E–07	1.10E–07	244.89	264.91	2.57E–08
KFM08A	264.00	284.00	20.00	1.07E–05	2.96E–06			8.73E–06	6.08E–06	264.91	284.93	1.52E–06
KFM08A	284.00	304.00	20.00	2.50E–09	1.03E–09			4.37E–10	1.43E–09	284.94	304.97	3.39E–09
KFM08A	404.00	424.00	20.00	1.11E–07	1.23E–08			8.78E–08	1.37E–08	405.14	425.16	1.65E–08
KFM08A	424.00	444.00	20.00	–	6.58E–10			n.m. 5 m	n.m. 5 m	425.16	445.16	2.92E–09
KFM08A	444.00	464.00	20.00	9.28E–08	7.45E–08			7.53E–08	7.46E–08	445.16	465.16	4.44E–09
KFM08A	464.00	484.00	20.00	2.44E–07	3.34E–07			1.88E–07	3.20E–07	465.16	485.16	8.56E–08
KFM08A	484.00	504.00	20.00	–	5.88E–10			n.m. 5 m	n.m. 5 m	485.17	505.21	3.38E–09

Borehole Idcode	Secup inj/pulse (m)	Seclow inj/pulse (m)	L_w (m)	T_M inj. tests (m^2/ s)	T_R inj/pulse (m^2/s)	SUM T_M (20 m) inj. tests (m^2/s)	SUM T_R (20 m) inj/pulse (m^2/s)	SUM T_M (5 m) inj. tests (m^2/s)	SUM T_R (5 m) inj/pulse (m^2/s)	Secup diff-flow log (m)	Seclow diff-flow log (m)	SUM-T_D (5 m) diff-flow log (m^2/s)
KFM08A	604.00	624.00	20.00	–	3.94E–10			n.m. 5 m	n.m. 5 m	605.39	625.42	3.35E–09
KFM08A	624.00	644.00	20.00	–	2.22E–10			n.m. 5 m	n.m. 5 m	625.42	645.44	3.36E–09
KFM08A	644.00	664.00	20.00	–	1.80E–10			n.m. 5 m	n.m. 5 m	645.45	665.47	3.36E–09
KFM08A	664.00	684.00	20.00	–	1.92E–10			n.m. 5 m	n.m. 5 m	665.48	685.50	3.36E–09
KFM08A	684.00	704.00	20.00	1.91E–05	1.91E–05			1.45E–05	2.99E–05	685.51	705.58	1.91E–06
KFM08A	704.00	724.00	20.00	–	1.54E–10			n.m. 5 m	n.m. 5 m	705.58	725.56	3.37E–09
KFM08A	724.00	744.00	20.00	–	2.14E–10			n.m. 5 m	n.m. 5 m	725.56	745.57	3.37E–09
KFM08A	744.00	764.00	20.00	–	2.50E–10			n.m. 5 m	n.m. 5 m	745.58	765.60	3.37E–09
KFM08A	764.00	784.00	20.00	–	3.51E–10			n.m. 5 m	n.m. 5 m	765.61	785.64	3.37E–09
KFM08A	784.00	804.00	20.00	2.48E–09	1.37E–09			2.15E–09	2.07E–09	785.65	805.68	3.36E–09
KFM08A	904.00	924.00	20.00	–	3.50E–10			n.m. 5 m	n.m. 5 m	905.83	915.83	1.65E–09
KFM08A	924.00	944.00	20.00	–	4.40E–10			n.m. 5 m	n.m. 5 m			
KFM08A	944.00	964.00	20.00	–	2.39E–10			n.m. 5 m	n.m. 5 m			
KFM08A	964.00	984.00	20.00	–	1.90E–10			n.m. 5 m	n.m. 5 m			

1) Partly overlapping sections.

2) Measured intervals not identical.

n.m. = not measured.

In Figure 6-3, transmissivity values considered as the most representative for 100 m and 20 m sections (T_R-100 m and T_R-20 m, respectively) in KFM08A are plotted versus the sum of the transmissivity values considered most representative in 5 m sections in the corresponding intervals (SUM T_R-5 m). The lower measurement limit of T_M for the different section lengths (Q_p = 1 mL/min and an assumed pressure difference of 200 kPa) together with the cumulative measurement limit for the sum of 5 m sections are also shown in the figure.

Figure 6-3 indicates a good agreement between estimated transmissivity values in longer sections and summed transmissivity values in corresponding 5 m sections for the injection tests. However, a weak tendency that the data points are located slightly below the straight line may be noticed. This indicates that the sum of the transmissivity from the shorter sections is generally slightly higher than the estimated transmissivity in longer sections. Hydraulic interference between adjacent sections may contribute to an overestimation of the sum of transmissivity when summing the transmissivity from several sections together. Since also the measurement limit values are summed up, the sum of transmissivity in shorter sections can become higher than the estimated transmissivity value in the longer section for very low-conductive sections. There might also be other reasons for discrepancies. Interference between adjacent sections are noticed in the 5 m sections at 184.0–189.0 m, 189.0–194.0 m and 194.0–199.0 m, all within the same 20 m section 184.0–204.0 m.

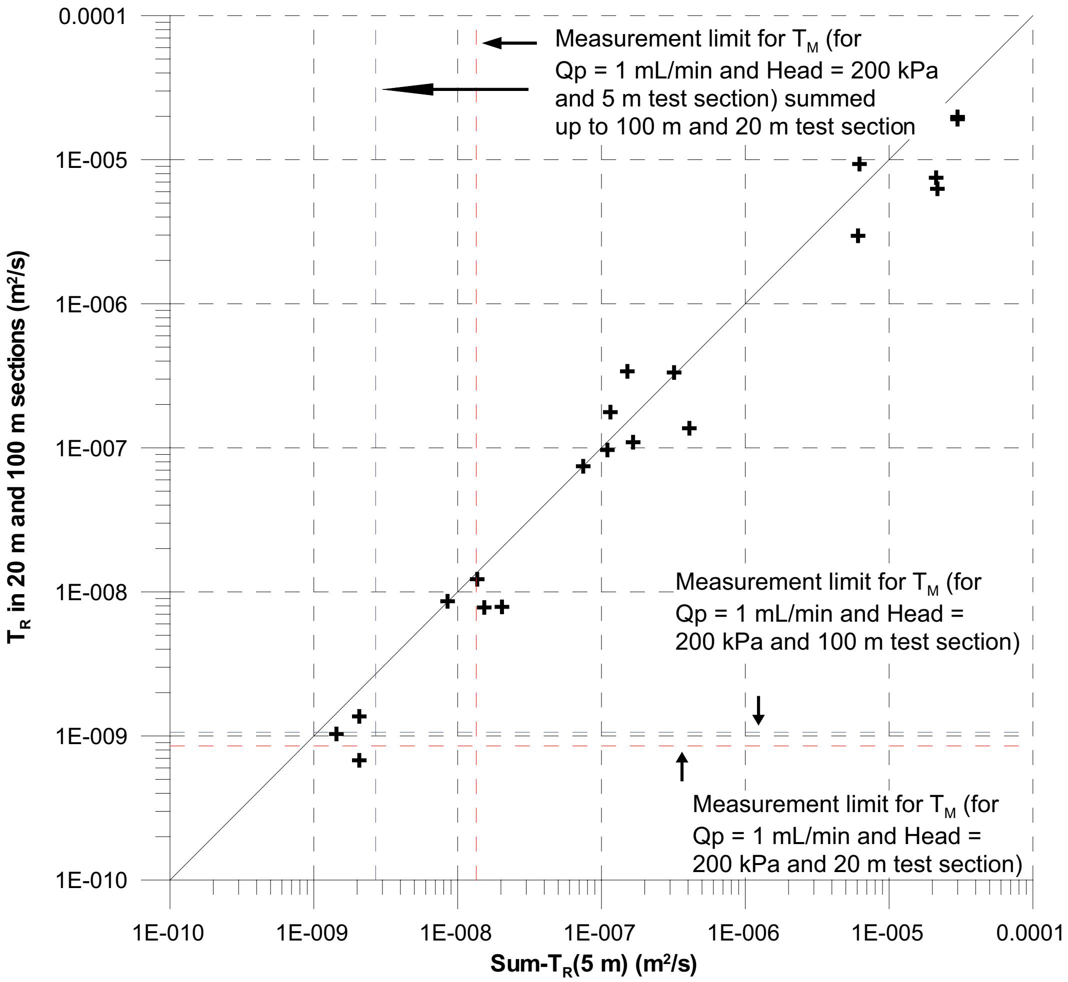

Figure 6-3. *Transmissivity values considered most representative (T_R and $T_{R,\,pulse}$) for 100 m and 20 m sections versus the sum of most representative transmissivity values (T_R and $T_{R,\,pulse}$) in 5 m sections in the corresponding borehole intervals from the injection tests in KFM08A together with the standard lower measurement limit at different scales.*

6.4 Comparison with results from the difference flow logging in KFM08A

As discussed in section 3.2, the position of the upper and lower limits of the measured sections for the injection tests and the difference flow logging deviated up to 1.82 m in KFM08A. In order to compare sections deviating more than 0.5 m in a correct way the results from the difference flow logging was used. The inferred position of the dominating flow anomaly in the actual section was utilized to decide which of two possible sections to be used in the comparison.

Figure 6-4 shows a comparison of the calculated steady-state (T_M) and most representative transmissivity (T_R) from the injection tests in 5 m sections with the calculated transmissivity values in the corresponding 5 m sections from the difference flow logging (T_D) in KFM08A. In Figure 6-5, T_R and T_D are plotted versus borehole length. The presented measurement limit for the difference flow logging is the practical lower measurement limit (varying along the borehole) in KFM08A which for most sections was approximately $8.4 \cdot 10^{-10}$ m²/s, cf Figure 6-5. This limit is higher than the corresponding test-specific measurement limit for the injection tests in KFM08A, cf Table 6-2. This is clearly seen in Figure 6-4 as a difference between T_D, T_M and T_R, respectively, for low transmissivity values.

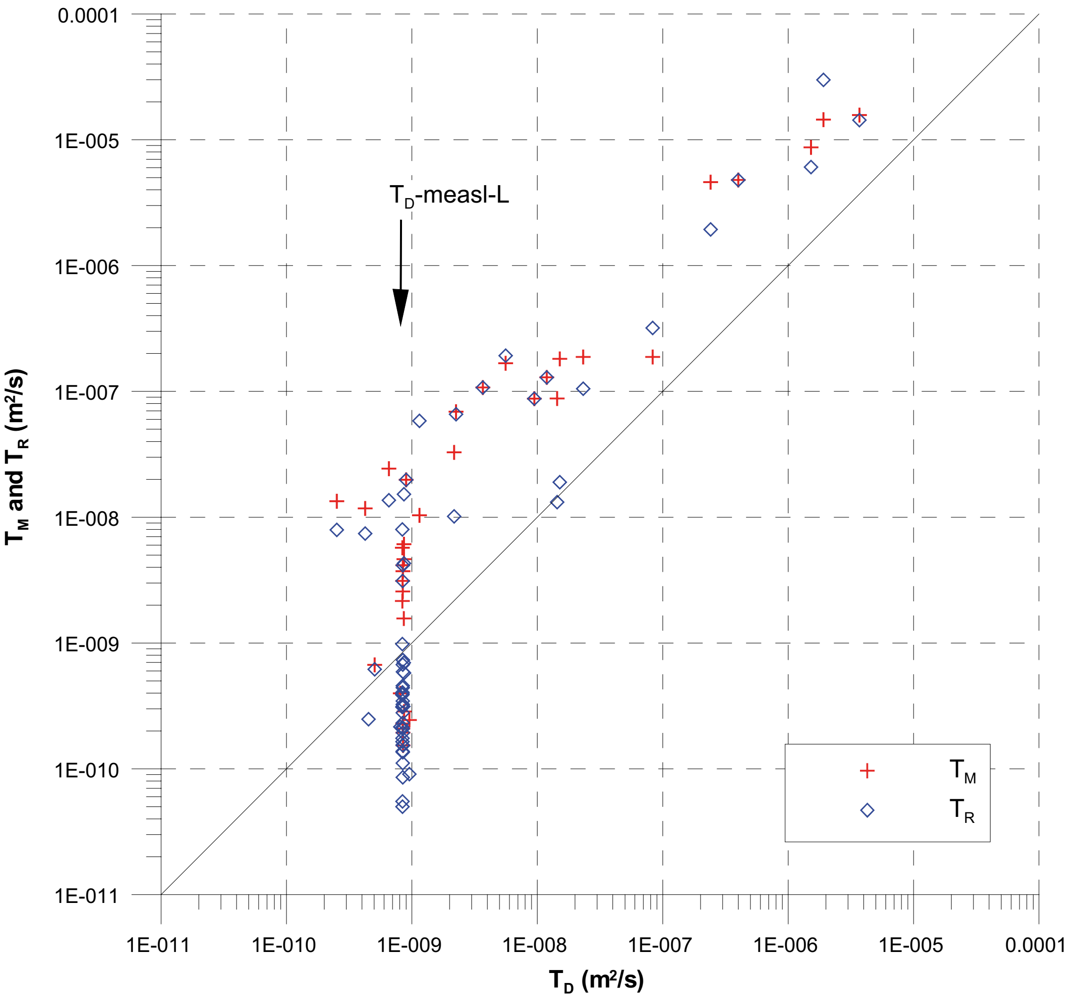

Figure 6-4. *Comparison of estimated steady-state (T_M) from the injection tests and most representative (T_R) transmissivity values from the injection and pressure pulse tests in 5 m sections with estimated transmissivity values in the corresponding 5 m sections from the previous difference flow logging (T_D) in KFM08A.*

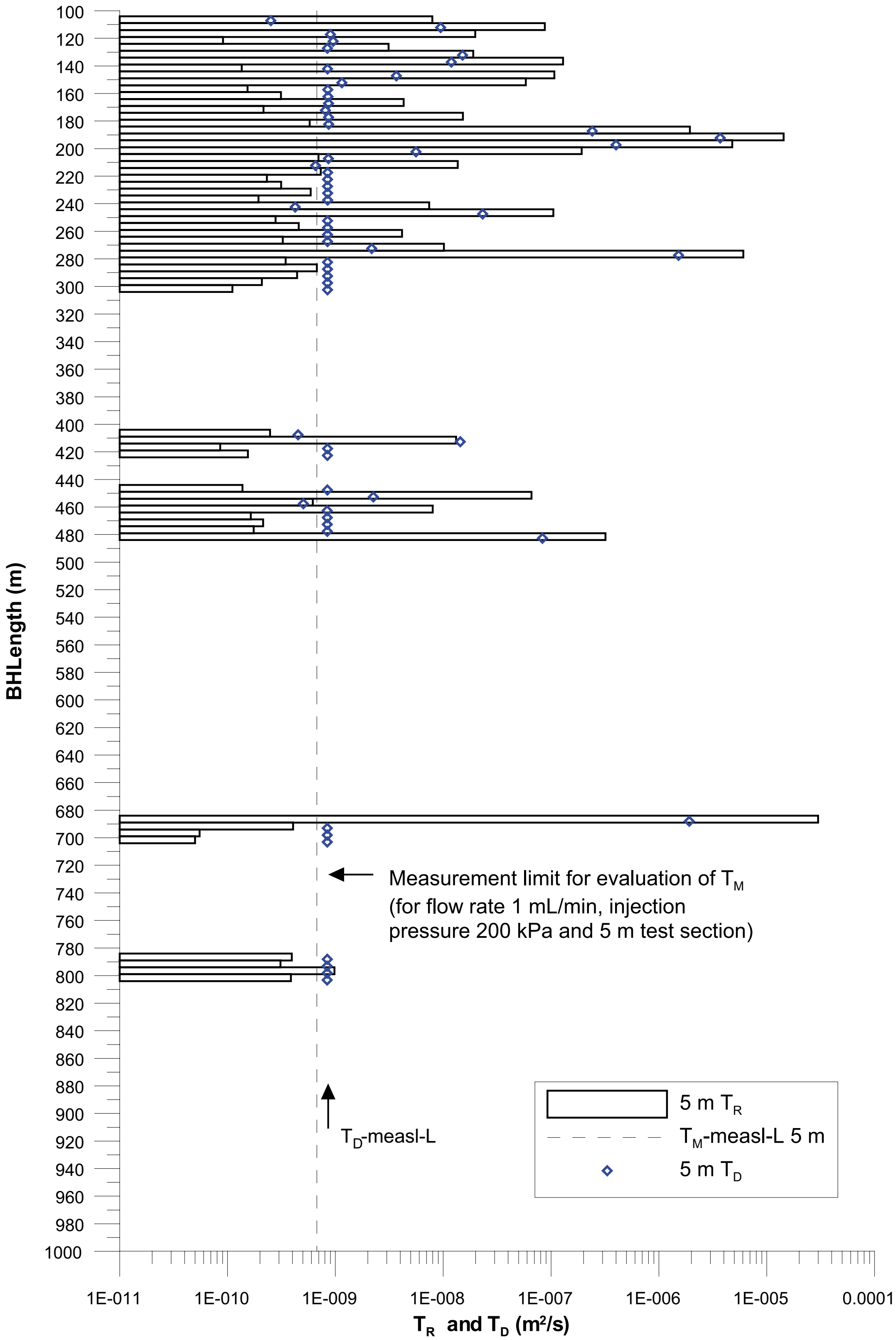

Figure 6-5. *Comparison of most representative (T_R) transmissivity values from the injection and pressure pulse tests in 5 m sections with estimated transmissivity values in the corresponding 5 m sections from the previous difference flow logging (T_D) in KFM08A.*

Figure 6-6 shows a comparison of the estimated steady-state transmissivity values from the injection tests in 100 m and 20 m test sections with summed transmissivity values for 5 m sections from the difference flow logging (SUM T_D(5 m)) in the corresponding borehole intervals. The latter sums are shown in Table 6-4. Figure 6-6 shows that the estimated transmissivity values from the injection tests in 100 m and 20 m sections are distributed over a much wider range than the sum of transmissivity values from the difference flow logging. This is partly a result of the lower measurement limit values being included in the sum for the difference flow logging. In Figure 6-7, T_R and SUM T_D(5 m) are plotted versus the borehole length for the injection test intervals in 20 m and 100 m sections.

Figures 6-4, 6-5, 6-6 and 6-7 show that the injection and pressure pulse tests results generally reveal higher estimated transmissivities than the results from the difference flow logging. This fact has also been observed in a few other boreholes in Forsmark, however not to this degree, cf /14, 15/ and /16/. For the difference flow logging, the preceding flow period in the borehole before the flow measurements was much longer than the short flow period for the injection tests. Therefore, the difference flow logging is assumed to predominantly measure interconnected, conductive fracture networks reaching further away from the borehole while the injection tests also may sample fractures with limited extension, close to the borehole. This fact may possibly explain the significantly higher T_R from the injection tests than T_D from difference flow logging

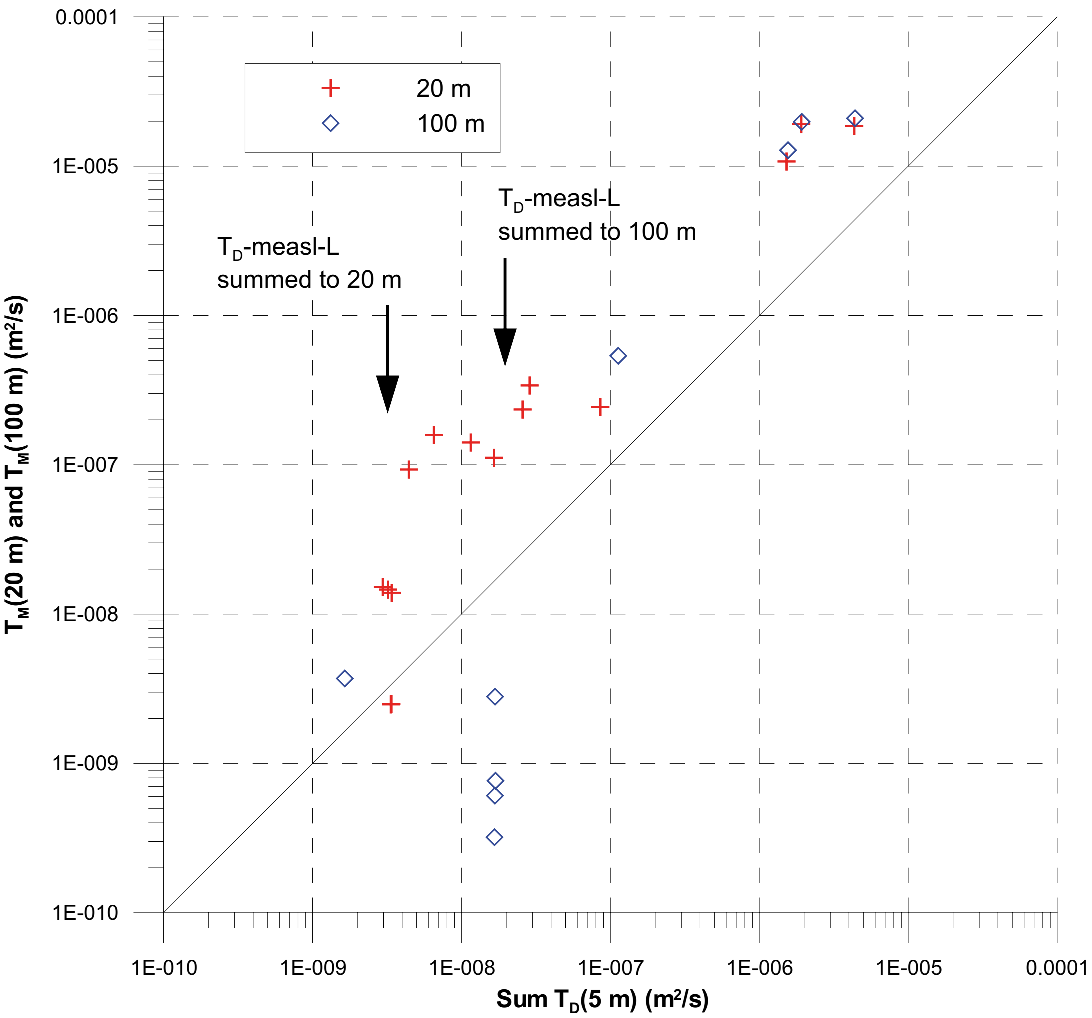

***Figure 6-6.** Comparison of estimated steady-state transmissivity values from injection and pressure pulse tests in 20 m and 100 m sections with summed transmissivity values in 5 m sections in the corresponding borehole intervals from difference flow logging in KFM08A.*

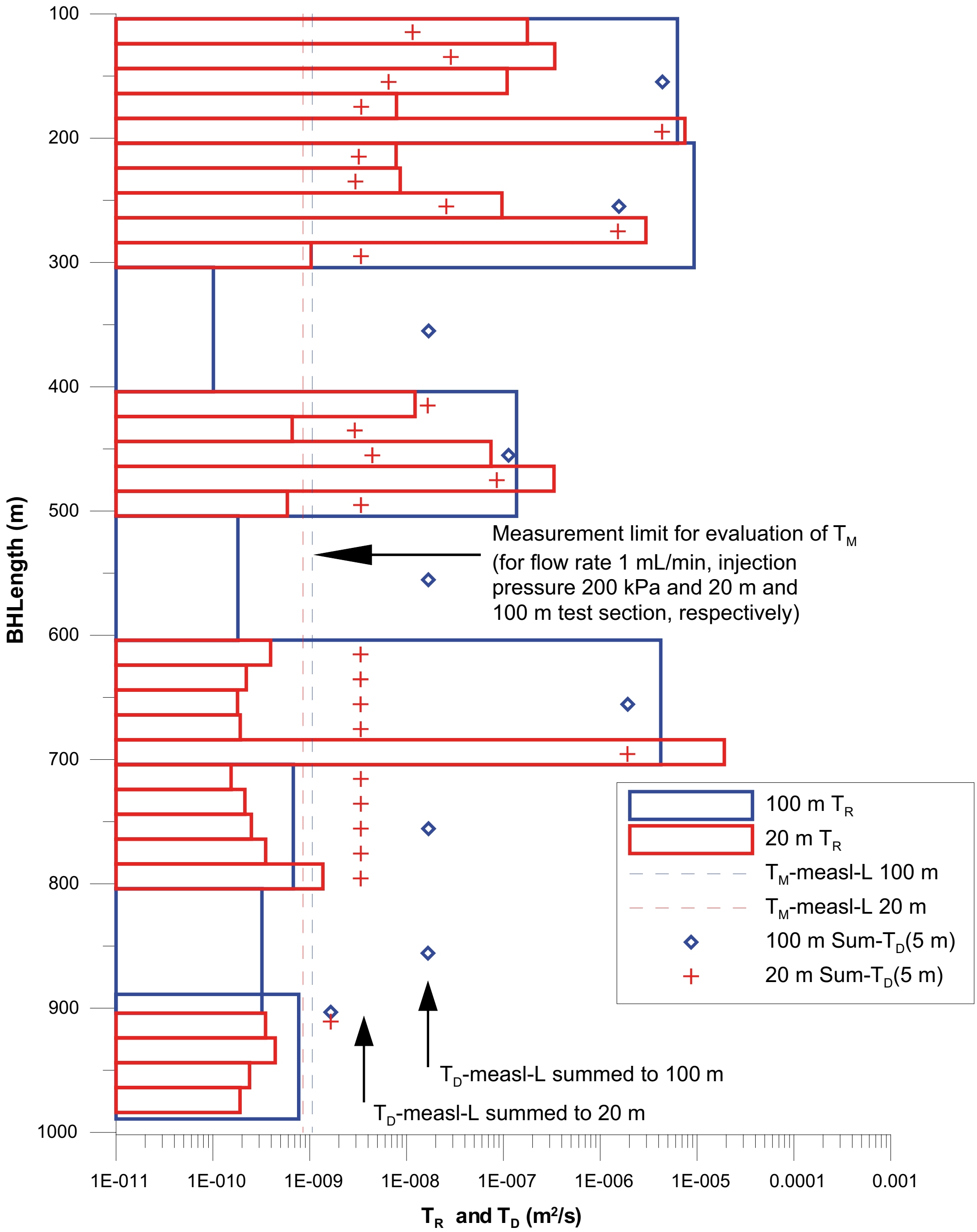

Figure 6-7. Comparison of most representative (TR) transmissivity values from injection and pressure pulse tests in 20 m and 100 m sections with summed transmissivity values in 5 m sections in the corresponding borehole intervals from difference flow logging in KFM08A.

in some sections, assuming that the fractures in these sections are of limited extent or with decreasing aperture away from the borehole and not connected to a larger fracture network. Thus, the transmissivity of such fractures is assumed to decrease with increasing flow times, eventually reflected by effects of apparent no-flow boundaries during the injection tests. As mentioned in Section 6.2.5, apparent no-flow boundaries were observed more frequently in KFM08A than in previously measured boreholes in Forsmark. However, during short injection tests, such effects may not always be seen. It should also be noted that the two methods differ regarding assumptions and associated uncertainties. Potential uncertainties for difference flow logging results are discussed in Ludvigson et al. (2002) /17/ and for injection tests in Andersson et al. (1993) /18/.

6.5 Basic statistics of hydraulic conductivity distributions in different scales

Some basic statistical parameters were derived for the hydraulic conductivity considered most representative (K_R) in different scales (100 m, 20 m and 5 m) including all tests, both injection- and pressure pulse tests in borehole KFM08A. The hydraulic conductivity is obtained by dividing the transmissivity by the section length, T_R/L_w. Results from tests where Q_p was below the estimated test-specific measurement limit were not included in the statistical analyses of K_R. In which the logarithm (base 10) of K_R was used. Selected results are shown in Table 6-6. It should be noted that the statistics for the different section lengths is based on different borehole intervals.

6.6 Comparison of results from different hydraulic tests in KFM08A

In Table 6-7 a comparison of the sum of estimated transmissivity values from different hydraulic tests with different section lengths in KFM08A is presented. It should be observed that the summed transmissivity values only include the tests actually performed for each section length. However, the most conductive sections are measured. It is also important to point out that this is a very rough way of comparing the tests in different test scales, since no consideration to overlapping sections are made. The tendency that the sum of transmissivities from shorter sections is higher than the transmissivity in the corresponding longer section can however be seen between 100 m and 20 m sections on T_R in Table 6-7.

Table 6-7 shows that the transmissivity evaluated from the difference flow logging is about 10 times lower than the transmissivity evaluated from the injection tests, see Section 6.4.

T_M values are only calculated for the injection tests; hence the sum of T_M does not include sections where pressure pulse tests were performed. However, in the sum of transmissivity values, the pressure pulse tests are insignificant.

Table 6-6. Basic statistical parameters for hydraulic conductivity considered most representative (K_R) in borehole KFM08A. L_w = section length, m = arithmetic mean, s = standard deviation.

Parameter	Unit	KFM08A L_w = 100 m	KFM08A L_w = 20 m	KFM08A L_w = 5 m
Measured borehole interval	M	104.0–989.0[2)]	104.0–984.0[3)]	104.0–804.0[4)]
Number of tests	–	9	29	60
N:o of tests below E.L.M.L.[1)]	–	1	9	6
m (Log10(KR))	Log10(m/s)	–9.64	–9.57139536	–9.2548875
s (Log10(KR))	–	2.18	1.55526848	1.4588482

[1)] Number of tests where Q_p could not be defined (E.L.M.L. = estimated test-specific lower measurement limit).

[2)] Sections 804.0–904.0 m and 889.0–989.0 m are partly overlapping.

[3)] Sections with very low or non-detectable flow (with 100 m section length) are not measured with 20 m section length.

[4)] Sections with very low or non-detectable flow (with 20 m section length) are not measured with 5 m section length.

Table 6-7. Comparison of calculated transmissivity values from different hydraulic tests in borehole KFM08A.

Hydraulic test method		Sum of T (m^2/s)
Injection tests	$\sum T_M$(100 m)[1)]	5.41E–05
	$\sum T_R$(100 m)[1)]	3.56E–05
	$\sum T_M$(20 m)[2)]	4.98E–05
	$\sum T_R$(20 m)[2)]	3.07E–05
	$\sum T_M$(5 m)[3)]	4.96E–05
	$\sum T_R$(5 m)[3)]	5.83E–05
Difference flow logging	$\sum T_D$(5 m)	8.07E–06
	$\sum T_{Df}$ (flow anomalies)	1.43E–06
Pumping test in conjunction with difference flow logging	T_M[4)]	8.26E–06
	T_R[4)]	4.79E–06

[1)] Measured interval contains partly overlapping sections.

[2)] Actual measured intervals were 104.0–304.0, 404.0–504.0, 604.0–804.0 and 904.0–984.0 m.

[3)] Actual measured intervals were 104.0–304.0, 404.0–424.0, 444.0–484.0, 684.0–704.0 and 784.0–804.0 m.

[4)] Actual measured intervals were 94.6–915.83 m.

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