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Site investigation SFR

Difference flow logging in boreholes KFR101 and KFR27

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PRG-Tec Oy

September 2008

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Abstract

The Posiva Flow Log/Difference flow method (PFL DIFF) uses a flowmeter that incorporates a flow guide and can be used for relatively quick determinations of hydraulic conductivity and hydraulic head in fractures/fractured zones in cored boreholes. This report presents the main principles of the methods as well as the results of measurements carried out in boreholes KFR101 and KFR27 at Forsmark, Sweden, in July and August 2008.

The first flow logging measurements were done with a 5 m test section by moving the measurement tool in 0.5 m steps. This method was used to flow log the entire measurable part of the borehole during natural (un-pumped) as well as pumped conditions. The flow measurements in pumped conditions were repeated in borehole KFR101, at the location of detected flow anomalies using a 1 m long test section, which was moved in 0.1 m steps.

Length calibration was made in borehole KFR101 based on length marks milled into the borehole wall at accurately determined positions along the borehole. The length marks were detected by caliper measurements and by single-point resistance (SPR) measurements using the SPR sensor of the flow logging tool. No length calibrations were made in borehole KFR27 since there are no length marks milled into the borehole wall.

A high-resolution absolute pressure sensor was used to measure the absolute total pressure along the borehole. These measurements were carried out together with the flow measurements.

The electrical conductivity (EC) and temperature of borehole water were also measured. The EC measurements were used to study the occurrence of saline water in the borehole during natural as well as pumped conditions. The EC of fracture-specific water was measured only in borehole KFR101 (1 m test section) for a selection of fractures.

The recovery of the groundwater level in the borehole was measured after the pumping of the borehole was stopped.

Sammanfattning

Posiva Flow Log/Differensflödesloggning (PFL DIFF) är en snabb metod för bestämning av transmissiviteten och hydraulisk tryckhöjd i borrhålssektioner och sprickor/sprickzoner i kärnborrhål. Denna rapport presenterar huvudprinciperna för metoden och resultat av mätningar utförda i borrhål KFR101 och KFR27 i Forsmark, Sverige, i juli och augusti 2008.

Flödet till eller från en 5 m lång testsektion (som förflyttades successivt med 0,5 m) mättes i borrhålet under såväl naturliga (icke-pumpade) som pumpade förhållanden. Flödesmätningarna upprepades under pumpade förhållande med en 1 m lång testsektion som förflyttades successivt i steg om 0,1 m vid lägena för de detekterade flödesanomalierna. Denna mätning gjordes dock endast i borrhål KFR101.

Längdkalibrering gjordes i borrhål KFR101 baserad på längdmärkena som frästs in i borrhålsväggen vid noggrant bestämda positioner längs borrhålet. Längdmärkena detekterades med caliper och punktresistansmätningar (SPR) med hjälp av sensorer anslutna på flödesloggningssonden. Ingen längdkalibrering har gjorts i borrhål KFR27 eftersom ingen spårfräsning var gjord i borrhålsväggen.

En högupplösande absoluttryckgivare användes för att mäta det absoluta totala trycket längs borrhålet. Dessa mätningar utfördes tillsammans med flödesmätningarna.

Elektrisk konduktivitet (EC) och temperatur på borrhålsvattnet mättes också. EC-mätningarna användes för att studera förekomsten av saltvatten i borrhålet under såväl naturliga som pumpade förhållanden. EC mättes även i ett antal utvalda sprickor i borrhål KFR101 (1 m lång testsektion).

Återhämtningen av grundvattennivån mättes efter att pumpningen i respektive hål avslutades.

Contents

1 Introduction

The core drilled boreholes KFR101 and KFR27 at Forsmark, Sweden were measured using The Posiva Flow Log/Difference flow method (PFL DIFF) also known as Difference flow logging which provides a swift, multifaceted characterization of a borehole. Borehole KFR27 was measured between July 22 and July 27, 2008 and borehole KFR101 was measured between July 28 and August 3, 2008.

KFR101 is 341.76 m long and its inclination at the ground level is 53° from the horizontal plane. The borehole was drilled using a telescopic drilling technique, where the c. 0–13.7 m interval was percussion drilled, and its inner diameter is 124 mm, whereas the rest of the borehole was core drilled with the diameter 76 mm. A stainless steel support casing with an inner diameter of 80 mm has been placed within the percussion drilled part.

Borehole KFR27 is vertical and c. 146 m long. The borehole interval through the soil, c. 12 m, is cased with an inner diameter of 77 mm. The rest of the borehole is core drilled with a diameter of c. 77 mm.

The locations of KFR101 and KFR27 at Forsmark are illustrated in Figure 1-1.

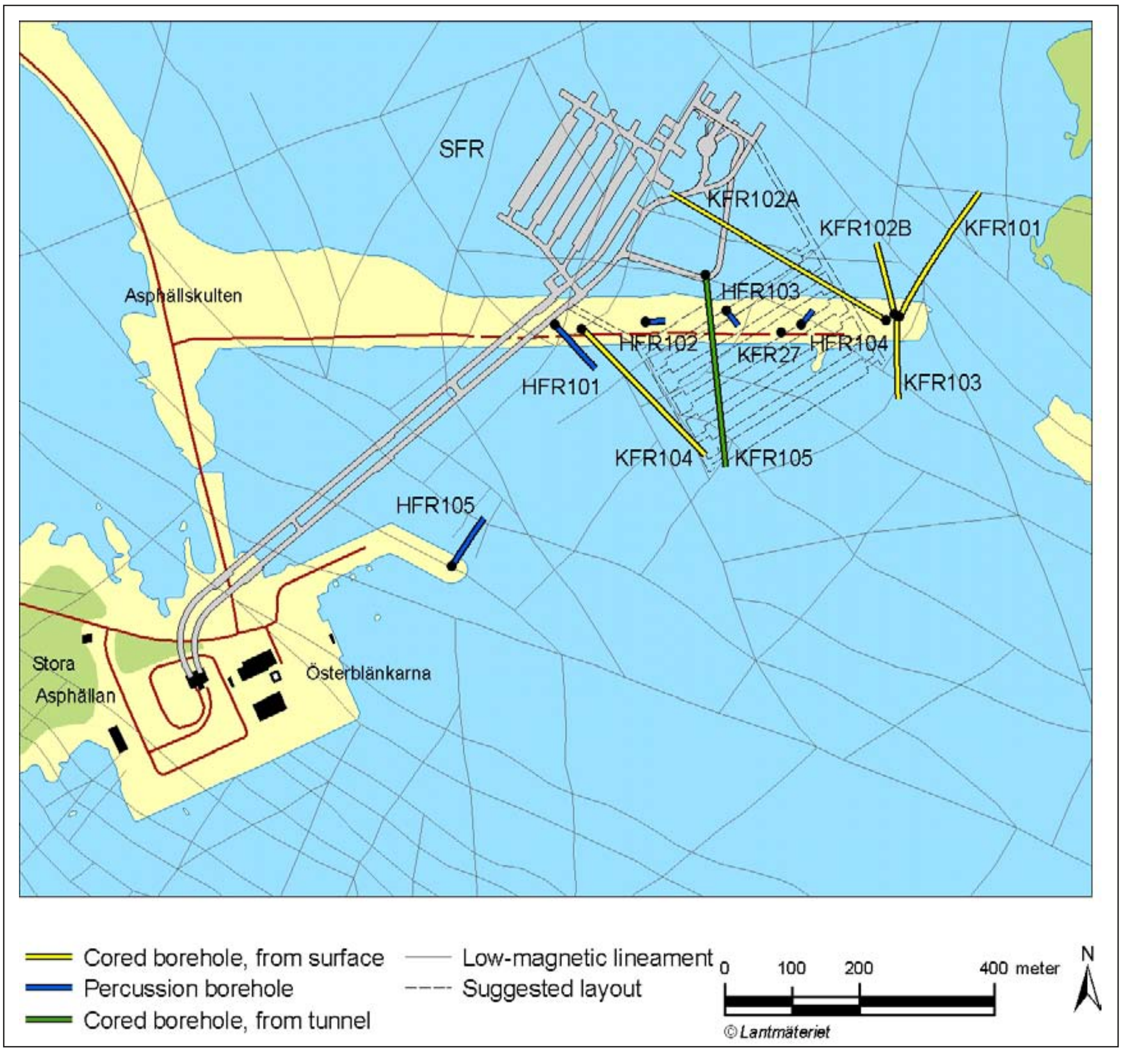

Figure 1-1. Location Map over the SFR facility and the location of the boreholes including KFR101 and KFR27.

The field work and the subsequent data interpretation were conducted by PRG-Tec Oy as Posiva Oy's subcontractor. PFL DIFF has previously been employed in Posiva's site characterisation programme in Finland as well as at the Äspö Hard Rock Laboratory at Simpevarp, Sweden. The commissions at the latter site included measurements in the 1,700 m long cored borehole KLX02 at Laxemar together with a methodology study /Ludvigson et al. 2002/. PFL DIFF has also been employed in SKB's site characterisation programme at Laxemar and Forsmark.

This document reports the results acquired by Difference flow logging in boreholes KFR101 and KFR27. The measurements were carried out as a part of a project named "Projekt SFR-utbyggnad" and in accordance to SKB's internal controlling document AP SFR-08-007. The controlling documents for performing according to this Activity Plan are listed in Table 1-1. The list of the controlling documents excludes the assignment-specific quality plans. Both the Activity Plan and the Method Descriptions are SKB's internal controlling documents. The measurement data and the results were delivered to the SKB site characterization database Sicada and are traceable by the Activity Plan number.

Table 1-1. SKB's internal controlling documents for the activities concerning this report.

Activity Plan	Number	Version
Difference flow logging in boreholes KFR101 and KFR27	AP SFR-08-007	1.0
Method Descriptions	**Number**	**Version**
Method Description for Difference flow logging	SKB MD 322.010e	2.0
Instruktion för rengöring av borrhålsutrustning och viss markbaserad utrustning	SKB MD 600.004	1.0
Instruction for length calibration in investigation of core boreholes	SKB MD 620.010e	2.0
Instruction for analysis of injection and single-hole pumping tests	SKB MD 320.004e	2.0

2 Objective and scope

The main objective of the PFL DIFF measurements in KFR101 and KFR27 was to identify water-conductive sections/fractures suitable for subsequent hydro-geochemical characterisation. Secondly, the measurements aimed at a hydrogeological characterisation, which includes the inspection of the prevailing water flow balance in the borehole and the hydraulic properties (transmissivity and undisturbed hydraulic head) of the tested sections. Based on the results of these investigations, a more detailed characterisation of flow anomalies along the borehole, e.g. an estimate of the conductive fracture frequency (CFF), may be obtained.

Besides Difference flow logging, the measurement programme also included supporting measurements, performed in order to gain a better understanding of the overall hydrogeochemical conditions. These measurements included the electrical conductivity (EC) and the temperature of the borehole fluid as well as the single-point resistance of the borehole wall. The electrical conductivity of a number of selected high-transmissive fractures in the borehole was also measured in borehole KFR101. Furthermore, the recovery of the groundwater level after pumping the borehole was registered.

A high-resolution pressure sensor was used to measure the absolute pressure along the borehole. These measurements were carried out together with the flow measurements. The results are used for the calculation of the hydraulic head along the borehole.

In borehole KFR101, single-point resistance measurements were also combined with caliper (borehole diameter) measurements to detect depth marks milled into the borehole wall at accurately determined positions. This procedure allowed for the length calibration of all other measurements.

No caliper (borehole diameter) measurements were made in borehole KFR27 since there are no length marks milled into the borehole wall.

3 Principles of measurement and interpretation

3.1 Measurements

Unlike traditional borehole flowmeters which measure the total cumulative flow rate along a borehole, PFL DIFF measures the flow rate into or out of defined borehole sections. The advantage that follows from measuring the flow rate in isolated sections is improved detection of incremental changes of flow along the borehole. As these are generally very small, they can easily be missed when using conventional flowmeters.

Rubber sealing disks located at the top and bottom of the probe are used to isolate the flow of water in the test section from the flow in the rest of the borehole, see Figure 3-1. Flow inside the test section is directed through the flow sensor. Flow along the borehole is directed around the test section by means of a bypass pipe and is discharged at either the upper or lower end of the probe. The entire structure is called the flow guide.

Flow rates into or out of the test section are monitored using thermistors, which track both the dilution (cooling) of a thermal pulse and its transfer by the moving water. The thermal dilution method is used in measuring flow rates because it is faster than the thermal pulse method, and the latter is used only to determine flow direction within a given time frame. Both methods are used simultaneously at each measurement location.

In addition to incremental changes in flow, the PFL DIFF probe can also be used to measure:

- The electrical conductivity (EC) of both borehole water and fracture-specific water. The electrode used in EC measurements is located at the top of the flow sensor, see Figure 3-1.
- The single-point resistance (SPR) of the borehole wall (grounding resistance). The electrode used for SPR measurements is located between the uppermost rubber sealing disks, see Figure 3-1, and is used for the high-resolution depth determination of fractures and geological structures.
- The prevailing water pressure profile in the borehole. Located inside the watertight electronics assembly, the pressure sensor transducer is connected to the borehole water through a tube, see Figure 3-2.
- The temperature of the water in the borehole. The temperature sensor is part of the flow sensor, see Figure 3-1.

The principles behind PFL DIFF measurements are shown in Figure 3-3. The flow sensor consists of three thermistors (Figure 3-3 a). The central thermistor, A, is used both as a heating element and to register temperature changes (Figures 3-3 b and c). The side thermistors, B1 and B2, serve as detectors of the moving thermal pulse caused by the heating of A.

Flow rate is measured by monitoring heat transients after constant power heating in thermistor A. The measurement begins by constant power (P_1) heating. After the power is cut off the flow rate is measured by monitoring transient thermal dilution (Figure 3-3 c). If the measured flow rate exceeds a certain limit, another constant power heating (P_2) period is started after which the flow rate is re-measured from the following heat transient.

Flows are measured when the probe is at rest. After transferring the probe to a new position, a waiting period (which can be adjusted according to the prevailing circumstances) is allowed to elapse before the heat pulse (Figure 3-3 b) is applied. The measurement period after the constant-power thermal pulse (normally 100 s each time the probe has moved a distance equal to the test section length and 10 s in every other location) can also be adjusted. The longer (100 s) measurement time is used to allow the direction of even the smallest measurable flows to be visible.

The flow rate measurement range is 30 mL/h–300,000 mL/h. The lower limit of measurement for the thermal dilution method is the theoretical lowest measurable value. Depending on conditions in the borehole, these limits may not always prevail. Examples of possible disturbances are drilling debris entrained in the borehole water, bubbles of gas in the water and high flow rates (some 30 L/min, i.e. 1,800,000 mL/h or more) along the borehole. If the disturbances encountered are significant, limits on practical measurements are calculated for each set of data.

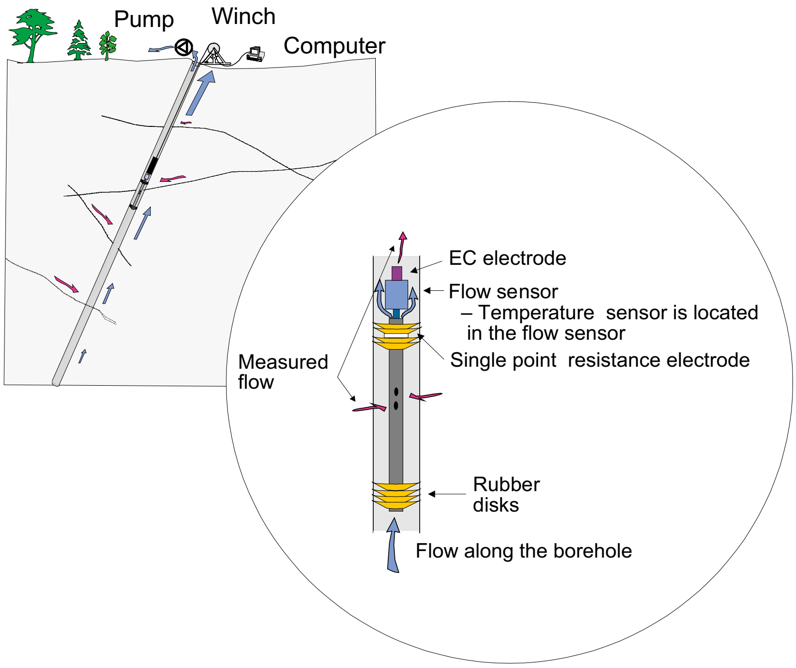

Figure 3-1. *Schematic of the probe used in the PFL DIFF.*

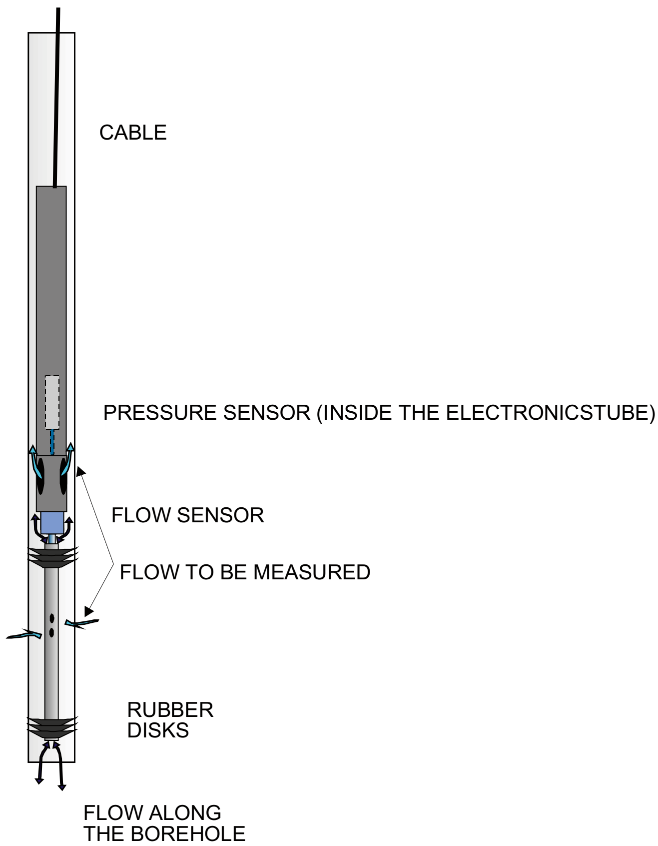

Figure 3-2. *The absolute pressure sensor is located inside the electronics assembly and connected to the borehole water through a tube.*

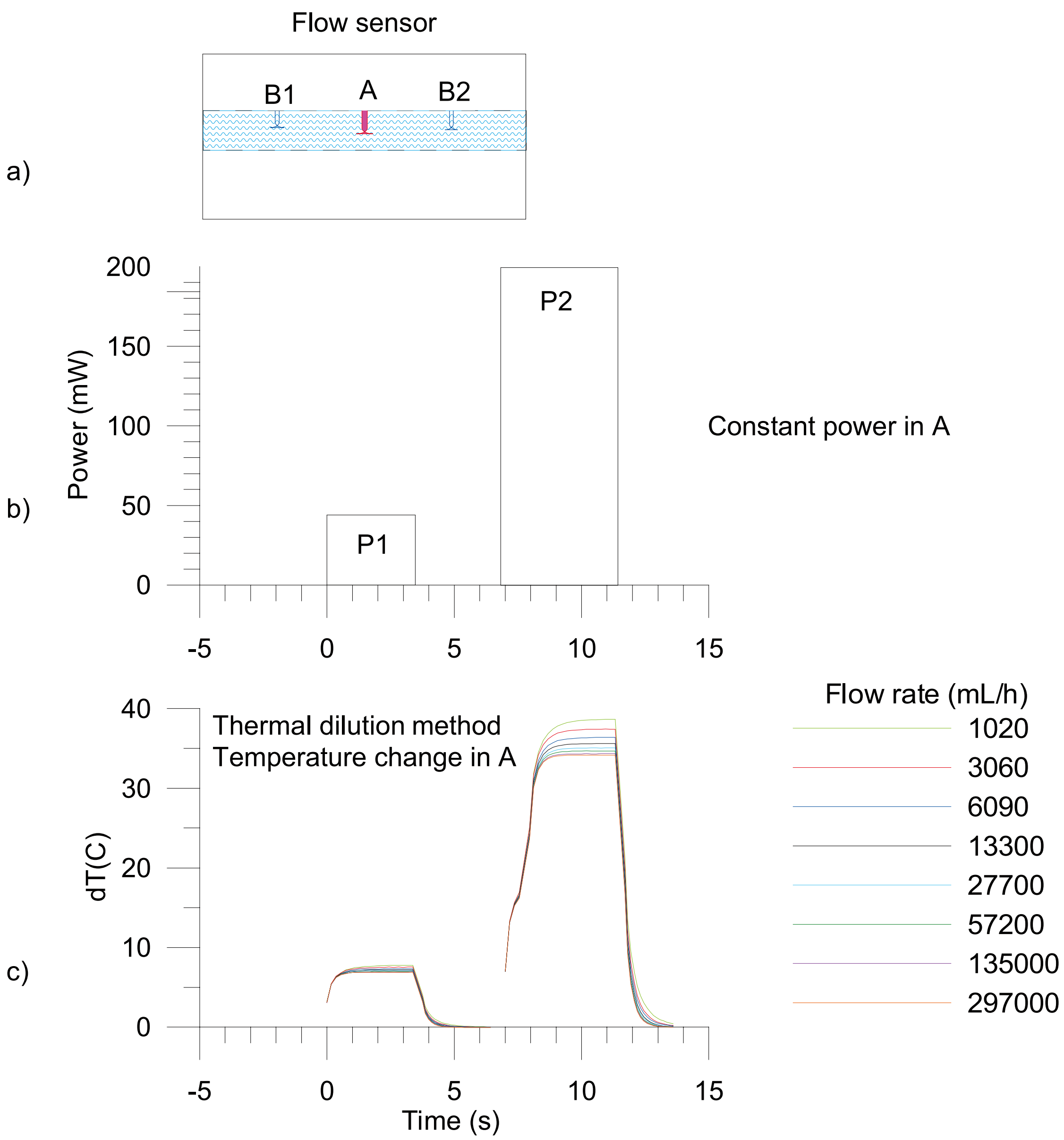

Figure 3-3. *Flow rate measurement.*

3.2 Interpretation

The interpretation of data is based on Thiem's or Dupuit's formula, which describes a steady state and two-dimensional radial flow into the borehole /Marsily 1986/:

$$h_s - h = Q/(T \cdot a) \qquad \text{3-1}$$

where h is the hydraulic head in the vicinity of the borehole and $h = h_s$ at the radius of influence (R),

Q is the flow rate into the borehole,

T is the transmissivity of the test section,

a is a constant depending on the assumed flow geometry. For cylindrical flow, the constant a is:

$$a = 2 \cdot \pi / \ln(R/r_0) \qquad \text{3-2}$$

where

r_0 is the radius of the well and

R is the radius of influence, i.e. the zone inside which the effect of pumping is felt.

If measurements of flow rate are carried out using two levels of hydraulic head in the borehole, i.e. natural and pump-induced heads, then the undisturbed (natural) hydraulic head and the transmissivity of the borehole sections tested can be calculated. Equation 3-1 can be reformulated in the following two ways:

$Q_{s0} = T_s \cdot a \cdot (h_s - h_0)$ 3-3

$Q_{s1} = T_s \cdot a \cdot (h_s - h_1)$ 3-4

where

h_0 and h_1 are the hydraulic heads in the borehole at the test levels,

Q_{s0} and Q_{s1} are the measured flow rates in the test section,

T_s is the transmissivity of the test section and

h_s is the undisturbed hydraulic head of the tested zone far from the borehole.

In general, since very little is known about the flow geometry, cylindrical flow without skin zones is assumed. Cylindrical flow geometry is also justified because the borehole is at a constant head, and no strong pressure gradients along the borehole exist except at its ends.

The radial distance R to the undisturbed hydraulic head h_s is not known and must be assumed. Here a value of 500 is selected for the quotient R/r_0.

The hydraulic head and the test section transmissivity can be deduced from the two measurements:

$h_s = (h_0 - b \cdot h_1)/(1 - b)$ 3-5

$T_s = (1/a)\ (Q_{s0} - Q_{s1})/(h_1 - h_0)$ 3-6

where

$b = Q_{s0}/Q_{s1}$

The transmissivity (T_f) and hydraulic head (h_f) of individual fractures can be calculated provided that the flow rates at the individual fractures are known. Similar assumptions to those employed above must be used (a steady-state cylindrical flow regime without skin zones).

$h_f = (h_0 - b \cdot h_1)/(1 - b)$ 3-7

$T_f = (1/a)\ (Q_{f0} - Q_{f1})/(h_1 - h_0)$ 3-8

where

Q_{f0} and Q_{f1} are the flow rates at a fracture and h_f and T_f are the hydraulic head (far away from borehole) and transmissivity of a fracture, respectively.

Since the actual flow geometry and any skin effects are unknown, transmissivity values should only be considered as an indication of the prevailing orders of magnitude. As the calculated hydraulic heads do not depend on geometrical properties but only on the ratio of the flows measured at different heads in the borehole, they should be less sensitive to unknown fracture geometry. A discussion of potential uncertainties in the calculation of transmissivity and hydraulic head can be found in /Ludvigson et al. 2002/.

The transmissivity of the entire borehole can be evaluated in several ways using the data from the flow period and recovery period. The assumptions above (cylindrical and steady-state flow) lead to Dupuits formula /Marsily 1986/:

$$T = \frac{Q}{s 2\pi} \ln\left(\frac{R}{r_0}\right) \quad 3\text{-}9$$

where

s is drawdown (m) and

Q is the pumping rate at the end of the flow period (m^3/s).

In Moye's formula /Moye 1967/ it is assumed the steady-state flow is cylindrical near the borehole (to a distance r = L/2, where L is the length of the test section) and spherical further away from the borehole:

$$T = \frac{Q}{s2\pi}\left[1 + \ln\left(\frac{L}{2r_0}\right)\right] \qquad 3\text{-}10$$

where L is length of the test section (m), in this case the water filled uncased part of the borehole and r_0 is the diameter of the borehole (m).

The transient recovery period is evaluated according to SKB MD 320.004 (SKB internal controlling document).

4 Equipment specifications

In the PFL DIFF method, the flow of groundwater into or out of a borehole section is monitored using a flow guide which employs rubber sealing disks to isolate any such flow from the flow of water along the borehole. This flow guide defines the test section being measured without altering the hydraulic head. Groundwater flowing into or out of the test section is guided to the flow sensor, and flow is measured using the thermal pulse and thermal dilution methods. Measured values are transferred to a computer in digital form.

Type of instrument:	PFL DIFF probe.
Borehole diameters:	56 mm, 66 mm and 76 mm (or larger).
Length of test section:	The flow guide length can be varied.
Method of flow measurement:	Thermal pulse and thermal dilution.
Range and accuracy of measurement:	See Table 4-1.
Additional measurements:	Temperature, single-point resistance, electrical conductivity of water, water pressure.
Winch:	Mount Sopris Wna 10, 0.55 kW, conductors, Gerhard-Owen cable head.
Depth determination:	Based on a digital distance counter.
Logging computer:	PC (Windows XP).
Software:	Based on MS Visual Basic.
Total power consumption:	1.5–2.5 kW depending on the type of pump employed.

The range and accuracy of the sensors used is shown in Table 4-1.

Table 4-1. Range and accuracy of sensors.

Sensor	Range	Accuracy
Flow	30–300,000 mL/h	± 10% curr.value
Temperature (central thermistor)	0–50°C	0.1°C
Temperature difference (between outer thermistors)	–2 – +2°C	0.0001°C
Electrical conductivity of water (EC)	0.02–11 S/m	± 5% curr.value
Single-point resistance (SPR)	5–500,000 W	± 10% curr.value
Groundwater level sensor	0–0.1 MPa	± 1% full-scale
Absolute pressure sensor	0–20 MPa	± 0.01% full-scale

5 Performance

5.1 General

The work commission was performed according to Activity Plan AP SFR-08-007 following the SKB Method Description 322.010e, Version 2.0 (Method description for Difference flow logging), see Table 1-1. The Activity Plan and the Method Description are both SKB's internal controlling documents. Prior to the measurements, the downhole tools and the measurement cable were disinfected. Time was synchronized to local Swedish time. The activity schedule of the borehole measurements is presented in Table 5-1. The items and activities in Table 5-1 are the same as in the Activity Plan. The boreholes were measured in the order KFR27 and KFR101.

Logging cables, wires, and pipe strings are exposed to stretching when lowered into a vertical or sub-vertical borehole. This will introduce a certain error in defining the position of a test tool connected to the end of a logging cable. Immediately after completion of the drilling operations in borehole KFR101, length marks were milled into the borehole wall at certain intervals to be used for length calibration of various logging tools. By using the known positions of the length marks, logging cables etc can be calibrated in order to obtain an accurate length correction of the testing tool. Each length mark consists of two 20 mm wide tracks in the borehole wall. The distance between the tracks is 100 mm. The upper track defines a reference level. There are no length marks milled into borehole KFR27.

Table 5-1. Flow logging and testing in KFR101 and KFR27. Activity schedule.

Item	Activity	Explanation	Date
2	Mobilisation at site (KFR27)	Unpacking the trailer.	2008-07-20 – 2008-07-21
8	Dummy logging	Borehole stability/risk evaluation.	2008-07-22
10	EC- and temp-logging of the borehole fluid	Logging without the lower rubber sealing disks, no pumping.	2008-07-22
11	Combined overlapping/sequential flow logging	Section length L_w=5 m. Step length dL=0.5 m, no pumping.	2008-07-23
12	Overlapping flow logging	Section length L_w=5 m. Step length dL=0.5 m, pumping.	2008-07-24 – 2008-07-26
15	EC- and temp-logging of the borehole fluid	Logging without the lower rubber sealing disks, pumping.	2008-07-26
16	Recovery transient	Measurement of water level and absolute pressure in the borehole after the pumping was stopped.	2008-07-26 – 2008-07-27
18 and 2	Demobilisation at KFR27 and mobilisation at KFR101	Packing the trailer. Moving to KFR101. Unpacking the trailer.	2008-07-27
8	Dummy logging	Borehole stability/risk evaluation.	2008-07-27
9	Calibration	SKB Caliper and SPR. Logging without the lower rubber sealing disks, no pumping.	2008-07-28
10	EC- and temp-logging of the borehole fluid	Logging without the lower rubber sealing disks, no pumping.	2008-07-29
11	Combined overlapping/sequential flow logging	Section length L_w=5 m. Step length dL=0.5 m, no pumping.	2008-07-29 – 2008-07-30
12	Overlapping flow logging	Section length L_w=5 m. Step length dL=0.5 m, pumping.	2008-07-30 – 2008-07-31
13/14	Overlapping flow logging and fracture-specific EC-measurements in pre-selected fractures	Section length L_w=1 m. Step length dL=0.1 m, pumping. Fracture-specific EC in pre-selected fractures.	2008-07-31 – 2008-08-02
15	EC- and temp-logging of the borehole fluid	Logging without the lower rubber sealing disks, pumping.	2008-08-02
16	Recovery transient	Measurement of water level and absolute pressure in the borehole after the pumping was stopped.	2008-08-02 – 2008-08-03
10	Demobilisation	Packing the trailer.	2008-08-03 – 2008-08-04

The dummy logging (Item 8) of the borehole is done in order to assure that the measurement tools do not get stuck in the borehole. The dummy also collects solid material from the borehole wall. The solid material in the dummy is used for evaluation whether it is safe to continue with the other logging tools.

Caliper measurements were used in combination with single-point resistance measurements for detection of length marks in borehole KFR101 (Item 9). These methods also reveal parts of the borehole widened for some reason (fracture zones, breakouts etc). The length calibration of KFR101 was performed before any other KFR101 measurements were started.

The electrical conductivity (EC) and temperature of borehole water (Item 10) during natural (un-pumped) conditions were measured before flow logging in boreholes KFR101 and KFR27.

The combined overlapping/sequential flow logging (Item 11) was carried out in the borehole with a 5 m section length and in 0.5 m length increments (step length). The measurements were performed during natural (un-pumped) conditions.

The pumping of borehole KFR27 was started on July 24, 2008. After a 4 hours waiting time (the minimum waiting time was set to 3 hours), overlapping flow logging (Item 12) was conducted using the same section and step lengths as before. In KFR101 the pumping was started on July 30, 2008. The waiting time after which the measurements (Item 12) were started was 5 h.

The overlapping flow logging in KFR101was continued by re-measuring previously detected flow anomalies with a 1 m section length and a 0.1 m step length (Item 13).

The fracture specific EC of water from some selected fractures (Item 14) was performed in conjunction with Item 13, in borehole KFR101. Items 13 and 14 were only in the KFR101 measurement programme.

The EC of borehole water (Item 15) was measured while the borehole was still pumped. After this, the pump was stopped and the recovery of the groundwater level was monitored (Item 16).

5.2 Nonconformities

Nonconformities in KFR101:

A 3 m drawdown was used instead of 5 m because the amount of outflow from the borehole to achieve a 5 m drawdown would have been so large that it would not have been possible to achieve it with the available pumps. The upper part of the borehole is cased with the inner diameter 80 mm preventing the installation of bigger pumps.

It was not physically possible to measure approximately 5.1 m of the bottom of the borehole, because there were weights (3) and a centralizer in the measurement device. The rubber sealing disks in the device must also be turned before the measurement begins. This reduces the measured distance for approximately 10 cm. There is about 6 m of rock debris in the bottom of KFR101. Altogether about 11 m of the bottom of the borehole was not measured.

Nonconformities in KFR27:

Before item 12 measurements the pump had a failure after half an hour pumping. There was an approximately half day delay due to repairing the pump. During the 5 m section flow logging measurement in pumped conditions (Item 12), there was some variation in drawdown at length interval between 95 m and 3 m. This interval was re-measured immediately. This did not cause any delays in the measurement schedule.

It was not physically possible to measure approximately 3.65 m of the bottom of the borehole, because there were weights (2) and a centralizer in the measurement device. The rubber sealing disks in the device must also be turned before the measurement begins. This reduces the measured distance for approximately 10 cm.

6 Results

6.1 Length calibration

6.1.1 Caliper and SPR measurement

An accurate length scale for the measurements is difficult to achieve in long boreholes. The main cause of inaccuracy is the stretching of the logging cable. The stretching depends on the tension on the cable, the magnitude of which in turn depends, among other things, on the inclination of the borehole and the roughness (friction properties) of the borehole wall. The cable tension is larger when the borehole is measured upwards. The cables, especially new cables, may also stretch out permanently.

Length marks on the borehole wall can be used to minimize the length errors. The length marks are initially detected with the SKB caliper tool. The length scale is first corrected according to the length marks. Single-point resistance is recorded simultaneously with the caliper logging. All flow measurement sequences can then be length corrected by synchronising the SPR results (SPR is recorded during all the measurements except borehole EC measurements) with the original caliper/SPR-measurement.

No length marks were made in the borehole wall of KFR27. Thereby no length calibration was possible in the measurements in borehole KFR27.

The procedure of the length correction in borehole KFR101 was the following:

- The caliper/SPR-measurements (Item 9) were initially length corrected in relation to the known length marks, Appendix KFR101.1.17, black curve. Corrections between the length marks were obtained by linear interpolation.
- The SPR curve of Item 9 was then compared with the SPR curves of Items 11, 12, 13, and 14 to obtain relative length errors of these measurement sequences.
- All SPR curves could then be synchronized, as can be seen in Appendices KFR101.1.2–KFR101.1.16.

The results of the caliper and single-point resistance measurements from all measurements in the entire borehole are presented in Appendix KFR101.1.1. Four SPR-curves are plotted together with the caliper-data. These measurements correspond to Items 9, 11, 12, 13 and 14.

Zoomed results of the caliper and SPR data are presented in Appendices KFR101.1.2–KFR101.1.16. The detectability of the length marks in borehole KFR101 is listed in Table 6-1. All the length marks were detected by the caliper tool.

All the length marks were also detected in the single-point resistance measurements. The SPR-anomaly is complicated due to the four rubber sealing disks used at the upper end of the section, two at each side of the resistance electrode, but it is often possible to successfully detect the length marks even if the caliper tool has not found the marks (which was not the case in this borehole).

Table 6-1. Detected length marks, KFR101.

Length marks given by SKB (m)	Length marks detected by caliper	Length marks detected by SPR
51	both	yes
100	both	yes
150	both	yes
200	both	yes
272	both	yes

The aim of the plots in Appendices KFR101.1.2–KFR101.1.16 is to verify the accuracy of the length correction. The curves in these plots represent length corrected results. These appendices also illustrate a few locations where such SPR anomalies were found that could be used to help in determining the location of the measurement tool in the borehole.

The magnitude of length correction along the borehole is presented in Appendix KFR101.1.17. The negative values of the error represent the situation where the logging cable has been extended, i.e. the cable is longer than the nominal length marked on it.

6.1.2 Estimated error in location of detected fractures

In spite of the length correction in described above, there can still be length errors due to the following reasons:

1. The point interval in the overlapping mode flow measurements is 0.1 m. This could cause an error of ± 0.05 m.
2. The length of the test section is not exact. The specified section length denotes the distance between the nearest upper and lower rubber sealing disks. Effectively, the section length can be larger. At the upper end of the test section there are four rubber sealing disks. The distance between them is 5 cm. This will cause rounded flow anomalies: a flow may be detected already when a fracture is situated between the upper rubber sealing disks. These phenomena can cause an error of ± 0.05 m when the short step length (0.1 m) is used.
3. Corrections between the length marks can be other than linear. This could cause an error of ± 0.1 m in the caliper/SPR-measurement.
4. SPR curves may be imperfectly synchronized. This could cause an error of ± 0.1 m.

In the worst case, the errors from sources 1, 2, 3 and 4 are summed and the total estimated error between the length marks would be ± 0.3 m.

The situation is slightly better near the length marks. In the worst case, the errors from sources 1, 2 and 4 are summed and the total estimated error would be ± 0.2 m.

In borehole KFR27 where are no length marks, source 3 is thereby excluded. The main error in borehole KFR27 is the stretching of logging cables. This could cause an error of ± 0.3 m at the length of c. 140 m. Total estimated error for fracture locations at the length of c. 140 m would be, in the worst case, ± 0.4 m. The error approaches zero when moving closer to the ground level.

Knowing the location accurately is important when different measurements are compared, for instance flow logging and borehole TV. In that case the situation may not be as severe as the worst case above, since some of the length errors are systematic and the error is nearly constant in fractures that are close to each other. However, the error from source 1 is random.

Fractures nearly parallel with the borehole may also be problematic. Fracture location may be difficult to define accurately in such cases.

6.2 Electrical conductivity and temperature

6.2.1 Electrical conductivity and temperature of borehole water

The electrical conductivity of the borehole water was initially measured when the borehole was at rest, i.e. at natural, un-pumped conditions. The measurement was performed downwards, see Appendices KFR27.1.1, KFR101.2.1 (logarithmic scale) and KFR101.2.2 (linear scale), blue curve.

The EC measurement was repeated during pumping (after a pumping period of approximately three days), see Appendices KFR27.1.1, KFR101.2.1 and KFR101.2.2, green curve.

The temperature of the borehole water was measured simultaneously with the EC measurements. The EC values are temperature corrected to 25°C to make them more comparable with other EC measurements /Heikkonen et al. 2002/. The temperature results in Appendices KFR27.1.2 and KFR101.2.3 have the same length axis as the EC results in Appendices KFR27.1.1, KFR101.2.1 and KFR101.2.2.

The length calibration of the borehole electrical conductivity measurements is not as accurate as in other measurements, because single-point resistance is not registered. The length correction of the SPR/caliper-measurement was applied to the borehole EC measurements (only KFR101), black curve in Appendix KFR101.1.17.

6.2.2 Electrical conductivity of fracture-specific water

Electrical conductivity of fracture-specific water measurements were made only in borehole KFR101.

The flow direction is always from the fractures into the borehole if the borehole is pumped with a sufficiently large drawdown. This enables the determination of electrical conductivity from fracture-specific water. Both electrical conductivity and temperature of flowing water from the fractures were measured.

The fractures detected in the flow measurements can be measured for electrical conductivity later. These fracture-specific measurements begin near the fracture which has been chosen for inspection. The tool is first moved stepwise closer to the fracture until the detected flow is larger than a predetermined limit. At this point the tool is stopped. The measurement is continued at the given position allowing the fracture-specific water to enter the section. The waiting time for the EC measurement can be automatically calculated from the measured flow rate. The aim is to flush the water volume within the test section sufficiently to gain accurate results. The measuring computer is programmed so that the water in the test section will be replaced approximately three times over. After the set of stationary measurements, the tool is once again moved stepwise past the fracture for a short distance. The electric conductivity is also measured during the stepwise movement before and after the set of stationary measurements.

The test section in these measurements was 1 m long and the tool was moved in 0.1 m steps. The water volume in a 1 m long test section is 3.6 L. The results are presented in Appendices KFR101.11.1–KFR101.11.4. The blue symbol represents the conductivity value when the tool was moved and the red symbol is used for the set of stationary measurements.

The borehole KFR101 lengths at the upper and lower ends of the section and the fracture locations as well as the final EC values are listed in Table 6-2.

For comparison, the fracture-specific EC and temperature results are also plotted with the EC and temperature results of borehole water, see Appendices KFR101.2.1–KFR101.2.3.

Table 6-2. Fracture-specific EC, KFR101.

Upper end of section (m)	Lower end of section (m)	Measured fractures (m)	EC (S/m) at 25°C
298.06	299.06	298.8	0.55
294.46	295.46	295.1	0.55
180.28	181.28	181.0	0.77
107.59	108.59	108.3	0.78
63.61	64.61	63.9, 64.3	0.84
32.14	33.14	32.8	0.95
12.95	13.95	13.8	0.81

6.3 Pressure measurements

Absolute pressure was registered together with the other measurements in Items 11–14 and 16. The pressure sensor measures the sum of hydrostatic pressure in the borehole and air pressure. Air pressure was also registered separately, see Appendices KFR27.6.2 and KFR101.10.2. The hydraulic head along the borehole at natural and pumped conditions is determined in the following way. First, the monitored air pressure at the site is subtracted from the measured absolute pressure. The hydraulic head (h) at a certain elevation (z) is calculated according to the following expression /Nordqvist 2001/:

$$h = (p_{abs} - p_b)/(\rho_{fw} \cdot g) + z \quad 6\text{-}1$$

where

h is the hydraulic head (m.a.s.l.) according to the RHB 70 reference system,

p_{abs} is the absolute pressure (Pa),

p_b is the barometric (air) pressure (Pa),

ρ_{fw} is the unit density, 1,000 kg/m^3

g is the standard gravity, 9.80665 m/s^2 and

z is the elevation of measurement (m.a.s.l.) according to the RHB 70 reference system.

An offset of 4.50 kPa is subtracted from absolute pressure results.

The calculated head distributions are presented in Appendices KFR27.6.1 and KFR101.10.1. The exact z-coordinates are important in head calculation. A 10 cm error in the z-coordinate means a 10 cm error in the head.

6.4 Flow logging

6.4.1 General comments on results

The measuring programme contained several flow logging sequences. They were gathered on the same diagram with single-point resistance (right hand side) and caliper plots (in the middle), see Appendices KFR27.2.1–KFR27.2.7 and KFR101.3.1–KFR101.3.17. SPR has a lower value on a fracture where flow is detected. Many other resistance anomalies result from other fractures and geological features. As the electrode of the SPR tool is located within the upper rubber sealing disks of the probe, the locations of resistance anomalies associated with leaky fractures coincide with the lower end of the flow anomalies.

The caliper tool has been adjusted and specified to change its output from a high voltage value to a low voltage value between borehole diameters 77 mm–78 mm.

The flow logging was first performed with a 5 m section length and with 0.5 m length increments. The method (overlapping flow logging) gives the length and the thickness of conductive zones with a length resolution of 0.5 m.

Under natural conditions or if the borehole isn't pumped using a sufficient drawdown the flow direction may be into the borehole or out from it. The direction of small flows (< 100 mL/h) cannot be detected in the normal overlapping mode (thermal dilution method). Therefore the measurement time was longer (so that the thermal pulse method could be used) at every 5 m interval in both 5 m section measurements.

The test section length determines the width of a flow anomaly of a single fracture. If the distance between flow yielding fractures is less than the section length, the anomalies will overlap, resulting in a stepwise flow data plot. The overlapping flow logging was repeated in borehole KFR101 in the vicinity of identified flow anomalies using a 1 m long test section and 0.1 m length increments.

The positions (borehole length) of the detected fractures are shown in the middle of the Appendices (KFR27) and on the caliper scale (KFR101). They are interpreted on the basis of the flow curves and therefore represent flowing fractures. A long line represents the location of a leaky fracture; a short line denotes that the existence of a leaky fracture is uncertain. The short line is used if the flow rate is less than 30 mL/h or the flow anomalies are overlapping or unclear because of noise. The overlapping flow logging using a 1 m long test section was not carried out in borehole KFR27. Due to that the locations of fractures are not as exact as in KFR101.

The coloured triangles show the magnitude of the measured flows. The triangles have the same colour than the corresponding curves.

The explanations to the tables in Appendices KFR27.4, KFR101.5 and KFR101.7 are given in Appendices KFR27.3 and KFR101.4.

6.4.2 Transmissivity and hydraulic head of borehole sections

The boreholes were flow logged with a 5 m section length and with 0.5 m length increments both in un-pumped and pumped conditions.

The results of the measurements with a 5 m section length are presented in tables, see Appendices KFR27.4 and KFR101.5. Only the results with 5 m length increments are used. All borehole sections are shown in Appendices KFR27.2.1–KFR27.2.7 and KFR101.3.1–KFR101.3.17. Secup and Seclow in Appendices KFR27.4 and KFR101.5 are the distances along the borehole from the reference level (top of the casing tube) to the upper end of the test section and to the lower end of the test section, respectively. The Secup and Seclow values for the two sequences (measurements at un-pumped and pumped conditions) are not exactly identical, due to a minor difference in the cable stretching. The difference between these two sequences was small. Secup and Seclow given in Appendices KFR27.4 and KFR101.5 are calculated as the average of these two values.

Pressure was measured and calculated as described in Section 6.3. h_{0FW} and h_{1FW} in Appendices KFR27.4 and KFR101.5 represent heads determined without and with pumping, respectively. The head in the borehole and calculated heads of borehole sections are given in RHB 70 scale.

The flow results in Appendices KFR27.4 and KFR101.5 (Q_0 and Q_1), representing the flow rates derived from measurements during un-pumped and pumped conditions, are presented side by side to make comparison easier. Flow rates are positive if the flow direction is from the bedrock into the borehole and vice versa.

With the borehole KFR27 at rest, 16 sections were detected as flow yielding, eleven of which had a flow direction from the borehole into the bedrock (negative flow). During pumping in borehole KFR27, all 19 detected flows were directed towards the borehole.

Without pumping in the borehole KFR101, 24 sections were detected as flow yielding, fourteen of which had a flow direction from the borehole into the bedrock (negative flow). During pumping in borehole KFR101, all 31 detected flows were directed towards the borehole.

It is also possible to detect the existence of flow anomalies below the measurement limit (30 mL/h = $8.33 \cdot 10^{-9}$ m^3/s), even though the exact numerical values below the limit are uncertain.

The flow data is presented as a plot, see Appendices KFR27.5.1 and KFR101.6.1. The left-hand plot in each diagram represents flow from the borehole into the bedrock for the respective test sections, while the right-hand plot represents flow from the bedrock into the borehole. If flow could not be detected (zero flow), no corresponding point will be visible on the logarithmic plots in the appendices.

The lower and upper measurement limits of the flow are also presented in the plots (Appendices KFR27.5.1 and KFR101.6.1) and in the tables (Appendices KFR27.4 and KFR101.5). There are theoretical and practical lower limits of flow, see Section 6.4.4.

The hydraulic head and transmissivity (T_D) of borehole sections can be calculated from the flow data using the method described in Chapter 3. The results are illustrated in Appendices KFR27.5.2 and KFR101.6.2. The hydraulic head of sections is presented in the plots if none of the two flow values at the same length is equal to zero. Transmissivity is presented if none or just one of the flows is equal to zero.

The measurement limits of transmissivity are also shown in Appendices KFR27.5.2, KFR101.6.2 and in Appendices KFR27.4 and KFR101.5. All the measurement limit values of transmissivity are based on the actual pressure difference in the borehole (h_{0FW} and h_{1FW} in Appendices KFR27.4 and KFR101.5).

In borehole KFR27 the sum of all the detected flows without pumping (Q_0) was $1.71 \cdot 10^{-7}$ m^3/s (0.6 L/h). In borehole KFR101 Q_0 was $4.22 \cdot 10^{-6}$ m^3/s (15 L/h). This sum should normally be zero if all the flows in the borehole are not disturbed by noise or other external factors, the borehole is not pumped, the water level is constant, the salinity distribution in the borehole is stabilized and the fractures are at steady state pressure. The measured flow balance without pumping was relatively good in both boreholes.

The weights and a centralizer in the measurement device prohibit measuring the borehole all the way to the bottom and it is always possible that there are also flows in this area.

6.4.3 Transmissivity and hydraulic head of fractures

The overlapping flow logging using a 1 m long test section was not carried out in borehole KFR27. Due to that fracture-specific transmissivities and heads were not calculated. Fracture locations for KFR27 have been interpreted based on the 5 m section length flow logging results, see Appendices KFR27.2.1–KFR27.2.7.

An attempt was made to evaluate the magnitude of fracture-specific flow rates. The results at borehole KFR101 for a 1 m section length and 0.1 m length increments were used for this purpose. The first step in this procedure is to identify the locations of individual flowing fractures and then evaluate their flow rates.

In cases where the fracture distance is less than one metre, it may be difficult to evaluate the flow rate. There are such cases for instance in Appendix KFR101.3.4. In these cases a stepwise increase or decrease in the flow data plot equals the flow rate of a specific fracture (filled triangles in the Appendices).

Since the 1 m long measurement section was not used during un-pumped conditions, the results for the 5 m section were used instead. The fracture locations are important when evaluating the flow rate in un-pumped conditions. The fracture locations are known on the basis of the 1 m section measurements. It is not a problem to evaluate the flow rate during un-pumped conditions when the distance between flowing fractures is more than 5 m. The evaluation may, however, be problematic when the distance between fractures is less than 5 m. In this case an increase or decrease of a flow anomaly at the fracture location determines the flow rate. However, this evaluation is used conservatively, i.e. only in the clearest of cases, and no flow value is usually evaluated during un-pumped conditions at densely fractured parts of bedrock. If the flow for a specific fracture can not be determined conclusively, the flow rate is marked with "–" and the value 0 is used in the transmissivity calculation, see Appendix KFR101.7. The flow direction is evaluated as well. The results of the evaluation are plotted in Appendix KFR101.3, blue filled triangle.

The total amount of detected flowing fractures in borehole KFR101 was 51, but only 24 of them could be defined without pumping. These 24 fractures could be used for head estimations and all 51 were used for transmissivity estimations. Transmissivity and hydraulic head of fractures are presented in Appendices KFR101.7 and KFR101.8.

Some fracture-specific results were classified to be "uncertain". The basis for this classification is either a minor flow rate (< 30 mL/h) or unclear fracture anomalies. Anomalies are considered unclear if the distance between them is less than one metre or their nature is unclear because of noise.

Fracture-specific transmissivities were compared with transmissivities of borehole KFR101 sections in Appendix KFR101.9. All fracture-specific transmissivities within each 5 m interval were first summed together to make them comparable with measurements with a 5 m section length. The results are fairly consistent between the two types of measurements. The decrease of flow as a function of pumping time can be seen in most fractures. The 1 m section measurements were carried out later than the 5 m section measurements and therefore flow rate and transmissivity are generally smaller in the 1 m section measurement results.

6.4.4 Theoretical and practical measurement limits of flow and transmissivity

The theoretical minimum for measurable flow rate in overlapping measurements is some 30 mL/h. The upper limit of flow measurement is 300,000 mL/h. As these upper and lower limits are determined by flow calibration, it is assumed that flows can be reliably detected between the upper and lower theoretical limits in favorable borehole conditions.

In practice, the minimum measurable flow rate may be much higher. Borehole conditions may have an influence on the flow base level (i.e. noise level). Noise levels can be evaluated in intervals along the borehole where there are no flowing fractures or other complicating structures, and may vary along a borehole.

There are several known reasons for increased noise in the flow:

1) Roughness of the borehole wall.

2) Solid particles such as clay or drilling debris in the water.

3) Gas bubbles entrained in the water.

4) High flow rate along the borehole.

Roughness in the borehole wall always results in high levels of noise, not only in the flow results, but also in the SPR results. The flow curve and SPR curves are typically spiky when the borehole wall is rough.

Drilling debris usually increases noise levels. This kind of noise is typical for both natural (un-pumped) and pumped conditions.

Pumping results in lower pressure in the borehole water and in the water in fractures located near the borehole. This may lead to the release of dissolved gas and increase the quantity of gas bubbles entrained in the water. Some fractures may produce more gas than others. Sometimes, when the borehole is being measured upwards, increased noise levels are observed just above certain fractures. The reason for this is assumed to be gas bubbles.

The effect of a high flow rate along the borehole can often be seen above fractures with a high flow. Any minor leakage in the seal provided by the lower rubber sealing disks will appear in the measurement as increased levels of noise.

A high level of noise in a flow will mask the "real" flow if this is smaller than the noise. Real flows are registered correctly if they are about ten times larger than the noise but are totally invisible if they are some ten times smaller than the noise. Experience indicates that real flows between one-tenth of the noise level and 10 times the noise level are summed with the noise. Noise levels could therefore be subtracted from measured flows to get real flows. This correction has not yet been carried out because the cases to which it is applicable are unclear.

The practical minimum for measurable flow rate is presented in Appendices KFR27.2.1–KFR27.2.7 and KFR101.3.1–KFR101.3.17 using a grey dashed line (Lower limit of flow rate). The practical minimum level of the measurable flow is always evaluated in pumped conditions since this measurement is the most important for transmissivity calculations. The limit is an approximation. It is evaluated to obtain a limit below which there may be fractures or structures that remain undetected.

The noise level in KFR27 was constantly 30 mL/h. The noise level in KFR101 varied between 30 mL/h and 300 mL/h. It is possible to detect the existence of flow anomalies below the theoretical limit of the thermal dilution method (30 mL/h). The noise line (grey dashed line) was never drawn below 30 mL/h, because the values of flow rate measured below 30 mL/h are uncertain.

In some boreholes the upper limit of flow measurement (300,000 mL/h) may be exceeded. Such fractures or structures hardly remain undetected (as the fractures below the lower limit). High flow fractures can be measured separately at a smaller drawdown. The measurement limit was not exceeded in the 5 m or 1 m measurements and therefore no re-measurements were needed.

The practical minimum for measurable flow rate is also presented in Appendices KFR27.4 and KFR101.5 (Q-lower limit P) and is obtained from the plots in Appendices KFR27.2 and KFR101.3 (Lower limit of flow rate). The practical minimum of measurable transmissivity can be evaluated using Q-lower limit and the actual head difference at each measurement location, see Appendices KFR27.4 and KFR101.5 (T_D-measl$_{LP}$). The theoretical minimum for measurable transmissivity (T_D-measl$_{LT}$) is evaluated using a Q value of 30 mL/h (the minimum theoretical flow rate using the thermal dilution method). The upper measurement limit for transmissivity can be evaluated using the maximum flow rate (300,000 mL/h) and the actual head difference as above, see Appendices KFR27.4 and KFR101.5 (T_D-measl$_U$).

All three flow limits are plotted with the measured flow rates, see Appendices KFR27.5.1 and KFR101.6.1. Theoretical minimum and maximum values are 30 mL/h and 300,000 mL/h, respectively.

The three transmissivity limits are also presented graphically, see Appendices KFR27.5.2 and KFR101.6.2.

Similar flow and transmissivity limits are not provided for the fracture-specific results as the limits for these are harder to define. The situation is similar for the upper flow limit. If several high-flowing fractures are positioned closer to one another than a distance of one metre, the upper flow limit will depend on the sum of these flows, and this must be below 300,000 mL/h.

6.5 Groundwater level and pumping rate

The level of the groundwater table in the borehole during the measurement sequences is presented in Appendices KFR27.6.2 and KFR101.10.2.

The borehole KFR27 was pumped between July 24 and July 26 with a drawdown of approximately 5 metres.

The borehole KFR101 pumping period was between July 30 and August 2 with a drawdown of approximately 3 metres.

The pumping rates were recorded, see Appendices KFR27.6.2 and KFR101.10.2.

The groundwater recovery of KFR27 was measured after the pumping period, between July 26 and 27. Recovery of KFR101 was measured after the pumping period, between August 2 and 3. The recovery was measured in both boreholes with two sensors, the water level sensor (pressure sensor for monitoring water level) and the absolute pressure sensor. The absolute pressure sensor was located at the length of 12.41 m in borehole KFR27 and at the length of 10.16 m in borehole KFR101.

6.5.1 Transmissivity of the entire borehole

(by J-E Ludvigson, Geosigma AB)

The pumping test during Difference flow logging and its subsequent recovery period is utilized to evaluate the transmissivity of the entire borehole. From the flow period the transmissivity is estimated by two steady-state methods together with transient analysis of the recovery period as described in Chapter 3. Only the pressure recovery measured by the water level sensor was analysed. The pressure recovery measured by the deeper sensor was similar, see Appendix KFR101.10.3 and KFR27.6.3 respectively.

Transient analysis is done on the pressure recovery period after the pumping in accordance with the methodology specified in SKB MD 320.004 (SKB internal controlling document). Briefly, it specifies that the transient analysis of the pressure recovery should be made versus Agarwal equivalent time in log-log and semi-log plots including the pressure derivative. The storativity S may be estimated from an empirical relationship between T and S. Furthermore, the skin factor and the borehole storage coefficient C should also be estimated. If the transmissivity changes during the test, e.g. due to hydraulic boundaries or intersecting hydraulic structures with deviating transmissivity, the estimated hydraulic properties (and radius of influence) should be based on the early response before any effects of hydraulic boundaries are observed.

KFR101

Steady-state analysis

The final flow rate Q_p during the flow period in KFR101 was 13.0 L/min and the drawdown of the water level was s_p = 3.04 m by the end of the flow period (Appendix KFR101.10.2). The transmissivity calculated with Dupuit's formula is $7.1 \cdot 10^{-5}$ m^2/s (Equation 3-9). In Dupuit's formula, R/r_0 is assumed to be 500, cf Chapter 3. In Moye's formula (Equation 3-10) the length of the test section L (open borehole interval) is 328.04 m and the borehole diameter $2r_0$ is 0.0758 m. The borehole is cased in the interval 0–13.72 m with an inner diameter of 0.0770 m. The transmissivity of the borehole calculated with Moye's formula is $1.1 \cdot 10^{-4}$ m^2/s.

Transient analysis

Figures 6-1a and b shows log-log and semi-log plots respectively of the transient pressure recovery of the water level during the pumping test in KFR101 which was used to estimate the transmissivity of the entire borehole. The pressure recovery clearly indicates an apparent negative hydraulic boundary, starting at Agarwal time of c. 1,000 s, cf Figures 6-1a and b. This fact is also supported by the response during the flow period (not shown here). This means that the dominating fracture(s) in the borehole either has a limited extension laterally or a decreasing aperture away from the borehole (or a combination of both features) resulting in a decreasing transmissivity with time and distance from the borehole.

The early transient response during the recovery period was simulated for an assumed storativity of S = $1.2 \cdot 10^{-5}$ (calculated from the empirical relationship between T and S). The best fit simulation on the early response yields a transmissivity T = $2.9 \cdot 10^{-4}$ m^2/s, a skin factor = –6.4 and a wellbore storage coefficient of C = $5.7 \cdot 10^{-7}$ m^3/Pa. The latter coefficient is calculated from the simulated effective casing radius of the borehole. The strongly negative skin factor indicates the presence of major conductive fractures in the borehole. As discussed above, the hydraulic properties of the conductive fracture(s) estimated before the effects of the observed hydraulic boundary should be estimated and reported. The long-term transmissivity in the borehole depends on the nature and properties of the apparent hydraulic boundary.

The estimated transmissivity of borehole KFR101 according to the three methods described above are given in Table 6-3. In this case, the transient transmissivity based on the early response was selected as the most representative for the borehole. It should however be noted that this transmissivity value should be accompanied by information on the apparent hydraulic boundary in Sicada (r_i and r_i-index) where r_i is the estimated distance to the apparent boundary and r_i-index shows the shape of the pressure derivative by the end of the test period. In this case, the derivative indicates an apparent negative hydraulic boundary (r_i-index = 1).

Table 6-3. Estimated transmissivity of the entire borehole KFR101.

Method	Transmissivity (m^2/s)
Dupuit	$6.1 \cdot 10^{-5}$
Moye	$1.1 \cdot 10^{-4}$
Transient	$2.9 \cdot 10^{-4}$ (based on the early response)

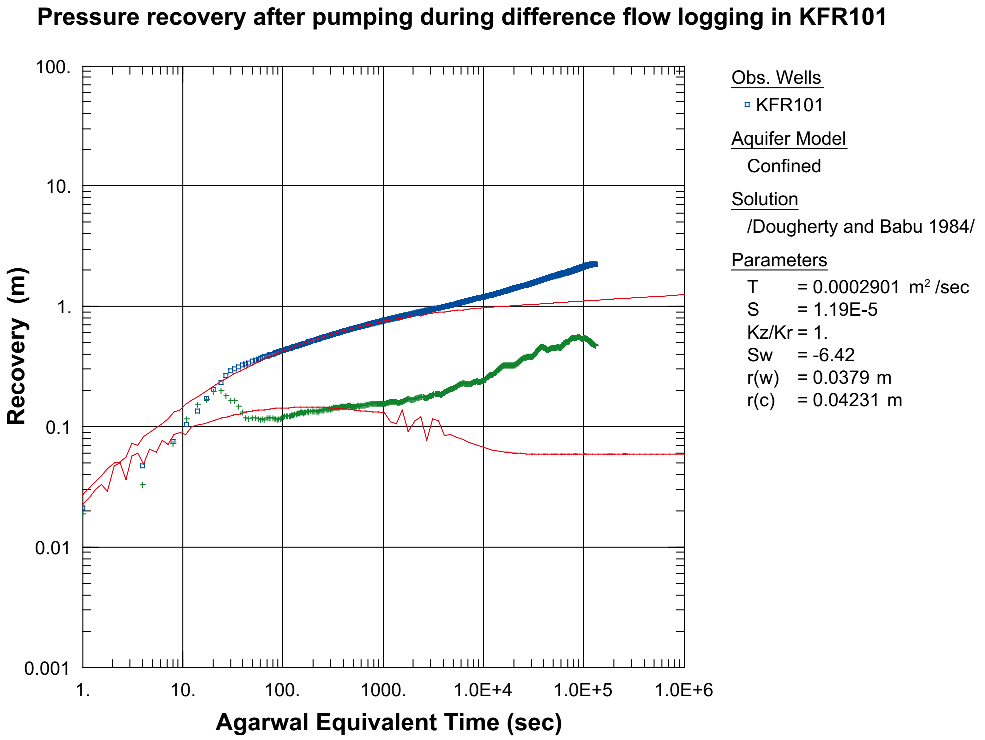

Figure 6-1a. *Log-log plot of the pressure recovery in KFR101 showing the observed pressure recovery of the water level (blue □) and associated derivative (green +) versus Agarwal equivalent time together with simulated best fit curves of the early part of the pressure recovery and its derivative (red -).*

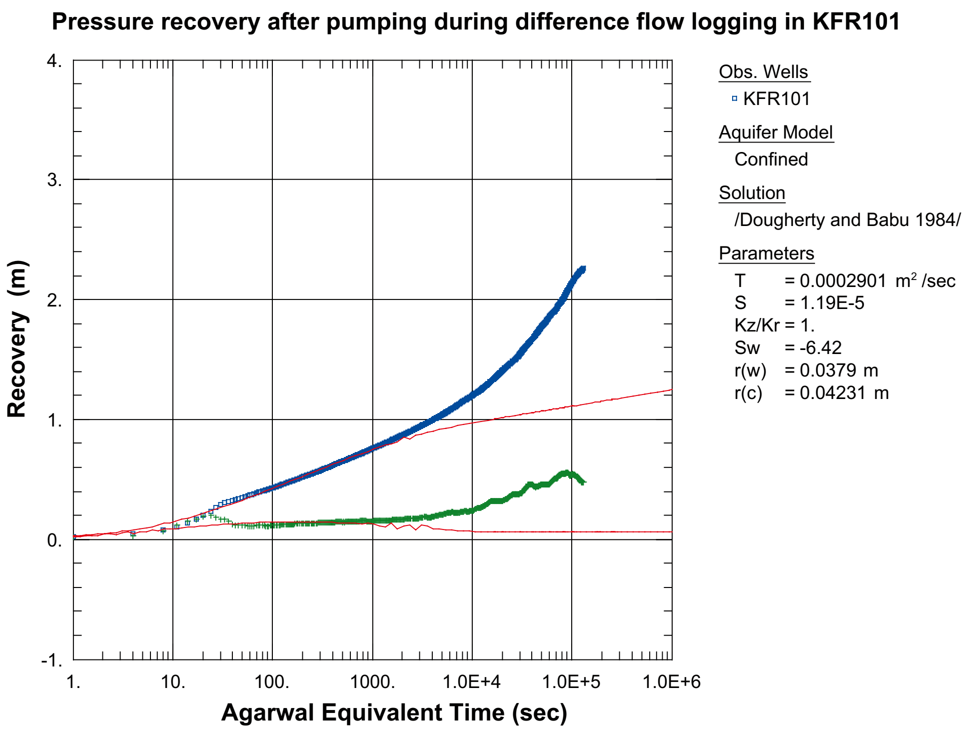

Figure 6-1b. *Lin-log plot of the pressure recovery in KFR101 showing the observed pressure recovery (blue □) and associated derivative (green +) versus Agarwal equivalent time together with simulated best fit curves of the early part of the pressure recovery and its derivative (red -).*

KFR27

Steady-state analysis

The final flow rate Q_p during the flow period in KFR27 was 3.7 L/min and the drawdown of the water level was s_p= 4.88 m by the end of the flow period (Appendix KFR27.6.2). The transmissivity calculated with Dupuit's formula is $1.2 \cdot 10^{-5}$ m²/s (Equation 3-9). In Dupuit's formula, R/r_0 is assumed to be 500, cf Chapter 3. The total borehole length of KFR27 was 148.51 m at the time of the Difference flow logging. In Moye's formula (Equation 3-10) the length of the test section L (open borehole interval) is 136.6 m and the borehole diameter $2r_0$ is 0.0765 m. The borehole is cased in the interval 0–11.91 m with an inner diameter of 0.0770 m. The transmissivity of the borehole calculated with Moye's formula is $1.7 \cdot 10^{-5}$ m²/s.

Transient analysis

Figures 6-2a and b respectively shows log-log and semi-log plots of the transient pressure recovery of the water level during the pumping test in KFR27 which was used to estimate the transmissivity of the entire borehole. The pressure recovery indicates initial wellbore storage transitioning to pseudo-radial flow and slightly leaky (pseudo-spherical) flow by the end, cf Figure 6-2a.

The transient response during the recovery period was simulated for an assumed storativity of $S = 1.7 \cdot 10^{-6}$ (calculated from the empirical relationship between T and S). The best fit simulation yields a transmissivity $T = 6.1 \cdot 10^{-6}$ m²/s, a skin factor = –6.0. No representative value on the well-bore storage coefficient could be estimated in this case due to slightly delayed response and pressure fluctuations in the beginning of the recovery period, cf Figure 6-2a. The estimated transmissivity of borehole KFR27 according to the three methods described above are given in Table 6-4. The transient transmissivity was selected as the most representative for the borehole.

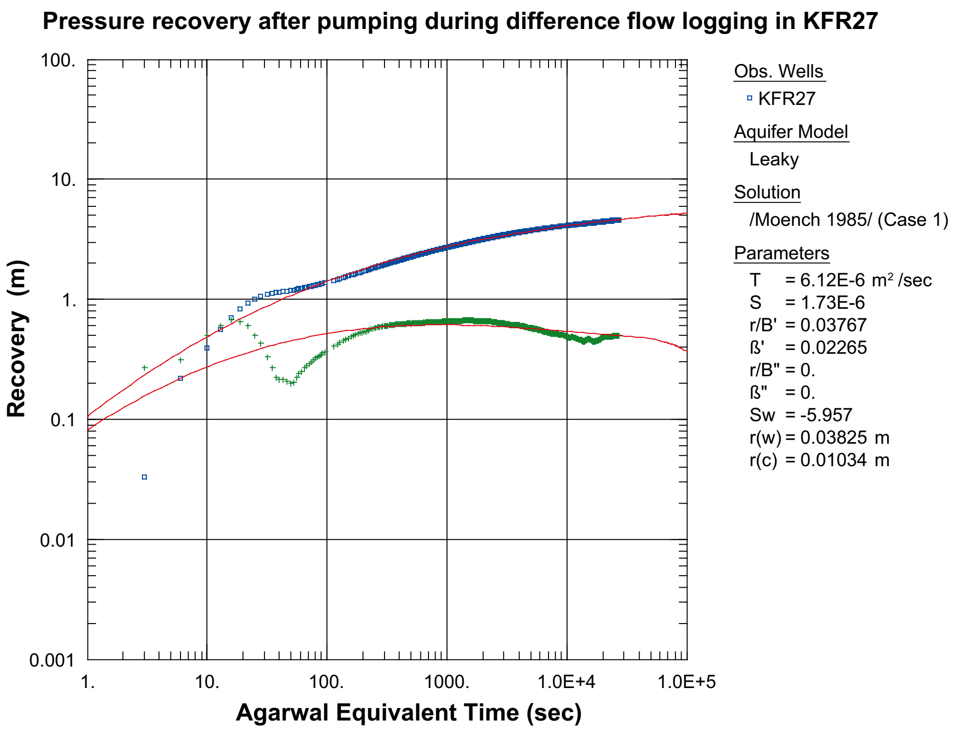

Figure 6-2a. *Log-log plot of the pressure recovery in KFR27 showing the observed pressure recovery of the water level (blue □) and associated derivative (green +) versus Agarwal equivalent time together with simulated best fit curves of the pressure recovery and its derivative (red -).*

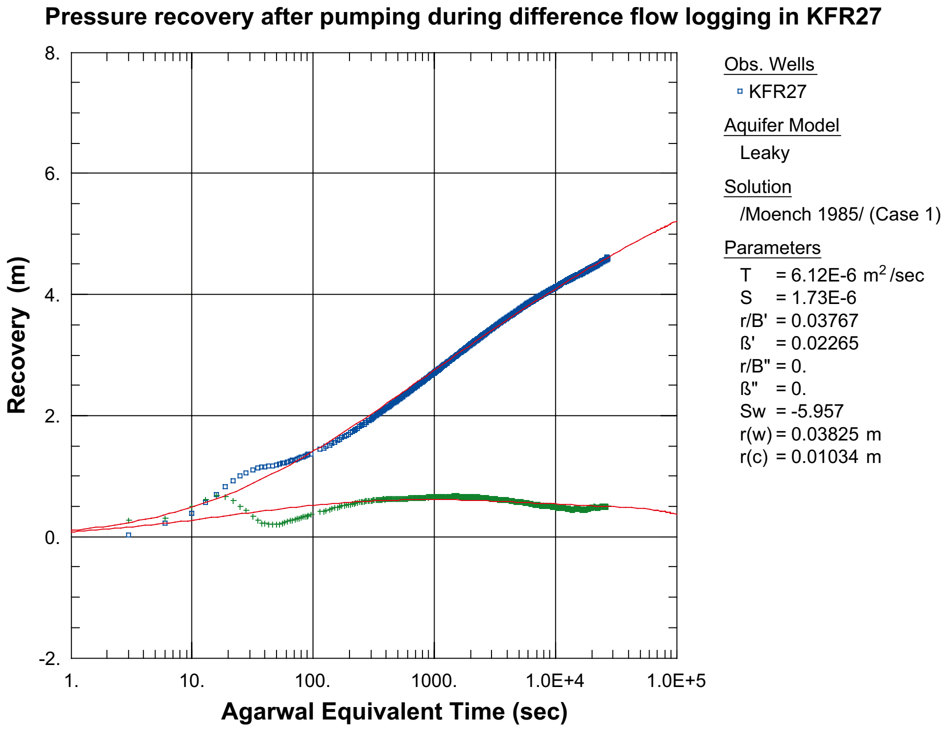

Figure 6-2b. *Lin-log plot of the pressure recovery in KFR27 showing the observed pressure recovery of the water level (blue □) and associated derivative (green +) versus Agarwal equivalent time together with simulated best fit curves of the pressure recovery and its derivative (red -).*

Table 6-4. Estimated transmissivity of the entire borehole KFR27.

Method	Transmissivity (m^2/s)
Dupuit	$1.2 \cdot 10^{-5}$
Moye	$1.7 \cdot 10^{-5}$
Transient	$6.1 \cdot 10^{-6}$

7 Summary

In this study, the Posiva Flow Log/Difference Flow method has been used to determine the location and flow rate of flowing fractures or structures in boreholes KFR101 and KFR27 at Forsmark, Sweden. Measurements were carried out both when the borehole was at rest and during pumping. A 5 m section length with 0.5 m length increments was used initially. The detected flow anomalies were re-measured in borehole KFR101 with a 1 m section and a 0.1 m measurement interval.

Length calibration was made in borehole KFR101 using the length marks in the borehole wall. The length marks were detected by caliper and single-point resistance logging. The latter method was also performed simultaneously with the flow measurements, and thus all flow results could be length calibrated by synchronizing the single-point resistance logs. There are no length marks milled into borehole KFR27.

The distribution of saline water along the borehole was logged by electrical conductivity and temperature measurements of the borehole water. In addition, electrical conductivity of fracture-specific water was measured in selected flowing fractures in borehole KFR101.

The water level in the borehole during pumping and its recovery after the pump was turned off was also measured.

In KFR27 the transmissivity and hydraulic head were calculated for borehole sections. The highest section transmissivity ($3.5 \cdot 10^{-6}$ m^2/s) was detected at depth interval 49.85–54.85 m. Other high-transmissive anomalies were found at depth intervals 24.85–29.85 m and 94.84–99.84 m. The overlapping flow logging using a 1 m long test section was not carried out in borehole KFR27. Due to that fracture-specific transmissivities and heads were not calculated.

In KFR101 the total amount of detected flowing fractures in was 51. Transmissivity and hydraulic head were calculated for borehole sections and fractures above 328.69 m. The highest fracture transmissivity ($1.3 \cdot 10^{-5}$ m^2/s) was detected at 181.0 m. Other high transmissive anomalies were found at 13.8 m, 108.3 m and 298.8 m. It should be noted that the flow anomaly at 13.8 m is the end of the casing. No flowing fractures were identified below 326.1 m.

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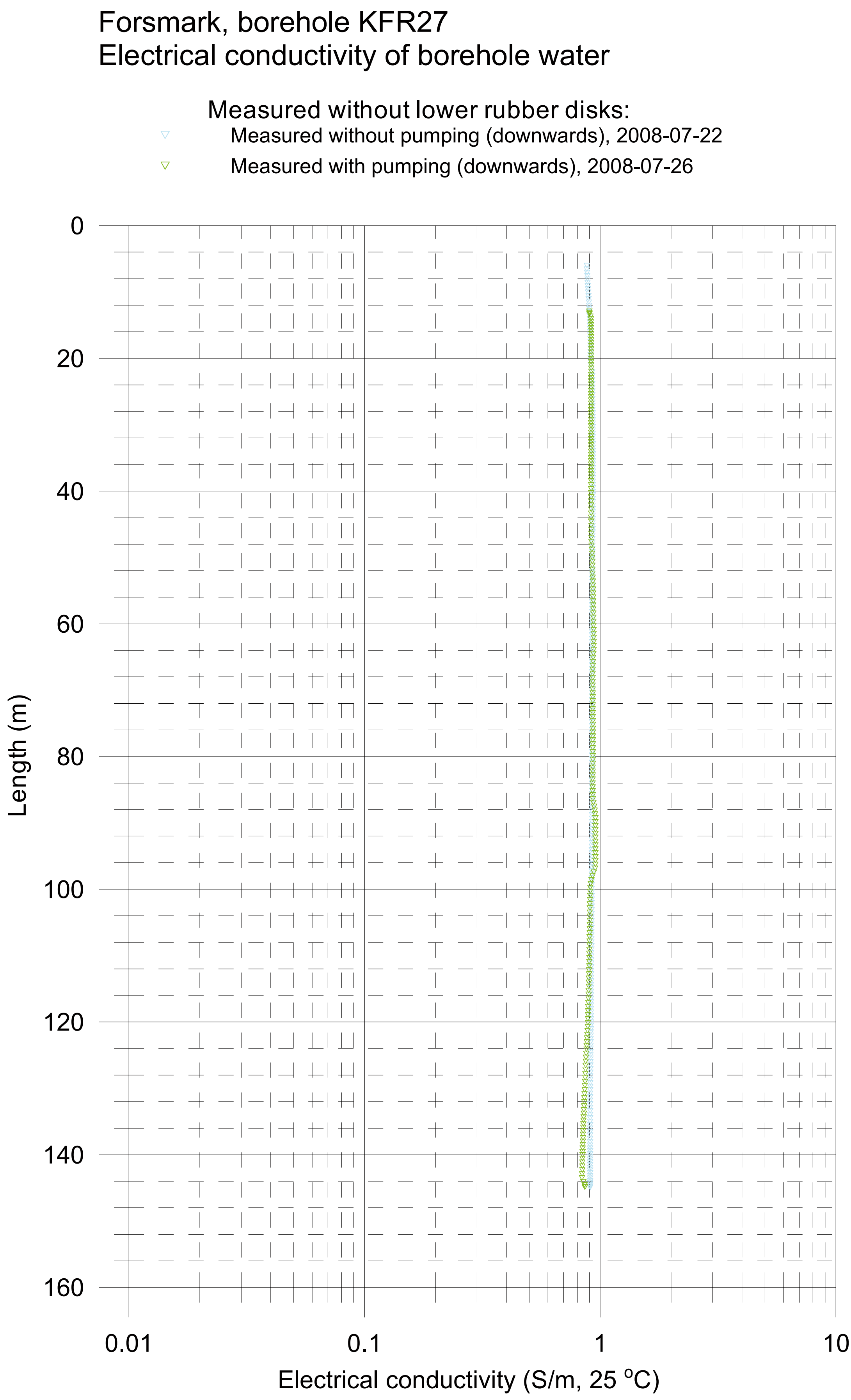
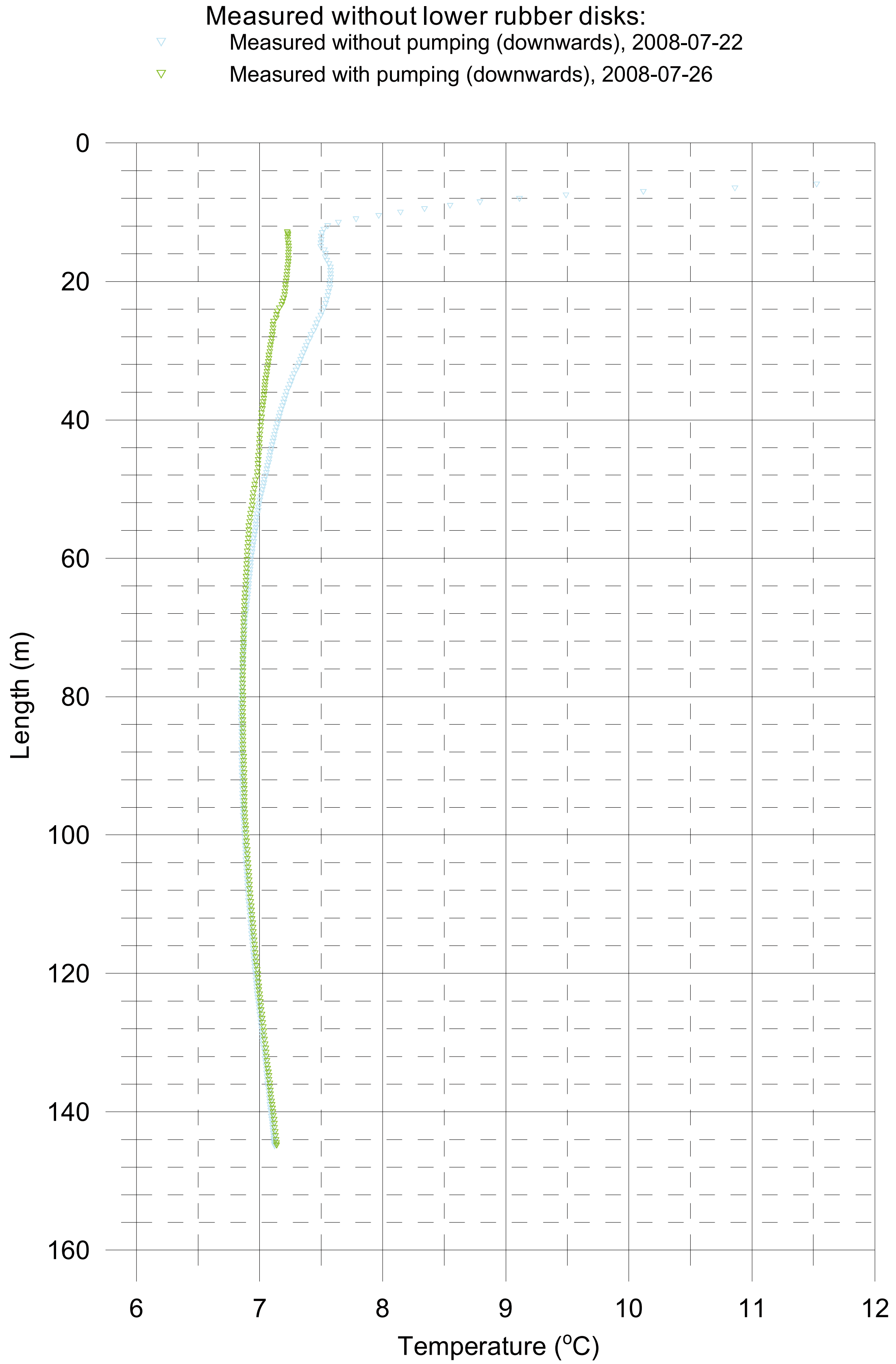
Appendices

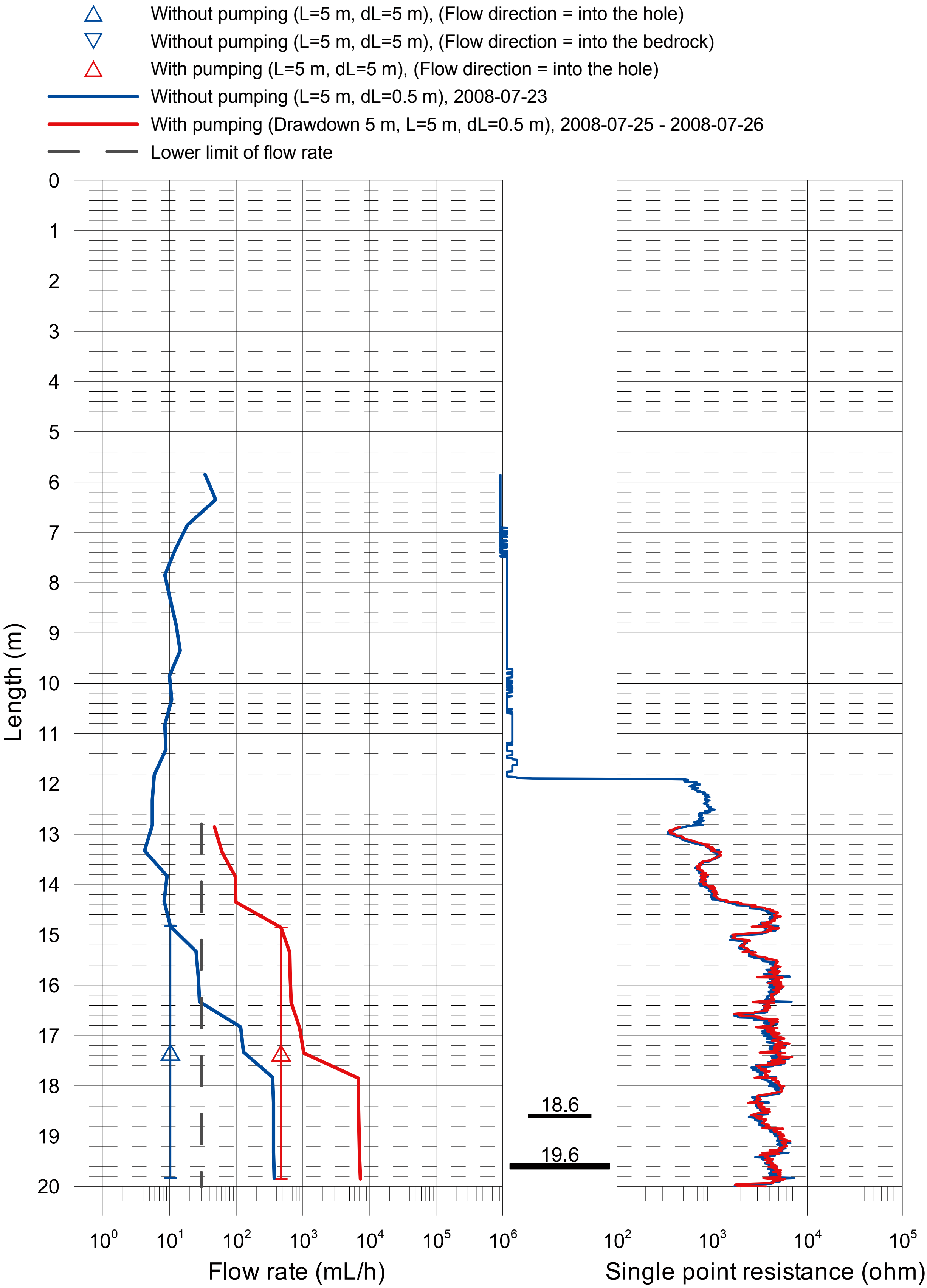
Appendix	KFR27.1.1	Electrical conductivity of borehole water
Appendix	KFR27.1.2	Temperature of borehole water
Appendices	KFR27.2.1–KFR27.2.7	Flow rate and Single-point resistance
Appendix	KFR27.3	Explanations for the tables in Appendices 4 and 5
Appendix	KFR27.4	Results of sequential flow logging
Appendix	KFR27.5.1	Plotted flow rates of 5 m sections
Appendix	KFR27.5.2	Plotted transmissivity and head of 5 m sections
Appendix	KFR27.6.1	Head in the borehole during flow logging
Appendix	KFR27.6.2	Air pressure, water level in the borehole and pumping rate during flow logging
Appendix	KFR27.6.3	Groundwater recovery after pumping
Appendices	KFR101.1.1–KFR101.1.16	SPR and Caliper results after length correction
Appendix	KFR101.1.17	Length correction
Appendix	KF101.2.1–KFR101.2.2	Electrical conductivity of borehole water
Appendix	KFR101.2.3	Temperature of borehole water
Appendices	KFR101.3.1–KFR101.3.17	Flow rate, Caliper and Single-point resistance
Appendix	KFR101.4	Explanations for the tables in Appendices 5 and 7
Appendices	KFR101.5	Results of sequential flow logging
Appendix	KFR101.6.1	Plotted flow rates of 5 m sections
Appendix	KFR101.6.2	Plotted transmissivity and head of 5 m sections
Appendices	KFR101.7	Inferred flow anomalies from overlapping flow logging
Appendix	KFR101.8	Plotted transmissivity and head of detected fractures
Appendix	KFR101.9	Comparison between section transmissivity and fracture transmissivity
Appendix	KFR101.10.1	Head in the borehole during flow logging
Appendix	KFR101.10.2	Air pressure, water level in the borehole and pumping rate during flow logging
Appendix	KFR101.10.3	Groundwater recovery after pumping
Appendices	KFR101.11.1–KFR101.11.4	Fracture-specific EC results


Forsmark, borehole KFR27
Electrical conductivity of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2008-07-22
Measured with pumping (downwards), 2008-07-26
0
20
40
60
80
100
120
140
160
Length (m)
0.01
0.1
1
10
Electrical conductivity (S/m, 25 °C)

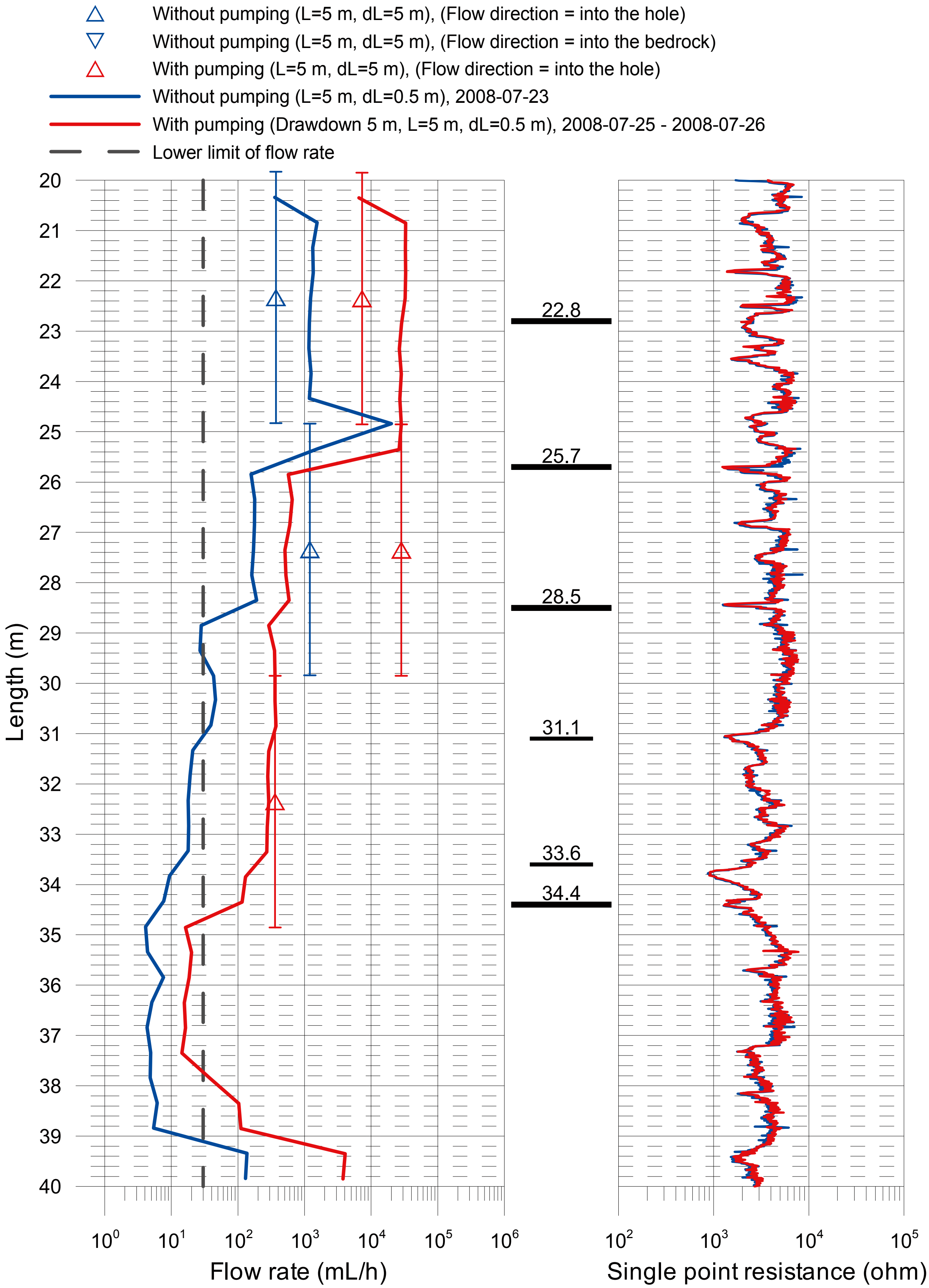
Forsmark, borehole KFR27
Temperature of borehole water



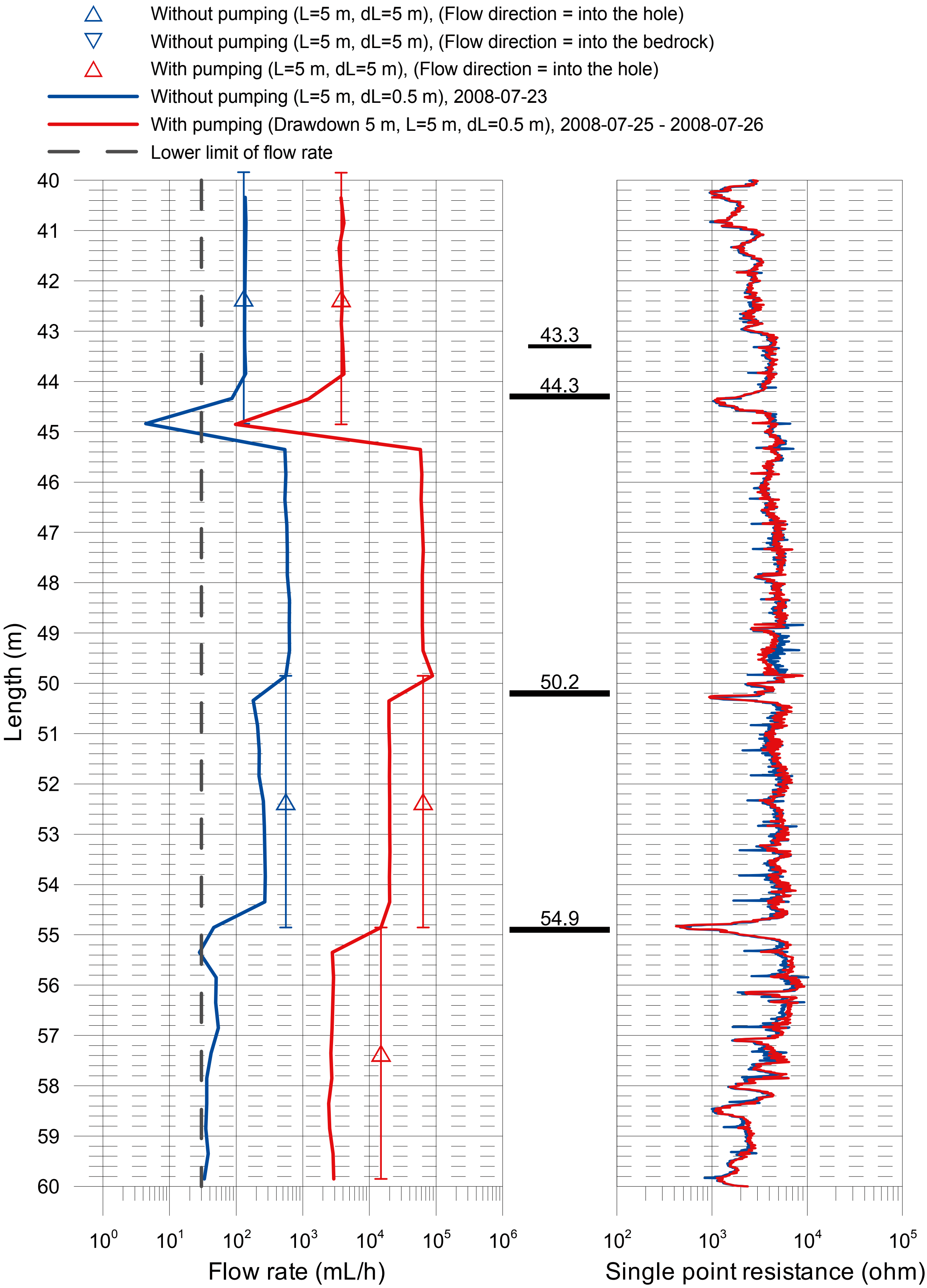
Forsmark, borehole KFR27
Flow rate, caliper and single point resistance



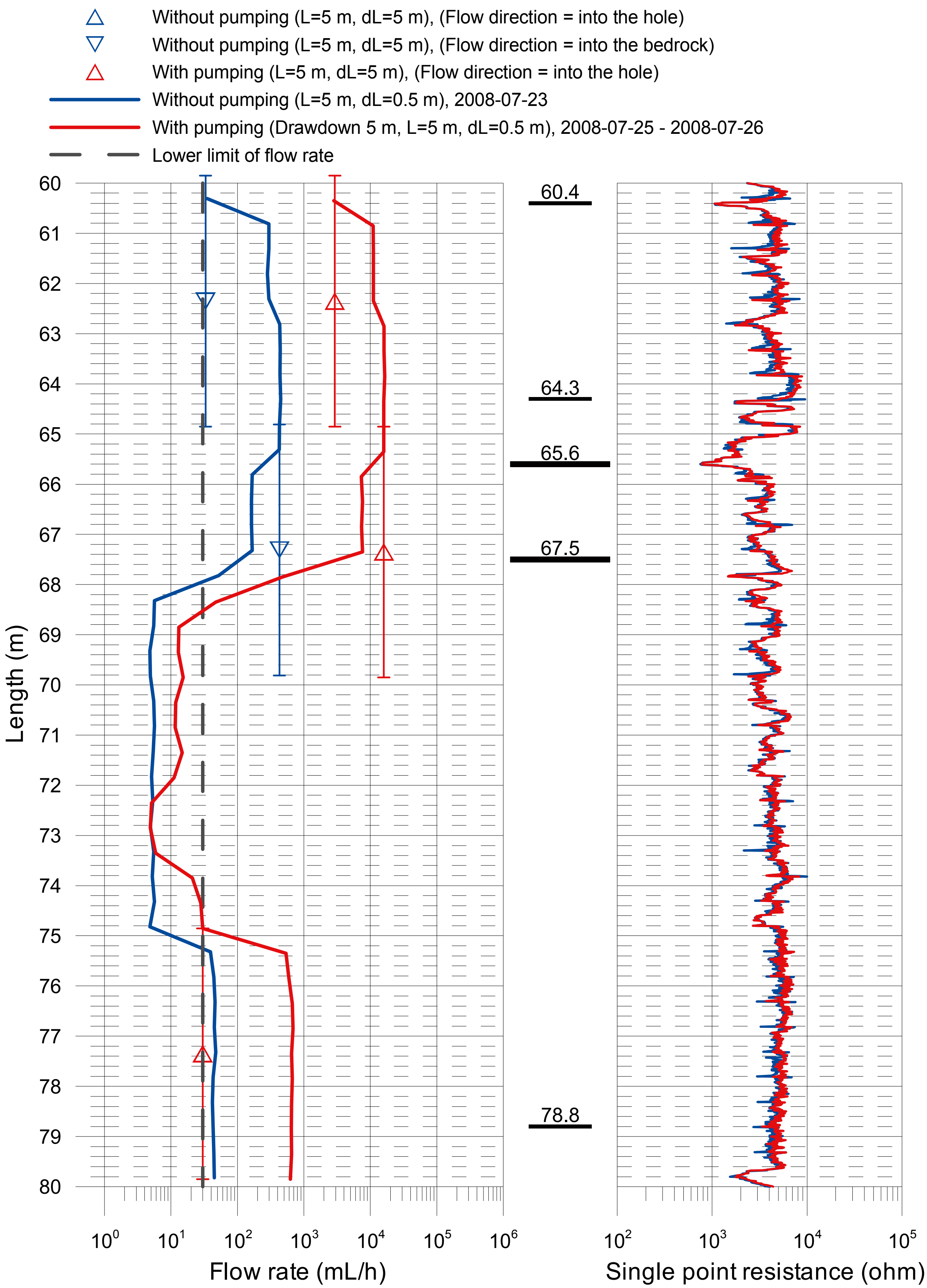
Forsmark, borehole KFR27
Flow rate, caliper and single point resistance



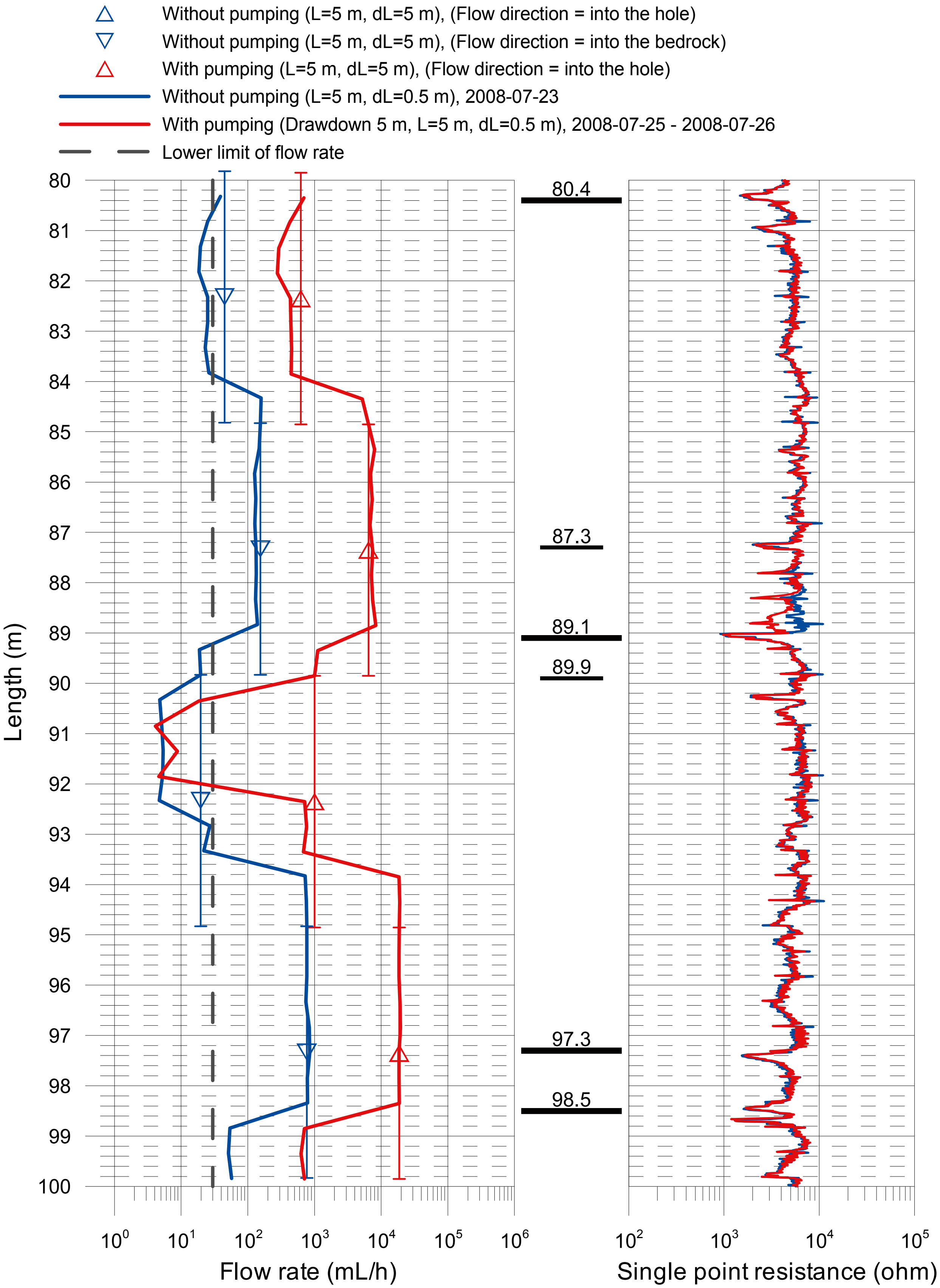
Forsmark, borehole KFR27
Flow rate, caliper and single point resistance



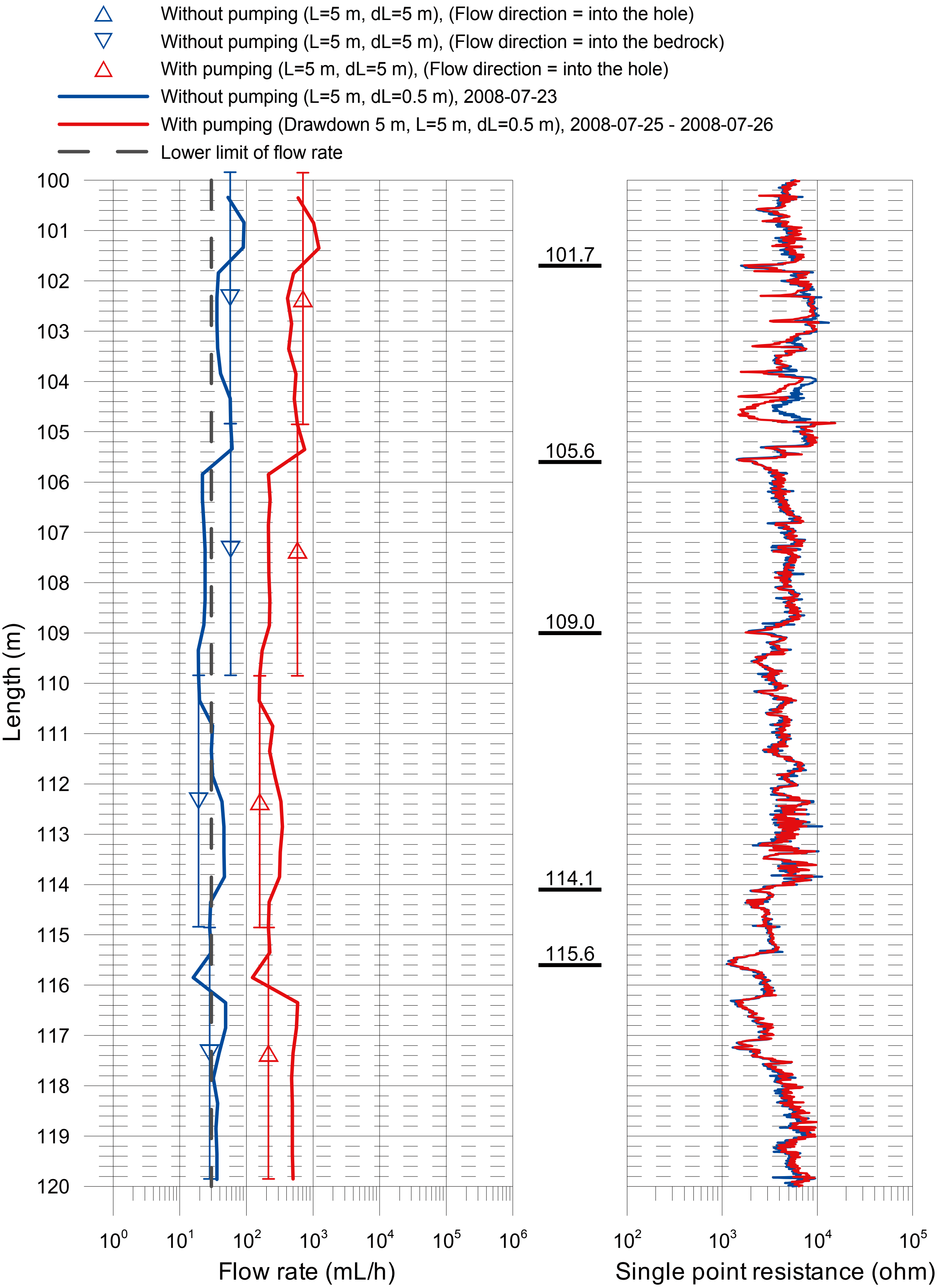
Forsmark, borehole KFR27
Flow rate, caliper and single point resistance



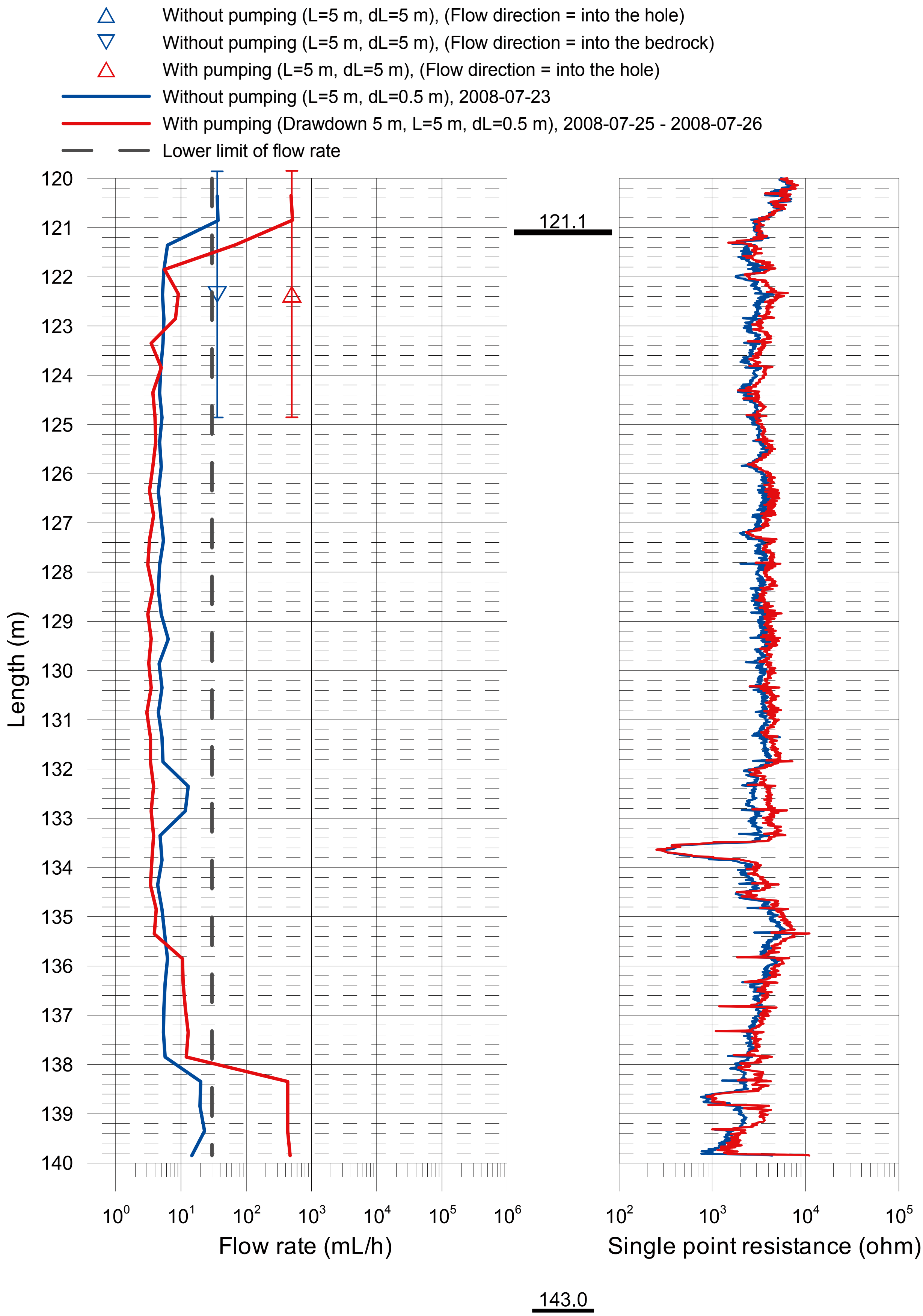
Forsmark, borehole KFR27
Flow rate, caliper and single point resistance



Forsmark, borehole KFR27
Flow rate, caliper and single point resistance



Forsmark, borehole KFR27
Flow rate, caliper and single point resistance

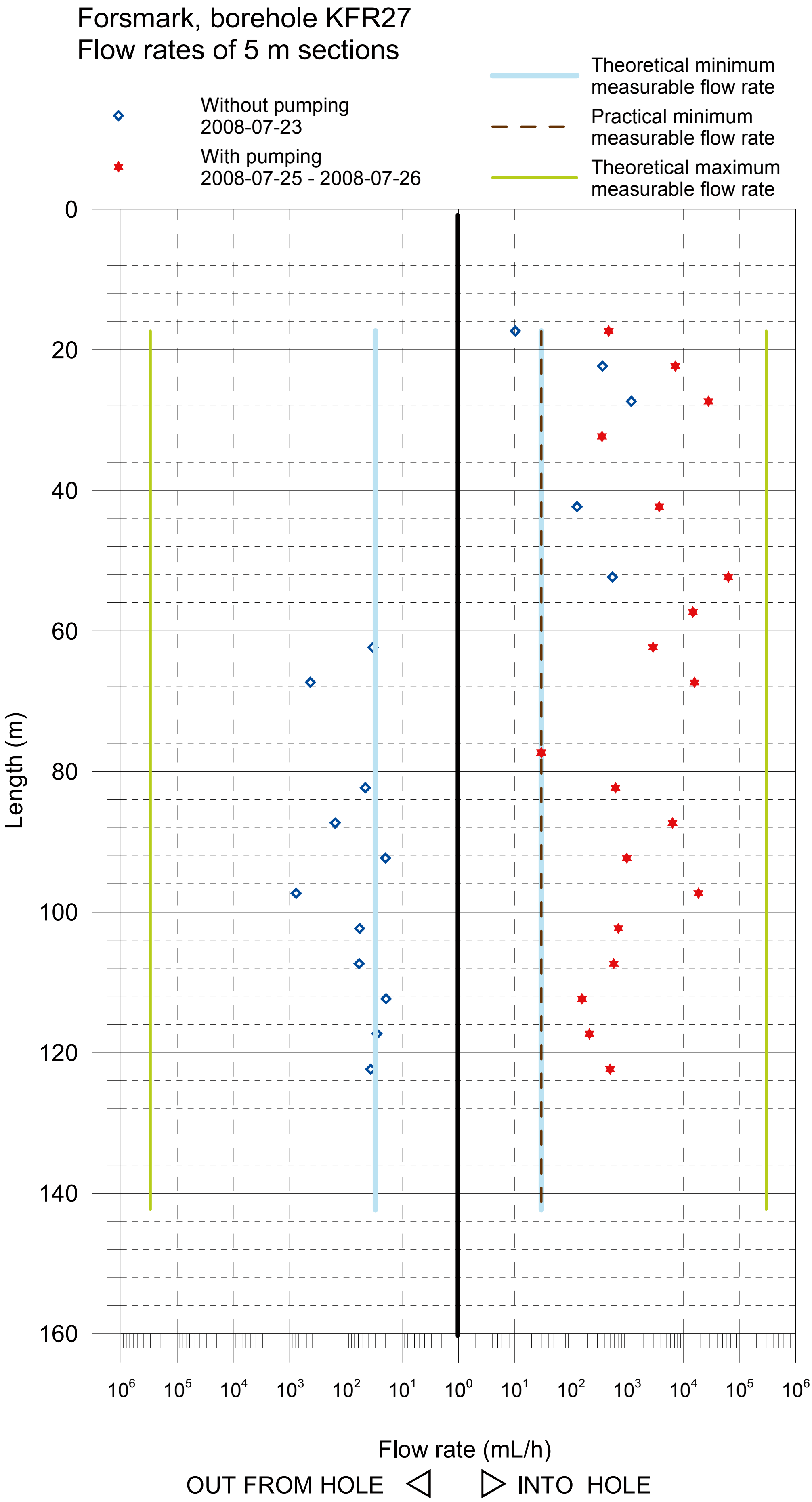


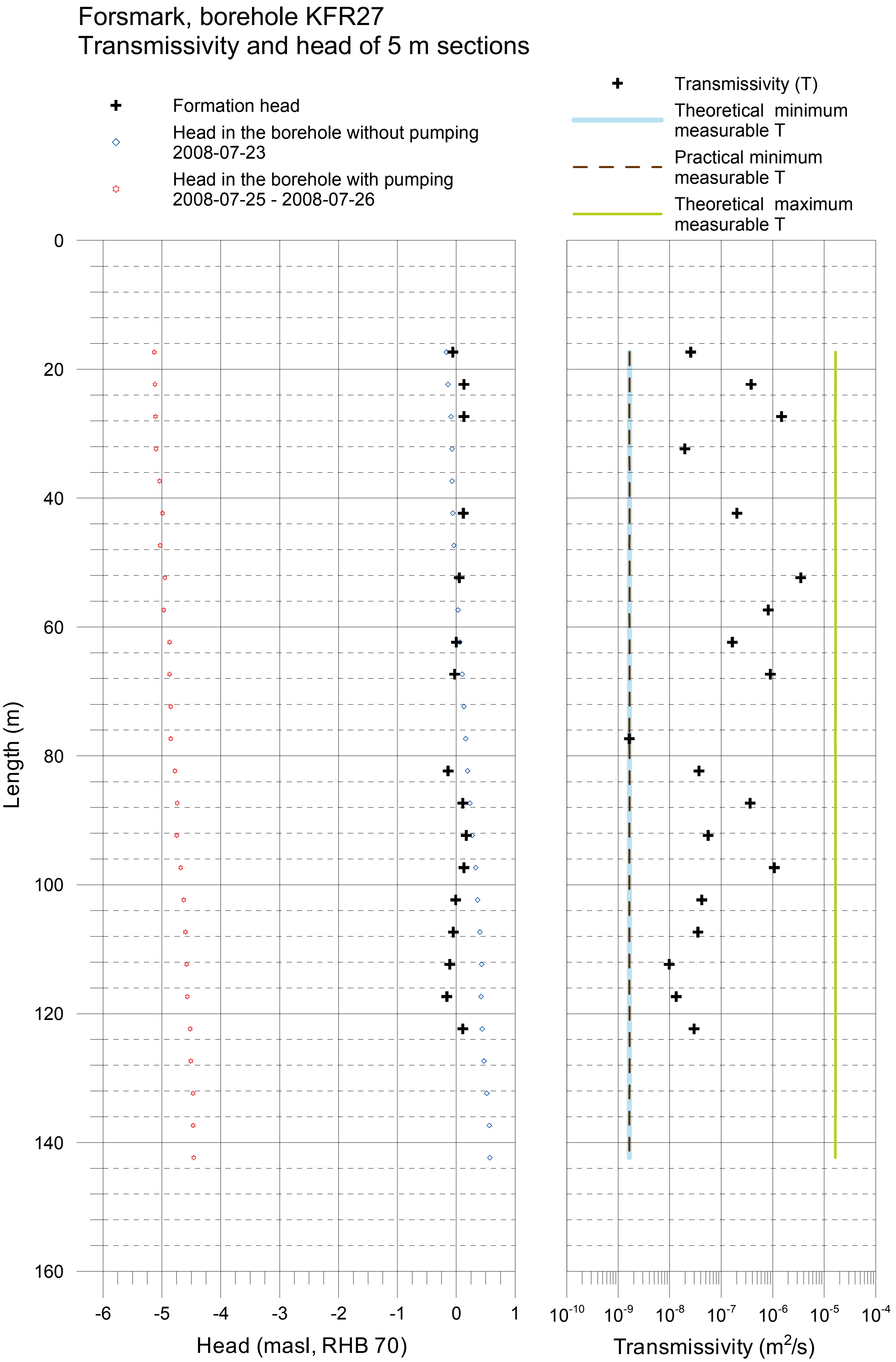
Explanations

Header	Unit	Explanations
Borehole		ID for borehole.
Secup	m	Length along the borehole for the upper limit of the test section (based on corrected length L).
Seclow	m	Length along the borehole for the lower limit of the test section (based on corrected length L).
L	m	Corrected length along borehole based on SKB procedures for length correction.
Length to flow anom.	m	Length along the borehole to inferred flow anomaly during overlapping flow logging.
Test type (1–6)	(–)	1A: Pumping test – wire-line eq. 1B: Pumping test – submersible pump, 1C: Pumping test – airlift pumping, 2: Interference test, 3: Injection test, 4: Slug test, 5A: Difference flow logging – PFL-DIFF – Sequential, 5B: Difference flow logging – PFL-DIFF – Overlapping, 6: Flow logging-Impeller.
Date of test, start	YY-MM-DD	Date for start of pumping.
Time of test, start	hh:mm	Time for start of pumping.
Date of flowl. start	YY-MM-DD	Date for start of the flow logging.
Time of flowl. start	hh:mm	Time for start of the flow logging.
Date of test, stop	YY-MM-DD	Date for stop of the test.
Time of test, stop	hh:mm	Time for stop of the test.
L_w	m	Section length used in the difference flow logging.
dL	m	Step length (increment) used in the difference flow logging.
Q_{p1}	m^3/s	Flow rate at surface by the end of the first pumping period of the flow logging.
Q_{p2}	m^3/s	Flow rate at surface by the end of the second pumping period of the flow logging.
t_{p1}	s	Duration of the first pumping period.
t_{p2}	s	Duration of the second pumping period.
t_{F1}	s	Duration of the first recovery period.
t_{F2}	s	Duration of the second recovery period.
h_0	m.a.s.l.	Initial hydraulic head before pumping. Elevation of water level in open borehole in the local co-ordinates system with z=0 m.
h_1	m.a.s.l.	Stabilised hydraulic head during the first pumping period. Elevation of water level in open borehole in the local co-ordinates system with z=0 m.
h_2	m.a.s.l.	Stabilised hydraulic head during the second pumping period. Elevation of water level in open borehole in the local co-ordinates system with z=0 m.
s_1	m	Drawdown of the water level in the borehole during first pumping period. Difference between the actual hydraulic head and the initial head ($s_1=h_1–h_0$).
s_2	m	Drawdown of the water level in the borehole during second pumping period. Difference between the actual hydraulic head and the initial head ($s_2=h_2–h_0$).
T	m^2/s	Transmissivity of the entire borehole.
Q_0	m^3/s	Measured flow rate through the test section or flow anomaly under natural conditions (no pumping) with $h=h_0$ in the open borehole.
Q_1	m^3/s	Measured flow rate through the test section or flow anomaly during the first pumping period.
Q_2	m^3/s	Measured flow rate through the test section or flow anomaly during the second pumping period.
h_{0FW}	m.a.s.l.	Corrected initial hydraulic head difference along the hole due to e.g. varying salinity conditions of the borehole fluid before pumping.
h_{1FW}	m.a.s.l.	Corrected hydraulic head difference along the hole due to e.g. varying salinity conditions of the borehole fluid during the first pumping period.
h_{2FW}	m.a.s.l.	Corrected hydraulic head difference along the hole due to e.g. varying salinity conditions of the borehole fluid during the second pumping period.
EC_w	S/m	Measured electric conductivity of the borehole fluid in the test section during difference flow logging.
Te_w	°C	Measured borehole fluid temperature in the test section during difference flow logging.
EC_f	S/m	Measured fracture-specific electric conductivity of the fluid in flow anomaly during difference flow logging.
Te_f	°C	Measured fracture-specific fluid temperature in flow anomaly during difference flow logging.
T_D	m^2/s	Transmissivity of section or flow anomaly based on 2D model for evaluation of formation properties of the test section based on PFL-DIFF.
$T\text{-measl}_{LT}$	m^2/s	Estimated theoretical lower measurement limit for evaluated T_D. If the estimated T_D equals T_D-measlim, the actual T_D is considered to be equal or less than T_D-measlim.
$T\text{-measl}_{LP}$	m^2/s	Estimated practical lower measurement limit for evaluated T_D. If the estimated T_D equals T_D-measlim, the actual T_D is considered to be equal or less than T_D-measlim.
$T\text{-measl}_{U}$	m^2/s	Estimated upper measurement limit for evaluated T_D. If the estimated T_D equals T_D-measlim, the actual T_D is considered to be equal or less than T_D-measlim.
h_i	m.a.s.l.	Calculated relative, natural freshwater head for test section or flow anomaly (undisturbed conditions).

Results of sequential flow logging

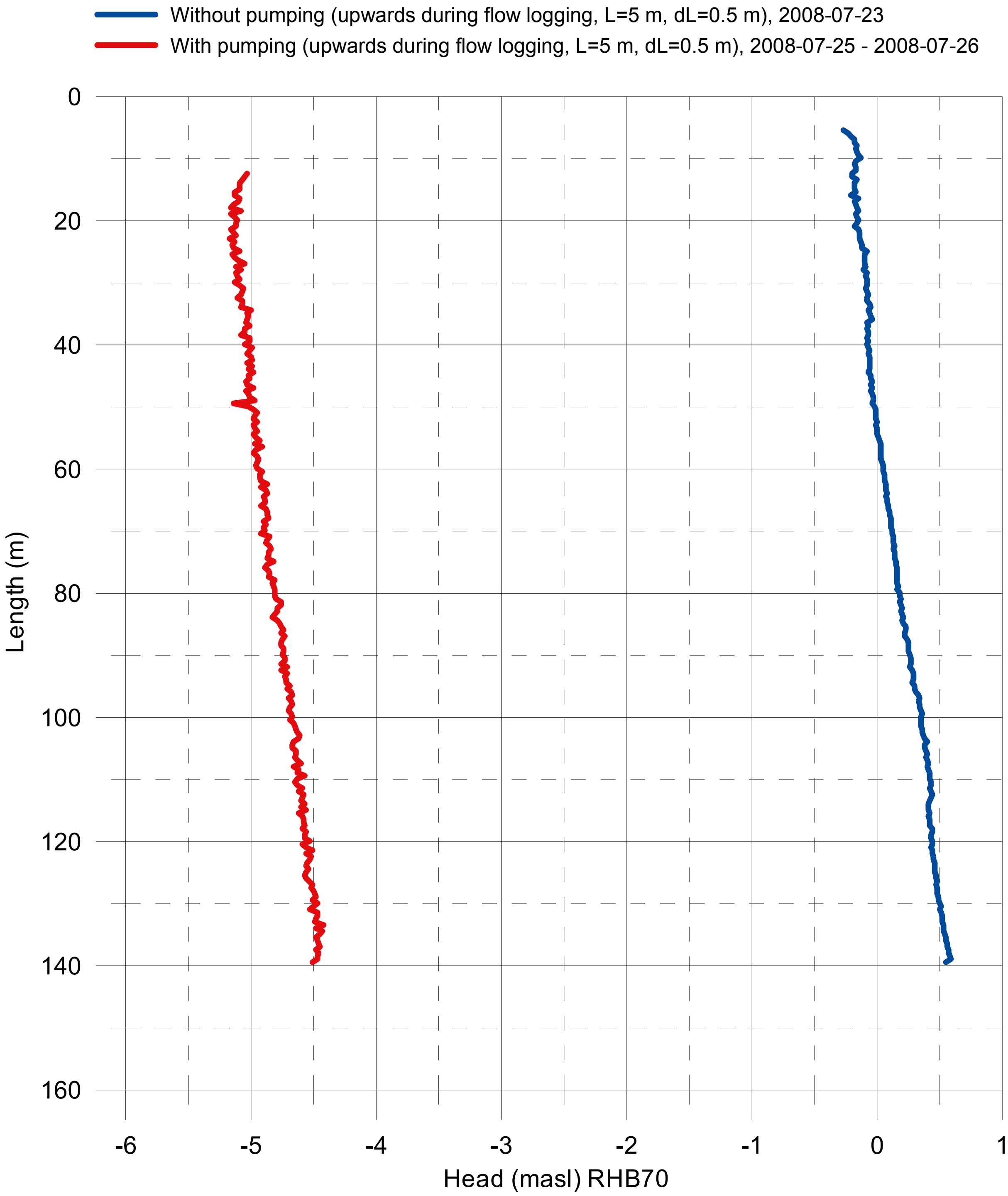
Borehole ID	Secup L(m)	Seclow L(m)	L_w (m)	Q_0 (m^3/s)	h_{0FW} (m.a.s.l.)	Q_1 (m^3/s)	h_{1FW} (m.a.s.l.)	T_D (m^2/s)	h_i (m.a.s.l.)	Q-lower limit P (mL/h)	T_D-measl$_{LT}$ (m^2/s)	TD- measl$_{LP}$ (m^2/s)	TD- measl$_U$ (m^2/s)	Comments
KFR27	14.84	19.84	5	2.86E–09	–0.17	1.31E–07	–5.13	2.6E–08	–0.1	30	1.7E–09	1.7E–09	1.7E–05	
KFR27	19.84	24.84	5	1.03E–07	–0.14	2.02E–06	–5.12	3.8E–07	0.1	30	1.7E–09	1.7E–09	1.7E–05	
KFR27	24.85	29.85	5	3.33E–07	–0.09	7.86E–06	–5.11	1.5E–06	0.1	30	1.6E–09	1.6E–09	1.6E–05	
KFR27	29.85	34.85	5	–	–0.07	1.00E–07	–5.10	2.0E–08	–	30	1.6E–09	1.6E–09	1.6E–05	
KFR27	34.85	39.85	5	–	–0.07	–	–5.04	–	–	30	1.7E–09	1.7E–09	1.7E–05	
KFR27	39.85	44.85	5	3.58E–08	–0.06	1.04E–06	–4.99	2.0E–07	0.1	30	1.7E–09	1.7E–09	1.7E–05	
KFR27	44.85	49.85	5	–	–0.04	–	–5.03	–	–	30	1.7E–09	1.7E–09	1.7E–05	
KFR27	49.85	54.85	5	1.54E–07	0.01	1.77E–05	–4.95	3.5E–06	0.1	30	1.7E–09	1.7E–09	1.7E–05	
KFR27	54.85	59.85	5	–	0.03	4.14E–06	–4.97	8.2E–07	–	30	1.6E–09	1.6E–09	1.6E–05	
KFR27	59.85	64.85	5	–9.17E–09	0.06	8.08E–07	–4.87	1.6E–07	–	30	1.7E–09	1.7E–09	1.7E–05	
KFR27	64.83	69.83	5	–1.19E–07	0.10	4.42E–06	–4.87	9.0E–07	0.0	30	1.7E–09	1.7E–09	1.7E–05	
KFR27	69.84	74.84	5	–	0.13	–	–4.85	–	–	30	1.7E–09	1.7E–09	1.7E–05	
KFR27	74.84	79.84	5	–	0.16	8.33E–09	–4.85	1.6E–09	–	30	1.6E–09	1.6E–09	1.6E–05	
KFR27	79.84	84.84	5	–1.25E–08	0.19	1.74E–07	–4.78	3.7E–08	–0.1	30	1.7E–09	1.7E–09	1.7E–05	
KFR27	84.84	89.84	5	–4.31E–08	0.23	1.79E–06	–4.74	3.7E–07	0.1	30	1.7E–09	1.7E–09	1.7E–05	
KFR27	89.84	94.84	5	–5.47E–09	0.27	2.77E–07	–4.75	5.6E–08	0.2	30	1.6E–09	1.6E–09	1.6E–05	
KFR27	94.84	99.84	5	–2.13E–07	0.33	5.19E–06	–4.68	1.1E–06	0.1	30	1.6E–09	1.6E–09	1.7E–05	
KFR27	99.85	104.85	5	–1.58E–08	0.36	1.96E–07	–4.63	4.2E–08	0.0	30	1.7E–09	1.7E–09	1.7E–05	
KFR27	104.85	109.85	5	–1.61E–08	0.40	1.62E–07	–4.60	3.5E–08	–0.1	30	1.6E–09	1.6E–09	1.7E–05	
KFR27	109.85	114.85	5	–5.33E–09	0.43	4.42E–08	–4.58	9.8E–09	–0.1	30	1.6E–09	1.6E–09	1.6E–05	
KFR27	114.85	119.85	5	–7.78E–09	0.42	5.97E–08	–4.57	1.3E–08	–0.2	30	1.7E–09	1.7E–09	1.7E–05	
KFR27	119.86	124.86	5	–1.00E–08	0.44	1.39E–07	–4.52	3.0E–08	0.1	30	1.7E–09	1.7E–09	1.7E–05	
KFR27	124.86	129.86	5	–	0.47	–	–4.51	–	–	30	1.7E–09	1.7E–09	1.7E–05	
KFR27	129.86	134.86	5	–	0.52	–	–4.47	–	–	30	1.7E–09	1.7E–09	1.7E–05	
KFR27	134.85	139.85	5	–	0.56	–	–4.47	–	–	30	1.6E–09	1.6E–09	1.6E–05	
KFR27	139.85	144.85	5	–	0.57	–	–4.46	–	–	30	1.6E–09	1.6E–09	1.6E–05	


Forsmark, borehole KFR27
Flow rates of 5 m sections
Without pumping
2008-07-23
With pumping
2008-07-25 - 2008-07-26
Theoretical minimum measurable flow rate
Practical minimum measurable flow rate
Theoretical maximum measurable flow rate
Length (m)
0
20
40
60
80
100
120
140
160
10^6 10^5 10^4 10^3 10^2 10^1 10^0 10^1 10^2 10^3 10^4 10^5 10^6
Flow rate (mL/h)
OUT FROM HOLE
INTO HOLE

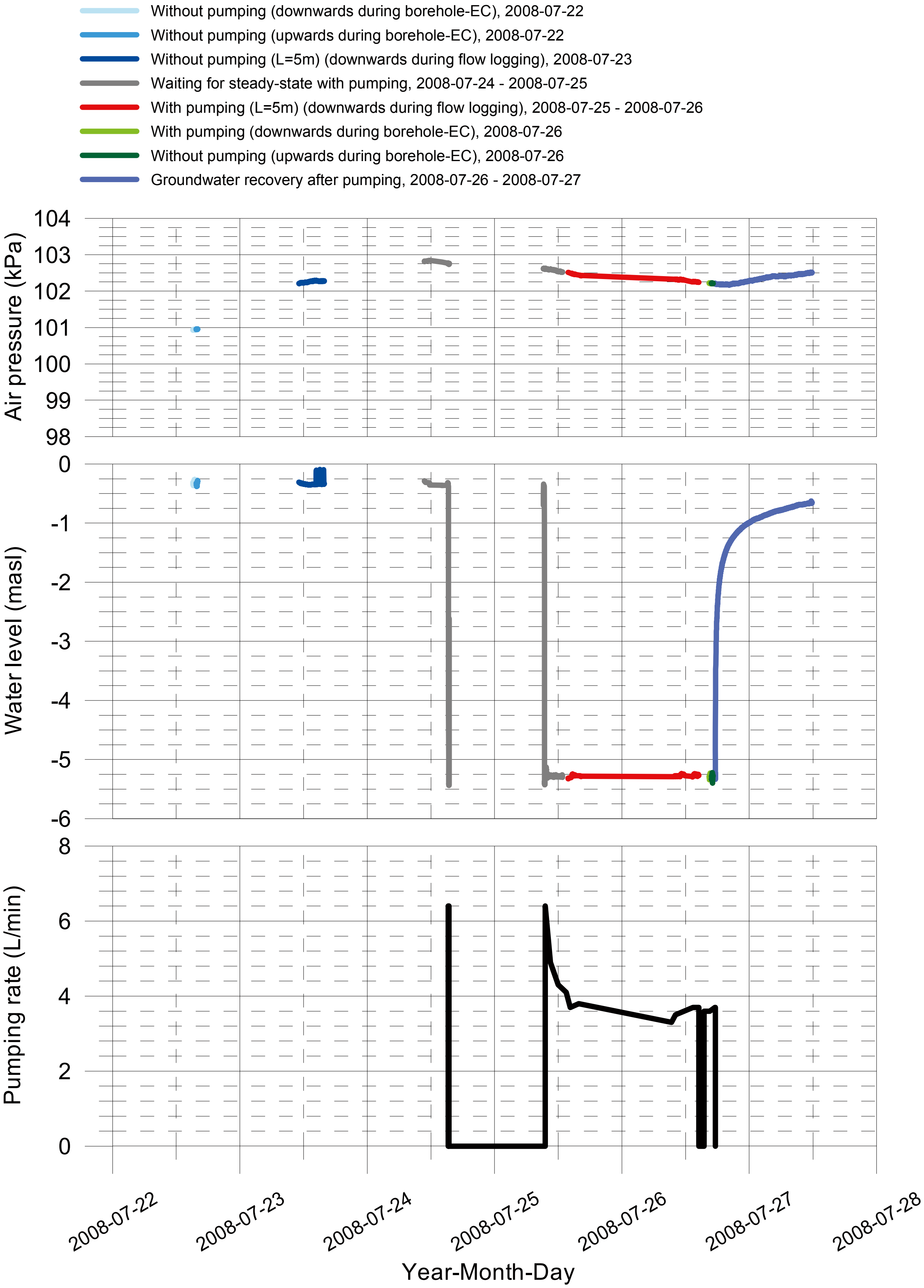

Forsmark, borehole KFR27
Transmissivity and head of 5 m sections
Formation head
Head in the borehole without pumping 2008-07-23
Head in the borehole with pumping 2008-07-25 - 2008-07-26
Transmissivity (T)
Theoretical minimum measurable T
Practical minimum measurable T
Theoretical maximum measurable T
Length (m)
Head (masl, RHB 70)
Transmissivity (m2/s)

Forsmark, borehole KFR27
Head in the borehole during flow logging

Head(masl)= (Absolute pressure (Pa) - Airpressure (Pa) + Offset) /(1000 kg/m^3 * 9.80665 m/s^2) + Elevation (m)
Offset = 4500 Pa (Correction for absolute pressure sensor)

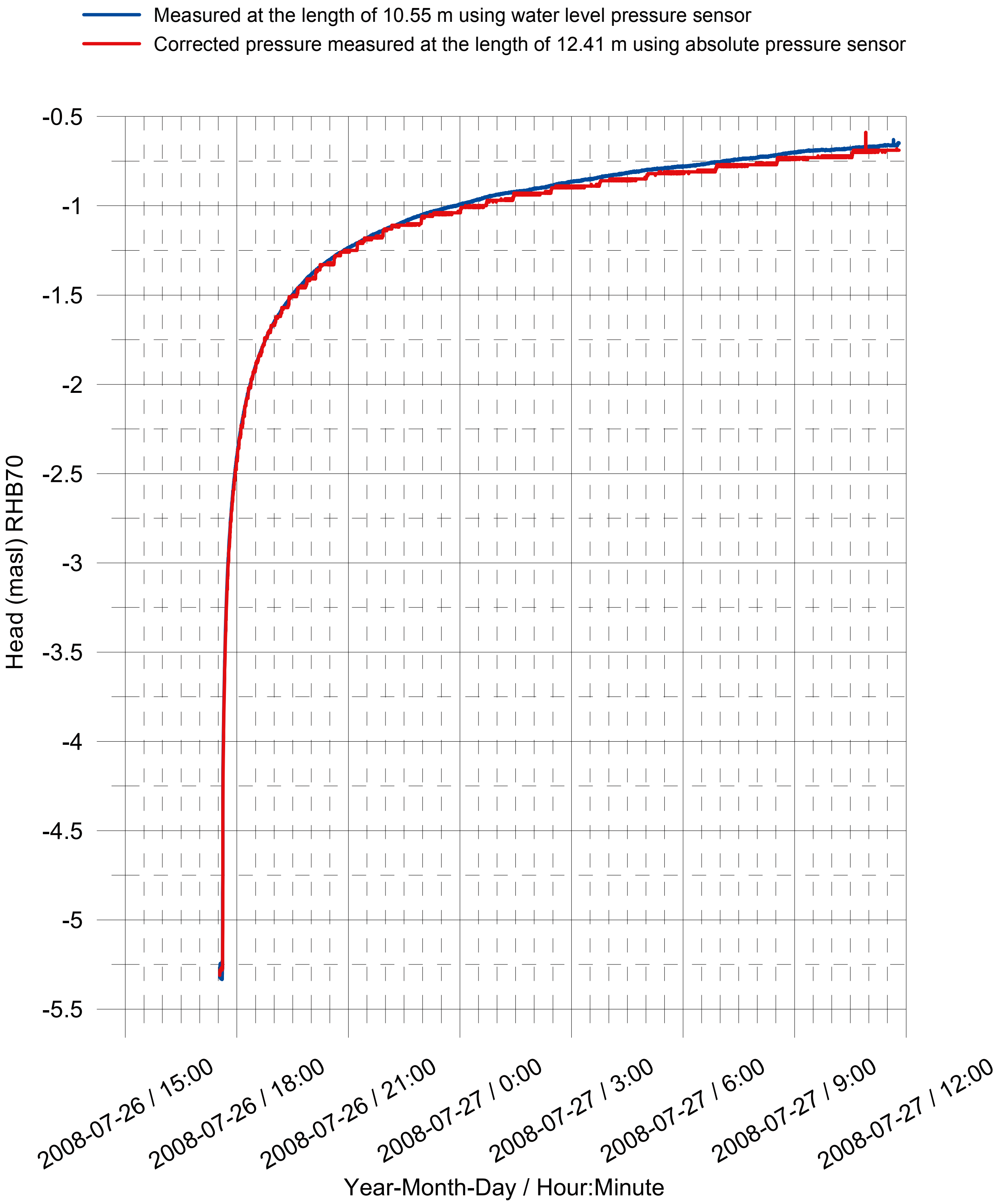


Forsmark, borehole KFR27
Air pressure, water level in the borehole and pumping rate during flow logging

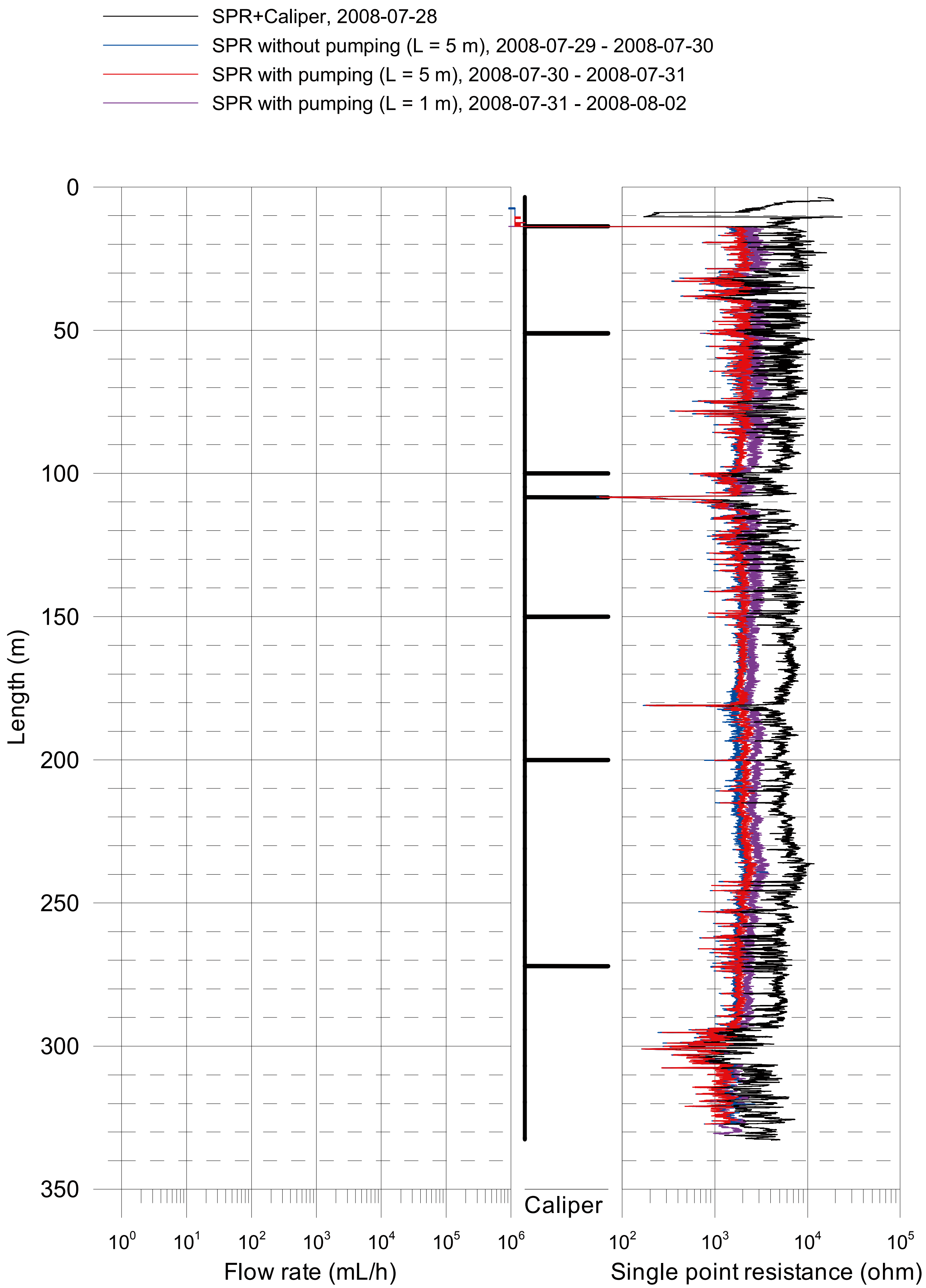


Forsmark, borehole KFR27
Groundwater recovery after pumping

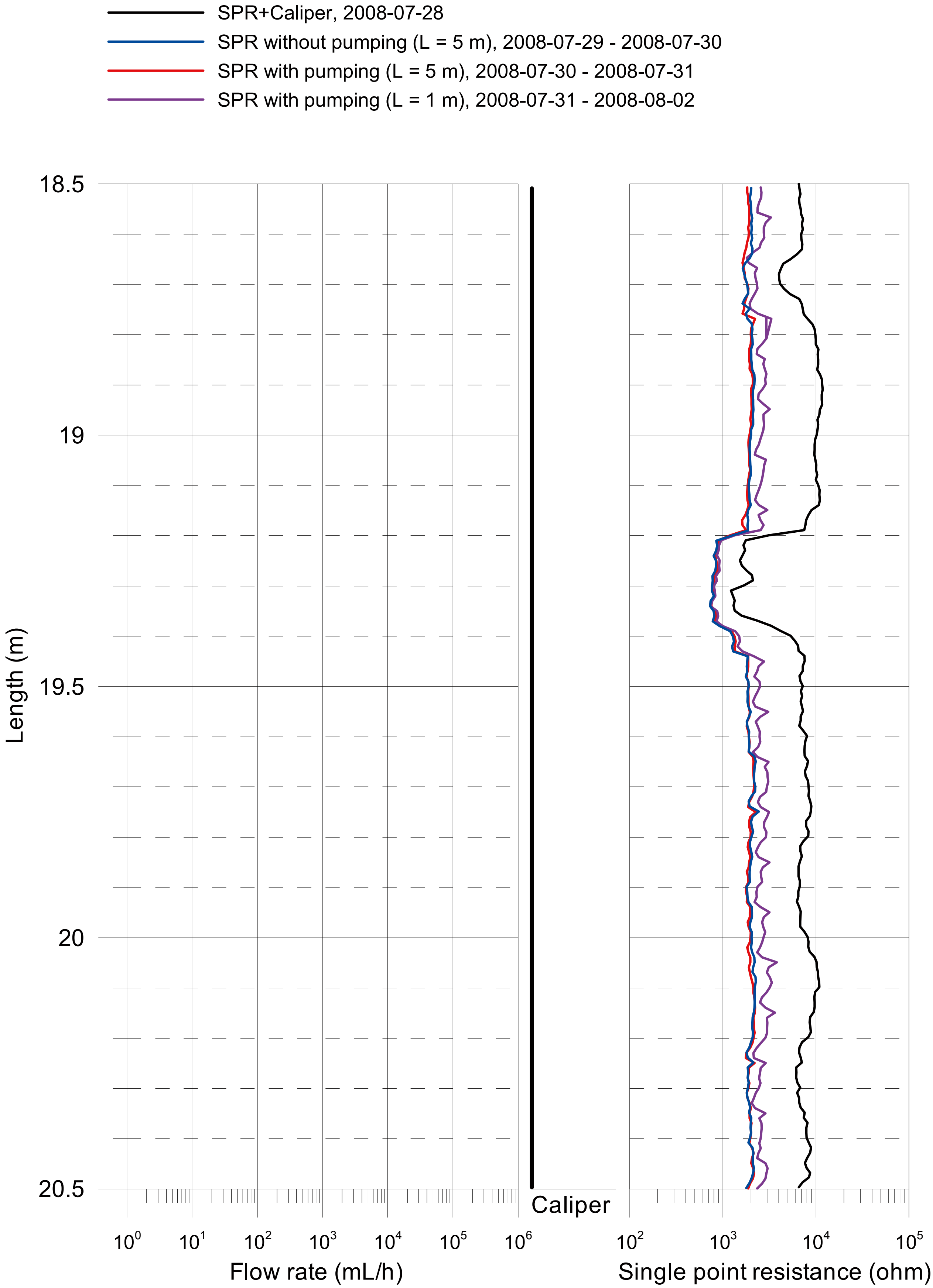
Head(masl)= (Absolute pressure (Pa) - Airpressure (Pa) + Offset) /(1000 kg/m^3 * 9.80665 m/s^2) + Elevation (m)
Offset = 4500 Pa (Correction for absolute pressure sensor)



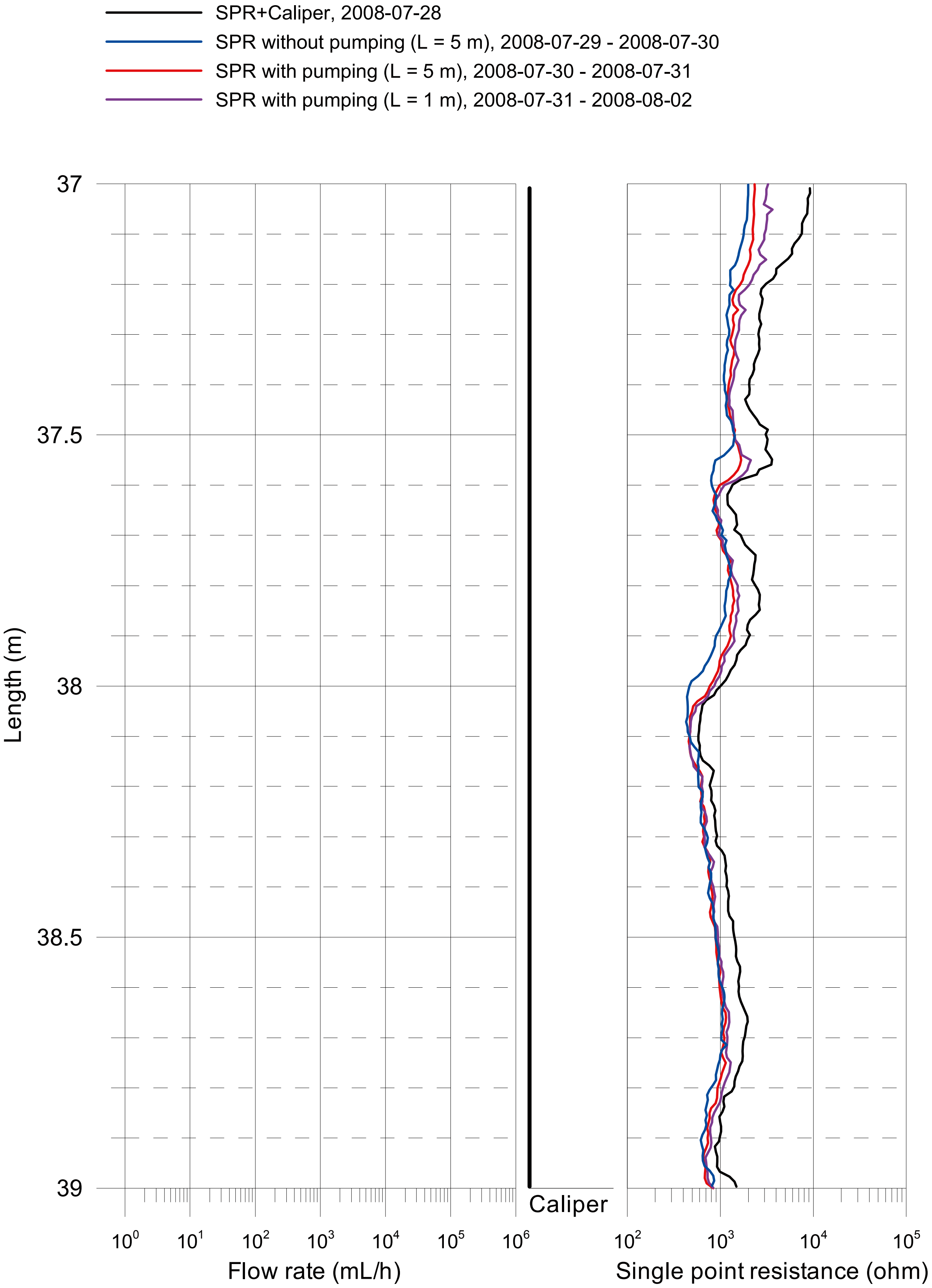
Forsmark, borehole KFR101
SPR and Caliper results after length correction



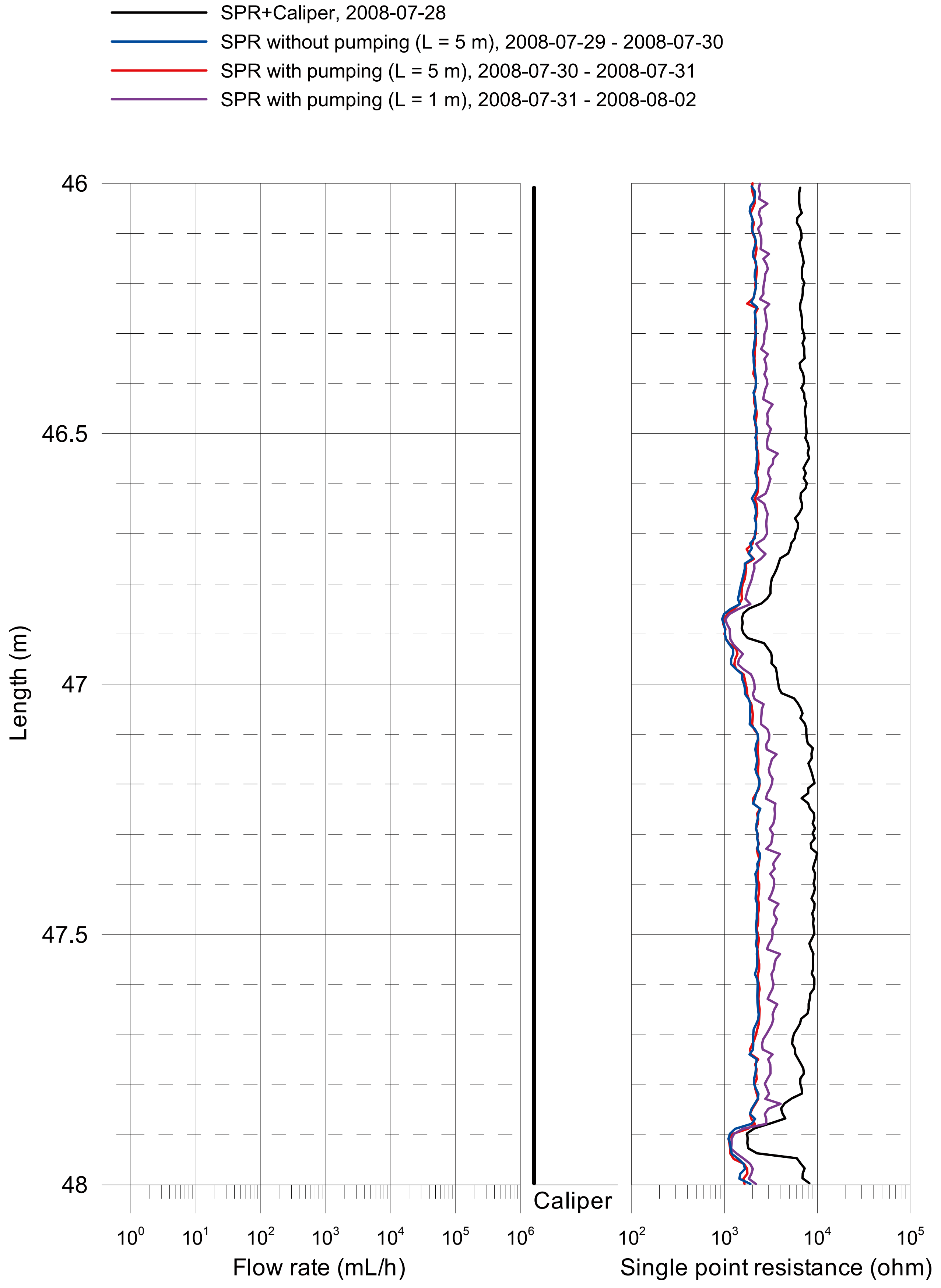
Forsmark, borehole KFR101
SPR and Caliper results after length correction



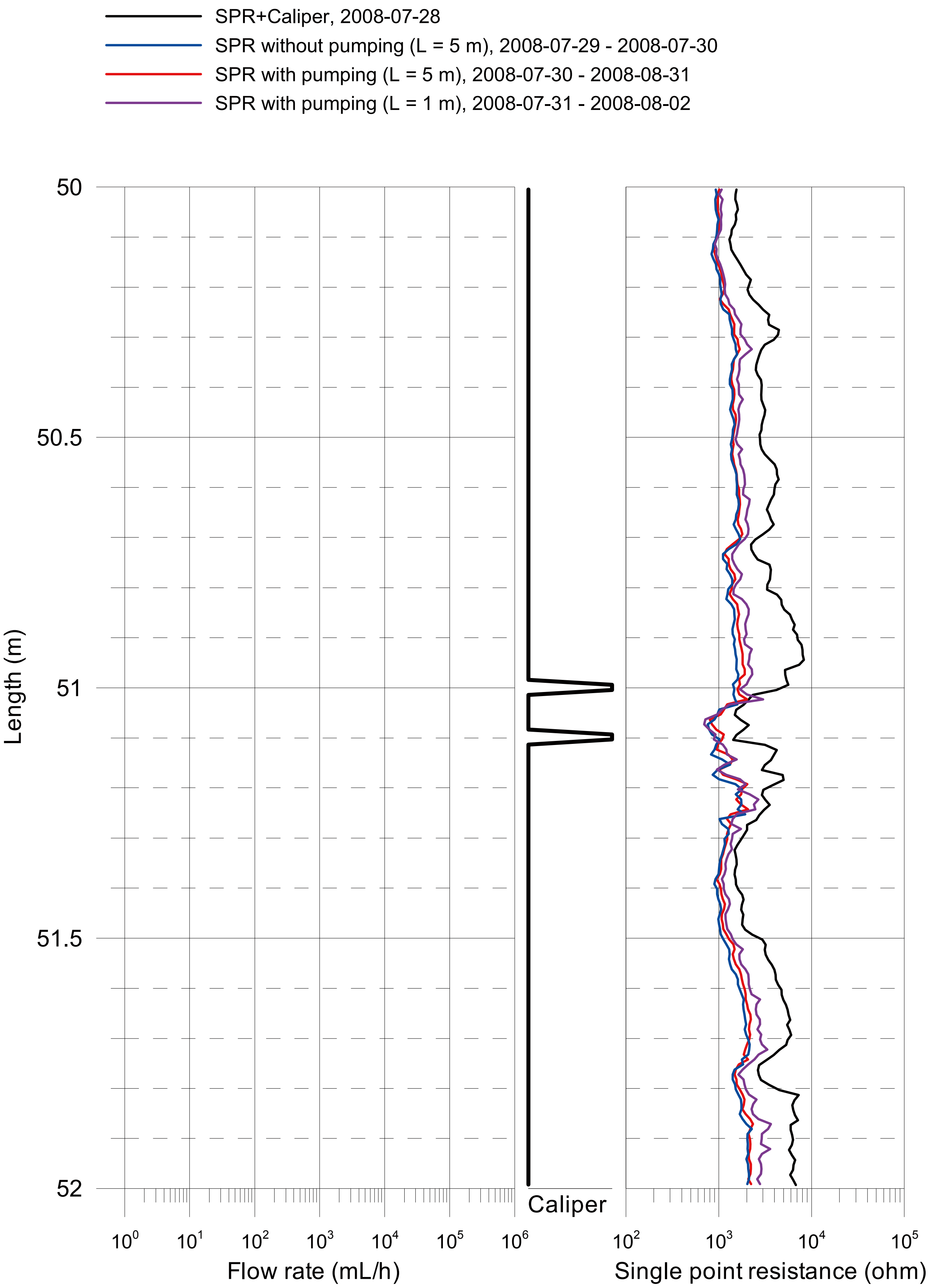
Forsmark, borehole KFR101
SPR and Caliper results after length correction



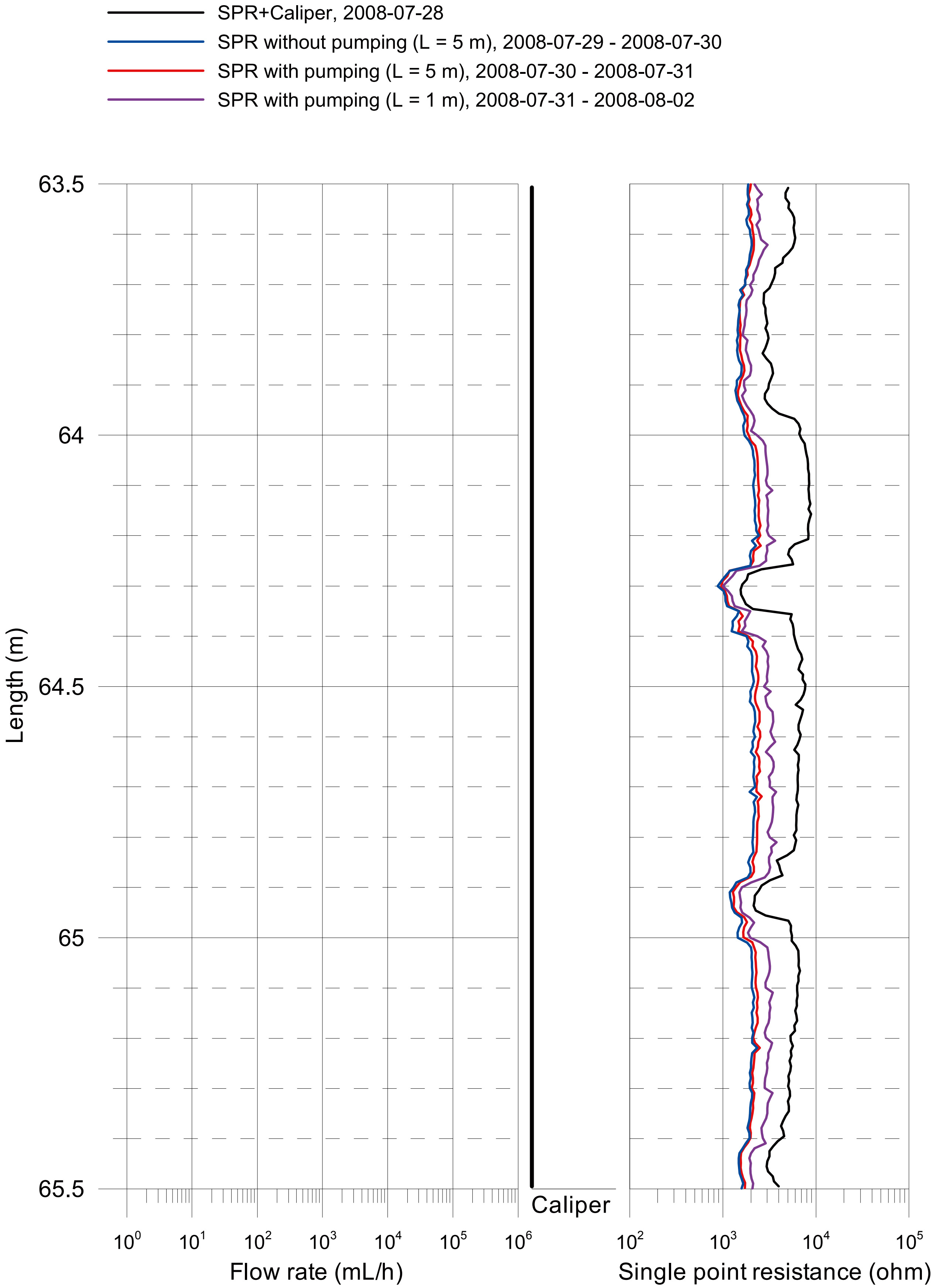
Forsmark, borehole KFR101
SPR and Caliper results after length correction



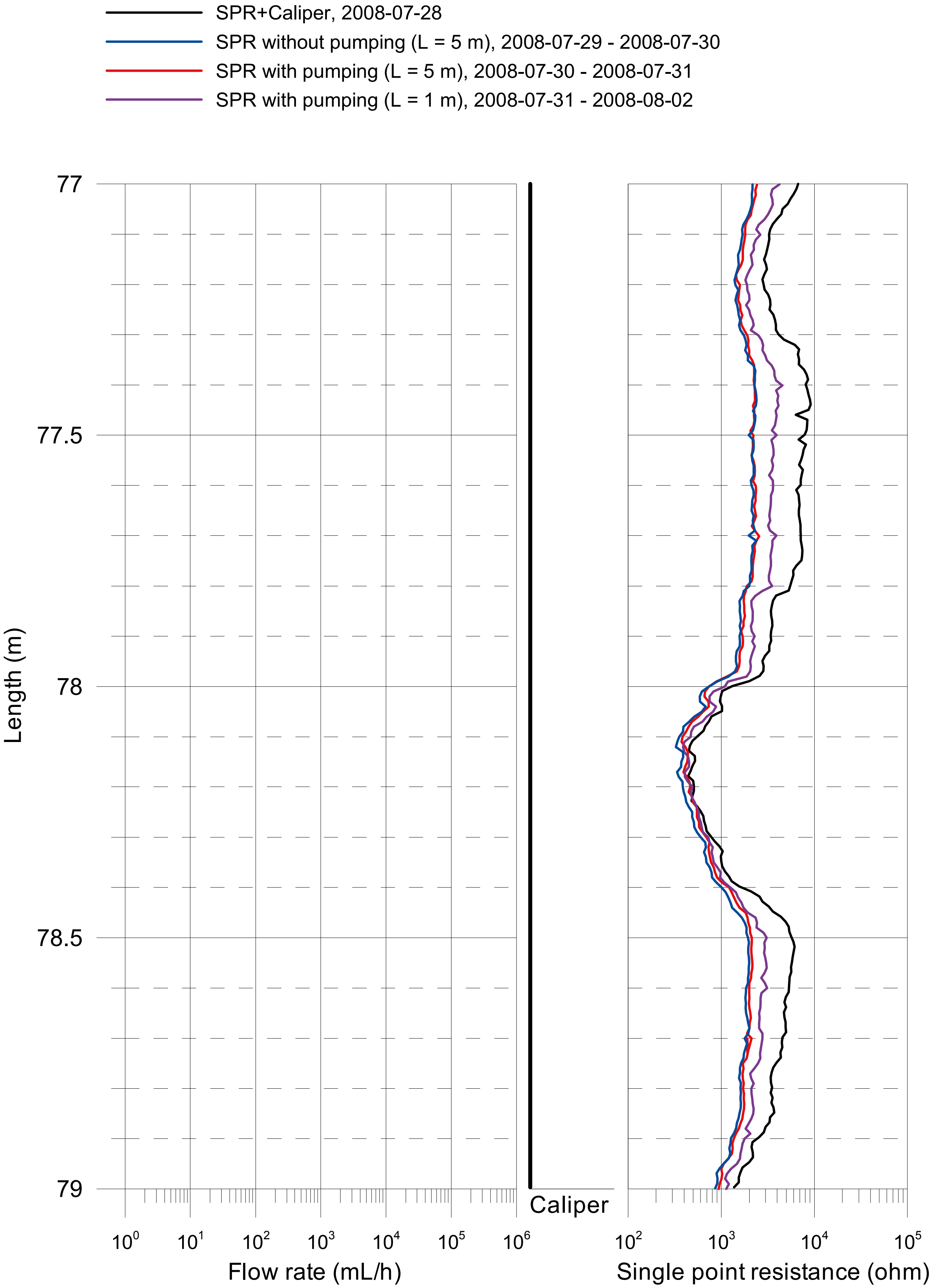
Forsmark, borehole KFR101
SPR and Caliper results after length correction



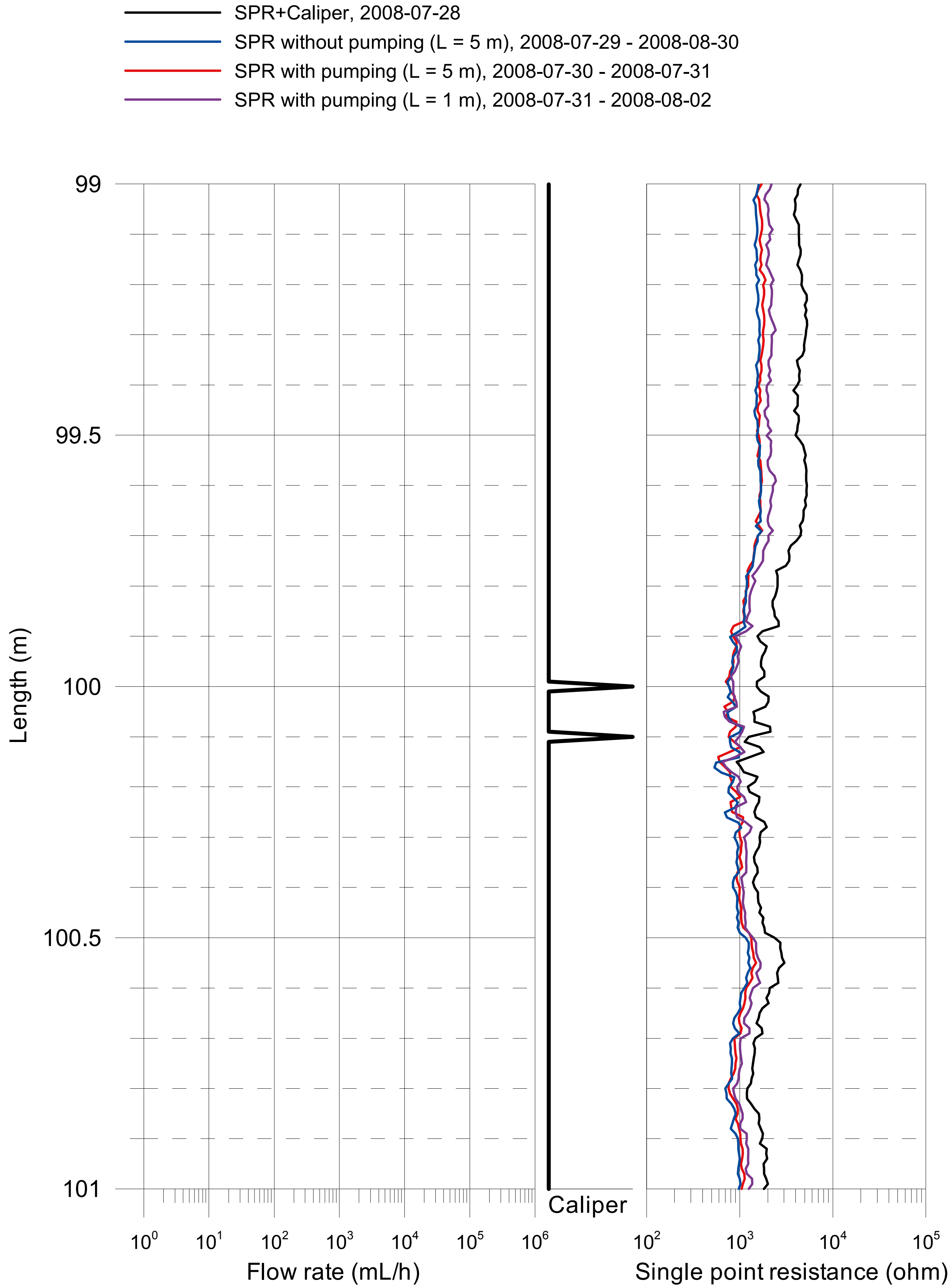
Forsmark, borehole KFR101
SPR and Caliper results after length correction

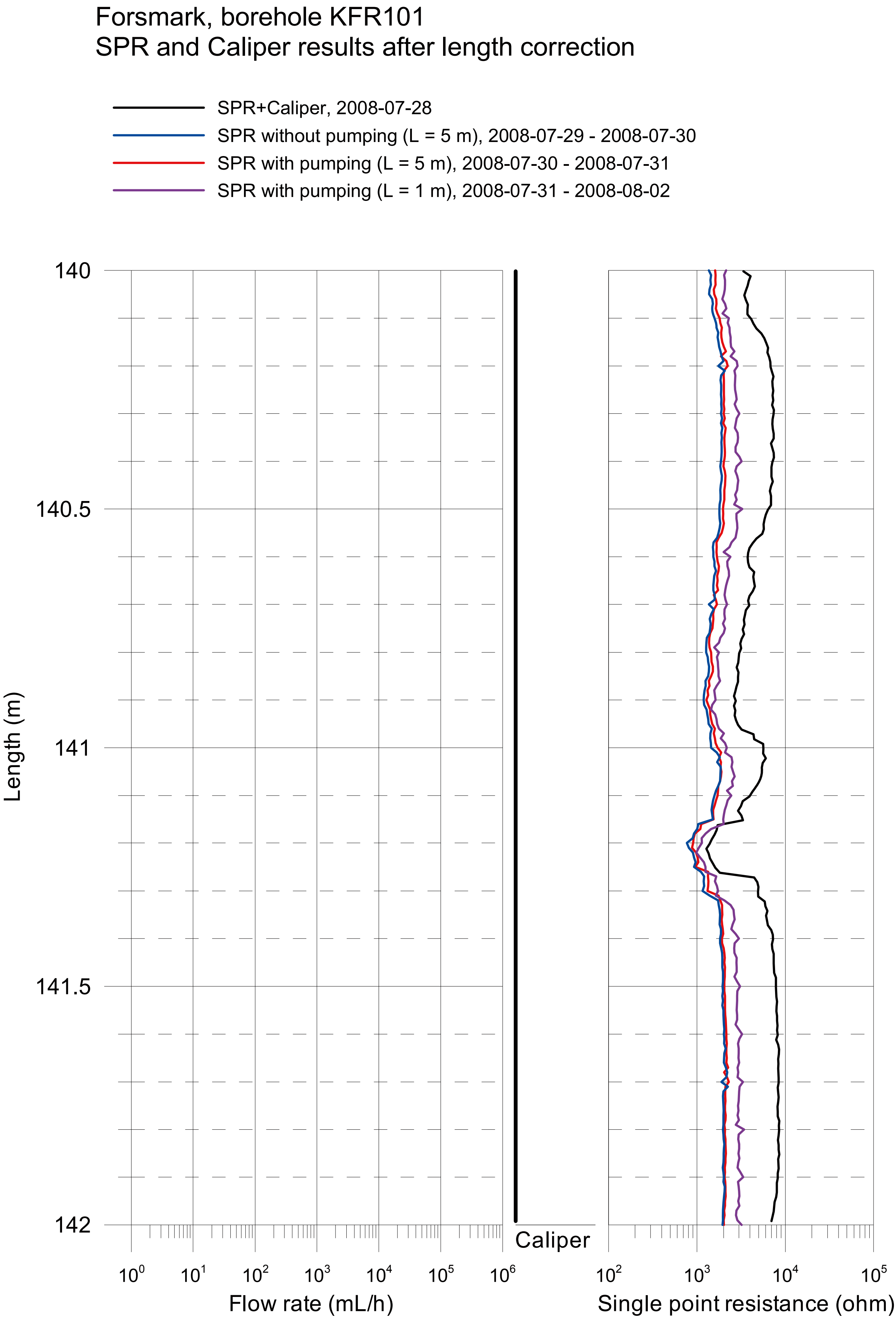


Forsmark, borehole KFR101
SPR and Caliper results after length correction

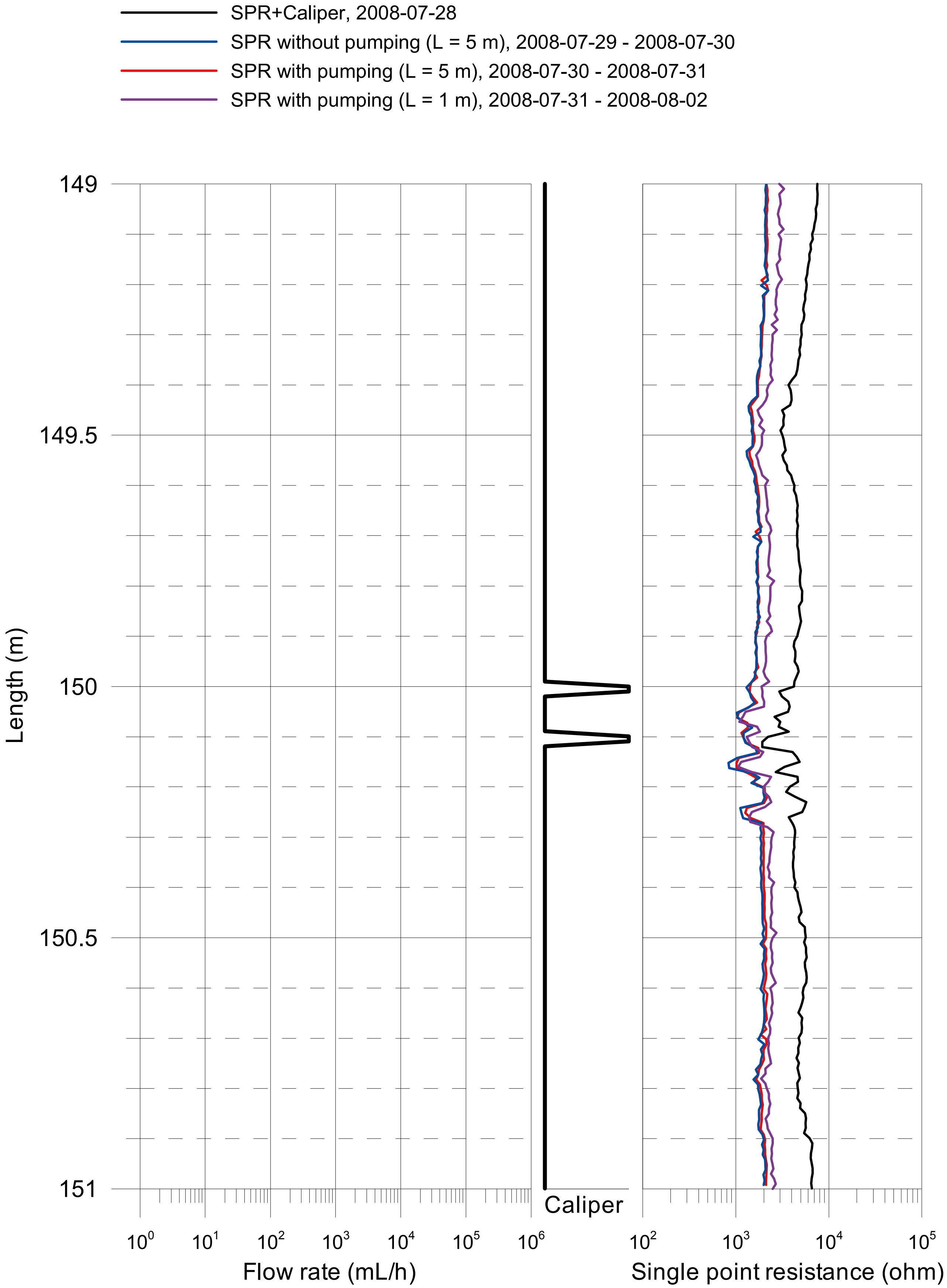


Forsmark, borehole KFR101
SPR and Caliper results after length correction

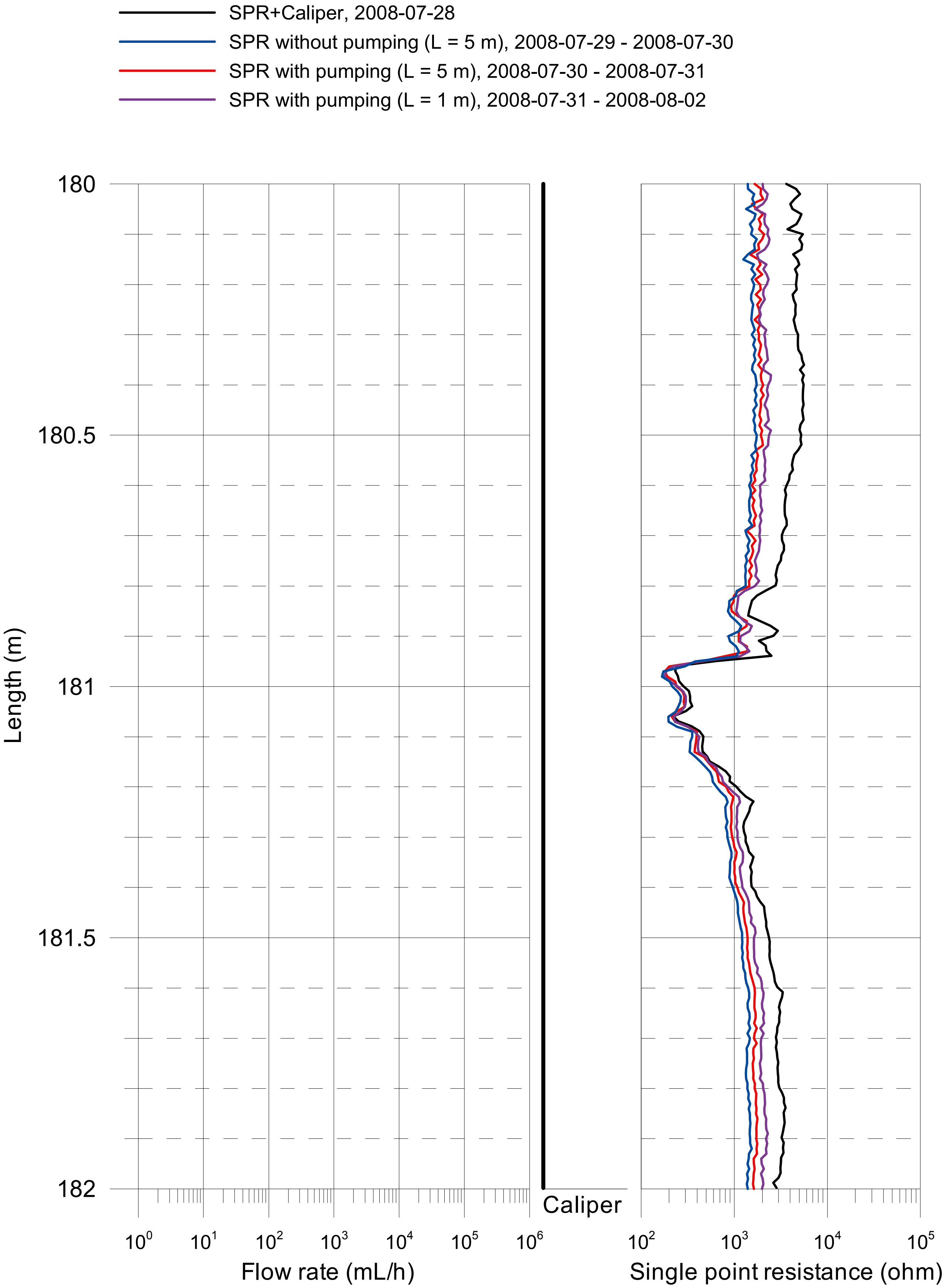



Forsmark, borehole KFR101
SPR and Caliper results after length correction
SPR+Caliper, 2008-07-28
SPR without pumping (L = 5 m), 2008-07-29 - 2008-07-30
SPR with pumping (L = 5 m), 2008-07-30 - 2008-07-31
SPR with pumping (L = 1 m), 2008-07-31 - 2008-08-02
Length (m)
140
140.5
141
141.5
142
Caliper
10^0 10^1 10^2 10^3 10^4 10^5 10^6
Flow rate (mL/h)
10^2 10^3 10^4 10^5
Single point resistance (ohm)

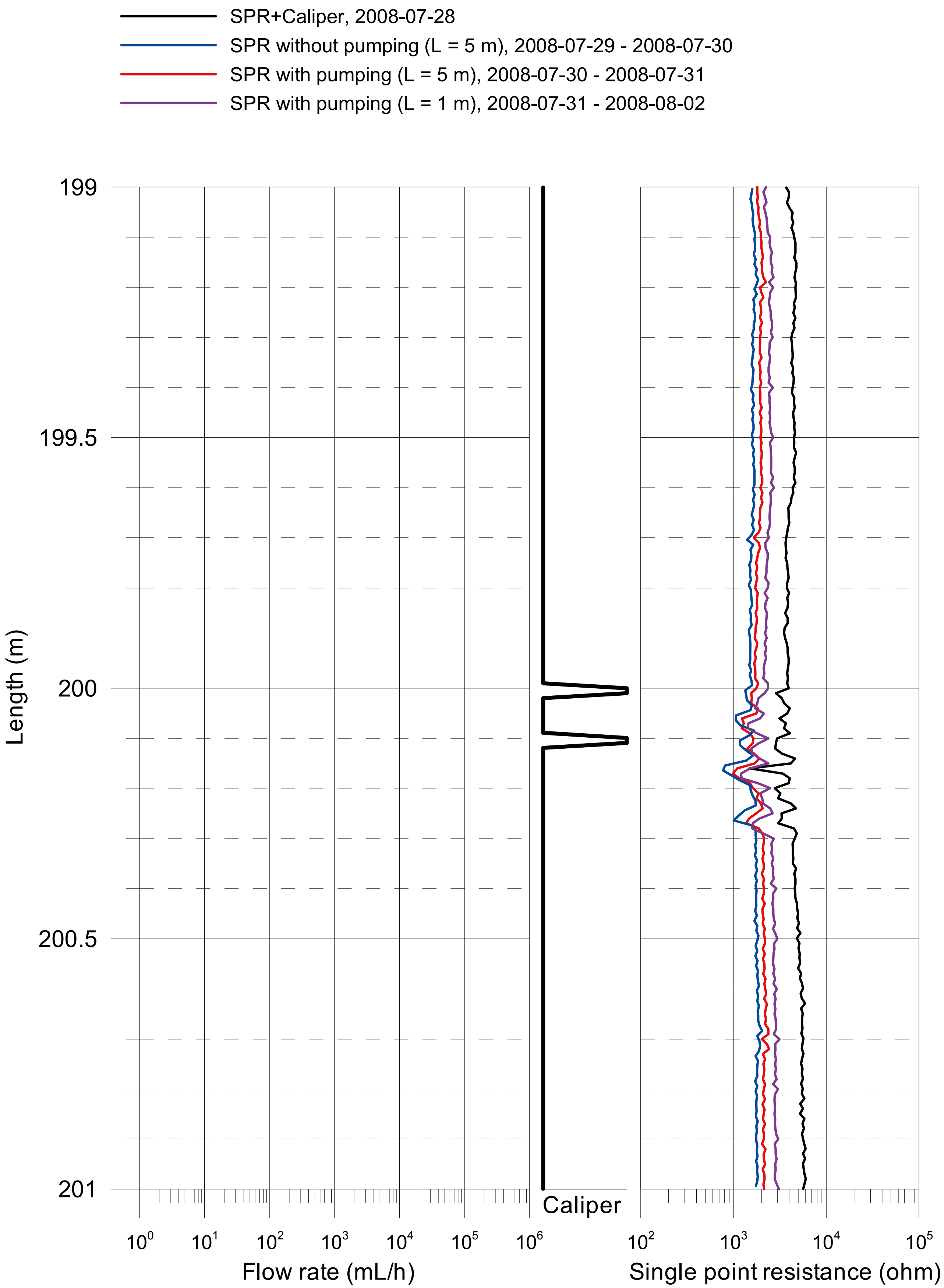
Forsmark, borehole KFR101
SPR and Caliper results after length correction



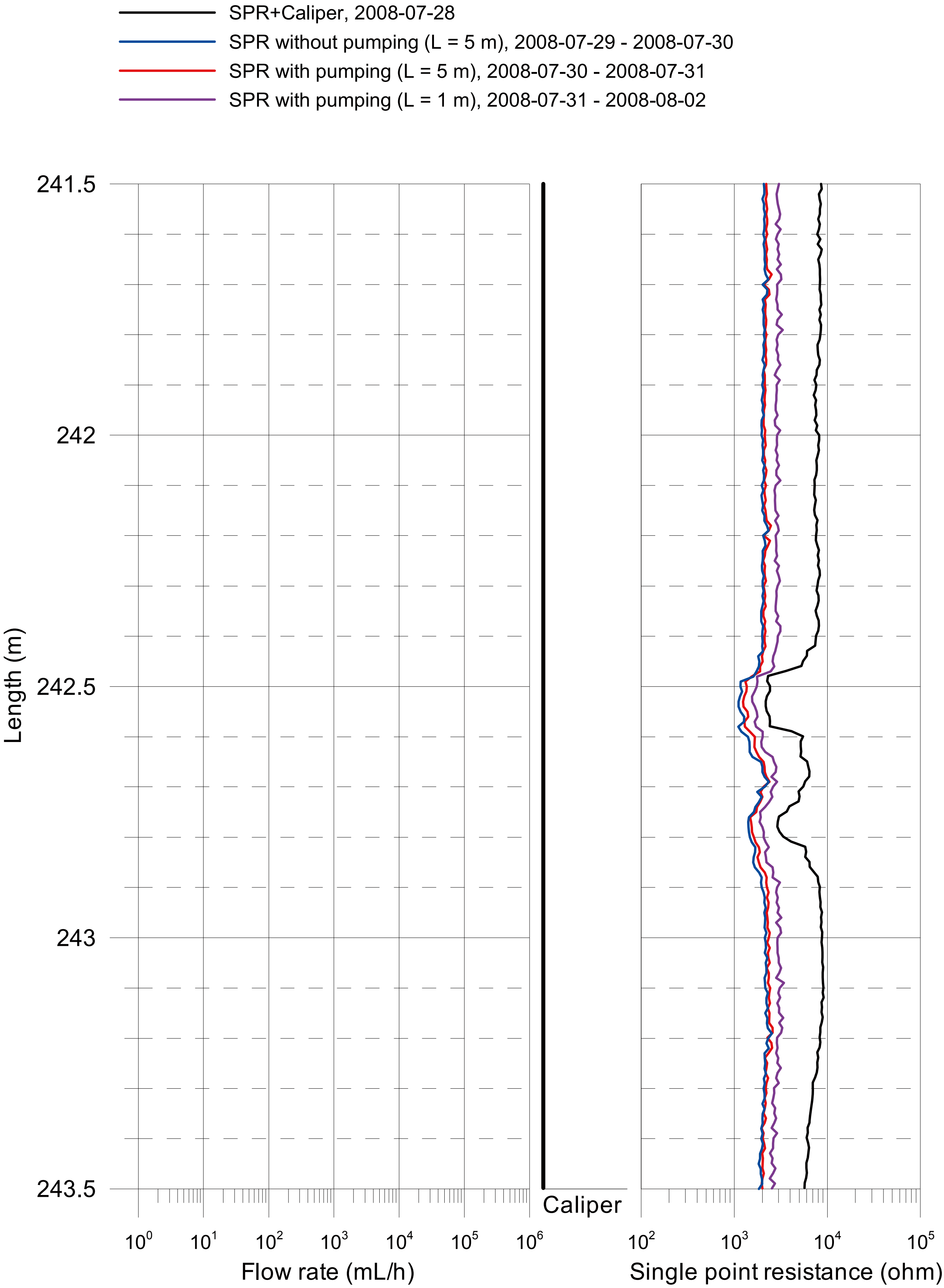
Forsmark, borehole KFR101
SPR and Caliper results after length correction



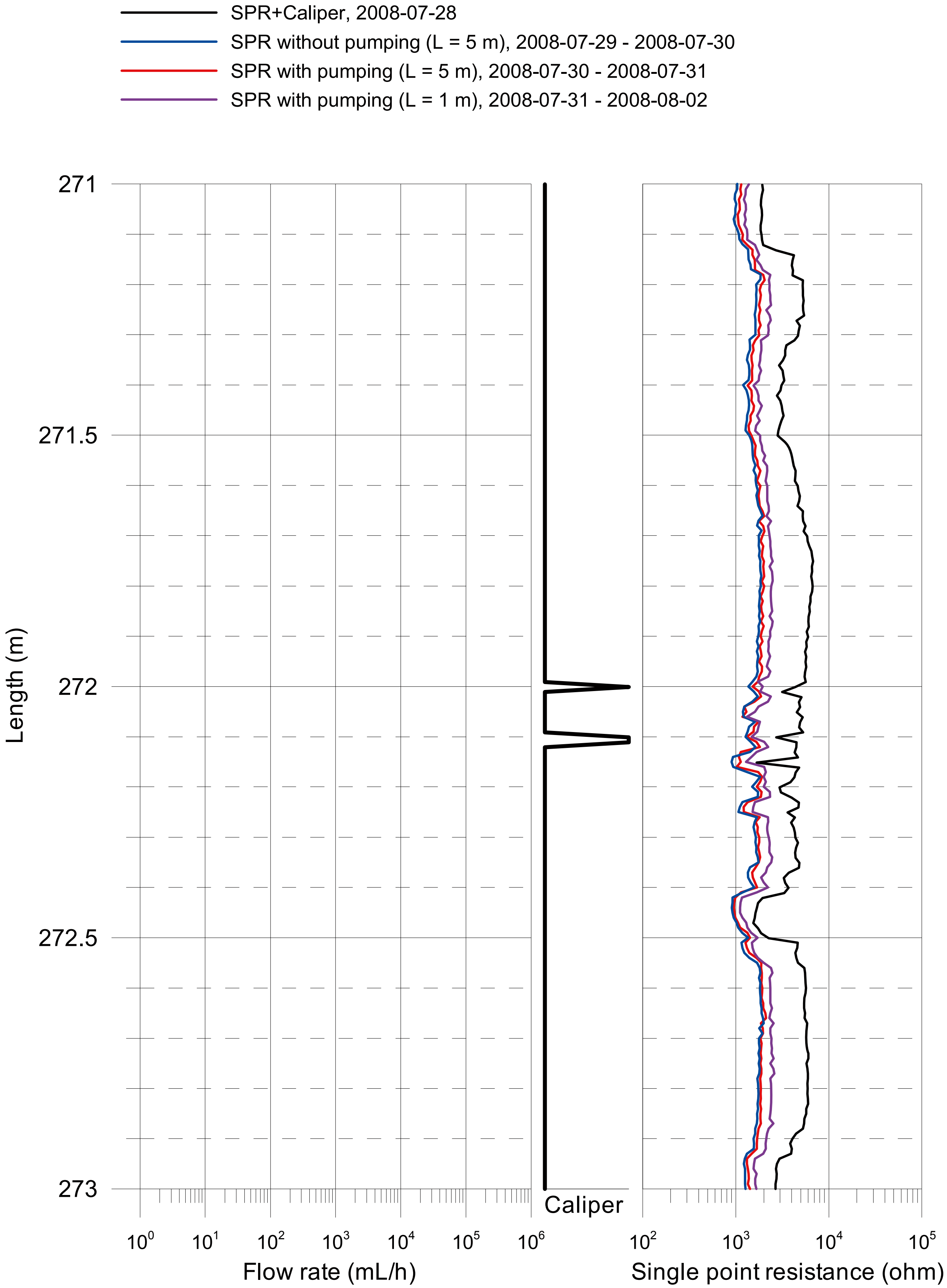
Forsmark, borehole KFR101
SPR and Caliper results after length correction



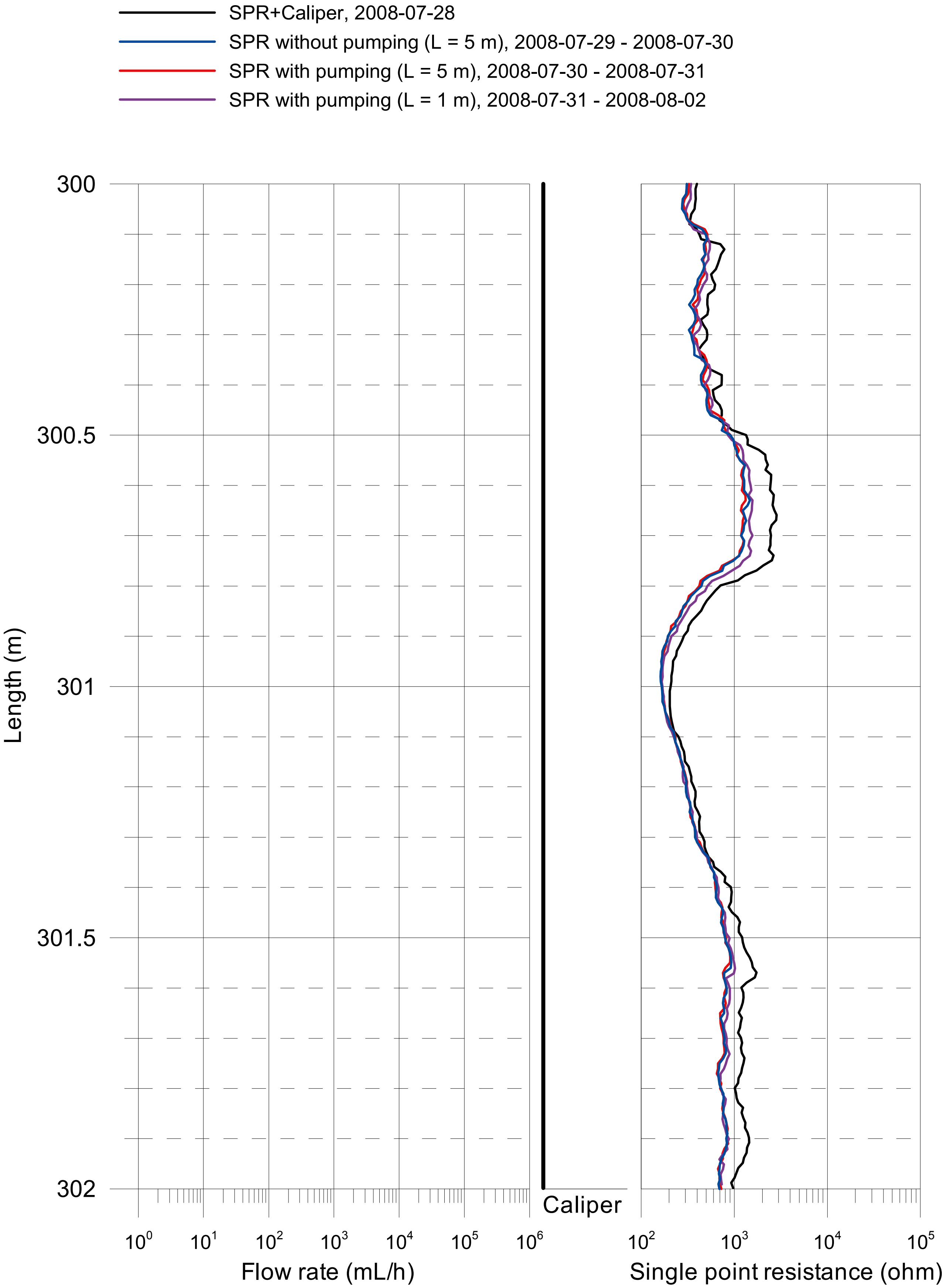
Forsmark, borehole KFR101
SPR and Caliper results after length correction



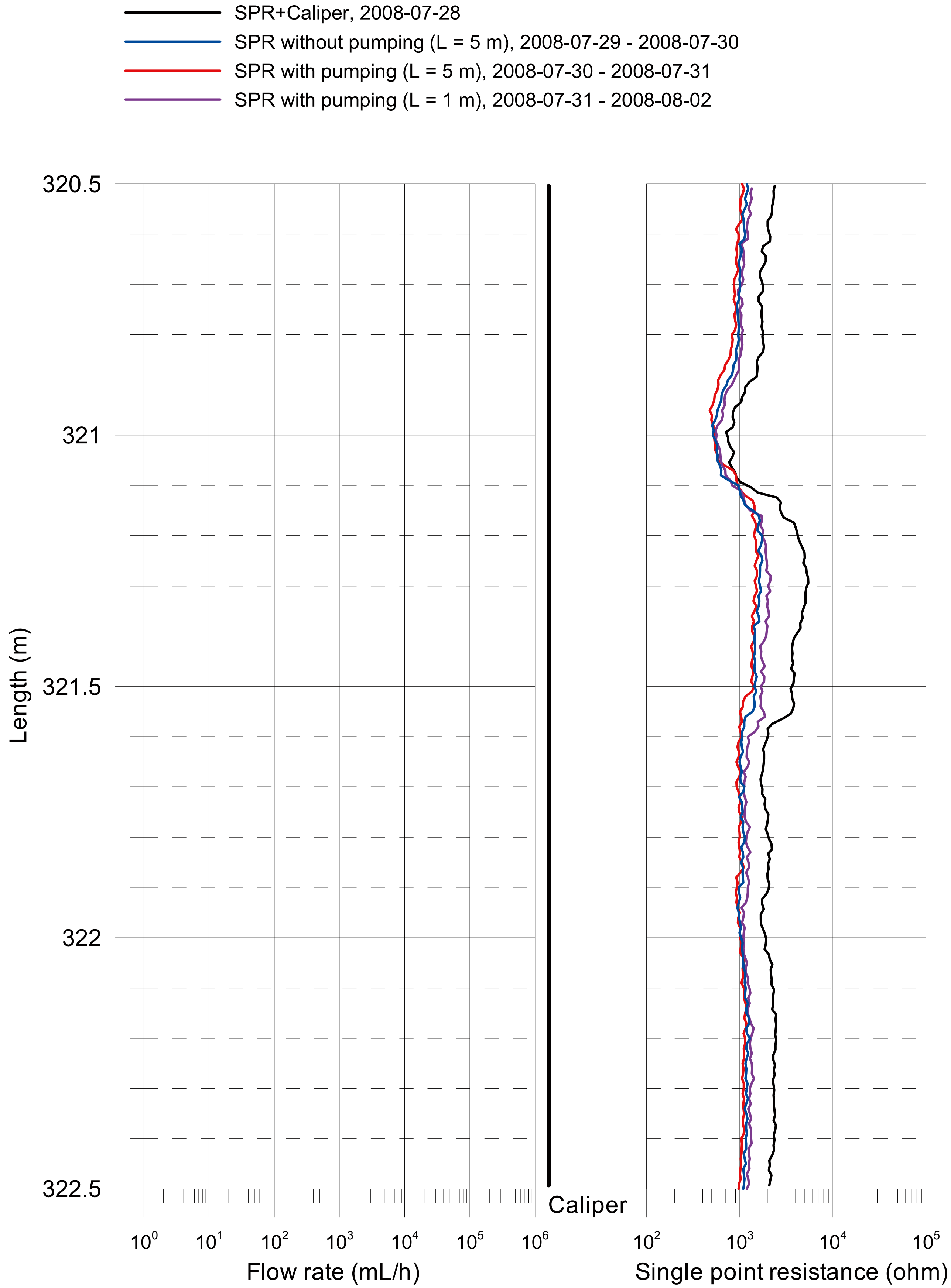
Forsmark, borehole KFR101
SPR and Caliper results after length correction



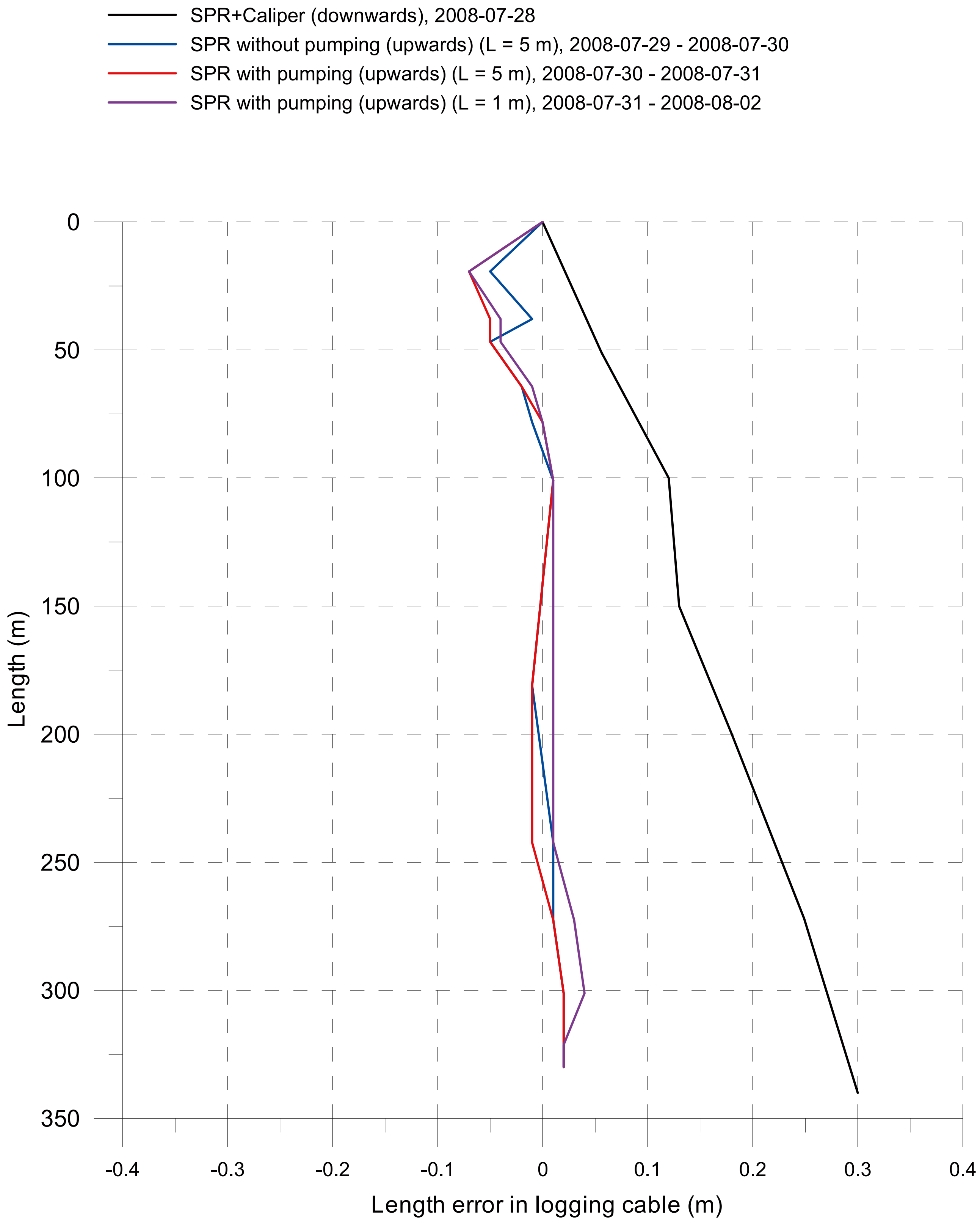
Forsmark, borehole KFR101
SPR and Caliper results after length correction

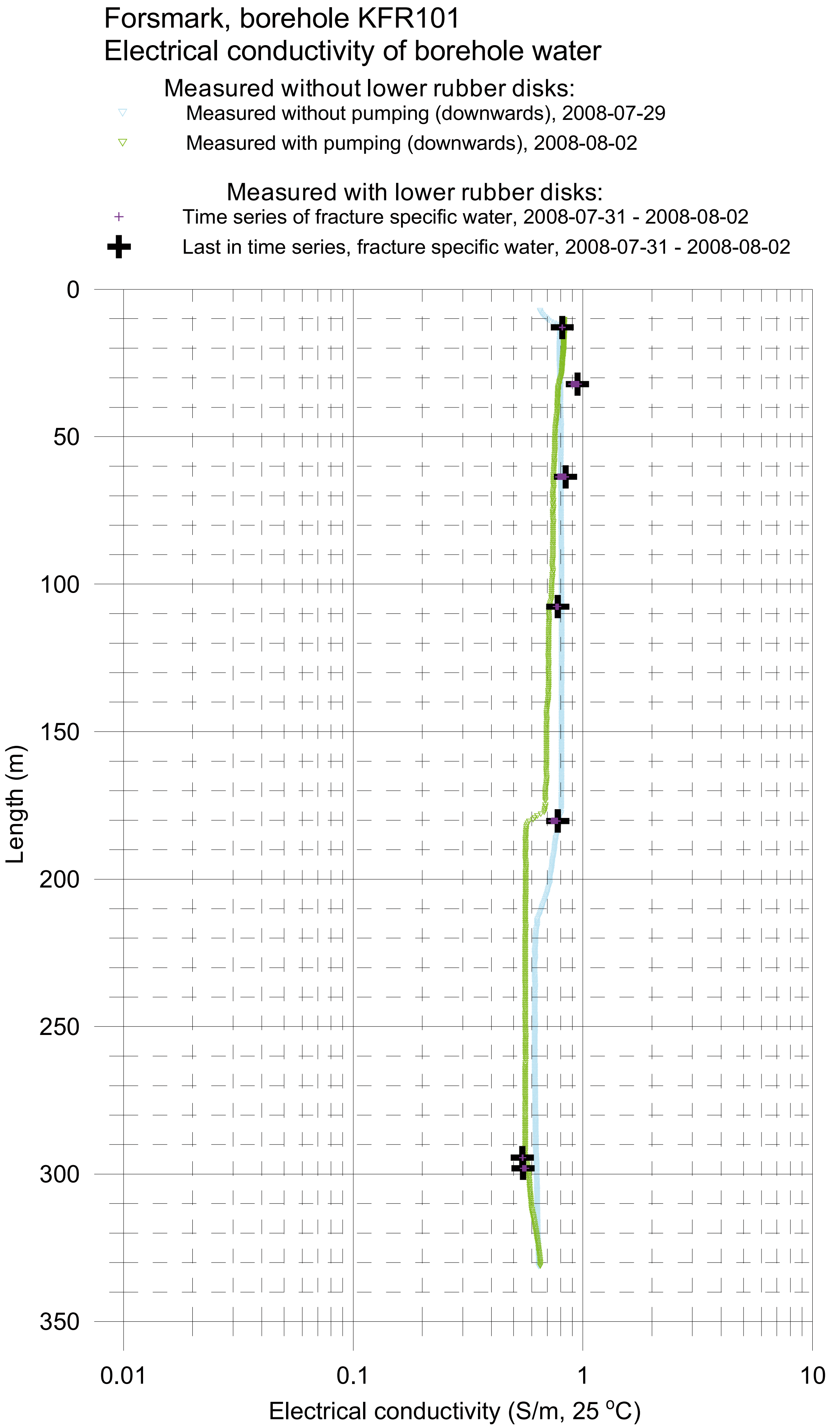


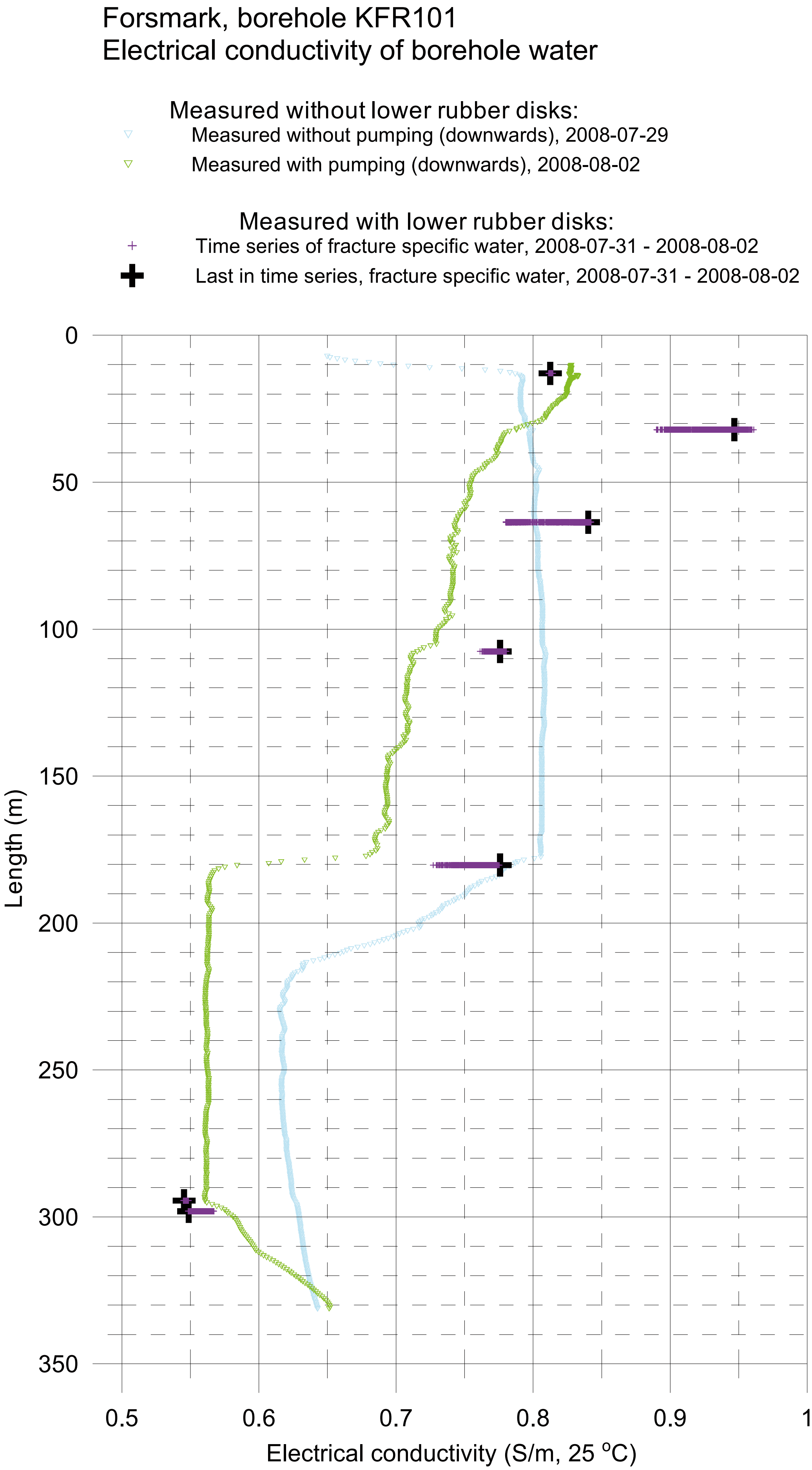
Forsmark, borehole KFR101
SPR and Caliper results after length correction

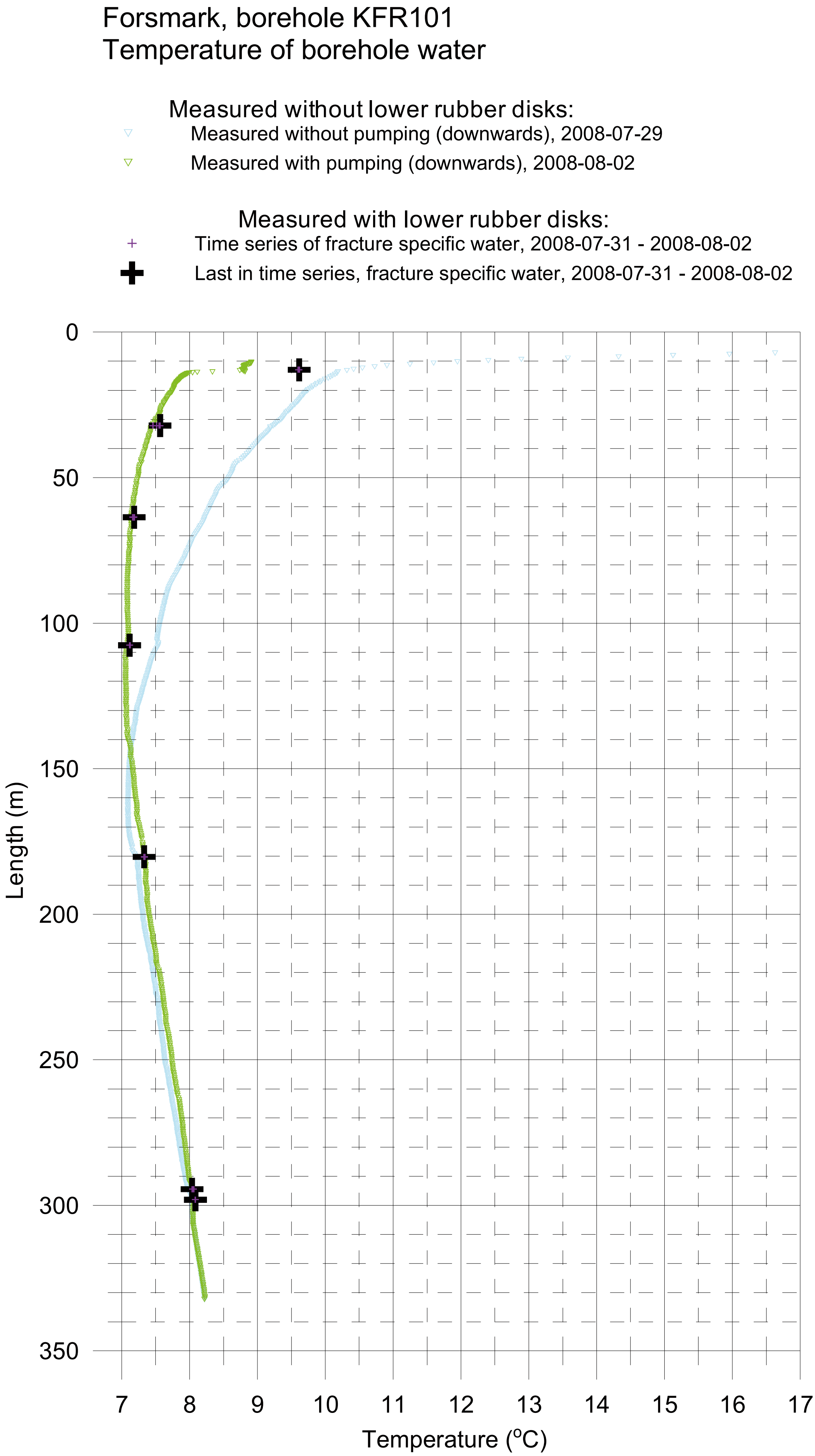


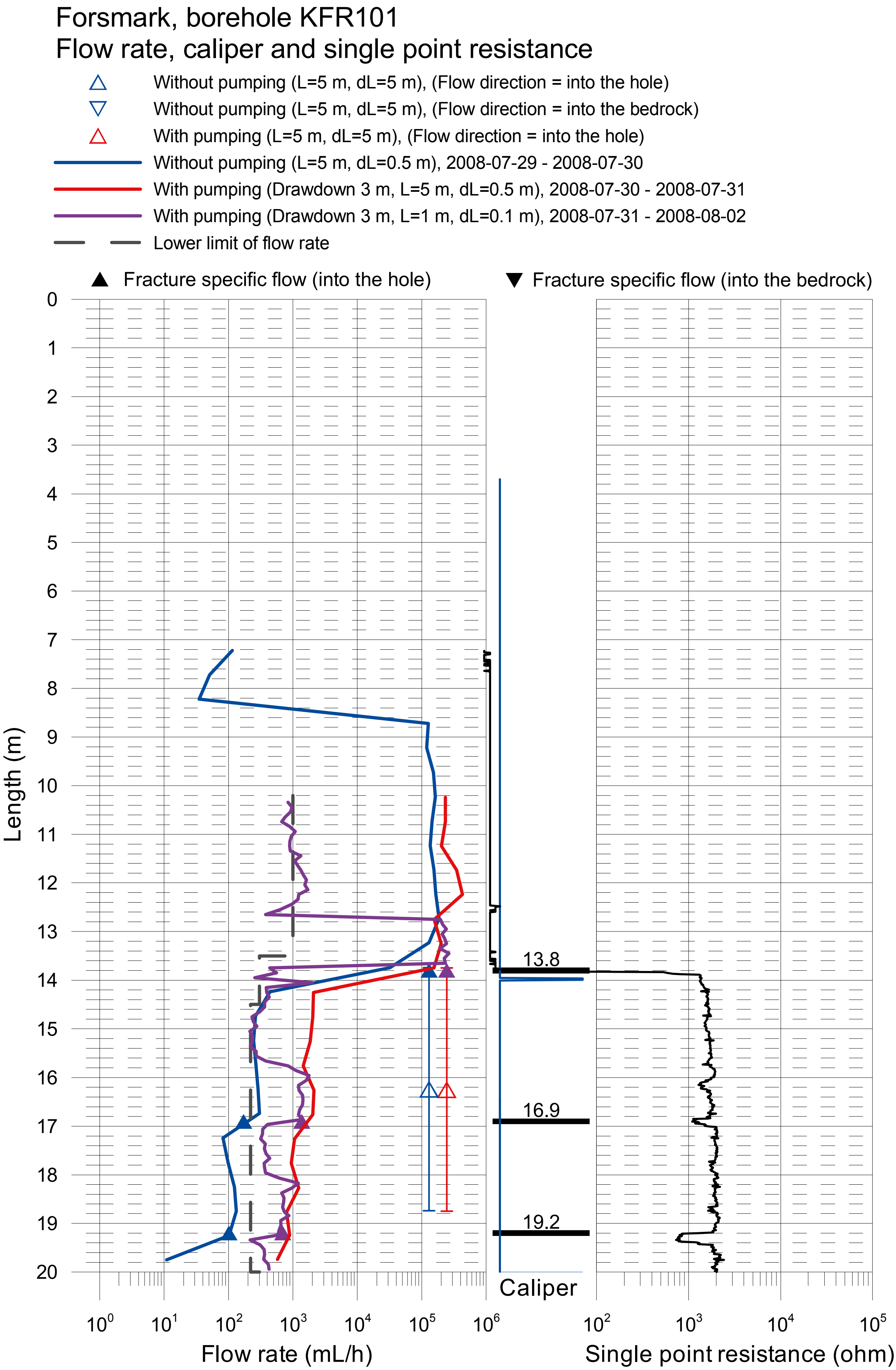
Forsmark, borehole KFR101
Length correction

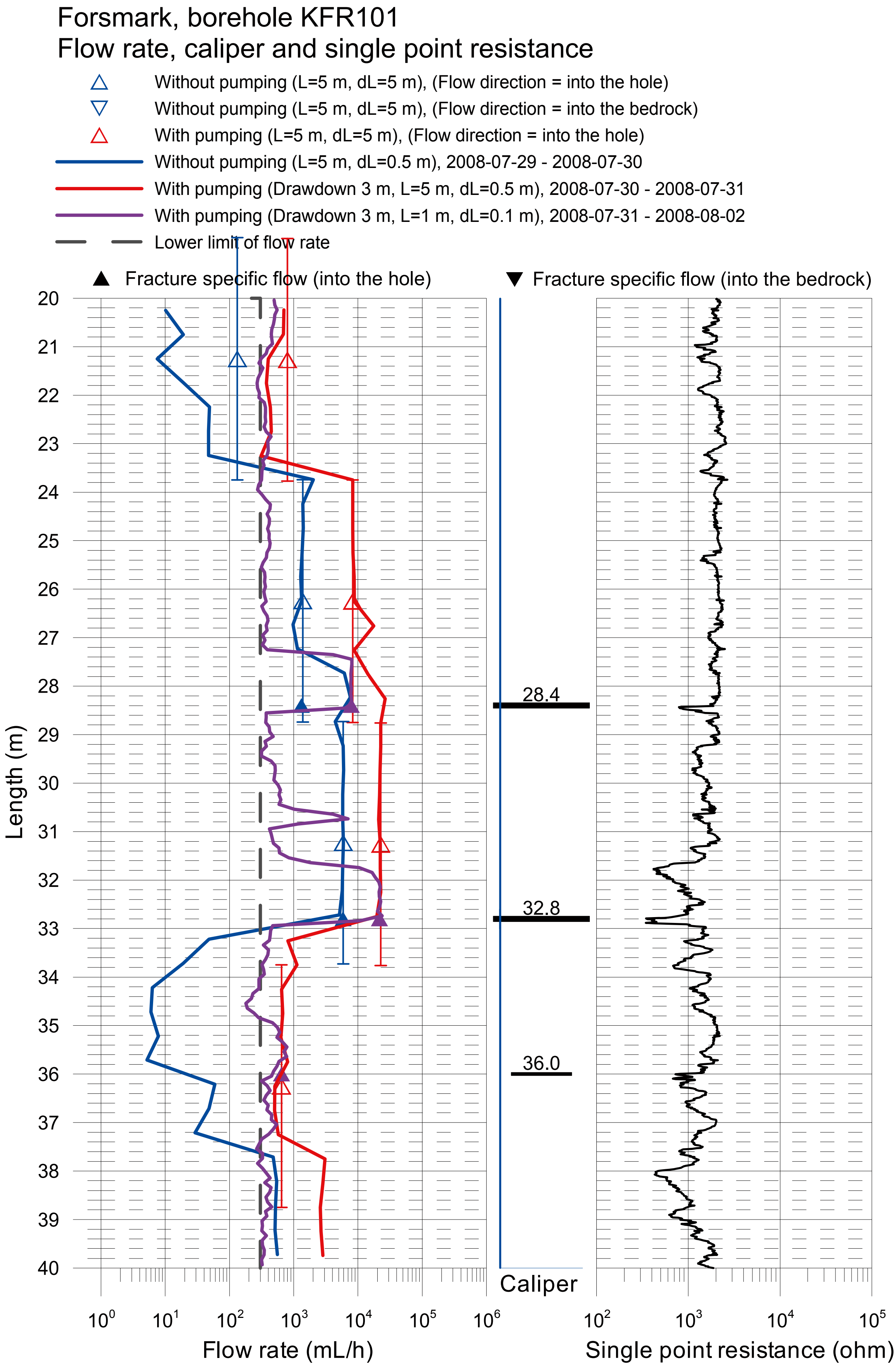


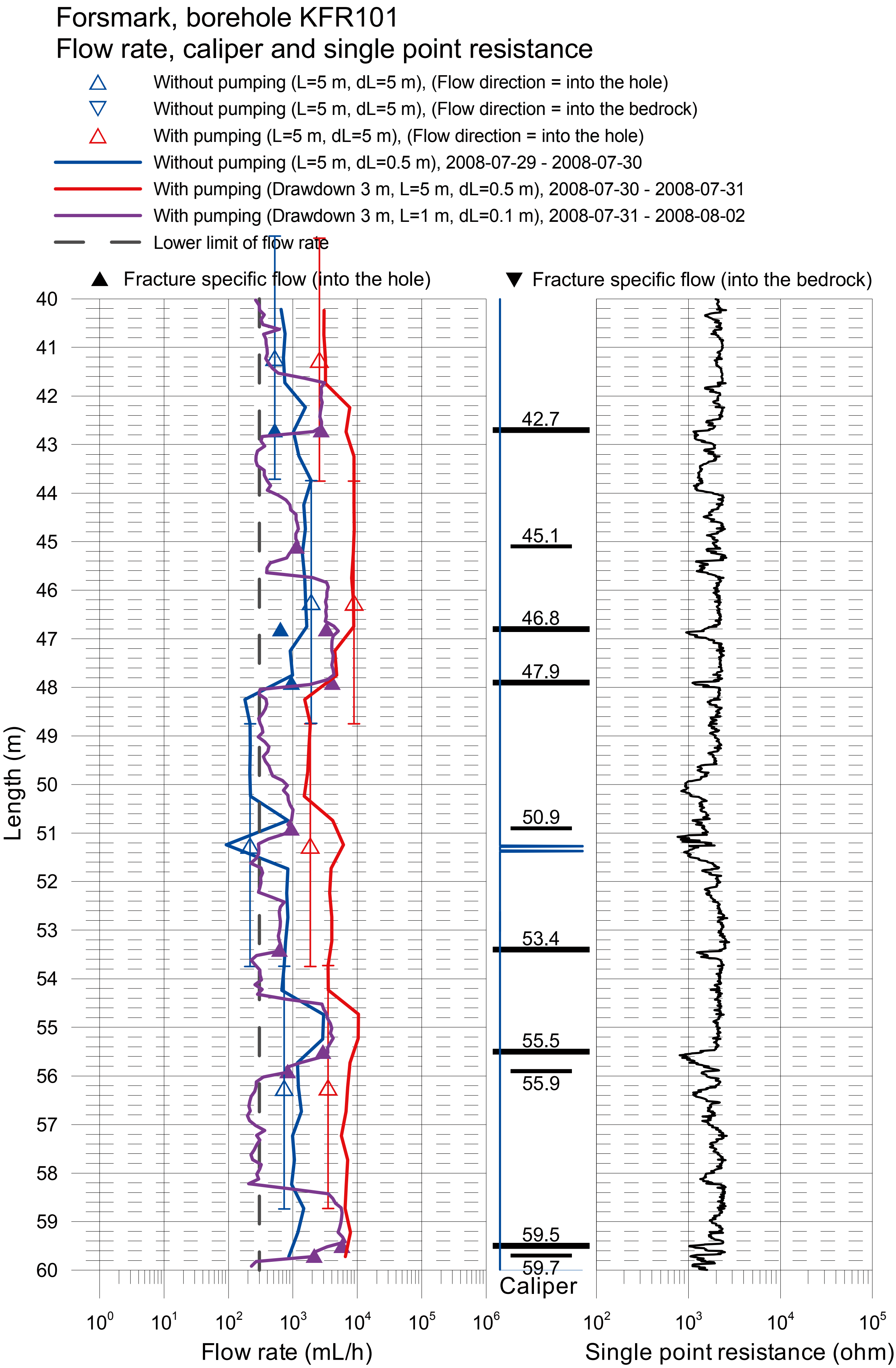

Forsmark, borehole KFR101
Electrical conductivity of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2008-07-29
Measured with pumping (downwards), 2008-08-02
Measured with lower rubber disks:
Time series of fracture specific water, 2008-07-31 - 2008-08-02
Last in time series, fracture specific water, 2008-07-31 - 2008-08-02
Length (m)
0
50
100
150
200
250
300
350
0.01
0.1
1
10
Electrical conductivity (S/m, 25 °C)

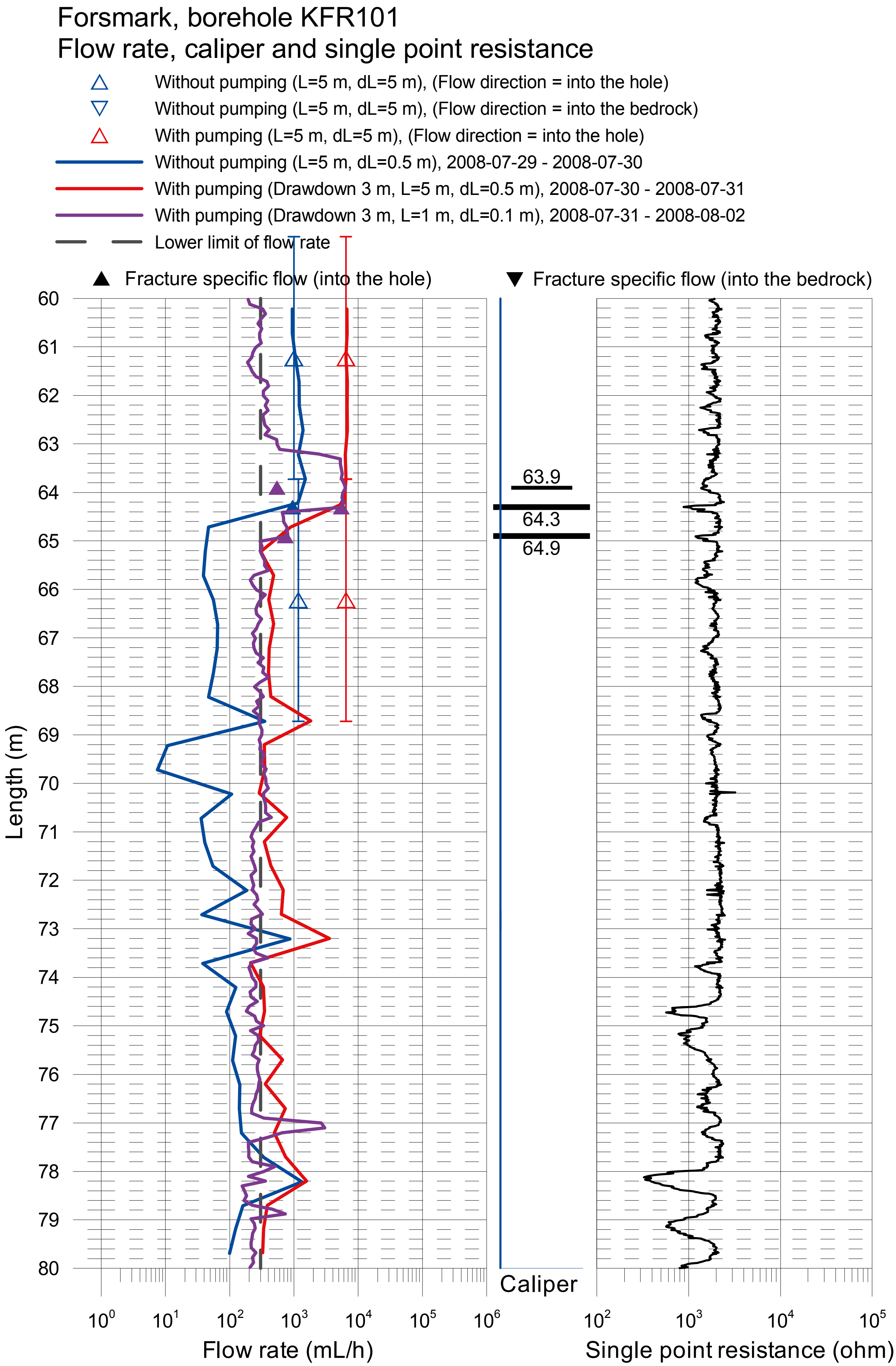

Forsmark, borehole KFR101
Electrical conductivity of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2008-07-29
Measured with pumping (downwards), 2008-08-02
Measured with lower rubber disks:
Time series of fracture specific water, 2008-07-31 - 2008-08-02
Last in time series, fracture specific water, 2008-07-31 - 2008-08-02
Length (m)
0
50
100
150
200
250
300
350
0.5
0.6
0.7
0.8
0.9
1
Electrical conductivity (S/m, 25 °C)


Forsmark, borehole KFR101
Temperature of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2008-07-29
Measured with pumping (downwards), 2008-08-02
Measured with lower rubber disks:
Time series of fracture specific water, 2008-07-31 - 2008-08-02
Last in time series, fracture specific water, 2008-07-31 - 2008-08-02
Length (m)
0
50
100
150
200
250
300
350
7
8
9
10
11
12
13
14
15
16
17
Temperature (°C)


Forsmark, borehole KFR101
Flow rate, caliper and single point resistance
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=0.5 m), 2008-07-29 - 2008-07-30
With pumping (Drawdown 3 m, L=5 m, dL=0.5 m), 2008-07-30 - 2008-07-31
With pumping (Drawdown 3 m, L=1 m, dL=0.1 m), 2008-07-31 - 2008-08-02
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
13.8
16.9
19.2
Caliper
Flow rate (mL/h)
Single point resistance (ohm)

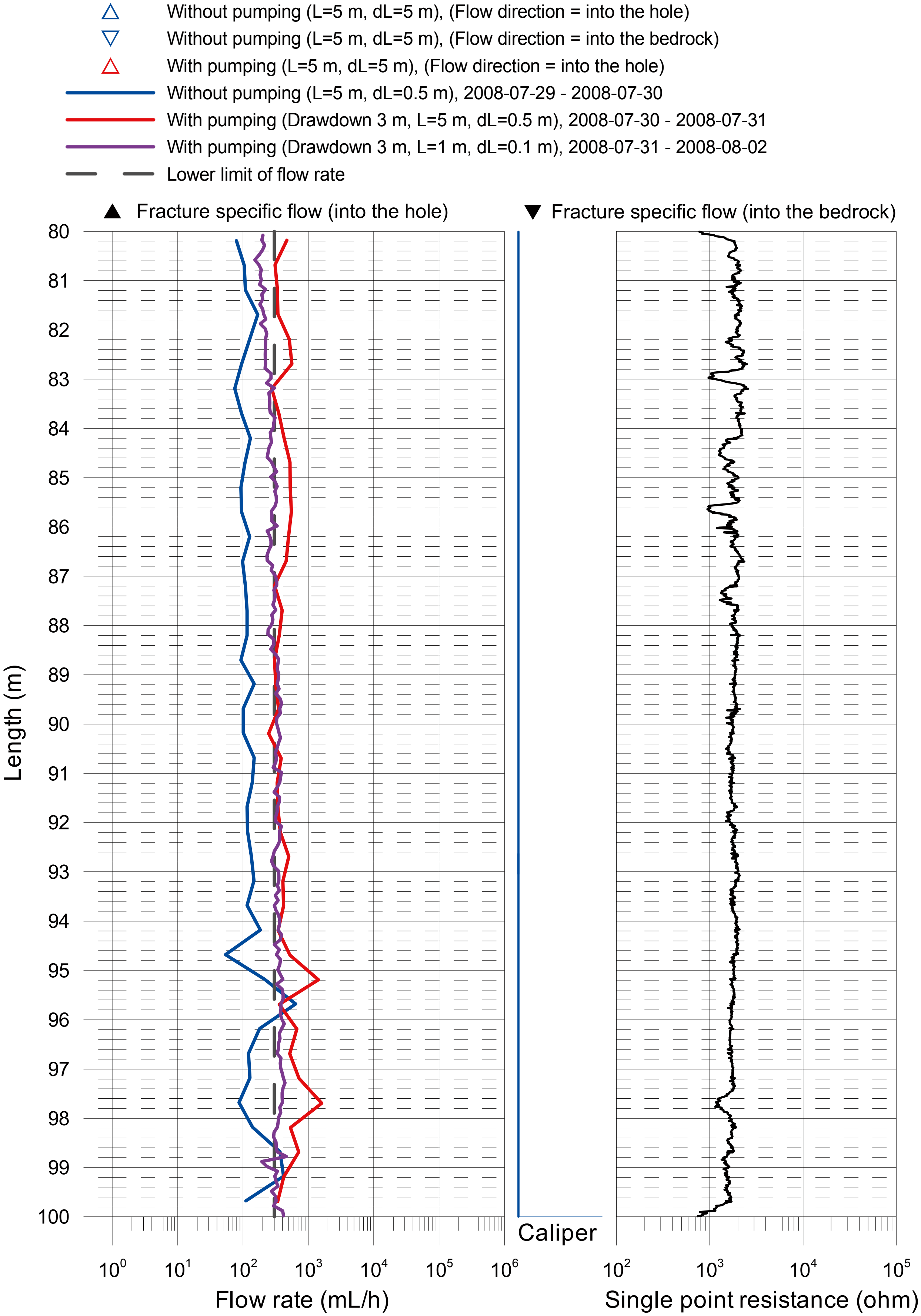

Forsmark, borehole KFR101
Flow rate, caliper and single point resistance
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=0.5 m), 2008-07-29 - 2008-07-30
With pumping (Drawdown 3 m, L=5 m, dL=0.5 m), 2008-07-30 - 2008-07-31
With pumping (Drawdown 3 m, L=1 m, dL=0.1 m), 2008-07-31 - 2008-08-02
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
28.4
32.8
36.0
Caliper
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Flow rate (mL/h)
10^2
10^3
10^4
10^5
Single point resistance (ohm)

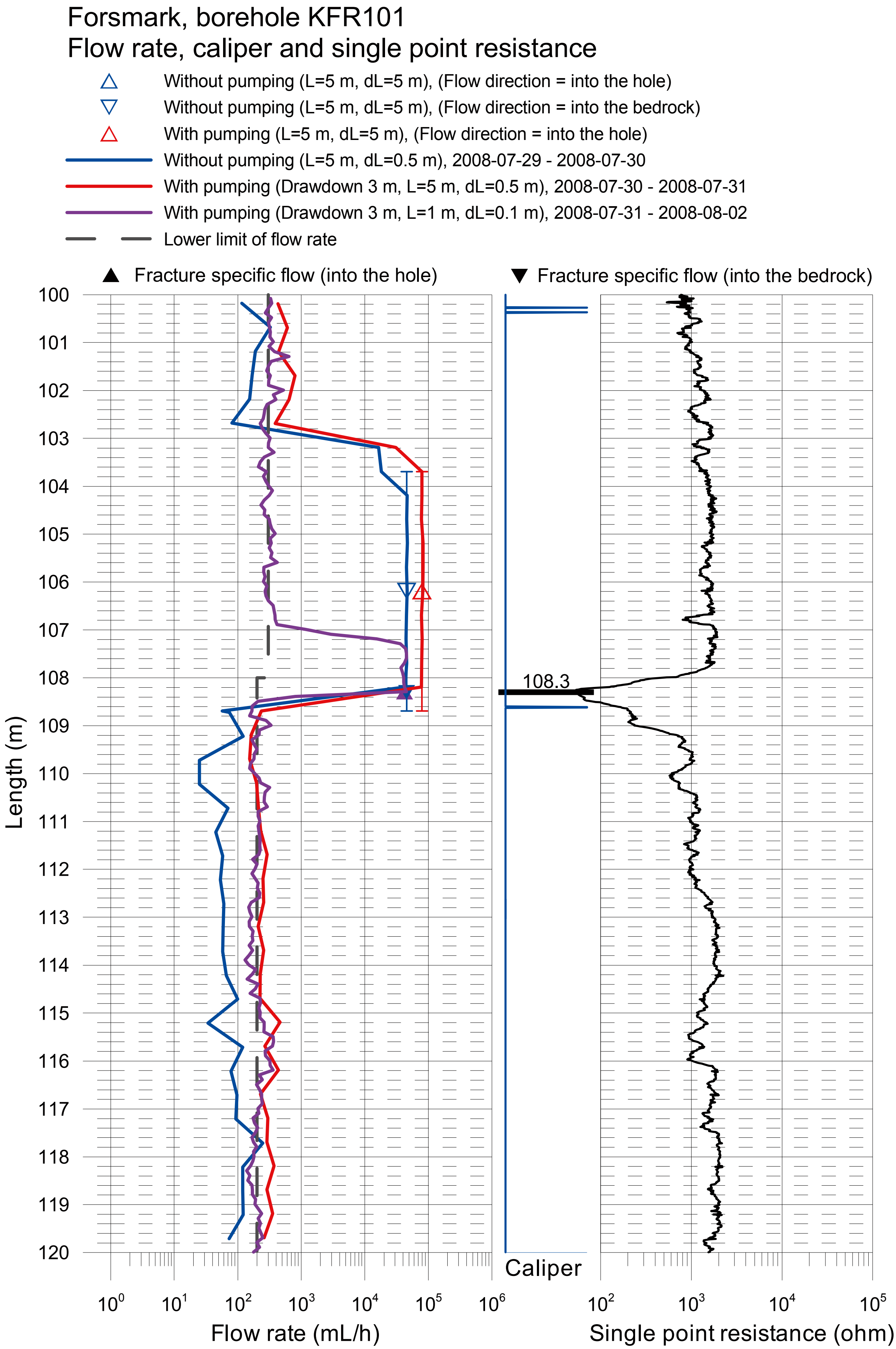

Forsmark, borehole KFR101
Flow rate, caliper and single point resistance
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=0.5 m), 2008-07-29 - 2008-07-30
With pumping (Drawdown 3 m, L=5 m, dL=0.5 m), 2008-07-30 - 2008-07-31
With pumping (Drawdown 3 m, L=1 m, dL=0.1 m), 2008-07-31 - 2008-08-02
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
42.7
45.1
46.8
47.9
50.9
53.4
55.5
55.9
59.5
59.7
Caliper
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Flow rate (mL/h)
10^2
10^3
10^4
10^5
Single point resistance (ohm)

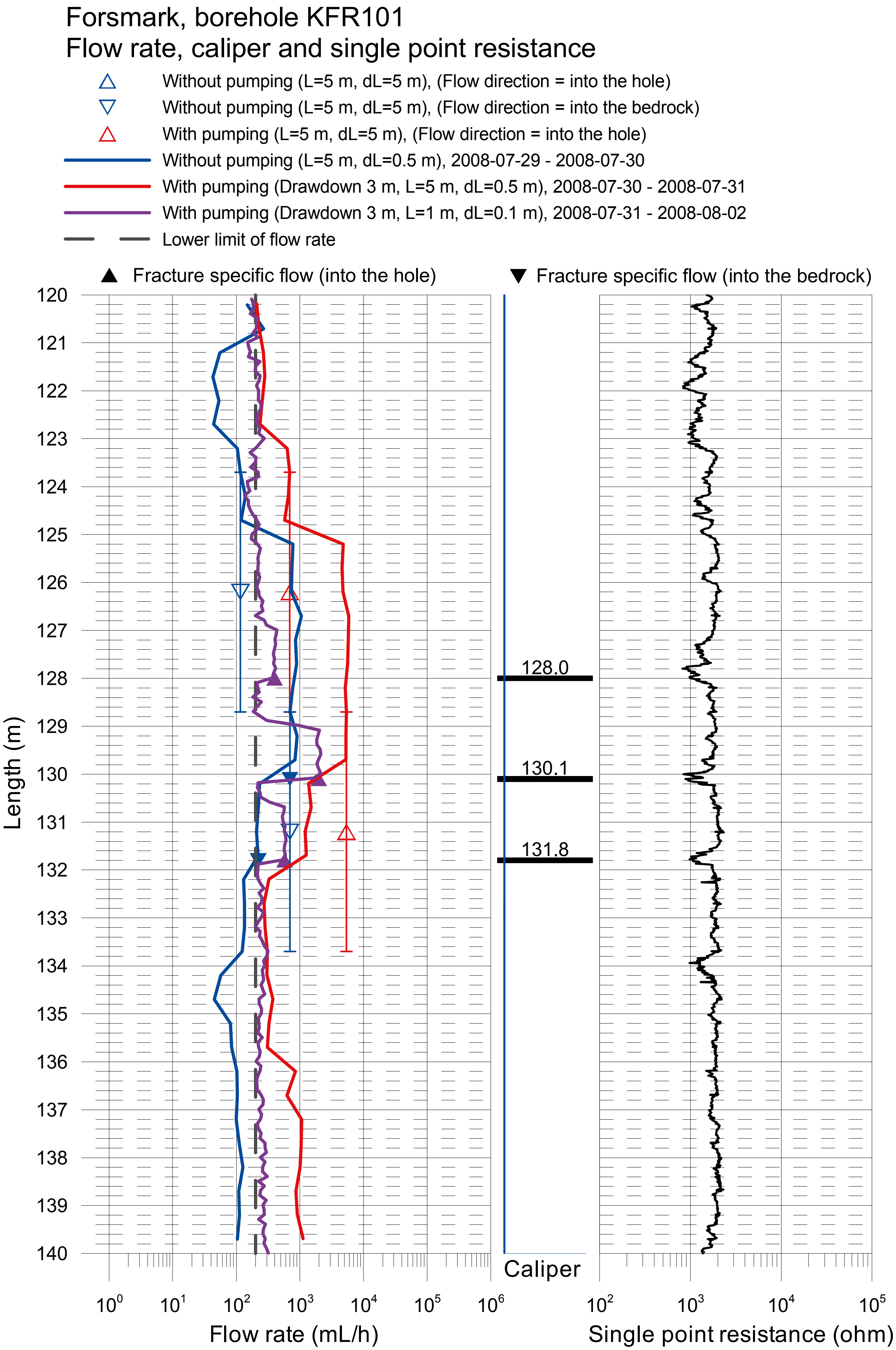


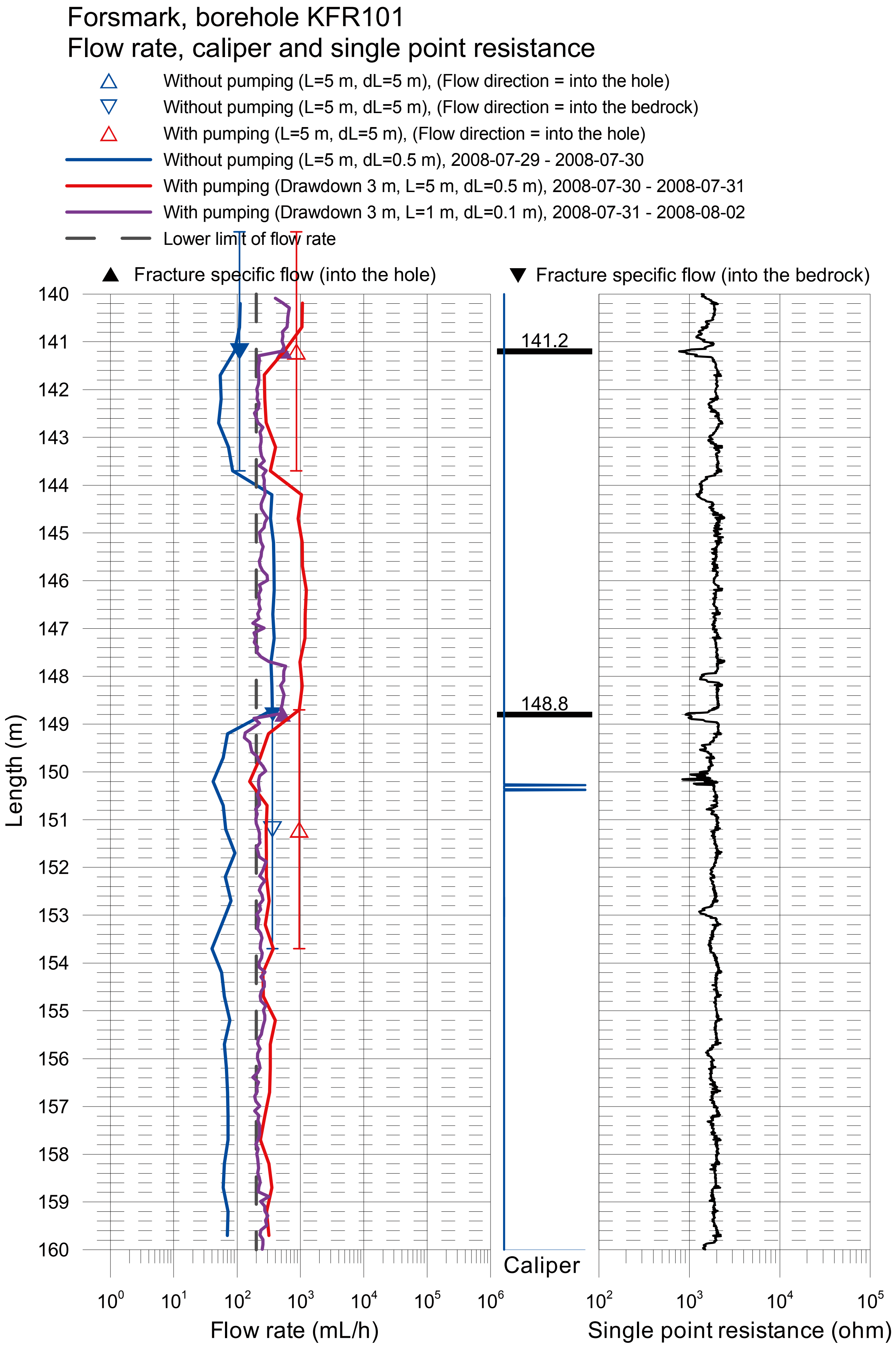
Forsmark, borehole KFR101
Flow rate, caliper and single point resistance
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=0.5 m), 2008-07-29 - 2008-07-30
With pumping (Drawdown 3 m, L=5 m, dL=0.5 m), 2008-07-30 - 2008-07-31
With pumping (Drawdown 3 m, L=1 m, dL=0.1 m), 2008-07-31 - 2008-08-02
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
63.9
64.3
64.9
Caliper
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Flow rate (mL/h)
10^2
10^3
10^4
10^5
Single point resistance (ohm)

Forsmark, borehole KFR101
Flow rate, caliper and single point resistance

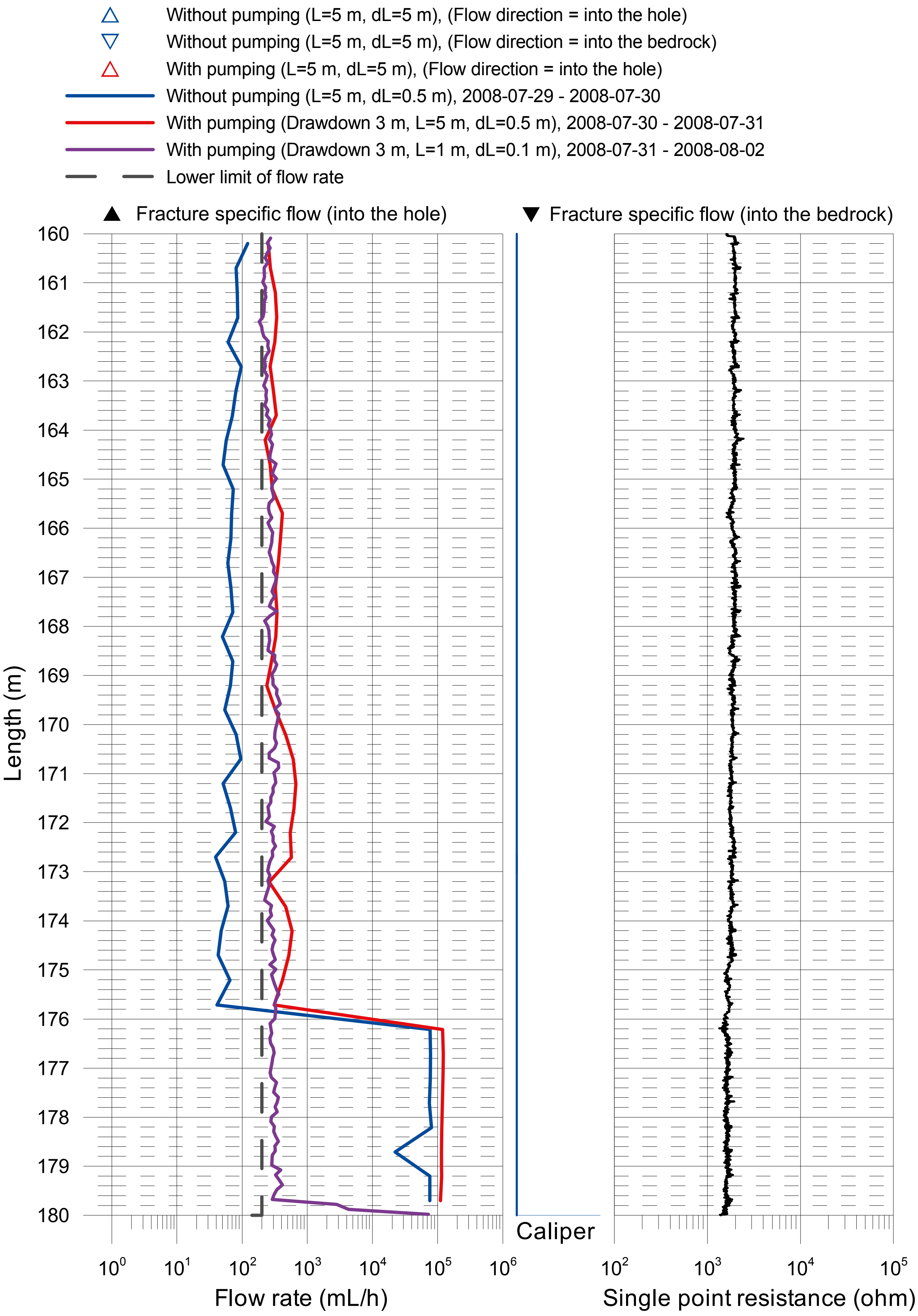


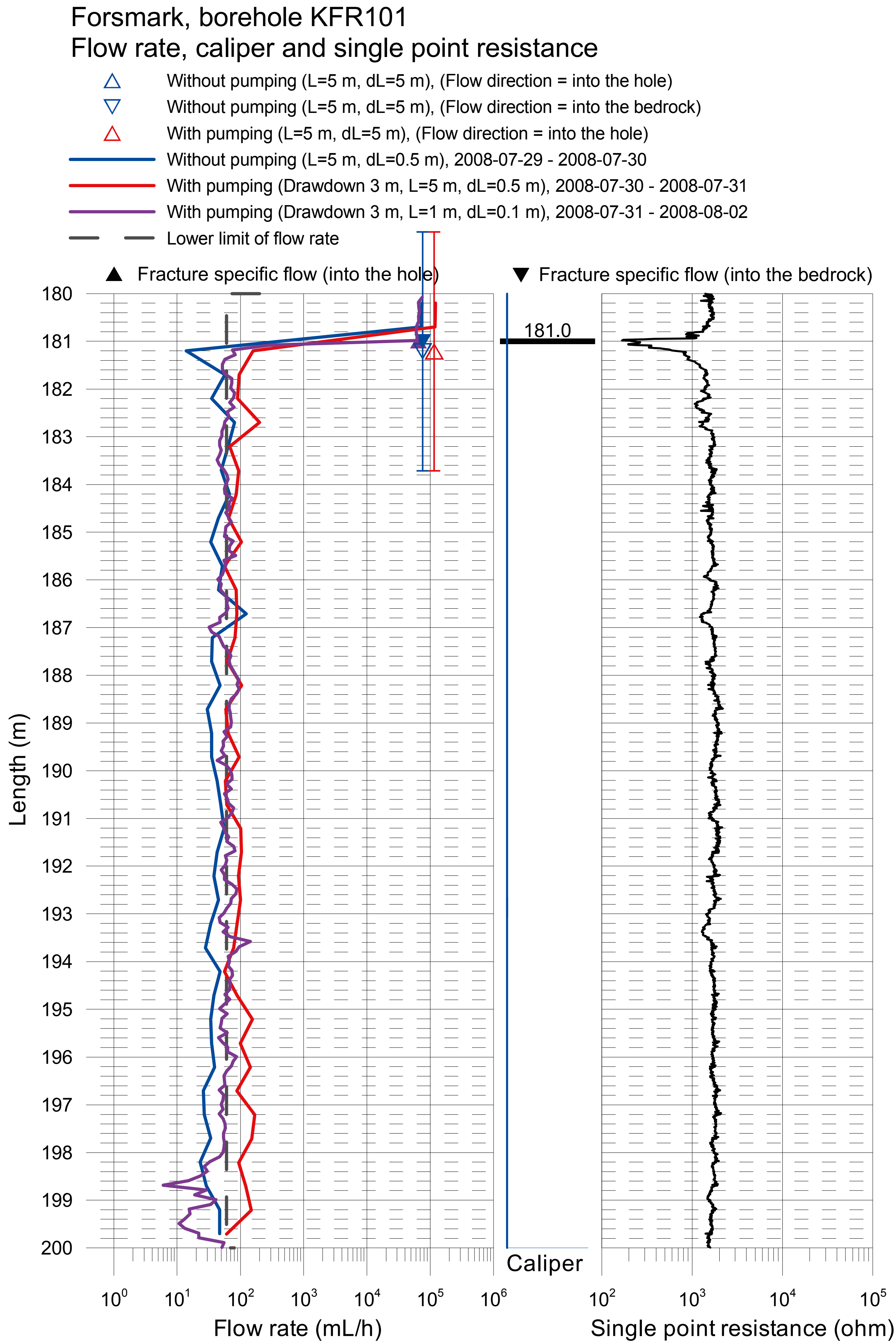

Forsmark, borehole KFR101
Flow rate, caliper and single point resistance
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=0.5 m), 2008-07-29 - 2008-07-30
With pumping (Drawdown 3 m, L=5 m, dL=0.5 m), 2008-07-30 - 2008-07-31
With pumping (Drawdown 3 m, L=1 m, dL=0.1 m), 2008-07-31 - 2008-08-02
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
108.3
Caliper
10^0 10^1 10^2 10^3 10^4 10^5 10^6
Flow rate (mL/h)
10^2 10^3 10^4 10^5
Single point resistance (ohm)

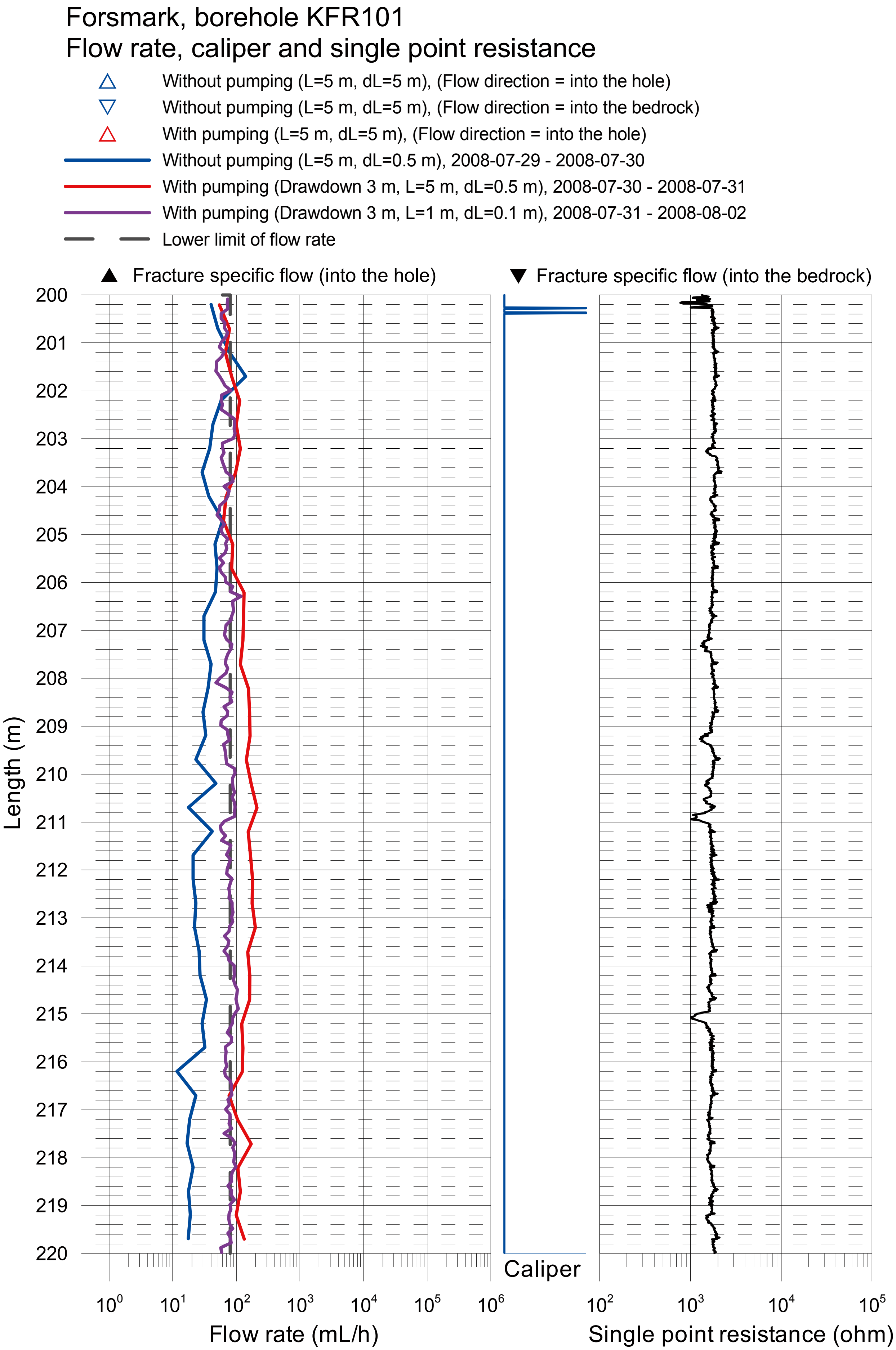

Forsmark, borehole KFR101
Flow rate, caliper and single point resistance
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=0.5 m), 2008-07-29 - 2008-07-30
With pumping (Drawdown 3 m, L=5 m, dL=0.5 m), 2008-07-30 - 2008-07-31
With pumping (Drawdown 3 m, L=1 m, dL=0.1 m), 2008-07-31 - 2008-08-02
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
120
121
122
123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
128.0
130.1
131.8
Caliper
10^0 10^1 10^2 10^3 10^4 10^5 10^6
Flow rate (mL/h)
10^2 10^3 10^4 10^5
Single point resistance (ohm)

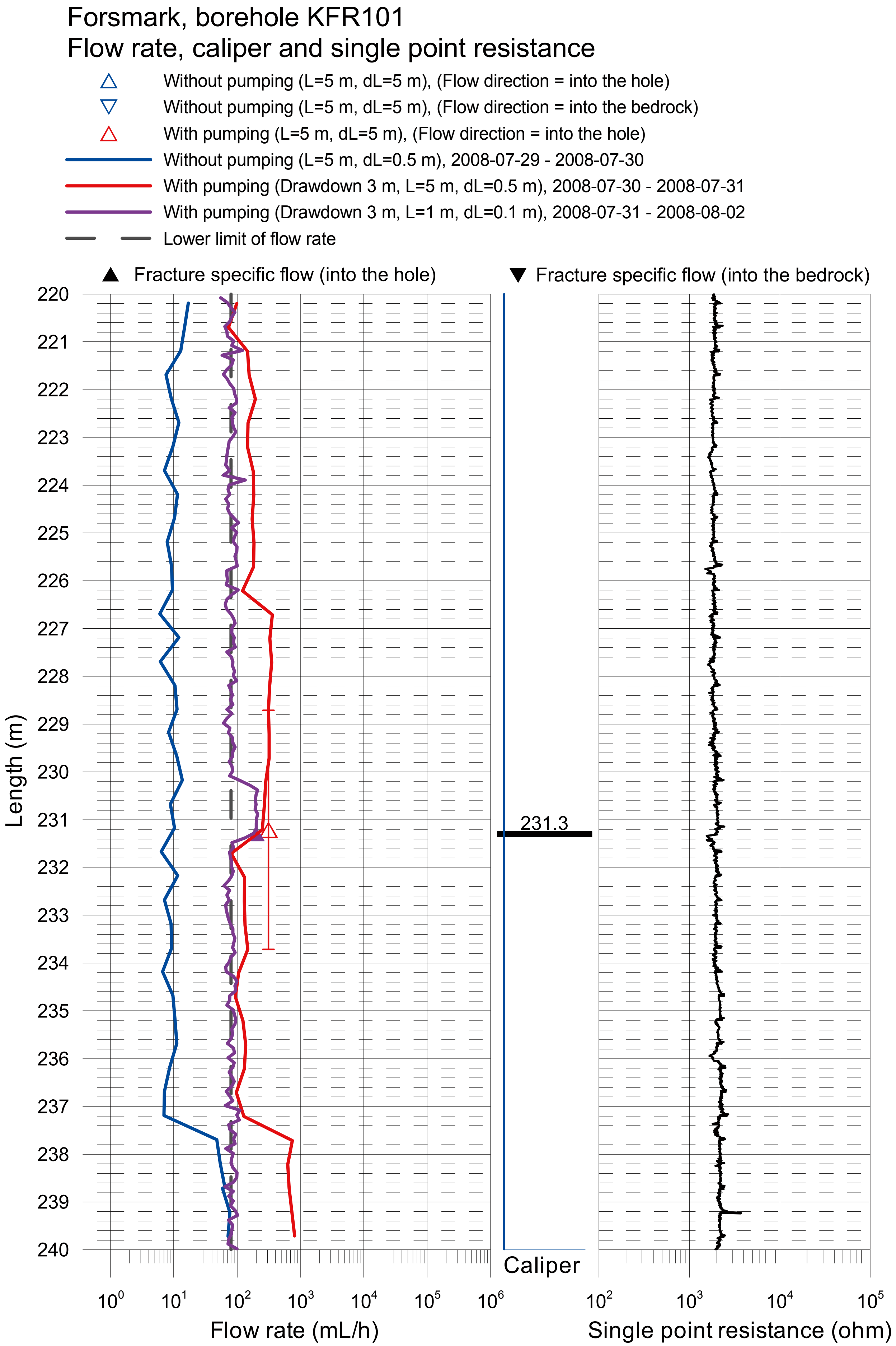

Forsmark, borehole KFR101
Flow rate, caliper and single point resistance
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=0.5 m), 2008-07-29 - 2008-07-30
With pumping (Drawdown 3 m, L=5 m, dL=0.5 m), 2008-07-30 - 2008-07-31
With pumping (Drawdown 3 m, L=1 m, dL=0.1 m), 2008-07-31 - 2008-08-02
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
141.2
148.8
Caliper
Flow rate (mL/h)
Single point resistance (ohm)

Forsmark, borehole KFR101
Flow rate, caliper and single point resistance



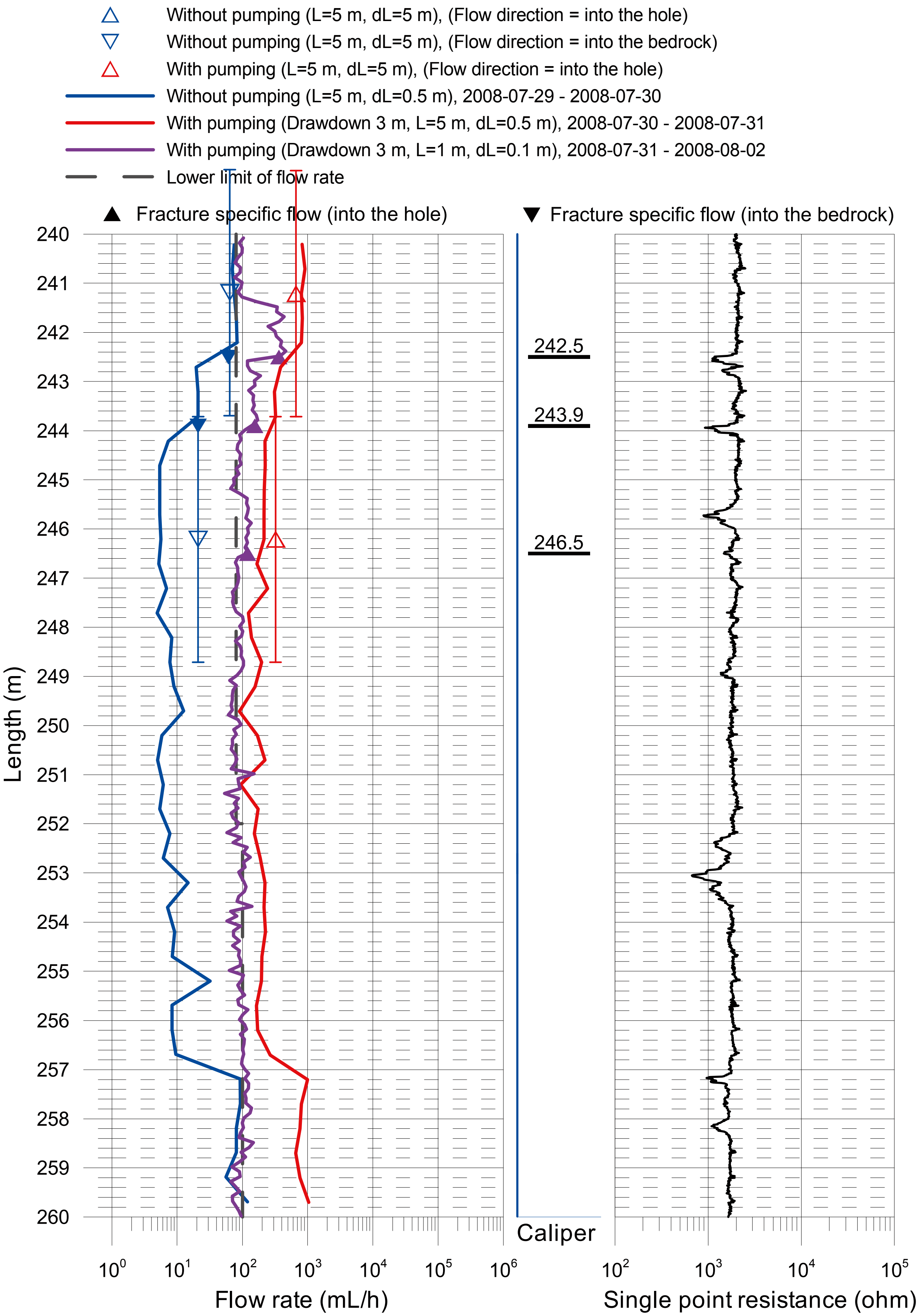

Forsmark, borehole KFR101
Flow rate, caliper and single point resistance
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=0.5 m), 2008-07-29 - 2008-07-30
With pumping (Drawdown 3 m, L=5 m, dL=0.5 m), 2008-07-30 - 2008-07-31
With pumping (Drawdown 3 m, L=1 m, dL=0.1 m), 2008-07-31 - 2008-08-02
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
181.0
Length (m)
Caliper
Flow rate (mL/h)
Single point resistance (ohm)

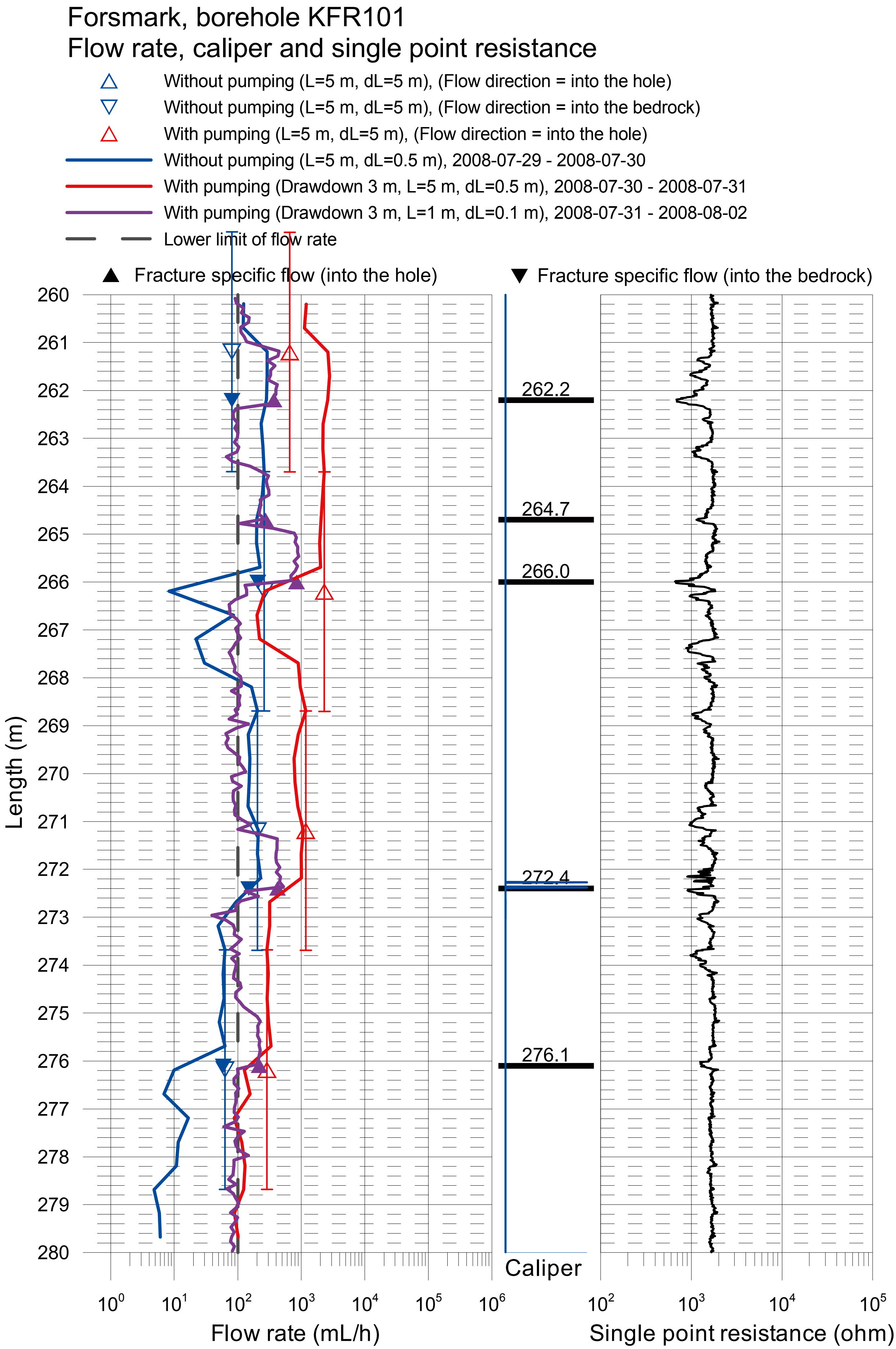

Forsmark, borehole KFR101
Flow rate, caliper and single point resistance
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=0.5 m), 2008-07-29 - 2008-07-30
With pumping (Drawdown 3 m, L=5 m, dL=0.5 m), 2008-07-30 - 2008-07-31
With pumping (Drawdown 3 m, L=1 m, dL=0.1 m), 2008-07-31 - 2008-08-02
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
Caliper
10^0 10^1 10^2 10^3 10^4 10^5 10^6
Flow rate (mL/h)
10^2 10^3 10^4 10^5
Single point resistance (ohm)



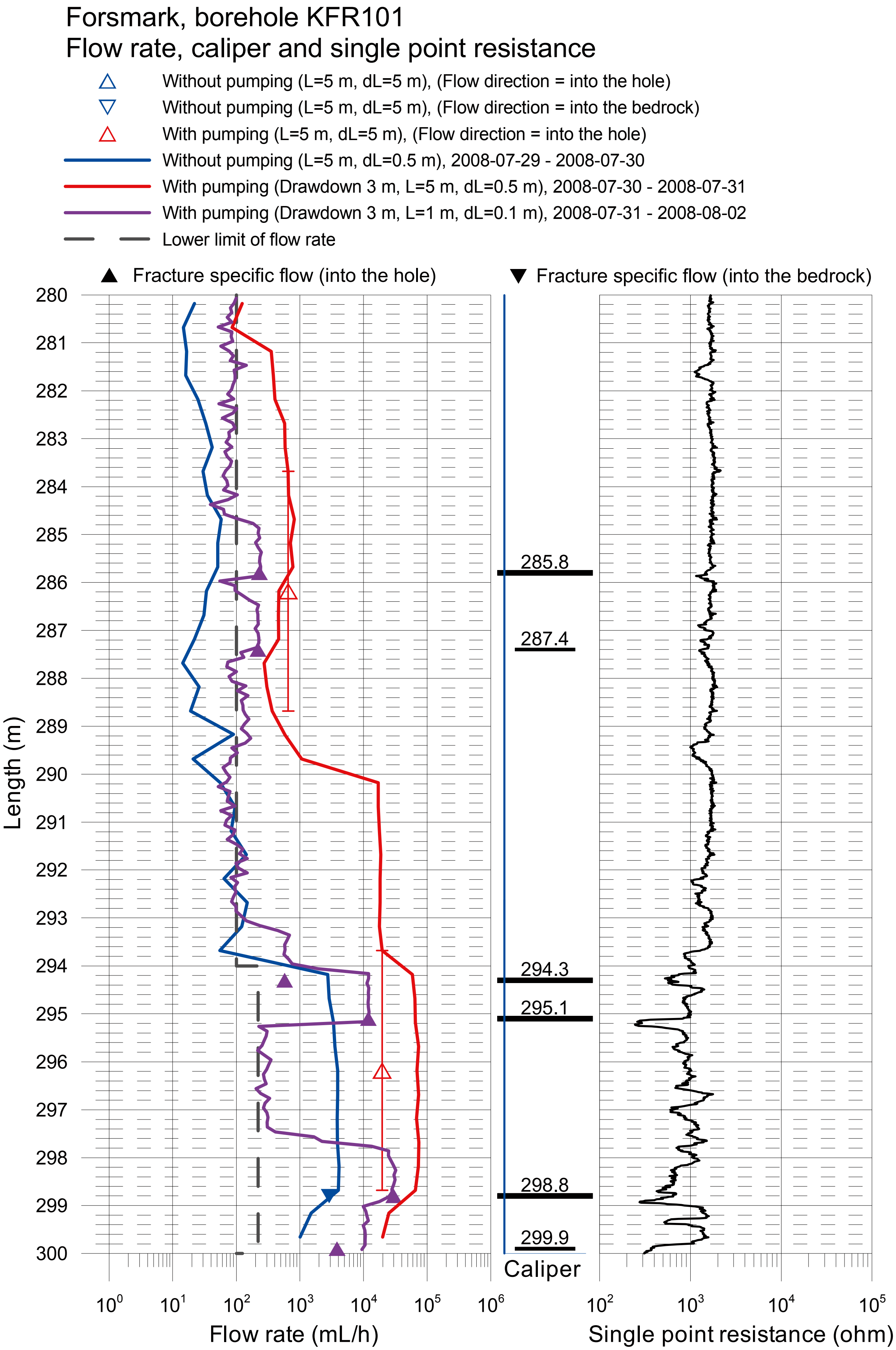
Forsmark, borehole KFR101
Flow rate, caliper and single point resistance
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=0.5 m), 2008-07-29 - 2008-07-30
With pumping (Drawdown 3 m, L=5 m, dL=0.5 m), 2008-07-30 - 2008-07-31
With pumping (Drawdown 3 m, L=1 m, dL=0.1 m), 2008-07-31 - 2008-08-02
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
220
221
222
223
224
225
226
227
228
229
230
231
232
233
234
235
236
237
238
239
240
231.3
Caliper
10^0 10^1 10^2 10^3 10^4 10^5 10^6
Flow rate (mL/h)
10^2 10^3 10^4 10^5
Single point resistance (ohm)

Forsmark, borehole KFR101
Flow rate, caliper and single point resistance

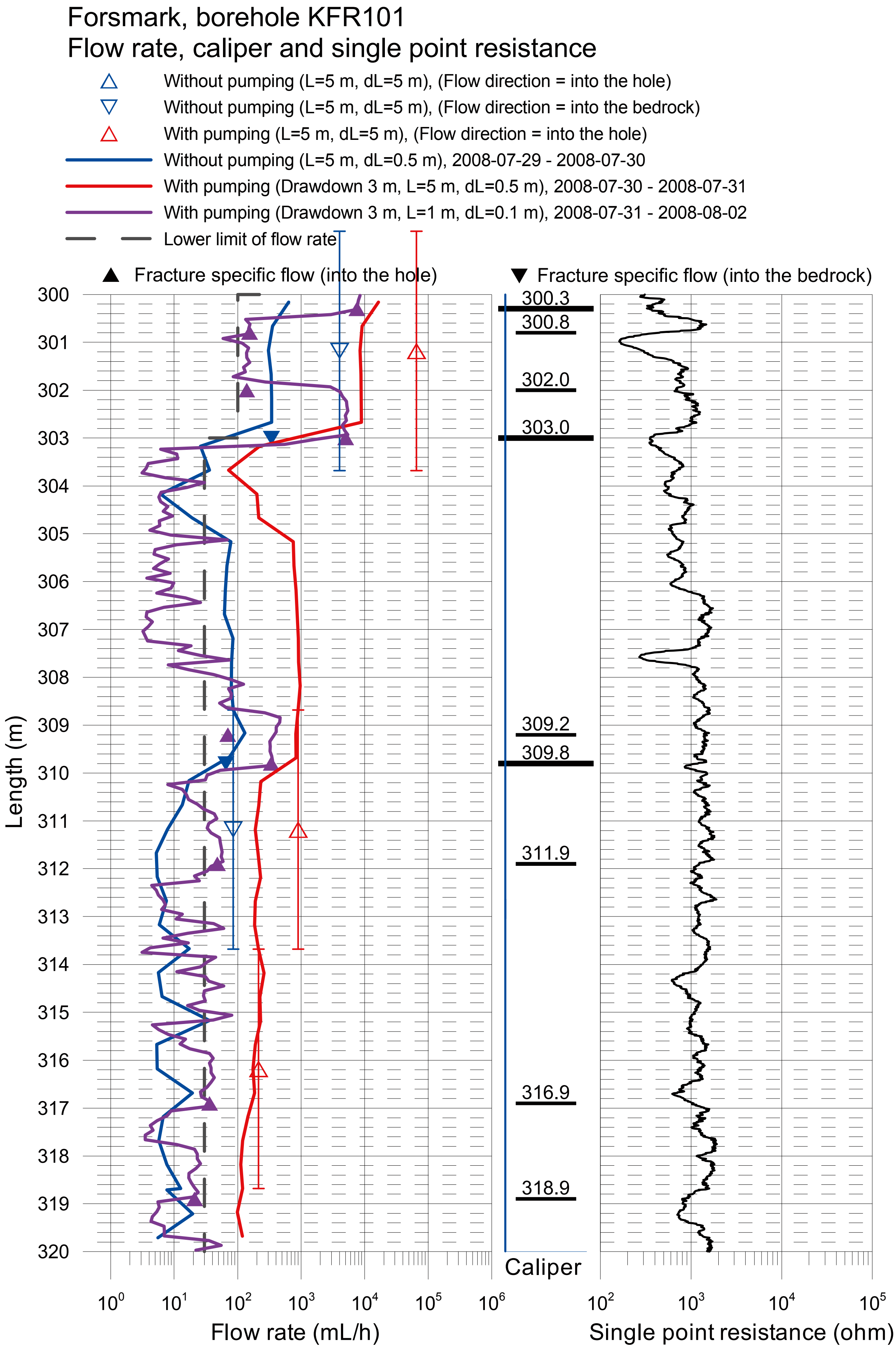


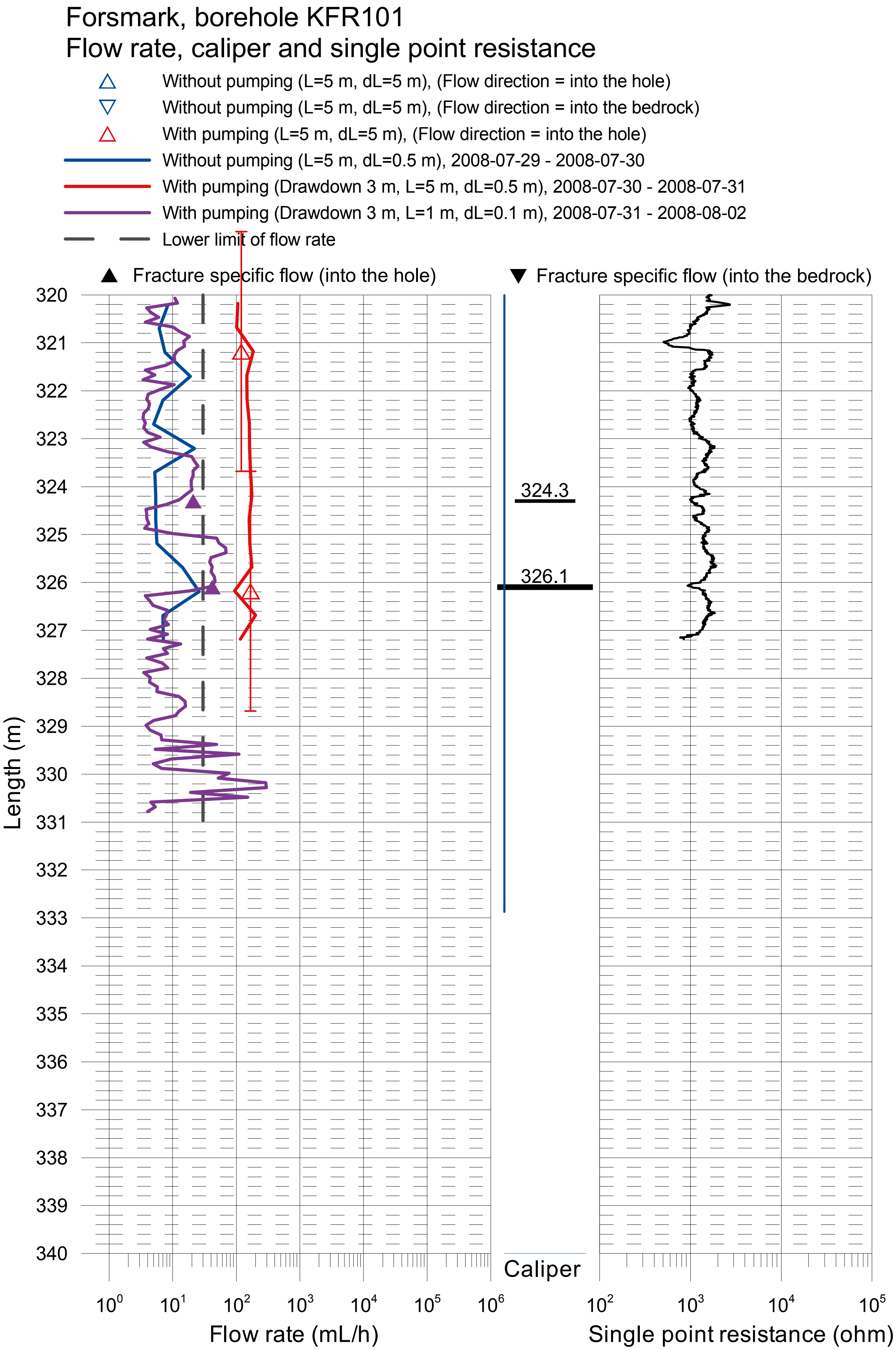


Forsmark, borehole KFR101
Flow rate, caliper and single point resistance
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=0.5 m), 2008-07-29 - 2008-07-30
With pumping (Drawdown 3 m, L=5 m, dL=0.5 m), 2008-07-30 - 2008-07-31
With pumping (Drawdown 3 m, L=1 m, dL=0.1 m), 2008-07-31 - 2008-08-02
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
260
261
262
263
264
265
266
267
268
269
270
271
272
273
274
275
276
277
278
279
280
262.2
264.7
266.0
272.4
276.1
Caliper
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Flow rate (mL/h)
10^2
10^3
10^4
10^5
Single point resistance (ohm)



Forsmark, borehole KFR101
Flow rate, caliper and single point resistance
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=0.5 m), 2008-07-29 - 2008-07-30
With pumping (Drawdown 3 m, L=5 m, dL=0.5 m), 2008-07-30 - 2008-07-31
With pumping (Drawdown 3 m, L=1 m, dL=0.1 m), 2008-07-31 - 2008-08-02
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
280
281
282
283
284
285
286
287
288
289
290
291
292
293
294
295
296
297
298
299
300
285.8
287.4
294.3
295.1
298.8
299.9
Caliper
10^0 10^1 10^2 10^3 10^4 10^5 10^6
Flow rate (mL/h)
10^2 10^3 10^4 10^5
Single point resistance (ohm)


Forsmark, borehole KFR101
Flow rate, caliper and single point resistance
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=0.5 m), 2008-07-29 - 2008-07-30
With pumping (Drawdown 3 m, L=5 m, dL=0.5 m), 2008-07-30 - 2008-07-31
With pumping (Drawdown 3 m, L=1 m, dL=0.1 m), 2008-07-31 - 2008-08-02
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
300
301
302
303
304
305
306
307
308
309
310
311
312
313
314
315
316
317
318
319
320
300.3
300.8
302.0
303.0
309.2
309.8
311.9
316.9
318.9
Caliper
10^0 10^1 10^2 10^3 10^4 10^5 10^6
Flow rate (mL/h)
10^2 10^3 10^4 10^5
Single point resistance (ohm)


Forsmark, borehole KFR101
Flow rate, caliper and single point resistance
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=0.5 m), 2008-07-29 - 2008-07-30
With pumping (Drawdown 3 m, L=5 m, dL=0.5 m), 2008-07-30 - 2008-07-31
With pumping (Drawdown 3 m, L=1 m, dL=0.1 m), 2008-07-31 - 2008-08-02
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
320
321
322
323
324
325
326
327
328
329
330
331
332
333
334
335
336
337
338
339
340
324.3
326.1
Caliper
10^0 10^1 10^2 10^3 10^4 10^5 10^6
Flow rate (mL/h)
10^2 10^3 10^4 10^5
Single point resistance (ohm)

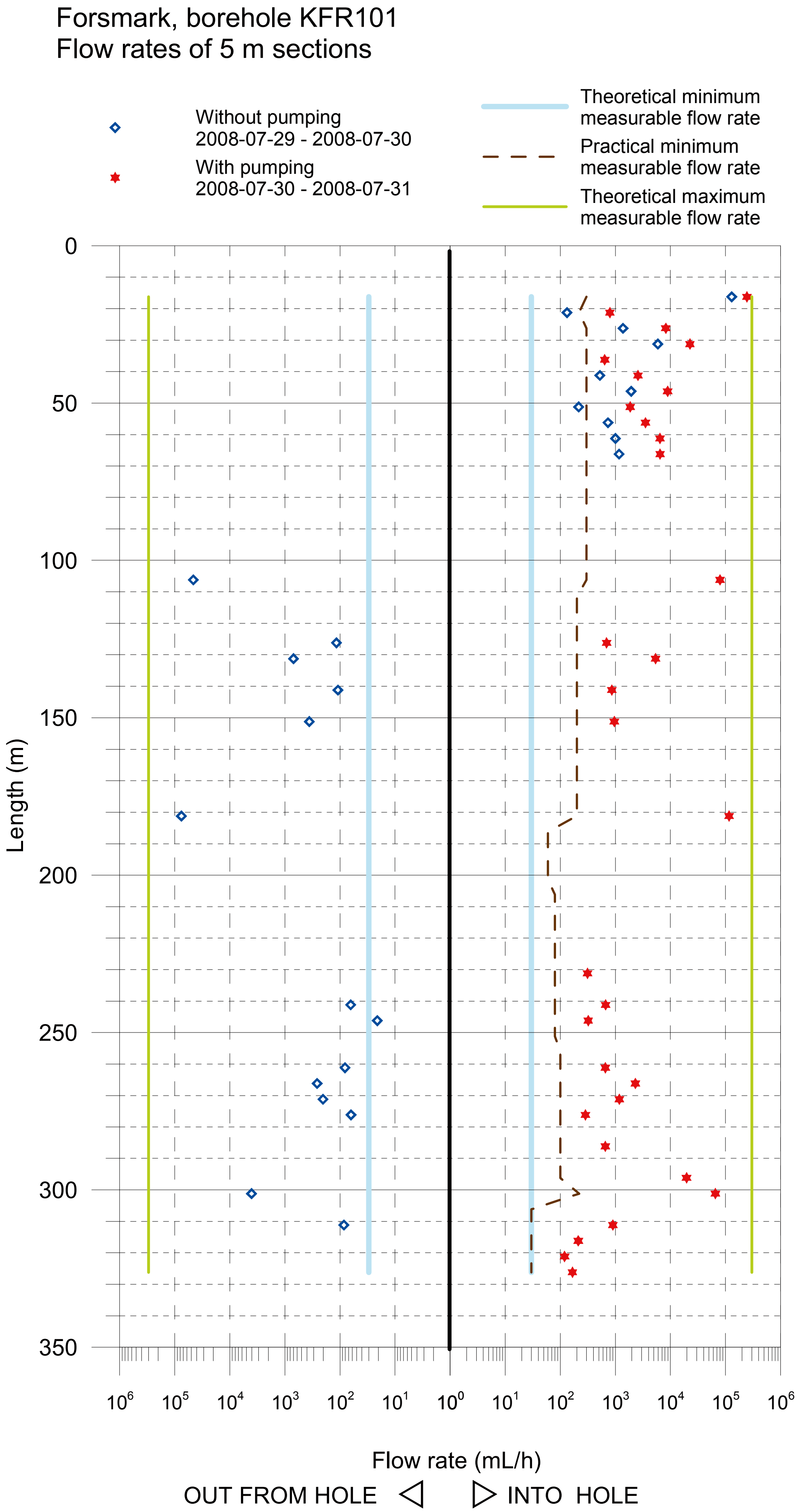
Explanations

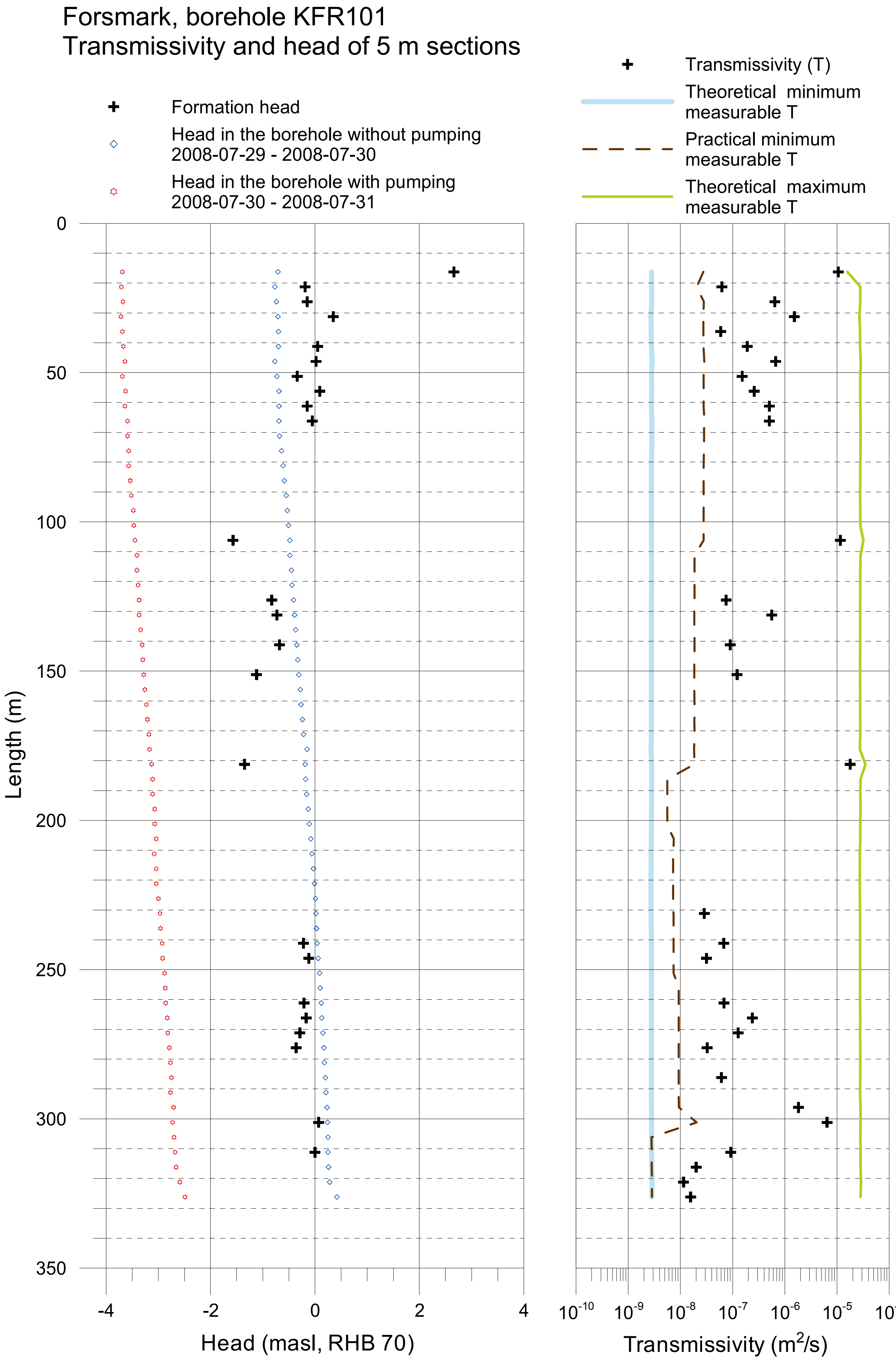
Header	Unit	Explanations
Borehole		ID for borehole.
Secup	m	Length along the borehole for the upper limit of the test section (based on corrected length L).
Seclow	m	Length along the borehole for the lower limit of the test section (based on corrected length L).
L	m	Corrected length along borehole based on SKB procedures for length correction.
Length to flow anom.	m	Length along the borehole to inferred flow anomaly during overlapping flow logging.
Test type (1–6)	(–)	1A: Pumping test – wire-line eq. 1B: Pumping test – submersible pump, 1C: Pumping test – airlift pumping, 2: Interference test, 3: Injection test, 4: Slug test, 5A: Difference flow logging – PFL-DIFF – Sequential, 5B: Difference flow logging – PFL-DIFF – Overlapping, 6: Flow logging-Impeller.
Date of test, start	YY-MM-DD	Date for start of pumping.
Time of test, start	hh:mm	Time for start of pumping.
Date of flowl. start	YY-MM-DD	Date for start of the flow logging.
Time of flowl. start	hh:mm	Time for start of the flow logging.
Date of test, stop	YY-MM-DD	Date for stop of the test.
Time of test, stop	hh:mm	Time for stop of the test.
L_w	m	Section length used in the difference flow logging.
dL	m	Step length (increment) used in the difference flow logging.
Q_{p1}	m^3/s	Flow rate at surface by the end of the first pumping period of the flow logging.
Q_{p2}	m^3/s	Flow rate at surface by the end of the second pumping period of the flow logging.
t_{p1}	s	Duration of the first pumping period.
t_{p2}	s	Duration of the second pumping period.
t_{F1}	s	Duration of the first recovery period.
t_{F2}	s	Duration of the second recovery period.
h_0	m.a.s.l.	Initial hydraulic head before pumping. Elevation of water level in open borehole in the local co-ordinates system with z=0 m.
h_1	m.a.s.l.	Stabilised hydraulic head during the first pumping period. Elevation of water level in open borehole in the local co-ordinates system with z=0 m.
h_2	m.a.s.l.	Stabilised hydraulic head during the second pumping period. Elevation of water level in open borehole in the local co-ordinates system with z=0 m.
s_1	m	Drawdown of the water level in the borehole during first pumping period. Difference between the actual hydraulic head and the initial head ($s_1=h_1–h_0$).
s_2	m	Drawdown of the water level in the borehole during second pumping period. Difference between the actual hydraulic head and the initial head ($s_2=h_2–h_0$).
T	m^2/s	Transmissivity of the entire borehole.
Q_0	m^3/s	Measured flow rate through the test section or flow anomaly under natural conditions (no pumping) with $h=h_0$ in the open borehole.
Q_1	m^3/s	Measured flow rate through the test section or flow anomaly during the first pumping period.
Q_2	m^3/s	Measured flow rate through the test section or flow anomaly during the second pumping period.
h_{0FW}	m.a.s.l.	Corrected initial hydraulic head difference along the hole due to e.g. varying salinity conditions of the borehole fluid before pumping.
h_{1FW}	m.a.s.l.	Corrected hydraulic head difference along the hole due to e.g. varying salinity conditions of the borehole fluid during the first pumping period.
h_{2FW}	m.a.s.l.	Corrected hydraulic head difference along the hole due to e.g. varying salinity conditions of the borehole fluid during the second pumping period.
EC_w	S/m	Measured electric conductivity of the borehole fluid in the test section during difference flow logging.
Te_w	°C	Measured borehole fluid temperature in the test section during difference flow logging.
EC_f	S/m	Measured fracture-specific electric conductivity of the fluid in flow anomaly during difference flow logging.
Te_f	°C	Measured fracture-specific fluid temperature in flow anomaly during difference flow logging.
T_D	m^2/s	Transmissivity of section or flow anomaly based on 2D model for evaluation of formation properties of the test section based on PFL-DIFF.
$T\text{-measl}_{LT}$	m^2/s	Estimated theoretical lower measurement limit for evaluated T_D. If the estimated T_D equals T_D-measlim, the actual T_D is considered to be equal or less than T_D-measlim.
$T\text{-measl}_{LP}$	m^2/s	Estimated practical lower measurement limit for evaluated T_D. If the estimated T_D equals T_D-measlim, the actual T_D is considered to be equal or less than T_D-measlim.
$T\text{-measl}_{U}$	m^2/s	Estimated upper measurement limit for evaluated T_D. If the estimated T_D equals T_D-measlim, the actual T_D is considered to be equal or less than T_D-measlim.
h_i	m.a.s.l.	Calculated relative, natural freshwater head for test section or flow anomaly (undisturbed conditions).

Results of sequential flow logging

Borehole ID	Secup L(m)	Seclow L(m)	L_w (m)	Q_0 (m³/s)	h_{0FW} (m.a.s.l.)	Q_1 (m³/s)	h_{1FW} (m.a.s.l.)	T_D (m²/s)	h_i (m.a.s.l.)	Q-lower limit P (mL/h)	TD-measl$_{LT}$ (m²/s)	TD- measl$_{LP}$ (m²/s)	TD- measl$_U$ (m²/s)	Comments
KFR101	13.75	18.75	5	3.61E–05	–0.71	6.81E–05	–3.69	1.1E–05	2.7	300	2.8E–09	2.8E–08	1.6E–05	
KFR101	18.76	23.76	5	3.67E–08	–0.77	2.21E–07	–3.71	6.2E–08	–0.2	220	2.8E–09	2.1E–08	2.8E–05	
KFR101	23.75	28.75	5	3.83E–07	–0.74	2.29E–06	–3.68	6.4E–07	–0.2	300	2.8E–09	2.8E–08	2.8E–05	
KFR101	28.75	33.75	5	1.64E–06	–0.71	6.28E–06	–3.72	1.5E–06	0.4	300	2.7E–09	2.7E–08	2.7E–05	
KFR101	33.74	38.74	5	–	–0.70	1.78E–07	–3.69	5.9E–08	–	300	2.8E–09	2.8E–08	2.8E–05	
KFR101	38.73	43.73	5	1.45E–07	–0.70	7.17E–07	–3.67	1.9E–07	0.1	300	2.8E–09	2.8E–08	2.8E–05	
KFR101	43.75	48.75	5	5.36E–07	–0.77	2.47E–06	–3.64	6.7E–07	0.0	300	2.9E–09	2.9E–08	2.9E–05	
KFR101	48.75	53.75	5	6.00E–08	–0.73	5.17E–07	–3.69	1.5E–07	–0.3	300	2.8E–09	2.8E–08	2.8E–05	
KFR101	53.74	58.74	5	2.04E–07	–0.69	9.78E–07	–3.63	2.6E–07	0.1	300	2.8E–09	2.8E–08	2.8E–05	
KFR101	58.73	63.73	5	2.78E–07	–0.69	1.79E–06	–3.64	5.1E–07	–0.2	300	2.8E–09	2.8E–08	2.8E–05	
KFR101	63.72	68.72	5	3.25E–07	–0.69	1.81E–06	–3.59	5.1E–07	–0.1	300	2.8E–09	2.8E–08	2.8E–05	
KFR101	68.72	73.72	5	–	–0.68	–	–3.59	–	–	300	2.8E–09	2.8E–08	2.8E–05	
KFR101	73.71	78.71	5	–	–0.64	–	–3.57	–	–	300	2.8E–09	2.8E–08	2.8E–05	
KFR101	78.71	83.71	5	–	–0.61	–	–3.57	–	–	300	2.8E–09	2.8E–08	2.8E–05	
KFR101	83.70	88.70	5	–	–0.59	–	–3.54	–	–	300	2.8E–09	2.8E–08	2.8E–05	
KFR101	88.70	93.70	5	–	–0.55	–	–3.52	–	–	300	2.8E–09	2.8E–08	2.8E–05	
KFR101	93.69	98.69	5	–	–0.53	–	–3.48	–	–	300	2.8E–09	2.8E–08	2.8E–05	
KFR101	98.69	103.69	5	–	–0.51	–	–3.47	–	–	300	2.8E–09	2.8E–08	2.8E–05	
KFR101	103.69	108.69	5	–1.28E–05	–0.48	2.21E–05	–3.45	1.2E–05	–1.6	300	2.8E–09	2.8E–08	3.2E–05	
KFR101	108.69	113.69	5	–	–0.48	–	–3.41	–	–	200	2.8E–09	1.9E–08	2.8E–05	
KFR101	113.71	118.71	5	–	–0.45	–	–3.41	–	–	200	2.8E–09	1.9E–08	2.8E–05	
KFR101	118.70	123.70	5	–	–0.44	–	–3.39	–	–	200	2.8E–09	1.9E–08	2.8E–05	
KFR101	123.70	128.70	5	–3.22E–08	–0.41	1.93E–07	–3.37	7.5E–08	–0.8	200	2.8E–09	1.9E–08	2.8E–05	
KFR101	128.70	133.70	5	–1.94E–07	–0.39	1.49E–06	–3.37	5.6E–07	–0.7	200	2.8E–09	1.8E–08	2.8E–05	
KFR101	133.70	138.70	5	–	–0.37	–	–3.34	–	–	200	2.8E–09	1.9E–08	2.8E–05	
KFR101	138.70	143.70	5	–3.03E–08	–0.35	2.39E–07	–3.31	9.0E–08	–0.7	200	2.8E–09	1.9E–08	2.8E–05	
KFR101	143.70	148.70	5	–	–0.33	–	–3.30	–	–	200	2.8E–09	1.9E–08	2.8E–05	
KFR101	148.70	153.70	5	–1.00E–07	–0.31	2.66E–07	–3.28	1.2E–07	–1.1	200	2.8E–09	1.9E–08	2.8E–05	
KFR101	153.70	158.70	5	–	–0.28	–	–3.26	–	–	200	2.8E–09	1.8E–08	2.8E–05	
KFR101	158.70	163.70	5	–	–0.27	–	–3.23	–	–	200	2.8E–09	1.9E–08	2.8E–05	

Borehole ID	Secup L(m)	Seclow L(m)	L_w (m)	Q_0 (m^3/s)	h_{0FW} (m.a.s.l.)	Q_1 (m^3/s)	h_{1FW} (m.a.s.l.)	T_D (m^2/s)	h_i (m.a.s.l.)	Q-lower limit P (mL/h)	TD-measl$_{LT}$ (m^2/s)	TD- measl$_{LP}$ (m^2/s)	TD- measl$_U$ (m^2/s)	Comments
KFR101	163.71	168.71	5	–	–0.24	–	–3.21	–	–	200	2.8E–09	1.9E–08	2.8E–05	
KFR101	168.71	173.71	5	–	–0.22	–	–3.18	–	–	200	2.8E–09	1.9E–08	2.8E–05	
KFR101	173.71	178.71	5	–	–0.15	–	–3.17	–	–	200	2.7E–09	1.8E–08	2.7E–05	
KFR101	178.71	183.71	5	–2.11E–05	–0.19	3.22E–05	–3.13	1.8E–05	–1.4	200	2.8E–09	1.9E–08	3.5E–05	
KFR101	183.71	188.71	5	–	–0.18	–	–3.11	–	–	60	2.8E–09	5.6E–09	2.8E–05	
KFR101	188.71	193.71	5	–	–0.16	–	–3.11	–	–	60	2.8E–09	5.6E–09	2.8E–05	
KFR101	193.71	198.71	5	–	–0.13	–	–3.07	–	–	60	2.8E–09	5.6E–09	2.8E–05	
KFR101	198.71	203.71	5	–	–0.11	–	–3.07	–	–	60	2.8E–09	5.6E–09	2.8E–05	
KFR101	203.71	208.71	5	–	–0.08	–	–3.04	–	–	80	2.8E–09	7.4E–09	2.8E–05	
KFR101	208.71	213.71	5	–	–0.06	–	–3.08	–	–	80	2.7E–09	7.3E–09	2.7E–05	
KFR101	213.70	218.70	5	–	–0.03	–	–3.04	–	–	80	2.7E–09	7.3E–09	2.7E–05	
KFR101	218.71	223.71	5	–	–0.01	–	–3.04	–	–	80	2.7E–09	7.3E–09	2.7E–05	
KFR101	223.70	228.70	5	–	0.01	–	–3.00	–	–	80	2.7E–09	7.3E–09	2.7E–05	
KFR101	228.70	233.70	5	–	0.02	8.67E–08	–2.97	2.9E–08	–	80	2.8E–09	7.4E–09	2.8E–05	
KFR101	233.70	238.70	5	–	0.03	–	–2.96	–	–	80	2.8E–09	7.4E–09	2.8E–05	
KFR101	238.70	243.70	5	–1.78E–08	0.04	1.85E–07	–2.93	6.8E–08	–0.2	80	2.8E–09	7.4E–09	2.8E–05	
KFR101	243.71	248.71	5	–5.83E–09	0.06	8.92E–08	–2.92	3.2E–08	–0.1	80	2.8E–09	7.4E–09	2.8E–05	
KFR101	248.71	253.71	5	–	0.09	–	–2.88	–	–	80	2.8E–09	7.4E–09	2.8E–05	
KFR101	253.70	258.70	5	–	0.10	–	–2.87	–	–	100	2.8E–09	9.3E–09	2.8E–05	
KFR101	258.70	263.70	5	–2.25E–08	0.12	1.83E–07	–2.86	6.8E–08	–0.2	100	2.8E–09	9.2E–09	2.8E–05	
KFR101	263.70	268.70	5	–7.22E–08	0.13	6.42E–07	–2.83	2.4E–07	–0.2	100	2.8E–09	9.3E–09	2.8E–05	
KFR101	268.69	273.69	5	–5.64E–08	0.15	3.28E–07	–2.82	1.3E–07	–0.3	100	2.8E–09	9.3E–09	2.8E–05	
KFR101	273.68	278.68	5	–1.75E–08	0.17	7.97E–08	–2.79	3.2E–08	–0.4	100	2.8E–09	9.3E–09	2.8E–05	
KFR101	278.69	283.69	5	–	0.18	–	–2.77	–	–	100	2.8E–09	9.3E–09	2.8E–05	
KFR101	283.68	288.68	5	–	0.20	1.83E–07	–2.75	6.1E–08	–	100	2.8E–09	9.3E–09	2.8E–05	
KFR101	288.68	293.68	5	–	0.21	–	–2.77	–	–	100	2.8E–09	9.2E–09	2.8E–05	
KFR101	293.68	298.68	5	–	0.23	5.44E–06	–2.71	1.8E–06	–	100	2.8E–09	9.3E–09	2.8E–05	
KFR101	298.68	303.68	5	–1.12E–06	0.24	1.82E–05	–2.73	6.4E–06	0.1	220	2.8E–09	2.0E–08	2.8E–05	
KFR101	303.67	308.67	5	–	0.25	–	–2.70	–	–	30	2.8E–09	2.8E–09	2.8E–05	
KFR101	308.68	313.68	5	–2.36E–08	0.25	2.50E–07	–2.68	9.2E–08	–	30	2.8E–09	2.8E–09	2.8E–05	
KFR101	313.68	318.68	5	–	0.26	5.92E–08	–2.66	2.0E–08	–	30	2.8E–09	2.8E–09	2.8E–05	
KFR101	318.68	323.68	5	–	0.28	3.33E–08	–2.59	1.2E–08	–	30	2.9E–09	2.9E–09	2.9E–05	
KFR101	323.69	328.69	5	–	0.42	4.61E–08	–2.49	1.6E–08	–	30	2.8E–09	2.8E–09	2.8E–05	


Forsmark, borehole KFR101
Flow rates of 5 m sections
Without pumping
2008-07-29 - 2008-07-30
With pumping
2008-07-30 - 2008-07-31
Theoretical minimum
measurable flow rate
Practical minimum
measurable flow rate
Theoretical maximum
measurable flow rate
Length (m)
0
50
100
150
200
250
300
350
10^6 10^5 10^4 10^3 10^2 10^1 10^0 10^1 10^2 10^3 10^4 10^5 10^6
Flow rate (mL/h)
OUT FROM HOLE ◁ ▷ INTO HOLE

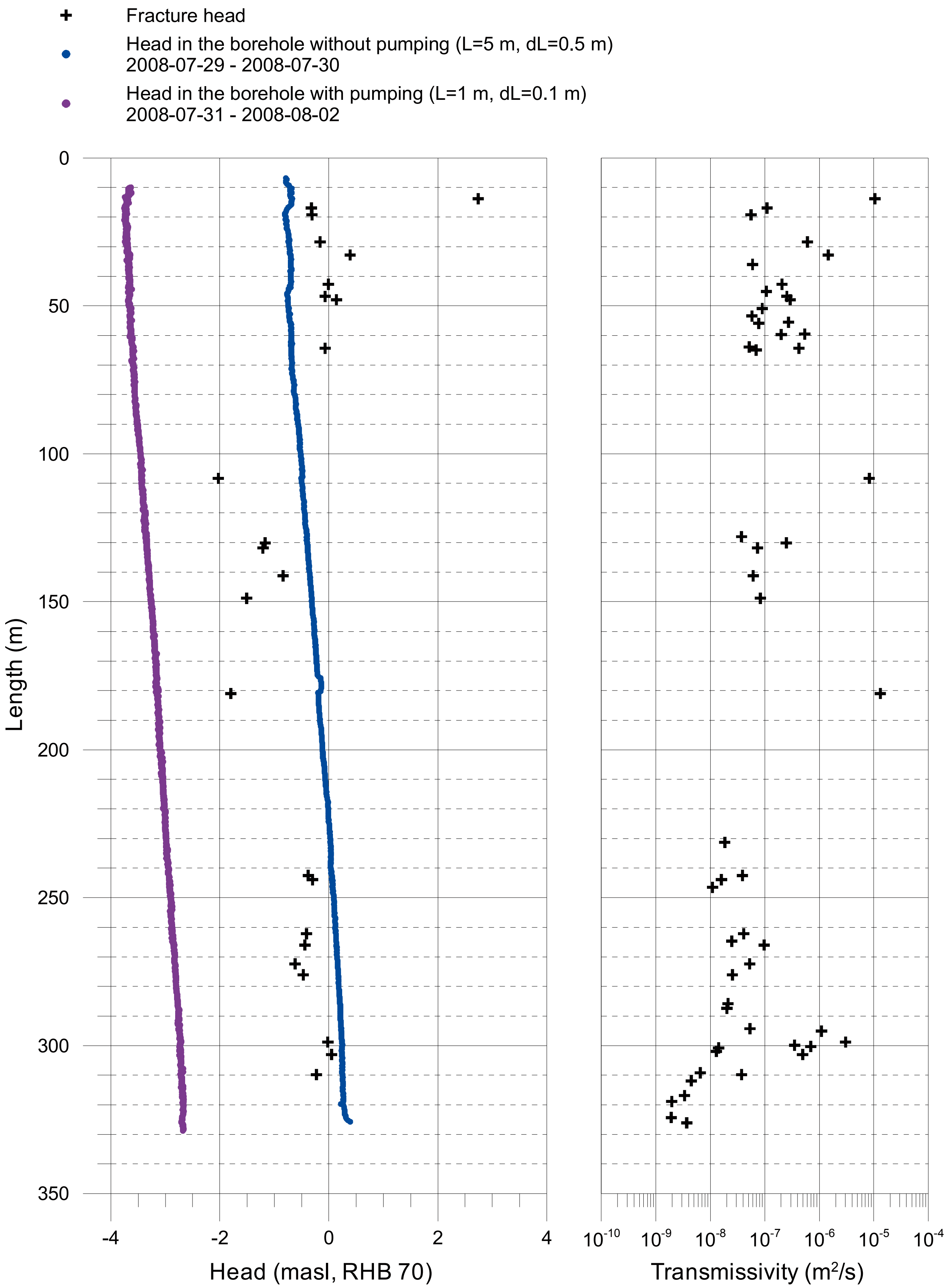

Forsmark, borehole KFR101
Transmissivity and head of 5 m sections
Formation head
Head in the borehole without pumping
2008-07-29 - 2008-07-30
Head in the borehole with pumping
2008-07-30 - 2008-07-31
Transmissivity (T)
Theoretical minimum measurable T
Practical minimum measurable T
Theoretical maximum measurable T
Length (m)
0
50
100
150
200
250
300
350
-4
-2
0
2
4
Head (masl, RHB 70)
10-10
10-9
10-8
10-7
10-6
10-5
10-4
Transmissivity (m2/s)

Inferred flow anomalies from overlapping flow logging

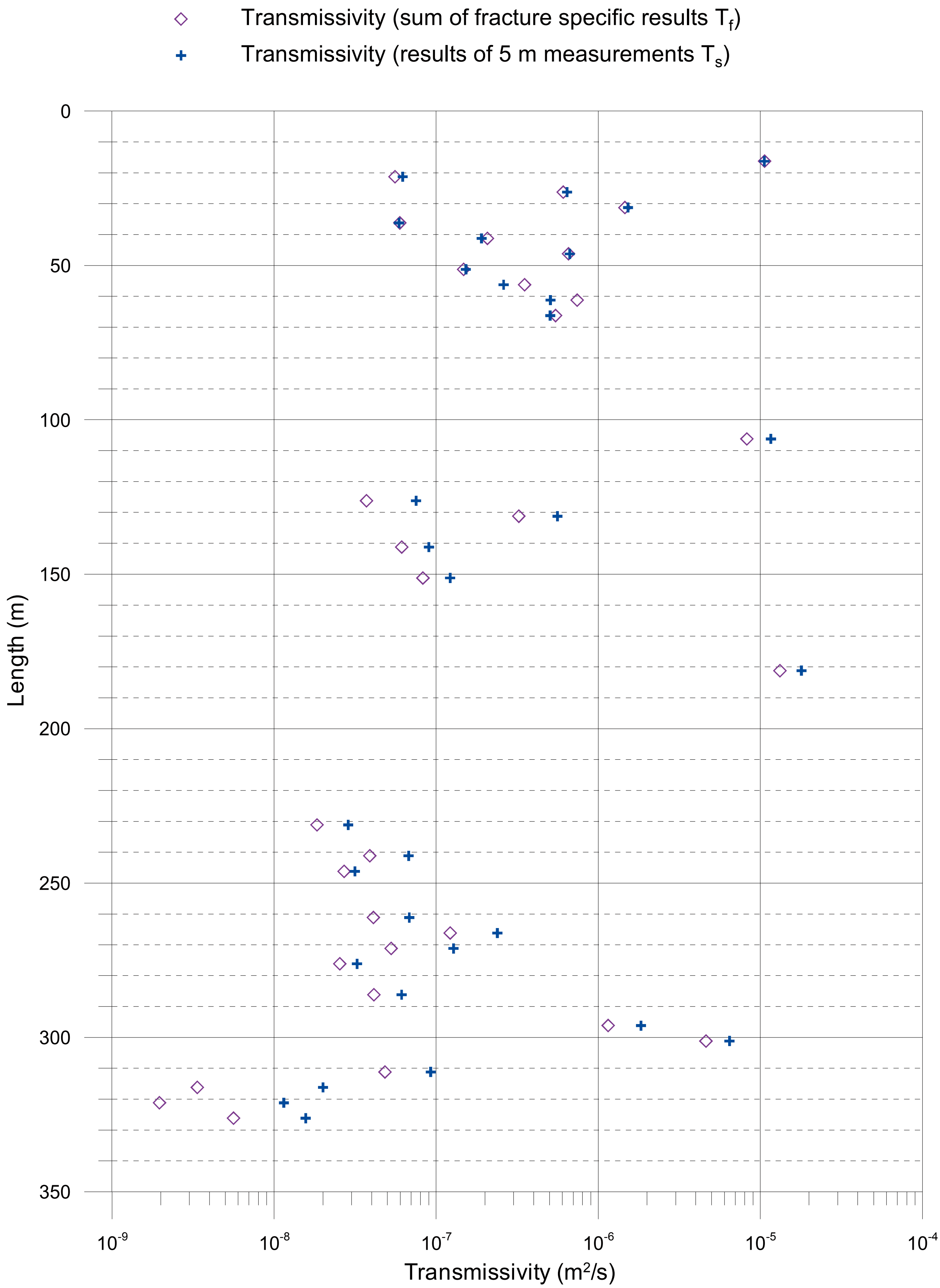
Borehole ID	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_0 (m³/s)	h_{0FW} (m.a.s.l.)	Q_1 (m³/s)	h_{1FW} (m.a.s.l.)	T_D (m²/s)	h_i (m.a.s.l.)	Comments
KFR101	13.8	1	0.1	3.61E–05	–0.67	6.81E–05	–3.69	1.1E–05	2.7	
KFR101	16.9	1	0.1	4.75E–08	–0.75	3.81E–07	–3.74	1.1E–07	–0.3	
KFR101	19.2	1	0.1	2.81E–08	–0.81	1.93E–07	–3.73	5.6E–08	–0.3	
KFR101	28.4	1	0.1	3.64E–07	–0.75	2.18E–06	–3.71	6.1E–07	–0.2	
KFR101	32.8	1	0.1	1.62E–06	–0.70	5.97E–06	–3.64	1.5E–06	0.4	
KFR101	36.0	1	0.1	–	–0.70	1.78E–07	–3.66	6.0E–08	–	*
KFR101	42.7	1	0.1	1.45E–07	–0.70	7.64E–07	–3.66	2.1E–07	0.0	
KFR101	45.1	1	0.1	–	–0.75	3.17E–07	–3.67	1.1E–07	–	*
KFR101	46.8	1	0.1	1.78E–07	–0.76	9.22E–07	–3.66	2.5E–07	–0.1	
KFR101	47.9	1	0.1	2.64E–07	–0.75	1.13E–06	–3.68	2.9E–07	0.1	
KFR101	50.9	1	0.1	–	–0.73	2.62E–07	–3.62	9.0E–08	–	*
KFR101	53.4	1	0.1	–	–0.73	1.71E–07	–3.65	5.8E–08	–	
KFR101	55.5	1	0.1	–	–0.71	8.11E–07	–3.65	2.7E–07	–	
KFR101	55.9	1	0.1	–	–0.70	2.31E–07	–3.65	7.8E–08	–	*
KFR101	59.5	1	0.1	–	–0.69	1.60E–06	–3.62	5.4E–07	–	
KFR101	59.7	1	0.1	–	–0.69	5.94E–07	–3.63	2.0E–07	–	*
KFR101	63.9	1	0.1	–	–0.69	1.51E–07	–3.58	5.2E–08	–	*
KFR101	64.3	1	0.1	2.65E–07	–0.69	1.51E–06	–3.60	4.2E–07	–0.1	
KFR101	64.9	1	0.1	–	–0.69	2.04E–07	–3.61	6.9E–08	–	
KFR101	108.3	1	0.1	–1.27E–05	–0.51	1.18E–05	–3.44	8.3E–06	–2.0	
KFR101	128.0	1	0.1	–	–0.40	1.11E–07	–3.35	3.7E–08	–	
KFR101	130.1	1	0.1	–1.94E–07	–0.40	5.50E–07	–3.35	2.5E–07	–1.2	
KFR101	131.8	1	0.1	–6.11E–08	–0.39	1.59E–07	–3.35	7.4E–08	–1.2	
KFR101	141.2	1	0.1	–3.03E–08	–0.35	1.52E–07	–3.29	6.1E–08	–0.8	
KFR101	148.8	1	0.1	–1.01E–07	–0.31	1.46E–07	–3.26	8.3E–08	–1.5	
KFR101	181.0	1	0.1	–2.12E–05	–0.20	1.81E–05	–3.16	1.3E–05	–1.8	
KFR101	231.3	1	0.1	–	0.02	5.58E–08	–2.98	1.8E–08	–	
KFR101	242.5	1	0.1	–1.69E–08	0.05	1.01E–07	–2.94	3.9E–08	–0.4	*
KFR101	243.9	1	0.1	–5.83E–09	0.06	4.28E–08	–2.94	1.6E–08	–0.3	*
KFR101	246.5	1	0.1	–	0.06	3.33E–08	–2.93	1.1E–08	–	*
KFR101	262.2	1	0.1	–2.25E–08	0.13	1.02E–07	–2.88	4.1E–08	–0.4	
KFR101	264.7	1	0.1	–	0.13	7.53E–08	–2.87	2.5E–08	–	
KFR101	266.0	1	0.1	–5.72E–08	0.14	2.34E–07	–2.83	9.7E–08	–0.4	
KFR101	272.4	1	0.1	–4.14E–08	0.16	1.18E–07	–2.82	5.3E–08	–0.6	
KFR101	276.1	1	0.1	–1.64E–08	0.17	6.03E–08	–2.81	2.5E–08	–0.5	
KFR101	285.8	1	0.1	–	0.20	6.36E–08	–2.78	2.1E–08	–	
KFR101	287.4	1	0.1	–	0.21	6.06E–08	–2.76	2.0E–08	–	*
KFR101	294.3	1	0.1	–	0.23	1.60E–07	–2.74	5.3E–08	–	
KFR101	295.1	1	0.1	–	0.23	3.31E–06	–2.74	1.1E–06	–	
KFR101	298.8	1	0.1	–8.06E–07	0.24	8.25E–06	–2.71	3.0E–06	0.0	
KFR101	299.9	1	0.1	–	0.25	1.06E–06	–2.73	3.5E–07	–	*
KFR101	300.3	1	0.1	–	0.24	2.10E–06	–2.74	7.0E–07	–	
KFR101	300.8	1	0.1	–	0.24	4.25E–08	–2.72	1.4E–08	–	*
KFR101	302.0	1	0.1	–	0.24	3.86E–08	–2.72	1.3E–08	–	*
KFR101	303.0	1	0.1	–9.42E–08	0.24	1.39E–06	–2.72	5.0E–07	0.1	
KFR101	309.2	1	0.1	–	0.24	1.94E–08	–2.69	6.6E–09	–	*
KFR101	309.8	1	0.1	–1.81E–08	0.25	9.36E–08	–2.71	3.7E–08	–0.2	
KFR101	311.9	1	0.1	–	0.25	1.33E–08	–2.69	4.5E–09	–	*
KFR101	316.9	1	0.1	–	0.26	1.00E–08	–2.68	3.4E–09	–	*
KFR101	318.9	1	0.1	–	0.27	5.83E–09	–2.68	2.0E–09	–	*
KFR101	324.3	1	0.1	–	0.31	5.83E–09	–2.69	1.9E–09	–	*
KFR101	326.1	1	0.1	–	0.42	1.17E–08	–2.70	3.7E–09	–	

* Uncertain = The flow rate is less than 30 mL/h or the flow anomalies are overlapping or they are unclear because of noise.

Forsmark, borehole KFR101
Transmissivity and head of detected fractures

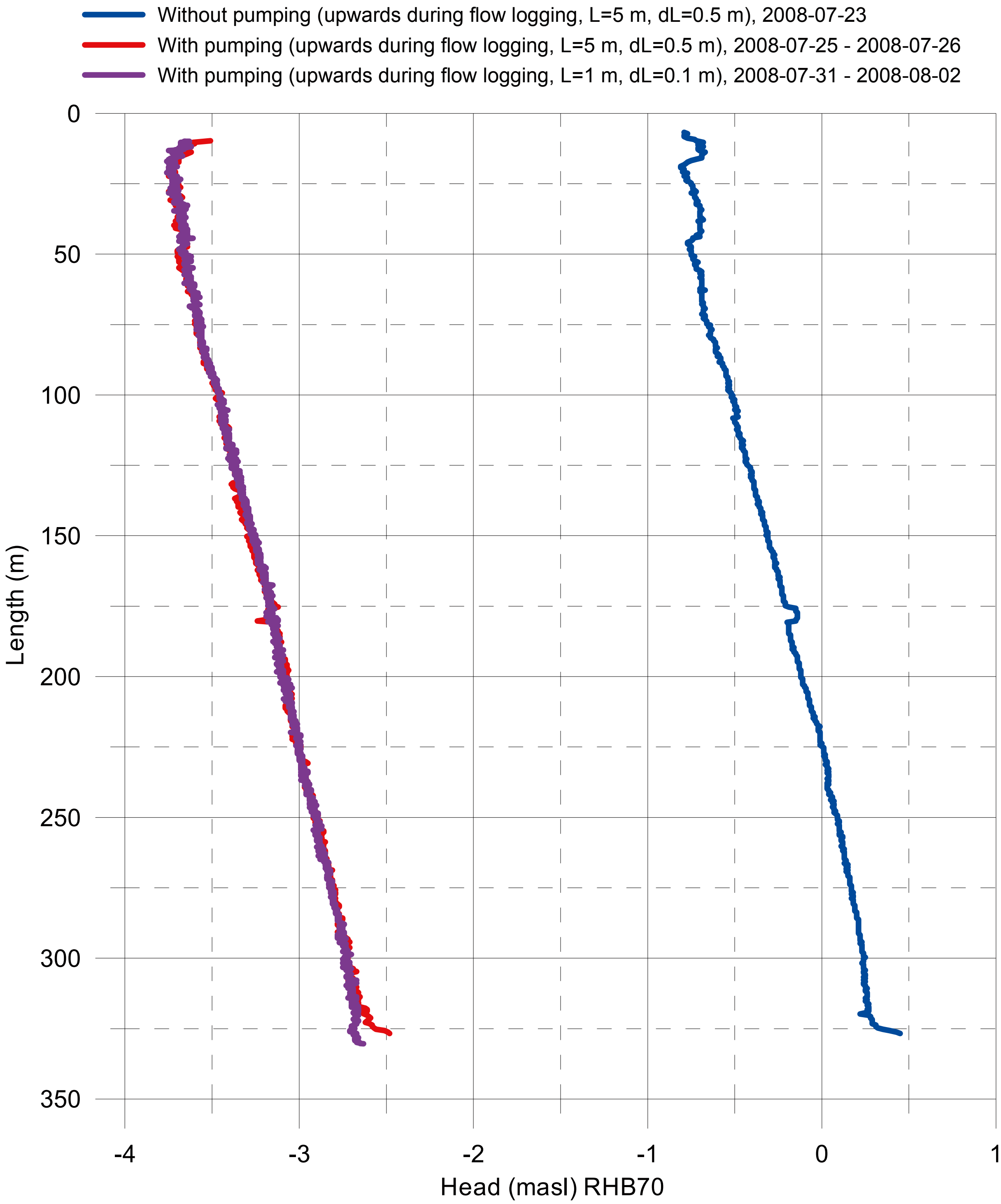


Forsmark, borehole KFR101
Comparison between section transmissivity and fracture transmissivity

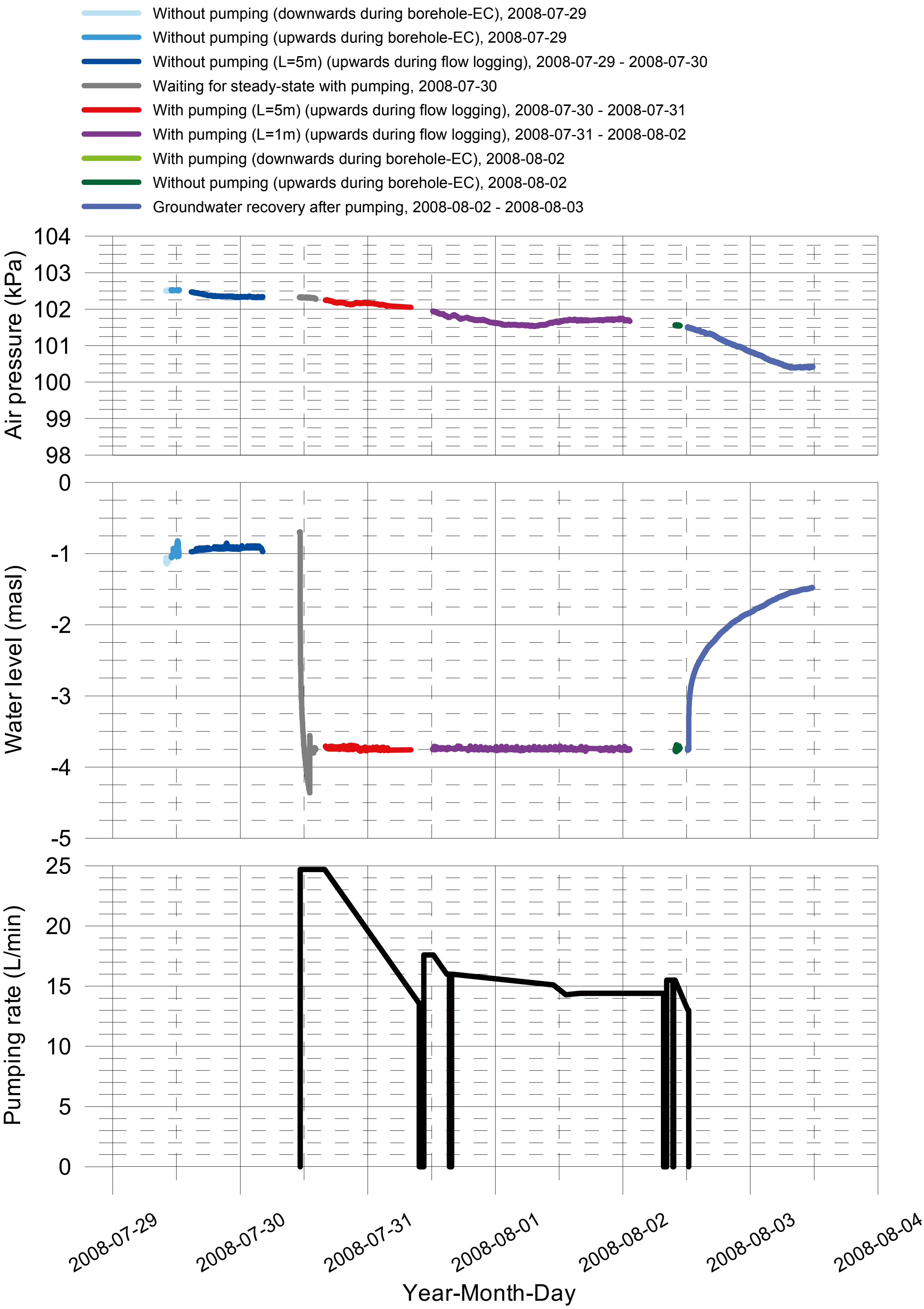


Forsmark, borehole KFR101
Head in the borehole during flow logging

Head(masl)= (Absolute pressure (Pa) - Airpressure (Pa) + Offset) /(1000 kg/m^3 * 9.80665 m/s^2) + Elevation (m)
Offset = 4500 Pa (Correction for absolute pressure sensor)

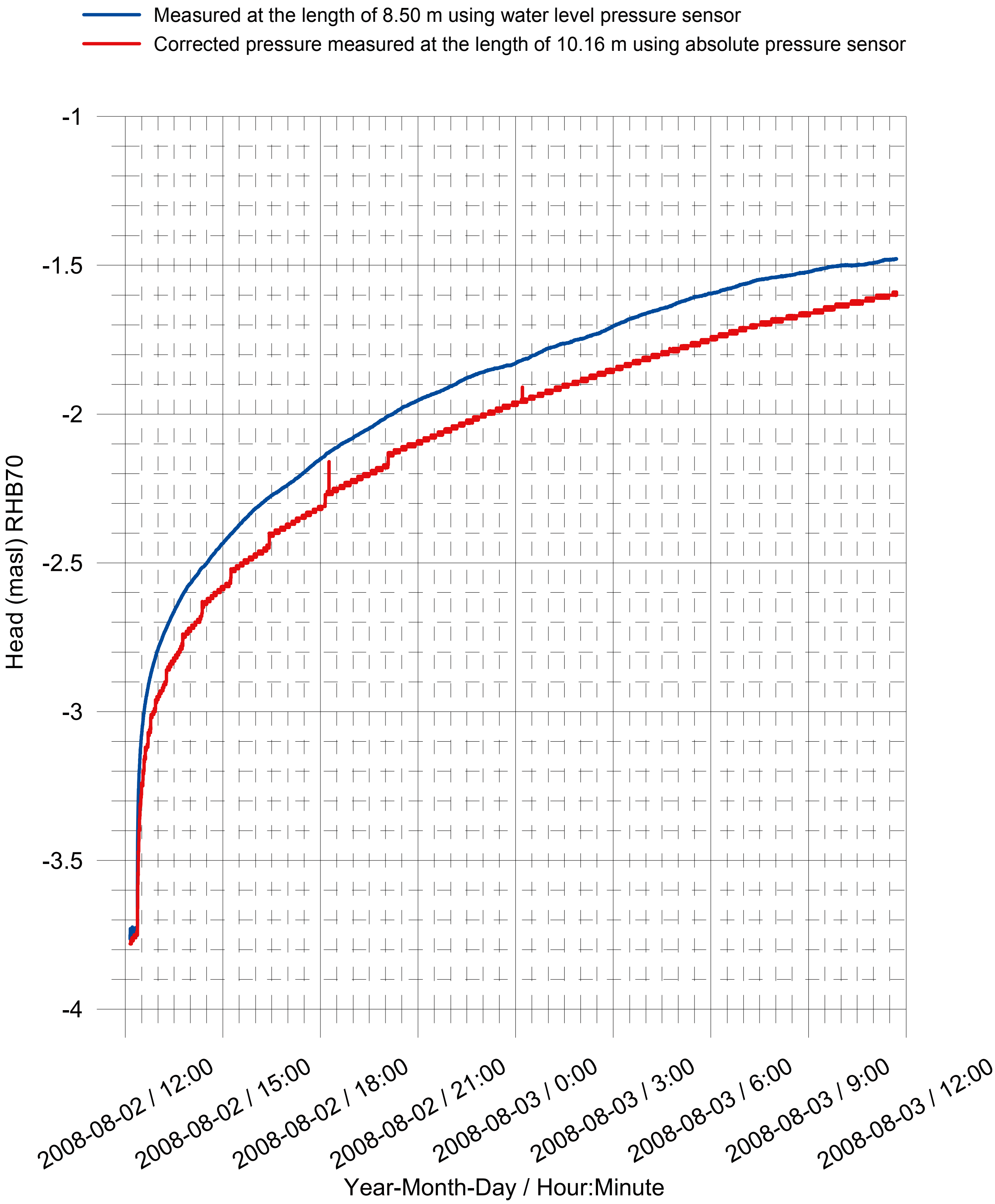


Forsmark, borehole KFR101
Air pressure, water level in the borehole and pumping rate during flow logging

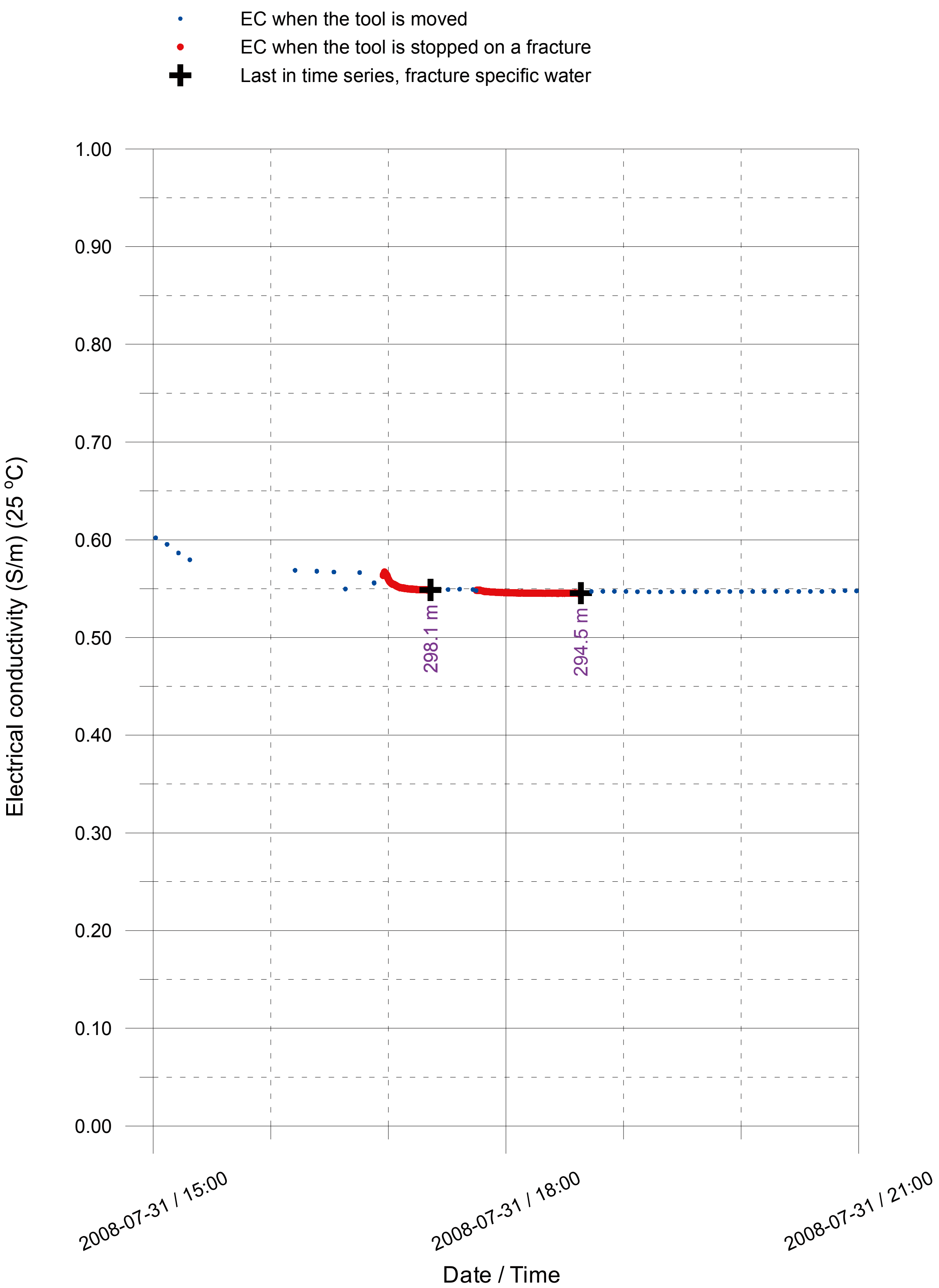


Forsmark, borehole KFR101
Groundwater recovery after pumping

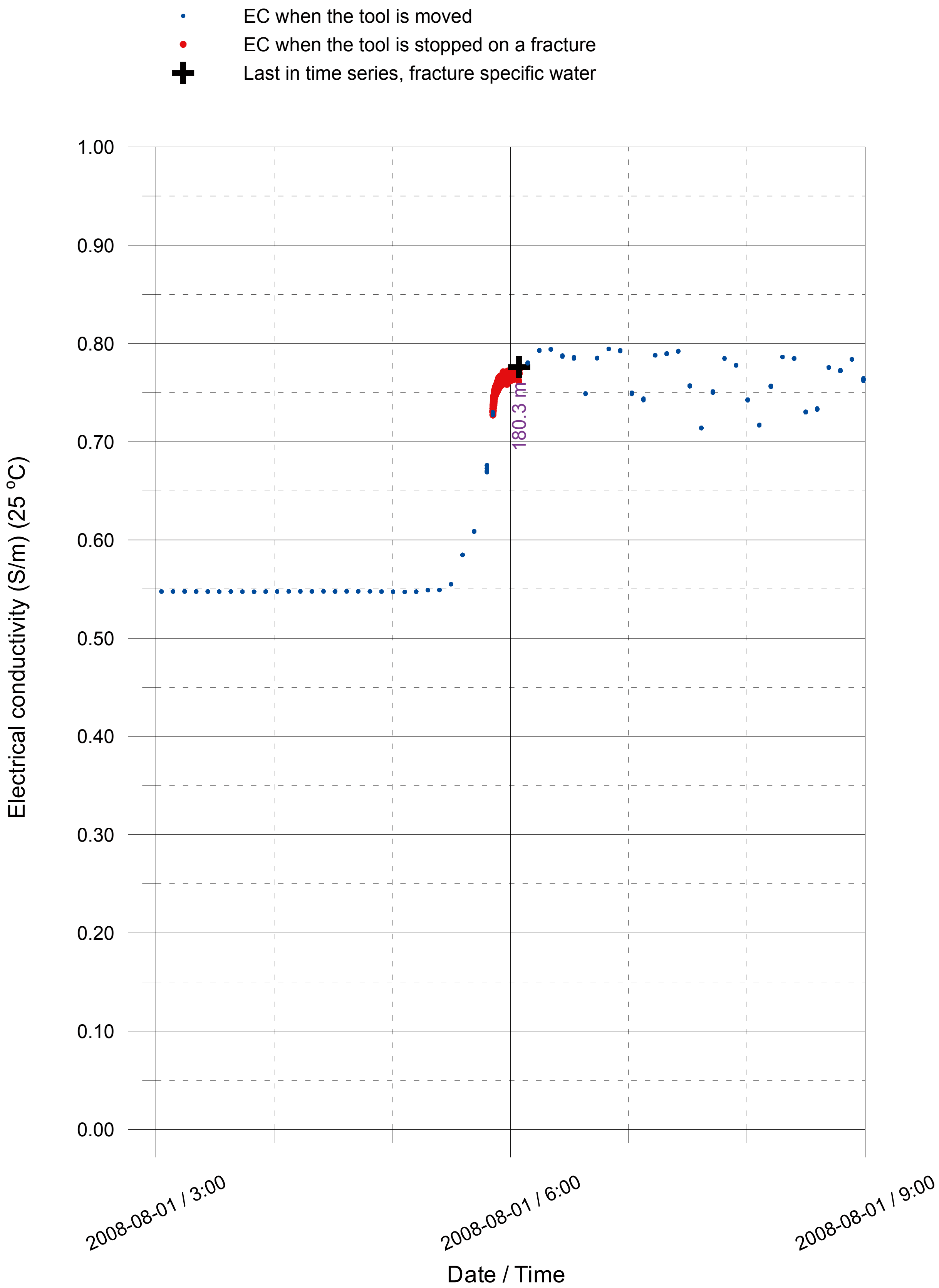
Head(masl)= (Absolute pressure (Pa) - Airpressure (Pa) + Offset) /(1000 kg/m^3 * 9.80665 m/s^2) + Elevation (m)
Offset = 4500 Pa (Correction for absolute pressure sensor)



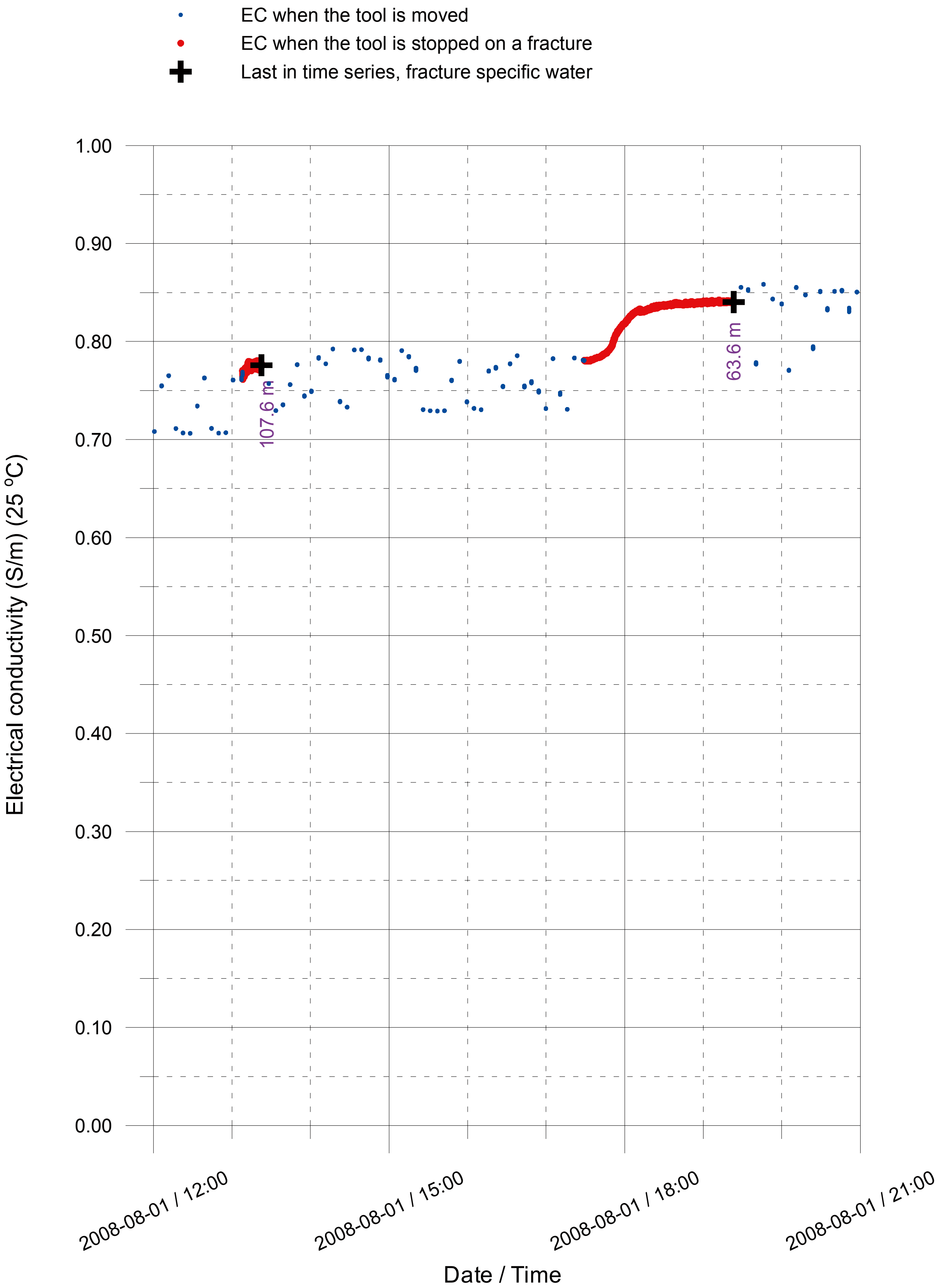
Forsmark, borehole KFR101
Fracture-specific EC results by date



Forsmark, borehole KFR101
Fracture-specific EC results by date



Forsmark, borehole KFR101
Fracture-specific EC results by date



Forsmark, borehole KFR101
Fracture-specific EC results by date