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Site investigation SFR

Difference flow logging in boreholes KFR102B and KFR103

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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 KFR102B and KFR103 at Forsmark, Sweden, in September 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, 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 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.

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 (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 KFR102B och KFR103 i Forsmark, Sverige, i september 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.

Längdkalibrering gjordes med hjälp av de längdmärken som finns infrästa vid noggrant bestämda positioner längs borrhålet. Längdmärkena detekterades med caliper och punktresistansmätningar (SPR) med hjälp av sensorer anslutna på flödesloggningssonden.

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 (1 m lång testsektion).

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

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1 Introduction

The core drilled boreholes KFR102B and KFR103 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 KFR102B was measured between September 15 and September 21, 2008 and borehole KFR103 was measured between September 21 and September 26, 2008.

KFR102B is 180.1 m long and its inclination at the ground level is 54° from the horizontal plane. KFR103 is 200.5 m long and its inclination at the ground level is 54° from the horizontal plane. The boreholes were drilled using a telescopic drilling technique, where the c. 0–14 m interval in KFR102B and the c. 0–13 m interval in KFR103, were percussion drilled, and their inner diameter is 130 mm, whereas the rest of the boreholes were core drilled with the diameter of 76 mm. A stainless steel support casing with an inner diameter of 77 mm has been placed within the percussion drilled part of both boreholes.

The locations of KFR102B and KFR103 at Forsmark are illustrated in Figure 1-1.

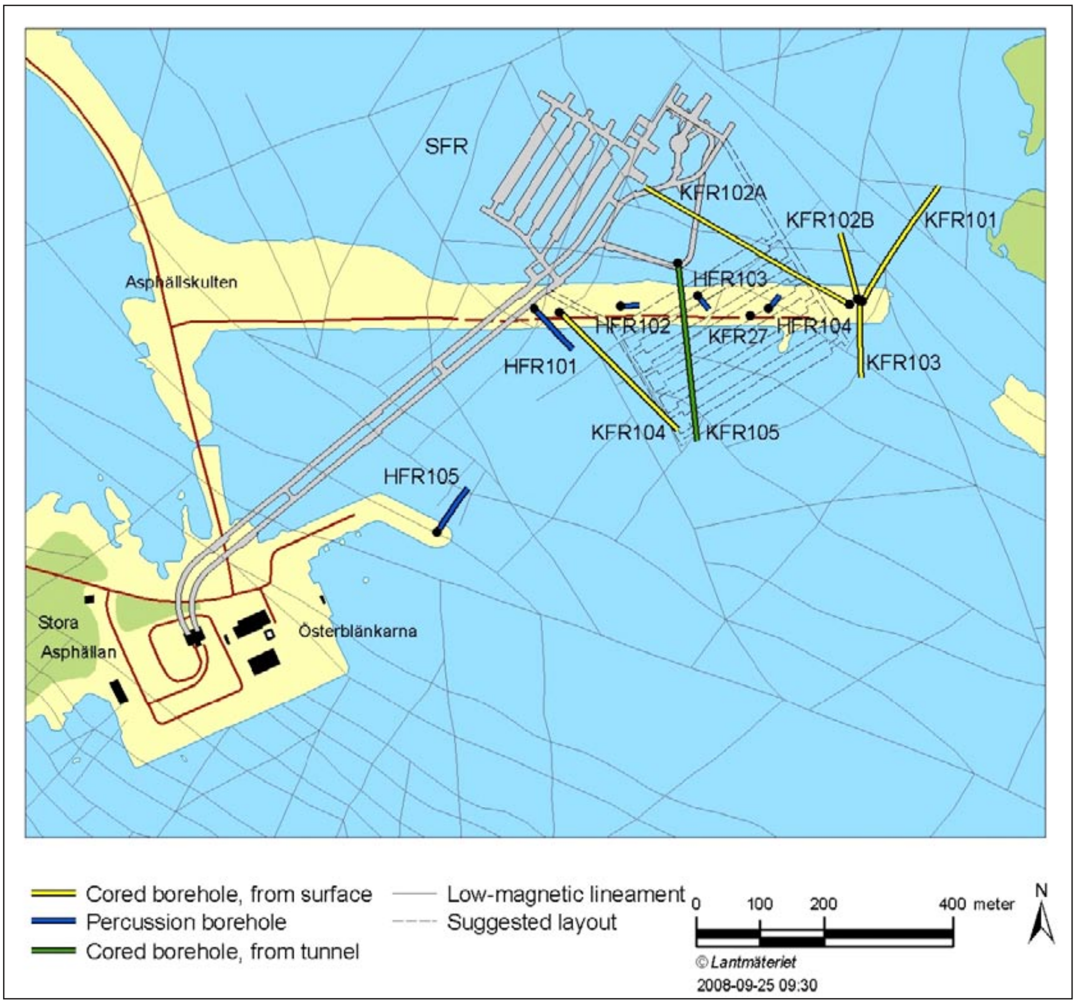

Figure 1-1. Location Map over the SFR facility and the location of the boreholes, including KFR102B and KFR103.

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 PFL DIFF in boreholes KFR102B and KFR103. 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-08-016. 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 KFR102B and KFR103	AP SFR-08-016	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
Instruktion för analys av injektions- och enhålspumptester	SKB MD 320.004	2.0

2 Objective and scope

The main objective of the PFL DIFF measurements in KFR102B and KFR103 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. 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.

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.

3 Principles of measurement and interpretation

3.1 Measurements

Unlike conventional 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.

Generally two separate measurements with two different section lengths (e.g. 5 m and 1 m) are used. The 5 m setup is usually used first to obtain a general picture of the flow anomalies. It is also good for measuring larger (less than 5 m in length) fractured zones. The 1 m section setup can separate anomalies which are close to each other. There are also many other advantages to using different section lengths.

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 /Öhberg and Rouhiainen 2000, 11–13/. 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.

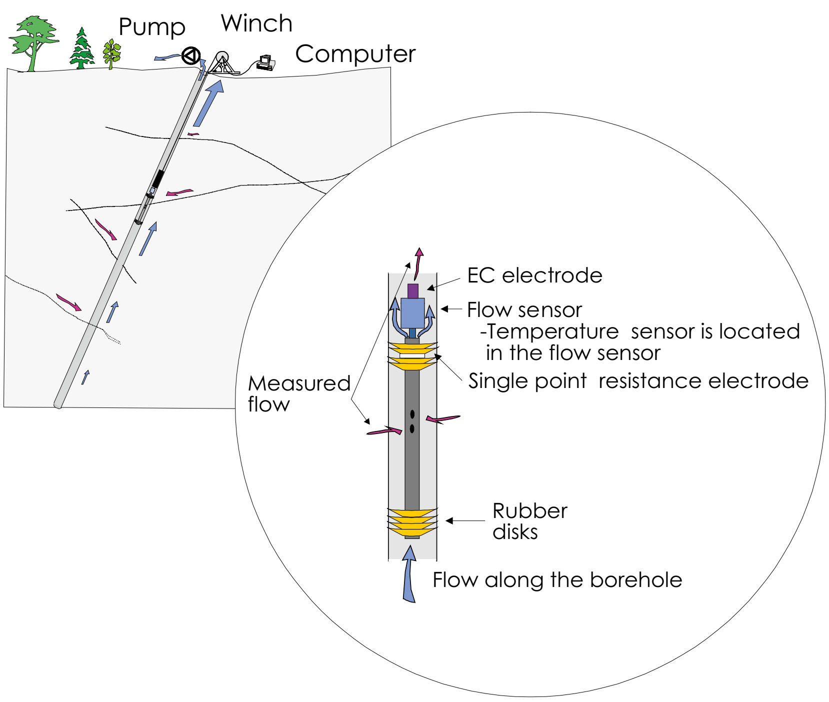

Figure 3-1. *Schematic of the probe used in the PFL DIFF.*

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 3-3a). The central thermistor, A, is used both as a heating element and to register temperature changes (Figures 3-3b 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 3-3c). 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.

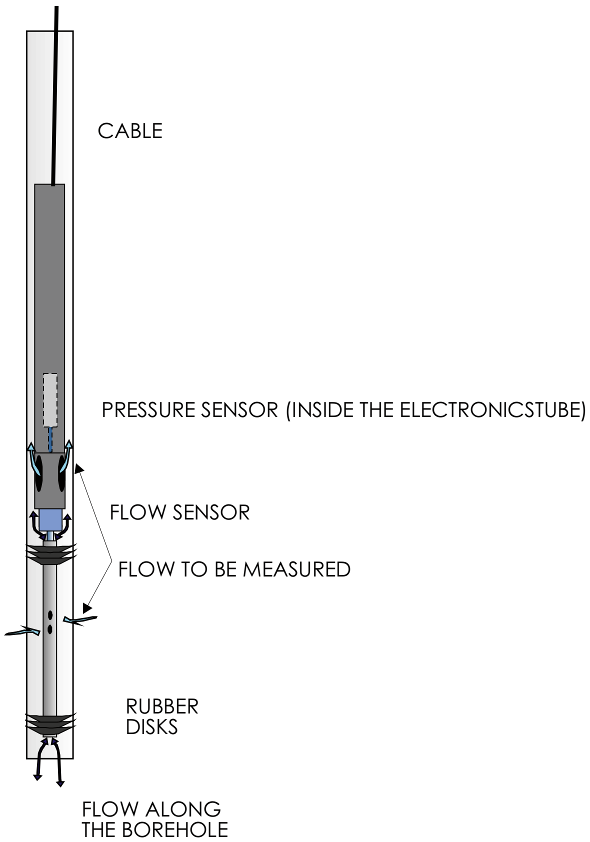

Figure 3-2. *The absolute pressure sensor is located inside the electronics assembly and connected to the borehole water through a tube.*

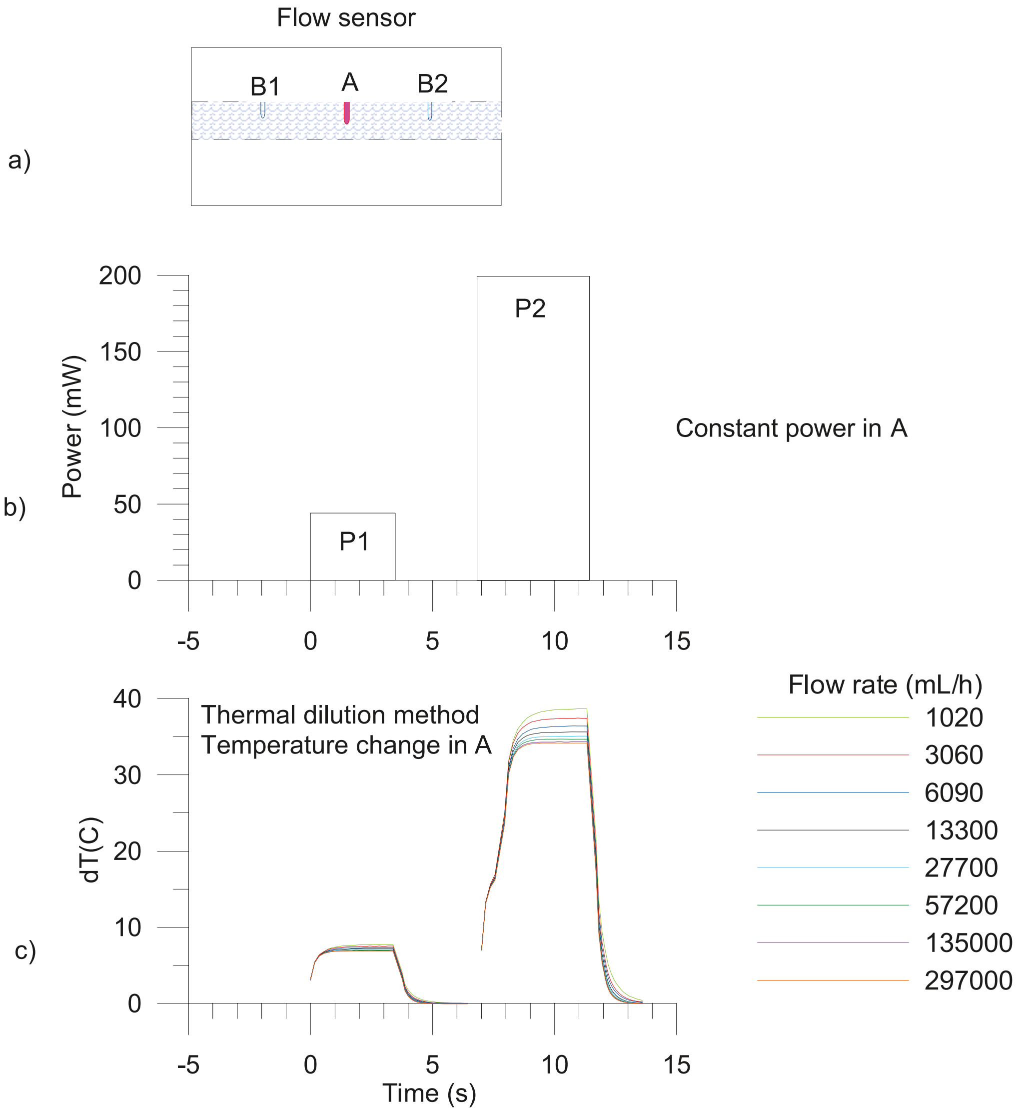

Figure 3-3. *Flow rate measurement.*

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 3-3b) 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 flow 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.

The device depth reference point in the PFL DIFF is situated at the upper end of the test section.

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/:

$h_s - h = Q/(T \cdot a)$ 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:

$a = 2 \cdot \pi / \ln(R/r_0)$ 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/:

$$T = \frac{Q}{s2\pi}\ln\left(\frac{R}{r_0}\right) \qquad 3\text{-}9$$

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 specification

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 pumps are not mentioned anywhwre !!!]
Calibration of FL sensor:	December 2007

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 Ω	± 10% curr.value
Groundwater level sensor	0 – 0.1 MPa	± 1% full-scale
Air pressure sensor	800 – 1,060 hPa	± 5 hPa
Absolute pressure sensor	0 – 20 MPa	± 0.01% full-scale

5 Execution of measurements

5.1 General

The work commission was performed according to Activity Plan AP SFR-08-016 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 KFR102B and KFR103.

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, 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.

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 (Item 9). These methods also reveal parts of the borehole widened for some reason (fracture zones, breakouts etc). The length calibration was performed before any other measurements were started.

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

The combined overlapping/sequential flow logging (Item 11) was carried out in the boreholes 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 KFR102B was started on September 18, 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 KFR103 the pumping was started on September 23, 2008. The waiting time after which the measurements (Item 12) were started was 3.5 h.

The overlapping flow logging was 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.

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).

Table 5-1. Flow logging and testing in KFR102B and KFR103. Activity schedule.

Item	Activity	Explanation	Date
2	Mobilisation at site (KFR102B)	Unpacking the trailer.	2008-09-15
8	Dummy logging	Borehole stability/risk evaluation.	2008-09-15–2008-09-16
9	Calibration	SKB Caliper and SPR. Logging without the lower rubber sealing disks, no pumping.	2008-09-16
10	EC- and temp-logging of the borehole fluid	Logging without the lower rubber sealing disks, no pumping.	2008-09-17
11	Combined overlapping/sequential flow logging	Section length L_w=5 m. Step length dL=0.5 m, no pumping.	2008-09-17
12	Overlapping flow logging	Section length L_w=5 m. Step length dL=0.5 m, pumping.	2008-09-18–2008-09-19
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.	2008-09-19–2008-09-20
15	EC- and temp-logging of the borehole fluid	Logging without the lower rubber sealing disks, pumping.	2008-09-20
16	Recovery transient	Measurement of water level and absolute pressure in the borehole after the pumping was stopped.	2008-09-20–2008-09-21
18 & 2	Demobilisation at KFR102B and mobilisation at KFR103	Packing the trailer. Moving to KFR103. Unpacking the trailer.	2008-09-21
8	Dummy logging	Borehole stability/risk evaluation.	2008-09-21
9	Calibration	SKB Caliper and SPR. Logging without the lower rubber sealing disks, no pumping.	2008-09-21
10	EC- and temp-logging of the borehole fluid	Logging without the lower rubber sealing disks, no pumping.	2008-09-22
11	Combined overlapping/sequential flow logging	Section length L_w=5 m. Step length dL=0.5 m, no pumping.	2008-09-22–2008-09-23
12	Overlapping flow logging	Section length L_w=5 m. Step length dL=0.5 m, pumping.	2008-09-23–2008-09-24
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.	2008-09-24–2008-09-25
15	EC- and temp-logging of the borehole fluid	Logging without the lower rubber sealing disks, pumping.	2008-09-25
16	Recovery transient	Measurement of water level and absolute pressure in the borehole after the pumping was stopped.	2008-09-25–2008-09-26
18	Demobilisation	Packing the trailer.	2008-09-26

5.2 Nonconformities

Nonconformities in KFR102B

It was not physically possible to measure approximately 6.3 m of the bottom of the borehole, because there were weights (3) and a centralizer in the measurement device and because there possibly is drilling debris on the bottom of the borehole. The rubber sealing disks in the device must also be turned before the measurement begins. This reduces the measured distance for approximately 10 cm.

Nonconformities in KFR103

A 0.7 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 an inner diameter of 77 mm preventing the installation of bigger pumps.

The repeated flow logging measurement with a 1 m section during pumping produced lower flow rates than the measurement with a 5 m section during pumping. The PFL DIFF probe was investigated to clarify that it was clean (which it was). During the checking procedure the pump was turned off. When testing the probe shortly after the pump had been turned on again, similar flow results as in the measurement with the 5 m section were obtained. The flow rate however decreased relatively suddenly. One possible conclusion from this is that the borehole was not in a sufficiently stable state during the measurement with the 5 m section.

It was not physically possible to measure approximately 6.5 m of the bottom of the borehole, because there were weights (2) and a centralizer in the measurement device and because there possibly is drilling debris on the bottom of the borehole. 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.

The procedure of the length correction was as follows:

- The caliper/SPR-measurements (Item 9) were initially length corrected in relation to the known length marks, Appendices KFR102B.1.11 and KFR103.1.13, 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 KFR102B.1.2–KFR102B.1.10 and KFR103.1.2–KFR103.1.12.

The results of the caliper and single-point resistance measurements from all measurements in the entire borehole are presented in Appendices KFR102B.1.1 and KFR103.1.1. Three 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 KFR102B.1.2–KFR102B.1.10 and KFR103.1.2–KFR103.1.12. The detectability of the length marks in borehole KFR102B is listed in Table 6-1 and KFR103 in Table 6-2. All the length marks were at least partially detected by the caliper tool.

All the length marks were 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.

The aim of the plots in Appendices KFR102B.1.2–KFR101.1.10 and KFR103.1.2–KFR103.1.12 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 SPR anomalies that could be used to help in determining the location of the measurement tool in the borehole were found.

The magnitude of length correction along the borehole is presented in Appendices KFR102B.1.11 and KFR103.1.13. 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.

Table 6-1. Detected length marks, KFR102B.

Length marks given by SKB (m)	Length marks detected by caliper	Length marks detected by SPR
50	both	yes
100	both	yes
149	both	yes

Table 6-2. Detected length marks, KFR103.

Length marks given by SKB (m)	Length marks detected by caliper	Length marks detected by SPR
50	only lower	yes
101	both	yes
150	both	yes
190	both	yes

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.

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 KFR102B.2.1, KFR103.2.1 (logarithmic scale), KFR102B.2.2 and KFR103.2.2 (linear scale), blue curve.

The EC measurement was repeated during pumping (after a pumping period of approximately three days), see Appendices KFR102B.2.1, KFR102B.2.2, KFR103.2.1 and KFR103.2.2, 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 KFR102B.2.3 and KFR103.2.3 have the same length axis as the EC results in KFR102B.2.1, KFR102B.2.2, KFR103.2.1 and KFR103.2.2.

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, black curve in Appendices KFR102B.1.11 and KFR103.1.13.

6.2.2 Electrical conductivity of fracture-specific water

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. 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 KFR102B.11.1 – KFR102B.11.2 and KFR103.11.1 – KFR103.11.4. The blue symbol represents the conductivity value when the tool was moved and the red symbol is used for the set of stationary measurements.

Lengths to the upper and lower ends of the section, fracture locations and the final EC values for boreholes KFR102B and KFR103 are listed in Table 6-3 and Table 6-4.

For comparison, the fracture-specific EC and temperature results are also plotted with the EC and temperature results of borehole water, see Appendices KFR102B.2.1–KFR102B.2.3 and KFR103.2.1–KFR103.2.3.

Table 6-3. Fracture-specific EC, KFR102B.

Upper end of section (m)	Lower end of section (m)	Measured fractures (m)	EC (S/m) at 25°C
48.01	49.01	48.2, 48.7	0.95
67.03	68.03	67.7	0.92
129.63	130.63	130.3	0.91
149.25	150.25	149.8	0.93
171.38	172.38	172.0	0.91

Table 6-4. Fracture-specific EC, KFR103.

Upper end of section (m)	Lower end of section (m)	Measured fractures (m)	EC (S/m) at 25°C
19.69	20.69	20.4	0.78
63.36	64.36	64.0	0.82
85.24	86.24	85.7	0.83
86.04	87.04	86.8	0.83
181.22	182.22	182.0	0.83

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 KFR102B.10.2 and KFR103.10.2. 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/:

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

where

h is the hydraulic head (masl) 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 (masl) according to the RHB 70 reference system.

A sensor-specific offset of –1.03 kPa is added to absolute pressure results.

The calculated head distributions are presented in Appendices KFR102B.10.1 and KFR103.10.1. 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 KFR102B.3.1–KFR102B.3.9 and KFR103.3.1–KFR103.3.10. 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 77–78 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 metre 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 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 on the caliper scale. 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 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 KFR102B.5, KFR102B.7, KFR103.5 and KFR103.7 are given in Appendices KFR102B.4 and KFR103.4.

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 KFR102B.5.and KFR103.5. Only the results with 5 m length increments are used. All borehole sections are shown in Appendices KFR102B.3.1–KFR102B.3.9 and KFR103.3.1–KFR103.3.10. Secup and Seclow in Appendices KFR102B.5.and KFR103.5 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 KFR102B.5 and KFR103.5 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 KFR102B.5 and KFR103.5 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 KFR102B.5 and KFR103.5 (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 KFR102B at rest, 20 sections were detected as flow yielding, six of which had a flow direction from the borehole into the bedrock (negative flow). During pumping in borehole KFR102B, all 28 detected flows were directed towards the borehole.

Without pumping in the borehole KFR103, 16 sections were detected as flow yielding, 15 of which had a flow direction from the borehole into the bedrock (negative flow). During pumping in borehole KFR103, all 20 detected flows were directed towards the borehole. In addition to these there was one noteworthy flow yielding part of the borehole at the end of the casing tube. This was only partially measured with a 5 m section length because the pump was too close to it.

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 KFR102B.6.1 and KFR103.6.1. 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 KFR102B.6.1 and KFR103.6.1) and in the tables (Appendices KFR102B.5 and KFR103.5). 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 KFR102B.6.2 and KFR103.6.2. 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 KFR102B.6.2, KFR103.6.2 and in Appendices KFR102B.5 and KFR103.5. All the measurement limit values of transmissivity are based on the actual pressure difference in the borehole (h_{0FW} and h_{1FW} in Appendices KFR102B.5 and KFR103.5).

In borehole KFR102B the sum of all the detected flows without pumping (Q_0) was $6.59 \cdot 10^{-7}$ m^3/s (2.4 L/h). In borehole KFR103 the sum was $5.09 \cdot 10^{-6}$ m^3/s (1.8 L/h). The flow rates are calculated from the fracture flows since full section length could not be measured at the lower end of the casing tube in KFR103. 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. In KFR103 the result is uncertain because the borehole conditions were altered when the device was located at 13.3 m. Although this is marked as a fracture it is possible the casing leaking rather than a single fracture. The alternation in the borehole conditions can be seen in Appendix KFR103.10.1 as a spike in the measured head.

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

An attempt was made to evaluate the magnitude of fracture-specific flow rates. The results 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 Appendices KFR102B.3.9 and KFR103.3.2. 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 cannot be determined conclusively, the flow rate is marked with "–" and the value 0 is used in the transmissivity calculation, see Appendices KFR102B.7 and KFR103.7. The flow direction is evaluated as well. The results of the evaluation are plotted in Appendices KFR102B.3 and KFR103.3, blue filled triangle.

The total amount of detected flowing fractures in borehole KFR102B was 89, but only 17 of them could be defined without pumping. These 17 fractures could be used for head estimations and all 89 were used for transmissivity estimations.

The total amount of detected flowing fractures in borehole KFR103 was 43, but only 11 of them could be defined without pumping. These 11 fractures could be used for head estimations and all 43 were used for transmissivity estimations. The result for the 13.3 m fracture is uncertain. It is the end of the casing, so it is possible the casing leaking rather than a fracture. When the device was at that location, the borehole conditions were altered because of flow friction. This can be seen in Appendices KFR103.10.1 and KFR103.10.2. The pumping rate was reduced to only approximately 5 L/min and the measured head in the borehole changed significantly. A change in the head is also visible in the flow measurement without pumping. The actual transmissivity value at 13.3 m can be an order of magnitude higher than presented in Appendix KFR103.7, because of problems both in flow and pressure measurements. Drawdown was exceptionally small in this borehole and the head change because of friction losses in the flow sensor can be significant. Absolute pressure is measured just above the section and may not be correct for the section in a case of this kind. Therefore the result, especially in pumped conditions, is unreliable.

Transmissivity and hydraulic head of fractures are presented in Appendices KFR102B.7, KFR102B.8, KFR103.7 and KFR103.8.

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 sections in Appendices KFR102B.9 and KFR103.9. 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 some fractures. The 1 m section measurements were carried out later than the 5 m section measurements and therefore flow rate and transmissivity can be 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 (unpumped) 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 KFR102B.3.1–KFR102B.3.9 and KFR101.3.1–KFR101.3.10 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 KFR102B and KFR103 was constantly 30 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 KFR102B.5 and KFR103.5 (Q-lower limit P) and is obtained from the plots in Appendices KFR102B.3 and KFR103.3 (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 KFR102B.5 and KFR103.5 (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 KFR102B.5 and KFR103.5 (T_D-measl$_U$).

All three flow limits are plotted with the measured flow rates, see Appendices KFR102B.6.1 and KFR103.6.1. 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 KFR102B.6.2 and KFR103.6.2.

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 KFR102B.10.2 and KFR103.10.2.

The borehole KFR102B was pumped between September 18 and September 20 with a drawdown of approximately 5 metres.

The borehole KFR103 pumping period was between September 23 and September 25 with a drawdown of approximately 0.7 metres.

The pumping rates were recorded, see Appendices KFR102B.10.2 and KFR103.10.2.

The groundwater recovery of KFR102B was measured after the pumping period, between September 20 and 21, see Appendix KFR102B.10.3. Recovery of KFR103 was measured after the pumping period, between September 25 and 26, see Appendix KFR103.10.3. 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 15.67 m in borehole KFR102B and at the length of 14.46 m in borehole KFR103.

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 KFR102B.10.3 and KFR103.10.3 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.

KFR102B

Steady-state analysis

The final flow rate Q_p during the flow period in KFR102B was 6.6 L/min and the drawdown of the water level was s_p = 4.92 m by the end of the flow period (Appendix KFR102B.10.2). The transmissivity calculated with Dupuit's formula is $2.2 \cdot 10^{-5}$ m^2/s (Equation 3-9). In Dupuit's formula, R/r0 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 166.13 m and the borehole diameter $2r_0$ is 0.0758 m. The borehole is cased in the interval 0–13.95 m with an inner diameter of 0.0770 m. The transmissivity of the borehole calculated with Moye's formula is $3.1 \cdot 10^{-5}$ 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 KFR102B which was used to estimate the transmissivity of the entire borehole. The pressure recovery is dominated by wellbore storage during the first c. 100 s. After a transition period, slightly pseudo-spherical (leaky) flow occurs, cf. Figure 6-1a.

The transient response during the recovery period was simulated for an assumed storativity of $S = 4.6 \cdot 10^{-6}$ (calculated from the empirical relationship between T and S). The best fit simulation yields a transmissivity $T = 4.3 \cdot 10^{-5}$ m^2/s, a skin factor of 0.6 and a wellbore storage coefficient of $C = 6.5 \cdot 10^{-7}$ m^3/Pa. The latter coefficient is calculated from the simulated effective casing radius of the borehole. The estimated transmissivity of borehole KFR102B according to the three methods described above is given in Table 6-5. The transient transmissivity T_T was selected as the most representative for the borehole.

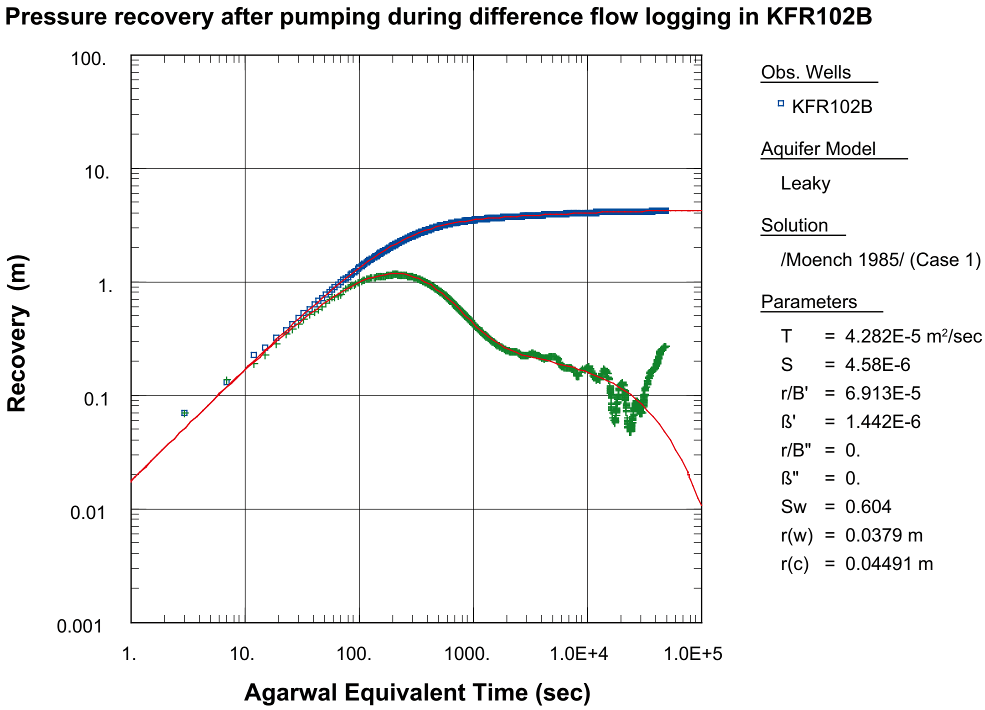

Figure 6-1a. *Log-log plot of the pressure recovery in KFR102B showing the observed pressure recovery of the water level (□) and associated derivative (+) versus Agarwal equivalent time together with simulated best fit curves of the pressure recovery and its derivative (–).*

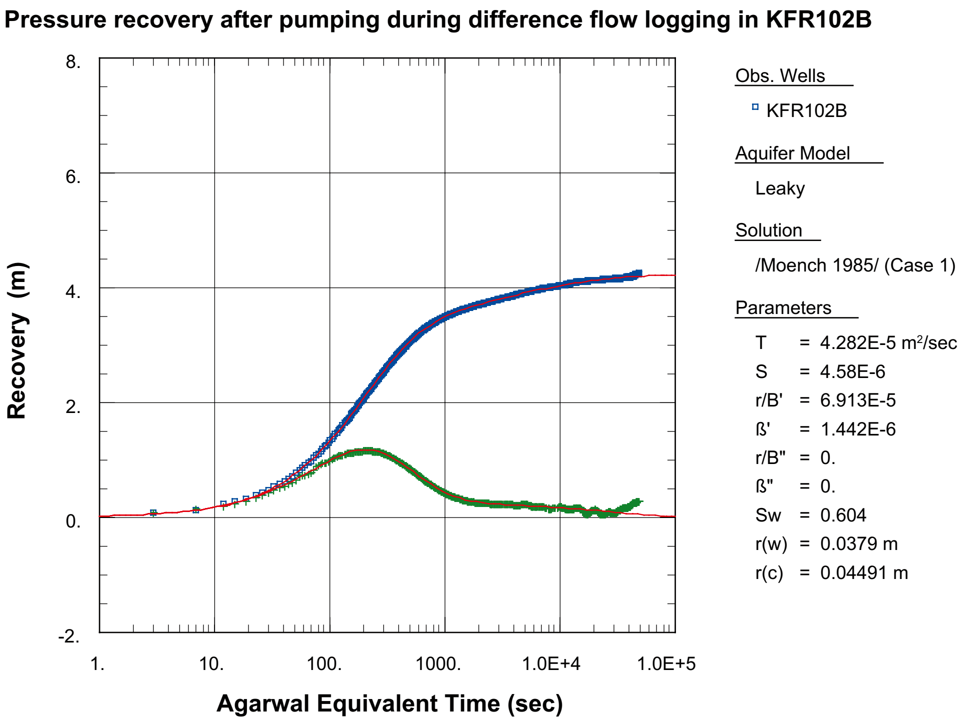

Figure 6-1b. *Lin-log plot of the pressure recovery in KFR102B showing the observed pressure recovery of the water level (□) and associated derivative (+) versus Agarwal equivalent time together with simulated best fit curves of the pressure recovery and its derivative (–).*

Table 6-5. Estimated transmissivity of borehole KFR102B.

Method	Transmissivity (m^2/s)
Dupuit	$2.2 \cdot 10^{-5}$
Moye	$3.1 \cdot 10^{-5}$
Transient	$4.3 \cdot 10^{-5}$

KFR103

Steady-state analysis

The final flow rate Q_p during the flow period in KFR103 was 32.0 L/min and the drawdown of the water level was $s_p = 0.56$ m by the end of the flow period (Appendix KFR103.10.2). The transmissivity calculated with Dupuit's formula is $9.4 \cdot 10^{-4}$ m^2/s (Equation 3-9). In Dupuit's formula, R/r0 is assumed to be 500, cf. Chapter 3. The total borehole length of KFR103 is 200.5 m. In Moye's formula (Equation 3-10) the length of the test section L (open borehole interval) is 187.17 m and the borehole diameter $2r_0$ is 0.0758 m. The borehole is cased in the interval 0–13.33 m with an inner diameter of 0.0770 m. The transmissivity of the borehole calculated with Moye's formula is $1.3 \cdot 10^{-3}$ m^2/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 KFR103 from which the transmissivity of the entire borehole was estimated. The pressure recovery period shows wellbore storage during the first few seconds transitioning to a short period of pseudo-radial flow and pseudo-stationary flow by the end, cf. Figure 6-2a.

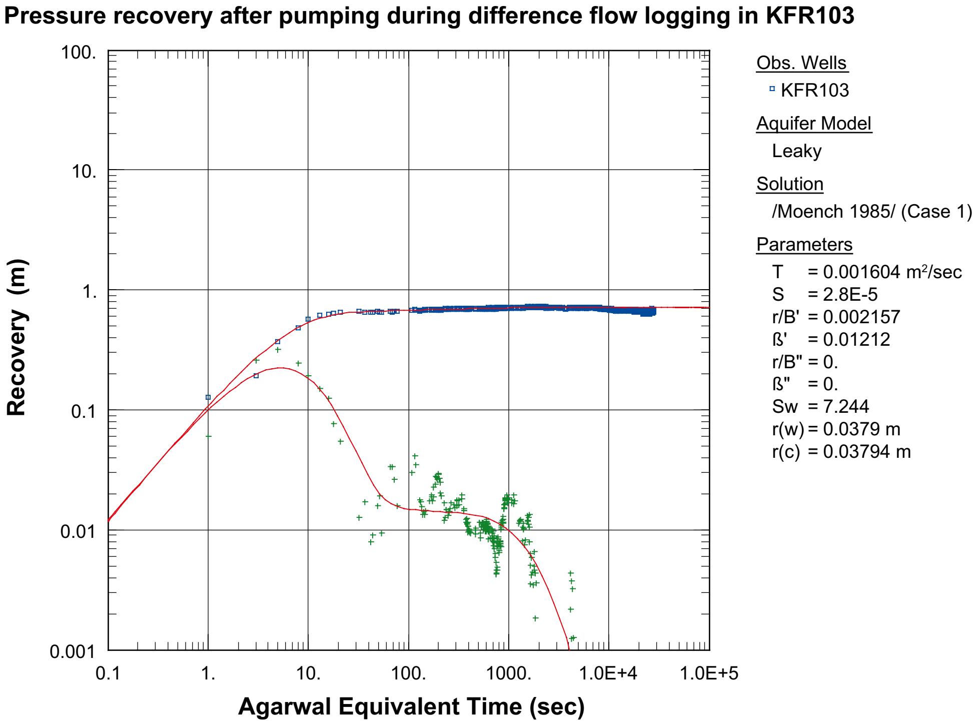

***Figure 6-2a.** Log-log plot of the pressure recovery in KFR103 showing the observed pressure recovery of the water level (□) and associated derivative (+) versus Agarwal equivalent time together with simulated best fit curves of the pressure recovery and its derivative (–).*

Pressure recovery after pumping during difference flow logging in KFR103

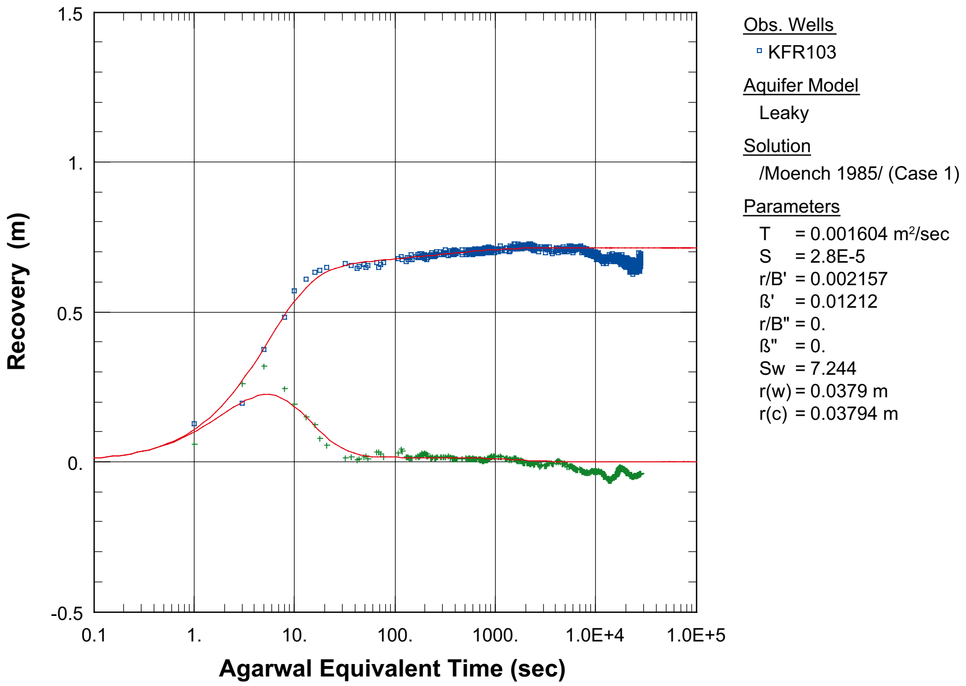

Figure 6-2b. *Lin-log plot of the pressure recovery in KFR103 showing the observed pressure recovery of the water level (□) and associated derivative (+) versus Agarwal equivalent time together with simulated best fit curves of the pressure recovery and its derivative (–).*

The transient pressure recovery was simulated for an assumed storativity of $S = 2.8 \cdot 10^{-5}$. The best fit simulation yields a transmissivity $T = 1.6 \cdot 10^{-3}$ m²/s, a skin factor = 7.2 and a wellbore storage coefficient of $C = 4.6 \cdot 10^{-7}$ m³/Pa.

The estimated transmissivity of borehole KFR103 according to the three methods described above are given in Table 6-6. The transient transmissivity T_T was selected as the most representative for the borehole. Due to the leak in the casing shoe at 13.3 m as discussed above the transmissivity values presented probably do not represent the open borehole interval in this case but also include the interval above the casing shoe.

Table 6-6. Estimated transmissivity of borehole KFR103.

Method	Transmissivity (m²/s)
Dupuit	$9.4 \cdot 10^{-4}$
Moye	$1.3 \cdot 10^{-3}$
Transient	$1.6 \cdot 10^{-3}$

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 KFR102B and KFR103 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 with a 1 m section and a 0.1 m measurement interval.

Length calibration was made in 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.

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.

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

Transmissivity and hydraulic head were calculated for borehole sections. The highest section transmissivity in KFR102B ($5.4 \cdot 10^{-6}$ m^2/s) was detected at depth interval 145.76–150.76 m and in KFR103 ($1.5 \cdot 10^{-5}$ m^2/s) at depth interval 84.95–89.95 m. Other high-transmissive sections were found in KFR102B at depth intervals 125.74–130.74 m and 45.72–50.72 m and in KFR103 at depth intervals 180.02–185.02 m and 19.92–24.92 m.

The total amount of detected flowing fractures was 89 in KFR102B and 44 in KFR103. Transmissivity and hydraulic head were calculated for borehole sections and fractures. The highest fracture transmissivity in KFR102B ($5.0 \cdot 10^{-6}$ m^2/s) was detected at 149.8 m. The highest transmissivity in KFR103 is at 13.3 m but could not be reliably measured, the fracture with the highest reliably measured transmissivity ($2.81 \cdot 10^{-5}$ m^2/s) is at 14 m. Other high transmissive anomalies were found at 48.7 m and 130.3 m in KFR102B and at 20.4 m, 85.7 m, 86.8 m and 182.0 m in KFR103.

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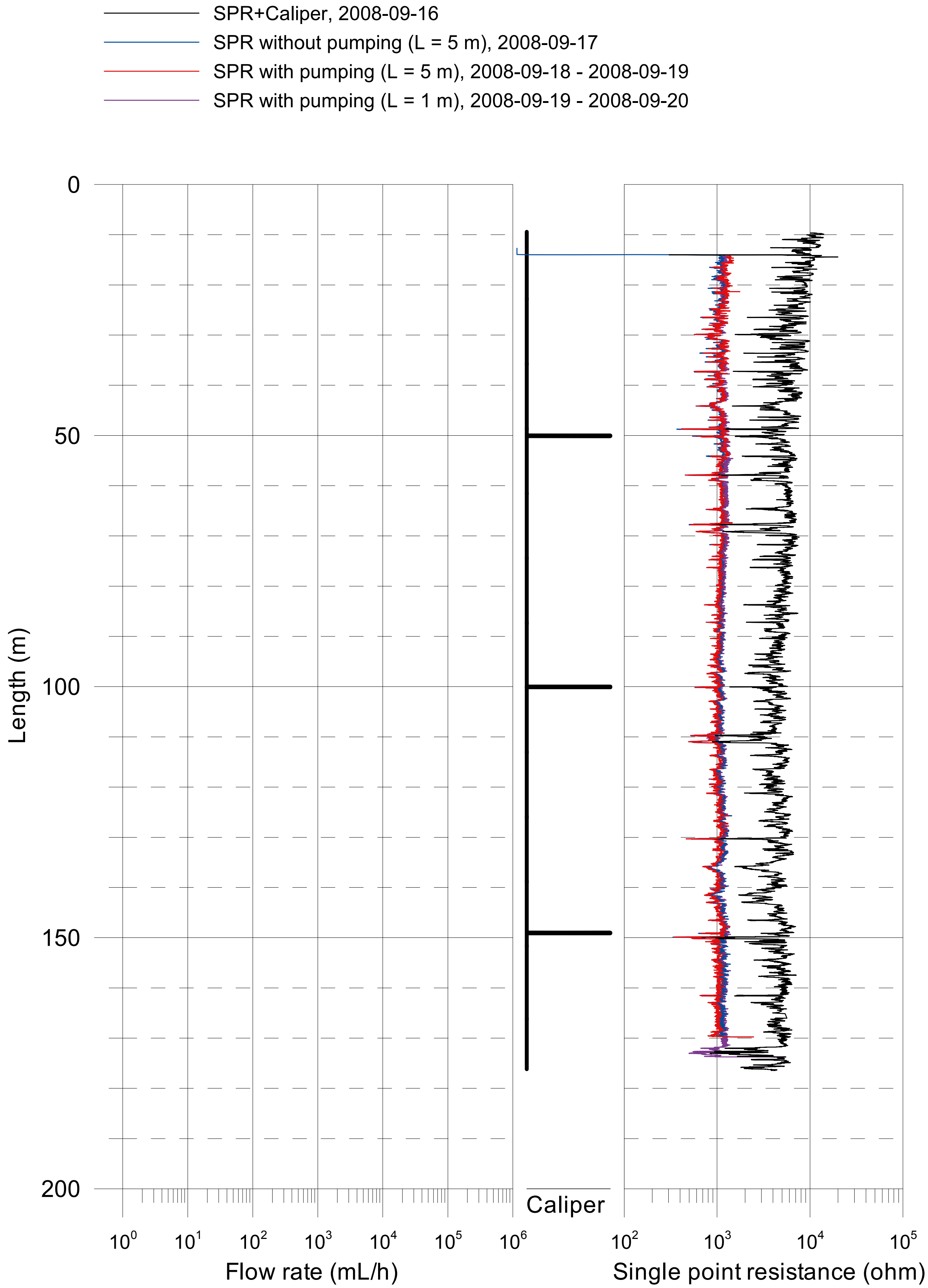
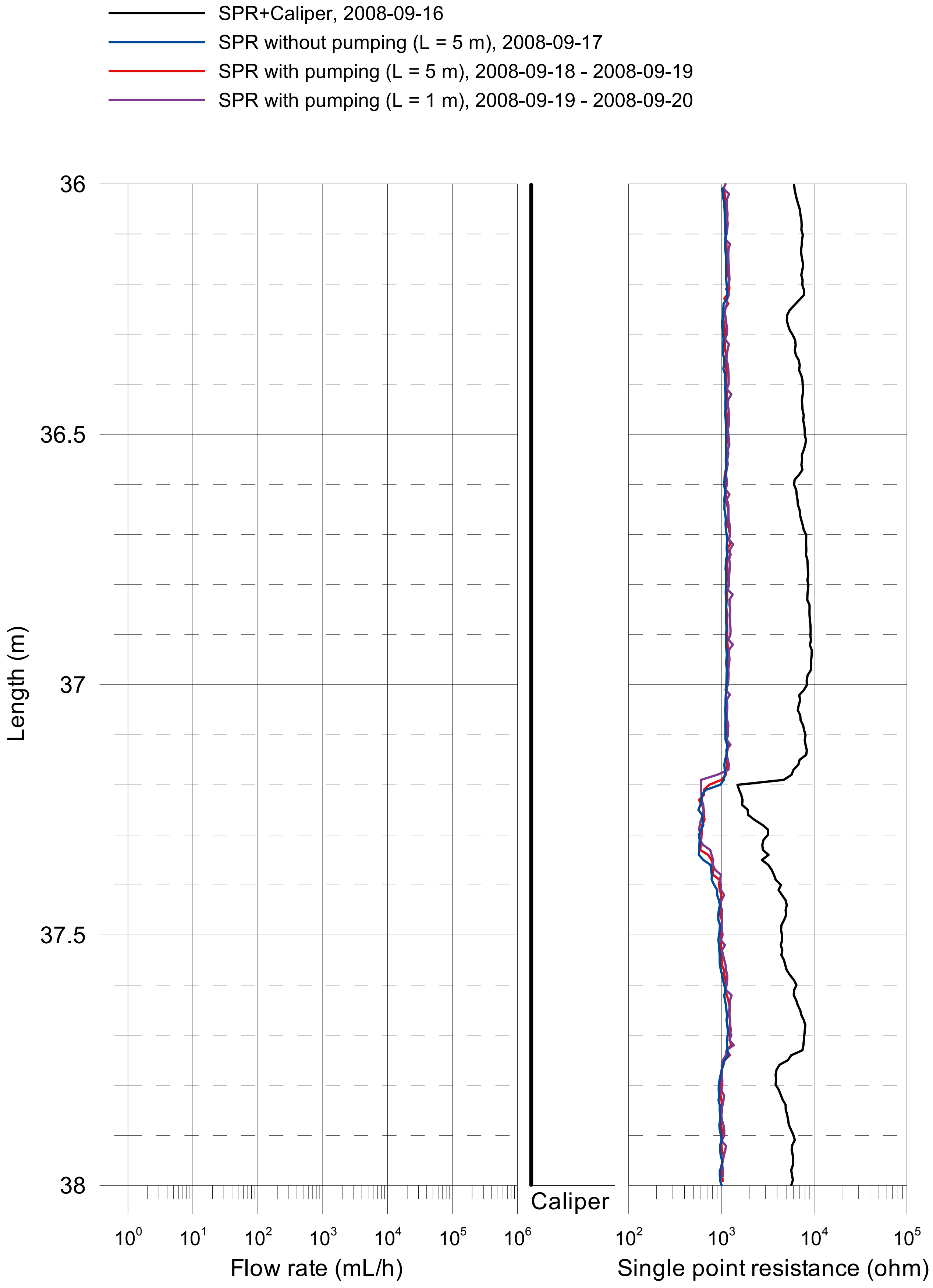
Appendices KFR102B

Appendices	KFR102B.1.1–KFR102B.1.10	SPR and Caliper results after length correction
Appendix	KFR102B.1.11	Length correction
Appendices	KFR102B.2.1–KFR102B.2.2	Electrical conductivity of borehole water
Appendix	KFR102B.2.3	Temperature of borehole water
Appendices	KFR102B.3.1–KFR102B.3.9	Flow rate, caliper and single point resistance
Appendix	KFR102B.4	Explanations for the tables in Appendices 5 and 7
Appendix	KFR102B.5	Results of sequential flow logging
Appendix	KFR102B.6.1	Plotted flow rates of 5 m sections
Appendix	KFR102B.6.2	Plotted transmissivity and head of 5 m sections
Appendix	KFR102B.7	Inferred flow anomalies from overlapping flow logging
Appendix	KFR102B.8	Plotted transmissivity and head of detected fractures
Appendix	KFR102B.9	Comparison between section transmissivity and fracture transmissivity
Appendix	KFR102B.10.1	Head in the borehole during flow logging
Appendix	KFR102B.10.2	Air pressure, water level in the borehole and pumping rate during flow logging
Appendix	KFR102B.10.3	Groundwater recovery after pumping
Appendices	KFR102B.11.1–KFR102B.11.2	Fracture-specific EC results by date

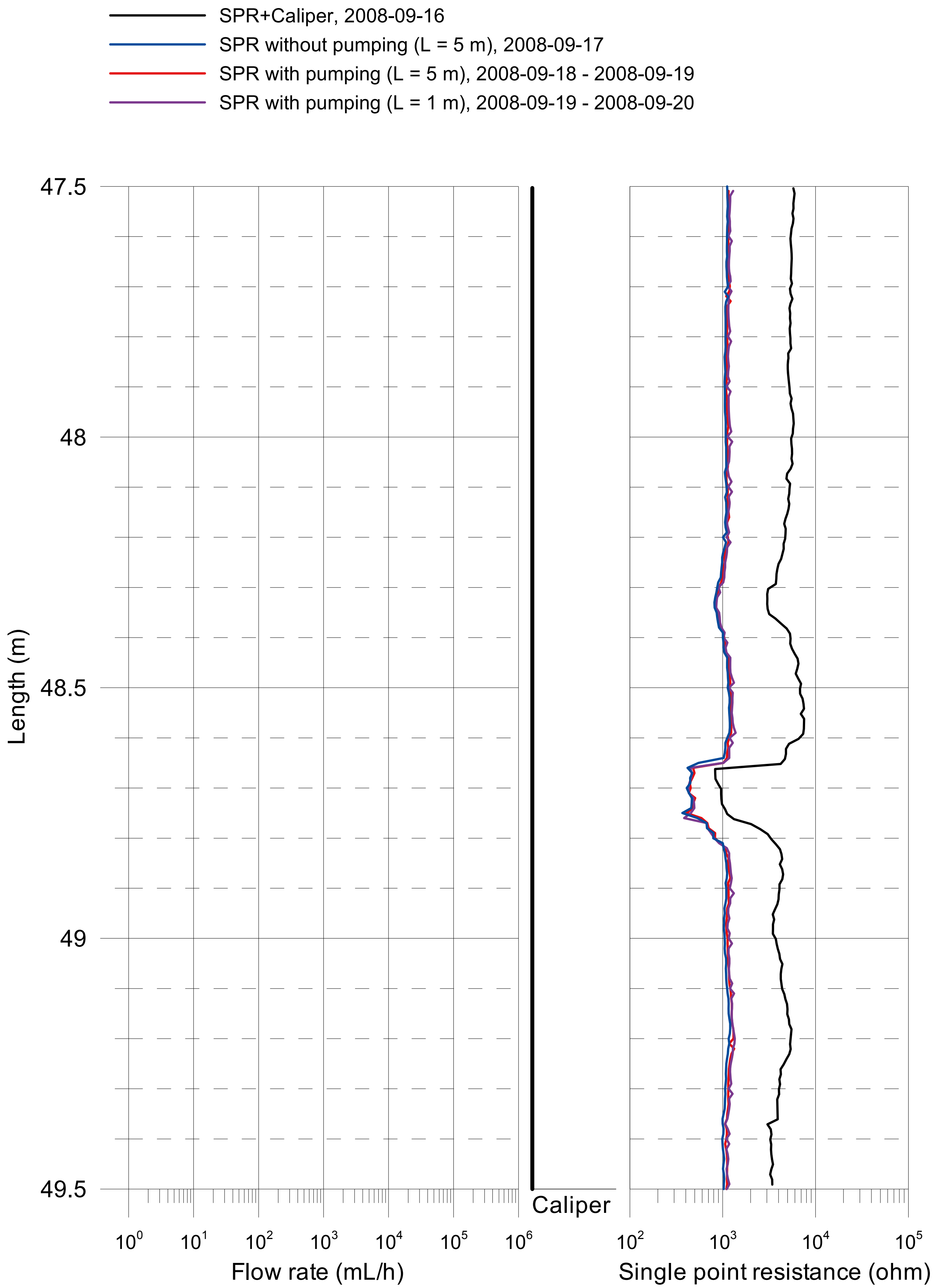
Forsmark, borehole KFR102B
SPR and Caliper results after length correction



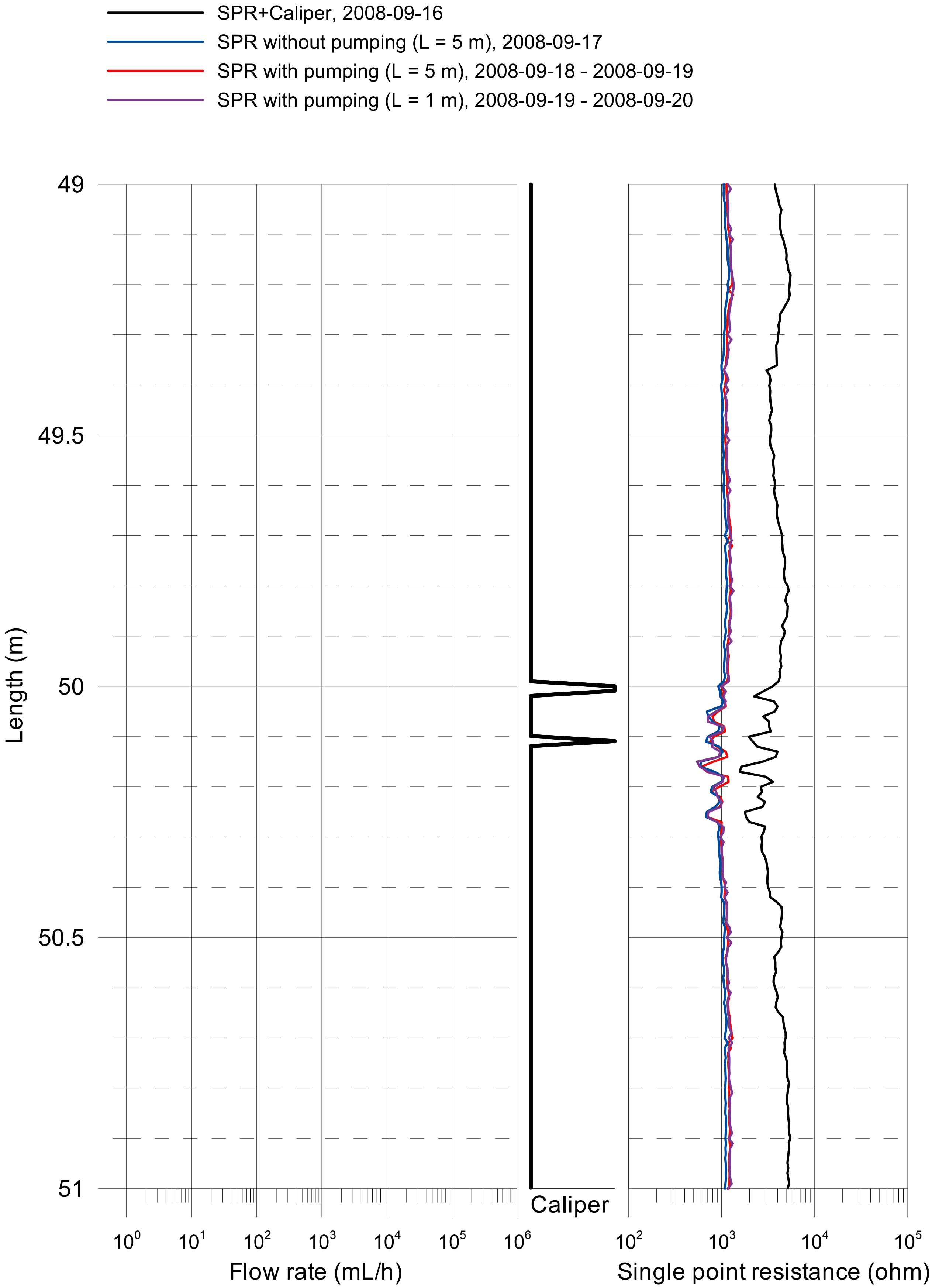
Forsmark, borehole KFR102B
SPR and Caliper results after length correction



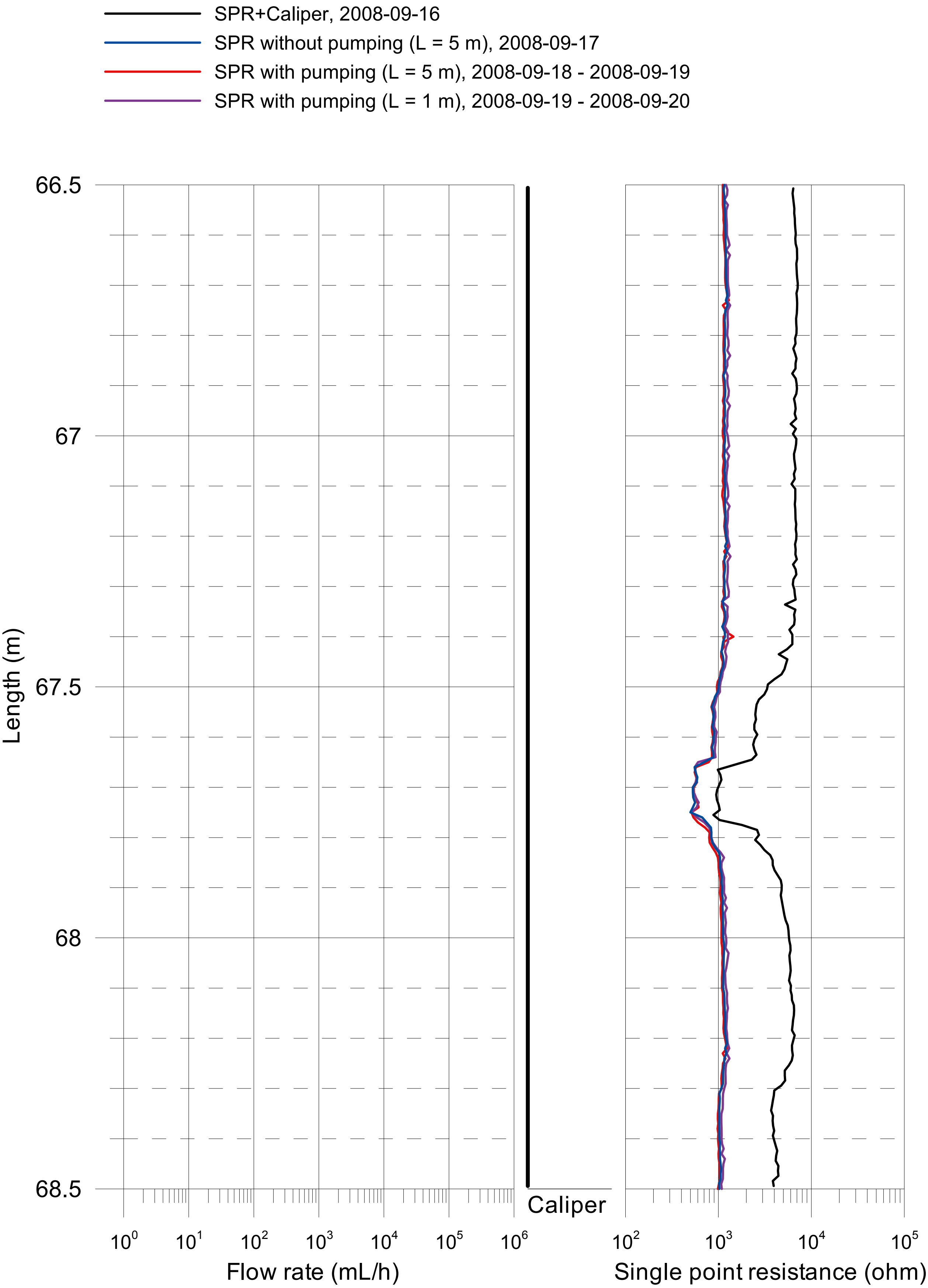
Forsmark, borehole KFR102B
SPR and Caliper results after length correction



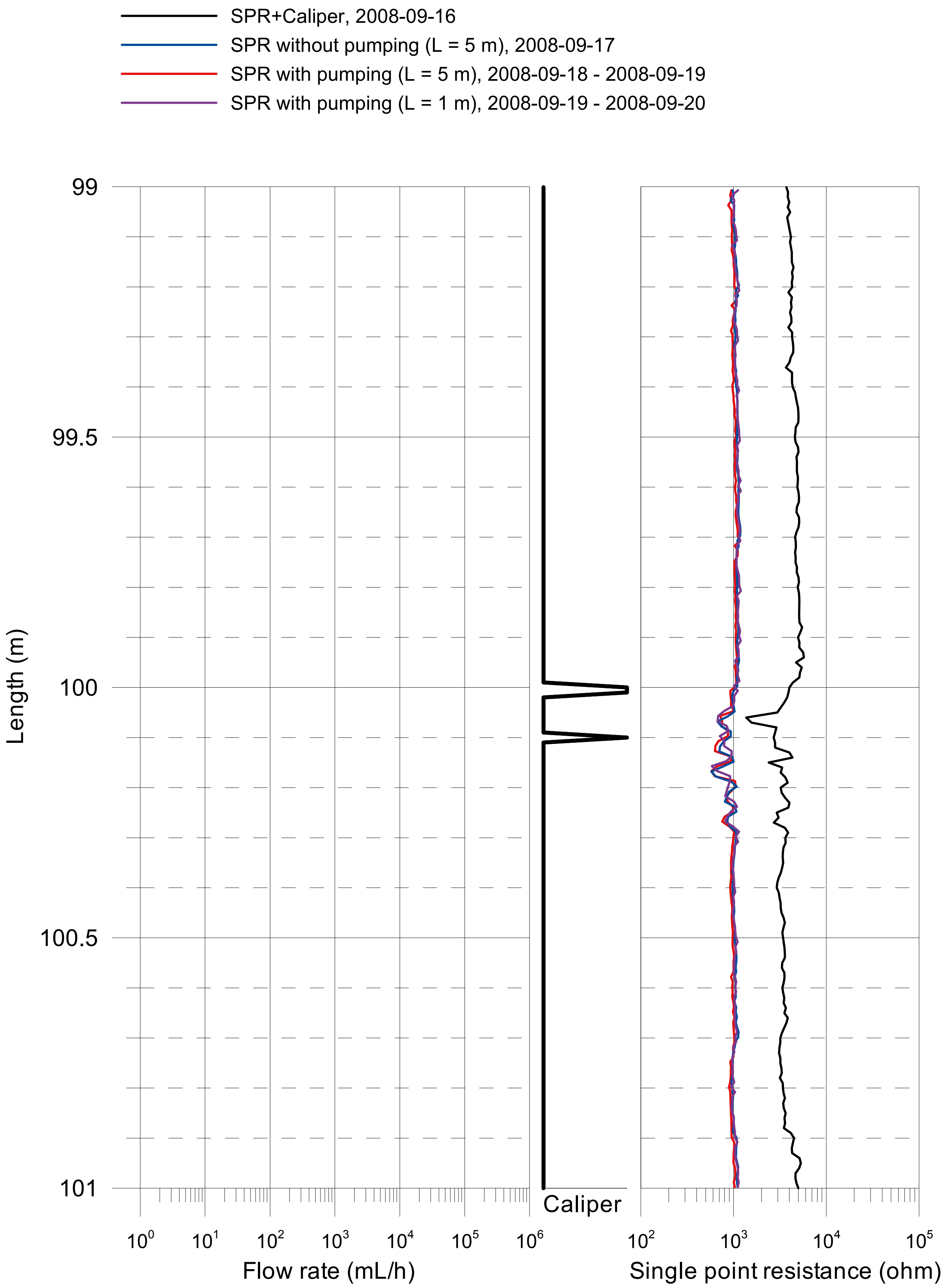
Forsmark, borehole KFR102B
SPR and Caliper results after length correction



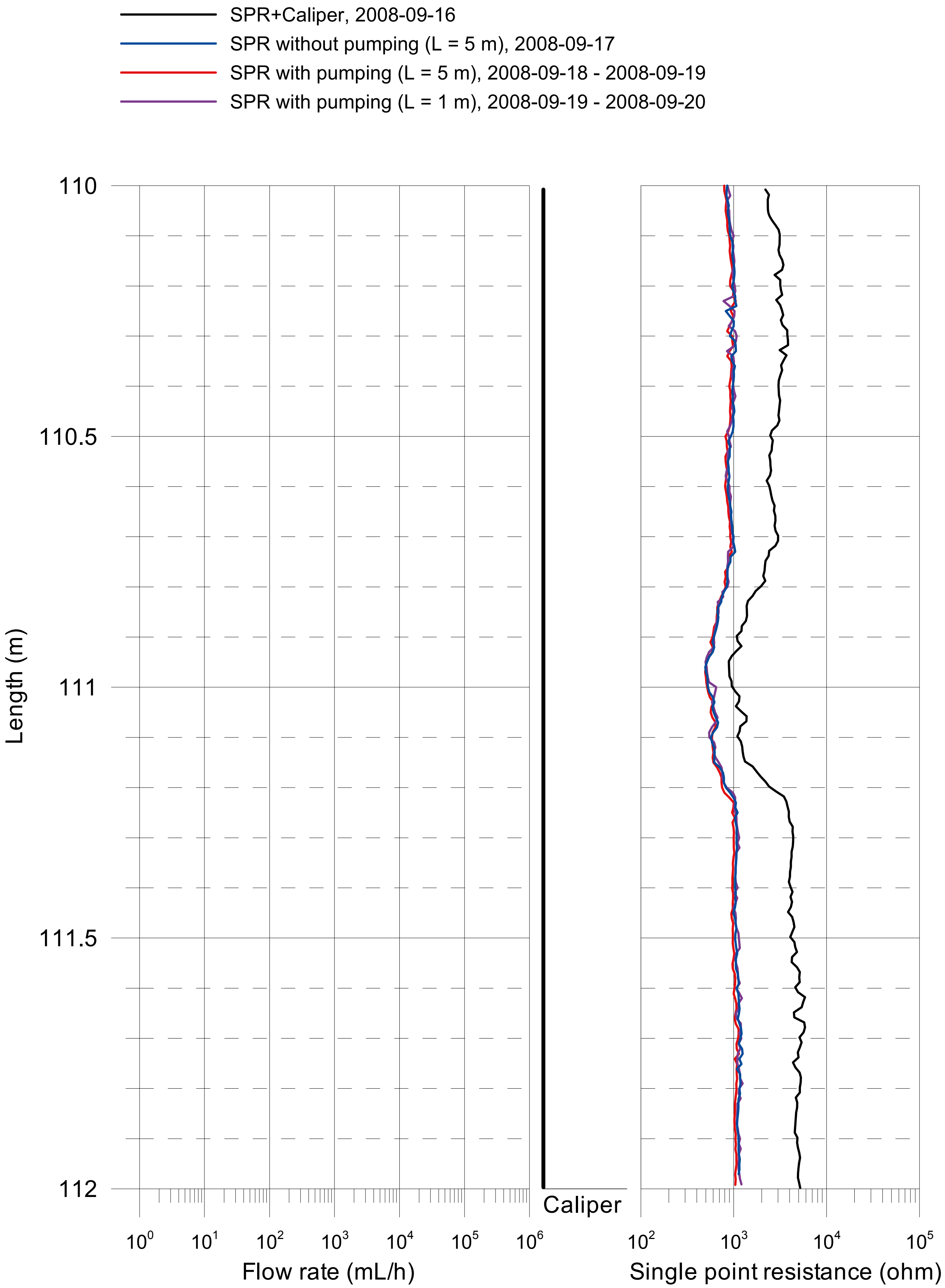
Forsmark, borehole KFR102B
SPR and Caliper results after length correction



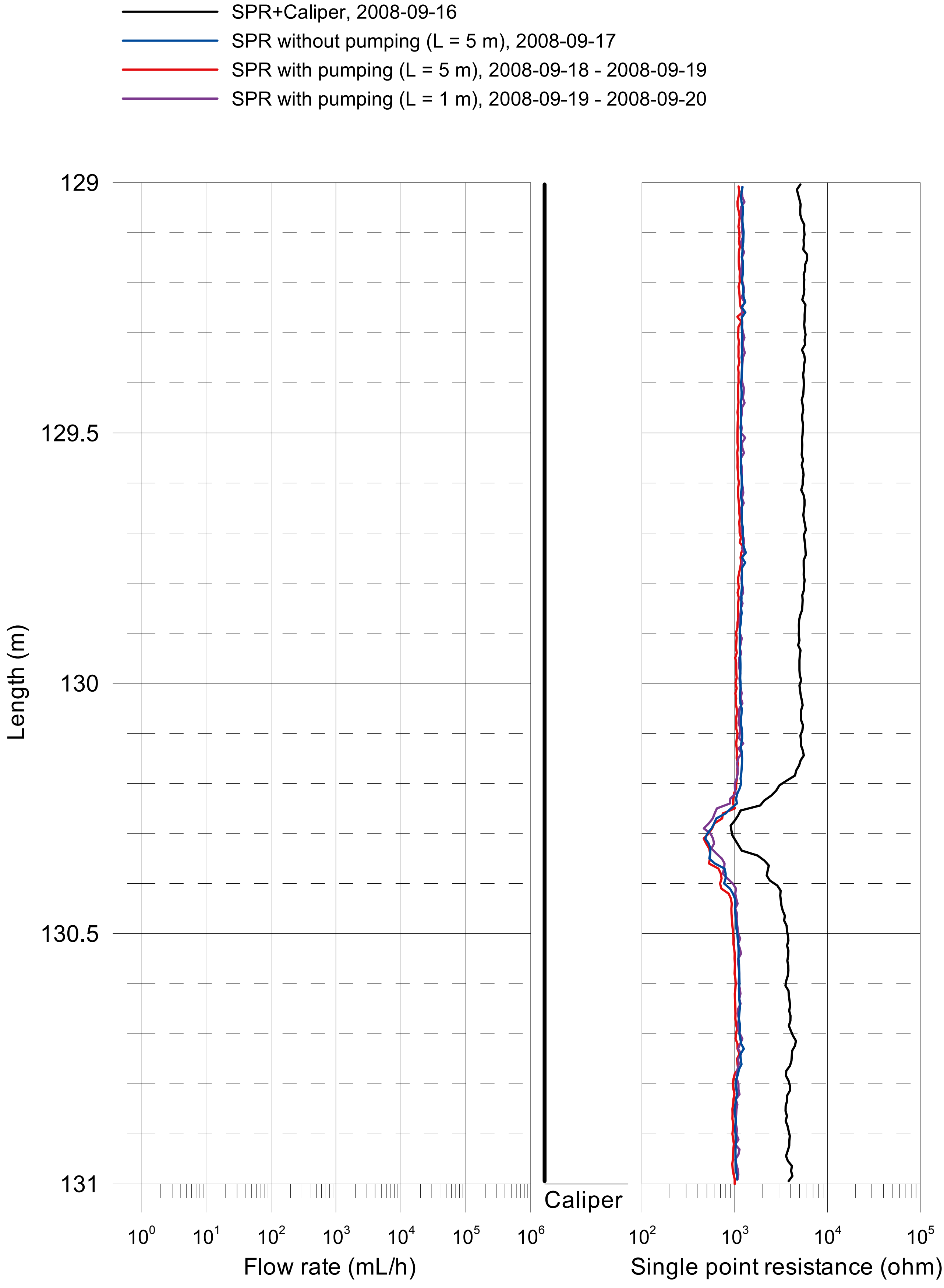
Forsmark, borehole KFR102B
SPR and Caliper results after length correction



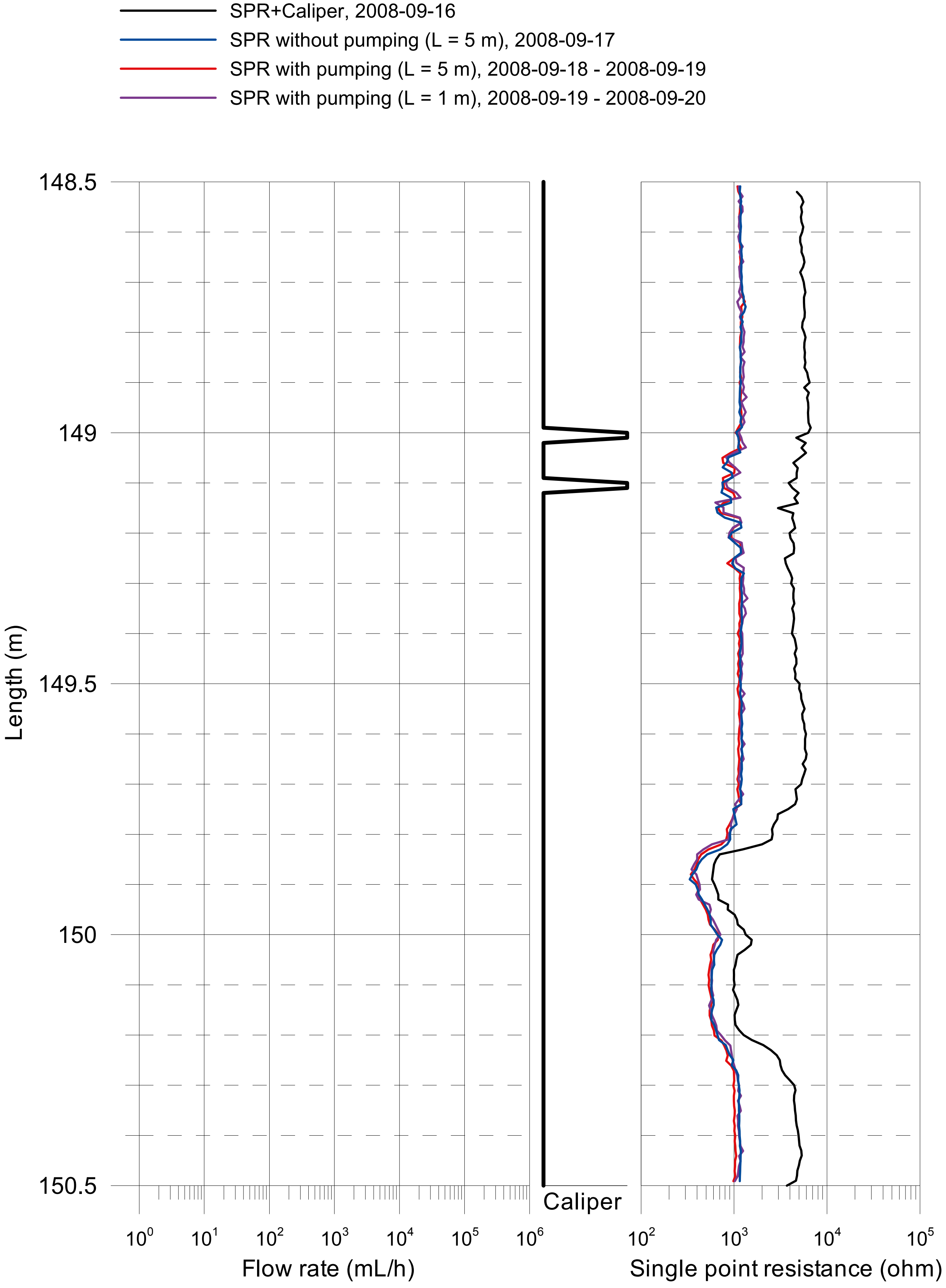
Forsmark, borehole KFR102B
SPR and Caliper results after length correction



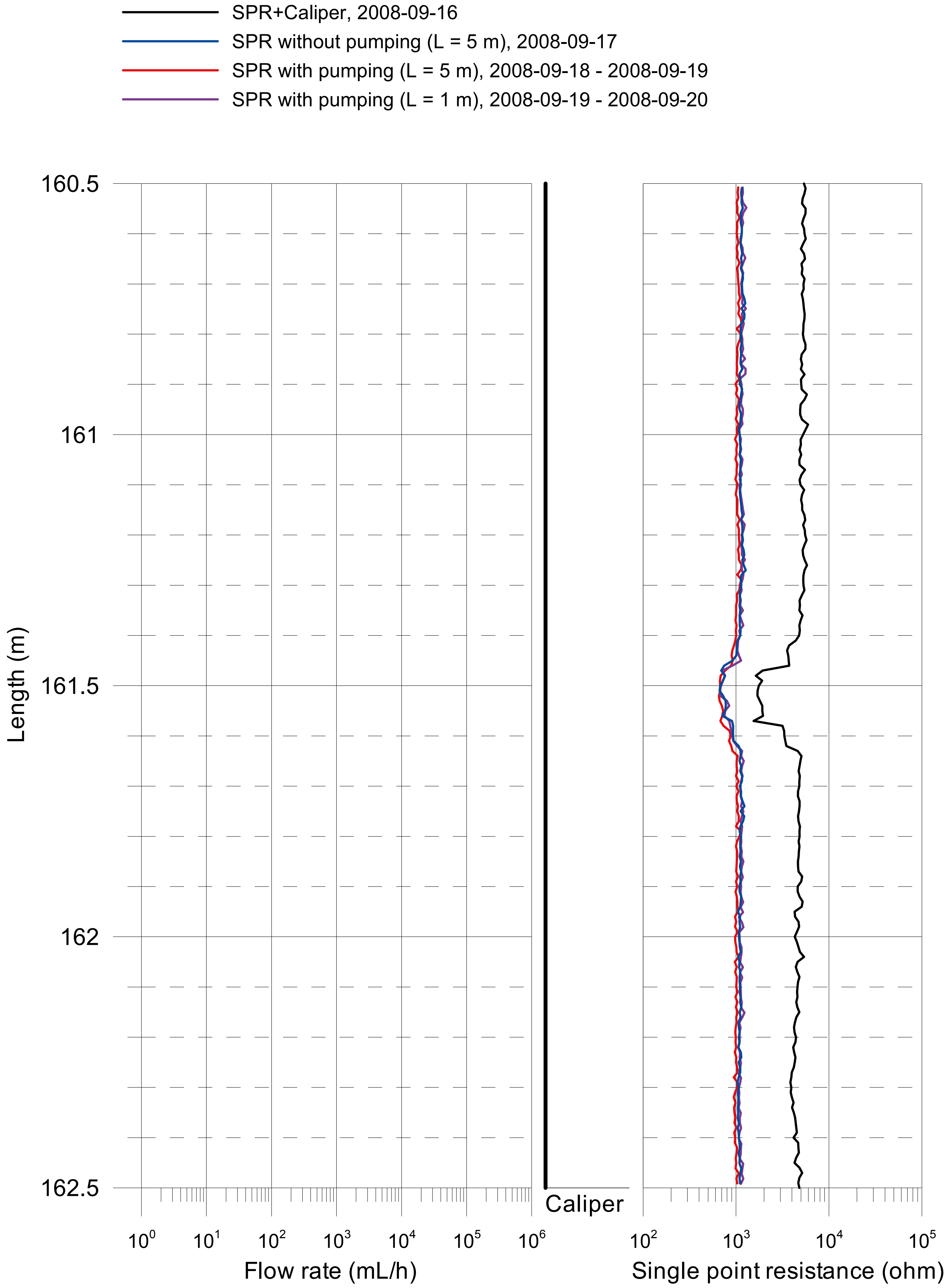
Forsmark, borehole KFR102B
SPR and Caliper results after length correction



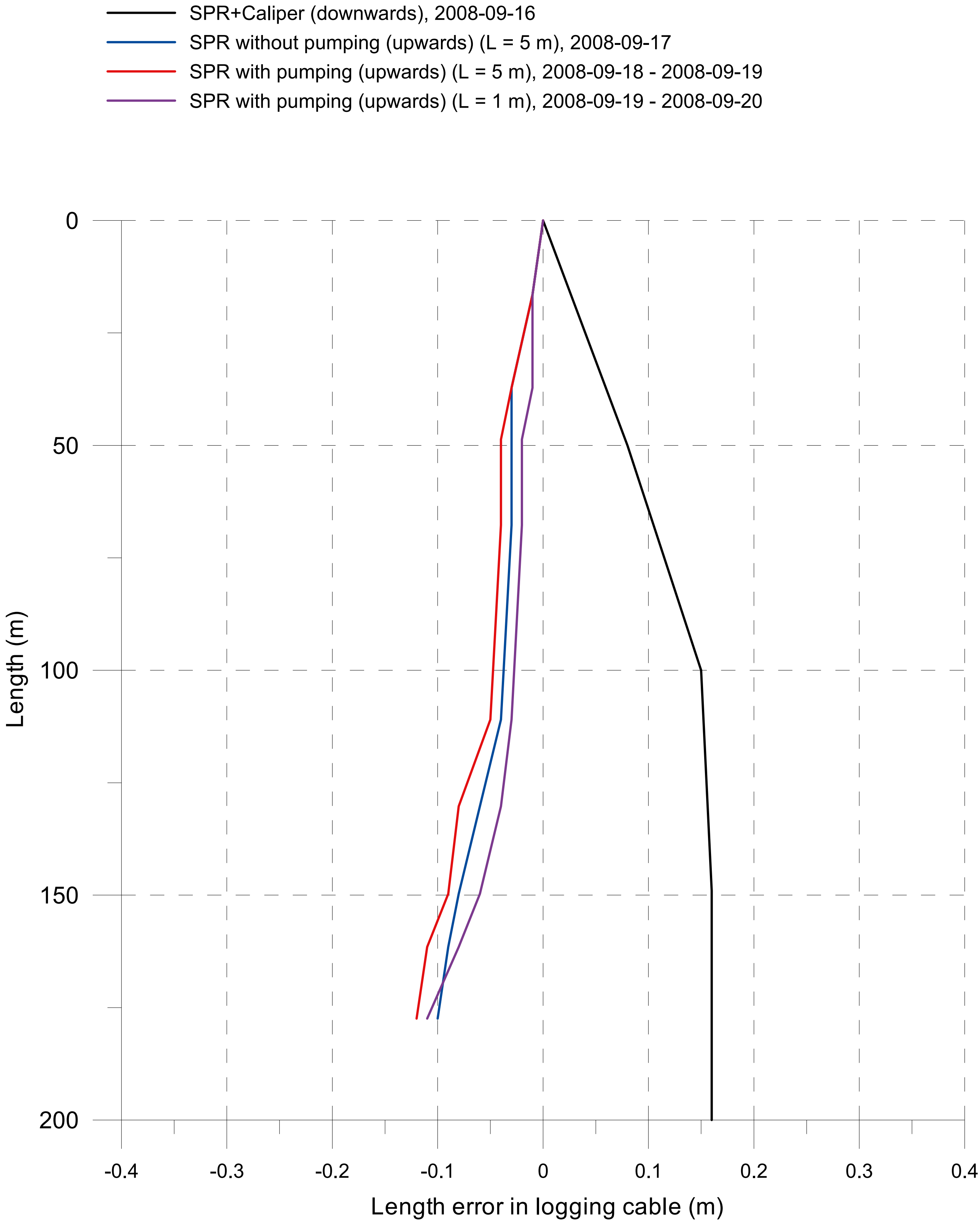
Forsmark, borehole KFR102B
SPR and Caliper results after length correction

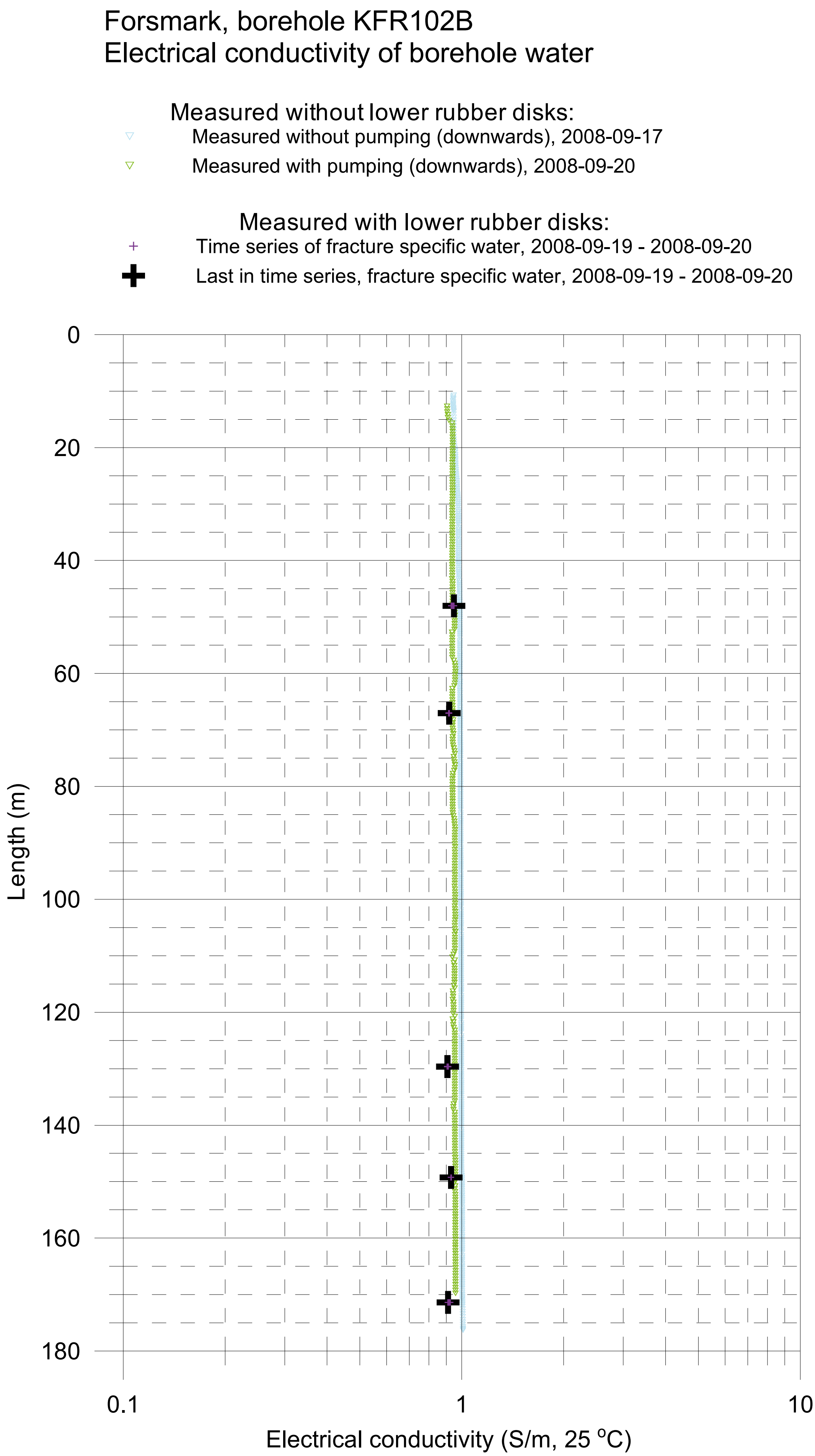


Forsmark, borehole KFR102B
SPR and Caliper results after length correction

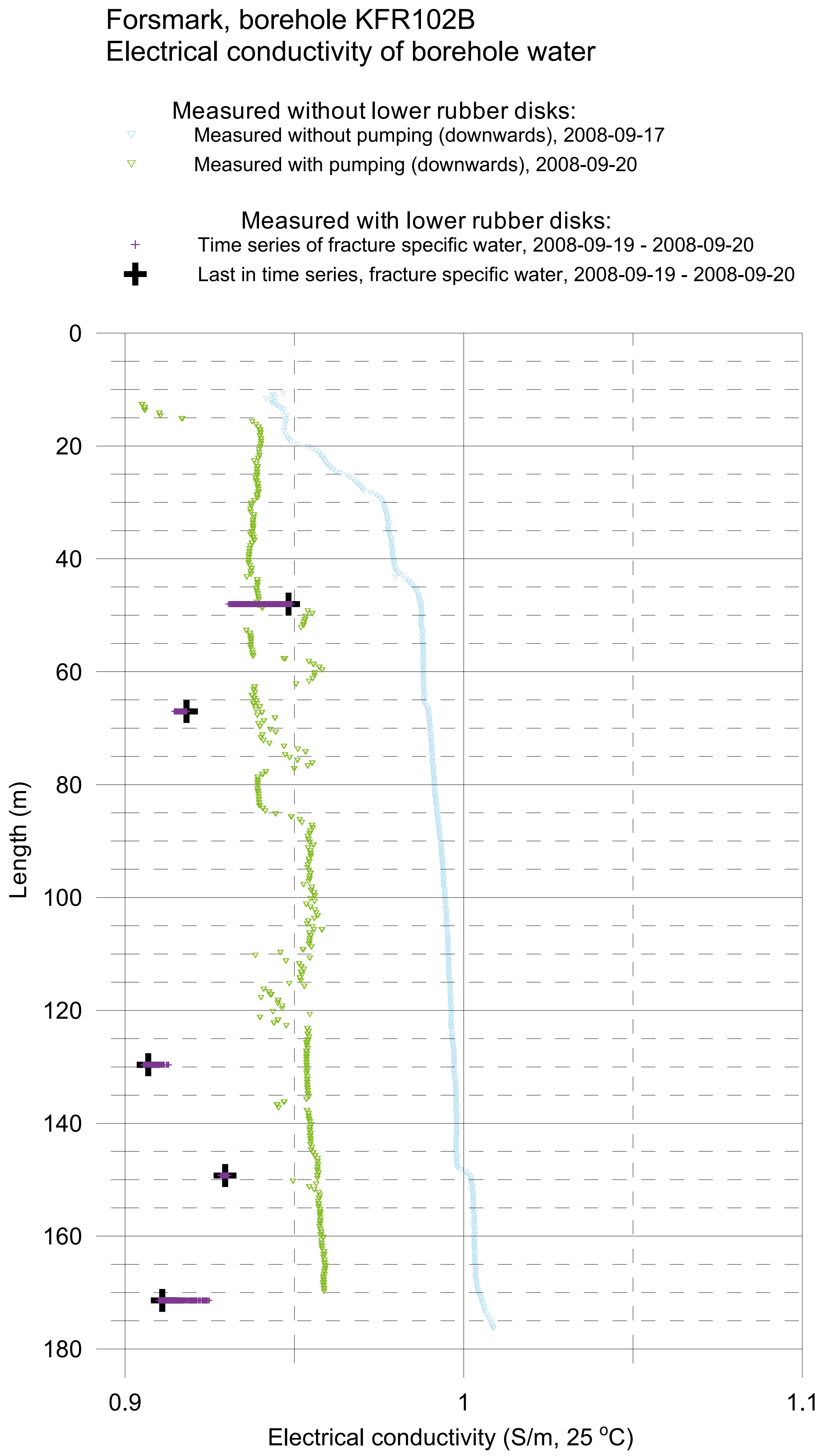


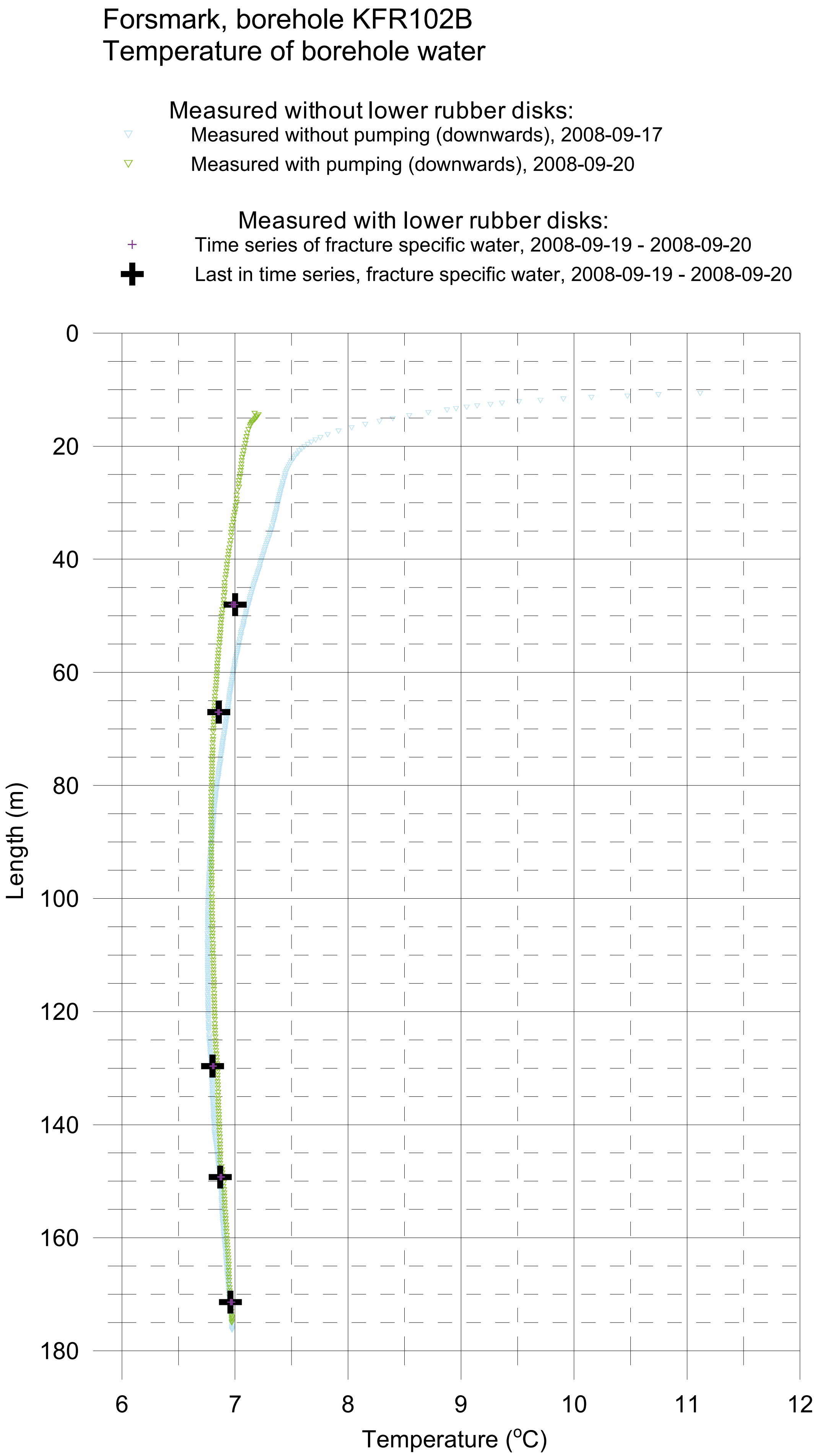
Forsmark, borehole KFR102B
Length correction



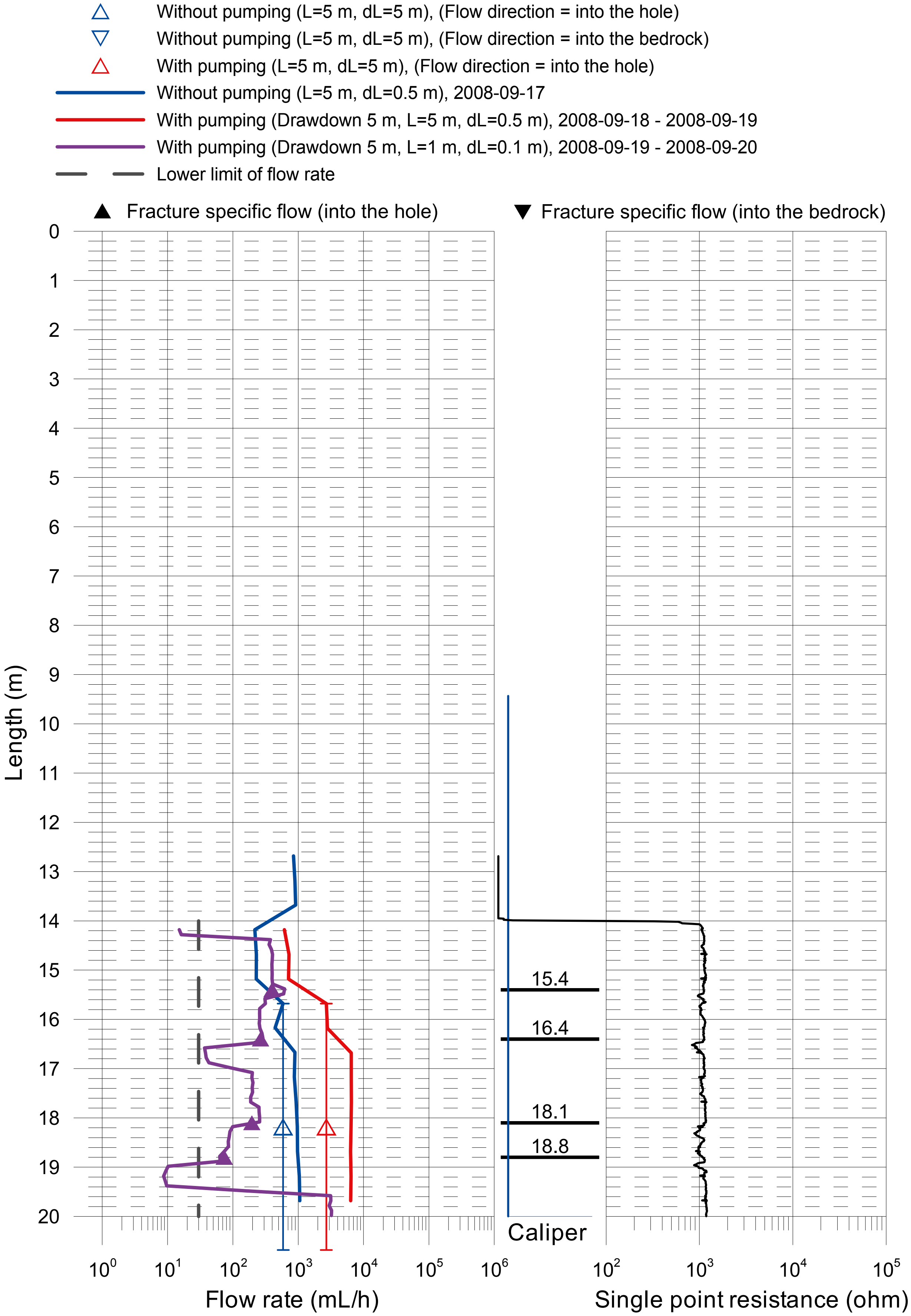


Forsmark, borehole KFR102B
Electrical conductivity of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2008-09-17
Measured with pumping (downwards), 2008-09-20
Measured with lower rubber disks:
Time series of fracture specific water, 2008-09-19 - 2008-09-20
Last in time series, fracture specific water, 2008-09-19 - 2008-09-20
Length (m)
0
20
40
60
80
100
120
140
160
180
0.1
1
10
Electrical conductivity (S/m, 25 °C)

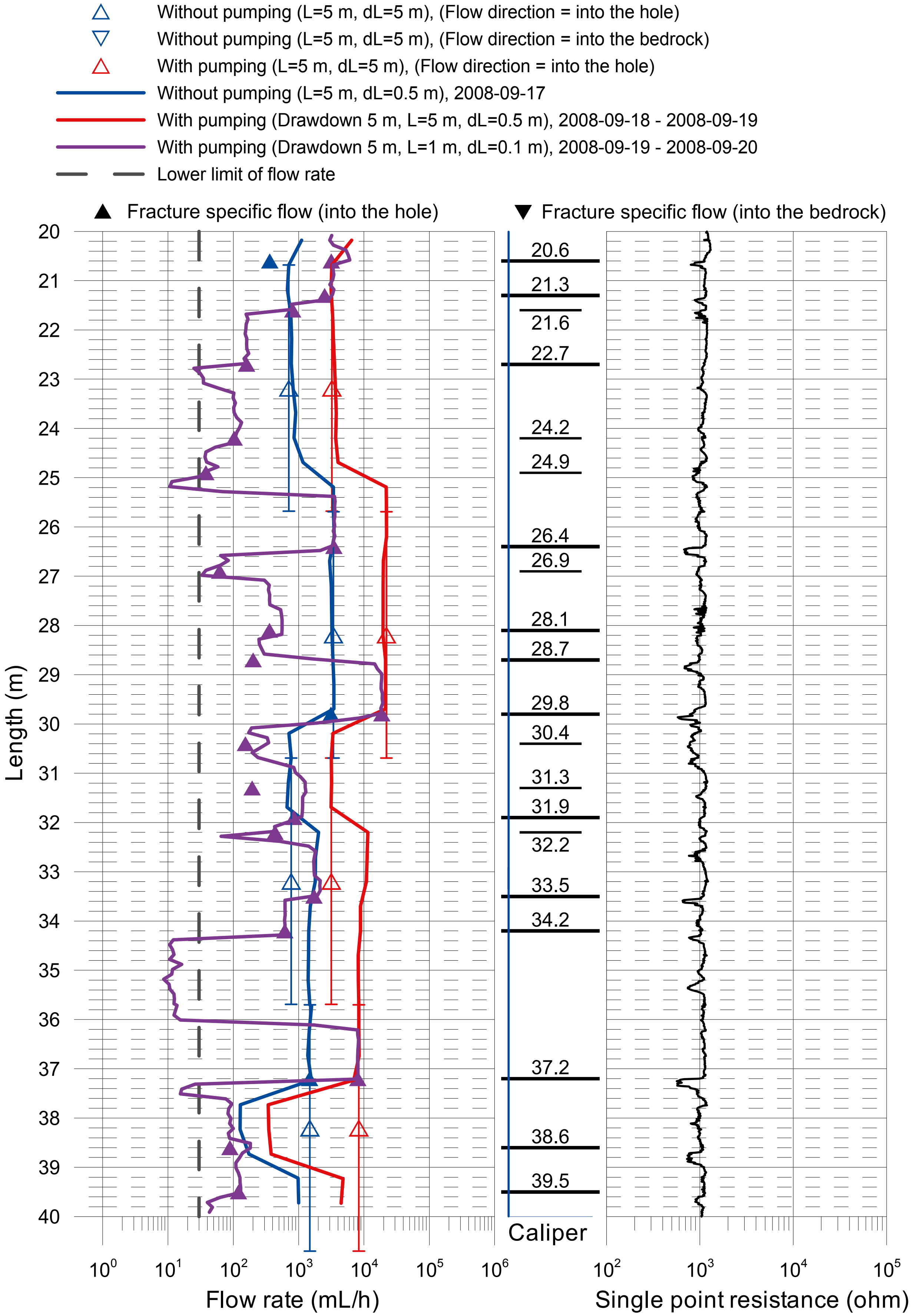

Forsmark, borehole KFR102B
Electrical conductivity of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2008-09-17
Measured with pumping (downwards), 2008-09-20
Measured with lower rubber disks:
Time series of fracture specific water, 2008-09-19 - 2008-09-20
Last in time series, fracture specific water, 2008-09-19 - 2008-09-20
0
20
40
60
80
100
120
140
160
180
Length (m)
0.9
1
1.1
Electrical conductivity (S/m, 25 °C)


Forsmark, borehole KFR102B
Temperature of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2008-09-17
Measured with pumping (downwards), 2008-09-20
Measured with lower rubber disks:
Time series of fracture specific water, 2008-09-19 - 2008-09-20
Last in time series, fracture specific water, 2008-09-19 - 2008-09-20
0
20
40
60
80
100
120
140
160
180
Length (m)
6
7
8
9
10
11
12
Temperature (°C)

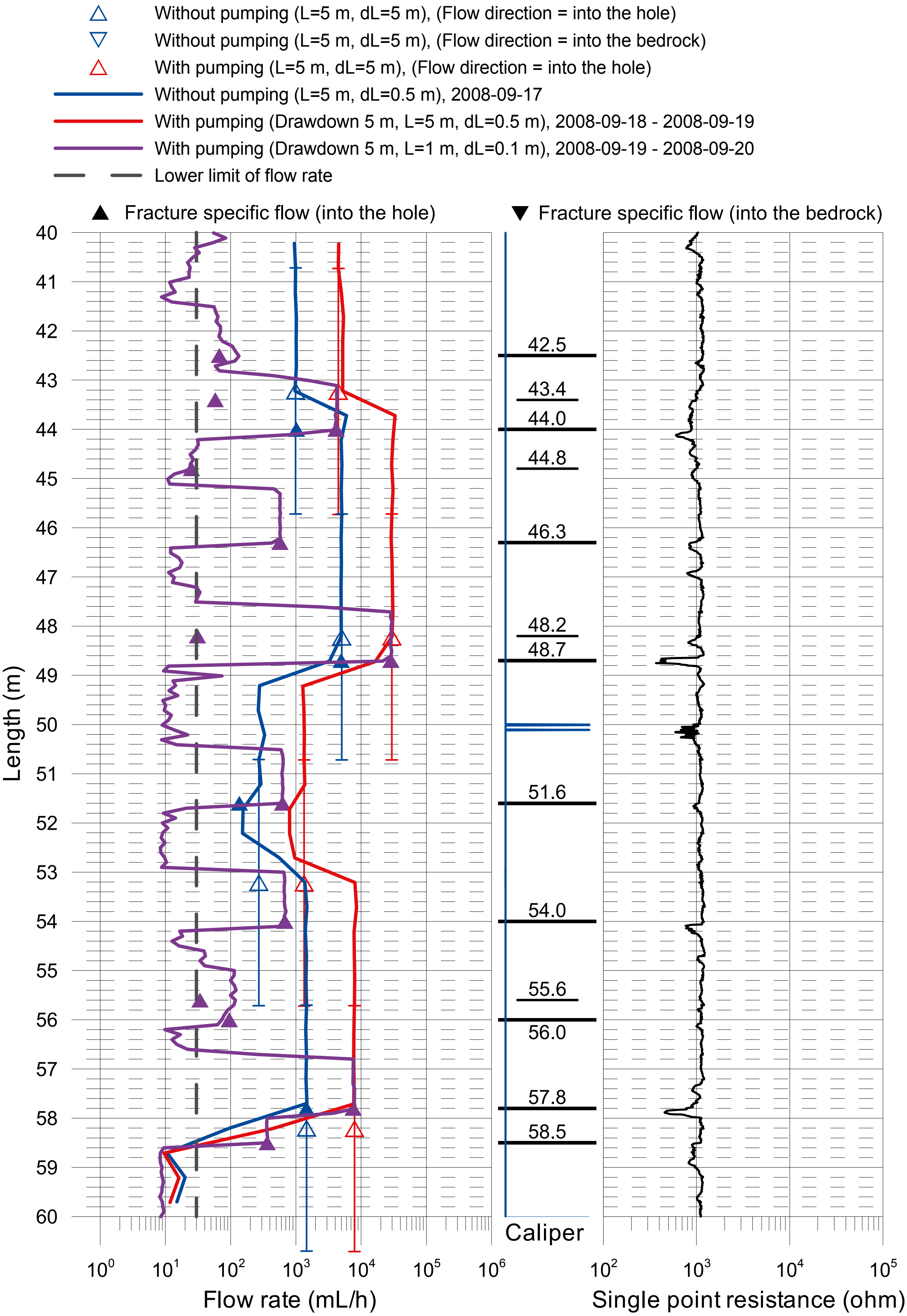
Forsmark, borehole KFR102B
Flow rate, caliper and single point resistance



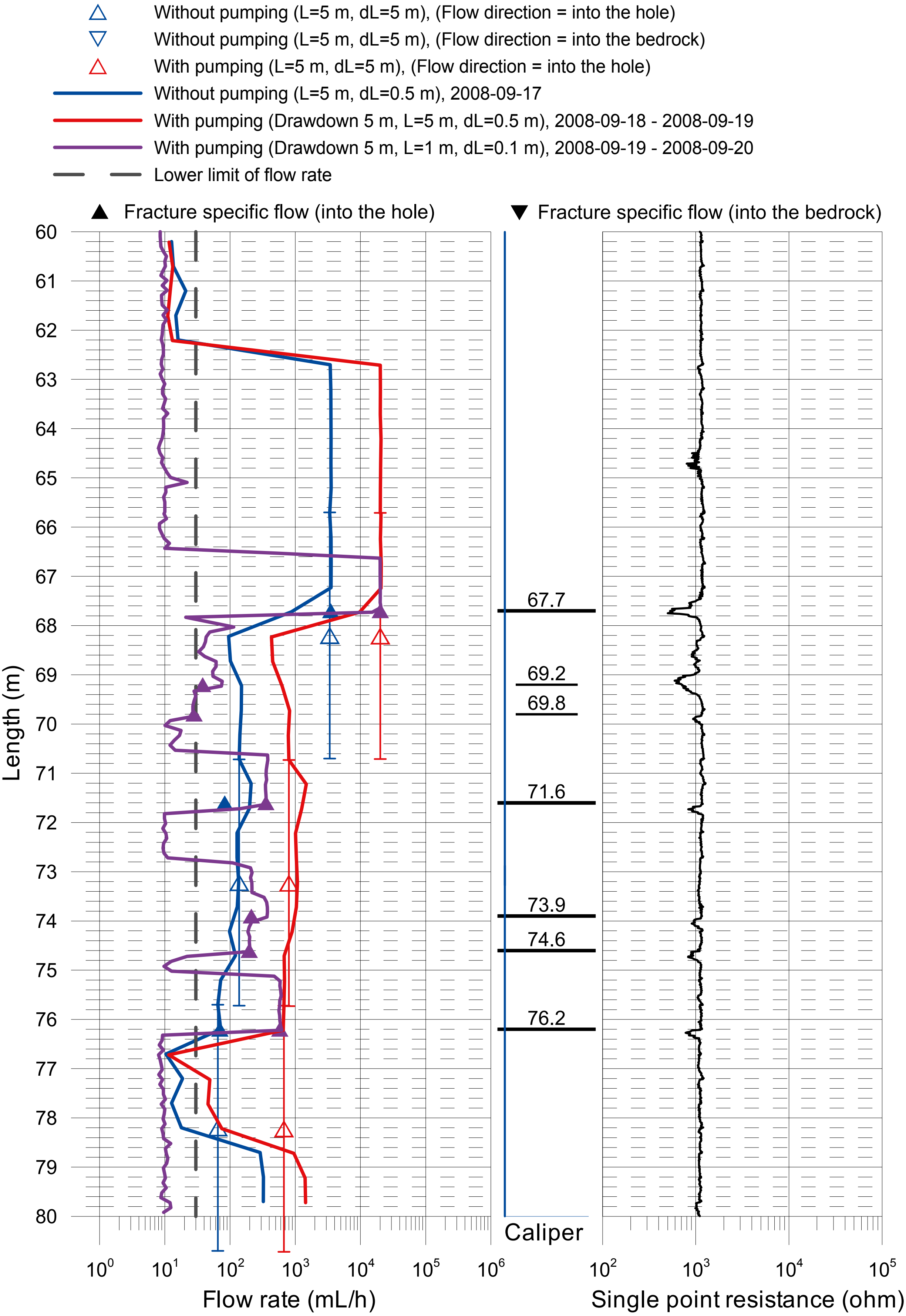
Forsmark, borehole KFR102B
Flow rate, caliper and single point resistance



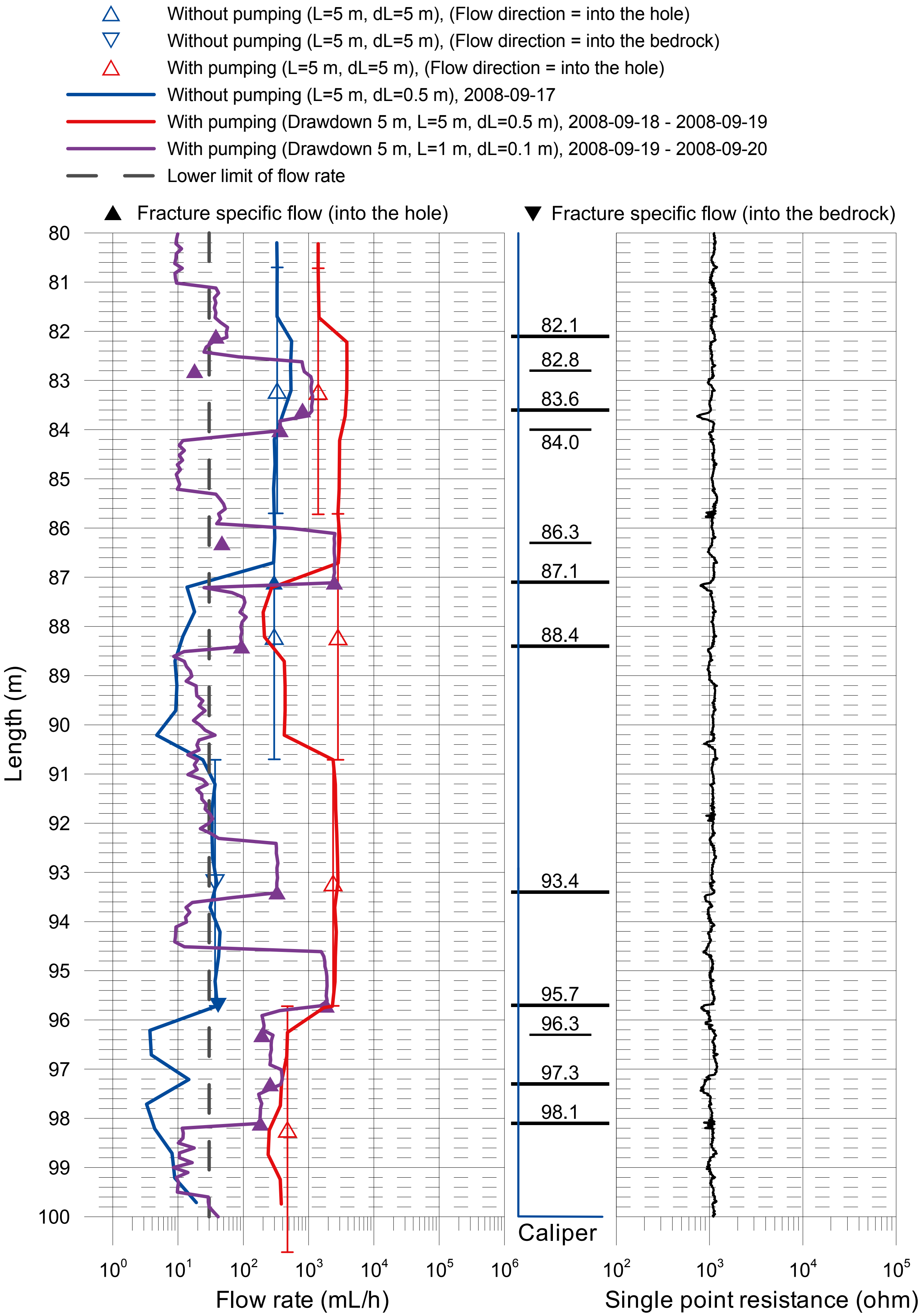
Forsmark, borehole KFR102B
Flow rate, caliper and single point resistance



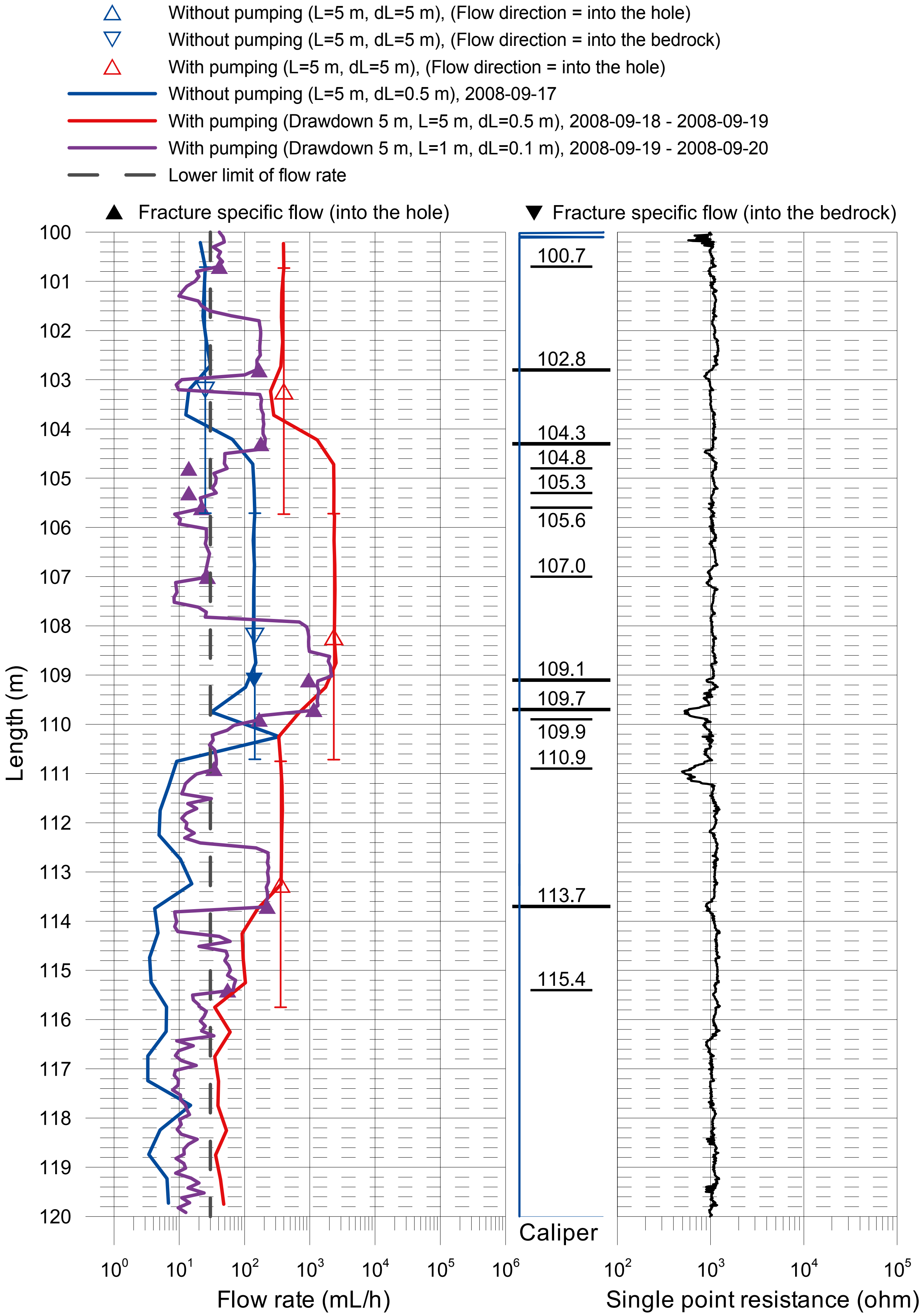
Forsmark, borehole KFR102B
Flow rate, caliper and single point resistance

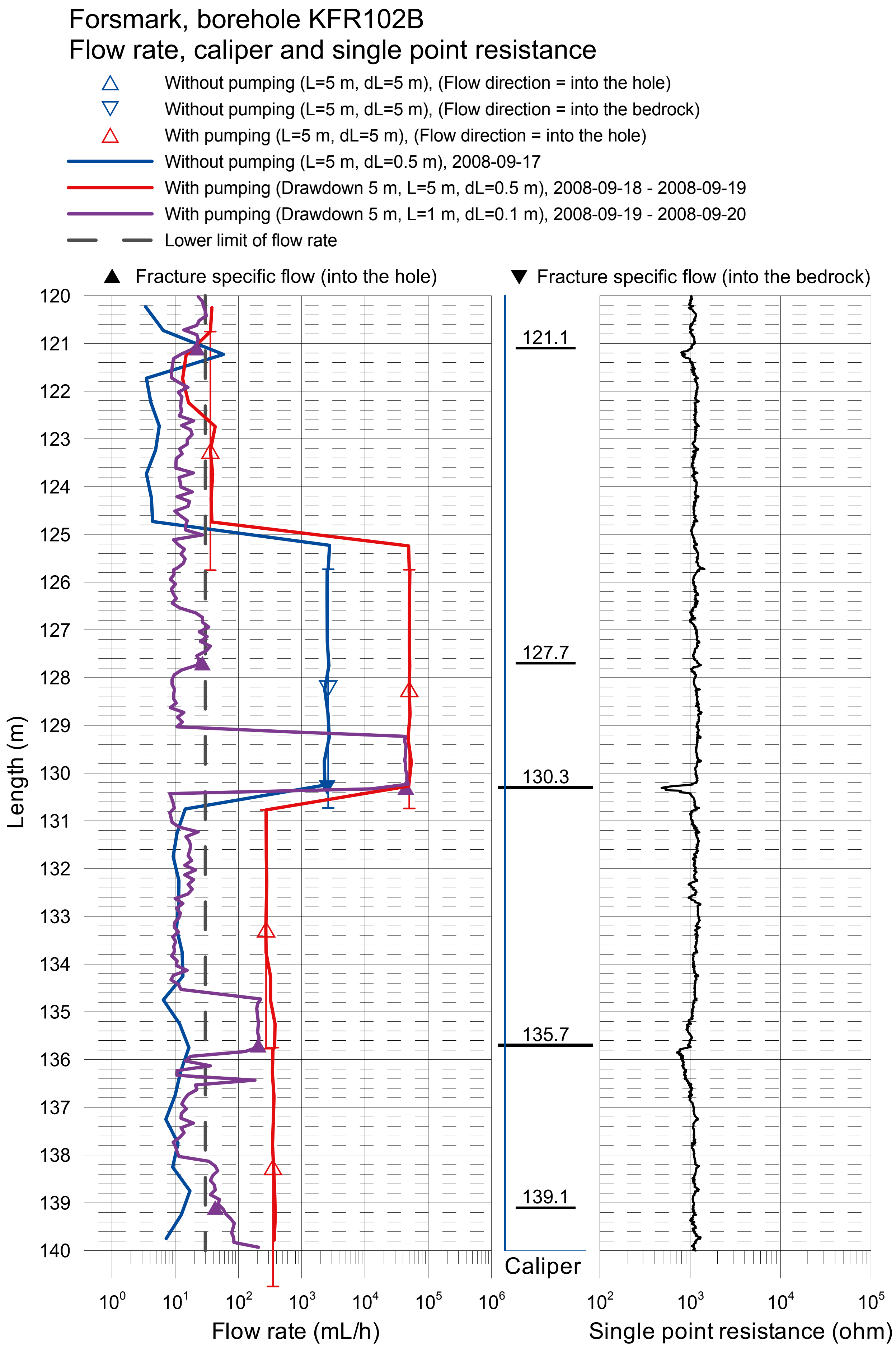


Forsmark, borehole KFR102B
Flow rate, caliper and single point resistance

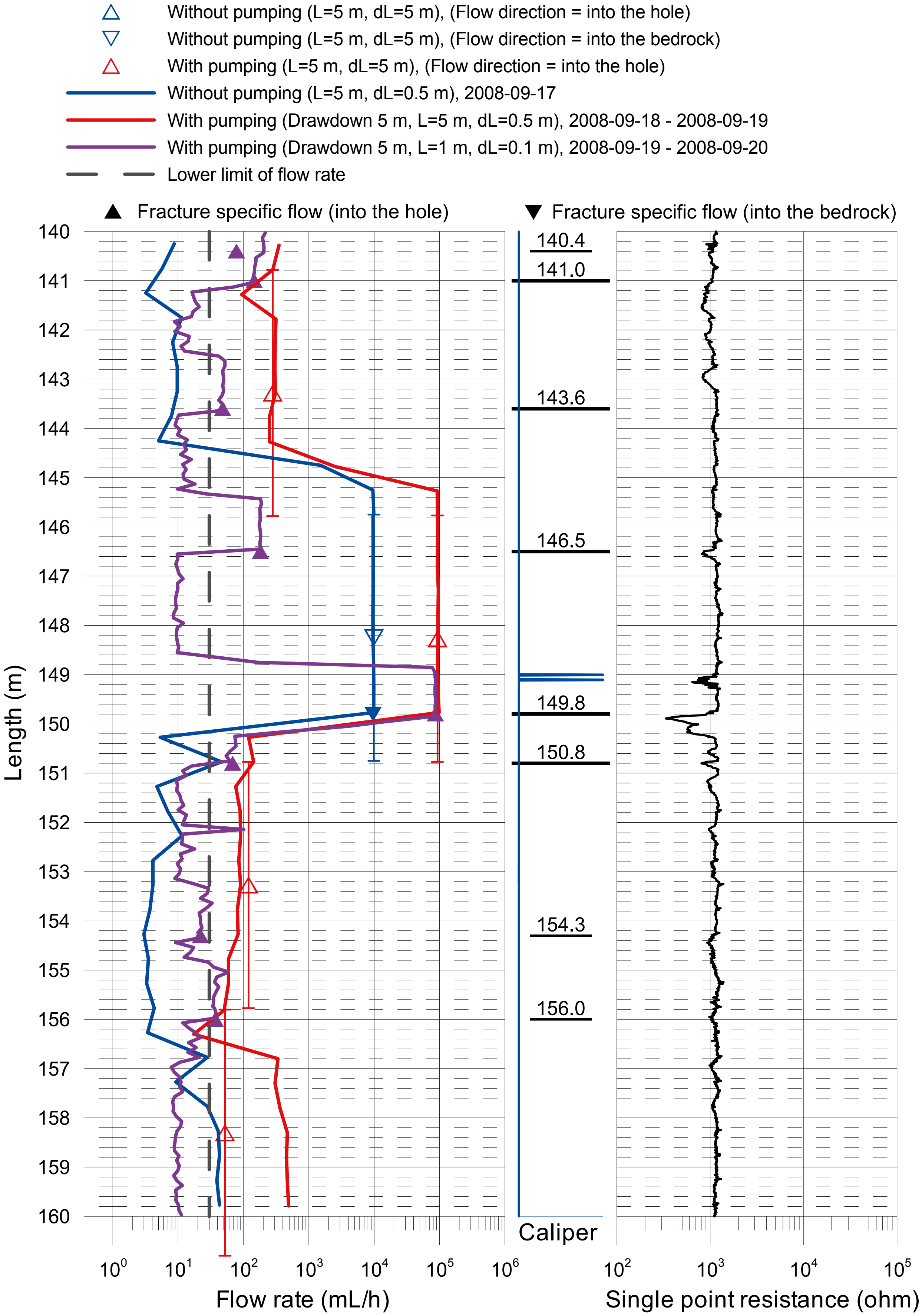


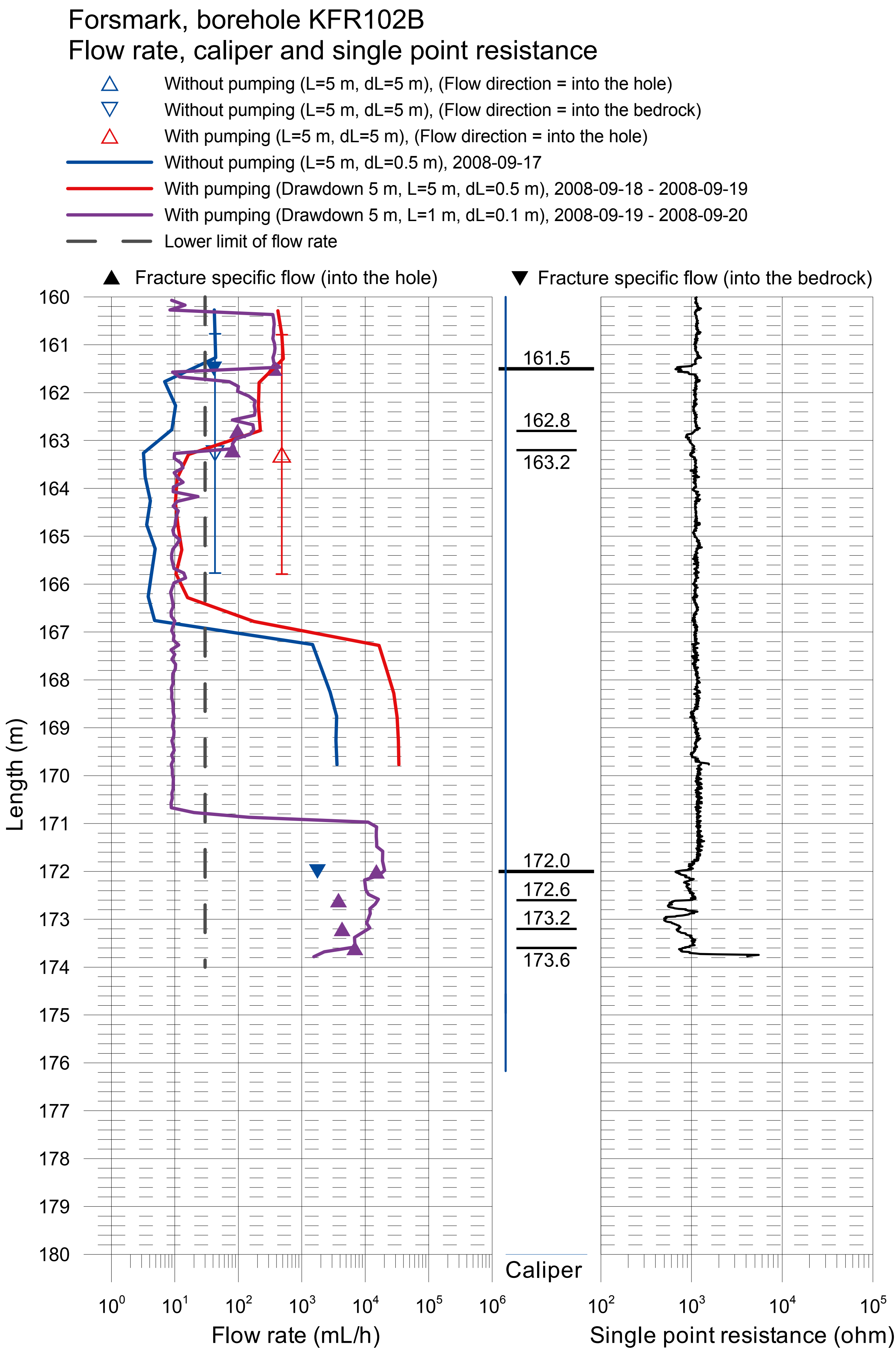
Forsmark, borehole KFR102B
Flow rate, caliper and single point resistance




Forsmark, borehole KFR102B
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), 2008-09-17
With pumping (Drawdown 5 m, L=5 m, dL=0.5 m), 2008-09-18 - 2008-09-19
With pumping (Drawdown 5 m, L=1 m, dL=0.1 m), 2008-09-19 - 2008-09-20
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
121.1
127.7
130.3
135.7
139.1
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 KFR102B
Flow rate, caliper and single point resistance




Forsmark, borehole KFR102B
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), 2008-09-17
With pumping (Drawdown 5 m, L=5 m, dL=0.5 m), 2008-09-18 - 2008-09-19
With pumping (Drawdown 5 m, L=1 m, dL=0.1 m), 2008-09-19 - 2008-09-20
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
161.5
162.8
163.2
172.0
172.6
173.2
173.6
Caliper
Flow rate (mL/h)
Single point resistance (ohm)

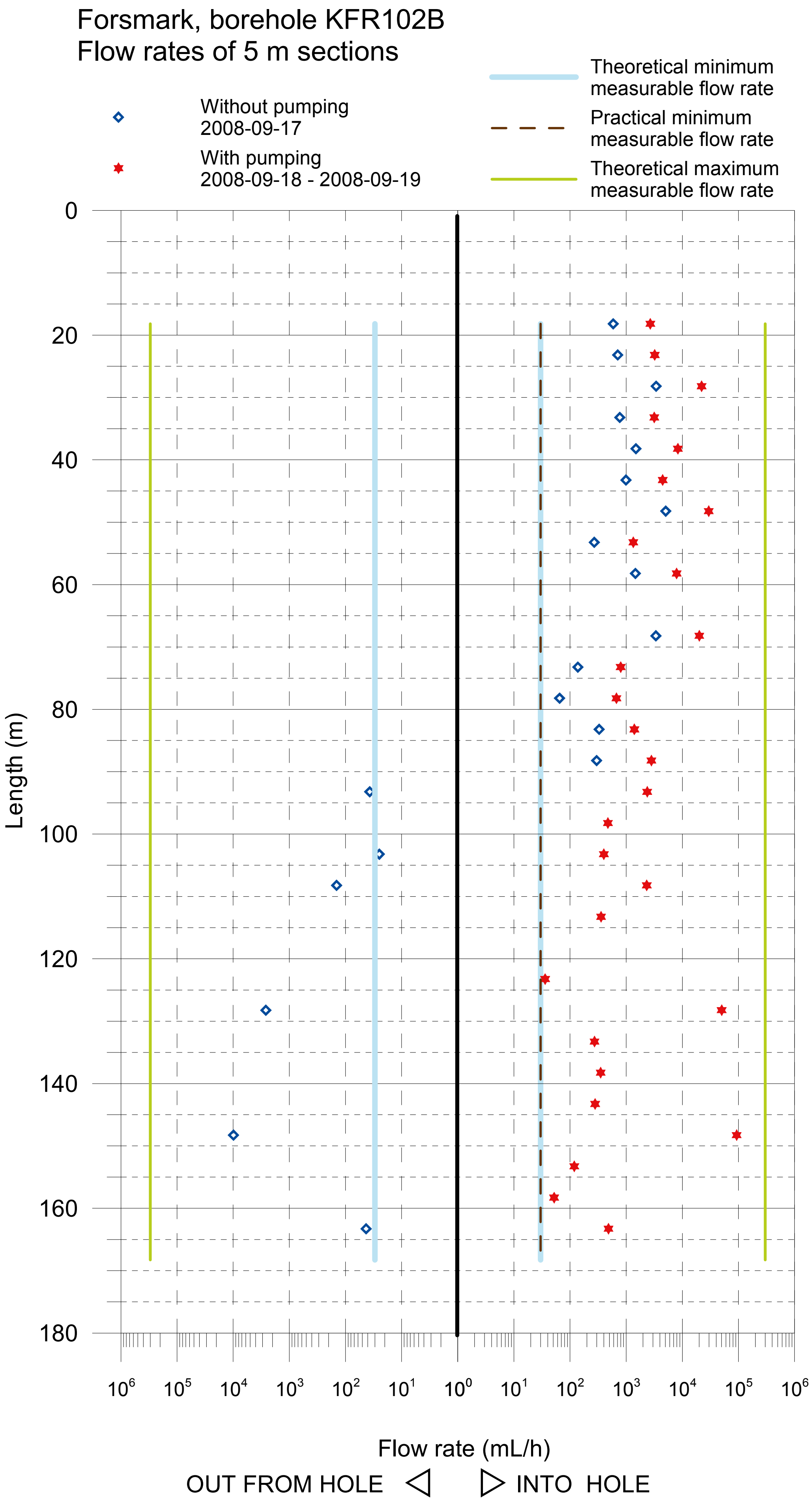
Explanations

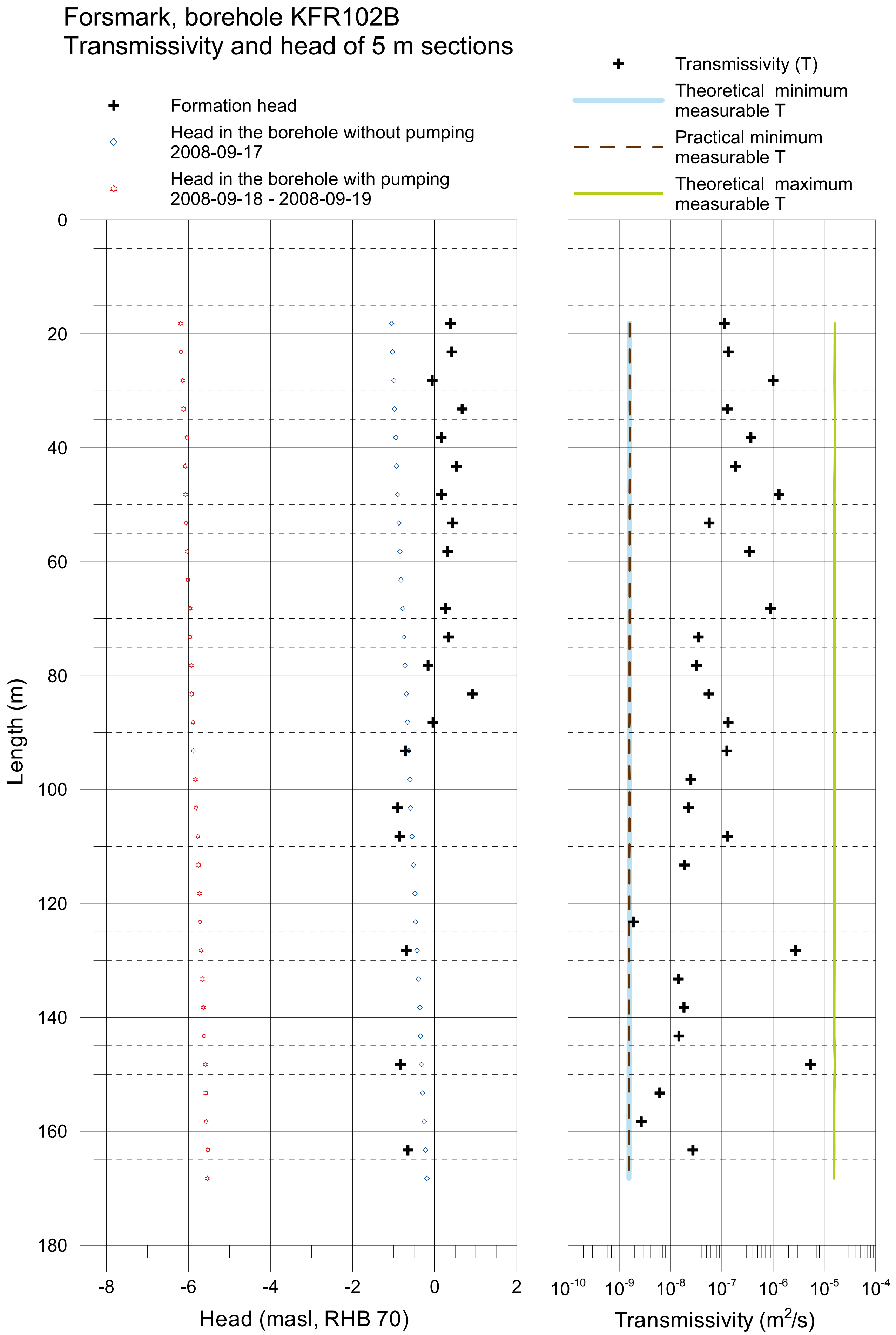
Header	Unit	Explanations
Borehole		ID for borehole.
Secup	m	Length along the borehole for the upper limit of the test section (based on corrected length L).
Seclow	m	Length along the borehole for the lower limit of the test section (based on corrected length L).
L	m	Corrected length along borehole based 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-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-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-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)	T_D- measl$_{LP}$ (m^2/s)	T_D- measl$_U$ (m^2/s)	Comments
KFR102B	15.68	20.68	5	1.64E–07	–1.05	7.47E–07	–6.19	1.1E–07	0.4	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	20.68	25.68	5	1.97E–07	–1.03	8.97E–07	–6.18	1.3E–07	0.4	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	25.69	30.69	5	9.50E–07	–1.00	6.14E–06	–6.14	1.0E–06	–0.1	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	30.69	35.69	5	2.14E–07	–0.98	8.78E–07	–6.12	1.3E–07	0.7	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	35.70	40.70	5	4.14E–07	–0.95	2.31E–06	–6.04	3.7E–07	0.2	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	40.73	45.73	5	2.75E–07	–0.93	1.24E–06	–6.08	1.9E–07	0.5	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	45.72	50.72	5	1.41E–06	–0.90	8.22E–06	–6.07	1.3E–06	0.2	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	50.72	55.72	5	7.50E–08	–0.87	3.72E–07	–6.06	5.7E–08	0.4	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	55.71	60.71	5	4.06E–07	–0.85	2.20E–06	–6.03	3.4E–07	0.3	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	60.71	65.71	5	–	–0.82	–	–6.01	–	–	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	65.71	70.71	5	9.39E–07	–0.78	5.58E–06	–5.96	8.9E–07	0.3	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	70.73	75.73	5	3.83E–08	–0.75	2.22E–07	–5.96	3.5E–08	0.3	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	75.71	80.71	5	1.81E–08	–0.72	1.86E–07	–5.93	3.2E–08	–0.2	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	80.71	85.71	5	9.17E–08	–0.69	3.89E–07	–5.92	5.6E–08	0.9	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	85.71	90.71	5	8.28E–08	–0.66	7.83E–07	–5.89	1.3E–07	0.0	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	90.71	95.71	5	–1.03E–08	–0.63	6.58E–07	–5.88	1.3E–07	–0.7	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	95.72	100.72	5	–	–0.60	1.31E–07	–5.83	2.5E–08	–	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	100.72	105.72	5	–6.94E–09	–0.59	1.11E–07	–5.81	2.2E–08	–0.9	30	1.6E–09	1.6E–09	1.6E–05	*
KFR102B	105.72	110.72	5	–4.00E–08	–0.55	6.47E–07	–5.77	1.3E–07	–0.9	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	110.75	115.75	5	–	–0.51	9.92E–08	–5.75	1.9E–08	–	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	115.75	120.75	5	–	–0.48	–	–5.73	–	–	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	120.74	125.74	5	–	–0.46	1.00E–08	–5.72	1.9E–09	–	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	125.74	130.74	5	–7.28E–07	–0.43	1.39E–05	–5.69	2.8E–06	–0.7	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	130.76	135.76	5	–	–0.40	7.58E–08	–5.66	1.4E–08	–	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	135.75	140.75	5	–	–0.36	9.75E–08	–5.64	1.8E–08	–	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	140.77	145.77	5	–	–0.34	7.78E–08	–5.62	1.5E–08	–	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	145.76	150.76	5	–2.75E–06	–0.32	2.58E–05	–5.59	5.4E–06	–0.8	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	150.77	155.77	5	–	–0.29	3.31E–08	–5.58	6.2E–09	–	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	155.79	160.79	5	–	–0.25	1.44E–08	–5.57	2.7E–09	–	30	1.6E–09	1.6E–09	1.5E–05	
KFR102B	160.78	165.78	5	–1.19E–08	–0.22	1.34E–07	–5.53	2.7E–08	–0.7	30	1.6E–09	1.6E–09	1.6E–05	
KFR102B	165.77	170.77	5	–	–0.19	–	–5.54	–	–	30	1.5E–09	1.5E–09	1.5E–05	

* Uncertain flow rate (less than 30 mL/h).


Forsmark, borehole KFR102B
Flow rates of 5 m sections
Without pumping
2008-09-17
With pumping
2008-09-18 - 2008-09-19
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
180
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 KFR102B
Transmissivity and head of 5 m sections
Formation head
Head in the borehole without pumping 2008-09-17
Head in the borehole with pumping 2008-09-18 - 2008-09-19
Transmissivity (T)
Theoretical minimum measurable T
Practical minimum measurable T
Theoretical maximum measurable T
Length (m)
0
20
40
60
80
100
120
140
160
180
-8
-6
-4
-2
0
2
Head (masl, RHB 70)
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
Transmissivity (m^2/s)

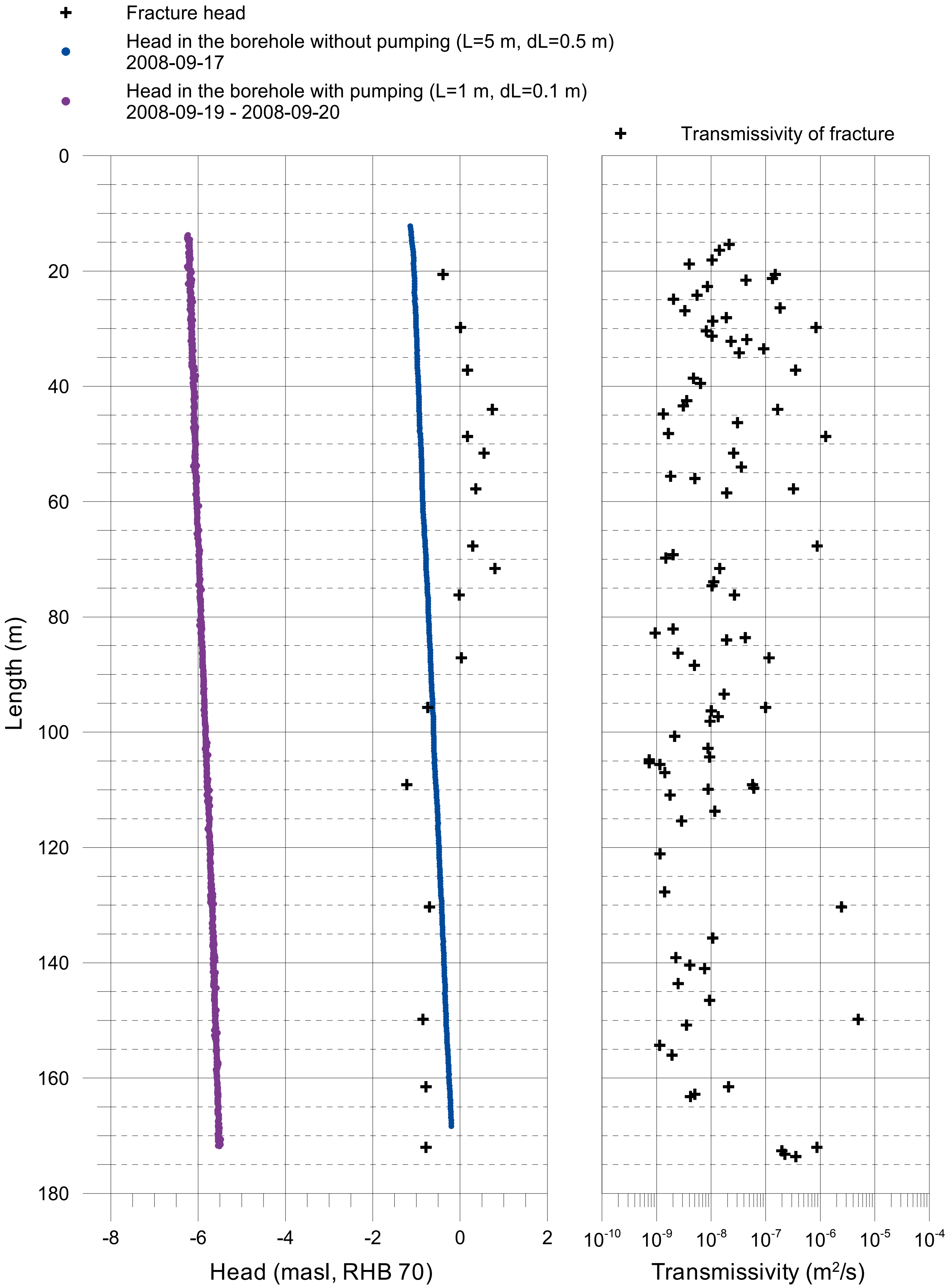
Inferred flow anomalies from overlapping flow logging

Borehole ID	Length to flow anom. L (m)	L_w (m)	dL (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.)	Comments
KFR102B	15.4	1	0.1	–	–1.10	1.11E–07	–6.21	2.1E–08	–	
KFR102B	16.4	1	0.1	–	–1.08	7.33E–08	–6.20	1.4E–08	–	
KFR102B	18.1	1	0.1	–	–1.06	5.42E–08	–6.19	1.0E–08	–	
KFR102B	18.8	1	0.1	–	–1.07	2.06E–08	–6.19	4.0E–09	–	
KFR102B	20.6	1	0.1	1.01E–07	–1.05	8.81E–07	–6.19	1.5E–07	–0.4	
KFR102B	21.3	1	0.1	–	–1.04	6.94E–07	–6.19	1.3E–07	–	
KFR102B	21.6	1	0.1	–	–1.04	2.25E–07	–6.15	4.4E–08	–	*
KFR102B	22.7	1	0.1	–	–1.04	4.44E–08	–6.17	8.6E–09	–	
KFR102B	24.2	1	0.1	–	–1.04	2.86E–08	–6.17	5.5E–09	–	*
KFR102B	24.9	1	0.1	–	–1.03	1.06E–08	–6.16	2.0E–09	–	*
KFR102B	26.4	1	0.1	–	–1.02	9.61E–07	–6.18	1.8E–07	–	
KFR102B	26.9	1	0.1	–	–1.02	1.72E–08	–6.17	3.3E–09	–	*
KFR102B	28.1	1	0.1	–	–1.01	9.92E–08	–6.16	1.9E–08	–	
KFR102B	28.7	1	0.1	–	–1.01	5.58E–08	–6.15	1.1E–08	–	
KFR102B	29.8	1	0.1	8.67E–07	–1.01	5.22E–06	–6.16	8.4E–07	0.0	
KFR102B	30.4	1	0.1	–	–1.00	4.25E–08	–6.15	8.2E–09	–	*
KFR102B	31.3	1	0.1	–	–1.00	5.39E–08	–6.15	1.0E–08	–	*
KFR102B	31.9	1	0.1	–	–0.99	2.34E–07	–6.13	4.5E–08	–	
KFR102B	32.2	1	0.1	–	–0.99	1.21E–07	–6.16	2.3E–08	–	*
KFR102B	33.5	1	0.1	–	–0.99	4.78E–07	–6.14	9.2E–08	–	
KFR102B	34.2	1	0.1	–	–0.99	1.71E–07	–6.15	3.3E–08	–	
KFR102B	37.2	1	0.1	4.08E–07	–0.97	2.23E–06	–6.08	3.5E–07	0.2	
KFR102B	38.6	1	0.1	–	–0.96	2.47E–08	–6.12	4.7E–09	–	
KFR102B	39.5	1	0.1	–	–0.96	3.33E–08	–6.12	6.4E–09	–	
KFR102B	42.5	1	0.1	–	–0.94	1.86E–08	–6.10	3.6E–09	–	
KFR102B	43.4	1	0.1	–	–0.94	1.61E–08	–6.08	3.1E–09	–	*
KFR102B	44	1	0.1	2.83E–07	–0.94	1.15E–06	–6.09	1.7E–07	0.7	
KFR102B	44.8	1	0.1	–	–0.93	6.94E–09	–6.10	1.3E–09	–	*
KFR102B	46.3	1	0.1	–	–0.93	1.59E–07	–6.09	3.0E–08	–	
KFR102B	48.2	1	0.1	–	–0.91	8.61E–09	–6.07	1.7E–09	–	*
KFR102B	48.7	1	0.1	1.38E–06	–0.91	7.94E–06	–6.07	1.3E–06	0.2	
KFR102B	51.6	1	0.1	3.78E–08	–0.89	1.73E–07	–6.07	2.6E–08	0.6	
KFR102B	54	1	0.1	–	–0.88	1.88E–07	–6.07	3.6E–08	–	
KFR102B	55.6	1	0.1	–	–0.87	9.44E–09	–6.03	1.8E–09	–	*
KFR102B	56	1	0.1	–	–0.87	2.64E–08	–6.05	5.0E–09	–	
KFR102B	57.8	1	0.1	4.03E–07	–0.87	2.09E–06	–6.05	3.2E–07	0.4	
KFR102B	58.5	1	0.1	–	–0.86	1.01E–07	–6.03	1.9E–08	–	
KFR102B	67.7	1	0.1	9.72E–07	–0.80	5.58E–06	–5.98	8.8E–07	0.3	
KFR102B	69.2	1	0.1	–	–0.78	1.06E–08	–5.98	2.0E–09	–	*
KFR102B	69.8	1	0.1	–	–0.78	7.78E–09	–5.98	1.5E–09	–	*
KFR102B	71.6	1	0.1	2.31E–08	–0.78	9.86E–08	–5.96	1.4E–08	0.8	
KFR102B	73.9	1	0.1	–	–0.76	5.92E–08	–5.97	1.1E–08	–	
KFR102B	74.6	1	0.1	–	–0.75	5.47E–08	–5.98	1.0E–08	–	
KFR102B	76.2	1	0.1	1.94E–08	–0.74	1.61E–07	–5.96	2.7E–08	0.0	
KFR102B	82.1	1	0.1	–	–0.71	1.06E–08	–5.90	2.0E–09	–	
KFR102B	82.8	1	0.1	–	–0.71	5.00E–09	–5.95	9.4E–10	–	*
KFR102B	83.6	1	0.1	–	–0.70	2.24E–07	–5.93	4.2E–08	–	
KFR102B	84	1	0.1	–	–0.70	1.02E–07	–5.93	1.9E–08	–	*
KFR102B	86.3	1	0.1	–	–0.68	1.31E–08	–5.91	2.5E–09	–	*
KFR102B	87.1	1	0.1	8.22E–08	–0.68	6.89E–07	–5.90	1.2E–07	0.0	
KFR102B	88.4	1	0.1	–	–0.67	2.61E–08	–5.90	4.9E–09	–	
KFR102B	93.4	1	0.1	–	–0.64	9.14E–08	–5.87	1.7E–08	–	

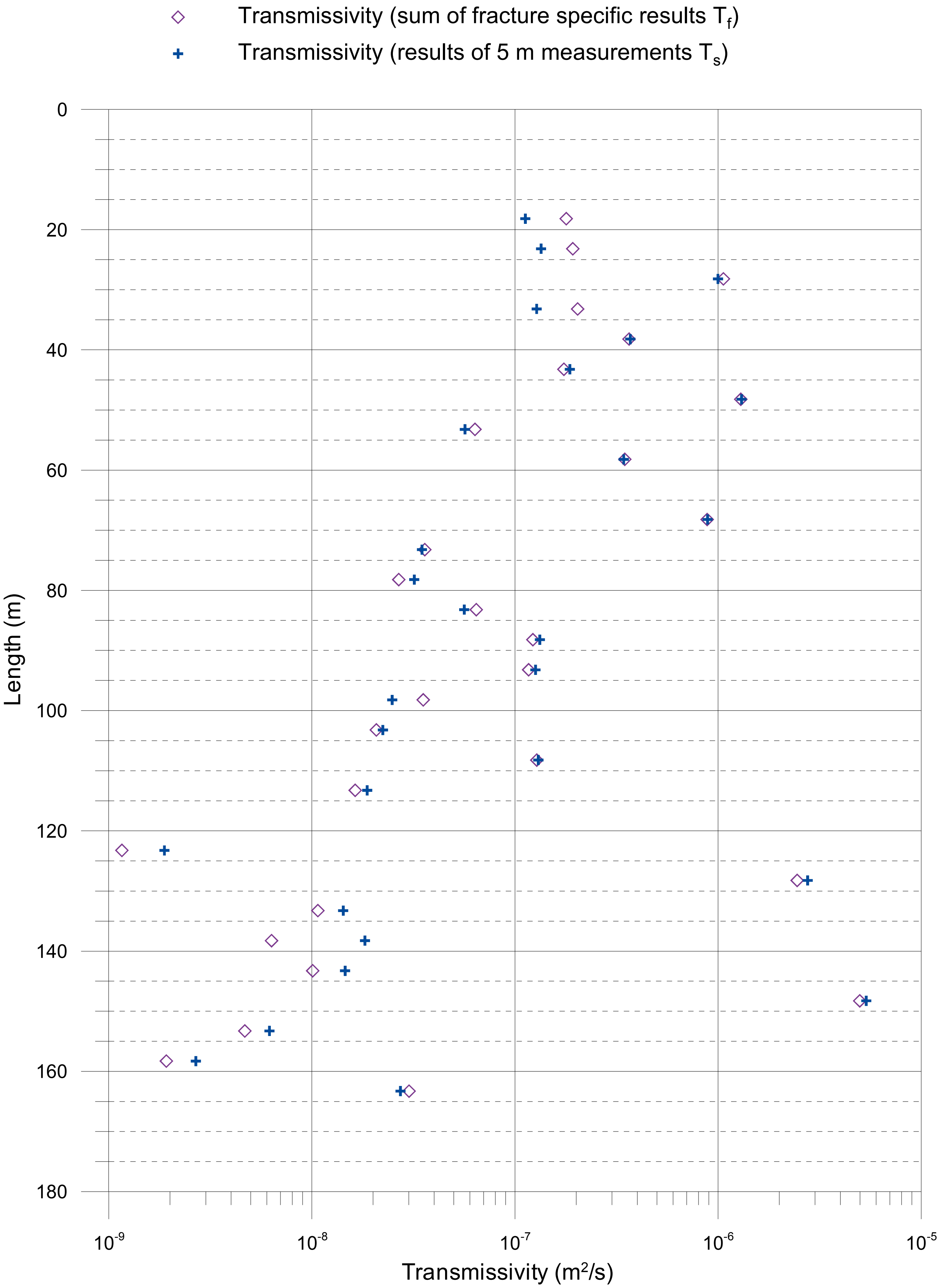
Borehole ID	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_0 (m^3/s)	h_{0FW} (m.a.s.l.)	Q_1 (m^3/s)	h_{1FW} (m.a.s.l.)	T_D (m^2/s)	h_i (m.a.s.l.)	Comments
KFR102B	95.7	1	0.1	–1.14E–08	–0.63	5.14E–07	–5.85	1.0E–07	–0.7	
KFR102B	96.3	1	0.1	–	–0.63	5.36E–08	–5.86	1.0E–08	–	*
KFR102B	97.3	1	0.1	–	–0.61	7.17E–08	–5.85	1.4E–08	–	
KFR102B	98.1	1	0.1	–	–0.61	5.06E–08	–5.84	9.6E–09	–	
KFR102B	100.7	1	0.1	–	–0.60	1.14E–08	–5.83	2.2E–09	–	*
KFR102B	102.8	1	0.1	–	–0.60	4.64E–08	–5.83	8.8E–09	–	
KFR102B	104.3	1	0.1	–	–0.59	4.94E–08	–5.81	9.4E–09	–	
KFR102B	104.8	1	0.1	–	–0.58	3.89E–09	–5.80	7.4E–10	–	*
KFR102B	105.3	1	0.1	–	–0.59	3.89E–09	–5.81	7.4E–10	–	*
KFR102B	105.6	1	0.1	–	–0.58	6.11E–09	–5.82	1.2E–09	–	*
KFR102B	107	1	0.1	–	–0.57	7.50E–09	–5.79	1.4E–09	–	*
KFR102B	109.1	1	0.1	–3.89E–08	–0.55	2.66E–07	–5.79	5.8E–08	–1.2	
KFR102B	109.7	1	0.1	–	–0.55	3.19E–07	–5.78	6.0E–08	–	
KFR102B	109.9	1	0.1	–	–0.55	4.67E–08	–5.79	8.8E–09	–	*
KFR102B	110.9	1	0.1	–	–0.54	9.44E–09	–5.81	1.8E–09	–	*
KFR102B	113.7	1	0.1	–	–0.52	6.17E–08	–5.75	1.2E–08	–	
KFR102B	115.4	1	0.1	–	–0.51	1.53E–08	–5.75	2.9E–09	–	*
KFR102B	121.1	1	0.1	–	–0.48	6.11E–09	–5.71	1.2E–09	–	*
KFR102B	127.7	1	0.1	–	–0.44	7.50E–09	–5.70	1.4E–09	–	*
KFR102B	130.3	1	0.1	–7.00E–07	–0.42	1.23E–05	–5.67	2.5E–06	–0.7	
KFR102B	135.7	1	0.1	–	–0.39	5.69E–08	–5.65	1.1E–08	–	
KFR102B	139.1	1	0.1	–	–0.37	1.19E–08	–5.60	2.3E–09	–	*
KFR102B	140.4	1	0.1	–	–0.37	2.17E–08	–5.64	4.1E–09	–	*
KFR102B	141	1	0.1	–	–0.36	4.06E–08	–5.64	7.6E–09	–	
KFR102B	143.6	1	0.1	–	–0.34	1.33E–08	–5.63	2.5E–09	–	
KFR102B	146.5	1	0.1	–	–0.34	5.03E–08	–5.64	9.4E–09	–	
KFR102B	149.8	1	0.1	–2.67E–06	–0.32	2.39E–05	–5.61	5.0E–06	–0.9	
KFR102B	150.7	1	0.1	–	–0.32	1.89E–08	–5.60	3.5E–09	–	
KFR102B	154.3	1	0.1	–	–0.29	6.11E–09	–5.58	1.1E–09	–	*
KFR102B	156	1	0.1	–	–0.28	1.03E–08	–5.57	1.9E–09	–	*
KFR102B	161.5	1	0.1	–1.14E–08	–0.24	1.01E–07	–5.55	2.1E–08	–0.8	
KFR102B	162.8	1	0.1	–	–0.23	2.69E–08	–5.54	5.0E–09	–	*
KFR102B	163.2	1	0.1	–	–0.23	2.25E–08	–5.54	4.2E–09	–	*
KFR102B	172	1	0.1	–4.89E–07	–0.22	4.17E–06	–5.52	8.7E–07	–0.8	
KFR102B	172.6	1	0.1	–	–0.21	1.06E–06	–5.49	2.0E–07	–	*
KFR102B	173.2	1	0.1	–	–0.21	1.20E–06	–5.50	2.3E–07	–	*
KFR102B	173.6	1	0.1	–	–0.21	1.91E–06	–5.50	3.6E–07	–	*

* 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 KFR102B
Transmissivity and head of detected fractures

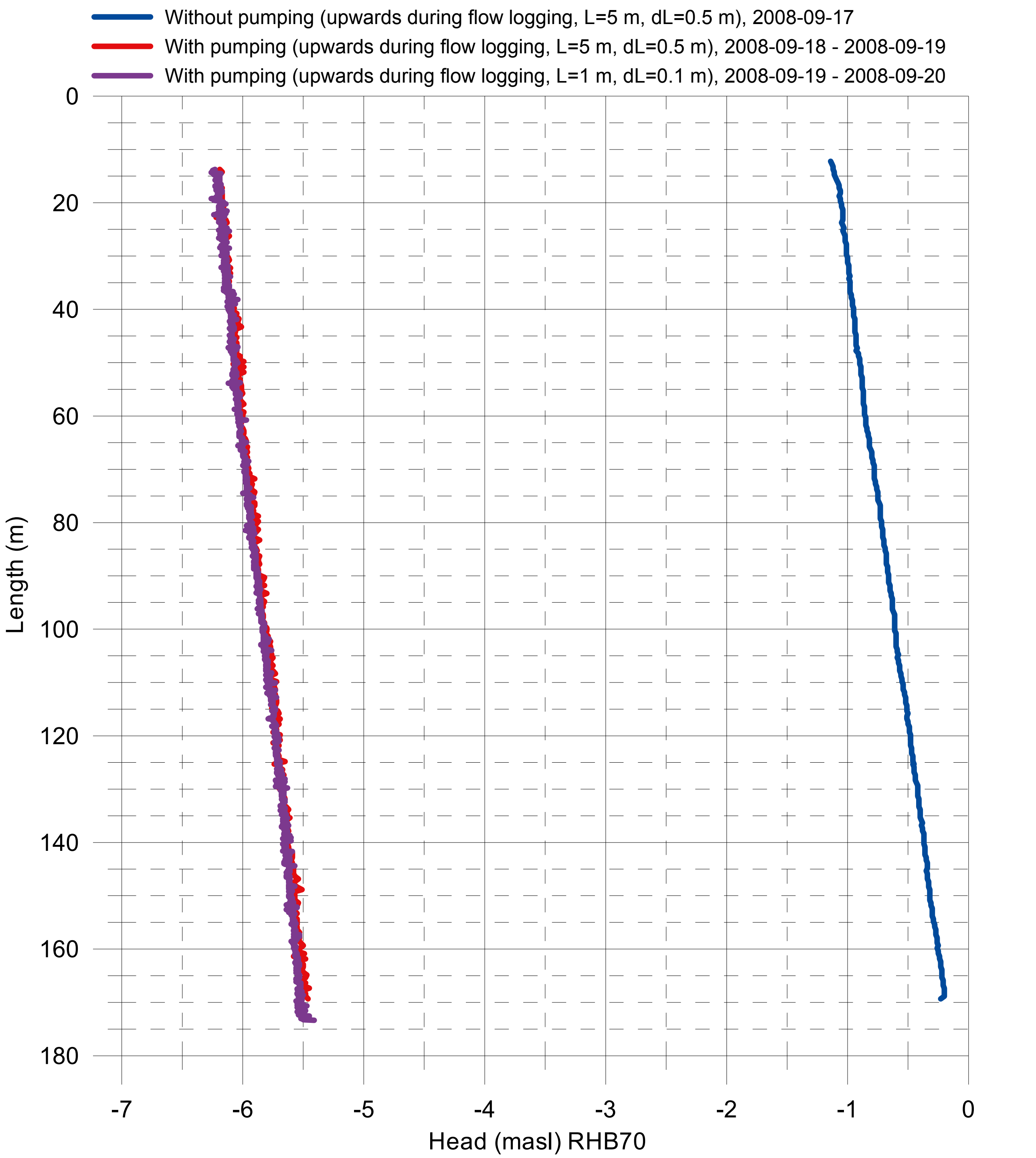


Forsmark, borehole KFR102B
Comparison between section transmissivity and fracture transmissivity

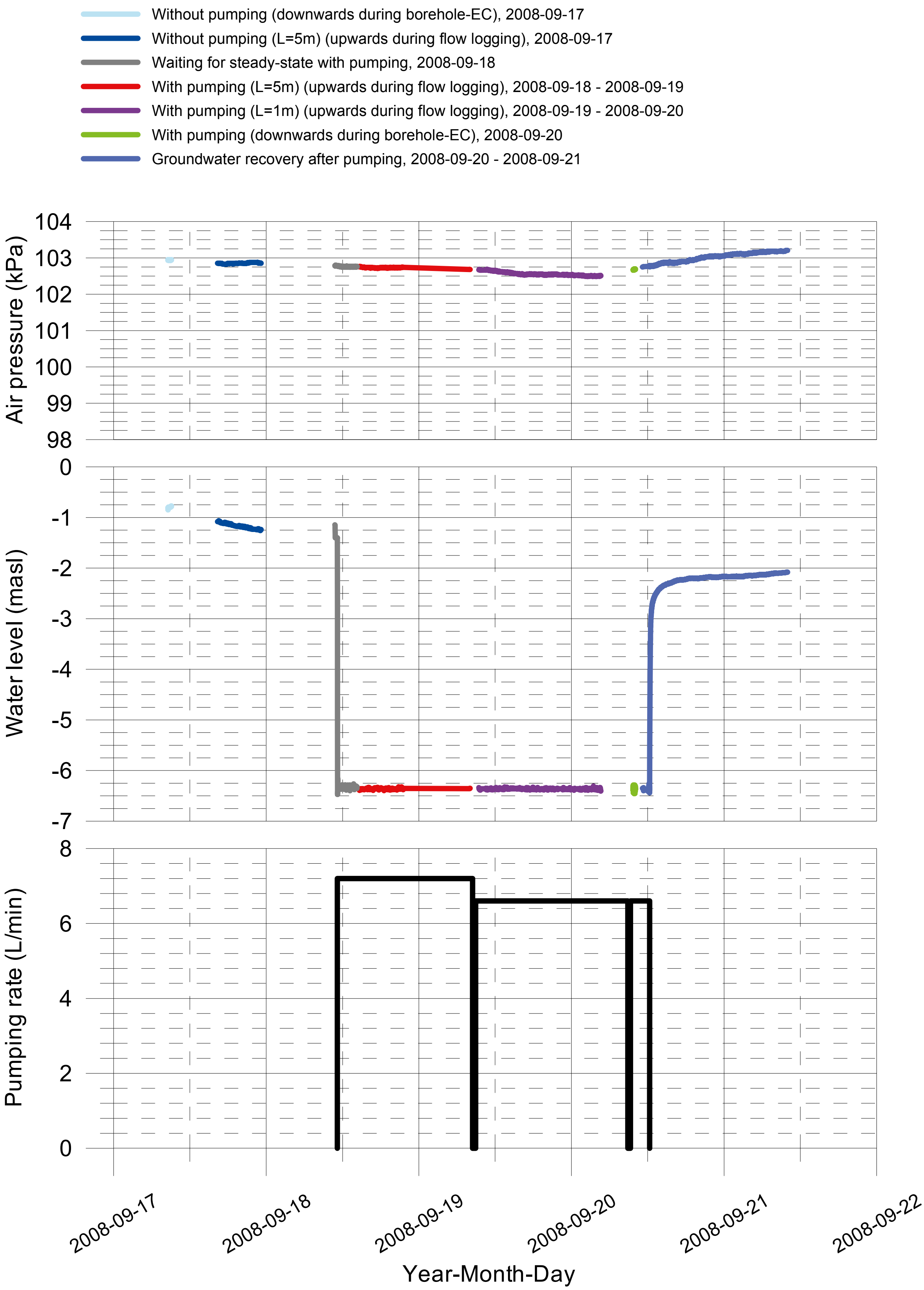


Forsmark, borehole KFR102B
Head in the borehole during flow logging

Head(masl)= (Absolute pressure (Pa) - Airpressure (Pa) + Offset) /(1000 kg/m^3 * 9.80665 m/s^2) + Elevation (m)
Offset = -1029 Pa (Correction for absolute pressure sensor)

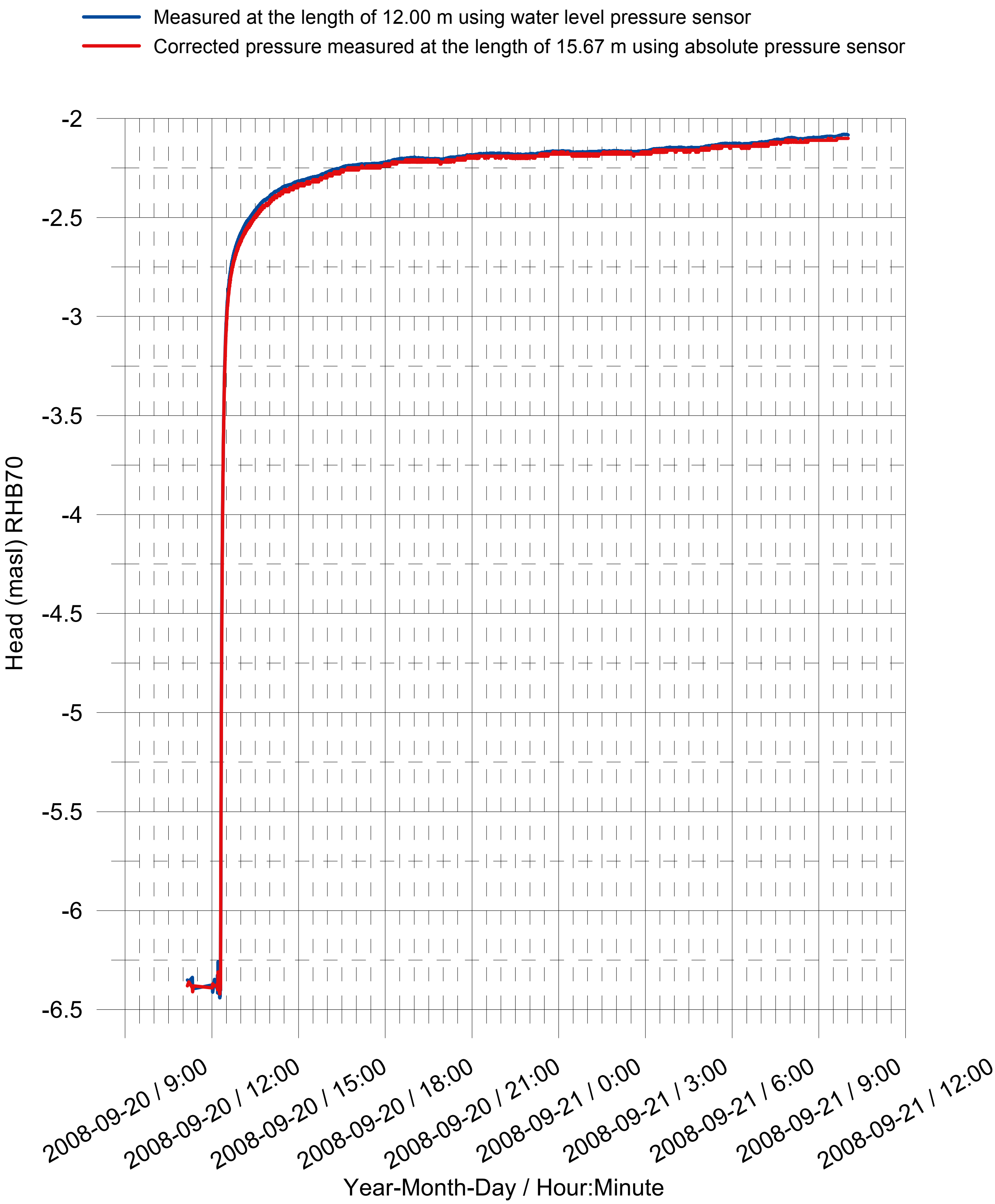


Forsmark, borehole KFR102B
Air pressure, water level in the borehole and pumping rate during flow logging

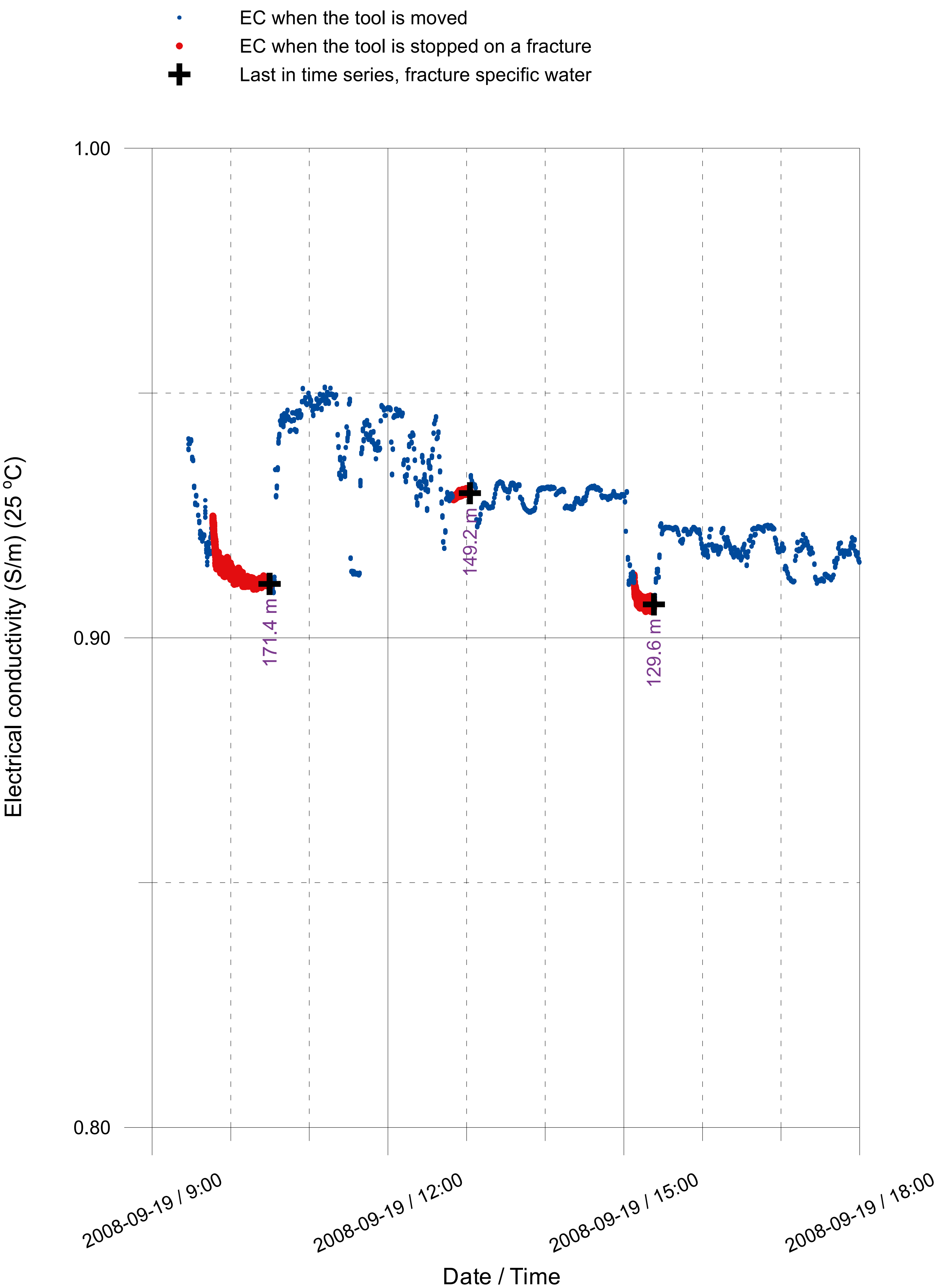


Forsmark, borehole KFR102B
Groundwater recovery after pumping

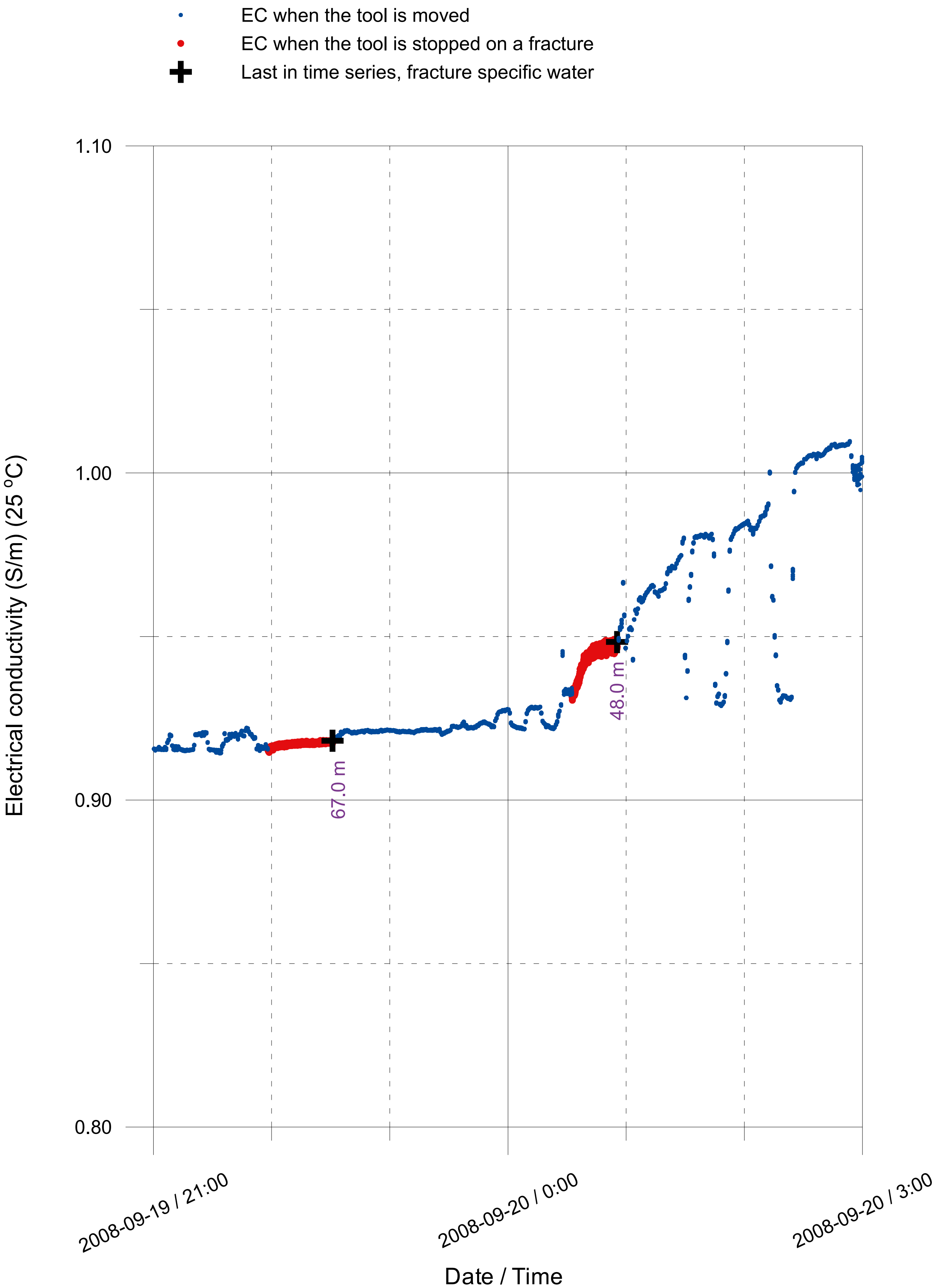
Head(masl)= (Absolute pressure (Pa) - Airpressure (Pa) + Offset) /(1000 kg/m^3 * 9.80665 m/s^2) + Elevation (m)
Offset = -1029 Pa (Correction for absolute pressure sensor)



Forsmark, borehole KFR102B
Fracture-specific EC results by date



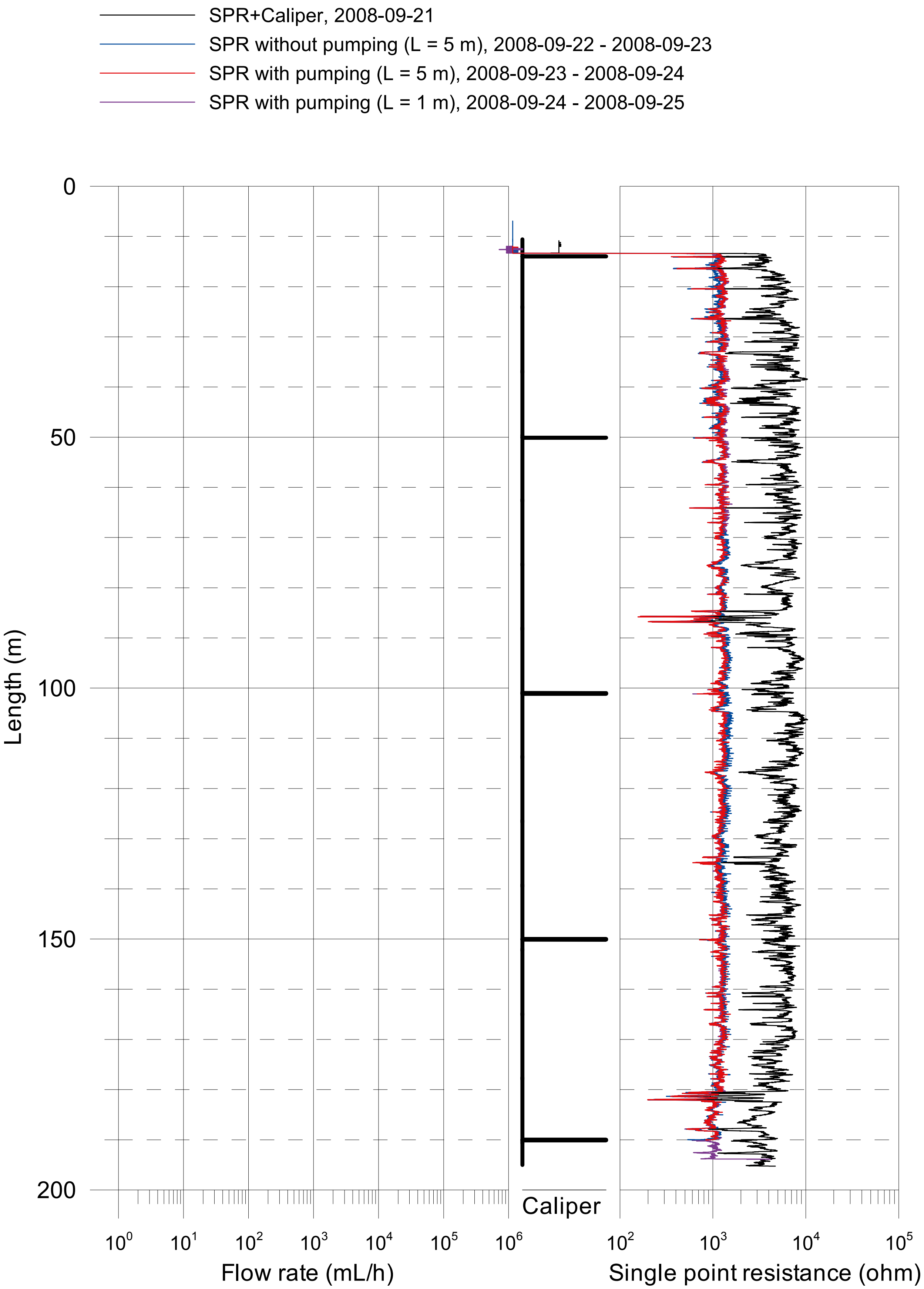
Forsmark, borehole KFR102B
Fracture-specific EC results by date



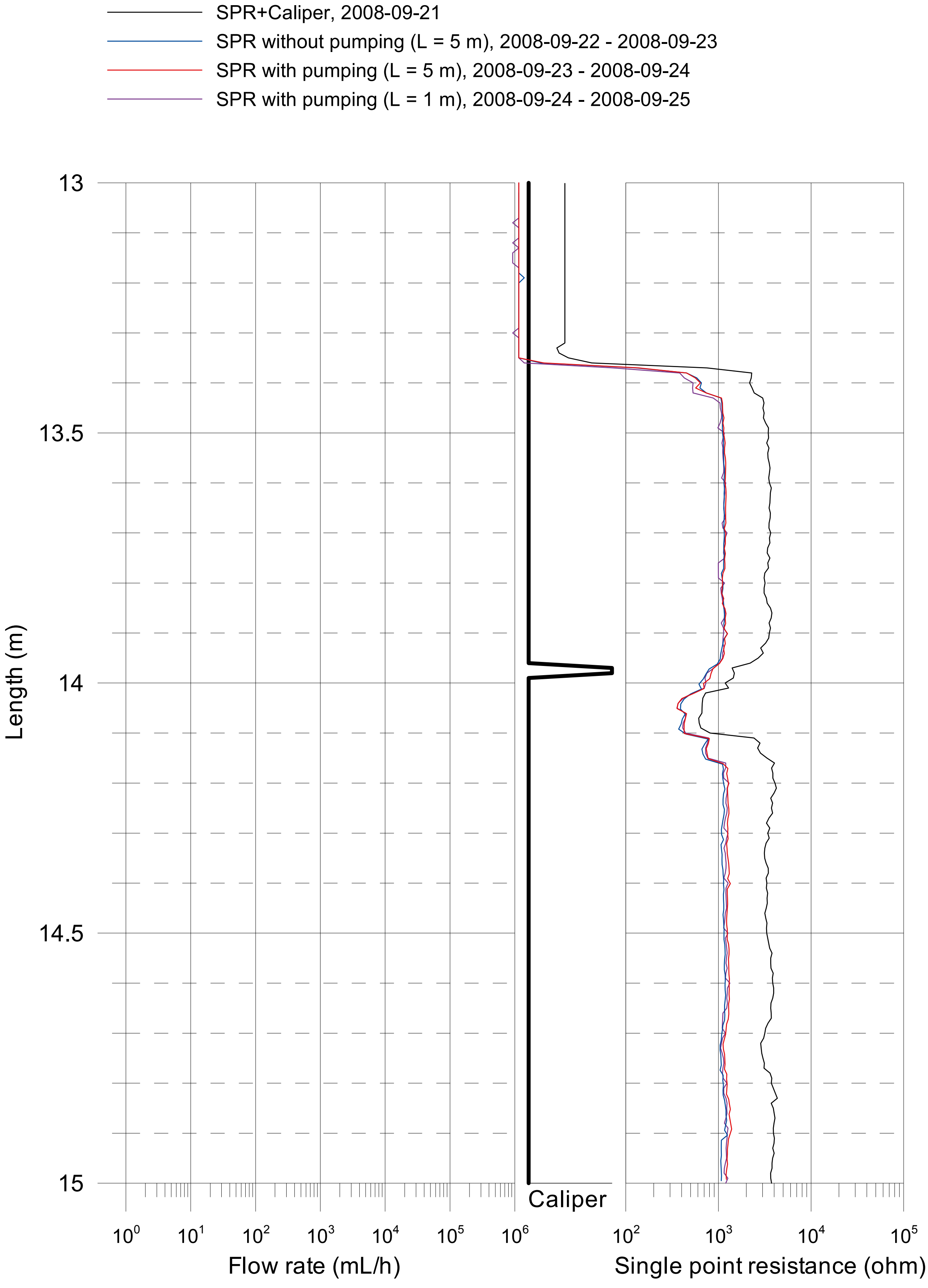
Appendices KFR103

Appendices	KFR103.1.1–KFR103.1.12	SPR and Caliper results after length correction
Appendix	KFR103.1.1.13	Length correction
Appendices	KFR103.2.1–KFR103.2.2	Electrical conductivity of borehole water
Appendix	KFR103.2.3	Temperature of borehole water
Appendices	KFR103.3.1–KFR103.3.10	Flow rate, caliper and single point resistance
Appendix	KFR103.4	Explanations for the tables in Appendices 5 and 7
Appendix	KFR103.5	Results of sequential flow logging
Appendix	KFR103.6.1	Plotted flow rates of 5 m sections
Appendix	KFR103.6.2	Plotted transmissivity and head of 5 m sections
Appendix	KFR103.7	Inferred flow anomalies from overlapping flow logging
Appendix	KFR103.8	Plotted transmissivity and head of detected fractures
Appendix	KFR103.9	Comparison between section transmissivity and fracture transmissivity
Appendix	KFR103.10.1	Head in the borehole during flow logging
Appendix	KFR103.10.2	Air pressure, water level in the borehole and pumping rate during flow logging
Appendix	KFR103.10.3	Groundwater recovery after pumping
Appendices	KFR103.11.1–KFR103.11.4	Fracture-specific EC results by date

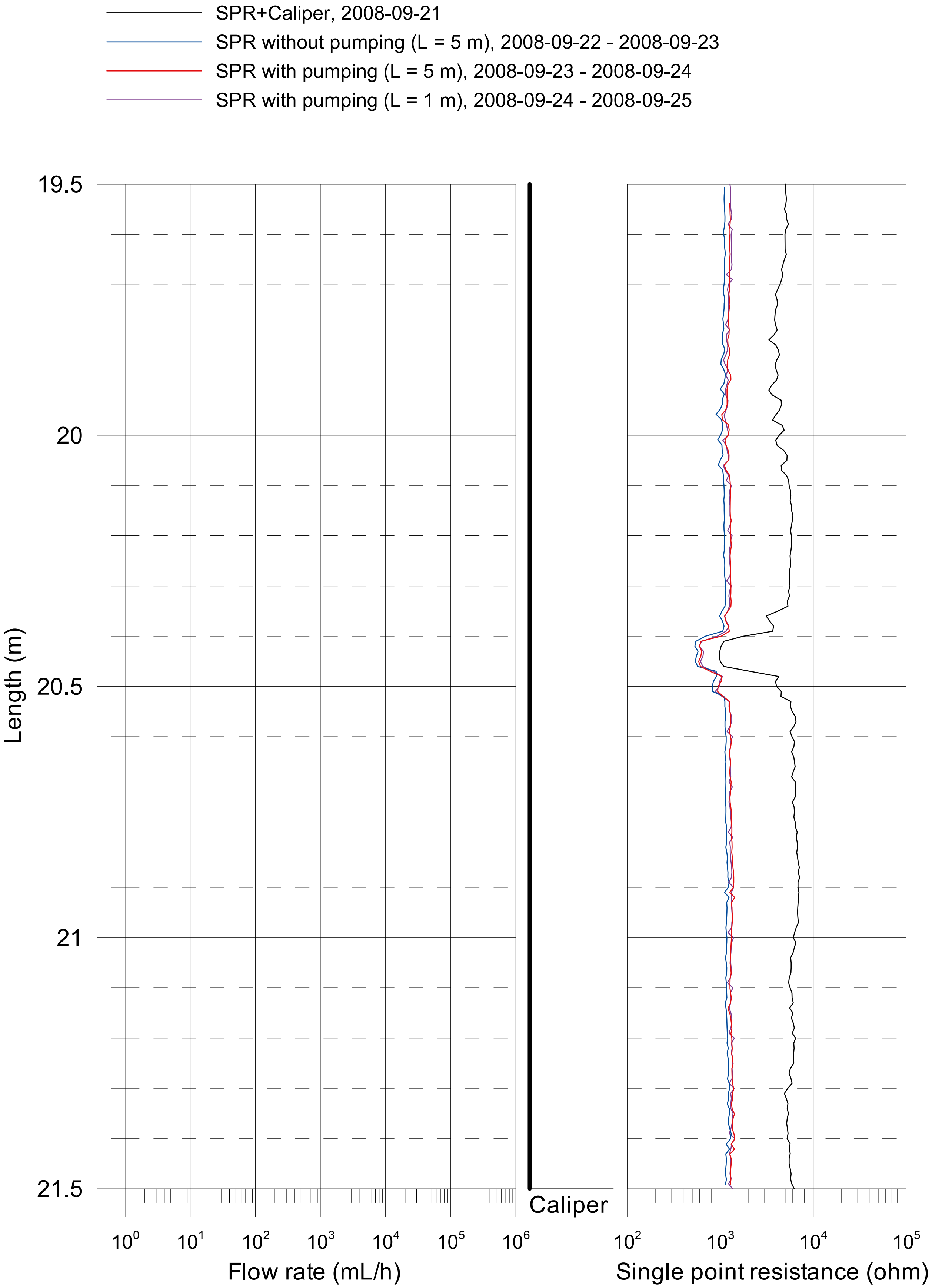
Forsmark, borehole KFR103
SPR and Caliper results after length correction



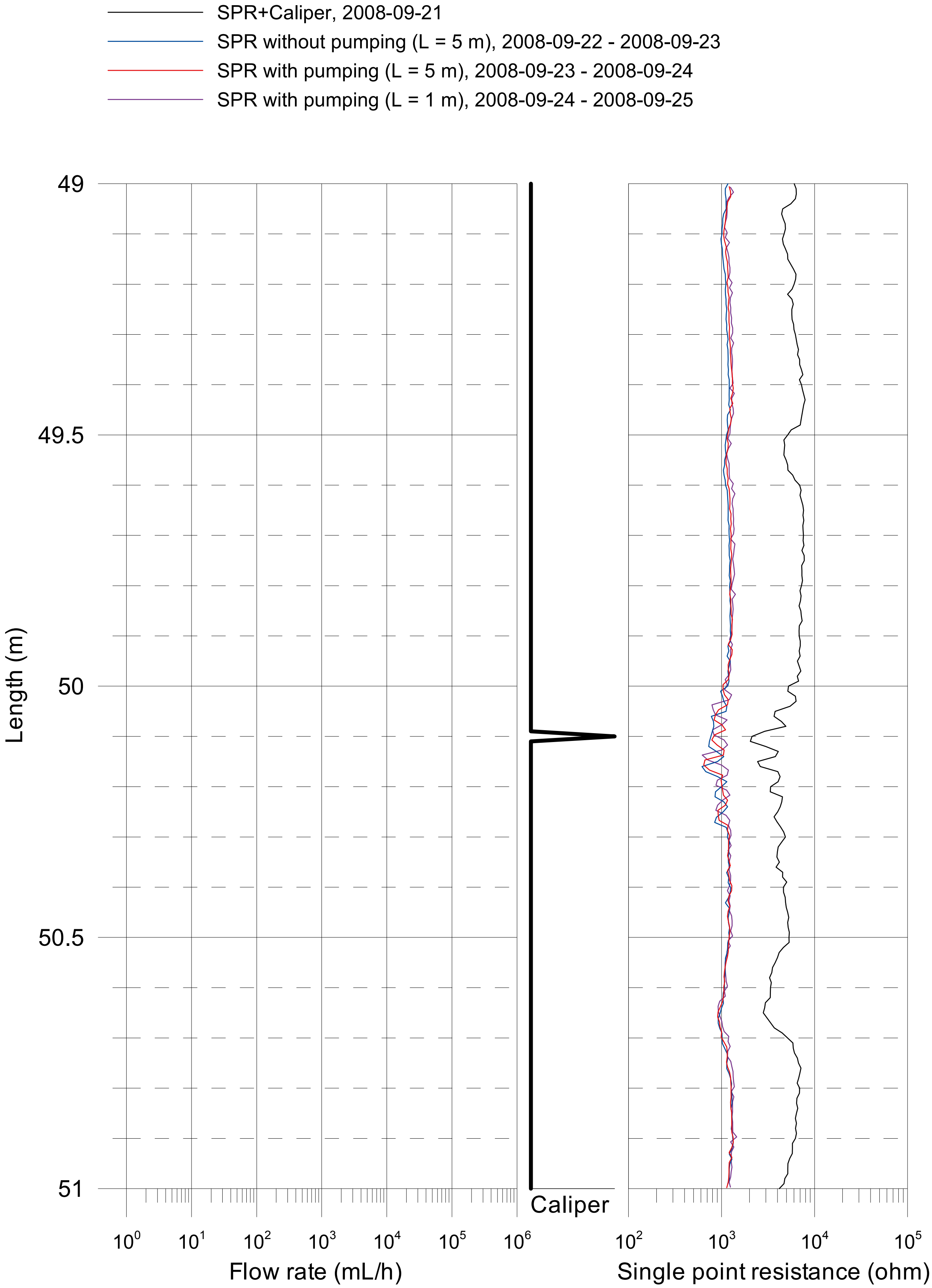
Forsmark, borehole KFR103
SPR and Caliper results after length correction



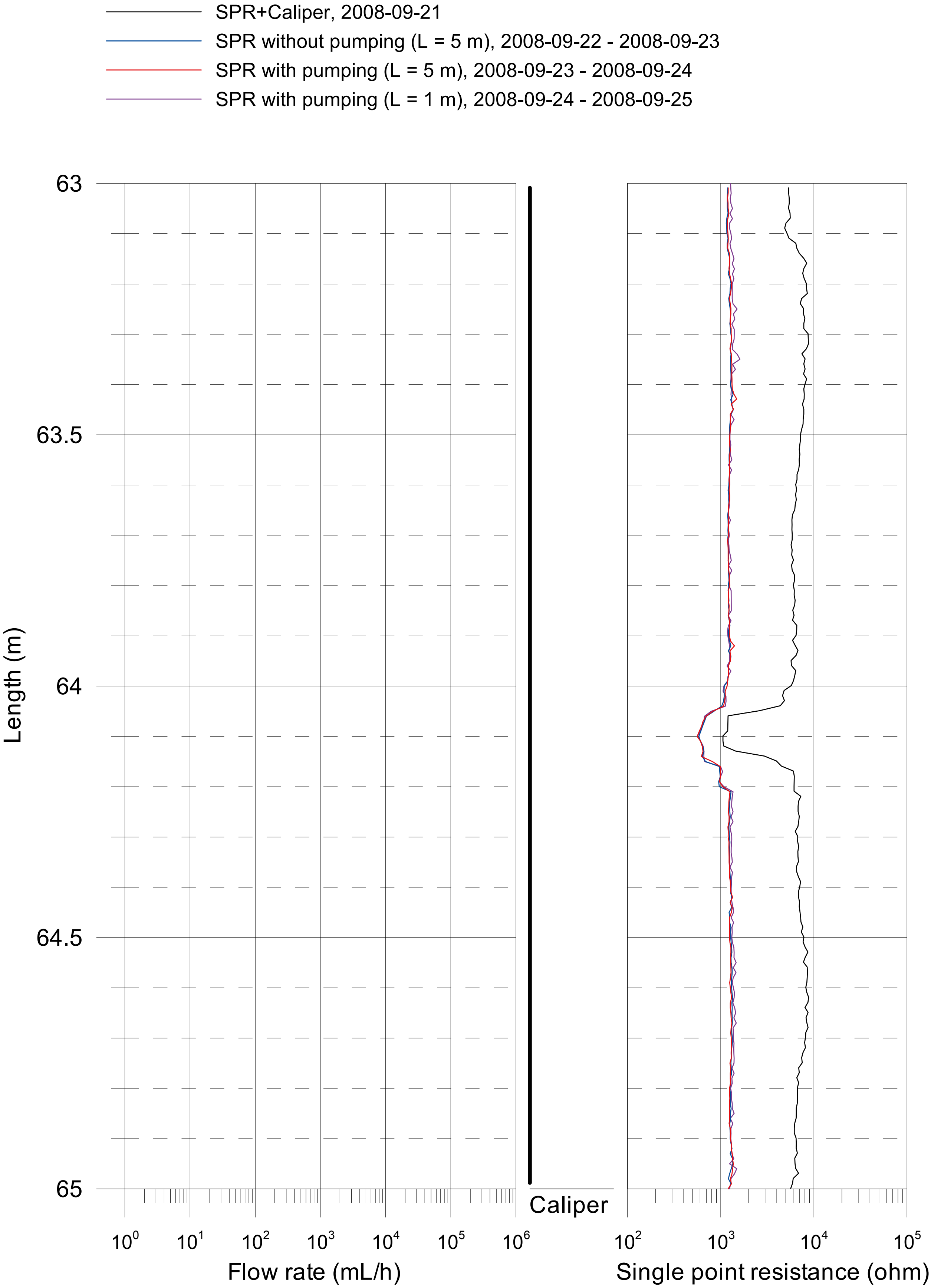
Forsmark, borehole KFR103
SPR and Caliper results after length correction



Forsmark, borehole KFR103
SPR and Caliper results after length correction



Forsmark, borehole KFR103
SPR and Caliper results after length correction



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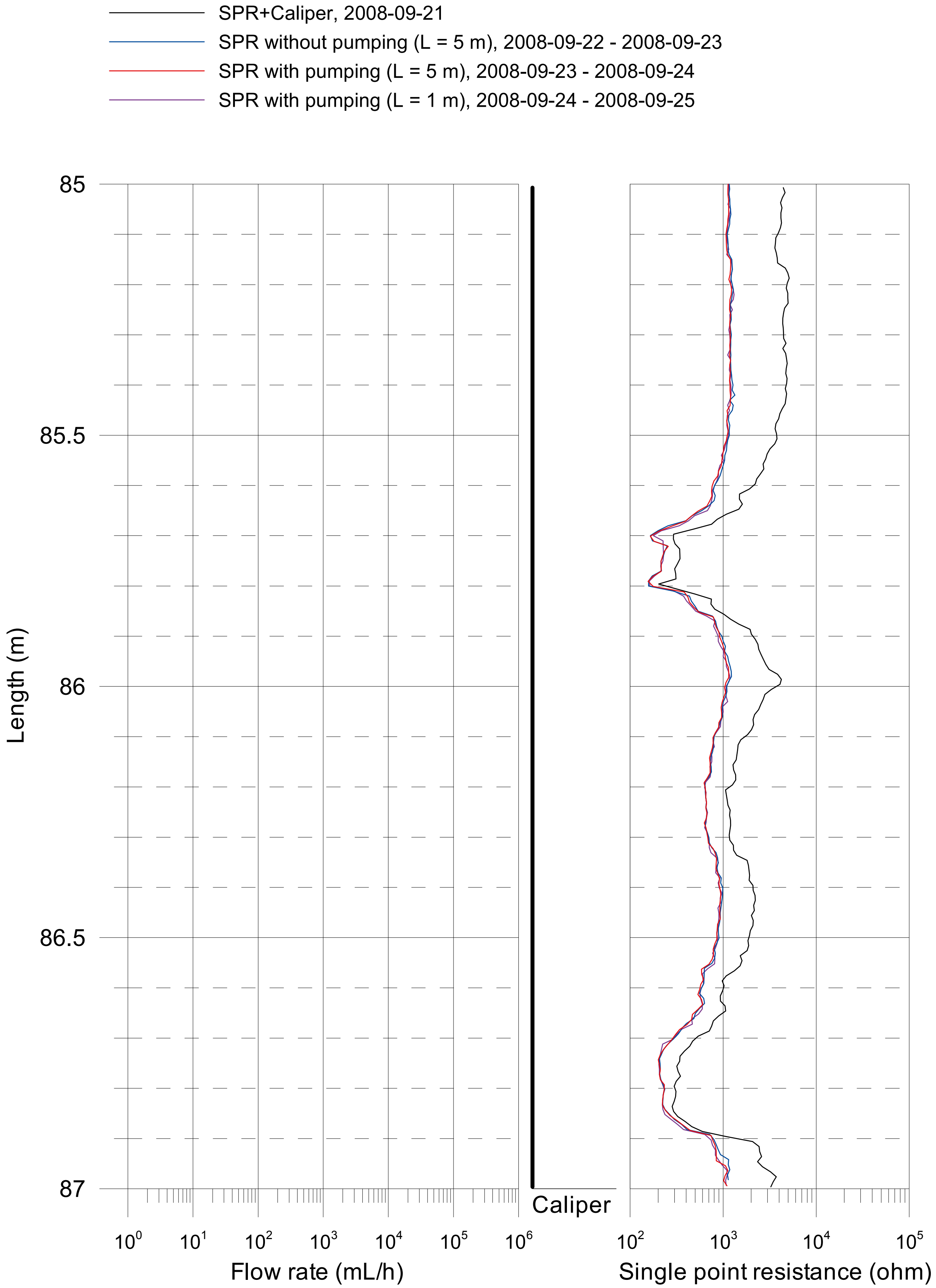
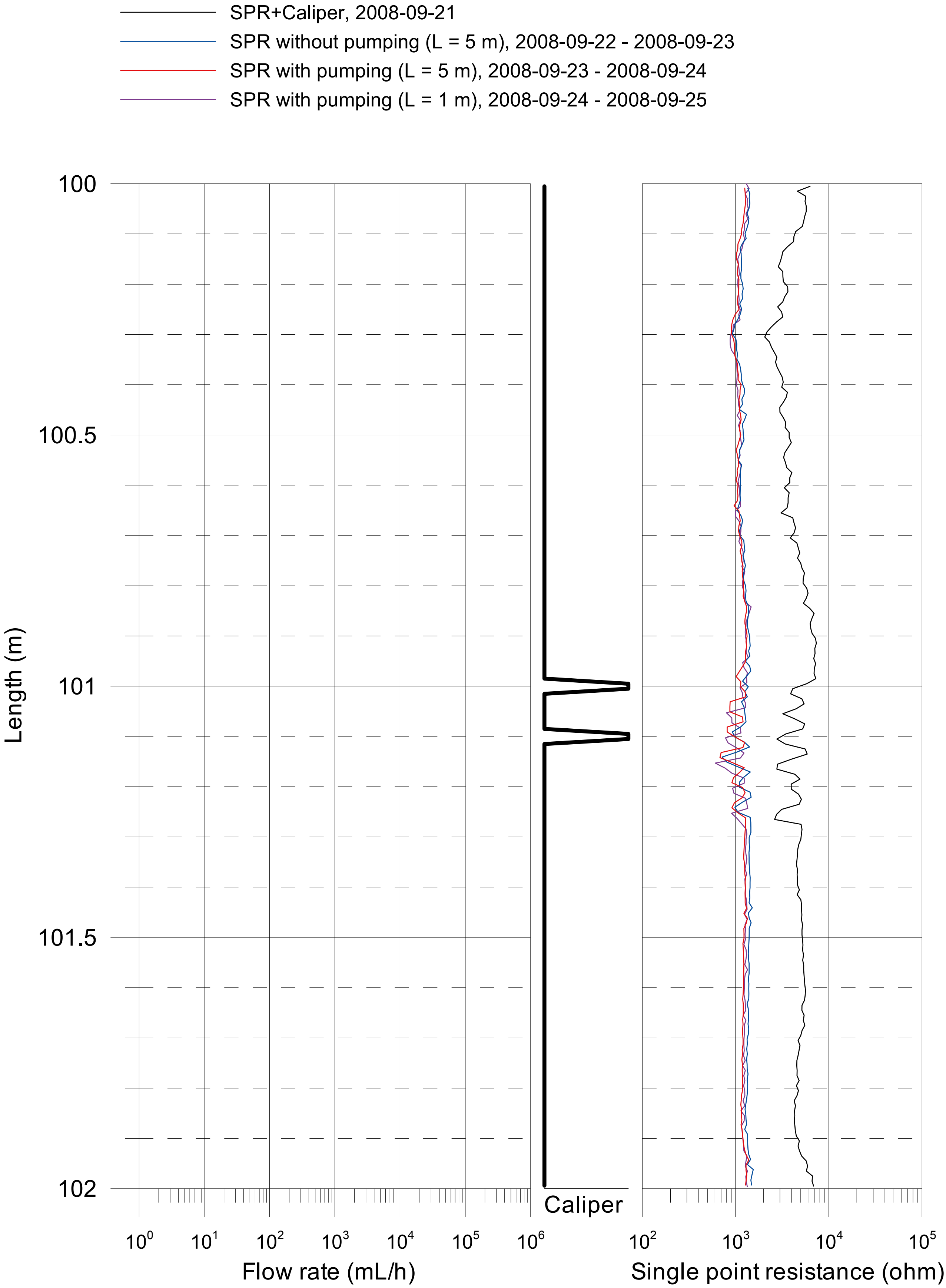
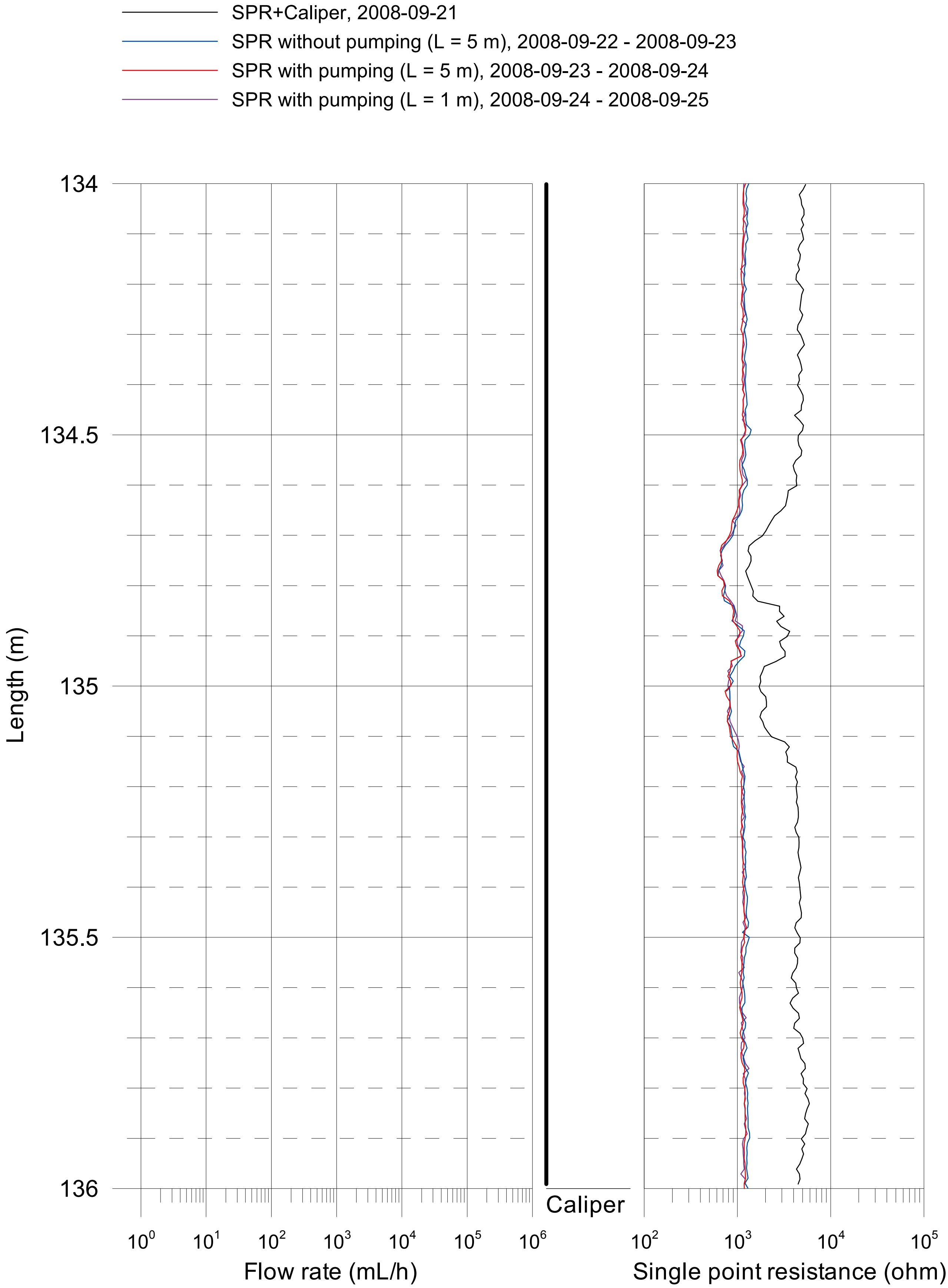
SPR and Caliper results after length correction



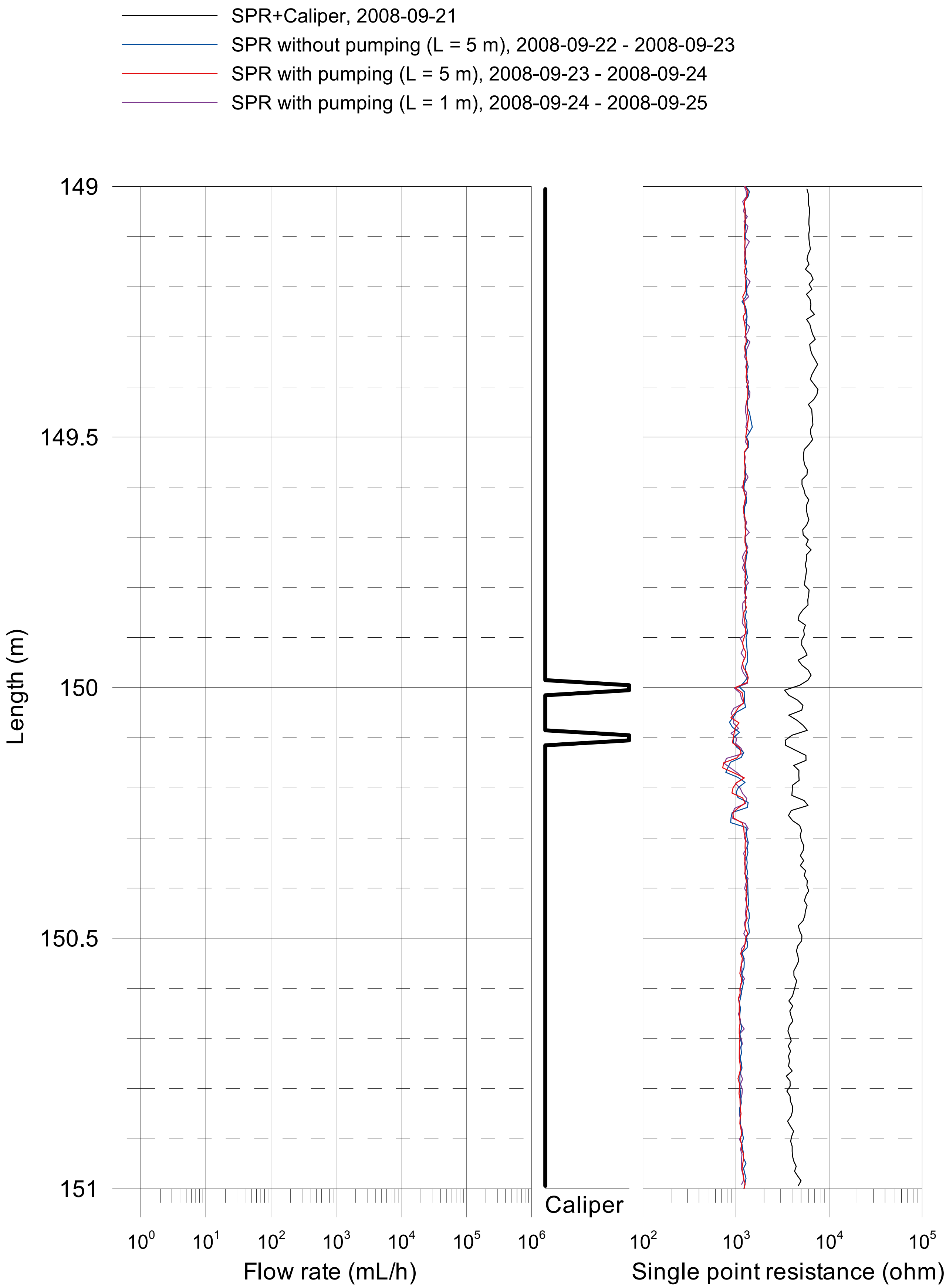
Forsmark, borehole KFR103
SPR and Caliper results after length correction



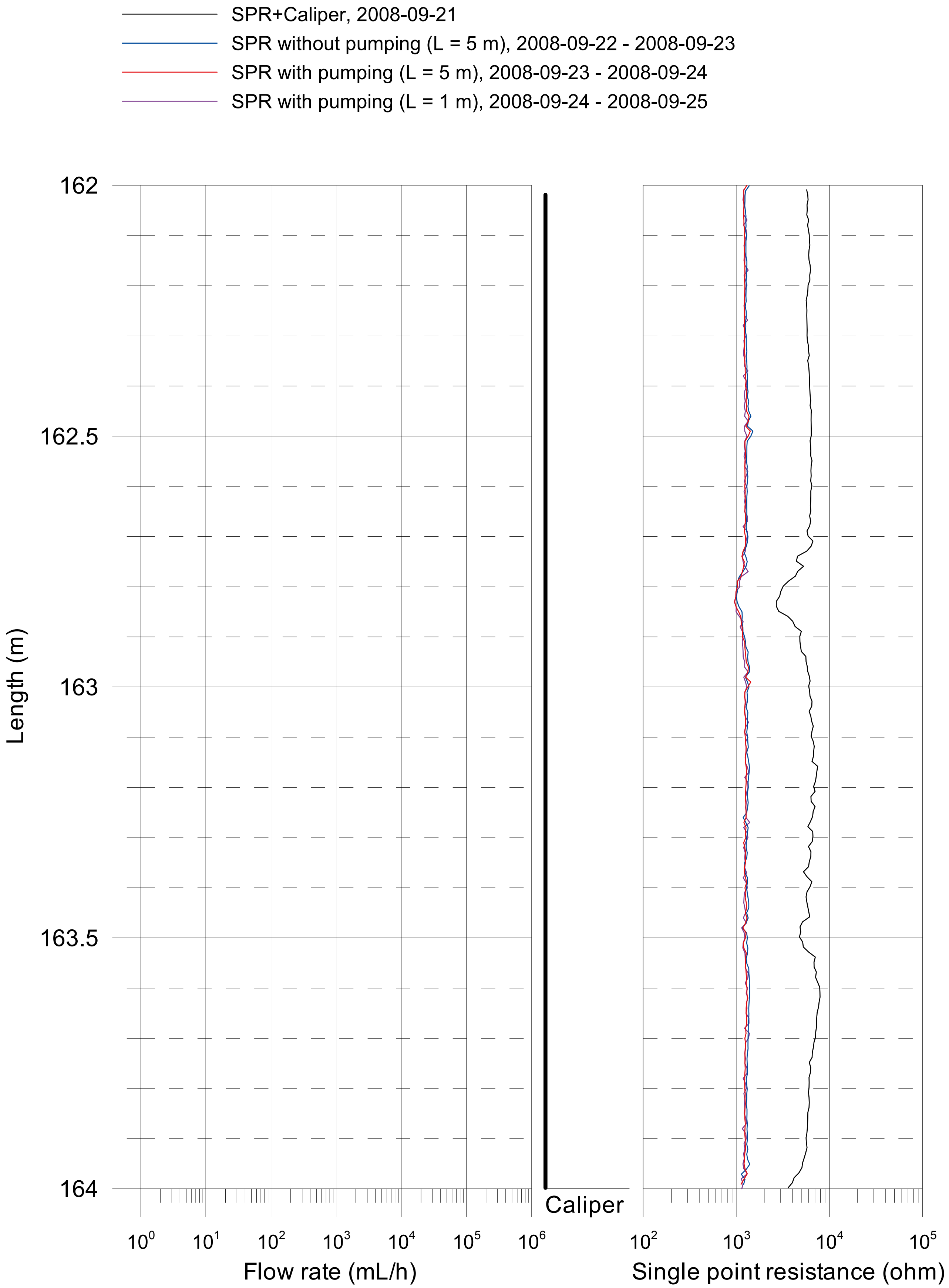
Forsmark, borehole KFR103
SPR and Caliper results after length correction



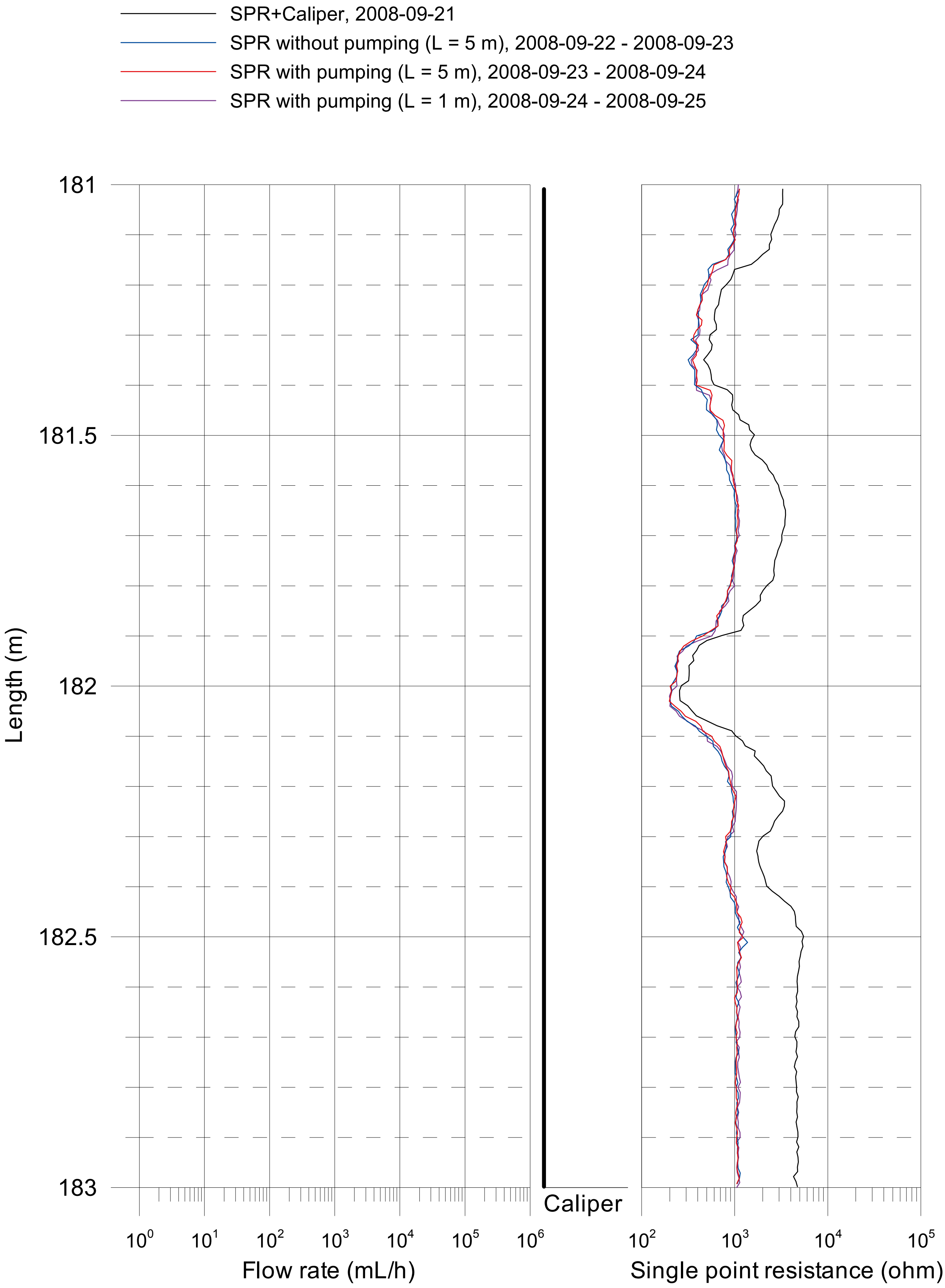
Forsmark, borehole KFR103
SPR and Caliper results after length correction



Forsmark, borehole KFR103
SPR and Caliper results after length correction



Forsmark, borehole KFR103
SPR and Caliper results after length correction



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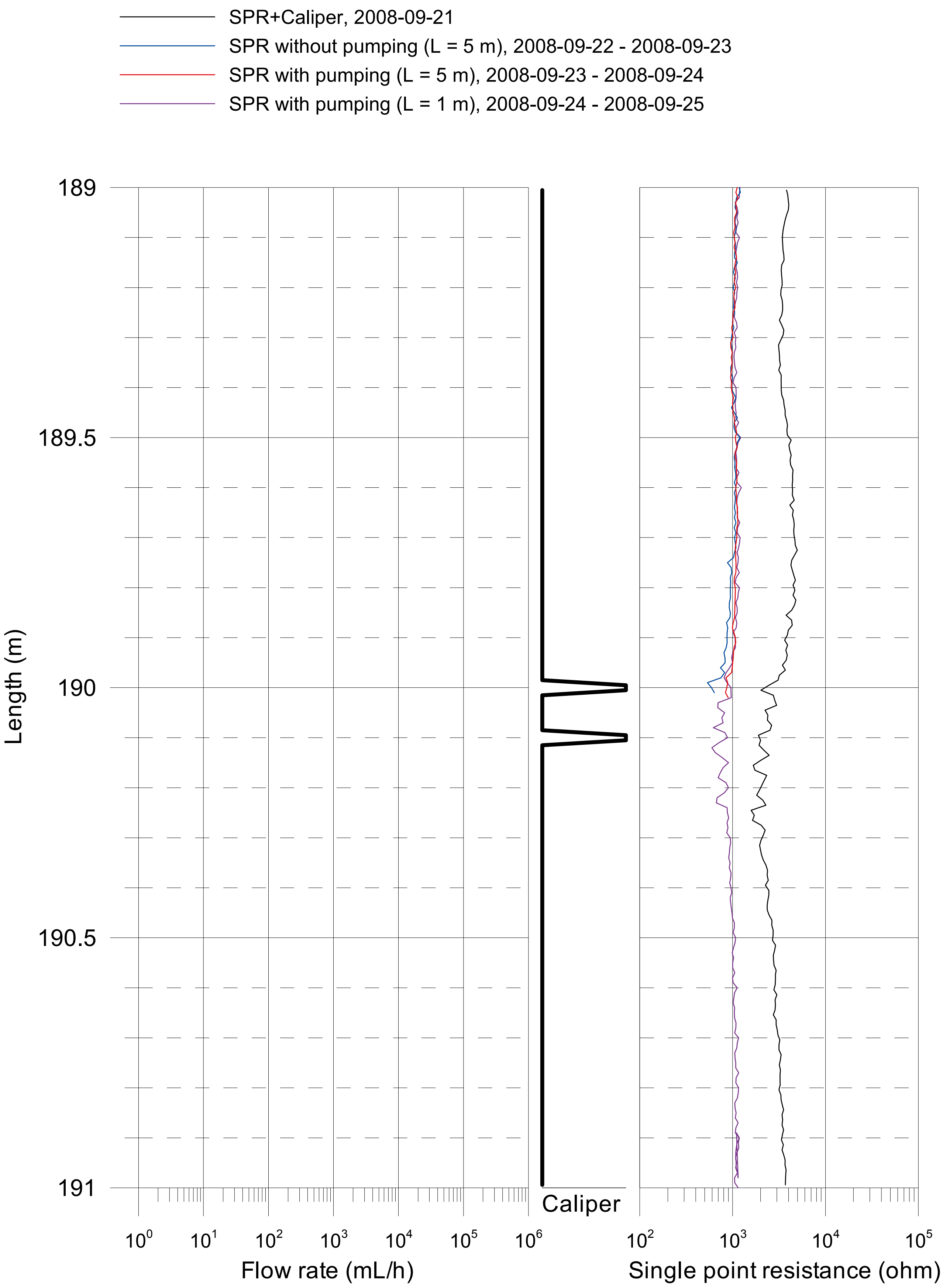
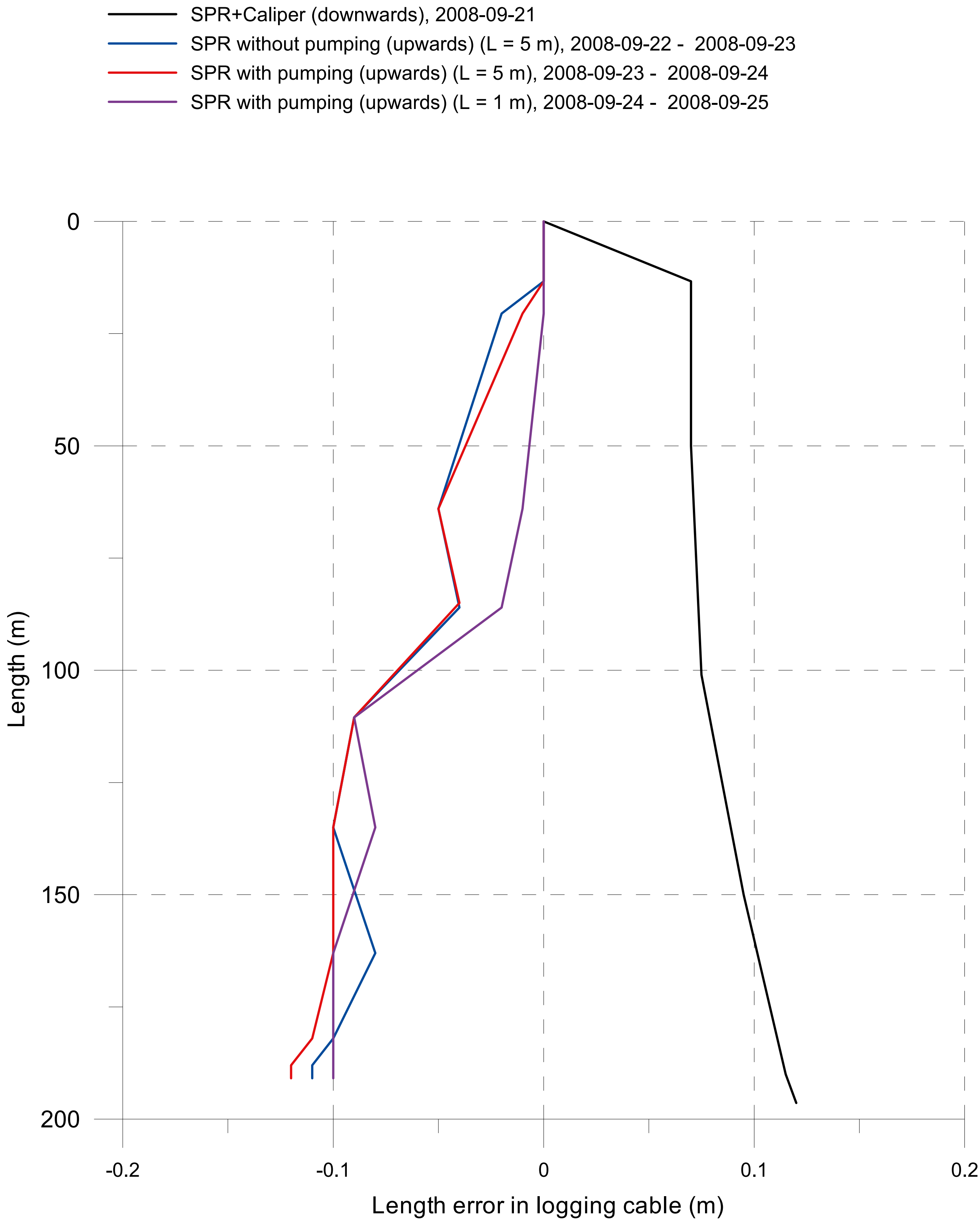
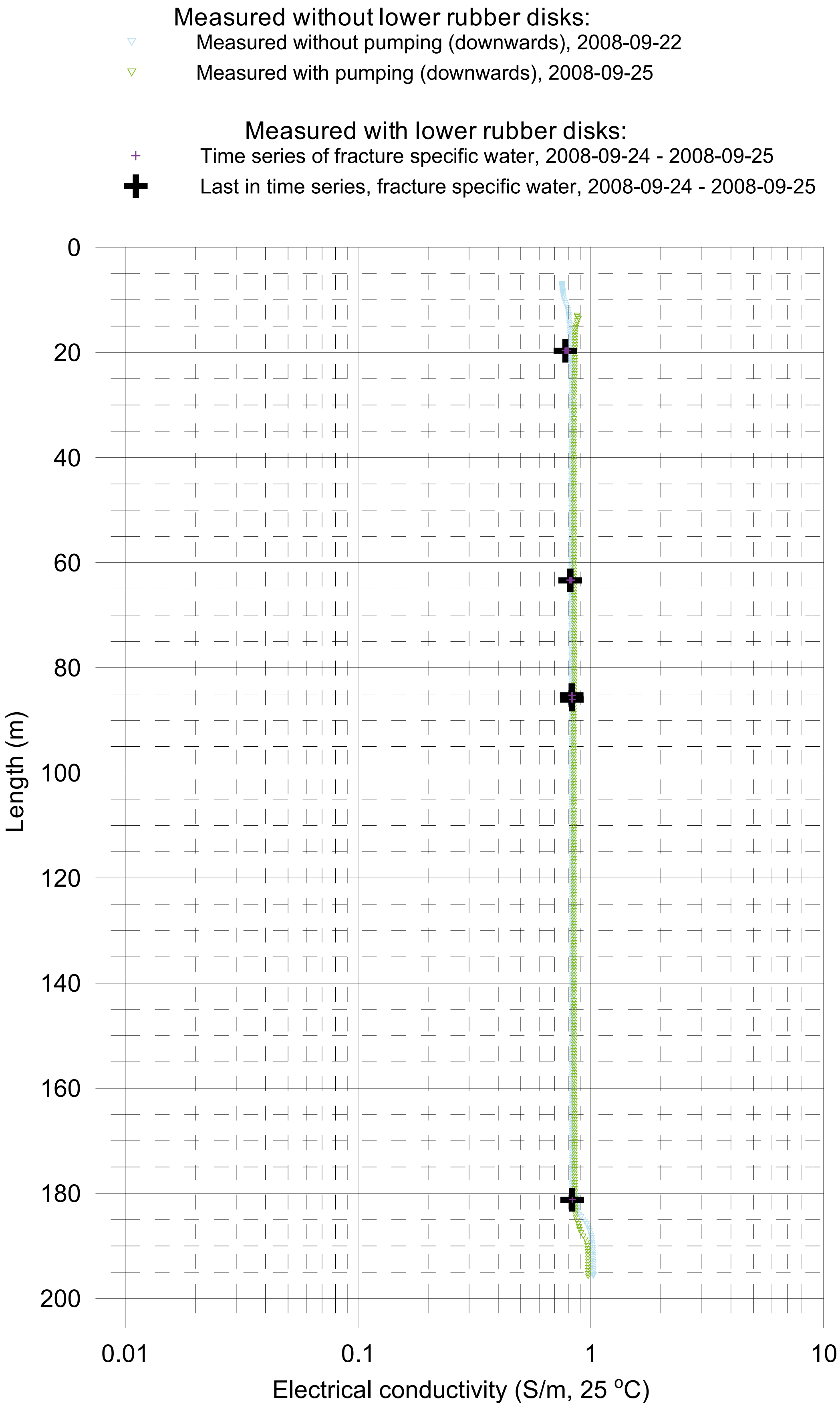
SPR and Caliper results after length correction

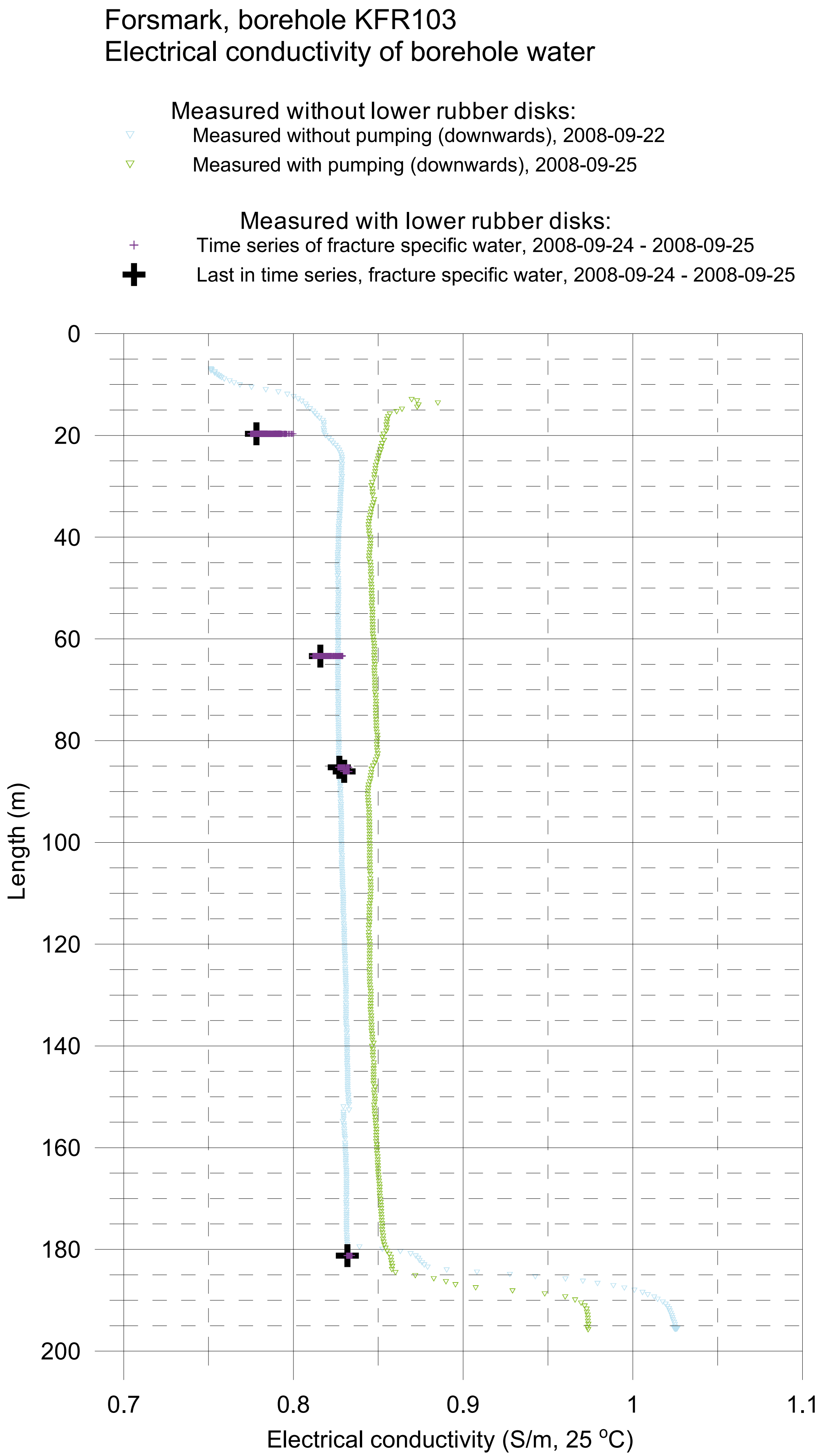


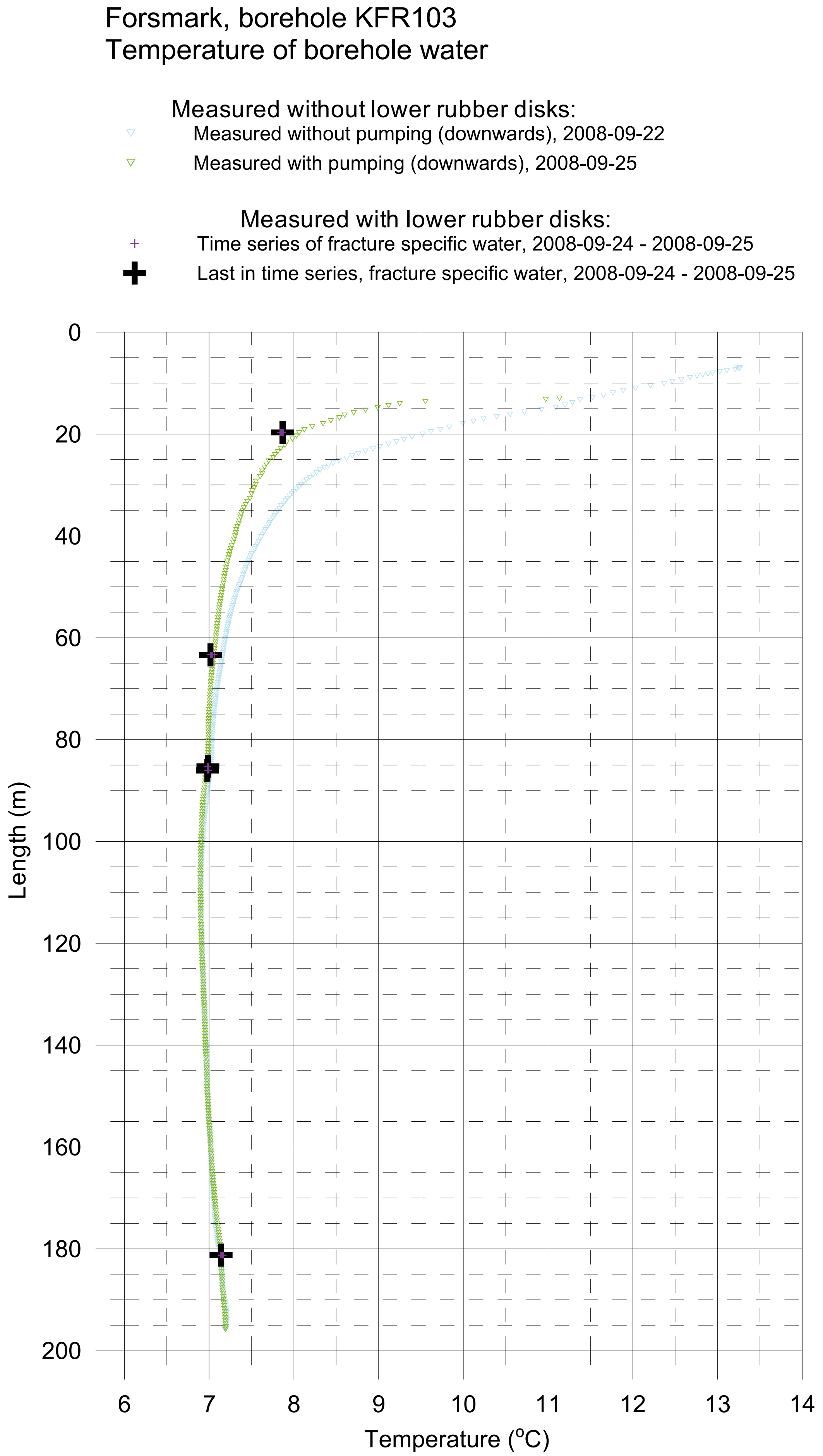
Forsmark, borehole KFR103
Length correction

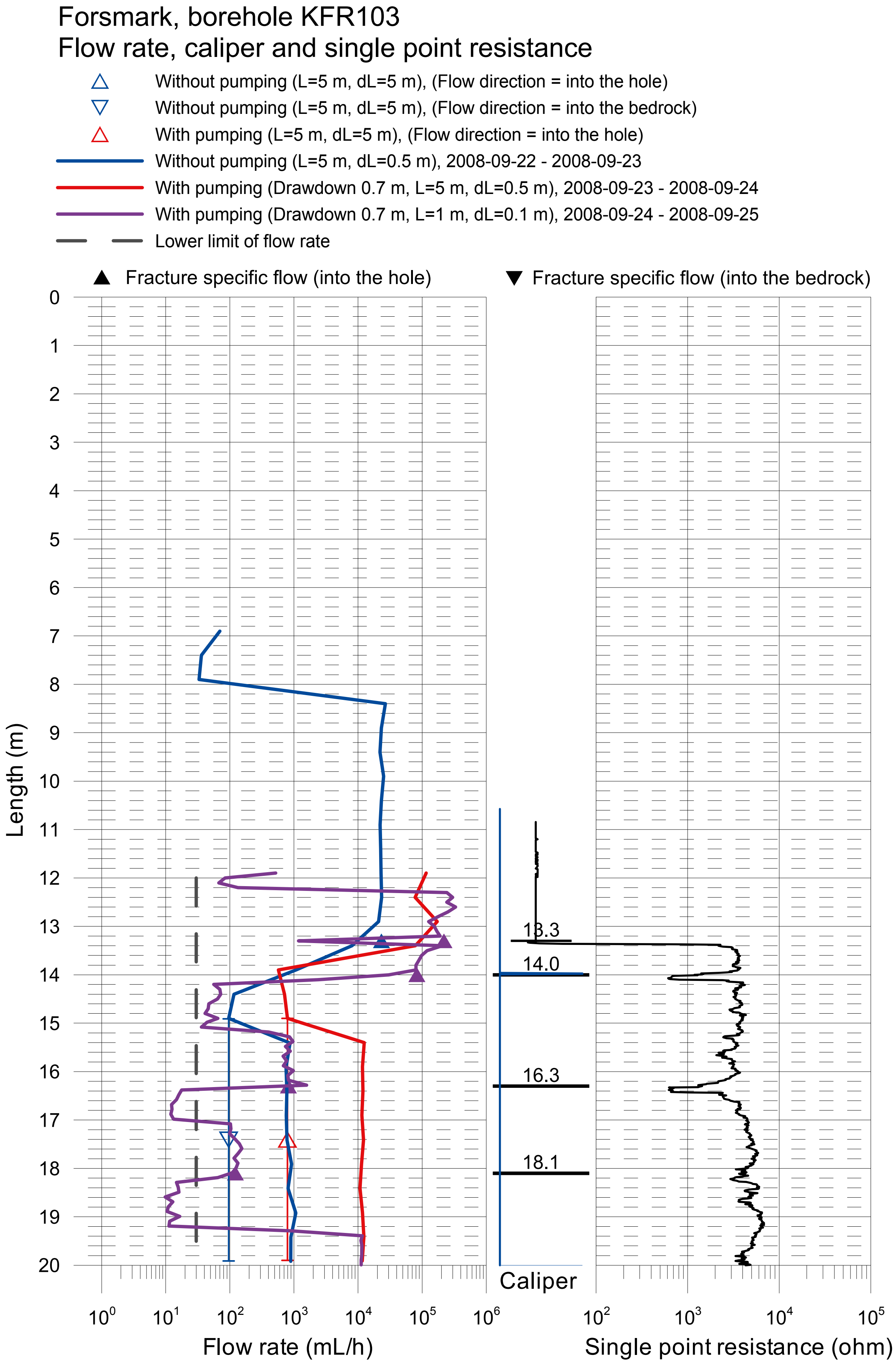


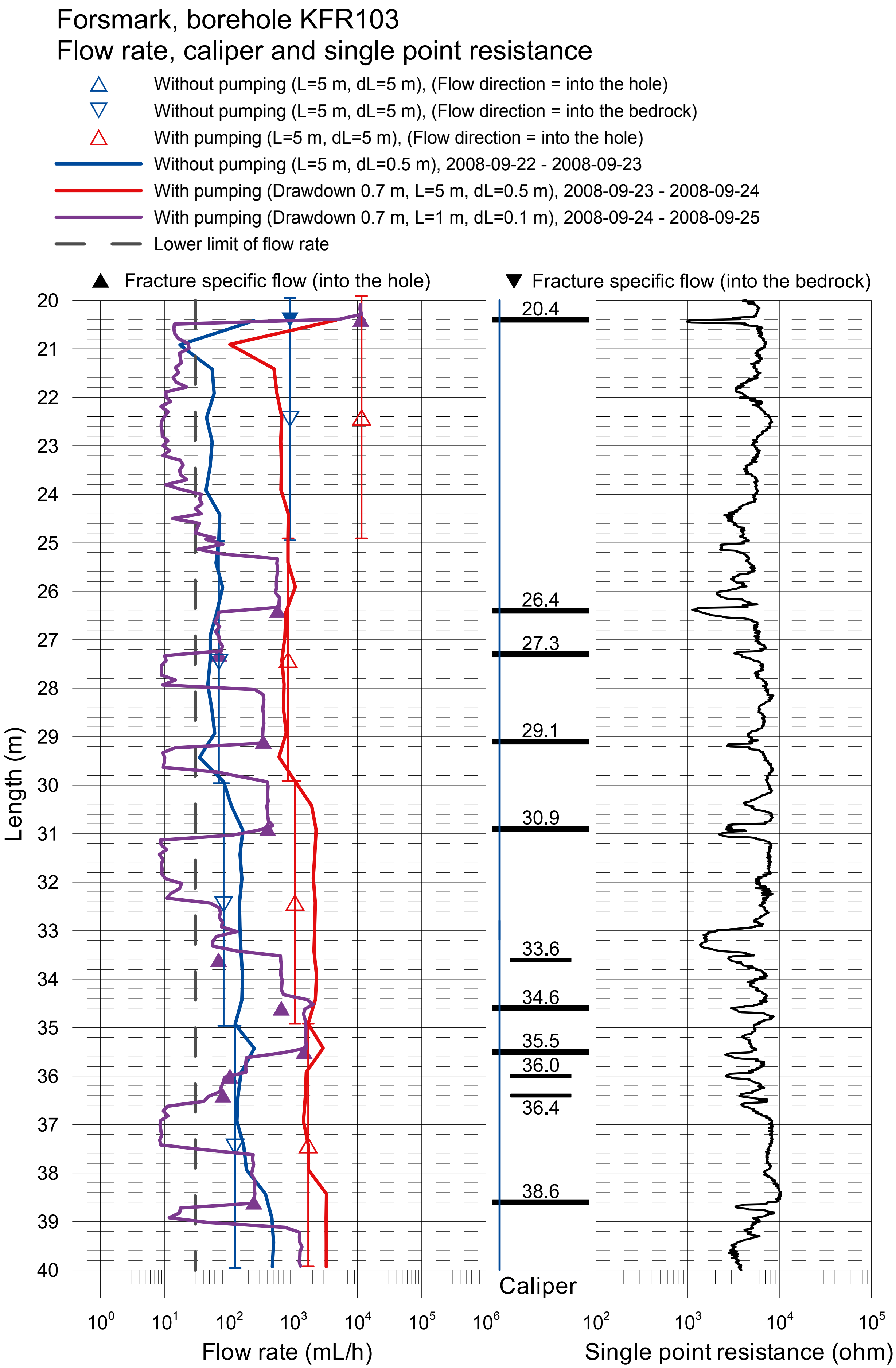
Forsmark, borehole KFR103
Electrical conductivity of borehole water



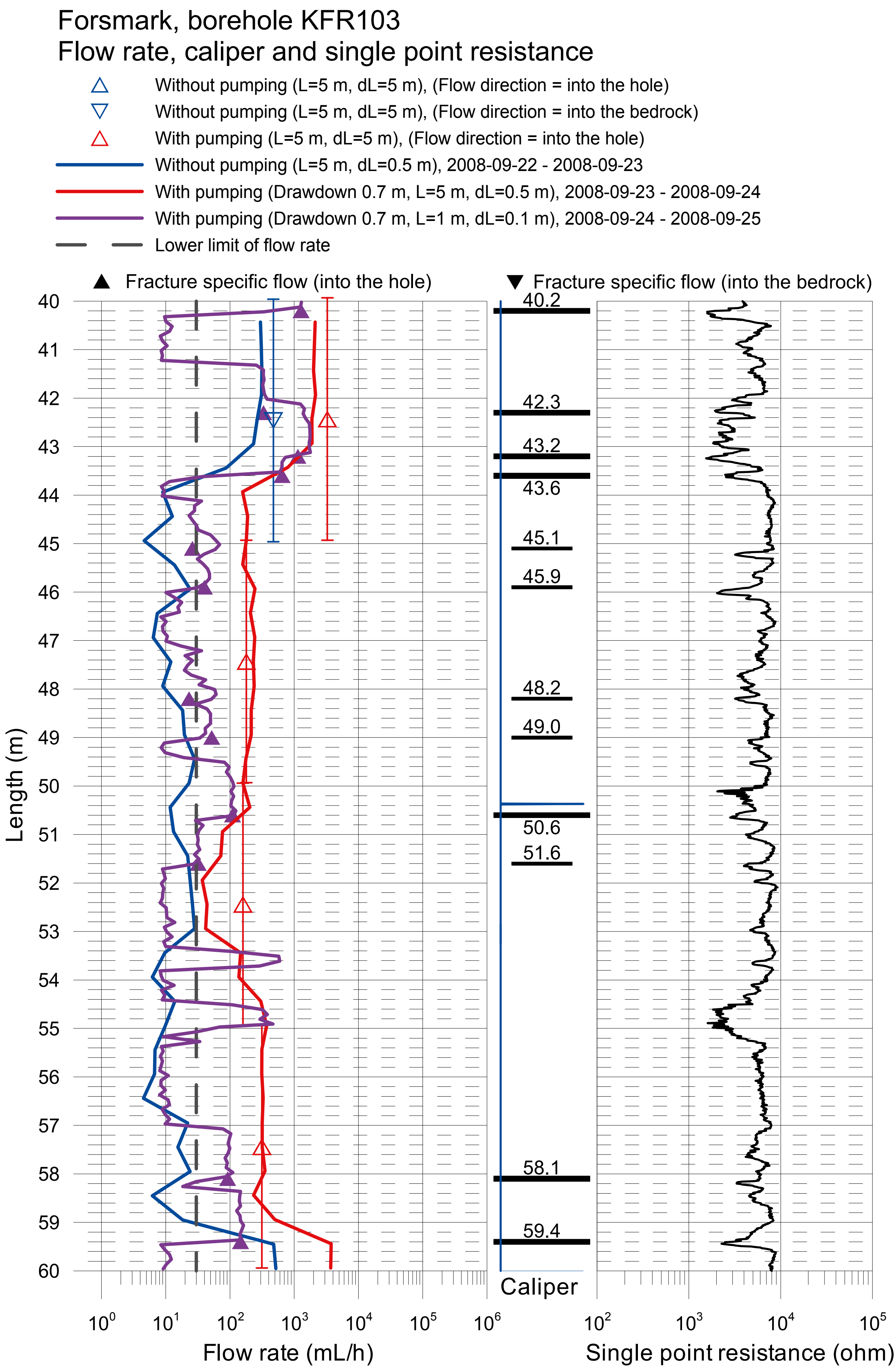

Forsmark, borehole KFR103
Electrical conductivity of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2008-09-22
Measured with pumping (downwards), 2008-09-25
Measured with lower rubber disks:
Time series of fracture specific water, 2008-09-24 - 2008-09-25
Last in time series, fracture specific water, 2008-09-24 - 2008-09-25
Length (m)
0
20
40
60
80
100
120
140
160
180
200
0.7
0.8
0.9
1
1.1
Electrical conductivity (S/m, 25 °C)


Forsmark, borehole KFR103
Temperature of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2008-09-22
Measured with pumping (downwards), 2008-09-25
Measured with lower rubber disks:
Time series of fracture specific water, 2008-09-24 - 2008-09-25
Last in time series, fracture specific water, 2008-09-24 - 2008-09-25
Length (m)
0
20
40
60
80
100
120
140
160
180
200
6
7
8
9
10
11
12
13
14
Temperature (°C)

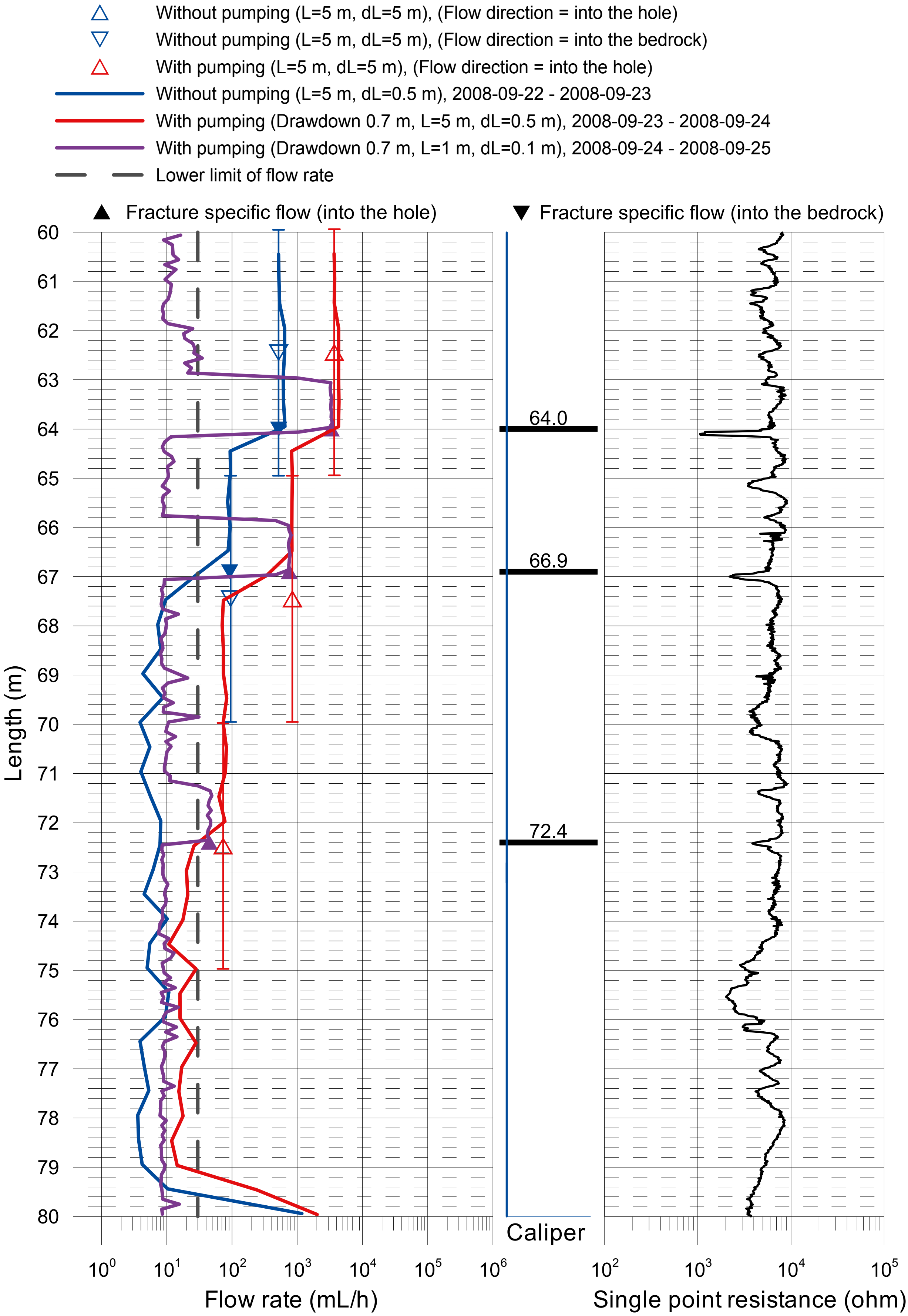

Forsmark, borehole KFR103
Flow rate, caliper and single point resistance
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=0.5 m), 2008-09-22 - 2008-09-23
With pumping (Drawdown 0.7 m, L=5 m, dL=0.5 m), 2008-09-23 - 2008-09-24
With pumping (Drawdown 0.7 m, L=1 m, dL=0.1 m), 2008-09-24 - 2008-09-25
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
13.3
14.0
16.3
18.1
Caliper
Flow rate (mL/h)
Single point resistance (ohm)

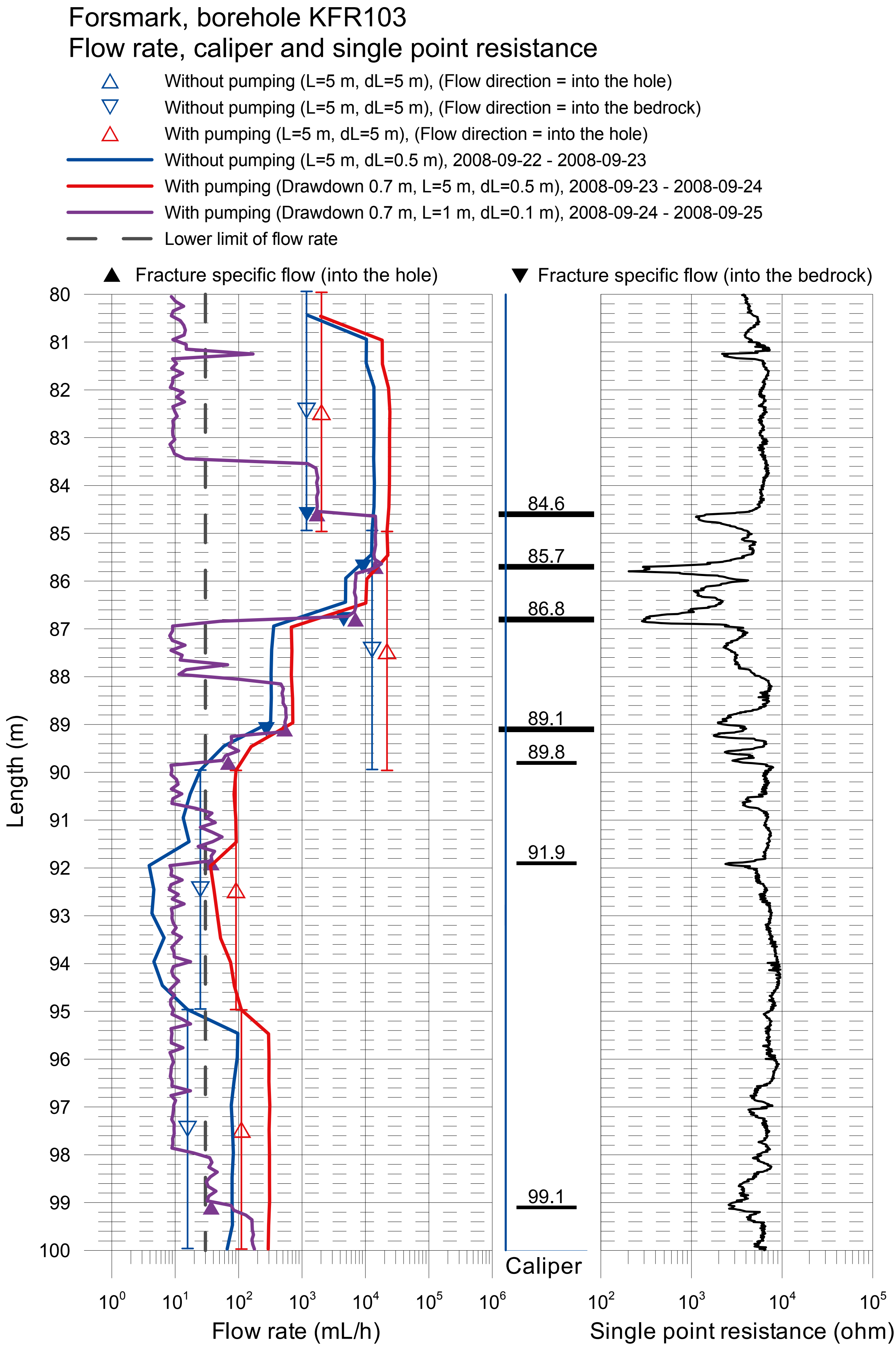


Forsmark, borehole KFR103
Flow rate, caliper and single point resistance
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=0.5 m), 2008-09-22 - 2008-09-23
With pumping (Drawdown 0.7 m, L=5 m, dL=0.5 m), 2008-09-23 - 2008-09-24
With pumping (Drawdown 0.7 m, L=1 m, dL=0.1 m), 2008-09-24 - 2008-09-25
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
20.4
26.4
27.3
29.1
30.9
33.6
34.6
35.5
36.0
36.4
38.6
Caliper
Flow rate (mL/h)
Single point resistance (ohm)

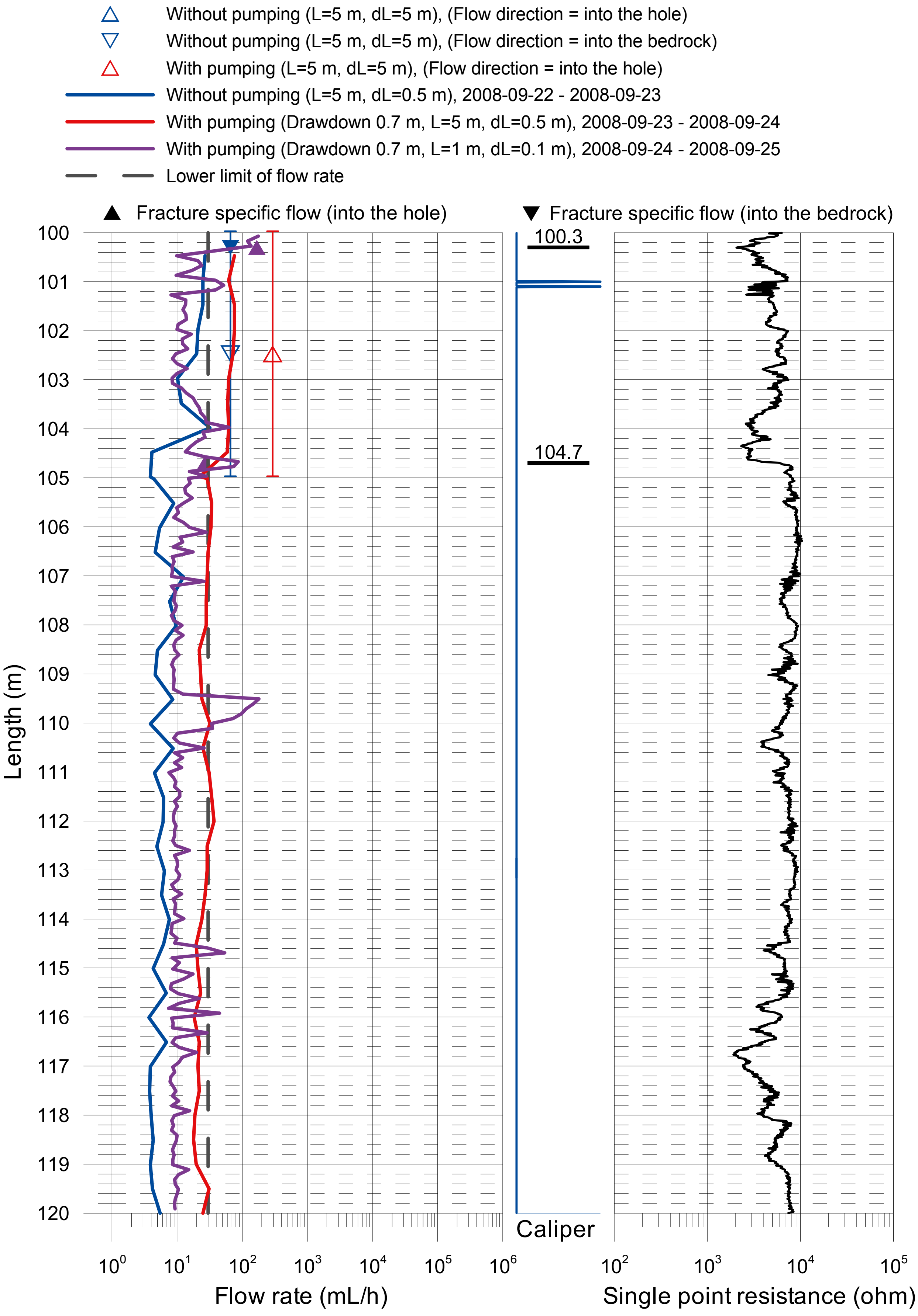

Forsmark, borehole KFR103
Flow rate, caliper and single point resistance
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=0.5 m), 2008-09-22 - 2008-09-23
With pumping (Drawdown 0.7 m, L=5 m, dL=0.5 m), 2008-09-23 - 2008-09-24
With pumping (Drawdown 0.7 m, L=1 m, dL=0.1 m), 2008-09-24 - 2008-09-25
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
40.2
42.3
43.2
43.6
45.1
45.9
48.2
49.0
50.6
51.6
58.1
59.4
Caliper
Flow rate (mL/h)
Single point resistance (ohm)

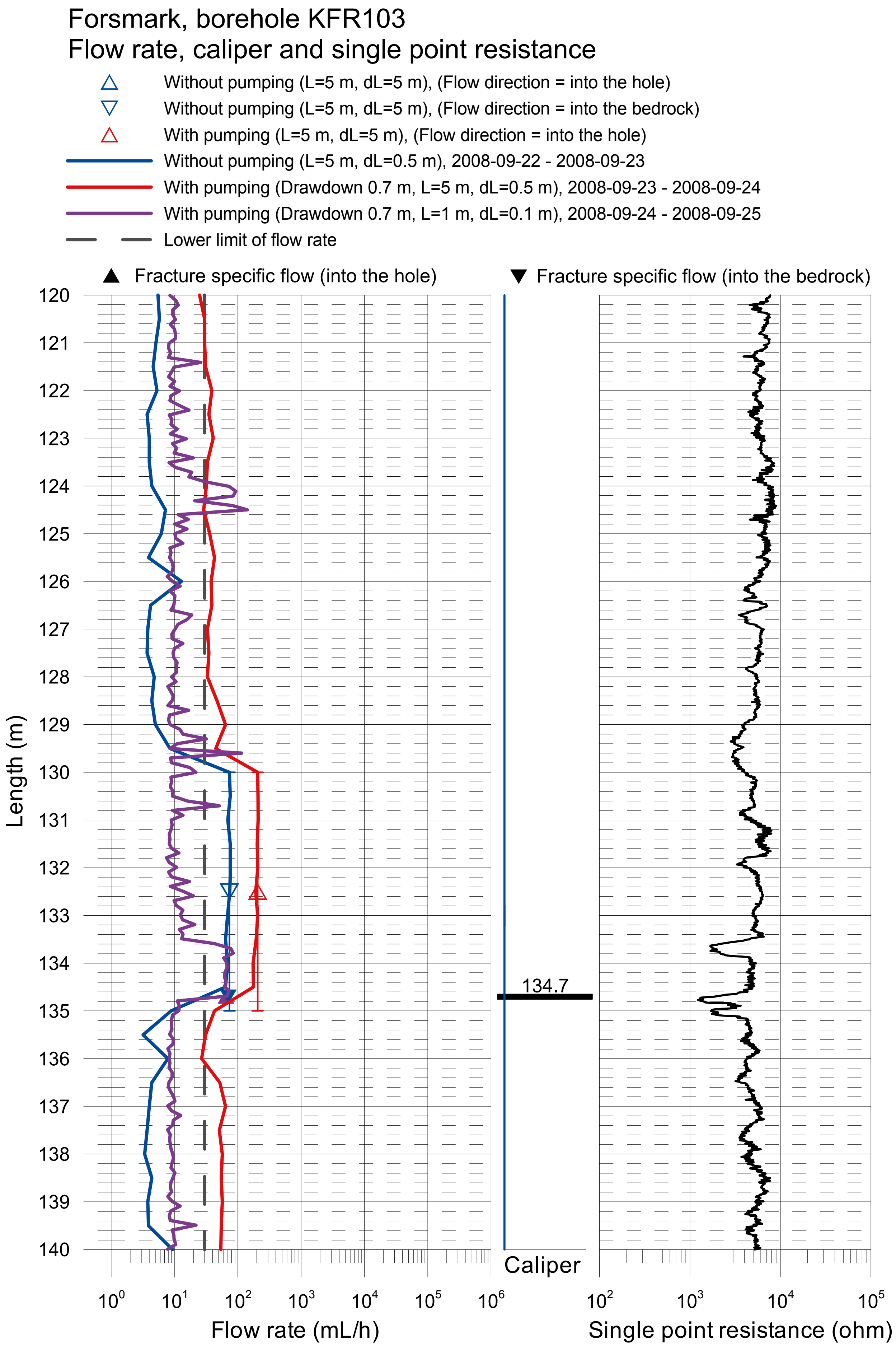
Forsmark, borehole KFR103
Flow rate, caliper and single point resistance




Forsmark, borehole KFR103
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), 2008-09-22 - 2008-09-23
With pumping (Drawdown 0.7 m, L=5 m, dL=0.5 m), 2008-09-23 - 2008-09-24
With pumping (Drawdown 0.7 m, L=1 m, dL=0.1 m), 2008-09-24 - 2008-09-25
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
84.6
85.7
86.8
89.1
89.8
91.9
99.1
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)

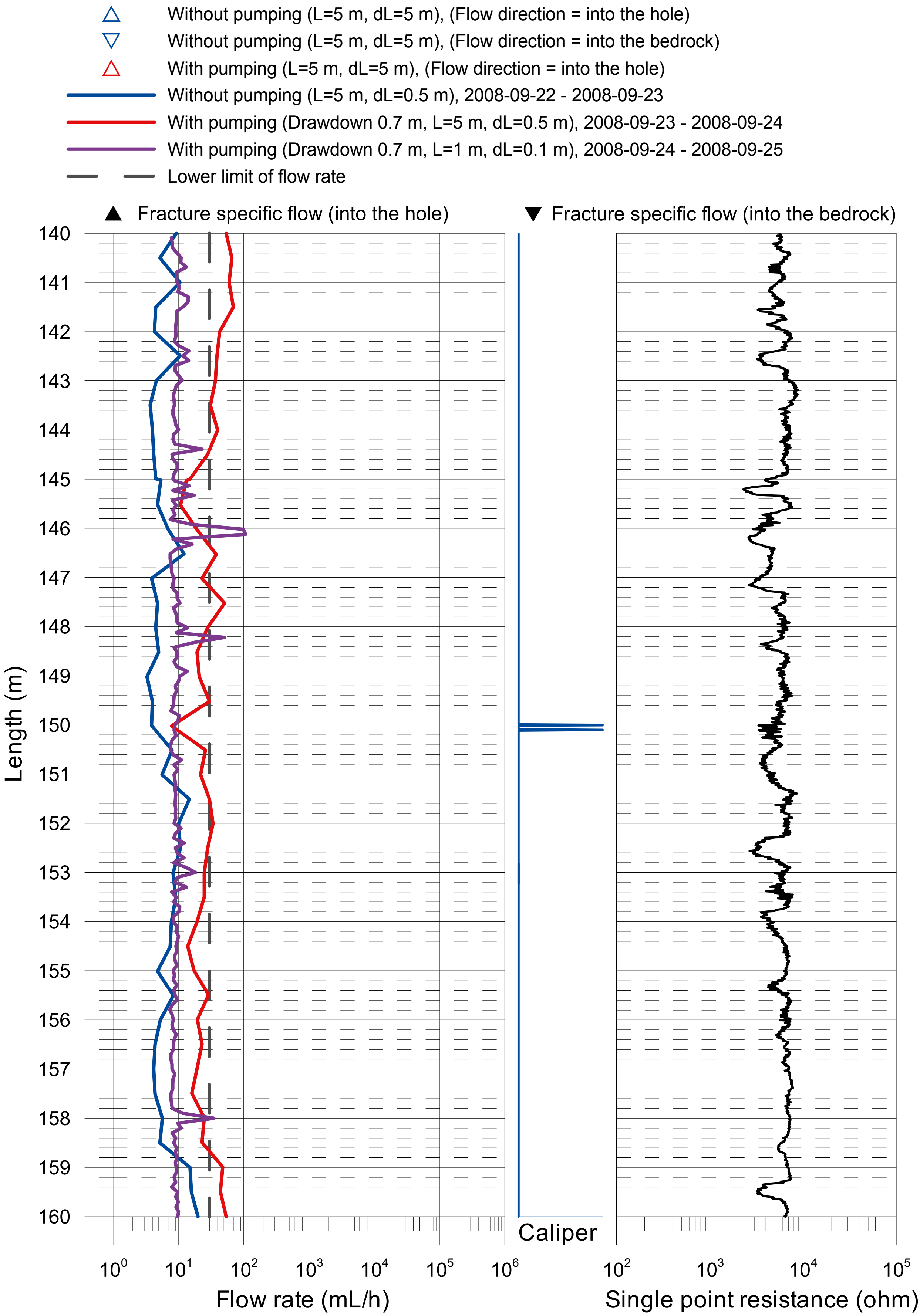
Forsmark, borehole KFR103
Flow rate, caliper and single point resistance

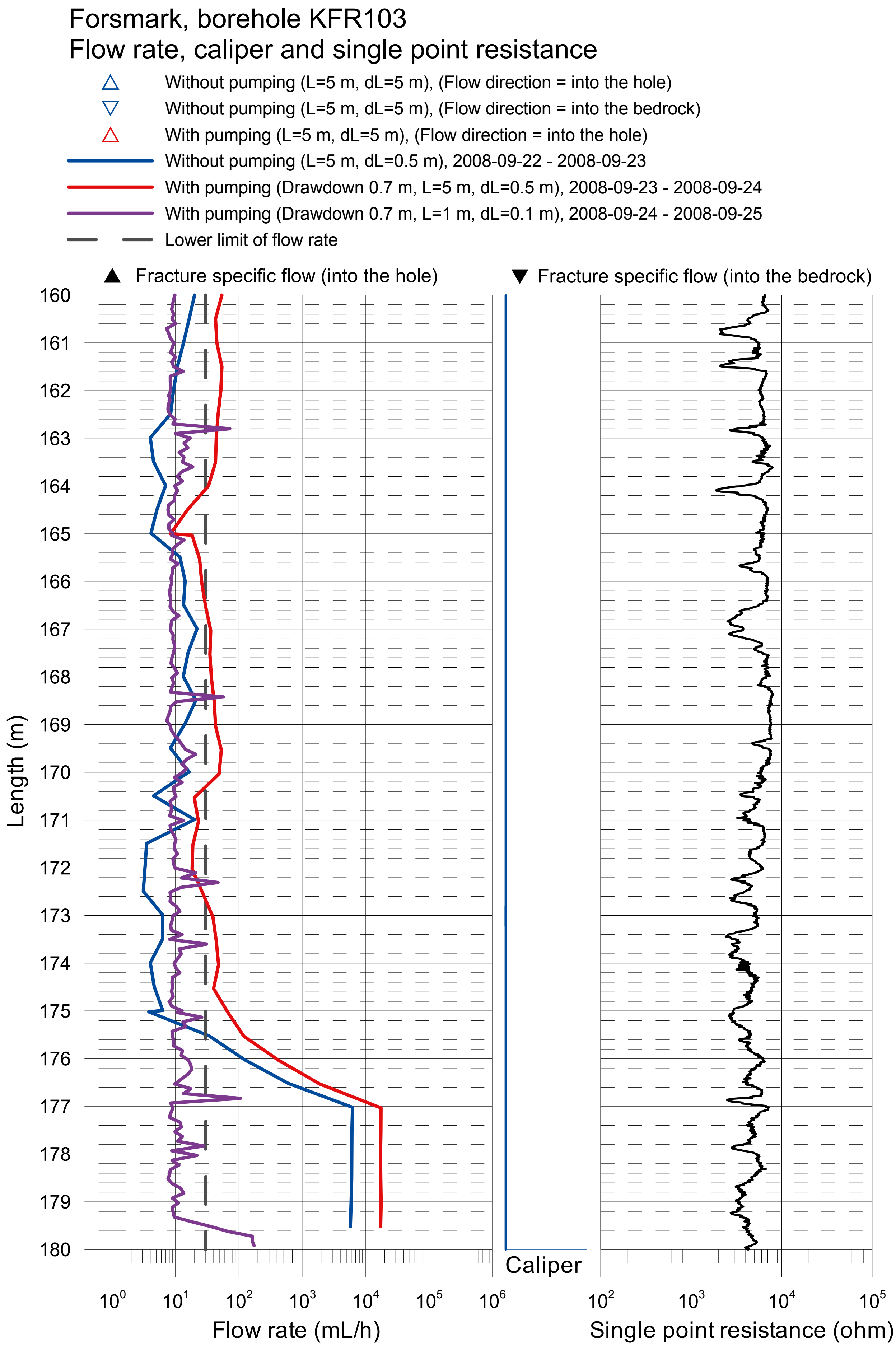




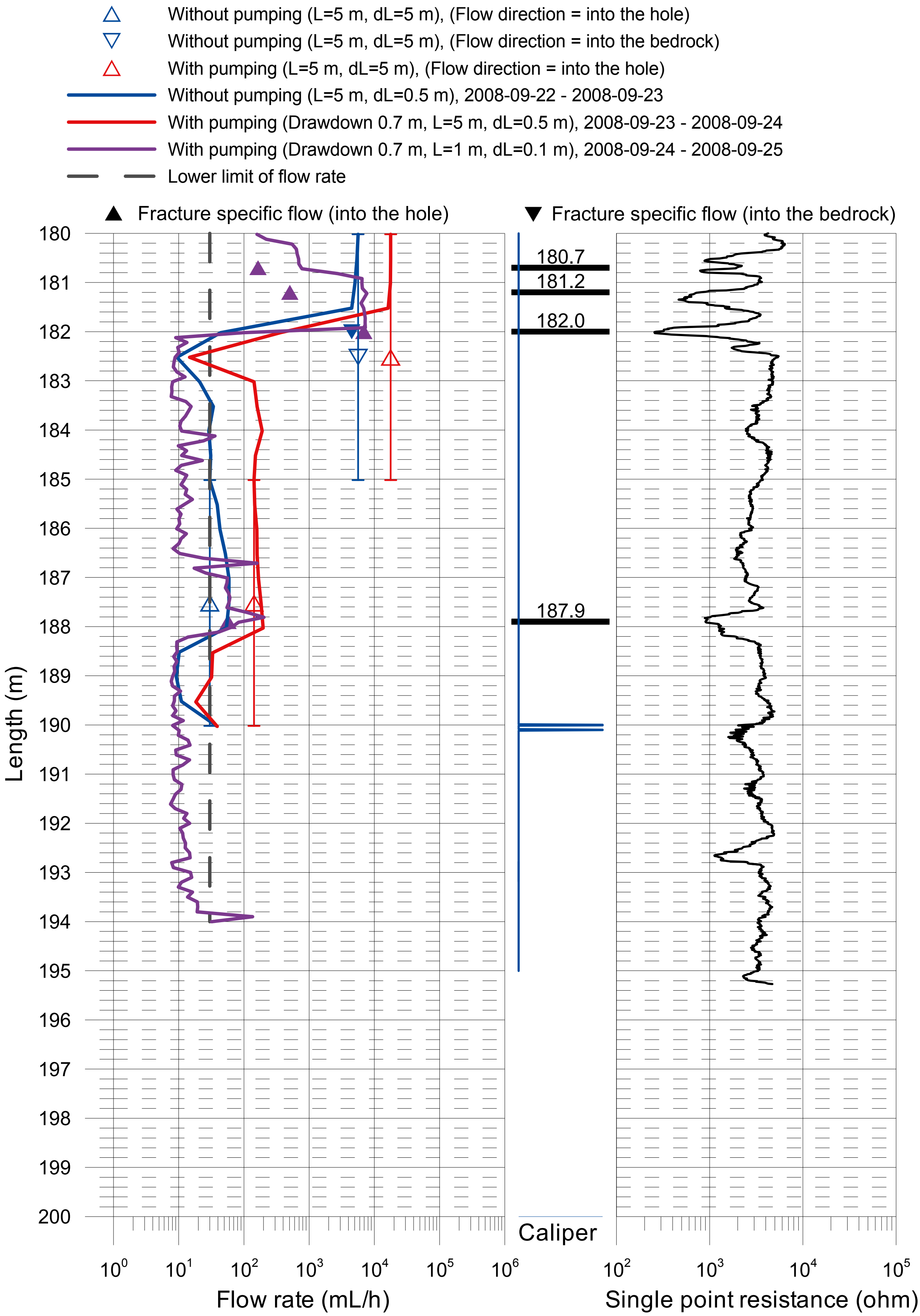
Forsmark, borehole KFR103
Flow rate, caliper and single point resistance
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=0.5 m), 2008-09-22 - 2008-09-23
With pumping (Drawdown 0.7 m, L=5 m, dL=0.5 m), 2008-09-23 - 2008-09-24
With pumping (Drawdown 0.7 m, L=1 m, dL=0.1 m), 2008-09-24 - 2008-09-25
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
134.7
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 KFR103
Flow rate, caliper and single point resistance




Forsmark, borehole KFR103
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), 2008-09-22 - 2008-09-23
With pumping (Drawdown 0.7 m, L=5 m, dL=0.5 m), 2008-09-23 - 2008-09-24
With pumping (Drawdown 0.7 m, L=1 m, dL=0.1 m), 2008-09-24 - 2008-09-25
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179
180
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 KFR103
Flow rate, caliper and single point resistance



Explanations

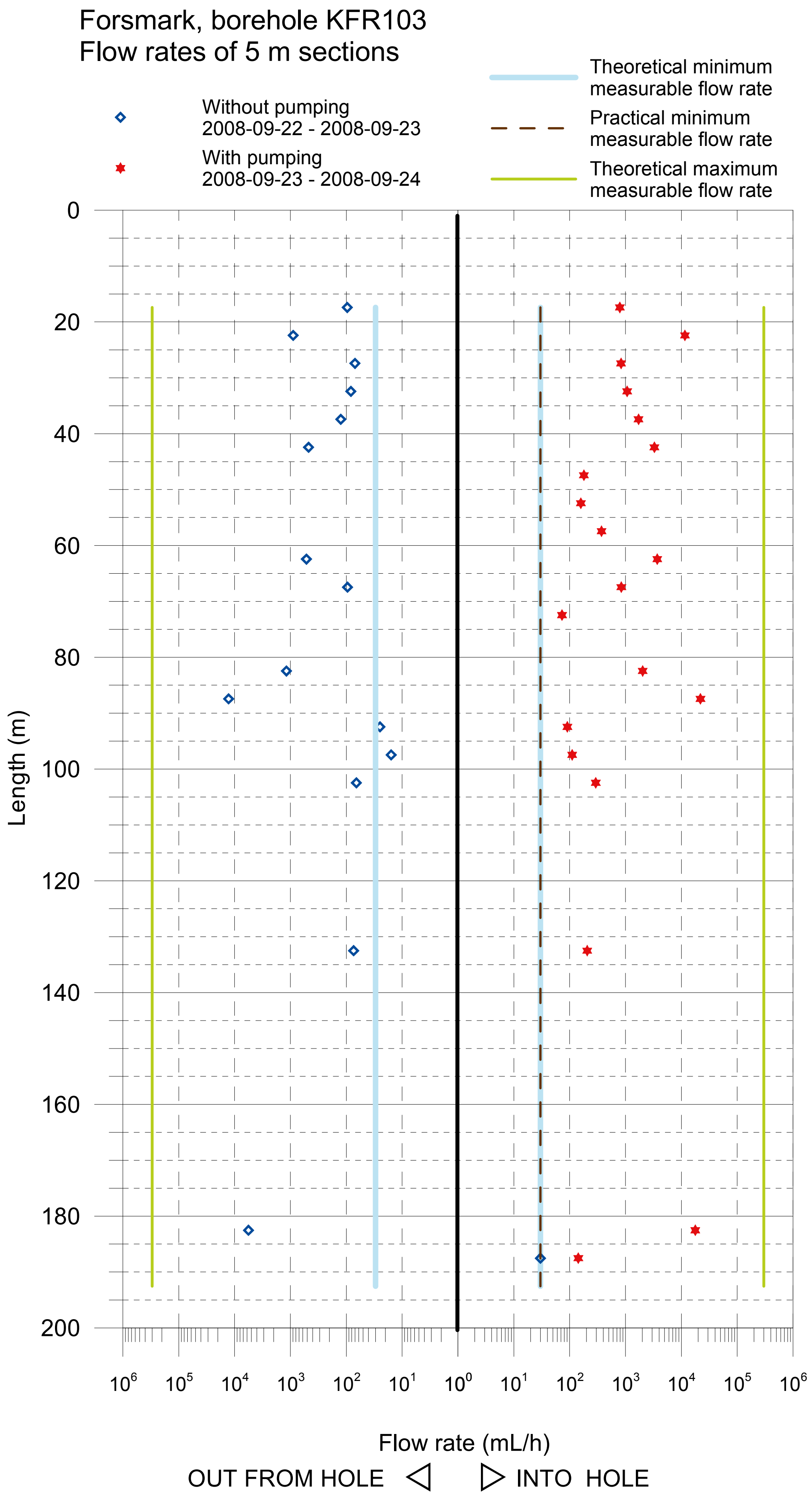
Header	Unit	Explanations
Borehole		ID for borehole.
Secup	m	Length along the borehole for the upper limit of the test section (based on corrected length L).
Seclow	m	Length along the borehole for the lower limit of the test section (based on corrected length L).
L	m	Corrected length along borehole based 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).

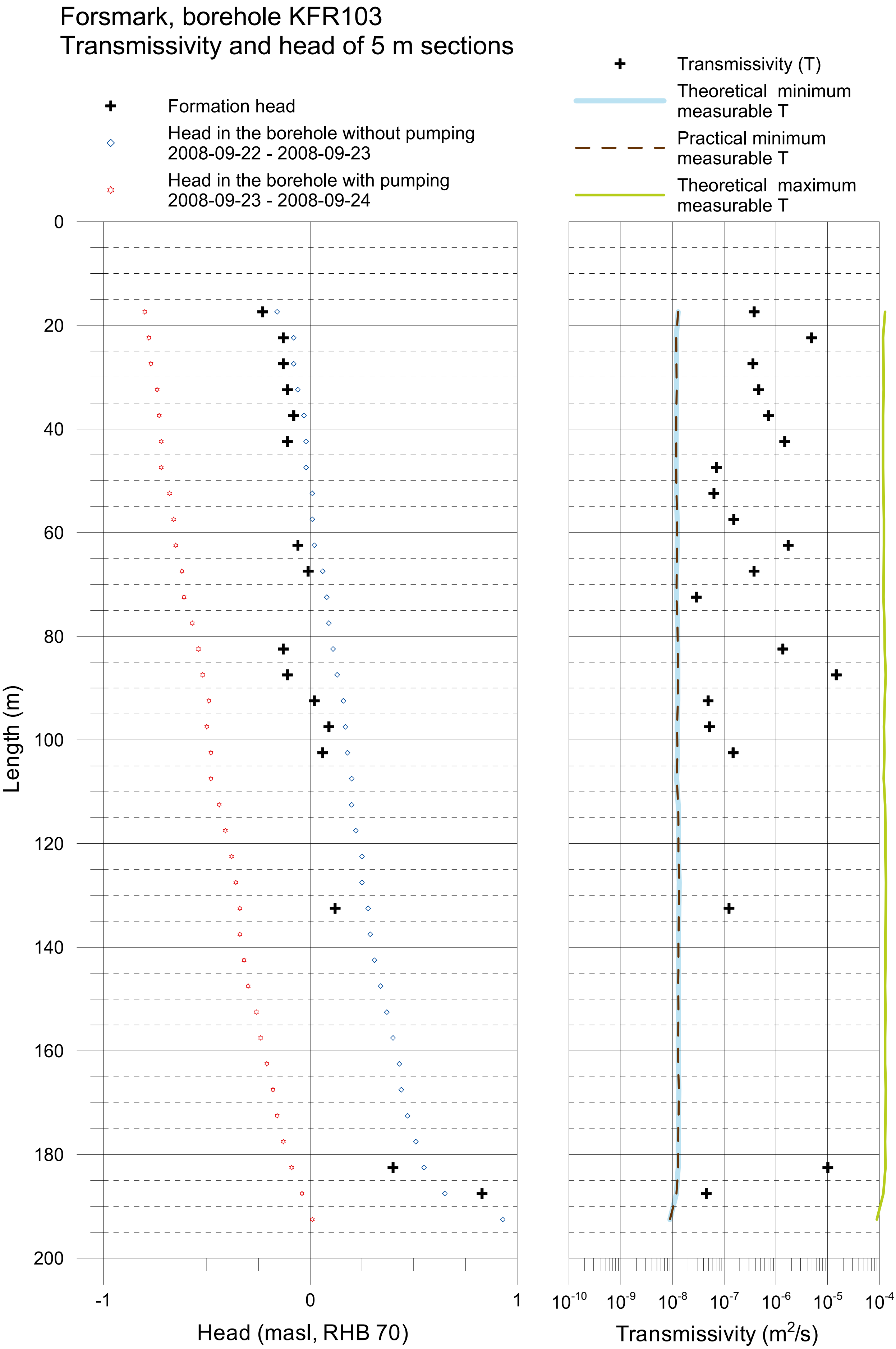
Results of sequential flow logging

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)	TD-measl$_{LT}$ (m^2/s)	TD- measl$_{LP}$ (m^2/s)	TD- measl$_U$ (m^2/s)	Comments
KFR103	9.90	14.90	5	–	–	–	–	–	–	–	–	–	–	**
KFR103	14.90	19.90	5	–2.67E–08	–0.16	2.19E–07	–0.80	3.8E–07	–0.2	30	1.3E–08	1.3E–08	1.3E–04	
KFR103	19.92	24.92	5	–2.48E–07	–0.08	3.22E–06	–0.78	4.9E–06	–0.1	30	1.2E–08	1.2E–08	1.2E–04	
KFR103	24.92	29.92	5	–1.94E–08	–0.08	2.31E–07	–0.77	3.6E–07	–0.1	30	1.2E–08	1.2E–08	1.2E–04	
KFR103	29.93	34.93	5	–2.31E–08	–0.06	2.97E–07	–0.74	4.7E–07	–0.1	30	1.2E–08	1.2E–08	1.2E–04	
KFR103	34.93	39.93	5	–3.47E–08	–0.03	4.75E–07	–0.73	7.2E–07	–0.1	30	1.2E–08	1.2E–08	1.2E–04	
KFR103	39.93	44.93	5	–1.31E–07	–0.02	9.14E–07	–0.72	1.5E–06	–0.1	30	1.2E–08	1.2E–08	1.2E–04	
KFR103	44.94	49.94	5	–	–0.02	5.00E–08	–0.72	7.1E–08	–	30	1.2E–08	1.2E–08	1.2E–04	
KFR103	49.94	54.94	5	–	0.01	4.42E–08	–0.68	6.3E–08	–	30	1.2E–08	1.2E–08	1.2E–04	
KFR103	54.94	59.94	5	–	0.01	8.72E–08	–0.66	1.5E–07	–	30	1.2E–08	1.2E–08	1.2E–04	
KFR103	59.95	64.95	5	–1.44E–07	0.02	1.03E–06	–0.65	1.7E–06	–0.1	30	1.2E–08	1.2E–08	1.2E–04	
KFR103	64.95	69.95	5	–2.64E–08	0.06	2.34E–07	–0.62	3.8E–07	0.0	30	1.2E–08	1.2E–08	1.2E–04	
KFR103	69.97	74.97	5	–	0.08	2.03E–08	–0.61	2.9E–08	–	30	1.2E–08	1.2E–08	1.2E–04	
KFR103	74.96	79.96	5	–	0.09	–	–0.57	–	–	30	1.3E–08	1.3E–08	1.3E–04	
KFR103	79.95	84.95	5	–3.28E–07	0.11	5.64E–07	–0.54	1.4E–06	–0.1	30	1.3E–08	1.3E–08	1.3E–04	
KFR103	84.95	89.95	5	–3.56E–06	0.13	6.11E–06	–0.52	1.5E–05	–0.1	30	1.3E–08	1.3E–08	1.3E–04	
KFR103	89.96	94.96	5	–6.94E–09	0.16	2.53E–08	–0.49	4.9E–08	0.0	30	1.3E–08	1.3E–08	1.3E–04	*
KFR103	94.97	99.97	5	–4.36E–09	0.17	3.08E–08	–0.50	5.2E–08	0.1	30	1.2E–08	1.2E–08	1.2E–04	*
KFR103	99.97	104.97	5	–1.83E–08	0.18	8.14E–08	–0.48	1.5E–07	0.1	30	1.3E–08	1.3E–08	1.3E–04	
KFR103	104.98	109.98	5	–	0.20	–	–0.48	–	–	30	1.2E–08	1.2E–08	1.2E–04	
KFR103	110.02	115.02	5	–	0.20	–	–0.44	–	–	30	1.3E–08	1.3E–08	1.3E–04	
KFR103	115.01	120.01	5	–	0.22	–	–0.41	–	–	30	1.3E–08	1.3E–08	1.3E–04	
KFR103	120.00	125.00	5	–	0.25	–	–0.38	–	–	30	1.3E–08	1.3E–08	1.3E–04	
KFR103	125.00	130.00	5	–	0.25	–	–0.36	–	–	30	1.4E–08	1.4E–08	1.4E–04	
KFR103	130.00	135.00	5	–2.06E–08	0.28	5.72E–08	–0.34	1.2E–07	0.1	30	1.3E–08	1.3E–08	1.3E–04	
KFR103	135.00	140.00	5	–	0.29	–	–0.34	–	–	30	1.3E–08	1.3E–08	1.3E–04	
KFR103	140.00	145.00	5	–	0.31	–	–0.32	–	–	30	1.3E–08	1.3E–08	1.3E–04	
KFR103	145.00	150.00	5	–	0.34	–	–0.30	–	–	30	1.3E–08	1.3E–08	1.3E–04	
KFR103	150.02	155.02	5	–	0.37	–	–0.26	–	–	30	1.3E–08	1.3E–08	1.3E–04	
KFR103	155.01	160.01	5	–	0.40	–	–0.24	–	–	30	1.3E–08	1.3E–08	1.3E–04	
KFR103	160.00	165.00	5	–	0.43	–	–0.21	–	–	30	1.3E–08	1.3E–08	1.3E–04	
KFR103	160.00	165.00	5	–	0.43	–	–0.21	–	–	30	1.3E–08	1.3E–08	1.3E–04	
KFR103	165.00	170.00	5	–	0.44	–	–0.18	–	–	30	1.3E–08	1.3E–08	1.3E–04	
KFR103	170.01	175.01	5	–	0.47	–	–0.16	–	–	30	1.3E–08	1.3E–08	1.3E–04	
KFR103	175.01	180.01	5	–	0.51	–	–0.13	–	–	30	1.3E–08	1.3E–08	1.3E–04	
KFR103	180.02	185.02	5	–1.56E–06	0.55	4.94E–06	–0.09	1.0E–05	0.4	30	1.3E–08	1.3E–08	1.3E–04	
KFR103	185.02	190.02	5	8.33E–09	0.65	3.97E–08	–0.04	4.5E–08	0.8	30	1.2E–08	1.2E–08	1.2E–04	
KFR103	190.03	195.03	5	–	0.93	–	0.01	–	–	30	9.0E–09	9.0E–09	9.0E–05	

* Uncertain flow rate (less than 30 mL/h).

** It was not possible to obtain a result for this section from the measured data. The flow rates in this section would be significant.


Forsmark, borehole KFR103
Flow rates of 5 m sections
Without pumping
2008-09-22 - 2008-09-23
With pumping
2008-09-23 - 2008-09-24
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
180
200
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



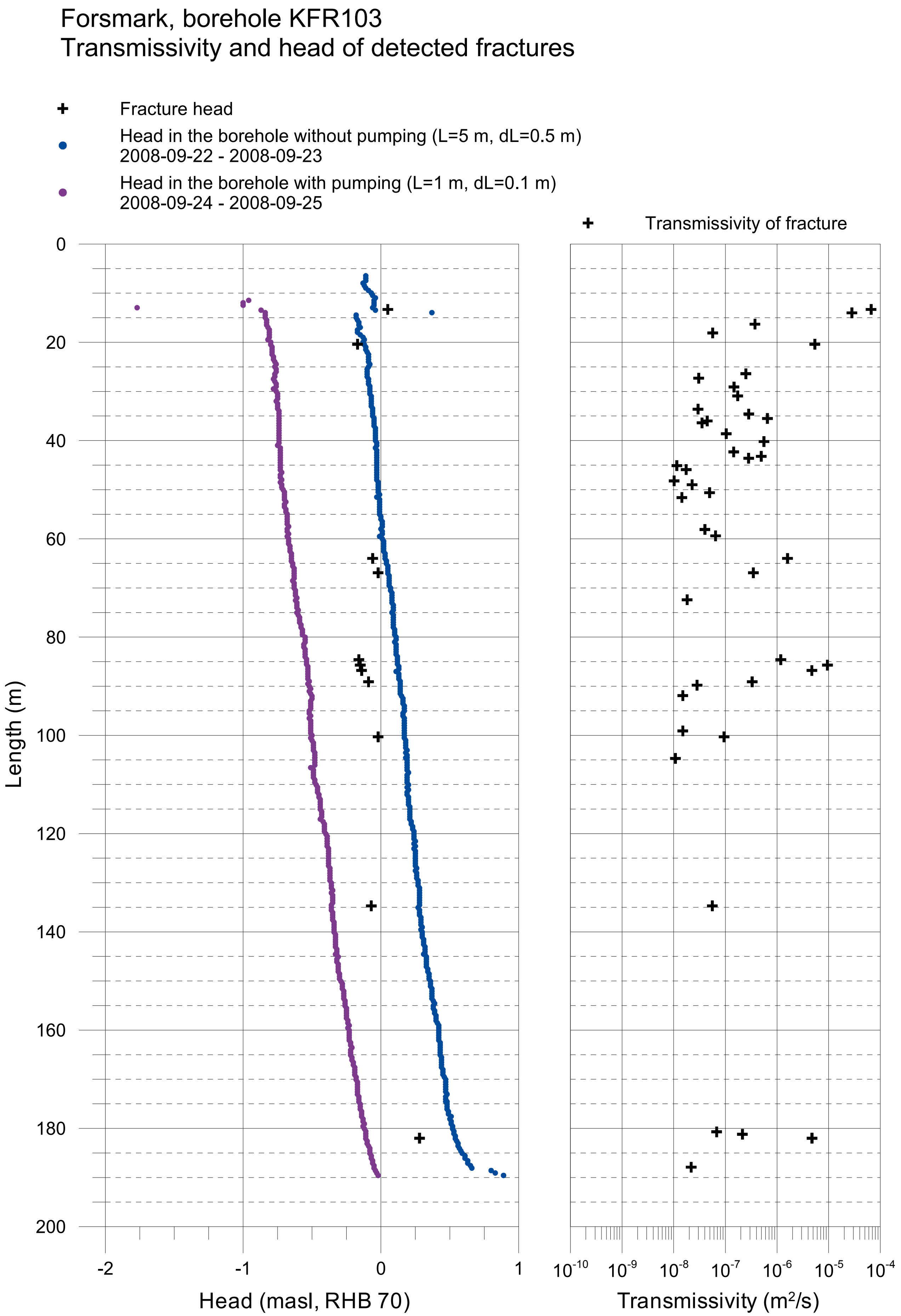
Forsmark, borehole KFR103
Transmissivity and head of 5 m sections
Formation head
Head in the borehole without pumping
2008-09-22 - 2008-09-23
Head in the borehole with pumping
2008-09-23 - 2008-09-24
Transmissivity (T)
Theoretical minimum measurable T
Practical minimum measurable T
Theoretical maximum measurable T
Length (m)
0
20
40
60
80
100
120
140
160
180
200
-1
0
1
Head (masl, RHB 70)
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
Transmissivity (m^2/s)

Inferred flow anomalies from overlapping flow logging

Borehole ID	Length to flow anom. L (m)	L_w (m)	dL (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.)	Comments
KFR103	13.3	1	0.1	6.44E–06	–0.05	6.08E–05	–0.86	6.6E–05	0.1	*, **
KFR103	14.0	1	0.1	–	–0.05	2.30E–05	–0.86	2.8E–05	–	
KFR103	16.3	1	0.1	–	–0.16	2.27E–07	–0.76	3.7E–07	–	
KFR103	18.1	1	0.1	–	–0.16	3.39E–08	–0.75	5.7E–08	–	
KFR103	20.4	1	0.1	–2.48E–07	–0.12	3.14E–06	–0.74	5.4E–06	–0.2	
KFR103	26.4	1	0.1	–	–0.10	1.58E–07	–0.73	2.5E–07	–	
KFR103	27.3	1	0.1	–	–0.09	1.94E–08	–0.72	3.1E–08	–	
KFR103	29.1	1	0.1	–	–0.08	9.53E–08	–0.72	1.5E–07	–	
KFR103	30.9	1	0.1	–	–0.07	1.12E–07	–0.71	1.7E–07	–	
KFR103	33.6	1	0.1	–	–0.06	1.92E–08	–0.70	3.0E–08	–	*
KFR103	34.6	1	0.1	–	–0.06	1.81E–07	–0.69	2.8E–07	–	
KFR103	35.5	1	0.1	–	–0.05	4.14E–07	–0.68	6.5E–07	–	
KFR103	36.0	1	0.1	–	–0.05	2.89E–08	–0.69	4.5E–08	–	*
KFR103	36.4	1	0.1	–	–0.05	2.25E–08	–0.68	3.5E–08	–	*
KFR103	38.6	1	0.1	–	–0.04	6.75E–08	–0.68	1.0E–07	–	
KFR103	40.2	1	0.1	–	–0.04	3.56E–07	–0.67	5.6E–07	–	
KFR103	42.3	1	0.1	–	–0.03	9.25E–08	–0.66	1.5E–07	–	
KFR103	43.2	1	0.1	–	–0.03	3.17E–07	–0.66	5.0E–07	–	
KFR103	43.6	1	0.1	–	–0.03	1.79E–07	–0.66	2.8E–07	–	
KFR103	45.1	1	0.1	–	–0.03	7.22E–09	–0.65	1.2E–08	–	*
KFR103	45.9	1	0.1	–	–0.03	1.11E–08	–0.66	1.7E–08	–	*
KFR103	48.2	1	0.1	–	–0.03	6.39E–09	–0.65	1.0E–08	–	*
KFR103	49.0	1	0.1	–	–0.02	1.44E–08	–0.65	2.3E–08	–	*
KFR103	50.6	1	0.1	–	–0.02	3.06E–08	–0.63	5.0E–08	–	
KFR103	51.6	1	0.1	–	–0.03	8.89E–09	–0.64	1.4E–08	–	*
KFR103	58.1	1	0.1	–	–0.01	2.56E–08	–0.64	4.0E–08	–	
KFR103	59.4	1	0.1	–	–0.01	4.06E–08	–0.63	6.5E–08	–	
KFR103	64.0	1	0.1	–1.44E–07	0.03	9.22E–07	–0.63	1.6E–06	–0.1	
KFR103	66.9	1	0.1	–2.56E–08	0.05	2.10E–07	–0.62	3.5E–07	0.0	
KFR103	72.4	1	0.1	–	0.08	1.25E–08	–0.60	1.8E–08	–	
KFR103	84.6	1	0.1	–3.33E–07	0.12	4.81E–07	–0.56	1.2E–06	–0.2	
KFR103	85.7	1	0.1	–2.56E–06	0.12	3.97E–06	–0.56	9.5E–06	–0.2	
KFR103	86.8	1	0.1	–1.26E–06	0.12	1.94E–06	–0.55	4.7E–06	–0.1	
KFR103	89.1	1	0.1	–7.61E–08	0.14	1.48E–07	–0.53	3.3E–07	–0.1	
KFR103	89.8	1	0.1	–	0.14	1.92E–08	–0.53	2.8E–08	–	*
KFR103	91.9	1	0.1	–	0.15	1.03E–08	–0.53	1.5E–08	–	*
KFR103	99.1	1	0.1	–	0.17	1.03E–08	–0.51	1.5E–08	–	*
KFR103	100.3	1	0.1	–1.83E–08	0.17	4.67E–08	–0.51	9.5E–08	0.0	*
KFR103	104.7	1	0.1	–	0.18	7.50E–09	–0.51	1.1E–08	–	*
KFR103	134.7	1	0.1	–1.97E–08	0.28	1.81E–08	–0.39	5.6E–08	–0.1	
KFR103	180.7	1	0.1	–	0.53	4.58E–08	–0.14	6.8E–08	–	
KFR103	181.2	1	0.1	–	0.53	1.41E–07	–0.12	2.1E–07	–	
KFR103	182.0	1	0.1	–1.25E–06	0.54	1.92E–06	–0.12	4.8E–06	0.3	
KFR103	187.9	1	0.1	–	0.66	1.58E–08	–0.06	2.2E–08	–	

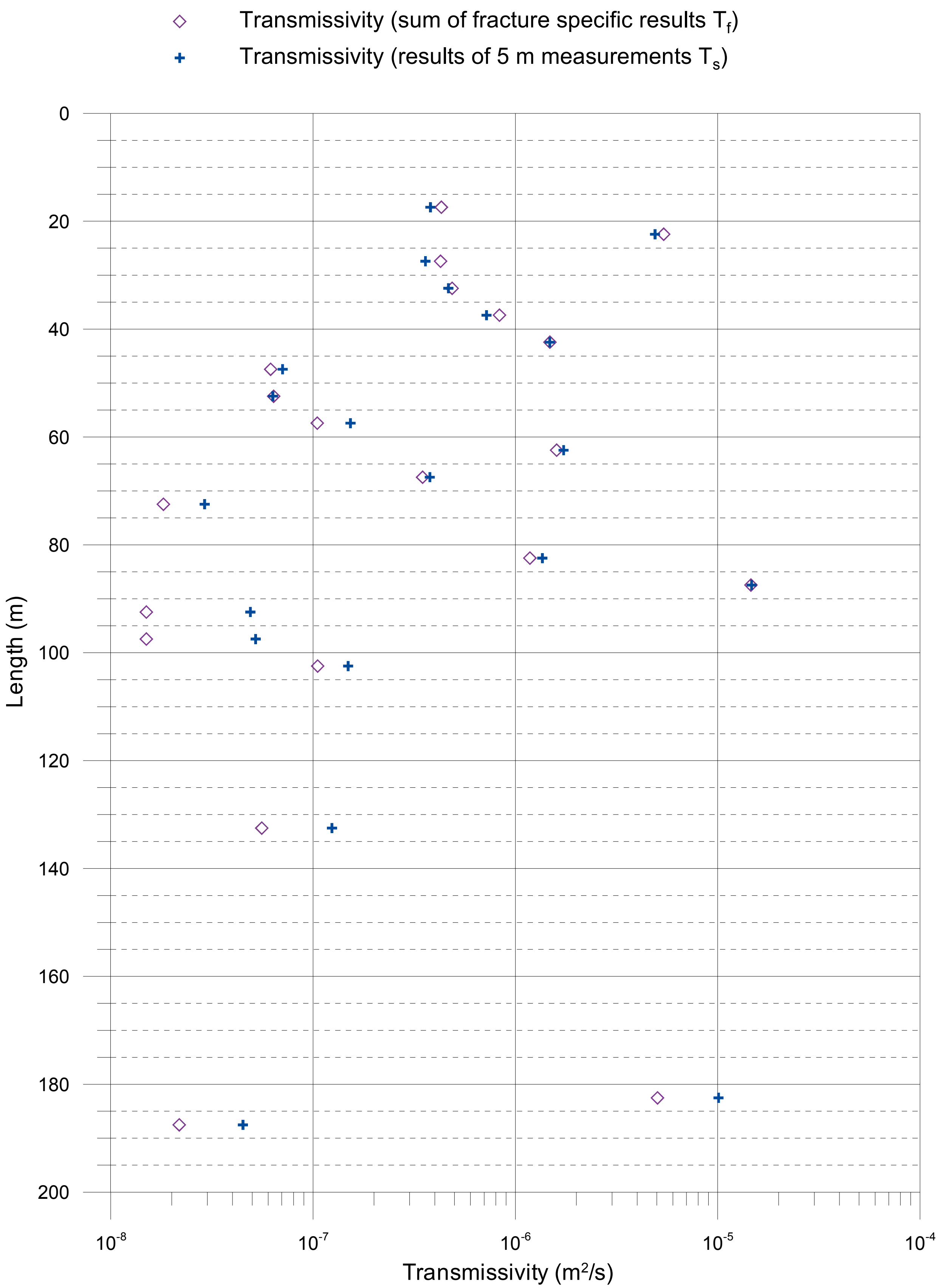
* Uncertain = The flow rate is less than 30 mL/h or the flow anomalies are overlapping or they are unclear because of noise.

** The results are unreliable as well as the calculated $\mathbf{T_D}$ and $\mathbf{h_i}$.



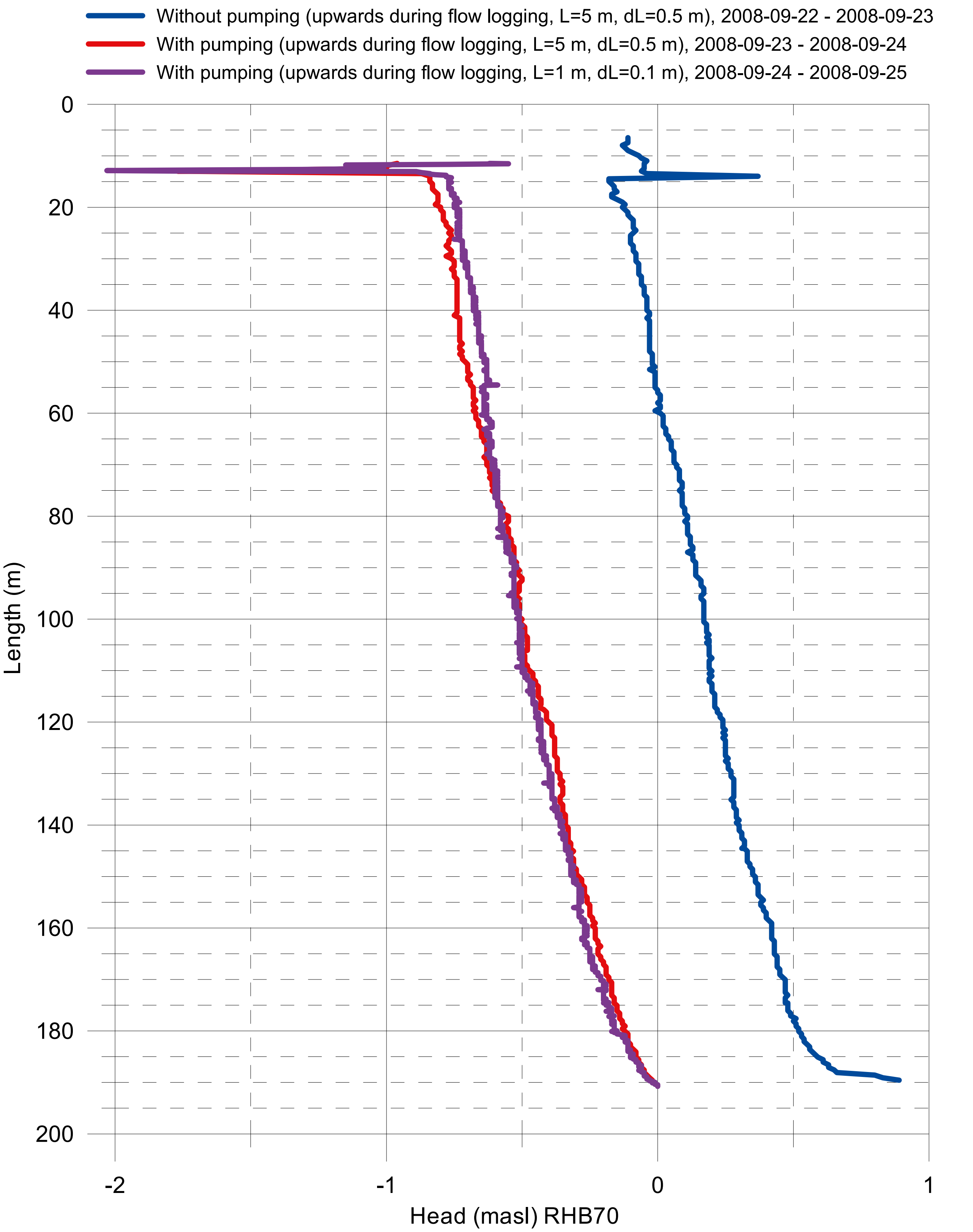
Forsmark, borehole KFR103
Transmissivity and head of detected fractures
Fracture head
Head in the borehole without pumping (L=5 m, dL=0.5 m)
2008-09-22 - 2008-09-23
Head in the borehole with pumping (L=1 m, dL=0.1 m)
2008-09-24 - 2008-09-25
Transmissivity of fracture
Length (m)
Head (masl, RHB 70)
Transmissivity (m²/s)

Forsmark, borehole KFR103
Comparison between section transmissivity and fracture transmissivity

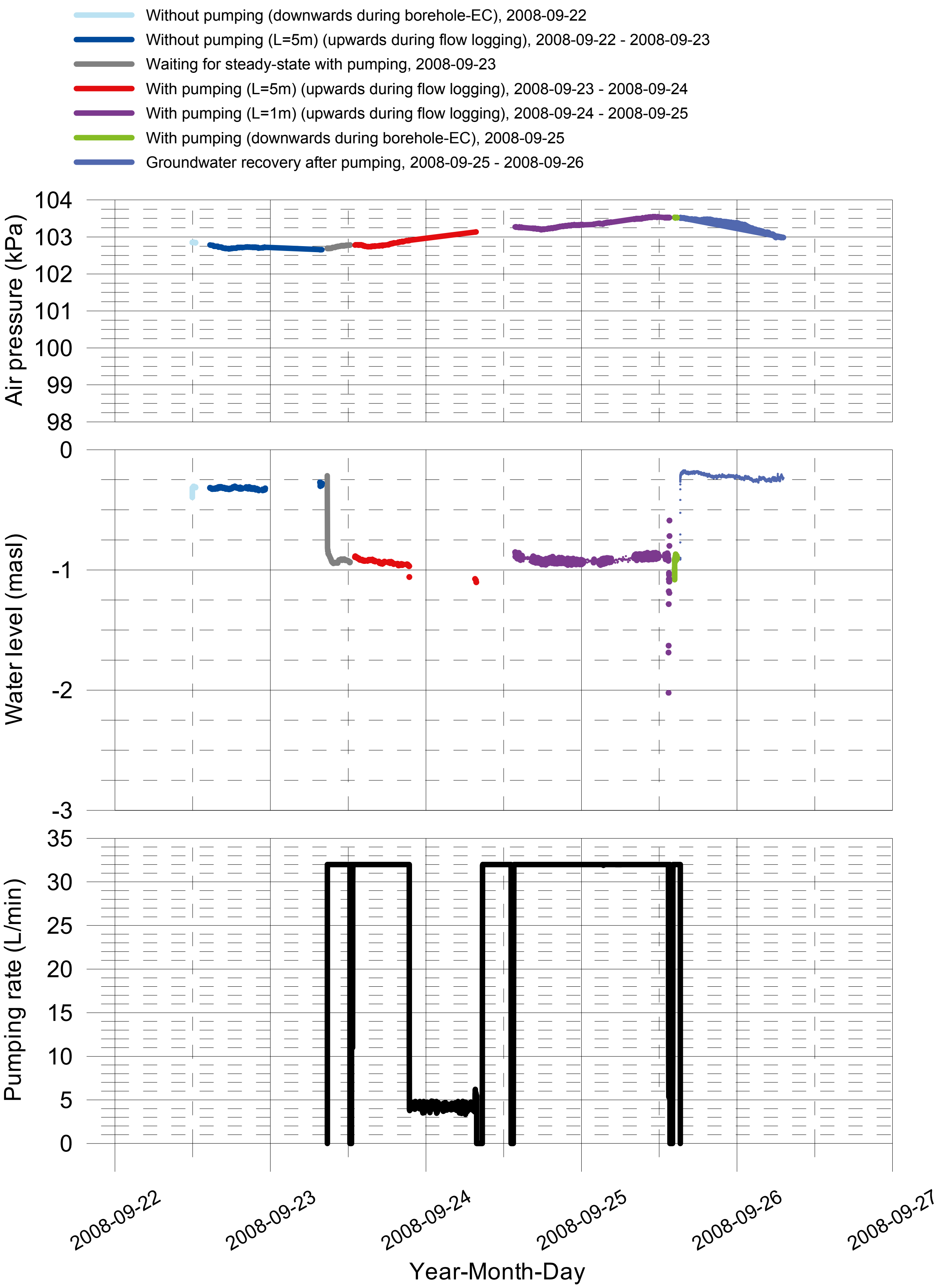


Forsmark, borehole KFR103
Head in the borehole during flow logging

Head(masl)= (Absolute pressure (Pa) - Airpressure (Pa) + Offset) /(1000 kg/m^3 * 9.80665 m/s^2) + Elevation (m)
Offset = -1029 Pa (Correction for absolute pressure sensor)

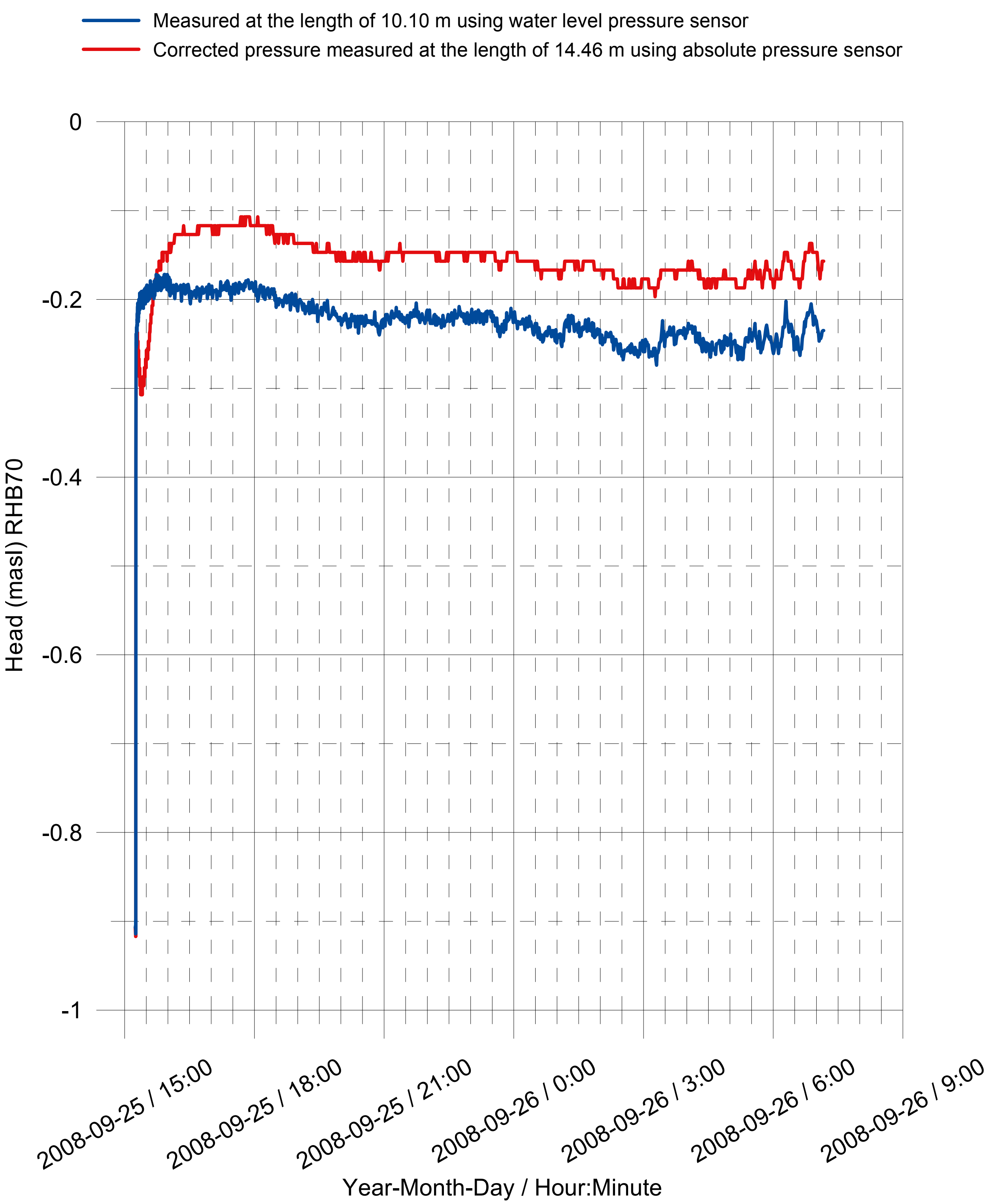


Forsmark, borehole KFR103
Air pressure, water level in the borehole and pumping rate during flow logging

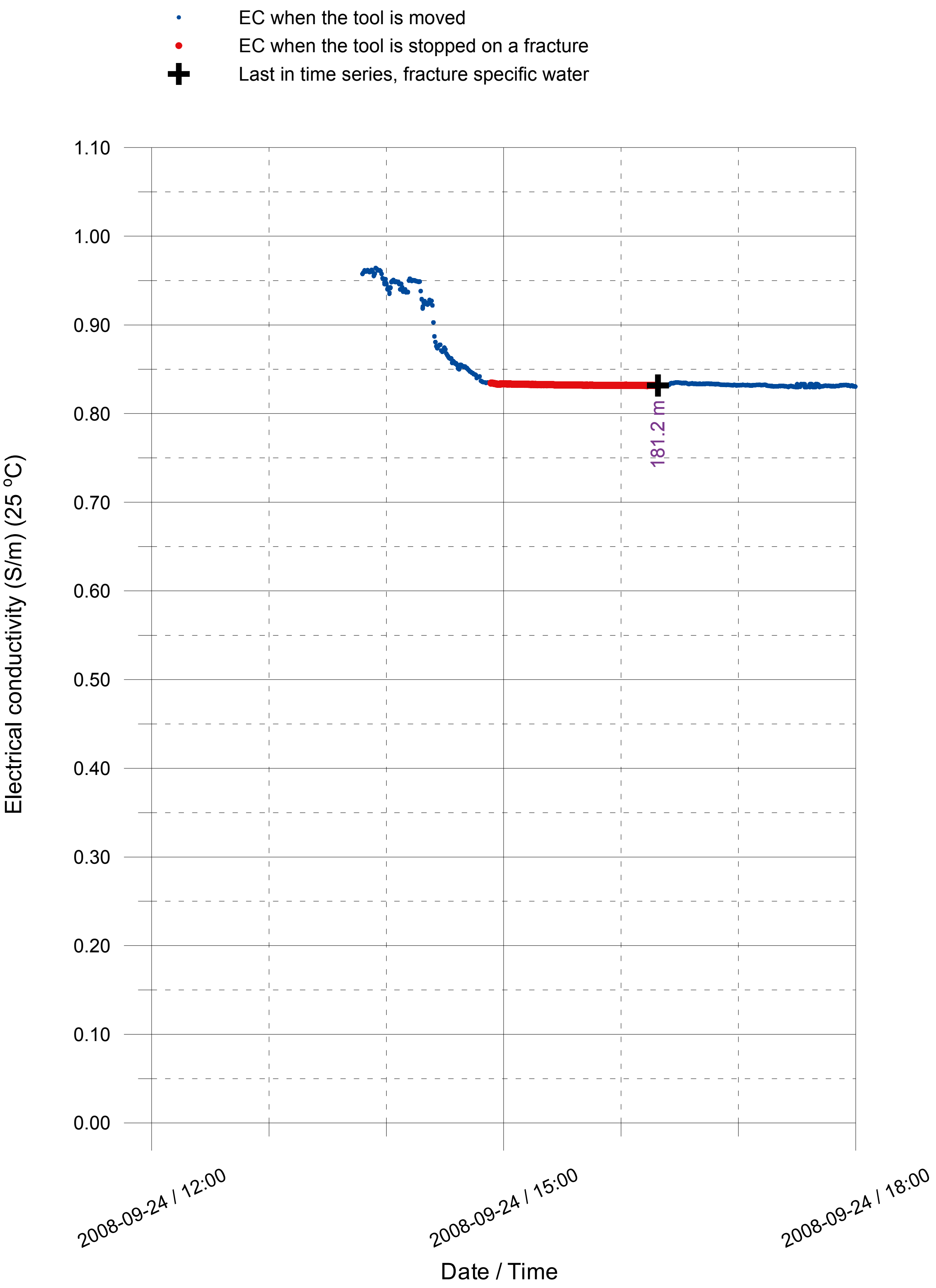


Forsmark, borehole KFR103
Groundwater recovery after pumping

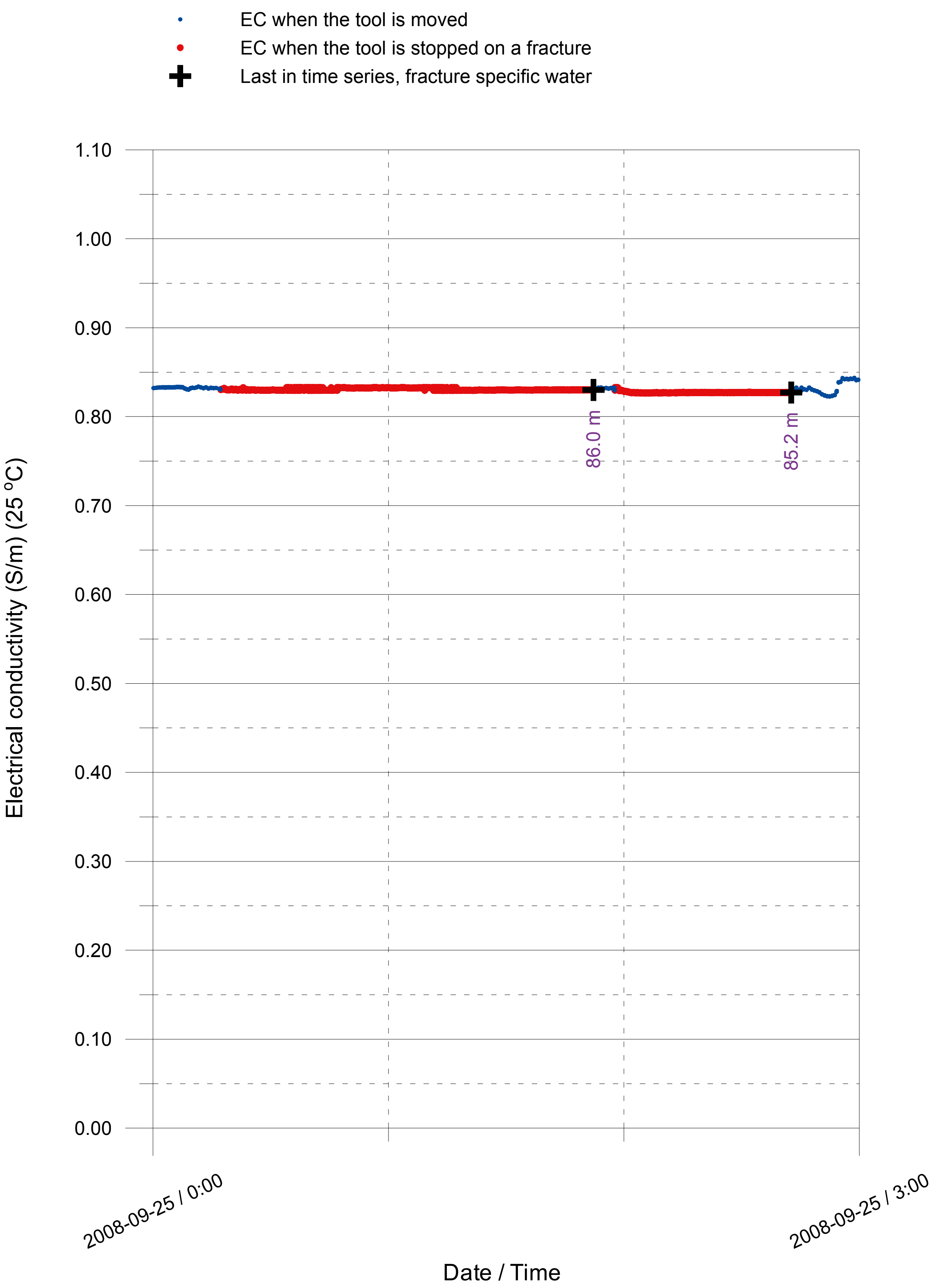
Head(masl)= (Absolute pressure (Pa) - Airpressure (Pa) + Offset) /(1000 kg/m^3 * 9.80665 m/s^2) + Elevation (m)
Offset = -1029 Pa (Correction for absolute pressure sensor)



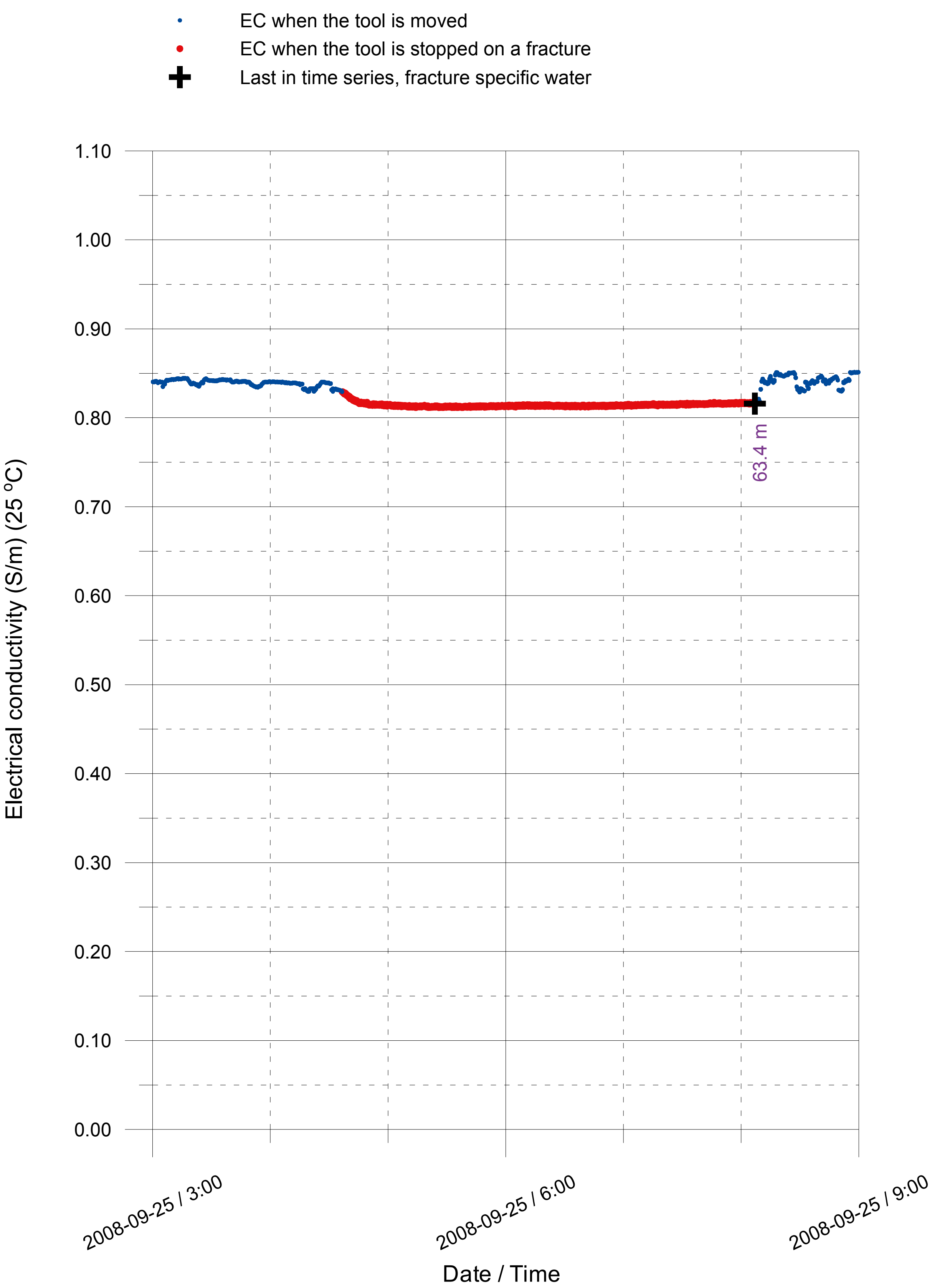
Forsmark, borehole KFR103
Fracture-specific EC results by date



Forsmark, borehole KFR103
Fracture-specific EC results by date



Forsmark, borehole KFR103
Fracture-specific EC results by date



Forsmark, borehole KFR103
Fracture-specific EC results by date