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Site investigation SFR

Difference flow logging in borehole KFR106

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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 borehole KFR106 at Forsmark, Sweden, in September and October 2009.

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 PFL DIFF probe.

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 KFR106 i Forsmark, Sverige, i september och oktober 2009.

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 PFL DIFF sonden.

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

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

Återhämtningen av grundvattennivån mättes efter att pumpningen hålet avslutats.

Contents

1 Introduction

The core drilled borehole KFR106 at Forsmark, Sweden was measured using the Posiva Flow Log, Difference Flow Method (PFL DIFF) which provides a swift, multifaceted characterization of a borehole. The borehole was measured between September 30–October 7, 2009.

KFR106 is 300.13 m long and its inclination at the ground level is c 70° from the horizontal plane. The borehole was drilled using a telescopic drilling technique, where the c 0 m–9 m interval was percussion drilled, and its inner diameter is 77 mm. A stainless steel support casing has been inserted into this part. The rest of the borehole was core drilled with a diameter of c 76 mm.

The location of KFR106 at Forsmark is illustrated in Figure 1-1.

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.

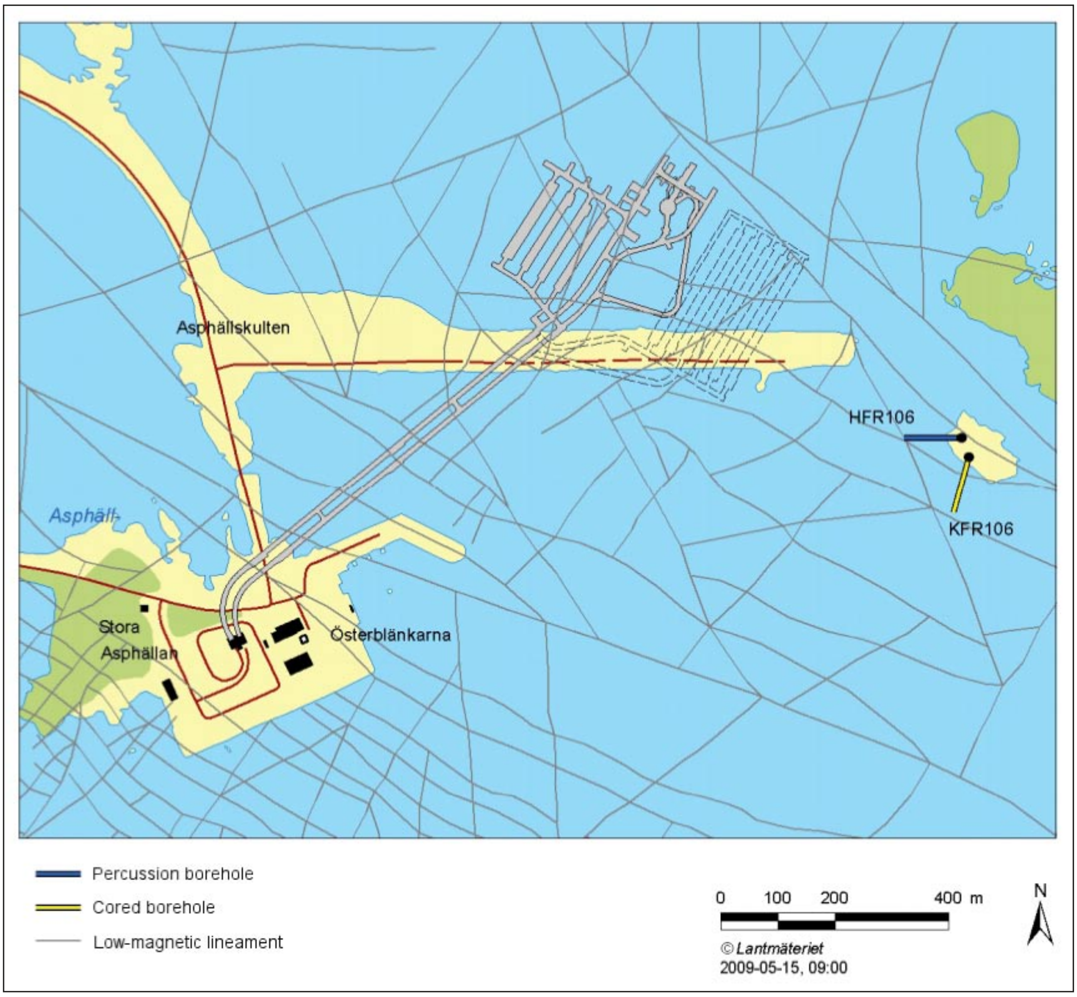

Figure 1-1. Location Map over the SFR facility and the location of the borehole KFR106.

This document reports the results acquired by PFL DIFF in borehole KFR106. 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-09-025. 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 borehole KFR106	AP SFR-09-025	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 KFR106 was to identify water-conductive sections/fractures suitable for subsequent hydro-geochemical characterisation. Secondly, the measurements aimed at a hydro-geological 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 hydro-geochemical 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 (the electrical conductivity of the water in the 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 probe 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. Different section lengths are also used to confirm that a flow anomaly is real and not caused for instance by a leak at the rubber disks.

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/. The thermal dilution method is used in measuring flow rates because it is faster than the thermal pulse method, and the latter is used only to determine flow direction within a given time frame. Both methods are used simultaneously at each measurement location.

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

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

The principles behind PFL DIFF flow 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.

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.

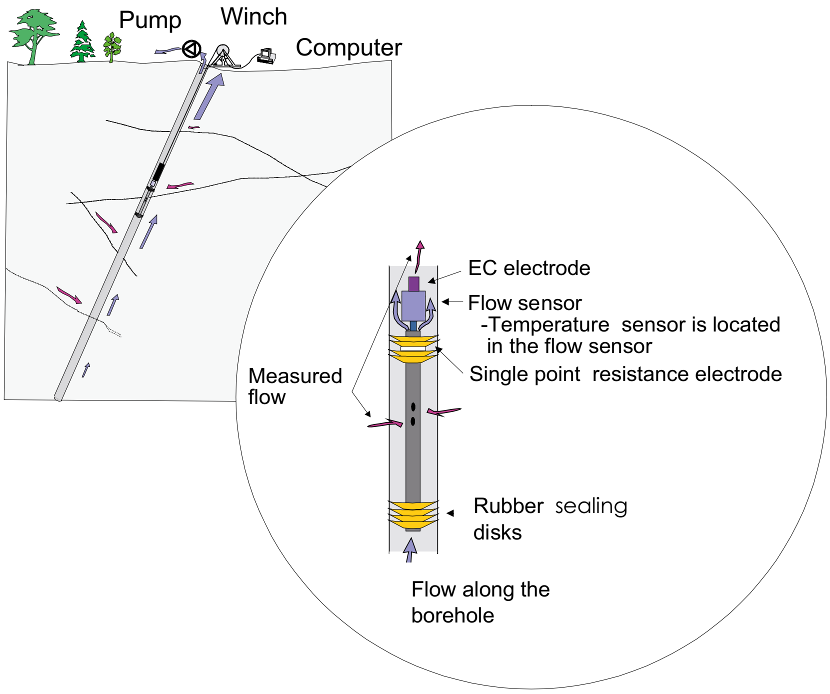

Figure 3-1. *Schematic of the probe used in the PFL DIFF.*

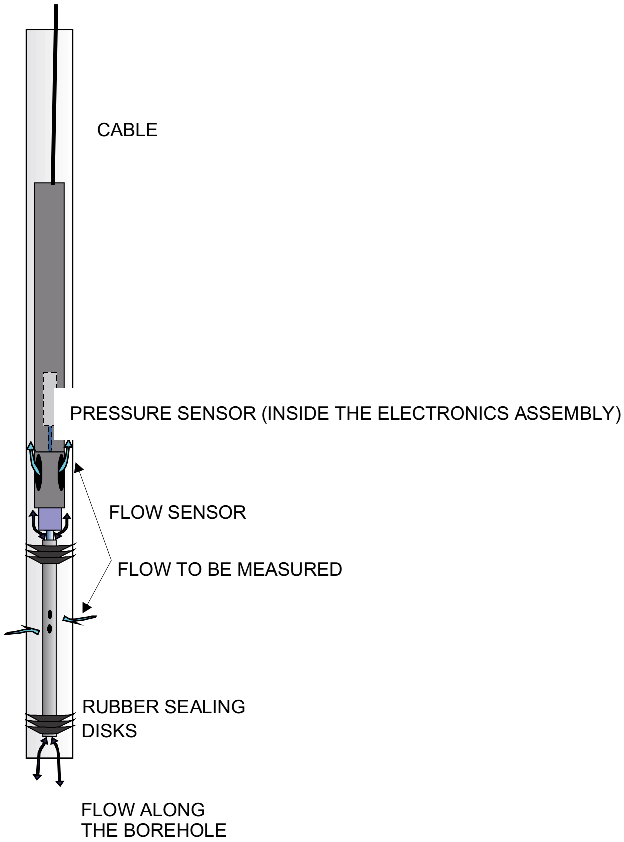

Figure 3-2. *The absolute pressure sensor is located inside the electronics assembly and connected to the borehole water through a tube.*

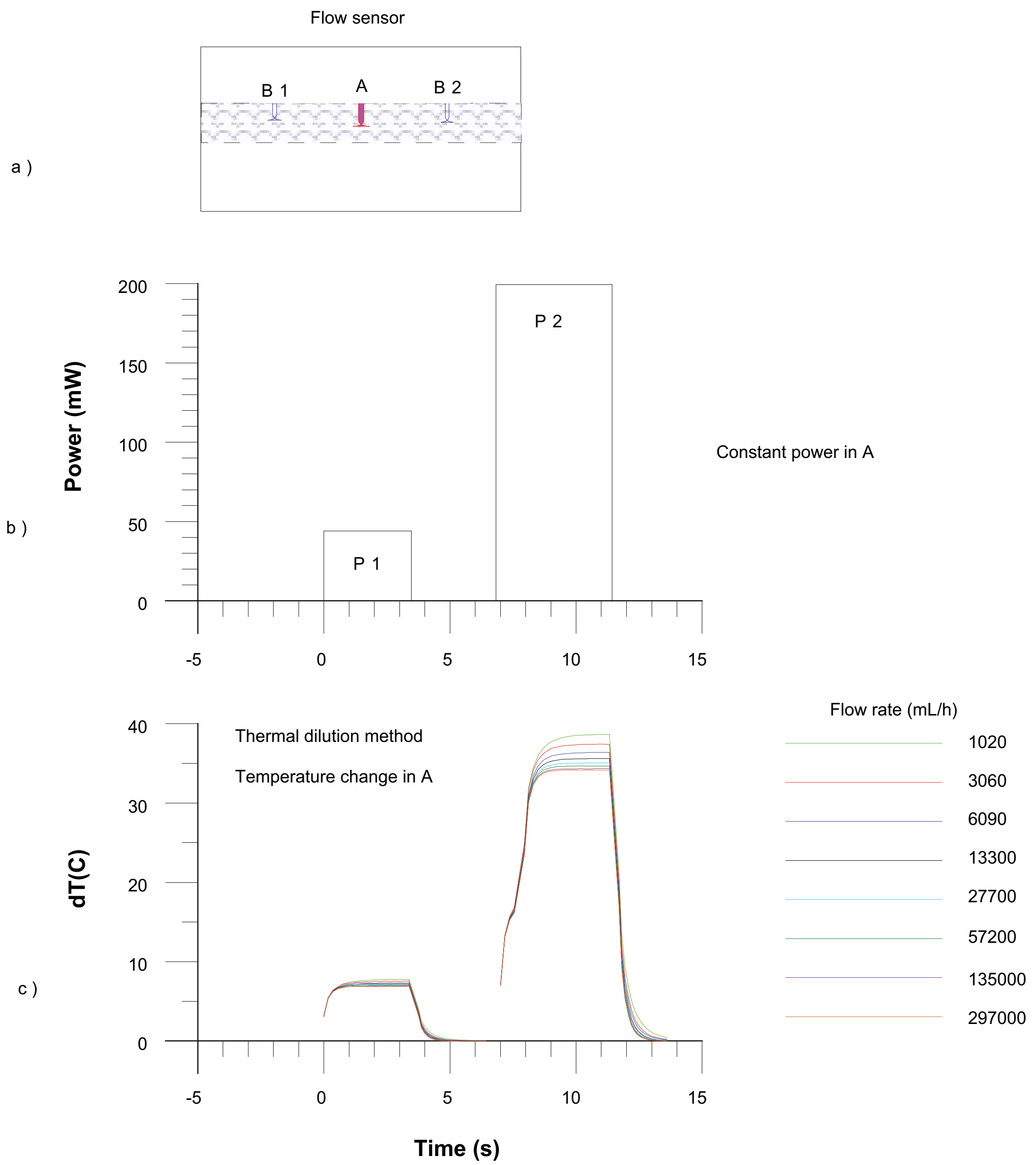

Figure 3-3. *Flow rate measurement.*

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 = hs 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,

Ts is the transmissivity of the test section and

hs 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 hs 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:

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

$Ts = (1/a)\ (Q_{s0} – Q_{s1})/(h_1 – h_0)$ 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/:

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

where

s is drawdown (m) and

Q is the pumping rate at the end of the flow period (m3/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:

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

where L is length of the test section (m), in this case the water filled uncased part of the borehole and r0 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
Calibration of flow probe:	September 2009 (Probe FL5)

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-09-025 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.

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 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 borehole with a 5 m section length and in 0.5 m length increments (step length). The measurements were performed during natural (un-pumped) conditions.

The pumping was started on October 3, 2009. After a five and a half hours waiting time (the minimum waiting time was set to three hours), overlapping flow logging (Item 12) was conducted using the same section and step lengths as before.

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 logged while the measured 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 KFR106. Activity schedule.

Item	Activity	Explanation	Date
8	Dummy logging	Borehole stability/risk evaluation.	2009-09-30–2009-10-01
9	Calibration	SKB Caliper and SPR. Logging without the lower rubber disks, no pumping.	2009-10-01
10	Borehole fluid logging	Logging without the lower rubber disks, no pumping.	2009-10-01
11	Combined sequential/overlapping flow logging	Section length L_w=5 m, step length dL=0.5 m, no pumping.	2009-10-01–2009-10-02
12	Combined sequential/overlapping flow logging	Section length L_w=5 m, step length dL=0.5 m, with pumping.	2009-10-03–2009-10-04
13–14	Overlapping flow logging and fracture-EC	Section length L_w=1 m, step length dL=0.1 m, with pumping.	2009-10-05–2009-10-06
15	Borehole fluid before pump stop	Logging without the lower rubber disks, with pumping.	2009-10-07
16	Transient registration of recovery	Measurement of water level and absolute pressure in the borehole after the pumping was stopped. The measurement was continued on 2009-10-07 and after that by SKB's pressure logger.	2009-10-07

5.2 Nonconformities

A 3 m drawdown was used instead of 5 m because the amount of outflow from the borehole in order to achieve a 5 m drawdown would have been so large that it would not have been possible with the available pumps. The upper part of the borehole is cased with an inner diameter of 77 mm preventing the installation of larger pumps.

After the five and a half hours waiting time after the pumping had started, the achieved drawdown was only 2.5 m. The measurement with a 5 m section stopped at 268 m due to a computer failure in the evening. The drawdown then grew to 3 m during the night. Since no flow anomalies were detected below 268 m it was decided to continue the measurements with the 3 m drawdown and not to re-measure the bottom of the borehole. The change in the head can be seen in Appendix KFR106.10.1.

The SPR results from the caliper measurement were rather diffuse. The SPR results from the natural state flow measurement have been used instead in Appendices KFR106.3.1–KFR106.3.15. The SPR results from the caliper measurement were however clear enough to perform length corrections.

It was not physically possible to measure approximately 6.5 m of the bottom of the borehole. There were weights (3) and a centralizer in the measurement device, which reduce the measured distance by c 5.1 m. The rubber sealing disks in the device must also be flipped before the measurement begins. This reduces the measured distance for approximately 10 cm. It is possible that there were also drill cuttings at the bottom of the borehole.

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, Appendix KFR106.1.16, 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 and 13/14 to obtain relative length errors of these measurement sequences.
- All SPR curves could then be synchronized, as can be seen in Appendices KFR106.1.2–KFR106.1.15.

The results of the caliper and single-point resistance measurements from all measurements in the entire borehole are presented in Appendix KFR106.1.1. Three SPR-curves are plotted together with the caliper-data. These measurements correspond to Items 9, 11, 12 and 13/14.

Zoomed results of the caliper and SPR data are presented in Appendices KFR106.1.2–KFR106.1.15. The detectability of the length marks is listed in Table 6-1. 4 out of 6 length marks were detected by the caliper tool.

6 out of 6 length marks were adequately 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.

Table 6-1. Detected length marks.

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
200	none	yes
250	upper	yes
280	none	yes

The aim of the plots in Appendices KFR106.1.2–KFR106.1.15 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. A length correction was also performed at the lower end of the steel guide as can be seen in Appendix KFR106.1.2.

The magnitude of length correction along the borehole is presented in Appendix KFR106.1.16. The negative values of the error represent the situation where the logging cable has been extended, i.e. the cable is longer than the nominal length marked on it.

6.1.2 Estimated error in location of detected fractures

In spite of the length correction 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, see Figure 6-1.

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 KFR106.2.1 (linear scale) and KFR106.2.2 (logarithmic scale), cyan curve.

The EC measurement was repeated during pumping (after a pumping period of approximately four days), see Appendices KFR106.2.1 and KFR106.2.2, 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 Appendix KFR106.2.3 have the same length axis as the EC results in KFR106.2.1 and KFR106.2.2.

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 Appendix KFR106.1.16.

Figure 6-1. *BIPS image showing the vertical fracture zone 16.4 m–19.4 m.*

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 probe is first moved stepwise closer to the fracture until the detected flow is larger than a predetermined limit. At this point the probe 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 electrical 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 KFR106.11.1–KFR106.11.4. 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 borehole are listed in Table 6-3.

For comparison, the fracture-specific EC and temperature results are also plotted with the EC and temperature results of borehole water, see Appendices KFR106.2.1–KFR106.2.3.

Table 6-3. Fracture-specific EC.

Upper end of section (m)	Lower end of section (m)	Measured fractures (m)	EC (S/m) at 25°C
57.53	58.53	58.2	0.79
67.62	68.62	68.3	0.82
70.81	71.81	71.6	0.82
72.31	73.31	73.1	0.81
84.7	85.7	84.7, 85.4	0.84
100.1	101.1	100.7	0.90
110.37	111.37	111.1	0.91
112.47	113.47	113.1	0.87
153.69	154.69	154.3, 154.6	0.92
155.39	156.39	156.0	0.92
187.24	188.24	188.0	1.05
261.74	262.74	262.7	0.82

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 Appendix KFR106.10.2. 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 4.5 kPa is added to absolute pressure results.

The calculated head distributions are presented in Appendix KFR106.10.1. 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 KFR106.3.1–KFR106.3.15. SPR has a lower value on a fracture where flow is detected. Many other resistance anomalies result from other fractures and geological features. As the electrode of the SPR tool is located within the upper rubber sealing disks of the probe, the locations of resistance anomalies associated with leaky fractures coincide with the lower end of the flow anomalies.

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

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

Under natural conditions or if the borehole is not 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 and direction of the measured flows. The triangles have the same colour than the corresponding curves.

The explanations to the tables in Appendices KFR106.5 and KFR106.7 are given in Appendix KFR106.4.

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 KFR106.5.1–KFR106.5.2. Only the results with 5 m length increments are used. All borehole sections are shown in Appendices KFR106.3.1–KFR106.3.15. Secup and Seclow in Appendices KFR106.5.1–KFR106.5.2 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 in 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 KFR106.5.1–KFR106.5.2 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 KFR106.5.1–KFR106.5.2 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 KFR106.5.1–KFR106.5.2 (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 at rest, 22 sections were detected as flow yielding, 6 of which had a flow direction from the borehole into the bedrock (negative flow). During pumping, all 37 detected flow yielding sections were directed towards the borehole (positive flow).

The section 6.35 m–11.35 m was only measured during un-pumped conditions, this was because the drawdown during pumping forced the water level below this section.

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 Appendix KFR106.6.1. 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 plot (Appendix KFR106.6.1) and in the tables (Appendix KFR106.5). 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 Appendix KFR106.6.2. 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 Appendix KFR106.6.2 and in Appendix KFR106.5. All the measurement limit values of transmissivity are based on the actual pressure difference in the borehole (h_{0FW} and h_{1FW} in Appendix KFR106.5).

The sum of all the detected flows without pumping (Q_0) was $-6.02 \cdot 10^{7}$ m^3/s (–2.17 L/h). This sum should normally be zero if all the flows in the borehole are not disturbed by noise or other external factors, the borehole is not pumped, the water level is constant, the salinity distribution in the borehole is stabilized and the fractures are at steady state pressure. In this case inflows and outflows were relatively well balanced.

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 Appendix KFR106.3.6. 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 Appendix KFR106.7. The flow direction is evaluated as well. The results of the evaluation are plotted in Appendix KFR106.3, blue filled triangle.

The total amount of detected flowing fractures was 69, but only 13 of them could be defined without pumping. 12 of these fractures could be used for head estimations and 68 were used for transmissivity estimations. The fracture at 9.8 m could not be measured during pumping, since the drawdown forced the water level below this fracture. The transmissivity and hydraulic head of fractures are presented in Appendices KFR106.7 and KFR106.8.

The fracture marked at 16.8 m is a vertical fracture zone spanning from 16.4 m to 19.4 m (see Figure 6-1).

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 1 m or their nature is unclear because of noise.

Fracture-specific transmissivities were compared with transmissivities of sections in Appendix KFR106.9. 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 sometimes 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.

The sum of the detected fracture flows (~17 L/min) was smaller than the average pumping rate (~27 L/min). Approximately one meter of the borehole close to the casing tube could not be measured during pumping due to drawdown and pump equipment. The natural state flow measurement shows a fracture at 9.8 m. It is possible that, if not all, at least a part of the missing flow could be coming from this fracture. Another reason can be that the borehole contains a large amount of high yield fractures close to the upper measurement limit of the flow probe. It is possible that there might be pressure drops when the water passes the flow sensor at those fractures, which results in slightly lower measured flows than when the flow sensor is not placed over those fractures. The transmissivity of these high yielding fractures might be underestimated. This is apparent in the fracture at 156.0 m where an anomaly in the absolute pressure was detected, see Appendix KFR106.10.1. This location is commented in Appendix KFR106.5 and Appendix KFR106.7.

6.4.4 Theoretical and practical measurement limits of flow and transmissivity

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

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

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

1) Roughness of the borehole wall.

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

3) Gas bubbles entrained in the water.

4) High flow rate along the borehole.

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

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

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

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

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

The practical minimum for measurable flow rate is presented in Appendices KFR106.3.1–KFR106.3.15 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 varied between 30 mL/h and 200 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. There was no need for any such additional measurements during this campaign.

The practical minimum for measurable flow rate is also presented in Appendix KFR106.5 (Q-lower limit P) and is obtained from the plots in Appendix KFR106.3 (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 Appendix KFR106.5 (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 Appendix KFR106.5 (T_D-measl$_U$).

All three flow limits are plotted with the measured flow rates, see Appendix KFR106.6.1.

The three transmissivity limits are also presented graphically, see Appendix KFR106.6.2.

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 1 m, 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 Appendix KFR106.10.2. Borehole was pumped between October 3 and October 7 with a drawdown of approximately 3 m. The pumping rates were recorded, see Appendix KFR106.10.2.

The groundwater recovery was measured after the pumping period, during October 7, see Appendix KFR106.10.3. The recovery was measured 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 9.38 m.

After that the recovery was measured using SKB's water level sensor, green line in Appendix KFR106.10.2 and Appendix KFR106.10.3.

6.5.1 Transmissivity of the entire borehole

(by J-E Ludvigson, Geosigma AB)

The pumping test during difference flow logging in KFR106 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. The transient analysis of the recovery period was made as described in Chapter 3. The initial pressure recovery was measured by the PRG water level sensor and then continued by the SKB water level sensor. The measured pressure recovery until 2009-10-09 06:00 was included in the transient analysis, see Appendix KFR106.10.3.

Transient analysis on the pressure recovery period after pumping was made 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 was estimated from an empirical relationship between T and S described in the MD above. Furthermore, the skin factor and the borehole storage coefficient C should 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 (or intersections with other structures) are observed.

Steady-state analysis

The final flow rate Q_p during the flow period in KFR106 was c 27 L/min and the drawdown of the water level was s_p= c 3 m by the end of the flow period (Appendix KFR106.10.2). The steady-state transmissivity calculated with Dupuit's formula (Equation 3-9) and Moye's equation (Equation 3-10), respectively is shown in Table 6-4. In Dupuit's formula, the ratio R/r_0 is assumed to be 500, cf Chapter 3. In Moye's formula, the length of the test section L (open borehole interval) is 291.00 m and the borehole diameter 2_{r0} is 0.0757 m. The borehole is cased in the interval 0–9.13 m with an inner diameter of 0.0770 m.

Transient analysis

Figures 6-2a and b shows log-log and semi-log plots respectively of the transient pressure recovery of the water level during the pumping test in KFR106 which was used to estimate the transmissivity of the entire borehole. The pressure recovery clearly indicates an apparent negative (no-flow) hydraulic boundary, starting at Agarwal time of c 100 s, cf. Figures 6-2a and b. This means that the dominating fracture(s) in the borehole either has a limited extension laterally or a decreasing aperture away from the borehole (or a combination of both features) resulting in a decreasing transmissivity with time and distance from the borehole.

At intermediate times the pressure derivative stabilizes during the Agarwal time interval between c 4,000–20,000 s, possibly reflecting the hydraulic properties at a longer distance from the borehole. In such a case, the response can be interpreted as a dual-permeability system with higher transmissivity near the borehole. Both the early and intermediate transient evaluations are shown below in Figures 6.2a-b and 6.3a-b, respectively. At longer times, the pressure recovery seems to be influenced by natural pressure fluctuations. Notably is that the total pressure recovery (c 2 m) is less than the total drawdown (c 3 m), indicating the presence of an apparent no-flow boundary.

The early transient response was simulated for an estimated storativity from the empirical relationship between T and S described above. The best fit simulation on the early response yields a transmissivity $T = 3.3 \cdot 10^{-4}$ m²/s, a skin factor = –3.9 and a wellbore storage coefficient of $C=2.6 \cdot 10^{-7}$ m³/Pa. The latter coefficient is calculated from the simulated effective casing radius of the borehole. The strongly negative skin factor indicates the presence of a major conductive fracture(s) in the borehole.

As discussed above, the hydraulic properties of the conductive fracture(s) estimated before the effects of the observed hydraulic boundary should be reported to Sicada. The long-term transmissivity in the borehole depends on the nature and properties of the apparent hydraulic boundary.

The estimated transmissivity of borehole KFR106 according to the three methods described above are given in Table 6-4. In this case, the estimated transmissivity from the transient evaluation of the early response was selected as the most representative.

Table 6-4. Estimated transmissivity of borehole KFR106.

Method	Transmissivity (m²/s)
Dupuit	$1.5 \cdot 10^{-4}$
Moye, T_M	$2.2 \cdot 10^{-4}$
Transient, T_T (early)	$3.3 \cdot 10^{-4}$
Transient, T_T (intermediate)	$1.3 \cdot 10^{-4}$

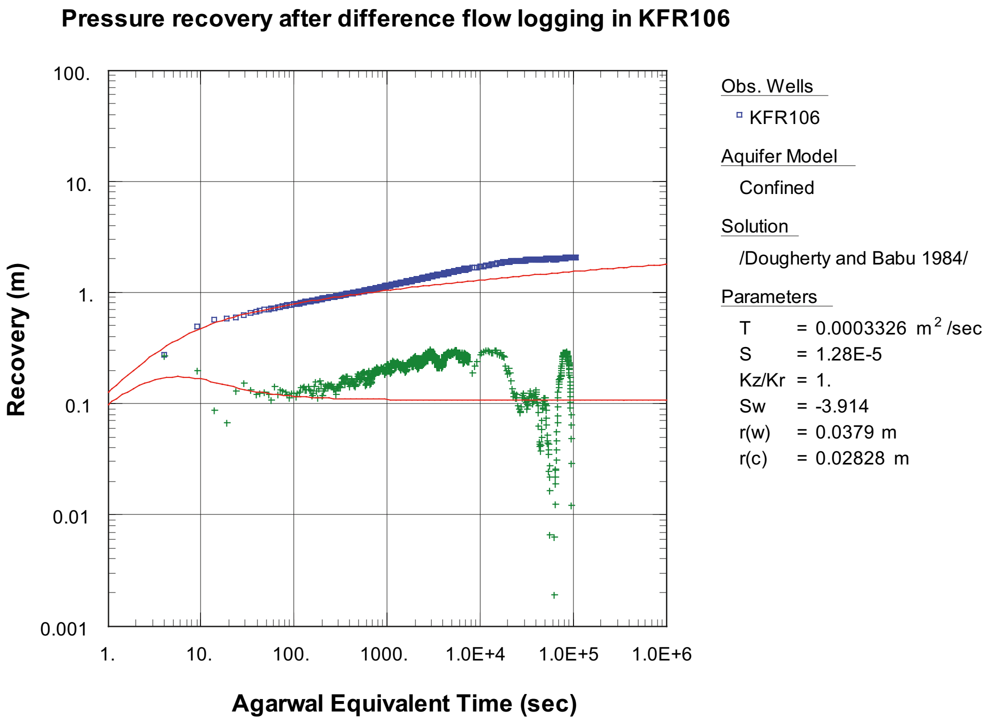

Figure 6-2a. *Log-log plot of the pressure recovery in KFR106 showing the observed pressure recovery of the water level (□) and associated derivative (+) versus Agarwal equivalent time together with simulated best fit curves of the pressure recovery and its derivative (-). The evaluation is made on the early response.*

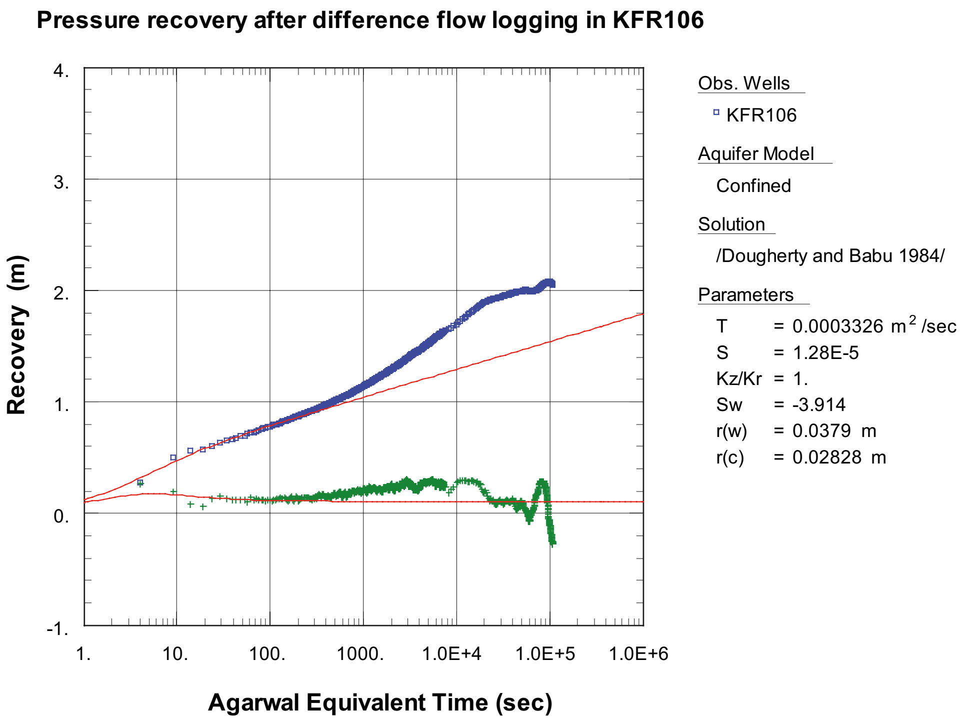

Figure 6-2b. *Lin-log plot of the pressure recovery in KFR106 showing the observed pressure recovery of the water level (□) and associated derivative (+) versus Agarwal equivalent time together with simulated best fit curves of the pressure recovery and its derivative (-).The evaluation is made on the early response.*

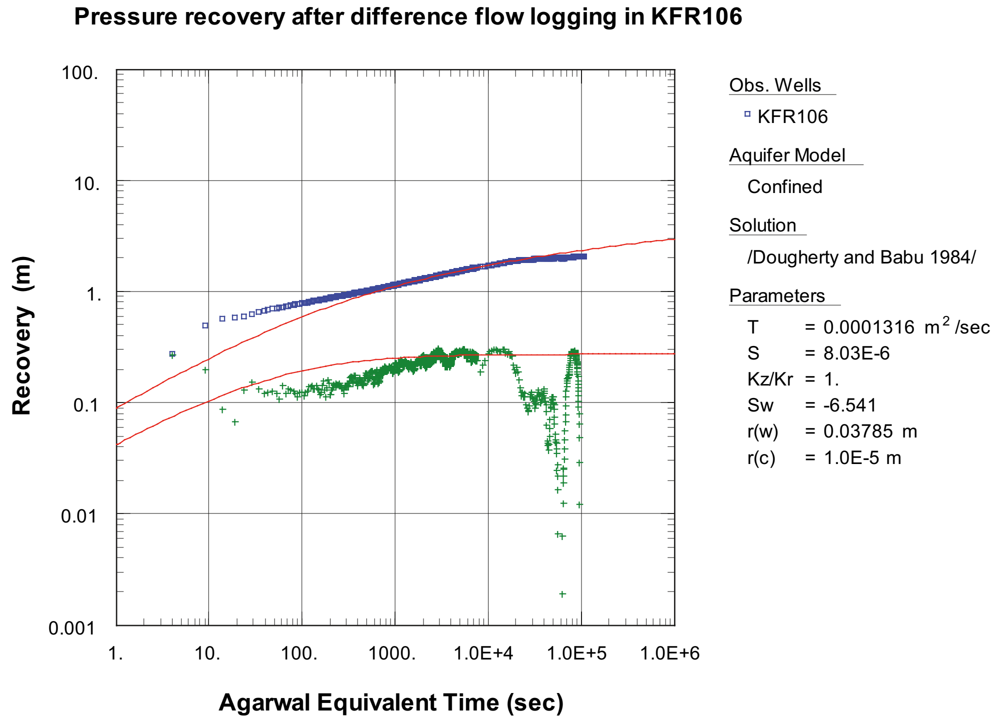

Figure 6-3a. *Log-log plot of the pressure recovery in KFR106 showing the observed pressure recovery of the water level (□) and associated derivative (+) versus Agarwal equivalent time together with simulated best fit curves of the pressure recovery and its derivative (-). The evaluation is made on the intermediate response.*

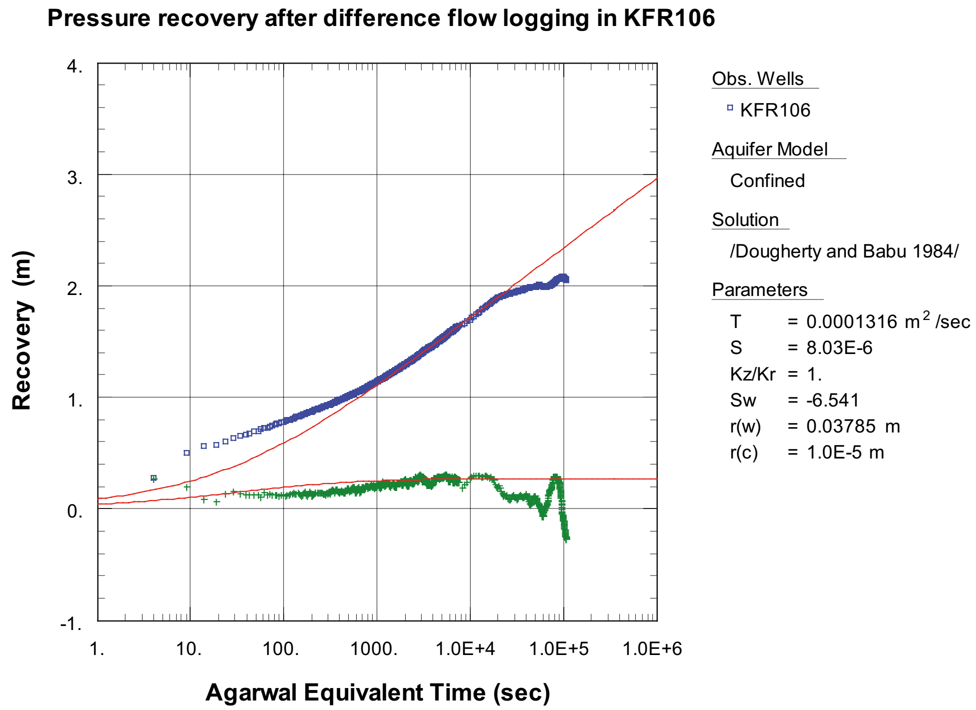

Figure 6-3b. *Lin-log plot of the pressure recovery in KFR106 showing the observed pressure recovery of the water level (□) and associated derivative (+) versus Agarwal equivalent time together with simulated best fit curves of the pressure recovery and its derivative (-).The evaluation is made on the intermediate response.*

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 borehole KFR106 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, the 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 were also measured.

The total amount of detected flowing fractures was 69. Transmissivity and hydraulic head were calculated for measured borehole sections and fractures. The highest estimated fracture transmissivity ($1.8 \cdot 10^{5}$ m^2/s) was at 156.0 m. The highest section transmissivity ($2.5 \cdot 10^{-5}$ m^2/s) was detected at length interval 151.51 m–156.51 m. Other high-transmissive sections were found at length intervals 66.42 m–76.43 m, 81.41 m–86.41 m, 96.44 m–101.44 m and 261.67 m–266.67 m.

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Appendices

Appendices	KFR106.1.1–KFR106.1.15	SPR and Caliper results after length correction
Appendix	KFR106.1.16	Length correction
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Appendix	KFR106.2.3	Temperature of borehole water
Appendices	KFR106.3.1–KFR106.3.15	Flow rate, caliper and single point resistance
Appendix	KFR106.4	Explanations for the tables in Appendices 5 and 7
Appendices	KFR106.5.1–KFR106.5.2	Results of sequential flow logging
Appendix	KFR106.6.1	Plotted flow rates of 5 m sections
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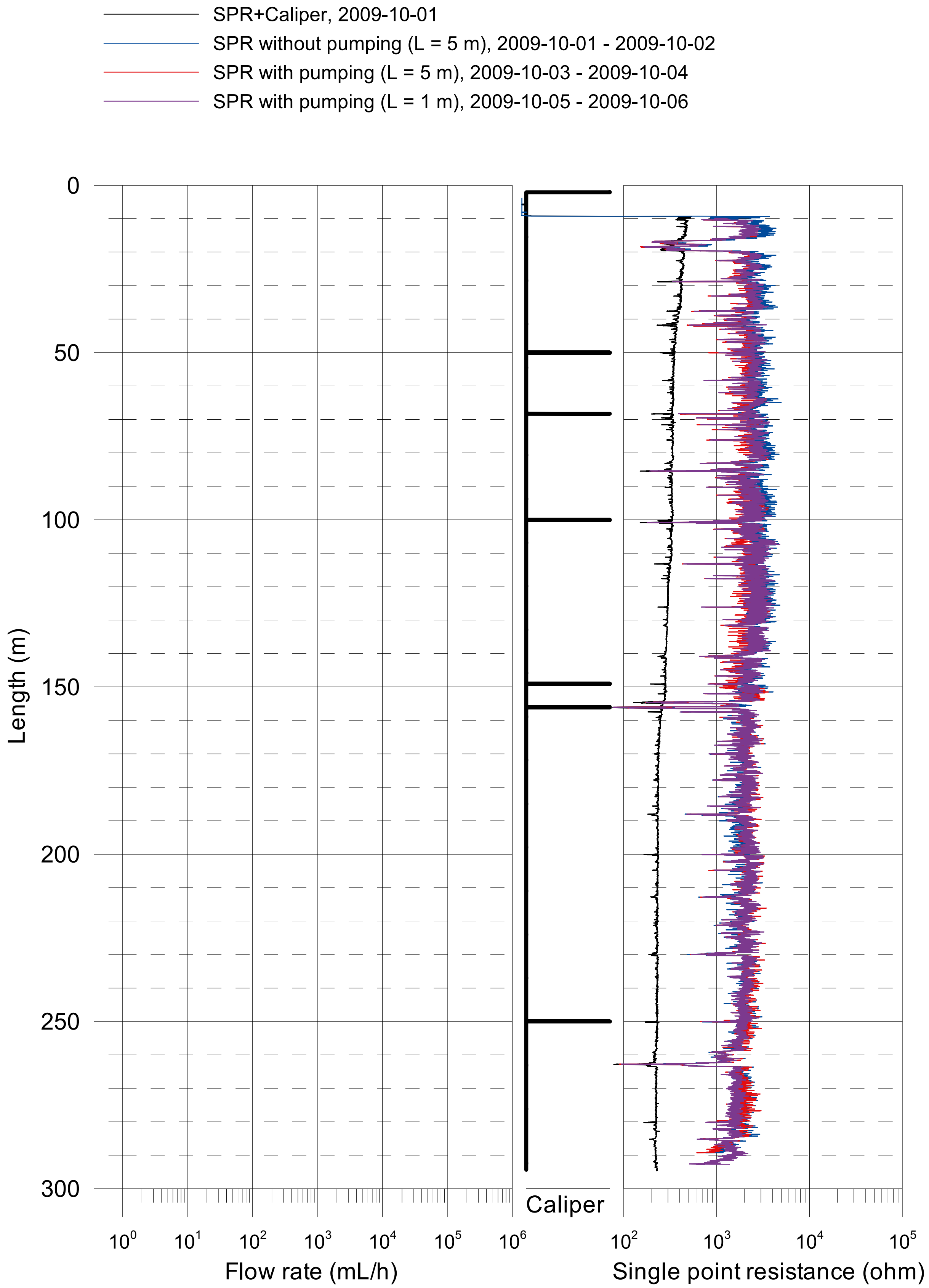
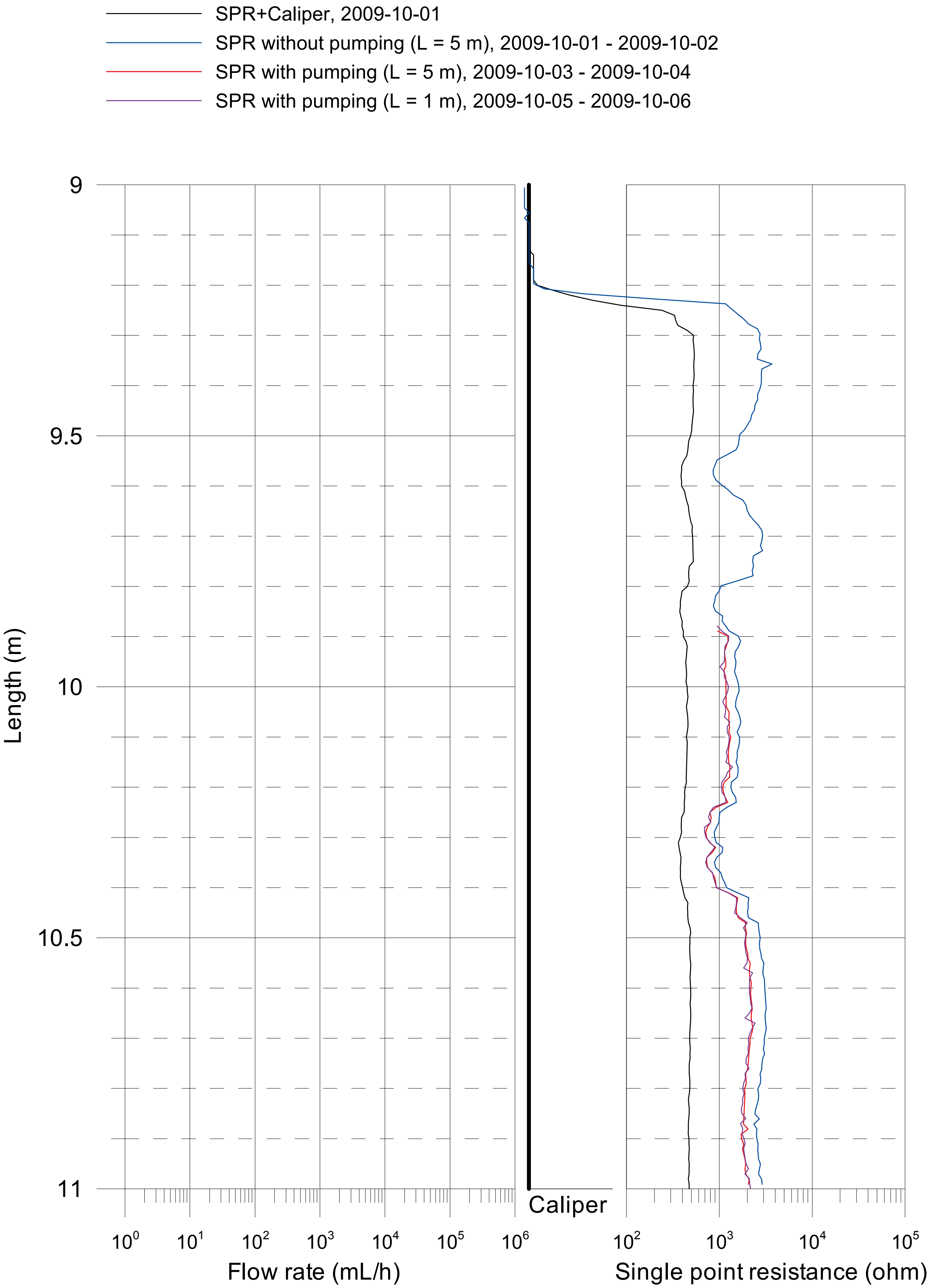
Appendices	KFR106.11.1–KFR106.11.4	Fracture-specific EC results by date

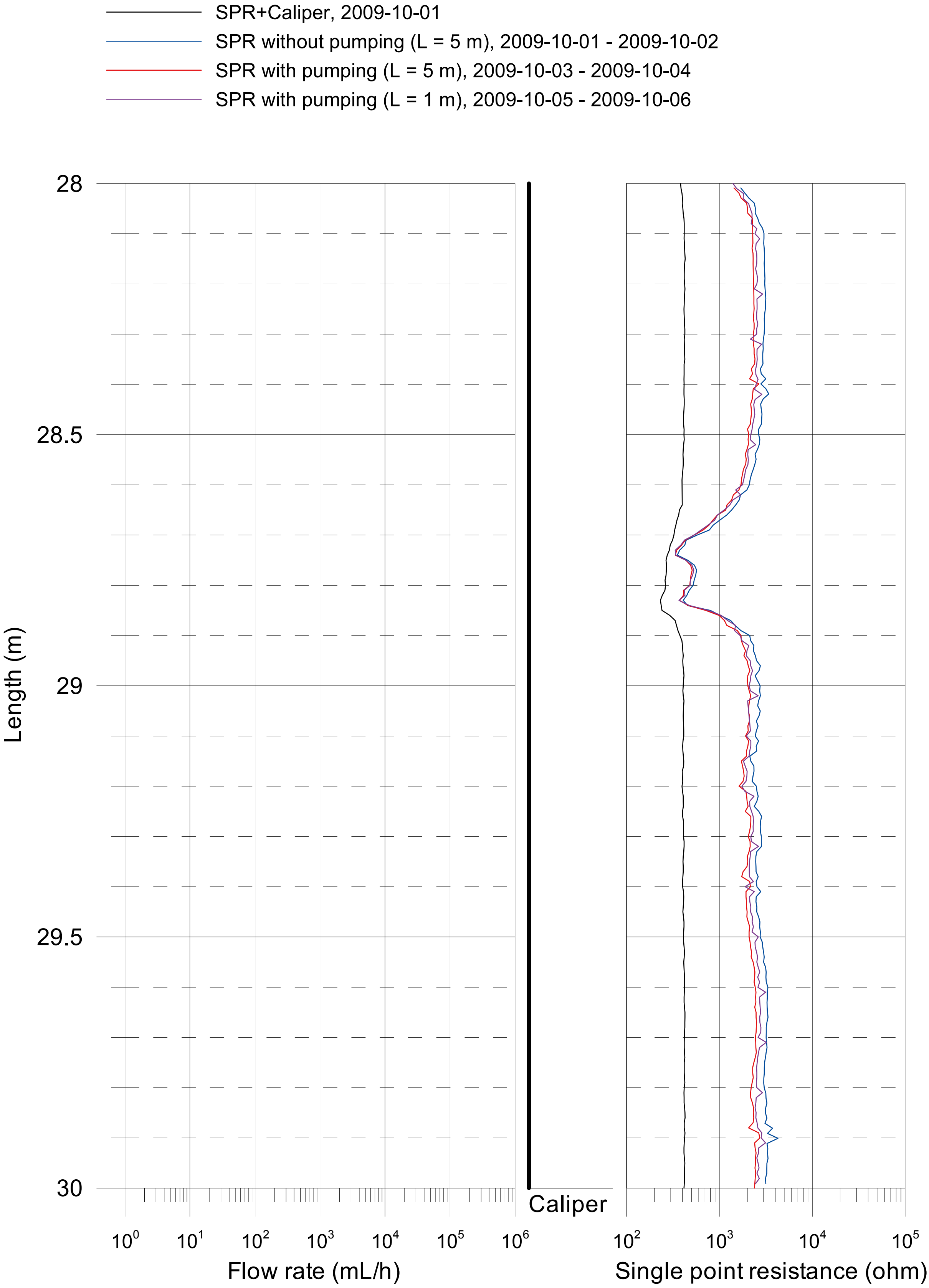
Forsmark, borehole KFR106
SPR and Caliper results after length correction



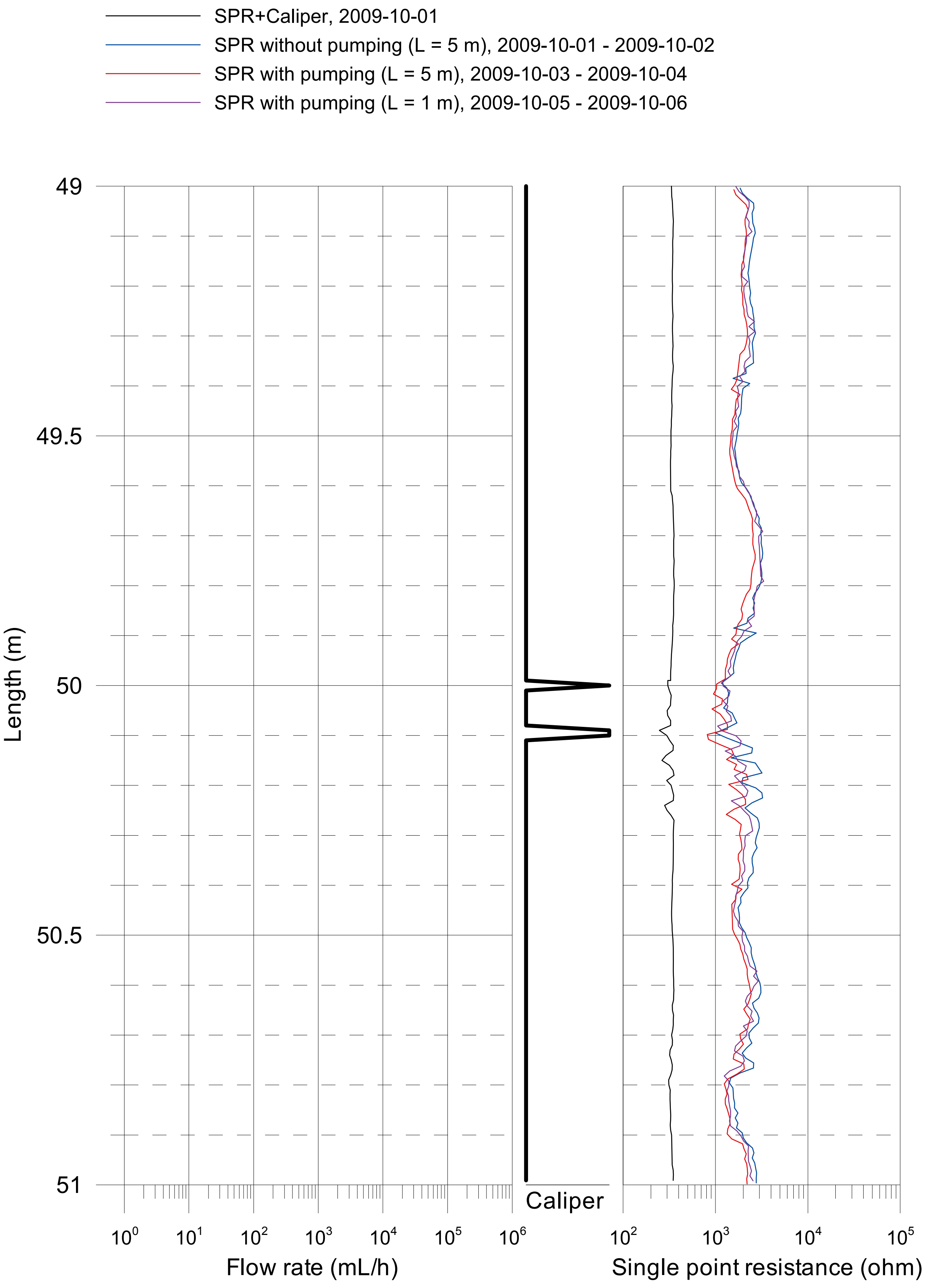
Forsmark, borehole KFR106
SPR and Caliper results after length correction



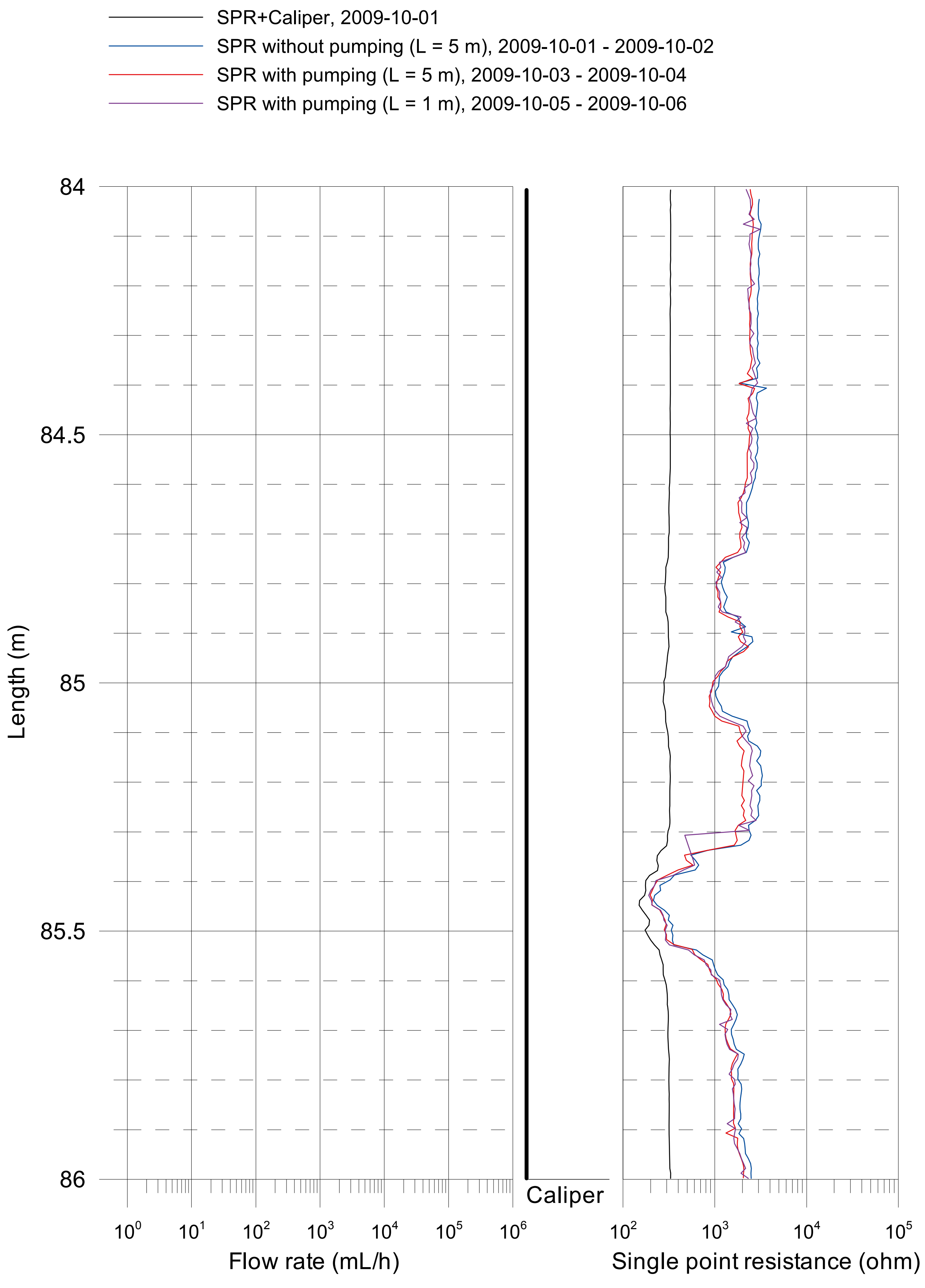
Forsmark, borehole KFR106
SPR and Caliper results after length correction



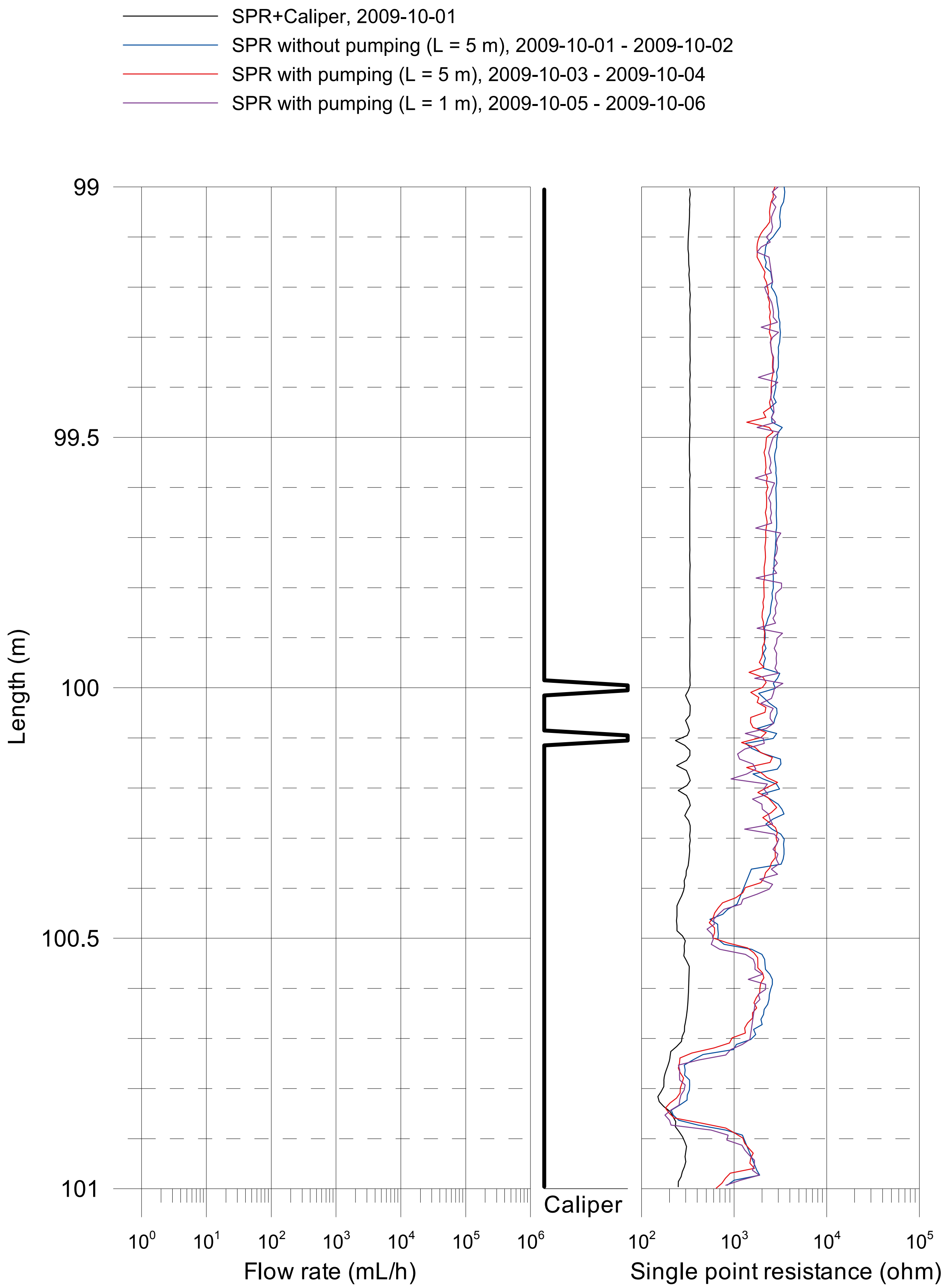
Forsmark, borehole KFR106
SPR and Caliper results after length correction



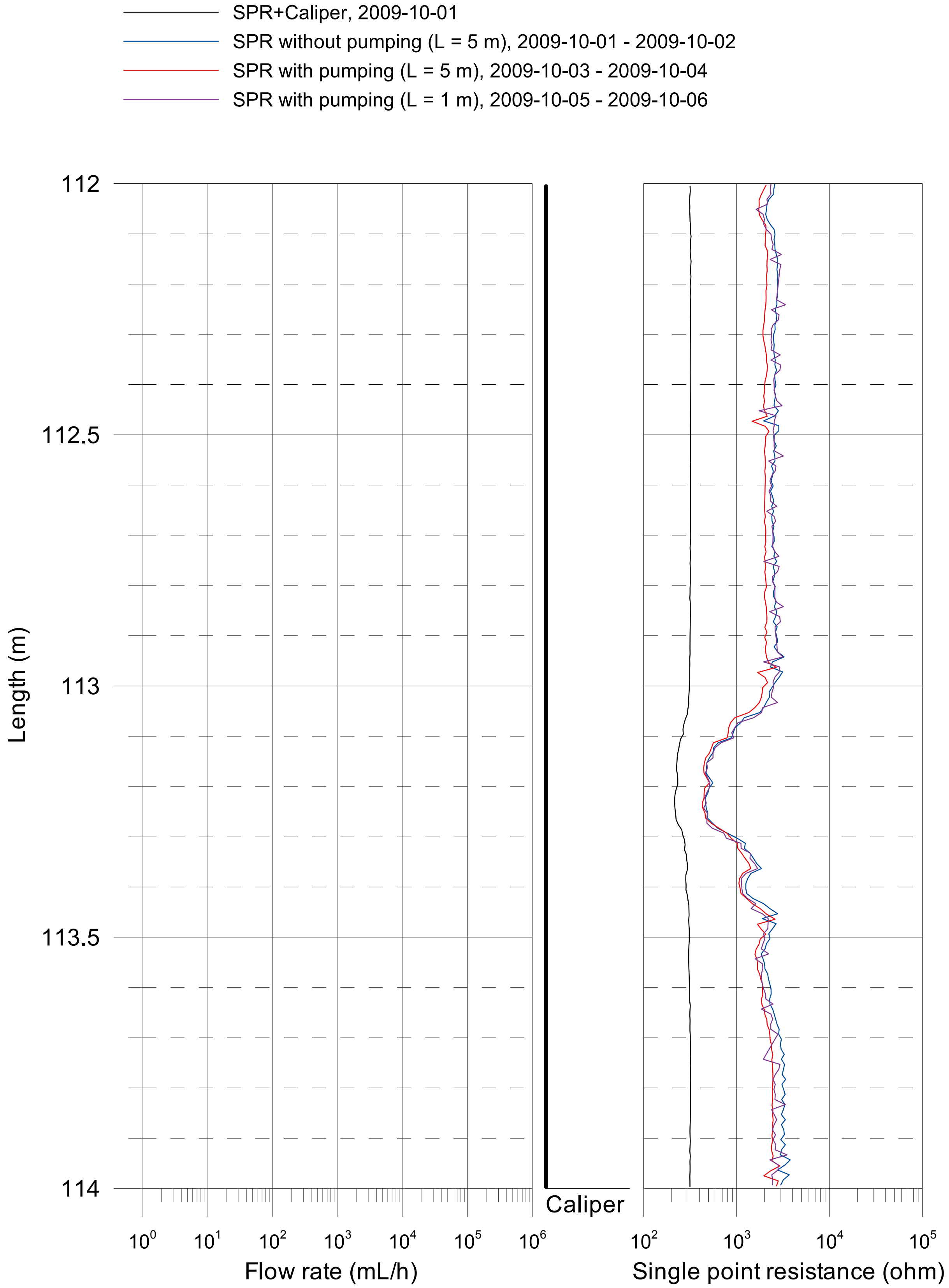
Forsmark, borehole KFR106
SPR and Caliper results after length correction



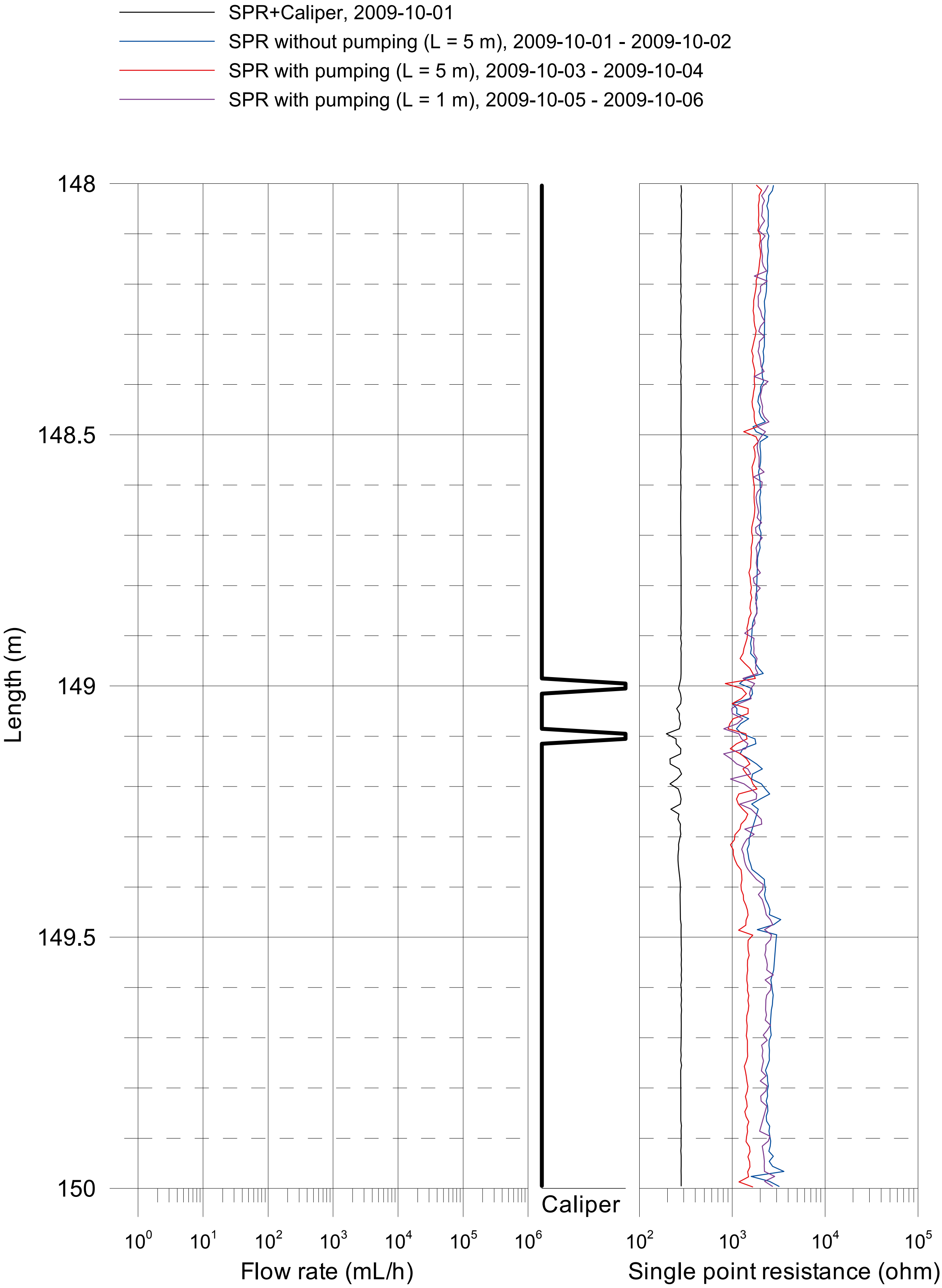
Forsmark, borehole KFR106
SPR and Caliper results after length correction



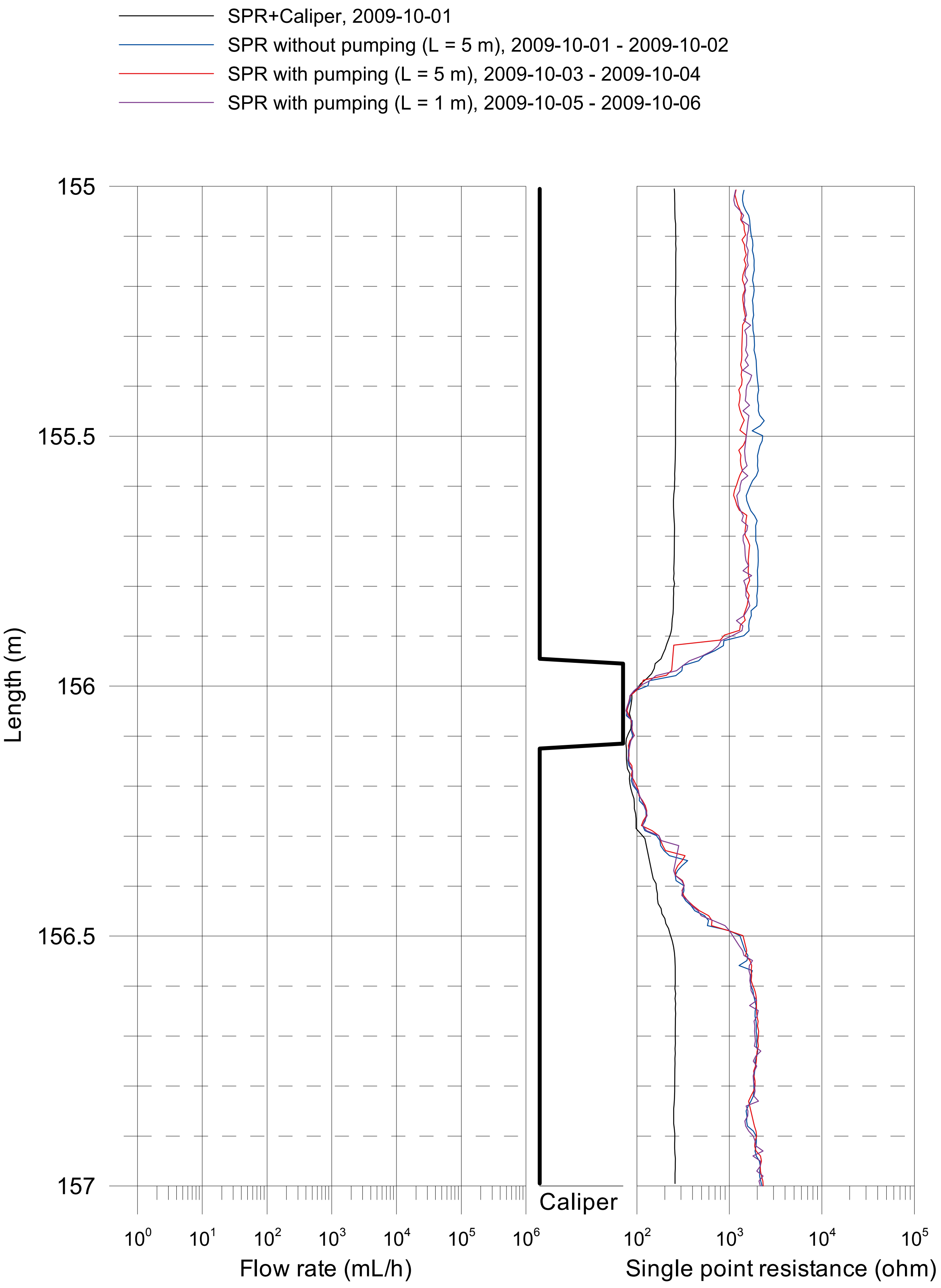
Forsmark, borehole KFR106
SPR and Caliper results after length correction



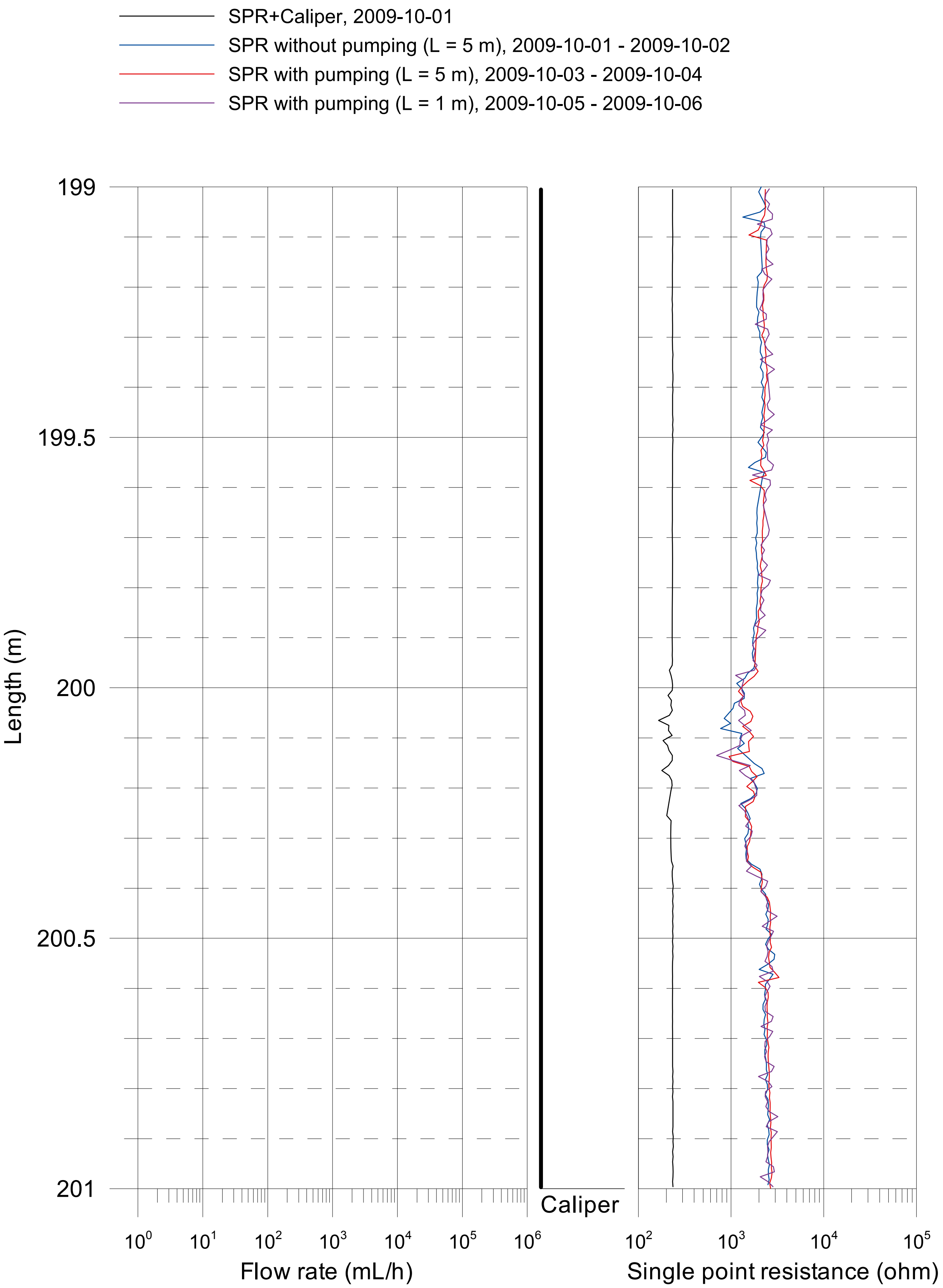
Forsmark, borehole KFR106
SPR and Caliper results after length correction



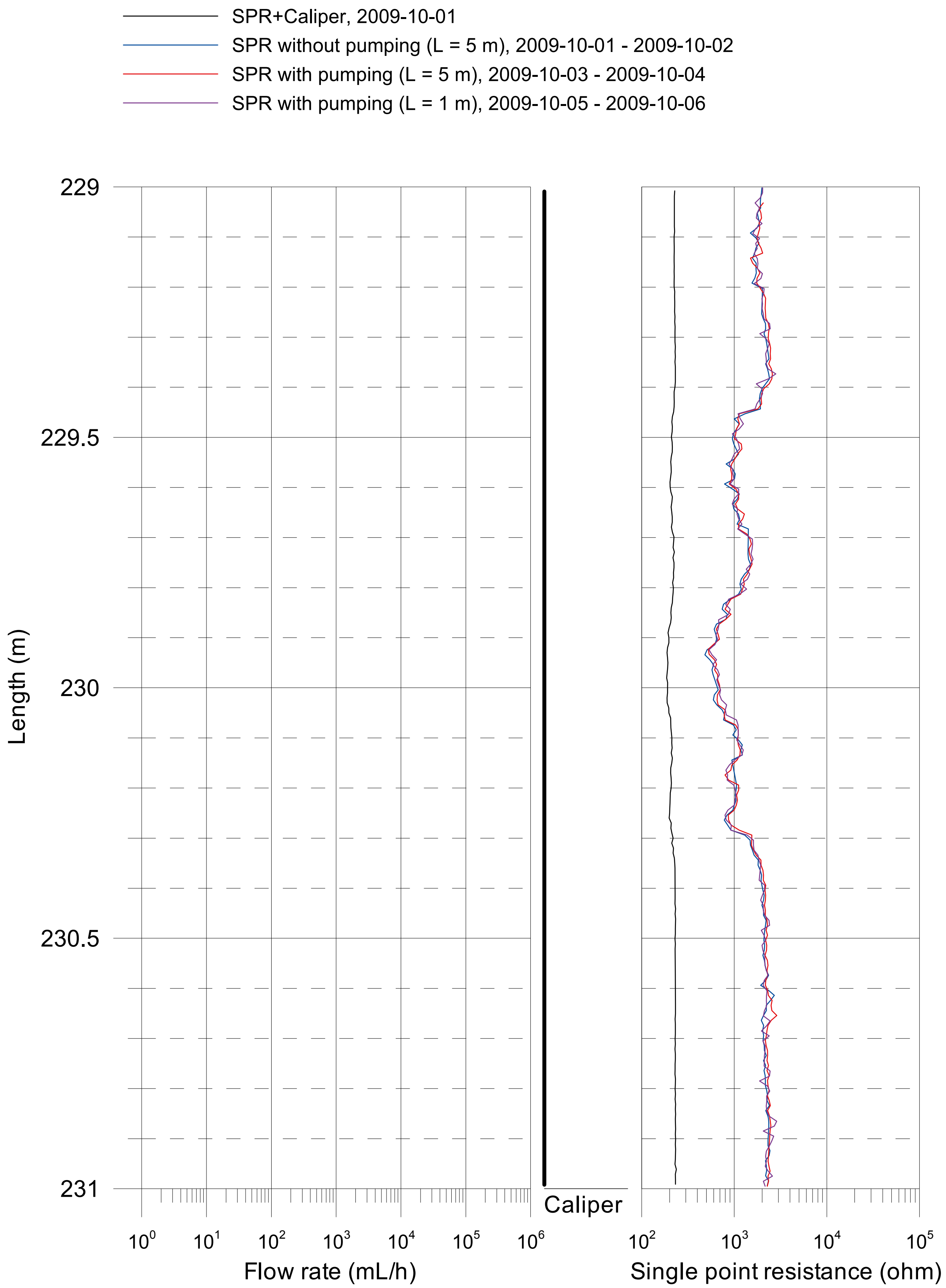
Forsmark, borehole KFR106
SPR and Caliper results after length correction



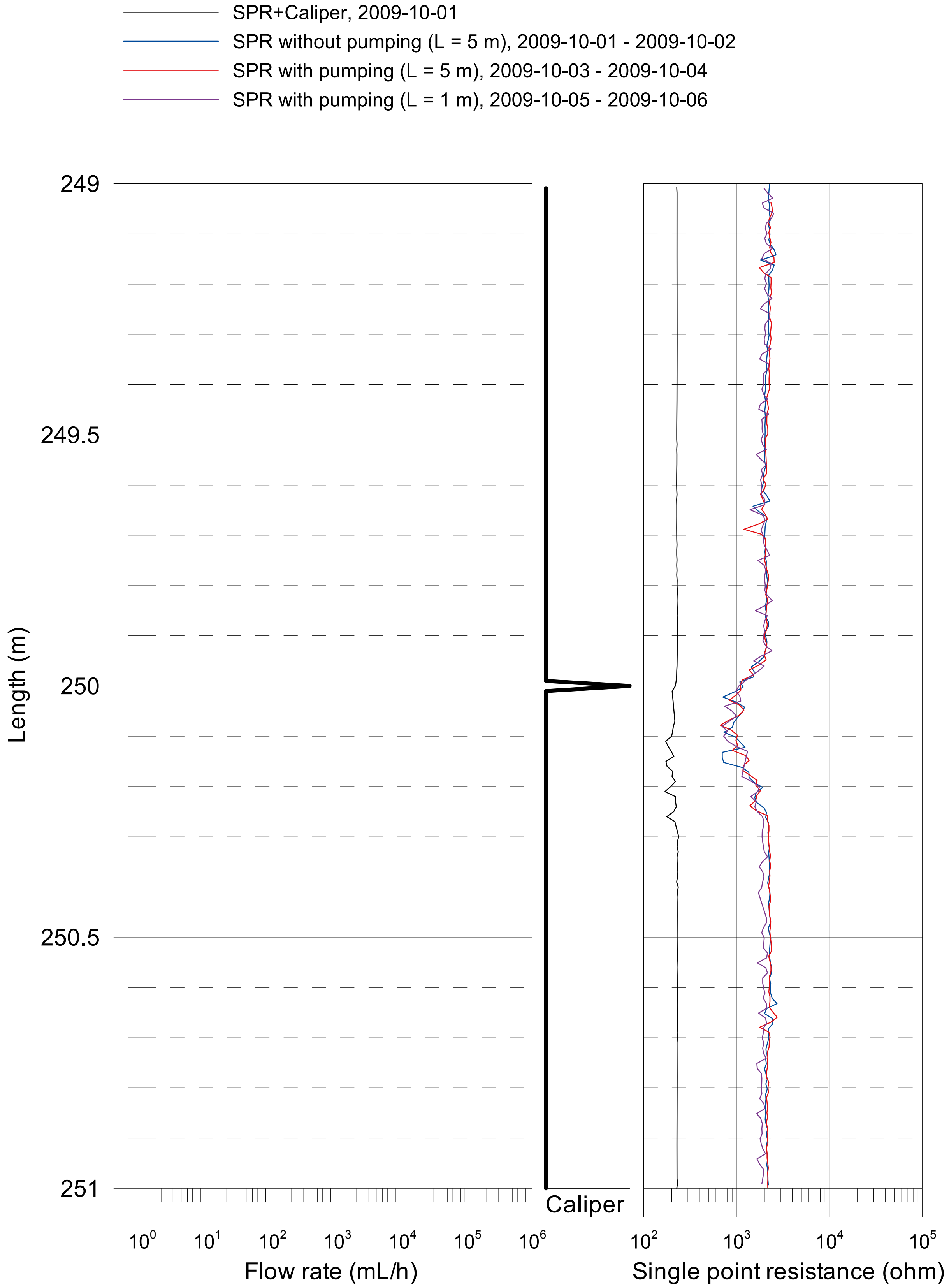
Forsmark, borehole KFR106
SPR and Caliper results after length correction



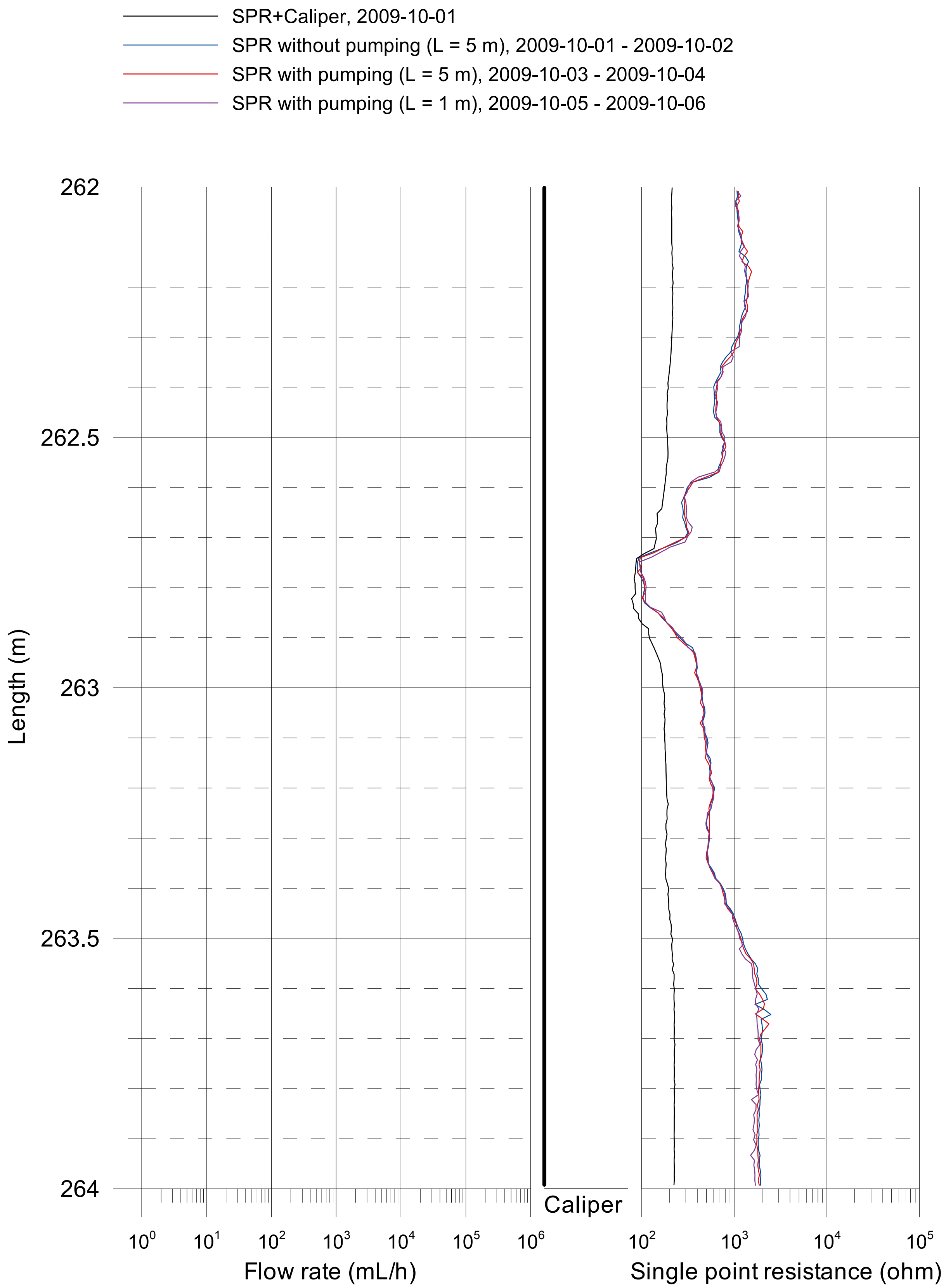
Forsmark, borehole KFR106
SPR and Caliper results after length correction



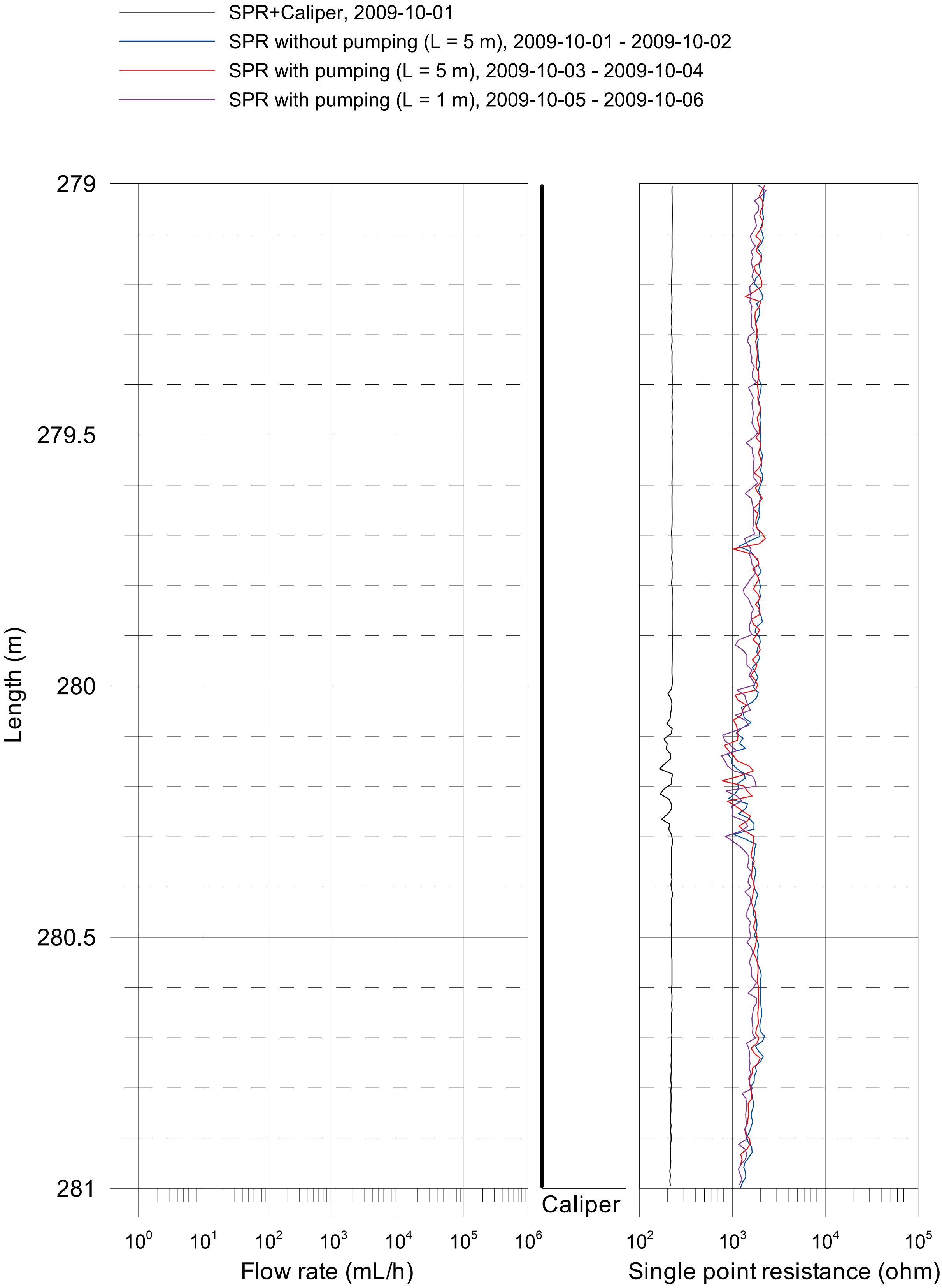
Forsmark, borehole KFR106
SPR and Caliper results after length correction



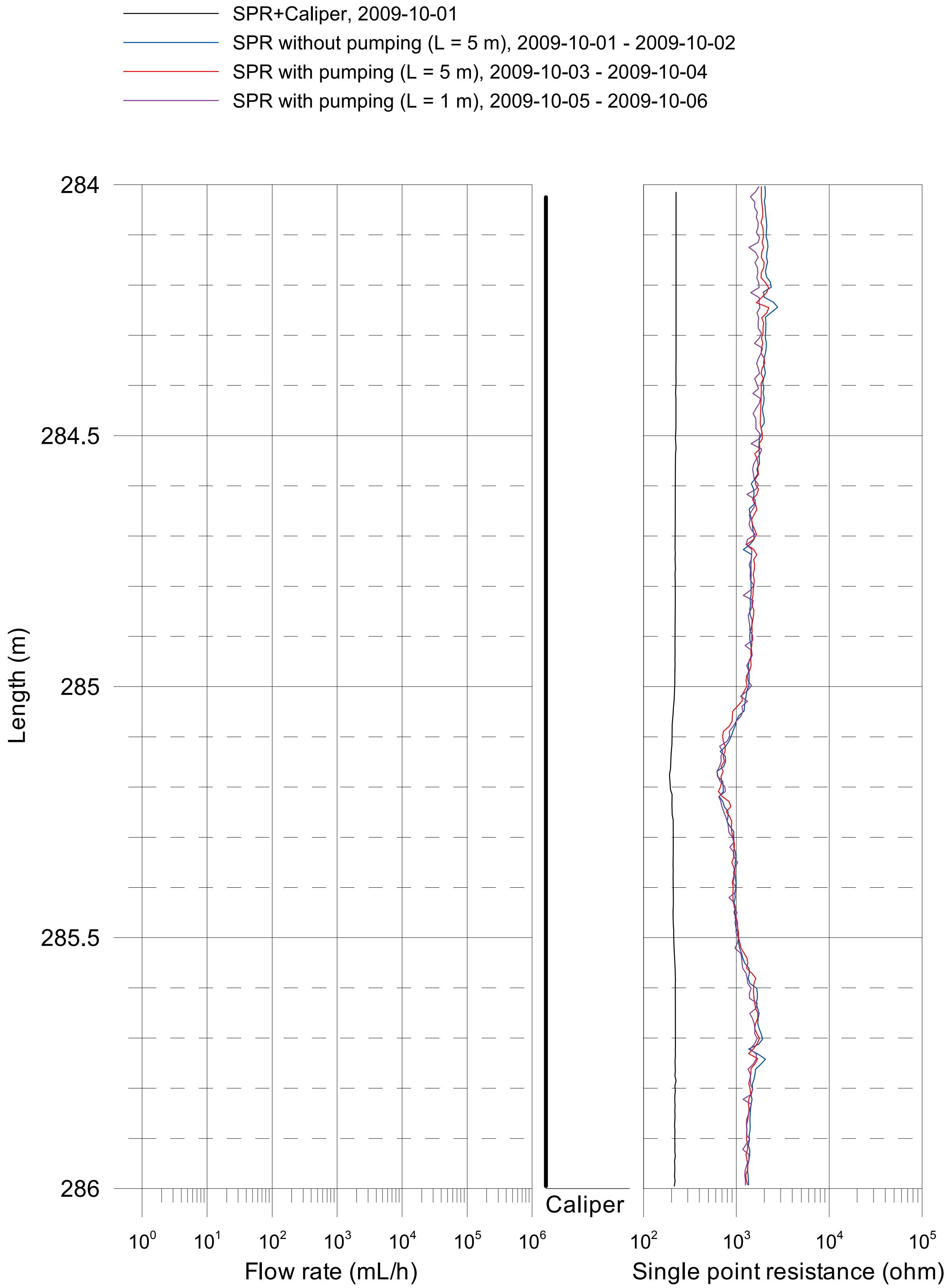
Forsmark, borehole KFR106
SPR and Caliper results after length correction



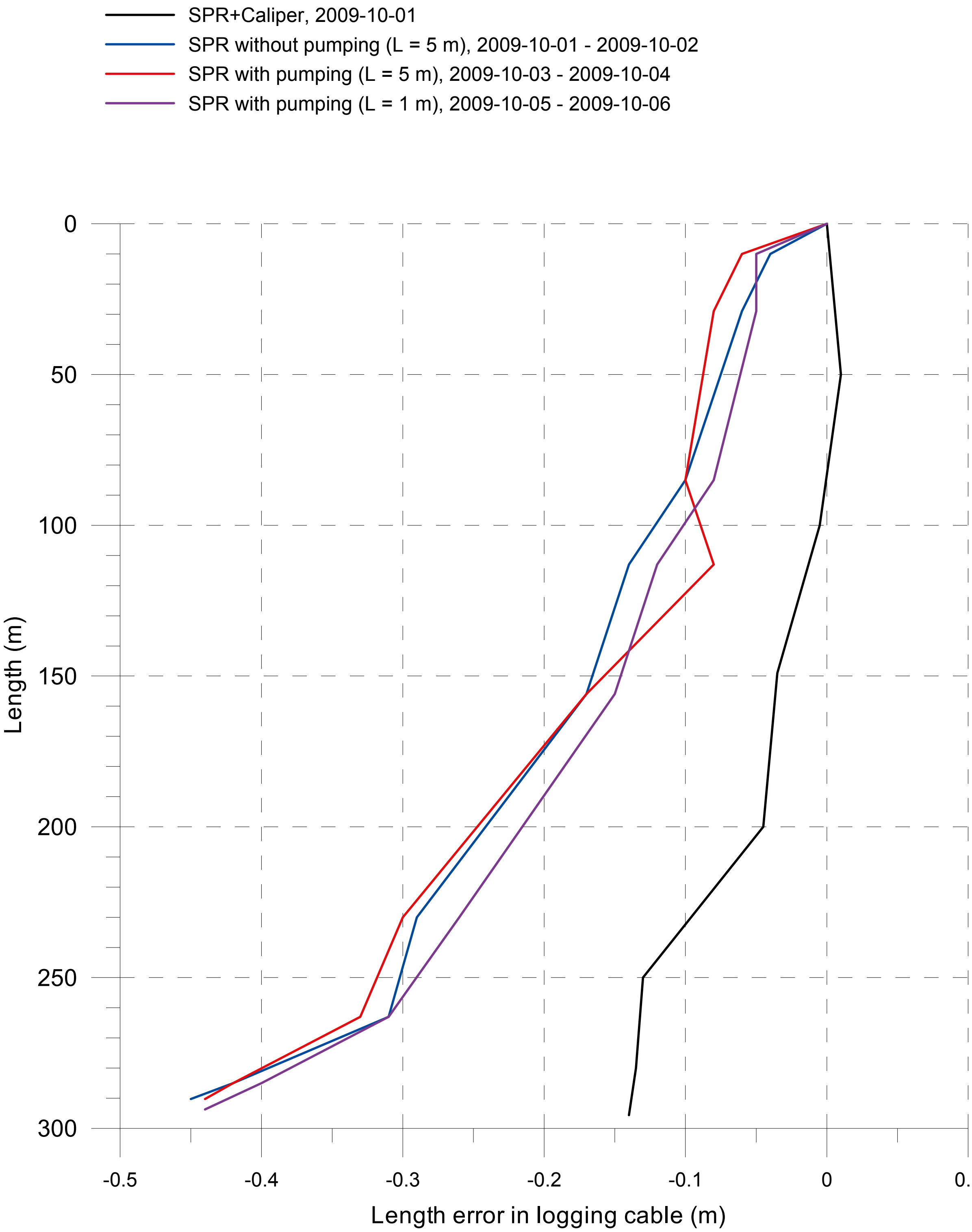
Forsmark, borehole KFR106
SPR and Caliper results after length correction



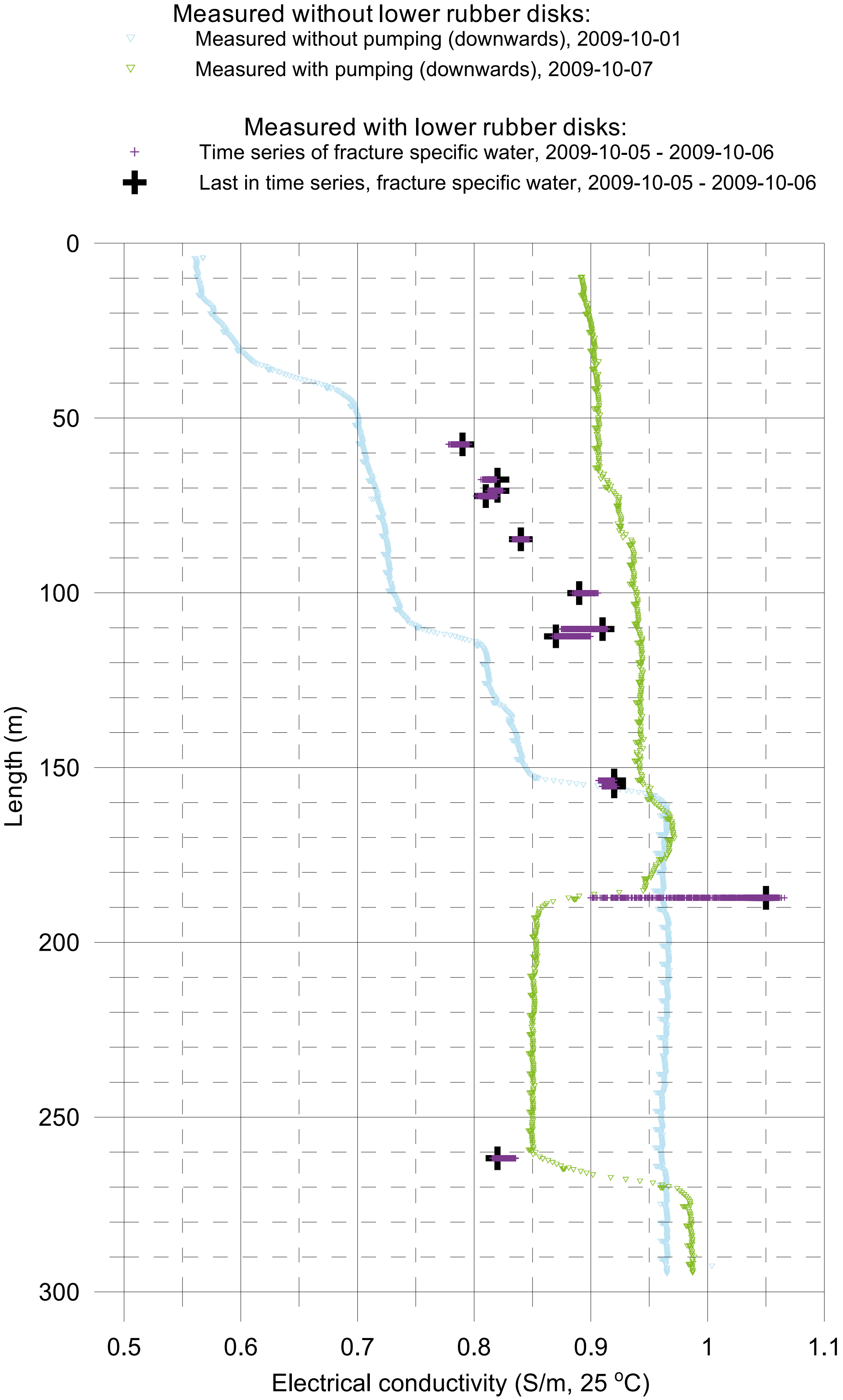
Forsmark, borehole KFR106
SPR and Caliper results after length correction

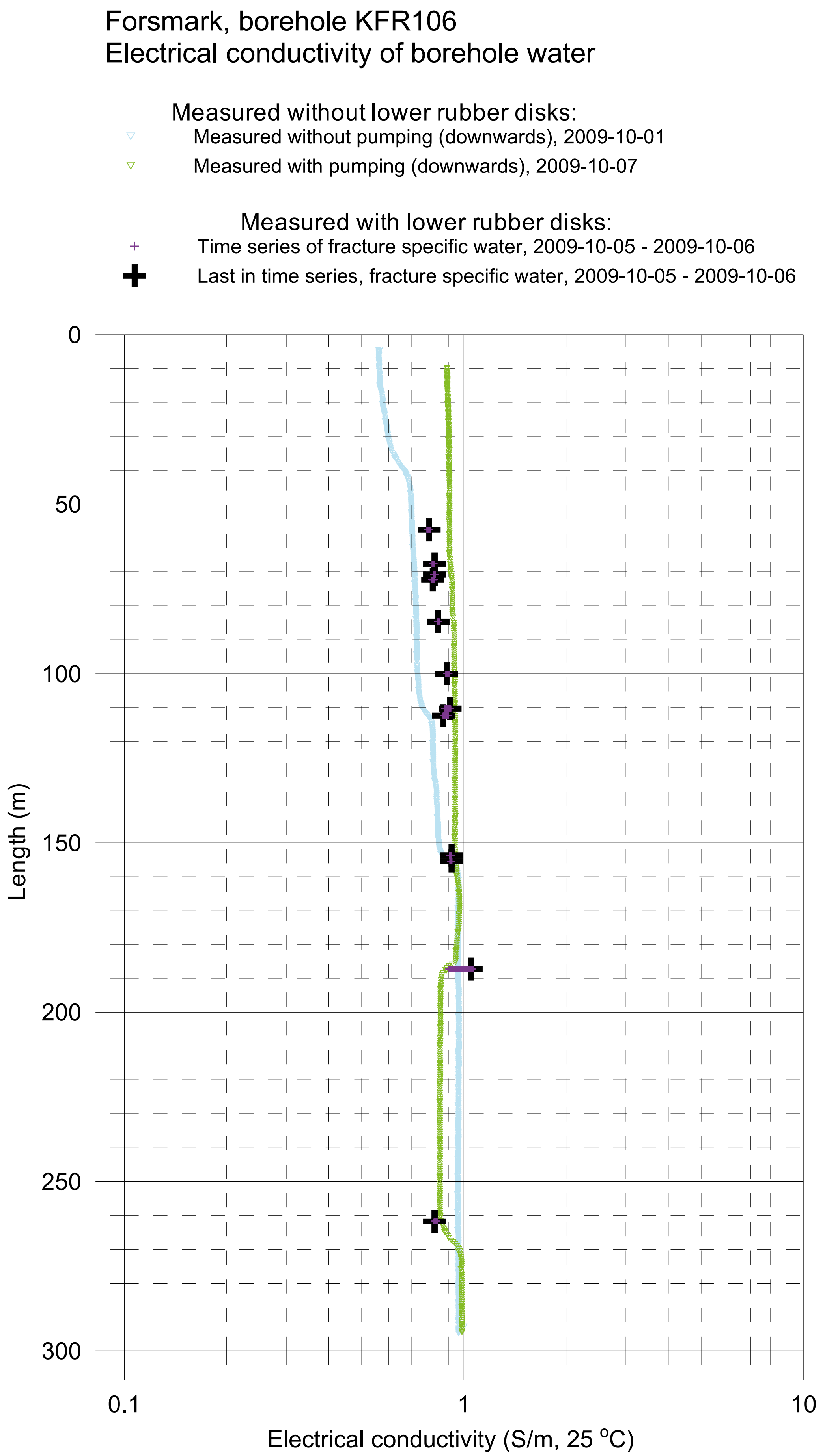


Forsmark, borehole KFR106
Length correction

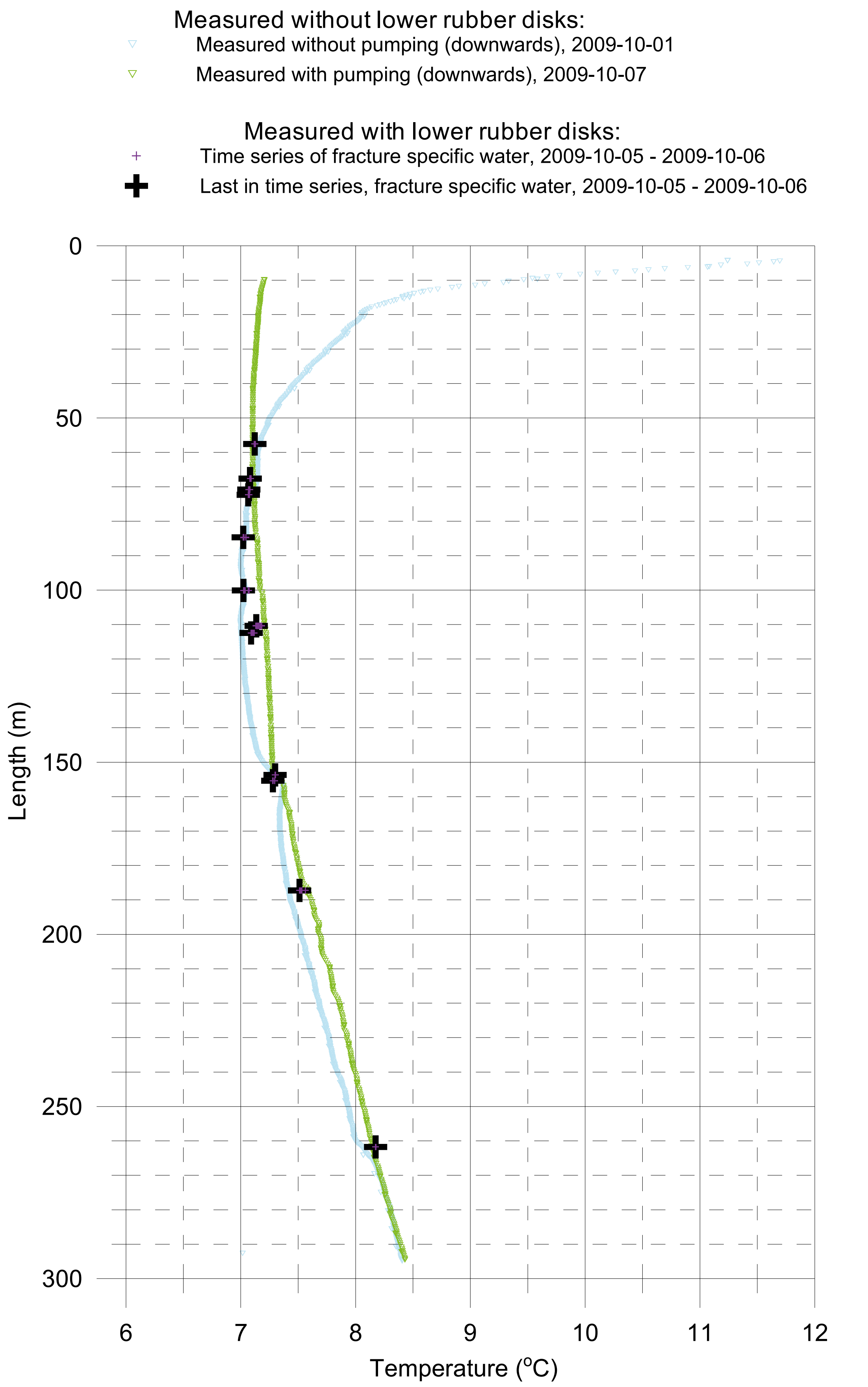


Forsmark, borehole KFR106
Electrical conductivity of borehole water

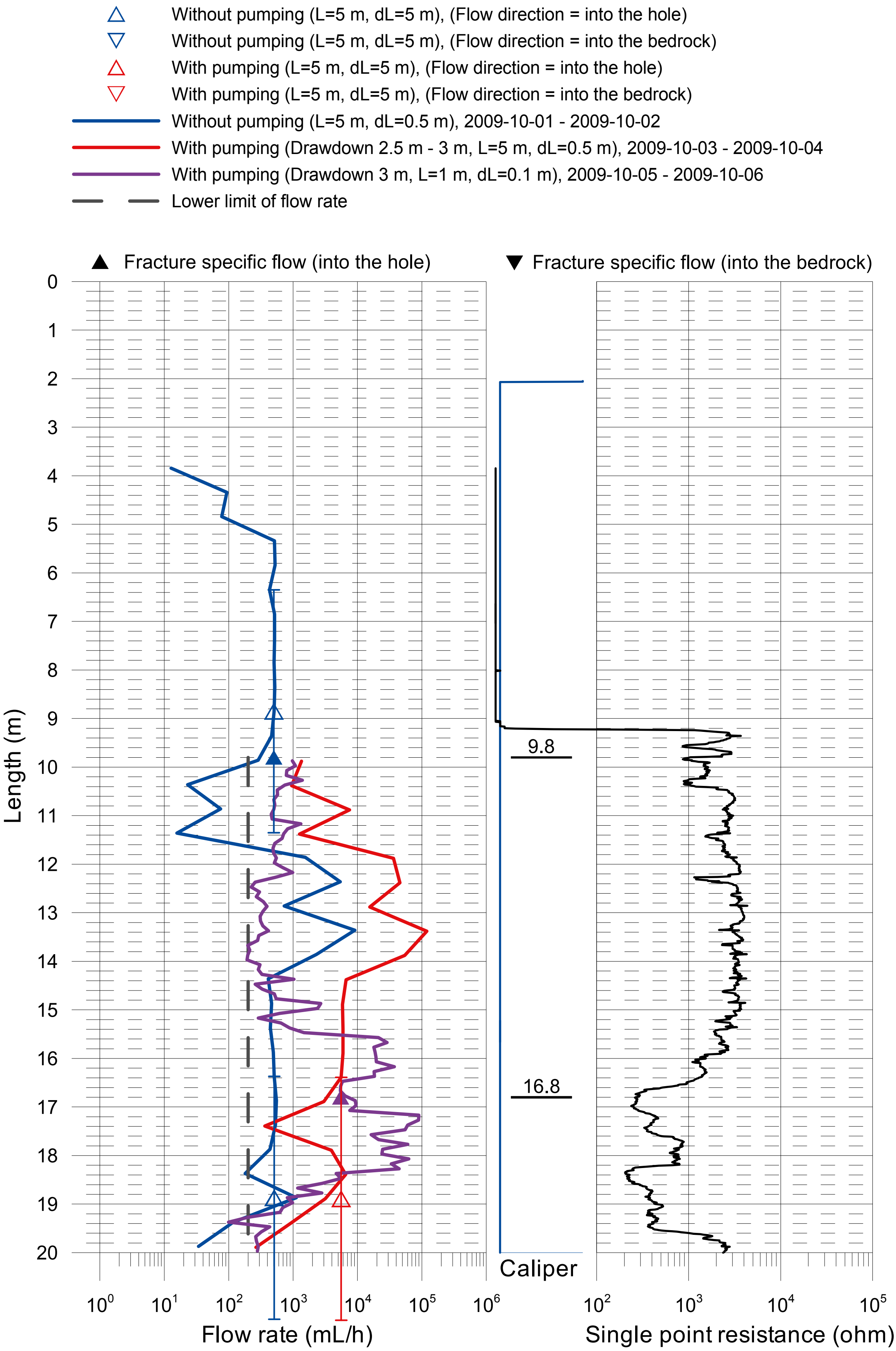



Forsmark, borehole KFR106
Electrical conductivity of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2009-10-01
Measured with pumping (downwards), 2009-10-07
Measured with lower rubber disks:
Time series of fracture specific water, 2009-10-05 - 2009-10-06
Last in time series, fracture specific water, 2009-10-05 - 2009-10-06
0
50
100
150
200
250
300
Length (m)
0.1
1
10
Electrical conductivity (S/m, 25 °C)

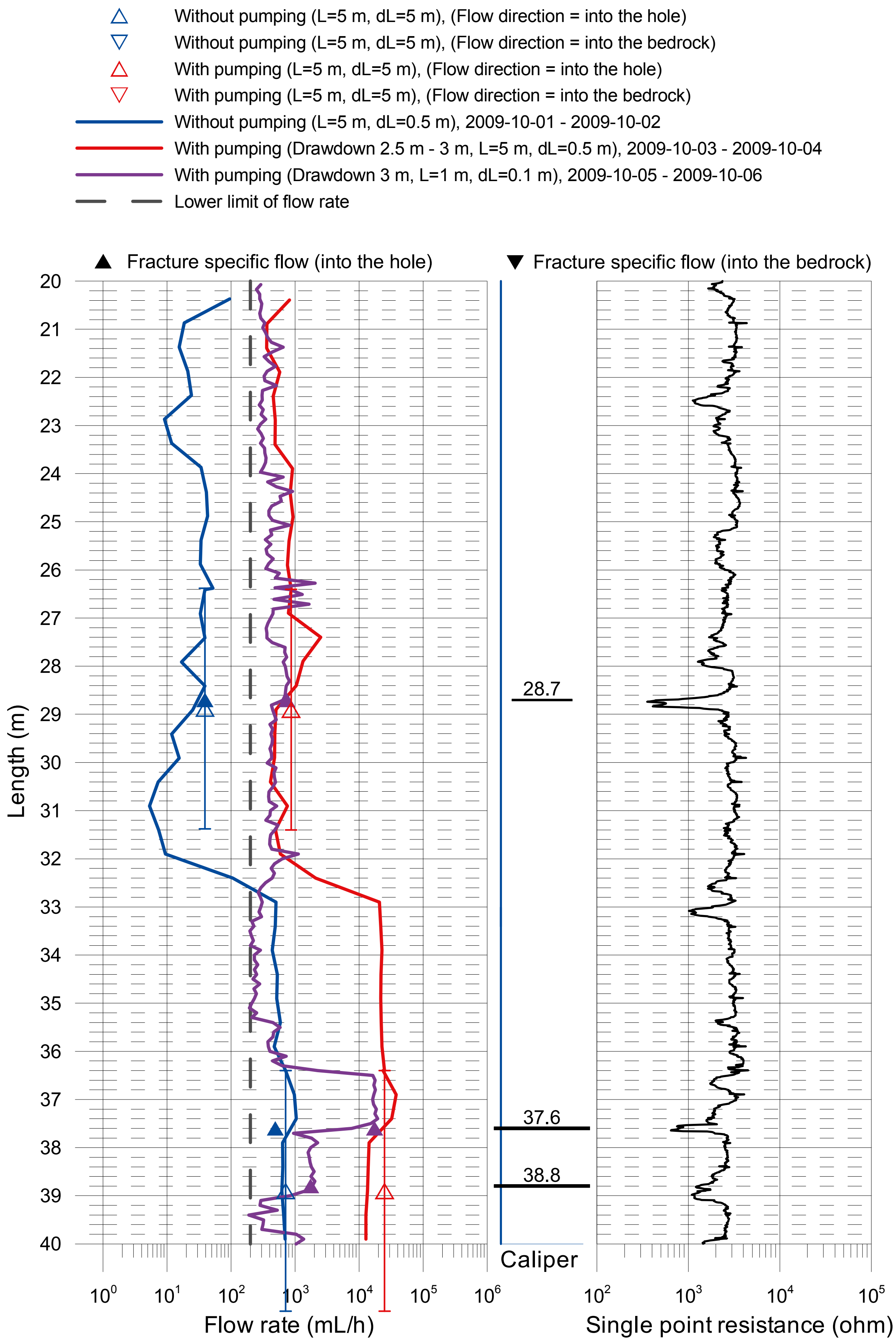
Forsmark, borehole KFR106
Temperature of borehole water



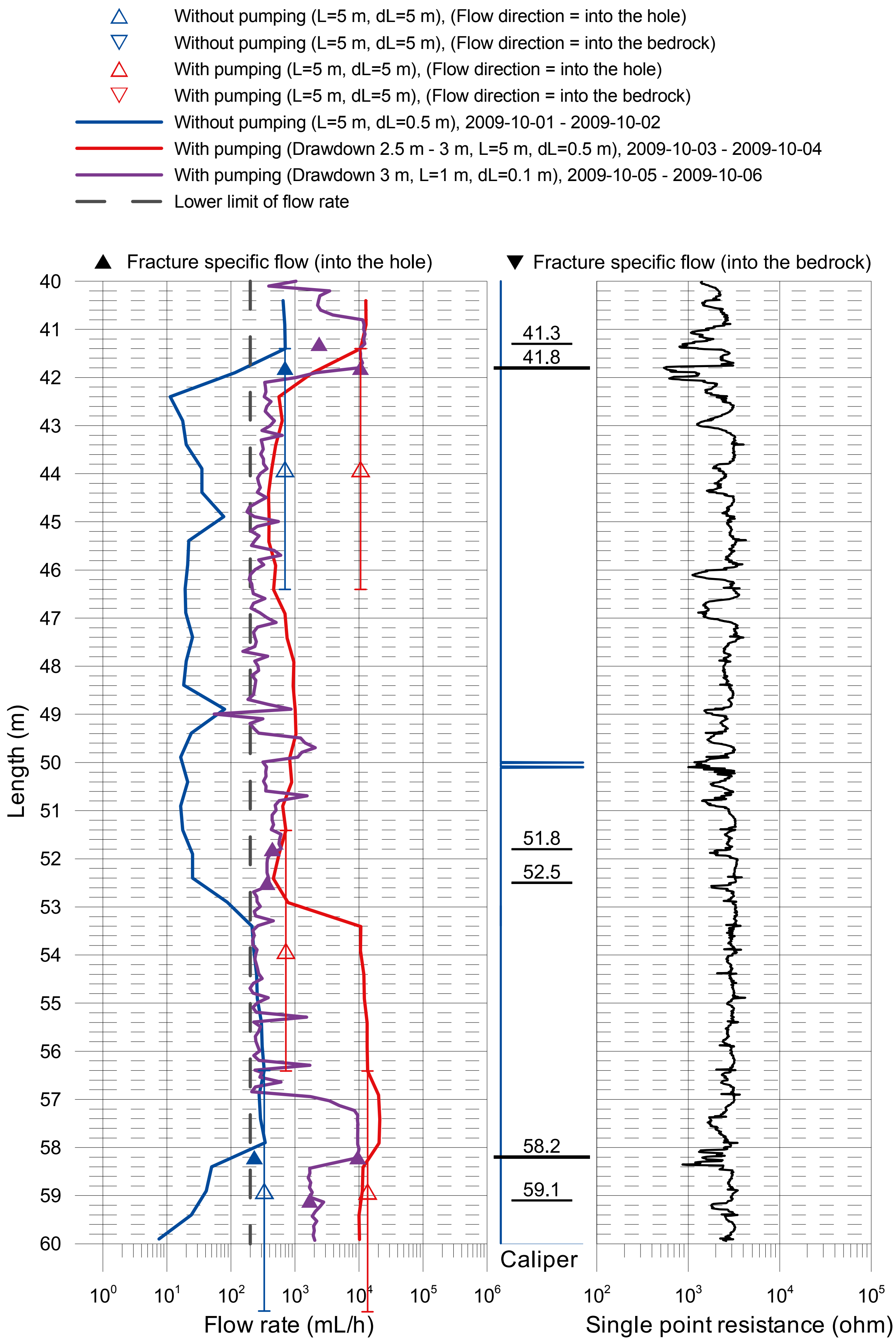
Forsmark, borehole KFR106
Flow rate, caliper and single point resistance



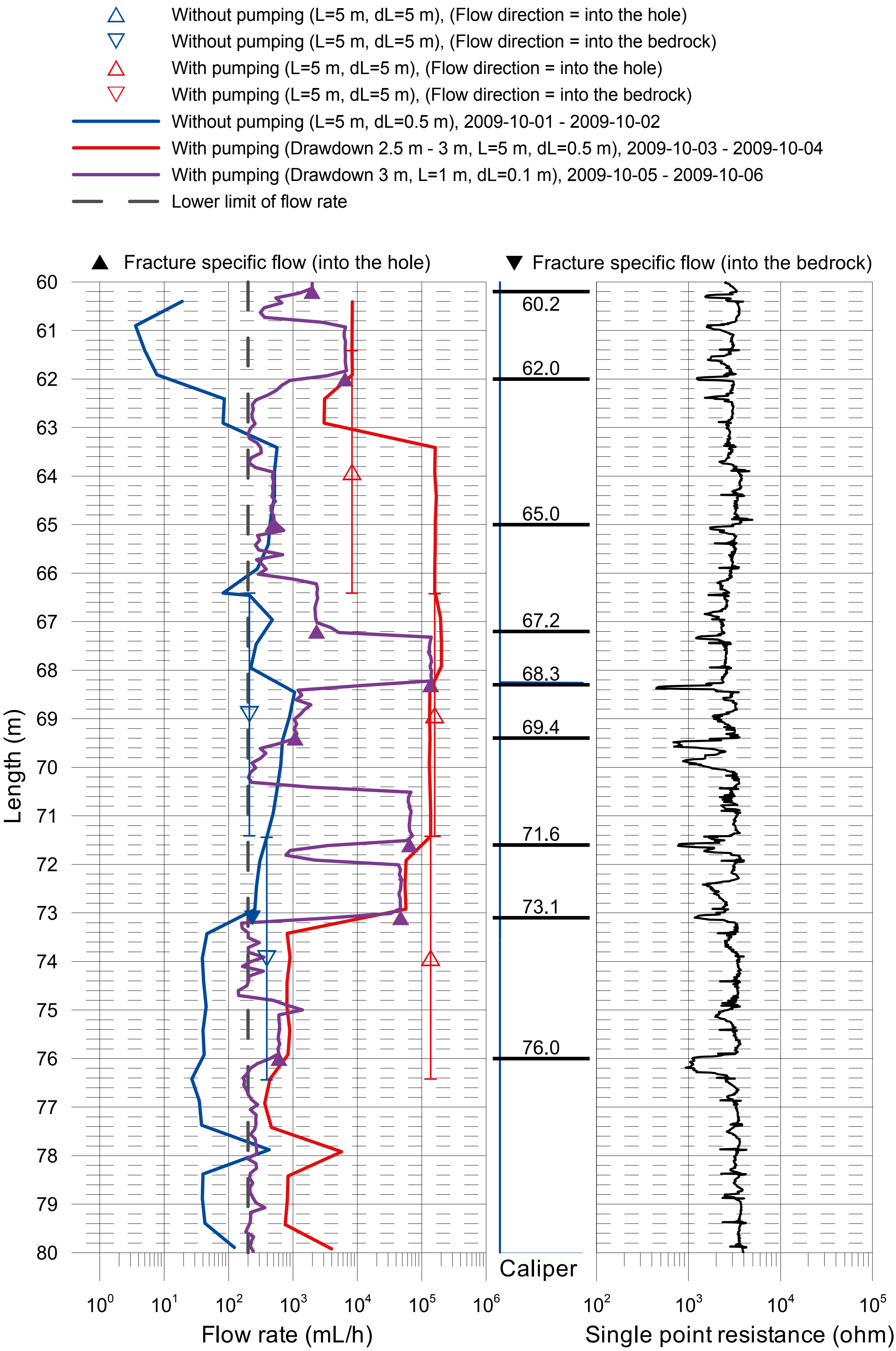
Forsmark, borehole KFR106
Flow rate, caliper and single point resistance



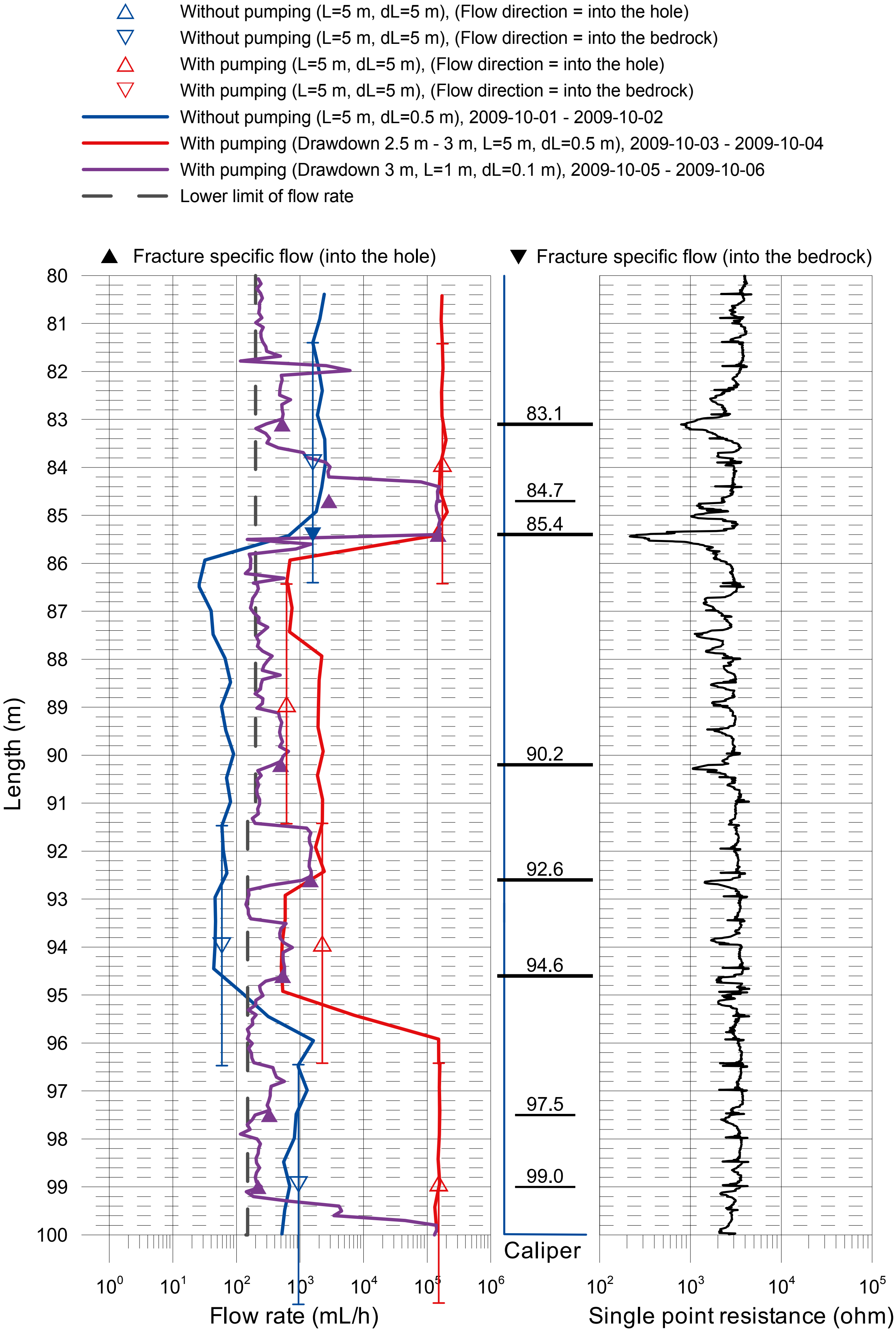
Forsmark, borehole KFR106
Flow rate, caliper and single point resistance



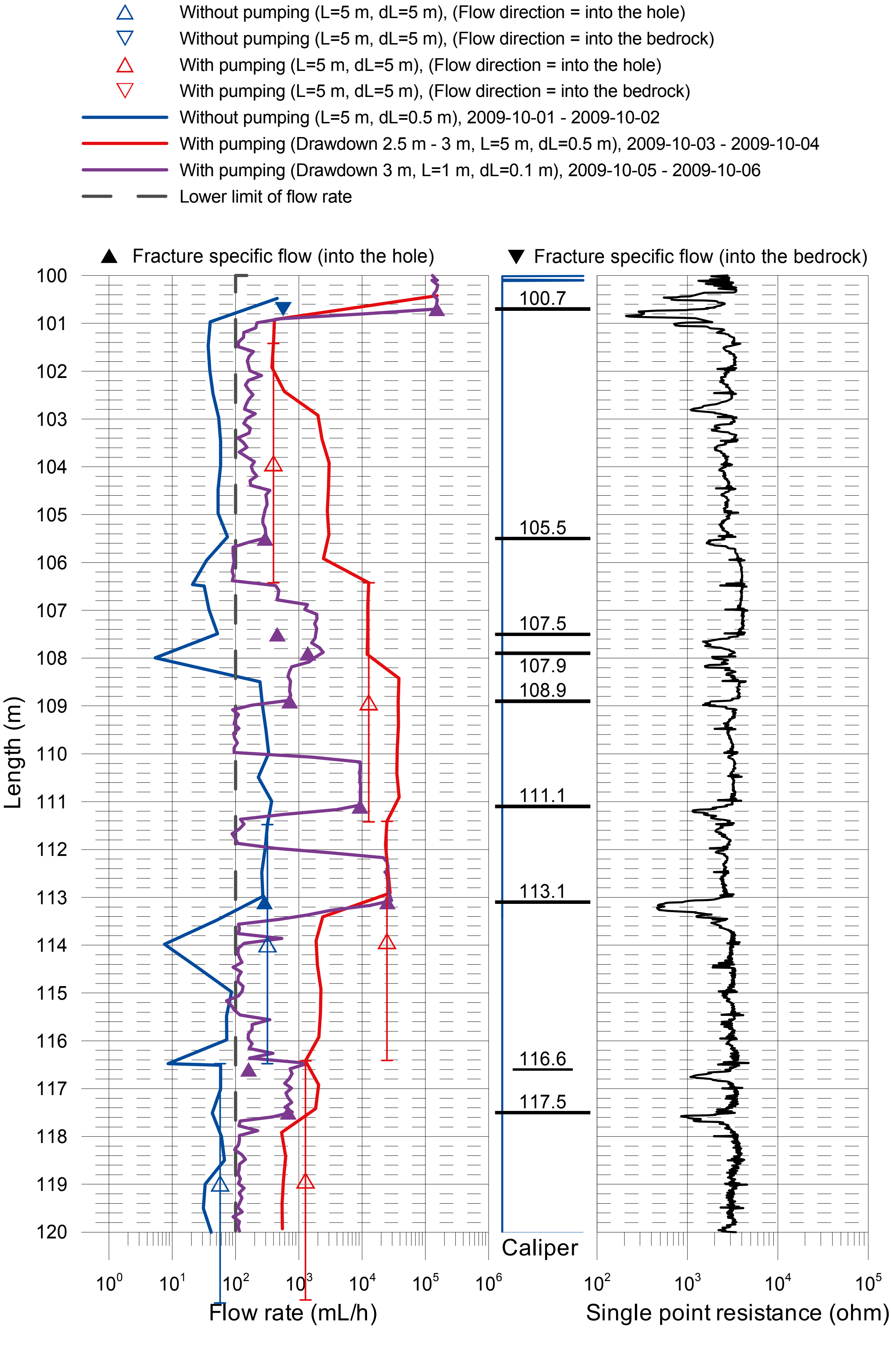
Forsmark, borehole KFR106
Flow rate, caliper and single point resistance



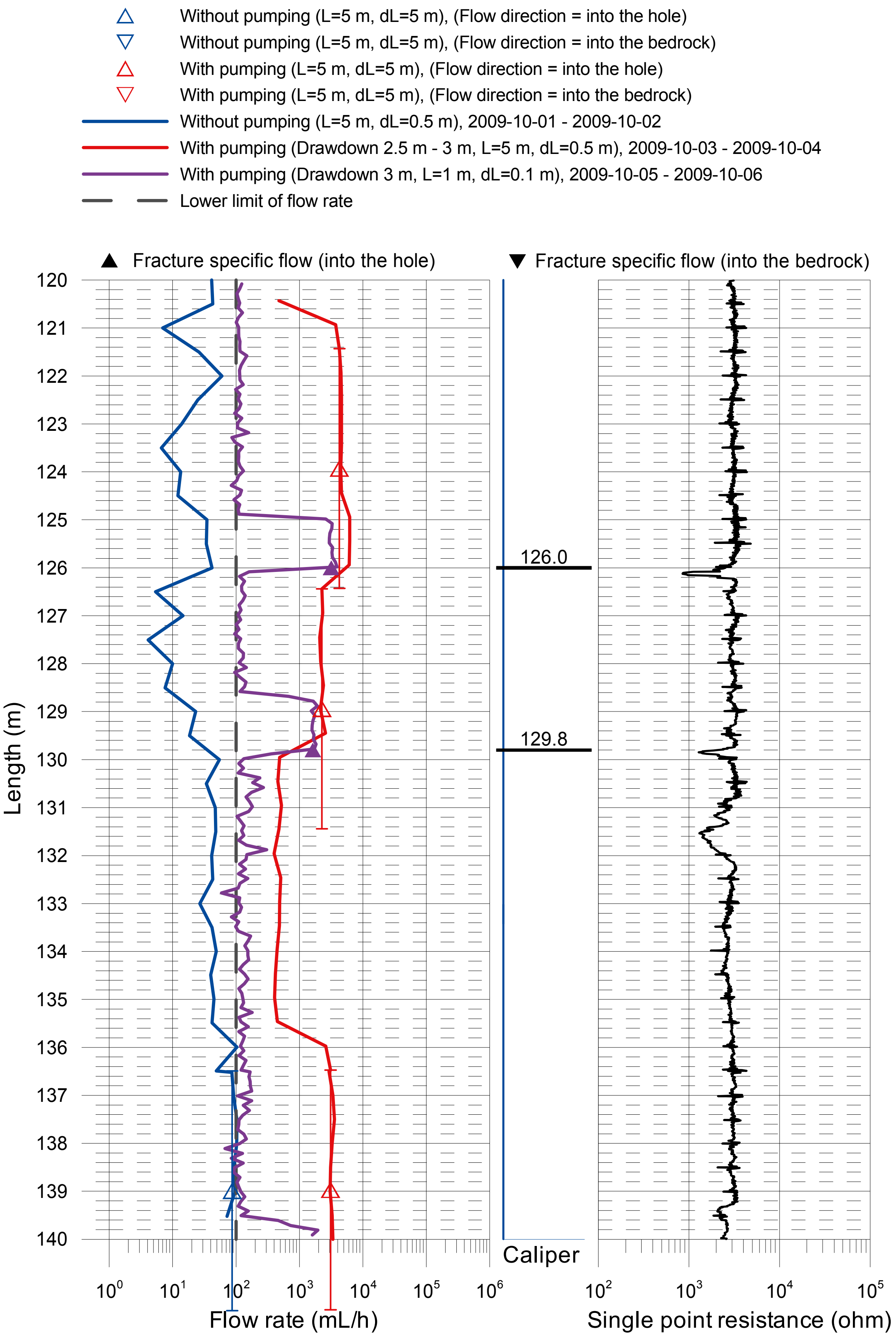
Forsmark, borehole KFR106
Flow rate, caliper and single point resistance



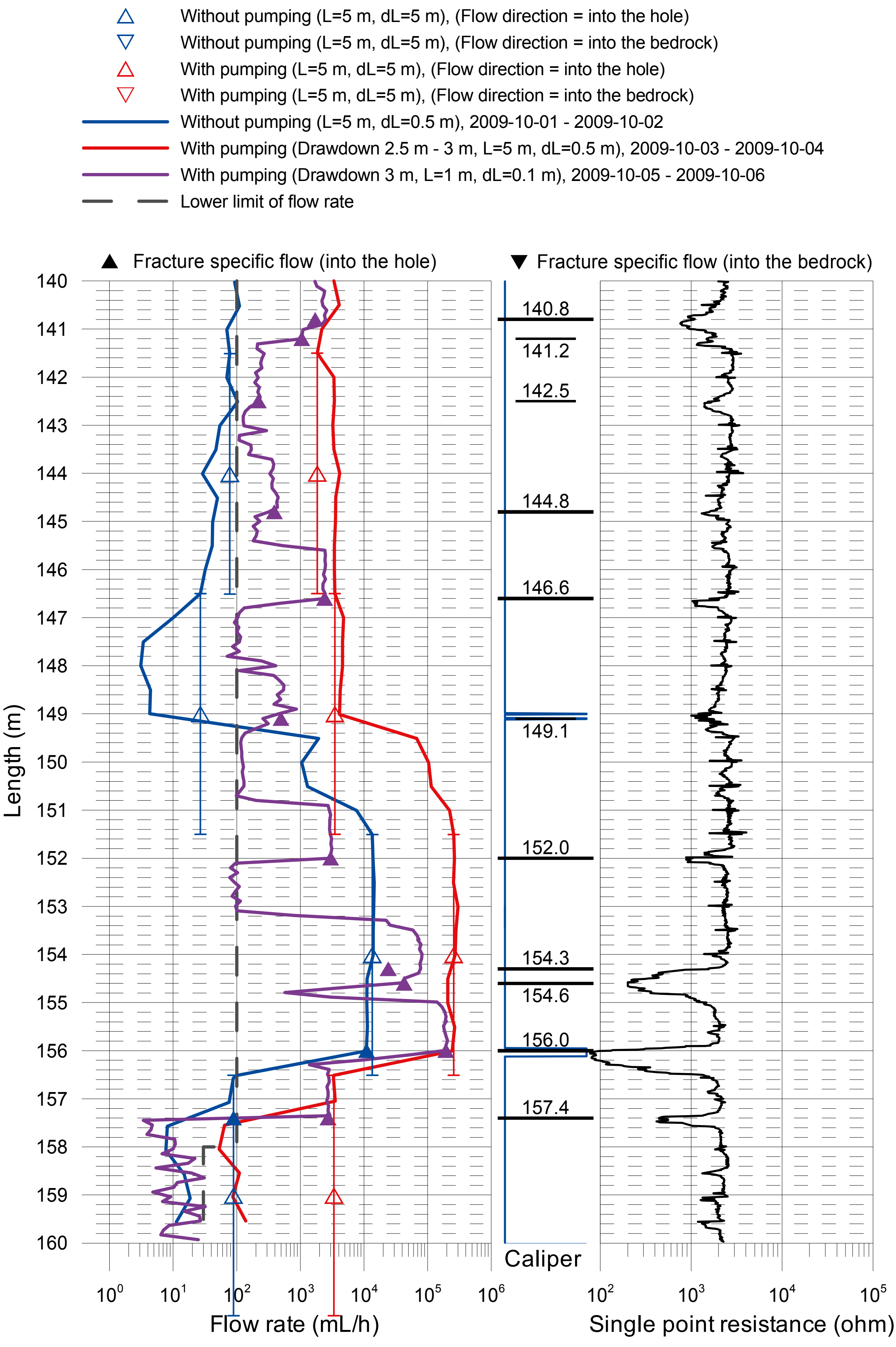
Forsmark, borehole KFR106
Flow rate, caliper and single point resistance



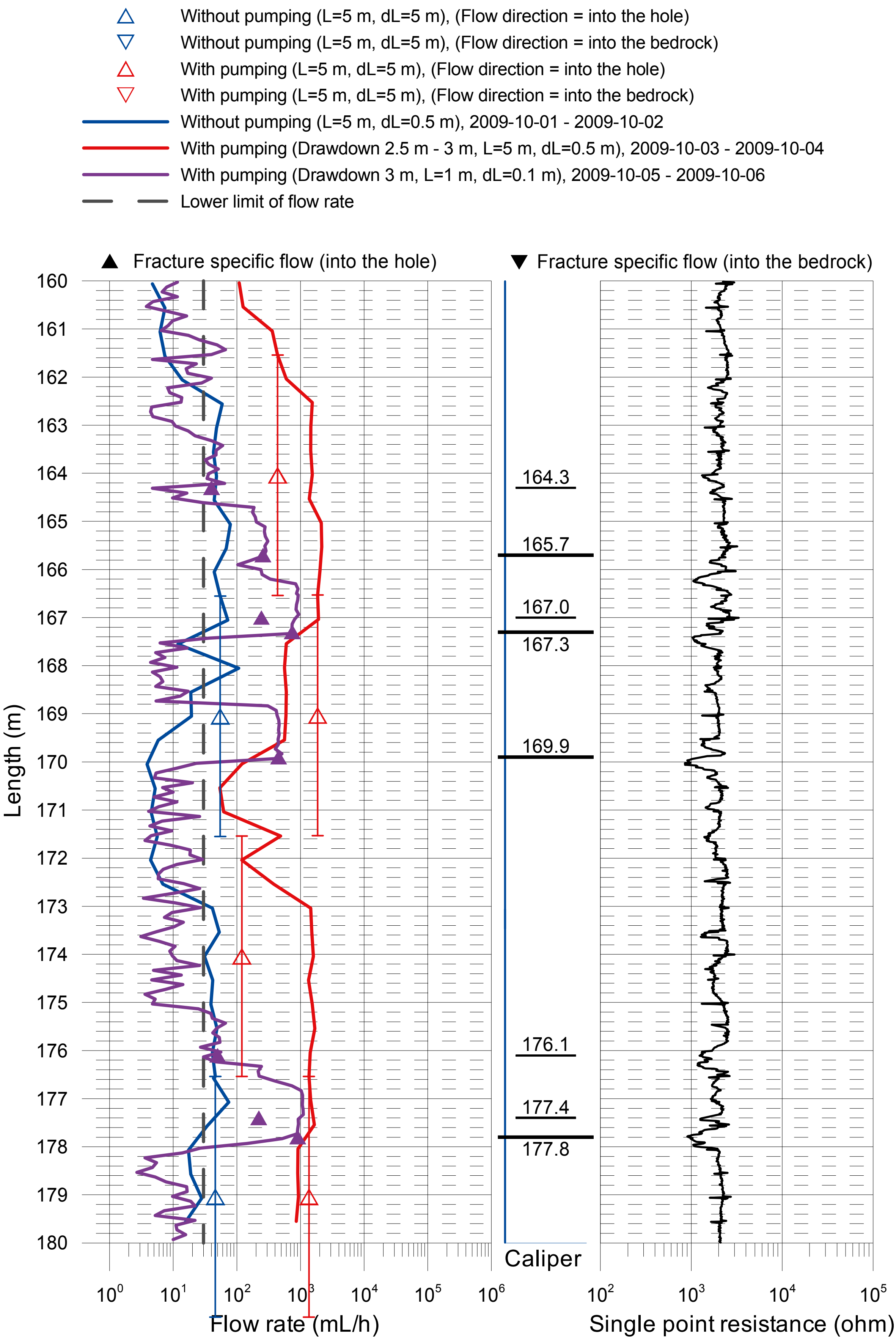
Forsmark, borehole KFR106
Flow rate, caliper and single point resistance



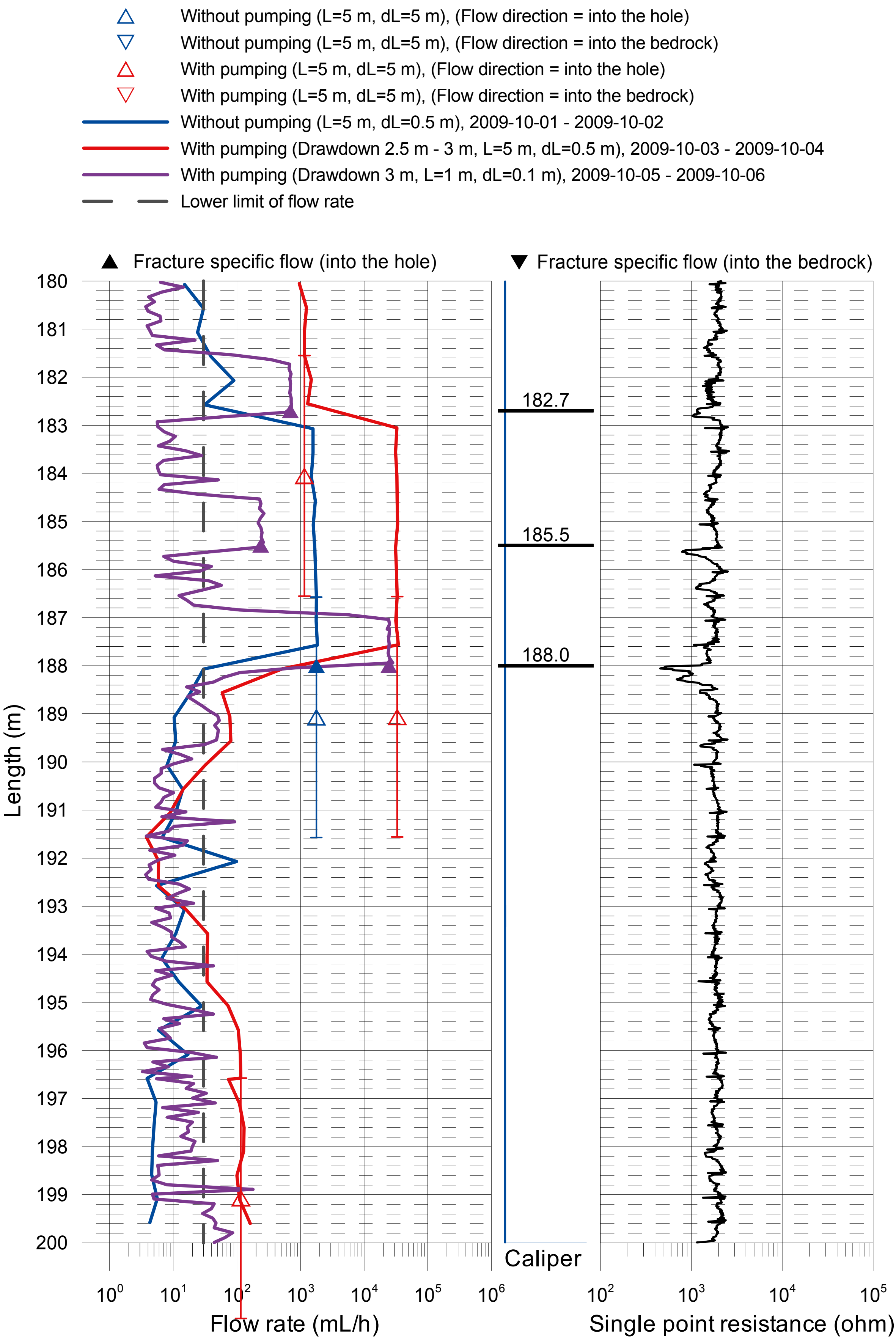
Forsmark, borehole KFR106
Flow rate, caliper and single point resistance



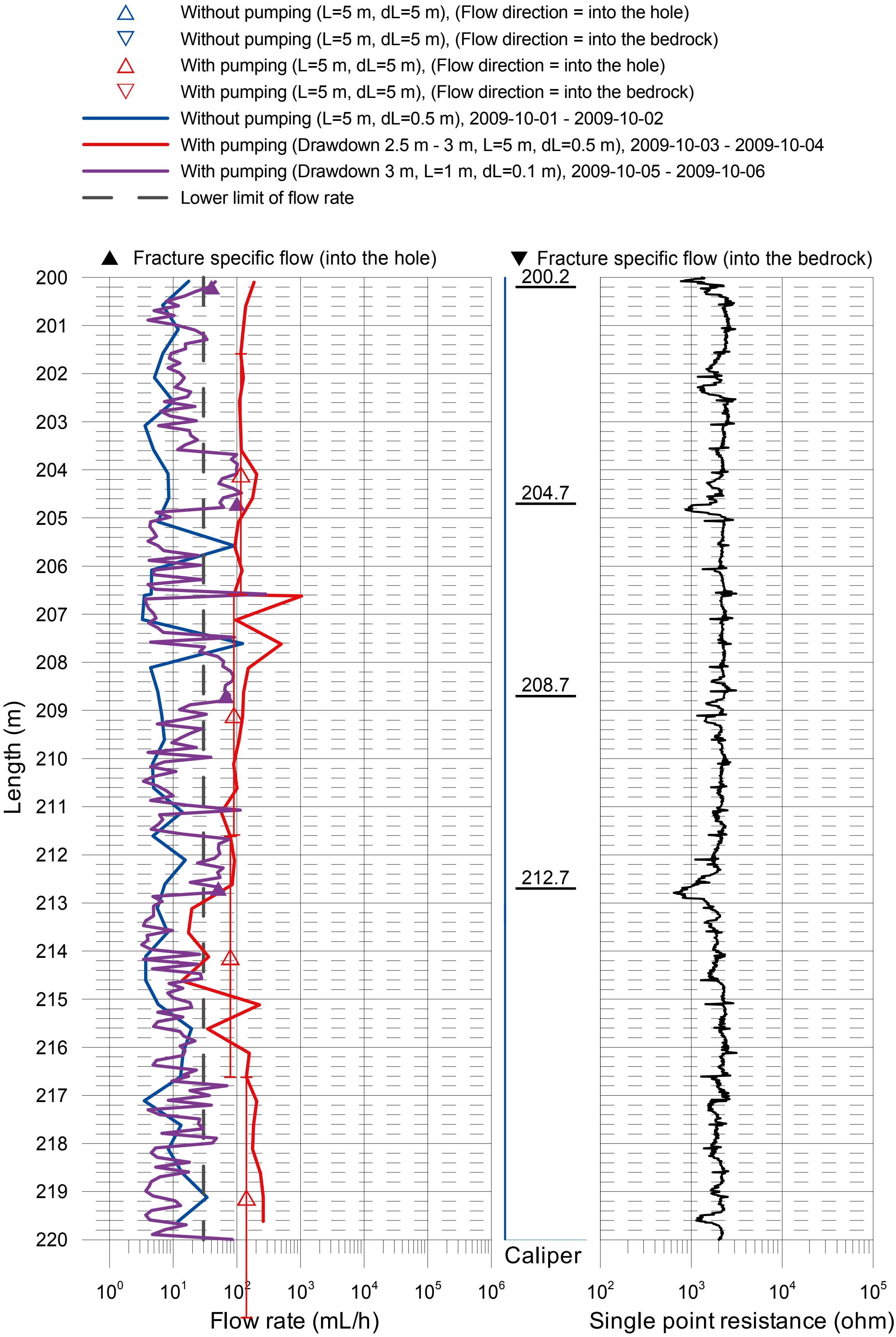
Forsmark, borehole KFR106
Flow rate, caliper and single point resistance



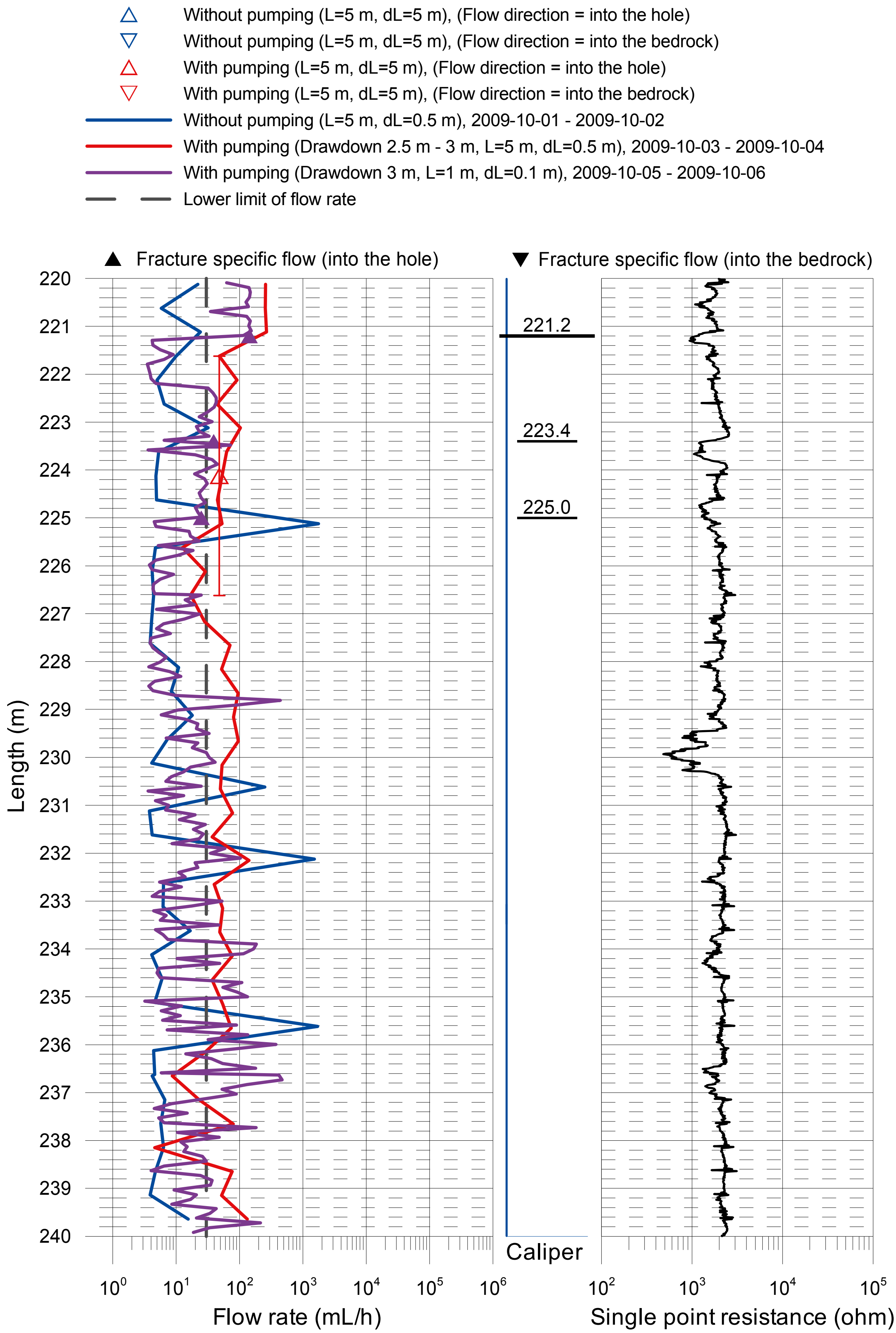
Forsmark, borehole KFR106
Flow rate, caliper and single point resistance



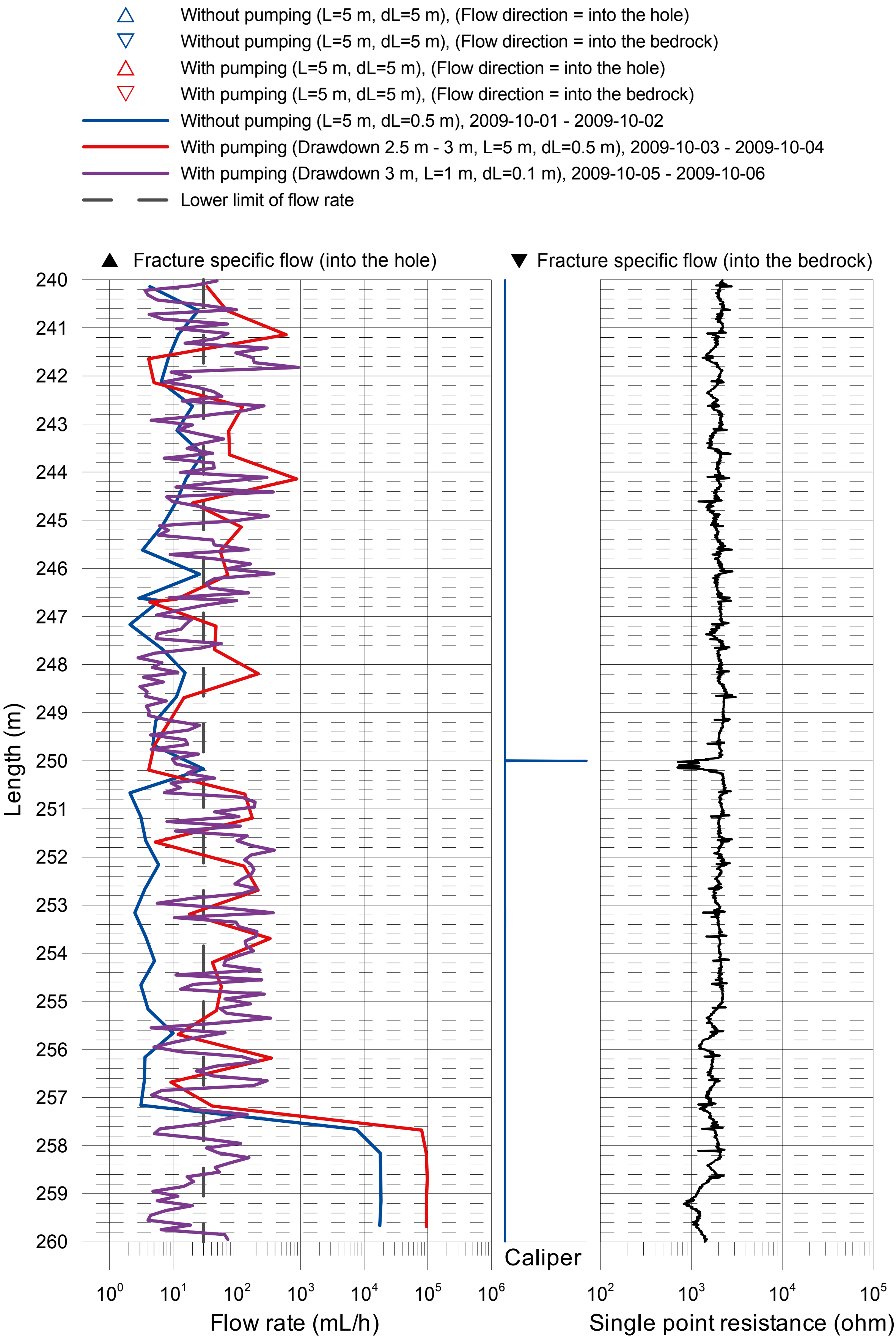
Forsmark, borehole KFR106
Flow rate, caliper and single point resistance



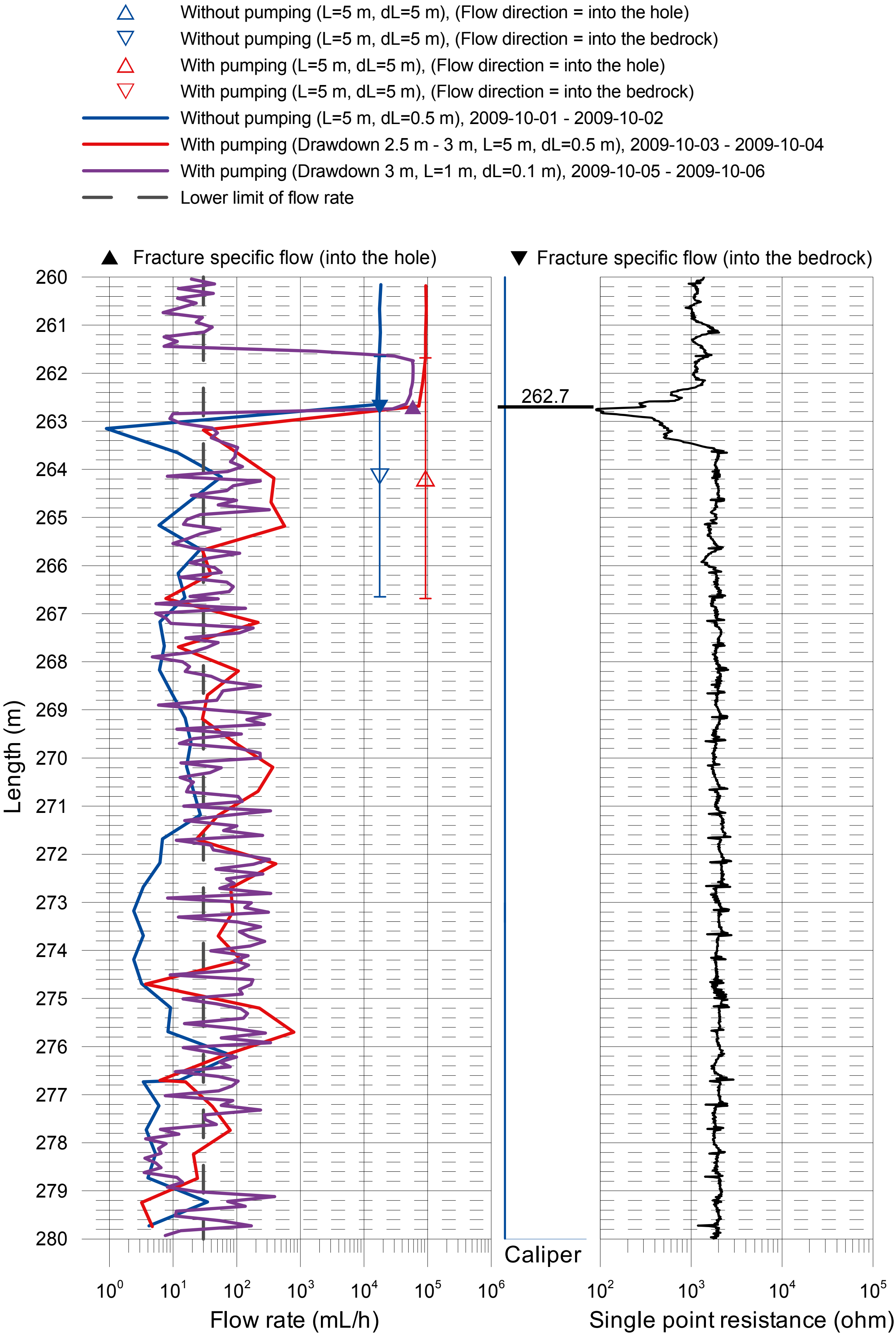
Forsmark, borehole KFR106
Flow rate, caliper and single point resistance



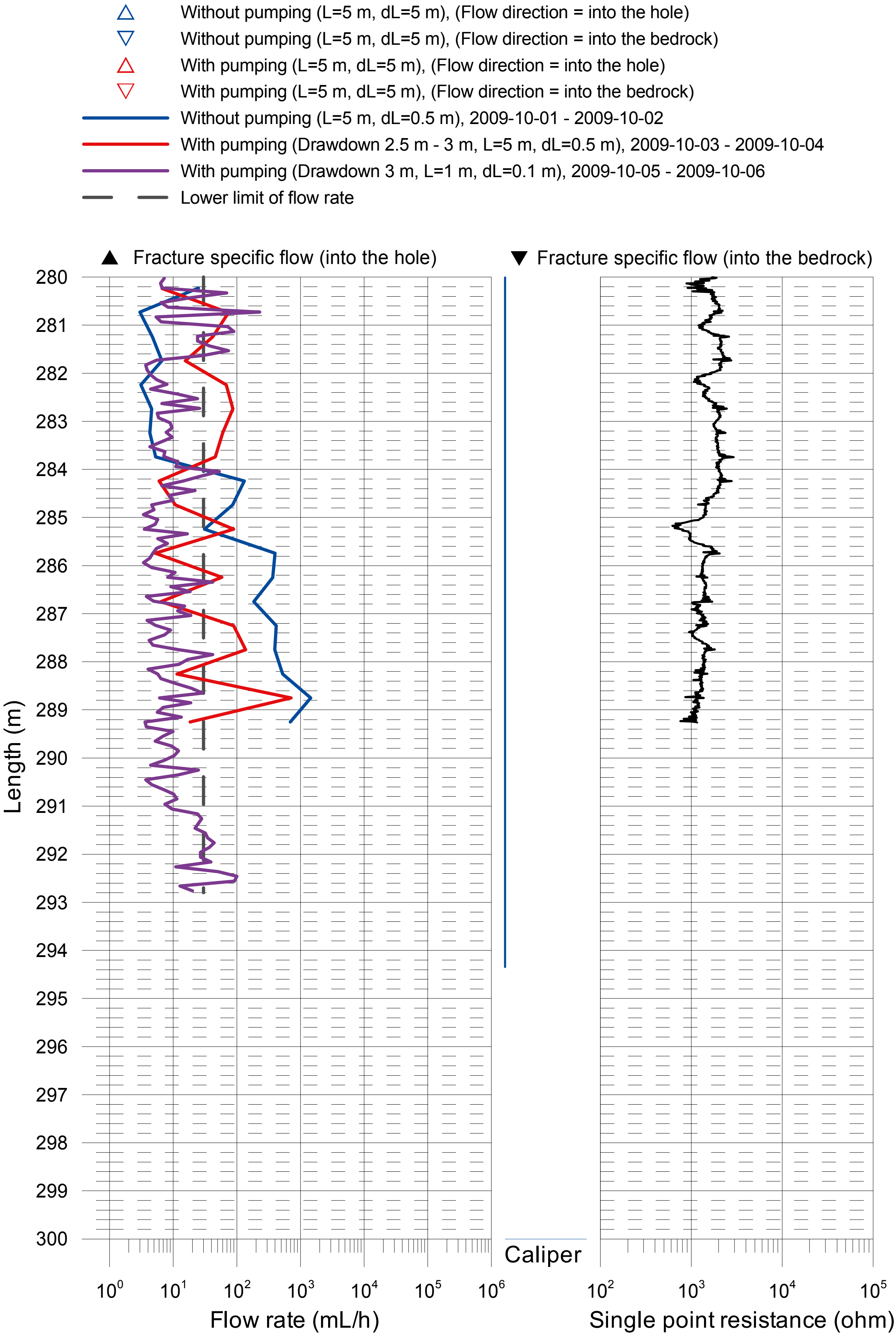
Forsmark, borehole KFR106
Flow rate, caliper and single point resistance



Forsmark, borehole KFR106
Flow rate, caliper and single point resistance



Forsmark, borehole KFR106
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} (masl)	Q_1 (m^3/s)	h_{1FW} (masl)	T_D (m^2/s)	h_i (masl)	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
KFR106	6.35	11.35	5	1.39E-07	0.00	–	–	–	–	200	2.9E-09	2.0E-08	2.9E-05	***
KFR106	11.37	16.37	5	–	0.00	–	–2.80	–	–	200	2.9E-09	2.0E-08	2.9E-05	
KFR106	16.38	21.38	5	1.41E-07	–0.01	1.55E-06	–2.81	5.0E-07	0.3	200	2.9E-09	2.0E-08	2.9E-05	**
KFR106	21.38	26.38	5	–	–0.01	–	–2.79	–	–	200	3.0E-09	2.0E-08	3.0E-05	
KFR106	26.39	31.39	5	1.08E-08	0.00	2.39E-07	–2.77	8.2E-08	0.1	200	3.0E-09	2.0E-08	3.0E-05	
KFR106	31.40	36.40	5	–	0.00	–	–2.72	–	–	200	3.0E-09	2.0E-08	3.0E-05	
KFR106	36.40	41.40	5	1.98E-07	0.03	6.94E-06	–2.70	2.4E-06	0.1	200	3.0E-09	2.0E-08	3.0E-05	
KFR106	41.40	46.40	5	1.93E-07	0.06	2.94E-06	–2.68	9.9E-07	0.3	200	3.0E-09	2.0E-08	3.0E-05	
KFR106	46.40	51.40	5	–	0.08	–	–2.68	–	–	200	3.0E-09	2.0E-08	3.0E-05	
KFR106	51.41	56.41	5	–	0.10	2.01E-07	–2.66	7.2E-08	–	200	3.0E-09	2.0E-08	3.0E-05	
KFR106	56.41	61.41	5	9.19E-08	0.11	3.78E-06	–2.65	1.3E-06	0.2	200	3.0E-09	2.0E-08	3.0E-05	
KFR106	61.41	66.41	5	–	0.13	2.29E-06	–2.59	8.3E-07	–	200	3.0E-09	2.0E-08	3.0E-05	
KFR106	66.42	71.42	5	–5.83E-08	0.16	4.42E-05	–2.49	1.7E-05	0.2	200	3.1E-09	2.1E-08	3.1E-05	
KFR106	71.43	76.43	5	–1.09E-07	0.19	3.81E-05	–2.46	1.4E-05	0.2	200	3.1E-09	2.1E-08	3.1E-05	
KFR106	76.42	81.42	5	–	0.20	–	–2.47	–	–	200	3.1E-09	2.1E-08	3.1E-05	
KFR106	81.41	86.41	5	–4.42E-07	0.19	4.83E-05	–2.45	1.8E-05	0.2	200	3.1E-09	2.1E-08	3.1E-05	
KFR106	86.43	91.43	5	–	0.20	1.71E-07	–2.34	6.6E-08	–	200	3.3E-09	2.2E-08	3.3E-05	
KFR106	91.45	96.45	5	–1.64E-08	0.24	6.22E-07	–2.31	2.5E-07	0.2	150	3.2E-09	1.6E-08	3.2E-05	
KFR106	96.44	101.44	5	–2.62E-07	0.25	4.22E-05	–2.23	1.7E-05	0.2	150	3.3E-09	1.7E-08	3.3E-05	
KFR106	101.45	106.45	5	–	0.28	1.10E-07	–2.20	4.4E-08	–	100	3.3E-09	1.1E-08	3.3E-05	
KFR106	106.44	111.44	5	–	0.33	3.56E-06	–2.17	1.4E-06	–	100	3.3E-09	1.1E-08	3.3E-05	
KFR106	111.45	116.45	5	8.89E-08	0.40	6.89E-06	–2.14	2.7E-06	0.4	100	3.3E-09	1.1E-08	3.2E-05	
KFR106	116.45	121.45	5	1.58E-08	0.42	3.56E-07	–2.13	1.3E-07	0.5	100	3.2E-09	1.1E-08	3.2E-05	
KFR106	121.47	126.47	5	–	0.45	1.19E-06	–2.12	4.6E-07	–	100	3.2E-09	1.1E-08	3.2E-05	
KFR106	126.47	131.47	5	–	0.48	6.28E-07	–2.10	2.4E-07	–	100	3.2E-09	1.1E-08	3.2E-05	
KFR106	131.48	136.48	5	–	0.51	–	–2.08	–	–	100	3.2E-09	1.1E-08	3.2E-05	
KFR106	136.48	141.48	5	2.42E-08	0.54	8.58E-07	–2.06	3.2E-07	0.6	100	3.2E-09	1.1E-08	3.2E-05	
KFR106	141.51	146.51	5	2.17E-08	0.55	5.11E-07	–2.05	1.9E-07	0.7	100	3.2E-09	1.1E-08	3.2E-05	
KFR106	146.50	151.50	5	7.50E-09	0.59	9.67E-07	–2.07	3.6E-07	0.6	100	3.1E-09	1.0E-08	3.1E-05	*
KFR106	151.51	156.51	5	3.75E–06	0.62	7.14E-05	–2.01	2.5E-05	0.8	100	3.1E-09	1.1E-08	3.0E-05	****

Borehole ID	Secup L (m)	Seclow L (m)	L_w (m)	Q_0 (m^3/s)	h_{0FW} (masl)	Q_1 (m^3/s)	h_{1FW} (masl)	T_D (m^2/s)	h_i (masl)	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
KFR106	156.51	161.51	5	2.47E-08	0.66	9.39E-07	–1.95	3.5E-07	0.7	100	3.2E-09	1.1E-08	3.2E-05	
KFR106	161.55	166.55	5	–	0.69	1.22E-07	–1.93	4.6E-08	–	30	3.2E-09	3.2E-09	3.2E-05	
KFR106	166.54	171.54	5	1.53E-08	0.72	5.17E-07	–1.90	1.9E-07	0.8	30	3.2E-09	3.2E-09	3.2E-05	
KFR106	171.55	176.55	5	–	0.76	3.33E-08	–1.88	1.3E-08	–	30	3.1E-09	3.1E-09	3.1E-05	
KFR106	176.54	181.54	5	1.28E-08	0.79	3.78E-07	–1.85	1.4E-07	0.9	30	3.1E-09	3.1E-09	3.1E-05	
KFR106	181.56	186.56	5	–	0.81	3.19E-07	–1.83	1.2E-07	–	30	3.1E-09	3.1E-09	3.1E-05	
KFR106	186.57	191.57	5	4.94E-07	0.83	9.22E-06	–1.79	3.3E-06	1.0	30	3.2E-09	3.2E-09	3.1E-05	
KFR106	191.57	196.57	5	–	0.85	–	–1.76	–	–	30	3.2E-09	3.2E-09	3.2E-05	
KFR106	196.58	201.58	5	–	0.88	3.22E-08	–1.72	1.2E-08	–	30	3.2E-09	3.2E-09	3.2E-05	
KFR106	201.59	206.59	5	–	0.90	3.22E-08	–1.68	1.2E-08	–	30	3.2E-09	3.2E-09	3.2E-05	
KFR106	206.59	211.59	5	–	0.95	2.50E-08	–1.66	9.5E-09	–	30	3.2E-09	3.2E-09	3.2E-05	
KFR106	211.62	216.62	5	–	0.98	2.19E-08	–1.64	8.3E-09	–	30	3.2E-09	3.2E-09	3.2E-05	
KFR106	216.62	221.62	5	–	1.01	3.94E-08	–1.62	1.5E-08	–	30	3.1E-09	3.1E-09	3.1E-05	
KFR106	221.62	226.62	5	–	1.02	1.33E-08	–1.59	5.1E-09	–	30	3.2E-09	3.2E-09	3.2E-05	
KFR106	226.62	231.62	5	–	1.05	–	–1.57	–	–	30	3.2E-09	3.2E-09	3.2E-05	
KFR106	231.64	236.64	5	–	1.08	–	–1.53	–	–	30	3.2E-09	3.2E-09	3.2E-05	
KFR106	236.64	241.64	5	–	1.09	–	–1.50	–	–	30	3.2E-09	3.2E-09	3.2E-05	
KFR106	241.64	246.64	5	–	1.15	–	–1.48	–	–	30	3.1E-09	3.1E-09	3.1E-05	
KFR106	246.63	251.63	5	–	1.17	–	–1.47	–	–	30	3.1E-09	3.1E-09	3.1E-05	
KFR106	251.68	256.68	5	–	1.20	–	–1.44	–	–	30	3.1E-09	3.1E-09	3.1E-05	
KFR106	256.67	261.67	5	–	1.24	–	–1.43	–	–	30	3.1E-09	3.1E-09	3.1E-05	
KFR106	261.67	266.67	5	–4.94E-06	1.28	2.57E-05	–1.40	1.1E-05	0.9	30	3.1E-09	3.1E-09	3.3E-05	
KFR106	266.67	271.67	5	–	1.28	–	–0.91	–	–	30	3.8E-09	3.8E-09	3.8E-05	
KFR106	271.69	276.69	5	–	1.32	–	–0.87	–	–	30	3.8E-09	3.8E-09	3.8E-05	
KFR106	276.72	281.72	5	–	1.31	–	–0.82	–	–	30	3.9E-09	3.9E-09	3.9E-05	
KFR106	281.74	286.74	5	–	1.34	–	–0.79	–	–	30	3.9E-09	3.9E-09	3.9E-05	
KFR106	286.75	291.75	5	–	1.31	–	–0.80	–	–	30	3.9E-09	3.9E-09	3.9E-05	

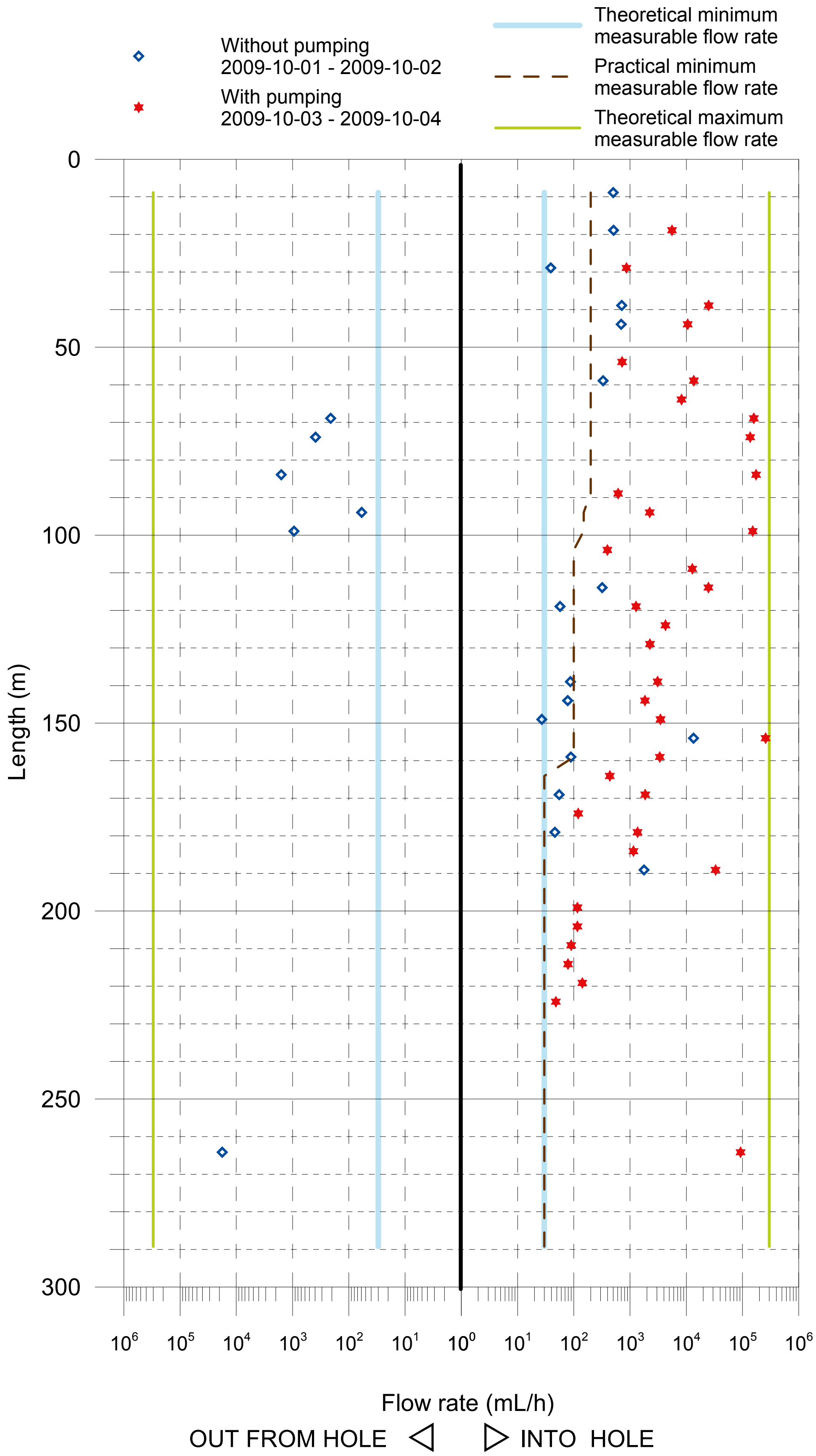
* Flow rate Flow0 and/or Flow1 below 30 mL/h

** Vertical fracture zone (Fracture zone between 16.4 m–19.4 m, based on SKB’s bips image and SPR data).

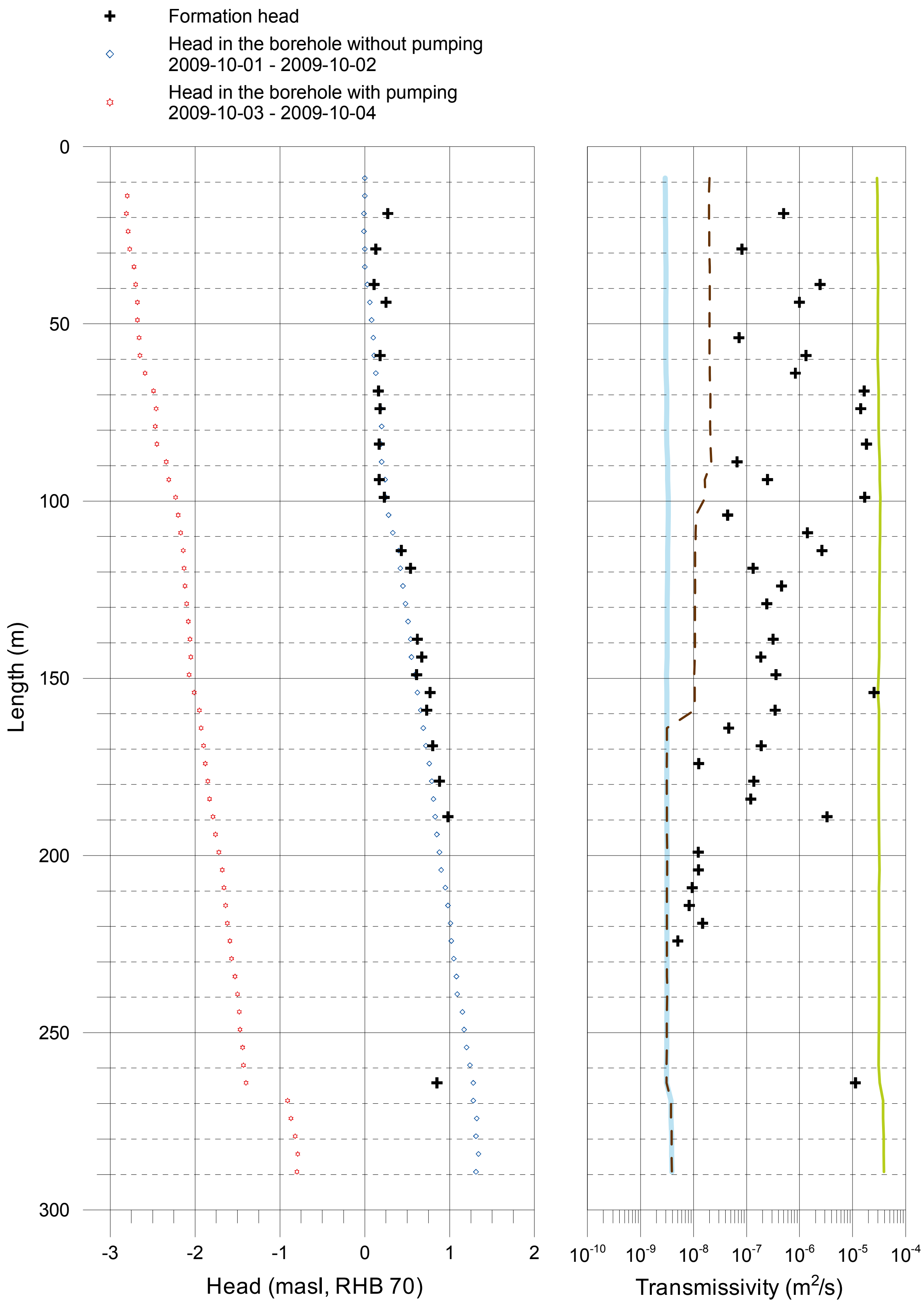
*** Not measured during pumping due to drawdown.

**** Pressure drop because of flow friction. True TD larger than presented. H1FW taken from the average of the adjacent values.

Forsmark, borehole KFR106
Flow rates of 5 m sections



Forsmark, borehole KFR106
Transmissivity and head of 5 m sections



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} (masl)	Q_1 (m^3/s)	h_{1FW} (masl)	T_D (m^2/s)	h_i (masl)	Comments
KFR106	9.8	1	0.1	1.39E-07	–0.01	–	–	–	–	*,***
KFR106	16.8	1	0.1	–	–0.02	1.52E-06	–3.08	4.9E-07	–	*,**
KFR106	28.7	1	0.1	1.08E-08	–0.01	2.06E-07	–3.01	6.4E-08	0.2	*
KFR106	37.6	1	0.1	1.36E-07	0.02	4.83E-06	–2.92	1.6E-06	0.1	
KFR106	38.8	1	0.1	–	0.03	4.83E-07	–2.92	1.6E-07	–	
KFR106	41.3	1	0.1	–	0.04	6.61E-07	–2.91	2.2E-07	–	*
KFR106	41.8	1	0.1	1.93E-07	0.04	2.92E-06	–2.91	9.1E-07	0.3	
KFR106	51.8	1	0.1	–	0.09	1.23E-07	–2.86	4.1E-08	–	*
KFR106	52.5	1	0.1	–	0.10	1.02E-07	–2.84	3.4E-08	–	*
KFR106	58.2	1	0.1	6.42E-08	0.08	2.65E-06	–2.81	8.9E-07	0.2	
KFR106	59.1	1	0.1	–	0.11	4.69E-07	–2.81	1.6E-07	–	*
KFR106	60.2	1	0.1	–	0.11	5.50E-07	–2.80	1.9E-07	–	
KFR106	62.0	1	0.1	–	0.12	1.79E-06	–2.78	6.1E-07	–	
KFR106	65.0	1	0.1	–	0.13	1.36E-07	–2.76	4.7E-08	–	
KFR106	67.2	1	0.1	–	0.14	6.44E-07	–2.72	2.2E-07	–	
KFR106	68.3	1	0.1	–	0.14	3.81E-05	–2.72	1.3E-05	–	
KFR106	69.4	1	0.1	–	0.16	3.00E-07	–2.68	1.0E-07	–	
KFR106	71.6	1	0.1	–	0.17	1.80E-05	–2.66	6.3E-06	–	
KFR106	73.1	1	0.1	–6.53E-08	0.18	1.30E-05	–2.65	4.6E-06	0.2	
KFR106	76.0	1	0.1	–	0.20	1.68E-07	–2.63	5.9E-08	–	
KFR106	83.1	1	0.1	–	0.19	1.45E-07	–2.64	5.1E-08	–	
KFR106	84.7	1	0.1	–	0.18	7.94E-07	–2.64	2.8E-07	–	*
KFR106	85.4	1	0.1	–4.42E-07	0.18	4.14E-05	–2.62	1.5E-05	0.2	
KFR106	90.2	1	0.1	–	0.21	1.38E-07	–2.59	4.9E-08	–	
KFR106	92.6	1	0.1	–	0.23	4.06E-07	–2.57	1.4E-07	–	
KFR106	94.6	1	0.1	–	0.23	1.48E-07	–2.55	5.3E-08	–	
KFR106	97.5	1	0.1	–	0.24	9.14E-08	–2.53	3.3E-08	–	*
KFR106	99.0	1	0.1	–	0.25	6.08E-08	–2.52	2.2E-08	–	*
KFR106	100.7	1	0.1	–1.57E-07	0.25	4.22E-05	–2.48	1.5E-05	0.2	
KFR106	105.5	1	0.1	–	0.29	8.17E-08	–2.43	3.0E-08	–	
KFR106	107.5	1	0.1	–	0.31	1.27E-07	–2.45	4.6E-08	–	
KFR106	107.9	1	0.1	–	0.32	3.86E-07	–2.44	1.4E-07	–	
KFR106	108.9	1	0.1	–	0.33	1.99E-07	–2.41	7.2E-08	–	
KFR106	111.1	1	0.1	–	0.34	2.58E-06	–2.42	9.2E-07	–	
KFR106	113.1	1	0.1	8.89E-08	0.33	6.97E-06	–2.40	2.5E-06	0.4	
KFR106	116.6	1	0.1	–	0.41	4.47E-08	–2.36	1.6E-08	–	*
KFR106	117.5	1	0.1	–	0.42	1.89E-07	–2.35	6.7E-08	–	
KFR106	126.0	1	0.1	–	0.46	8.81E-07	–2.30	3.2E-07	–	
KFR106	129.8	1	0.1	–	0.48	4.53E-07	–2.29	1.6E-07	–	
KFR106	140.8	1	0.1	–	0.54	4.75E-07	–2.23	1.7E-07	–	
KFR106	141.2	1	0.1	–	0.54	2.92E-07	–2.23	1.0E-07	–	*
KFR106	142.5	1	0.1	–	0.55	6.08E-08	–2.22	2.2E-08	–	*
KFR106	144.8	1	0.1	–	0.54	1.08E-07	–2.22	3.9E-08	–	
KFR106	146.6	1	0.1	–	0.59	6.69E-07	–2.21	2.4E-07	–	
KFR106	149.1	1	0.1	–	0.59	1.38E-07	–2.19	4.9E-08	–	*

Borehole ID	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_0 (m^3/s)	h_{0FW} (masl)	Q_1 (m^3/s)	h_{1FW} (masl)	T_D (m^2/s)	h_i (masl)	Comments
KFR106	152.0	1	0.1	–	0.61	8.31E-07	–2.17	3.0E-07	–	
KFR106	154.3	1	0.1	–	0.62	6.67E-06	–2.22	2.3E-06	–	
KFR106	154.6	1	0.1	–	0.62	1.19E-05	–2.32	4.0E-06	–	
KFR106	156.0	1	0.1	3.06E-06	0.62	5.36E-05	–2.15	1.8E-05	0.8	****
KFR106	157.4	1	0.1	2.47E-08	0.64	7.58E-07	–2.14	2.6E-07	0.7	
KFR106	164.3	1	0.1	–	0.69	1.11E-08	–2.07	4.0E-09	–	*
KFR106	165.7	1	0.1	–	0.70	7.14E-08	–2.06	2.6E–08	–	
KFR106	167.0	1	0.1	–	0.71	6.78E-08	–2.05	2.4E-08	–	*
KFR106	167.3	1	0.1	–	0.71	2.06E-07	–2.05	7.4E-08	–	
KFR106	169.9	1	0.1	–	0.72	1.26E-07	–2.04	4.5E-08	–	
KFR106	176.1	1	0.1	–	0.75	1.39E-08	–2.01	5.0E-09	–	*
KFR106	177.4	1	0.1	–	0.77	6.14E-08	–2.01	2.2E-08	–	*
KFR106	177.8	1	0.1	–	0.77	2.52E-07	–2.00	9.0E-08	–	
KFR106	182.7	1	0.1	–	0.80	1.92E-07	–1.98	6.8E-08	–	
KFR106	185.5	1	0.1	–	0.81	6.58E-08	–1.96	2.4E-08	–	
KFR106	188.0	1	0.1	4.94E-07	0.83	6.83E-06	–1.93	2.3E-06	1.1	
KFR106	200.2	1	0.1	–	0.88	1.11E-08	–1.88	4.0E-09	–	*
KFR106	204.7	1	0.1	–	0.91	2.78E-08	–1.85	1.0E-08	–	*
KFR106	208.7	1	0.1	–	0.95	1.86E-08	–1.84	6.6E-09	–	*
KFR106	212.7	1	0.1	–	0.96	1.42E-08	–1.82	5.0E-09	–	*
KFR106	221.2	1	0.1	–	1.01	3.97E-08	–1.76	1.4E-08	–	
KFR106	223.4	1	0.1	–	1.01	1.08E-08	–1.74	3.9E-09	–	*
KFR106	225.0	1	0.1	–	1.03	6.94E-09	–1.73	2.5E-09	–	*
KFR106	262.7	1	0.1	–4.94E-06	1.27	1.63E-05	–1.51	7.6E-06	0.6	

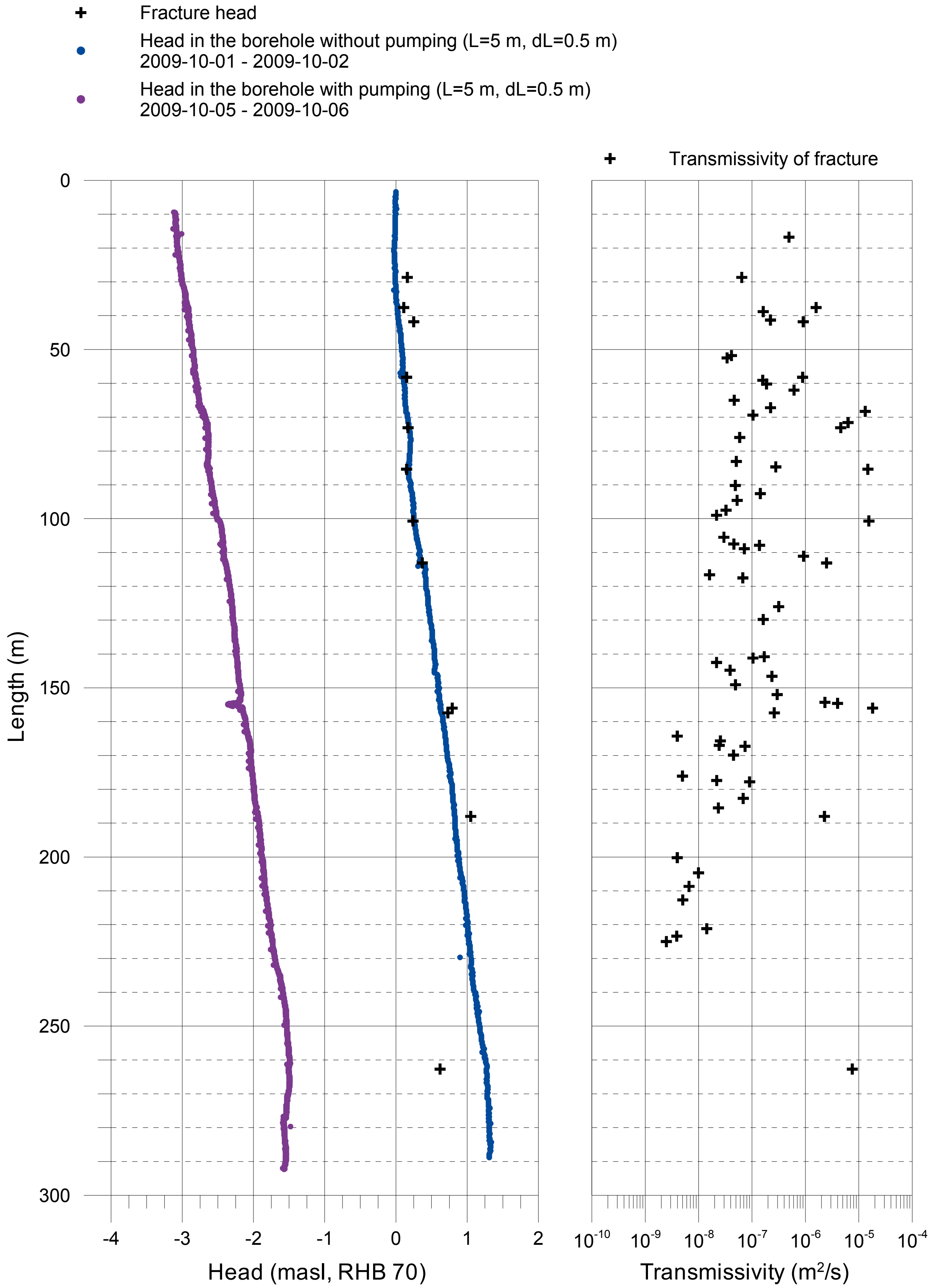
* Uncertain = The flow rate is less than 30 mL/h or the flow anomalies are overlapping or they are unclear because of noise.

** Vertical fracture zone (Fracture zone between 16.4 m–19.4 m, based on SKB's bips image and SPR data).

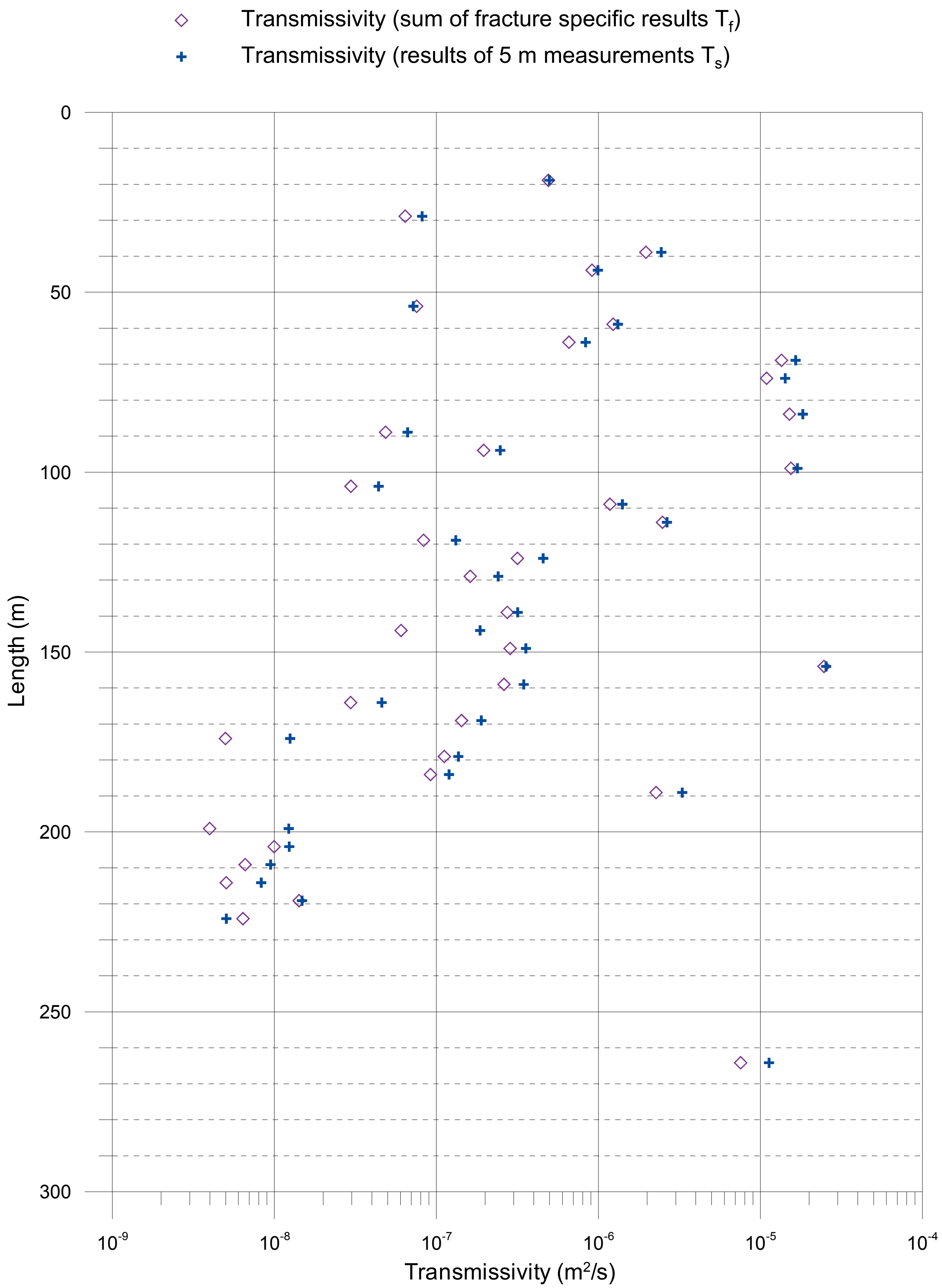
*** Not measured during pumping due to drawdown.

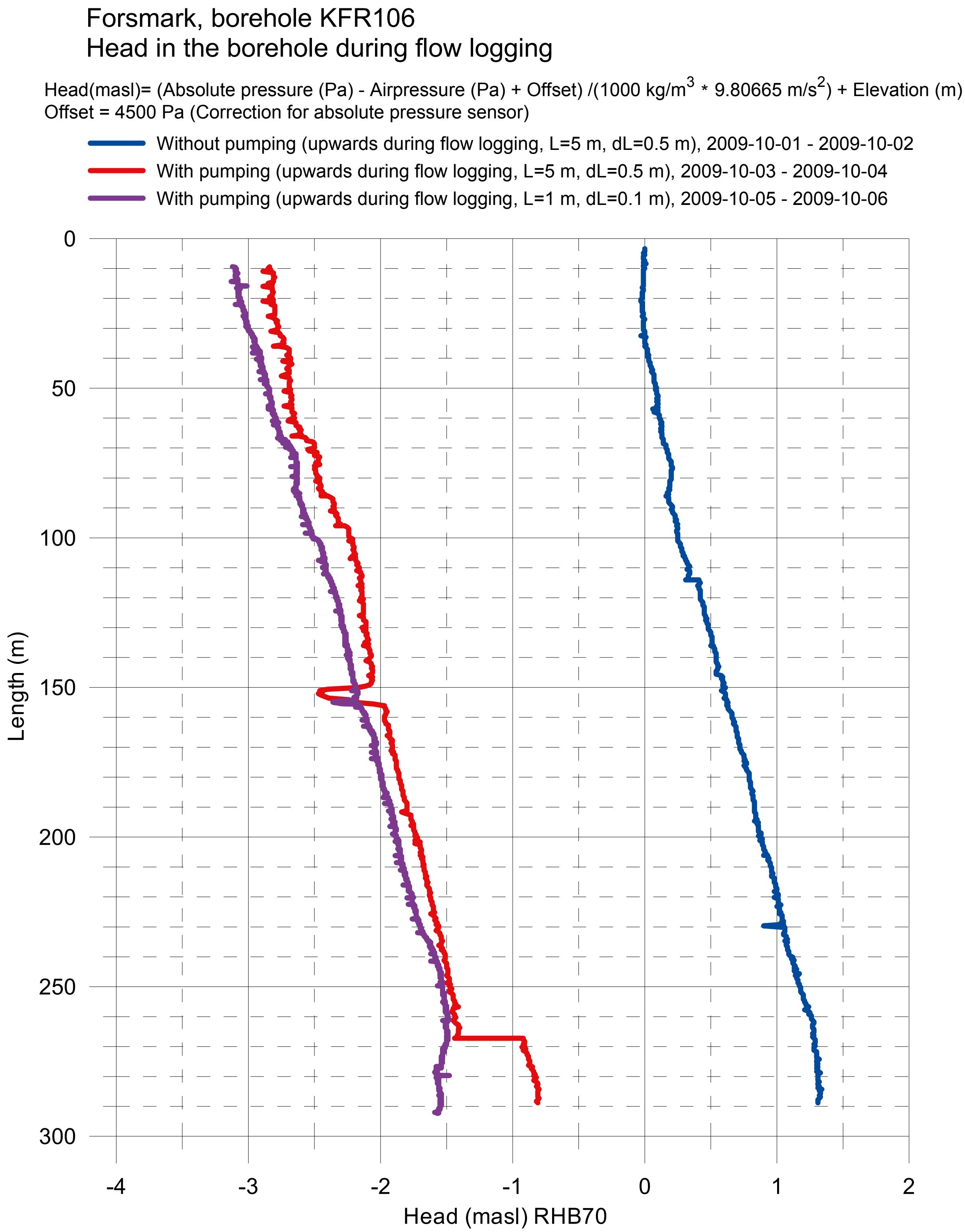
**** Pressure drop because of flow friction. True TD probably larger than presented.

Forsmark, borehole KFR106
Transmissivity and head of detected fractures

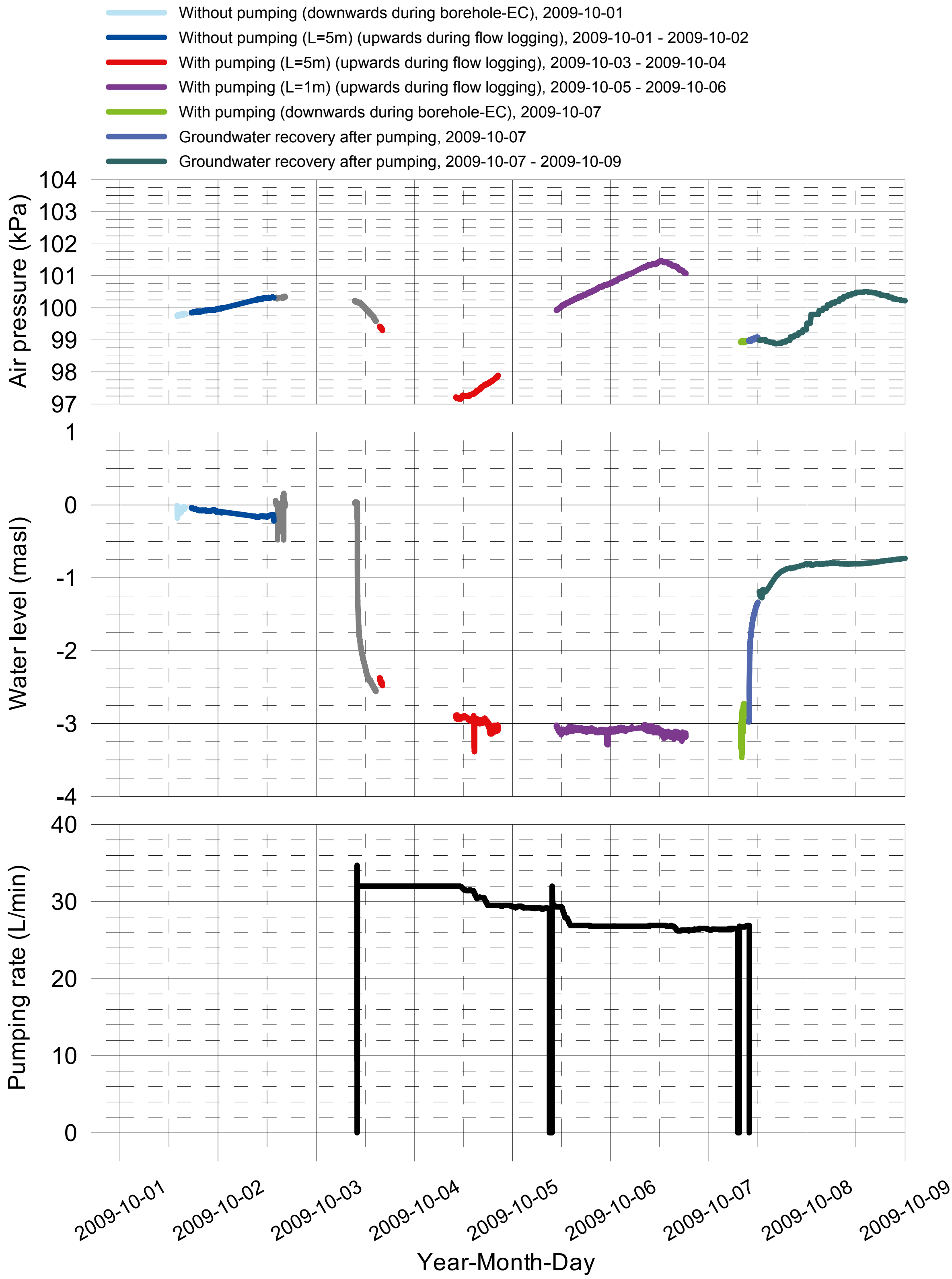


Forsmark, borehole KFR106
Comparison between section transmissivity and fracture transmissivity



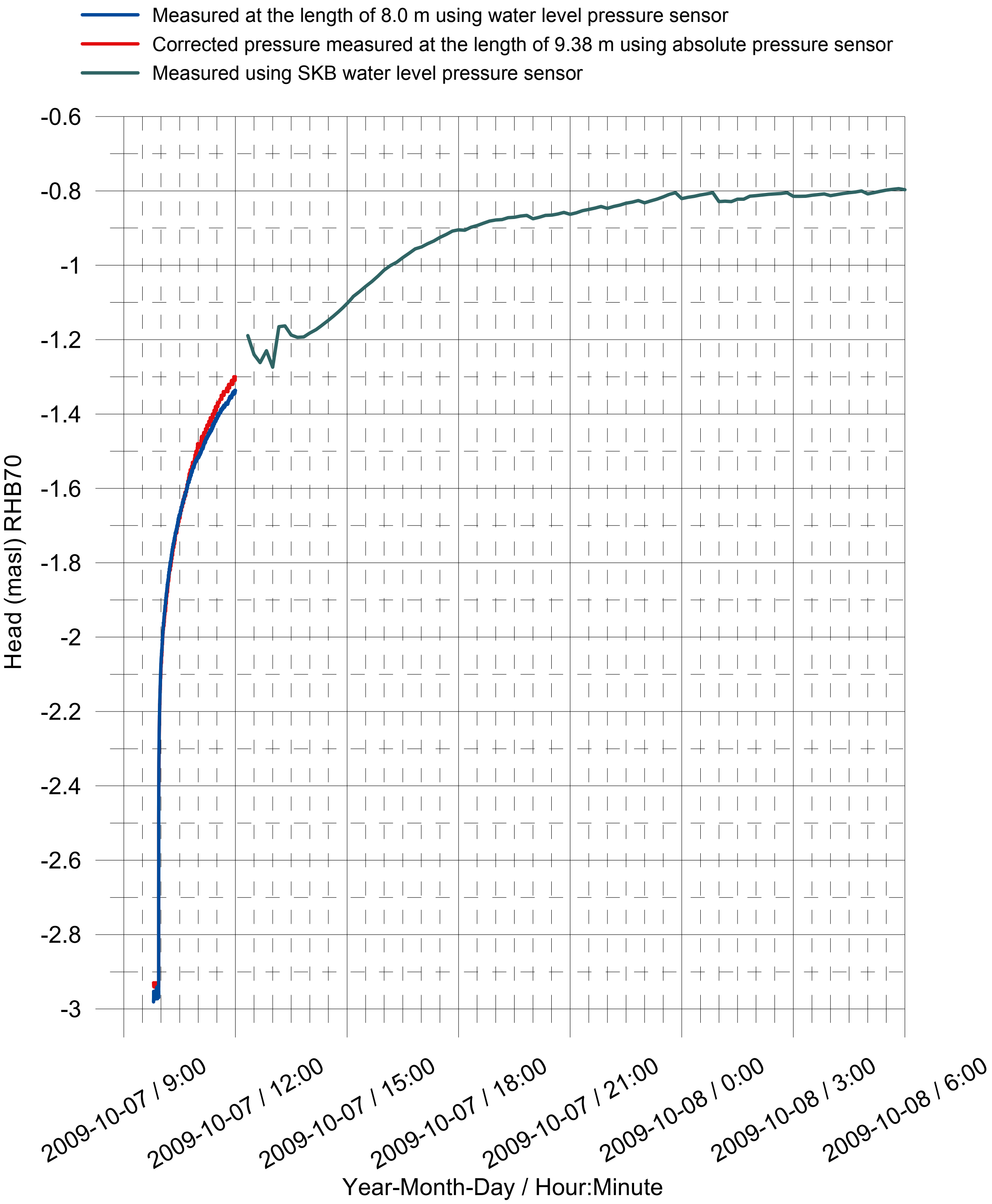

Forsmark, borehole KFR106
Head in the borehole during flow logging
Head(masl)= (Absolute pressure (Pa) - Airpressure (Pa) + Offset) /(1000 kg/m3 * 9.80665 m/s2) + Elevation (m)
Offset = 4500 Pa (Correction for absolute pressure sensor)
Without pumping (upwards during flow logging, L=5 m, dL=0.5 m), 2009-10-01 - 2009-10-02
With pumping (upwards during flow logging, L=5 m, dL=0.5 m), 2009-10-03 - 2009-10-04
With pumping (upwards during flow logging, L=1 m, dL=0.1 m), 2009-10-05 - 2009-10-06
Length (m)
0
50
100
150
200
250
300
-4
-3
-2
-1
0
1
2
Head (masl) RHB70

Forsmark, borehole KFR106
Air pressure, water level in the borehole and pumping rate during flow logging

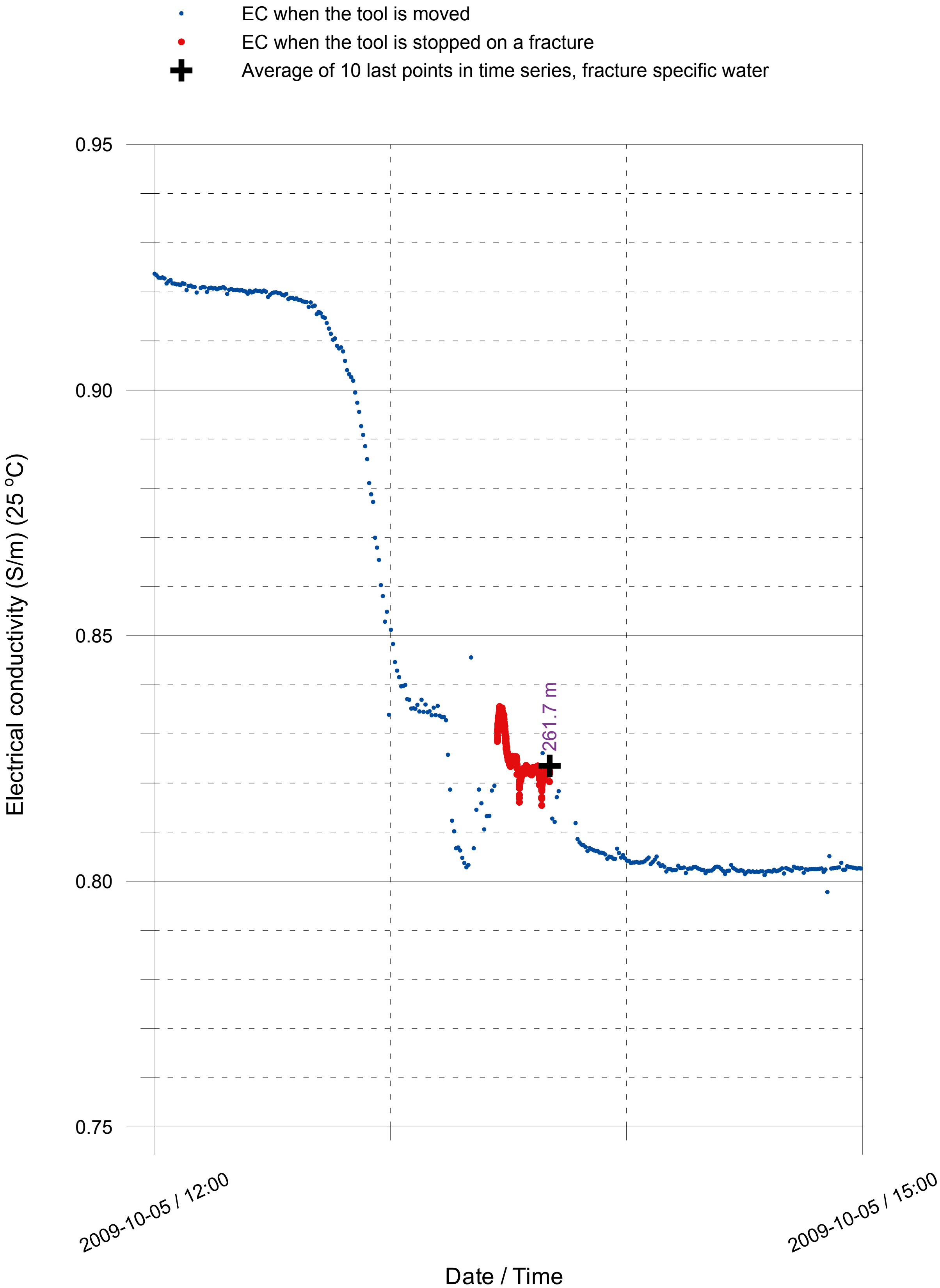


Forsmark, borehole KFR106
Groundwater recovery after pumping

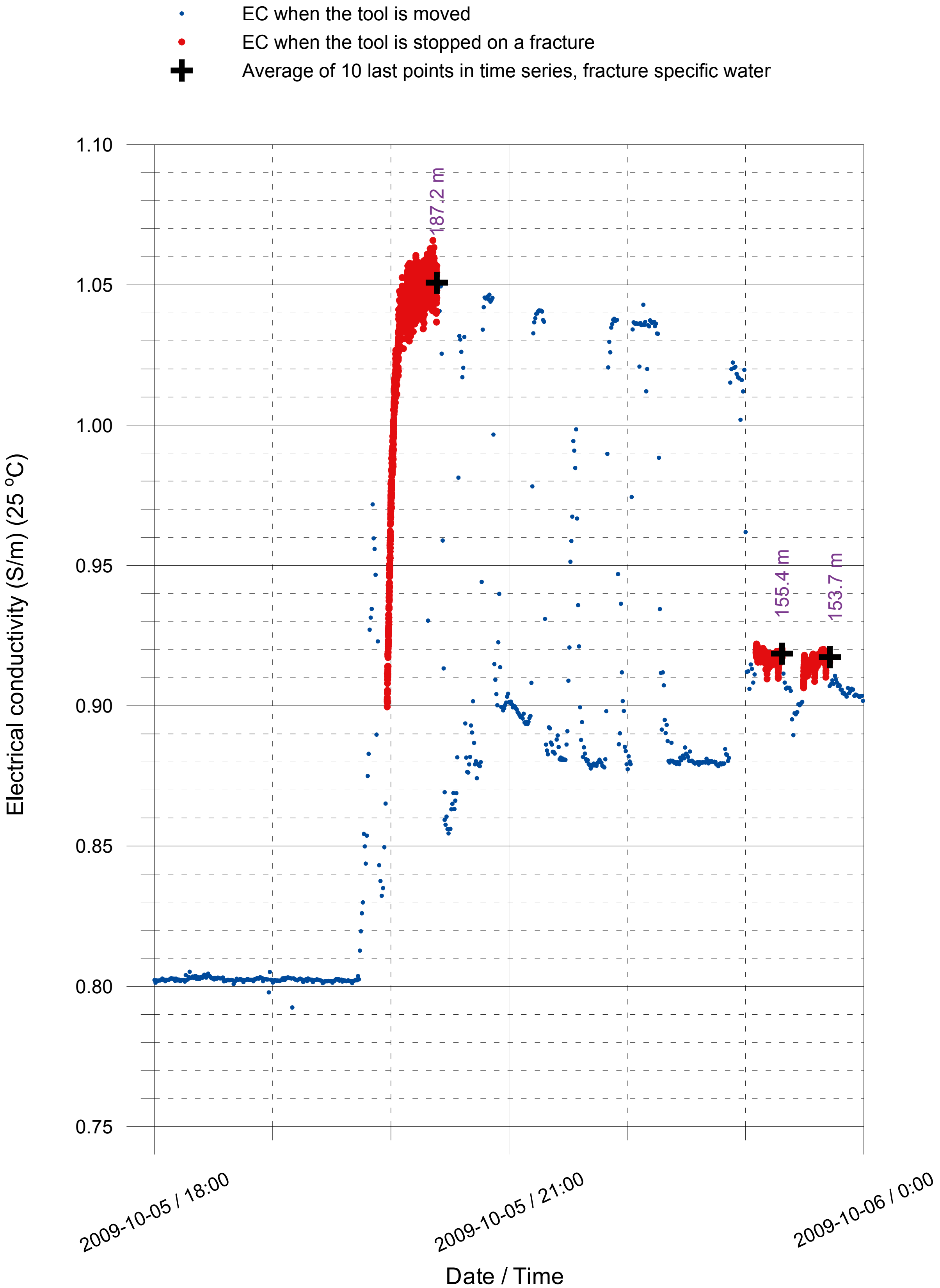
Head(masl)= (Absolute pressure (Pa) - Airpressure (Pa) + Offset) /(1000 kg/m^3 * 9.80665 m/s^2) + Elevation (m)
Offset = 4500 Pa (Correction for absolute pressure sensor)



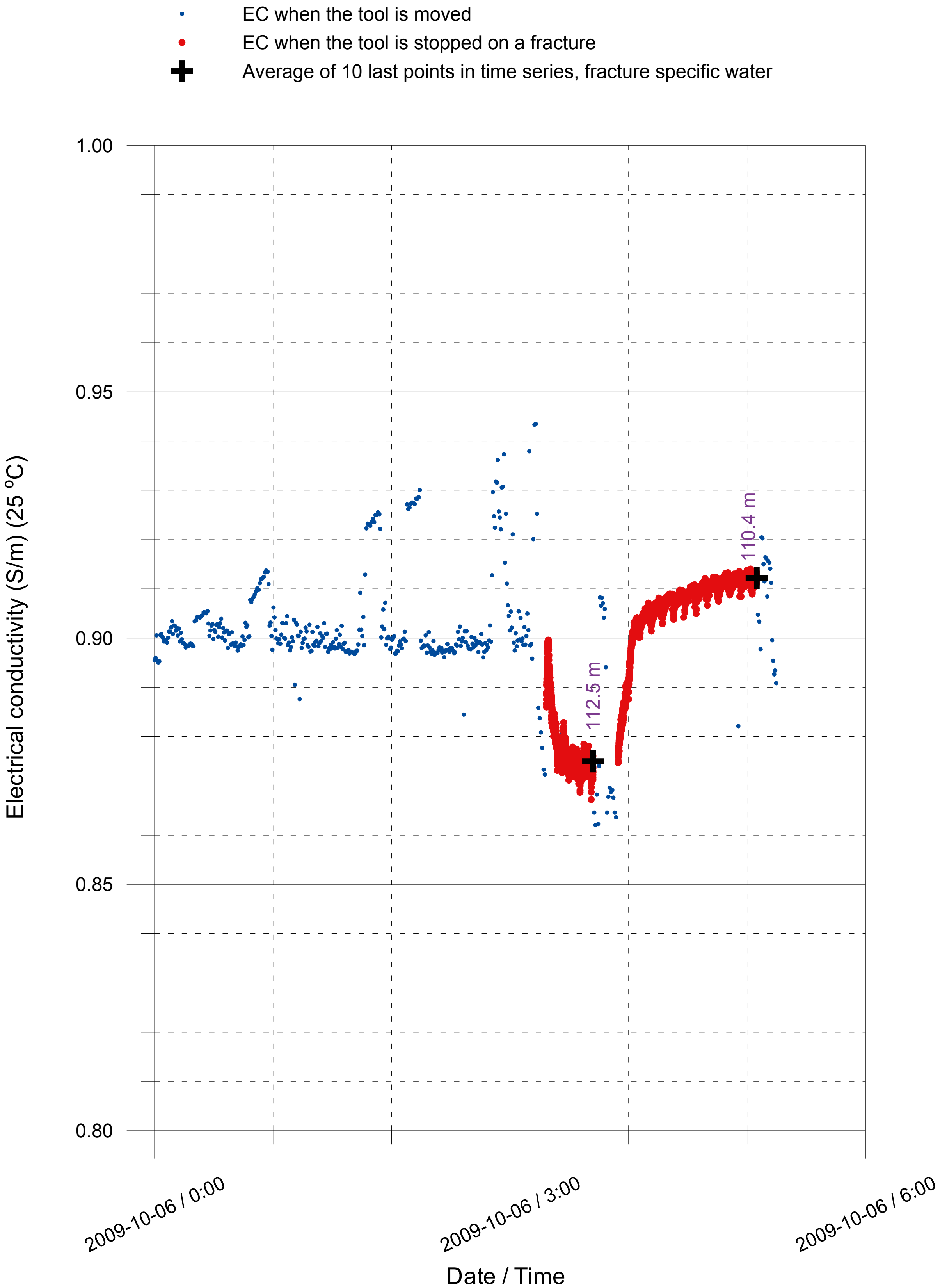
Forsmark, borehole KFR106
Fracture-specific EC results by date



Forsmark, borehole KFR106
Fracture-specific EC results by date



Forsmark, borehole KFR106
Fracture-specific EC results by date



Forsmark, borehole KFR106
Fracture-specific EC results by date