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Forsmark site investigation

Difference flow logging in borehole KFM02B

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PRG-Tec Oy

April 2007

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Abstract

Difference flow logging is a swift method for the determination of the transmissivity and the hydraulic head in borehole sections and fractures/fracture zones in core drilled boreholes. This report presents the main principles of the methods as well as the results of measurements carried out in borehole KFM02B at Forsmark, Sweden, in February and March 2007, using Posiva Flow Log. Posiva Flow Log is a multipurpose measurement instrument developed by PRG-Tec Oy for the use of Posiva Oy. The primary aim of the measurements was to determine the position and flow rate of flow yielding fractures in the borehole prior to groundwater sampling.

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 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 measurements using sensors connected to 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 electric 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 also 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

Differensflödesloggning 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 KFM02B i Forsmark, Sverige, i februari och mars 2007 med Posiva flödesloggningsmetod (Posiva Flow Log). Posiva Flow Log är ett mångsidigt instrument utvecklad av PRG-Tec Oy för Posiva Oy. Det primära syftet med mätningarna var att bestämma läget och flödet för vattenförande sprickor i borrhålet före grundvattenprovtagning.

Flödet till eller från en 5 m långa testsektioner (som förflyttades successivt med 0,5 m) mättes i borrhålet under såväl naturliga (icke-pumpade) som pumpade förhållanden. Flödesmätningarna upprepades vid lägena för de detekterade flödesanomalierna med en 1 m lång testsektion som förflyttades successivt i steg om 0,1 m.

Längdkalibrering gjordes baserad på längdmärkena som frästs in i borrhålsväggen vid noggrant bestämda positioner längs borrhålet. Längdmärkena detekterades med caliper och punktresistans-mätningar 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 och temperatur på borrhålsvattnet mättes också. EC-mätningarna användes för att studera förekomsten av saltvatten i borrhålet under såväl naturliga som pumpade förhållanden. Även EC på vattnet i ett antal utvalda sprickor mättes (1 m lång testsektion).

Återhämtningen av grundvattennivån mättes efter att pumpningen i hålet avslutades.

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1 Introduction

The core drilled borehole KFM02B at Forsmark, Sweden was measured using Difference flow logging between February 26 and March 7, 2007. Difference flow logging is a swift method for a multifaceted characterization of a borehole. KFM02B is 573.87 m long and its inclination at the ground level is 80.27° from the horizontal plane. The borehole was drilled using a telescopic drilling technique, where the c. 0–87 m interval was percussion drilled and cased, and its inner diameter is c. 200 mm. A steel guide was inserted into the borehole between 83.51 m and 88.55 m. Below 88.61 m the borehole was core-drilled and its diameter is 76 mm. The location of KFM02B 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. The Posiva Flow Log/Difference flow logging method 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/.

This document reports the results acquired by the Difference flow logging method in the borehole KFM02B. The measurements were carried out as a part of the Forsmark site investigation and in accordance to SKB's internal controlling document AP PF 400-07-007. The controlling documents for performing according to this Activity Plan are listed in Table 1-1. The list of the controlling documents excludes the assignment-specific quality plans. Both the Activity Plan and the method documents 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.

Original data from the reported activity are stored in the primary database Sicada. Data are traceable in Sicada by the Activity Plan number (AP PF 400-07-007). Only data in SKB's databases are accepted for further interpretation and modelling. The data presented in this report are regarded as copies of the original data. Data in the databases may be revised, if needed. Such revisions will not necessarily result in a revision of the P-report, although the normal procedure is that major data revisions entail a revision of the P-report. Minor data revisions are normally presented as supplements, available at *www.skb.se*.

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

Activity plan	Number	Version
Difference flow logging in borehole KFM02B	AP PF 400-07-007	1.0
Method documents	**Number**	**Version**
Method description for difference flow logging	SKB MD 322.010e	2.0
Instruktion för rengöring av borrhålsutrustning och viss markbaserad utrustning	SKB MD 600.004	1.0
Instruction for length calibration in investigation of core boreholes	SKB MD 620.010e	2.0
Instruction for analysis of injection and single-hole pumping tests	SKB MD 320.004e	1.0

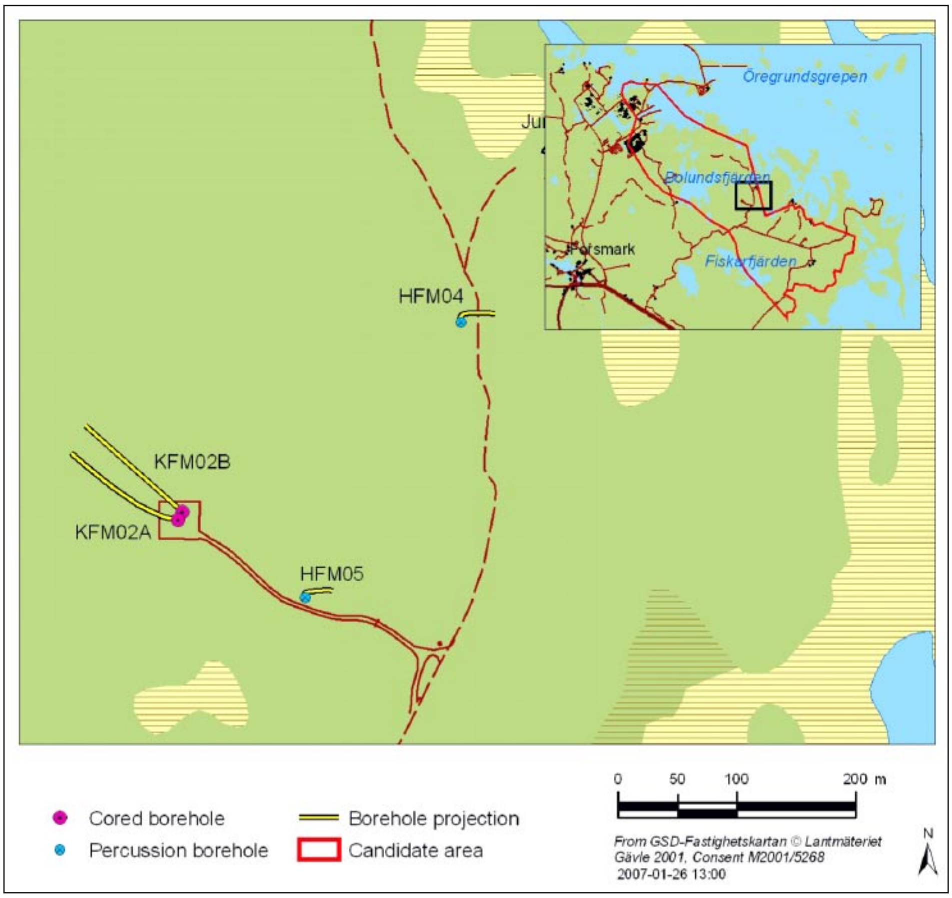

Figure 1-1. *Location of the drill site DS2 at Forsmark and detailed maps of all the boreholes within the site.*

2 Objective and scope

The main objective of the difference flow logging in KFM02B was to identify water-conductive sections/fractures suitable for subsequent hydrogeochemical 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 electric conductivity (EC) and the temperature of the borehole fluid as well as the single-point resistance of the borehole wall. The electric 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 and interpreted hydraulically.

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 traditional types of borehole flowmeters, the Difference flowmeter measures the flow rate into or out of limited sections of the borehole instead of measuring the total cumulative flow rate along the borehole. The advantage of measuring the flow rate in isolated sections is a better detection of the incremental changes of flow along the borehole, which are generally very small and can easily be missed using traditional types of flowmeters.

Rubber disks at both ends of the downhole tool are used to isolate the flow in the test section from that in the rest of the borehole, see Figure 3-1. The flow inside the test section goes through its own tube and passes through the area where the flow sensors are located. The flow along the borehole outside the isolated test section passes through the test section by means of a bypass pipe and is discharged at the upper end of the downhole tool. This entire structure is called the flow guide.

The Difference flowmeter can be used in two modes, a sequential mode and an overlapping mode. In the sequential mode, the measurement increment is as long as the section length. It is used for determining the transmissivity and the hydraulic head /Öhberg and Rouhiainen 2000/. In the overlapping mode, the measurement increment is shorter than the section length. It is mostly used to determine the location of hydraulically conductive fractures and to classify them based on their flow rates.

The Difference flowmeter measures the flow rate into or out of the test section by means of thermistors, which track both the dilution (cooling) of a thermal pulse and the transfer of a thermal pulse with moving water. In the sequential mode, both methods are used, whereas in the overlapping mode, only the thermal dilution method is used because it is faster than the thermal pulse method.

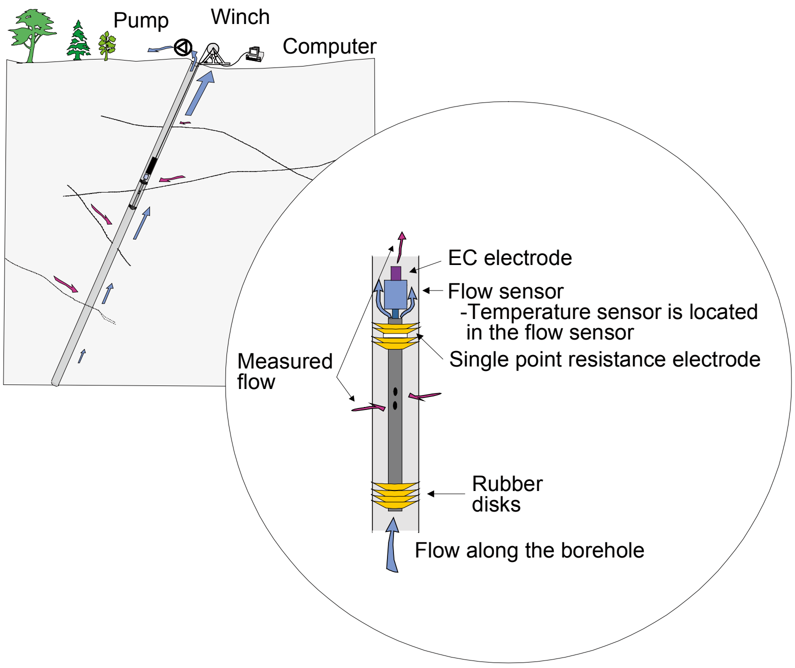

Figure 3-1. *Schematic of the downhole equipment used in the Difference flowmeter.*

Besides incremental changes of flow, the downhole tool of the Difference flowmeter can be used to measure:

- The electric conductivity (EC) of the borehole water and fracture-specific water. The electrode for the EC measurements is located on the top of the flow sensor, Figure 3-1.
- The single-point resistance (SPR) of the borehole wall (grounding resistance). The electrode of the single-point resistance tool is located in between the uppermost rubber disks, see Figure 3-1. This method is used for high resolution depth/length determination of fractures and geological structures.
- The diameter of the borehole (caliper). The caliper tool, combined with SPR, is used for the detection of the depth/length marks milled into the borehole wall, see Chapter 2. This enables an accurate depth/length calibration of the flow measurements.
- The prevailing water pressure profile in the borehole. The pressure sensor is located inside the electronics tube and connected via another tube to the borehole water, Figure 3-2.
- Temperature of the borehole water. The temperature sensor is located in the flow sensor, Figure 3-1.

All of the above measurements were performed in KFM02B.

The principles of difference flow measurements are described in Figures 3-3 and 3-4. The flow sensor consists of three thermistors, see Figure 3-3a. The central thermistor, A, is used both as a heating element and for the registration of temperature changes, Figures 3-3b and c. The side thermistors, B1 and B2, serve to detect the moving thermal pulse, Figure 3-3d, caused by constant power heating in A, Figure 3-3b.

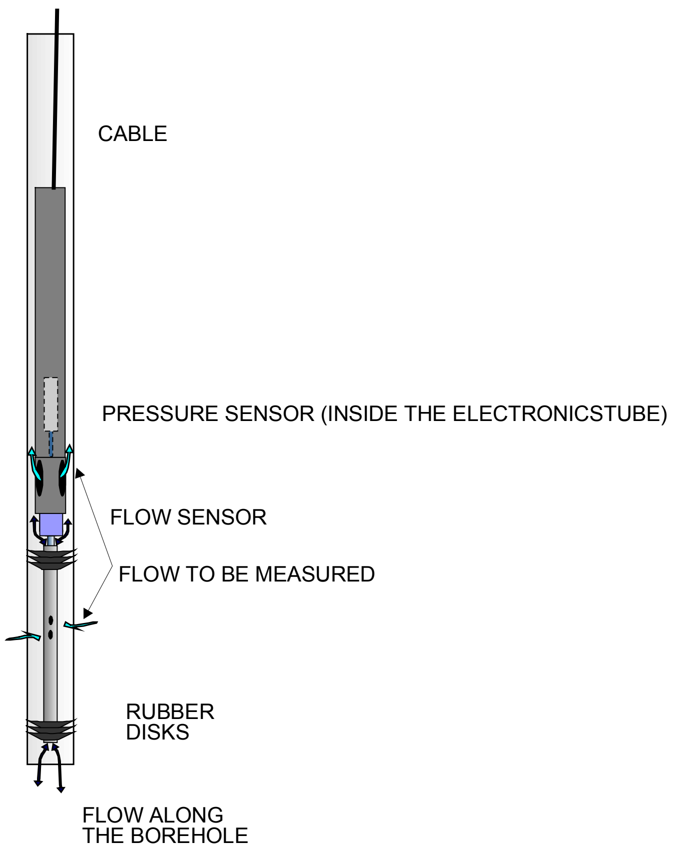

Figure 3-2. *The absolute pressure sensor is located inside the electronics tube and connected through a tube to the borehole water.*

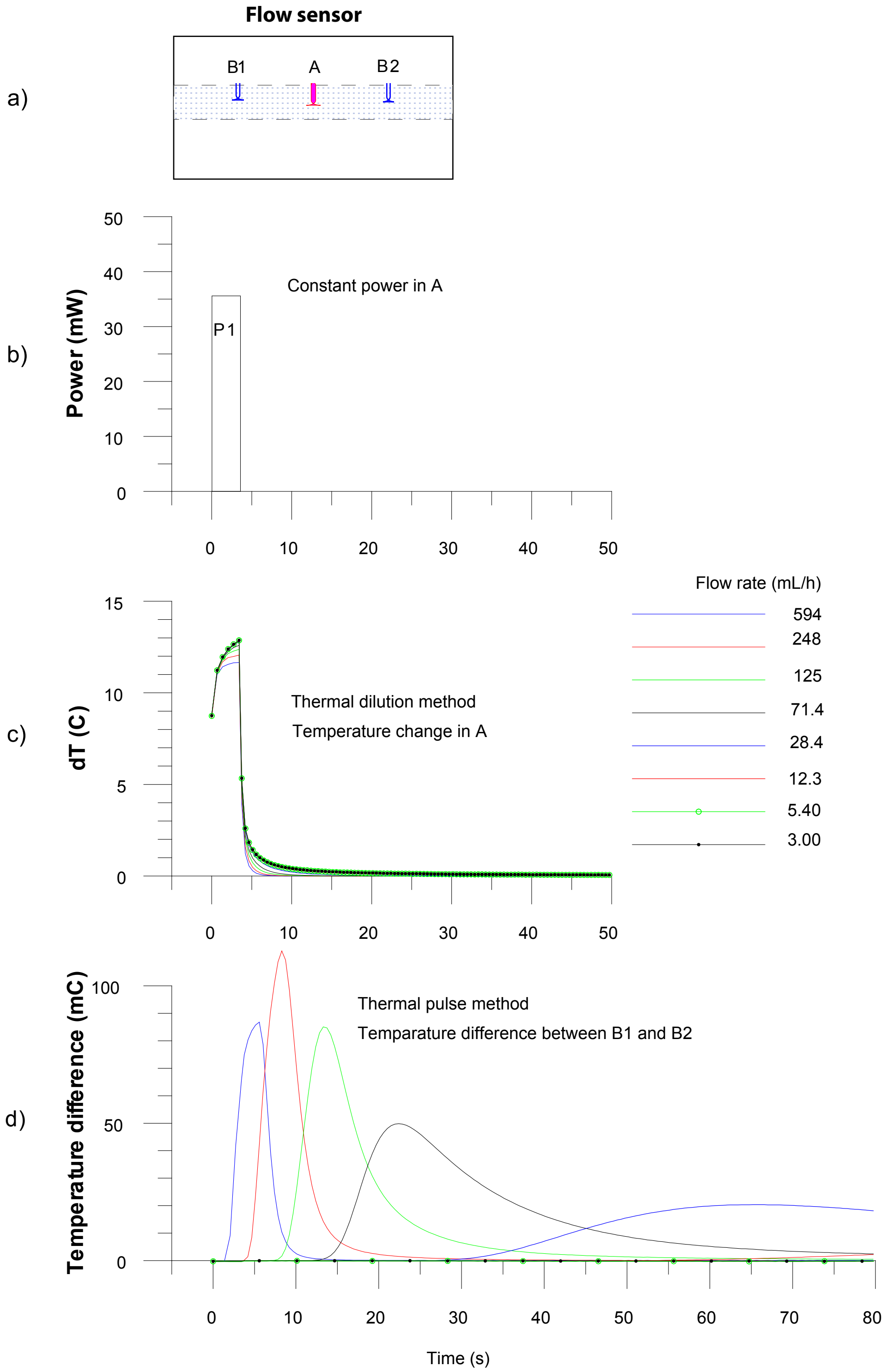

Figure 3-3. *Flow measurement, flow rate < 1,200 mL/h.*

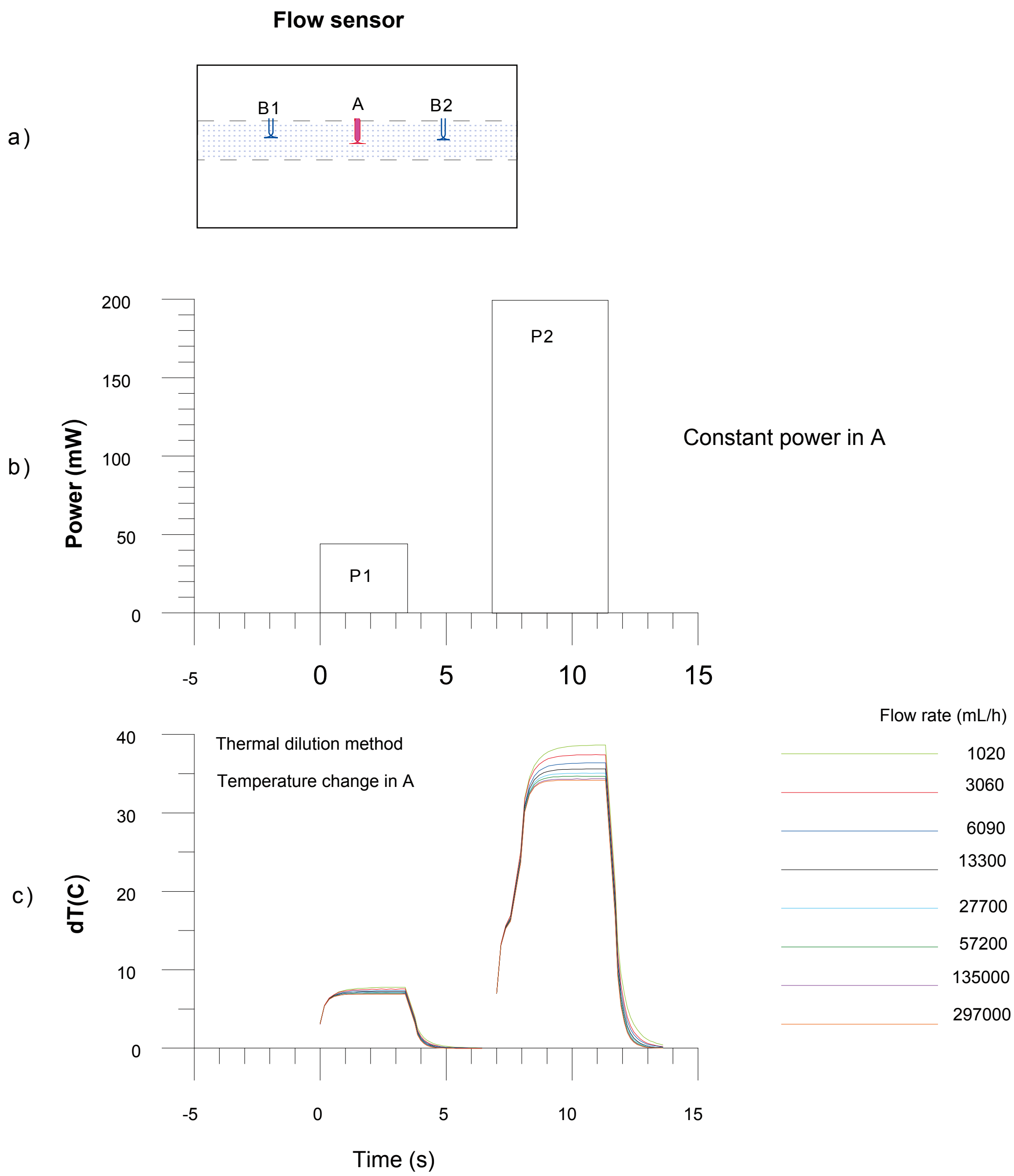

Figure 3-4. *Flow measurement, flow rate > 1,200 mL/h.*

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 is measured by monitoring the transient thermal dilution and the thermal pulse response (Figures 3-3c and d). If the measured flow rate exceeds 1,200 mL/h, another constant power heating (P_2) period is started after which the flow is re-measured from the following heat transient. When applying the thermal pulse method, thermal dilution is also measured. The same heat pulse is used for both methods.

The flow is measured when the tool is at rest. After the tool is transferred to a new position, there is a waiting time (the duration of which can be adjusted according to the prevailing circumstances) before the heat pulse (Figure 3-3b) is applied. The waiting time after the constant power thermal pulse can also be adjusted, but it is normally 10 s long for thermal dilution and 100 s long for thermal pulse. The measurement range of each method is given in Table 3-1.

Table 3-1. Ranges of flow measurements.

Method	Range of measurement (mL/h)
Thermal dilution P1-transient	30–3,000
Thermal dilution P2-transient	1,200–300,000
Thermal pulse	6–600

The lower end limits of the thermal dilution and the thermal pulse methods in Table 3-1 correspond to the theoretical lowest measurable values. Depending on the borehole conditions, these limits may not always prevail. Examples of disturbing conditions are floating drilling debris and gas bubbles in the borehole water, and high flow rates (above about 30 L/min) along the borehole. If the disturbing conditions are significant, a practical measurement limit is calculated for each set of data.

3.2 Interpretation

The interpretation of data is based on Thiem's or Dupuit's formula that describes a steady state and a 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 the pumping is felt.

If flow rate measurements are carried out using two levels of hydraulic head in the borehole, i.e. natural or pump-induced hydraulic heads, then the undisturbed (natural) hydraulic head and transmissivity of the tested borehole sections can be calculated. Two equations can be written directly from equation 3-1:

$Q_{s0} = T_s \cdot a \cdot (h_s – h_0)$ 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.

Since, in general, very little is known of the flow geometry, a cylindrical flow without any skin zones is assumed. Cylindrical flow geometry is also justified because the borehole is at a constant head and there are no strong pressure gradients along the borehole, 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 of individual fractures are known. Similar assumptions as above have to be used (a steady state cylindrical flow regime without skin zones).

$h_f = (h_0 – b\ h_1)/(1 – b)$ 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 the skin effects are unknown, transmissivity values should be taken only as an indication of the 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 geometries. A discussion of potential uncertainties in the calculation of transmissivity and hydraulic head is provided in /Ludvigson et al. 2002/.

4 Equipment specifications

The Posiva Flow Log/Difference flowmeter monitors the flow of groundwater into or out from a borehole by means of a flow guide (which uses rubber disks to isolate the flow). The flow guide thereby defines the test section to be measured without altering the hydraulic head. Groundwater flowing into or out from the test section is guided to the flow sensor. The flow is measured using the thermal pulse and/or thermal dilution methods. Measured values are transferred into a computer in digital form.

Type of instrument:	Posiva Flow Log/Difference flowmeter.
Borehole diameters:	56 mm, 66 mm and 76–77 mm.
Length of test section:	A variable length flow guide is used.
Method of flow measurement:	Thermal pulse and/or thermal dilution.
Range and accuracy of measurement:	See Table 4-1.
Additional measurements:	Temperature, Single-point resistance, Electric conductivity of water, Caliper, Water pressure.
Winch:	Mount Sopris Wna 10, 0.55 kW, 220V/50Hz. Steel wire cable 1,500 m, four conductors, Gerhard-Owen cable head.
Length determination:	Based on the marked cable and on the digital length counter.
Logging computer:	PC, Windows XP.
Software:	Based on MS Visual Basic.
Total power consumption:	1.5–2.5 kW depending on the pumps.
Calibrated:	February 2007.
Calibration of cable length:	Using length marks in the borehole.

Range and accuracy of sensors is presented in Table 4-1.

Table 4-1. Range and accuracy of sensors.

Sensor	Range	Accuracy
Flow	6–300,000 mL/h	± 10% curr.value
Temperature (middle thermistor)	0–50°C	0.1°C
Temperature difference (between outer thermistors)	–2 – +2°C	0.0001°C
Electric conductivity of water (EC)	0.02–11 S/m	± 5% curr.value
Single point resistance	5–500,000 Ω	± 10% curr.value
Groundwater level sensor	0–0.1 Mpa	± 1% full-scale
Absolute pressure sensor	0–20 MPa	± 0.01% full-scale

5 Performance

5.1 General

The Commission was performed according to Activity Plan AP PF 400-07-007 following the SKB Method Description 322.010, 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 in borehole KFM02B, 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.

The Difference Flowmeter system uses caliper measurements 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 of KFM02B was performed before any other measurements were started.

The electric conductivity (EC) and temperature of the borehole water (Item 10) during natural (un-pumped) conditions were measured after the calibration.

The combined overlapping/sequential flow logging (Item 12) 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 telescopic part of the borehole was flow logged next (Item 11).

Pumping was started on March 1, 2007. After c. 21 hours waiting time, overlapping flow logging (Item 13) was conducted using the same section and step lengths as before.

The overlapping flow logging was then continued by re-measuring previously detected flow anomalies with a 1 m section length and a 0.1 m step length (Item 14).

The fracture specific EC of water from some selected fractures (Item 15) was also measured.

The EC of borehole water (Item 16) was measured while the borehole was still pumped. After this, the pump was stopped and the recovery of the groundwater level was monitored (Item 17).

Table 5-1. Flow logging and testing in KFM02B. Activity schedule.

Item	Activity	Explanation	Date
8	Dummy logging	Borehole stability/risk evaluation.	2007-02-26
8_Extra1	Dummy logging	Borehole stability/risk evaluation.	2007-02-27
9	Calibration	SKB Caliper and SPR. Logging without the lower rubber disks, no pumping.	2007-02-27
10	EC- and temp-logging of the borehole fluid	Logging without the lower rubber disks, no pumping.	2007-02-28
12	Combined overlapping/ sequential flow logging	Section length L_w = 5 m. Step length dL = 0.5 m, no pumping.	2007-02-28–2007-03-01
11	Telescopic part of borehole flow logging	Logging without the lower rubber disks, no pumping.	2007-03-01
13	Overlapping flow logging	Section length L_w = 5 m. Step length dL = 0.5 m, pumping (includes 1 day of waiting after the pumping was started).	2007-03-01–2007-03-03
14	Overlapping flow logging	Section length L_w = 1 m. Step length dL = 0.1 m, pumping.	2007-03-03–2007-03-05
15	Fracture-specific EC-measurements in pre-selected fractures	Section length L_w = 1 m, pumping, in pre-selected fractures.	2007-03-05–2007-03-06
16	EC- and temp-logging of the borehole fluid	Logging without the lower rubber discs, pumping.	2007-03-06
17	Recovery transient	Measurement of water level and absolute pressure in the borehole after the pumping was stopped. The measurement was continued between 2007-03-07 and 2007-03-08 by SKB.	2007-03-06–2007-03-07

5.2 Nonconformities

Item 8 was conducted twice, because in the first run the amount and size of collected rock pieces in the dummy was large. The second dummy logging has been labelled Item 8_Extra1 in Table 5-1.

A 2 m drawdown was used instead of 10 m because the amount of outflow from the borehole that would have been required was so large that it is not possible to achieve it with the pumps that were available.

It was not physically possible to measure approximately 3.56 m of the bottom of the borehole, because there are weights and a centralizer in the measurement device. The rubber disks in the device must also be turned before the measurement begins. This reduces the measured distance for at least 50 cm. It is also possible that there were fallen rocks and debris at the bottom of the borehole. Altogether 4.87 m of the bottom of the borehole was not measured.

During the 5 m section flow logging measurement in pumped conditions, the pumping had slowed down in the approximate interval between 379 m and 371 m. This interval was re-measured immediately. This did not cause any delays in the measurement schedule.

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 the following:

- The caliper/SPR-measurements (Item 9) were initially length corrected in relation to the known length marks, Appendix 1.19, 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 12, 13, 14, and 15 to obtain relative length errors of these measurement sequences.
- All SPR curves could then be synchronized, as can be seen in Appendices 1.2–1.18.

The results of the caliper and single-point resistance measurements from all measurements in the entire borehole are presented in Appendix 1.1. Five SPR-curves are plotted together with the caliper-data. These measurements correspond to Items 9, 12, 13, 14 and 15.

Zoomed results of the caliper and SPR data are presented in Appendices 1.2–1.18. The detectability of the length marks is listed in Table 6-1. All the length marks were detected by the caliper tool.

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

Table 6-1. Detected length marks.

Length marks given by SKB (m)	Length marks detected by caliper	Length marks detected by SPR
110	both	yes
150	both	yes
200	both	yes
250	both	yes
300	both	yes
350	both	yes
400	both	yes
452	both	yes
510	both	yes

The aim of the plots in Appendices 1.2–1.18 is to verify the accuracy of the length correction. The curves in these plots represent length corrected results. These appendices also illustrate a few locations where such SPR anomalies were found that could be used to help in determining the location of the measurement tool in the borehole.

The magnitude of length correction along the borehole is presented in Appendix 1.19. 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 disks. Effectively, the section length can be larger. At the upper end of the test section there are four rubber 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 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 (Item 9).
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 Electric conductivity and temperature

6.2.1 Electric conductivity and temperature of borehole water

The electric 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 2.1 (logarithmic scale) and 2.2 (linear scale), blue curve.

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

The length calibration of the borehole electric 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 1.19.

6.2.2 Electric 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 electric conductivity and temperature of flowing water from the fractures were measured.

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

The test section in these measurements was 1 m long and the tool was moved in 0.1 m steps. The water volume in a one metre long test section is 3.6 L. The results are presented in Appendices 12.1–12.3. The blue symbol represents the conductivity value when the tool was moved and the red symbol is used for the set of stationary measurements.

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

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

Table 6-2. Fracture-specific EC.

Upper end of section (m)	Lower end of section (m)	Measured fractures (m)	EC (S/m) at 25°C
157.23	158.23	158.1	1.26
329.99	330.99	330.7	1.47
413.72	414.72	414.5	1.55
422.53	423.53	423.3	1.52
469.97	470.97	470.2	1.61
470.77	471.77	471, 471.5	1.61
499.30	500.30	500	1.56
500.10	501.10	500.8, 501	1.58

6.3 Pressure measurements

Absolute pressure was registered together with the other measurements in Items 11–15 and 17. The pressure sensor measures the sum of hydrostatic pressure in the borehole and air pressure. Air pressure was also registered separately, see Appendix 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 by the pressure sensor. The hydraulic head (h) at a certain elevation (z) is calculated according to the following expression /Nordqvist 2001/:

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

where

h is the hydraulic head (metres above sea level) 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 (metres above sea level) according to the RHB 70 reference system.

An offset of 2.60 kPa is subtracted from absolute pressure results.

The calculated head distributions are presented in Appendix 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 3.1–3.25. Single-point resistance is usually lower in value on a fracture where a flow is detected. There are also many other resistance anomalies caused by other fractures and geological features. The electrode of the single-point resistance tool is located within the upper rubber disks. Thus, the locations of the resistance anomalies of leaky fractures coincide with the lower end of the flow anomalies.

The caliper 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. To obtain quick results, only the thermal dilution method was used for flow rate determination.

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 metres interval in both 5 m section measurements. In the 1 m section measurements the thermal pulse method was also used, if it was deemed necessary based on the 5 m section measurements in pumped conditions. The thermal pulse method was only used to detect the flow direction.

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 therefore 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 as the corresponding curves.

The flow along the borehole was also logged for the telescopic part of the borehole (Item 11). This was done by removing the lower rubber disks and guiding all flow along the borehole through the flow sensor. The location of the measurement was at 89.01 m at the intact bedrock just below the telescopic part of the borehole. The results are presented in Appendix 11. It can be seen from the data that the water level remained constant and a detected flow upwards along the borehole slowly dropped to zero during a period of more than an hour.

A 2 m drawdown instead of 10 m was used in the measurements in pumped conditions, because the pumps that were used could not pump enough water to cause a 10 m drawdown.

There is probably a porous section at the depth interval from c. 167 m to 169 m.

The explanations to all the table headings and other symbols that are used in the appendices are given in Appendix 4.

6.4.2 Transmissivity and hydraulic head of borehole sections

The borehole was flow logged with a 5 m section length and with 0.5 m length increments both under un-pumped and pumped conditions. All the flow logging results presented in this report are derived from the measurements that utilized the thermal dilution method to measure the flow rate.

The results of the measurements with a 5 m section length are presented in tables, see Appendix 5. Only the results with 5 m length increments are used. All borehole sections are shown in Appendices 3.1–3.25. Secup and Seclow in Appendix 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 Appendix 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 Appendix 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 Appendix 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 at rest, 12 sections were detected as flow yielding, nine of which had a flow direction from the borehole into the bedrock (negative flow). During pumping, all 20 detected flows were directed towards the borehole.

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

The flow data are presented as a plot, see Appendix 6.1. The left hand side of each diagram represents flow from the borehole into the bedrock for the respective test sections, whereas the right hand side represents the opposite. If the measured flow was zero (below the measurement limit), it is not visible in the logarithmic scale of the appendices.

The lower and upper measurement limits of the flow are also presented in the plots (Appendix 6.1) and in the tables (Appendix 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 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 6.2 and in Appendix 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 5).

The sum of all the detected flows without pumping (Q_0) was $-8.49 \cdot 10^{-7}$ m^3/s (–3,056 mL/h). This sum should normally be zero if all the flows in the borehole are correctly measured, 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 measurement of the flow along the borehole at 89.01 m shows a slowly decreasing upwards current which eventually becomes nearly zero. If the measured flow anomaly above 89.01 m is not taken into account, the sum of flows is $9.89 \cdot 10^{-8}$ m^3/s (–356 mL/h), which is close to zero. The anomaly in question (88.6 m) is probably a leak at the contact between the steel guide and the borehole.

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 Appendix 3.17. In these cases a stepwise increase or decrease in the flow data plot equals the flow rate of a specific fracture (filled triangles in the appendices).

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

The total amount of detected flowing fractures was 41, but only 9 of them could be defined without pumping. These 9 fractures could be used for head estimations and all 41 were used for transmissivity estimations. Transmissivity and hydraulic head of fractures are presented in Appendices 7 and 8.

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

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

6.4.4 Theoretical and practical measurement limits of flow and transmissivity

The theoretical minimum of the measurable flow rate in the overlapping measurements (thermal dilution method only) is approximately 30 mL/h. The thermal pulse method can also be used. Its theoretical lower limit is about 6 mL/h. In this borehole the thermal pulse method was only used to detect the flow direction and not the flow rate. The upper limit of the flow measurements is 300,000 mL/h. These limits are determined on the basis of flow calibration. It is assumed that a flow can be reliably detected between the upper and lower theoretical limits during favourable borehole conditions.

In practice, the minimum measurable flow rate might, however, be much higher. Borehole conditions may have an influence on the base level of flow (noise level). The noise level can be evaluated on such intervals of the borehole where there are no flowing fractures or other structures. The noise level may vary along the borehole.

There are several known reasons for increased noise levels:

1) Rough borehole wall.

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

3) Gas bubbles in water.

4) High flow rate along the borehole.

A rough borehole wall always causes a high noise level, not only in the flow results but also in the single-point resistance results. The flow curve and the SPR curves are typically spiky when the borehole wall is rough.

Drilling debris usually increases the noise level. Typically this kind of noise is seen in both un-pumped and pumped conditions.

Pumping causes the pressure to drop in the borehole water column and the water in the fractures near the borehole. This may lead to the release of dissolved gas and increase the amount of gas bubbles in the water. Some fractures may produce more gas than others. Sometimes the noise level is higher just above certain fractures (when the borehole is measured upwards). The reason for this is assumed to be gas bubbles. The bubbles may cause a decrease of the average density of water and therefore also decrease the measured head in the borehole.

The effect of a high flow rate along the borehole can often be seen above high flowing fractures. Any minor leak at the lower rubber disks is directly measured as increased noise.

A high noise level in a flow masks the "real" flow if it is smaller than the noise. Real flows are totally invisible if they are approximately ten times smaller than the noise and they are registered correctly if they are approximately ten times larger than the noise. Based on experience, real flows between 1/10 times the noise level and 10 times the noise level are summed with the noise. Therefore the noise level could be subtracted from the measured flow to get the real flow. This correction has not been done so far, because it is unclear whether it is applicable in each case.

The practical minimum of the measurable flow rate is evaluated and presented in Appendices 3.1–3.25 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 KFM02B varied between 30 mL/h and 150 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 exceeded in one section in the 5 m measurements in pumped conditions. However the limit was not exceeded in the 1 m measurements and therefore no re-measurements were needed.

The practical minimum of measurable flow rate is presented in Appendix 5 (Q-lower limit P). It is taken from the plotted curve in Appendix 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 5 (T_D-measl$_{LP}$). The theoretical minimum measurable transmissivity (T_D-measl$_{LT}$) is evaluated using a Q value of 30 mL/h (minimum theoretical flow rate with the thermal dilution method). The upper measurement limit of transmissivity can be evaluated using the maximum flow rate (300,000 mL/h) at the actual head difference as above, see Appendix 5 (T_D-measl$_U$).

All three flow limits are also plotted with the measured flow rates, see Appendix 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 Appendix 6.2.

Similar flow and transmissivity limits are not given for the fracture-specific results in Appendix 7. Approximately the same limits would though be valid also for these results. The limits for fracture-specific results are more difficult to define. For instance, it may be difficult to observe a small flow rate near (< 1 m) a high flowing fracture. The situation is similar for the upper flow limit. If there are several high flowing fractures less than one metre apart from each other, the upper flow limit depends on the sum of flows which 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 10.2. The borehole was pumped between March 1 and 6 with a drawdown of approximately 2 metres. The pumping rate was recorded, see Appendix 10.2.

The groundwater recovery was measured after the pumping period, between March 6 and 7 and was continued by SKB after that, Appendix 10.3. The recovery was measured with two sensors, the water level sensor (pressure sensor for monitoring water level) and the absolute pressure sensor located at the borehole length of 21.27 m.

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 KFM02B 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 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 electric conductivity and temperature measurements of the borehole water. In addition, electric 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.

The total amount of detected flowing fractures was 41. Transmissivity and hydraulic head were calculated for borehole sections and fractures above 567.11 m. The highest fracture transmissivity ($1.7 \cdot 10^{-5}$ m^2/s) was detected at 500.8 m. Other high transmissive anomalies were found at 414.5 m, 471.5 m and 500.0 m. No flowing fractures were identified below 502.0 m.

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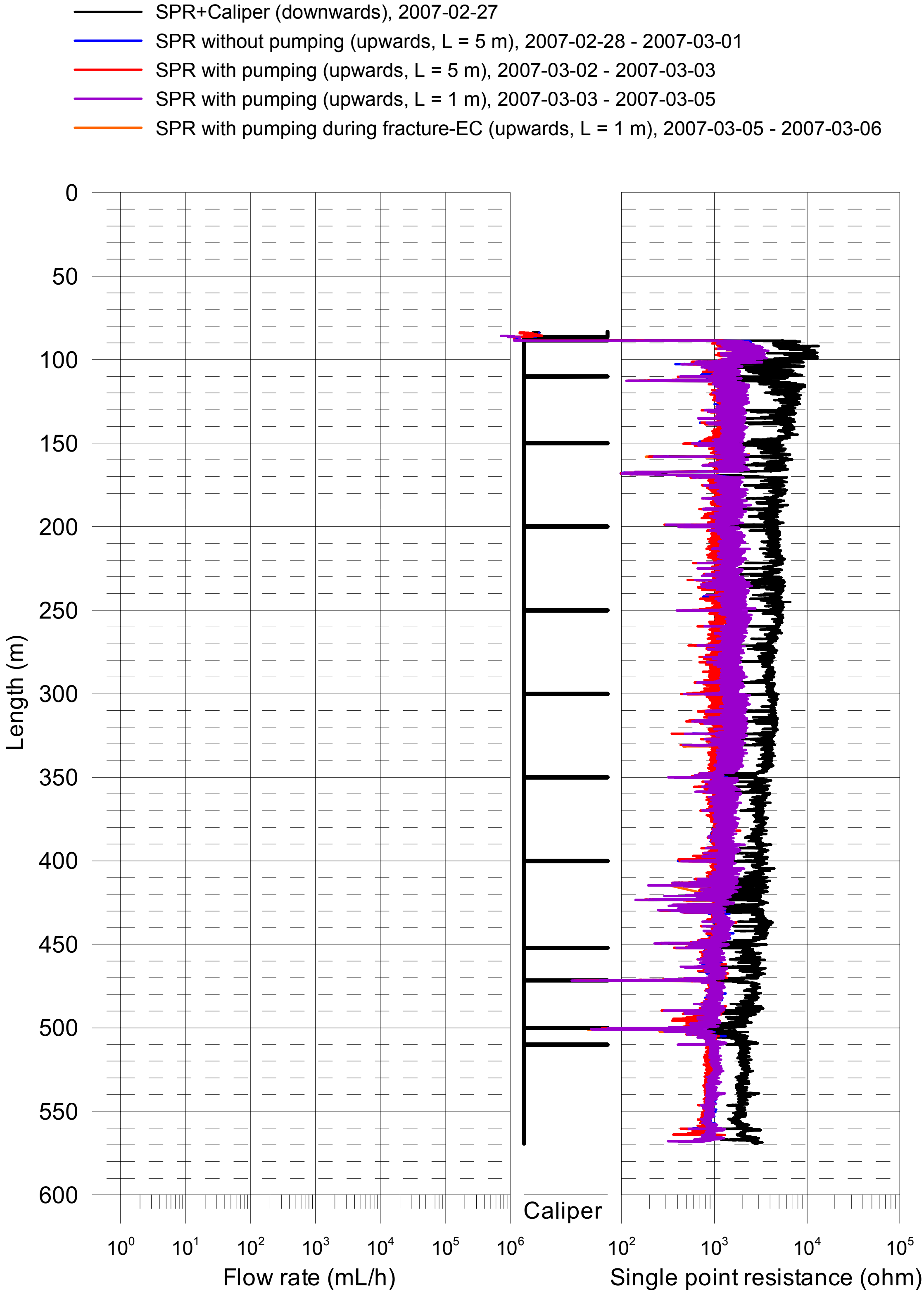
Appendices

Appendices 1.1–1.18	SPR and Caliper results after length correction
Appendix 1.19	Length correction
Appendices 2.1–2.2	Electric conductivity of borehole water
Appendix 2.3	Temperature of borehole water
Appendices 3.1–3.25	Flow rate, Caliper and Single point resistance
Appendix 4	Explanations for the tables in Appendices 5–7
Appendices 5	Table of transmissivity and head of 5 m sections
Appendix 6.1	Flow rates of 5 m sections
Appendix 6.2	Transmissivity and head of 5 m sections
Appendix 7	Table of transmissivity and head of detected fractures
Appendix 8	Transmissivity and head of detected fractures
Appendix 9	Comparison between section transmissivity and fracture transmissivity
Appendix 10.1	Head in the borehole during flow logging
Appendix 10.2	Air pressure, water level in the borehole and pumping rate during flow logging
Appendix 10.3	Groundwater recovery after pumping
Appendix 11	Vertical flow along the borehole at 89.01m
Appendices 12.1–12.3	Fracture-specific EC results

Forsmark, borehole KFM02B
SPR and Caliper results after length correction



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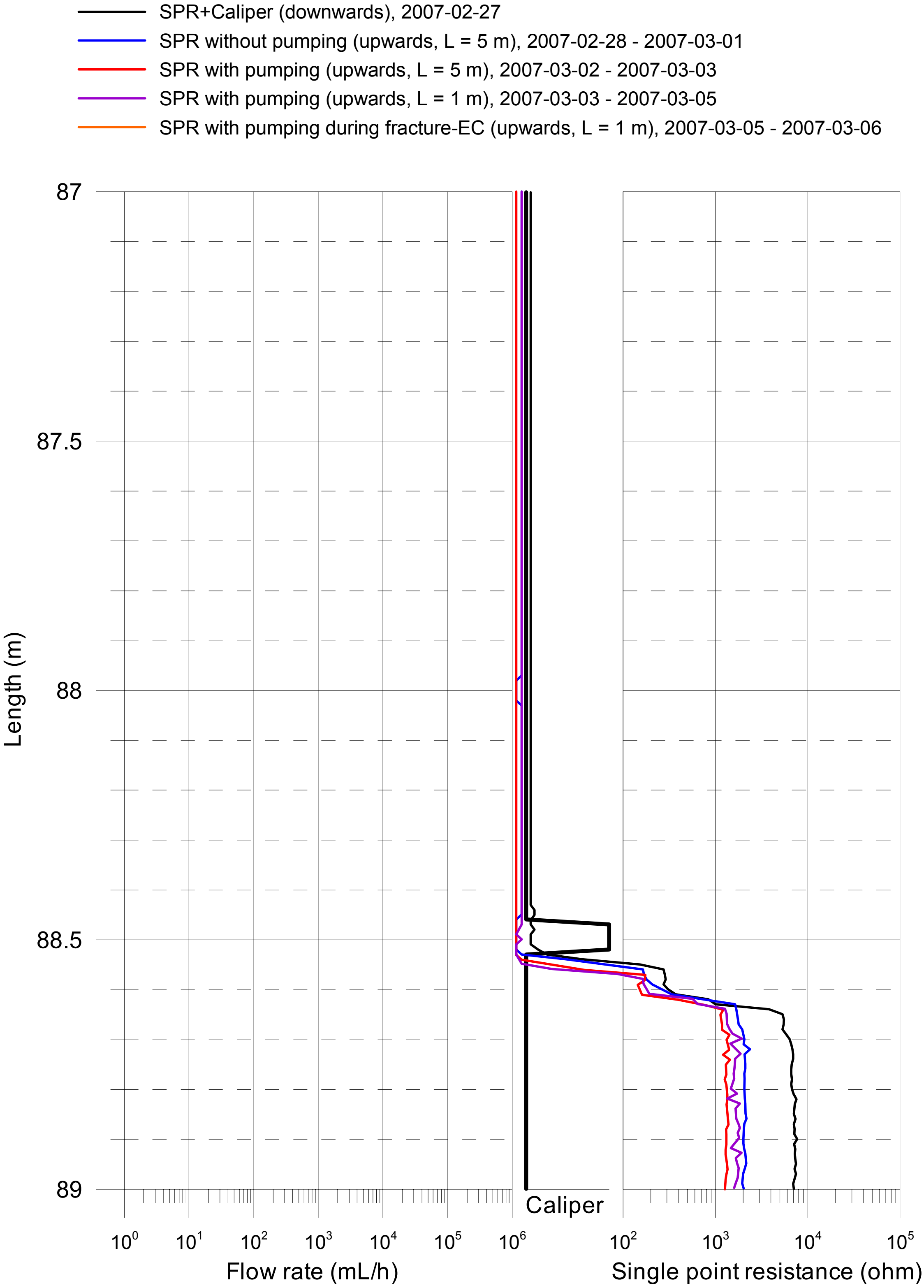
SPR and Caliper results after length correction



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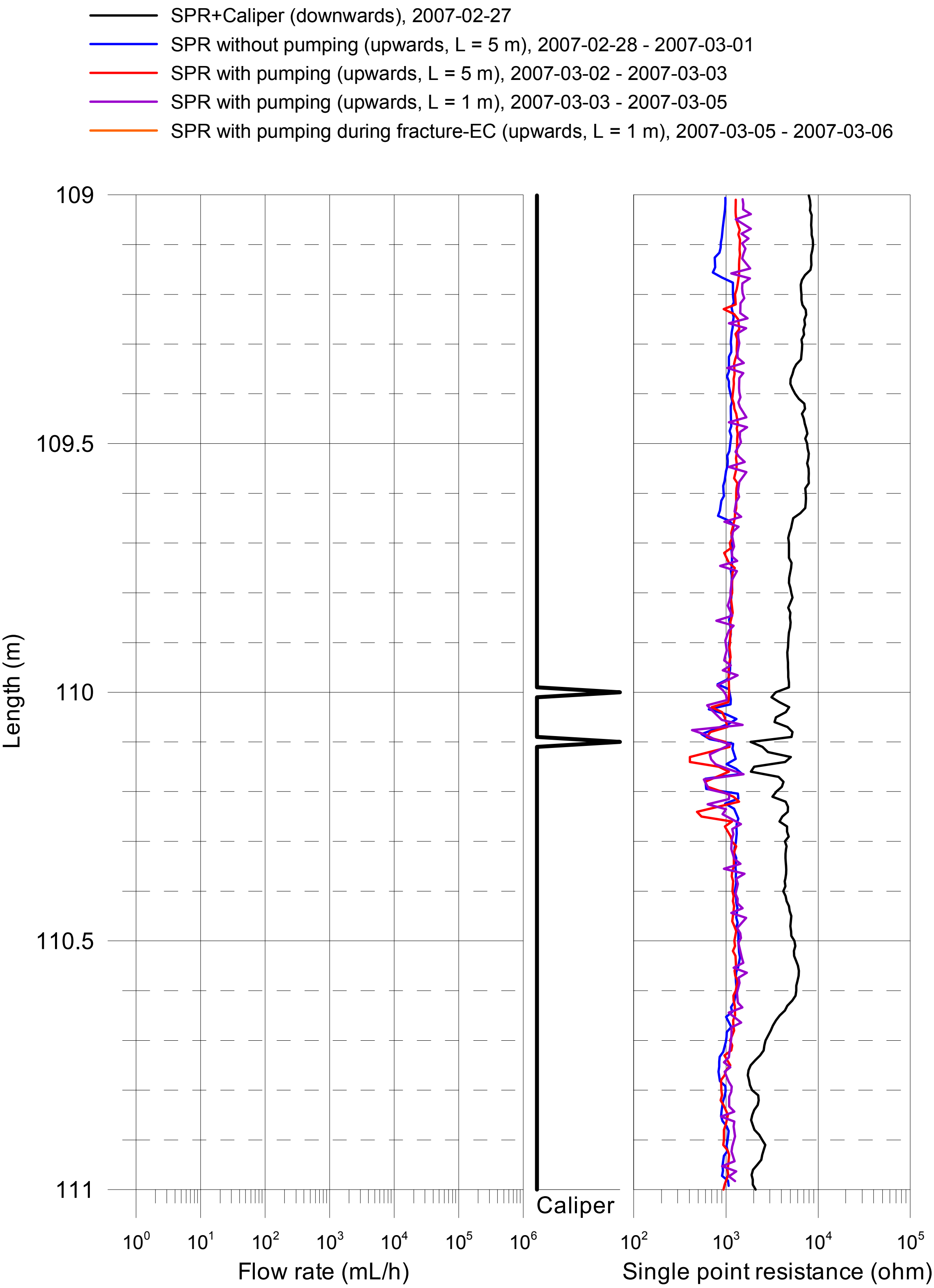

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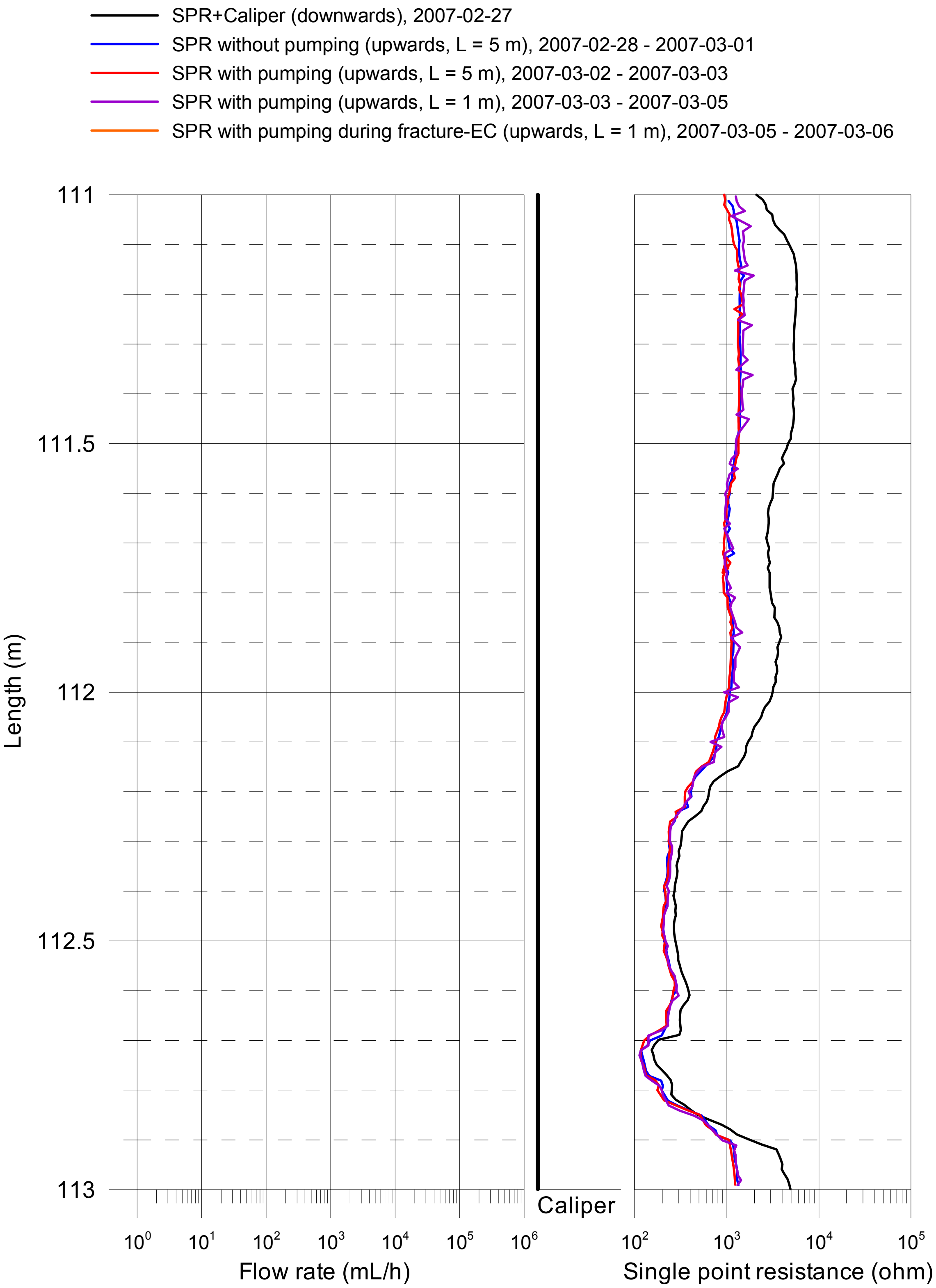
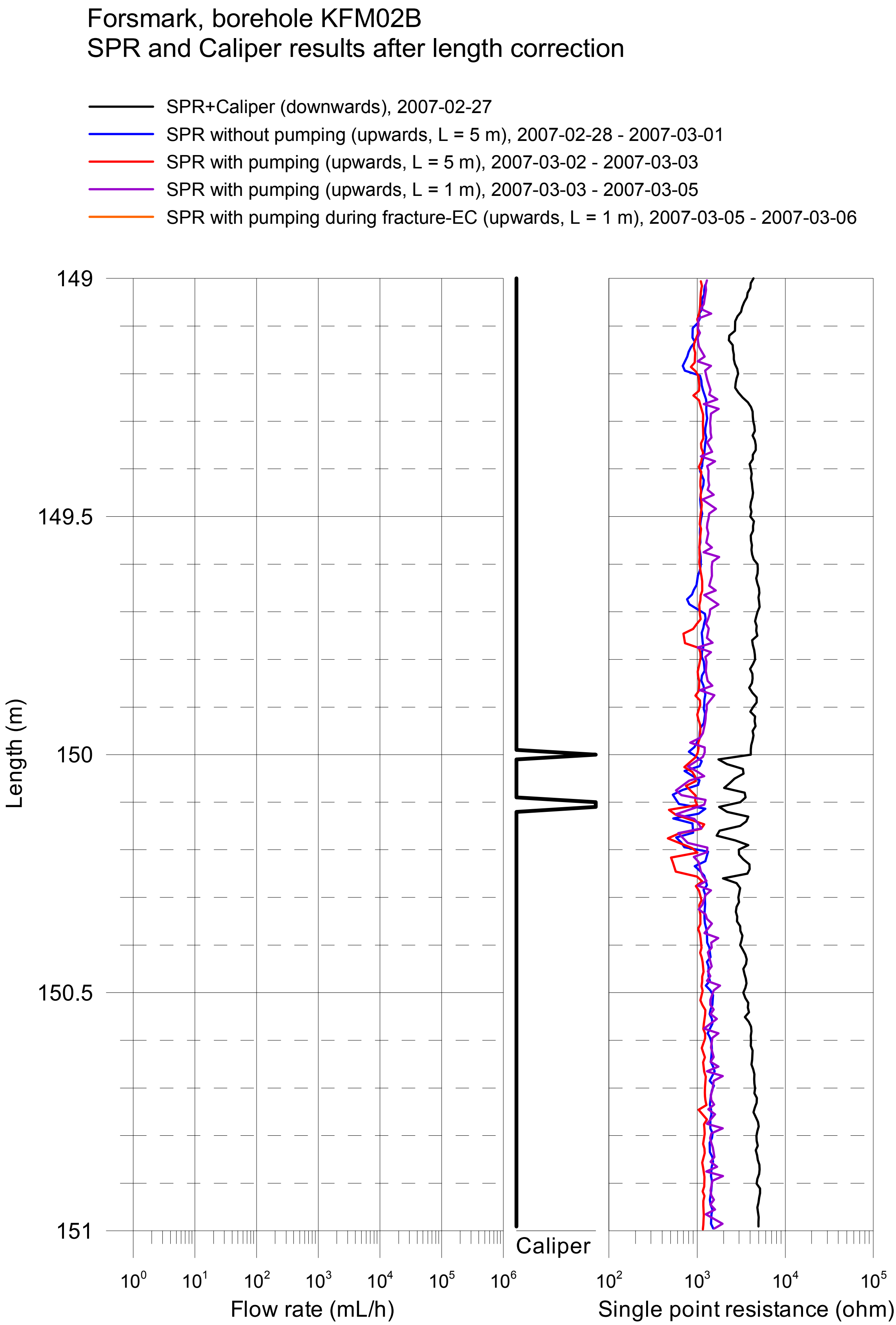
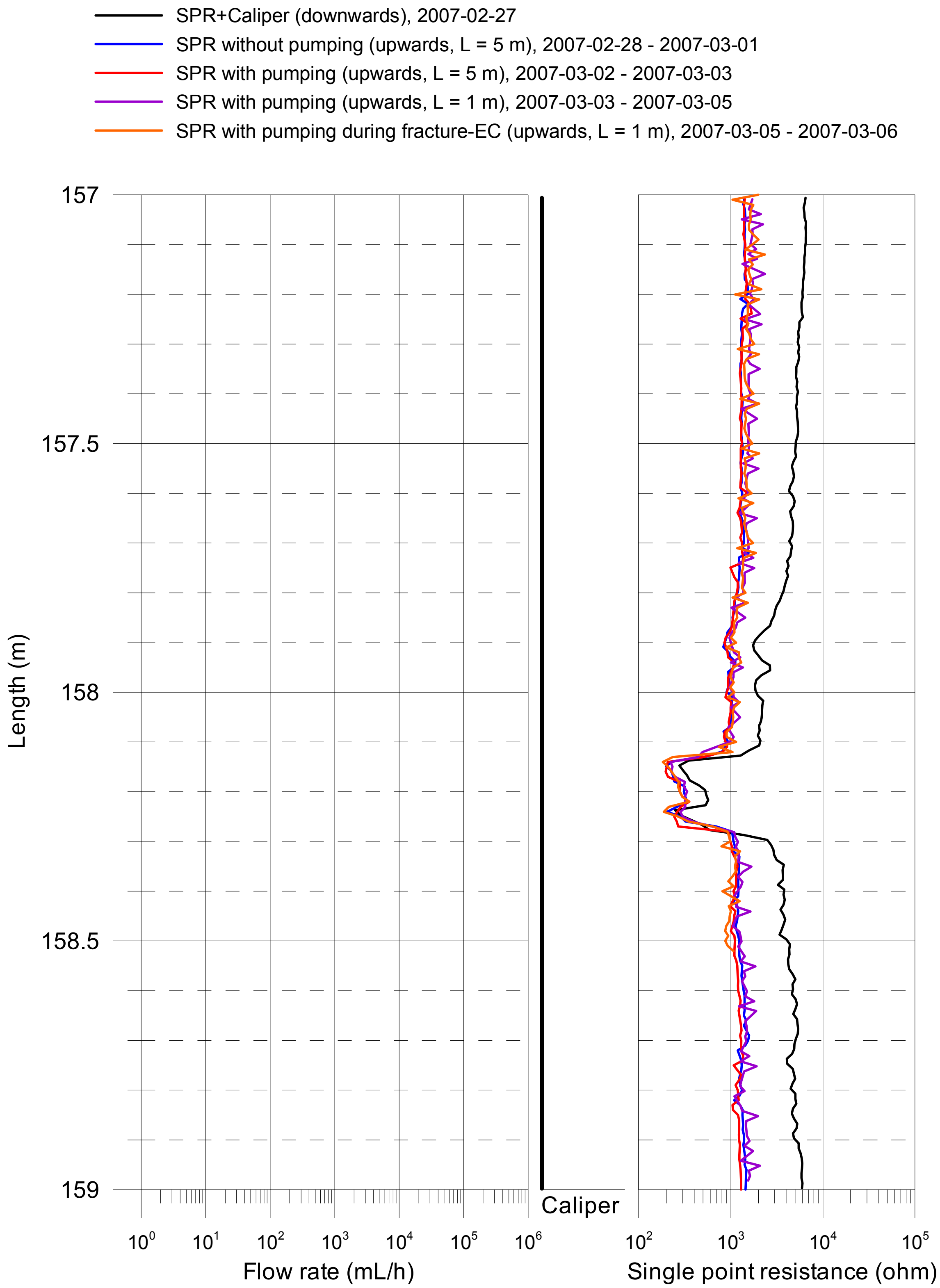




Forsmark, borehole KFM02B
SPR and Caliper results after length correction
SPR+Caliper (downwards), 2007-02-27
SPR without pumping (upwards, L = 5 m), 2007-02-28 - 2007-03-01
SPR with pumping (upwards, L = 5 m), 2007-03-02 - 2007-03-03
SPR with pumping (upwards, L = 1 m), 2007-03-03 - 2007-03-05
SPR with pumping during fracture-EC (upwards, L = 1 m), 2007-03-05 - 2007-03-06
149
149.5
150
150.5
151
Length (m)
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 KFM02B
SPR and Caliper results after length correction



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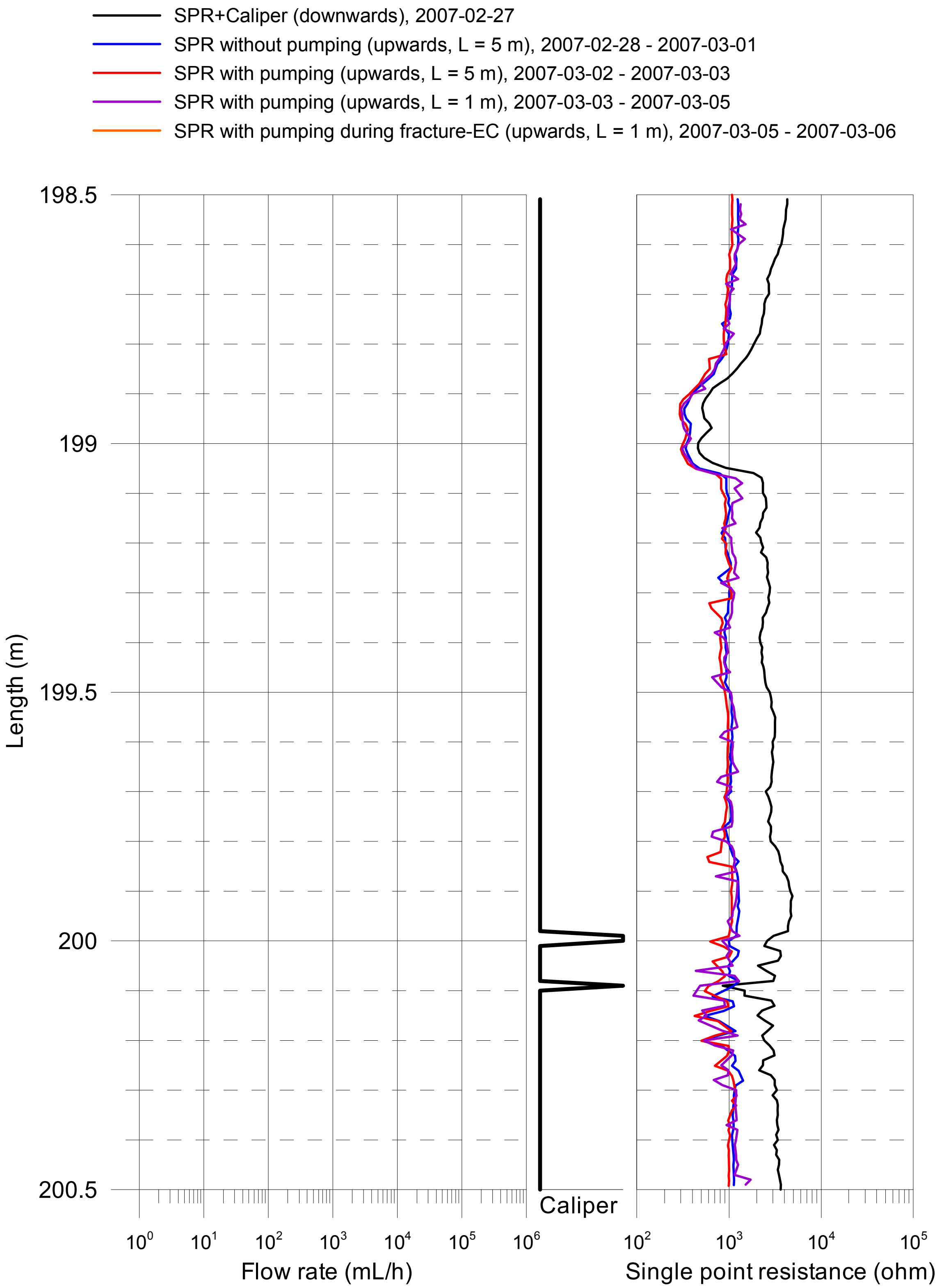
SPR and Caliper results after length correction



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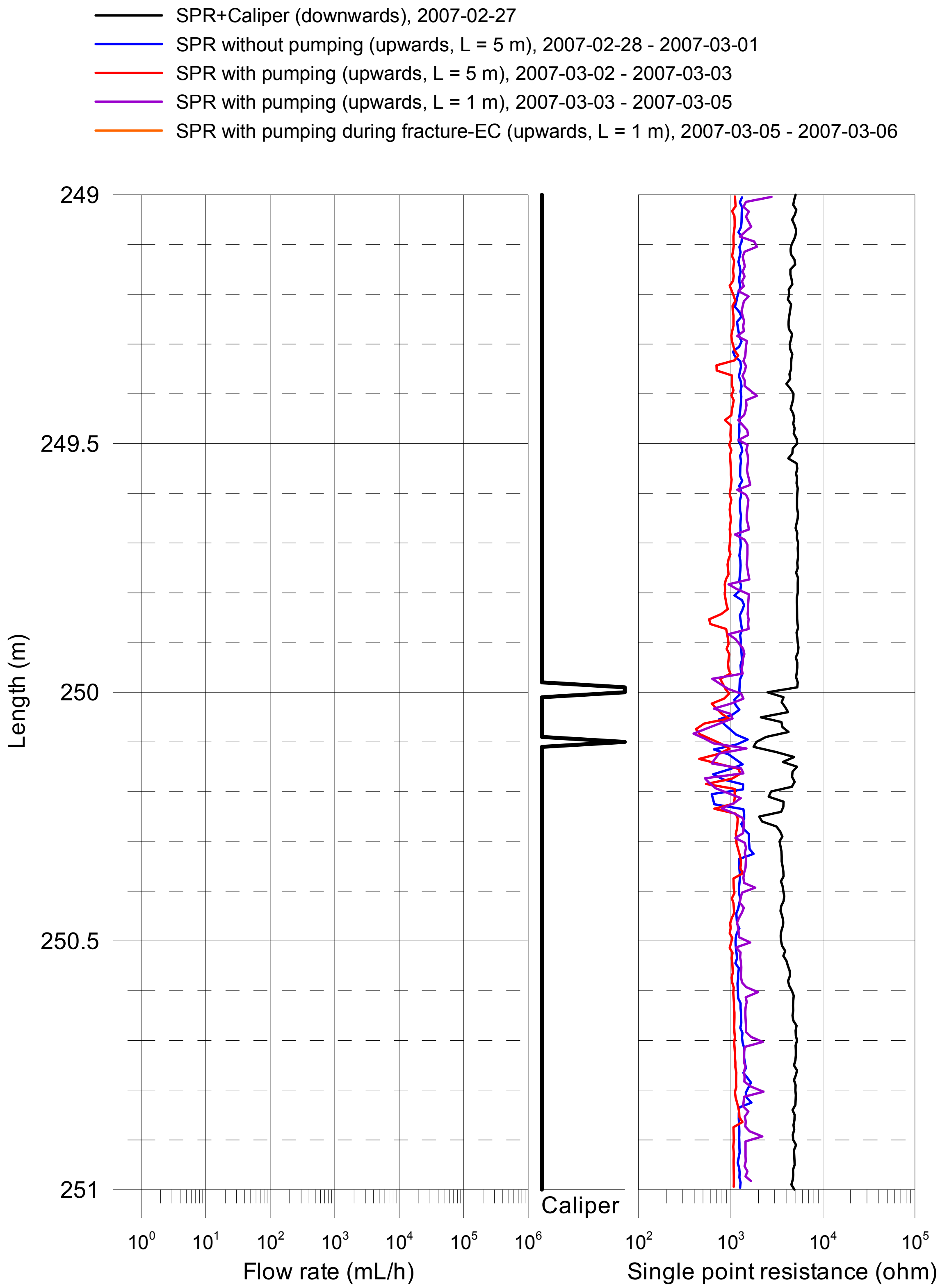
SPR and Caliper results after length correction



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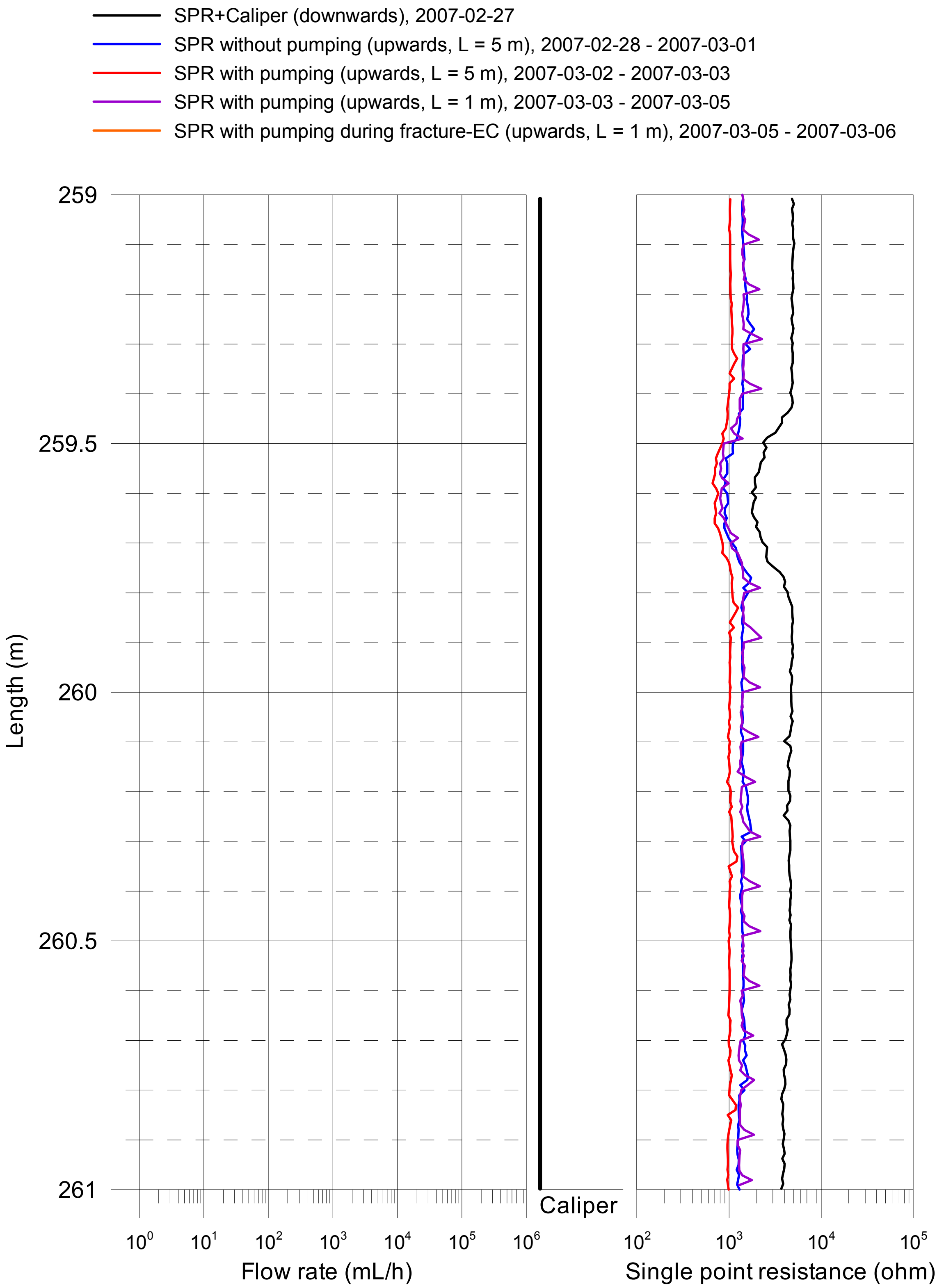

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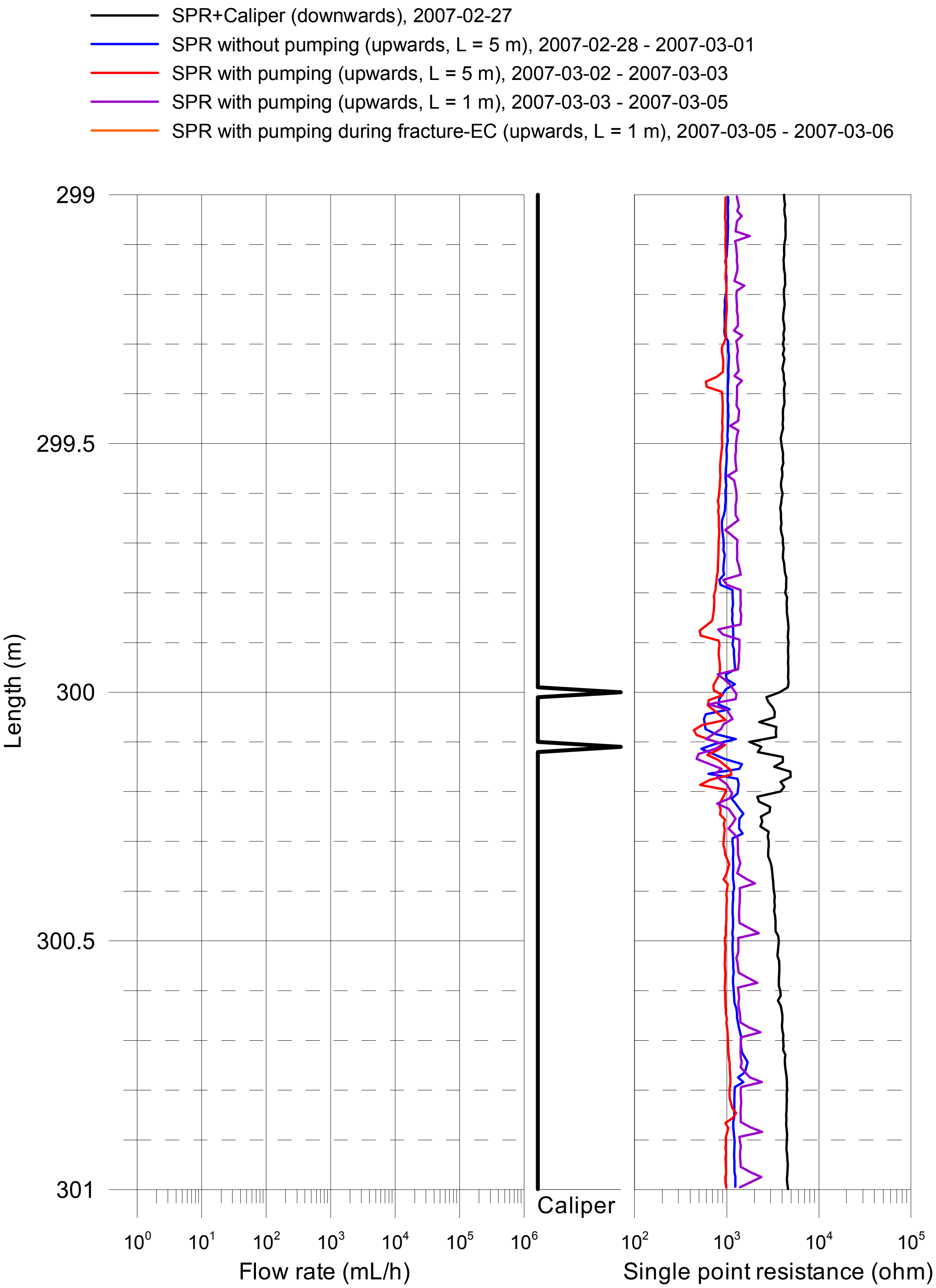
SPR and Caliper results after length correction



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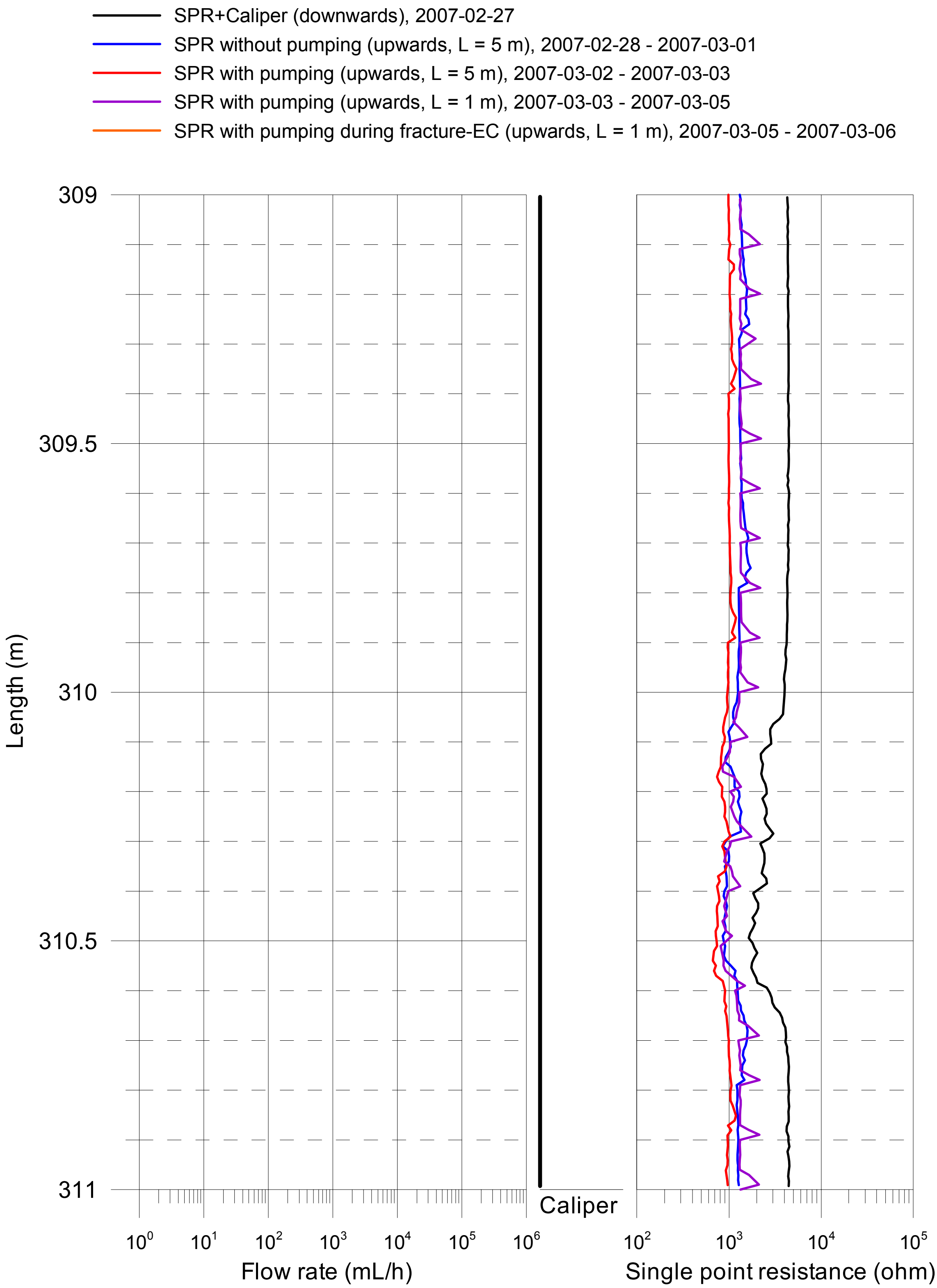
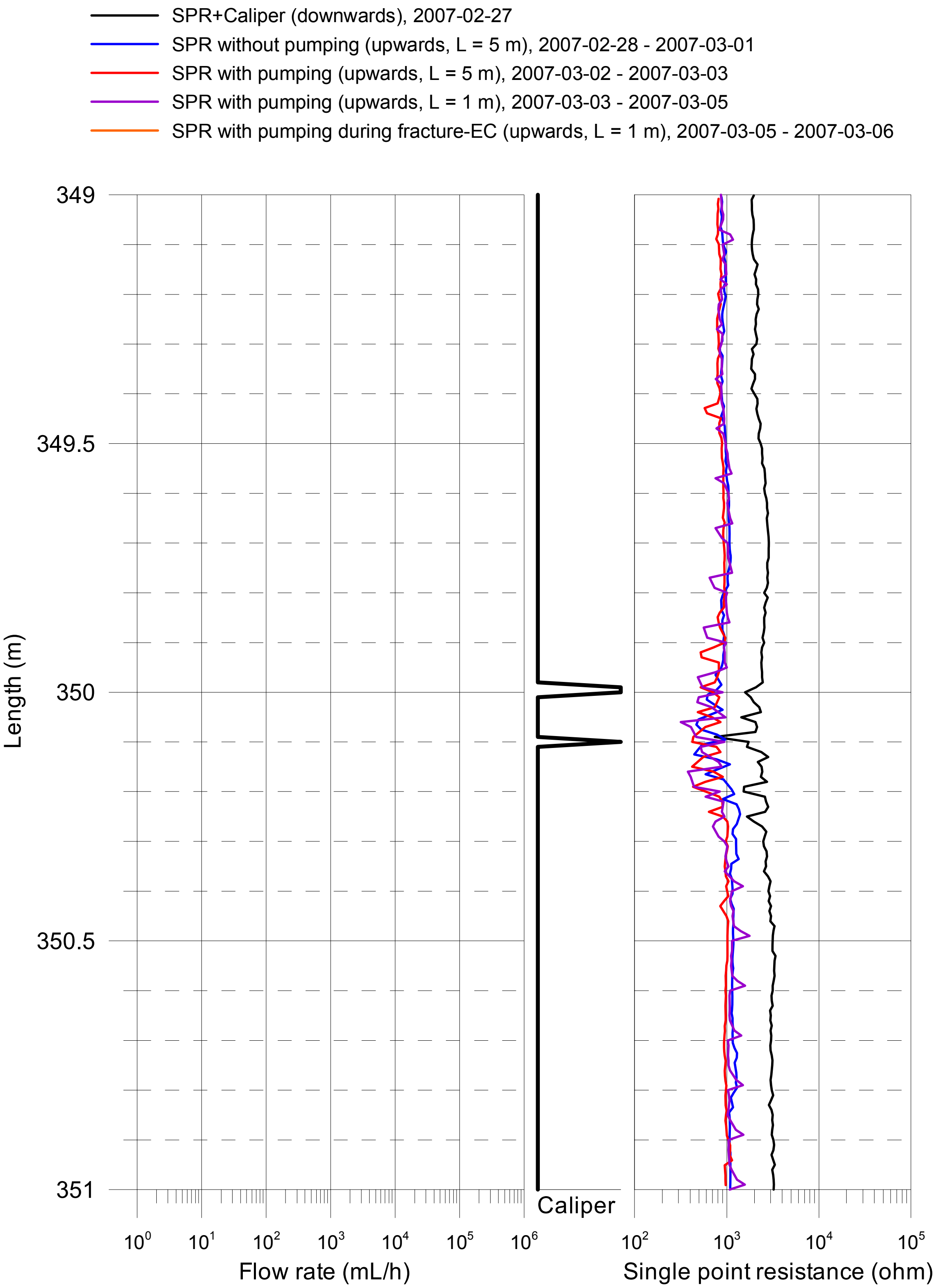
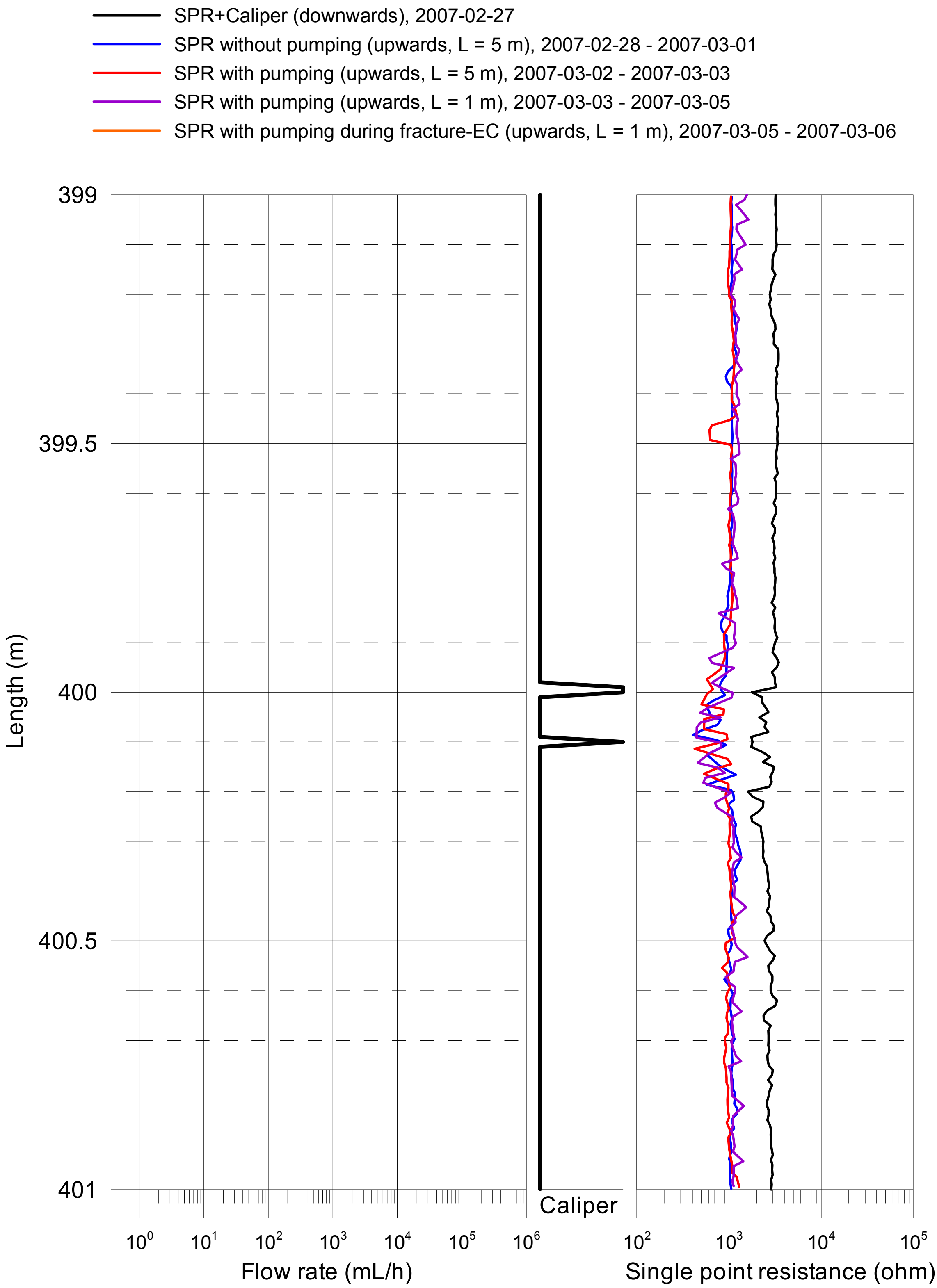
SPR and Caliper results after length correction



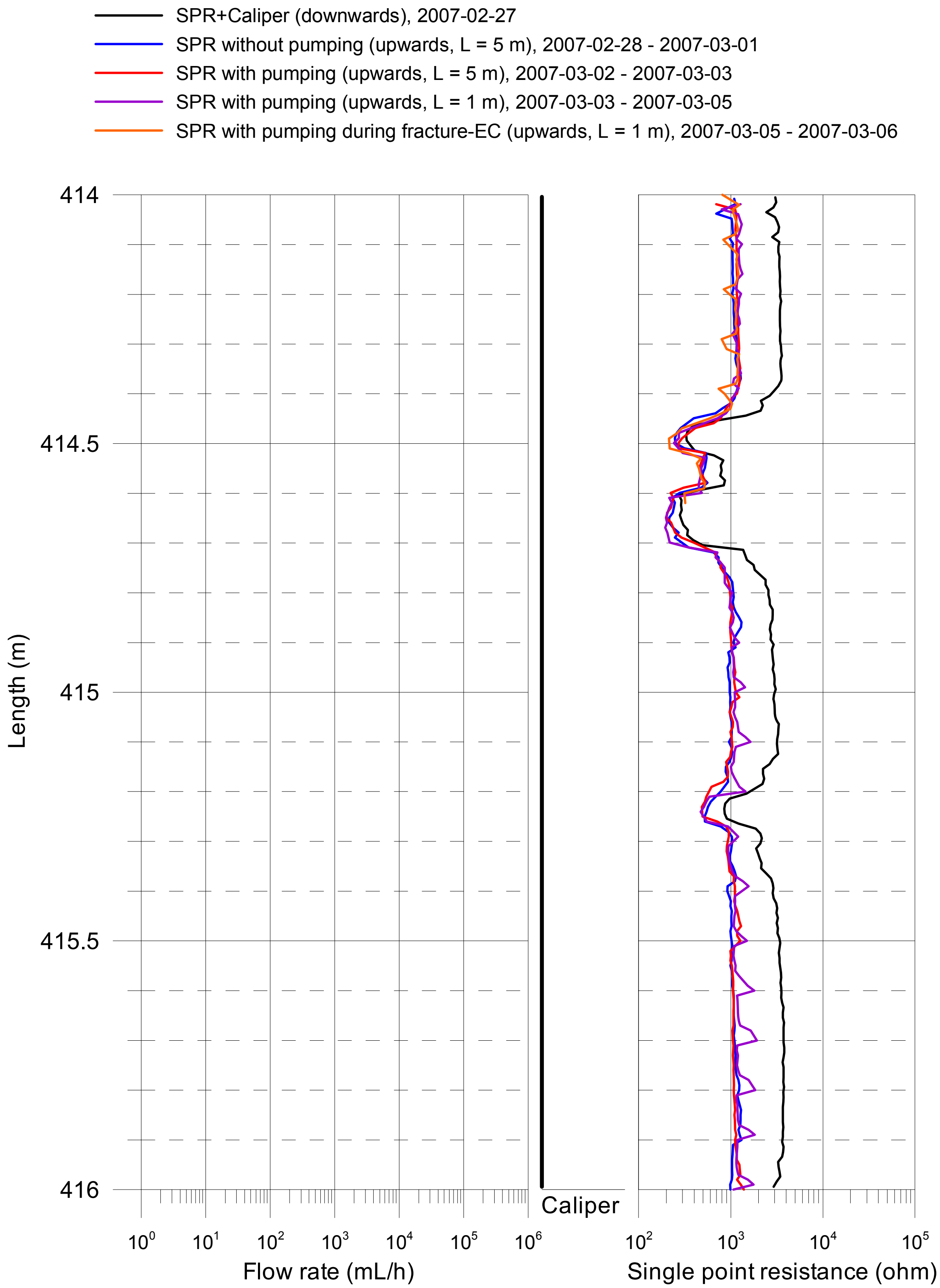
Forsmark, borehole KFM02B
SPR and Caliper results after length correction



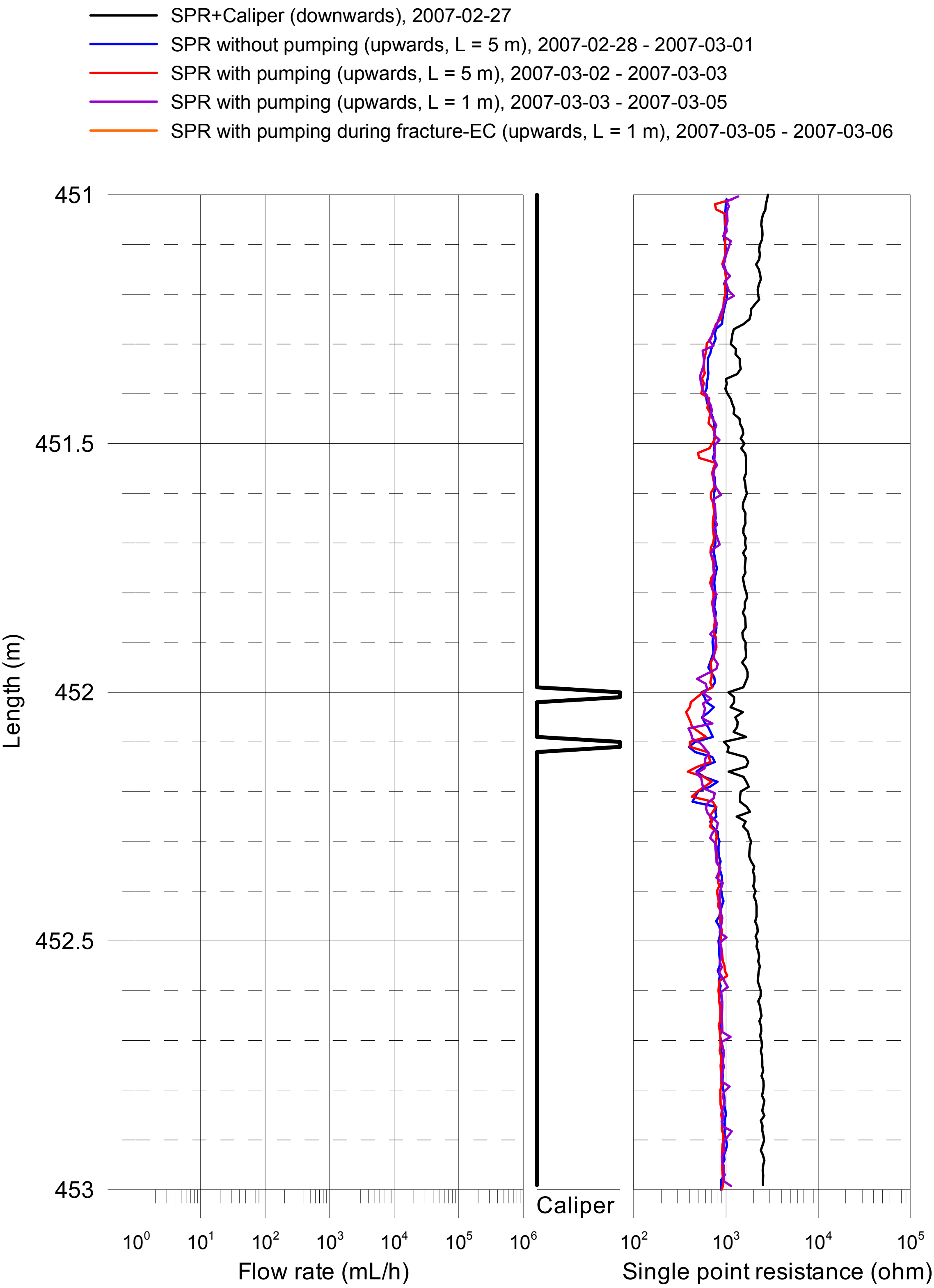
Forsmark, borehole KFM02B
SPR and Caliper results after length correction



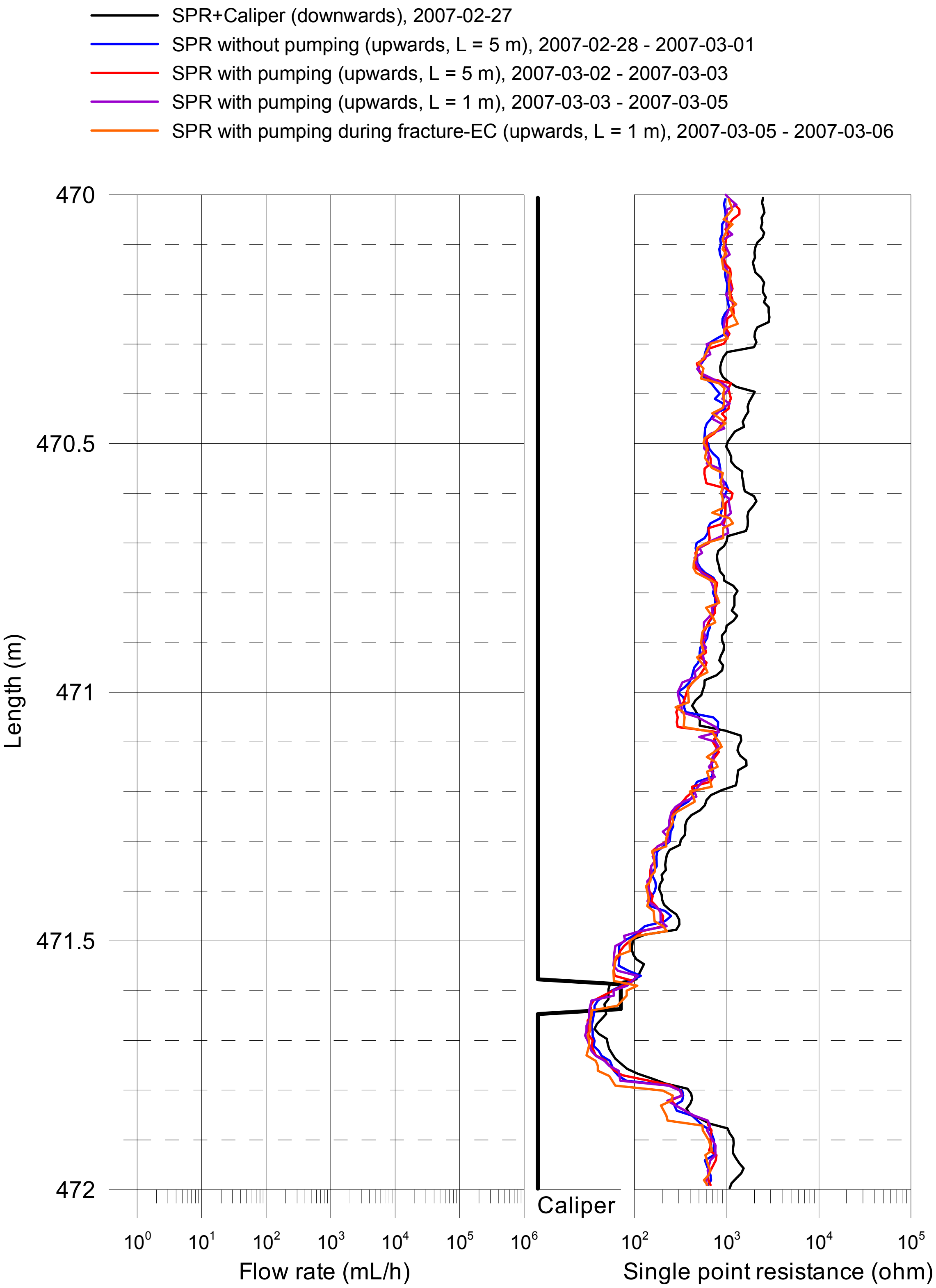
Forsmark, borehole KFM02B
SPR and Caliper results after length correction



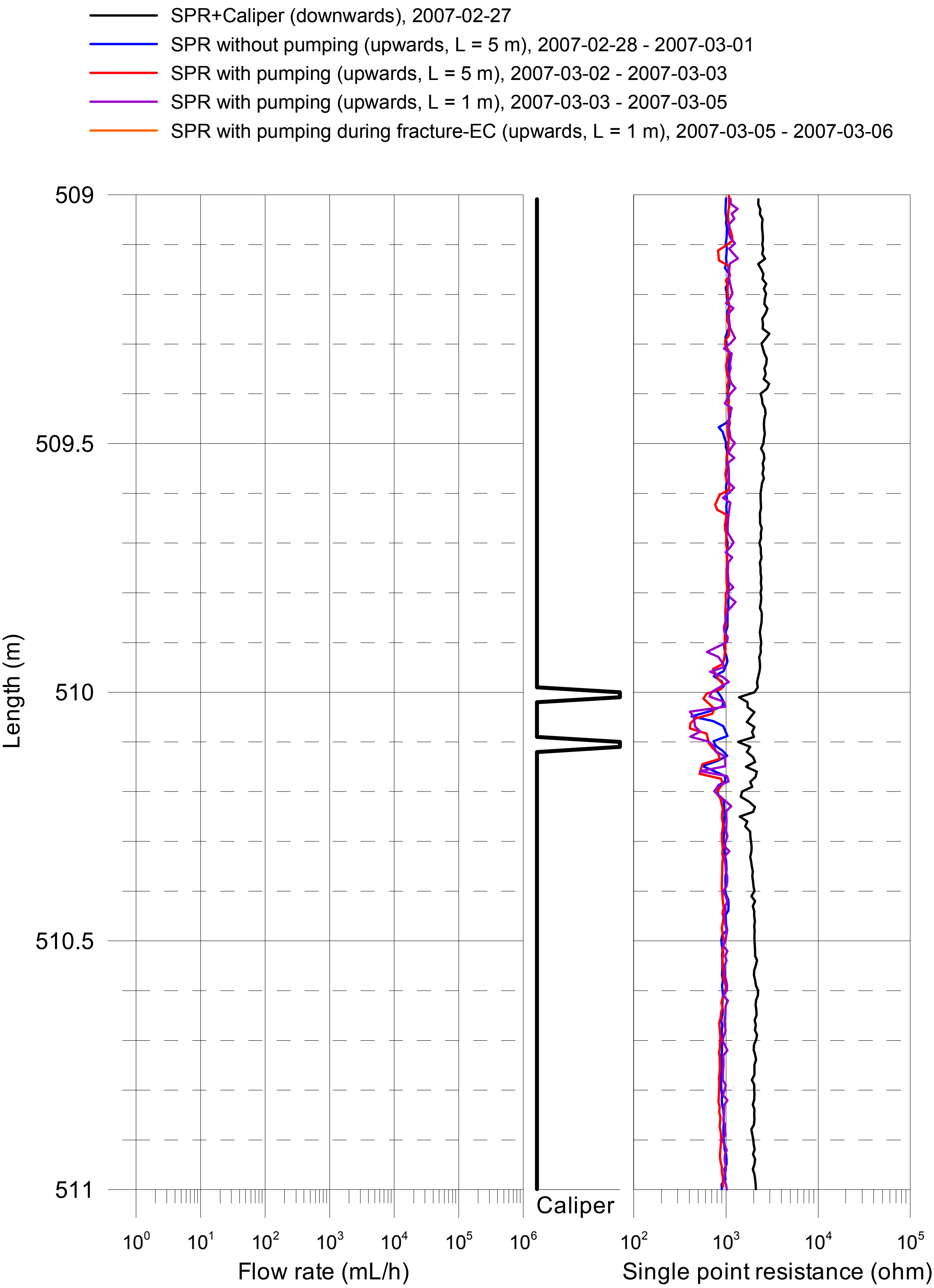
Forsmark, borehole KFM02B
SPR and Caliper results after length correction



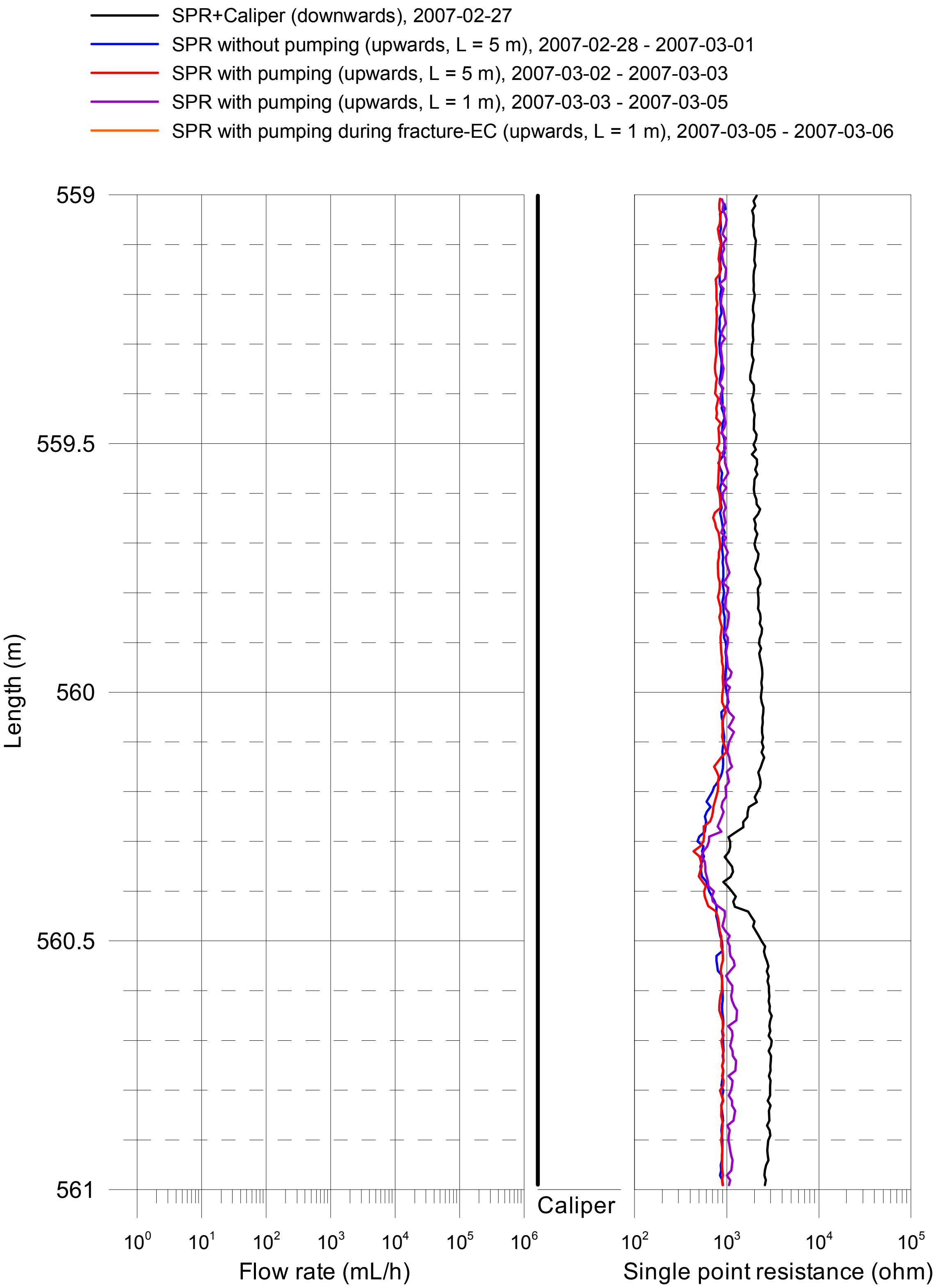
Forsmark, borehole KFM02B
SPR and Caliper results after length correction



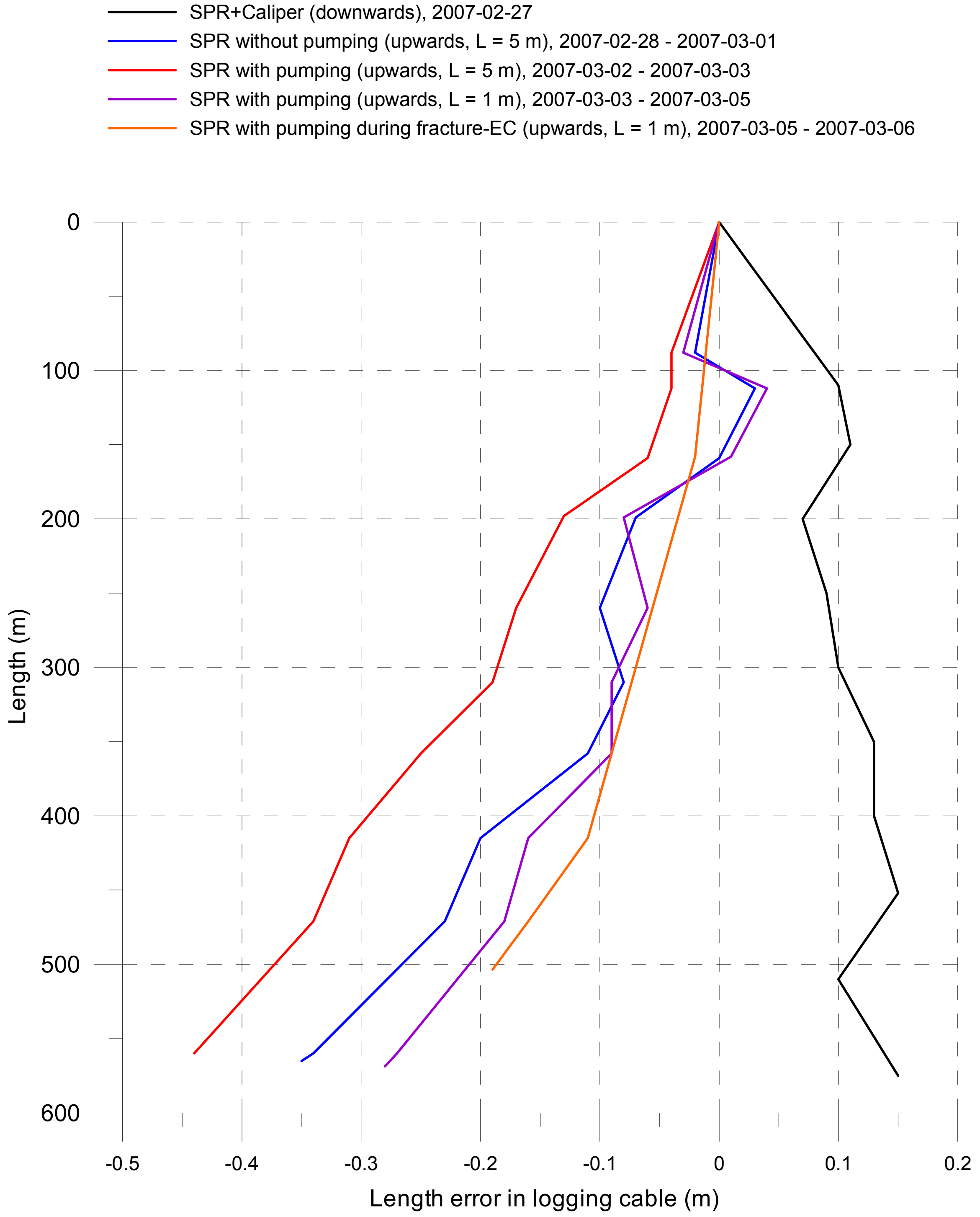
Forsmark, borehole KFM02B
SPR and Caliper results after length correction

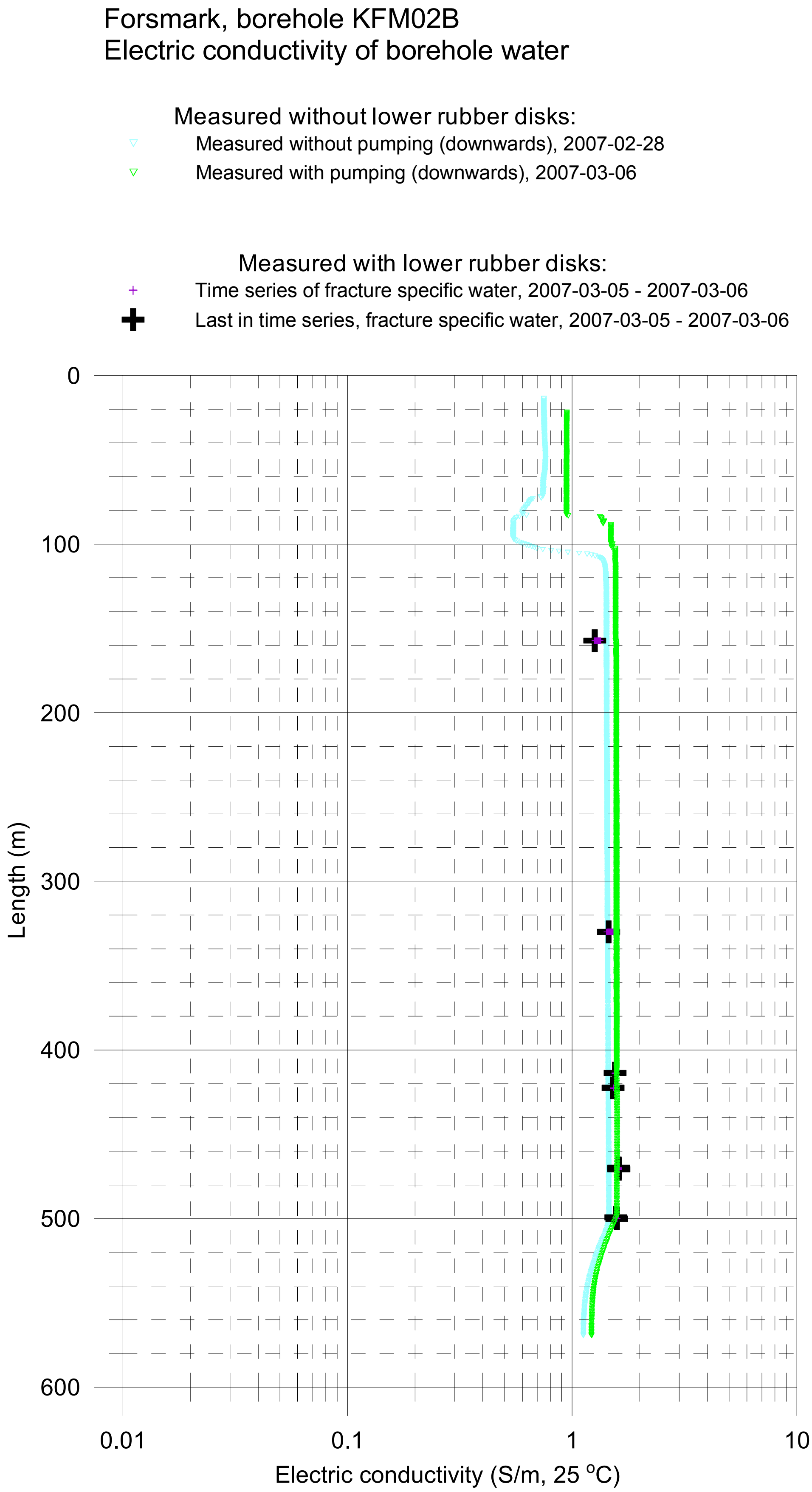


Forsmark, borehole KFM02B
SPR and Caliper results after length correction

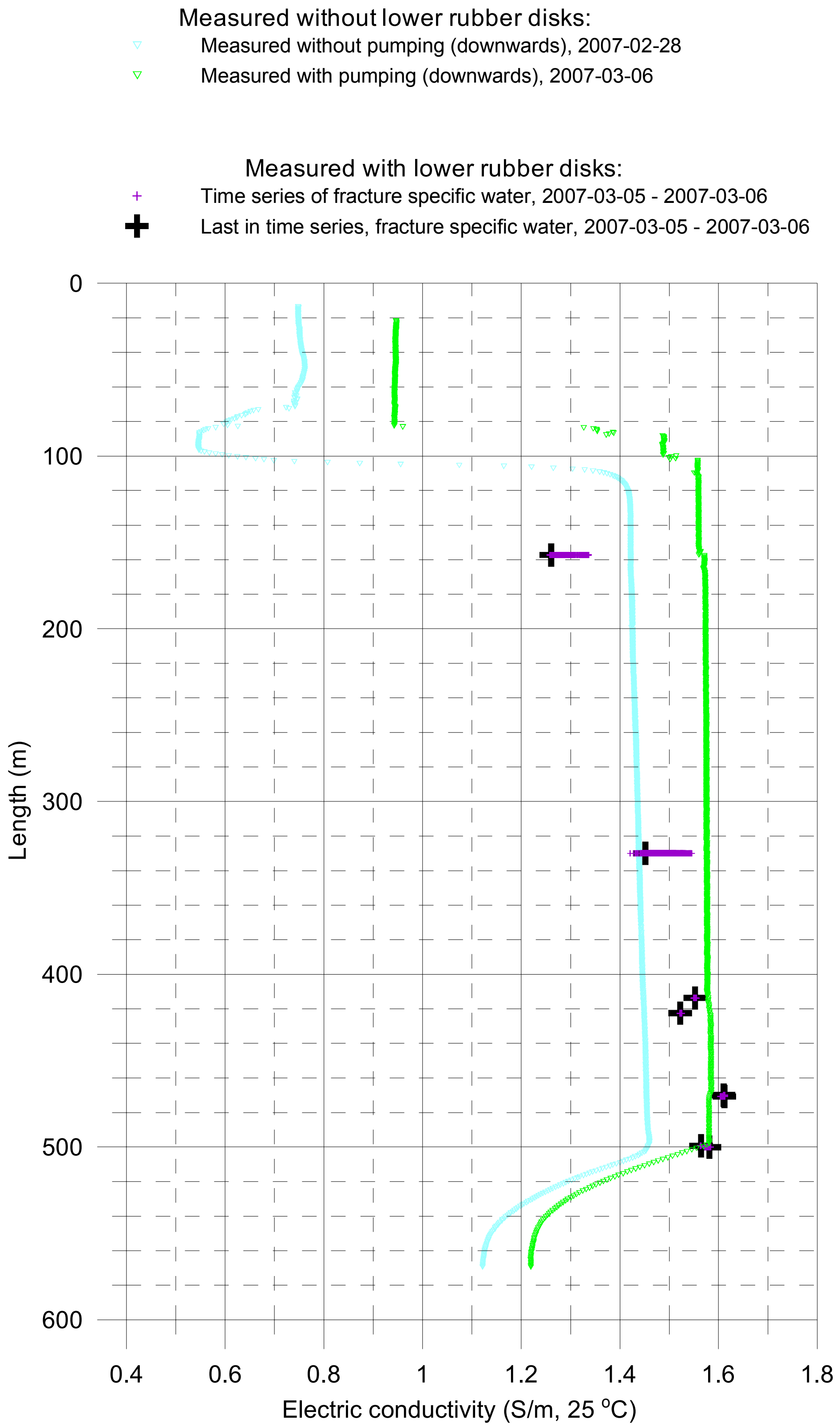


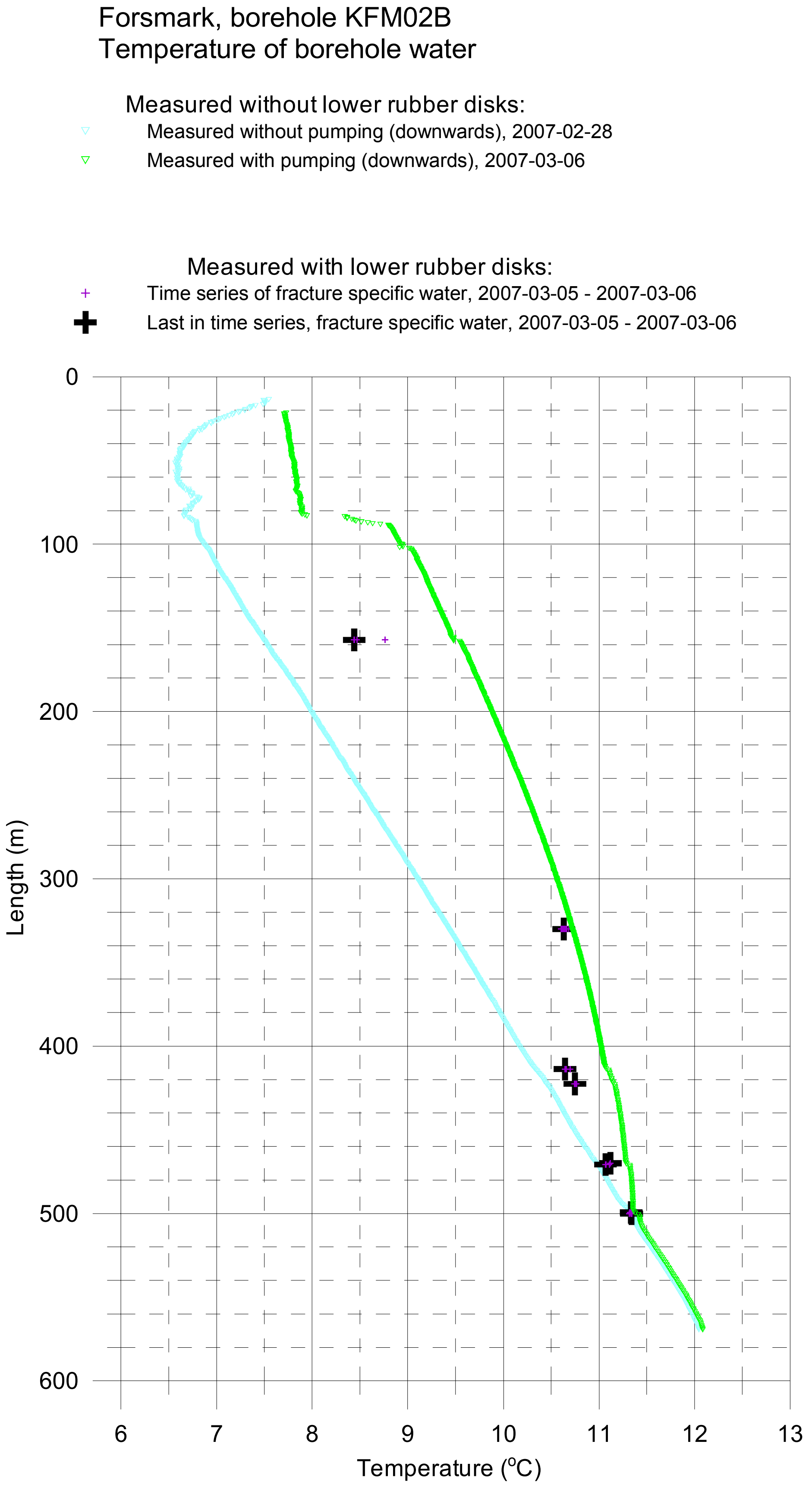
Forsmark, borehole KFM02B
Length correction



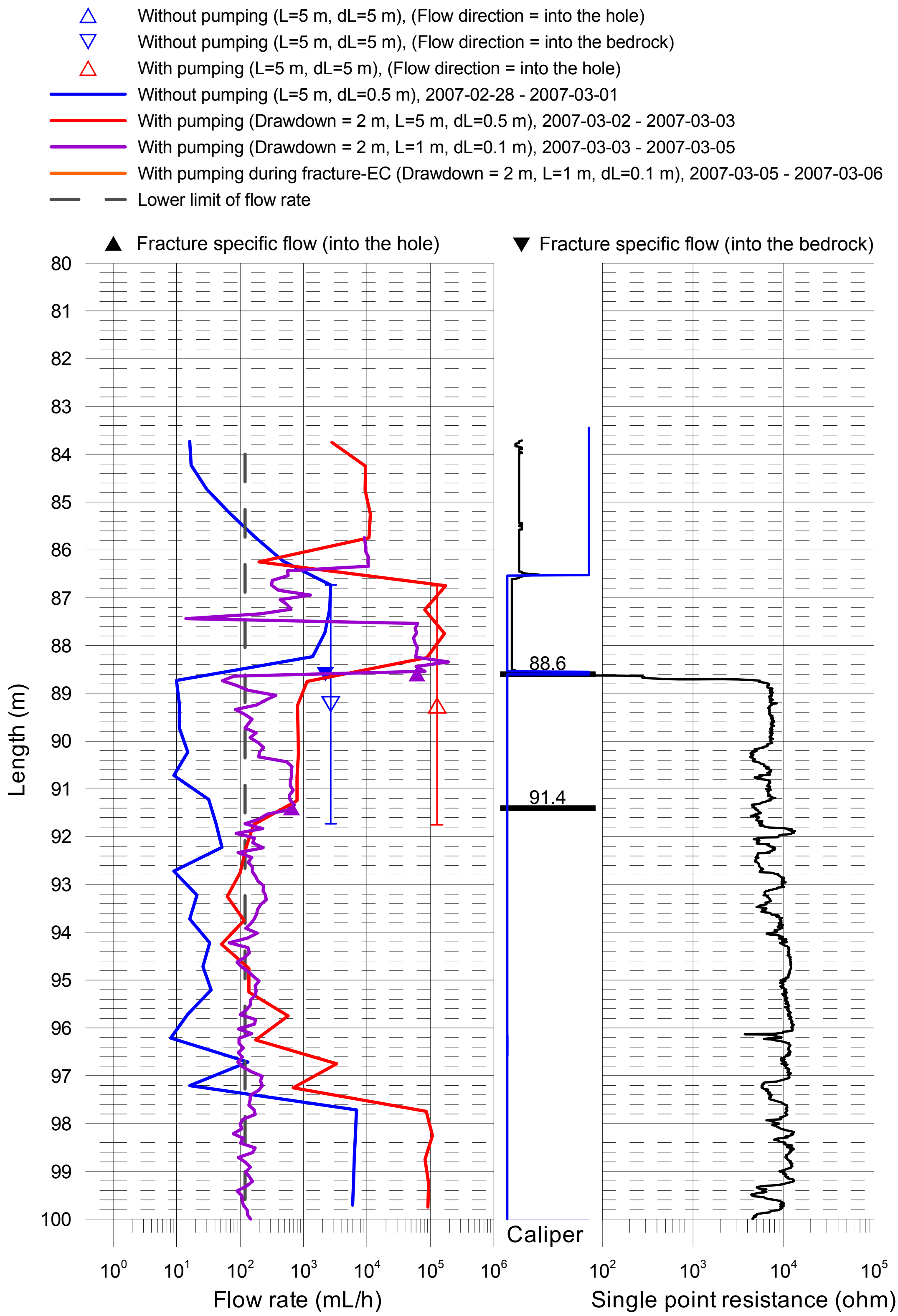

Forsmark, borehole KFM02B
Electric conductivity of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2007-02-28
Measured with pumping (downwards), 2007-03-06
Measured with lower rubber disks:
Time series of fracture specific water, 2007-03-05 - 2007-03-06
Last in time series, fracture specific water, 2007-03-05 - 2007-03-06
0
100
200
300
400
500
600
Length (m)
0.01
0.1
1
10
Electric conductivity (S/m, 25 °C)

Forsmark, borehole KFM02B
Electric conductivity of borehole water

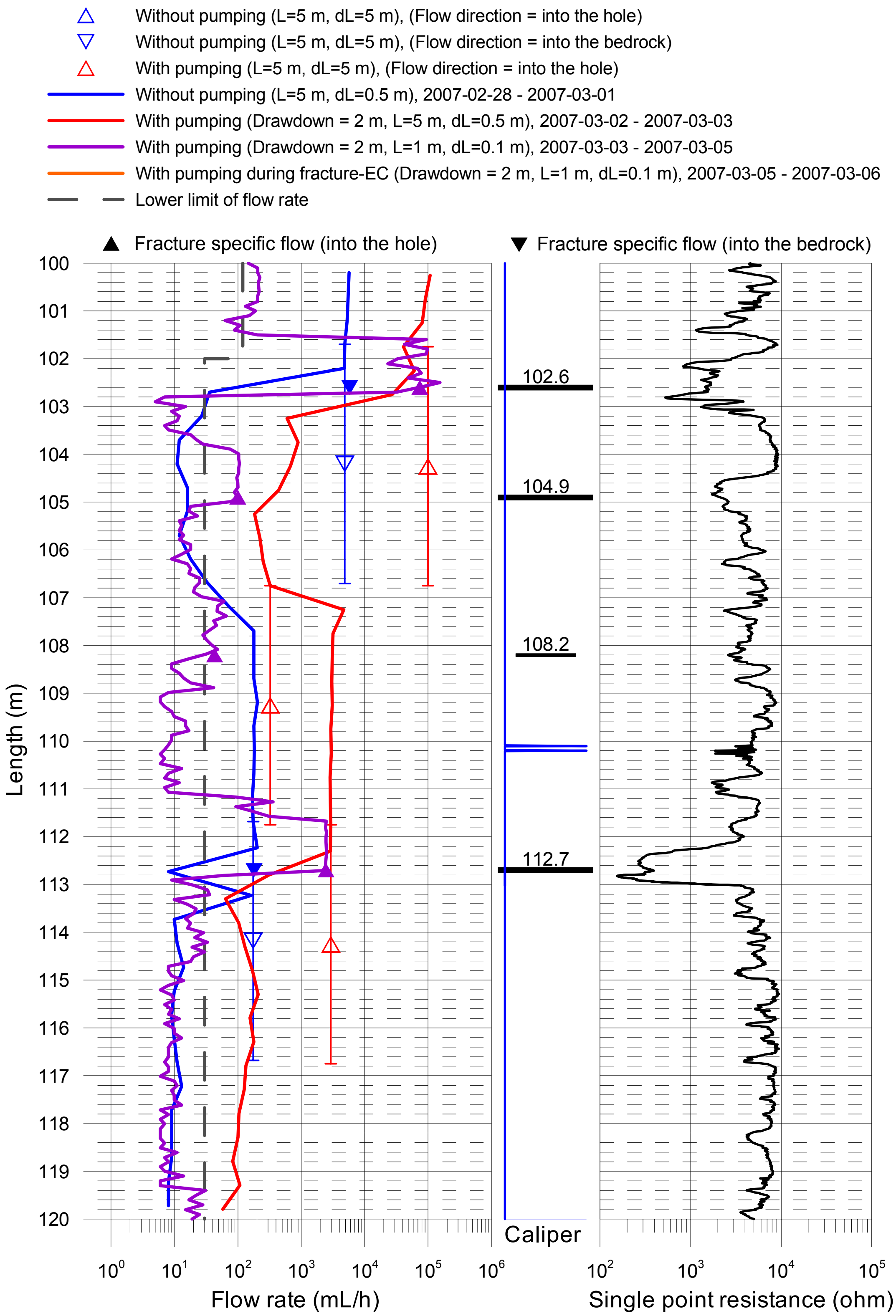



Forsmark, borehole KFM02B
Temperature of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2007-02-28
Measured with pumping (downwards), 2007-03-06
Measured with lower rubber disks:
Time series of fracture specific water, 2007-03-05 - 2007-03-06
Last in time series, fracture specific water, 2007-03-05 - 2007-03-06
Length (m)
0
100
200
300
400
500
600
6
7
8
9
10
11
12
13
Temperature (°C)

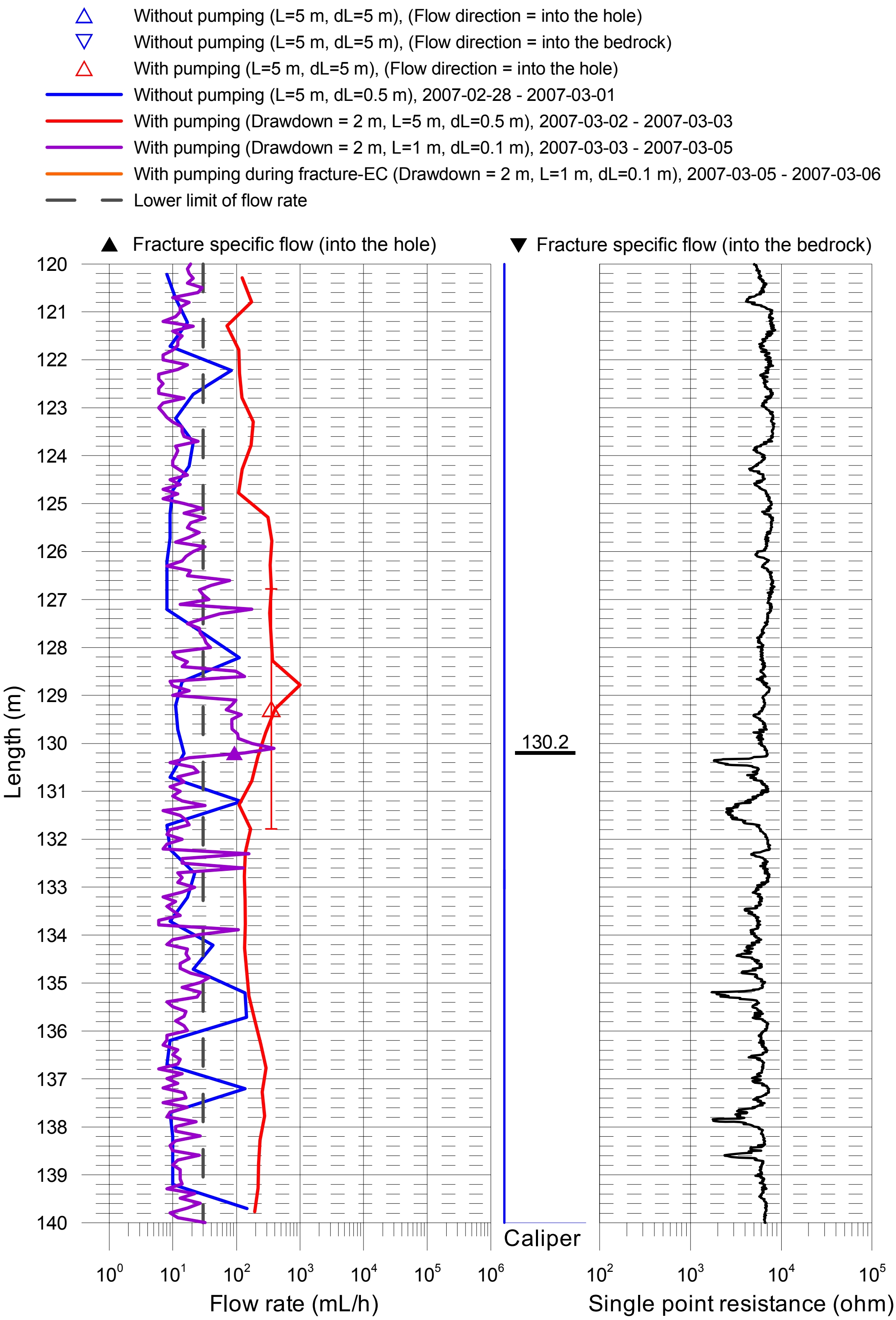
Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance



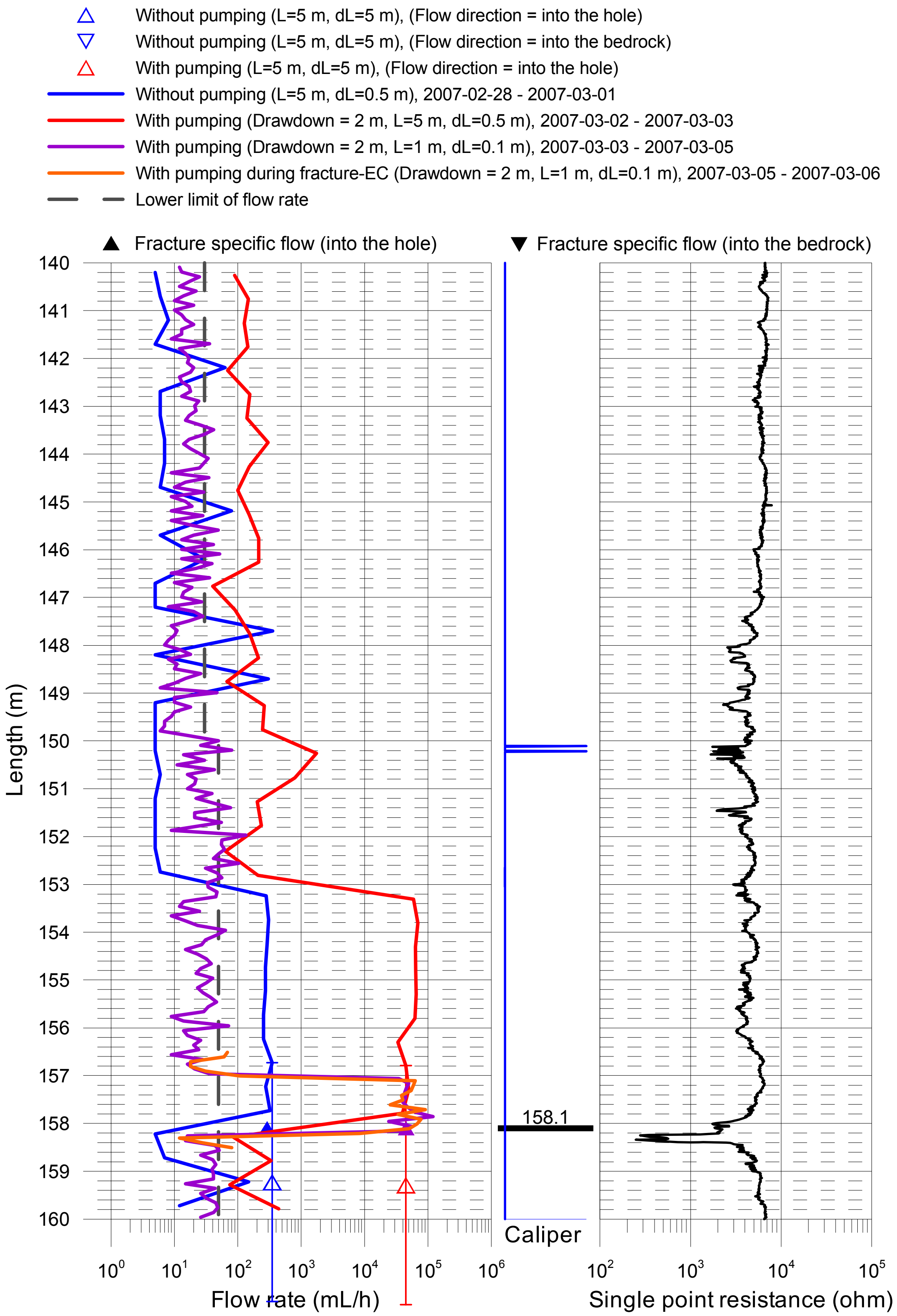
Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance



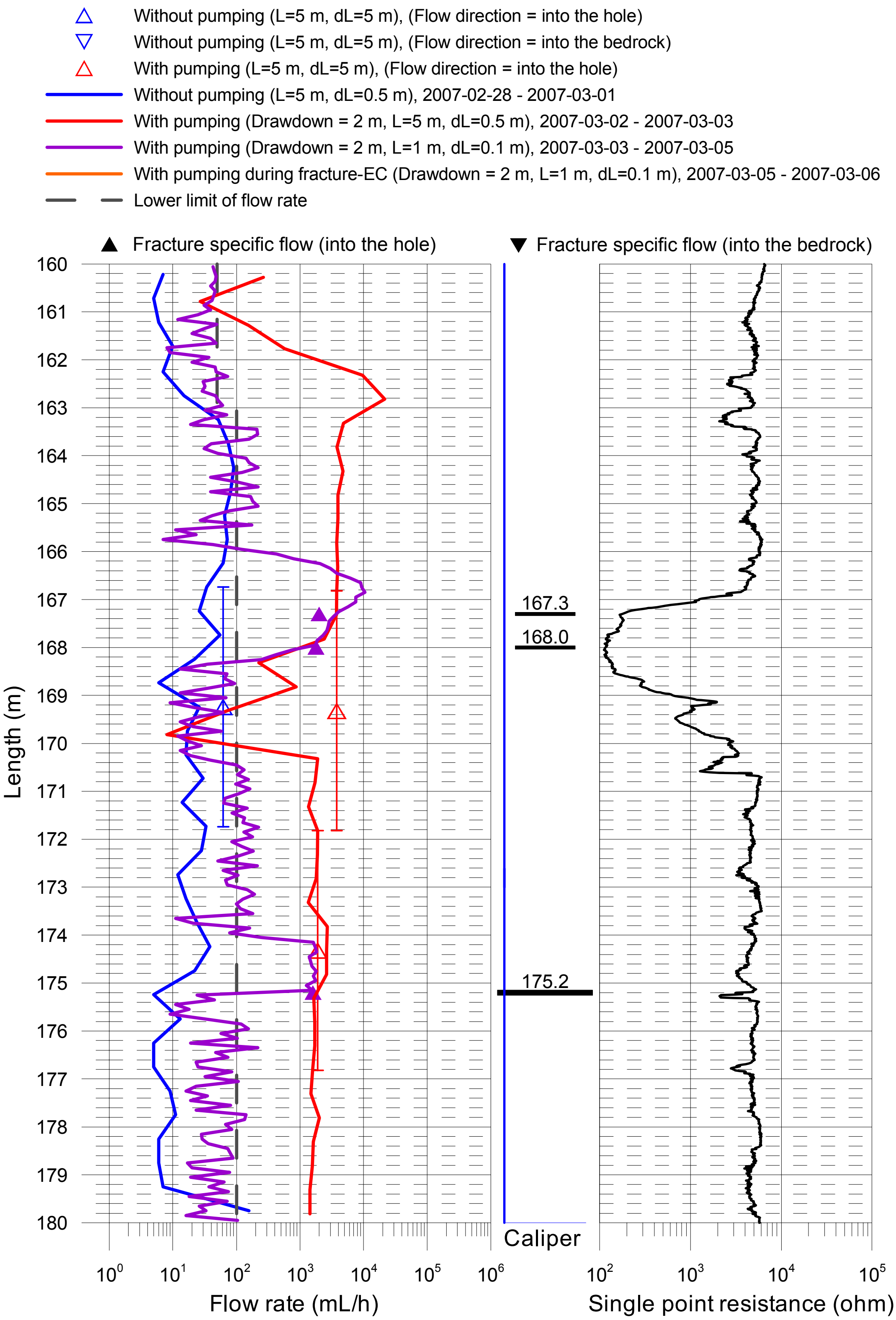
Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance



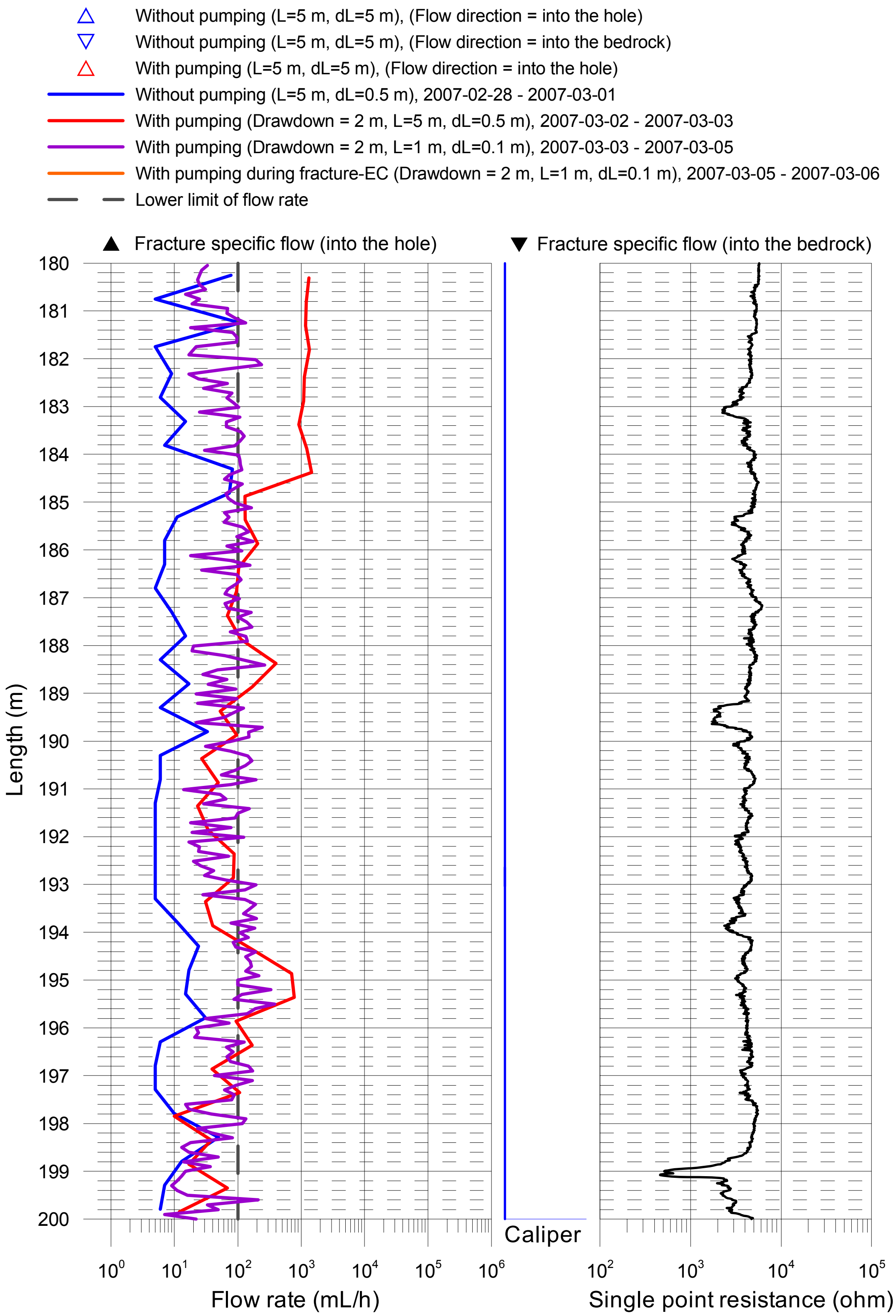
Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance



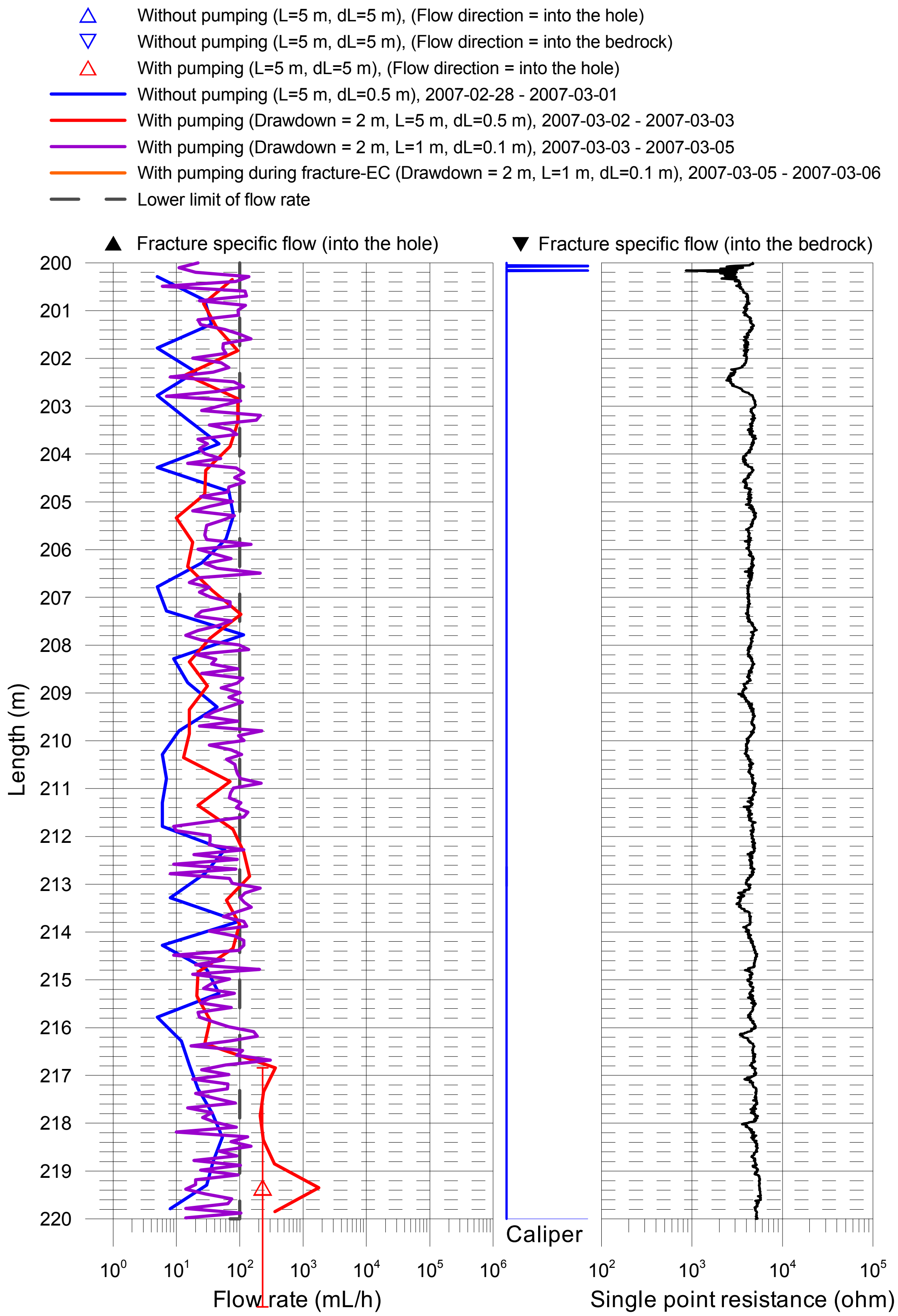
Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance



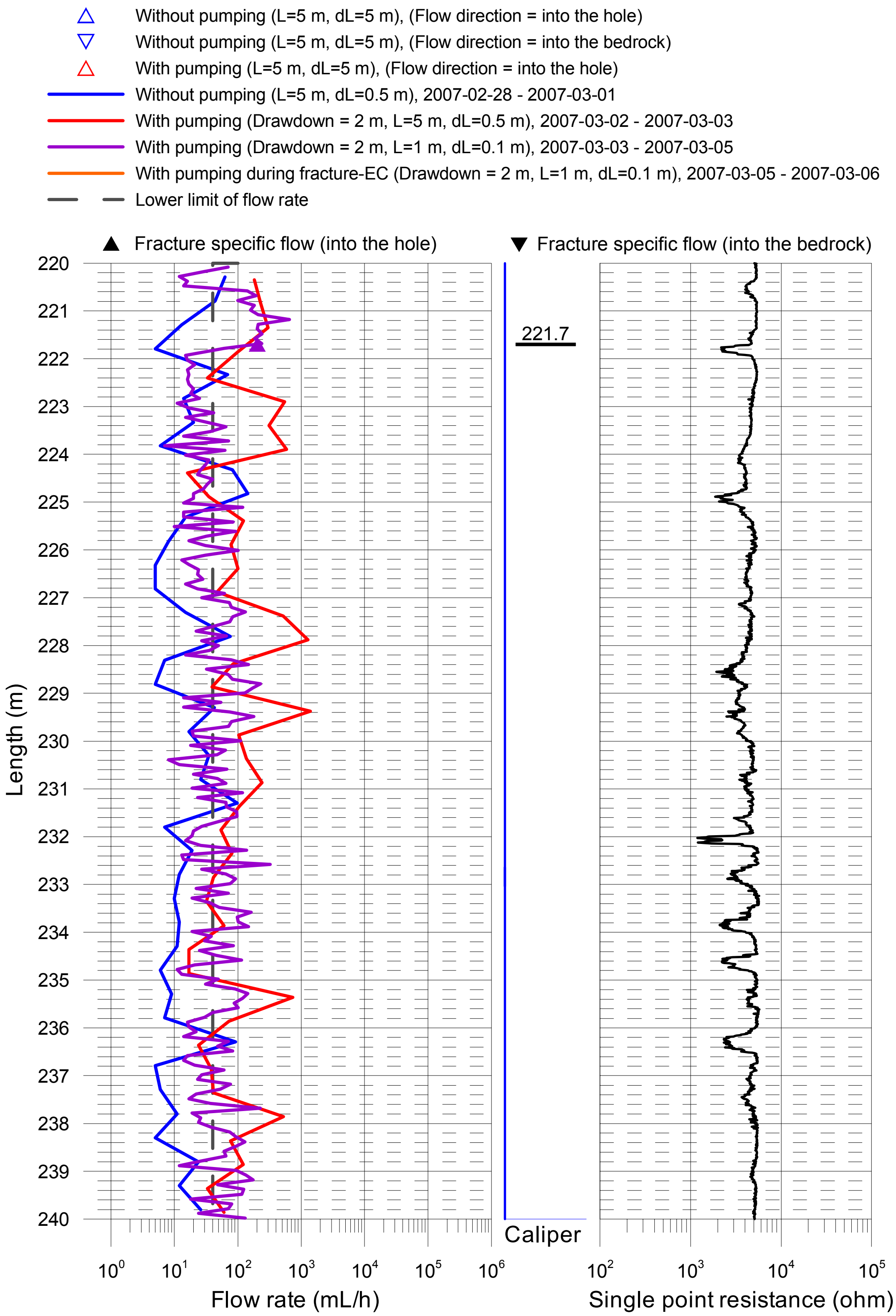
Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance



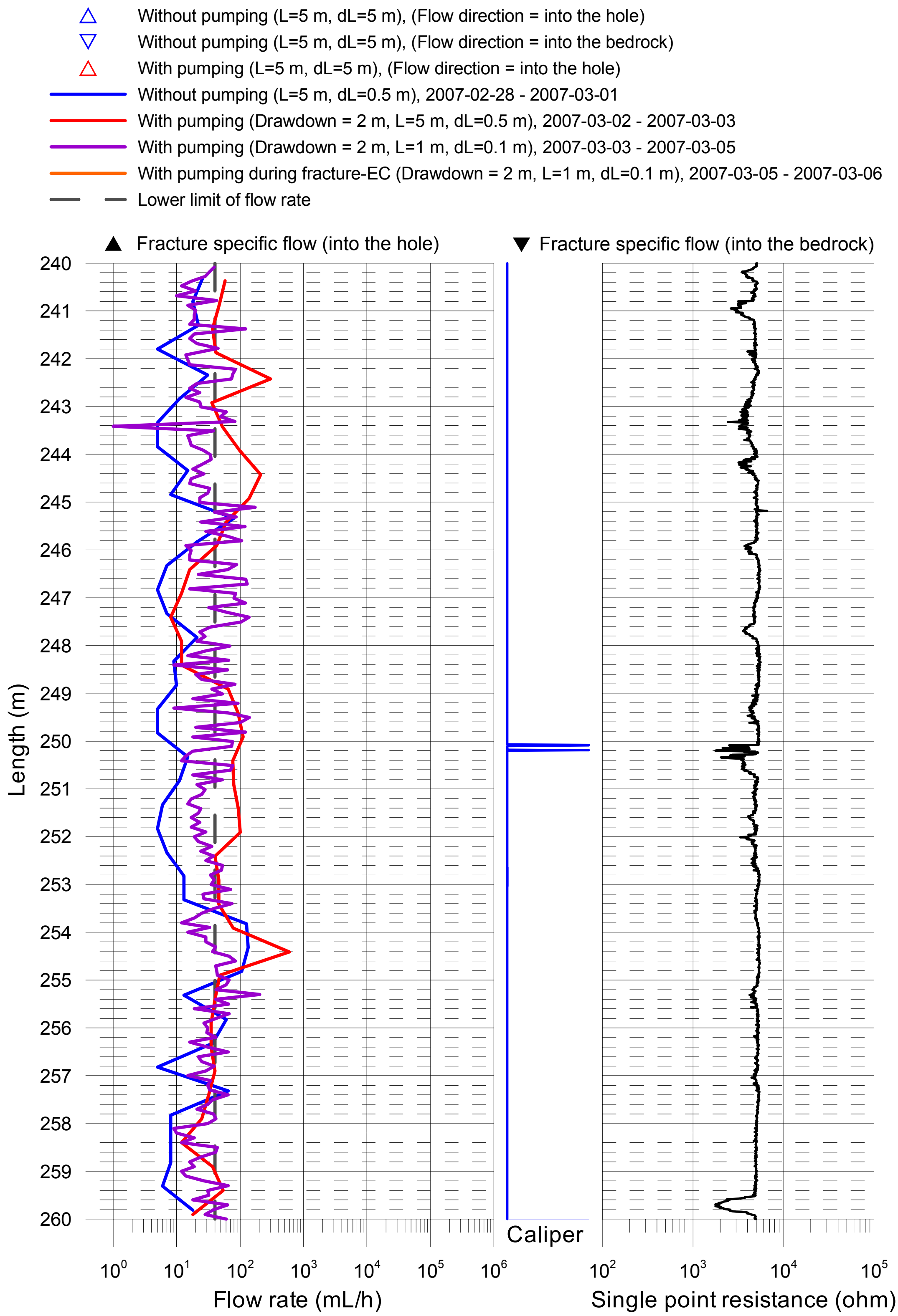
Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance



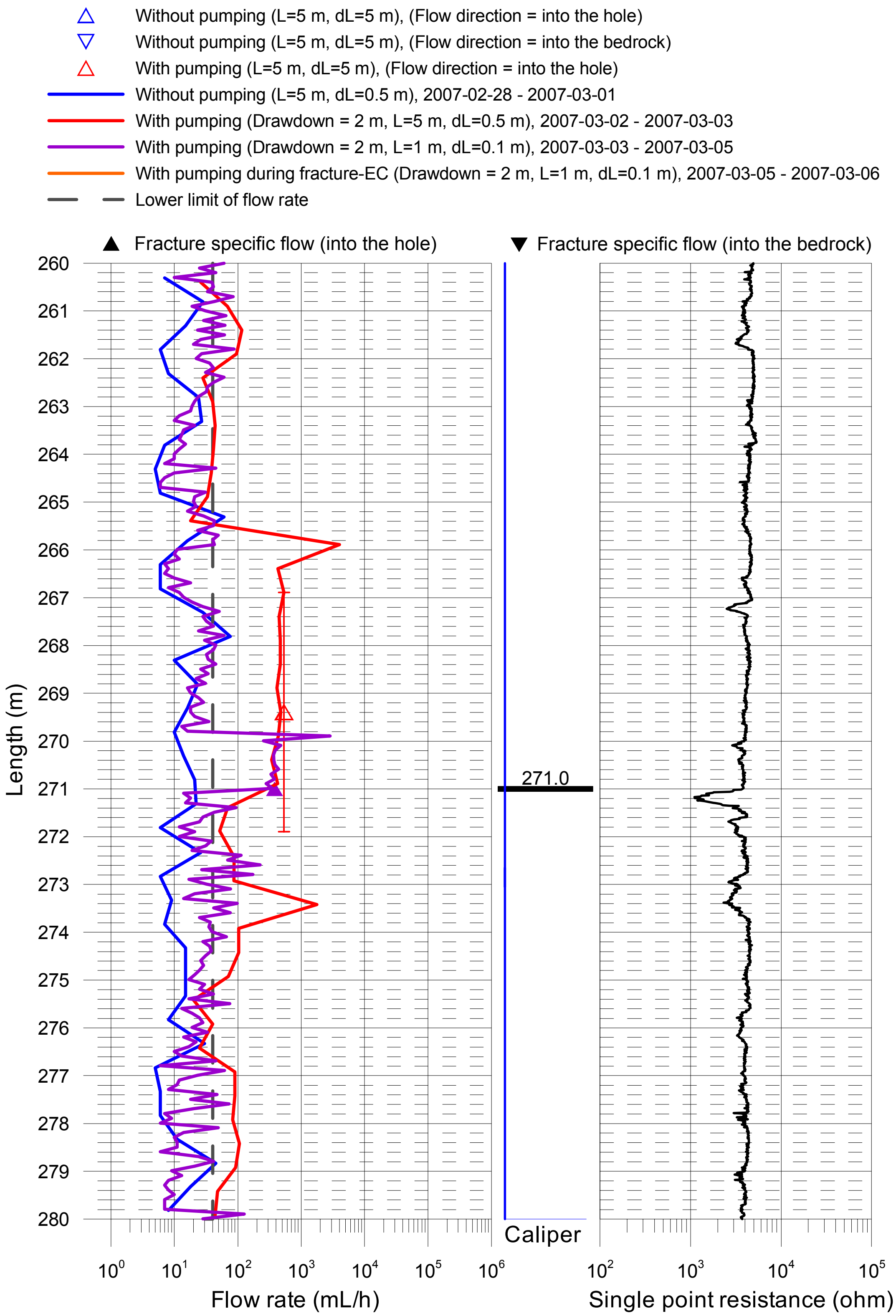
Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance



Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance

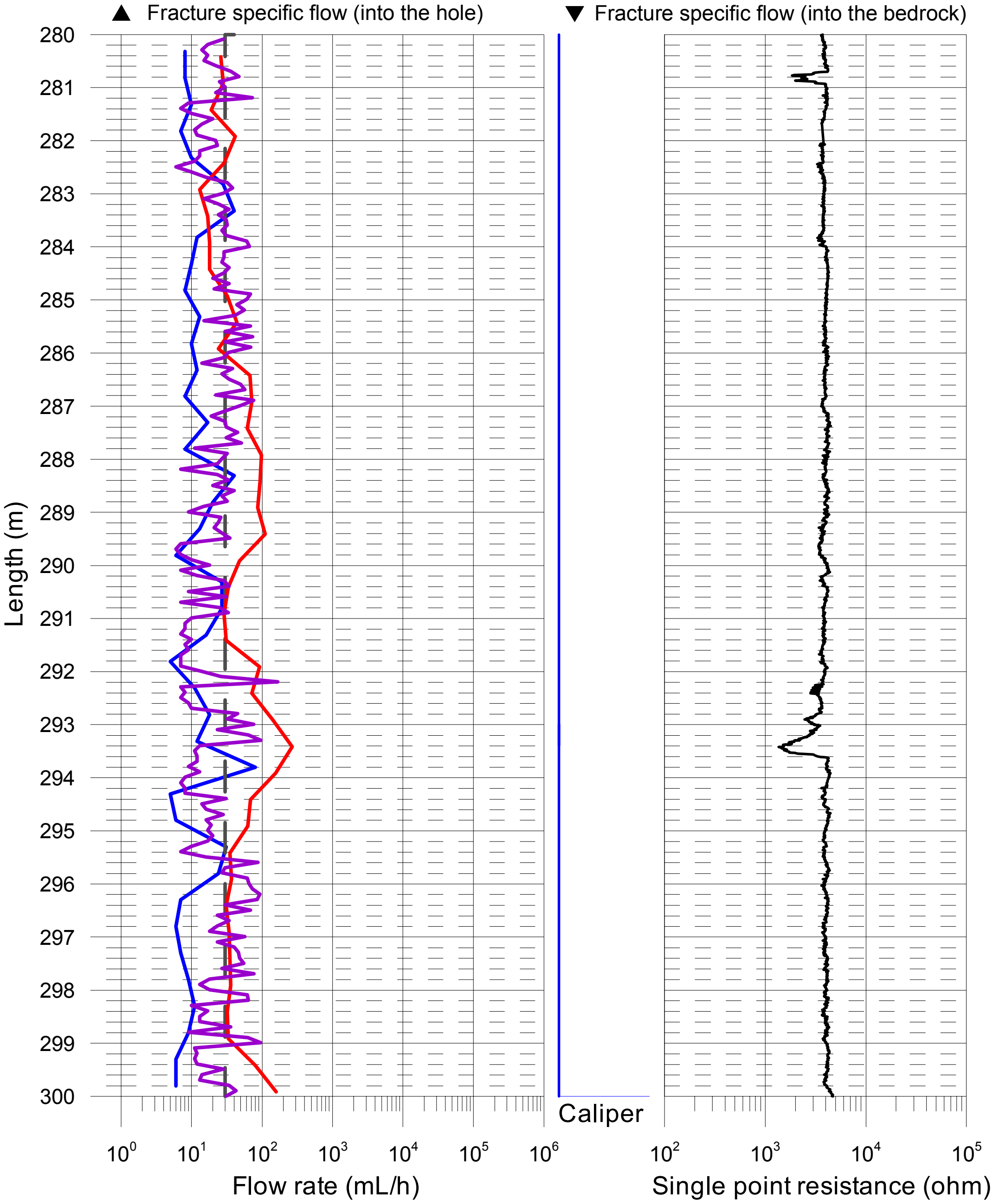


Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance

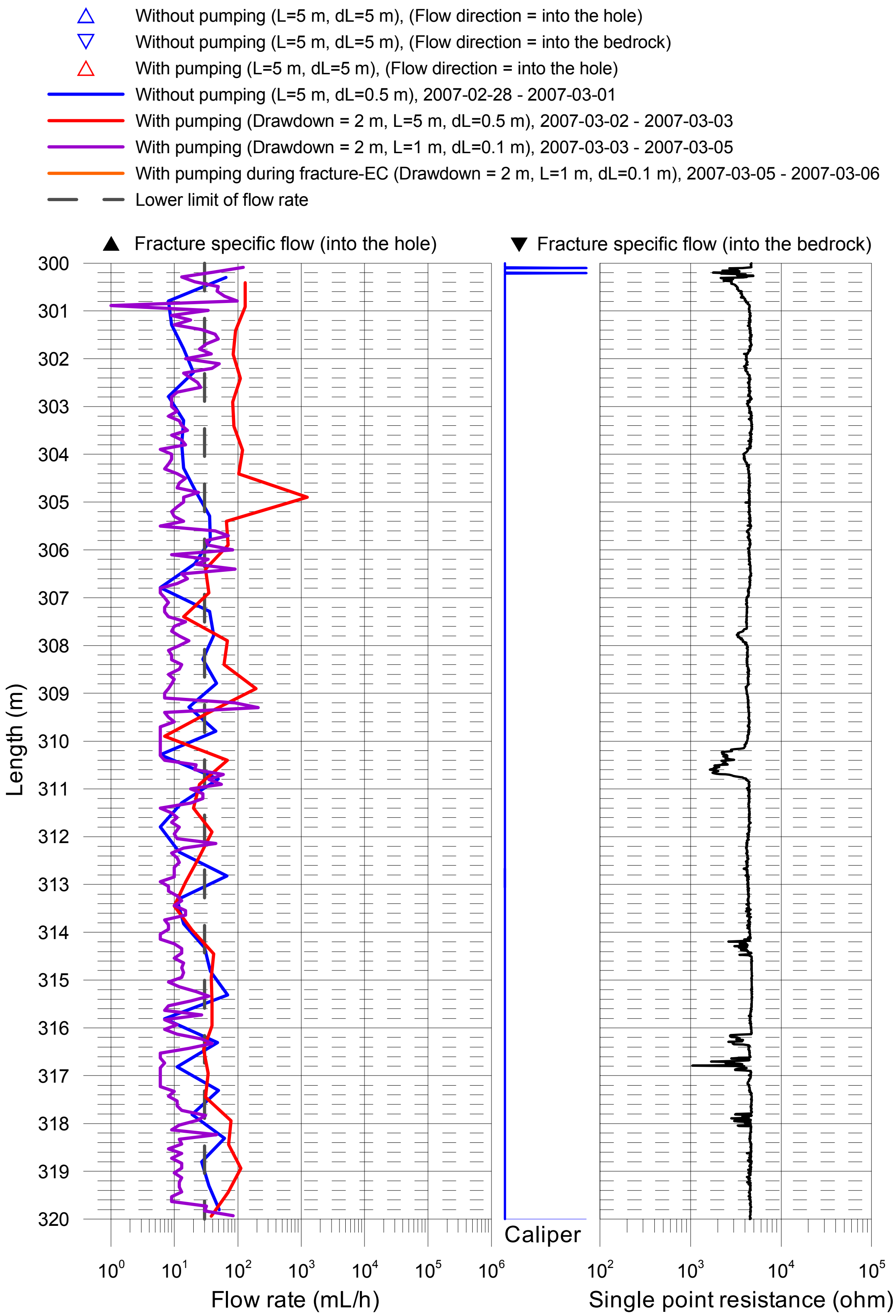


Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance

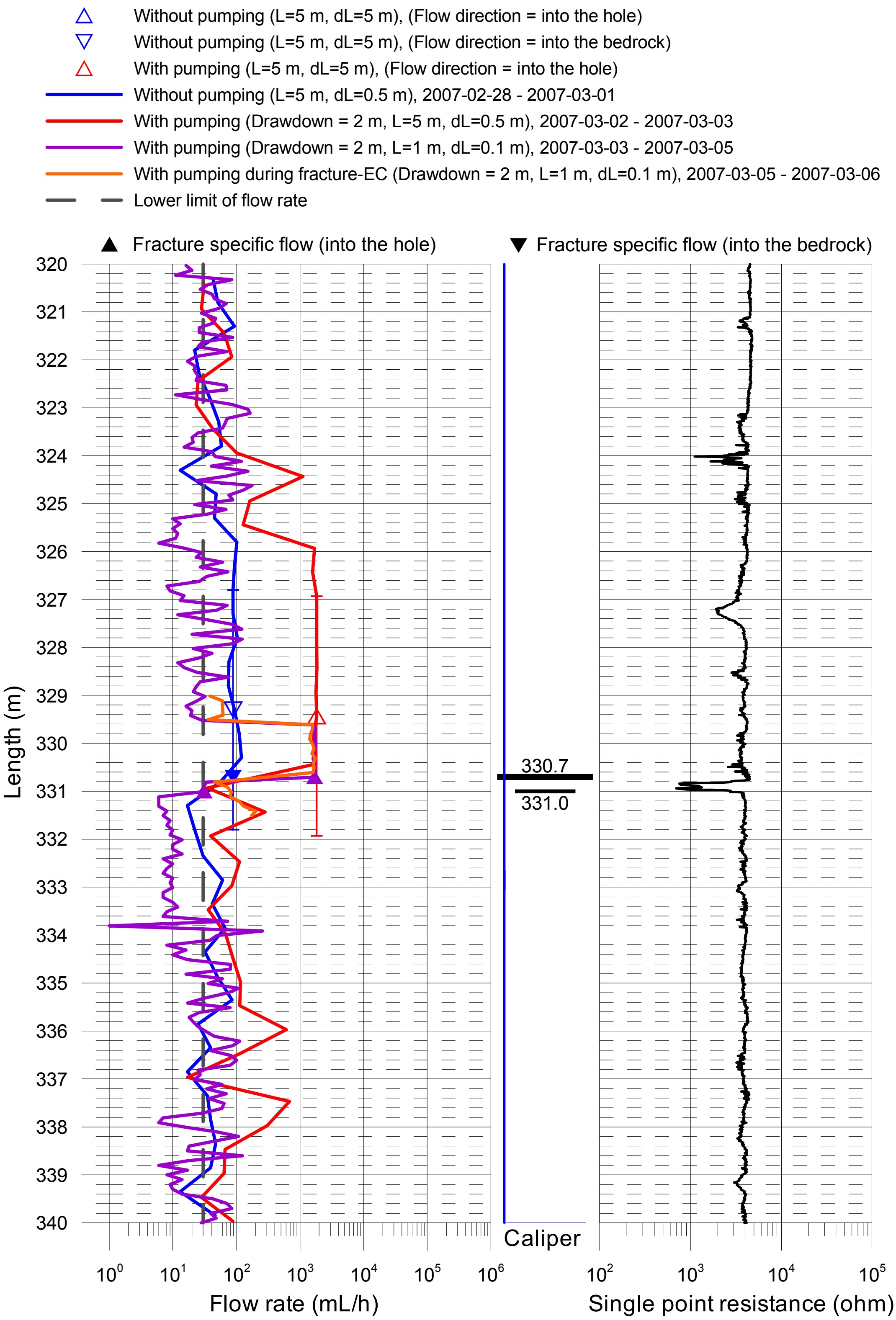
△ Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
▽ Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
△ With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=0.5 m), 2007-02-28 - 2007-03-01
With pumping (Drawdown = 2 m, L=5 m, dL=0.5 m), 2007-03-02 - 2007-03-03
With pumping (Drawdown = 2 m, L=1 m, dL=0.1 m), 2007-03-03 - 2007-03-05
With pumping during fracture-EC (Drawdown = 2 m, L=1 m, dL=0.1 m), 2007-03-05 - 2007-03-06
Lower limit of flow rate



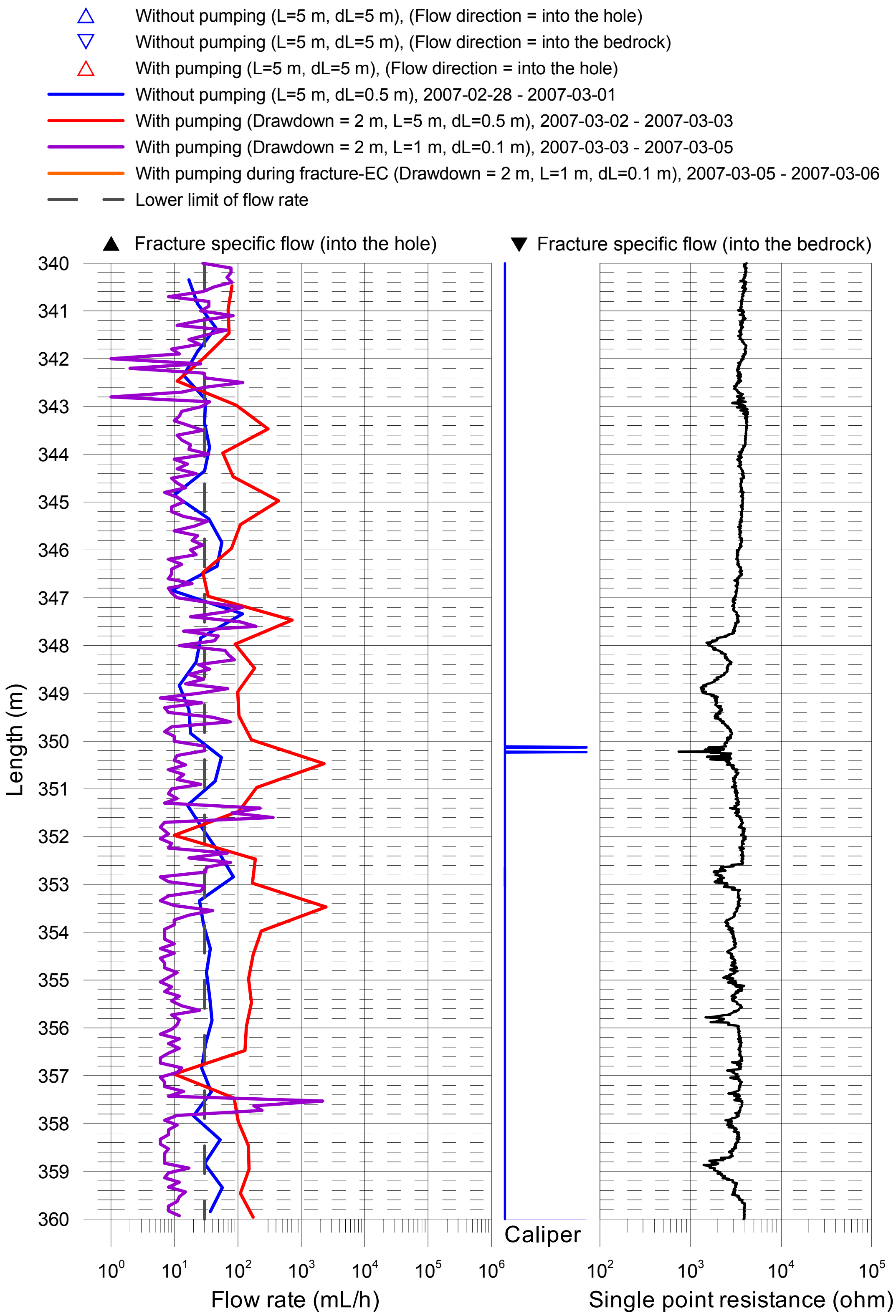
Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance



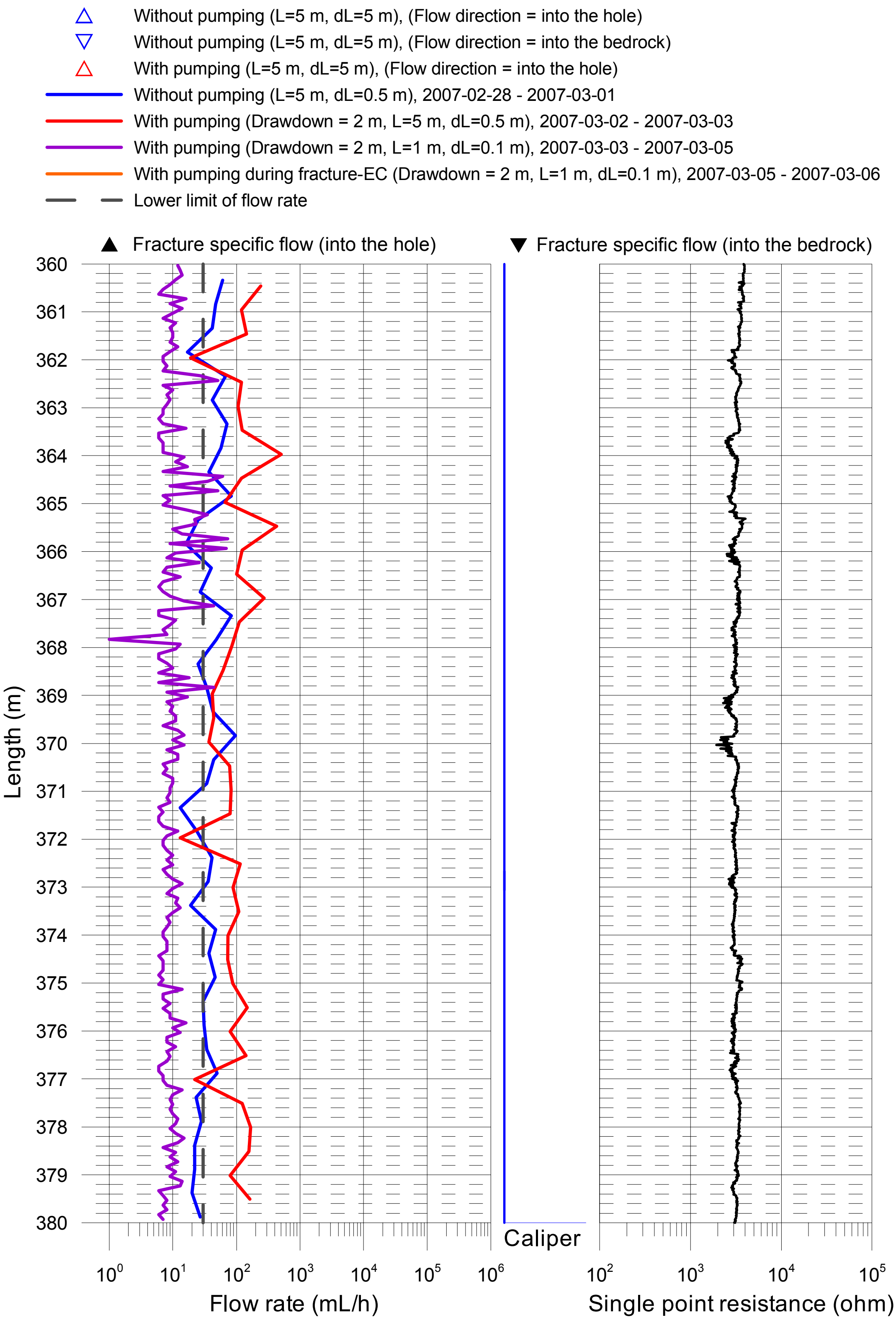
Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance



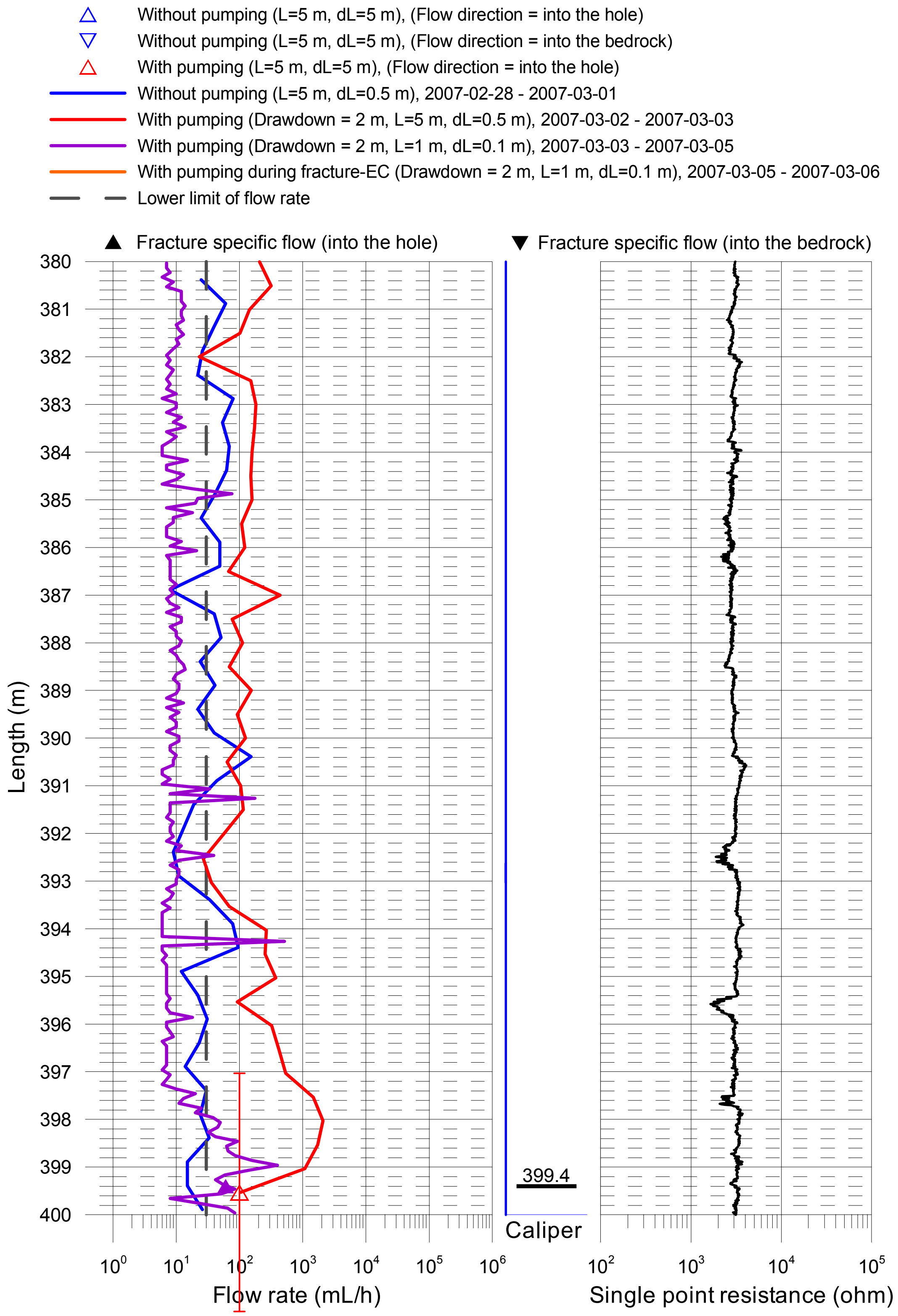
Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance



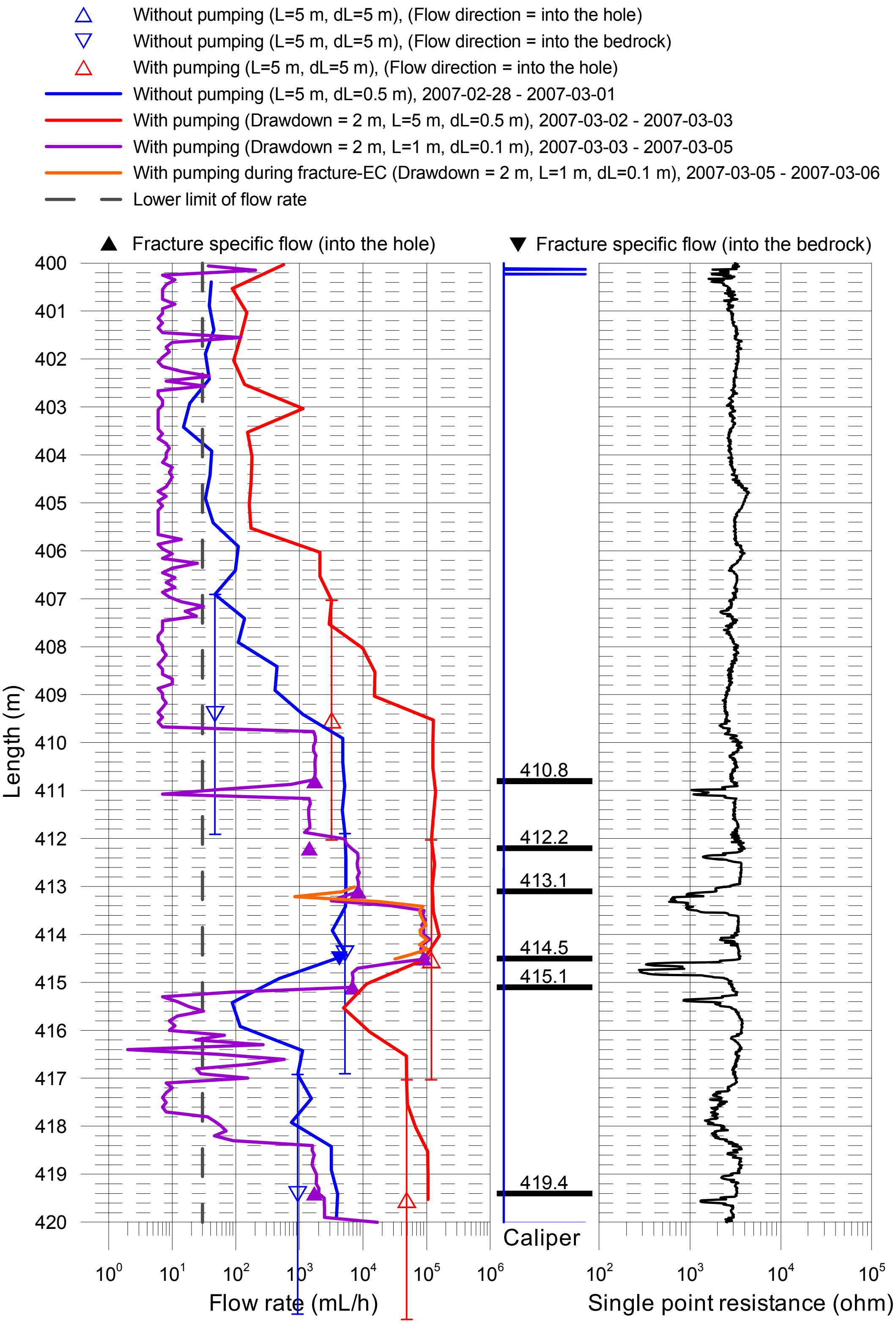
Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance



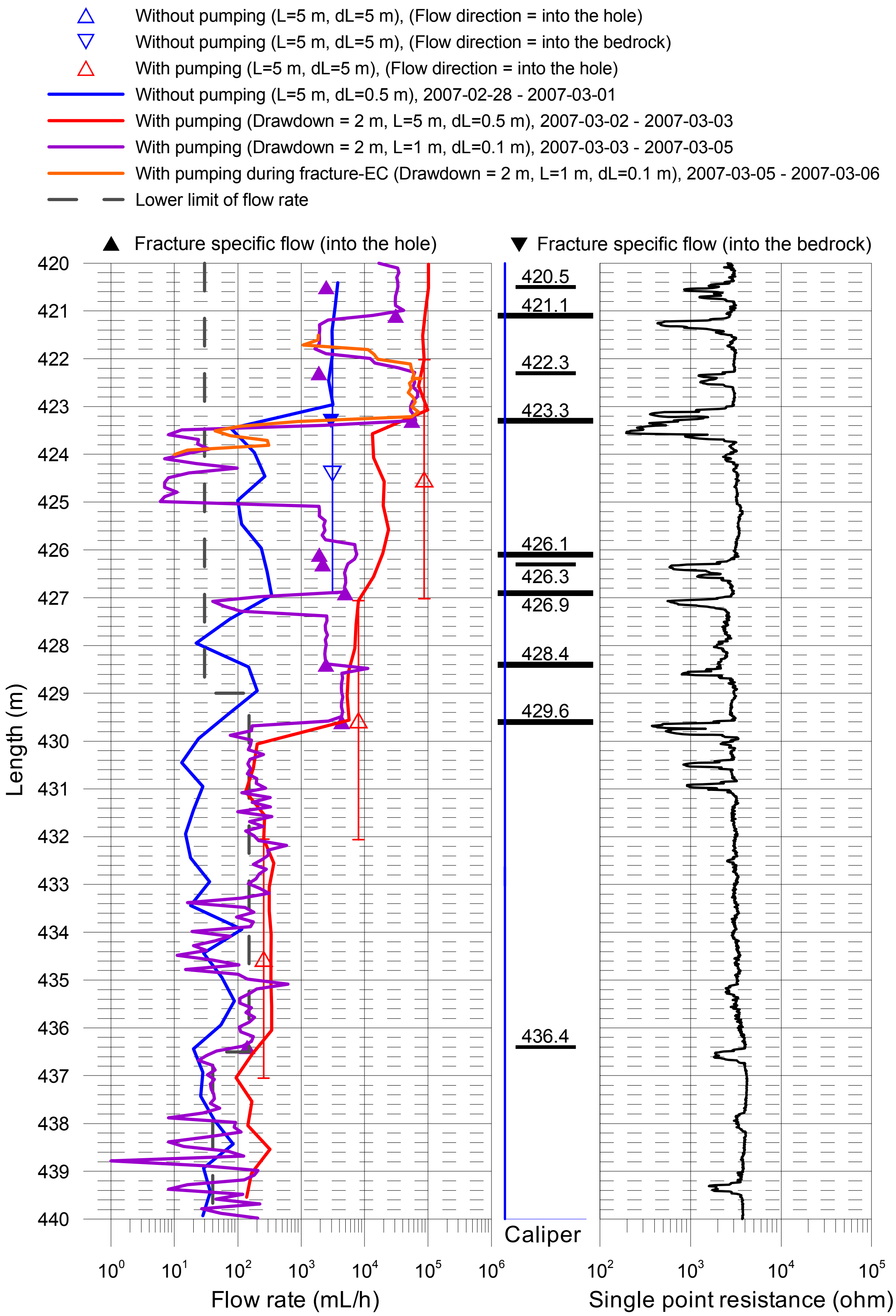
Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance



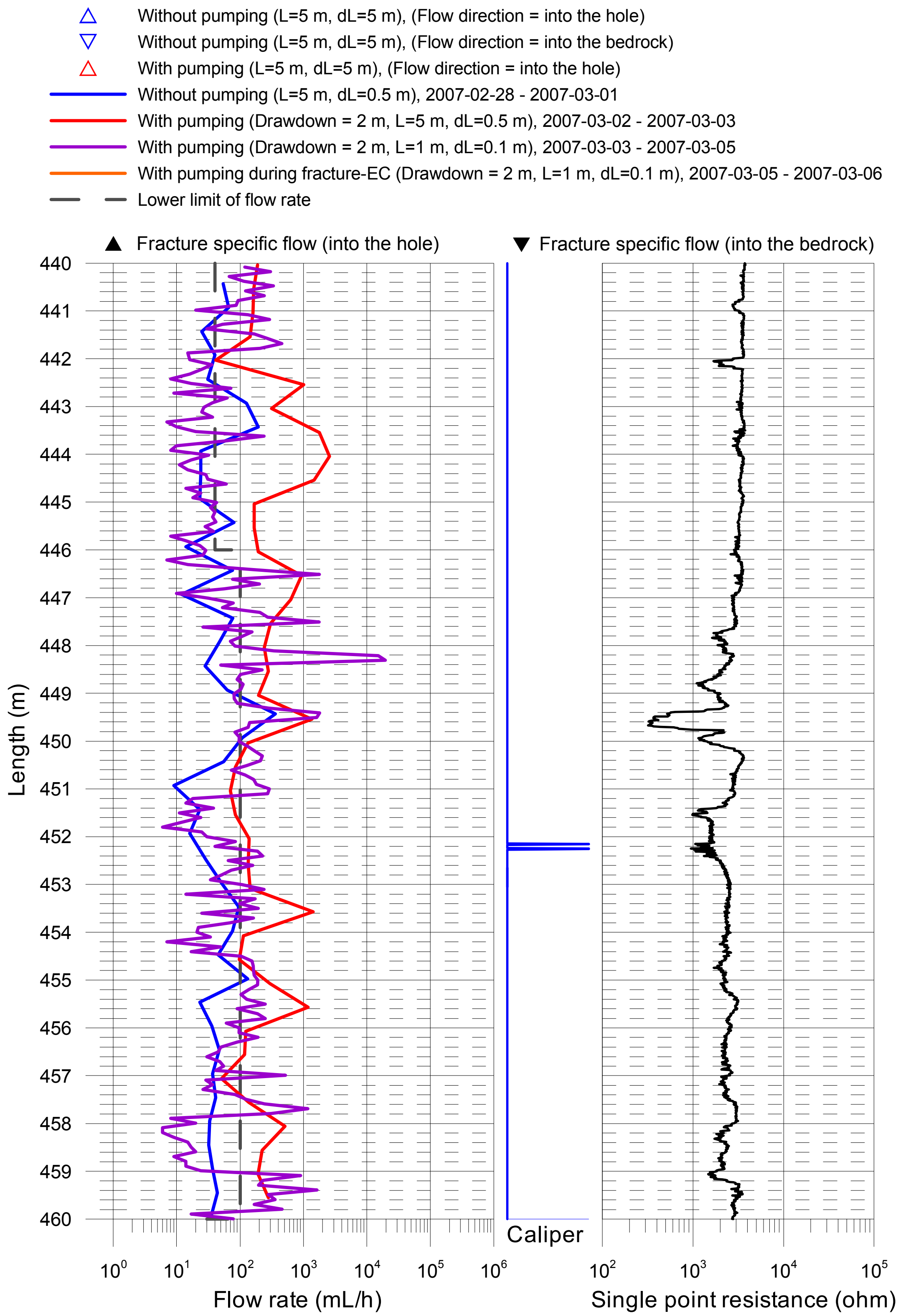
Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance



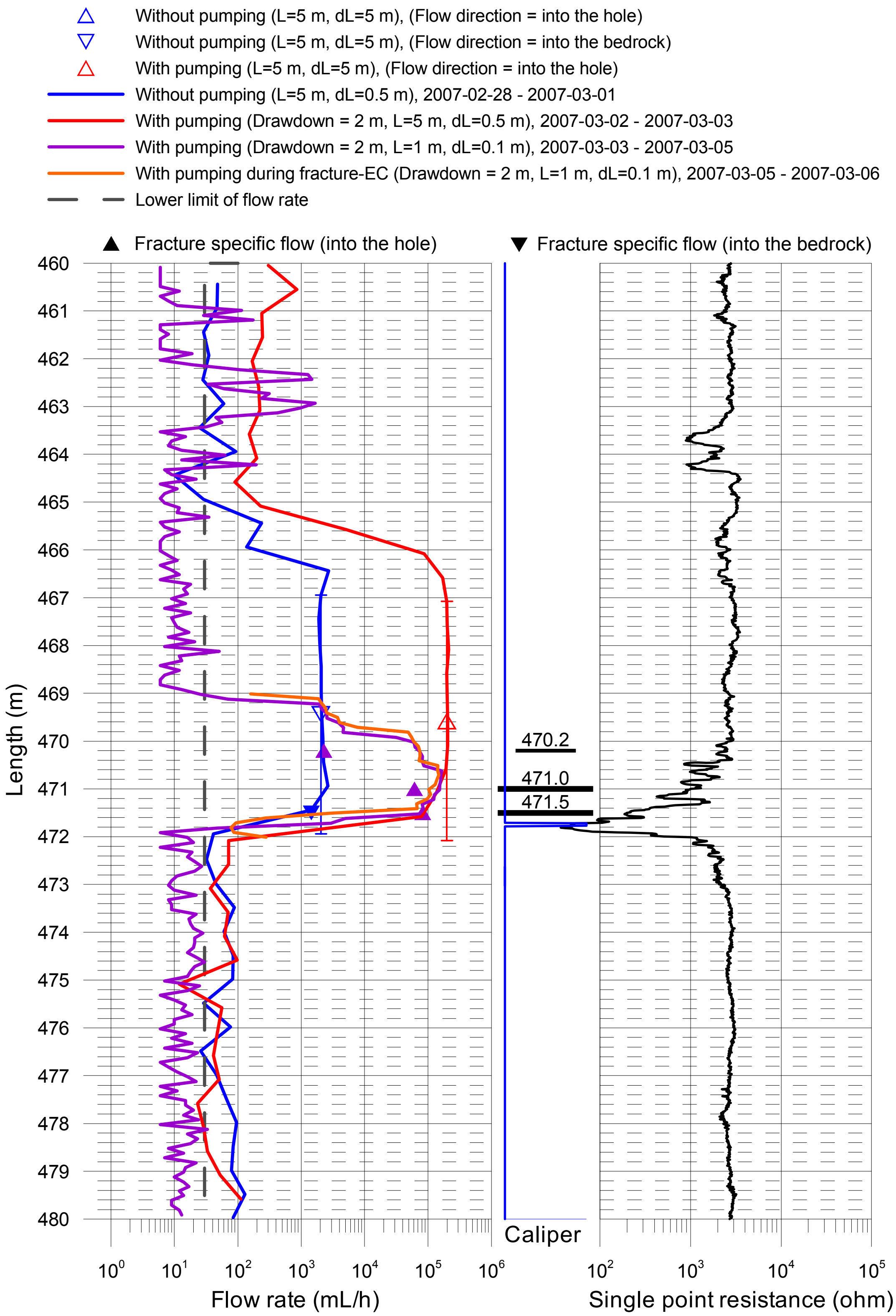
Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance



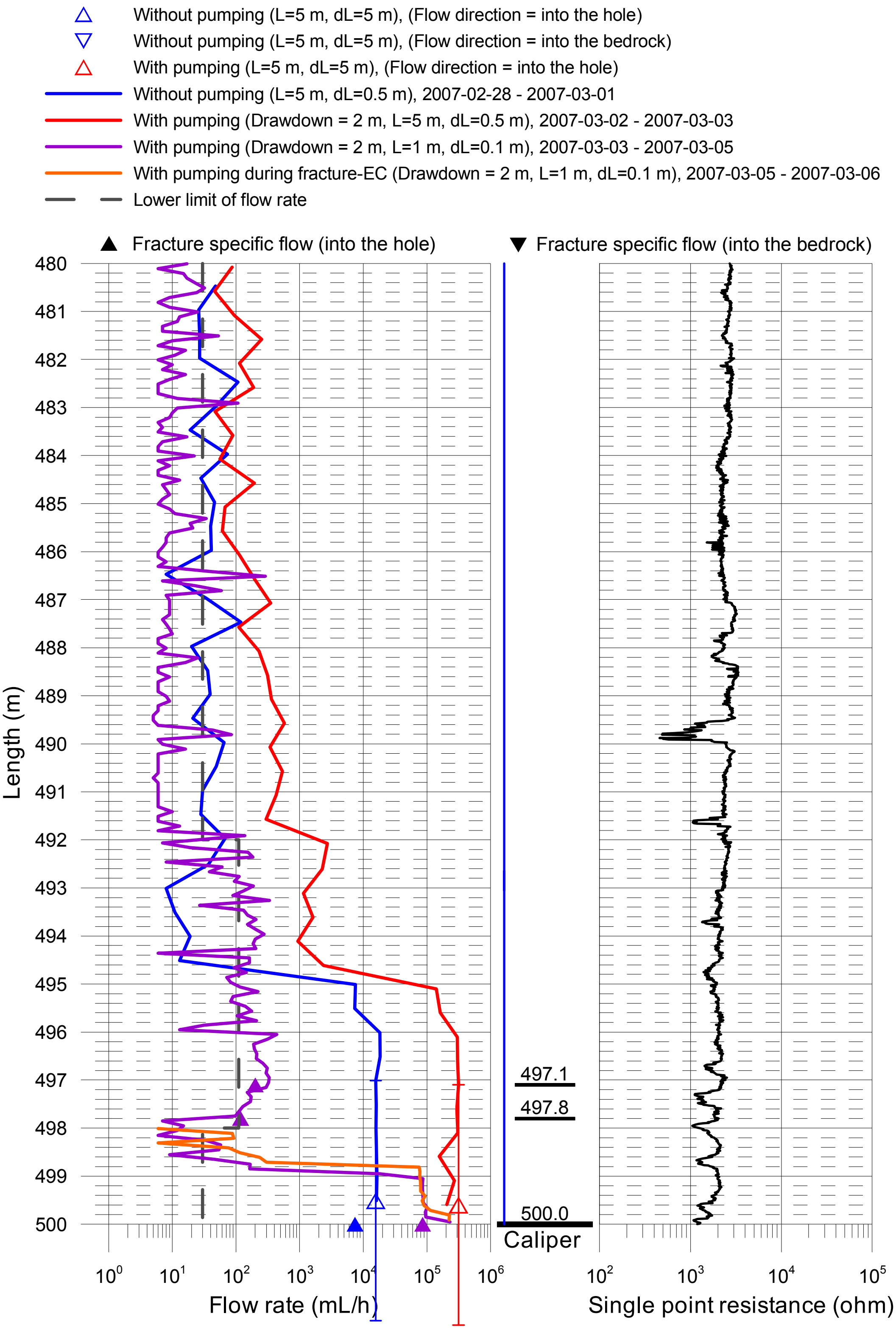
Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance



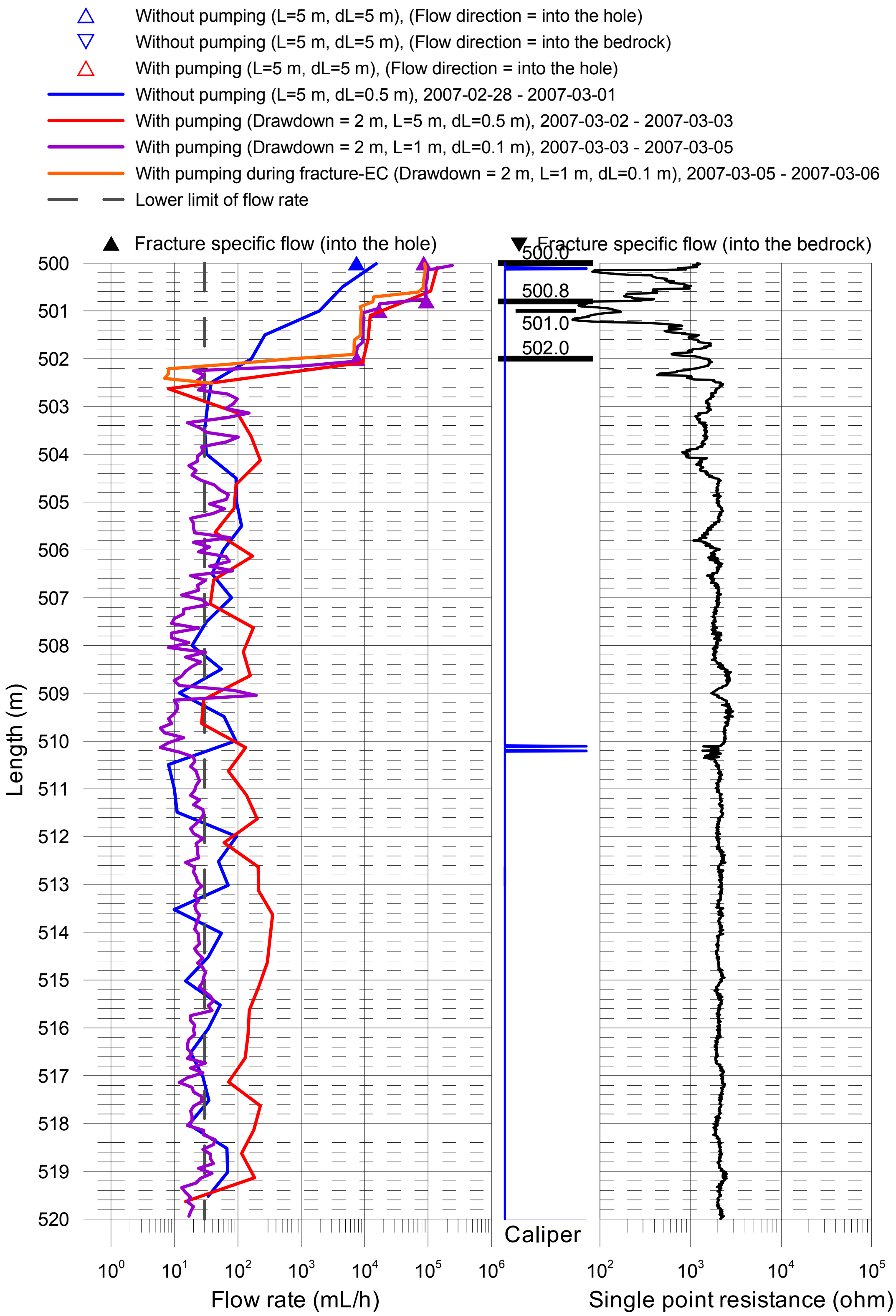
Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance



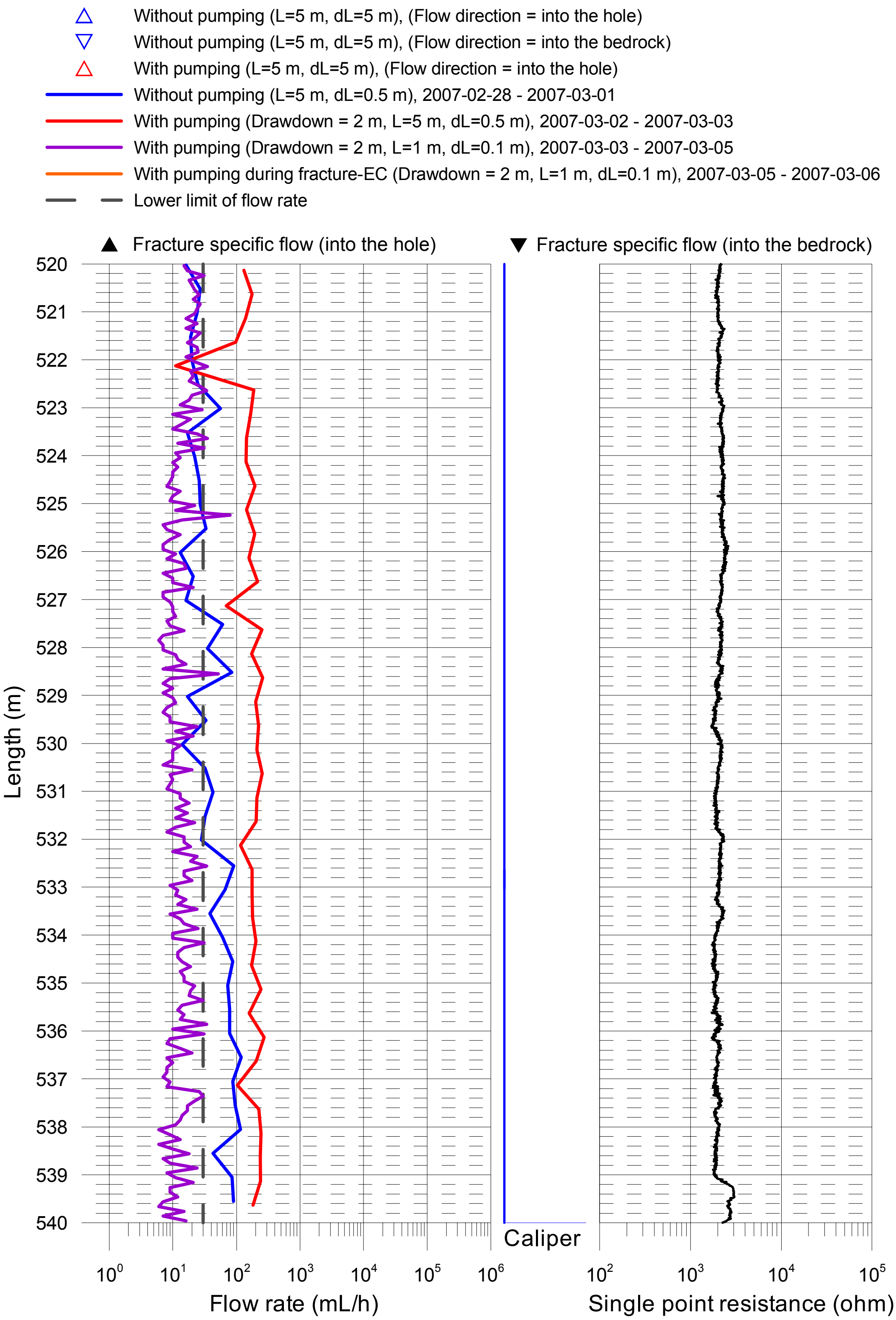
Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance



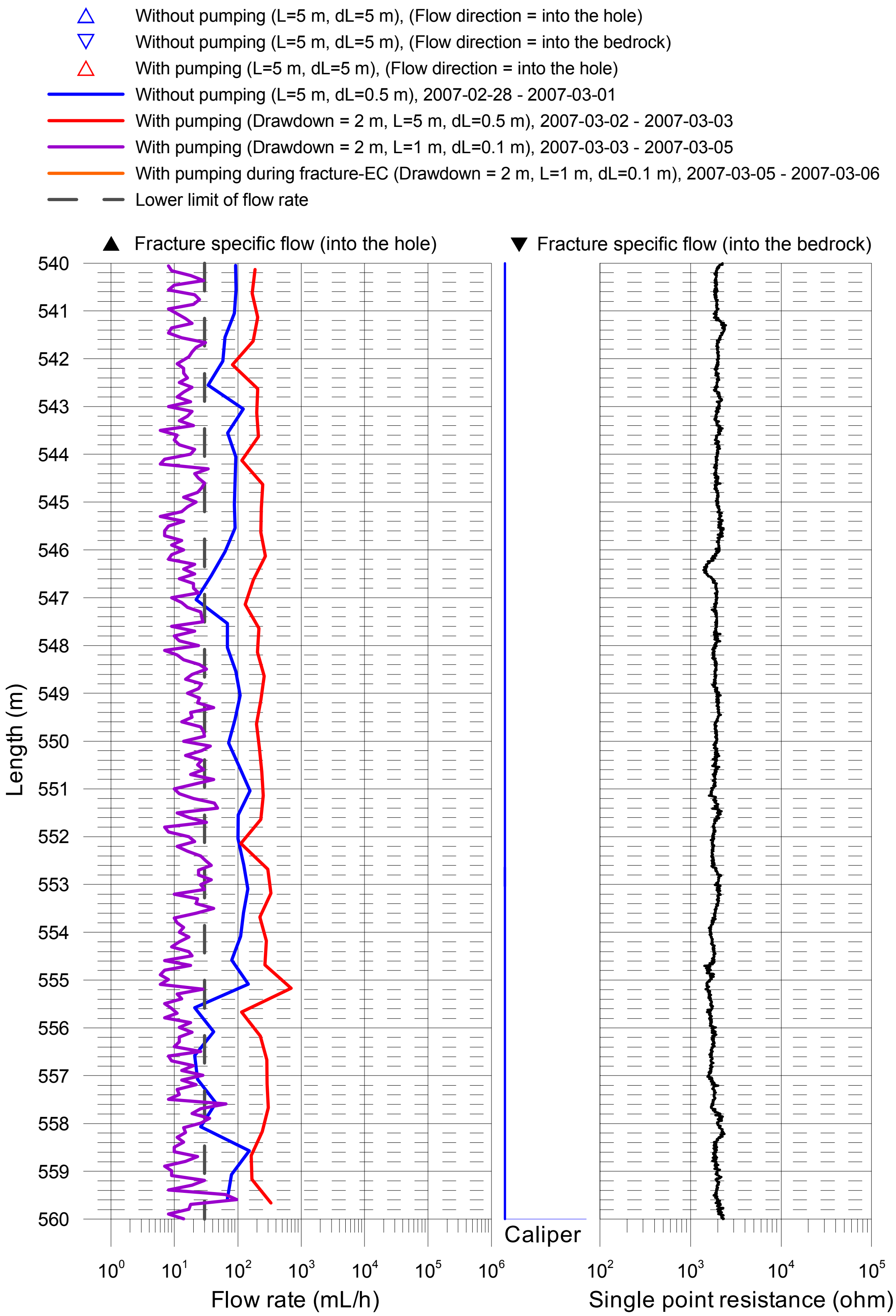
Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance

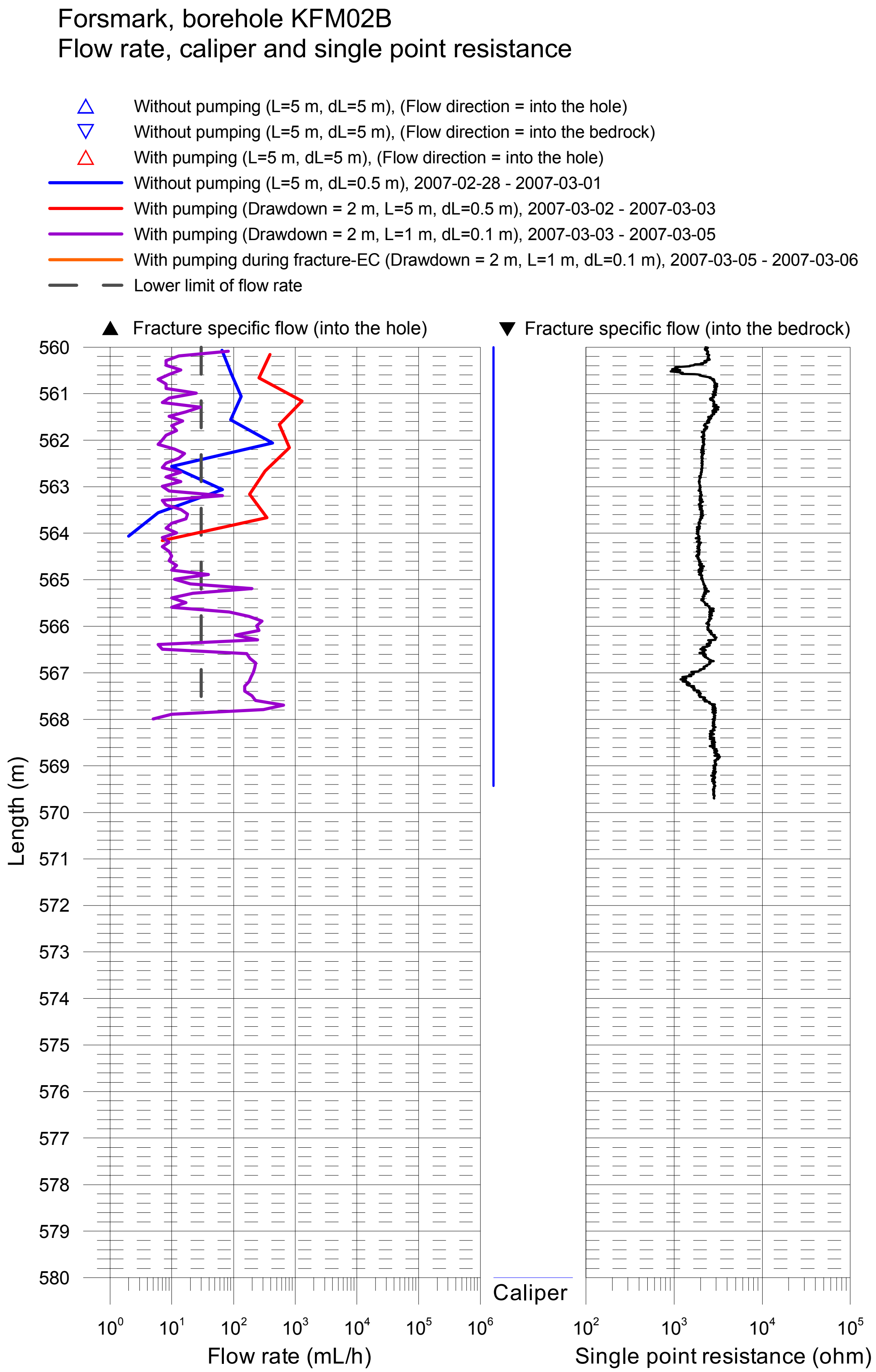


Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance



Forsmark, borehole KFM02B
Flow rate, caliper and single point resistance




Forsmark, borehole KFM02B
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), 2007-02-28 - 2007-03-01
With pumping (Drawdown = 2 m, L=5 m, dL=0.5 m), 2007-03-02 - 2007-03-03
With pumping (Drawdown = 2 m, L=1 m, dL=0.1 m), 2007-03-03 - 2007-03-05
With pumping during fracture-EC (Drawdown = 2 m, L=1 m, dL=0.1 m), 2007-03-05 - 2007-03-06
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
560
561
562
563
564
565
566
567
568
569
570
571
572
573
574
575
576
577
578
579
580
Caliper
10^0 10^1 10^2 10^3 10^4 10^5 10^6
Flow rate (mL/h)
10^2 10^3 10^4 10^5
Single point resistance (ohm)

Explanations

Header	Unit	Explanations
Borehole		ID for borehole.
Secup	m	Length along the borehole for the upper limit of the test section (based on corrected length L).
Seclow	m	Length along the borehole for the lower limit of the test section (based on corrected length L).
L	m	Corrected length along borehole based on SKB procedures for length correction.
Length to flow anom.	m	Length along the borehole to inferred flow anomaly during overlapping flow logging.
Test type (1–6)	(–)	1A: Pumping test–wire-line eq., 1B:Pumping test-submersible pump, 1C: Pumping test-airlift pumping, 2: Interference test, 3: Injection test, 4: Slug test, 5A: Difference flow logging –PFL-DIFF-Sequential, 5B: Difference flow logging –PFL-DIFF-Overlapping, 6: Flow logging-Impeller.
Date of test, start	YY-MM-DD	Date for start of pumping.
Time of test, start	hh:mm	Time for start of pumping.
Date of flowl., start	YY-MM-DD	Date for start of the flow logging.
Time of flowl., start	hh:mm	Time for start of the flow logging.
Date of test, stop	YY-MM-DD	Date for stop of the test.
Time of test, stop	hh:mm	Time for stop of the test.
L_w	m	Section length used in the difference flow logging.
d_L	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.	Stabilized 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.	Stabilized hydraulic head during the second pumping period. Elevation of water level in open borehole in the local co-ordinates system with z=0 m.

Explanations

Header	Unit	Explanations
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 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 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 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).

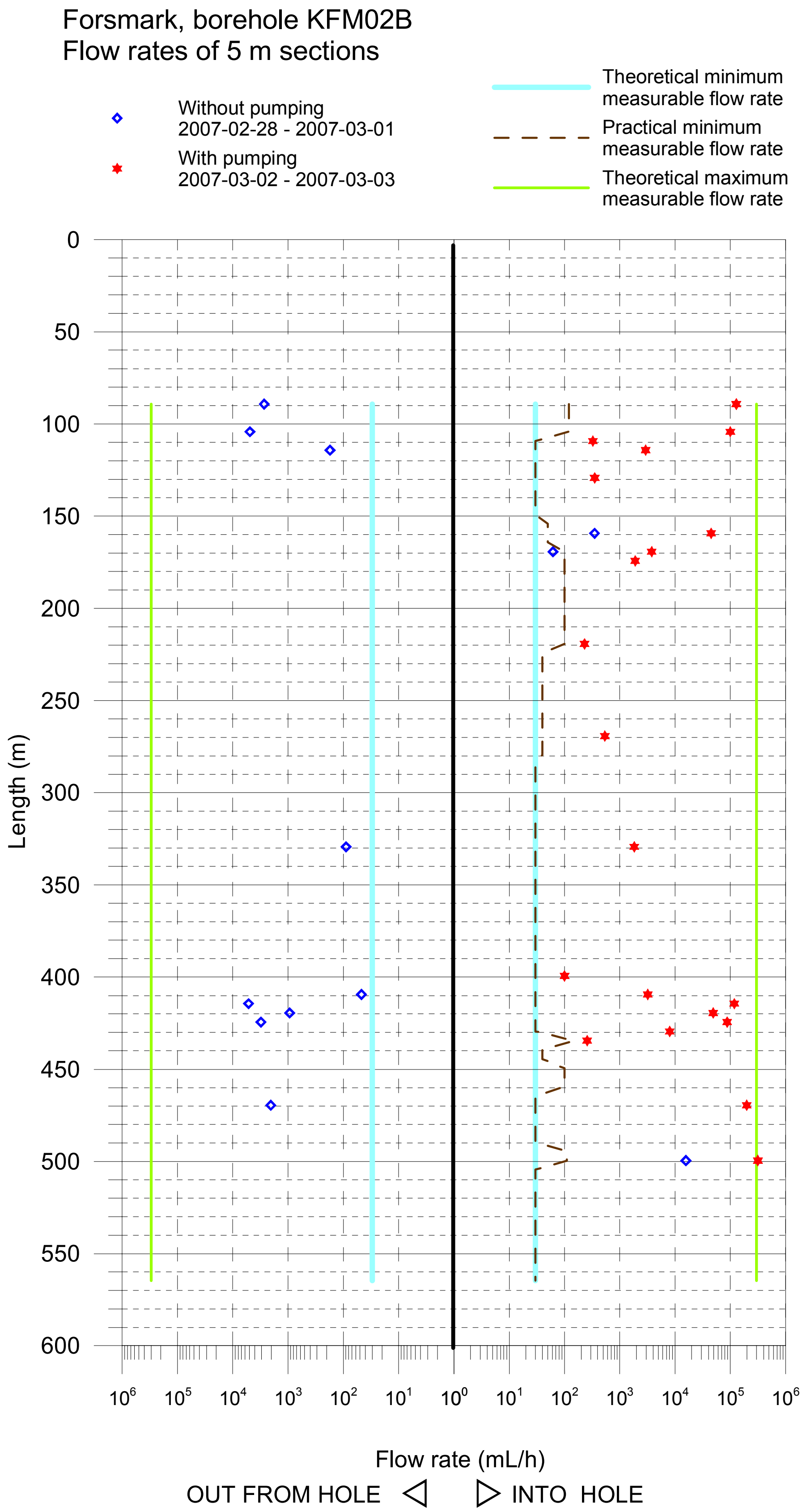
Difference flow logging – Sequential flow logging

Borehole ID	Secup L (m)	Seclow L (m)	L_w (m)	Q_0 (m³/s)	h_{0FW} (m.a.s.l.)	Q_1 (m³/s)	h_{1FW} (m.a.s.l.)	T_D (m²/s)	h_i (m.a.s.l.)	Q-lower $limit_P$ (mL/h)	T_D-$measl_{LT}$ (m²/s)	T_D-$measl_{LP}$ (m²/s)	T_D-$measl_U$ (m²/s)	Comments
KFM02B	86.74	91.74	5	–7.50E–07	1.12	3.56E–05	–0.83	1.8E–05	1.1	120	4.2E–09	1.7E–08	4.3E–05	
KFM02B	91.74	96.74	5	–	1.15	–	–0.78	–	–	120	4.3E–09	1.7E–08	4.3E–05	
KFM02B	96.73	101.73	5	–	1.20	–	–0.72	–	–	120	4.3E–09	1.7E–08	4.3E–05	
KFM02B	101.73	106.73	5	–1.35E–06	1.19	2.78E–05	–0.70	1.5E–05	1.1	120	4.4E–09	1.7E–08	4.4E–05	
KFM02B	106.72	111.72	5	–	1.25	9.06E–08	–0.66	4.7E–08	–	30	4.3E–09	4.3E–09	4.3E–05	
KFM02B	111.72	116.72	5	–4.86E–08	1.34	8.17E–07	–0.57	4.5E–07	1.2	30	4.3E–09	4.3E–09	4.3E–05	
KFM02B	116.76	121.76	5	–	1.38	–	–0.52	–	–	30	4.3E–09	4.3E–09	4.3E–05	
KFM02B	121.76	126.76	5	–	1.42	–	–0.49	–	–	30	4.3E–09	4.3E–09	4.3E–05	
KFM02B	126.75	131.75	5	–	1.44	9.78E–08	–0.46	5.1E–08	–	30	4.3E–09	4.3E–09	4.3E–05	
KFM02B	131.75	136.75	5	–	1.49	–	–0.40	–	–	30	4.4E–09	4.4E–09	4.4E–05	
KFM02B	136.74	141.74	5	–	1.50	–	–0.36	–	–	30	4.4E–09	4.4E–09	4.4E–05	
KFM02B	141.73	146.73	5	–	1.55	–	–0.34	–	–	30	4.4E–09	4.4E–09	4.4E–05	
KFM02B	146.73	151.73	5	–	1.54	–	–0.31	–	–	30	4.5E–09	4.5E–09	4.5E–05	
KFM02B	151.74	156.74	5	–	1.66	–	–0.21	–	–	50	4.4E–09	7.3E–09	4.4E–05	
KFM02B	156.76	161.76	5	9.67E–08	1.66	1.25E–05	–0.17	6.7E–06	1.7	50	4.5E–09	7.5E–09	4.5E–05	
KFM02B	161.74	166.74	5	–	1.74	–	–0.10	–	–	50	4.5E–09	7.5E–09	4.5E–05	
KFM02B	166.78	171.78	5	1.72E–08	1.75	1.05E–06	–0.07	5.6E–07	1.8	100	4.5E–09	1.5E–08	4.5E–05	
KFM02B	171.78	176.78	5	–	1.82	5.28E–07	–0.03	2.8E–07	–	100	4.5E–09	1.5E–08	4.5E–05	
KFM02B	176.78	181.78	5	–	1.82	–	–0.01	–	–	100	4.5E–09	1.5E–08	4.5E–05	
KFM02B	181.78	186.78	5	–	1.94	–	0.09	–	–	100	4.5E–09	1.5E–08	4.5E–05	
KFM02B	186.84	191.84	5	–	1.96	–	0.12	–	–	100	4.5E–09	1.5E–08	4.5E–05	
KFM02B	191.83	196.83	5	–	2.00	–	0.16	–	–	100	4.5E–09	1.5E–08	4.5E–05	
KFM02B	196.83	201.83	5	–	2.04	–	0.20	–	–	100	4.5E–09	1.5E–08	4.5E–05	
KFM02B	201.81	206.81	5	–	2.06	–	0.25	–	–	100	4.6E–09	1.5E–08	4.6E–05	
KFM02B	206.82	211.82	5	–	2.12	–	0.28	–	–	100	4.5E–09	1.5E–08	4.5E–05	
KFM02B	211.82	216.82	5	–	2.11	–	0.31	–	–	100	4.6E–09	1.5E–08	4.6E–05	
KFM02B	216.81	221.81	5	–	2.17	6.39E–08	0.32	3.4E–08	–	100	4.5E–09	1.5E–08	4.5E–05	

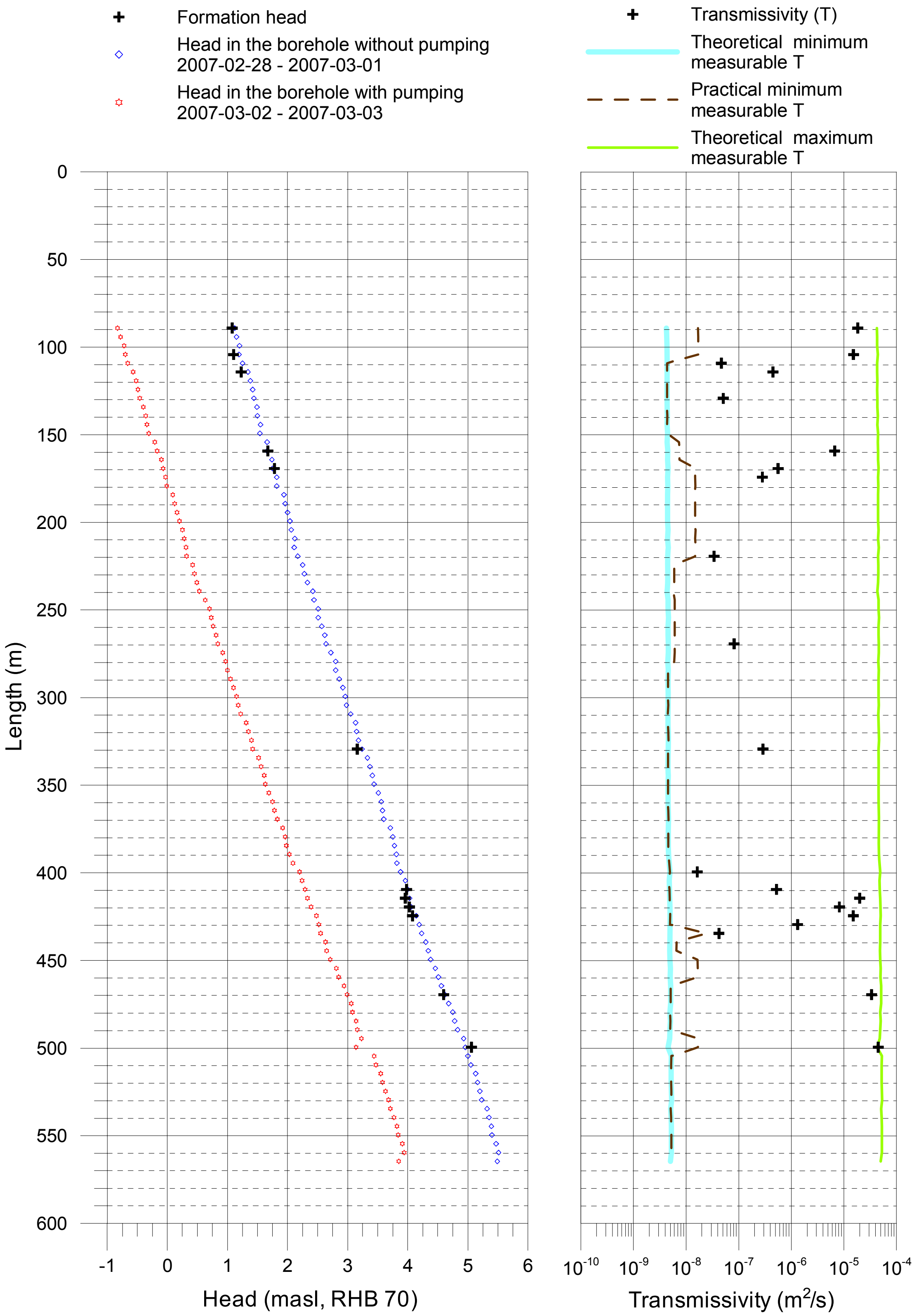
Borehole ID	Secup L (m)	Seclow L (m)	L_w (m)	Q_0 (m^3/s)	h_{0FW} (m.a.s.l.)	Q_1 (m^3/s)	h_{1FW} (m.a.s.l.)	T_D (m^2/s)	h_i (m.a.s.l.)	Q-lower $limit_P$ (mL/h)	T_D-$measl_{LT}$ (m^2/s)	T_D-$measl_{LP}$ (m^2/s)	T_D-$measl_U$ (m^2/s)	Comments
KFM02B	221.83	226.83	5	–	2.25	–	0.42	–	–	40	4.5E–09	6.0E–09	4.5E–05	
KFM02B	226.85	231.85	5	–	2.28	–	0.45	–	–	40	4.5E–09	6.0E–09	4.5E–05	
KFM02B	231.83	236.83	5	–	2.33	–	0.49	–	–	40	4.5E–09	6.0E–09	4.5E–05	
KFM02B	236.83	241.83	5	–	2.42	–	0.53	–	–	40	4.4E–09	5.8E–09	4.4E–05	
KFM02B	241.84	246.84	5	–	2.44	–	0.63	–	–	40	4.6E–09	6.1E–09	4.6E–05	
KFM02B	246.87	251.87	5	–	2.51	–	0.70	–	–	40	4.6E–09	6.1E–09	4.6E–05	
KFM02B	251.87	256.87	5	–	2.51	–	0.73	–	–	40	4.6E–09	6.2E–09	4.6E–05	
KFM02B	256.86	261.86	5	–	2.57	–	0.76	–	–	40	4.6E–09	6.1E–09	4.6E–05	
KFM02B	261.86	266.86	5	–	2.62	–	0.81	–	–	40	4.6E–09	6.1E–09	4.6E–05	
KFM02B	266.85	271.85	5	–	2.64	1.49E–07	0.84	8.2E–08	–	40	4.6E–09	6.1E–09	4.6E–05	
KFM02B	271.85	276.85	5	–	2.72	–	0.92	–	–	40	4.6E–09	6.1E–09	4.6E–05	
KFM02B	276.88	281.88	5	–	2.80	–	0.97	–	–	40	4.5E–09	6.0E–09	4.5E–05	
KFM02B	281.87	286.87	5	–	2.80	–	1.00	–	–	30	4.6E–09	4.6E–09	4.6E–05	
KFM02B	286.87	291.87	5	–	2.86	–	1.05	–	–	30	4.6E–09	4.6E–09	4.6E–05	
KFM02B	291.86	296.86	5	–	2.92	–	1.10	–	–	30	4.5E–09	4.5E–09	4.5E–05	
KFM02B	296.86	301.86	5	–	2.96	–	1.15	–	–	30	4.6E–09	4.6E–09	4.6E–05	
KFM02B	301.85	306.85	5	–	2.98	–	1.18	–	–	30	4.6E–09	4.6E–09	4.6E–05	
KFM02B	306.85	311.85	5	–	3.05	–	1.22	–	–	30	4.5E–09	4.5E–09	4.5E–05	
KFM02B	311.85	316.85	5	–	3.13	–	1.31	–	–	30	4.5E–09	4.5E–09	4.5E–05	
KFM02B	316.88	321.88	5	–	3.15	–	1.35	–	–	30	4.6E–09	4.6E–09	4.6E–05	
KFM02B	321.87	326.87	5	–	3.18	–	1.40	–	–	30	4.6E–09	4.6E–09	4.6E–05	
KFM02B	326.87	331.87	5	–2.47E–08	3.24	5.08E–07	1.42	2.9E–07	3.2	30	4.5E–09	4.5E–09	4.5E–05	
KFM02B	331.87	336.87	5	–	3.33	–	1.52	–	–	30	4.6E–09	4.6E–09	4.6E–05	
KFM02B	336.91	341.91	5	–	3.37	–	1.56	–	–	30	4.6E–09	4.6E–09	4.6E–05	
KFM02B	341.91	346.91	5	–	3.41	–	1.61	–	–	30	4.6E–09	4.6E–09	4.6E–05	
KFM02B	346.91	351.91	5	–	3.44	–	1.63	–	–	30	4.6E–09	4.6E–09	4.6E–05	
KFM02B	351.91	356.91	5	–	3.51	–	1.69	–	–	30	4.5E–09	4.5E–09	4.5E–05	
KFM02B	356.91	361.91	5	–	3.56	–	1.75	–	–	30	4.6E–09	4.6E–09	4.6E–05	
KFM02B	361.90	366.90	5	–	3.58	–	1.78	–	–	30	4.6E–09	4.6E–09	4.6E–05	

Borehole ID	Secup L (m)	Seclow L (m)	L_w (m)	Q_0 (m^3/s)	h_{0FW} (m.a.s.l.)	Q_1 (m^3/s)	h_{1FW} (m.a.s.l.)	T_D (m^2/s)	h_i (m.a.s.l.)	Q-lower $limit_P$ (mL/h)	T_D-$measl_{LT}$ (m^2/s)	T_D-$measl_{LP}$ (m^2/s)	T_D-$measl_U$ (m^2/s)	Comments
KFM02B	366.91	371.91	5	–	3.60	–	1.83	–	–	30	4.7E–09	4.7E–09	4.7E–05	
KFM02B	371.91	376.91	5	–	3.71	–	1.92	–	–	30	4.6E–09	4.6E–09	4.6E–05	
KFM02B	376.95	381.95	5	–	3.75	–	1.96	–	–	30	4.6E–09	4.6E–09	4.6E–05	
KFM02B	381.94	386.94	5	–	3.78	–	1.98	–	–	30	4.6E–09	4.6E–09	4.6E–05	
KFM02B	386.95	391.95	5	–	3.81	–	2.03	–	–	30	4.6E–09	4.6E–09	4.6E–05	
KFM02B	391.95	396.95	5	–	3.82	–	2.09	–	–	30	4.8E–09	4.8E–09	4.8E–05	
KFM02B	396.96	401.96	5	–	3.88	2.78E–08	2.20	1.6E–08	–	30	4.9E–09	4.9E–09	4.9E–05	
KFM02B	401.96	406.96	5	–	3.96	–	2.24	–	–	30	4.8E–09	4.8E–09	4.8E–05	
KFM02B	406.97	411.97	5	–1.31E–08	4.00	8.92E–07	2.29	5.2E–07	4.0	30	4.8E–09	4.8E–09	4.8E–05	
KFM02B	411.97	416.97	5	–1.44E–06	4.03	3.28E–05	2.33	2.0E–05	4.0	30	4.8E–09	4.8E–09	4.9E–05	
KFM02B	416.98	421.98	5	–2.60E–07	4.06	1.36E–05	2.39	8.2E–06	4.0	30	4.9E–09	4.9E–09	5.0E–05	
KFM02B	421.97	426.97	5	–8.61E–07	4.14	2.44E–05	2.48	1.5E–05	4.1	30	5.0E–09	5.0E–09	5.0E–05	
KFM02B	427.01	432.01	5	–	4.19	2.23E–06	2.52	1.3E–06	–	30	4.9E–09	4.9E–09	4.9E–05	
KFM02B	432.00	437.00	5	–	4.23	7.14E–08	2.55	4.2E–08	–	150	4.9E–09	2.5E–08	4.9E–05	
KFM02B	436.99	441.99	5	–	4.30	–	2.63	–	–	40	4.9E–09	6.6E–09	4.9E–05	
KFM02B	441.98	446.98	5	–	4.34	–	2.65	–	–	40	4.9E–09	6.5E–09	4.9E–05	
KFM02B	446.99	451.99	5	–	4.38	–	2.71	–	–	100	4.9E–09	1.6E–08	4.9E–05	
KFM02B	451.99	456.99	5	–	4.46	–	2.81	–	–	100	5.0E–09	1.7E–08	5.0E–05	
KFM02B	457.01	462.01	5	–	4.51	–	2.85	–	–	100	5.0E–09	1.7E–08	5.0E–05	
KFM02B	461.99	466.99	5	–	4.56	–	2.94	–	–	30	5.1E–09	5.1E–09	5.1E–05	
KFM02B	467.01	472.01	5	–5.69E–07	4.62	5.50E–05	2.99	3.4E–05	4.6	30	5.1E–09	5.1E–09	5.1E–05	
KFM02B	472.01	477.01	5	–	4.68	–	3.06	–	–	30	5.1E–09	5.1E–09	5.1E–05	
KFM02B	477.03	482.03	5	–	4.75	–	3.08	–	–	30	4.9E–09	4.9E–09	4.9E–05	
KFM02B	482.03	487.03	5	–	4.78	–	3.14	–	–	30	5.0E–09	5.0E–09	5.0E–05	
KFM02B	487.02	492.02	5	–	4.83	–	3.16	–	–	30	4.9E–09	4.9E–09	4.9E–05	
KFM02B	492.02	497.02	5	–	4.93	–	3.23	–	–	110	4.8E–09	1.8E–08	4.8E–05	
KFM02B	497.06	502.06	5	4.36E–06	4.96	8.75E–05	3.14	4.5E–05	5.1	110	4.5E–09	1.7E–08	4.3E–05	
KFM02B	502.04	507.04	5	–	5.00	–	3.44	–	–	30	5.3E–09	5.3E–09	5.3E–05	

Borehole ID	Secup L (m)	Seclow L (m)	L_w (m)	Q_0 (m^3/s)	h_{0FW} (m.a.s.l.)	Q_1 (m^3/s)	h_{1FW} (m.a.s.l.)	T_D (m^2/s)	h_i (m.a.s.l.)	Q-lower $limit_P$ (mL/h)	T_D-$measl_{LT}$ (m^2/s)	T_D-$measl_{LP}$ (m^2/s)	T_D-$measl_U$ (m^2/s)	Comments
KFM02B	507.07	512.07	5	–	5.05	–	3.47	–	–	30	5.2E–09	5.2E–09	5.2E–05	
KFM02B	512.06	517.06	5	–	5.13	–	3.55	–	–	30	5.2E–09	5.2E–09	5.2E–05	
KFM02B	517.08	522.08	5	–	5.16	–	3.58	–	–	30	5.2E–09	5.2E–09	5.2E–05	
KFM02B	522.08	527.08	5	–	5.20	–	3.63	–	–	30	5.3E–09	5.3E–09	5.3E–05	
KFM02B	527.08	532.08	5	–	5.23	–	3.68	–	–	30	5.3E–09	5.3E–09	5.3E–05	
KFM02B	532.08	537.08	5	–	5.32	–	3.71	–	–	30	5.1E–09	5.1E–09	5.1E–05	
KFM02B	537.09	542.09	5	–	5.35	–	3.77	–	–	30	5.2E–09	5.2E–09	5.2E–05	
KFM02B	542.09	547.09	5	–	5.39	–	3.82	–	–	30	5.3E–09	5.3E–09	5.3E–05	
KFM02B	547.09	552.09	5	–	5.40	–	3.84	–	–	30	5.3E–09	5.3E–09	5.3E–05	
KFM02B	552.09	557.09	5	–	5.47	–	3.91	–	–	30	5.3E–09	5.3E–09	5.3E–05	
KFM02B	557.13	562.13	5	–	5.51	–	3.94	–	–	30	5.3E–09	5.3E–09	5.3E–05	
KFM02B	562.11	567.11	5	–	5.49	–	3.85	–	–	30	5.0E–09	5.0E–09	5.0E–05	


Forsmark, borehole KFM02B
Flow rates of 5 m sections
Without pumping
2007-02-28 - 2007-03-01
With pumping
2007-03-02 - 2007-03-03
Theoretical minimum measurable flow rate
Practical minimum measurable flow rate
Theoretical maximum measurable flow rate
Length (m)
0
50
100
150
200
250
300
350
400
450
500
550
600
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 KFM02B
Transmissivity and head of 5 m sections



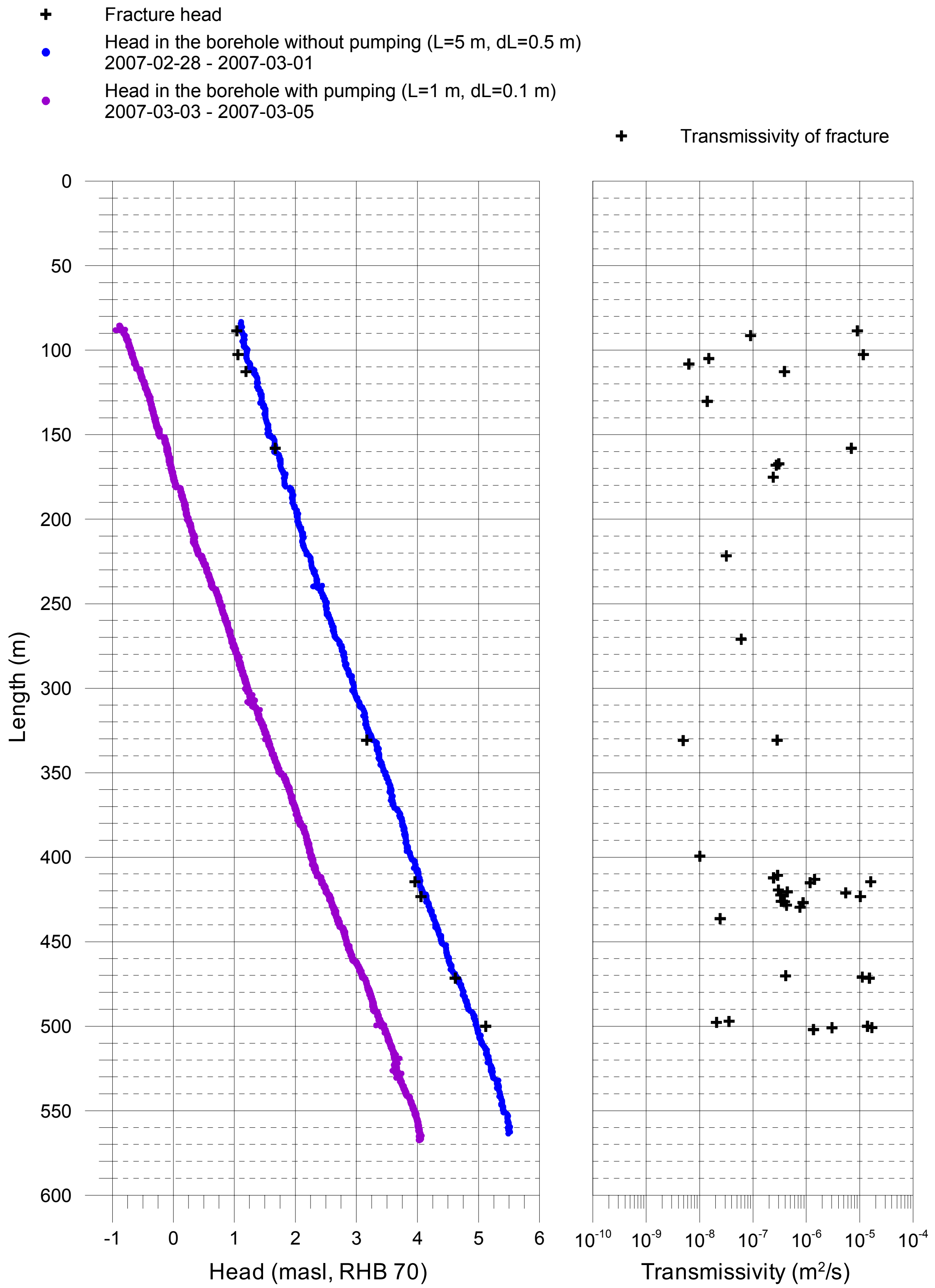
PFL – Difference flow logging – Inferred flow anomalies from overlapping flow logging

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
KFM02B	88.6	1	0.1	–6.14E–07	1.11	1.71E–05	–0.83	9.1E–06	1.0	
KFM02B	91.4	1	0.1	–	1.17	1.79E–07	–0.79	9.0E–08	–	
KFM02B	102.6	1	0.1	–1.61E–06	1.20	2.06E–05	–0.68	1.2E–05	1.1	
KFM02B	104.9	1	0.1	–	1.20	2.78E–08	–0.65	1.5E–08	–	
KFM02B	108.2	1	0.1	–	1.26	1.19E–08	–0.62	6.3E–09	–	*
KFM02B	112.7	1	0.1	–5.00E–08	1.32	6.83E–07	–0.55	3.9E–07	1.2	
KFM02B	130.2	1	0.1	–	1.44	2.58E–08	–0.38	1.4E–08	–	*
KFM02B	158.1	1	0.1	8.00E–08	1.66	1.25E–05	–0.10	7.0E–06	1.7	
KFM02B	167.3	1	0.1	–	1.76	5.56E–07	–0.05	3.0E–07	–	*, **
KFM02B	168.0	1	0.1	–	1.75	4.94E–07	–0.04	2.7E–07	–	*, **
KFM02B	175.2	1	0.1	–	1.83	4.44E–07	0.00	2.4E–07	–	
KFM02B	221.7	1	0.1	–	2.23	5.64E–08	0.47	3.2E–08	–	*
KFM02B	271.0	1	0.1	–	2.68	1.05E–07	0.95	6.0E–08	–	
KFM02B	330.7	1	0.1	–2.47E–08	3.26	4.69E–07	1.54	2.8E–07	3.2	
KFM02B	331.0	1	0.1	–	3.28	8.61E–09	1.56	5.0E–09	–	*
KFM02B	399.4	1	0.1	–	3.88	1.67E–08	2.25	1.0E–08	–	*
KFM02B	410.8	1	0.1	–	4.01	4.83E–07	2.36	2.9E–07	–	
KFM02B	412.2	1	0.1	–	4.03	3.97E–07	2.41	2.4E–07	–	
KFM02B	413.1	1	0.1	–	4.03	2.32E–06	2.42	1.4E–06	–	
KFM02B	414.5	1	0.1	–1.17E–06	4.03	2.49E–05	2.43	1.6E–05	4.0	
KFM02B	415.1	1	0.1	–	4.04	1.90E–06	2.44	1.2E–06	–	
KFM02B	419.4	1	0.1	–	4.06	4.75E–07	2.49	3.0E–07	–	
KFM02B	420.5	1	0.1	–	4.07	6.89E–07	2.52	4.4E–07	–	*
KFM02B	421.1	1	0.1	–	4.08	8.61E–06	2.52	5.5E–06	–	
KFM02B	422.3	1	0.1	–	4.13	5.28E–07	2.55	3.3E–07	–	*
KFM02B	423.3	1	0.1	–8.14E–07	4.14	1.56E–05	2.56	1.0E–05	4.1	
KFM02B	426.1	1	0.1	–	4.15	5.36E–07	2.59	3.4E–07	–	
KFM02B	426.3	1	0.1	–	4.14	6.08E–07	2.58	3.9E–07	–	*
KFM02B	426.9	1	0.1	–	4.17	1.38E–06	2.60	8.7E–07	–	
KFM02B	428.4	1	0.1	–	4.19	6.81E–07	2.61	4.3E–07	–	
KFM02B	429.6	1	0.1	–	4.20	1.22E–06	2.62	7.6E–07	–	
KFM02B	436.4	1	0.1	–	4.26	3.89E–08	2.68	2.4E–08	–	*
KFM02B	470.2	1	0.1	–	4.63	6.33E–07	3.10	4.1E–07	–	*
KFM02B	471.0	1	0.1	–	4.61	1.71E–05	3.11	1.1E–05	–	
KFM02B	471.5	1	0.1	–4.03E–07	4.65	2.30E–05	3.12	1.5E–05	4.6	
KFM02B	497.1	1	0.1	–	4.95	5.58E–08	3.40	3.6E–08	–	*
KFM02B	497.8	1	0.1	–	4.96	3.28E–08	3.39	2.1E–08	–	*
KFM02B	500.0	1	0.1	2.06E–06	4.97	2.39E–05	3.43	1.4E–05	5.1	
KFM02B	500.8	1	0.1	–	4.98	2.63E–05	3.44	1.7E–05	–	
KFM02B	501.0	1	0.1	–	4.98	4.69E–06	3.45	3.0E–06	–	*
KFM02B	502.0	1	0.1	–	4.98	2.09E–06	3.46	1.4E–06	–	

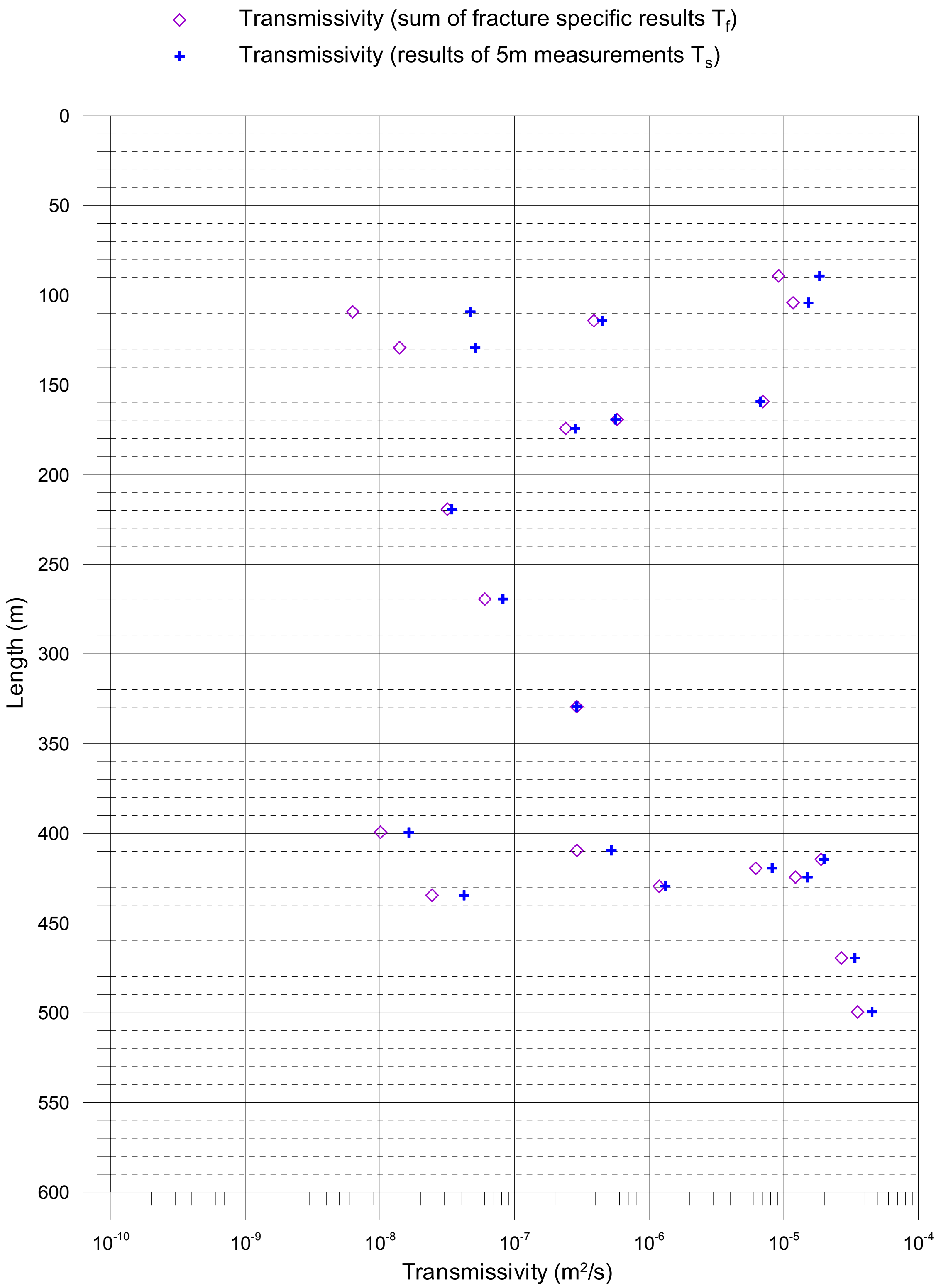
* Uncertain = The flow rate is less than 30 mL/h or the flow anomalies are overlapping or they are unclear because of noise.

** Probably porous section at detph interval 167–169 m.

Forsmark, borehole KFM02B
Transmissivity and head of detected fractures

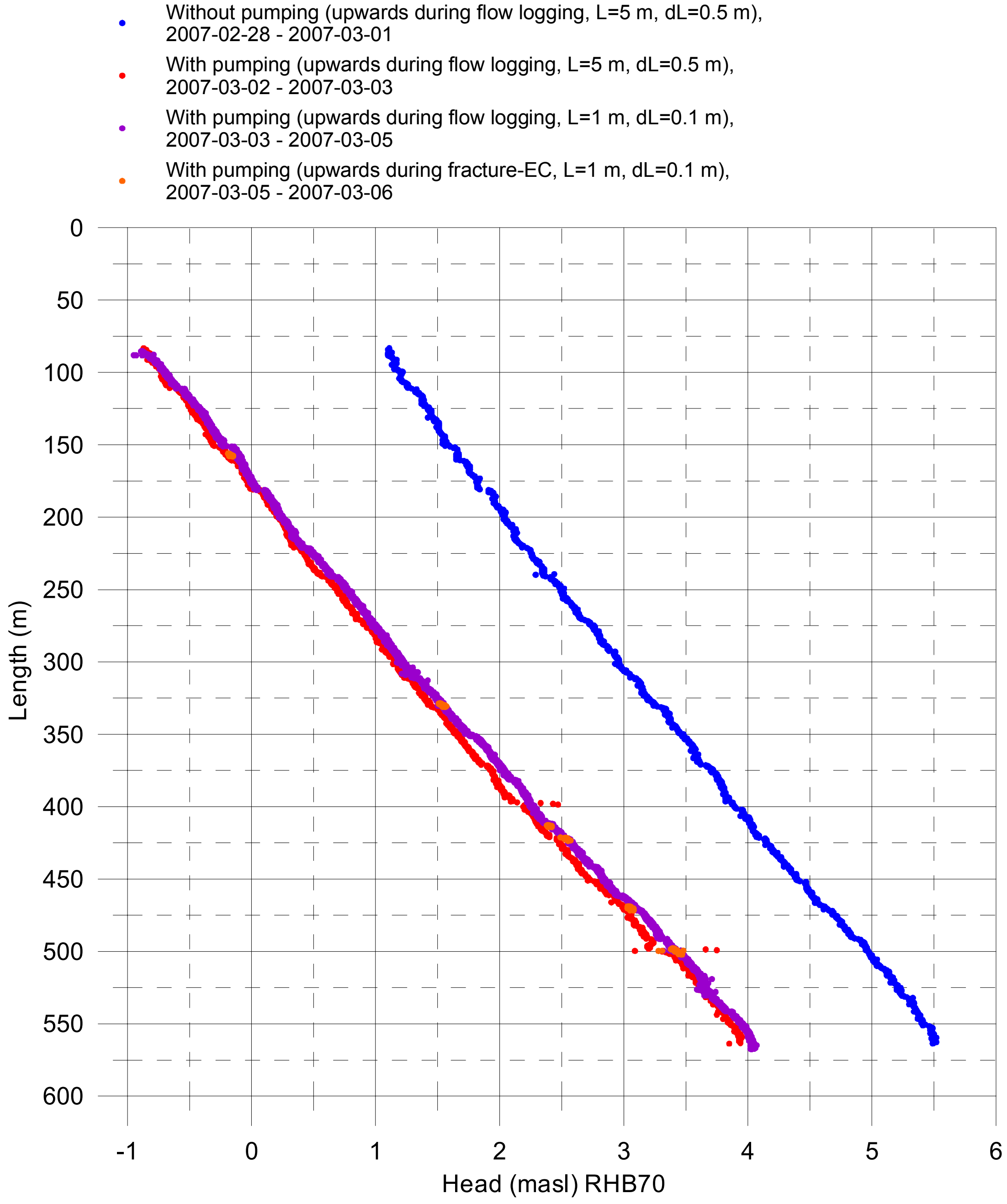


Forsmark, borehole KFM02B
Comparison between section transmissivity and fracture transmissivity

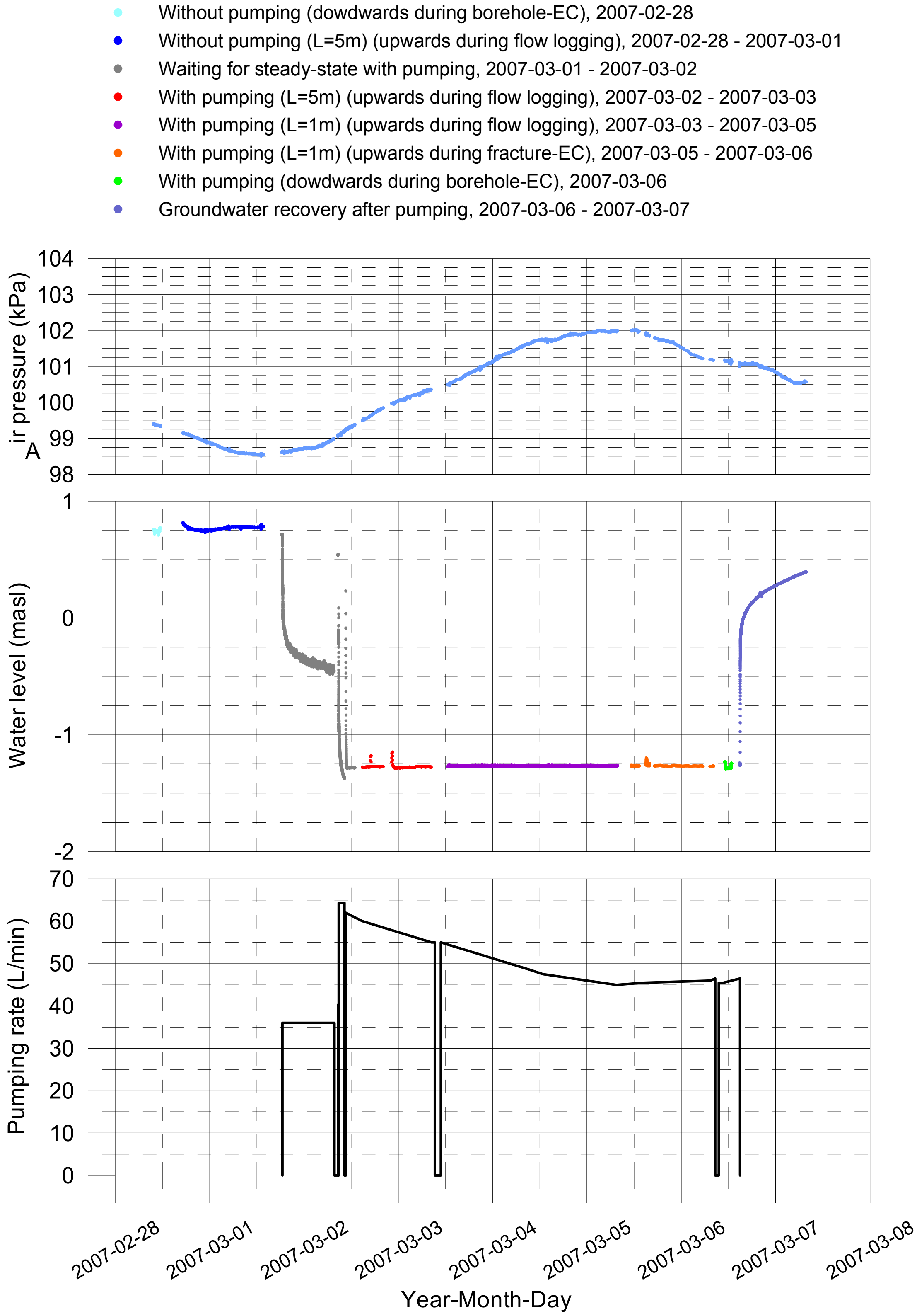


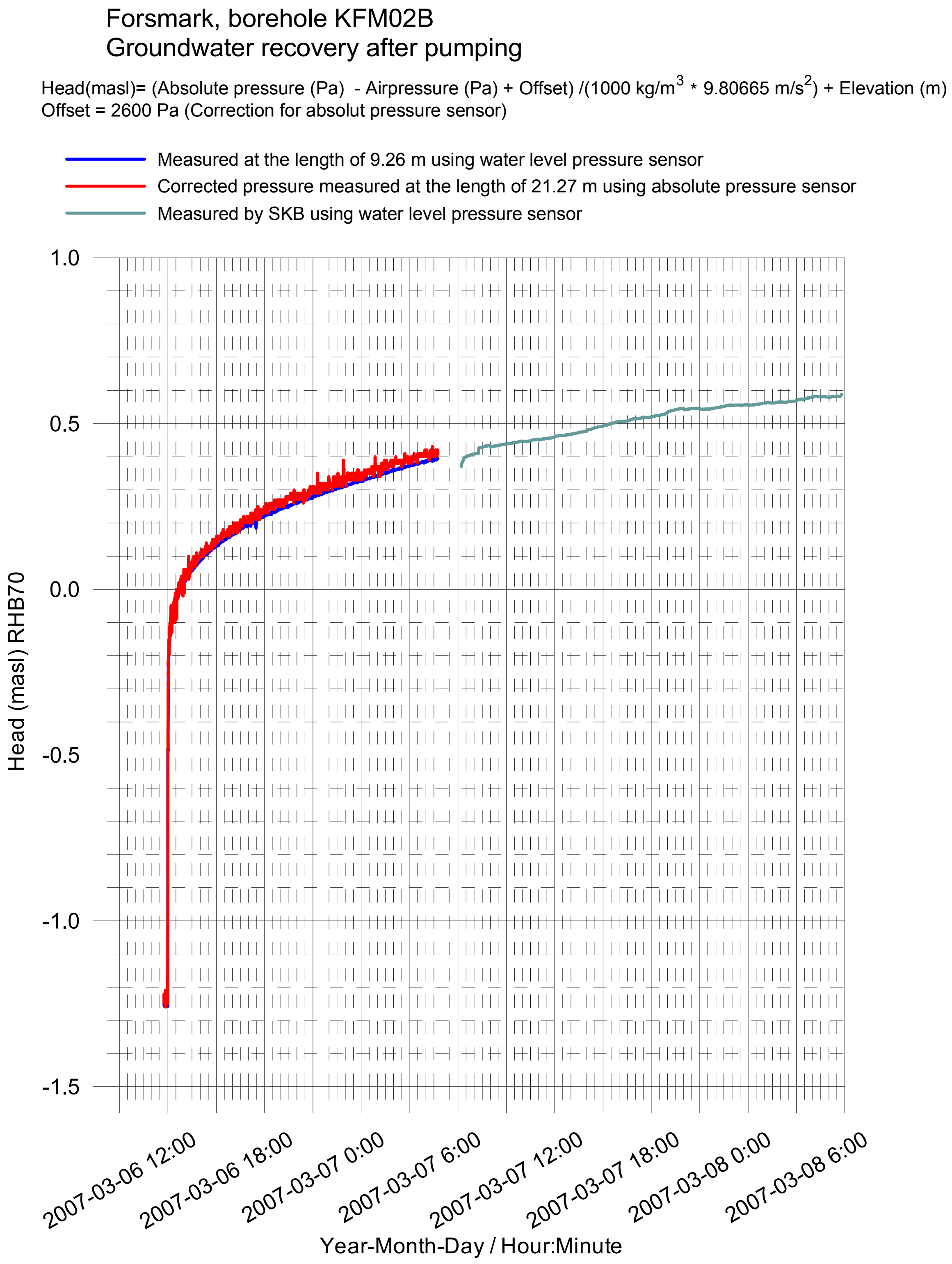
Forsmark, borehole KFM02B
Head in the borehole during flow logging

Head(masl)= (Absolute pressure (Pa) - Airpressure (Pa) + Offset) /(1000 kg/m^3 * 9.80665 m/s^2) + Elevation (m)
Offset = 2600 Pa (Correction for absolut pressure sensor)



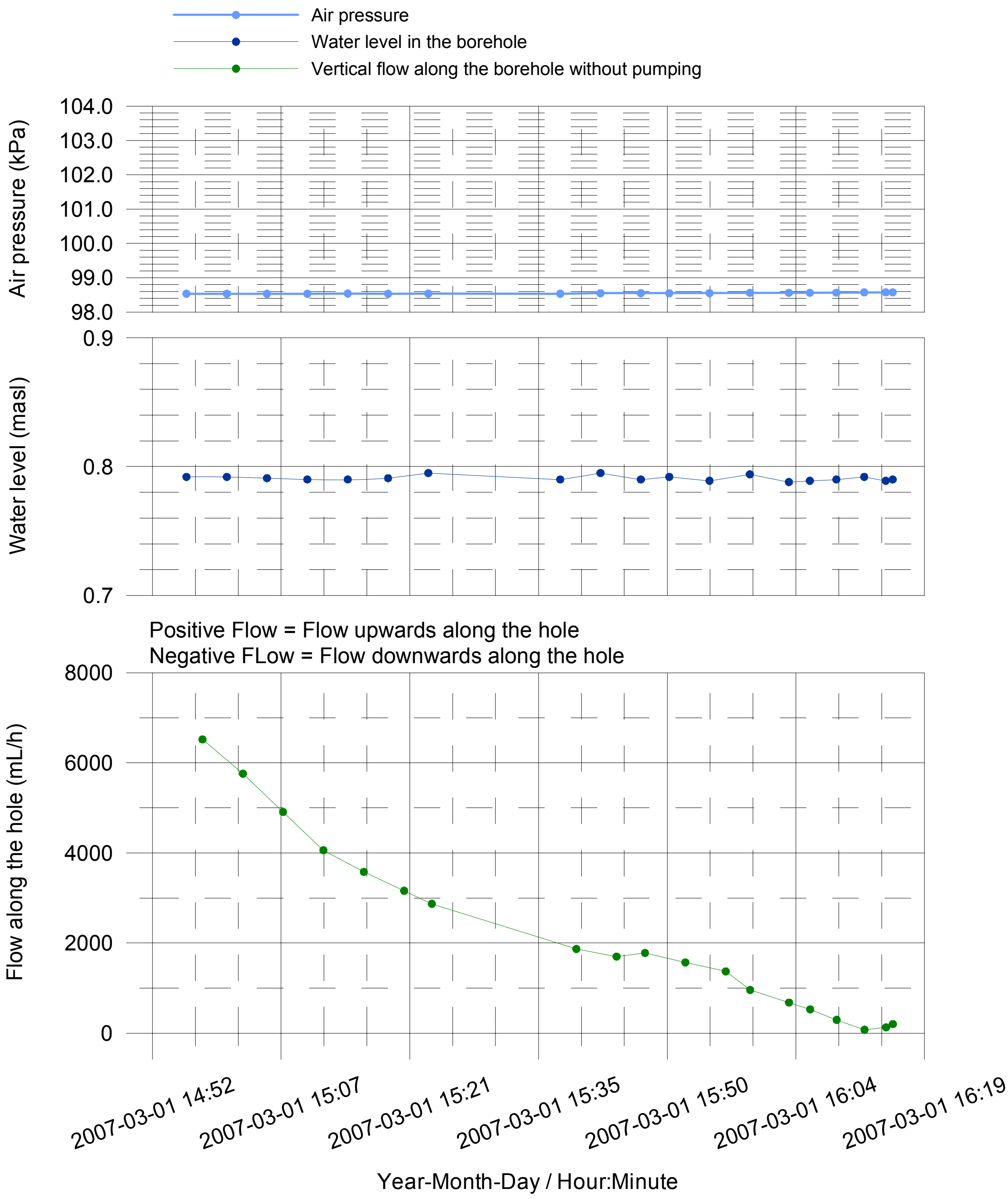
Forsmark, borehole KFM02B
Air pressure, water level in the borehole and pumping rate during flow logging



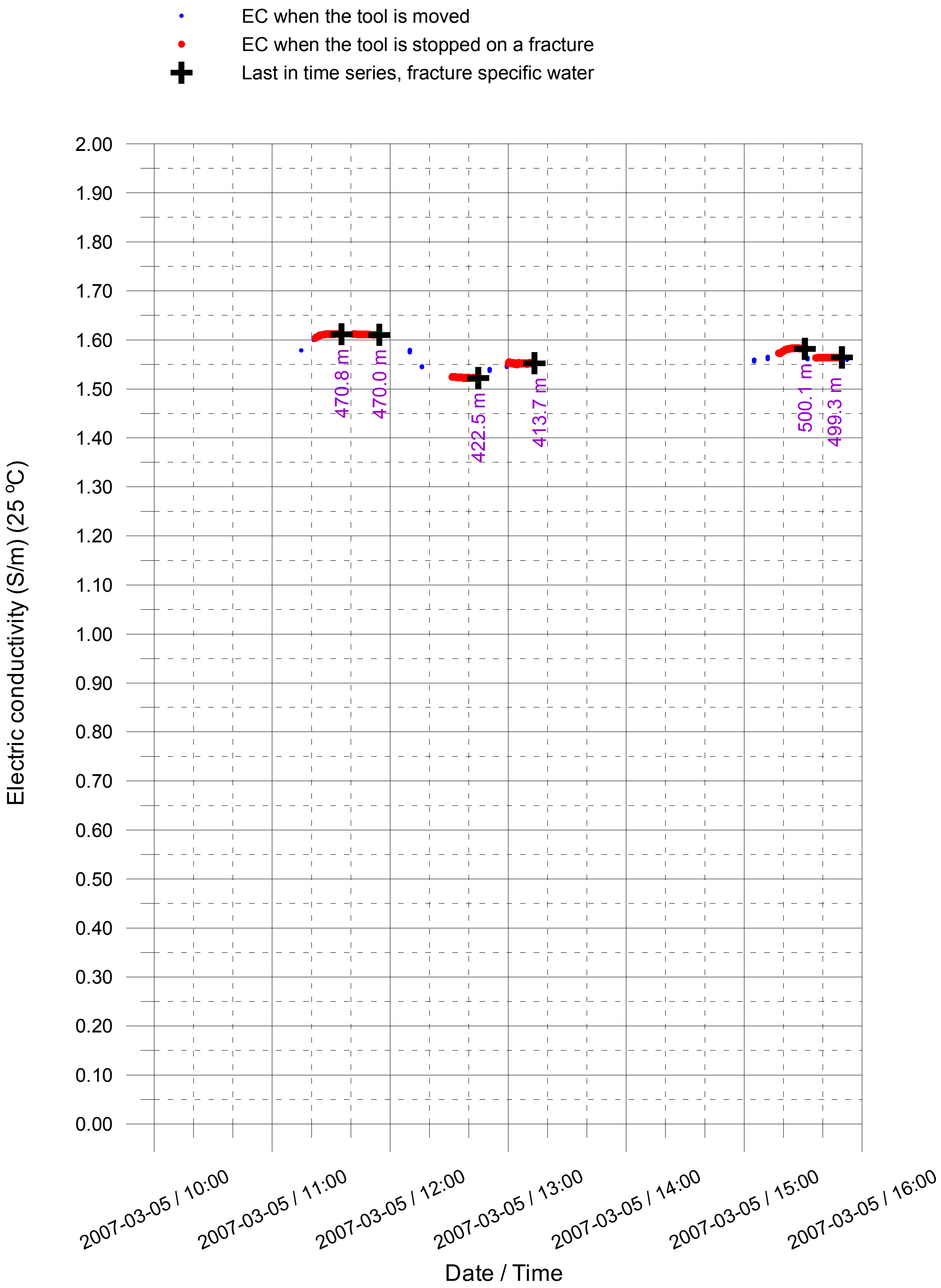


Forsmark, borehole KFM02B
Groundwater recovery after pumping
Head(masl)= (Absolute pressure (Pa) - Airpressure (Pa) + Offset) /(1000 kg/m3 * 9.80665 m/s2) + Elevation (m)
Offset = 2600 Pa (Correction for absolut pressure sensor)
Measured at the length of 9.26 m using water level pressure sensor
Corrected pressure measured at the length of 21.27 m using absolute pressure sensor
Measured by SKB using water level pressure sensor
1.0
0.5
0.0
-0.5
-1.0
-1.5
Head (masl) RHB70
2007-03-06 12:00
2007-03-06 18:00
2007-03-07 0:00
2007-03-07 6:00
2007-03-07 12:00
2007-03-07 18:00
2007-03-08 0:00
2007-03-08 6:00
Year-Month-Day / Hour:Minute

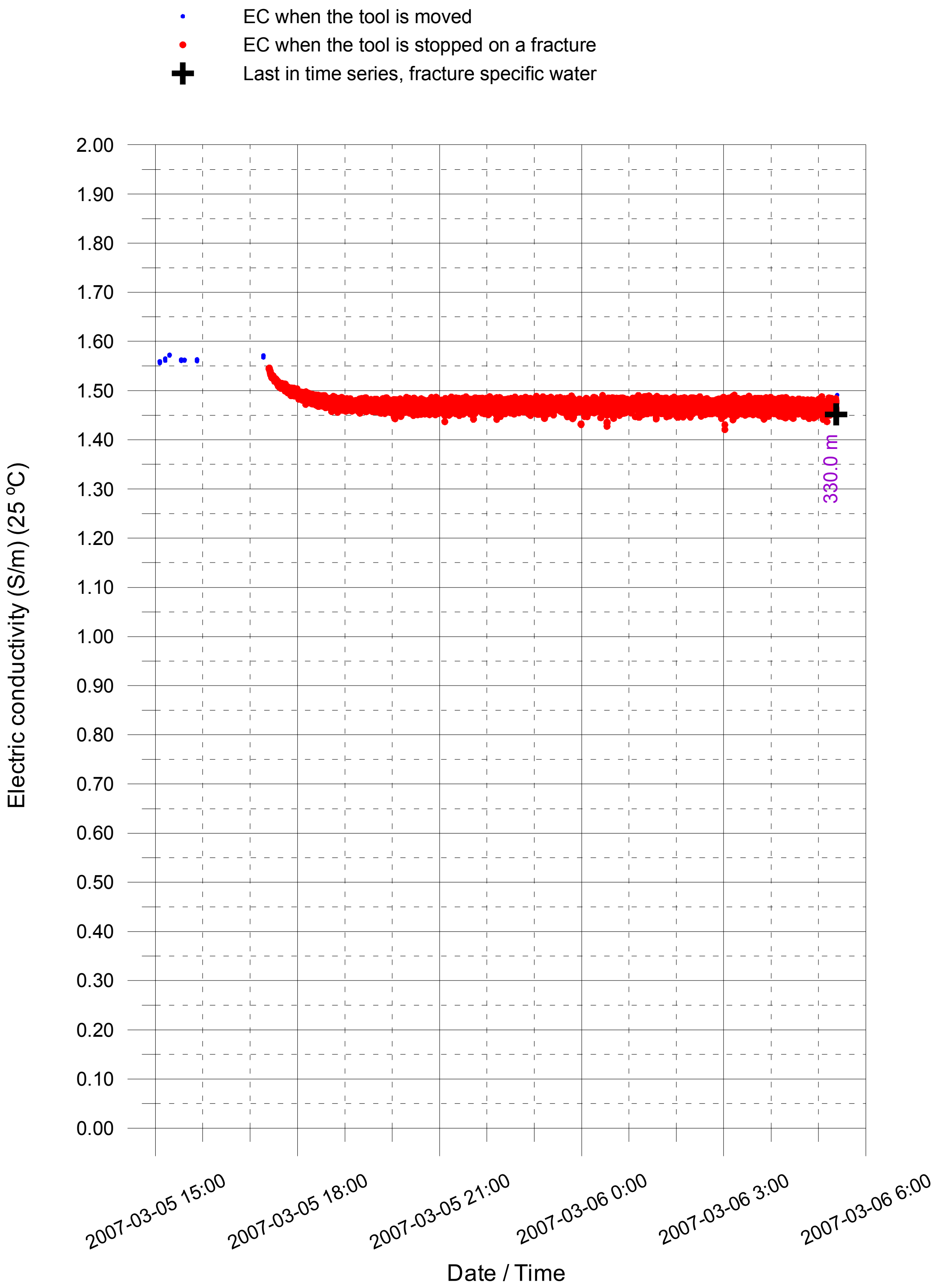
Forsmark, borehole KFM02B
Vertical flow along the borehole at the length of 89.01 m



Forsmark, borehole KFM02B
Fracture-specific EC results by date



Forsmark, borehole KFM02B
Fracture-specific EC results by date



Forsmark, borehole KFM02B
Fracture-specific EC results by date