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Forsmark site investigation

Difference flow logging in borehole KFM08A

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PRG-Tec Oy

August 2005

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Keywords: Forsmark, Hydrogeology, Hydraulic tests, Difference flow measurements, KFM08A, AP PF 400-05-007.

Foreword

The performance and evaluation of the difference flow logging campaign in borehole KFM08A was accomplished by PRG-Tec Oy.

The evaluation of the pumping test in conjunction with the difference flow logging (Section 6.6) was performed by Jan-Erik Ludvigson, Geosigma AB.

Abstract

Difference flow logging is a swift method for 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 method as well as results of measurements carried out in borehole KFM08A at Forsmark, Sweden, in May 2005, using the Posiva flow log. The primary aim of the measurements was to determine the position and flow rate of flow yielding fractures in borehole KFM08A prior to groundwater sampling.

The flow rate into or out of 5 m long test sections was measured between 94.60–919.84 m borehole length during natural (un-pumped) as well as pumped conditions. The flow measurements were repeated at the location of the detected flow anomalies using a 1 m long test section, successively transferred with an overlapping of 0.1 m.

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 pressure along the borehole. These measurements were carried out together with the flow measurements.

Electric conductivity (EC) and temperature of borehole water was also measured. The EC-measurements were used to study the distribution of saline water in the borehole during natural as well as pumped conditions. EC of fracture-specific water was measured at the same time as the flow measurements (1 m test section) for a selection of fractures.

The total transmissivity of the cored borehole KFM08A was estimated to $4.8 \cdot 10^{-6}$ m^2/s from the groundwater recovery after the pumping test during difference flow logging. This value is in good agreement with the cumulative transmissivities of the measured 5 m sections ($T_s = 8.0 \cdot 10^{-6}$ m^2/s) and of the flow anomalies identified ($T_s = 6.9 \cdot 10^{-6}$ m^2/s).

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 KFM08A i Forsmark, Sverige, i juni 2005 med Posiva flödesloggningsmetod. Det primära syftet med mätningarna var att bestämma läget och flödet för vattenförande sprickor i borrhål KFM08A före grundvattenprovtagning.

Flödet till eller från en 5 m lång testsektion mättes mellan 94,60–919,84 m borrhålslängd 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 med 0,1 m.

Längdkalibrering gjordes baserad på längdmärkena som frästs in i borrhålsväggen vid noggrant bestämda positioner längs borrhålet. Längdmärkena detekterades med caliper och punktresistansmätningar med hjälp av sensorer anslutna till flödesloggningssonden.

En högupplösande absoluttryckgivare användes för att mäta absoluttrycket längs borrhålet. Dessa mätningar utfördes tillsammans med flödesmätningarna.

Elektrisk konduktivitet och temperatur på borrhålsvattnet mättes också. EC-mätningarna användes för att studera saltvattenfördelningen i borrhålet under såväl naturliga som pumpade förhållanden. EC på vattnet i ett antal utvalda sprickor mättes samtidigt med flödesmätningarna (1 m lång testsektion).

Den totala transmissiviteten för KFM08A uppskattades till $4,8 \cdot 10^{-6}$ m^2/s utifrån återhämtningen från pumpningen under differensflödesloggningen. Värdet visar god samstämmighet med den kumulativa transmissiviteten från 5 m sektioner (T_s=$8,0 \cdot 10^{-6}$ m^2/s) och från identifierade flödesanomalier (T_s=$6,9 \cdot 10^{-6}$ m^2/s).

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1 Introduction

The difference flow logging in the core drilled borehole KFM08A at Forsmark was conducted between May 11–21, 2005. KFM08A is the eighth deep core drilled borehole in the Forsmark candidate area. The starting point of the borehole is inclined c 60° from the horizontal direction. Deviation measurements have revealed that the borehole is bending upwards versus depth, entailing that the lowermost parts are inclined only c 36°. The c 1,000 m long borehole is performed with telescopic drilling technique, where the interval c 0–100 m is percussion drilled and cased with the inner diameter 200 mm and the remaining interval, c 100–1,000 m, is core drilled with the diameter c 77.3 mm. The location of borehole KFM08A at drill site DS8 within the Forsmark area is shown in Figure 1-1.

The field work and the subsequent interpretations were conducted by PRG-Tec Oy. The Posiva Flow Log/Difference Flow 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 gained by the Difference flow logging in borehole KFM08A. The activity is performed as part of the Forsmark site investigation. The work was carried out in accordance to SKB's internal controlling document AP PF 400-05-007. Data and results were delivered to the SKB site characterization database SICADA and are traceable by the activity plan number.

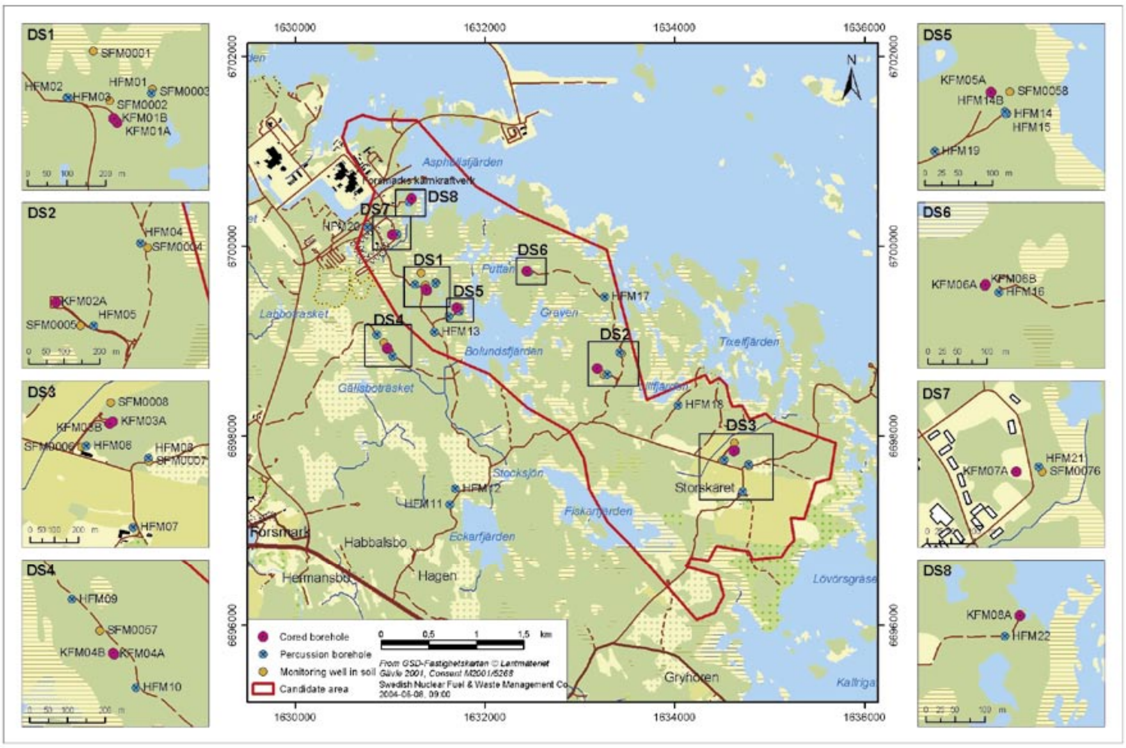

__Figure 1-1.__ Location of the drill sites DS1–8 at Forsmark. Detailed maps of all boreholes within the sites are shown.

2 Objective and scope

The main objective of the difference flow logging in KFM08A was to identify water-conductive sections/fractures suitable for subsequent hydro-geochemical characterisation. Secondly, the measurements aimed at a hydrogeological characterisation, including 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 hole, e.g. an estimate of the conductive fracture frequency (CFF), may be obtained.

Besides the difference flow logging, the measurement programme also included supporting measurements, performed for a better understanding of the overall hydrogeochemical conditions. These measurements included electric conductivity and temperature of the borehole fluid as well as single-point resistance of the borehole wall. The electric conductivity was also measured for a number of selected high-transmissive fractures in the borehole. Furthermore, the recovery of the groundwater level after pumping 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 simultaneously with the flow measurements. The results are used for calculation of hydraulic head along the borehole.

Single point resistance measurements were also combined with caliper (borehole diameter) measurements for detection of depth marks milled into the borehole wall at accurately determined positions along the borehole. This procedure was applied for length calibration of all measurements.

3 Principles of measurement and interpretation

3.1 Measurements

Unlike traditional types of borehole flowmeters, the Difference flowmeter method 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 along the borehole outside the isolated test section is conducted through the test section by means of a bypass pipe and is discharged at the upper end of the downhole tool.

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. This mode is mostly used to determine the location of hydraulically conductive fractures and to classify them with regard to 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 transfer of thermal pulse with moving water. In the sequential mode, both methods are used, whereas in the overlapping mode, only the thermal dilution method is applied because it operates faster than the thermal pulse method.

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 placed on 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 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 placed within the flow sensor, Figure 3-1.

All of the above measurements were performed in KFM08A.

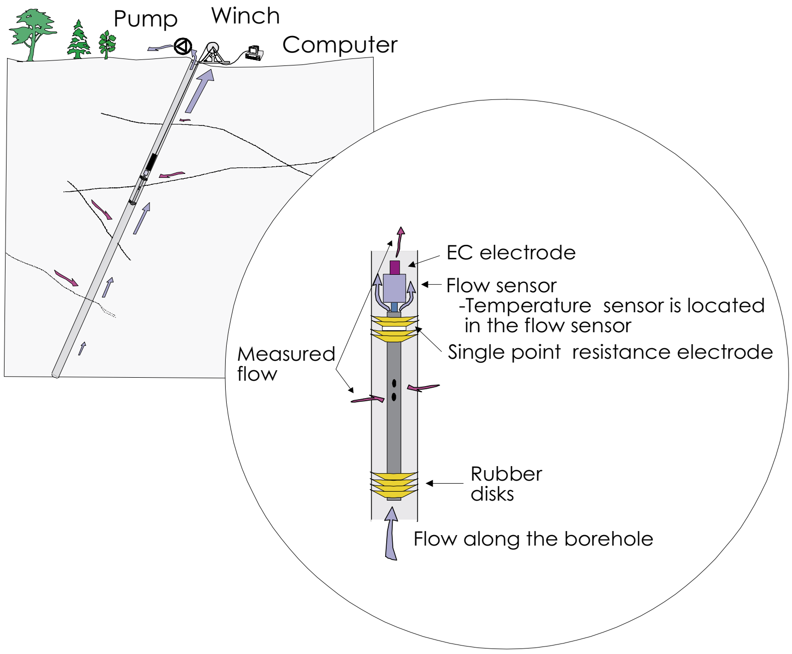

Figure 3-1. *Schematic of the downhole equipment used in the Difference flowmeter.*

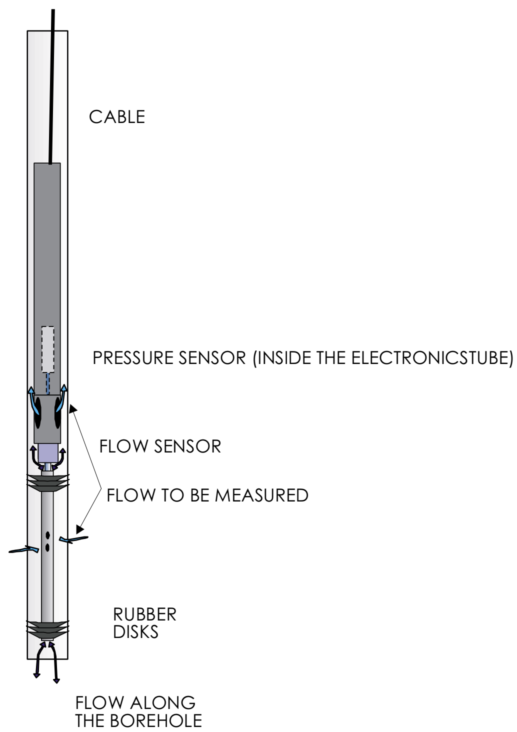

Figure 3-2. *The absolute pressure sensor is located inside the electronics tube and connected through a tube to the borehole water.*

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 for the thermal pulse method and for registration of temperature changes in the thermal dilution method, Figures 3-3b and c. The side thermistors, B1 and B2, serve to detect the moving thermal pulse, Figure 3-3d, caused by the constant power heating in A, Figure 3-3b.

Flow rate is measured during the constant power heating (Figure 3-3b). If the flow rate exceeds 600 mL/h, the constant power heating is increased, Figure 3-4a, and the thermal dilution method is applied.

If the flow rate during the constant power heating (Figure 3-3b) falls below 600 mL/h, the measurement continues with monitoring of transient thermal dilution and thermal pulse response (Figure 3-3d). When applying the thermal pulse method, also thermal dilution is always measured. The same heat pulse is used for both methods.

Flow is measured when the tool is at rest. After transfer to a new position, there is a waiting time (the duration can be adjusted according to the prevailing circumstances) before the heat pulse (Figure 3-3b) is launched. The waiting time after the constant power thermal pulse can also be adjusted, but is normally 10 s long for thermal dilution and 300 s long for thermal pulse. The measuring range of each method is given in Table 3-1.

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 be valid. Examples of disturbing conditions are floating drilling debris in the borehole water, gas bubbles in the water and high flow rates (above about 30 L/min) along the borehole. If disturbing conditions are significant, a practical measurement limit is calculated for each set of data.

Table 3-1. Ranges of flow measurements.

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

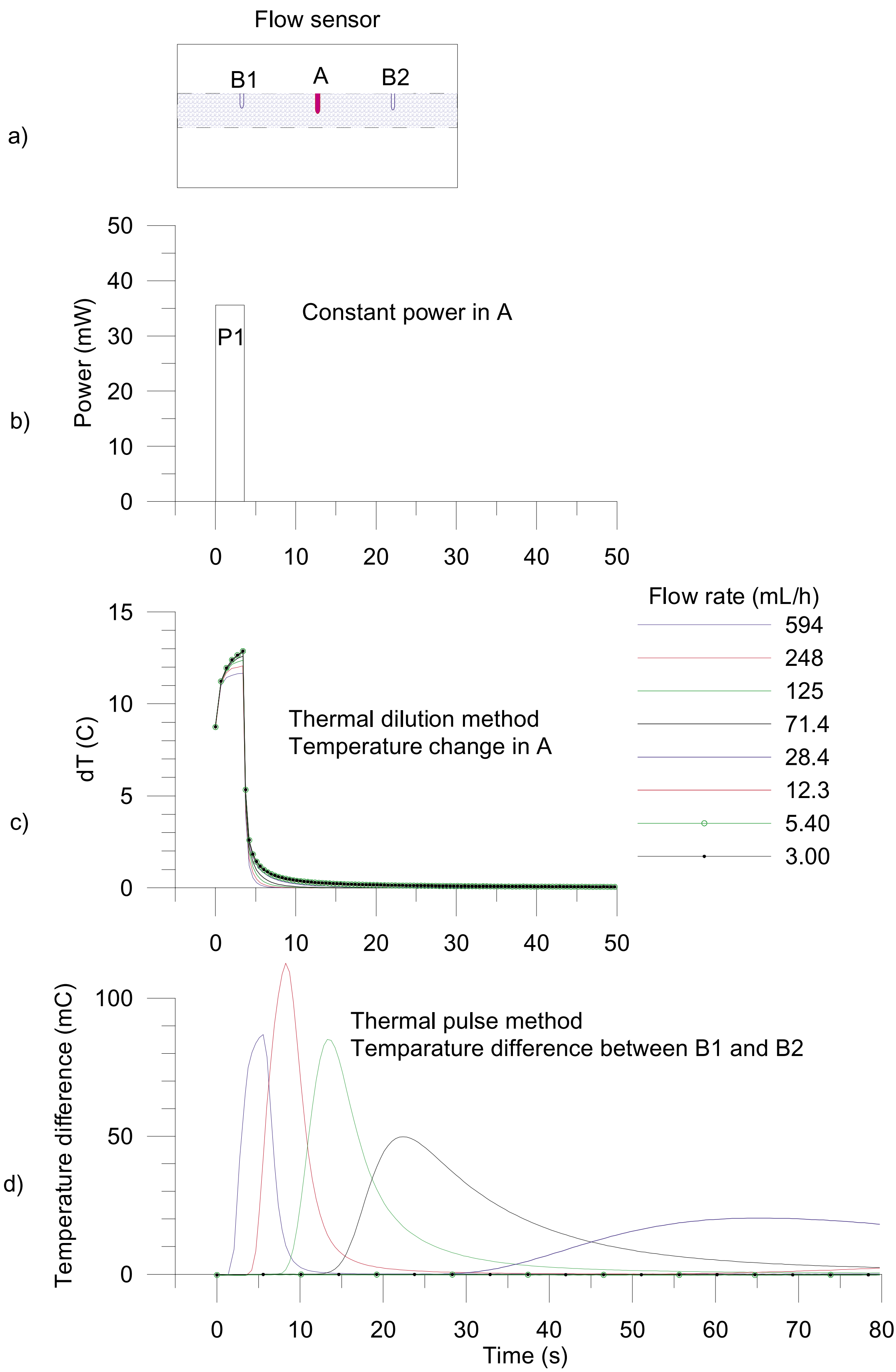

Figure 3-3. *Flow measurement, flow rate < 600 mL/h.*

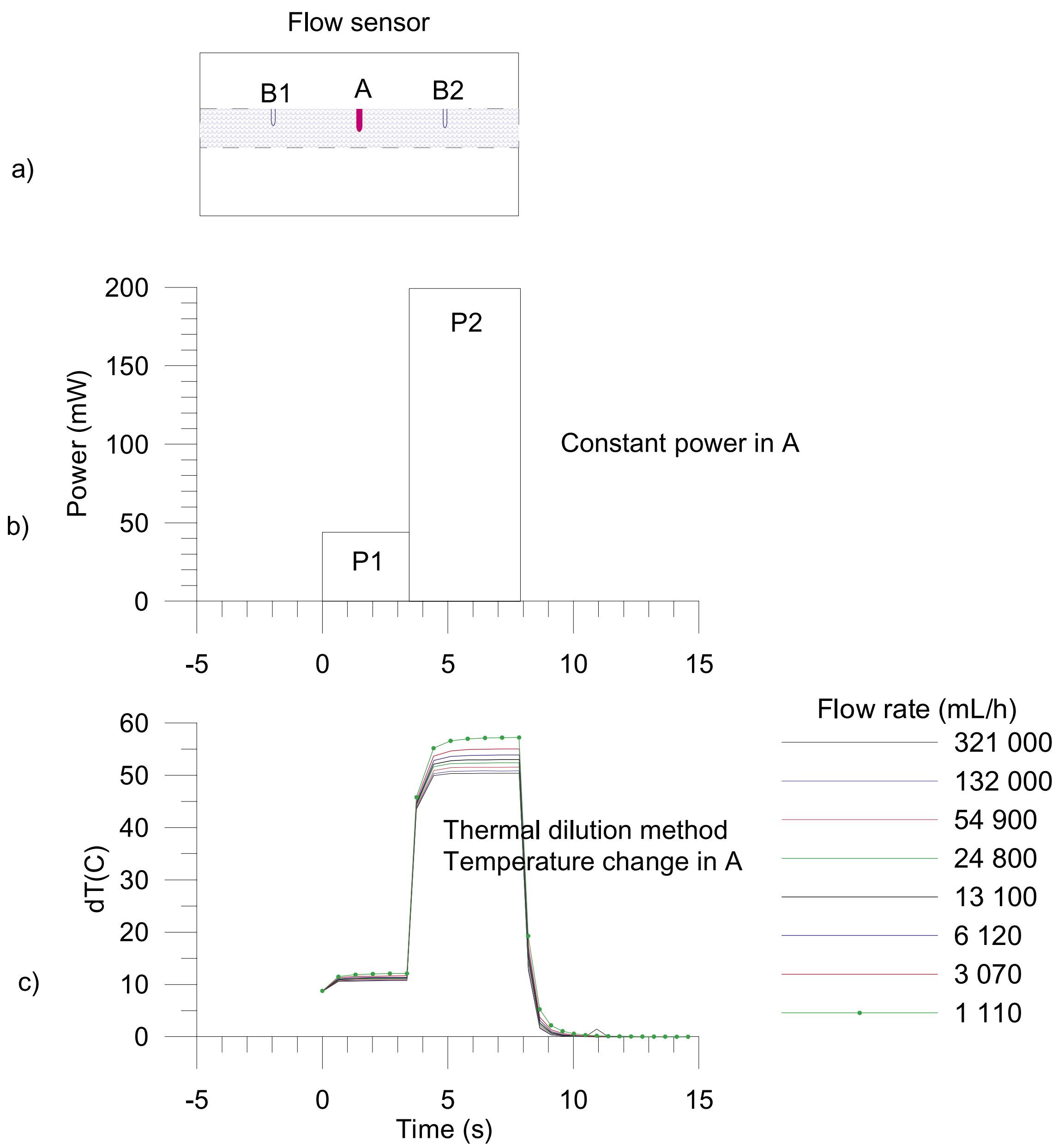

Figure 3-4. *Flow measurement, flow rate > 600 mL/h.*

3.2 Interpretation

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

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

where

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

Q is the flow rate into the borehole,

T is the transmissivity of the test section,

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

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

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 heads 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:

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

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

where

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

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, cylindrical flow without 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:

$$h_s = (h_0 - b \cdot h_1)/(1 - b) \qquad 3\text{-}5$$

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

where

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

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).

$h_f = (h_0 – b \cdot h_1)/(1 – b)$ 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 the transmissivity of a fracture, respectively.

Since the actual flow geometry and the skin effects are unknown, transmissivity values should be taken as indicating 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 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 (rubber disks). 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. Flow is measured using the thermal pulse and/or thermal dilution methods. Measured values are transferred in digital form to the PC computer.

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:	June 2005.
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% fullscale
Absolute pressure sensor	0 – 20 MPa	+/– 0.01% fullscale

5 Performance

5.1 Execution of the field work

The Commission was performed according to Activity Plan AP PF 400-05-007 following the SKB Method Description 322.010, Version 1.0 (Method description for difference flow logging). The Activity Plan and the Method Description are both SKB internal controlling documents. Prior to the measurements, the downhole tools and the measurement cable were disinfected. Time was synchronized with 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 e.g. a logging cable. Immediately after completion of the drilling operations in borehole KFM08A, 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 includes two 20 mm wide tracks in the borehole wall. The distance between the marks is 100 mm. The upper track represents the reference level. An inevitable condition for a successful length calibration is that all length marks, or at least the major part of them, are detectable. The Difference flow meter system uses caliper measurements in combination with single point resistance measurement (SPR) for this purpose, and these measurements were the first to be performed in borehole KFM08A (Item 6 in Table 5-1). These methods also reveal parts of the borehole widened for other reason (fracture zones, breakouts etc).

During the caliper/SPR-measurement the tool got stuck several times at c 920 m. To avoid damages, it was decided not to perform any measurements below this level.

The caliper/SPR-measurements were preceded by measurements of electric conductivity (EC) of the borehole water (Item 7) during natural (un-pumped) conditions.

The combined overlapping/sequential flow logging (Item 8) was carried out in the borehole interval 94.60–919.84 m. The section length was 5 m and the length increment (step length) 0.5 m. The measurements were performed during natural (un-pumped) conditions.

Pumping was started on May 15th, 2005. After c 24 hours waiting time, the overlapping flow logging (Item 9) was measured in the interval 94.60–919.84 m using the same section and step lengths as before.

The overlapping flow logging was then continued in the way that previously measured flow anomalies were re-measured with 1 m section length and 0.1 m step length (Item 10). Fracture specific EC on water from some selected fractures (Item 11) was measured together with Item 10.

Still during pumped conditions, the EC of borehole water (Item 12) was measured. After this, the pump was stopped and the recovery of the groundwater level was monitored (Item 13). SKB continued with groundwater level monitoring between May 21–30.

Table 5-1. Flow logging and testing in KFM08A. Activity schedule.

Item	Activity	Explanation	Date
6	Length calibration of the downhole tool	Dummy logging (SKB Caliper and SPR). Logging without the lower rubber disks, no pumping.	2005-05-12 2005-05-13
7	EC- and temp-logging of the borehole fluid	Logging without the lower rubber disks, no pumping.	2005-05-13
8	Combined overlapping/ sequential flow logging	Section length L_w=5 m. Step length dL=0.5 m. No pumping.	2005-05-13 2005-05-15
9	Overlapping flow logging	Section length L_w=5 m. Step length dL=0.5 m at pumping (includes 1 day waiting after beginning of pumping).	2005-05-15 2005-05-18
10	Overlapping flow logging	Section length L_w=1 m. Step length dL=0.1 m, at pumping.	2005-05-18 2005-05-20
11	Fracture-specific EC-measurements in pre-selected fractures	Section length L_w=1 m, at pumping (in pre-selected fractures). These measurements were performed together with Item 10.	2005-05-18 2005-05-20
12	EC- and temp- logging of the borehole fluid	Logging without the lower rubber disks, at pumping.	2005-05-20
13	Recovery transient	Measurement of water level and absolute pressure in the borehole after stop of pumping. The measurement continued between 21/5–30/5, 2005 by SKB.	2005-05-20 2005-05-21

5.2 Nonconformities

During the caliper/SPR-measurement the tool got stuck several times at about 920 m borehole length. To avoid damages, no measurements were performed below this length, except caliper/SPR-measurement, which was performed down to 992 m. The borehole is about 1,000 m long.

The reference length mark at 299.8 m was originally pointed out to be at 300 m. However, a more detailed study of length errors indicated that the real position is at 299.8 m. This was later confirmed by the borehole-TV and the drill core sample results.

6 Results

6.1 Length calibration

6.1.1 Caliper and SPR measurement

An accurate length scale of measurements is difficult to achieve in long boreholes. The main cause of inaccuracy is stretching of the logging cable. The stretching depends on the tension of the cable, the magnitude of which in turn depends, among other things, on the inclination of the borehole and on the friction against the borehole wall. The cable tension is larger when the borehole is measured upwards. The cables, especially new cables, may also stretch out permanently. In KFM08A the stretching of the cable was relatively high, since the measurements were performed from the bottom of the borehole in the upward direction.

Length marks on the borehole wall can be used to minimise the length errors. The length marks are detected with the SKB caliper tool. The length scale is firstly 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 measurements) with the original caliper/SPR-measurement.

The procedure of length correction was the following:

- The caliper/SPR-measurements (Item 6) were initially length corrected in relation to the known length marks, Appendix 1.40, black curve. Corrections between the length marks were obtained by linear interpolation.
- The SPR curve of Item 6 was then compared with the SPR curves of Items 8, 9 and 10/11 to obtain relative length errors of these measurement sequences.
- All SPR curves could then be synchronized, as can be seen in Appendices 1.2–1.39.

The results of the caliper and single point resistance measurements from all measurements in the entire borehole are presented in Appendix 1.1. Four SPR-curves are plotted together with caliper-data. These measurements correspond to Items 6, 8, 9 and 10/11 in Table 5-1.

Zoomed results of caliper and SPR are presented in Appendices 1.2–1.39. Detection of length marks is listed in Table 6-1. Every mark was detected at least partly with the caliper tool in the measured interval. They can also be seen in the SPR results. However, 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. A selection of length intervals, where clear SPR-anomalies were found, are plotted as well.

The length mark of 299.8 m was originally pointed to be at 300 m. In a more detailed study in cooperation with SKB the length mark was given a new position at 299.8 m.

Table 6-1. Detected length marks.

Length marks given by SKB (m)	Length marks detected by caliper	Length marks detected by SPR
151	both	yes
200	both	yes
250	only upper	yes
299.8	both	yes
350	both	yes
400	both	yes
450	both	yes
500	both	yes
552	both	yes
600	both	yes
650	both	yes
700	both	yes
750	both	yes
800	both	yes
850	only upper	yes
900	only lower	yes
950	only lower	yes
981	both	yes

The aim of the plots in Appendices 1.2–1.39 is to verify the accuracy of the length correction. The curves in these plots represent length corrected results. The same length corrections were applied to the flow- and EC measurements.

The magnitude of length correction along the borehole is presented in Appendix 1.40. The error is negative, due to the fact that the stretching extends the logging cable (i.e. the cable is longer than the nominal length marked on the cable).

6.1.2 Estimated error in location of detected fractures

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

1. The point interval in flow measurements is 0.1 m in overlapping mode. 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, however, be larger. At the upper end of the test section there are four rubber disks. The distance between these is 5 cm. This will cause rounded flow anomalies. Flow may be detected already when a fracture is situated between the upper rubber disks. These phenomena, which can only be seen with a short step length (0.1 m), could cause an error of +/– 0.05 m.
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 6).
4. SPR curves may be imperfectly synchronized. This could cause an error of +/– 0.1 m

In the worst case, the errors of points 1, 2, 3 and 4 are summed up. Then the total estimated error between the length marks would be +/– 0.3 m.

Near the length marks the situation is slightly better. In the worst case, the errors of points 1, 2 and 4 are summed up. Then the total estimated error near the length marks would be +/– 0.2 m.

Accurate location 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 for the worst case above, since part of the length errors are systematic and the length error is nearly constant for fractures near each other. However, the error of point 1 is of random type.

Fractures nearly parallel with the borehole may also be problematic. Fracture location may be difficult to accurately define 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 (EC) was initially measured when the borehole was at rest, i.e. at natural, un-pumped conditions. The measurement was performed in the downward direction, see Appendix 2.1, blue curve.

The EC measurement was repeated during pumping (after a pumping period of about five days), see Appendix 2.1, green curve. The results show a clear change to less saline water above the lengths of about 190 m and 270 m. These locations coincide with high transmissivities, see Appendices 7 and 8.

Temperature of 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 2.2 correspond to the EC results in Appendix 2.1.

The length calibration of the borehole EC measurements is not as accurate as for the other measurements, because SPR is not registered during the borehole EC measurements. The length correction of the SPR/caliper-measurement was applied to the borehole EC measurements, black curve in Appendix 1.40.

6.2.2 EC 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 electric conductivity from fracture-specific water. Both electric conductivity and temperature of flowing water from the fractures were measured.

The flow measurement makes it possible to find the fractures for the EC measurement. The tool is moved so that the fracture to be tested will be located within the test section (L = 1 m). The EC measurements begin if the flow rate is larger than a predetermined limit. The tool is kept on the selected fracture. The measurement is continued at the given length 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 well enough. The measuring computer is programmed to change the water volume within the test section about three times. The water volume in a one metre long test section was 3.6 L. In this case the waiting times were selected to be much longer than the calculated times.

Electric conductivity of fracture-specific water is presented on time scale, see Appendix 11. The blue symbol represents the value when the tool was moved (one metre point interval) and the red symbol means that the tool was stopped on a fracture for a fracture specific EC measurement.

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

Table 6-2. Fracture-specific EC.

Upper end of section (m)	Lower end of section (m)	Fractures measured (m)	EC (S/m) at 25°C
686.50	687.50	687.0	1.34
480.29	481.29	480.5	1.09
274.58	275.58	275.0, 275.2	0.86
189.85	190.85	190.5	0.62
189.15	190.15	189.8	0.62

6.3 Pressure measurements

The absolute pressure was registered together with the other measurements in Items 8–11 and 13 in Table 5-1. 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. Hydraulic head along the borehole at natural and pumped conditions respectively is determined in the following way. Firstly, 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 (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, 9.80065 m/s^2 and

z is the elevation of measurement (masl) according to the RHB 70 reference system.

An offset of 2.46 kPa is subtracted from absolute pressure results.The calculated head distributions are presented in Appendix 10.1. Exact z-coordinates are important in head calculation. 10 cm error in z-coordinate means 10 cm error in head.

6.4 Flow logging

6.4.1 General comments on results

The measuring program contains 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 3.1–3.41. Single point resistance usually shows a low resistance value on a fracture where flow is detected. There are also many other resistance anomalies from 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 the leaky fractures fit with the lower end of the flow anomalies.

The Caliper tool shows a low voltage when the borehole diameter is below 78 mm and a high voltage when the borehole diameter exceeds 78 mm.

The flow logging was firstly performed with a 5 m section length and with 0.5 m length increments, see Appendices 3.1–3.41 (red curve with pumping, dark blue curve without pumping). 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 initially for flow determination.

Under natural conditions flow direction may be into the borehole or out from it. For small flow rates (< 100 mL/h) flow direction cannot be seen in the normal overlapping mode (thermal dilution method). Therefore waiting time was longer for the thermal pulse method to determine flow direction at every 5 m. The thermal pulse method was used only for measuring flow direction, not for flow rate which would take even longer time. Longer flow direction measurements are necessary during un-pumped conditions.

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 be overlapped, resulting in a stepwise flow anomaly. 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.

Detected fractures are shown on the caliper scale with their positions (borehole length). 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. A short line is used if the flow rate is less than 30 mL/h or if the flow anomalies are overlapping, or they are unclear because of noise.

6.4.2 Transmissivity and hydraulic head of borehole sections

The borehole between 94.60 m and 915.83 m was flow logged with a 5 m section length and with 0.5 m length increments, both under unpumped and pumped conditions. All flow logging results presented in this report are derived from measurements with the thermal dilution method.

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 3.1–3.41. Secup presented in Appendix 5 is calculated as the distance along the borehole from the reference level (top of the casing tube) to the upper end of the test section. Seclow is calculated respectively to the lower end of the test section. Secup and seclow values for the two sequences (measurements at un-pumped and pumped conditions) are not exactly identical, due to a minor difference of the cable stretching. The difference between these two sequences was however small. Secup and seclow given in Appendix 5 are calculated as an average of these two values.

Pressure was measured and calculated as described in Section 6.3. dh_0 and dh_1 in Appendix 5 represent heads determined without respectively with pumping. 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 flow rates derived from measurements during un-pumped respectively 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, 10 sections were detected as flow yielding, of which 6 had a flow direction from the borehole into the bedrock (negative flow). During pumping, all 25 detected flows were directed towards the borehole.

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.

In the plots (Appendix 6.1) and in the tables (Appendix 5), also the lower and upper measurement limits of flow are presented. There are both theoretical and practical lower limits of flow, see Section 6.4.4.

Hydraulic head and transmissivity (T_D) of borehole sections can be calculated from flow data using the method described in Chapter 3. 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, see Appendix 6.2. 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 (dh_0 and dh_1 in Appendix 5).

The sum of detected flows without pumping (Q_0) was $3.39 \cdot 10^{-7}$ m^3/s (1,220 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. In this case the sum is close to zero, although the borehole was not measured below c 920 m.

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 for 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 to 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 3.5. Increase or decrease of a flow anomaly at the fracture location (marked with the lines in Appendix 3) is used for determination of flow rate.

Since sections with 1 m length were not used at un-pumped conditions, the results for a 5 m section length were applied instead. The fracture locations are important when evaluating flow rate at un-pumped conditions. The fracture locations are known on the basis of the measurements for a 1 m section length. It is not a problem to evaluate the flow rate at un-pumped conditions when the distance between flowing fractures is larger than 5 m.

The evaluation may though 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, and is applied only in the clearest cases. No flow value is usually evaluated at un-pumped conditions at densely fractured parts of the bedrock. If the flow for a specific fracture can not be determined conclusively, the flow rate is marked with "–" whereas the value 0 is used in transmissivity calculation, see Appendix 8. 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 is 41, but only 4 could be defined without pumping. These 4 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 rated to be "uncertain" results, see Appendix 7. The criterion of "uncertain" was in most cases a minor flow rate (< 30 mL/h). In some cases fracture anomalies were unclear, since the distance between fractures was less than one metre or since the form of anomaly was 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 up to make them comparable with measurements with a 5 m section length. The results are, in most cases, consistent between the two types of measurements. A decrease of flow during the period of pumping in some low flowing fractures can though be seen.

6.4.4 Theoretical and practical measurements limits of flow and transmissivity

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

The minimum measurable flow rate might however, be much higher in practice. The borehole conditions may have an influence on the base level of flow (noise level). The noise level can be evaluated for intervals of the borehole without flowing fractures or other structures. The noise level may vary along the borehole.

There are several known reasons for increased noise in flow:

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, not only in flow but also in single point resistance results. The flow curve and 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 both without pumping and with pumping.

Pumping causes a pressure drop in the borehole water and in fracture water near the borehole. This may lead to release of gas from dissolved form to gas bubbles. Some fractures may produce more gas than others. Sometimes an increased noise level is obtained just above certain fractures (when the borehole is measured upwards). The reason is assumed to be gas bubbles. Bubbles may cause decrease of the average density of water and therefore also a decrease of 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 in flow.

A high noise level in flow masks a "real" flow that is smaller than the noise. Real flows are totally invisible if they are about ten times smaller than the noise. Real flows are registered correctly if they are about ten times larger than the noise. By experience, real flows between 1/10 times noise and 10 times noise are summed up 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 not clear whether it is applicable in each case.

The noise level was not a problem in borehole KFM08A. The practical minimum level of flow rate is evaluated and presented in Appendices 3.1–3.41 using a grey dashed line (Lower limit of flow rate). Below this line there may be fractures or structures that remain undetected.

The noise level in KFM08A was between 5–30 mL/h. In many places it fell below 30 mL/h, i.e. below the theoretical limit of the thermal dilution method. However, the noise line (grey dashed line) was never drawn below 30 mL/h.

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. In KFM08A there was no need for this kind of extra measurements.

The practical minimum of measurable flow rate is also 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, 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 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, 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 nearer each other than one metre, the upper flow limit depends on the sum of flows which must fall 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 May 15 and 20 with a drawdown of about 10 m. Pumping rate was recorded, see Appendix 10.2.

The groundwater recovery was measured after the pumping period, on May 20–21, Appendix 10.3. The recovery was measured with two sensors, using the water level sensor (pressure sensor for monitoring water level) and the absolute pressure sensor located at the borehole length of 910.16 m. Water level monitoring continued by SKB between May 21–30, see Appendix 10.2.

6.6 Evaluation of pumping test

6.6.1 General

The total transmissivity of the entire cored borehole interval (c 100–1,000 m) of KFM08A was estimated from the recovery period after the pumping activity in conjunction with the difference flow logging campaign in the borehole. During the first part (c 1 day) of the recovery period the pressure was registered by both the high-resolution absolute pressure sensor at the bottom of the borehole (measuring the head at borehole length 910.16 m) and by the water level sensor located in the upper part of the borehole (at 14.85 m), cf Appendix 10.3. During the remainder of the recovery period, the pressure was measured by another water level sensor handled by SKB, cf Appendix 10.2. The borehole transmissivity was estimated from the entire pressure recovery period using complementary data from the two water level sensors. No measurements were made by the absolute pressure sensor during the later part of the recovery period.

In addition, the borehole transmissivity was estimated from the very first part (c 1.5 h) of the flow period before a constant drawdown of the water level of c 10 m was reached prior to the difference flow logging, cf Appendix 10.2. By the latter evaluation, data from both the absolute- and water level sensor were used. During this period the pumping rate was constant at c 15 L/min but was then decreasing to c 3 L/min by the end of the flow period, cf Appendix 10.2.

The main purposes of the analysis of the pumping test during the difference flow logging were to estimate the total transmissivity of the cored borehole interval and to deduce information on possible hydraulic outer hydraulic boundaries during the test. Furthermore, the results of the pumping test should be compared with the results of the difference flow logging in the borehole regarding estimated transmissivities of the measured 5 m sections and flow anomalies identified.

The registration of the water level, flow rate and pressure recovery was performed according to the Activity Plan AP PF 400-05-007 (SKB internal controlling document) and the methodology description for difference flow logging (SKB MD 322.010, Version 1.0). The evaluation of the pumping test was made in accordance with the Method Instruction SKB MD 320.004, Version 1.0 (Instruktion för analys av injektions- och enhålspumptester).

By the calculation of the pressure drawdown and -recovery from the absolute pressure sensor at depth, the atmospheric pressure was subtracted from the measured pressure. The variations of the atmospheric pressure during the test period are shown in Appendix 10.2. However, no such corrections are needed on the measured (gauge) pressure data from the superficial water level transducer. By the calculation of the pressure derivatives during the flow- and recovery periods, different values were applied on the filter coefficient (step length) to study its effect on the derivative. It is desired to achieve maximum smoothing of the derivative without altering the original shape of the data curve, i.e. the lowest possible step length.

Firstly, a qualitative evaluation was performed to identify the actual flow regimes during the flow- and recovery period (e.g. wellbore storage, pseudo-radial flow etc) and possible outer hydraulic boundary conditions. The qualitative analysis was made from the pressure responses together with the corresponding pressure derivatives versus time in log-log diagrams, mainly from the recovery period. The pressure recovery was plotted versus real time after stop of pumping (not Agarwal equivalent time), since both pressure and flow rate were rather stable at the end of the flow period, cf Appendix 10.2.

The quantitative, transient interpretation of hydraulic parameters from the pumping borehole (e.g. transmissivity and skin factor) was based on the identified flow regimes during the test using the code AQTESOLV. In addition, steady-state analysis (Moye's formula) was made from the last part of the flow period.

6.6.2 Results

The nomenclature and symbols used for the results of the pumping test are according to SKB MD 320.004. Additional symbols used are explained in the text. The nomenclature applied in the diagrams prepared by the code AQTESOLV is shown in Appendix 12. Since no data from observation boreholes were available, the storativity was assumed at $S^*=5\cdot10^{-5}$ by the calculation of the skin factor. The assumed storativity value was obtained from previous interference tests at Forsmark /Ludvigson and Jönsson, 2003/. A summary of the results from the pumping test in KFM08A is presented in Table 6-3. Selected test diagrams according to the Instruction for analysis of single-hole injection- and pumping tests together with simulated test responses are presented in Appendix 12.

Interpreted flow regimes

The pressure drawdown (measured by the water level sensor) during the first phase (c 1.5 h) of the flow period is shown in log-log and lin-log diagrams in Figures A12-1 and A12-2, respectively in Appendix 12. Wellbore storage effects (WBS) occurred during the first c 100 s of the flow period, cf Figure A12-1. After c 3,000 s, effects of an apparent no-flow boundary (NFB) are indicated. No pseudo-radial flow regime (PRF) was developed during the flow period. The recorded drawdown behaviour from the absolute pressure- and water level sensors respectively was very similar during this period.

Figures A12-3 to A12-8 in Appendix 12 show log-log- and lin-log graphs, respectively, of the pressure recovery versus time after stop of pumping using complementary data from the water level sensors handled by PRG-Tec and SKB. The latter data record begins at c 70,700 s (19.6 h). As for the flow period, Figure A12-3 shows wellbore storage effects during the first c 100 s of the pressure recovery in the (open) pumping borehole. After c 3,000 s, effects of an apparent NFB is indicated by the increase of the pressure derivative, similar to the response during the flow period. No well-defined pseudo-radial flow regime (PRF) was developed during the recovery period. A short period with apparent PRF is indicated at c 10,000 s.

At intermediate times, a characteristic straight line with a slope of 1:2 is developed during the recovery period, cf Figure A12-5. The observed response is similar to flow in a dominating high-transmissive, single horizontal fracture with a certain extent around the borehole, i. e. pseudo-linear flow (PLF), cf the simulated curves in Figures A12-5 and A12-6.

Interpreted parameters

Firstly, approximate transient analysis was made of the very first part of the flow- and recovery periods, before any effects of NFB were observed, cf Figures A12-1 and A12-2 respectively A12-3 and A12-4. Secondly, transient analysis based on a model of an equivalent high-transmissive single, horizontal fracture intersecting a porous medium /Gringarten and Ramey, 1974/ was performed in Figures A12-5 and A12-6. With this model, almost the entire recovery curve can be simulated, including the last part. This model does not account for wellbore storage at the beginning. For comparison, an approximate analysis was also made on the short segment with an apparent PRF regime at c 10,000 s of the recovery period, cf Figures A12-7 and A12-8. However, this analysis is considered uncertain due to the short period of apparent PRF.

From the single fracture model, the hydraulic conductivity of the rock in the radial direction (K_r) together with the radius of the apparent fracture around the borehole (R_f) can be estimated. For comparison, K_r was converted to equivalent transmissivity, T_T, of the rock by multiplying K_r by the open borehole interval (c 900 m). This transmissivity value, which is assumed to represent the hydraulic properties of the rock parallel to the assumed fracture can be compared with the calculated cumulative transmissivity of the 5 m sections and of the fractures identified along the borehole from the flow logging.

The results of the pumping test during difference flow logging in KFM08A are presented in Table 6-3. The results from the flow- and recovery period are consistent. The interpreted hydraulic parameters from the recovery period by the fracture model are considered as the most representative ones for the cored borehole interval on a semi-large scale. The high, negative value on the skin factor indicates that a fracture with large extent is intersecting the borehole. By the transient evaluation, the wellbore storage coefficient C was based on the actual casing diameter in the upper part of the borehole (inner casing diameter=0.200 m).

The calculated borehole transmissivity from the fracture model is consistent with the cumulative transmissivity of the measured 5 m sections ($T=8.0 \cdot 10^{-6}$ m^2/s) and of the fractures identified ($T=6.9 \cdot 10^{-6}$ m^2/s) from the difference flow logging, cf Appendix 5 and 7, respectively. According to the flow logging, the highest transmissivity fracture ($T=2.2 \cdot 10^{-6}$ m^2/s) in KFM08A is located at borehole length 189.8 m.

Table 6-3. Summary of calculated hydraulic parameters from the pumping test in conjunction with difference flow logging in borehole KFM08A.

Test period	Q/s (m^2/s)	T_M (m^2/s)	T_T (m^2/s)	S* (–)	ζ (–)	R_f (m)	C (m^3/Pa)*
Flow period	$5.0 \cdot 10^{-6}$	$8.26 \cdot 10^{-6}$					
early period			$1.98 \cdot 10^{-6}$	$5 \cdot 10^{-5}$	–6.24		$3.2 \cdot 10^{-6}$
Recovery period							
– early period			$3.33 \cdot 10^{-6}$	$5 \cdot 10^{-5}$	–6.67		$3.2 \cdot 10^{-6}$
– intermediate-late			$4.79 \cdot 10^{-6}$	$5 \cdot 10^{-5}$		244	$3.2 \cdot 10^{-6}$
– short PRF period			$1.26 \cdot 10^{-6}$	$5 \cdot 10^{-5}$	–7.04		$3.2 \cdot 10^{-6}$

* fixed value.
Q/s = specific flow.
T_M = steady-state transmissivity from Moye´s formula.
T_T = calculated transmissivity from transient evaluation of the test.
S* = assumed value on the storativity.
ζ = skin factor.
R_f = radius of equivalent single horizontal fracture.
C = wellbore storage coefficient.

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 KFM08A at Forsmark. 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 firstly. The measurements were repeated using 1 m section length with 0.1 m length increments over the flow anomalies. The tool got stuck in the borehole at c 920 m several times during the caliper/SPR-measurement. To avoid damage the measurements were not carried below this level.

Length calibration was made using the length marks on 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 was measured in selected flowing fractures.

The total amount of detected flowing fractures was 41. Transmissivity and hydraulic head were calculated for borehole sections and fractures above 920 m. The highest transmissivity ($2.20 \cdot 10^{-6}$ m^2/s) was detected in a fracture at the borehole length of 189.8 m. High-transmissive fractures were also found at 190.5 m, 275.2 m and 687.0 m. Below 687.0 m no flowing fractures were identified.

The total transmissivity of the cored borehole KFM08A was estimated at $4.8 \cdot 10^{-6}$ m^2/s from the groundwater recovery after the pumping test during difference flow logging. This value is in good agreement with the cumulative transmissivities of the measured 5 m sections ($T_s=8.0 \cdot 10^{-6}$ m^2/s) and of the flow anomalies identified ($T_s=6.9 \cdot 10^{-6}$ m^2/s). A pseudo-linear flow regime was developed during the recovery period, which may indicate that the borehole is intersected by a major sub-horizontal fracture with large lateral extent.

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Appendices

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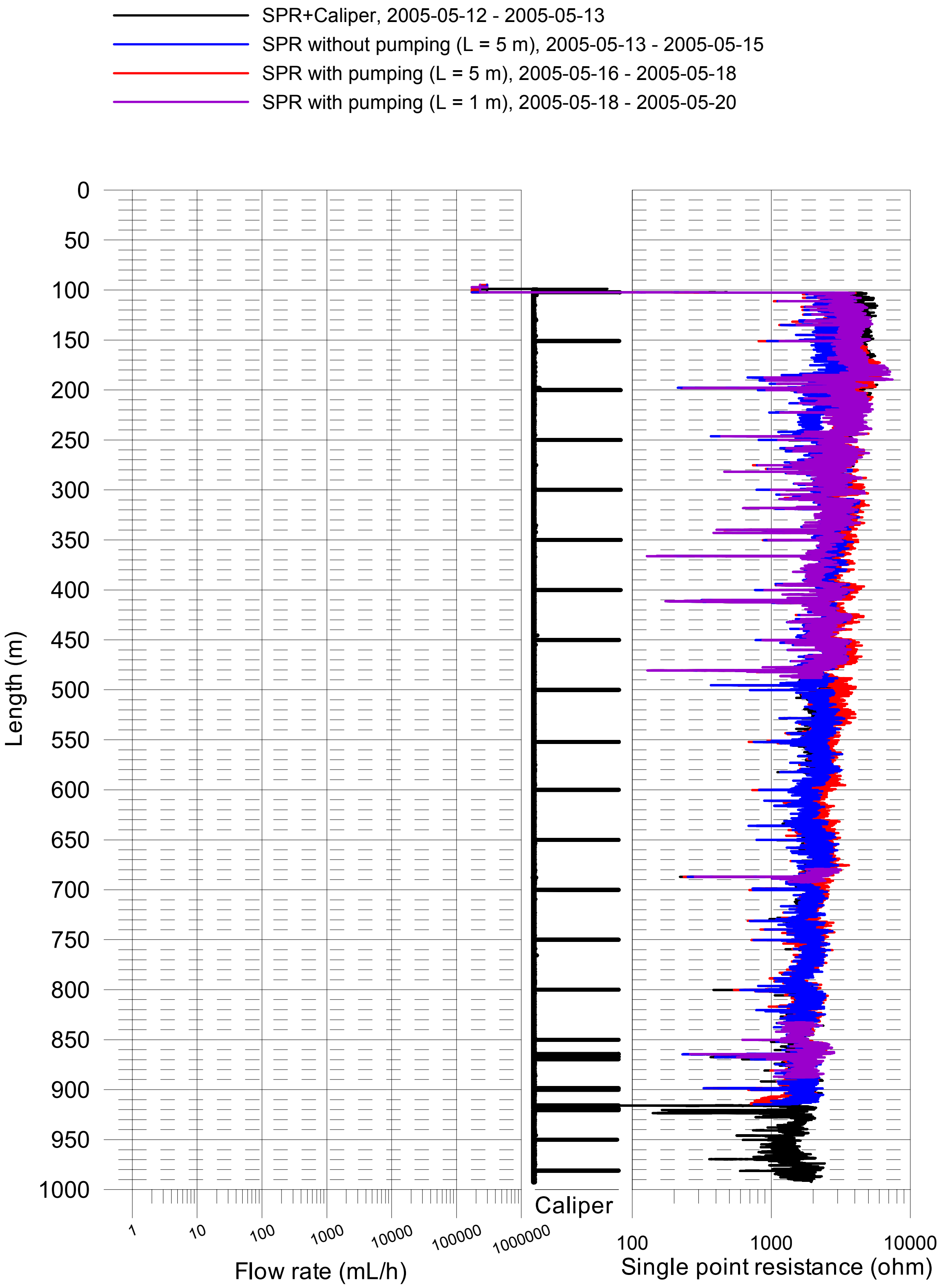
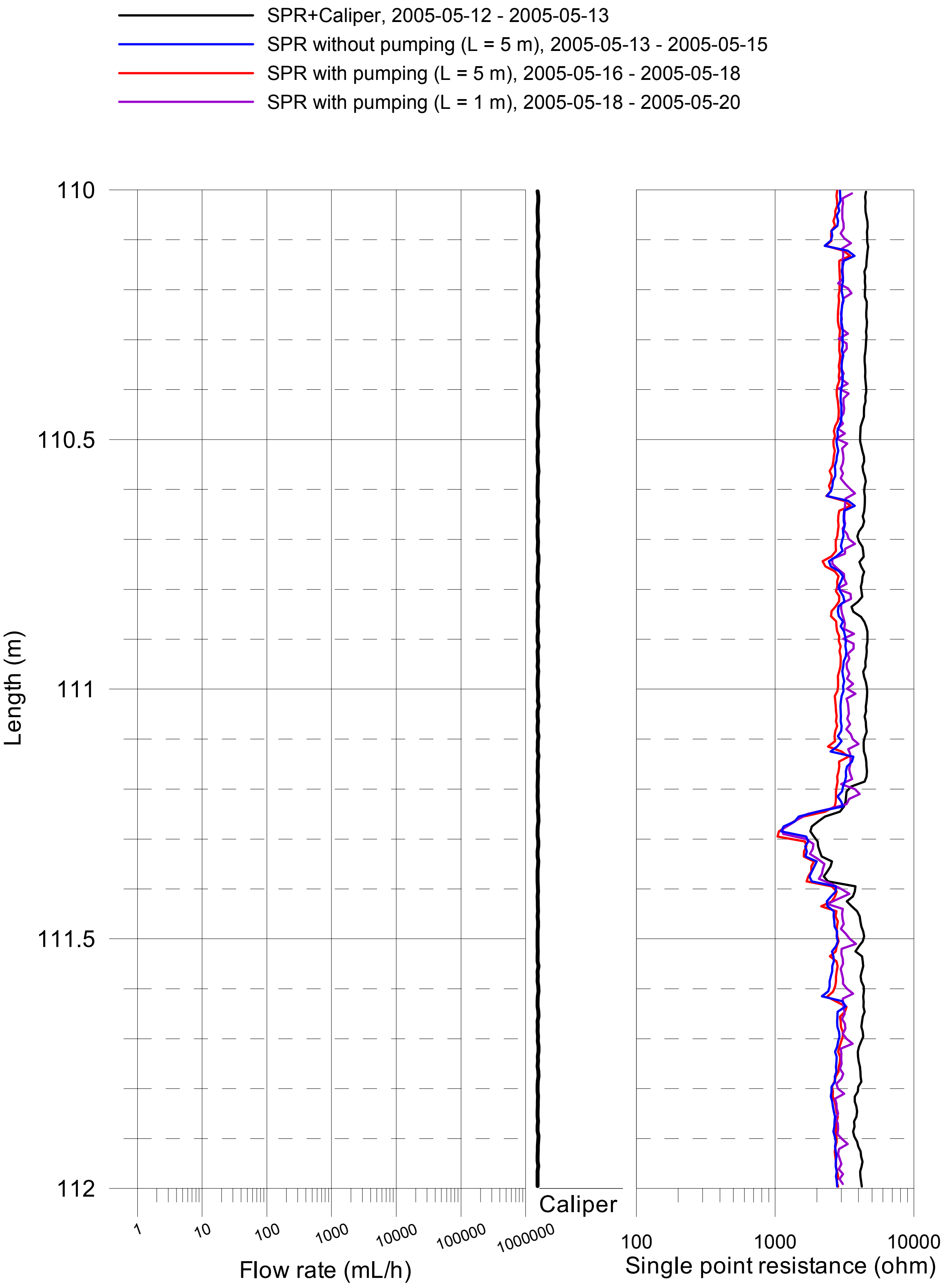
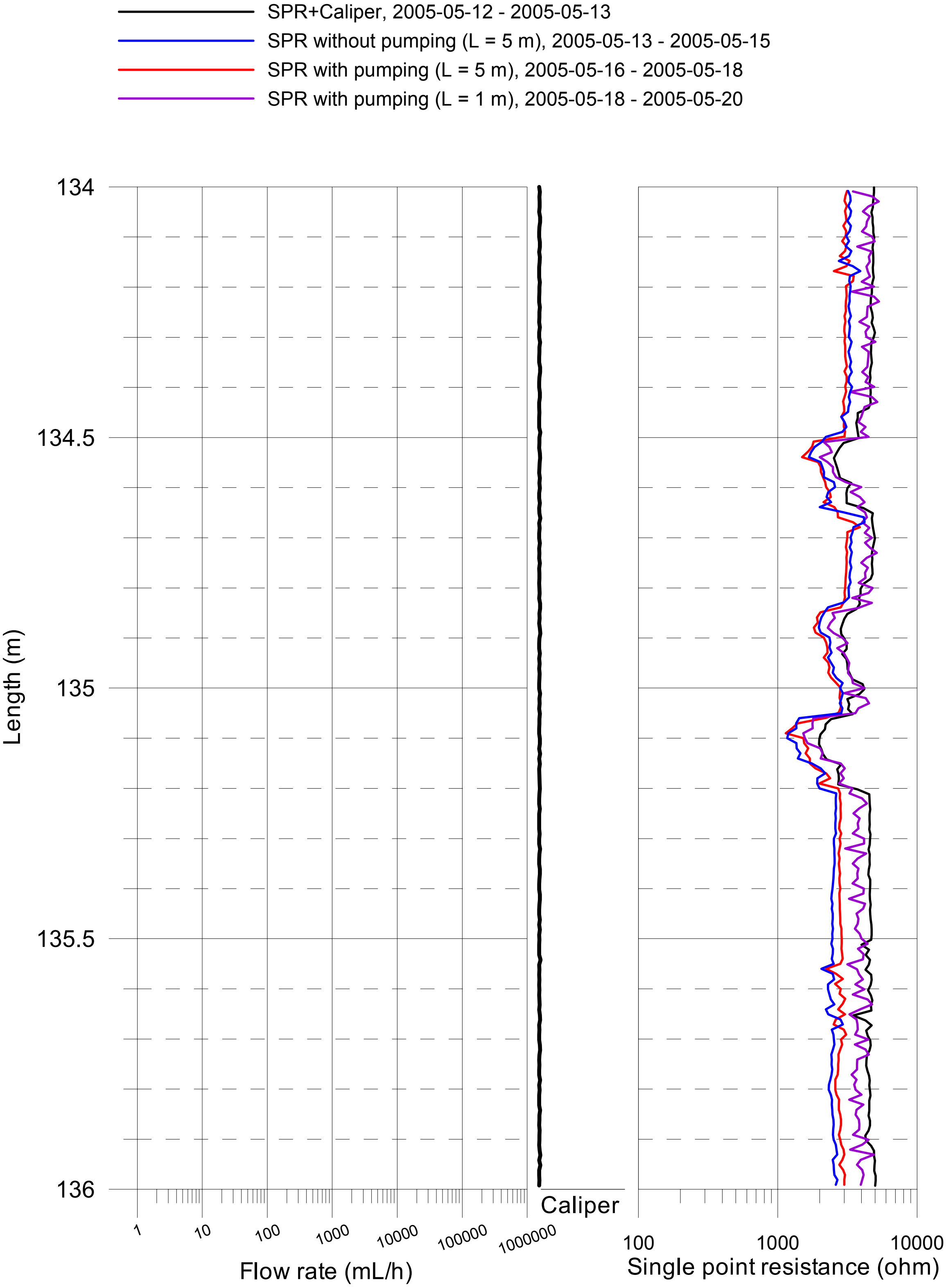
Forsmark, KFM08A
SPR and Caliper results after length correction



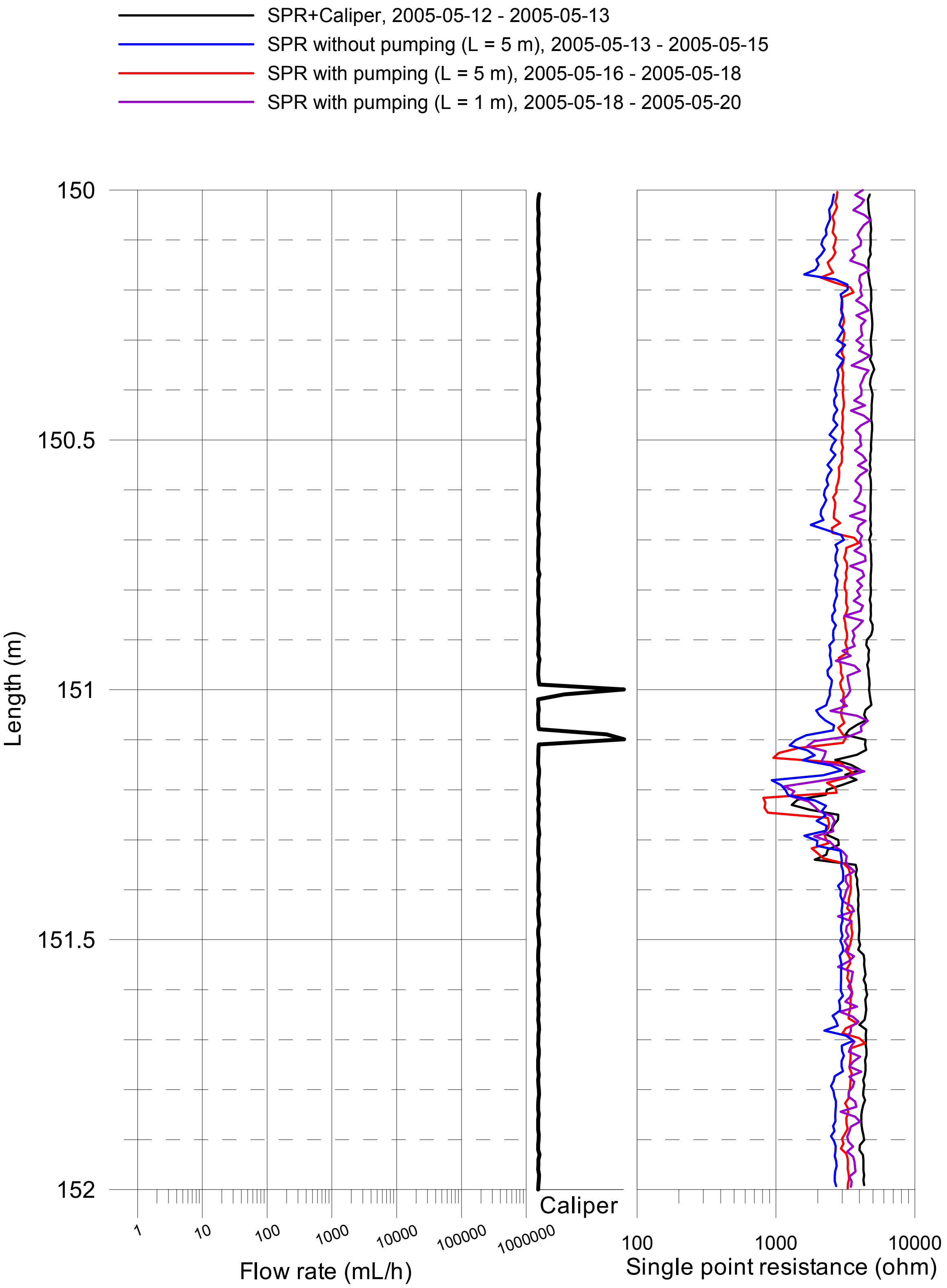
Forsmark, KFM08A
SPR and Caliper results after length correction



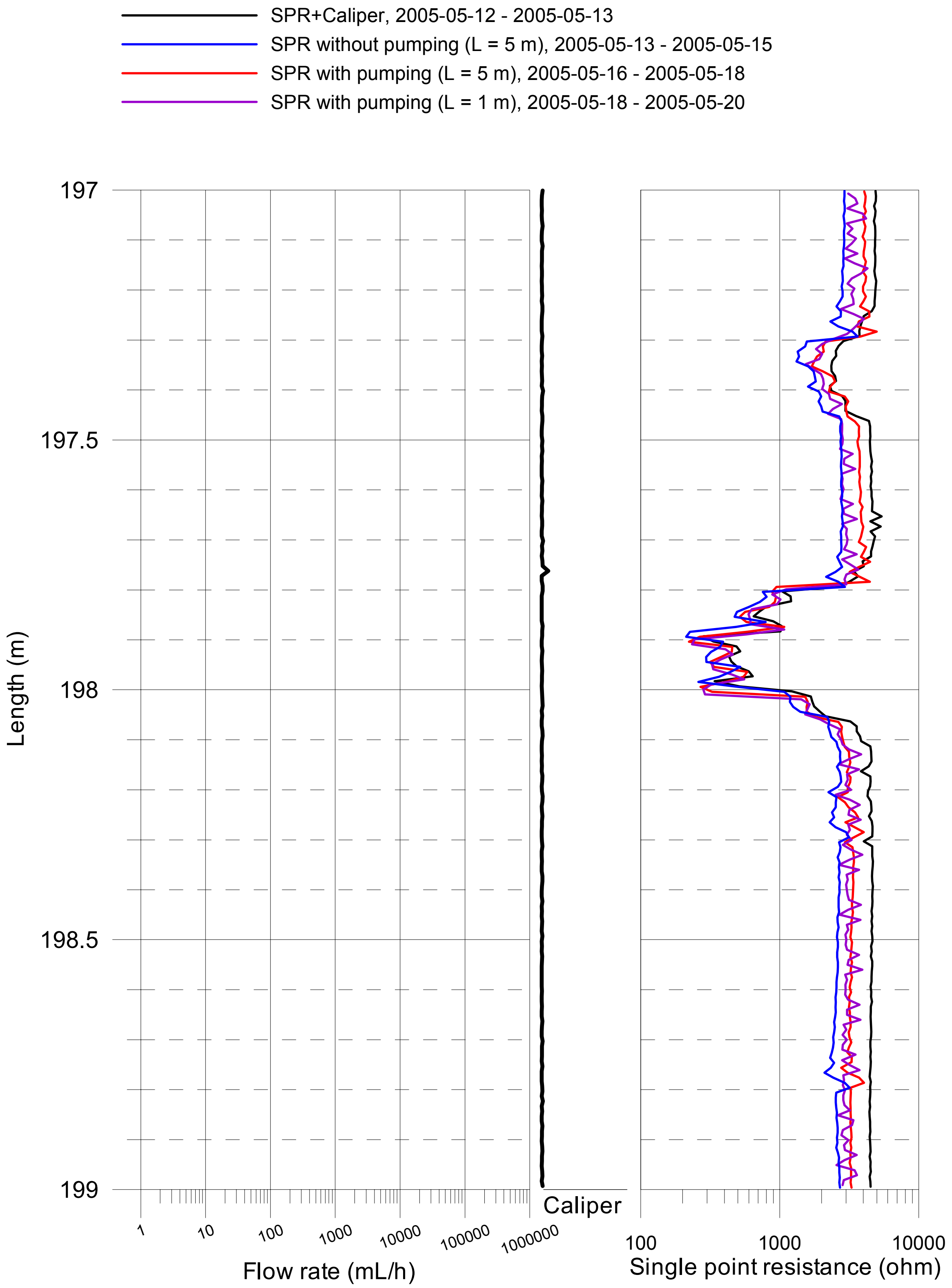
Forsmark, KFM08A
SPR and Caliper results after length correction



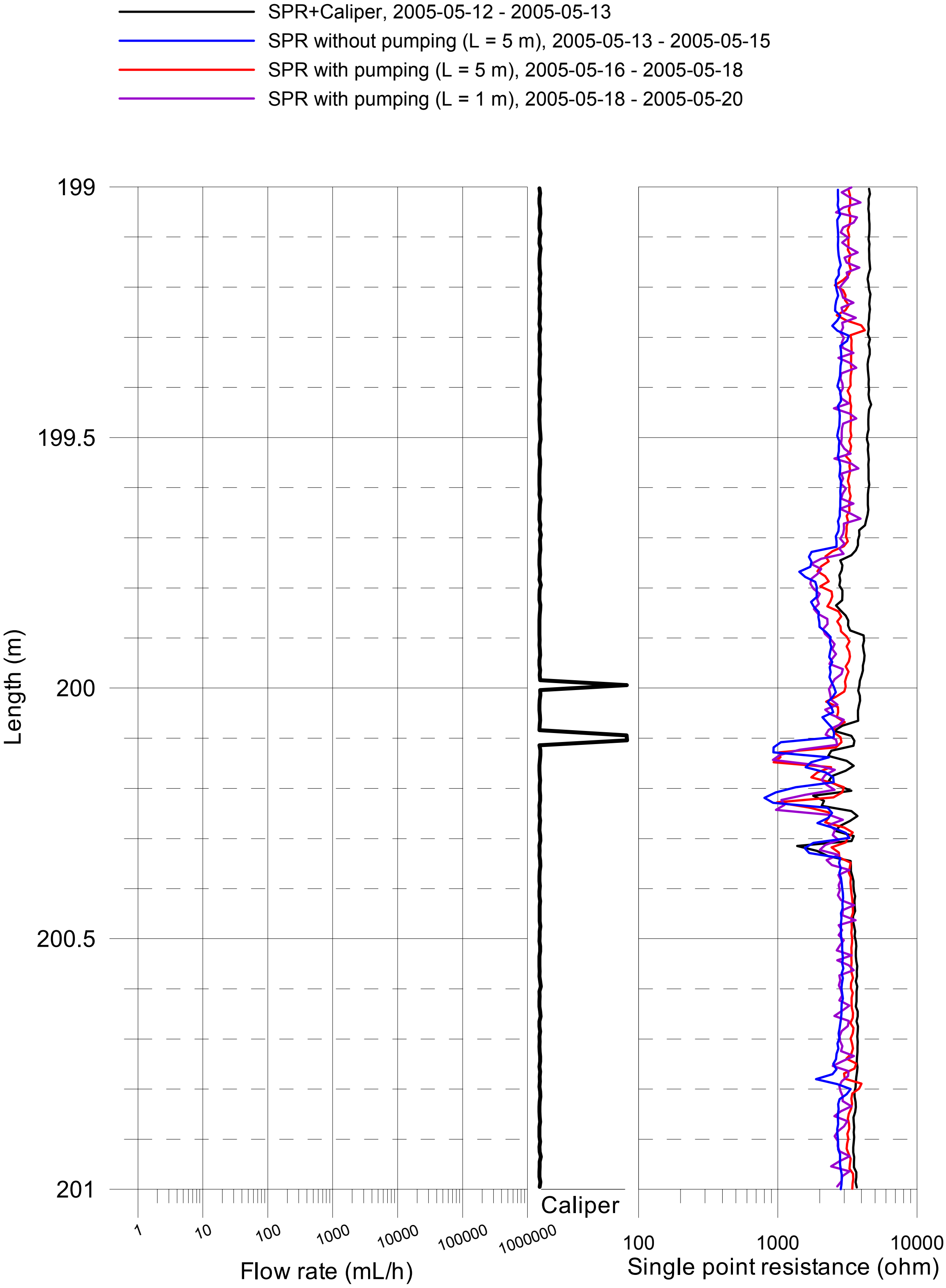
Forsmark, KFM08A
SPR and Caliper results after length correction



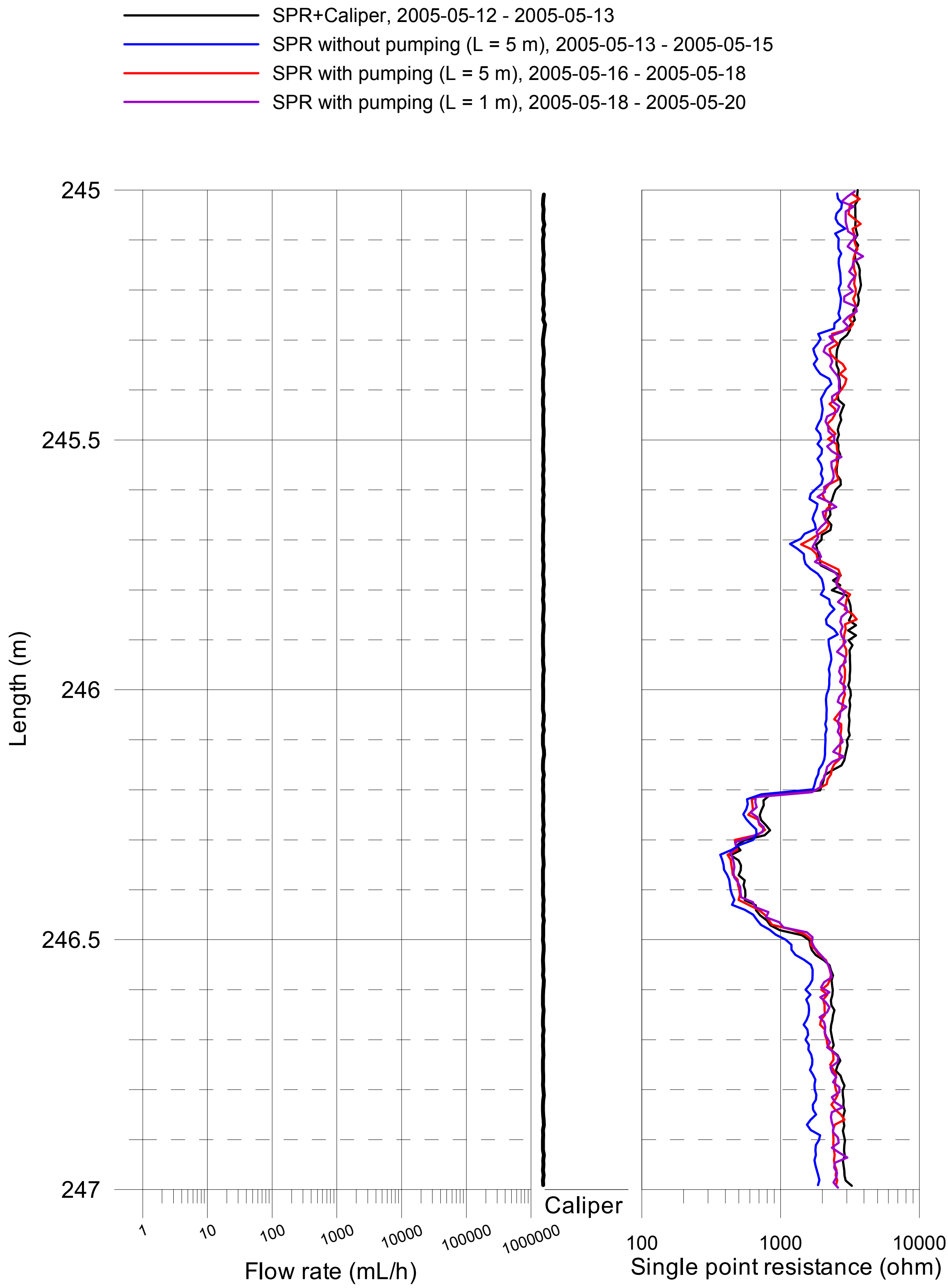
Forsmark, KFM08A
SPR and Caliper results after length correction



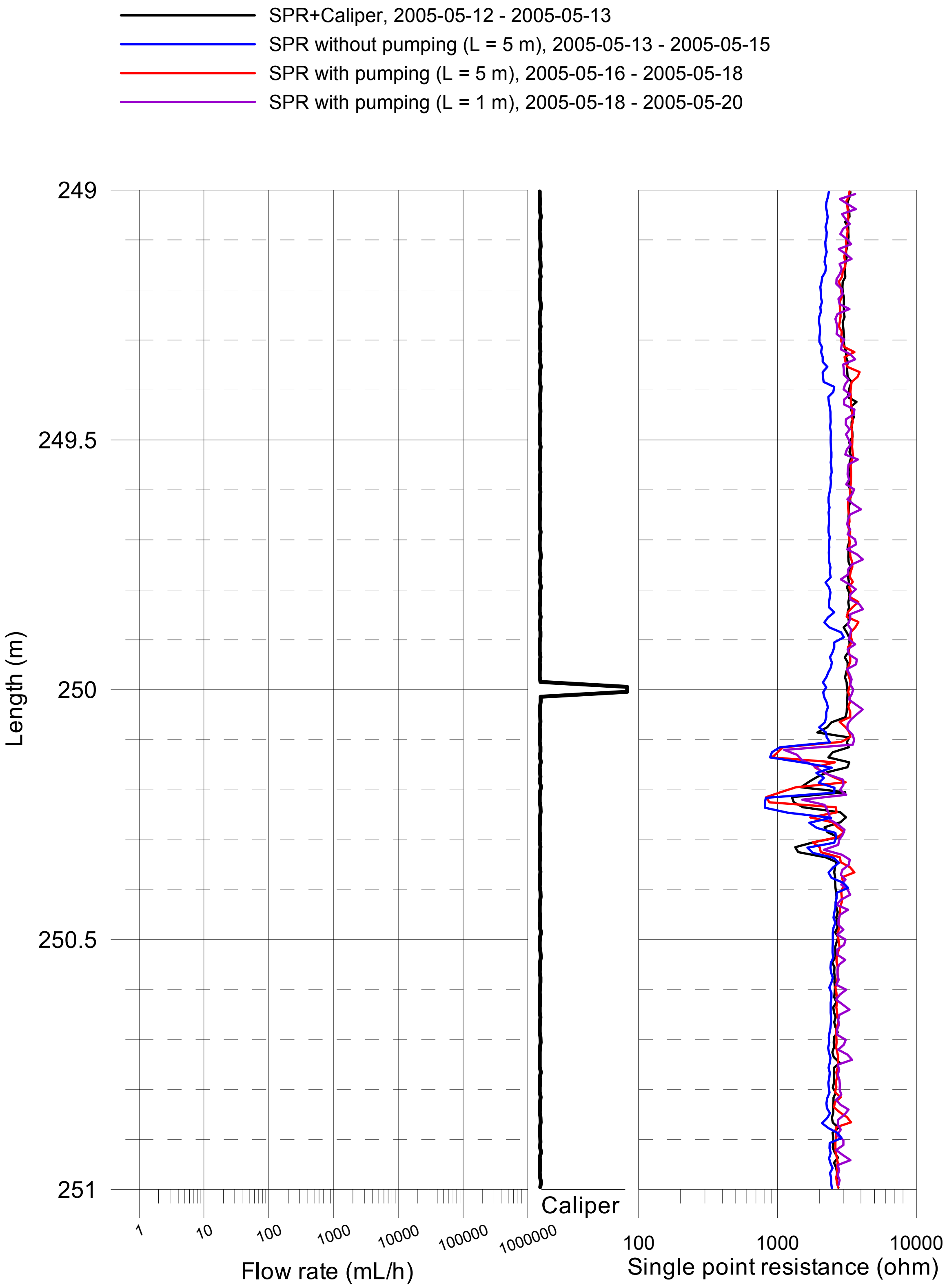
Forsmark, KFM08A
SPR and Caliper results after length correction



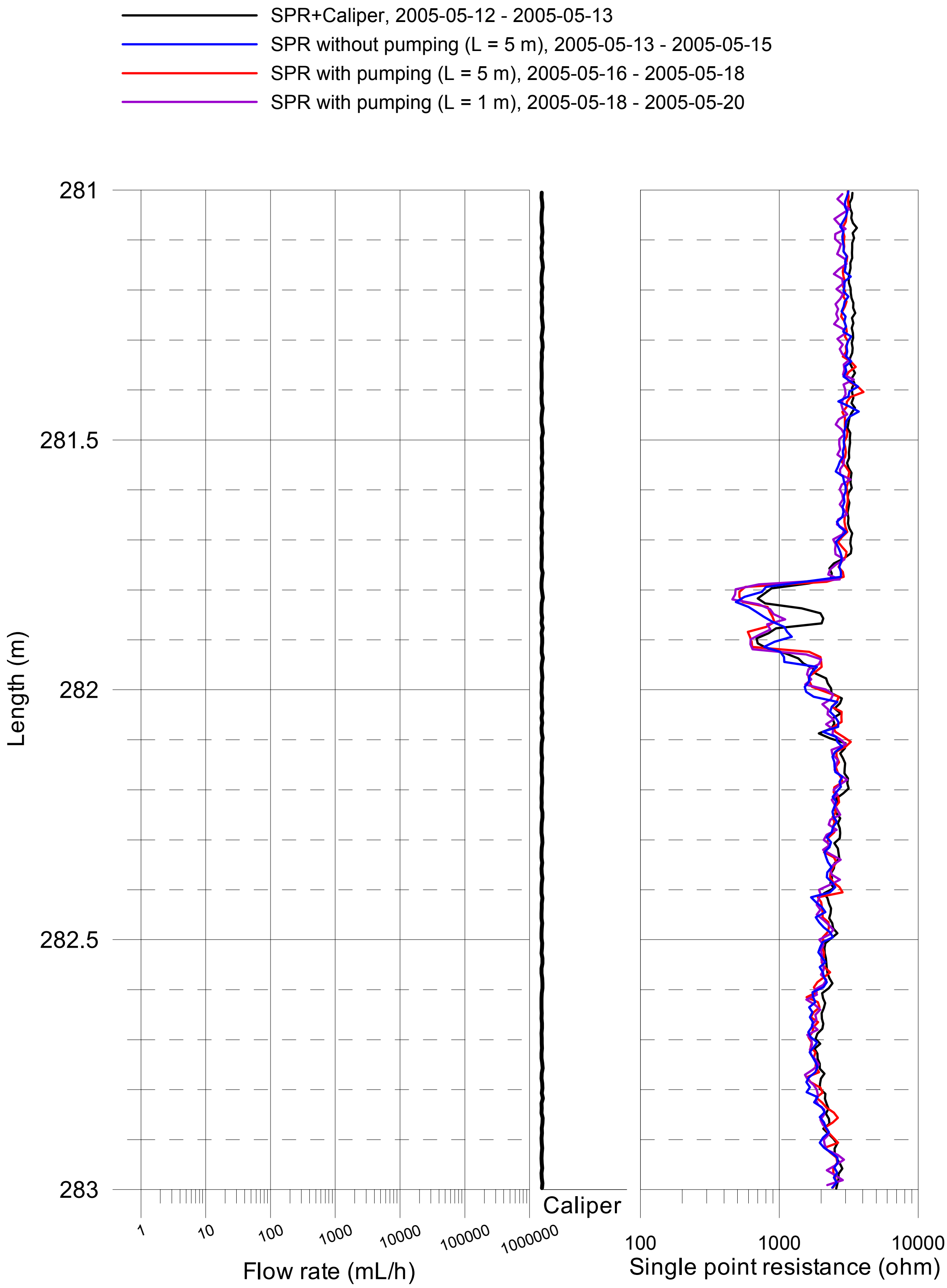
Forsmark, KFM08A
SPR and Caliper results after length correction

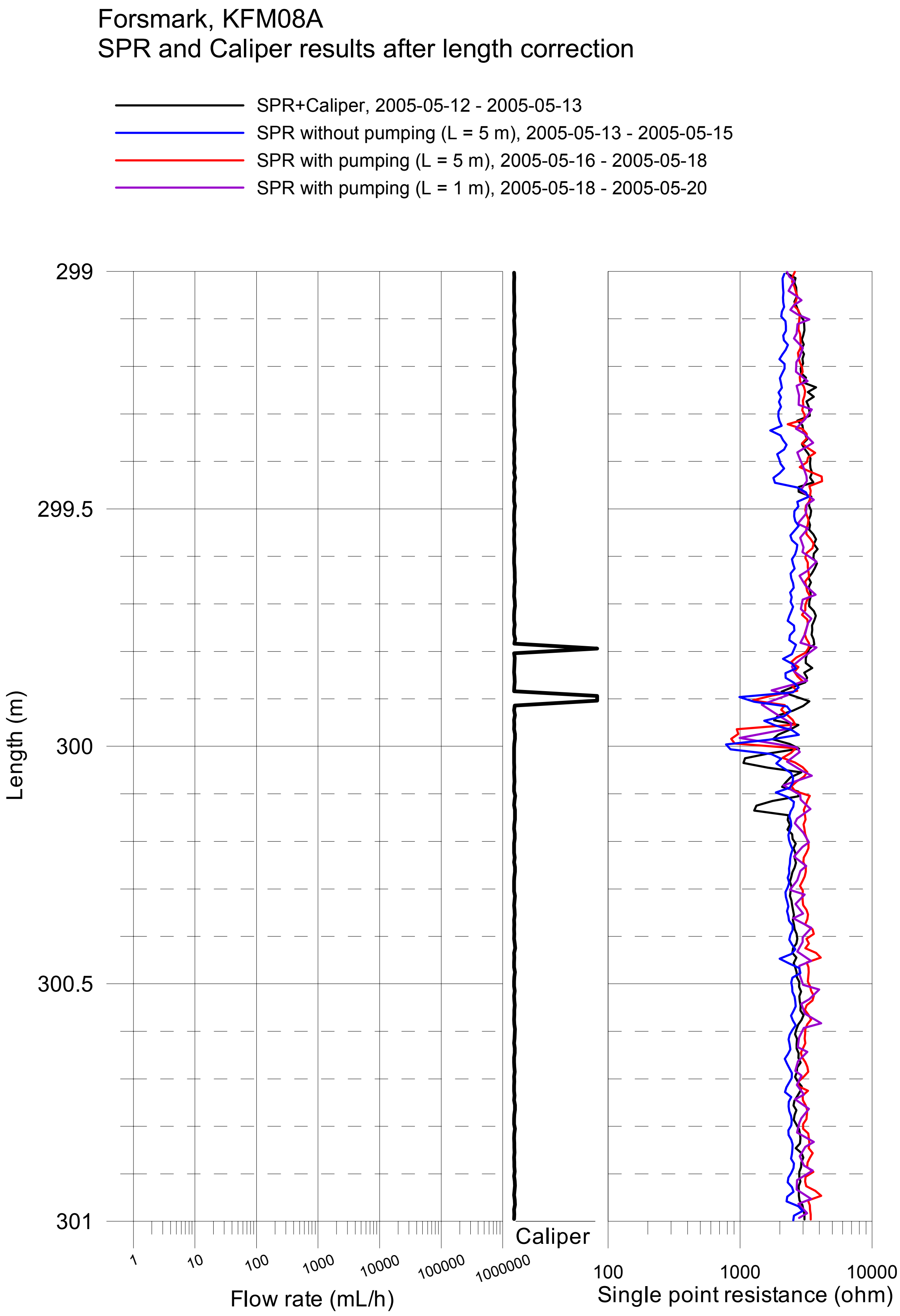


Forsmark, KFM08A
SPR and Caliper results after length correction



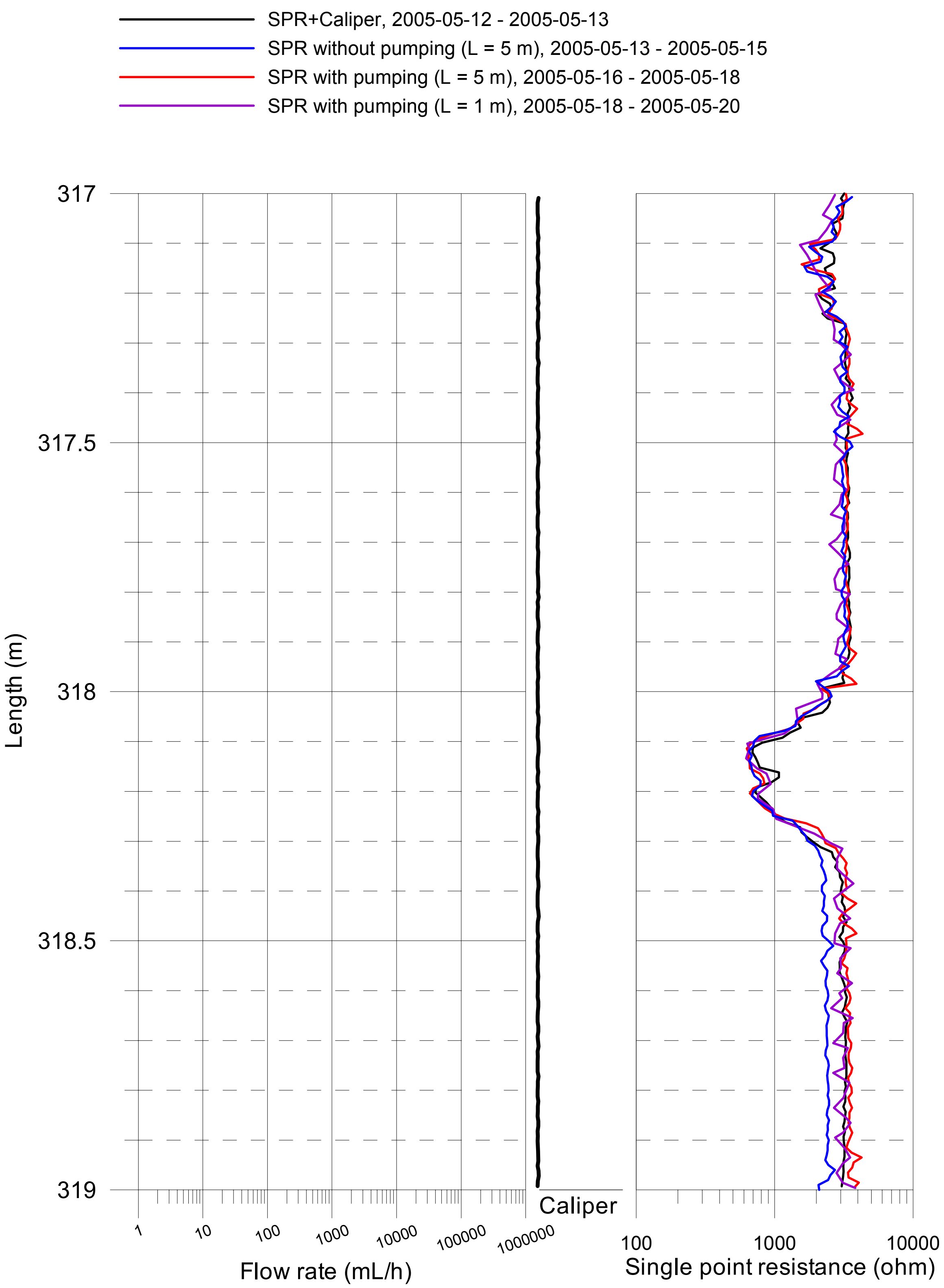
Forsmark, KFM08A
SPR and Caliper results after length correction



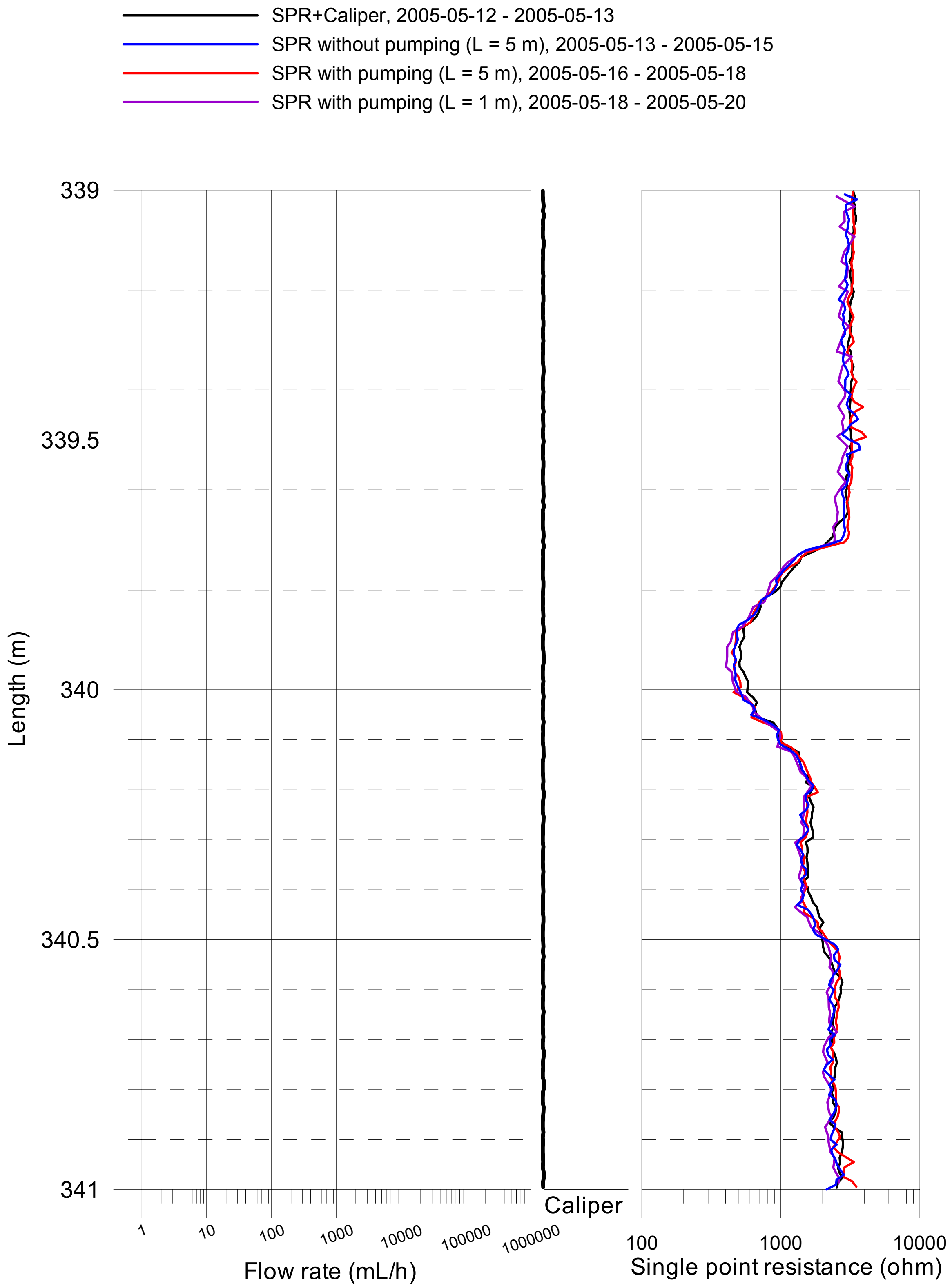


Forsmark, KFM08A
SPR and Caliper results after length correction
SPR+Caliper, 2005-05-12 - 2005-05-13
SPR without pumping (L = 5 m), 2005-05-13 - 2005-05-15
SPR with pumping (L = 5 m), 2005-05-16 - 2005-05-18
SPR with pumping (L = 1 m), 2005-05-18 - 2005-05-20
Length (m)
299
299.5
300
300.5
301
1
10
100
1000
10000
100000
1000000
Flow rate (mL/h)
Caliper
100
1000
10000
Single point resistance (ohm)

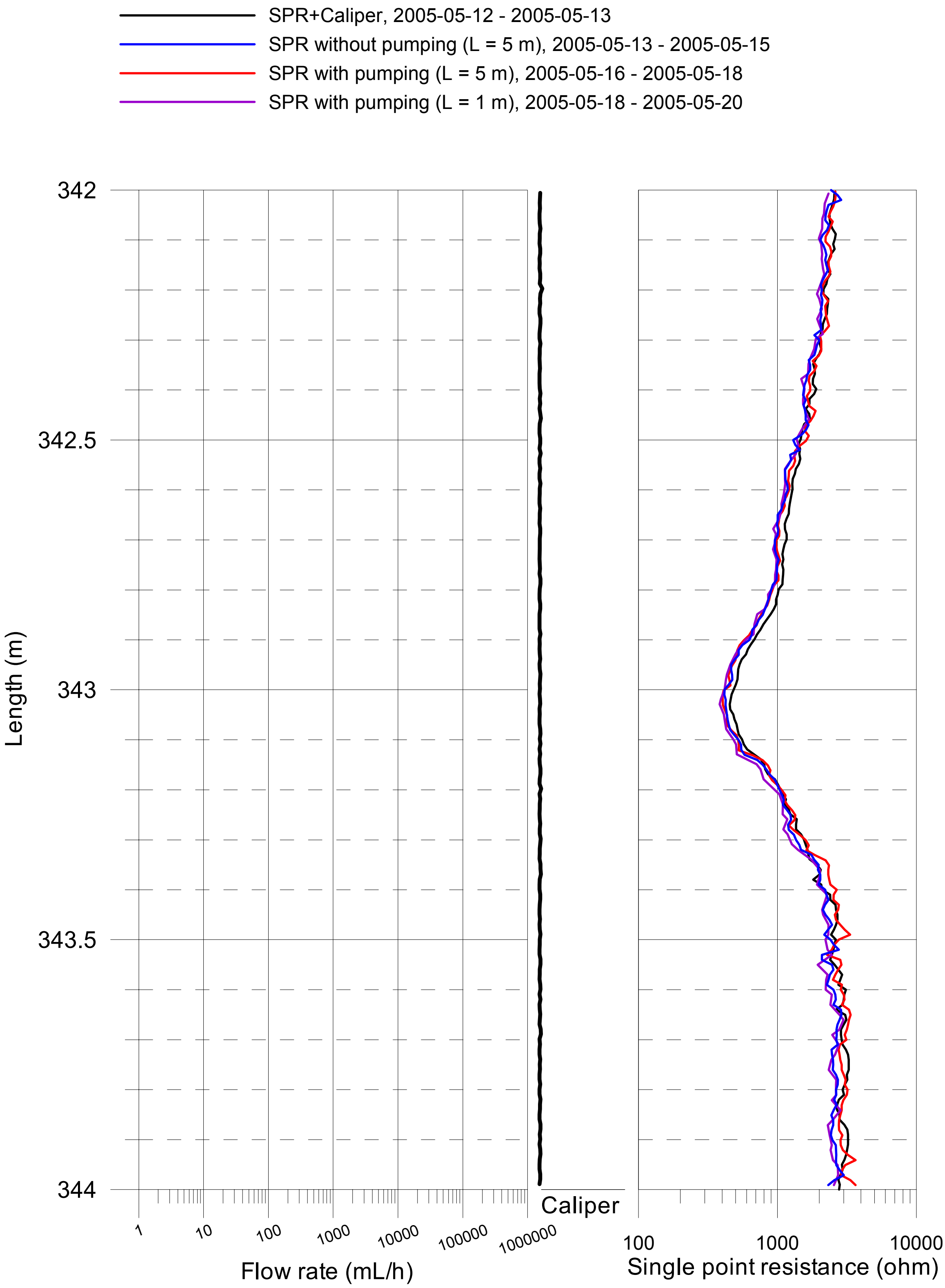
Forsmark, KFM08A
SPR and Caliper results after length correction



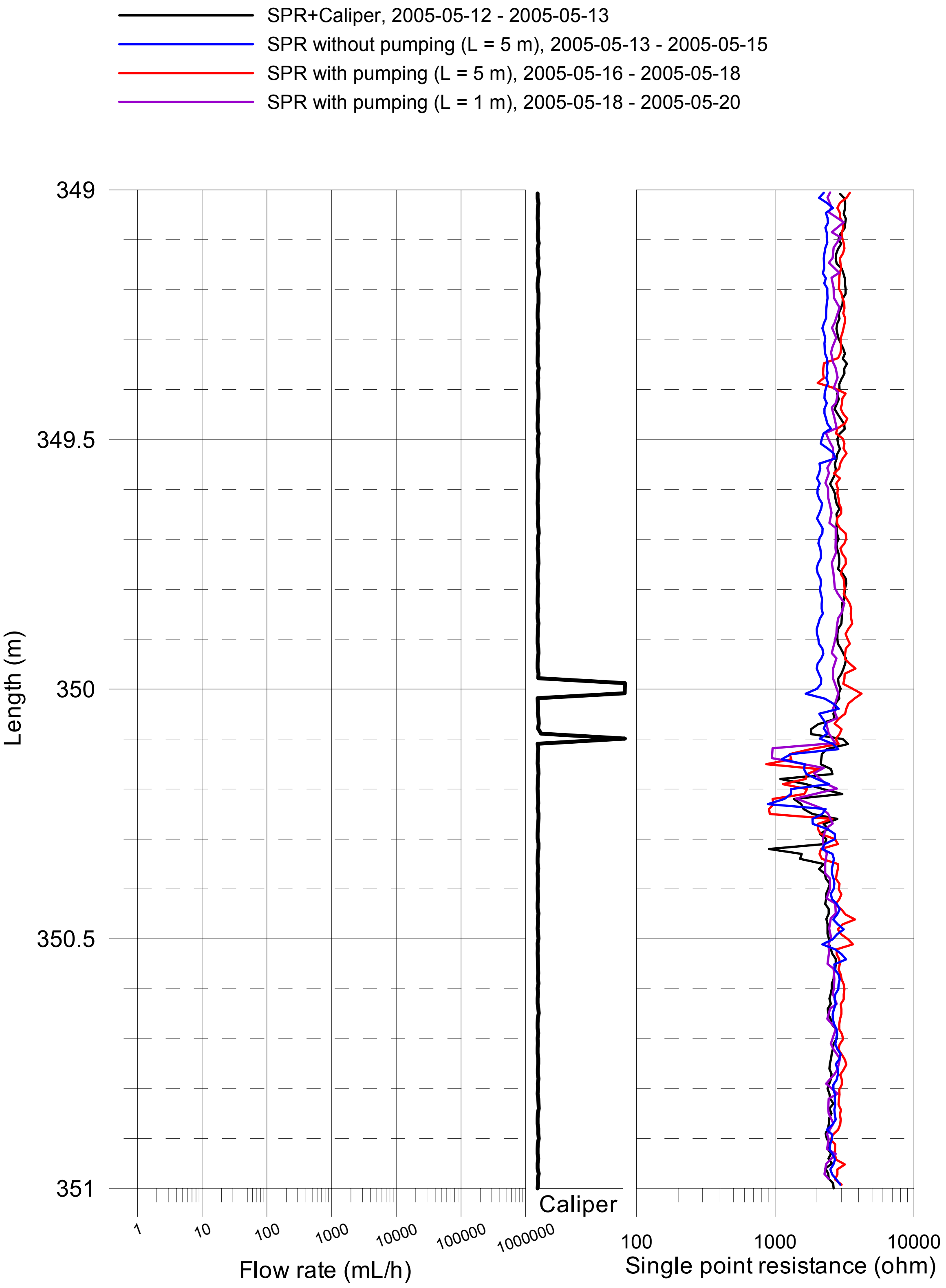
Forsmark, KFM08A
SPR and Caliper results after length correction

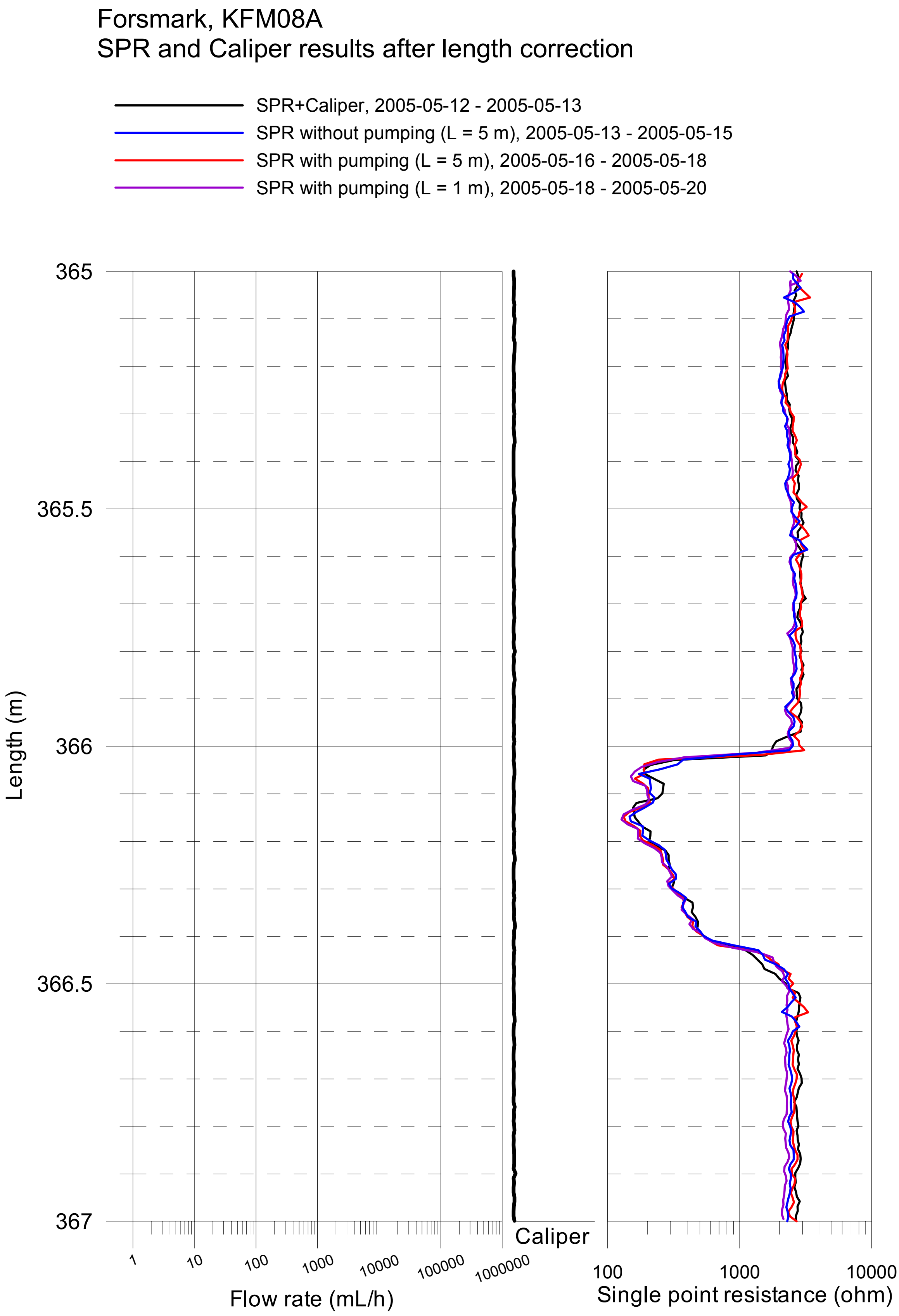


Forsmark, KFM08A
SPR and Caliper results after length correction

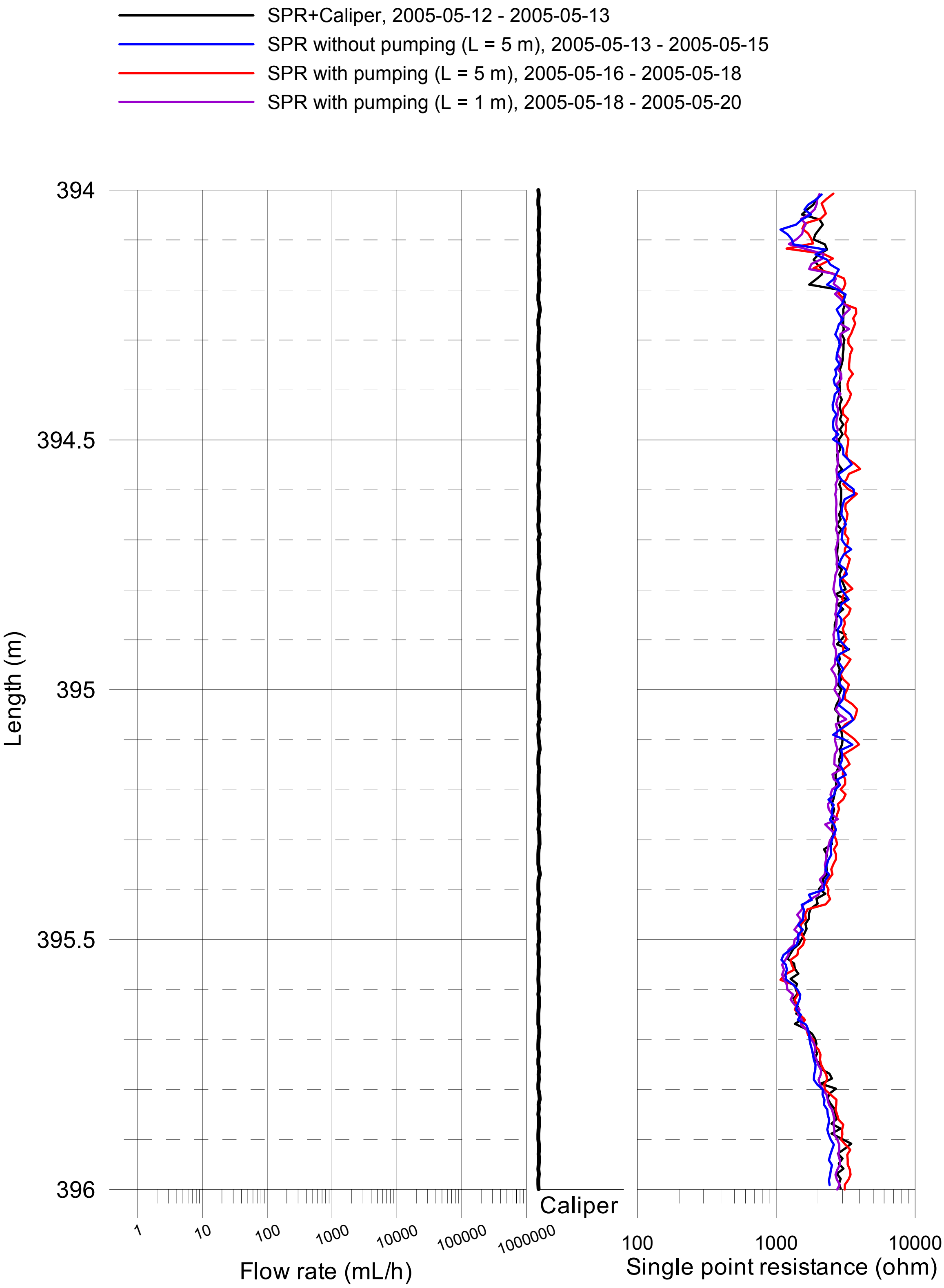


Forsmark, KFM08A
SPR and Caliper results after length correction

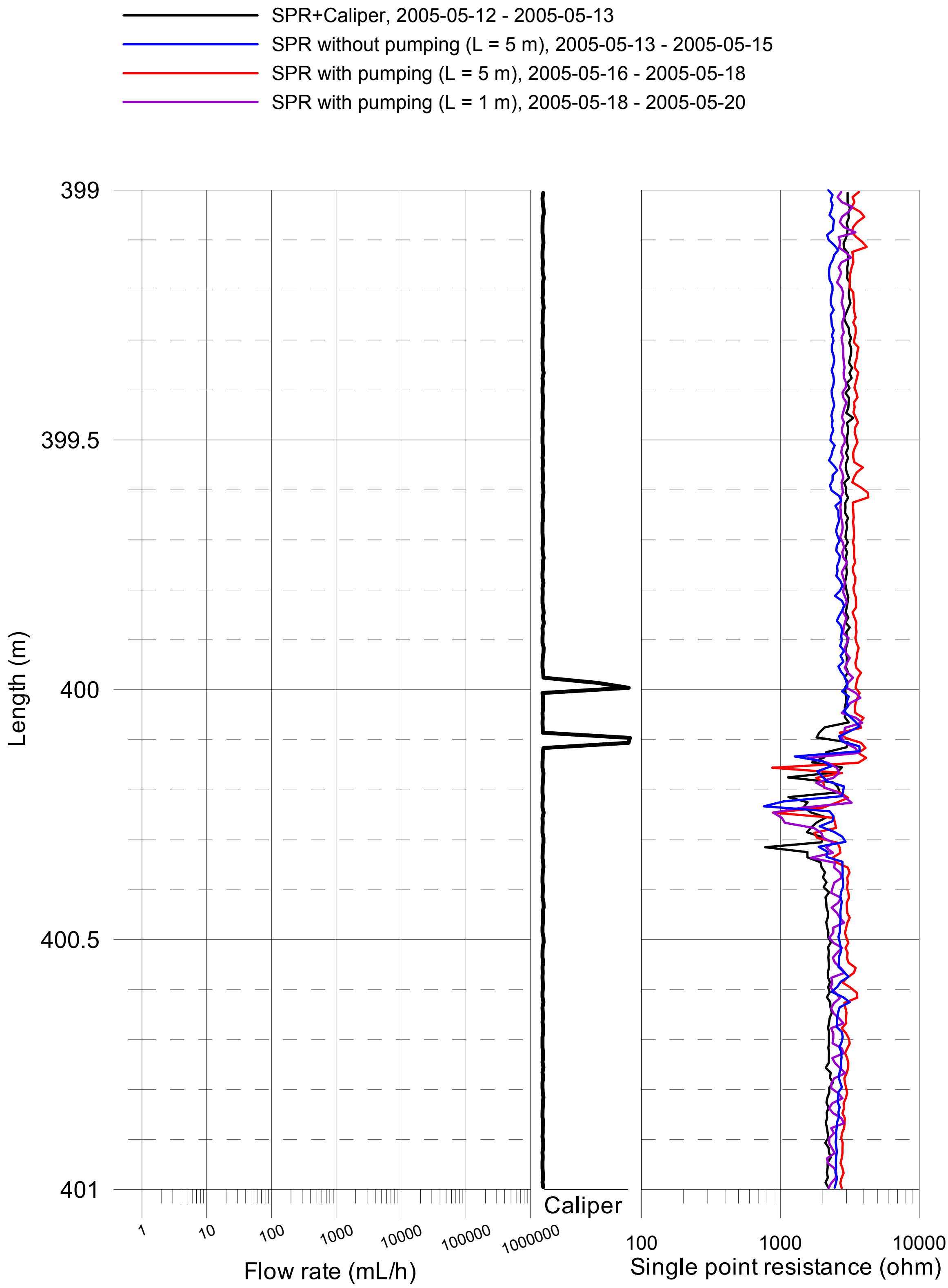



Forsmark, KFM08A
SPR and Caliper results after length correction
SPR+Caliper, 2005-05-12 - 2005-05-13
SPR without pumping (L = 5 m), 2005-05-13 - 2005-05-15
SPR with pumping (L = 5 m), 2005-05-16 - 2005-05-18
SPR with pumping (L = 1 m), 2005-05-18 - 2005-05-20
Length (m)
365
365.5
366
366.5
367
1
10
100
1000
10000
100000
1000000
Flow rate (mL/h)
Caliper
100
1000
10000
Single point resistance (ohm)

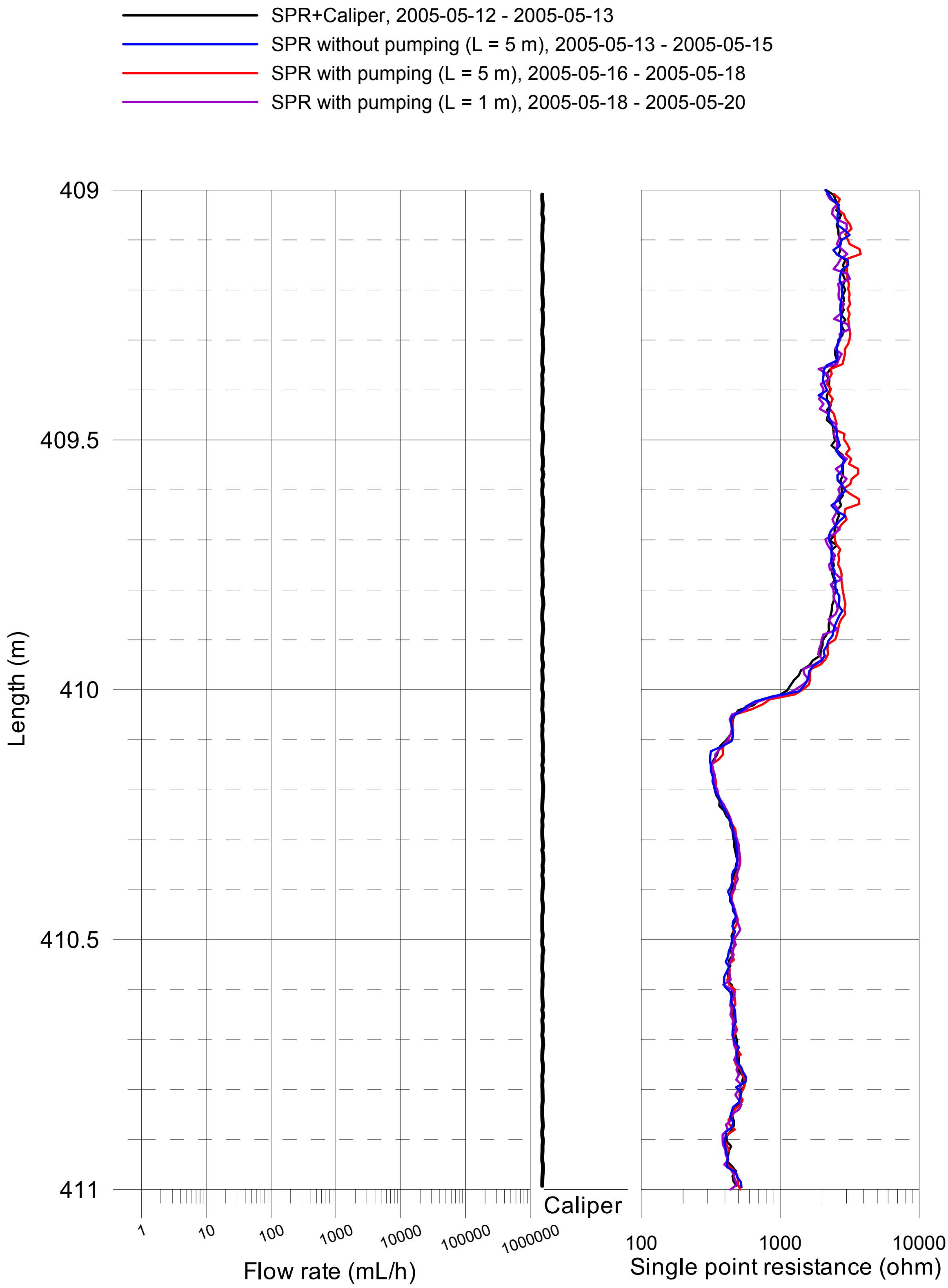
Forsmark, KFM08A
SPR and Caliper results after length correction



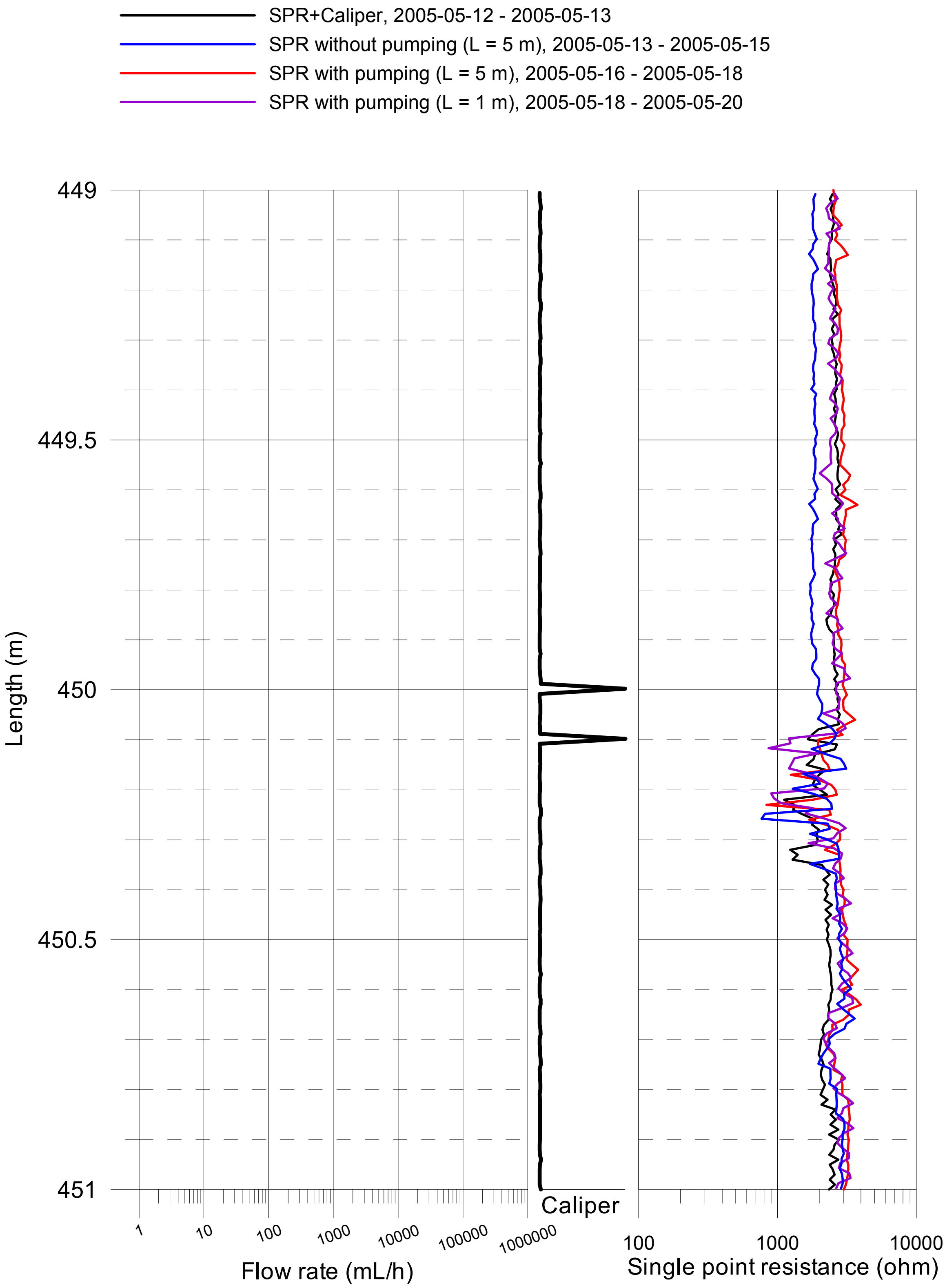
Forsmark, KFM08A
SPR and Caliper results after length correction



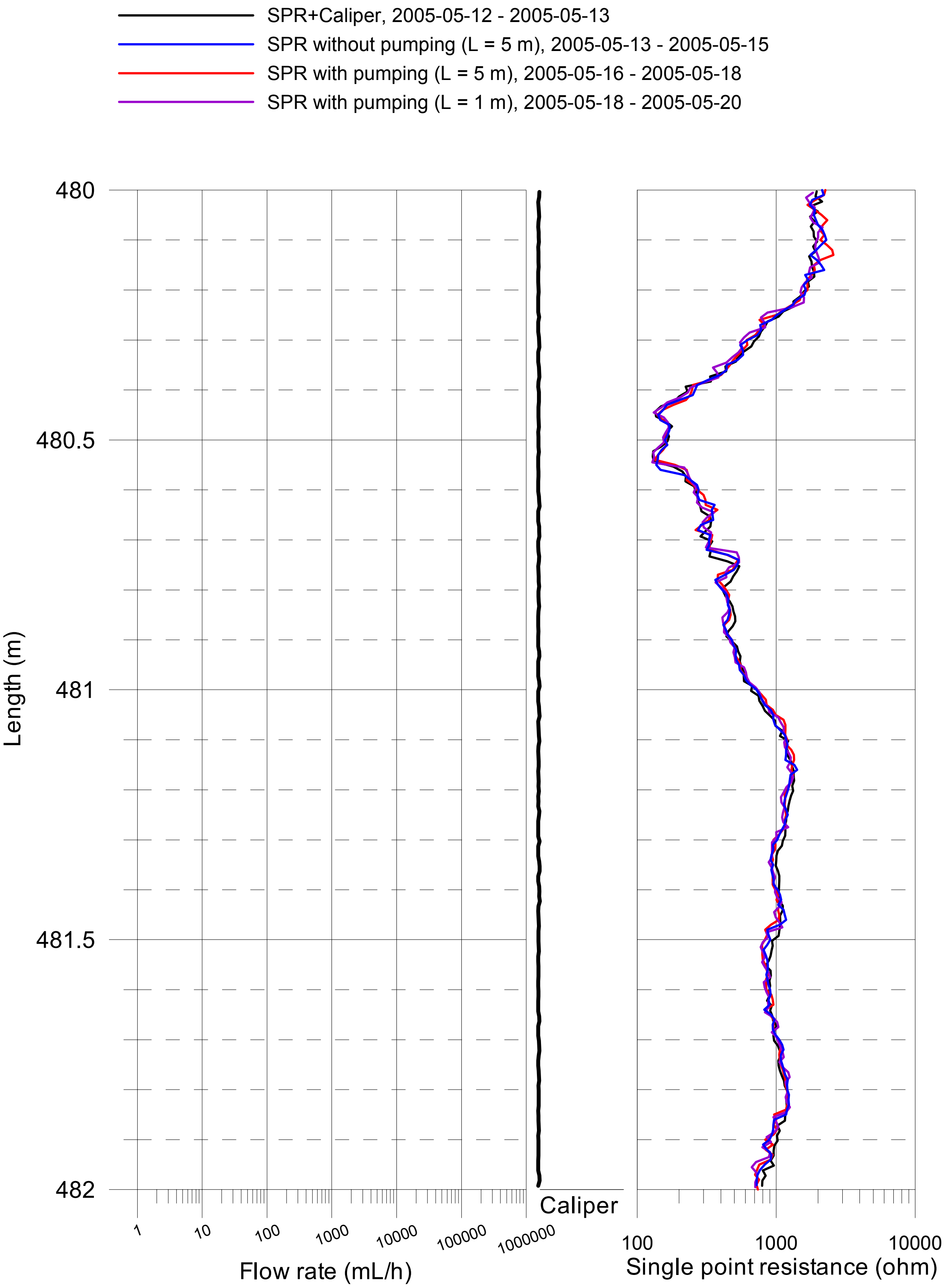
Forsmark, KFM08A
SPR and Caliper results after length correction



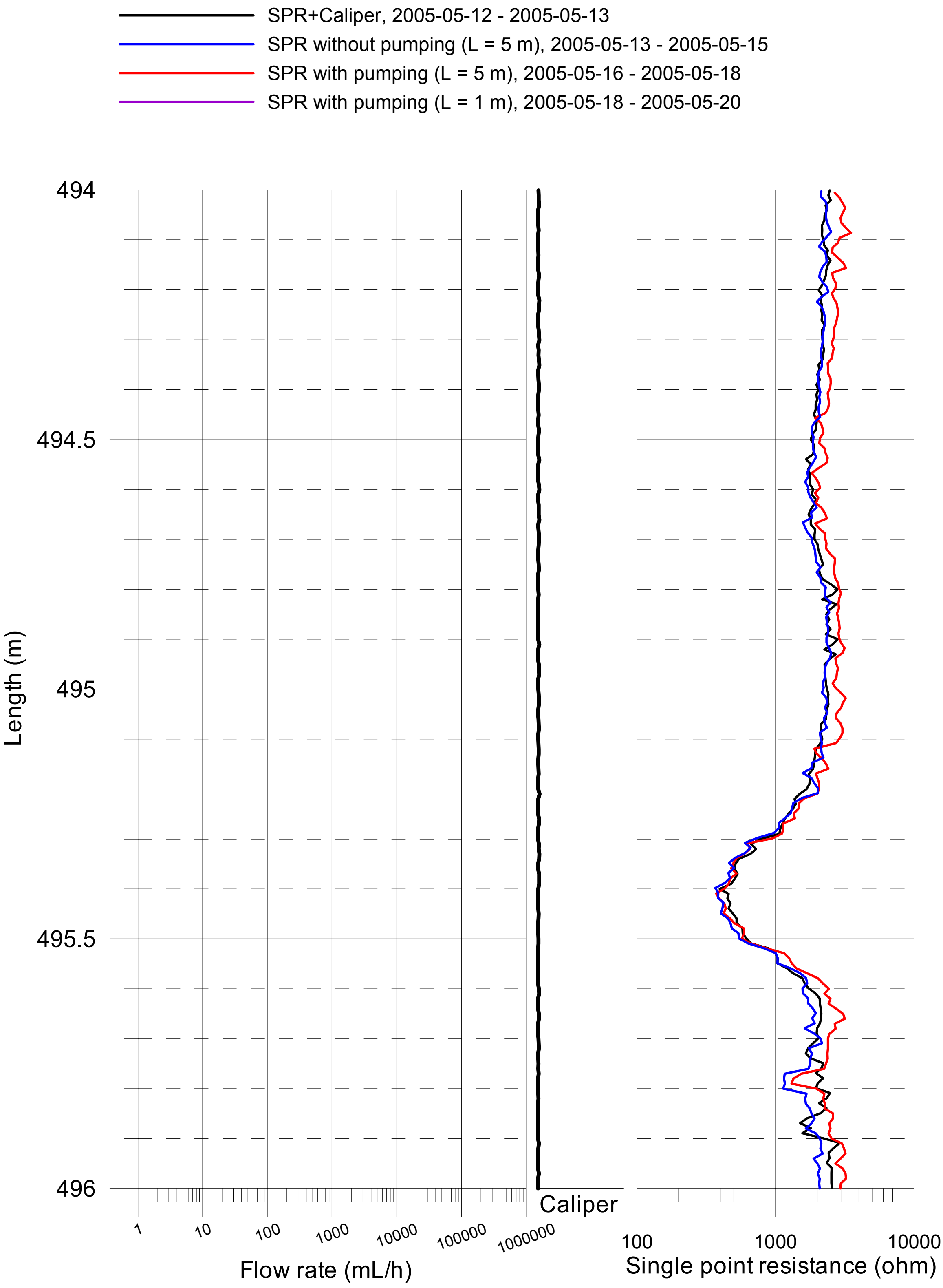
Forsmark, KFM08A
SPR and Caliper results after length correction



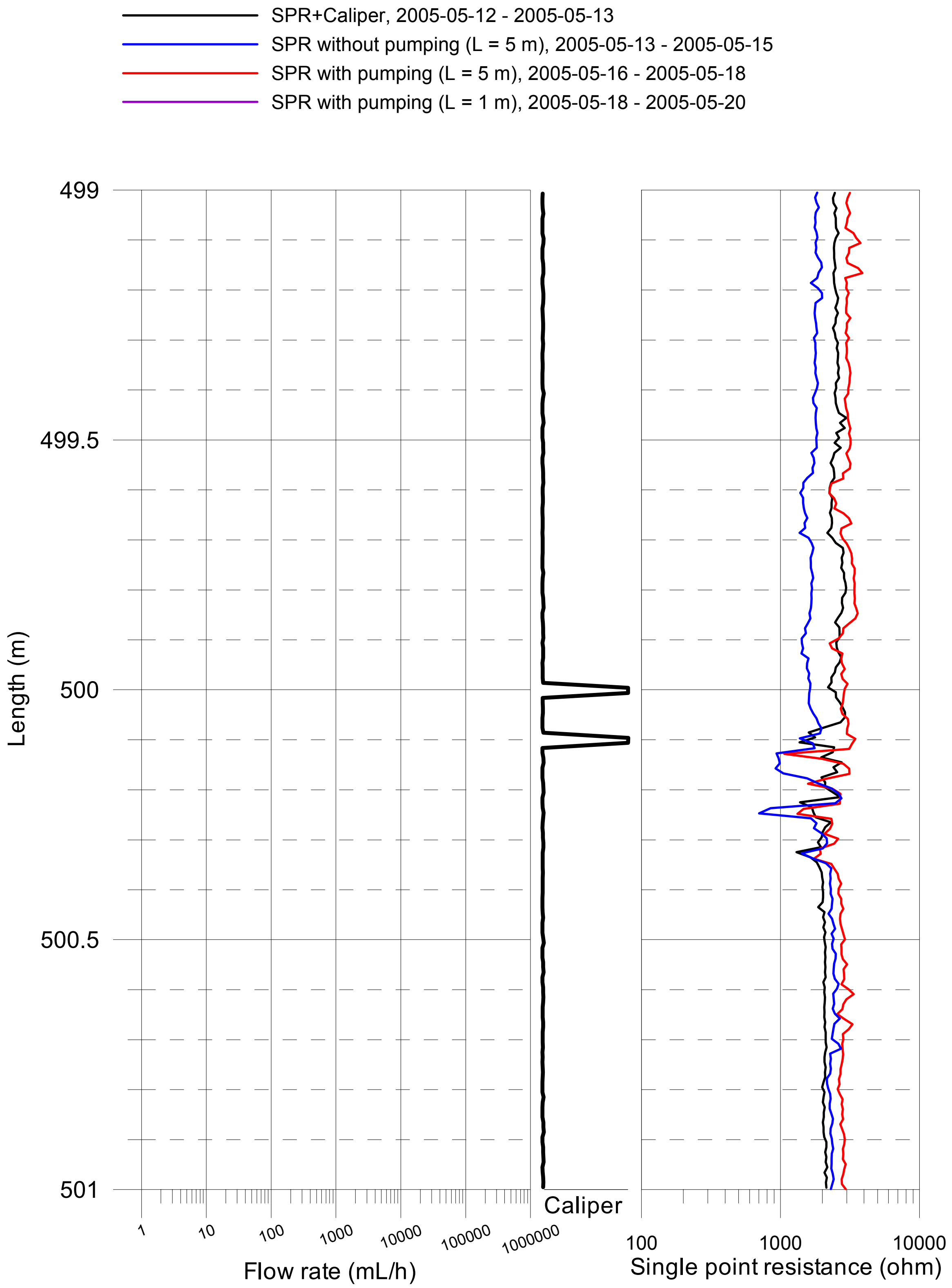
Forsmark, KFM08A
SPR and Caliper results after length correction



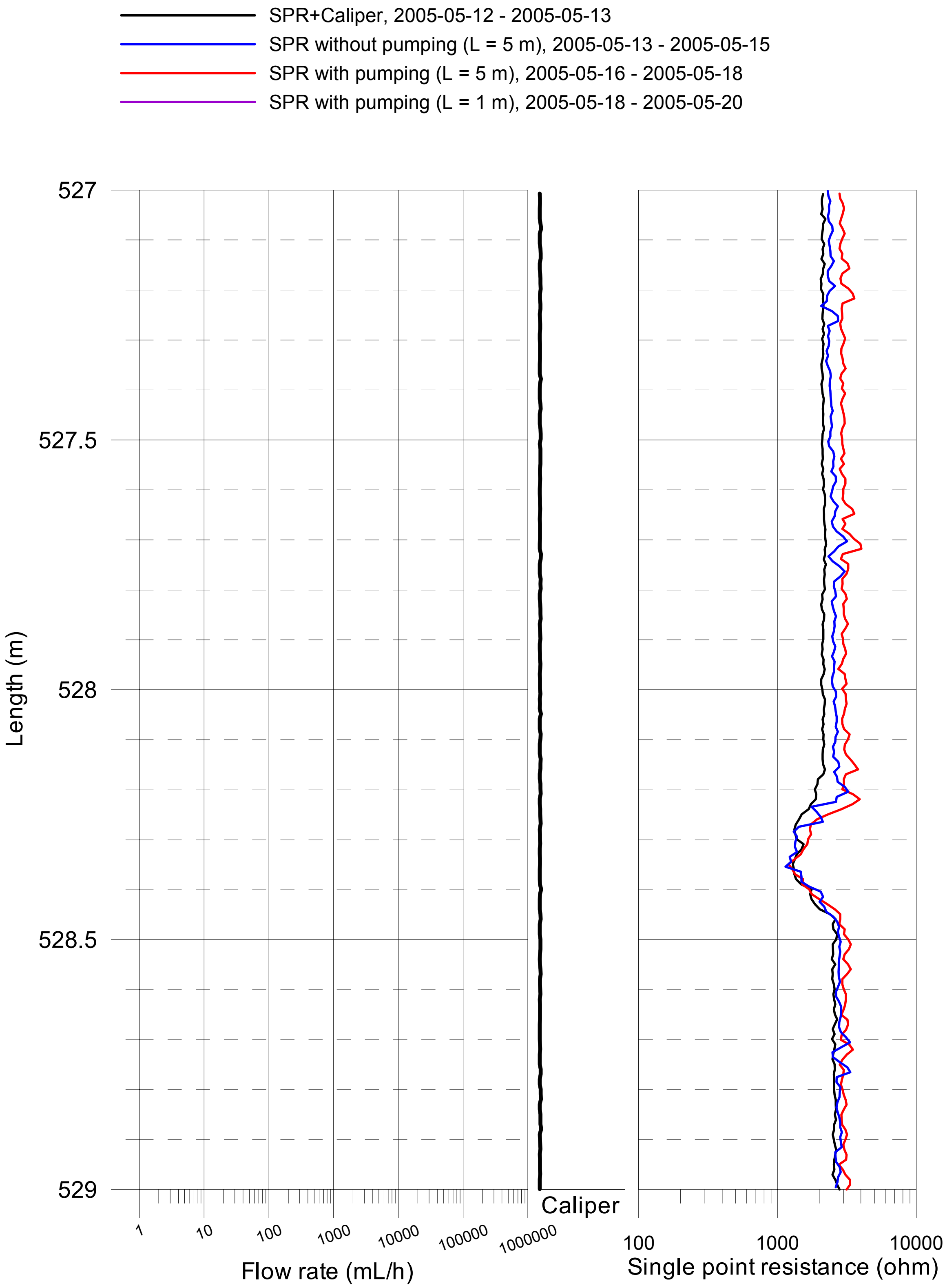
Forsmark, KFM08A
SPR and Caliper results after length correction



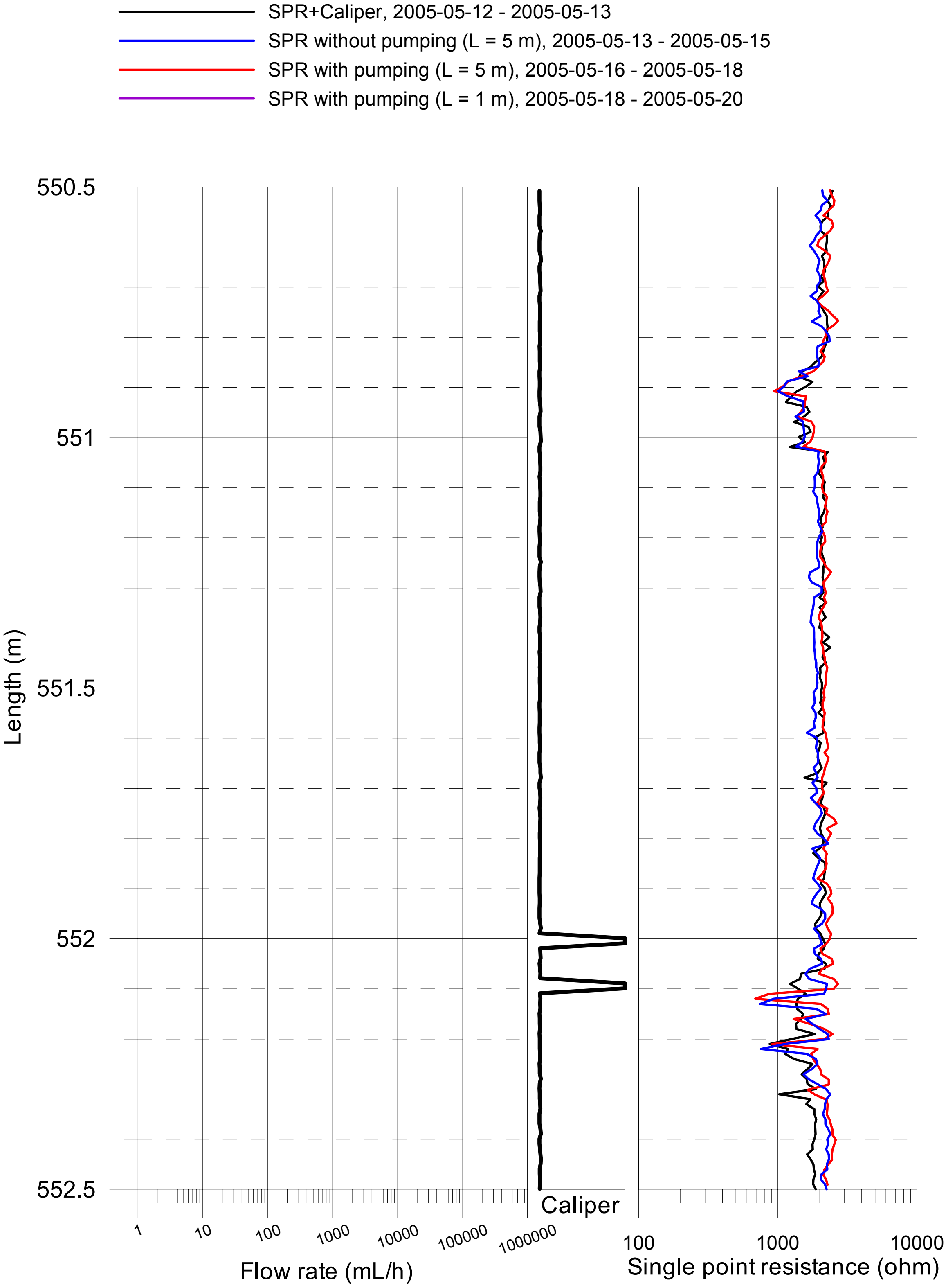
Forsmark, KFM08A
SPR and Caliper results after length correction



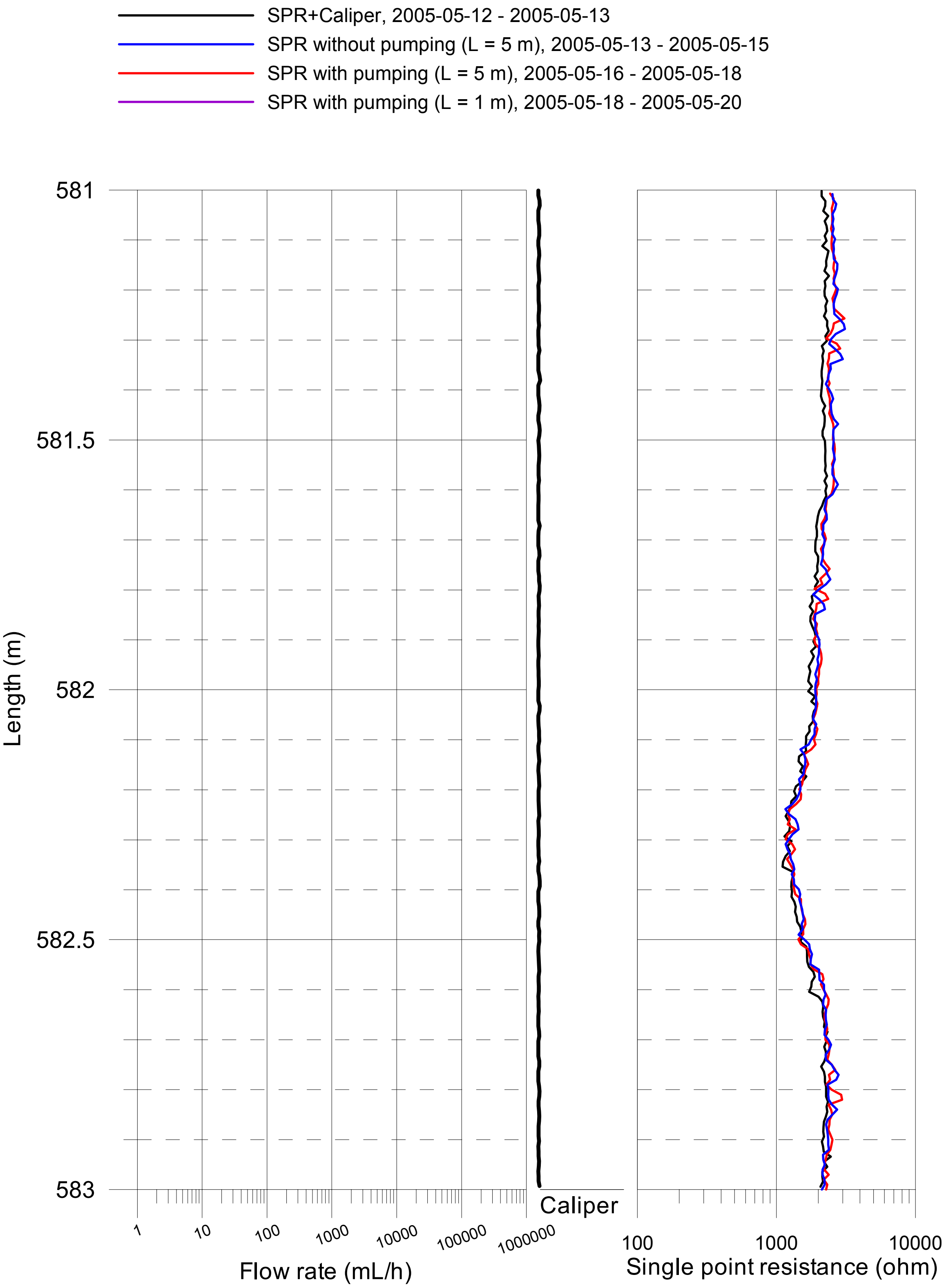
Forsmark, KFM08A
SPR and Caliper results after length correction



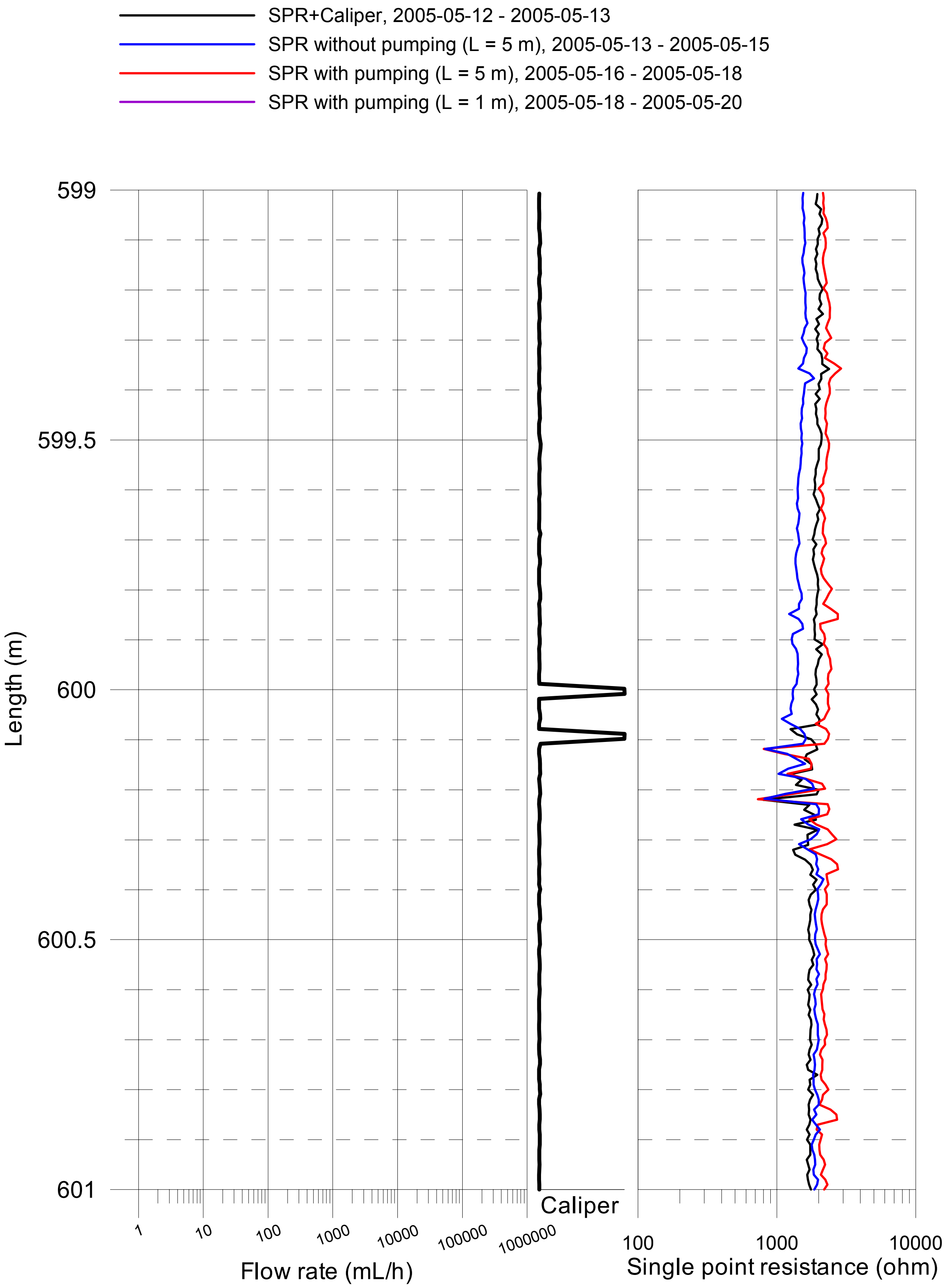
Forsmark, KFM08A
SPR and Caliper results after length correction



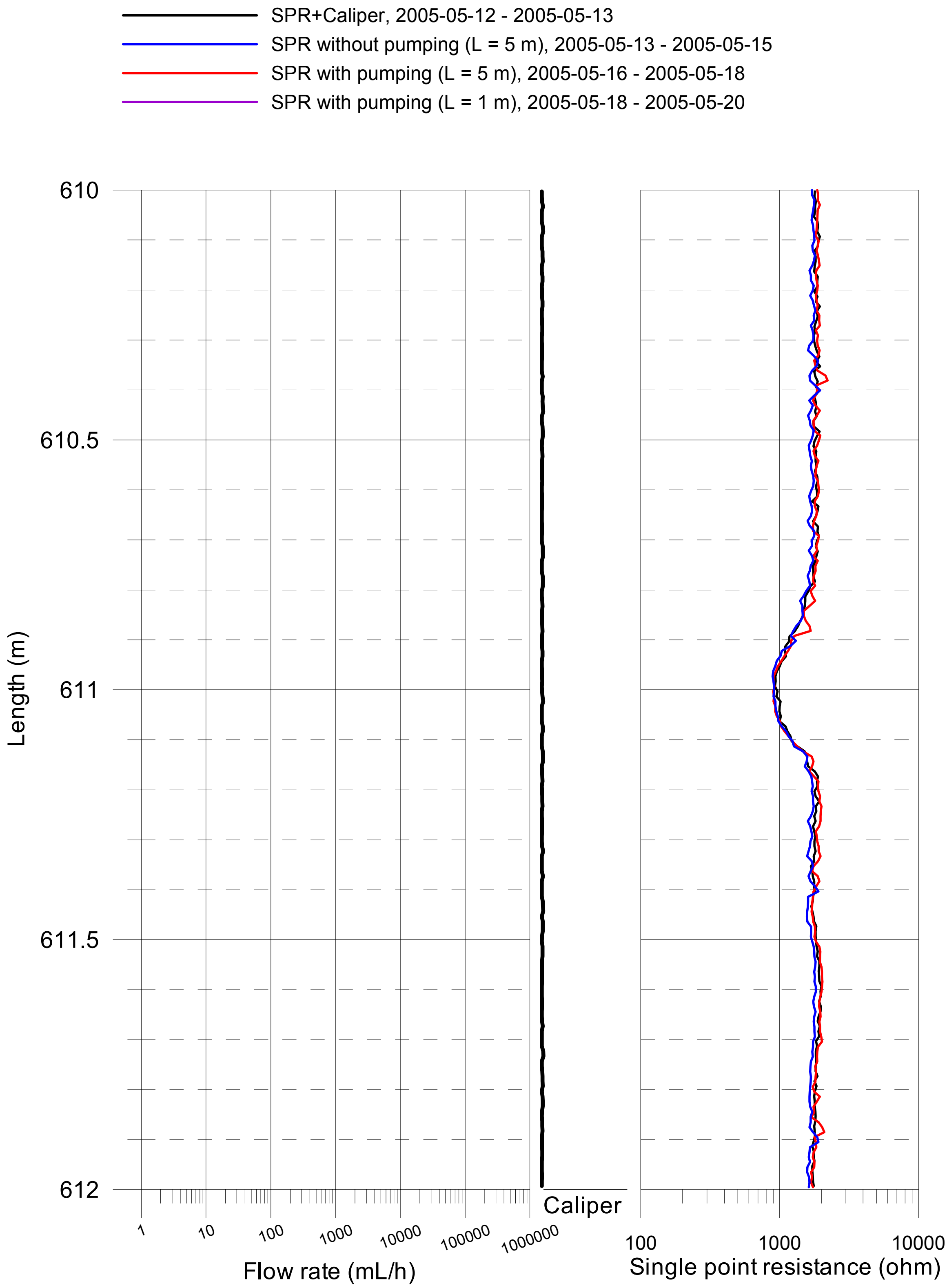
Forsmark, KFM08A
SPR and Caliper results after length correction



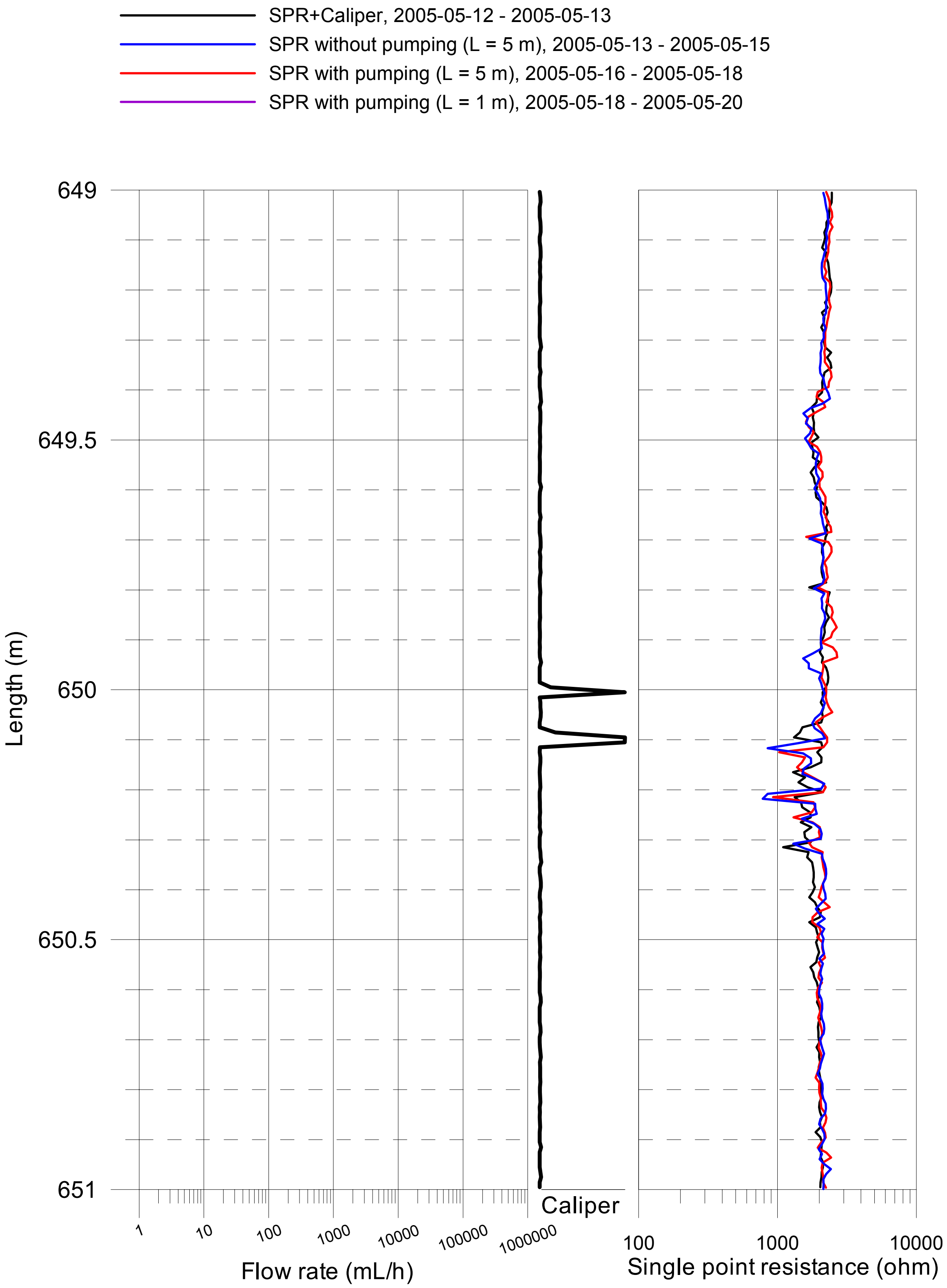
Forsmark, KFM08A
SPR and Caliper results after length correction



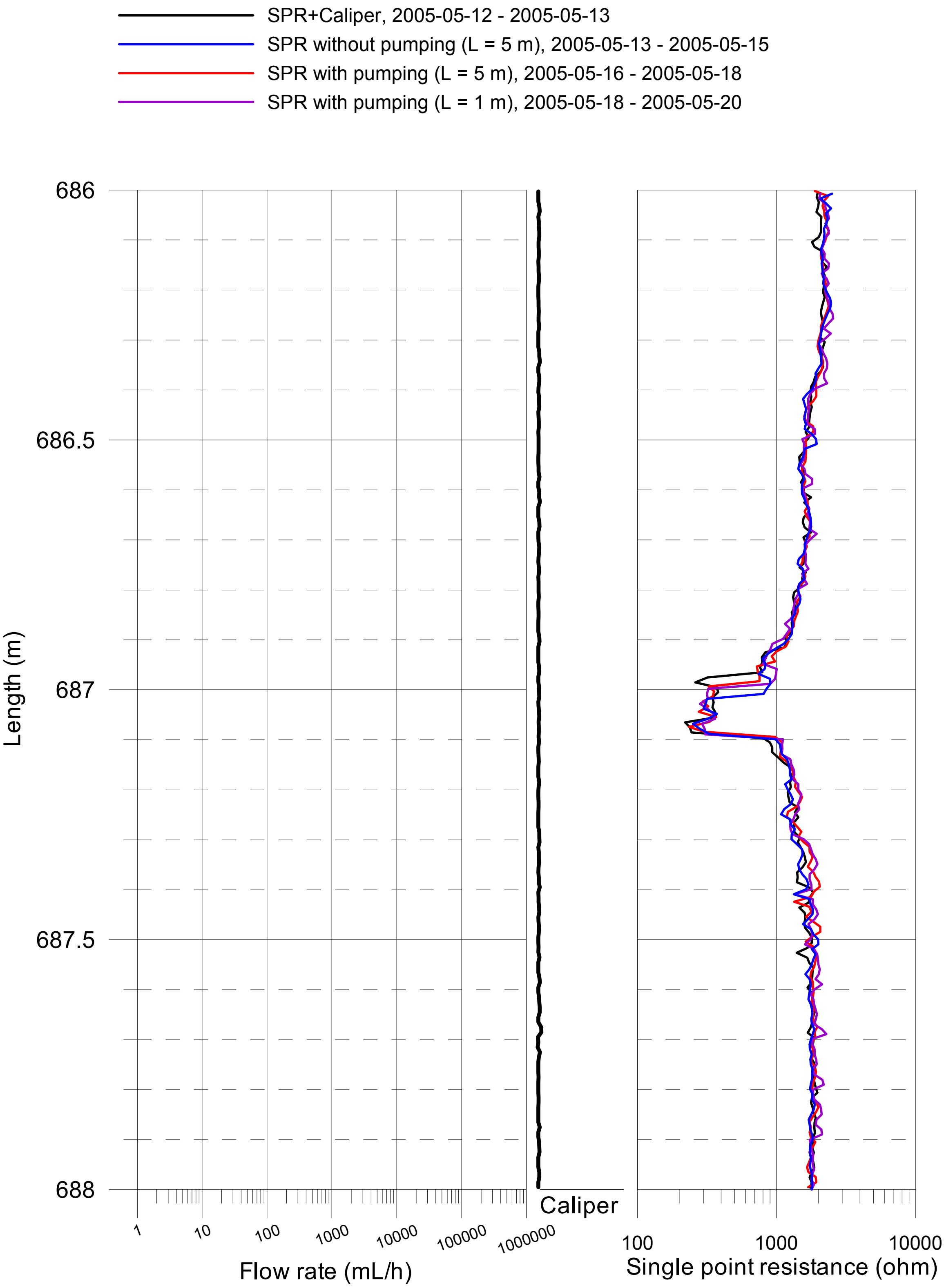
Forsmark, KFM08A
SPR and Caliper results after length correction



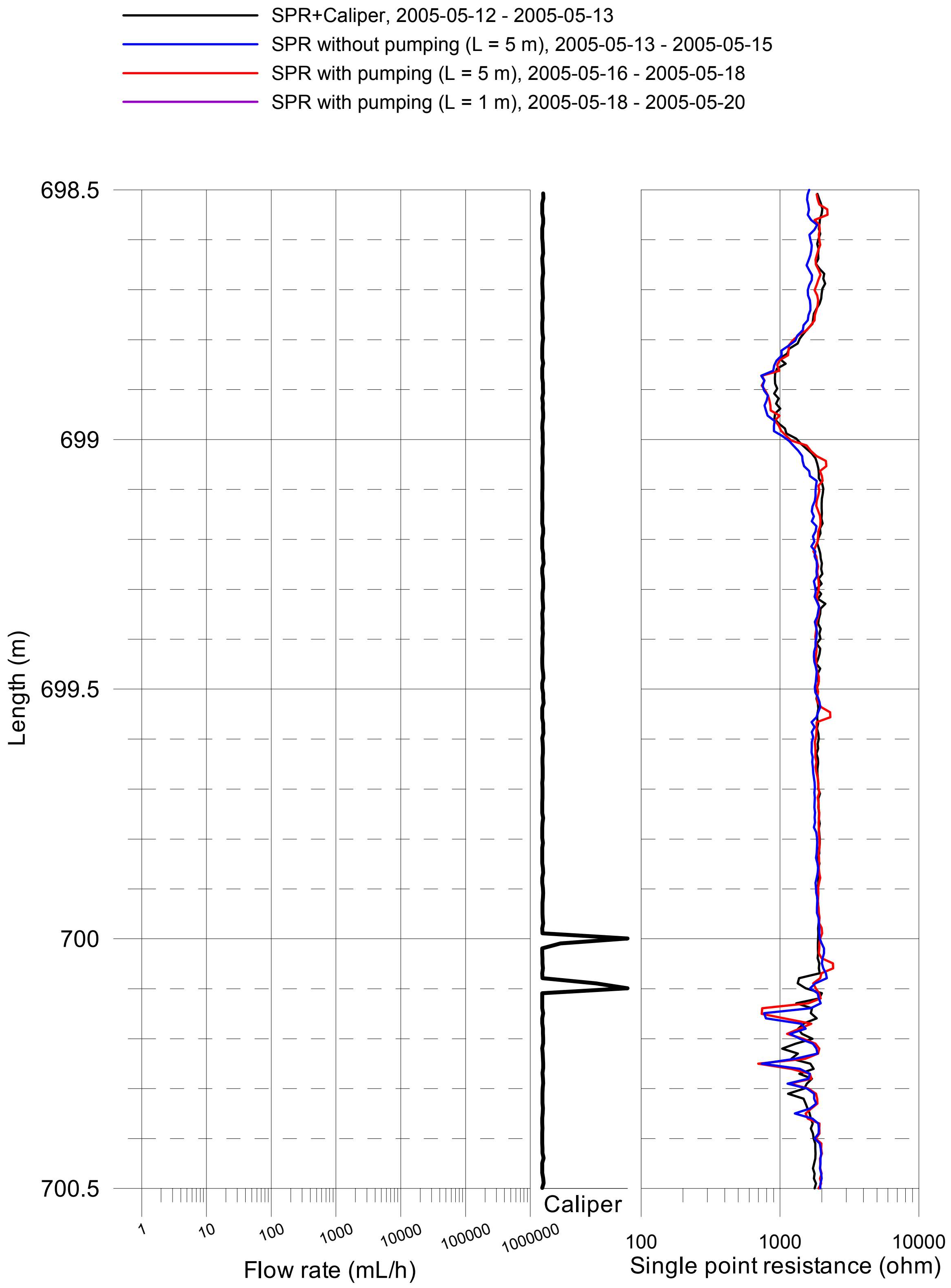
Forsmark, KFM08A
SPR and Caliper results after length correction



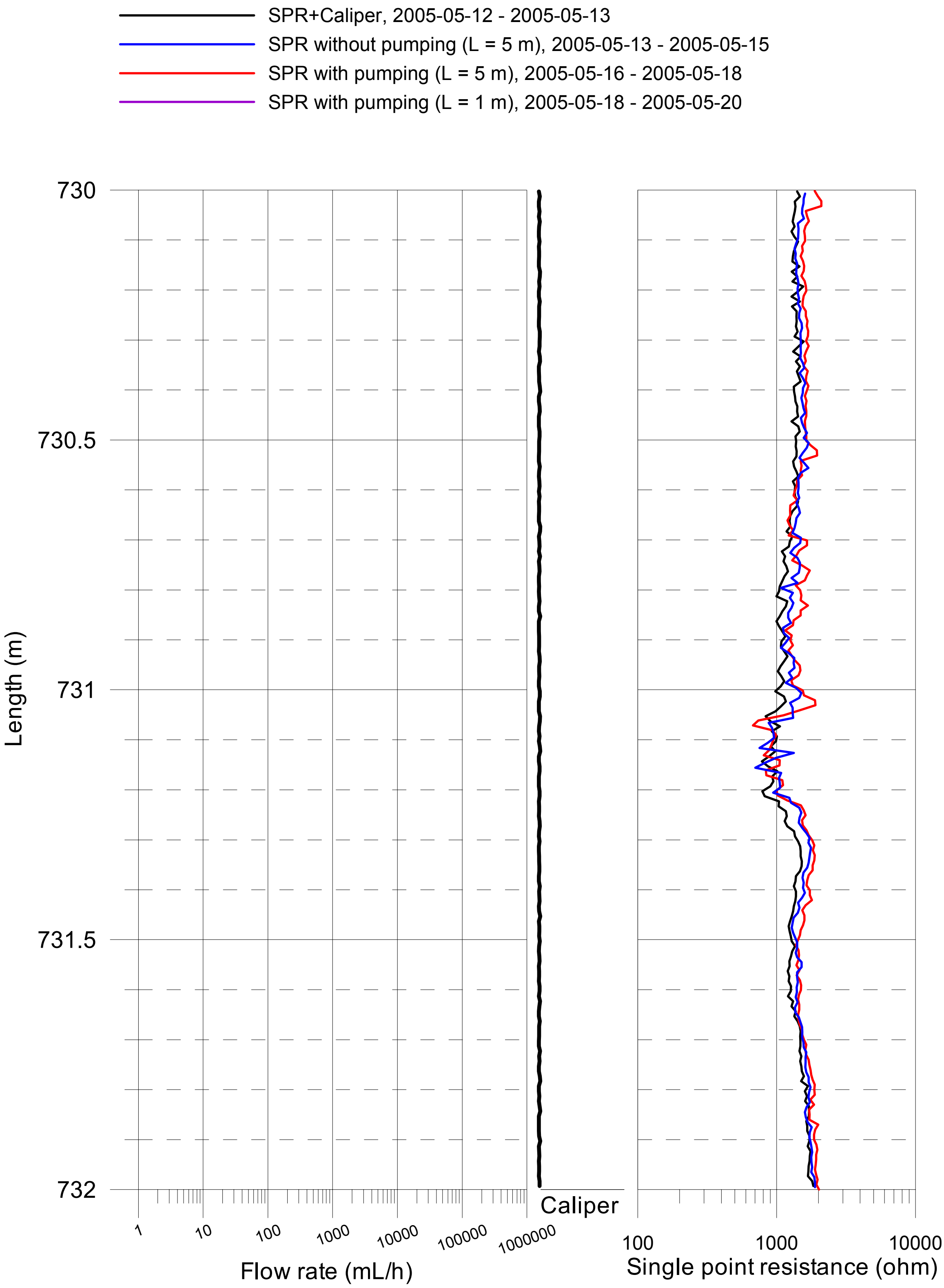
Forsmark, KFM08A
SPR and Caliper results after length correction



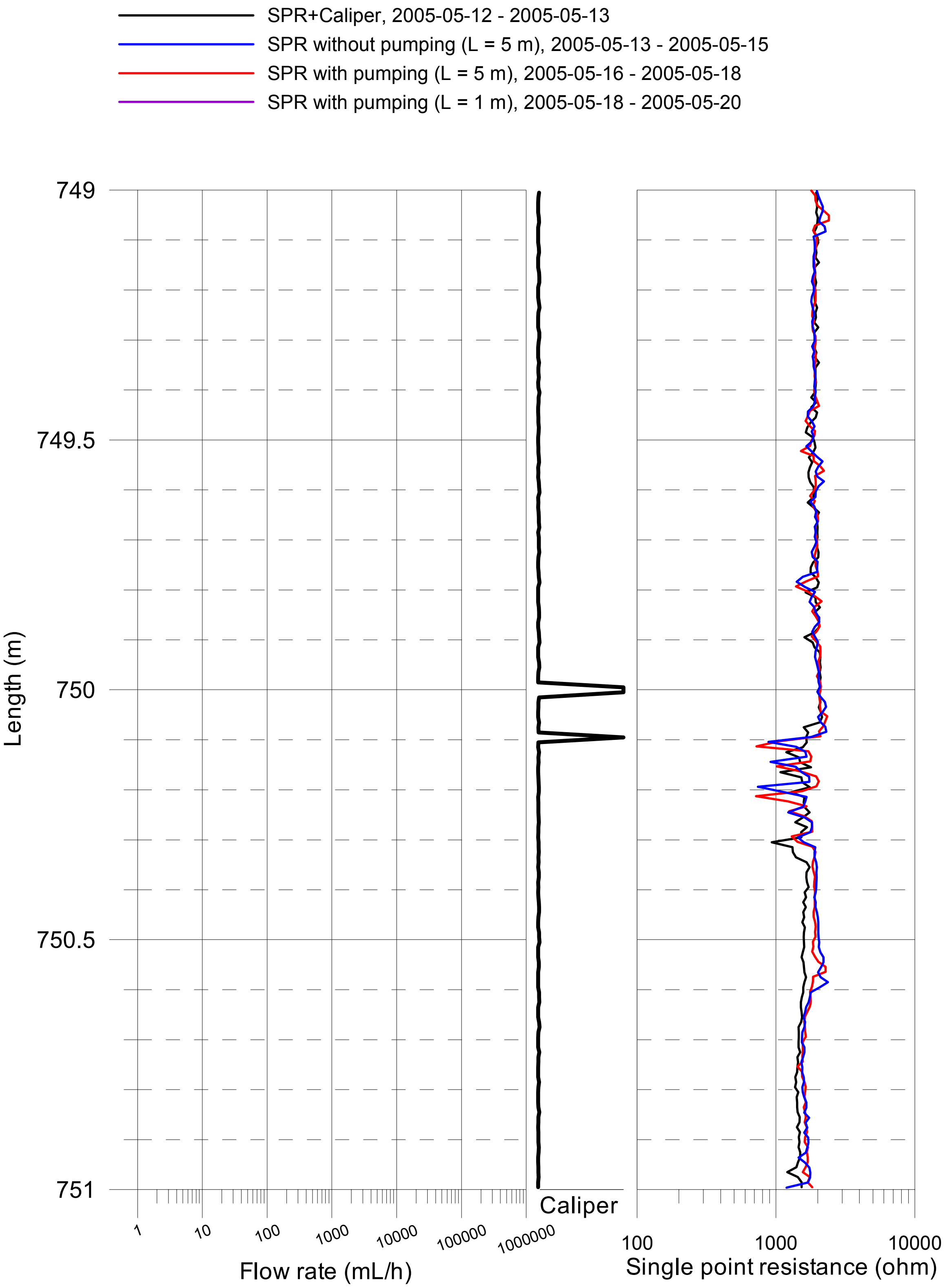
Forsmark, KFM08A
SPR and Caliper results after length correction



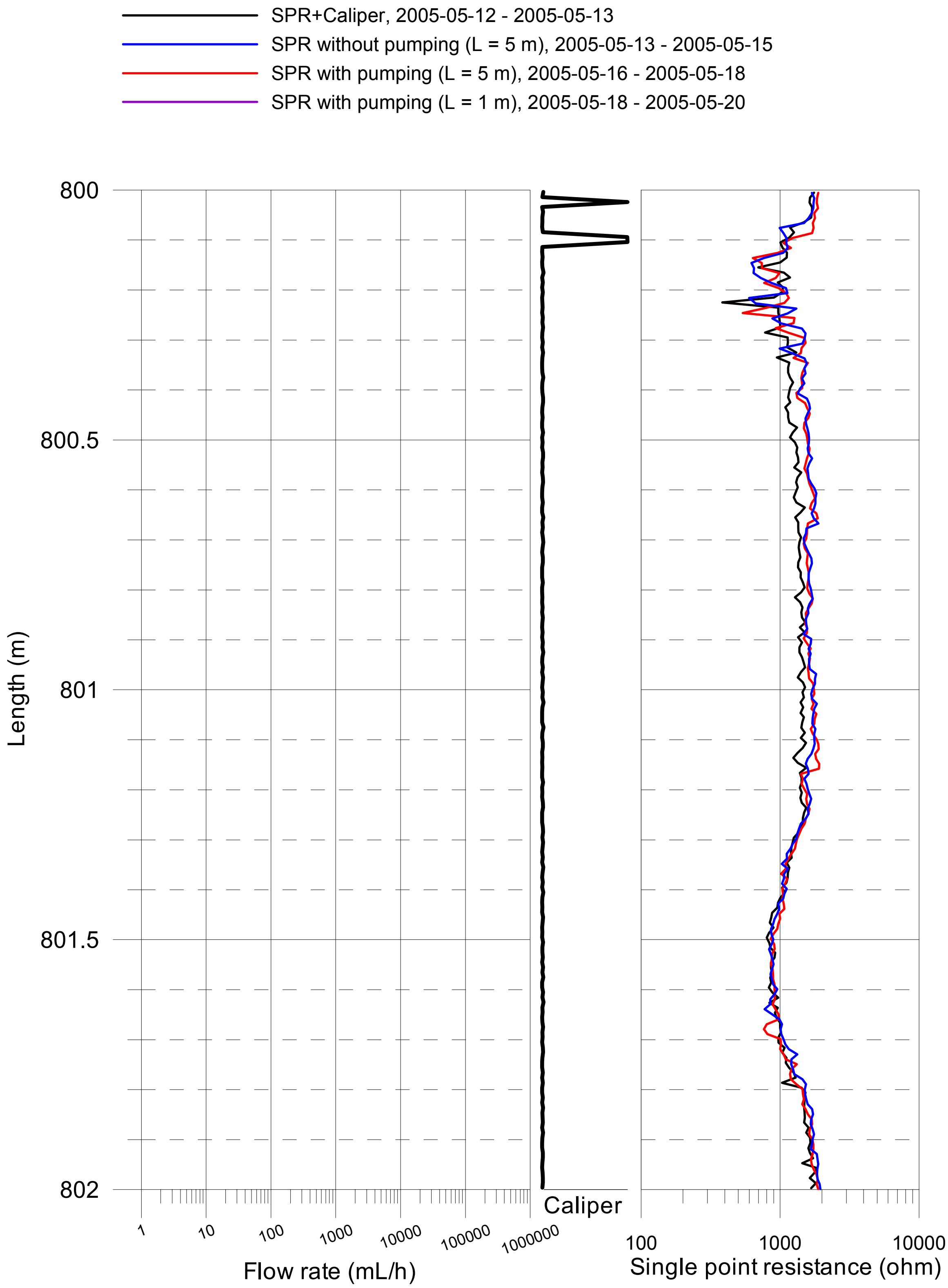
Forsmark, KFM08A
SPR and Caliper results after length correction



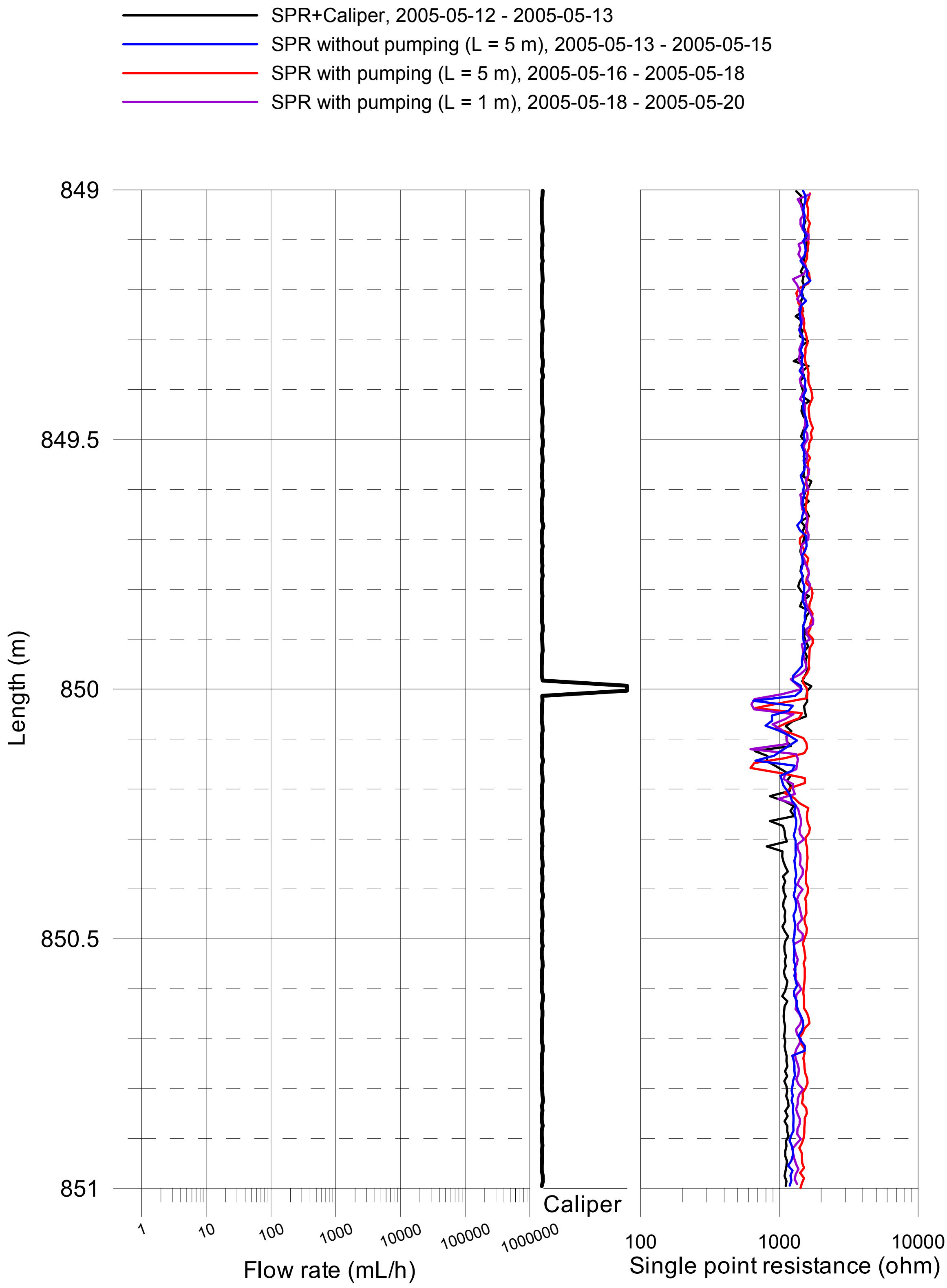
Forsmark, KFM08A
SPR and Caliper results after length correction



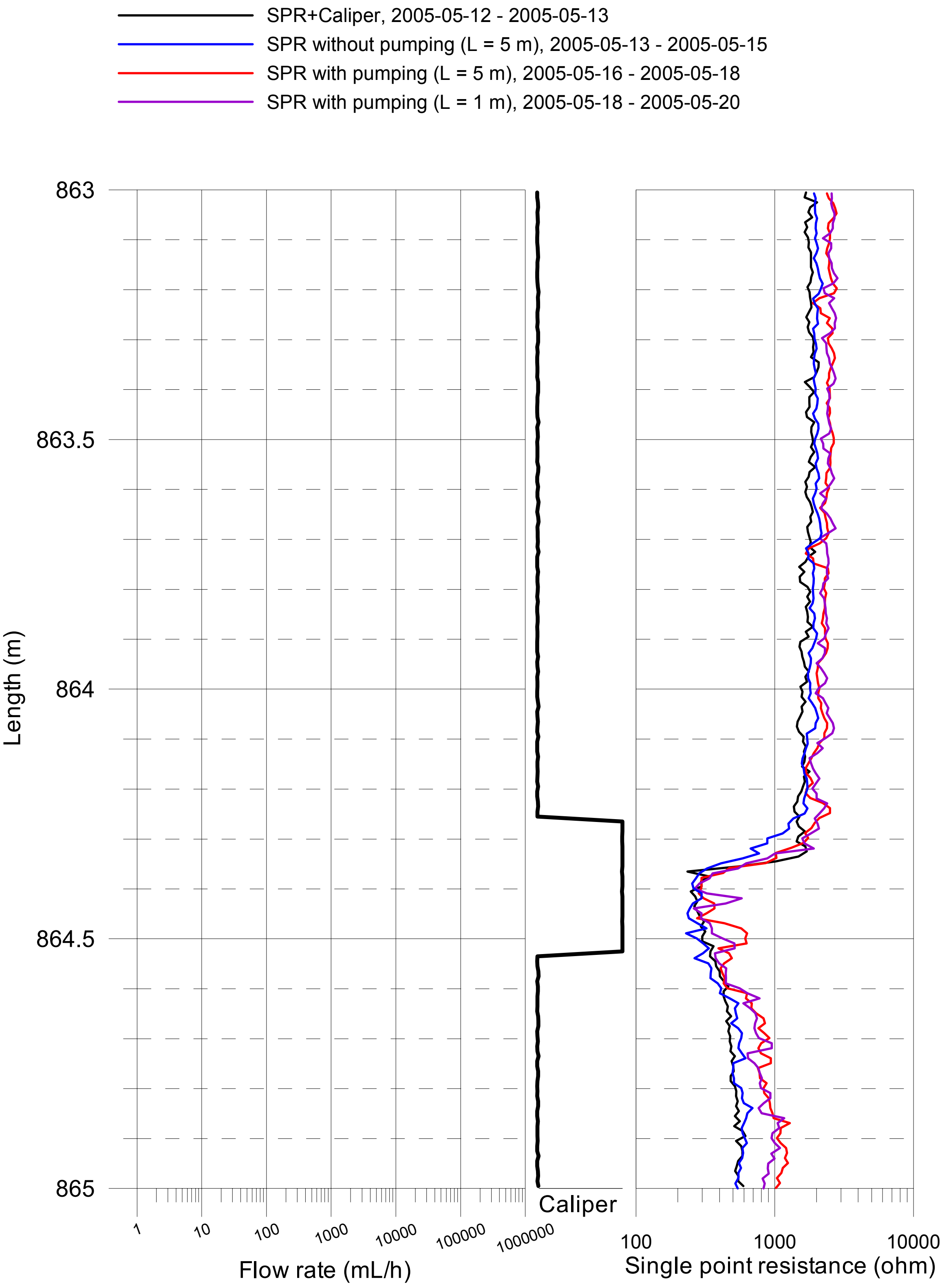
Forsmark, KFM08A
SPR and Caliper results after length correction



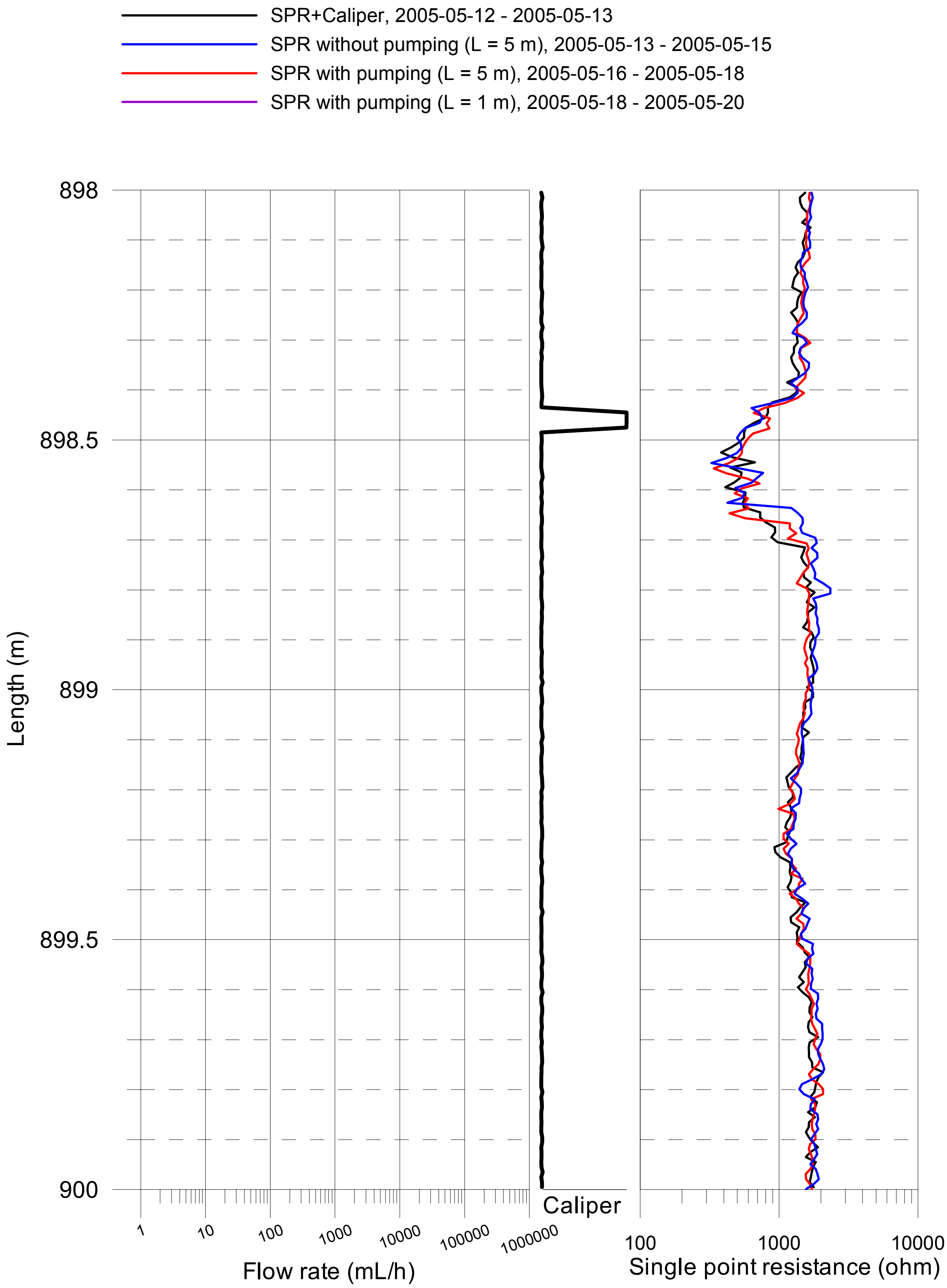
Forsmark, KFM08A
SPR and Caliper results after length correction



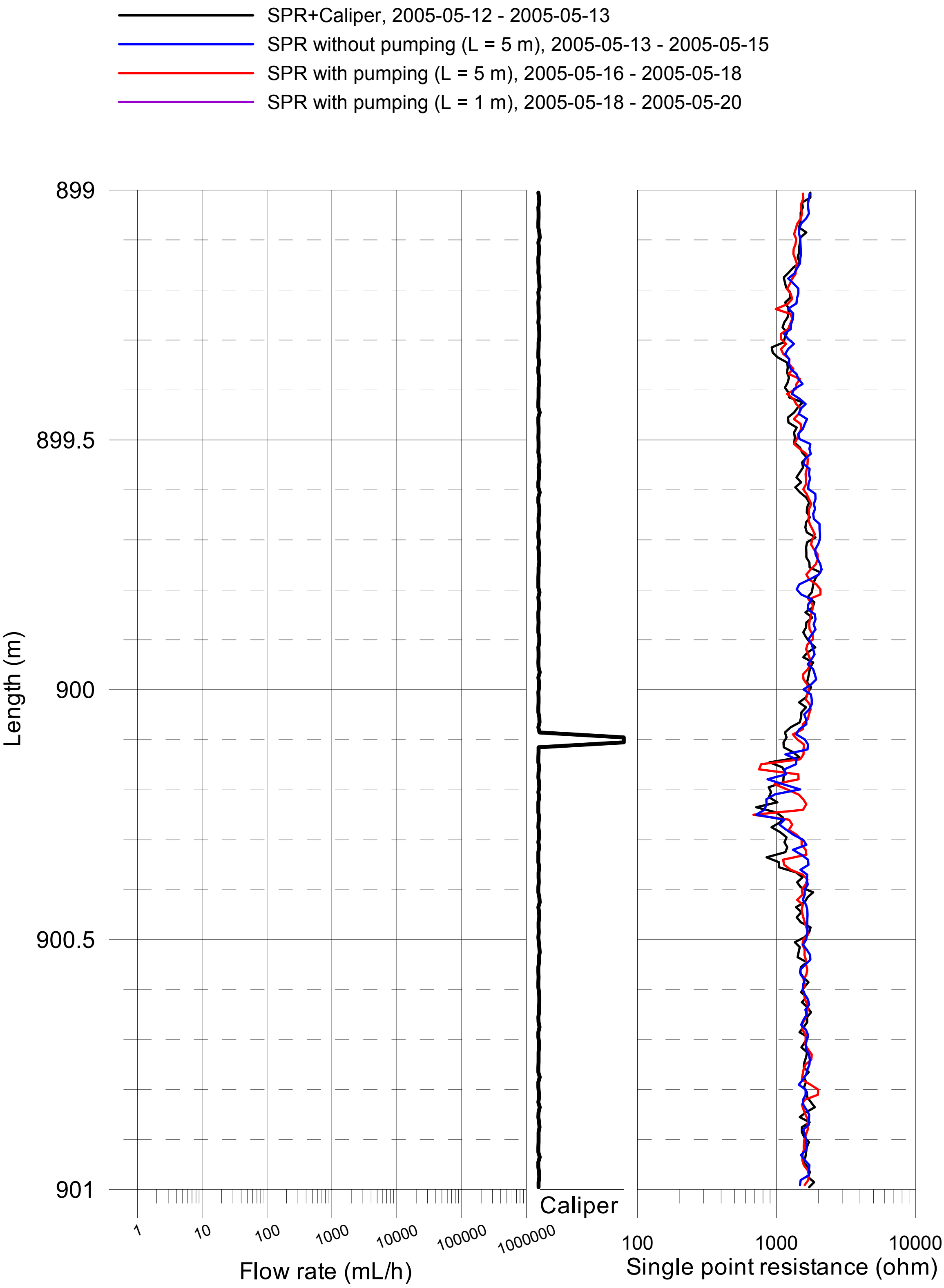
Forsmark, KFM08A
SPR and Caliper results after length correction



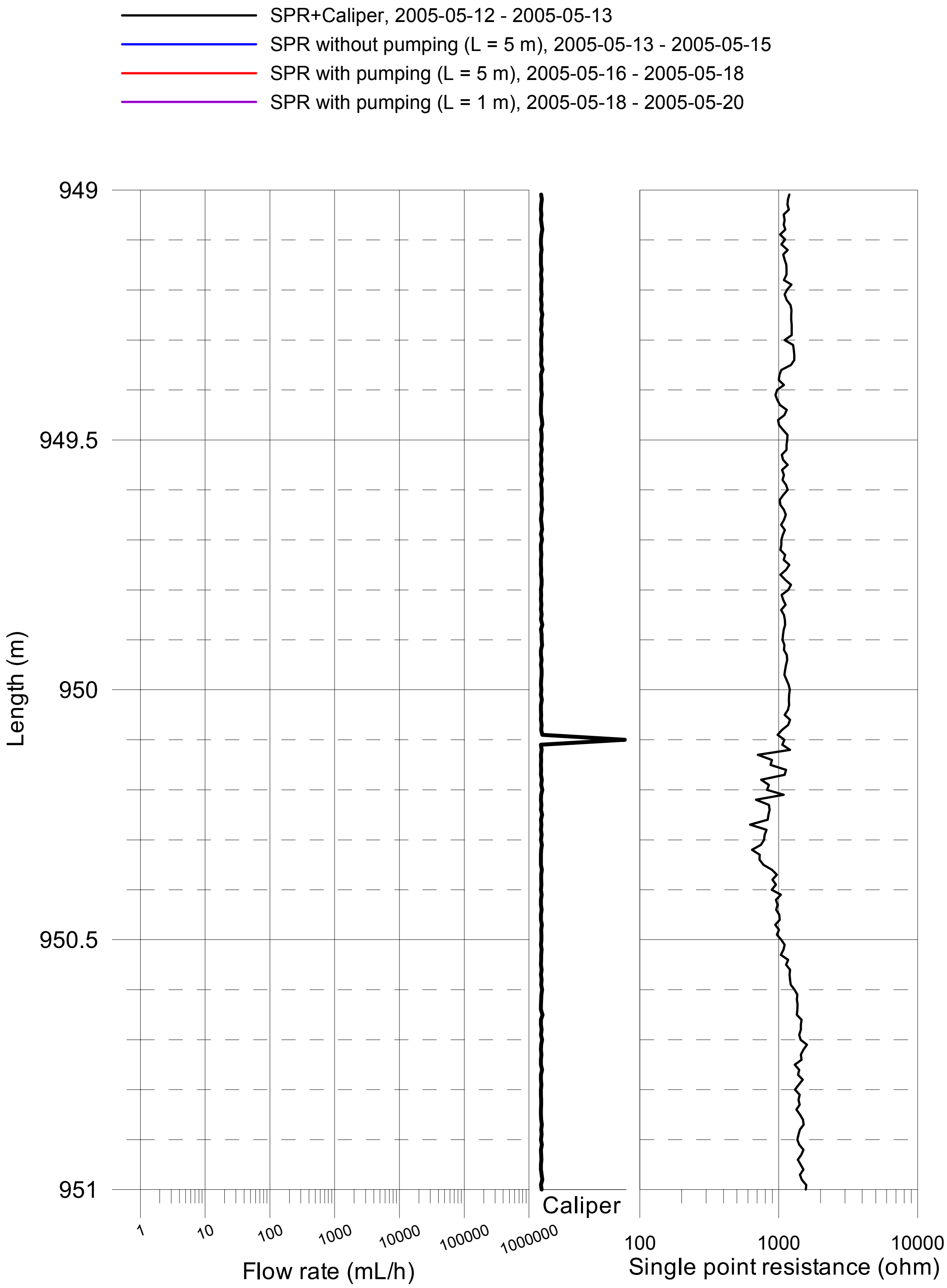
Forsmark, KFM08A
SPR and Caliper results after length correction

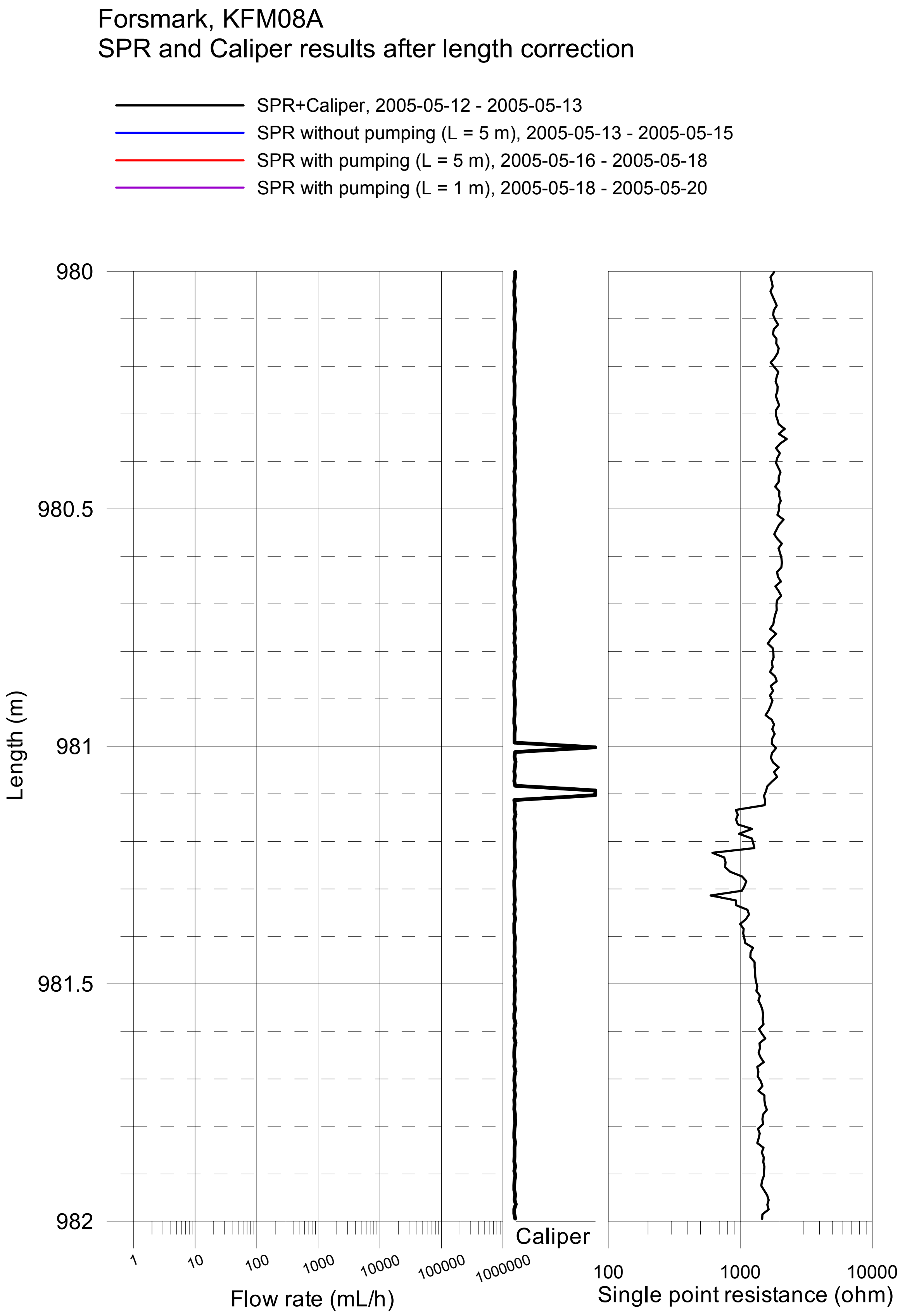


Forsmark, KFM08A
SPR and Caliper results after length correction

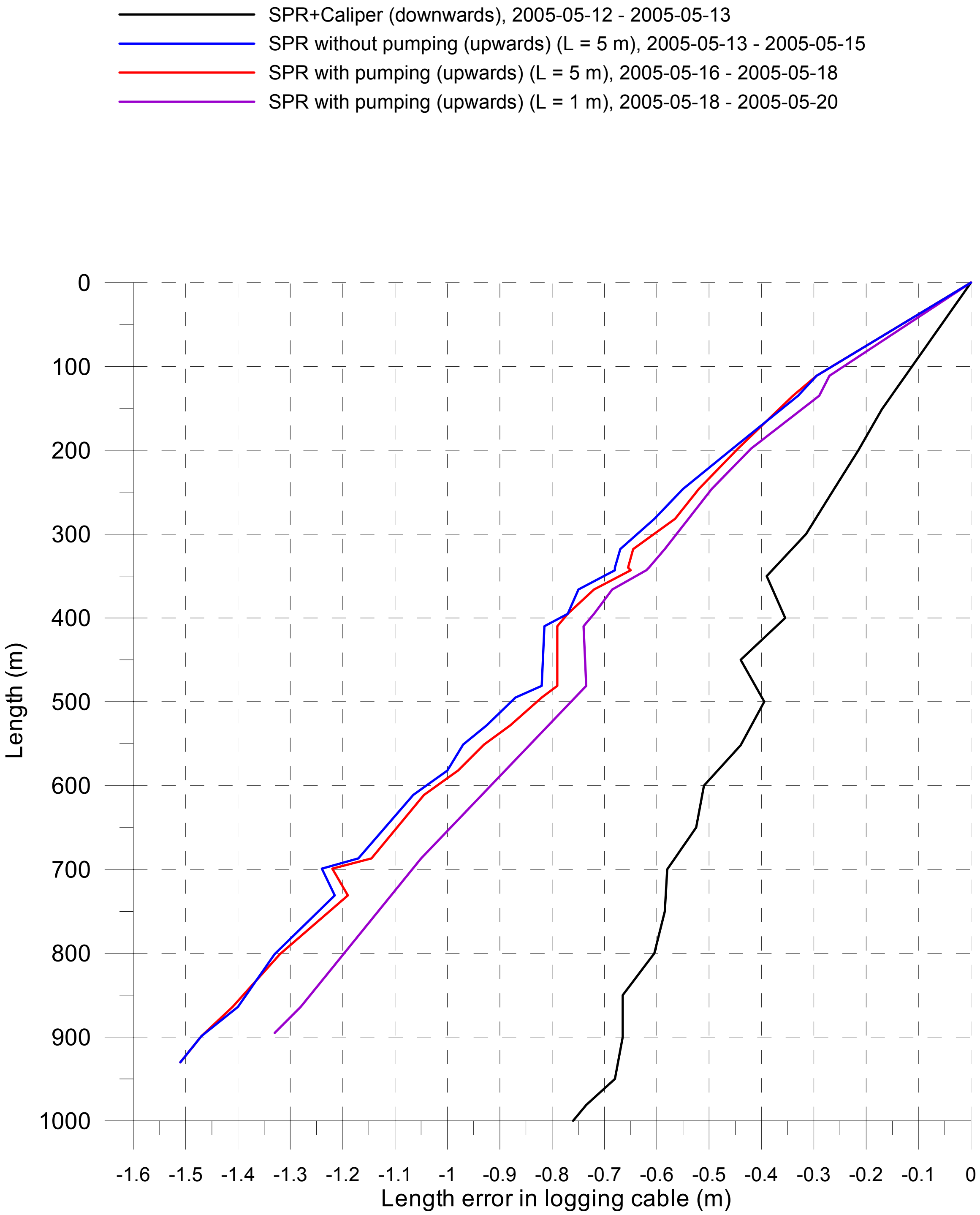


Forsmark, KFM08A
SPR and Caliper results after length correction

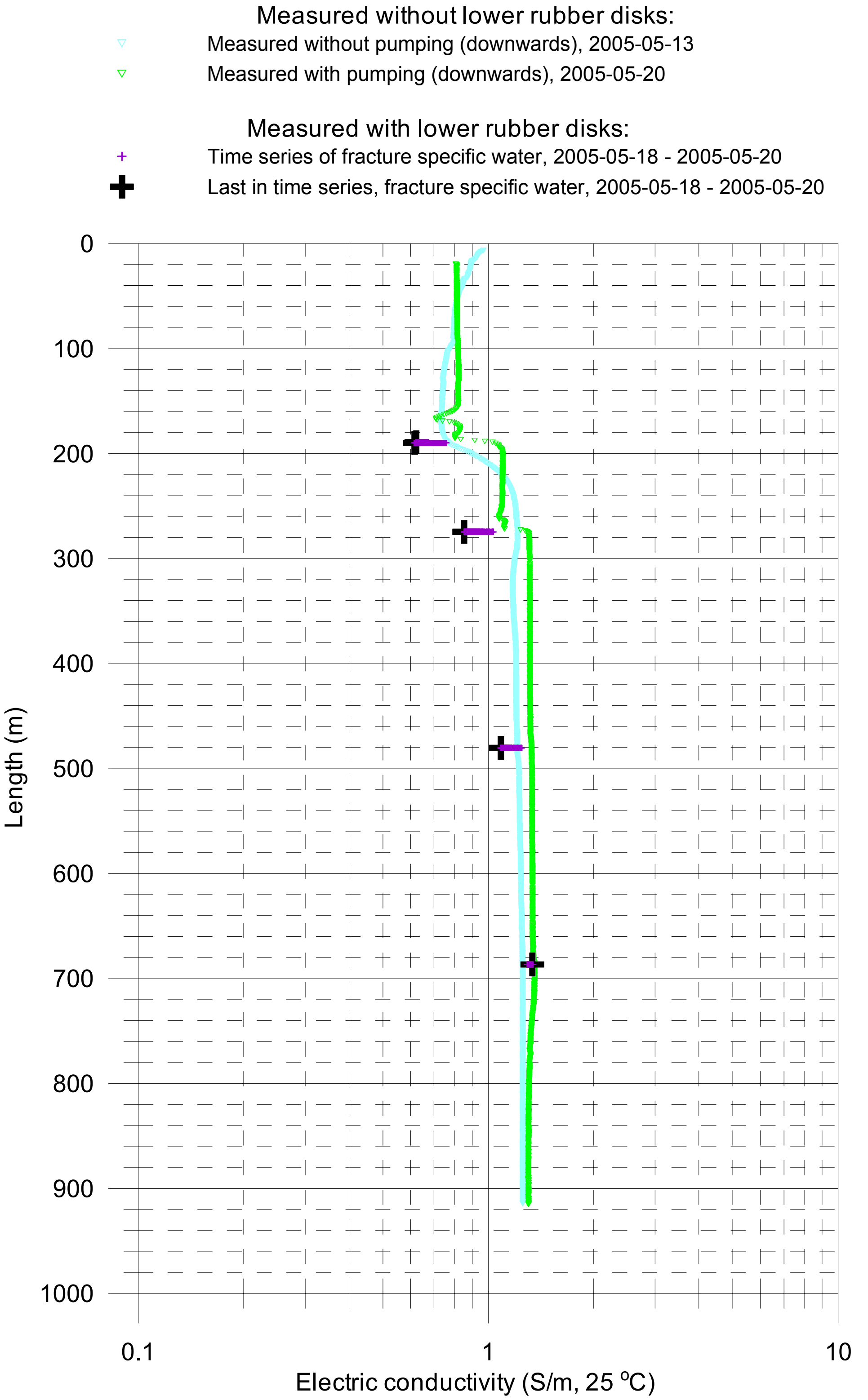


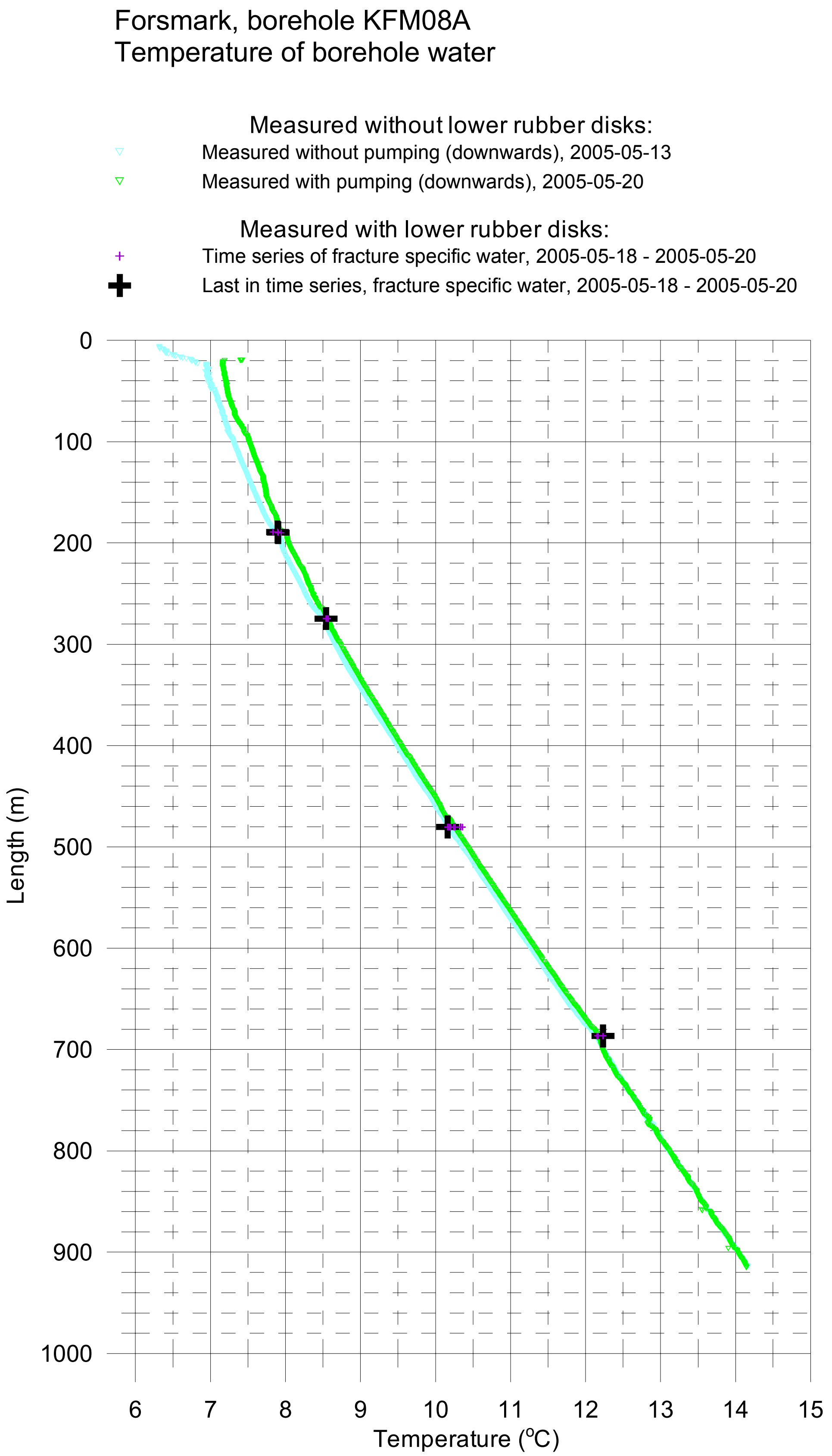

Forsmark, KFM08A
SPR and Caliper results after length correction
SPR+Caliper, 2005-05-12 - 2005-05-13
SPR without pumping (L = 5 m), 2005-05-13 - 2005-05-15
SPR with pumping (L = 5 m), 2005-05-16 - 2005-05-18
SPR with pumping (L = 1 m), 2005-05-18 - 2005-05-20
Length (m)
980
980.5
981
981.5
982
1
10
100
1000
10000
100000
1000000
Flow rate (mL/h)
Caliper
100
1000
10000
Single point resistance (ohm)

Forsmark, KFM08A
Length correction

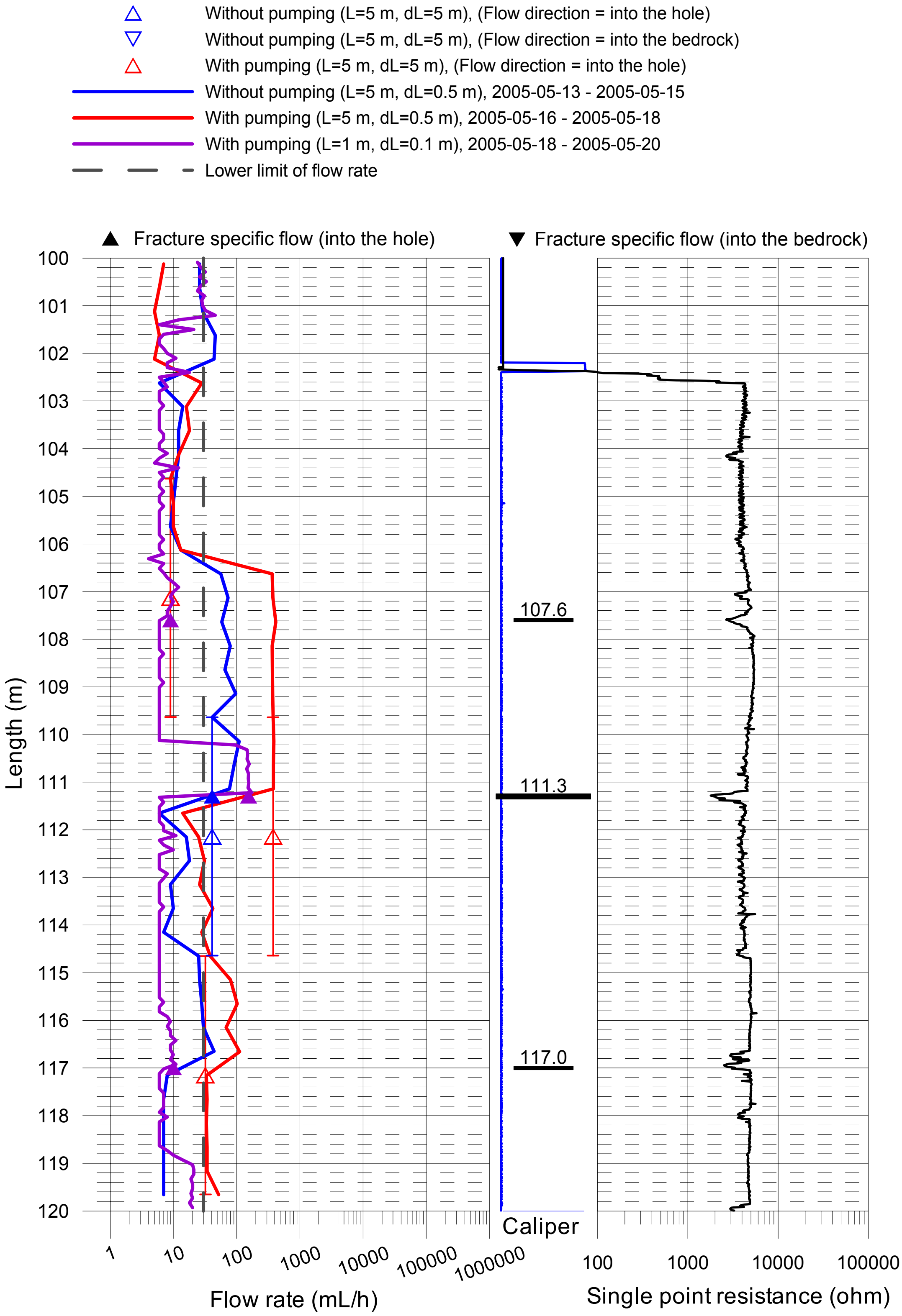


Forsmark, borehole KFM08A
Electric conductivity of borehole water

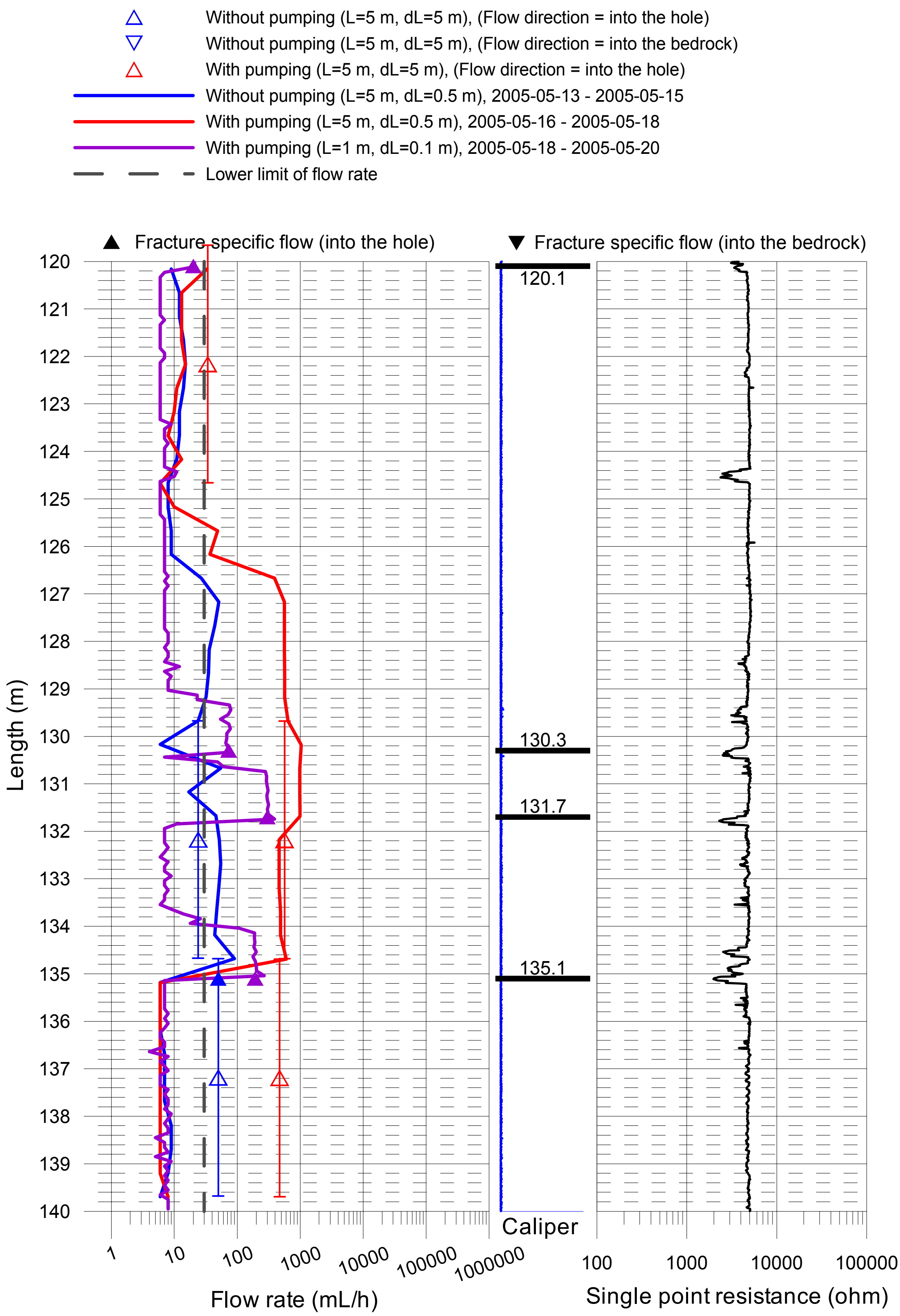



Forsmark, borehole KFM08A
Temperature of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2005-05-13
Measured with pumping (downwards), 2005-05-20
Measured with lower rubber disks:
Time series of fracture specific water, 2005-05-18 - 2005-05-20
Last in time series, fracture specific water, 2005-05-18 - 2005-05-20
Length (m)
0
100
200
300
400
500
600
700
800
900
1000
6
7
8
9
10
11
12
13
14
15
Temperature (°C)

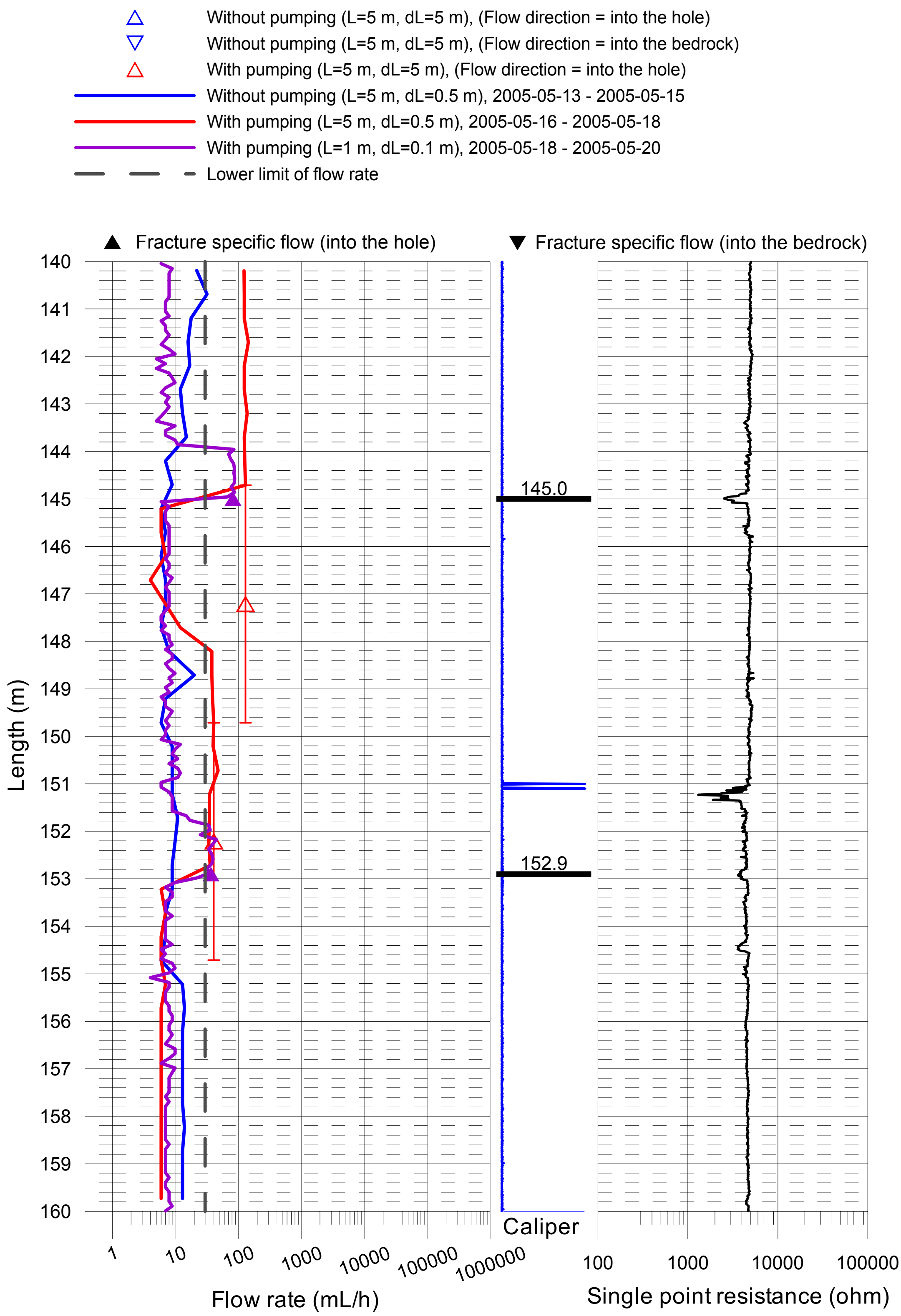
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



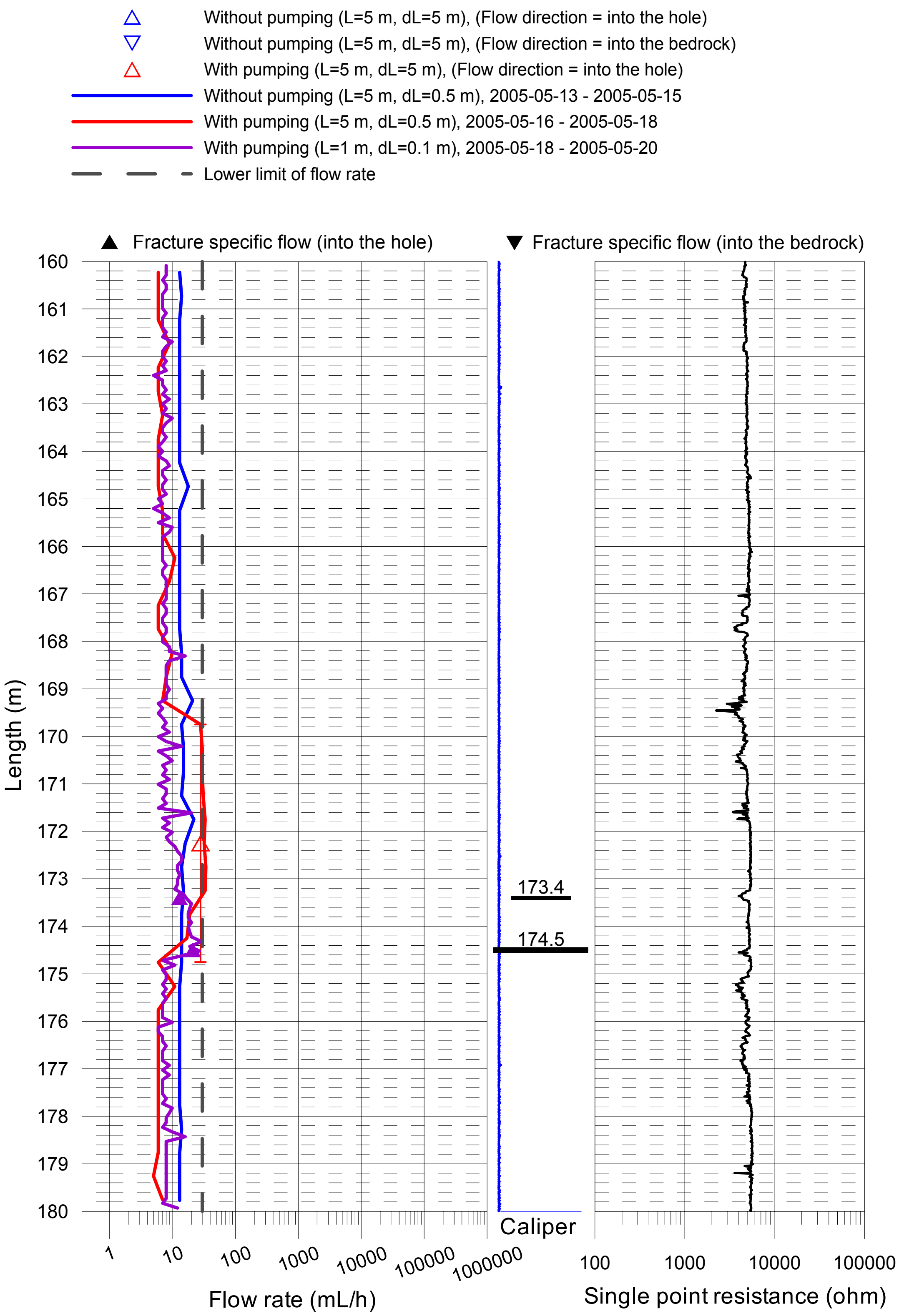
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



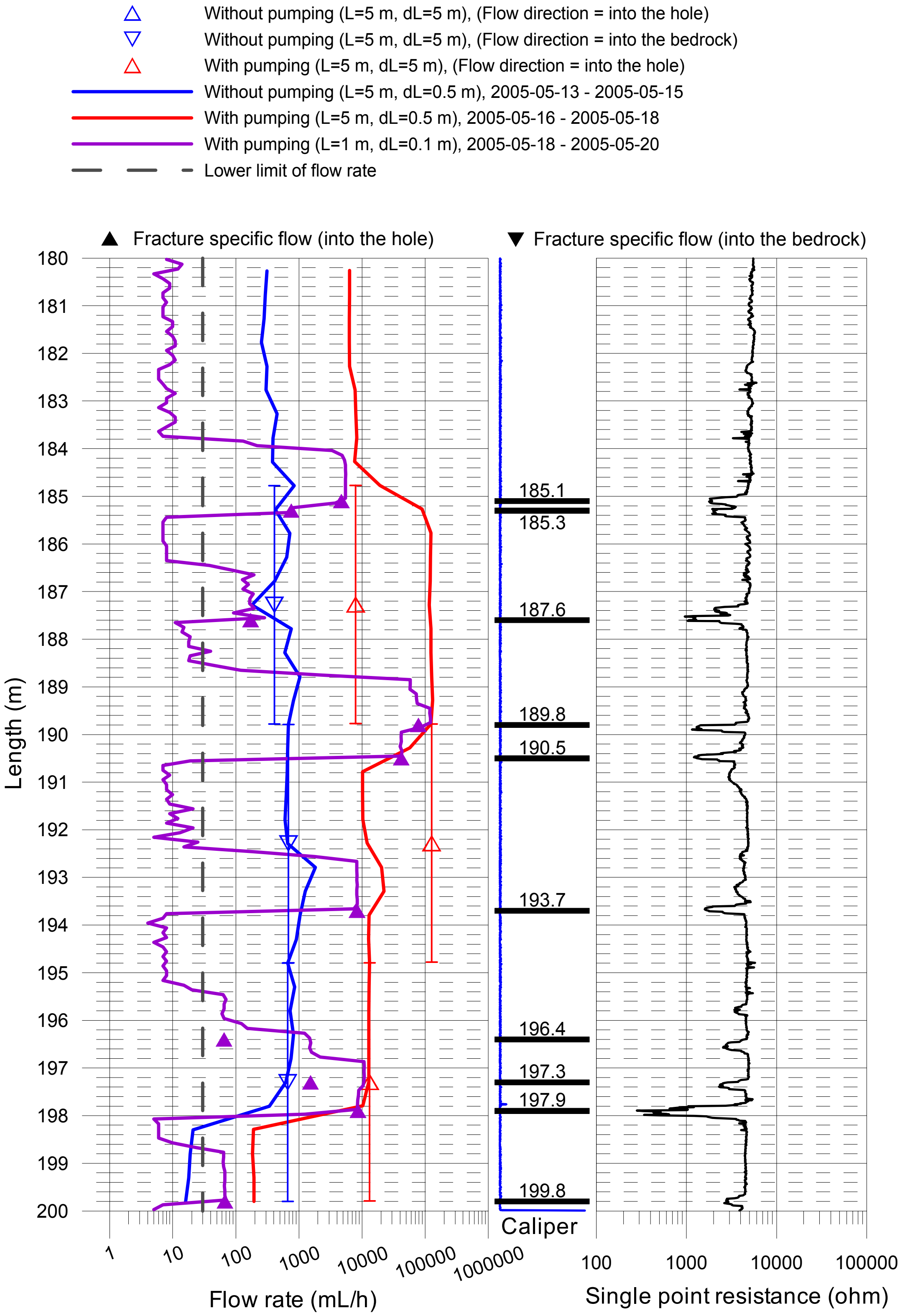
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



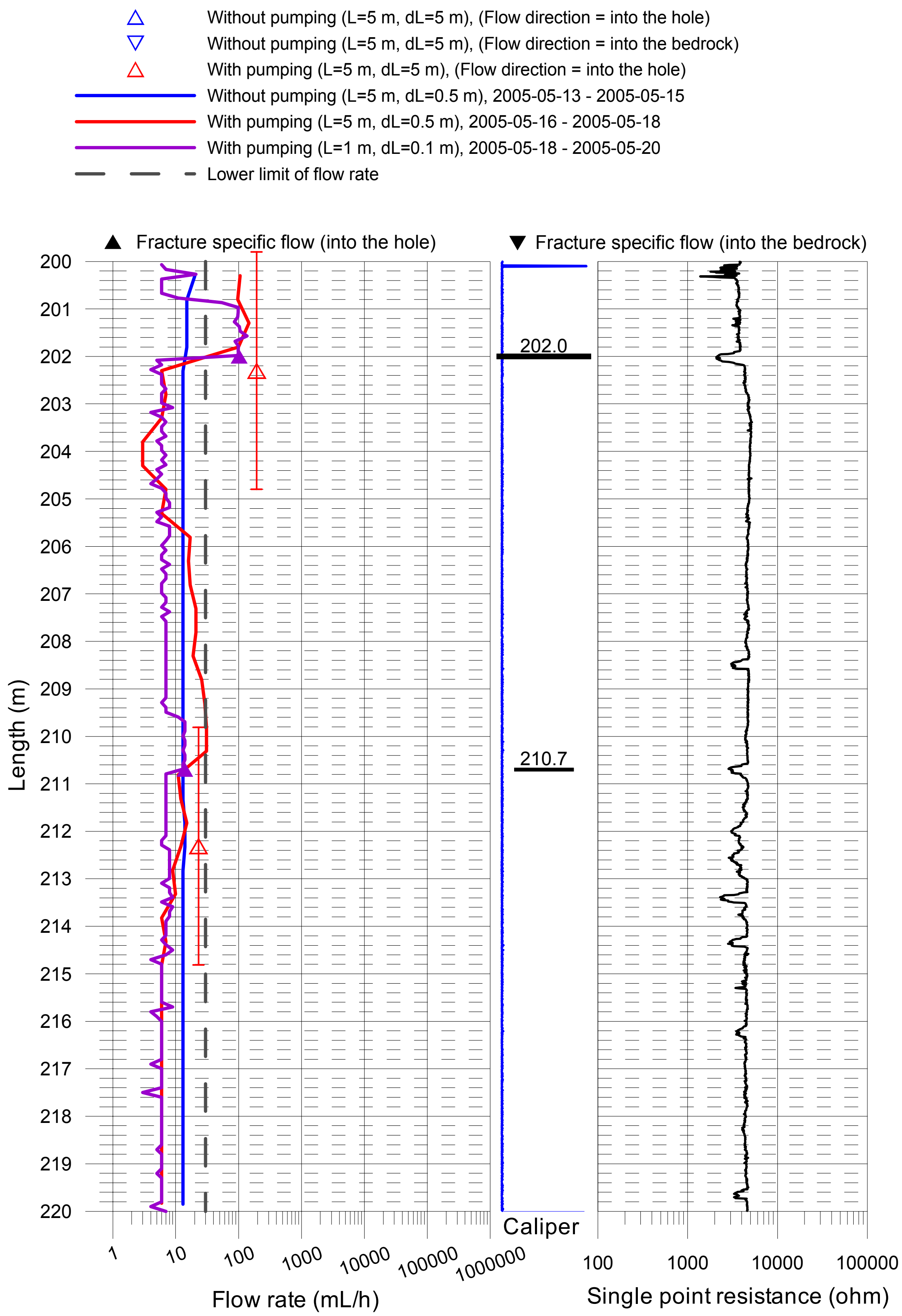
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



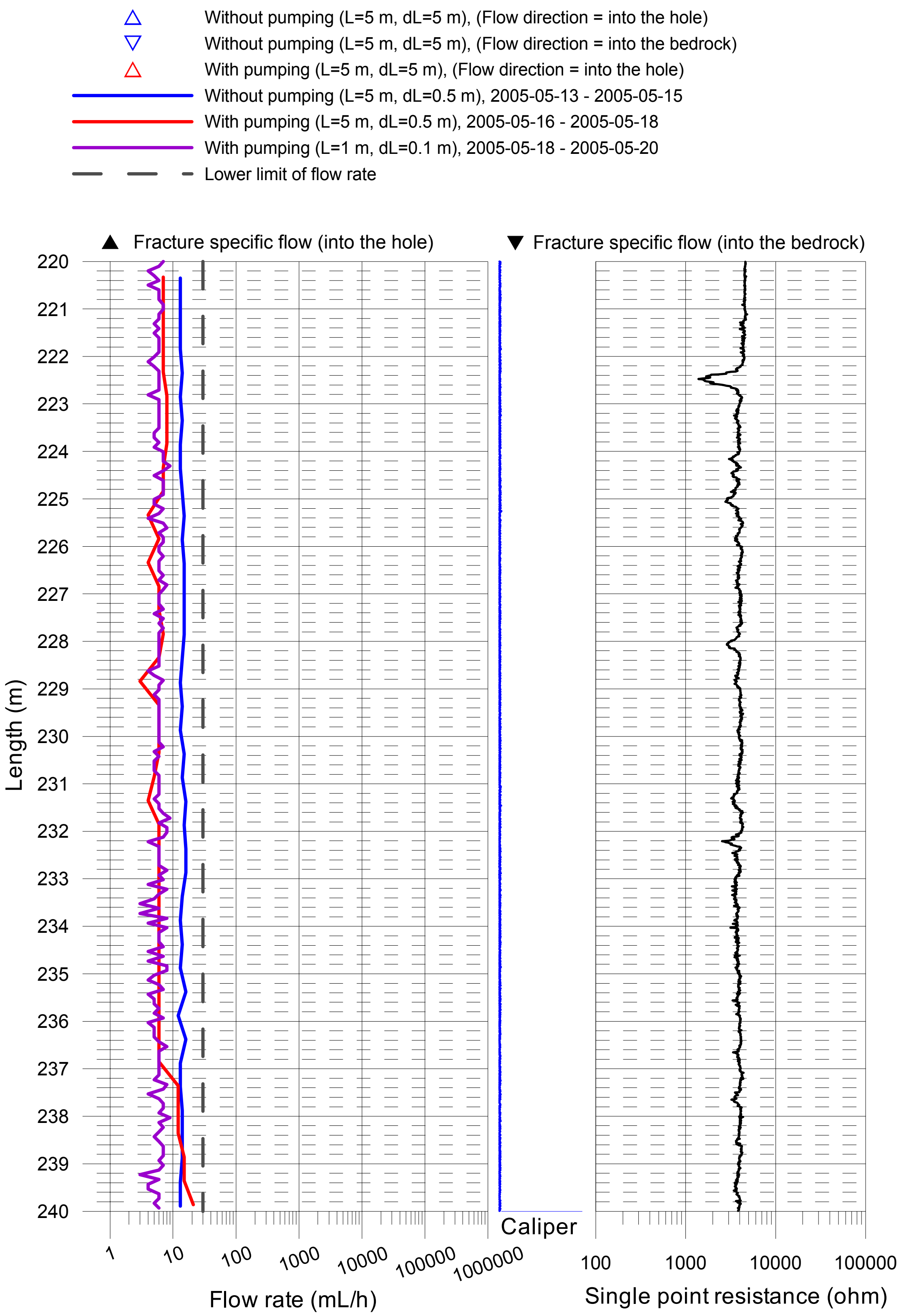
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



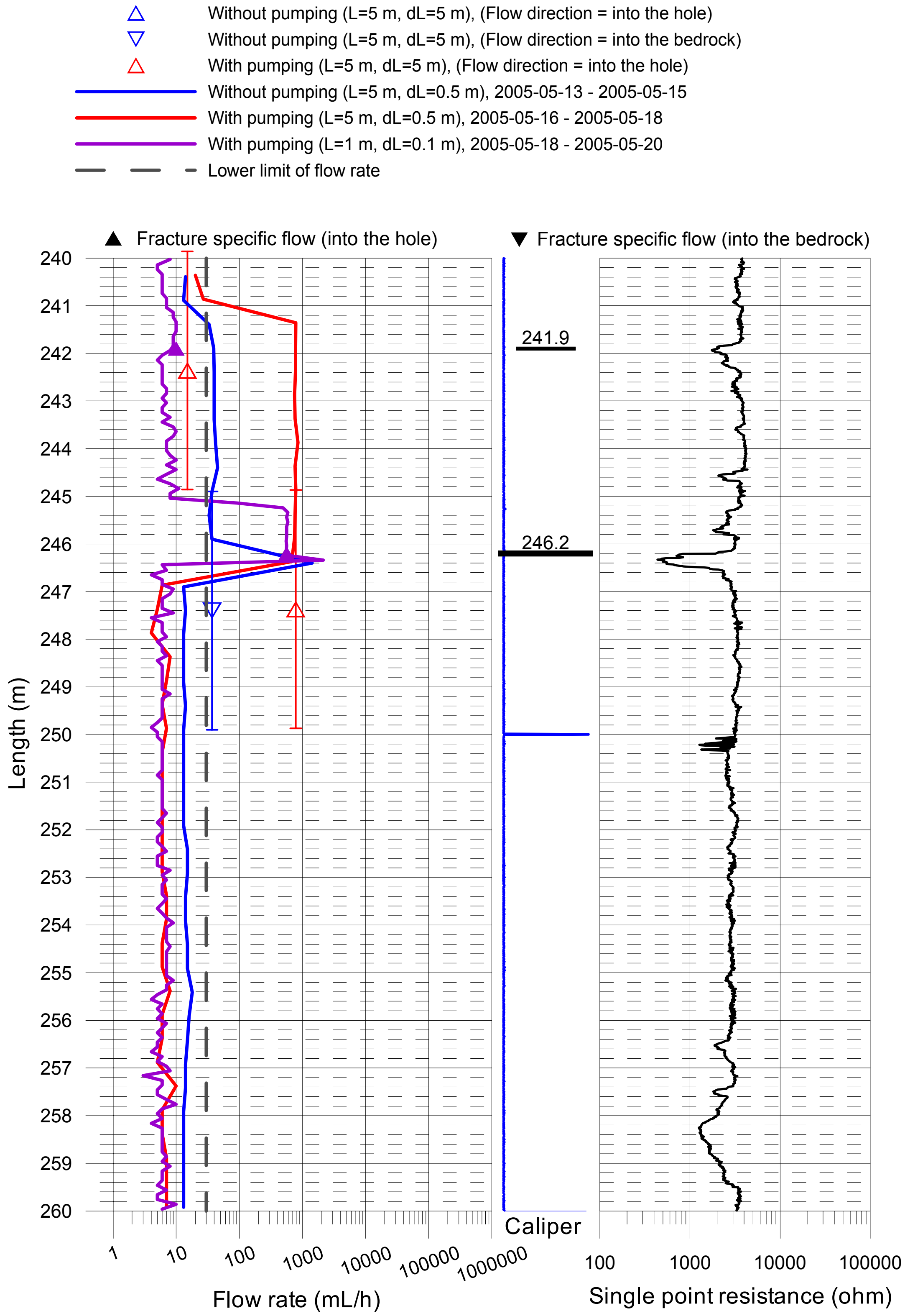
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



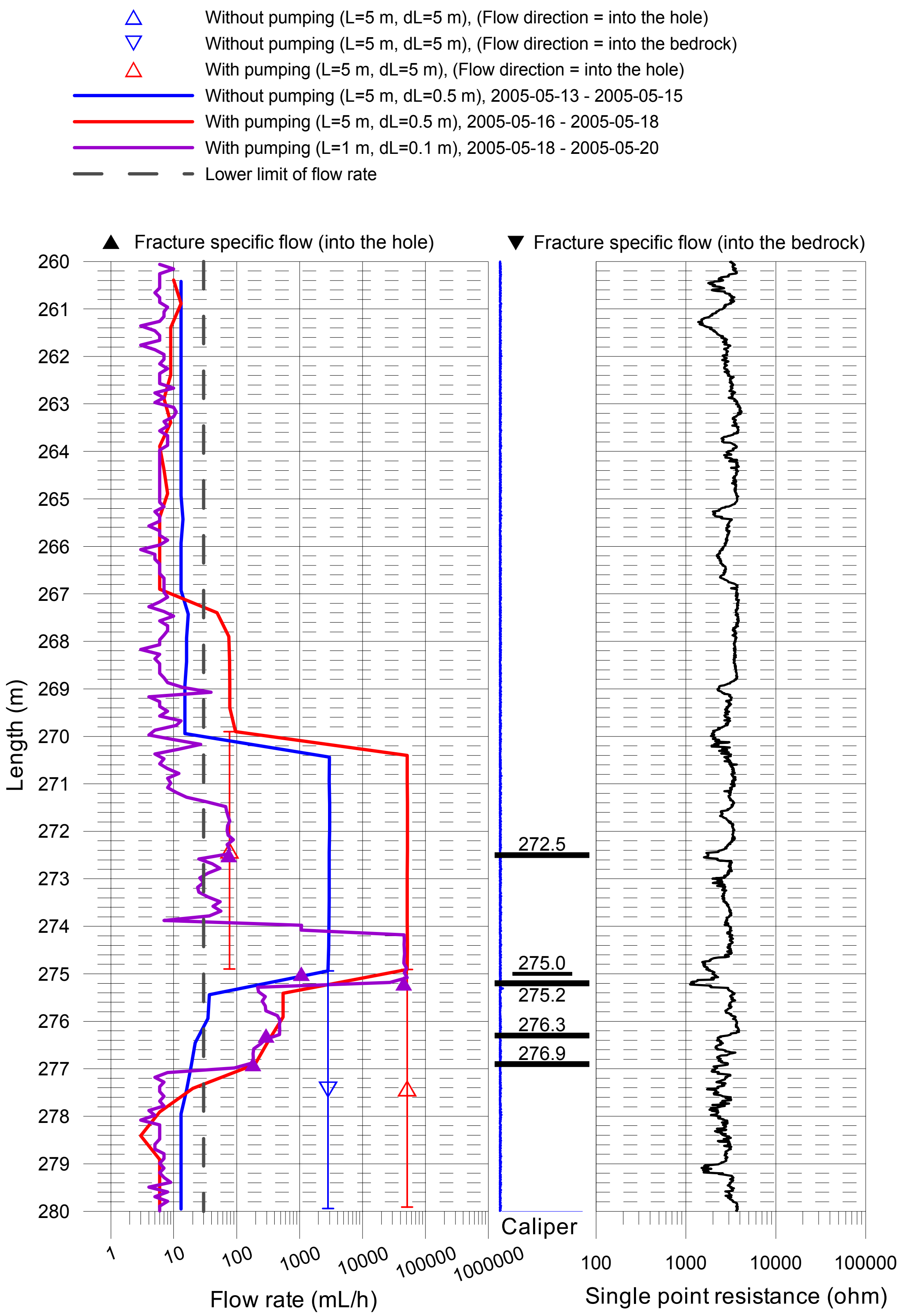
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



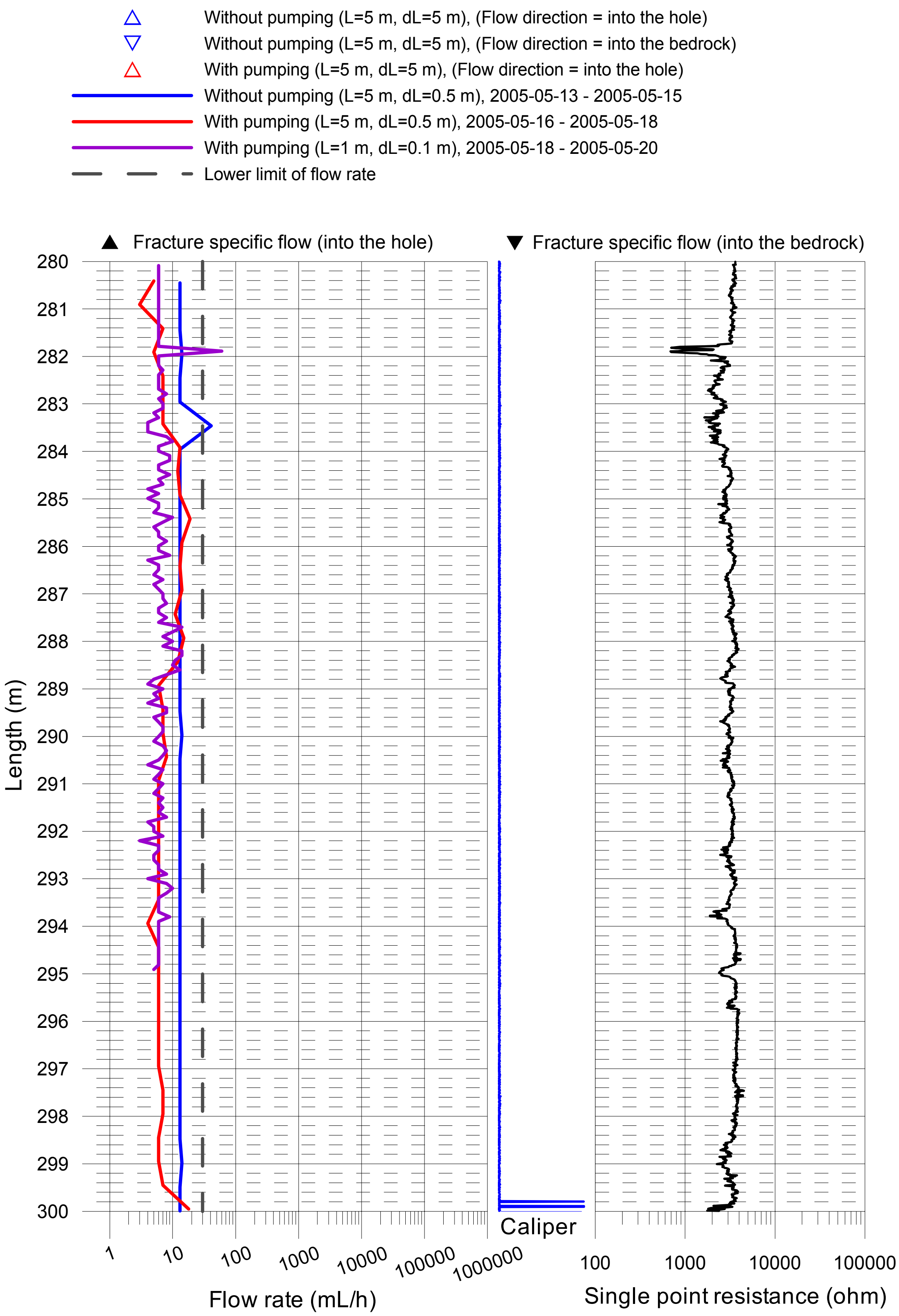
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



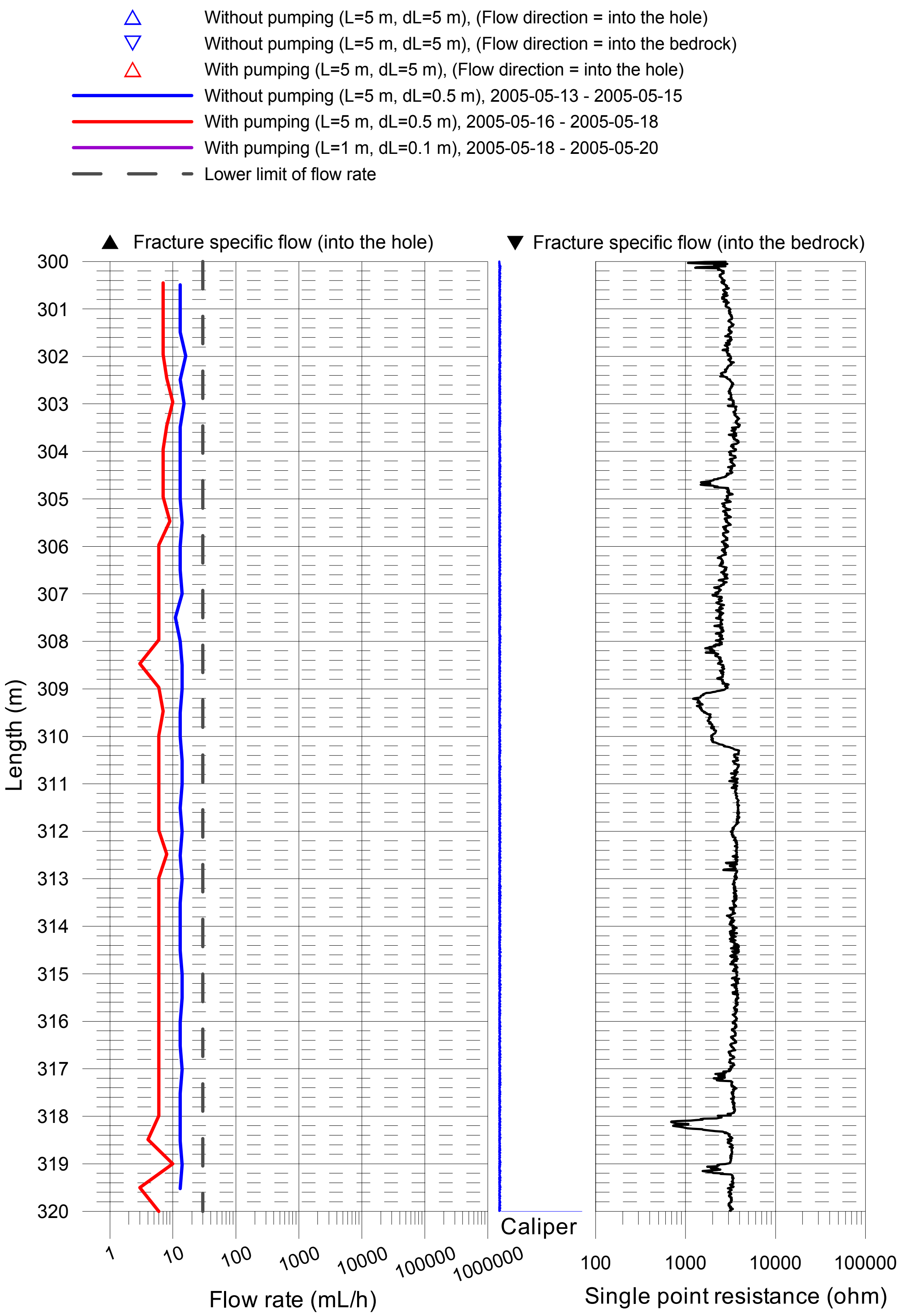
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



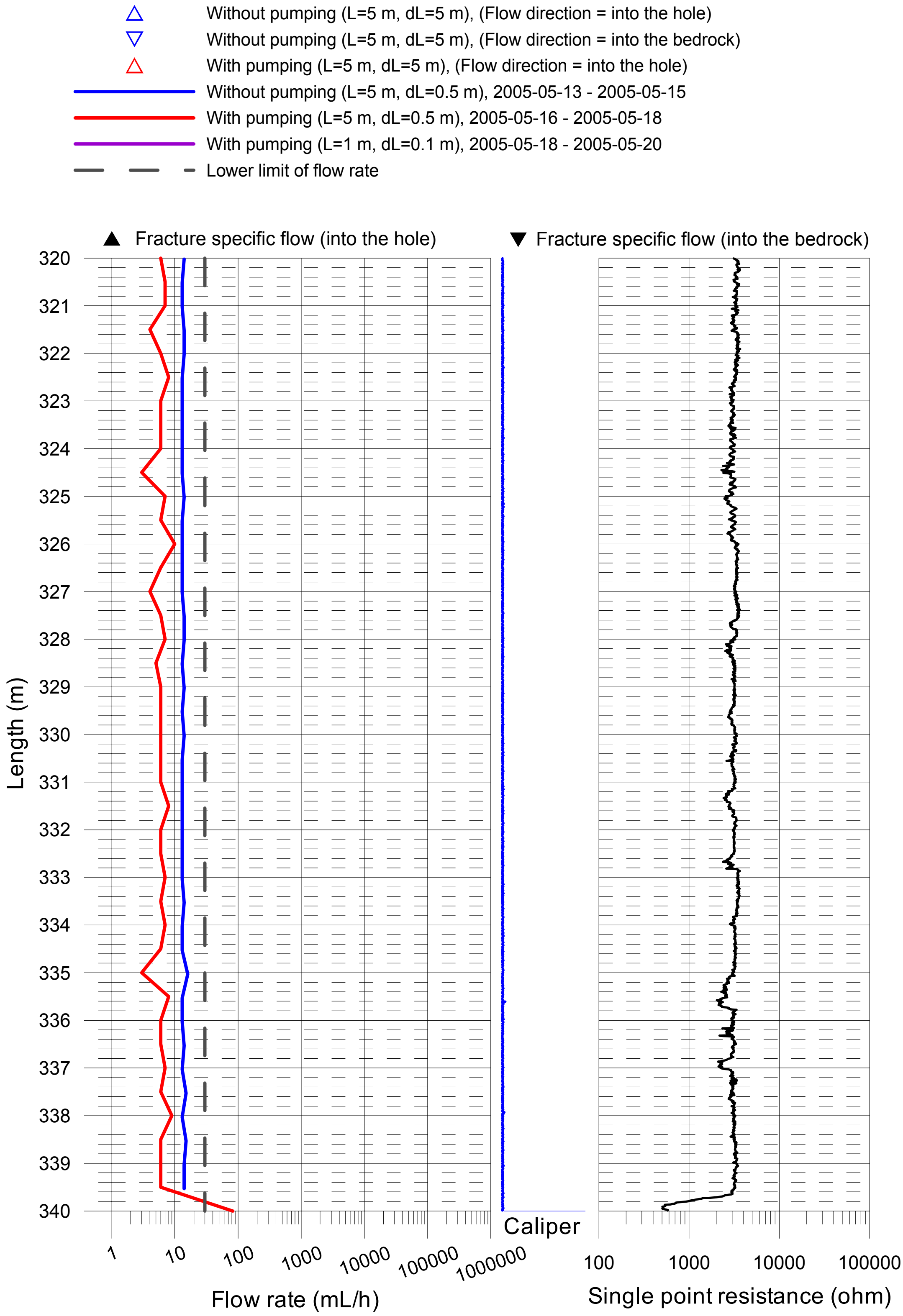
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



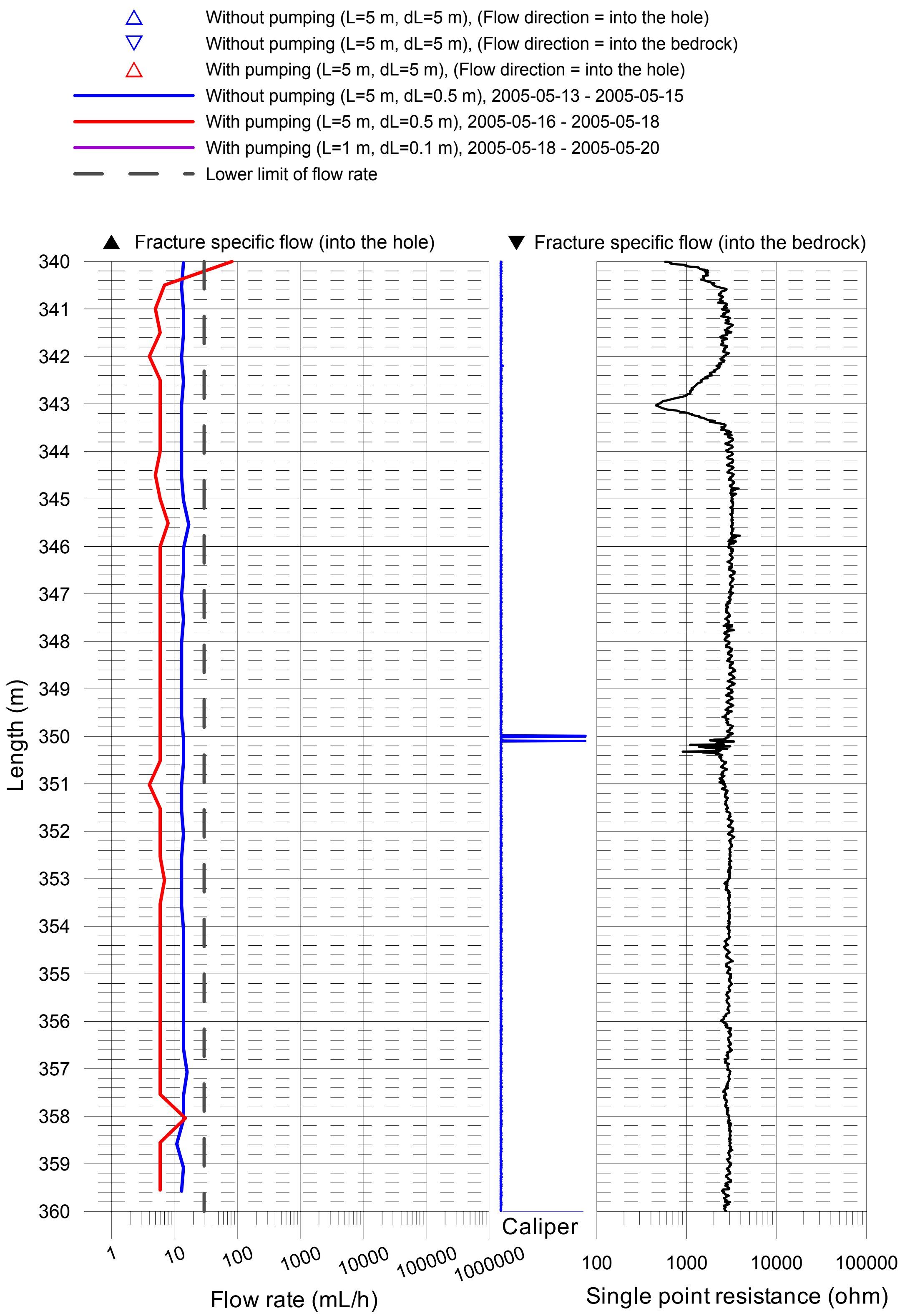
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



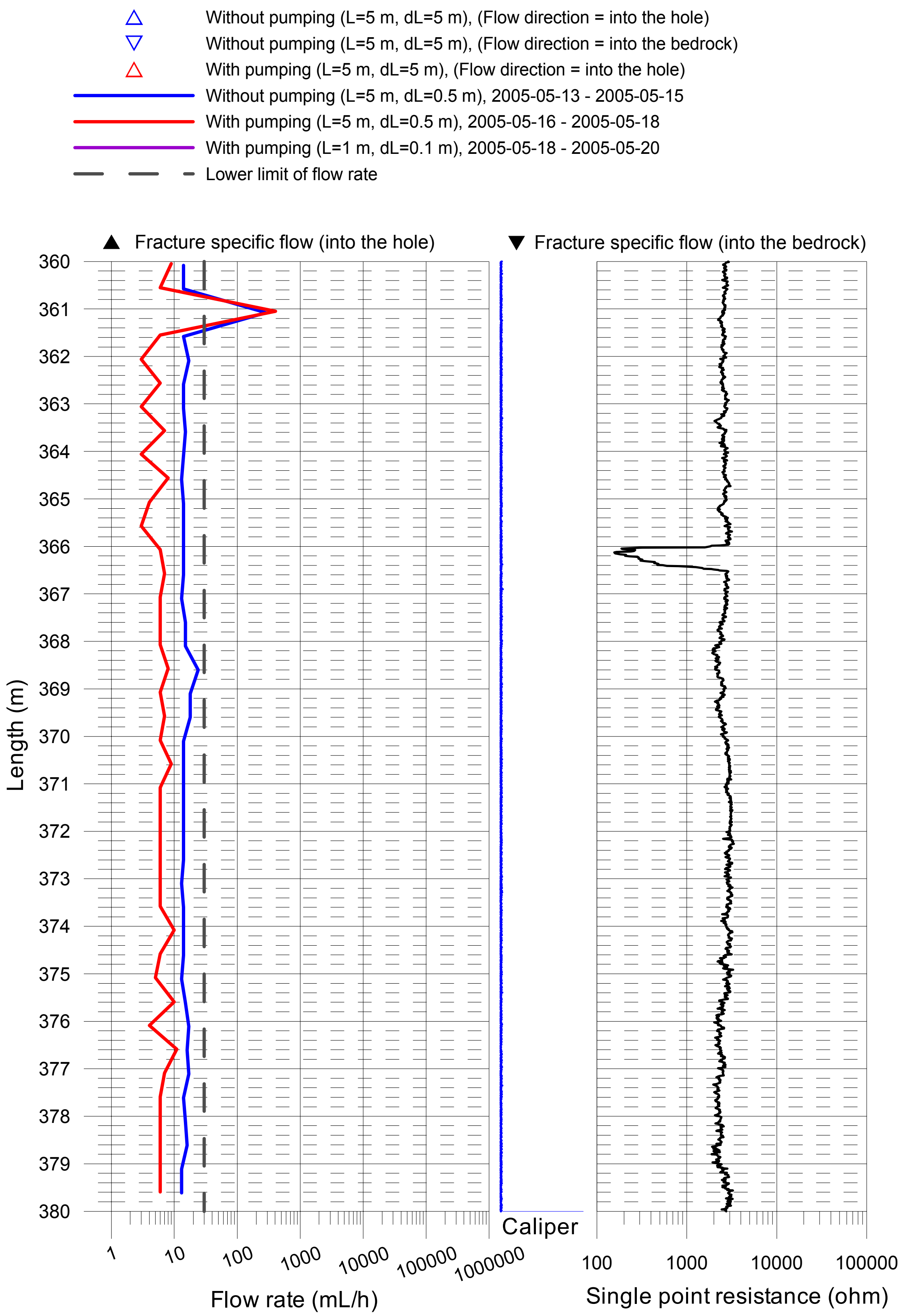
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



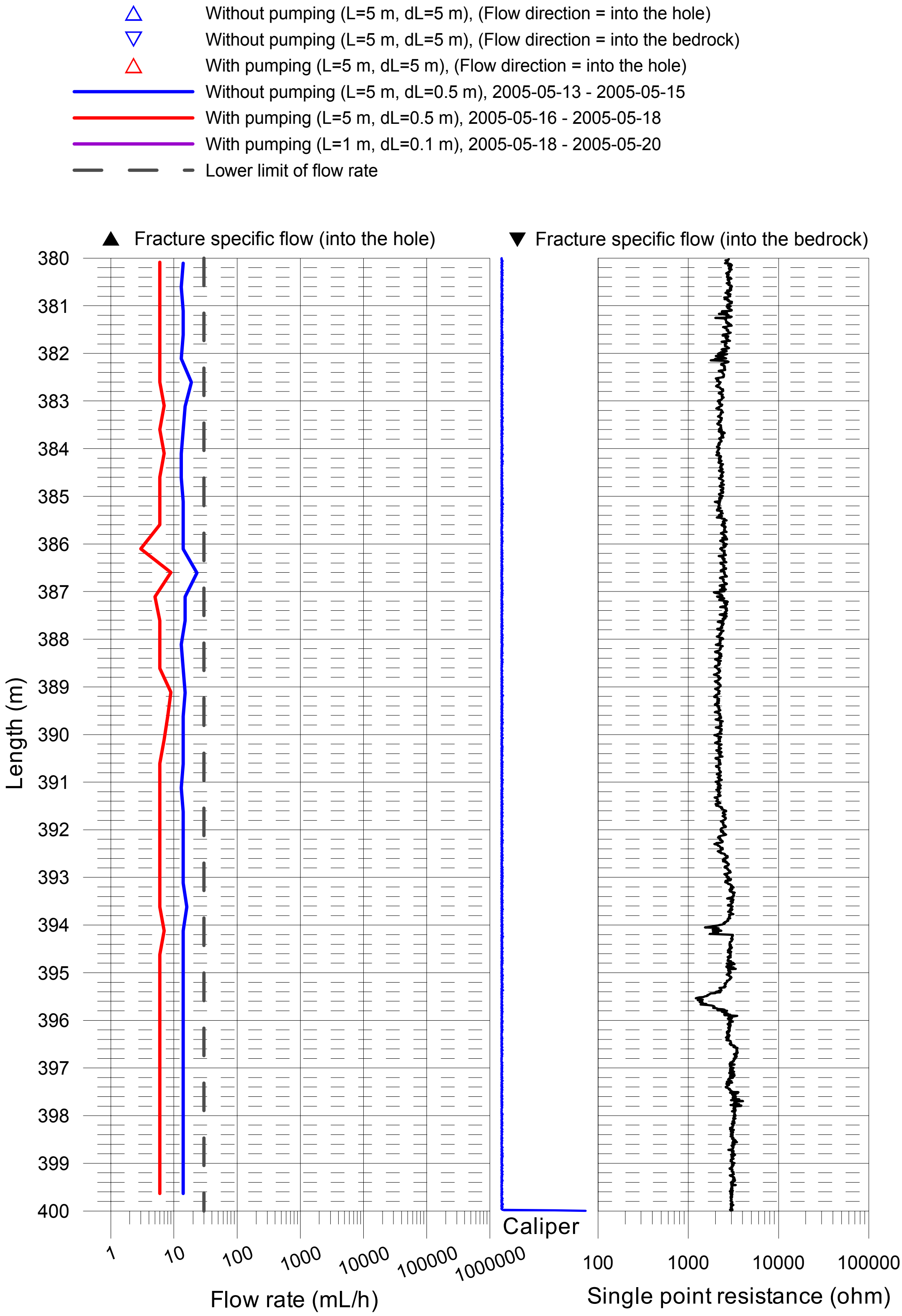
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



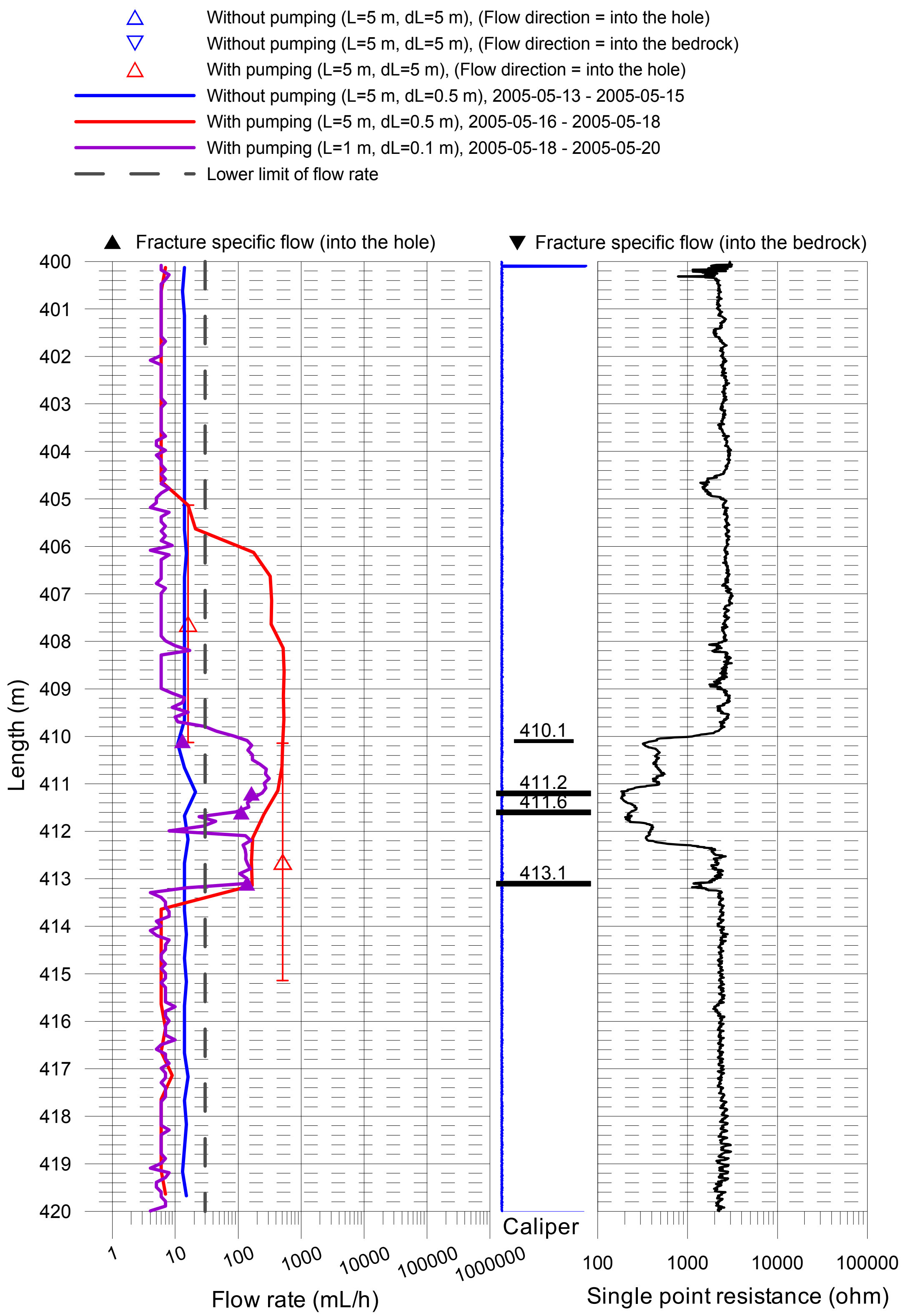
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



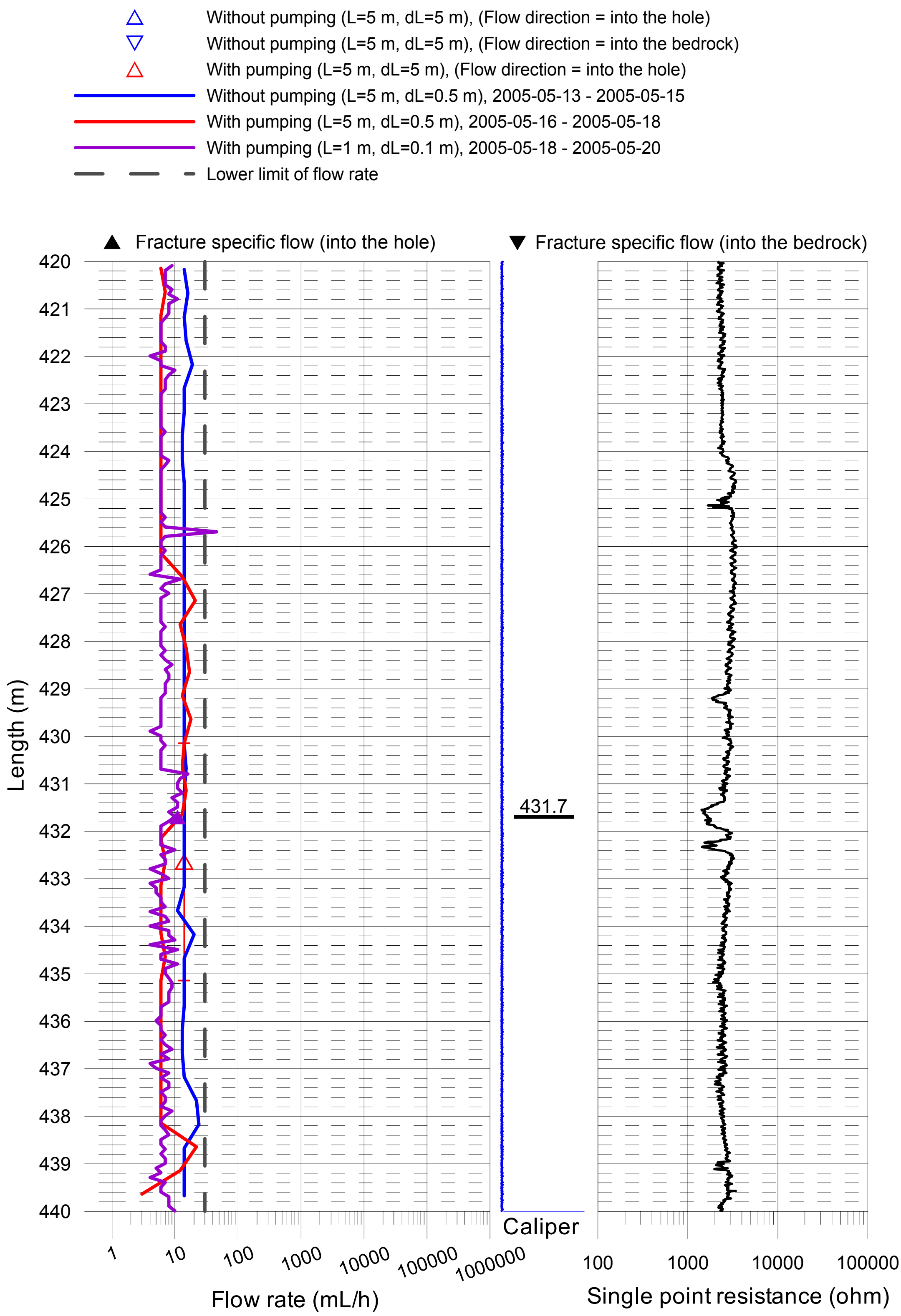
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



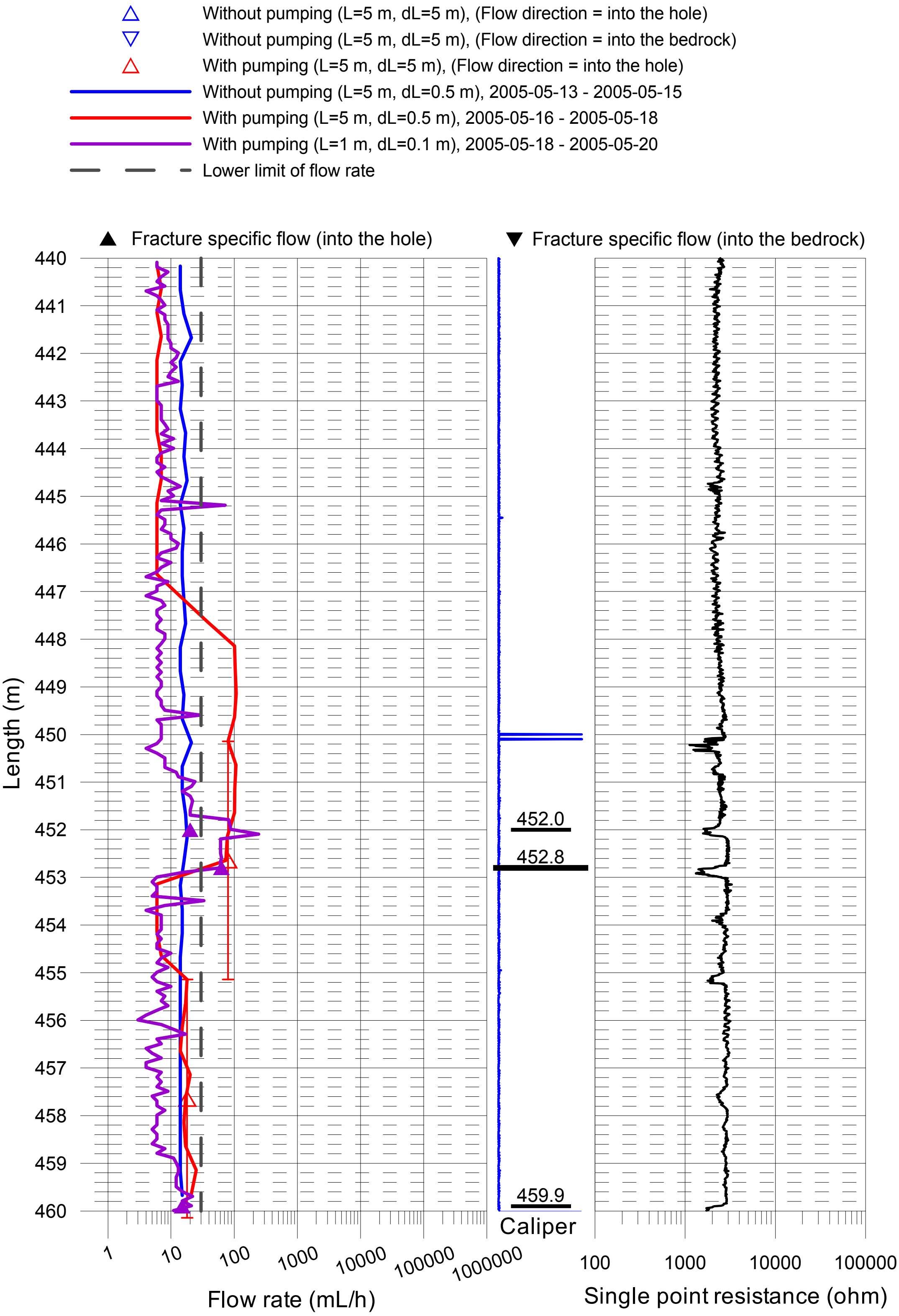
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



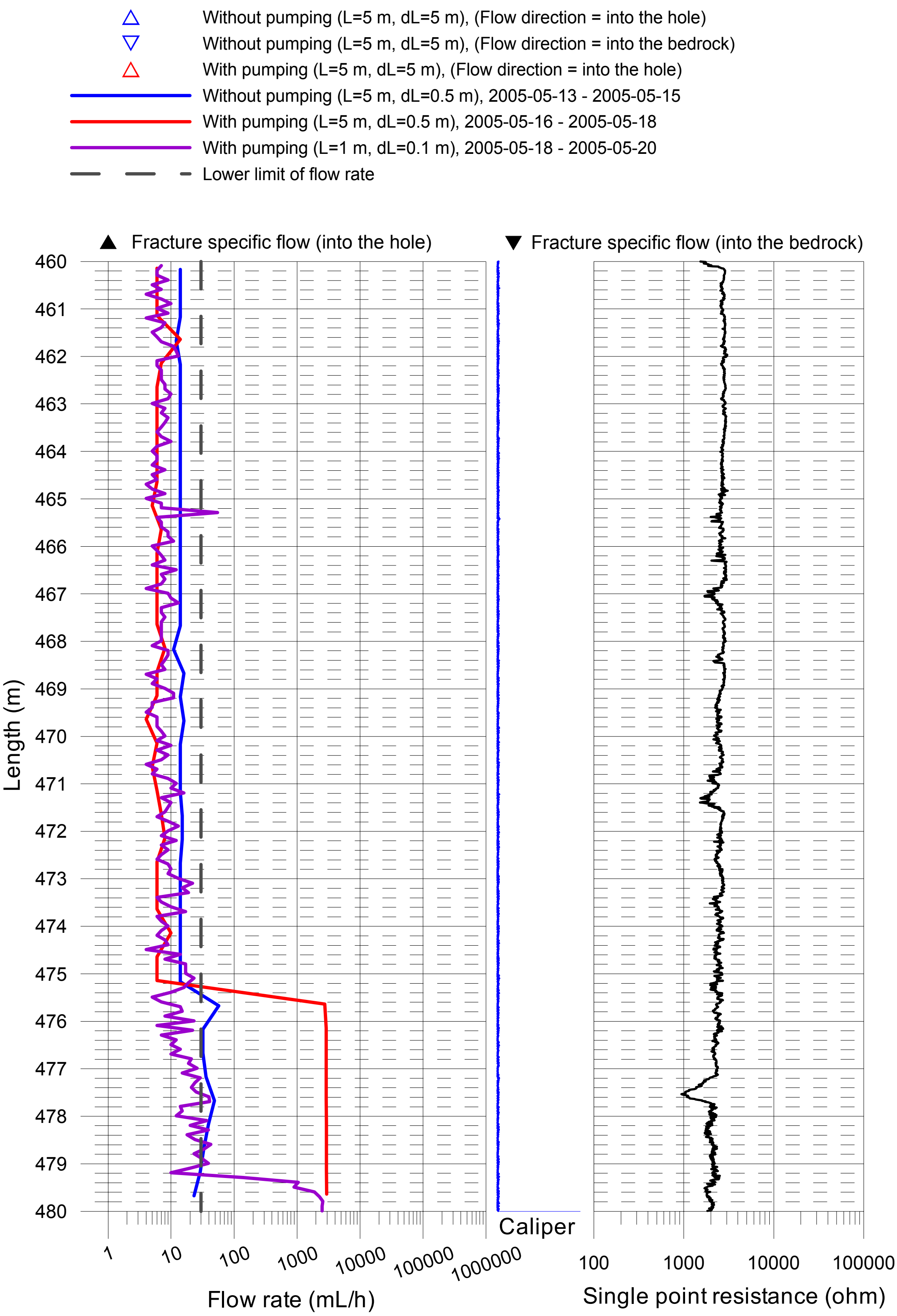
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



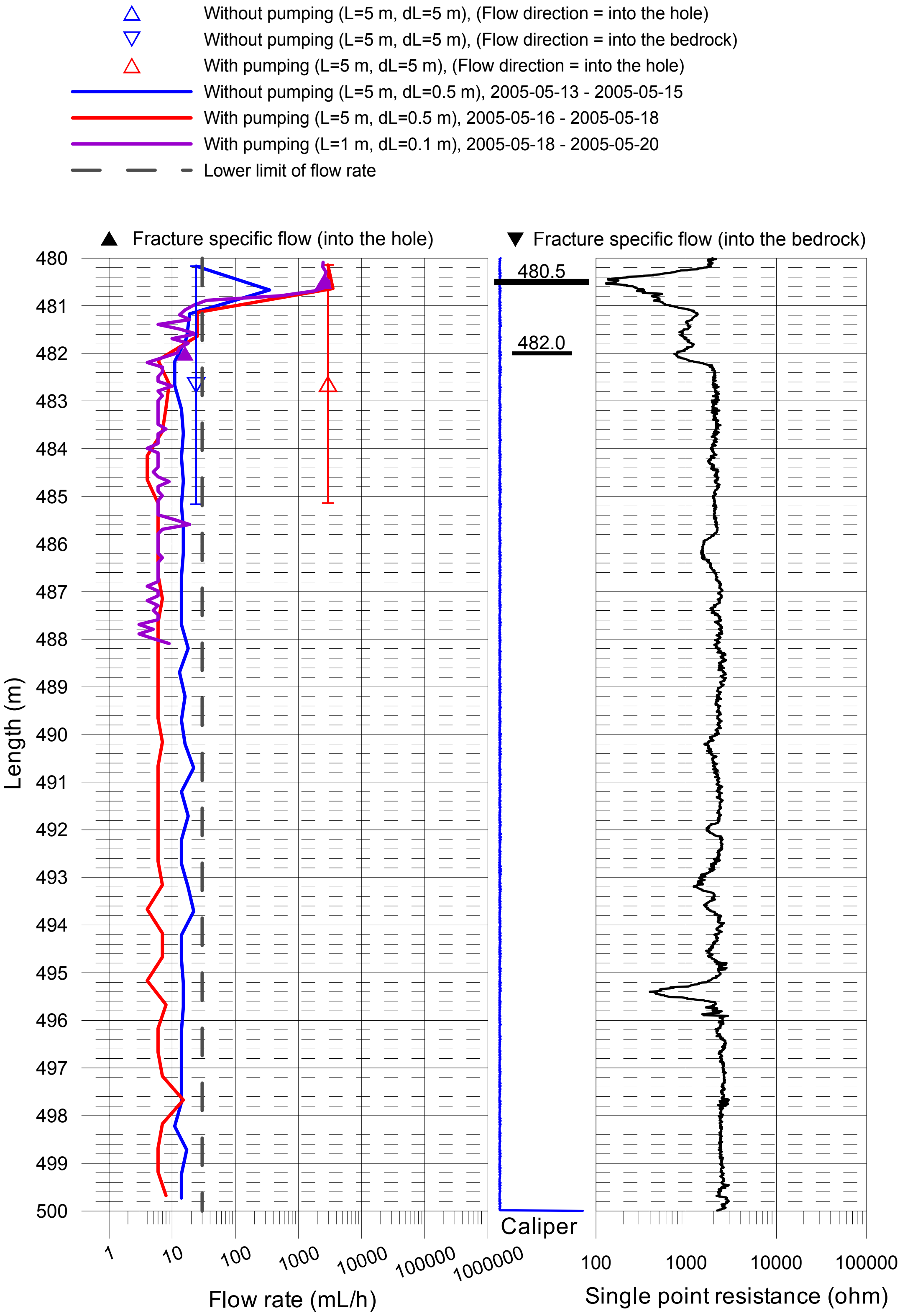
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



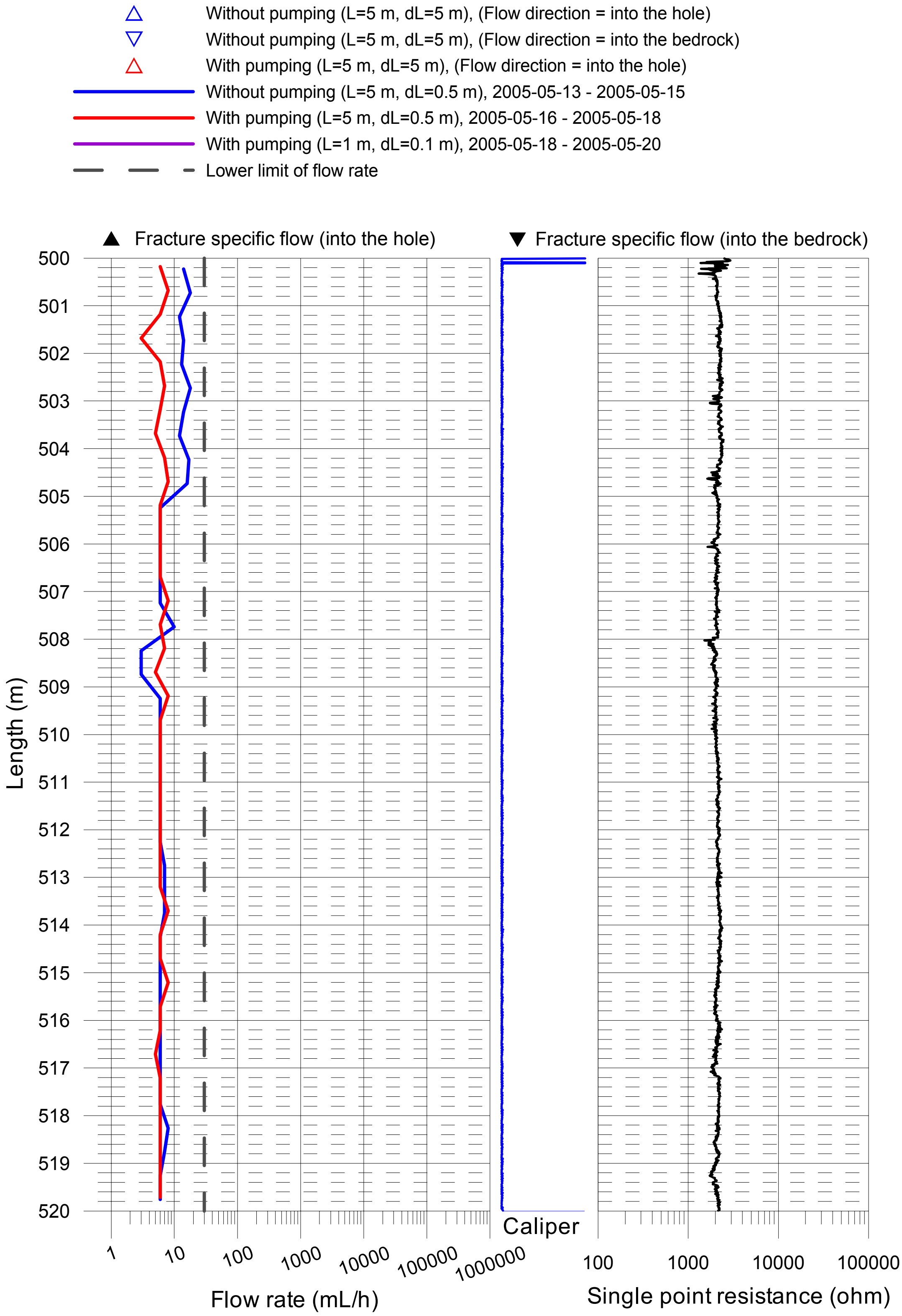
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



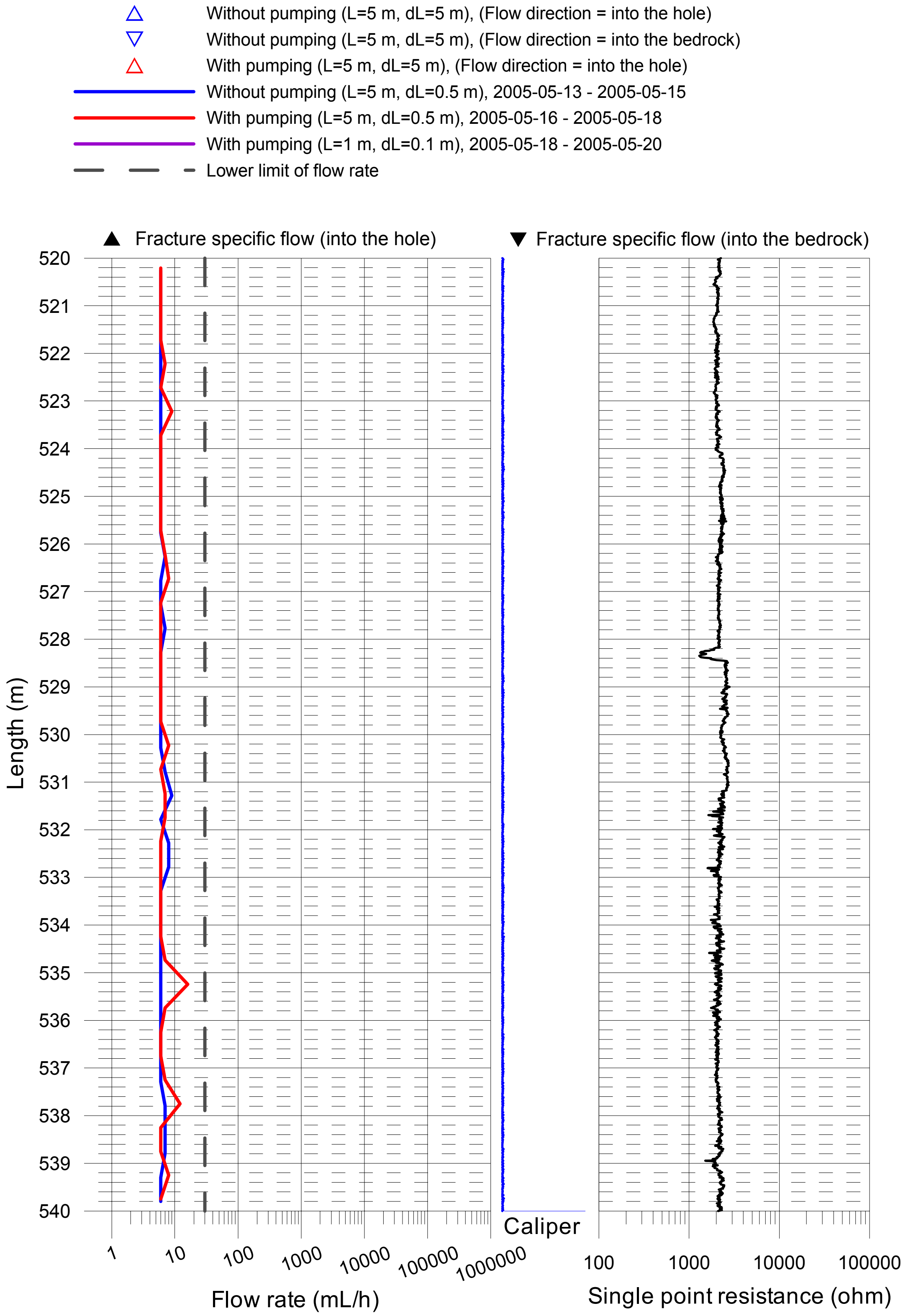
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



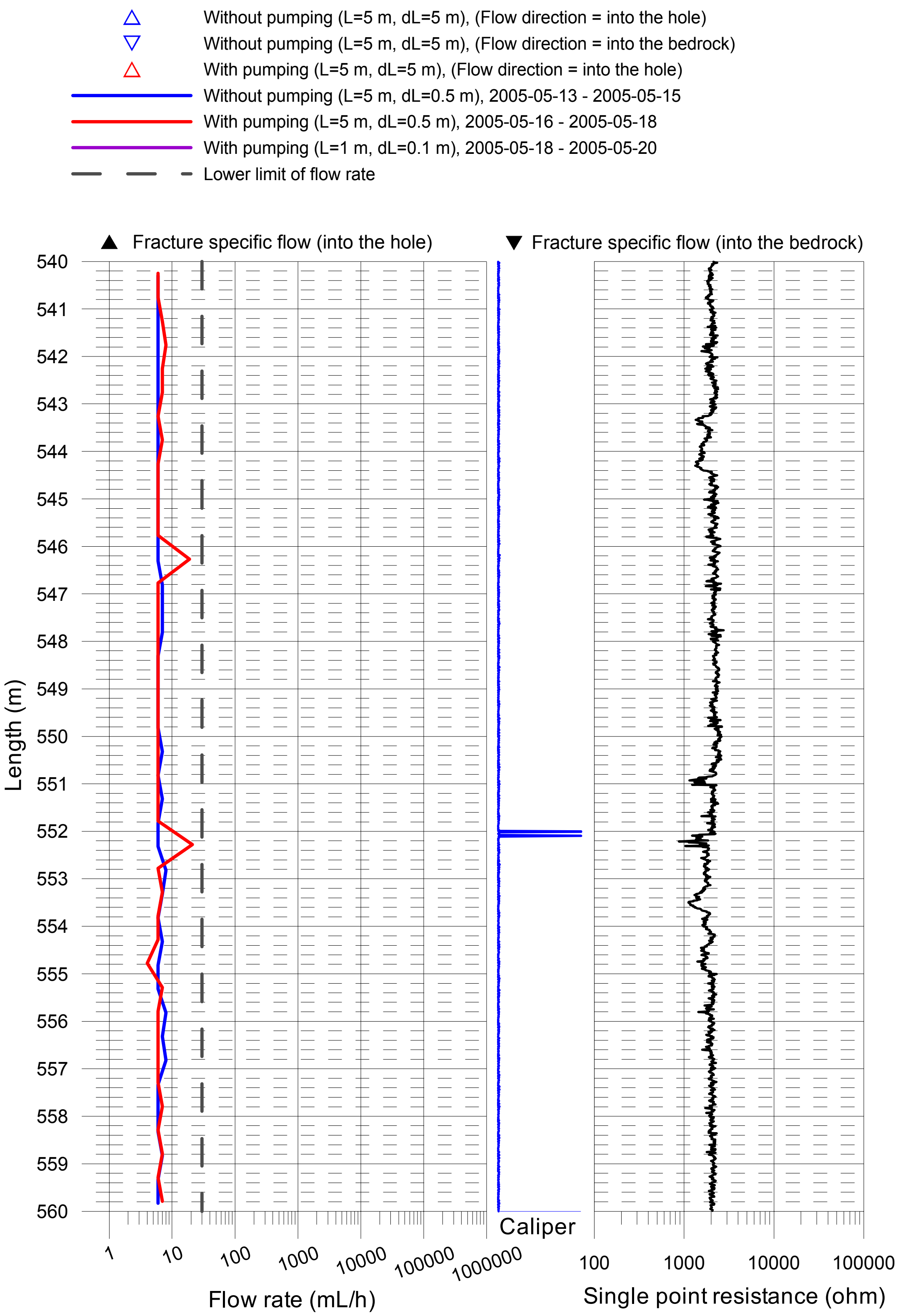
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



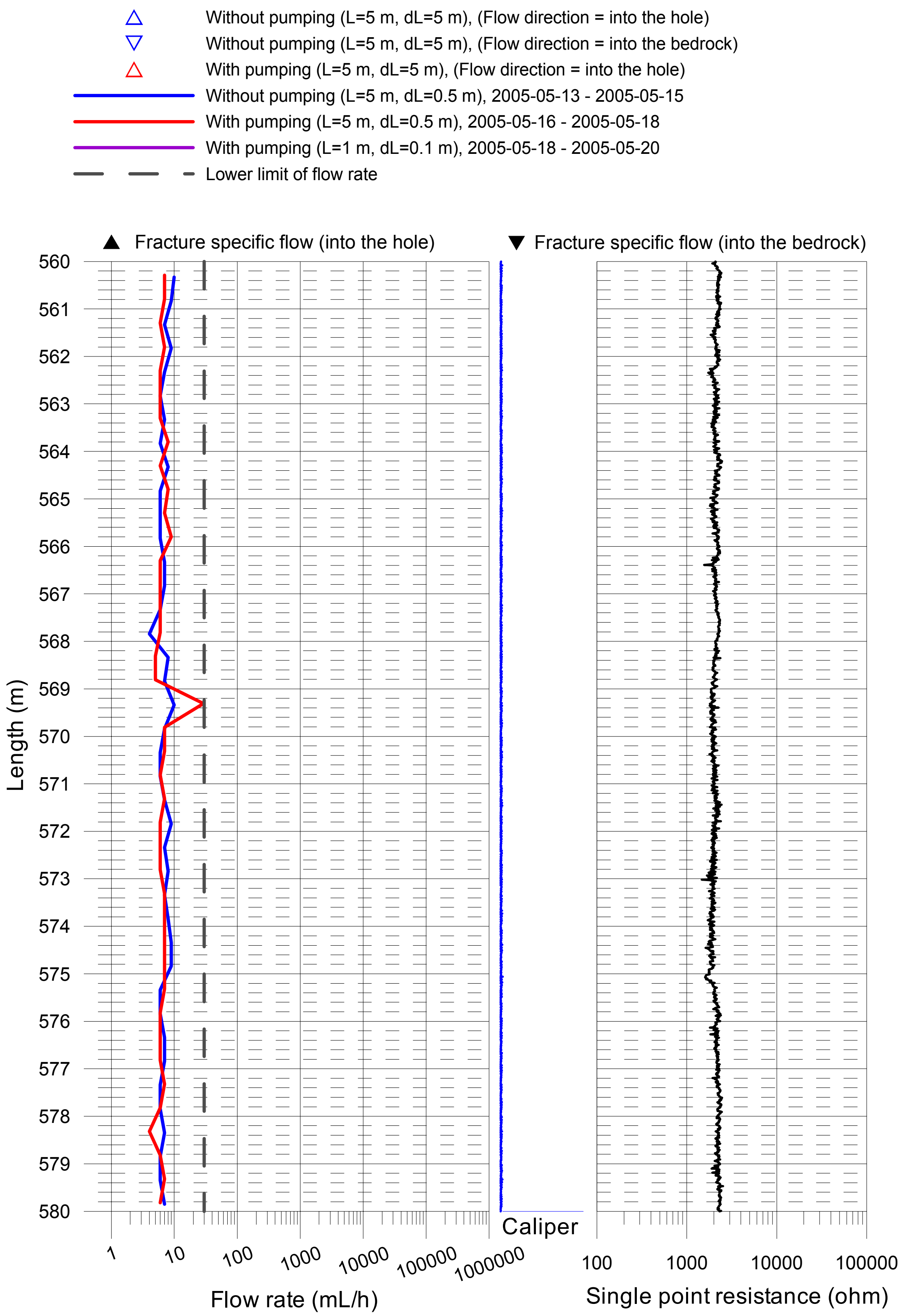
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



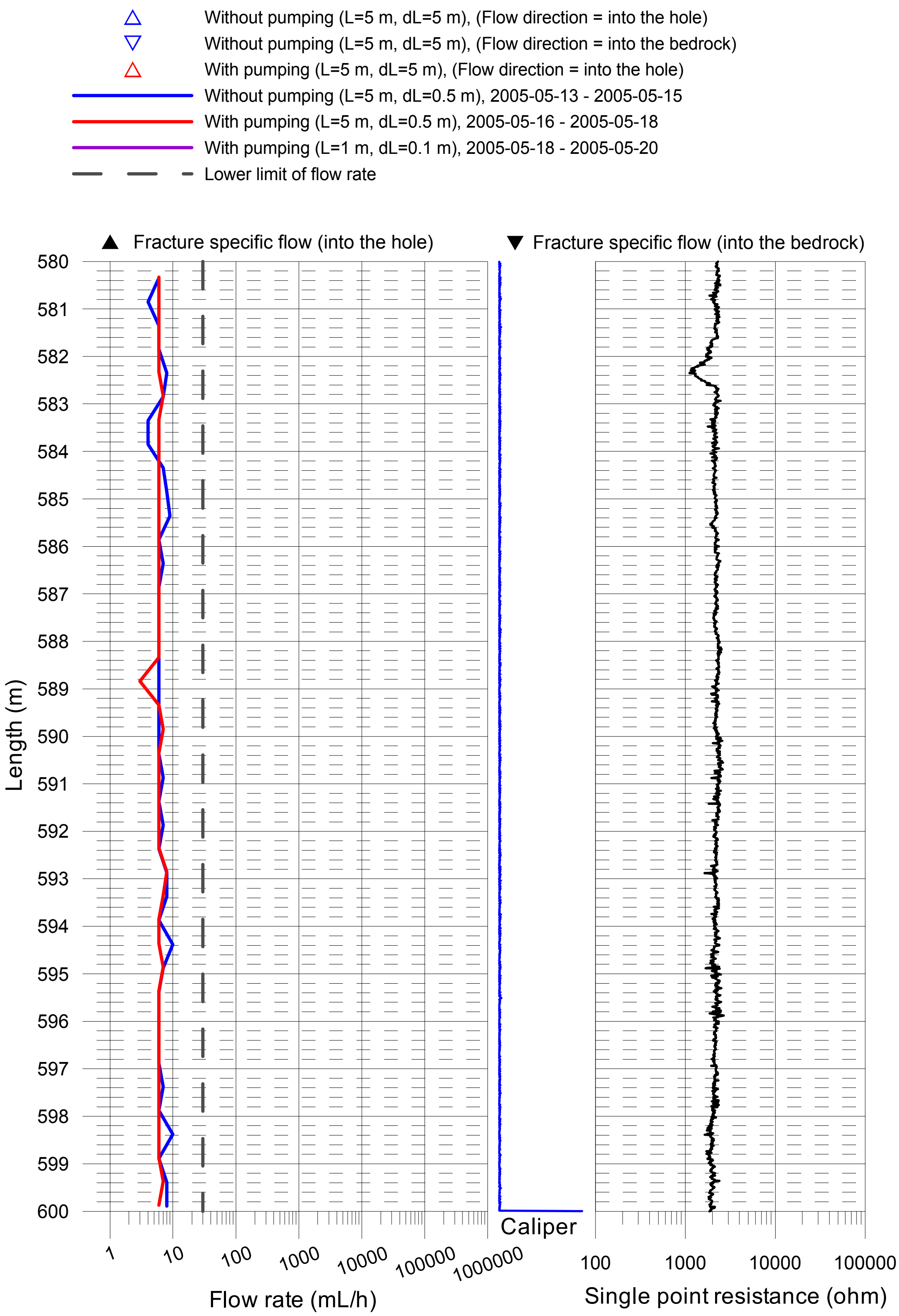
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



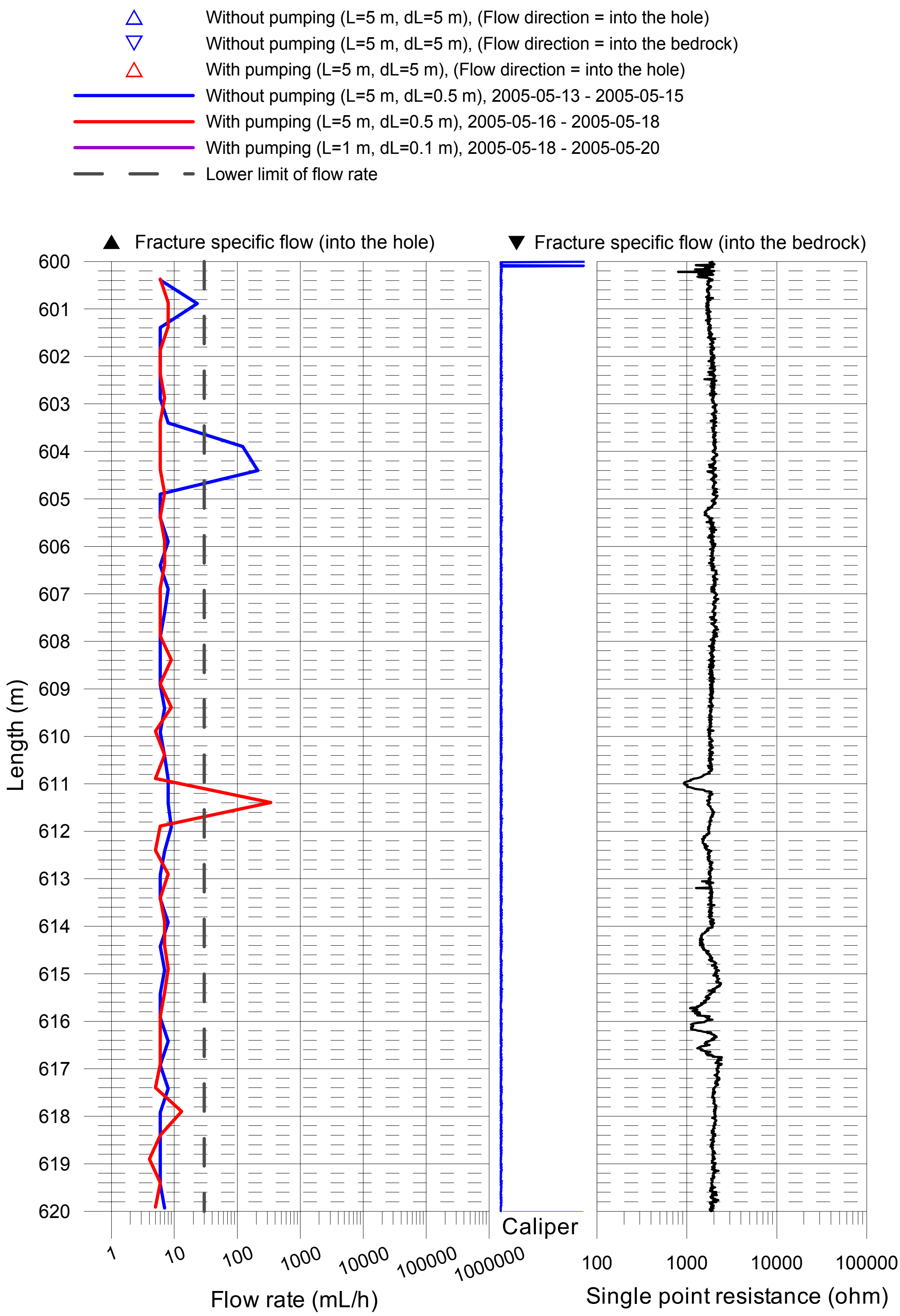
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



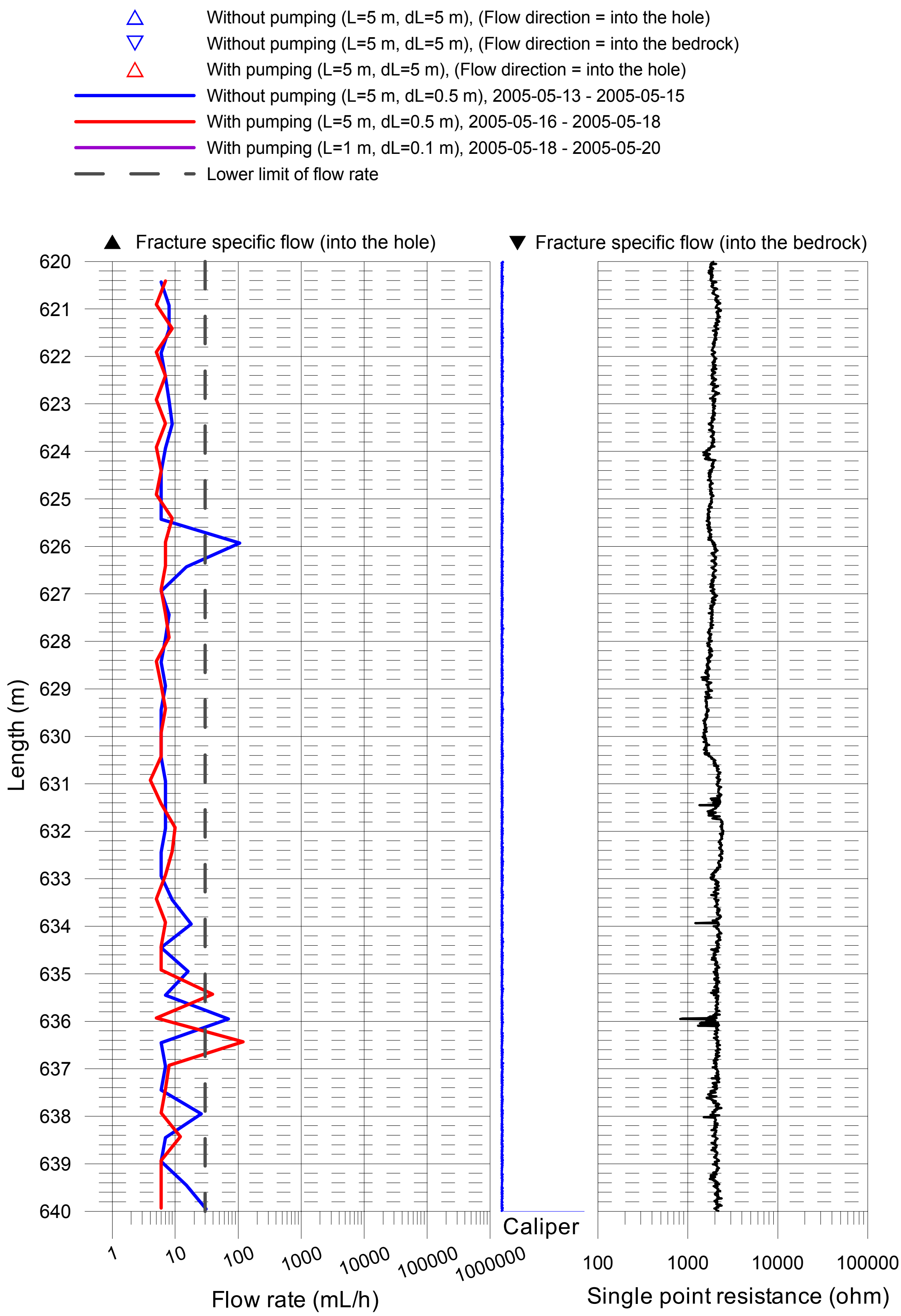
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



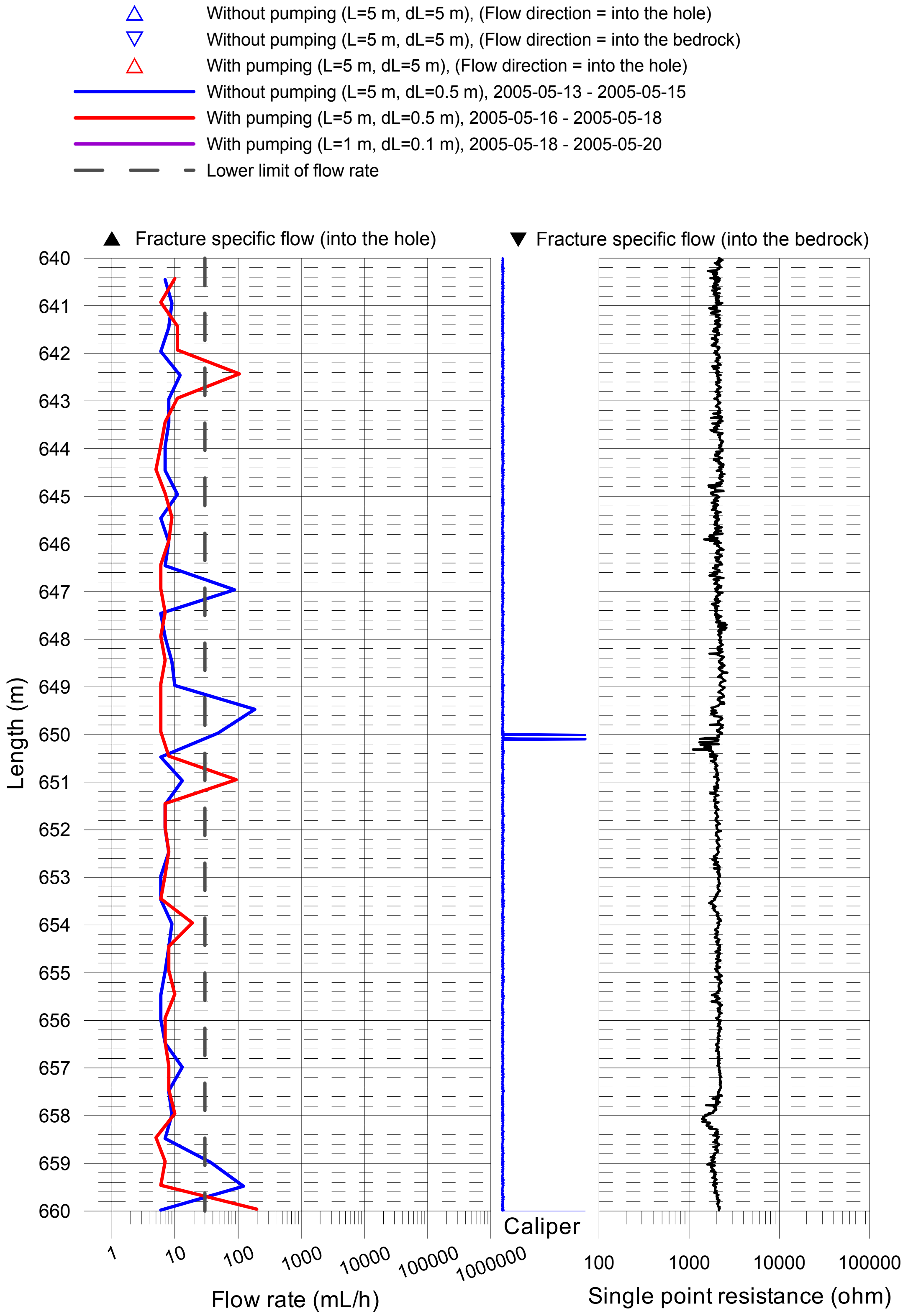
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



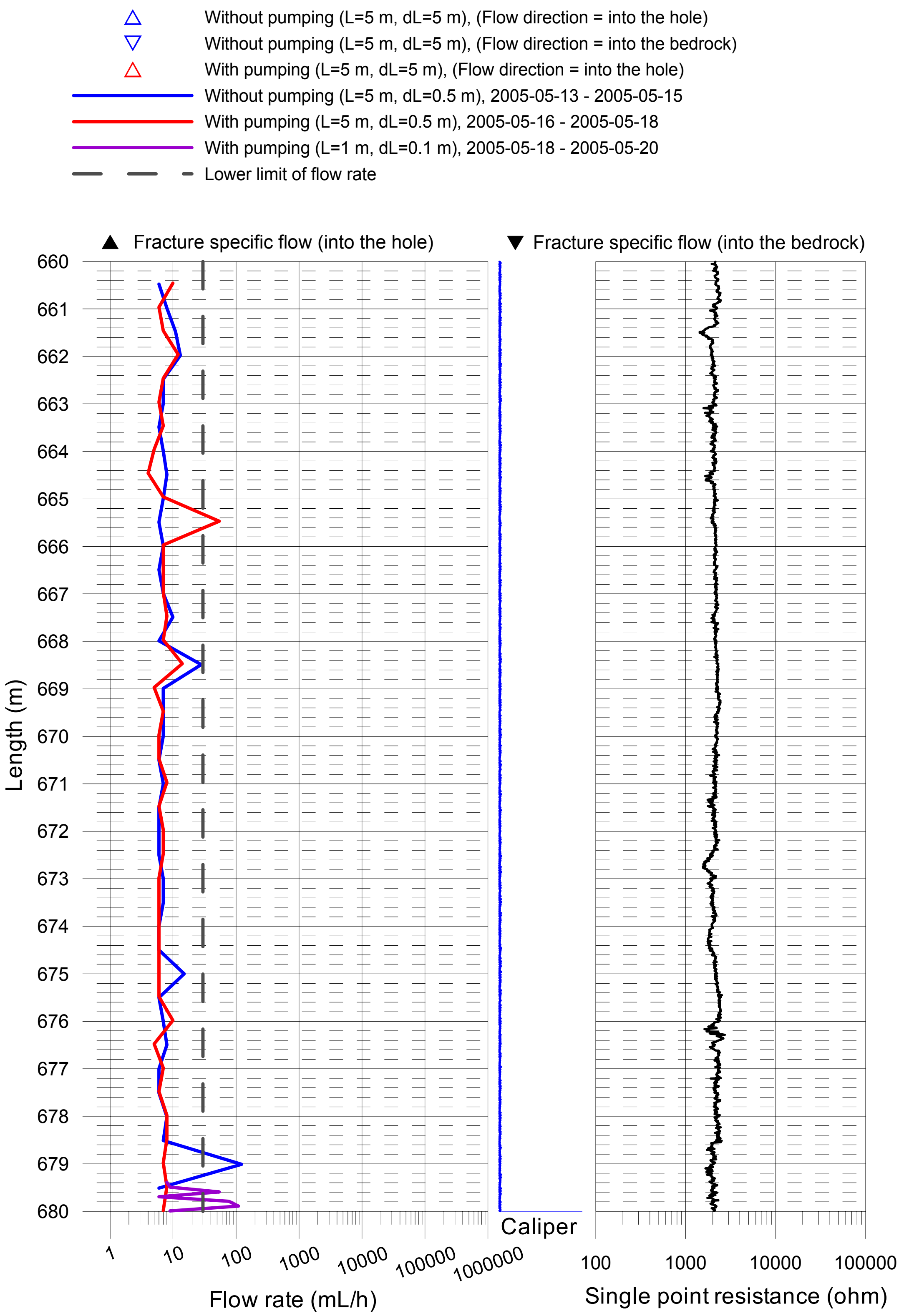
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



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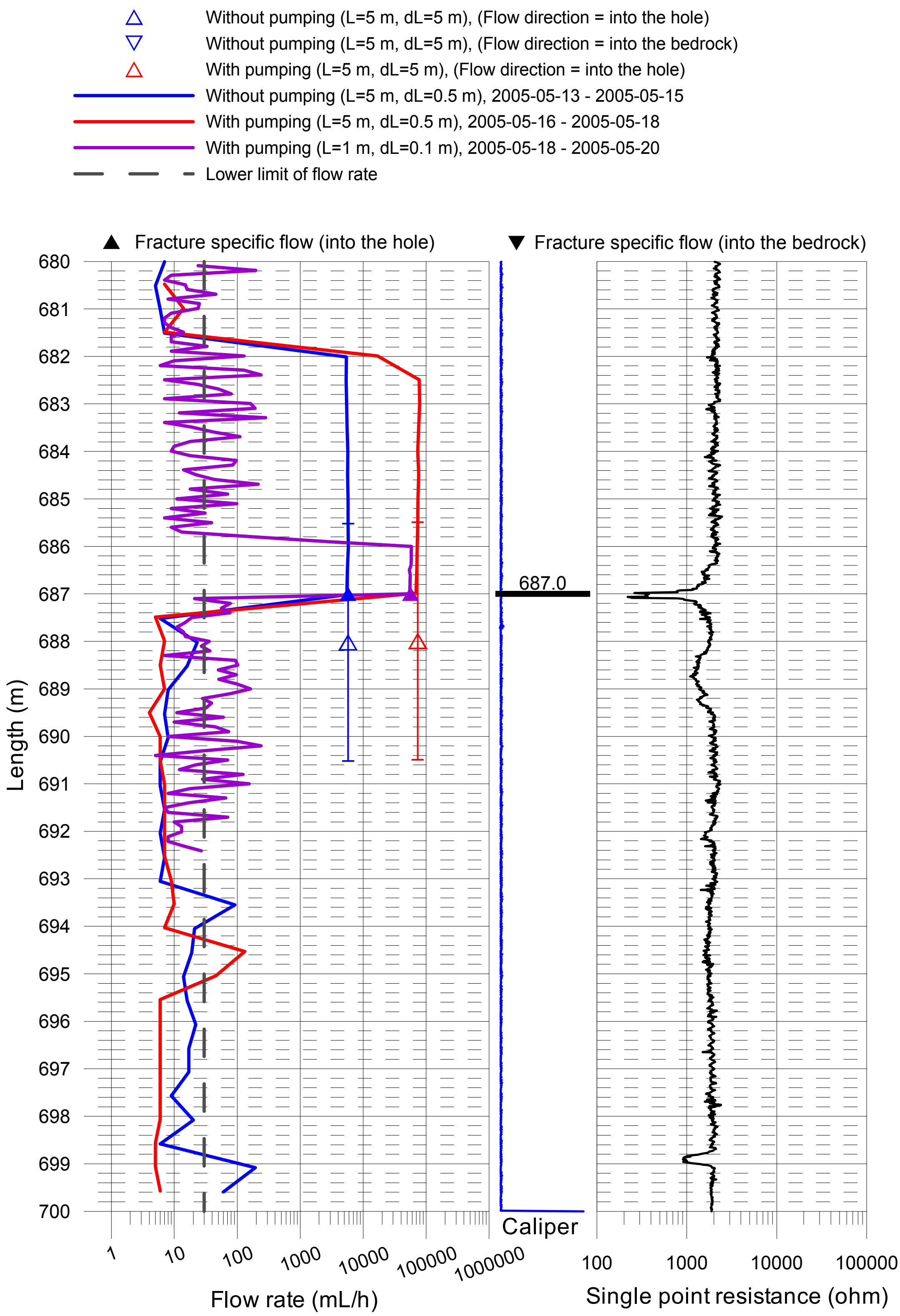
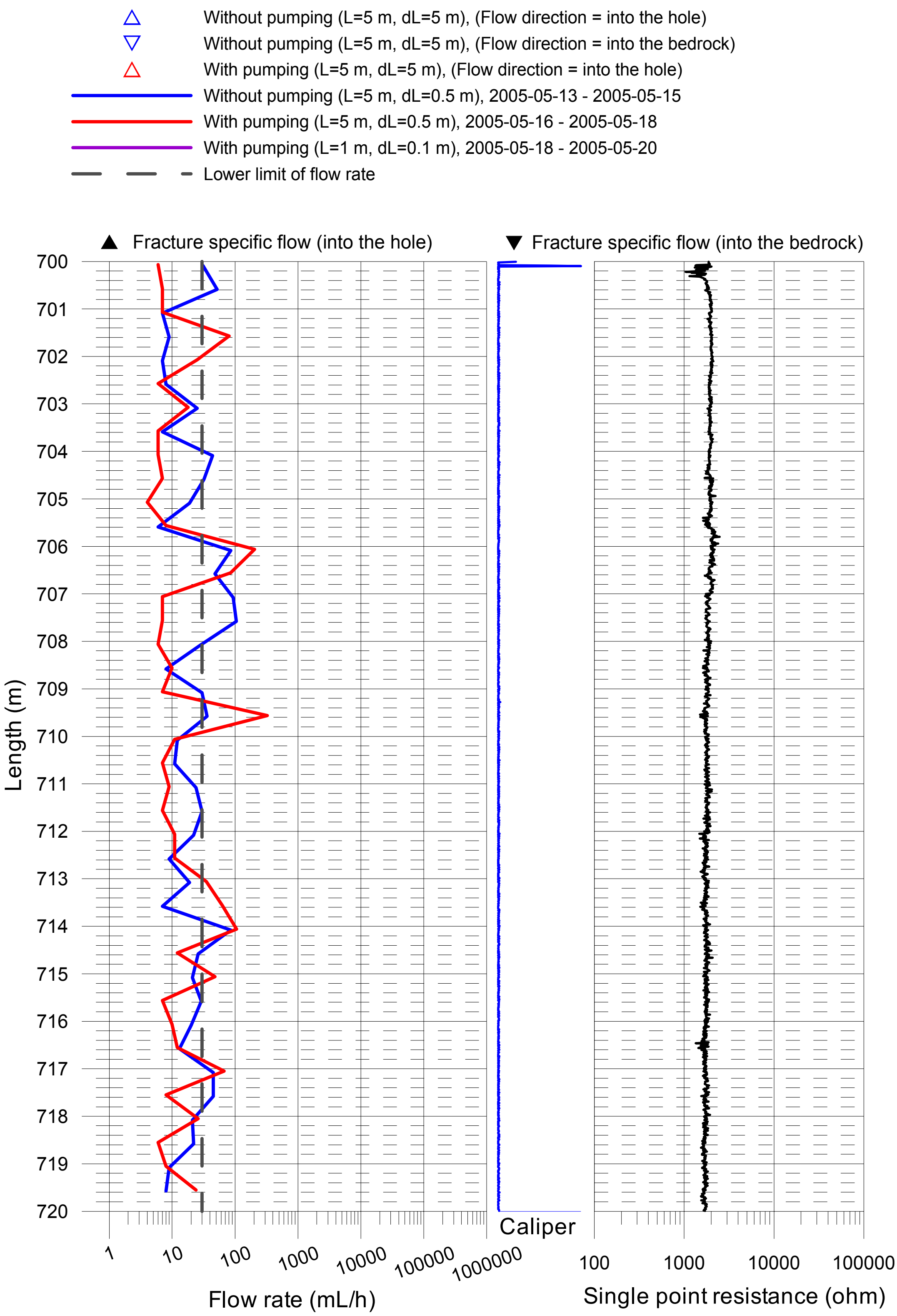
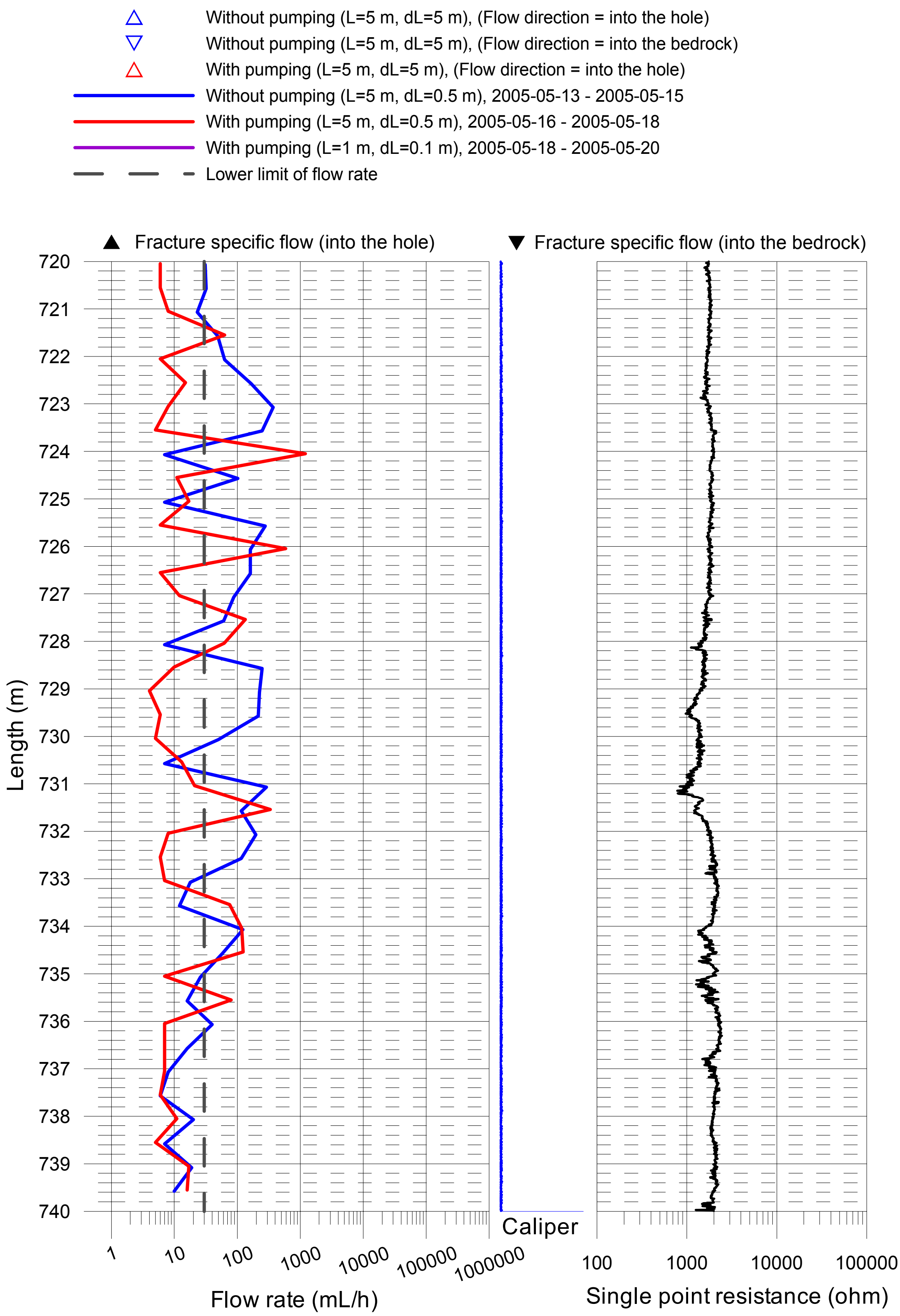
Flow rate, caliper and single point resistance



Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



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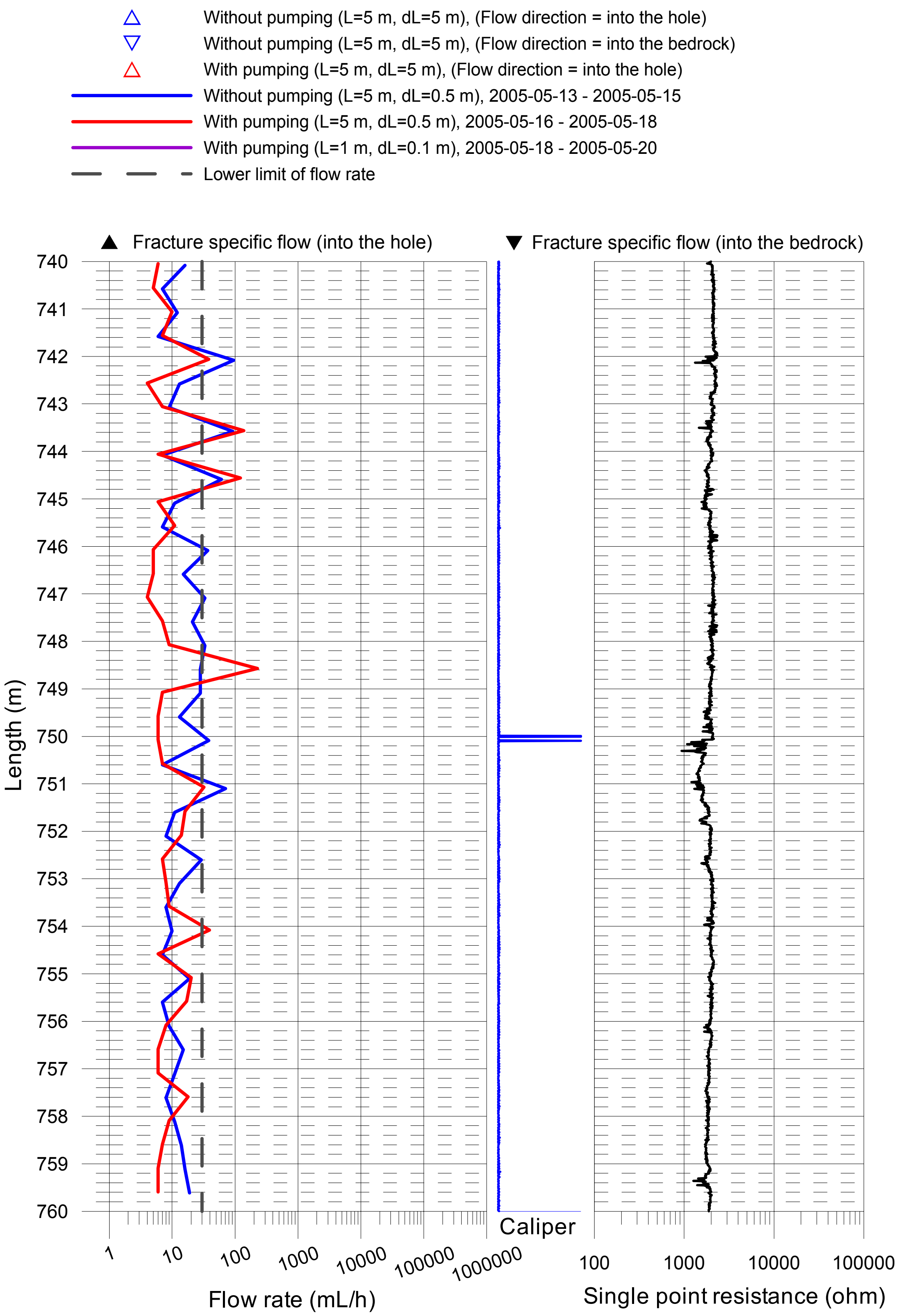
Flow rate, caliper and single point resistance



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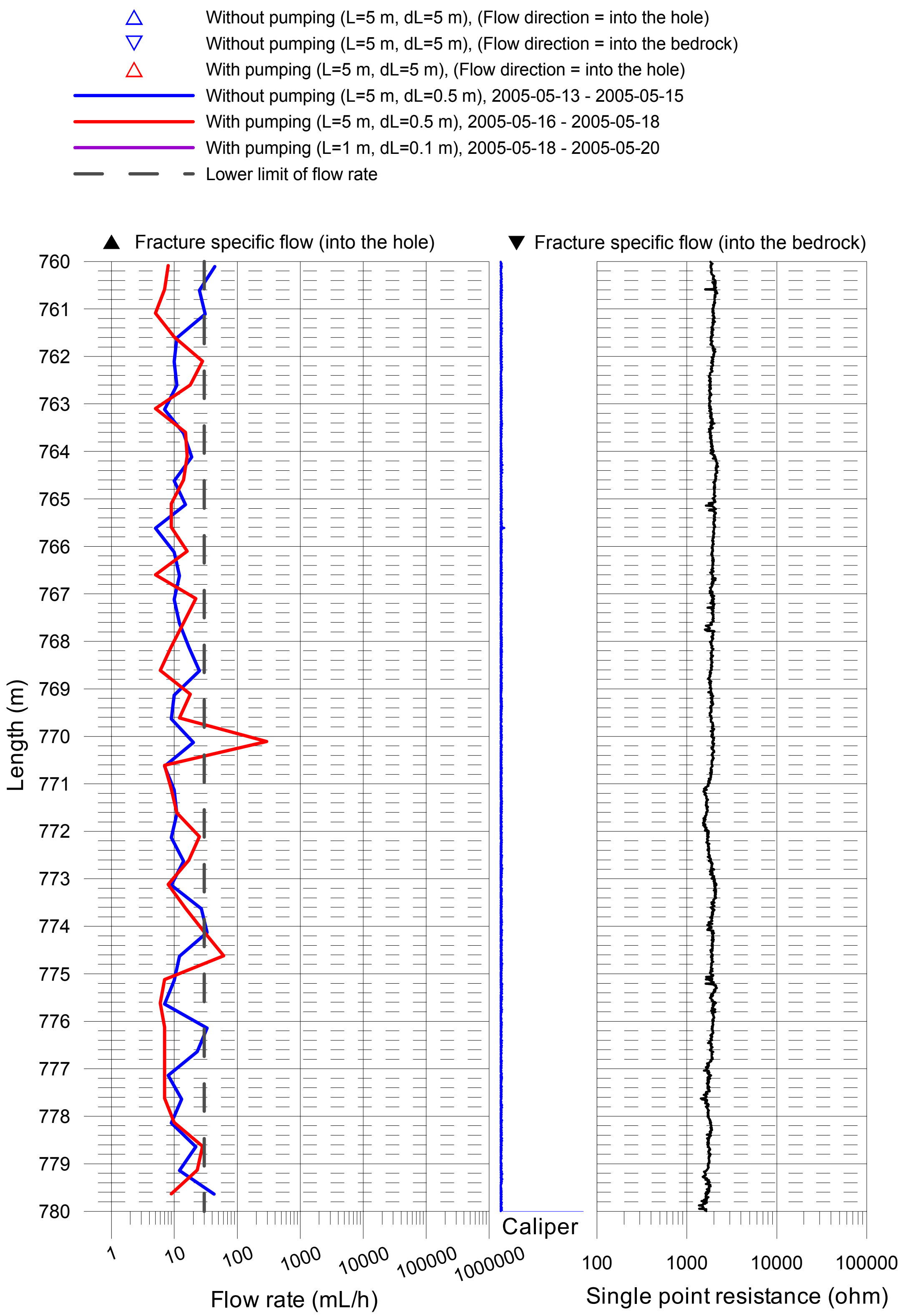
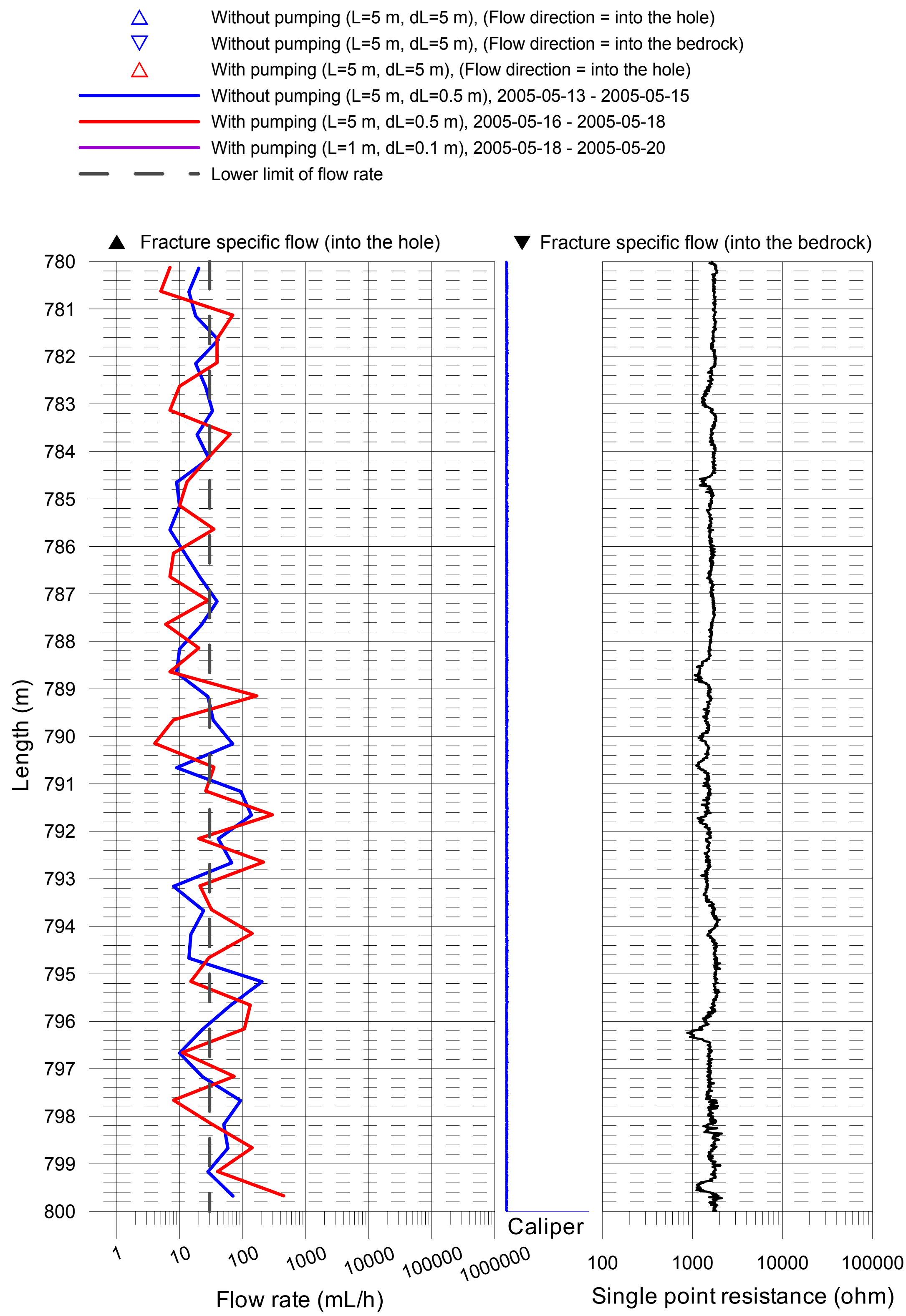
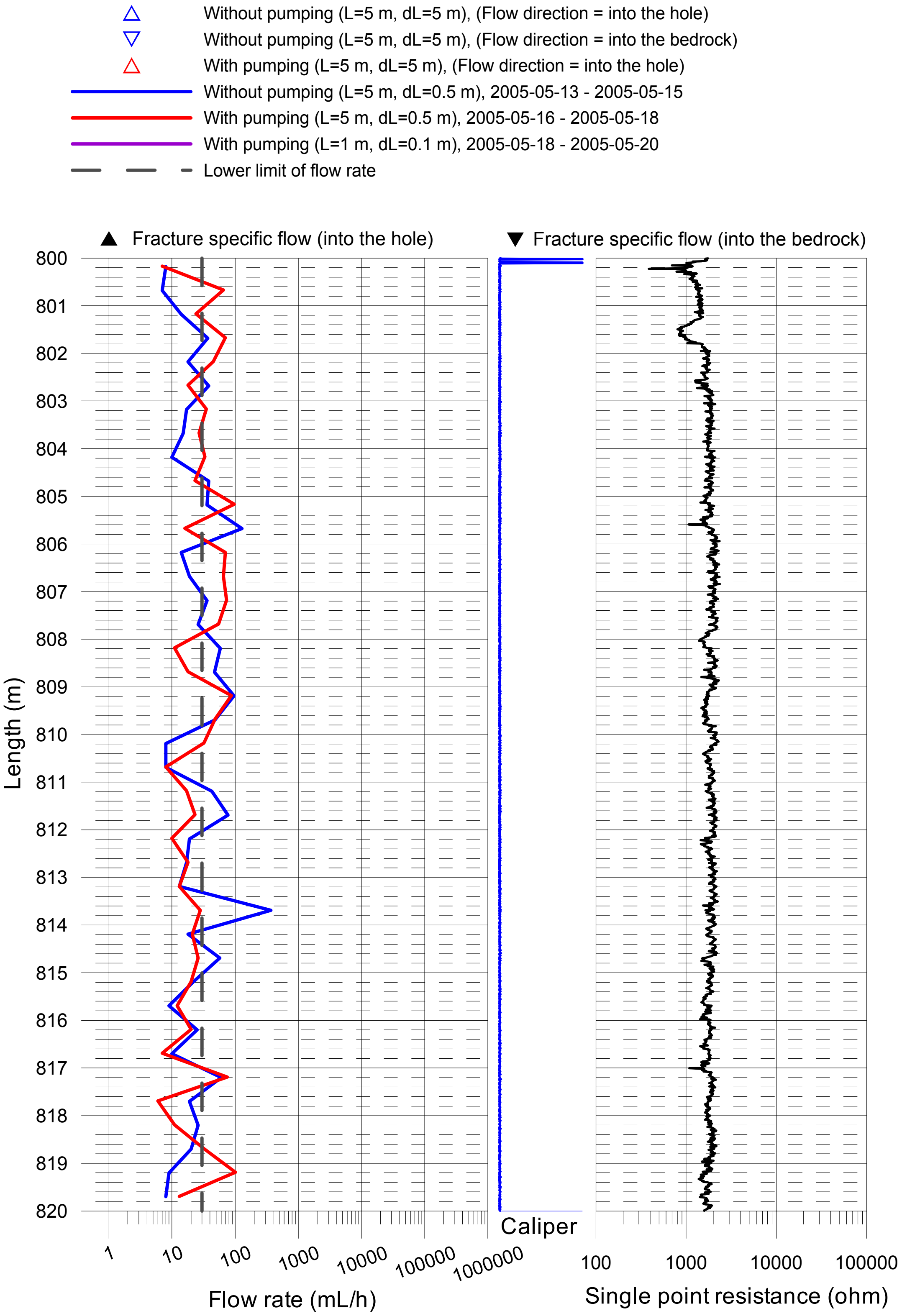
Flow rate, caliper and single point resistance



Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



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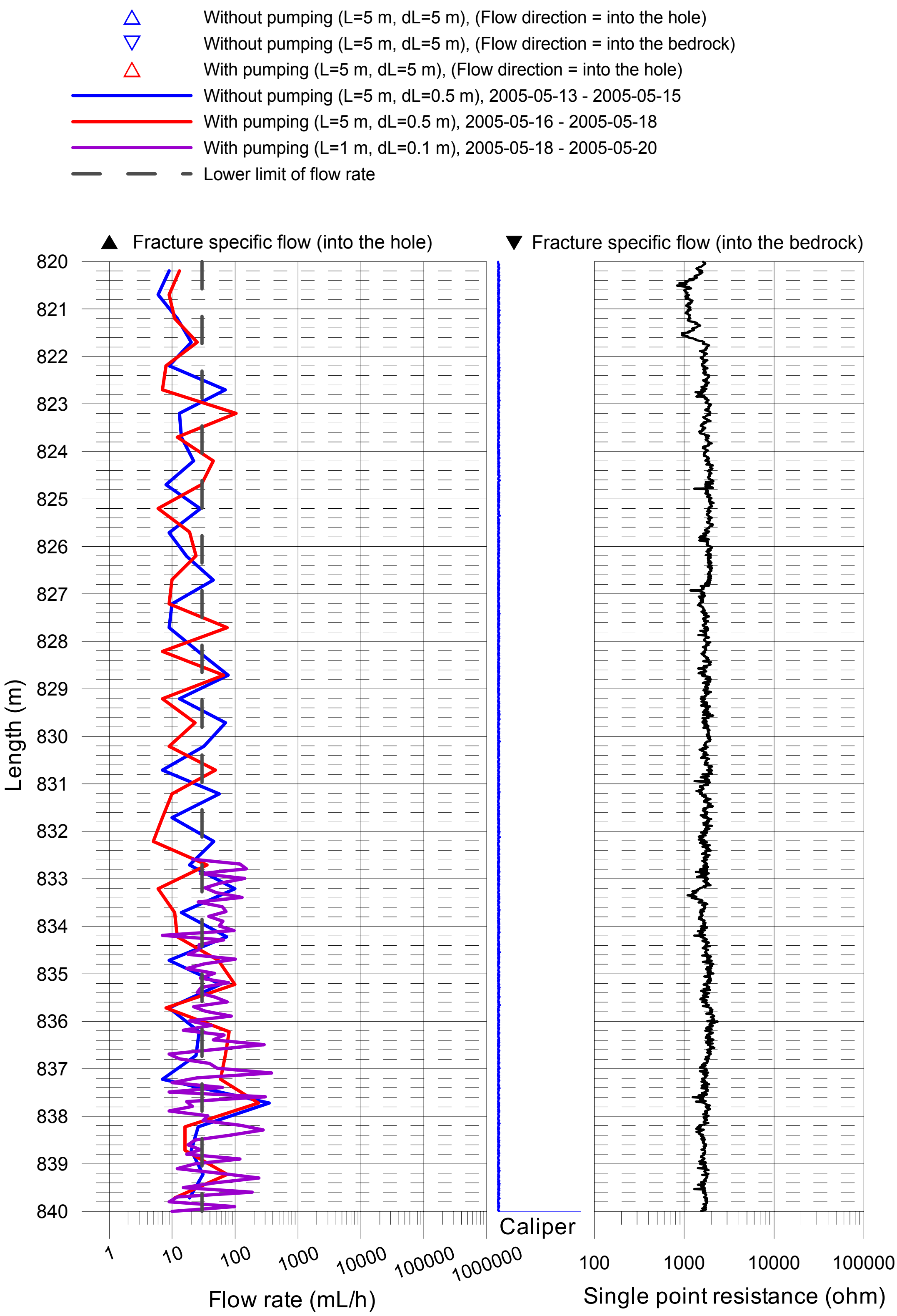
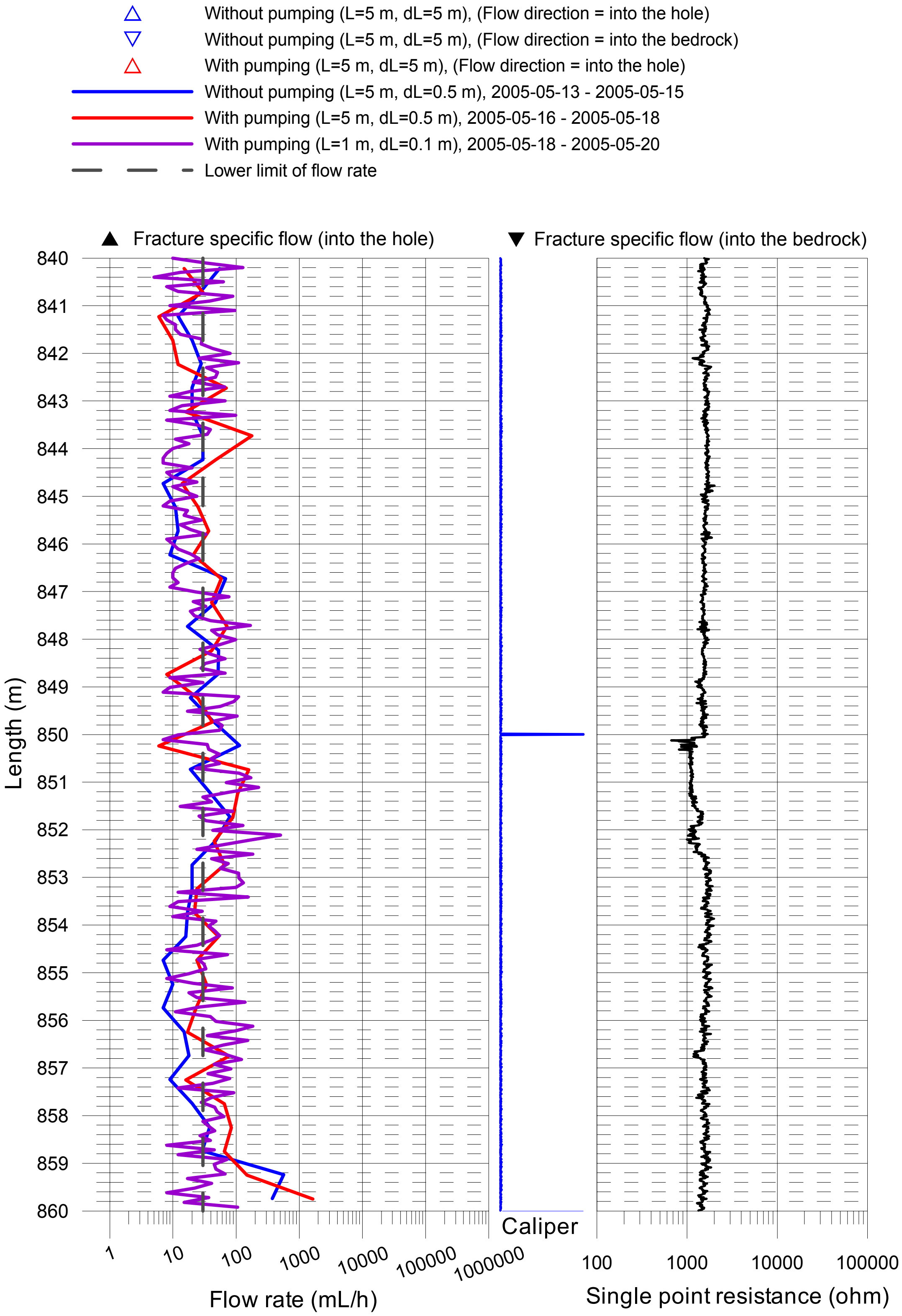
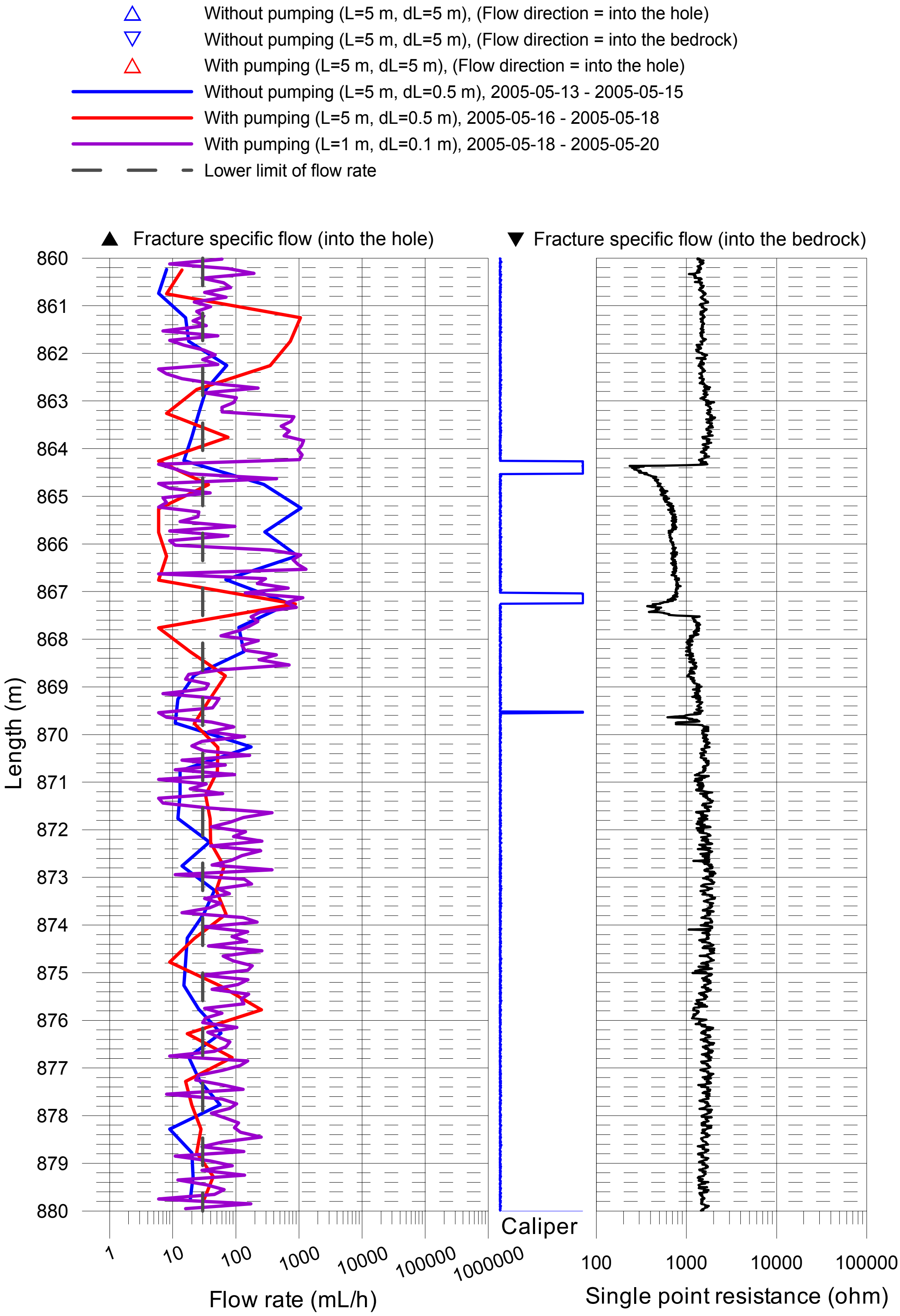
Flow rate, caliper and single point resistance



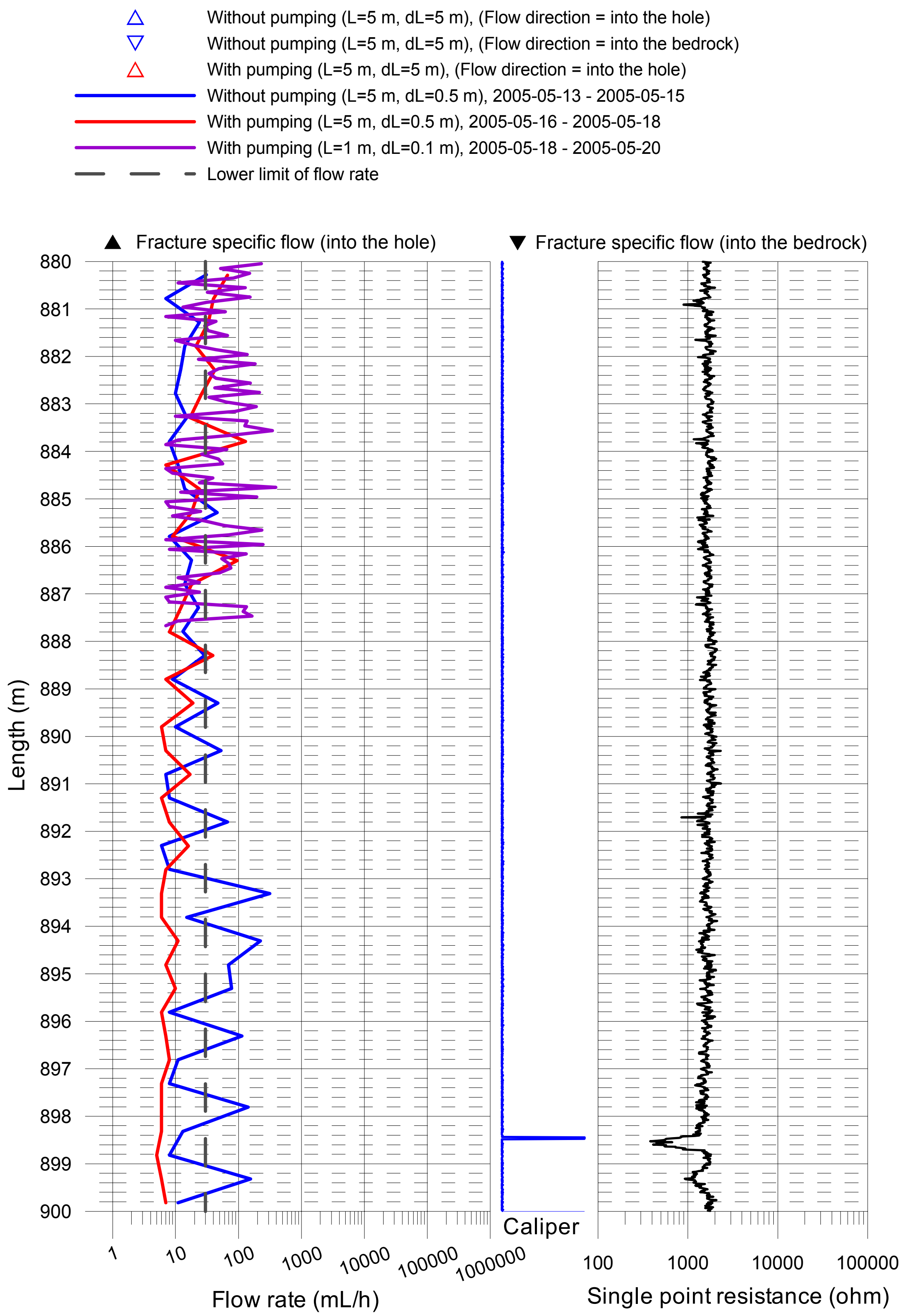
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



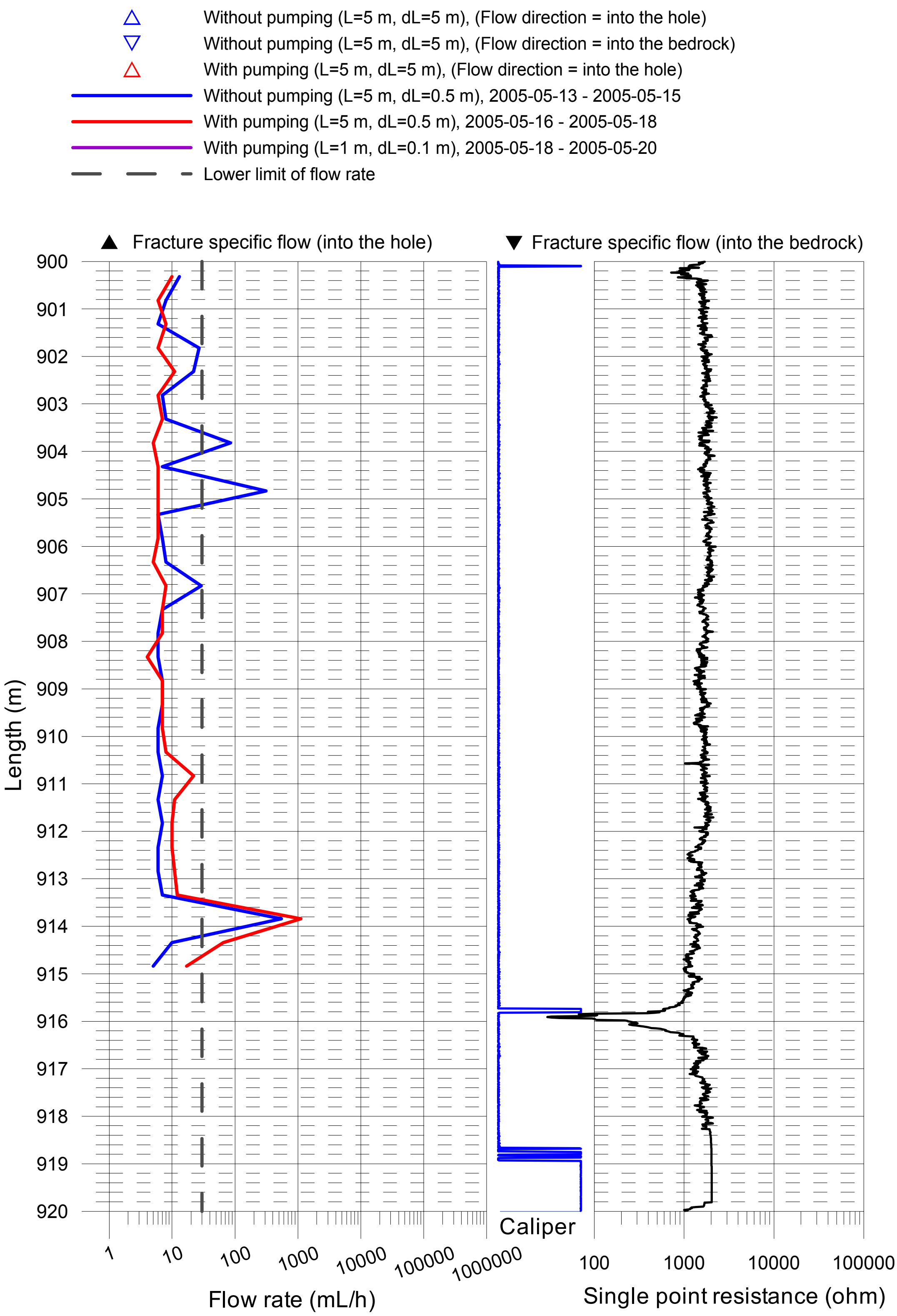
Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



Forsmark, borehole KFM08A
Flow rate, caliper and single point resistance



Forsmark, borehole KFM08A
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.
dh_0	m	Corrected initial hydraulic head difference along the hole due to e.g. varying salinity conditions of the borehole fluid before pumping.
dh_1	m	Corrected hydraulic head difference along the hole due to e.g. varying salinity conditions of the borehole fluid during the first pumping period.
dh_2	m	Corrected hydraulic head difference along the hole due to e.g. varying salinity conditions of the borehole fluid during the second pumping period.
EC_w	S/m	Measured electric conductivity of the borehole fluid in the test section during difference flow logging.
Te_w	°C	Measured borehole fluid temperature in the test section during difference flow logging.
EC_f	S/m	Measured fracture-specific electric conductivity of the fluid in flow anomaly during difference flow logging.
Te_f	°C	Measured fracture-specific fluid temperature in flow anomaly during difference flow logging.
T_D	m^2/s	Transmissivity of section or flow anomaly based on 2D model for evaluation of formation properties of the test section based on PFL-DIFF.
T-measl$_{LT}$	m^2/s	Estimated theoretical lower measurement limit for evaluated T_D. If the estimated T_D equals T_D-measlim, the actual T_D is considered to be equal or less than T_D-measlim.
T-measl$_{LP}$	m^2/s	Estimated practical lower measurement limit for evaluated T_D. If the estimated T_D equals T_D-measlim, the actual T_D is considered to be equal or less than T_D-measlim.
T-measl$_U$	m^2/s	Estimated upper measurement limit for evaluated T_D. If the estimated T_D equals T_D-measlim, the actual T_D is considered to be equal or less than T_D-measlim.
h_i	m	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)	Lw (m)	Q_0 (m^3/s)	dh_0 (m)	Q_1 (m^3/s)	dh_1 (m)	TD (m^2/s)	h_i (m)	Q-lower limit P (mL/h)	TD-$measl_{LT}$ (m^2/s)	TD-$measl_{LP}$ (m^2/s)	TD-$measl_U$ (m^2/s)	Comments
KFM08A	94.60	99.60	5	–	0.12	–	–9.71	–	–	30	8.39E–10	8.39E–10	8.39E–06	
KFM08A	99.61	104.61	5	–	0.15	–	–9.68	–	–	30	8.39E–10	8.39E–10	8.39E–06	
KFM08A	104.63	109.63	5	–	0.17	2.50E–09	–9.63	2.52E–10	–	30	8.41E–10	8.41E–10	8.41E–06	
KFM08A	109.64	114.64	5	1.14E–08	0.19	1.05E–07	–9.60	9.46E–09	1.38	30	8.42E–10	8.42E–10	8.42E–06	
KFM08A	114.65	119.65	5	–	0.21	8.89E–09	–9.57	8.99E–10	–	30	8.43E–10	8.43E–10	8.43E–06	
KFM08A	119.66	124.66	5	–	0.23	9.44E–09	–9.55	9.55E–10	–	30	8.43E–10	8.43E–10	8.43E–06	
KFM08A	124.67	129.67	5	–	0.26	–	–9.52	–	–	30	8.43E–10	8.43E–10	8.43E–06	
KFM08A	129.68	134.68	5	6.67E–09	0.28	1.56E–07	–9.51	1.51E–08	0.72	30	8.42E–10	8.42E–10	8.42E–06	
KFM08A	134.69	139.69	5	1.39E–08	0.30	1.31E–07	–9.47	1.19E–08	1.46	30	8.44E–10	8.44E–10	8.44E–06	
KFM08A	139.70	144.70	5	–	0.33	–	–9.43	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	144.71	149.71	5	–	0.39	3.64E–08	–9.39	3.68E–09	–	30	8.43E–10	8.43E–10	8.43E–06	
KFM08A	149.71	154.71	5	–	0.42	1.14E–08	–9.35	1.15E–09	–	30	8.44E–10	8.44E–10	8.44E–06	
KFM08A	154.72	159.72	5	–	0.45	–	–9.25	–	–	30	8.50E–10	8.50E–10	8.50E–06	
KFM08A	159.73	164.73	5	–	0.48	–	–9.17	–	–	30	8.54E–10	8.54E–10	8.54E–06	
KFM08A	164.74	169.74	5	–	0.50	–	–9.04	–	–	30	8.64E–10	8.64E–10	8.64E–06	
KFM08A	169.75	174.75	5	–	0.52	7.78E–09	–9.00	8.08E–10	–	30	8.66E–10	8.66E–10	8.66E–06	
KFM08A	174.76	179.76	5	–	0.57	–	–8.97	–	–	30	8.64E–10	8.64E–10	8.64E–06	
KFM08A	179.77	184.77	5	–	0.59	–	–8.93	–	–	30	8.66E–10	8.66E–10	8.66E–06	
KFM08A	184.78	189.78	5	–1.13E–07	0.60	2.20E–06	–8.91	2.41E–07	0.14	30	8.67E–10	8.67E–10	8.67E–06	
KFM08A	189.79	194.79	5	–1.89E–07	0.62	3.53E–05	–8.87	3.70E–06	0.57	30	8.69E–10	8.69E–10	8.69E–06	
KFM08A	194.80	199.80	5	–1.84E–07	0.68	3.67E–06	–8.84	4.00E–07	0.22	30	8.66E–10	8.66E–10	8.66E–06	
KFM08A	199.81	204.81	5	–	0.73	5.39E–08	–8.80	5.59E–09	–	30	8.65E–10	8.65E–10	8.65E–06	
KFM08A	204.81	209.81	5	–	0.80	–	–8.76	–	–	30	8.62E–10	8.62E–10	8.62E–06	
KFM08A	209.82	214.82	5	–	0.93	6.39E–09	–8.72	6.55E–10	–	30	8.54E–10	8.54E–10	8.54E–06	
KFM08A	214.83	219.83	5	–	1.03	–	–8.68	–	–	30	8.49E–10	8.49E–10	8.49E–06	
KFM08A	219.84	224.84	5	–	1.10	–	–8.64	–	–	30	8.46E–10	8.46E–10	8.46E–06	
KFM08A	224.85	229.85	5	–	1.14	–	–8.59	–	–	30	8.47E–10	8.47E–10	8.47E–06	
KFM08A	229.86	234.86	5	–	1.17	–	–8.55	–	–	30	8.48E–10	8.48E–10	8.48E–06	

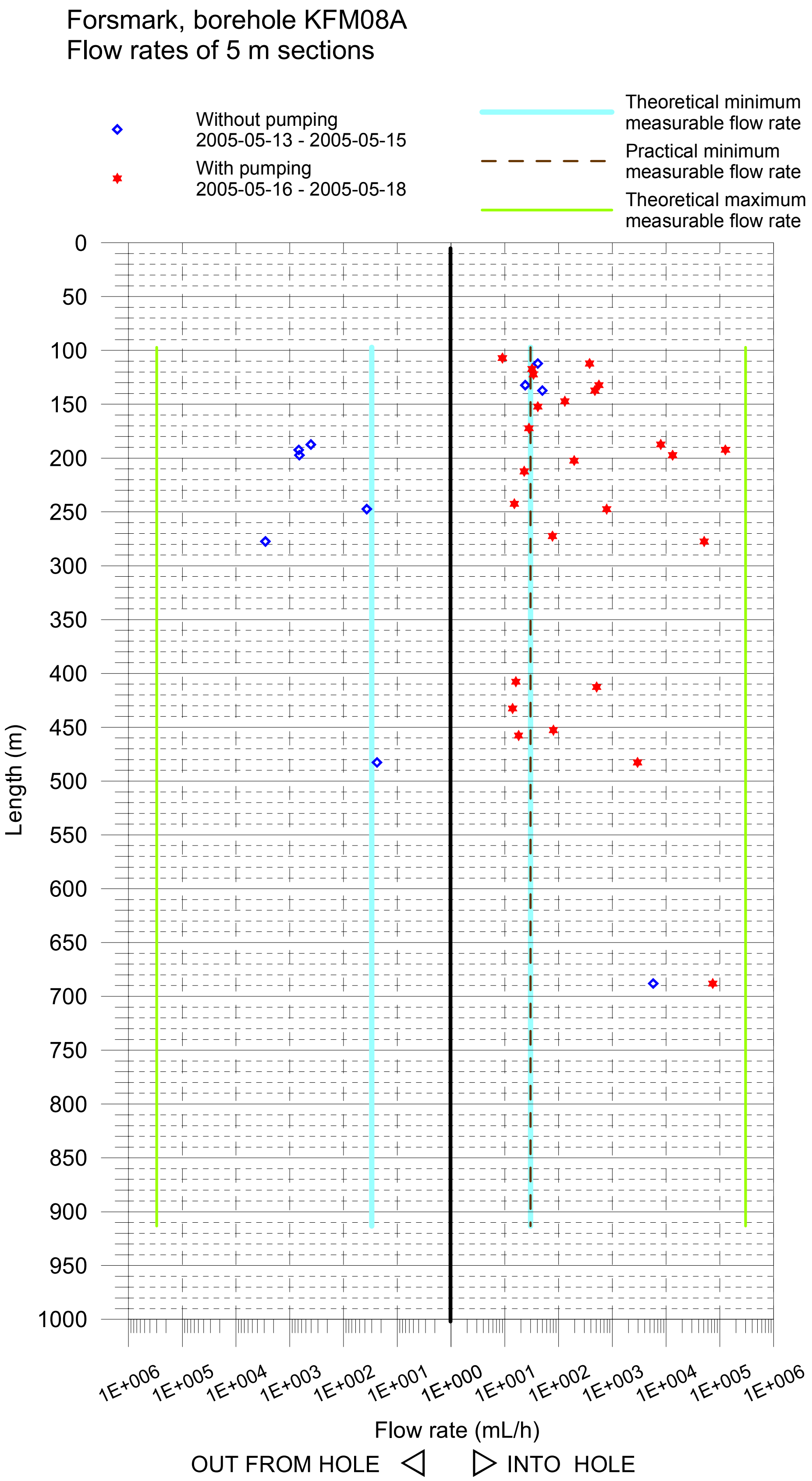
Borehole ID	Secup L(m)	Seclow L(m)	Lw (m)	Q_0 (m^3/s)	dh_0 (m)	Q_1 (m^3/s)	dh_1 (m)	TD (m^2/s)	h_i (m)	Q-lower limit P (mL/h)	TD-$measl_{LT}$ (m^2/s)	TD-$measl_{LP}$ (m^2/s)	TD-$measl_U$ (m^2/s)	Comments
KFM08A	234.87	239.87	5	–	1.22	–	–8.50	–	–	30	8.48E–10	8.48E–10	8.48E–06	
KFM08A	239.88	244.88	5	–	1.26	4.17E–09	–8.46	4.24E–10	–	30	8.48E–10	8.48E–10	8.48E–06	
KFM08A	244.89	249.89	5	–1.03E–08	1.31	2.18E–07	–8.42	2.32E–08	0.87	30	8.47E–10	8.47E–10	8.47E–06	
KFM08A	249.89	254.89	5	–	1.37	–	–8.38	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	254.90	259.90	5	–	1.41	–	–8.34	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	259.91	264.91	5	–	1.46	–	–8.29	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	264.91	269.91	5	–	1.50	–	–8.25	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	269.92	274.92	5	–	1.56	2.14E–08	–8.19	2.17E–09	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	274.93	279.93	5	–7.89E–07	1.60	1.43E–05	–8.16	1.52E–06	1.09	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	279.93	284.93	5	–	1.64	–	–8.09	–	–	30	8.47E–10	8.47E–10	8.47E–06	
KFM08A	284.94	289.94	5	–	1.66	–	–8.07	–	–	30	8.47E–10	8.47E–10	8.47E–06	
KFM08A	289.95	294.95	5	–	1.70	–	–8.03	–	–	30	8.47E–10	8.47E–10	8.47E–06	
KFM08A	294.96	299.96	5	–	1.78	–	–7.95	–	–	30	8.47E–10	8.47E–10	8.47E–06	
KFM08A	299.97	304.97	5	–	1.83	–	–7.91	–	–	30	8.46E–10	8.46E–10	8.46E–06	
KFM08A	304.98	309.98	5	–	1.87	–	–7.87	–	–	30	8.46E–10	8.46E–10	8.46E–06	
KFM08A	309.99	314.99	5	–	1.91	–	–7.83	–	–	30	8.46E–10	8.46E–10	8.46E–06	
KFM08A	315.00	320.00	5	–	1.95	–	–7.78	–	–	30	8.47E–10	8.47E–10	8.47E–06	
KFM08A	320.01	325.01	5	–	2.02	–	–7.72	–	–	30	8.46E–10	8.46E–10	8.46E–06	
KFM08A	325.01	330.01	5	–	2.03	–	–7.70	–	–	30	8.47E–10	8.47E–10	8.47E–06	
KFM08A	330.02	335.02	5	–	2.09	–	–7.64	–	–	30	8.47E–10	8.47E–10	8.47E–06	
KFM08A	335.02	340.02	5	–	2.14	–	–7.59	–	–	30	8.47E–10	8.47E–10	8.47E–06	
KFM08A	340.02	345.02	5	–	2.20	–	–7.53	–	–	30	8.47E–10	8.47E–10	8.47E–06	
KFM08A	345.02	350.02	5	–	2.26	–	–7.48	–	–	30	8.46E–10	8.46E–10	8.46E–06	
KFM08A	350.04	355.04	5	–	2.31	–	–7.44	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	355.05	360.05	5	–	2.34	–	–7.38	–	–	30	8.48E–10	8.48E–10	8.48E–06	
KFM08A	360.07	365.07	5	–	2.39	–	–7.33	–	–	30	8.48E–10	8.48E–10	8.48E–06	
KFM08A	365.09	370.09	5	–	2.44	–	–7.29	–	–	30	8.47E–10	8.47E–10	8.47E–06	
KFM08A	370.09	375.09	5	–	2.50	–	–7.23	–	–	30	8.47E–10	8.47E–10	8.47E–06	
KFM08A	375.10	380.10	5	–	2.56	–	–7.17	–	–	30	8.47E–10	8.47E–10	8.47E–06	
KFM08A	380.10	385.10	5	–	2.63	–	–7.11	–	–	30	8.46E–10	8.46E–10	8.46E–06	

Borehole ID	Secup L(m)	Seclow L(m)	Lw (m)	Q_0 (m³/s)	dh_0 (m)	Q_1 (m³/s)	dh_1 (m)	TD (m²/s)	h_i (m)	Q-lower limit P (mL/h)	TD-measl$_{LT}$ (m²/s)	TD-measl$_{LP}$ (m²/s)	TD-measl$_{U}$ (m²/s)	Comments
KFM08A	385.11	390.11	5	–	2.68	–	–7.07	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	390.12	395.12	5	–	2.75	–	–7.01	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	395.12	400.12	5	–	2.80	–	–6.95	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	400.13	405.13	5	–	2.85	–	–6.89	–	–	30	8.46E–10	8.46E–10	8.46E–06	
KFM08A	405.14	410.14	5	–	2.91	4.44E–09	–6.84	4.51E–10	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	410.15	415.15	5	–	2.97	1.42E–07	–6.78	1.44E–08	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	415.16	420.16	5	–	3.03	–	–6.73	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	420.16	425.16	5	–	3.09	–	–6.68	–	–	30	8.44E–10	8.44E–10	8.44E–06	
KFM08A	425.16	430.16	5	–	3.15	–	–6.63	–	–	30	8.43E–10	8.43E–10	8.43E–06	
KFM08A	430.16	435.16	5	–	3.23	3.89E–09	–6.59	3.92E–10	–	30	8.39E–10	8.39E–10	8.39E–06	
KFM08A	435.16	440.16	5	–	3.28	–	–6.51	–	–	30	8.42E–10	8.42E–10	8.42E–06	
KFM08A	440.16	445.16	5	–	3.36	–	–6.45	–	–	30	8.40E–10	8.40E–10	8.40E–06	
KFM08A	445.16	450.16	5	–	3.37	–	–6.40	–	–	30	8.44E–10	8.44E–10	8.44E–06	
KFM08A	450.16	455.16	5	–	3.44	2.22E–08	–6.34	2.25E–09	–	30	8.43E–10	8.43E–10	8.43E–06	
KFM08A	455.16	460.16	5	–	3.50	5.00E–09	–6.30	5.05E–10	–	30	8.41E–10	8.41E–10	8.41E–06	
KFM08A	460.16	465.16	5	–	3.57	–	–6.24	–	–	30	8.40E–10	8.40E–10	8.40E–06	
KFM08A	465.16	470.16	5	–	3.62	–	–6.18	–	–	30	8.41E–10	8.41E–10	8.41E–06	
KFM08A	470.16	475.16	5	–	3.70	–	–6.09	–	–	30	8.42E–10	8.42E–10	8.42E–06	
KFM08A	475.16	480.16	5	–	3.76	–	–6.03	–	–	30	8.42E–10	8.42E–10	8.42E–06	
KFM08A	480.16	485.16	5	–6.67E–09	3.82	8.14E–07	–5.95	8.31E–08	3.74	30	8.44E–10	8.44E–10	8.44E–06	
KFM08A	485.17	490.17	5	–	3.88	–	–5.89	–	–	30	8.44E–10	8.44E–10	8.44E–06	
KFM08A	490.18	495.18	5	–	3.93	–	–5.83	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	495.20	500.20	5	–	3.99	–	–5.77	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	500.21	505.21	5	–	4.07	–	–5.69	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	505.22	510.22	5	–	4.14	–	–5.62	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	510.22	515.22	5	–	4.19	–	–5.55	–	–	30	8.46E–10	8.46E–10	8.46E–06	
KFM08A	515.23	520.23	5	–	4.25	–	–5.50	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	520.24	525.24	5	–	4.33	–	–5.43	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	525.25	530.25	5	–	4.39	–	–5.35	–	–	30	8.46E–10	8.46E–10	8.46E–06	
KFM08A	530.26	535.26	5	–	4.47	–	–5.31	–	–	30	8.43E–10	8.43E–10	8.43E–06	

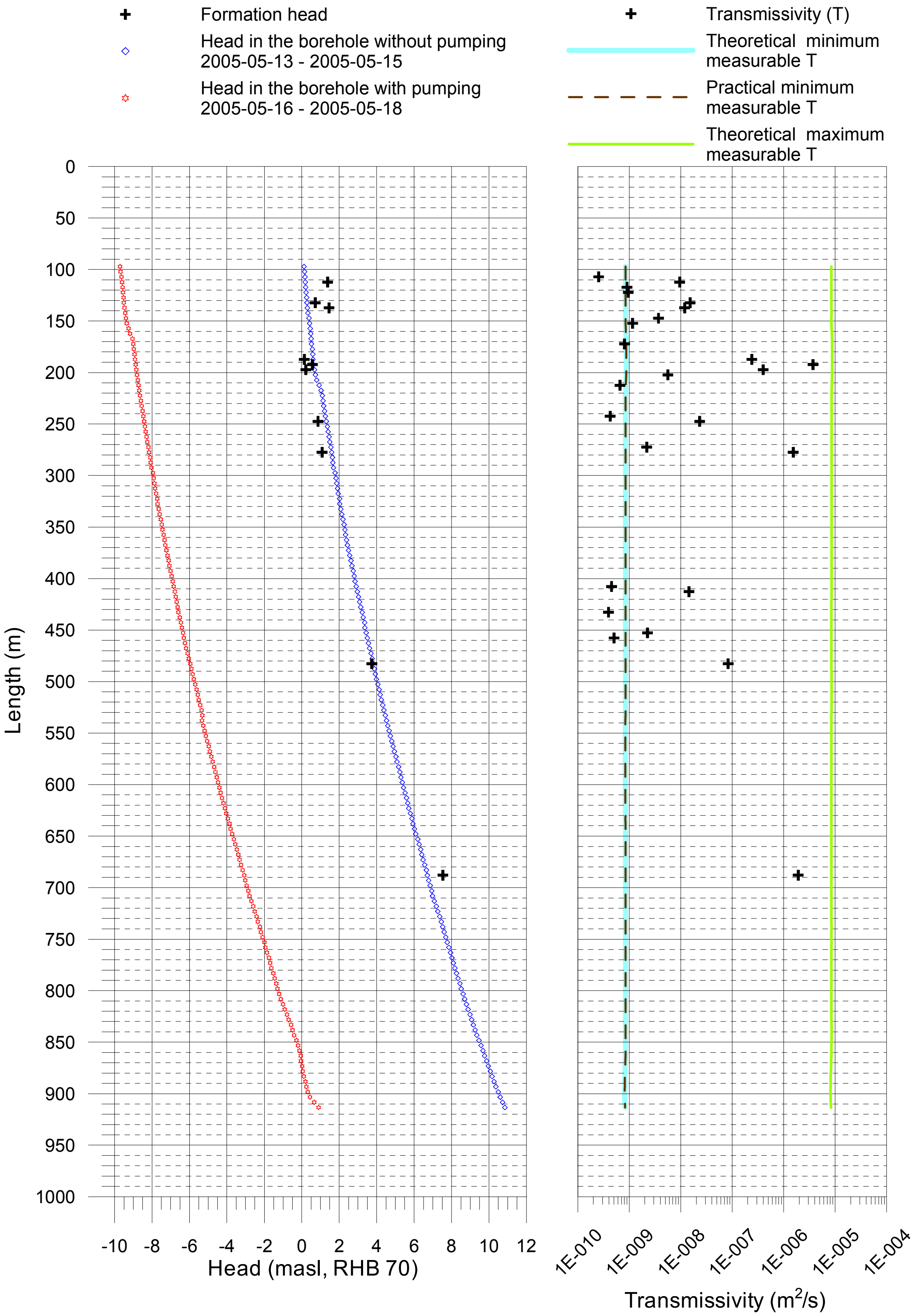
Borehole ID	Secup L(m)	Seclow L(m)	Lw (m)	Q_0 (m^3/s)	dh_0 (m)	Q_1 (m^3/s)	dh_1 (m)	TD (m^2/s)	h_i (m)	Q-lower limit P (mL/h)	TD-measl$_{LT}$ (m^2/s)	TD-measl$_{LP}$ (m^2/s)	TD-measl$_U$ (m^2/s)	Comments
KFM08A	535.27	540.27	5	–	4.53	–	–5.33	–	–	30	8.36E–10	8.36E–10	8.36E–06	
KFM08A	540.28	545.28	5	–	4.60	–	–5.26	–	–	30	8.36E–10	8.36E–10	8.36E–06	
KFM08A	545.29	550.29	5	–	4.67	–	–5.19	–	–	30	8.36E–10	8.36E–10	8.36E–06	
KFM08A	550.30	555.30	5	–	4.73	–	–5.12	–	–	30	8.37E–10	8.37E–10	8.37E–06	
KFM08A	555.31	560.31	5	–	4.81	–	–5.06	–	–	30	8.35E–10	8.35E–10	8.35E–06	
KFM08A	560.31	565.31	5	–	4.88	–	–4.97	–	–	30	8.37E–10	8.37E–10	8.37E–06	
KFM08A	565.32	570.32	5	–	4.95	–	–4.91	–	–	30	8.36E–10	8.36E–10	8.36E–06	
KFM08A	570.33	575.33	5	–	5.03	–	–4.83	–	–	30	8.36E–10	8.36E–10	8.36E–06	
KFM08A	575.33	580.33	5	–	5.09	–	–4.76	–	–	30	8.37E–10	8.37E–10	8.37E–06	
KFM08A	580.34	585.34	5	–	5.17	–	–4.68	–	–	30	8.37E–10	8.37E–10	8.37E–06	
KFM08A	585.35	590.35	5	–	5.24	–	–4.61	–	–	30	8.37E–10	8.37E–10	8.37E–06	
KFM08A	590.36	595.36	5	–	5.30	–	–4.54	–	–	30	8.38E–10	8.38E–10	8.38E–06	
KFM08A	595.37	600.37	5	–	5.37	–	–4.47	–	–	30	8.38E–10	8.38E–10	8.38E–06	
KFM08A	600.38	605.38	5	–	5.44	–	–4.40	–	–	30	8.38E–10	8.38E–10	8.38E–06	
KFM08A	605.39	610.39	5	–	5.52	–	–4.33	–	–	30	8.37E–10	8.37E–10	8.37E–06	
KFM08A	610.40	615.40	5	–	5.59	–	–4.26	–	–	30	8.37E–10	8.37E–10	8.37E–06	
KFM08A	615.41	620.41	5	–	5.66	–	–4.18	–	–	30	8.38E–10	8.38E–10	8.38E–06	
KFM08A	620.42	625.42	5	–	5.72	–	–4.10	–	–	30	8.39E–10	8.39E–10	8.39E–06	
KFM08A	625.42	630.42	5	–	5.80	–	–4.03	–	–	30	8.39E–10	8.39E–10	8.39E–06	
KFM08A	630.43	635.43	5	–	5.89	–	–3.95	–	–	30	8.38E–10	8.38E–10	8.38E–06	
KFM08A	635.44	640.44	5	–	5.94	–	–3.86	–	–	30	8.41E–10	8.41E–10	8.41E–06	
KFM08A	640.44	645.44	5	–	6.02	–	–3.80	–	–	30	8.39E–10	8.39E–10	8.39E–06	
KFM08A	645.45	650.45	5	–	6.09	–	–3.72	–	–	30	8.40E–10	8.40E–10	8.40E–06	
KFM08A	650.46	655.46	5	–	6.20	–	–3.63	–	–	30	8.39E–10	8.39E–10	8.39E–06	
KFM08A	655.46	660.46	5	–	6.27	–	–3.55	–	–	30	8.39E–10	8.39E–10	8.39E–06	
KFM08A	660.47	665.47	5	–	6.35	–	–3.47	–	–	30	8.39E–10	8.39E–10	8.39E–06	
KFM08A	665.48	670.48	5	–	6.41	–	–3.39	–	–	30	8.41E–10	8.41E–10	8.41E–06	
KFM08A	670.49	675.49	5	–	6.48	–	–3.32	–	–	30	8.41E–10	8.41E–10	8.41E–06	
KFM08A	675.49	680.49	5	–	6.57	–	–3.24	–	–	30	8.40E–10	8.40E–10	8.40E–06	
KFM08A	680.50	685.50	5	–	6.66	–	–3.16	–	–	30	8.39E–10	8.39E–10	8.39E–06	

Borehole ID	Secup L(m)	Seclow L(m)	Lw (m)	Q_0 (m^3/s)	dh_0 (m)	Q_1 (m^3/s)	dh_1 (m)	TD (m^2/s)	h_i (m)	Q-lower limit P (mL/h)	TD-$measl_{LT}$ (m^2/s)	TD-$measl_{LP}$ (m^2/s)	TD-$measl_U$ (m^2/s)	Comments
KFM08A	685.51	690.51	5	1.60E–06	6.71	2.04E–05	–3.07	1.91E–06	7.54	30	8.43E–10	8.43E–10	8.43E–06	
KFM08A	690.52	695.52	5	–	6.78	–	–3.02	–	–	30	8.41E–10	8.41E–10	8.41E–06	
KFM08A	695.55	700.55	5	–	6.86	–	–2.94	–	–	30	8.41E–10	8.41E–10	8.41E–06	
KFM08A	700.58	705.58	5	–	6.94	–	–2.85	–	–	30	8.42E–10	8.42E–10	8.42E–06	
KFM08A	705.58	710.58	5	–	6.99	–	–2.79	–	–	30	8.43E–10	8.43E–10	8.43E–06	
KFM08A	710.57	715.57	5	–	7.08	–	–2.69	–	–	30	8.44E–10	8.44E–10	8.44E–06	
KFM08A	715.57	720.57	5	–	7.19	–	–2.59	–	–	30	8.43E–10	8.43E–10	8.43E–06	
KFM08A	720.56	725.56	5	–	7.27	–	–2.51	–	–	30	8.43E–10	8.43E–10	8.43E–06	
KFM08A	725.56	730.56	5	–	7.37	–	–2.41	–	–	30	8.43E–10	8.43E–10	8.43E–06	
KFM08A	730.56	735.56	5	–	7.46	–	–2.35	–	–	30	8.40E–10	8.40E–10	8.40E–06	
KFM08A	735.56	740.56	5	–	7.53	–	–2.23	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	740.57	745.57	5	–	7.61	–	–2.18	–	–	30	8.42E–10	8.42E–10	8.42E–06	
KFM08A	745.58	750.58	5	–	7.69	–	–2.09	–	–	30	8.43E–10	8.43E–10	8.43E–06	
KFM08A	750.59	755.59	5	–	7.77	–	–1.99	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	755.59	760.59	5	–	7.86	–	–1.94	–	–	30	8.41E–10	8.41E–10	8.41E–06	
KFM08A	760.60	765.60	5	–	7.95	–	–1.86	–	–	30	8.40E–10	8.40E–10	8.40E–06	
KFM08A	765.61	770.61	5	–	8.02	–	–1.75	–	–	30	8.44E–10	8.44E–10	8.44E–06	
KFM08A	770.62	775.62	5	–	8.10	–	–1.69	–	–	30	8.42E–10	8.42E–10	8.42E–06	
KFM08A	775.63	780.63	5	–	8.18	–	–1.62	–	–	30	8.41E–10	8.41E–10	8.41E–06	
KFM08A	780.64	785.64	5	–	8.27	–	–1.52	–	–	30	8.42E–10	8.42E–10	8.42E–06	
KFM08A	785.65	790.65	5	–	8.35	–	–1.45	–	–	30	8.41E–10	8.41E–10	8.41E–06	
KFM08A	790.66	795.66	5	–	8.45	–	–1.36	–	–	30	8.40E–10	8.40E–10	8.40E–06	
KFM08A	795.67	800.67	5	–	8.52	–	–1.30	–	–	30	8.39E–10	8.39E–10	8.39E–06	
KFM08A	800.68	805.68	5	–	8.62	–	–1.21	–	–	30	8.39E–10	8.39E–10	8.39E–06	
KFM08A	805.68	810.68	5	–	8.70	–	–1.12	–	–	30	8.39E–10	8.39E–10	8.39E–06	
KFM08A	810.69	815.69	5	–	8.80	–	–1.00	–	–	30	8.41E–10	8.41E–10	8.41E–06	
KFM08A	815.69	820.69	5	–	8.89	–	–0.91	–	–	30	8.41E–10	8.41E–10	8.41E–06	
KFM08A	820.70	825.70	5	–	8.99	–	–0.79	–	–	30	8.43E–10	8.43E–10	8.43E–06	
KFM08A	825.71	830.71	5	–	9.08	–	–0.70	–	–	30	8.43E–10	8.43E–10	8.43E–06	
KFM08A	830.71	835.71	5	–	9.17	–	–0.57	–	–	30	8.46E–10	8.46E–10	8.46E–06	

Borehole ID	Secup L(m)	Seclow L(m)	Lw (m)	Q_0 (m^3/s)	dh_0 (m)	Q_1 (m^3/s)	dh_1 (m)	TD (m^2/s)	h_i (m)	Q-lower limit P (mL/h)	TD-$measl_{LT}$ (m^2/s)	TD-$measl_{LP}$ (m^2/s)	TD-$measl_U$ (m^2/s)	Comments
KFM08A	835.72	840.72	5	–	9.26	–	–0.49	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	840.72	845.72	5	–	9.35	–	–0.41	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	845.73	850.73	5	–	9.47	–	–0.28	–	–	30	8.45E–10	8.45E–10	8.45E–06	
KFM08A	850.74	855.74	5	–	9.58	–	–0.20	–	–	30	8.43E–10	8.43E–10	8.43E–06	
KFM08A	855.75	860.75	5	–	9.68	–	–0.12	–	–	30	8.41E–10	8.41E–10	8.41E–06	
KFM08A	860.75	865.75	5	–	9.77	–	–0.05	–	–	30	8.39E–10	8.39E–10	8.39E–06	
KFM08A	865.76	870.76	5	–	9.88	–	–0.04	–	–	30	8.31E–10	8.31E–10	8.31E–06	
KFM08A	870.77	875.77	5	–	9.97	–	0.02	–	–	30	8.28E–10	8.28E–10	8.28E–06	
KFM08A	875.78	880.78	5	–	10.07	–	0.05	–	–	30	8.23E–10	8.23E–10	8.23E–06	
KFM08A	880.79	885.79	5	–	10.17	–	0.11	–	–	30	8.19E–10	8.19E–10	8.19E–06	
KFM08A	885.79	890.79	5	–	10.27	–	0.20	–	–	30	8.19E–10	8.19E–10	8.19E–06	
KFM08A	890.80	895.80	5	–	10.37	–	0.25	–	–	30	8.15E–10	8.15E–10	8.15E–06	
KFM08A	895.81	900.81	5	–	10.50	–	0.32	–	–	30	8.10E–10	8.10E–10	8.10E–06	
KFM08A	900.82	905.82	5	–	10.60	–	0.44	–	–	30	8.11E–10	8.11E–10	8.11E–06	
KFM08A	905.83	910.83	5	–	10.73	–	0.67	–	–	30	8.19E–10	8.19E–10	8.19E–06	
KFM08A	910.83	915.83	5	–	10.85	–	0.90	–	–	30	8.28E–10	8.28E–10	8.28E–06	


Forsmark, borehole KFM08A
Flow rates of 5 m sections
Without pumping
2005-05-13 - 2005-05-15
With pumping
2005-05-16 - 2005-05-18
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
650
700
750
800
850
900
950
1000
1E+006
1E+005
1E+004
1E+003
1E+002
1E+001
1E+000
1E+001
1E+002
1E+003
1E+004
1E+005
1E+006
Flow rate (mL/h)
OUT FROM HOLE
INTO HOLE

Forsmark, borehole KFM08A
Transmissivity and head of 5 m sections

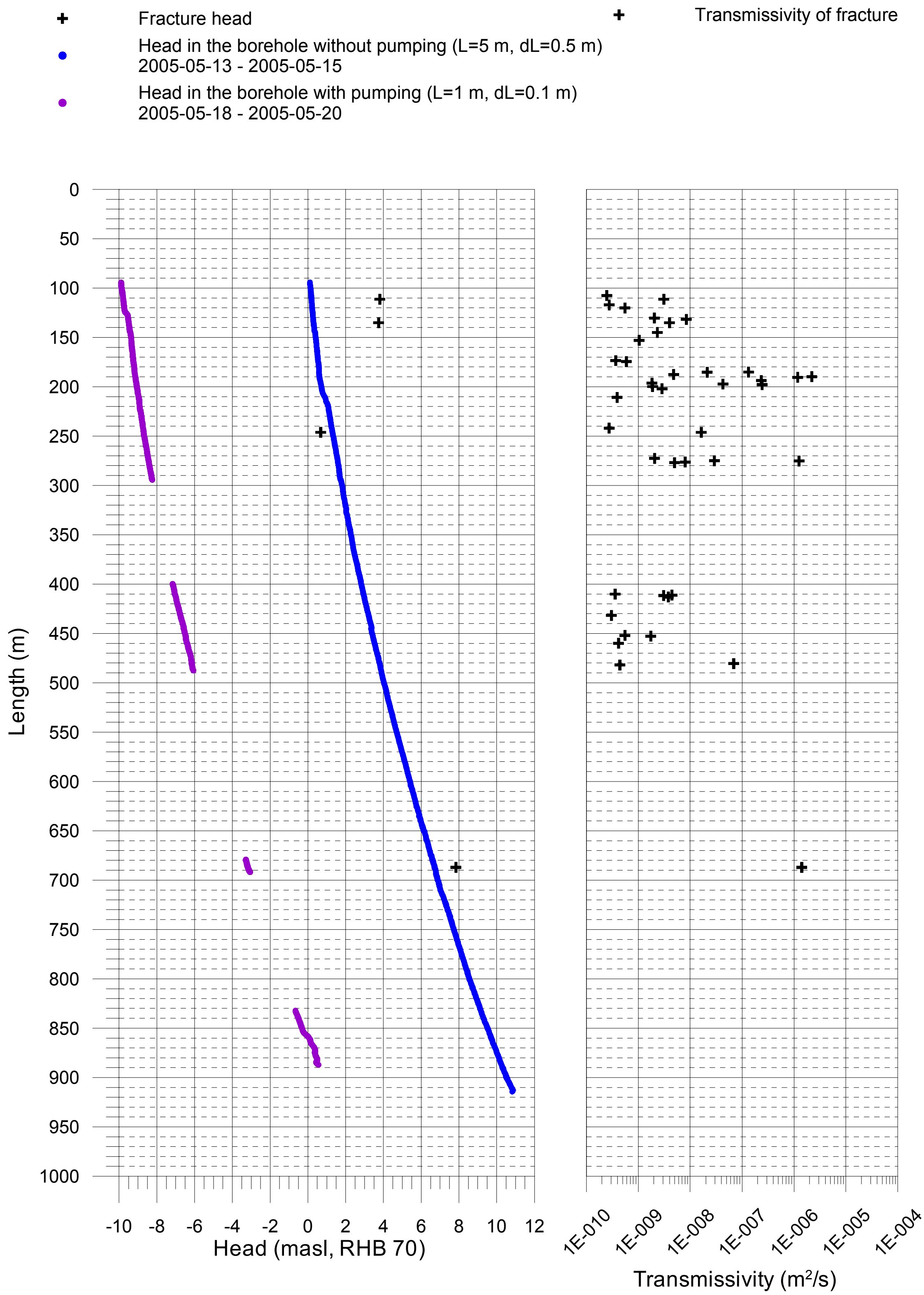


PFL – Difference flow logging – Inferred flow anomalies from overlapping flow logging

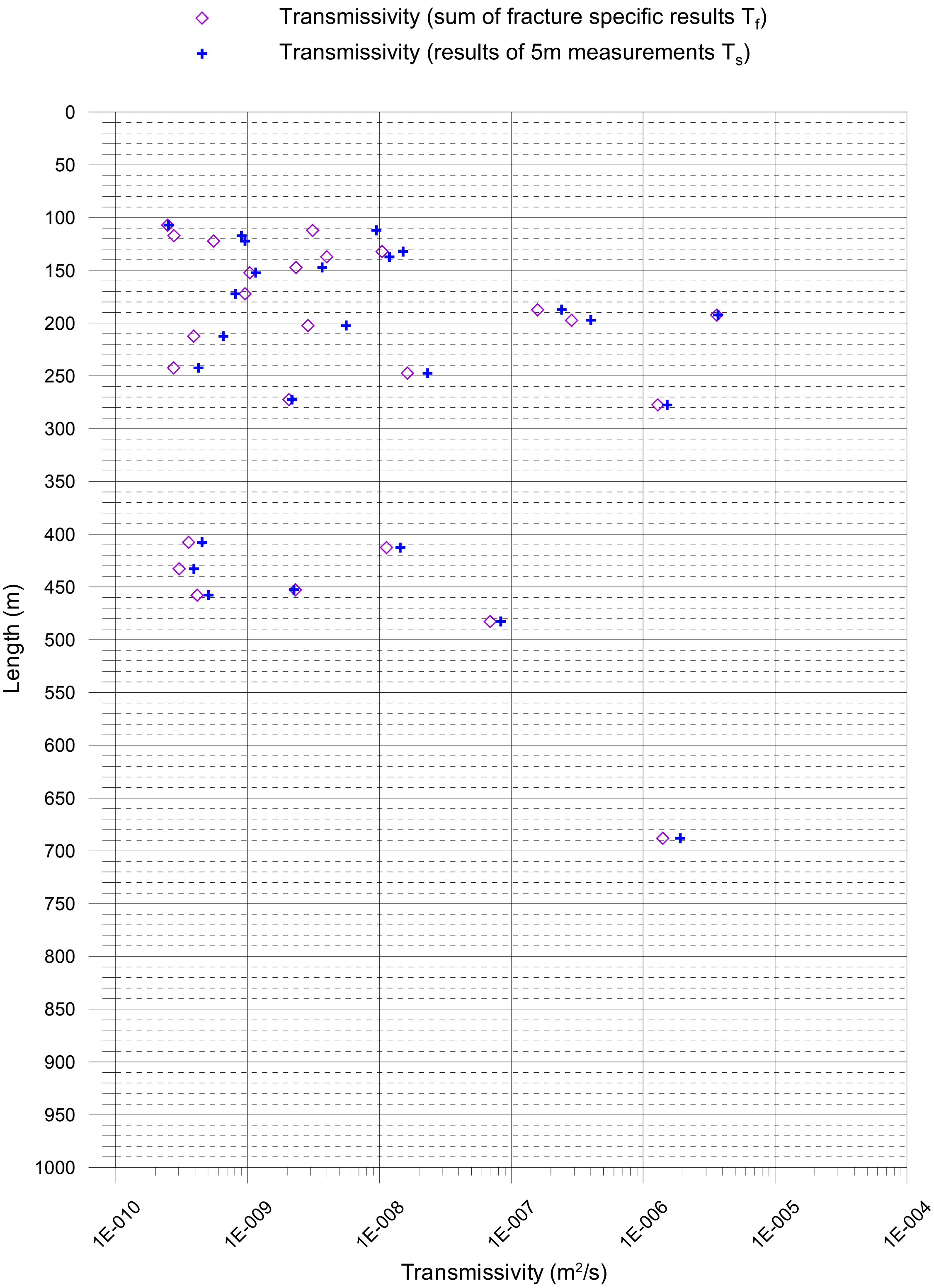
Borehole ID	Length to flow anom. L (m)	Lw (m)	dL (m)	Q_0 (m^3/s)	dh_0 (m)	Q_1 (m^3/s)	dh_1 (m)	TD (m^2/s)	h_i (m)	Comments
KFM08A	107.6	1.0	0.1	–	0.18	2.50E–09	–9.80	2.48E–10	–	*
KFM08A	111.3	1.0	0.1	1.14E–08	0.19	4.28E–08	–9.79	3.11E–09	3.81	
KFM08A	117.0	1.0	0.1	–	0.22	2.78E–09	–9.74	2.76E–10	–	*
KFM08A	120.1	1.0	0.1	–	0.22	5.56E–09	–9.72	5.53E–10	–	
KFM08A	130.3	1.0	0.1	–	0.28	2.03E–08	–9.53	2.04E–09	–	
KFM08A	131.7	1.0	0.1	–	0.28	8.33E–08	–9.51	8.42E–09	–	
KFM08A	135.1	1.0	0.1	1.39E–08	0.30	5.33E–08	–9.48	3.99E–09	3.74	
KFM08A	145.0	1.0	0.1	–	0.38	2.31E–08	–9.40	2.33E–09	–	
KFM08A	152.9	1.0	0.1	–	0.43	1.03E–08	–9.35	1.04E–09	–	
KFM08A	173.4	1.0	0.1	–	0.54	3.61E–09	–9.24	3.65E–10	–	*
KFM08A	174.5	1.0	0.1	–	0.54	5.83E–09	–9.25	5.89E–10	–	
KFM08A	185.1	1.0	0.1	–	0.59	1.31E–06	–9.19	1.32E–07	–	
KFM08A	185.3	1.0	0.1	–	0.59	2.09E–07	–9.17	2.12E–08	–	
KFM08A	187.6	1.0	0.1	–	0.61	4.75E–08	–9.15	4.81E–09	–	
KFM08A	189.8	1.0	0.1	–	0.61	2.17E–05	–9.14	2.20E–06	–	
KFM08A	190.5	1.0	0.1	–	0.62	1.16E–05	–9.13	1.18E–06	–	
KFM08A	193.7	1.0	0.1	–	0.64	2.31E–06	–9.12	2.34E–07	–	
KFM08A	196.4	1.0	0.1	–	0.68	1.81E–08	–9.09	1.83E–09	–	
KFM08A	197.3	1.0	0.1	–	0.69	4.22E–07	–9.09	4.27E–08	–	
KFM08A	197.9	1.0	0.1	–	0.70	2.40E–06	–9.08	2.42E–07	–	
KFM08A	199.8	1.0	0.1	–	0.71	1.86E–08	–9.05	1.89E–09	–	
KFM08A	202.0	1.0	0.1	–	0.73	2.83E–08	–9.05	2.87E–09	–	
KFM08A	210.7	1.0	0.1	–	0.91	3.89E–09	–8.95	3.90E–10	–	*
KFM08A	241.9	1.0	0.1	–	1.26	2.78E–09	–8.73	2.75E–10	–	*
KFM08A	246.2	1.0	0.1	–1.03E–08	1.30	1.55E–07	–8.70	1.63E–08	0.68	
KFM08A	272.5	1.0	0.1	–	1.56	2.08E–08	–8.46	2.06E–09	–	
KFM08A	275.0	1.0	0.1	–	1.58	2.97E–07	–8.44	2.93E–08	–	*
KFM08A	275.2	1.0	0.1	–	1.58	1.26E–05	–8.43	1.25E–06	–	
KFM08A	276.3	1.0	0.1	–	1.58	8.14E–08	–8.42	8.05E–09	–	
KFM08A	276.9	1.0	0.1	–	1.60	5.06E–08	–8.42	4.99E–09	–	
KFM08A	410.1	1.0	0.1	–	2.95	3.61E–09	–7.05	3.57E–10	–	*
KFM08A	411.2	1.0	0.1	–	2.96	4.50E–08	–7.03	4.46E–09	–	
KFM08A	411.6	1.0	0.1	–	2.97	3.11E–08	–7.02	3.08E–09	–	
KFM08A	413.1	1.0	0.1	–	2.99	3.81E–08	–6.99	3.77E–09	–	
KFM08A	431.7	1.0	0.1	–	3.22	3.06E–09	–6.75	3.03E–10	–	*
KFM08A	452.0	1.0	0.1	–	3.44	5.56E–09	–6.48	5.54E–10	–	*
KFM08A	452.8	1.0	0.1	–	3.44	1.75E–08	–6.47	1.75E–09	–	
KFM08A	459.9	1.0	0.1	–	3.53	4.17E–09	–6.39	4.15E–10	–	*
KFM08A	480.5	1.0	0.1	–	3.81	6.94E–07	–6.16	6.89E–08	–	
KFM08A	482.0	1.0	0.1	–	3.82	4.44E–09	–6.14	4.41E–10	–	*
KFM08A	687.0	1.0	0.1	1.60E–06	6.72	1.57E–05	–3.19	1.41E–06	7.84	

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

Forsmark, borehole KFM08A
Transmissivity and head of detected fractures

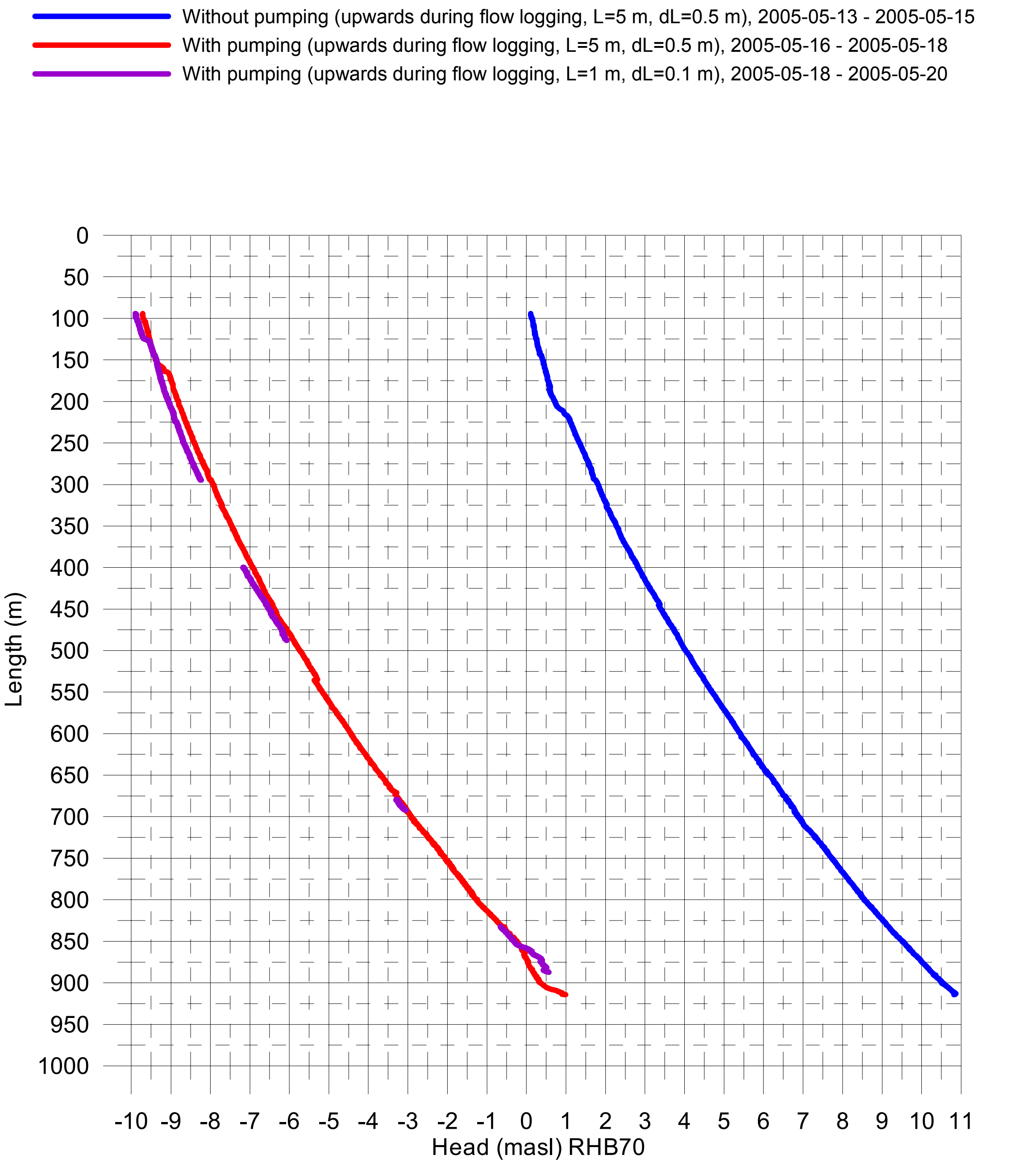


Forsmark, borehole KFM08A
Comparison between section transmissivity and fracture transmissivity

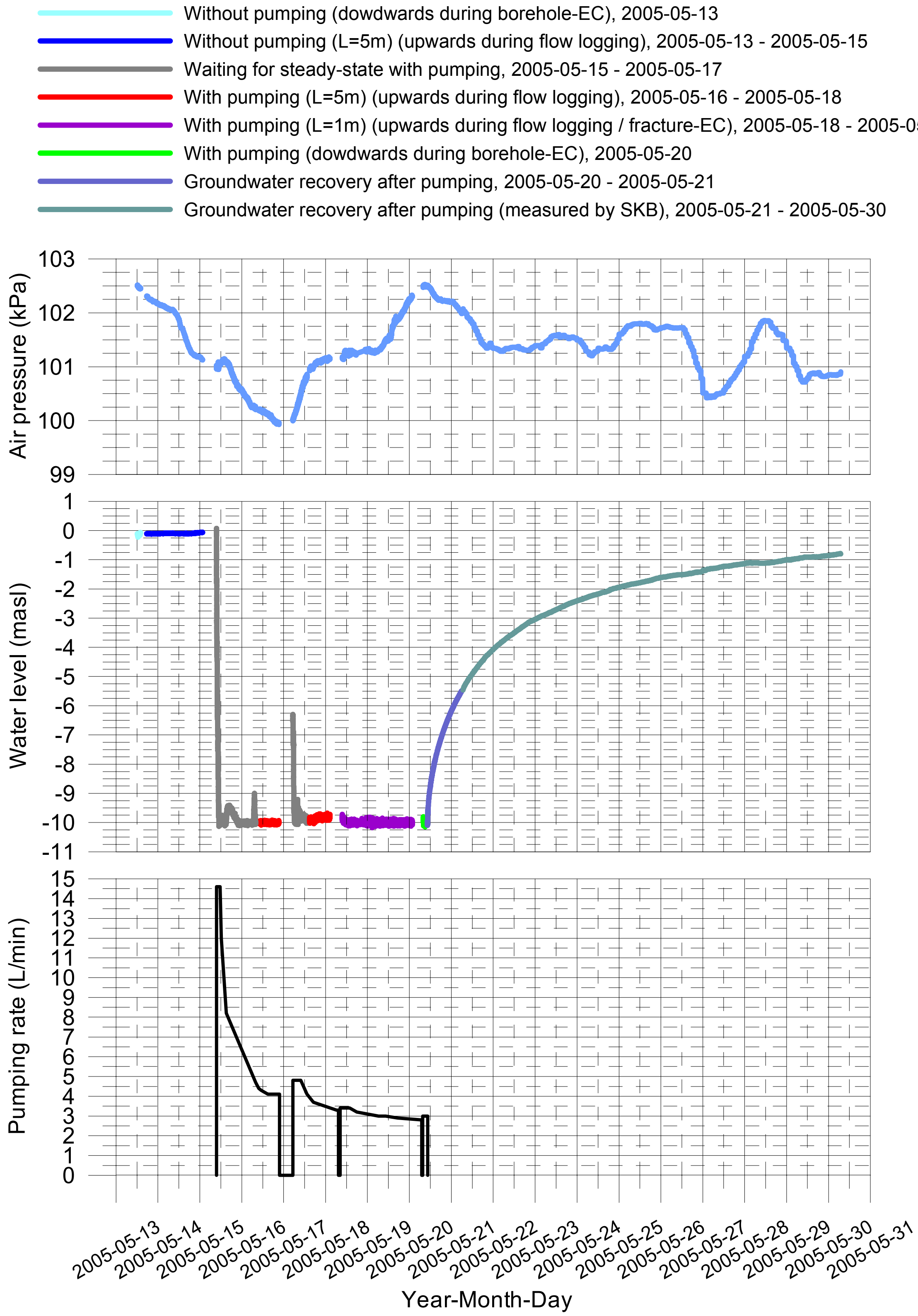


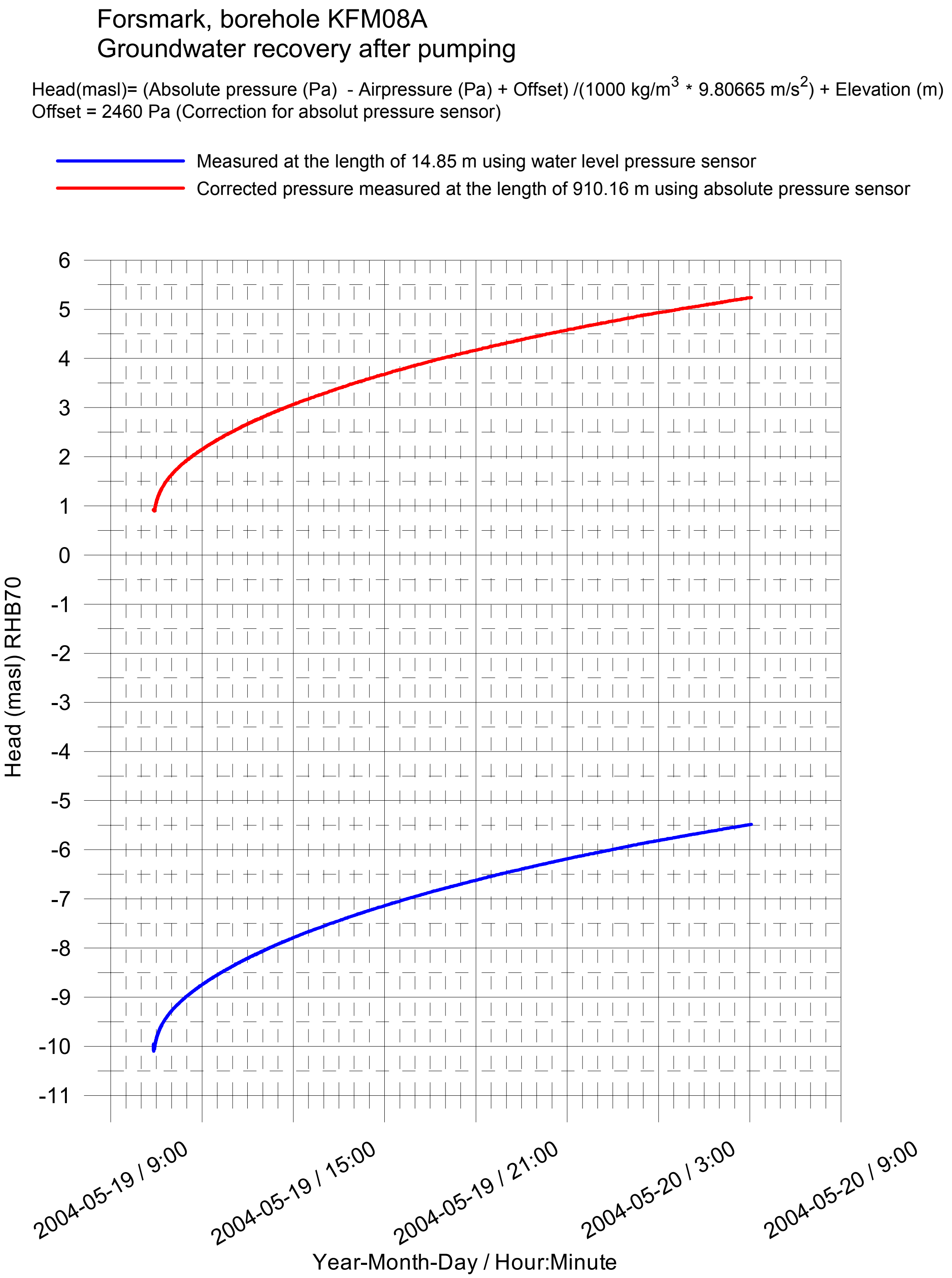
Forsmark, borehole KFM08A
Head in the borehole during flow logging

Head(masl)= (Absolute pressure (Pa) - Airpressure (Pa) + Offset) /(1000 kg/m^3 * 9.80665 m/s^2) + Elevation (m)
Offset = 2460 Pa (Correction for absolut pressure sensor)



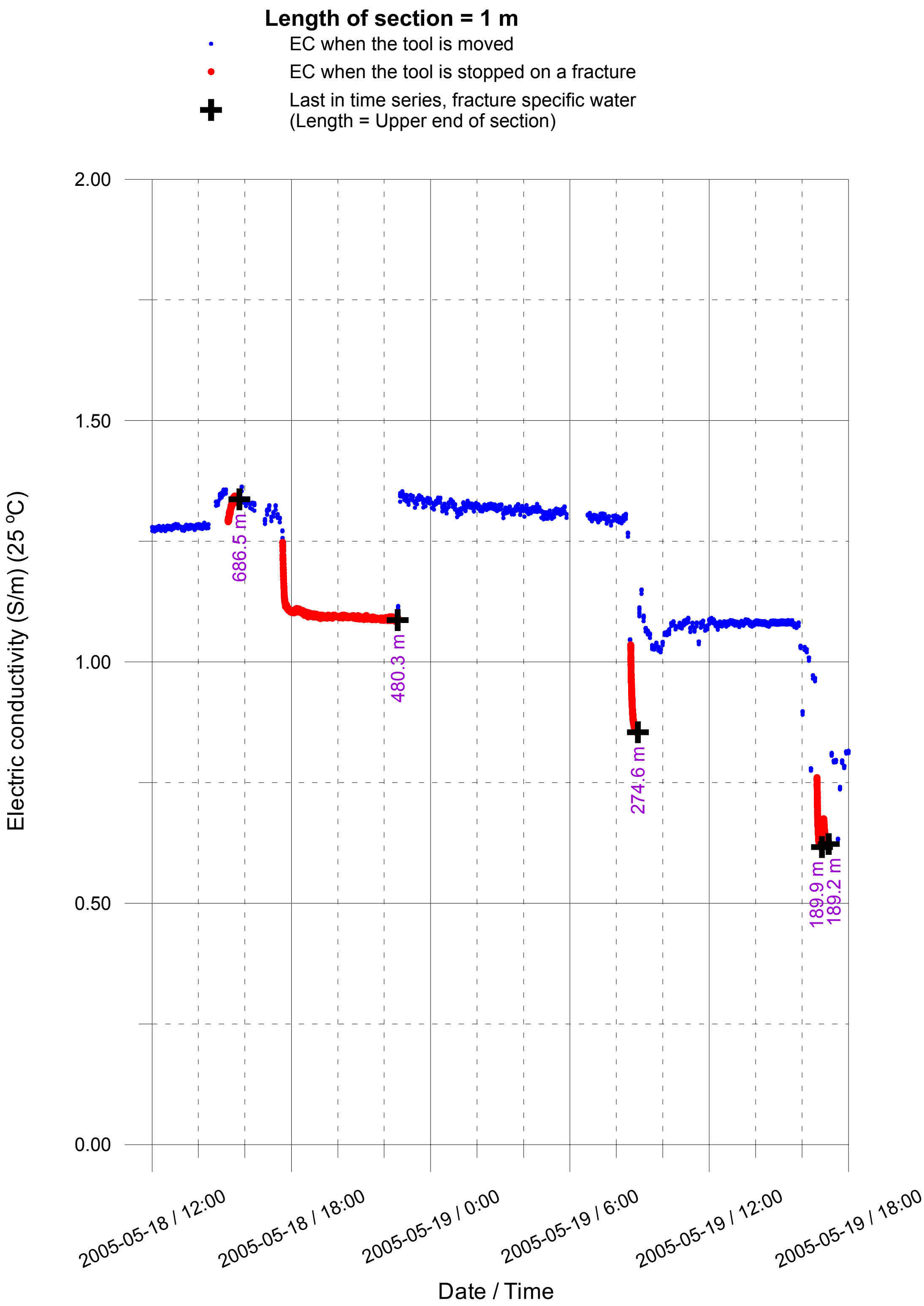
Forsmark, borehole KFM08A
Air pressure, water level in the borehole and pumping rate during flow logging





Forsmark, borehole KFM08A
Groundwater recovery after pumping
Head(masl)= (Absolute pressure (Pa) - Airpressure (Pa) + Offset) /(1000 kg/m3 * 9.80665 m/s2) + Elevation (m)
Offset = 2460 Pa (Correction for absolut pressure sensor)
Measured at the length of 14.85 m using water level pressure sensor
Corrected pressure measured at the length of 910.16 m using absolute pressure sensor
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
Head (masl) RHB70
2004-05-19 / 9:00
2004-05-19 / 15:00
2004-05-19 / 21:00
2004-05-20 / 3:00
2004-05-20 / 9:00
Year-Month-Day / Hour:Minute

Forsmark, borehole KFM08A
Fracture-specific EC results by date



Forsmark, borehole KFM08A

Test data diagrams from pumping test during difference flow logging

Nomenclature used in the test data diagrams from Aqtesolv

K_r = hydraulic conductivity of the rock in the radial direction

K_z = hydraulic conductivity of the rock in the vertical direction

K_Z/K_r = ratio of hydraulic conductivities in the vertical and radial direction (set to 1)

T = transmissivity (m^2/s)

S = storativity (–)

Ss = specific storativity (m^{-1})

S_w = skin factor

r(w) = borehole radius (m)

r(c) = effective casing radius (m)

R_f = radius of equivalent single horizontal fracture (m)

Diagrams presented

Flow period (log-log and lin-log)

Recovery period (log-log and lin-log)

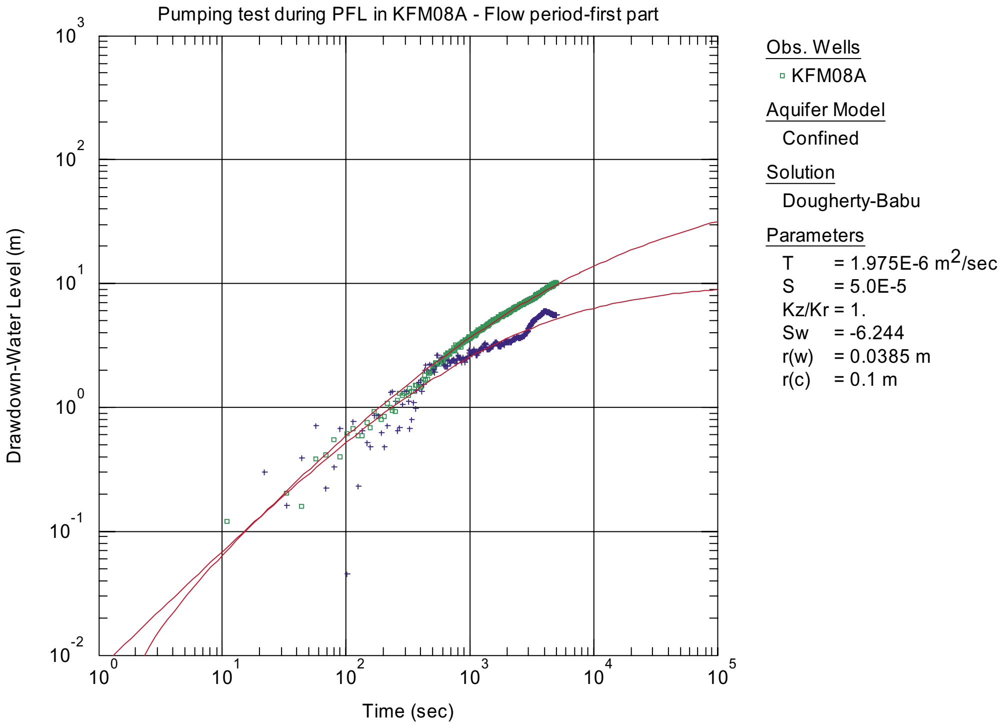


Figure A12-1. *Log-log plot of measured (green) and simulated (red) pressure drawdown and -derivative (blue) versus time during the first phase of the flow period of the pumping test in KFM08A. Evaluation based on the early part of the curve.*

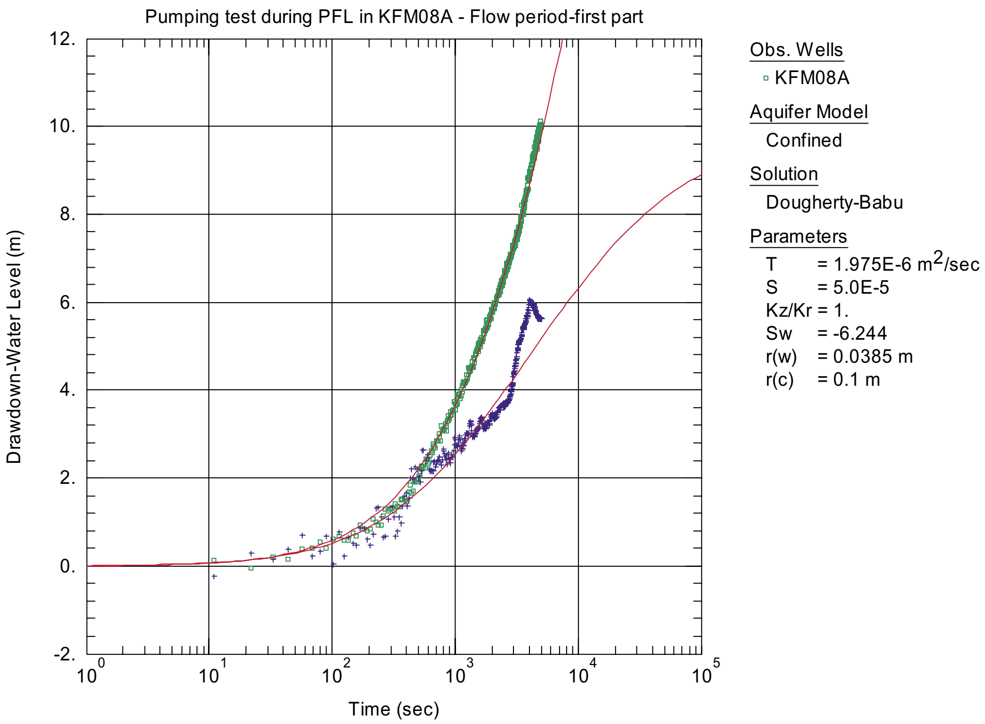


Figure A12-2. *Lin-log plot of measured (green) and simulated (red) pressure drawdown and -derivative (blue) versus time during the first phase of the flow period of the pumping test in KFM08A. Evaluation based on the early part of the curve.*

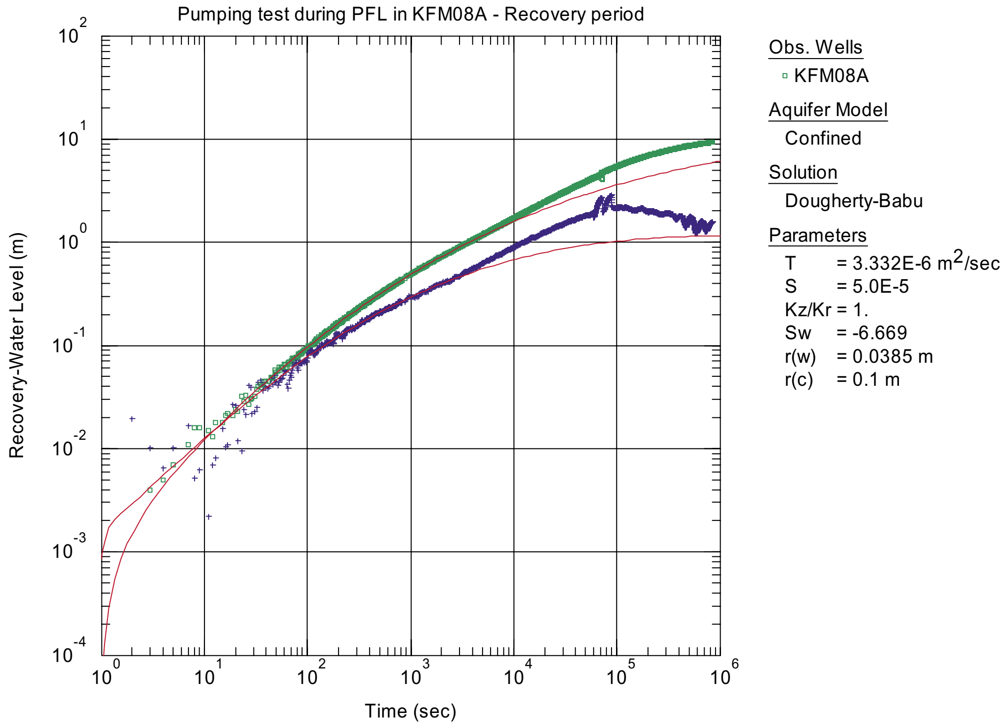


Figure A12-3. *Log-log plot of measured (green) and simulated (red) pressure drawdown and -derivative (blue) versus time during the total recovery period of the pumping test in KFM08A. Evaluation based on the early part of the curve.*

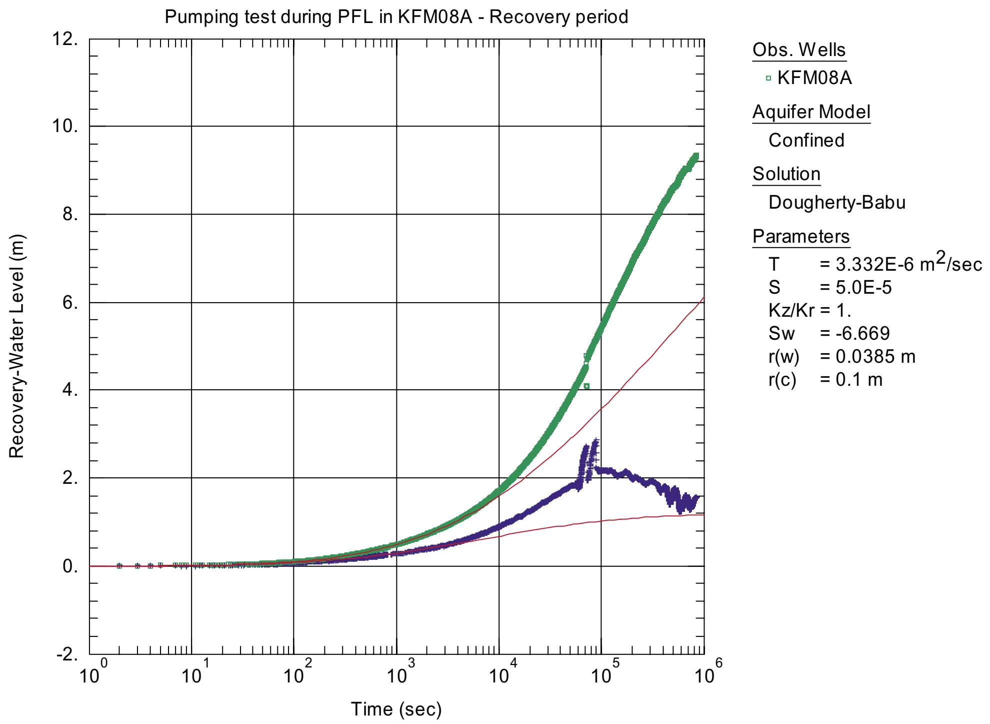


Figure A12-4. *Lin-log plot of measured (green) and simulated (red) pressure drawdown and -derivative (blue) versus time during the total recovery period of the pumping test in KFM08A. Evaluation based on the early part of the curve.*

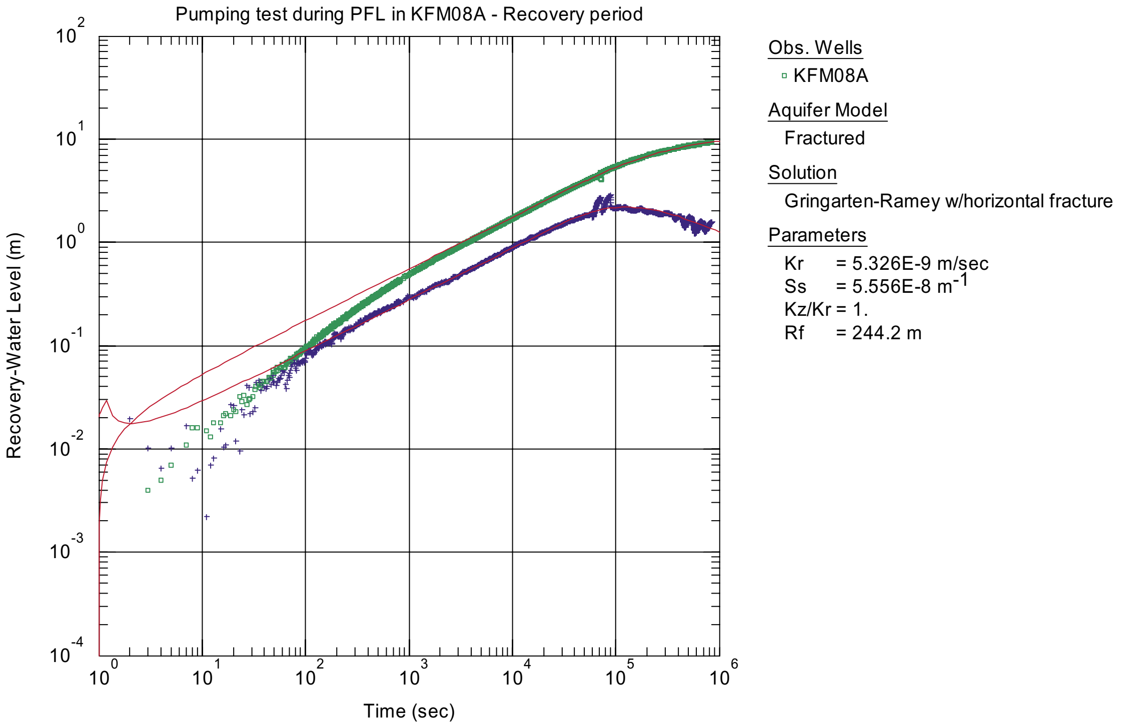


Figure A12-5. *Log-log plot of measured (green) and simulated (red) pressure recovery and -derivative (blue) versus time during the total recovery period of the pumping test in borehole KFM08A. Evaluation based on the intermediate and late part of the curve.*

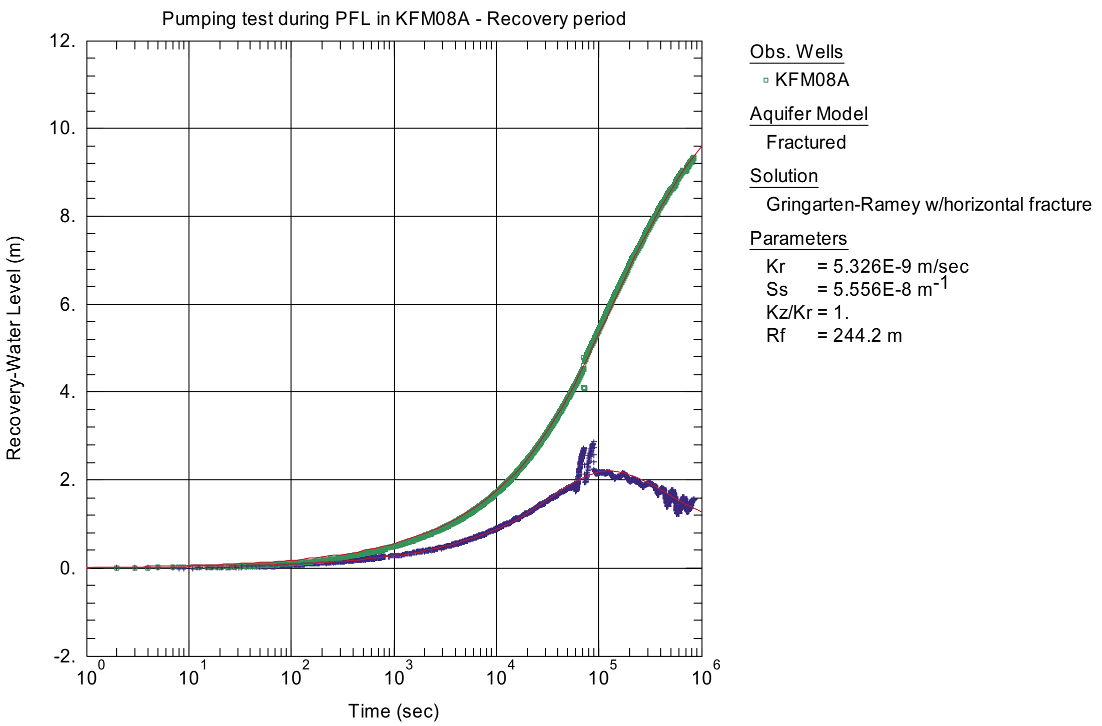


Figure A12-6. *Lin-log plot of measured (green) and simulated (red) pressure recovery and -derivative (blue) versus time during the total recovery period of the pumping test in borehole KFM08A. Evaluation based on the intermediate and late part of the curve.*

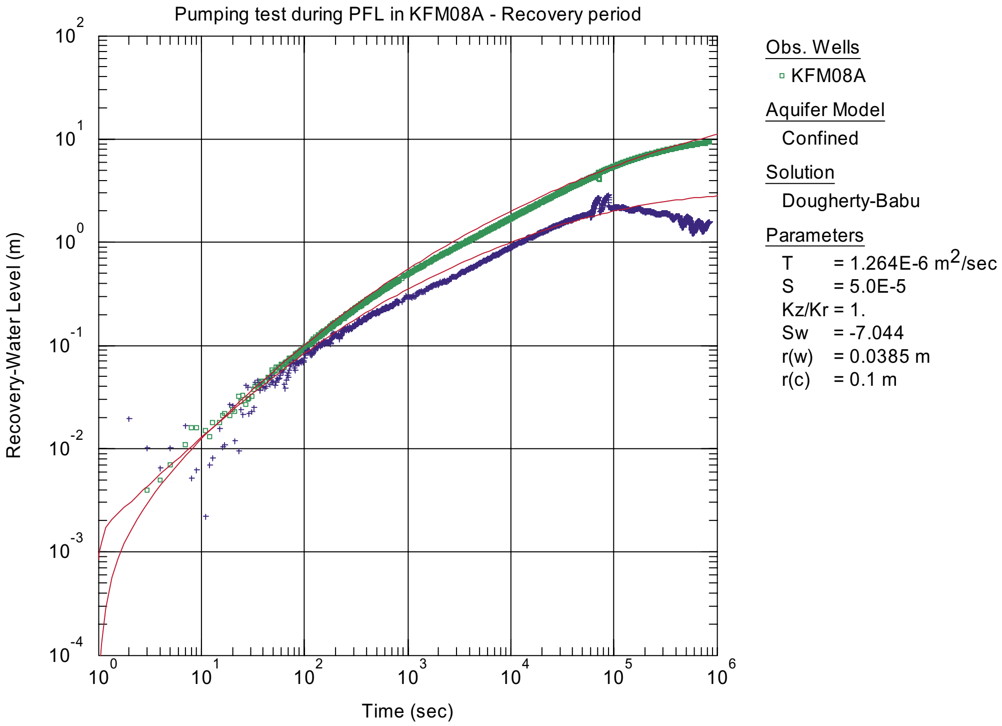


Figure A12-7. *Log-log plot of measured (green) and simulated (red) pressure recovery and -derivative (blue) versus time during the total recovery period of the pumping test in borehole KFM08A. Evaluation based on the short time interval with apparent PRF.*

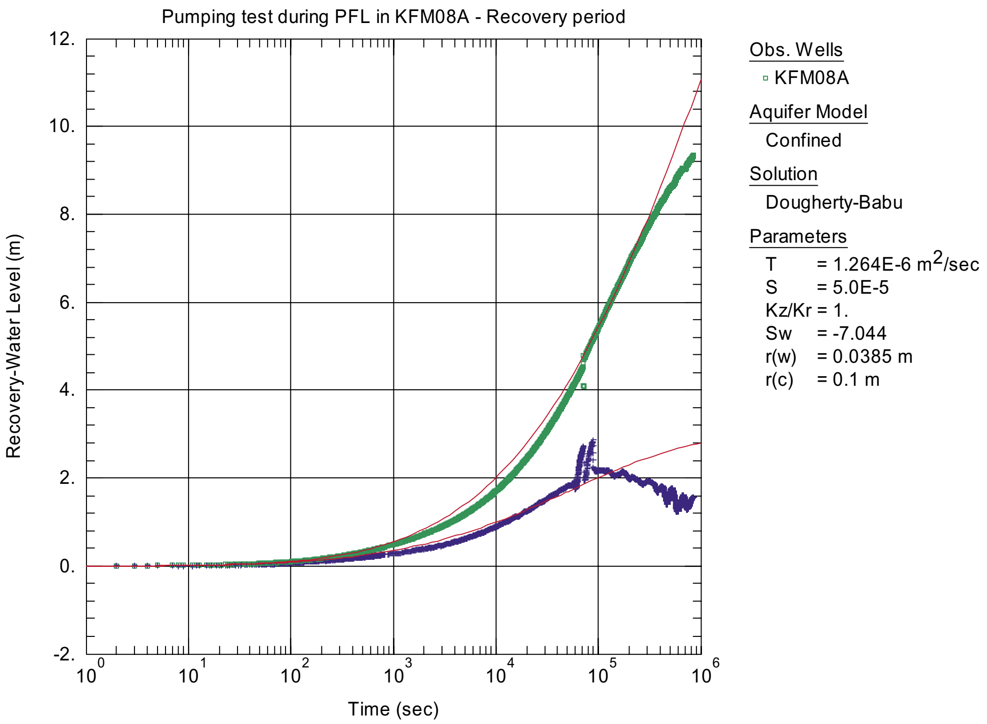


Figure A12-8. *Lin-log plot of measured (green) and simulated (red) pressure recovery and -derivative (blue) versus time during the total recovery period of the pumping test in borehole KFM08A. Evaluation based on the short time interval with apparent PRF.*