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Forsmark site investigation

Difference flow logging in borehole KFM02A during pumping in HFM16

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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 KFM02A at Forsmark, Sweden, in October 2004, using the Posiva flow log. The aim of the measurements was to identify the active fractures in the borehole KFM02A connected to the seismic reflector A2.

The flow rate into or out of 5 m long test sections was measured in KFM02A between 100.67–526.10 m borehole lengths. Flow rates were measured three times, once when no borehole was pumped and twice when HFM16 was pumped. The distance between borehole KFM02A and HFM16 is about 1.3 km.

Clear indications of connected flows between boreholes HFM16 and KFM02A were detected.

Sammanfattning

Differensflödesloggning är en snabb metod för bestämning av transmissivitet och hydraulisk tryckhöjd i borrhålssektioner och enskilda sprickor/sprickzoner i kärnborrhål. Denna rapport presenterar huvudprinciperna för metoden och resultat av mätningar utförda i borrhål KFM02A i Forsmark, Sverige, i oktober 2004 med Posiva flödesloggningsmetod. Det primära syftet med mätningarna var att identifiera sprickor i borrhål KFM02A som har hydraulisk förbindelse till den seismiska reflektorn A2.

Flödet till eller från en 5 m lång testsektion mättes mellan 100,67–526,10 m borrhålslängd i KFM02A. Flödet mättes tre gånger, en gång utan pumpning och två gånger med pumpning i HFM16. Avståndet mellan KFM02A och HFM16 är ca 1,3 km.

Klara flödeförbindelser mellan KFM02A och HFM16 detekterades.

Contents

1 Introduction

The difference flow logging in the core drilled borehole KFM02A at Forsmark was conducted between October 22–28, 2004. KFM02A is the second core drilled borehole in the Forsmark candidate area. The borehole is inclined c 85° from the horizontal direction. The c 1,000 m long borehole is performed with telescopic drilling technique, where the interval 0–100 m is percussion drilled with the diameter c 250 mm and the remaining interval, 100–1,000 m, is core drilled with the diameter 77.3 mm. The interval 0–c 100 m is cased with the inner diameter 200 mm. The location of borehole KFM02A at drilling site DS2 within the Forsmark area is shown in Figure 1-1. The percussion drilled borehole HFM16, which was pumped during the flow logging, is situated at drilling site DS6, Figure 1-1. The distance between KFM02A and HFM16 is about 1.3 km.

The flow rate into or out of 5 m long test sections was measured in KFM02A between 100.67–526.10 m borehole lengths. Flow rates were measured three times, the first time during natural conditions (no pumping in HFM16), the second time immediatley after start of pumping and the third time c 24 hours after start of pumping in HFM16. The same borehole interval was measured during all three occasions.

The locations of flow yielding fractures were known based on earlier measurements /Rouhiainen and Pöllänen, 2004/, so instead of measuring the entire borehole, only selected intervals were measured.

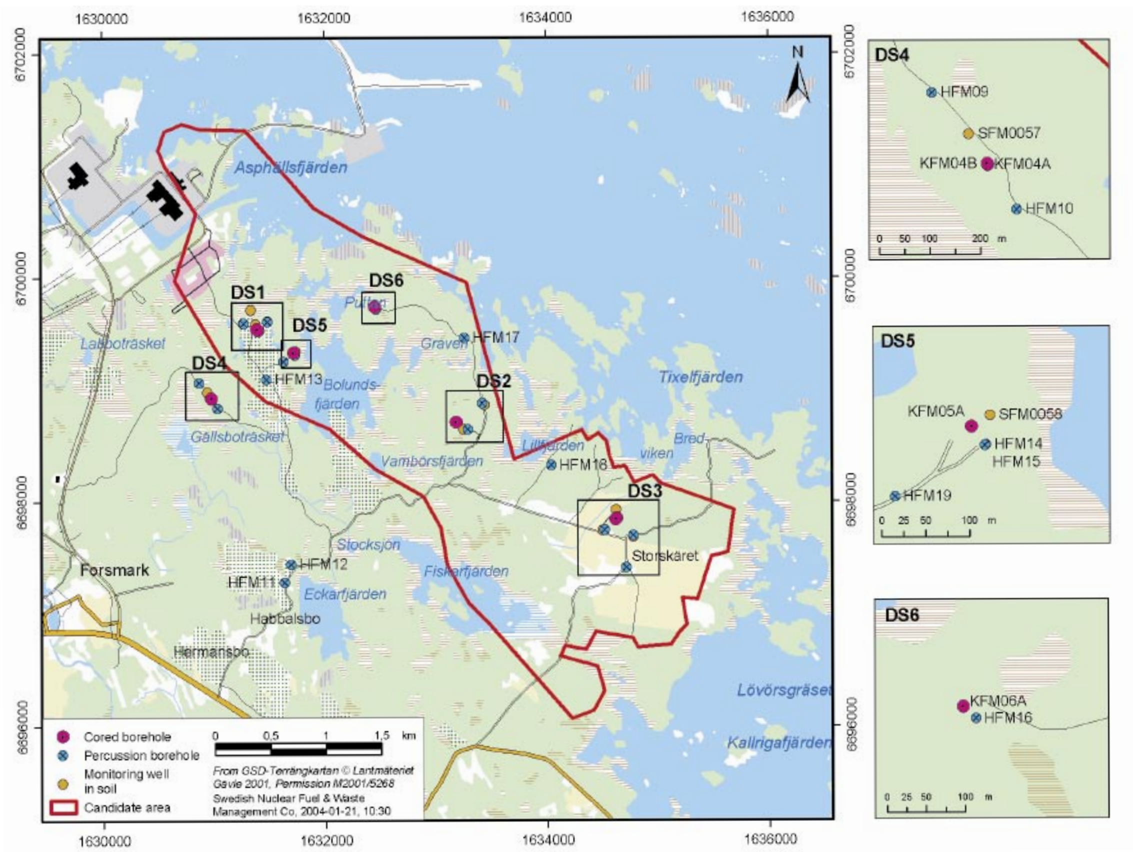

Figure 1-1. *Location of drill sites DS1-6 at Forsmark. For the drill sites DS4-6 detailed maps of all boreholes within the sites are shown.*

Length calibration was made based on length marks milled into the borehole wall at accurately determined positions along the borehole. The length marks had been detected earlier and the length correction was made by synchronising the new SPR results with the original caliper/SPR measurements.

A high-resolution absolute pressure sensor was used to measure the total 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. These measurements were performed during flow logging, so the accuracy of the results is not as good as when performed separately.

The field work and the subsequent interpretation were conducted by PRG-Tec Oy. The Posiva Flow Log/Difference Flow method has previously been employed in Posiva's site characterisation program 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 KFM02A before and during pumping in HFM16. The activity is performed within the Forsmark site investigation. The work was carried out in accordance to the SKB internal controlling document AP PF 400-04-107. Data and results were delivered to the SKB site characterization database SICADA.

2 Objective and scope

The main objective of the difference flow logging in KFM02A was to identify the hydraulically active fractures in the borehole connected to the seismic reflector A2 by investigating possible hydraulic connections between drill sites DS2 and DS6.

Besides the difference flow logging, the measurement program 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. A high-resolution pressure sensor was used to measure the total pressure along the borehole. These measurements were carried out together with the flow measurements.

The length correction was made by synchronising the SPR results with the original caliper/SPR measurement, which had been performed earlier /Rouhiainen and Pöllänen, 2004/.

3 Principles of measurement

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 connected 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. It 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 used because it is faster than the thermal pulse method.

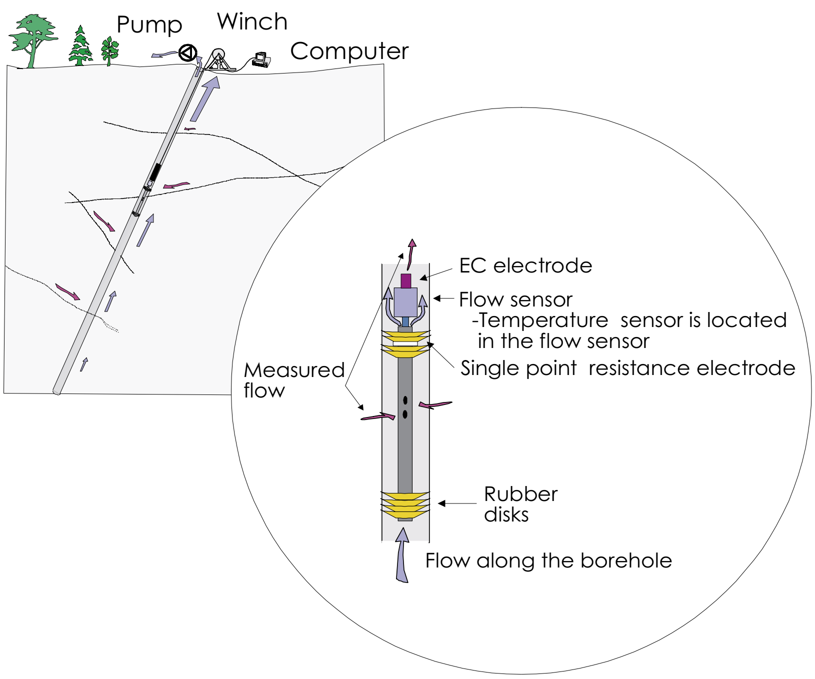

Figure 3-1. *Schematic of the downhole equipment used in the Difference flowmeter.*

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

- The electric conductivity (EC) of the borehole water and fracture-specific water. The electrode for the EC measurements is 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, except caliper measurement, were performed in KFM02A.

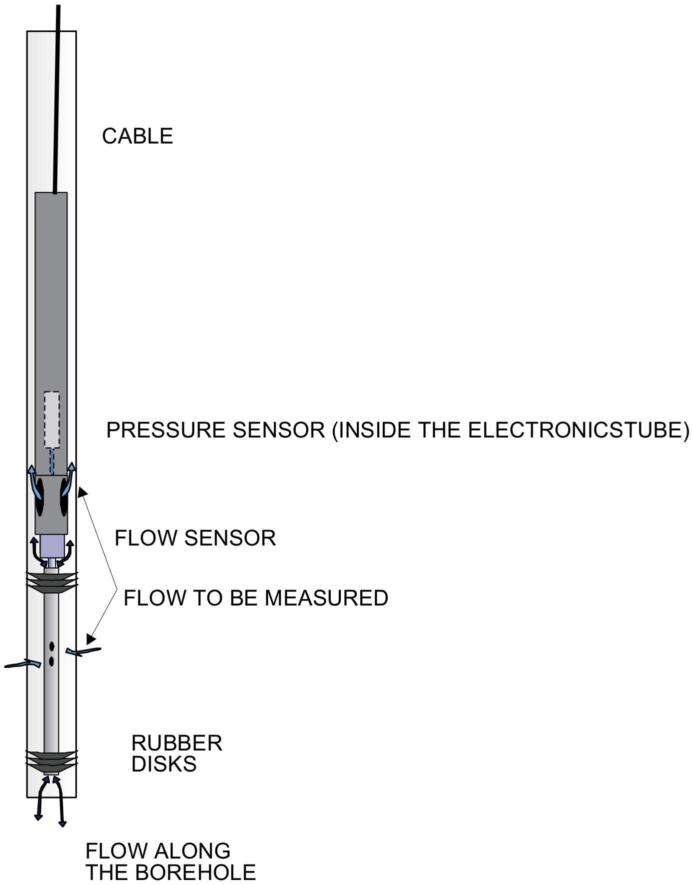

Figure 3-2. *The absolute pressure sensor is located inside the electronics tube and connected through a tube to the borehole water.*

The principles of difference flow measurements are described in Figures 3-3 and 3-4. The flow sensor consists of three thermistors, see Figure 3-3 a. 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 3-3 b and c The side thermistors, B1 and B2, serve to detect the moving thermal pulse, Figure 3-3 d, caused by the constant power heating in A, Figure 3-3 b.

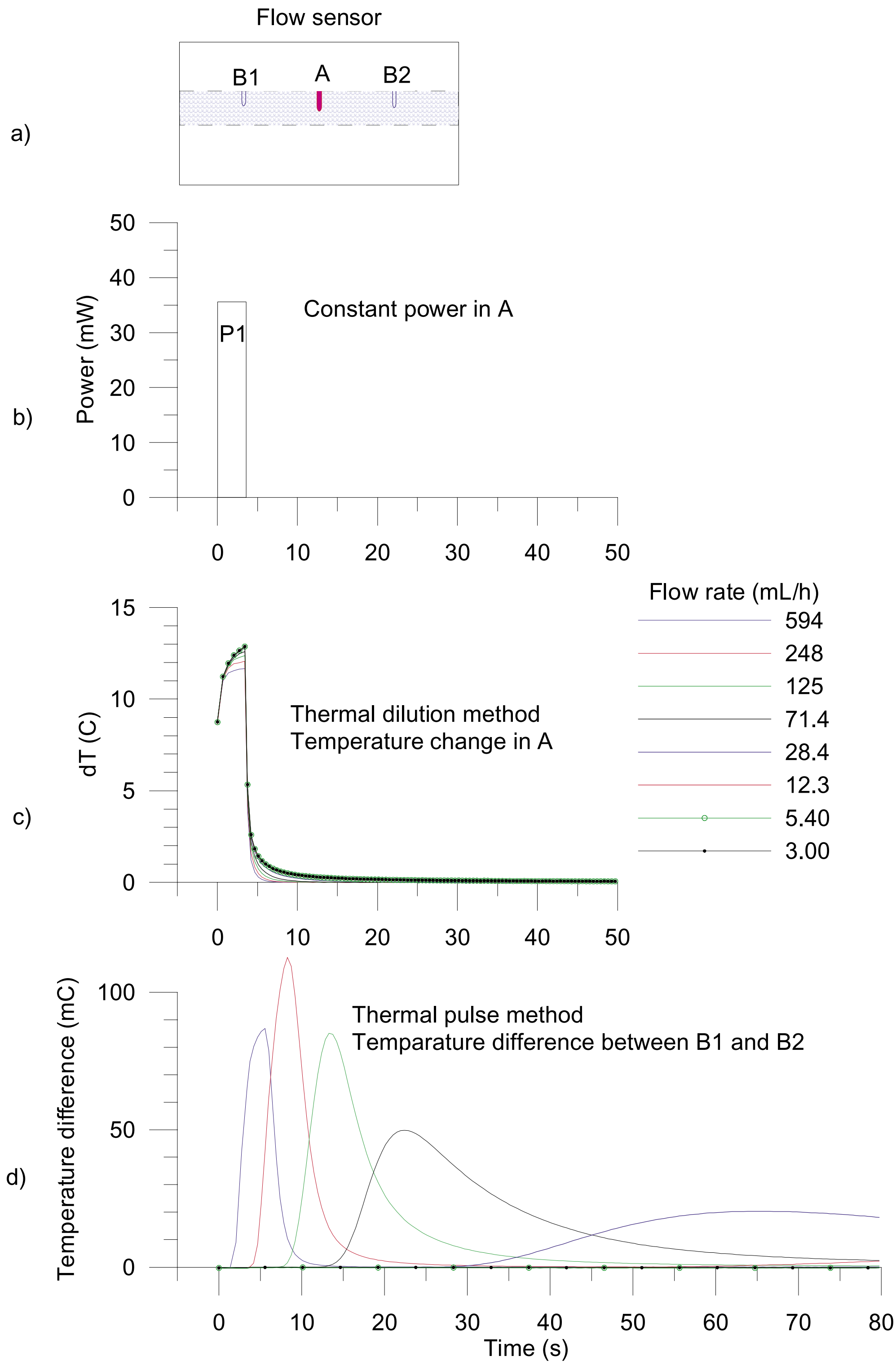

Figure 3-3. *Principles of difference flow measurements, flow rate < 600 mL/h.*

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

If the flow rate during the constant power heating (Figure 3-3 b) falls below 600 mL/h, the measurement continues with monitoring of transient thermal dilution and thermal pulse response (Figure 3-3 d). 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 3-3 b) 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 suspended drilling debris and 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.

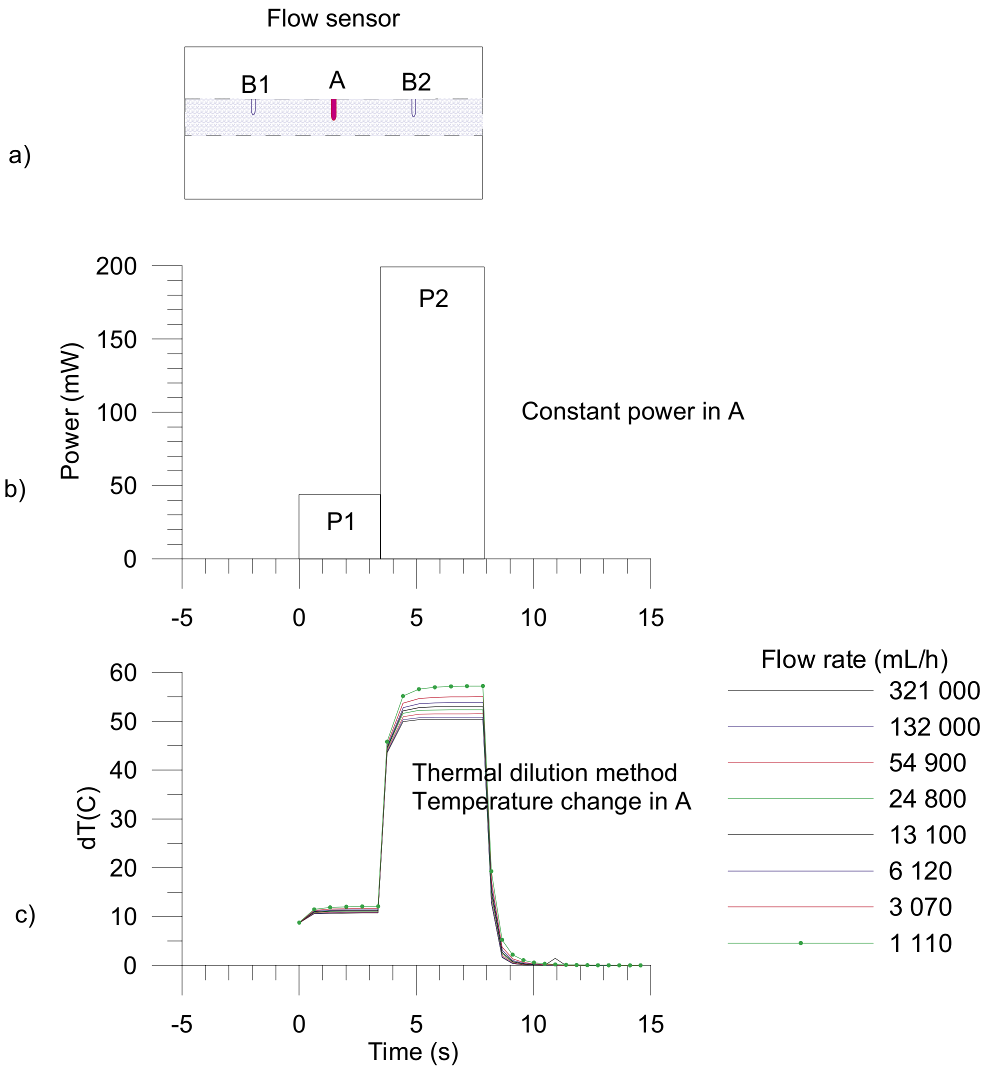

Figure 3-4. *Principles of difference flow measurements, flow rate > 600 mL/h.*

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

3.1.1 Theoretical and practical measurements limits of flow

The theoretical minimum of measurable flow rate in the overlapping measurements (thermal dilution method only) is about 30 mL/h. The upper limit of the 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 favorable borehole conditions.

The minimum measurable flow rate may, 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, on the other hand, 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.

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.

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 discs). 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:	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	April 2004.
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

The Commission was performed in compliance with to Activity Plan AP PF 400-04-107 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. 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 KFM02A, 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 metre system uses caliper measurements in combination with single point resistance measurement (SPR) for this purpose. The length marks in KFM02A had been detected earlier /Rouhiainen and Pöllänen, 2004/ and the length correction was made by synchronising the new SPR results with the original caliper/SPR measurement.

The overlapping flow logging (Item 1) was carried out in the borehole interval 100.67–526.10 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 in HFM16 was started on October 26th and the overlapping flow logging (Item 2 extra) was measured again within the interval, 100.67–526.10 m, using the same section and step lengths as before. After c 1 day waiting time, the overlapping flow logging (Item 2) was repeated in the same length interval.

Table 5-1. Flow logging and testing in KFM02A. Activity schedule.

Item	Activity	Explanation	Date
1	Overlapping flow logging	Section length L_w = 5 m. Step length dL = 0.5 m. No pumping.	2004-10-25 2004-10-26
2 extra	Overlapping flow logging	Section length L_w = 5 m. Step length dL = 0.5 m. Pumping at HFM16.	2004-10-26 2004-10-27
2	Overlapping flow logging	Section length L_w = 5 m. Step length dL = 0.5 m. Pumping at HFM16 (1 day after start of pumping).	2004-10-27

6 Results

6.1 Length calibration

6.1.1 Caliper and SPR measurement

Accurate length measurements are 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 KFM02A 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.

In this case the caliper/SPR measurement had been done earlier /Rouhiainen and Pöllänen, 2004/. To obtain relative length errors of the different measurement sequences, the SPR curves of Items 1, 2 extra, and 2 were compared with the SPR curve of the earlier caliper/SPR measurement (Appendices 1.1–1.13, black curve). All SPR curves could then be synchronized, as can be seen in Appendices 1.1–1.12.

The aim of the plots in Appendices 1.1–1.12 is to verify the accuracy of the length correction. The curves in these plots represent length corrected results. Five SPR curves are plotted together with caliper data. The three last measurements correspond to Items 1, 2 extra, and 2 in Table 5-1 and the two first are from the earlier flow logging test.

The magnitude of length correction along the borehole is presented in Appendix 1.13. The error is negative, due to fact that the stretching extends the logging cable (i.e. the cable is longer than the nominal length marked on the cable). The large discrepancy between the new and the earlier measurements depends on the different logging directions (upwards/downwards). The new measurements were carried out from the bottom and upwards implicating a larger cable tension.

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 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.
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 the 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 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 a 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 of borehole water

The logging of electric conductivity (EC) and temperature of the borehole water is usually performed as a separate measurement without the lower rubber discs. In this way transport of the water in the flow measurement section can be avoided and the measured values of EC and temperature correspond better with the actual conditions. In this measurement no separate EC and temperature loggings were carried out. However, the main features can anyway be seen in the results achived from the measurements performed during the flow logging. The EC and temperature values presented in Appendices 2.1 and 2.2 (light blue, light brown and brown curves) are measured during the respective flow loggings.

The temperature of the borehole water was measured simultaneously with the EC measurements. The EC values are temperature corrected to 25°C to make them more comparable with other EC measurements /Heikkonen et al. 2002/. The temperature results in Appendix 2.2 correspond to the EC results in Appendix 2.1.

6.3 Pressure measurements

The absolute pressure was registered together with the other measurements in Items 1, 2 extra and 2 in Table 5-1. The pressure sensor measures the sum of hydrostatic and air pressure in the borehole. Air pressure was also registered, see Appendix 6.2. 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/:

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

where

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

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

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

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

g is the standard gravity, 9.80065 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 all absolute pressure results.

The calculated head distributions are presented in Appendix 6.1. 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 three flow logging sequences. They are presented on the same plots as the single point resistance (right hand side) and caliper plots (in the middle), see Appendices 3.1–3.22. 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 (because the measurements were measured in the upward direction).

The Caliper tool shows a low voltage when the borehole diameter is below 77 mm and a high voltage when the borehole diameter exceeds 77 mm. The caliper measurement in borehole KFM02A had been done during earlier flow logging measurements in April 2003 /Rouhiainen and Pöllänen, 2004/.

The flow logging was performed three times with similar section and step lengths (5 m section length, 0.5 m steps). Firstly, before pumping was started in borehole HFM16, then just after pumping had started, and a third time after c 1 day from start of pumping. Since the borehole KFM02A had been flow logged earlier, the locations of leaky fractures were known and the measurements focused to the length interval 100.67–526.10 m. Fractures are shown on the caliper scale with their positions (borehole length).

The measured flow direction may be into the borehole or out from it. To obtain quick results, only the thermal dilution method was used for flow determination.

The test section length determines the width of a flow anomaly of a single fracture in the plots. If the distance between flow yielding fractures is less than the section length, the anomalies will be overlapped, resulting in a stepwise flow anomaly.

6.4.2 Flow rates of borehole sections

The borehole between 100.67 m and 526.10 m was flow logged three times with a 5 m section length and with 0.5 m length increments. All the flow logging results presented in this report are derived from measurements with the thermal dilution method.

All borehole sections are shown in Appendices 3.1–3.22. The older results are included in these plots for comparison.

The results of the measurements are presented in tables, see Appendices 4.1–4.2. Only the results with 5 m length increments are used. Secup presented in Appendices 4.1–4.2 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. The secup and seclow values for the three sequences are not exactly identical, due to a minor difference of the cable stretching. The difference between these three sequences was however small. Secup and seclow given in Appendices 4.1–4.2 are calculated as an average of these three values.

Pressure was measured and calculated as described in Chapter 6.3. Borehole head1, borehole head2 and borehole head3 in Appendices 4.1–4.2 represent heads determined with respective flow measurement. Head in the borehole is given in the RHB 70 scale.

The flow results presented in Appendices 4.1–4.2 (Flow1, Flow2 and Flow3), representing flow rates derived from the three measurements, 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.

In sections 105.68 m, 110.69 m, 115.70 m and 120.70 m (secup) the direction of the flow could not be identified in the measurements when HFM16 was pumped, even if high flow rates were detected. These sections are marked with an asterisk in Appendices 4.1–4.2. A detailed picture of this flow anomaly is presented in Appendix 7. Flow direction of each measurement point is shown on the left ("+" means positive flow, "–" means negative flow, "?" means that the flow direction could not be determined).

The flow direction was not systematic in this depth range. Elsewhere in the borehole there were no difficulties determining the flow direction. It is not fully known what happened here. The result suggests that the flow is fluctuating. Fractures in these sections have a high transmissivity and most probably the pressure difference between the fractures and the borehole was small and minor head changes in the borehole could change the flow direction.

Before the pumping started in borehole HFM16, 25 flow yielding sections were detected, of which 5 had a flow direction from the borehole into the bedrock (negative flow). Directly after pumping had started in HFM16, 31 sections were detected as flow yielding, of which 19 had a flow direction from the borehole into the bedrock (negative flow). Directions of 4 flows could not be determined.

One day after pumping had started in HFM16, 37 flow yielding sections were detected as, of which 25 had a flow direction from the borehole into the bedrock (negative flow). Directions of 4 flows could not be determined.

The flow data are presented as a plot in Appendix 5. The left hand side of the 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 below the measurement limit, it is not visible in the logarithmic scale of the appendices.

The flow measurement without pumping from the earlier campaign is included in this plot (blue circles in Appendix 5). It's not fully comparable with the new results because there is a depth shift between these.

Pumping in HFM16 had different effect in different parts of borehole KFM02A, see Appendix 5:

- Below 250 m pumping caused flow change to negative direction.
- Between 150 m and 250 m pumping caused flow change to positive direction.
- Between 100 m and 150 m flow change was undefined.

The sum of detected flows before pumping started in HFM16 (Flow1) was –32,094 mL/h. This sum should normally be zero if:

- All the flows in the borehole are measured correctly.
- 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 far from zero and the reason is not clear. The flow balance was good in the earlier measurement. It may be difficult to maintain full flow balance during the measurement when there are highly transmissive fractures in the borehole (such as the fractures between 105 m and 120 m). In such a case, minor changes in borehole head during the measurement can change the flow balance.

The flow balance of the two other measurement is not known since flow direction could not be determined in all sections.

Pumping in HFM16 caused changes in the salinity profile of the borehole KFM02A, see Appendix 2.1. Fresh water from the upper part of the borehole flowed downwards because of pumping in HFM16. This in turn caused decrease of the hydraulic head in the borehole, see Appendix 6.1.

6.5 Groundwater level and pumping rate

The level of the groundwater table in borehole KFM02A during the measurement sequences is presented in Appendix 6.3. The pumped borehole HFM16, which is situated at drill site DS6, see Figure 1-1, is located about 1.3 km from KFM02A. Borehole HFM16 was pumped between October 26 and 27 with a drawdown of about 6 metres, see Appendix 6.3. Appendix 6.3 also shows the flow logging periods in relation to the pumping phase. Pumping rate was about 400 L/min.

7 Summary

In this study, the Posiva Flow Log/Difference Flow method has been used to identify the active fractures in borehole KFM02A at Forsmark connected to the seismic reflector A2. The borehole was measured three times; first before pumping was started in borehole HFM16, then directly after pumping had started and a third time after c 1 day from start of pumping. The section length 5 m, with length increments of 0.5 m was used.

Length calibration was made using the length marks on the borehole wall. The length marks had been detected in earlier measurement /Rouhiainen and Pöllänen, 2004/ 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. This was done during flow logging.

The pumping in borehole HFM16 had different effect in different parts of borehole KFM02A:

- Below 250 m, pumping caused flow change to negative direction. The result indicates that this part is hydraulically connected to HFM16.
- Between 150 m and 250 m, pumping caused flow change to positive direction. The result suggest that there is no or a very limited flow connection with HFM16 in this range.
- Flow response remained undefined between 105 m –120 m.

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Nordqvist R, 2001. Grundvattentryck – Inventering och utarbetande av rekommendationer för det geovetenskapliga undersökningsprogrammet. Djupförvarsteknik. SKB TD-03-01, Svensk Kärnbränslehantering AB.

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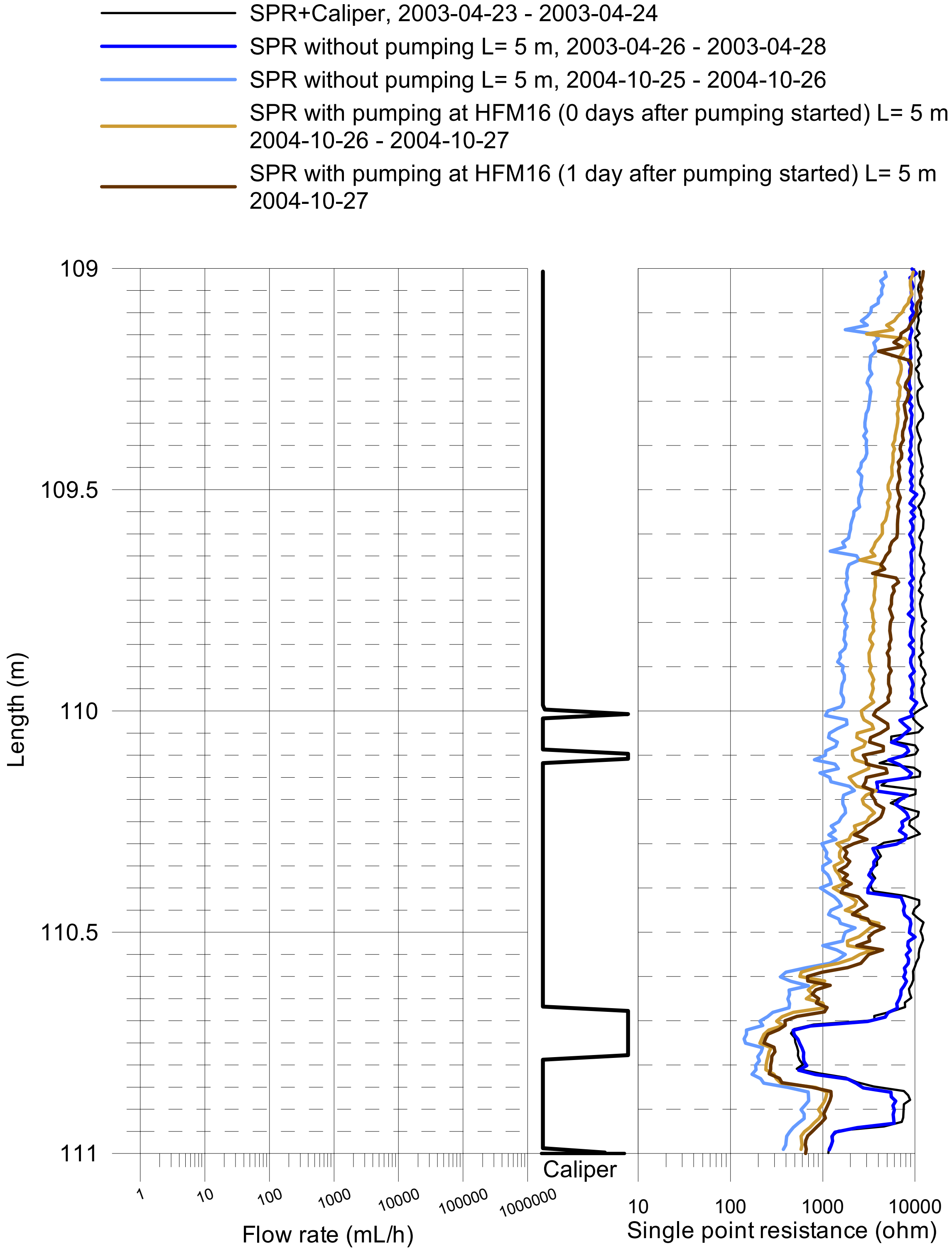
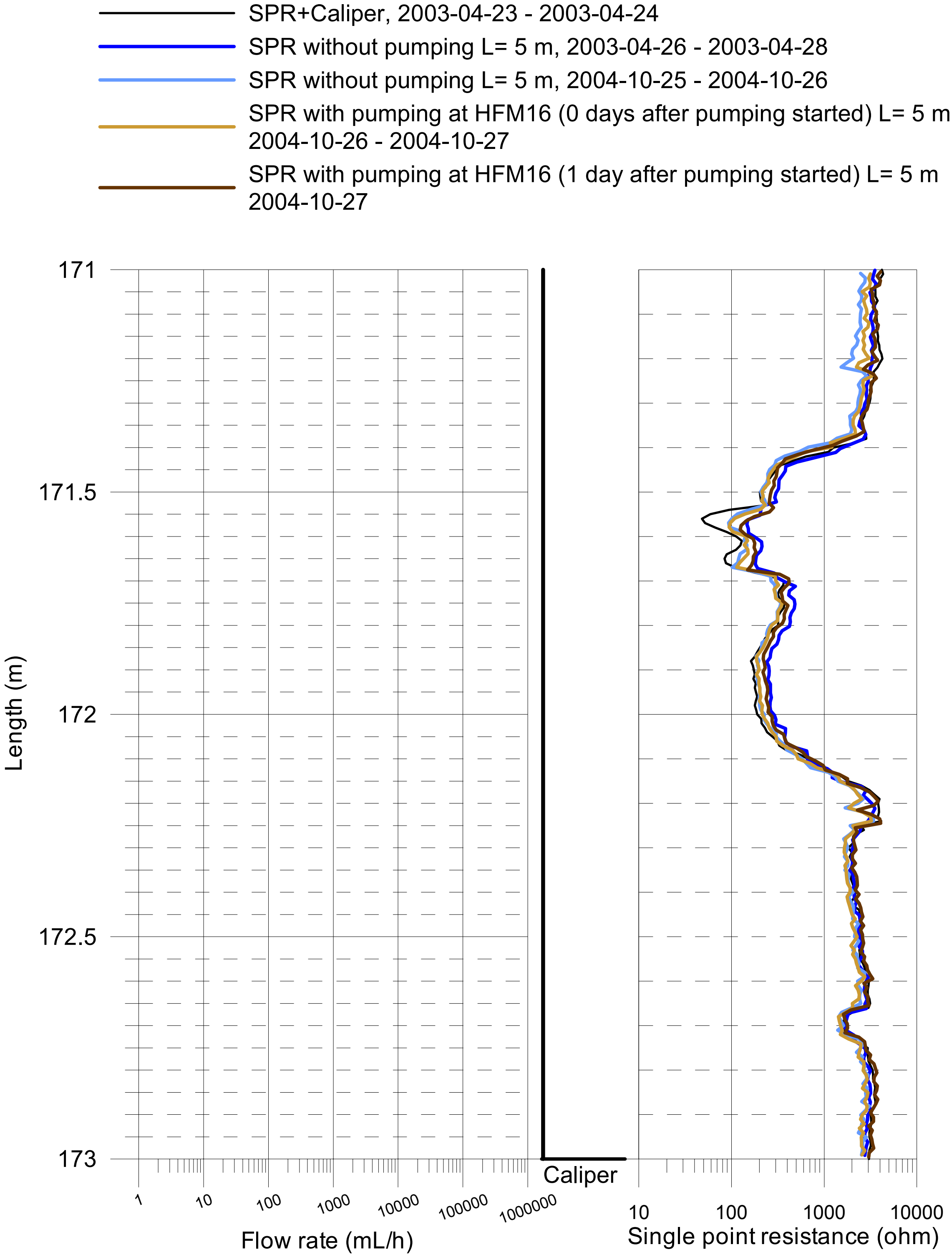
Öhberg A, Rouhiainen P, 2000. Posiva groundwater flow measuring techniques. Helsinki, Posiva Oy. Report POSIVA 2000-12.

Appendices

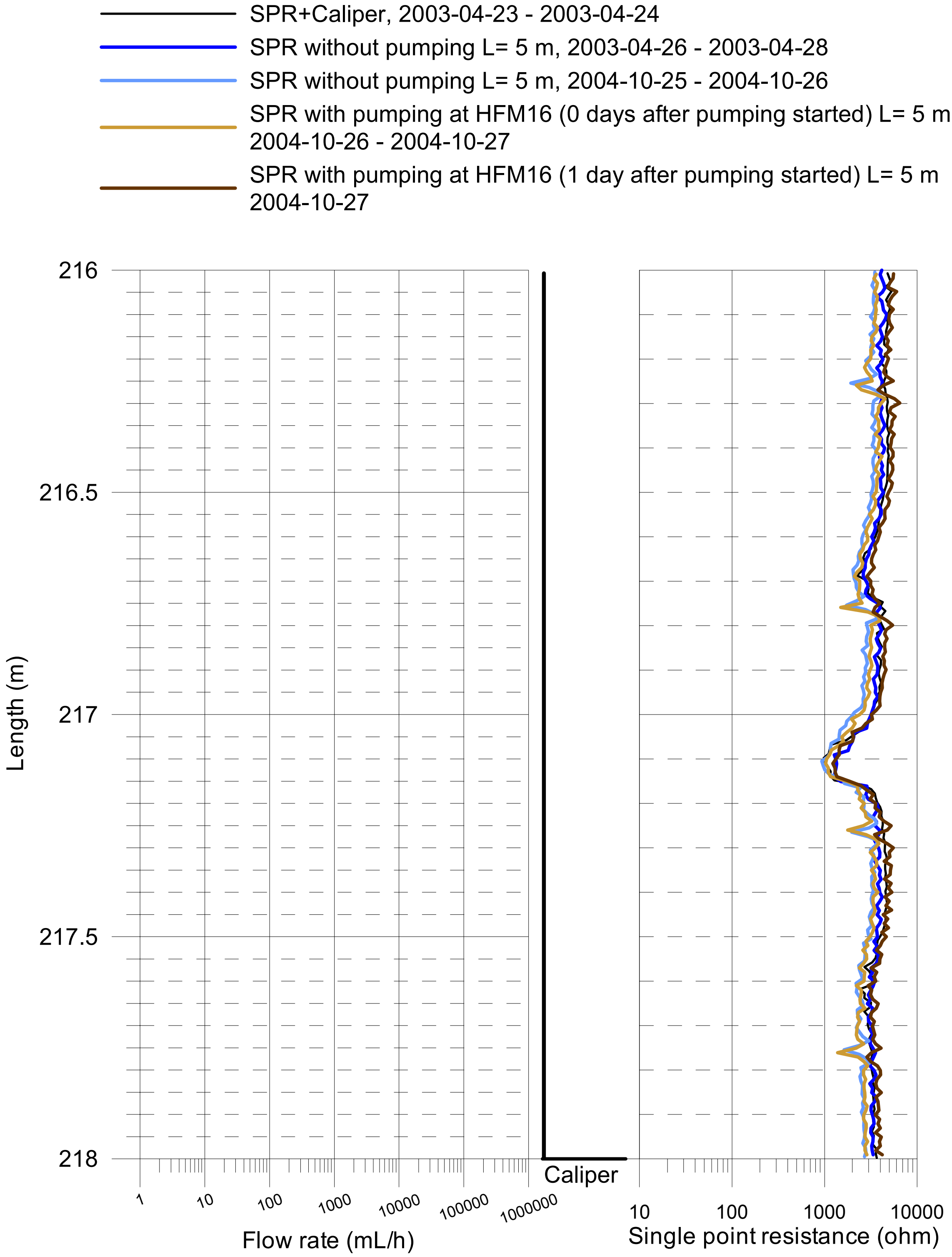
Forsmark, borehole KFM02A
SPR and Caliper results after length correction



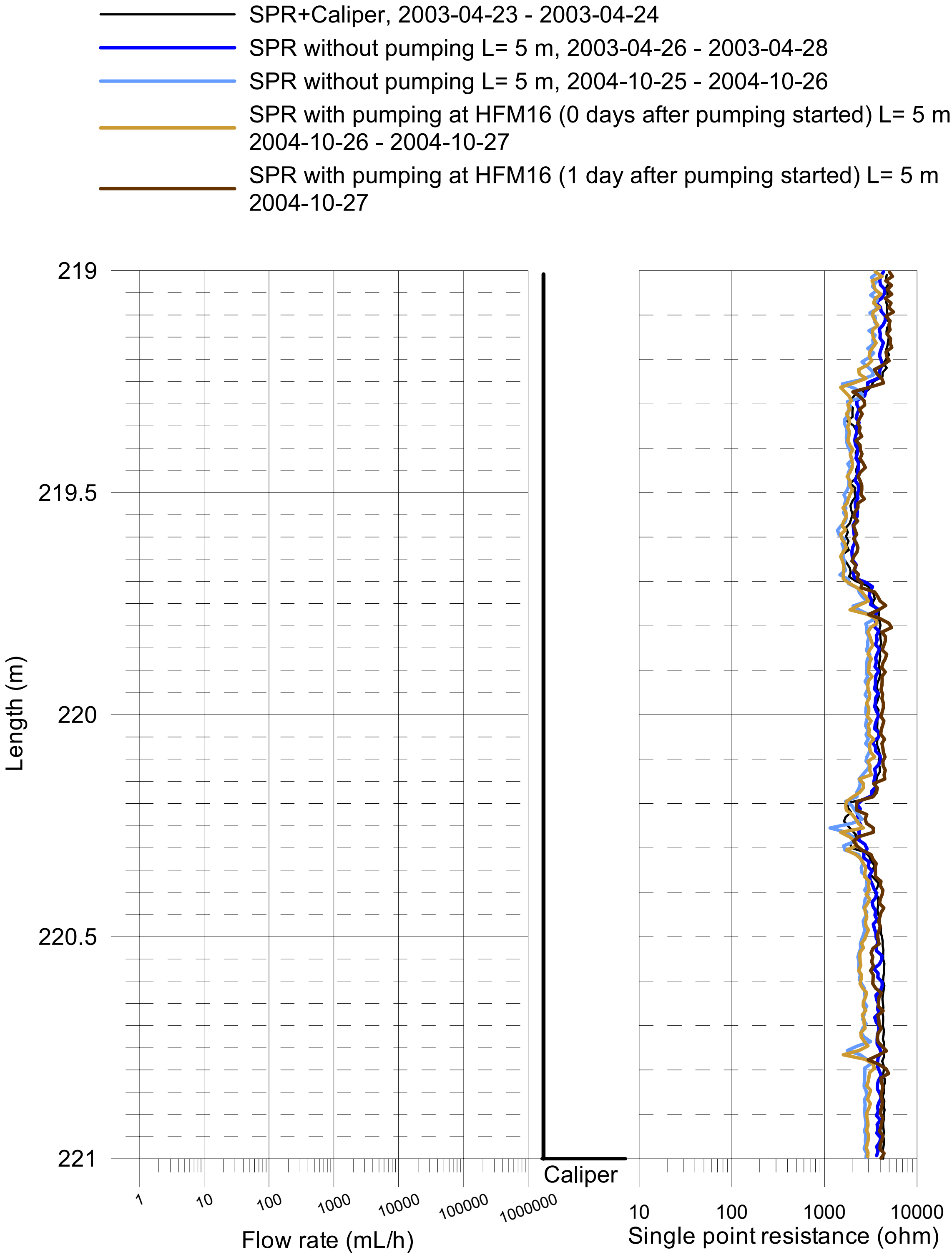
Forsmark, borehole KFM02A
SPR and Caliper results after length correction



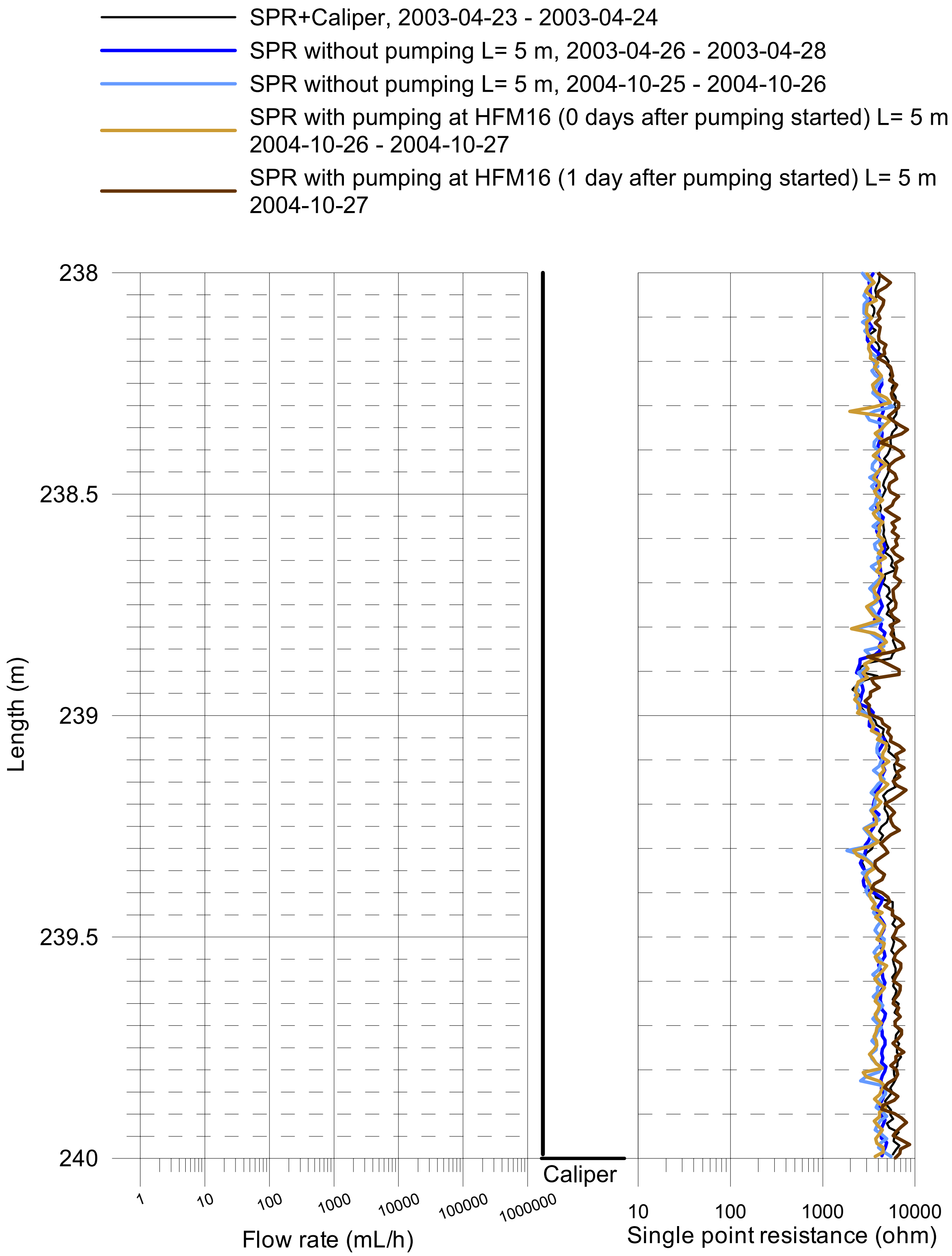
Forsmark, borehole KFM02A
SPR and Caliper results after length correction



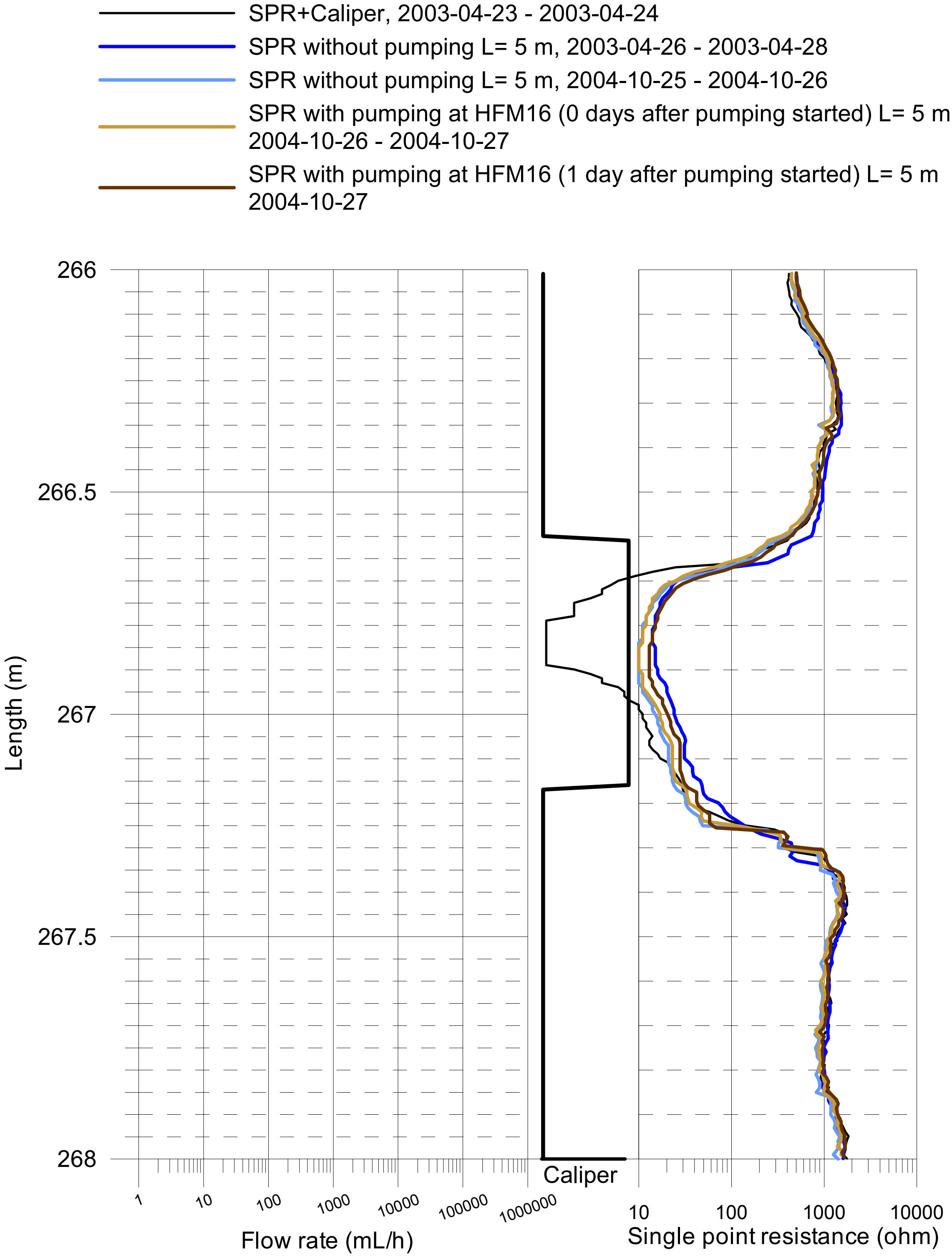
Forsmark, borehole KFM02A
SPR and Caliper results after length correction



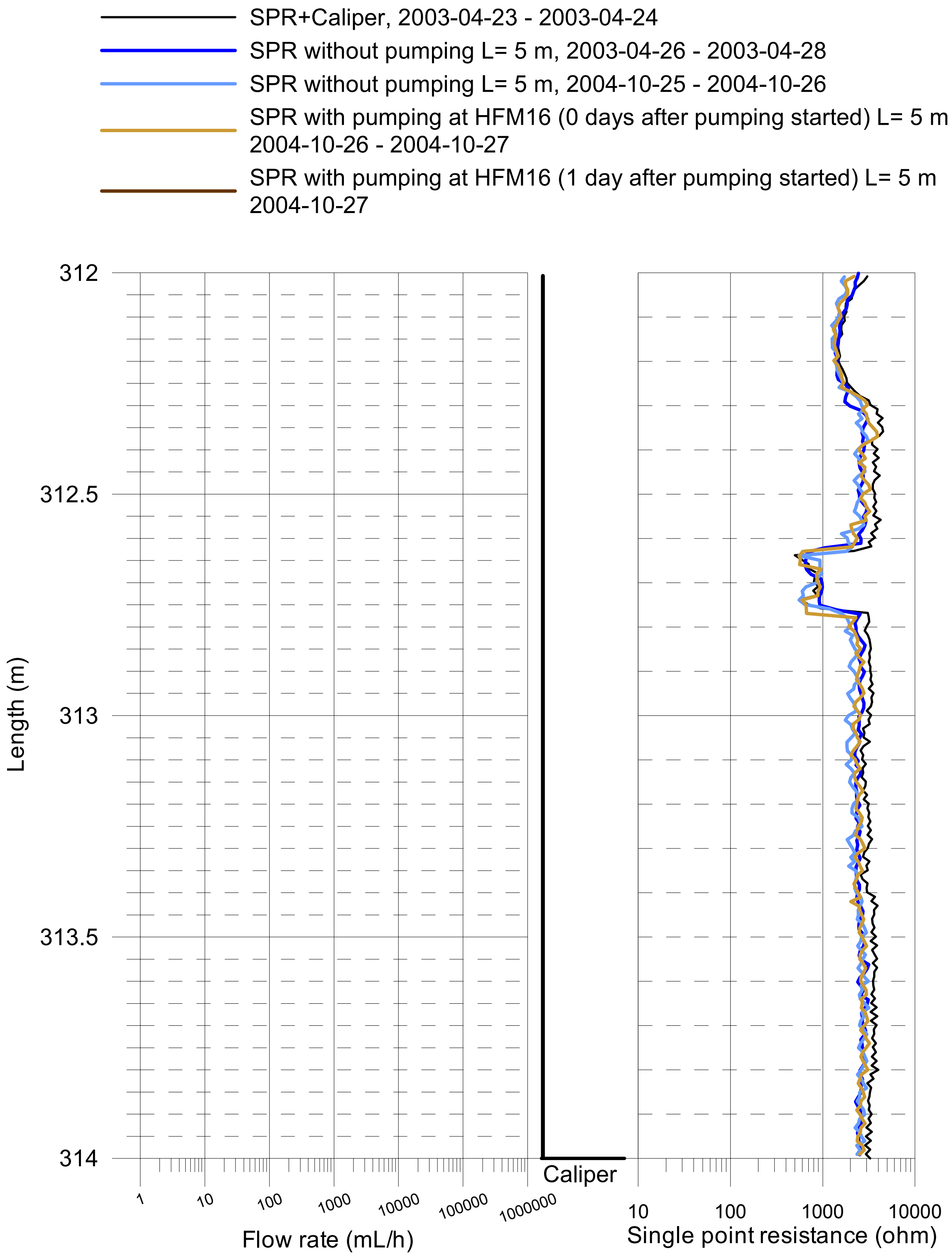
Forsmark, borehole KFM02A
SPR and Caliper results after length correction



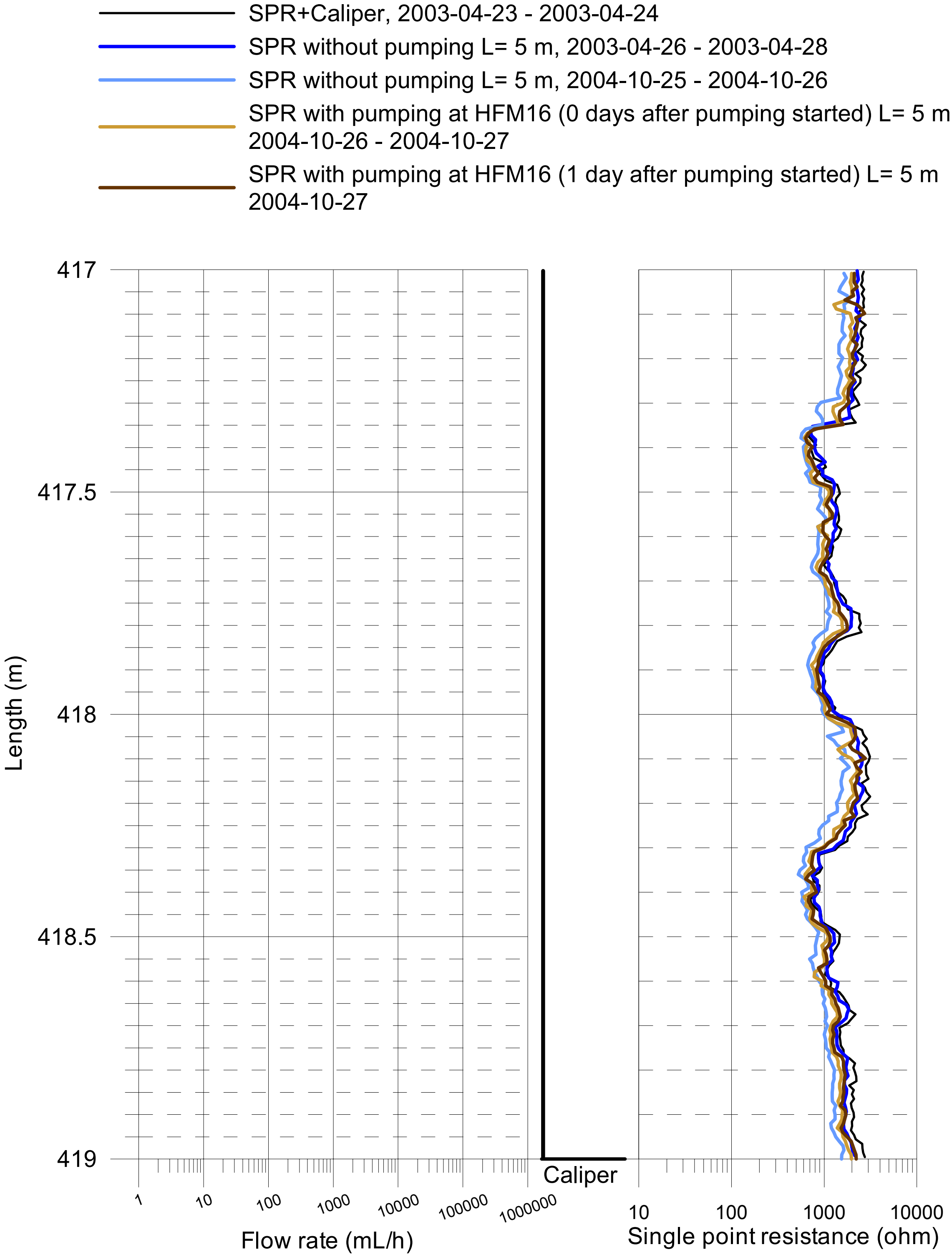
Forsmark, borehole KFM02A
SPR and Caliper results after length correction



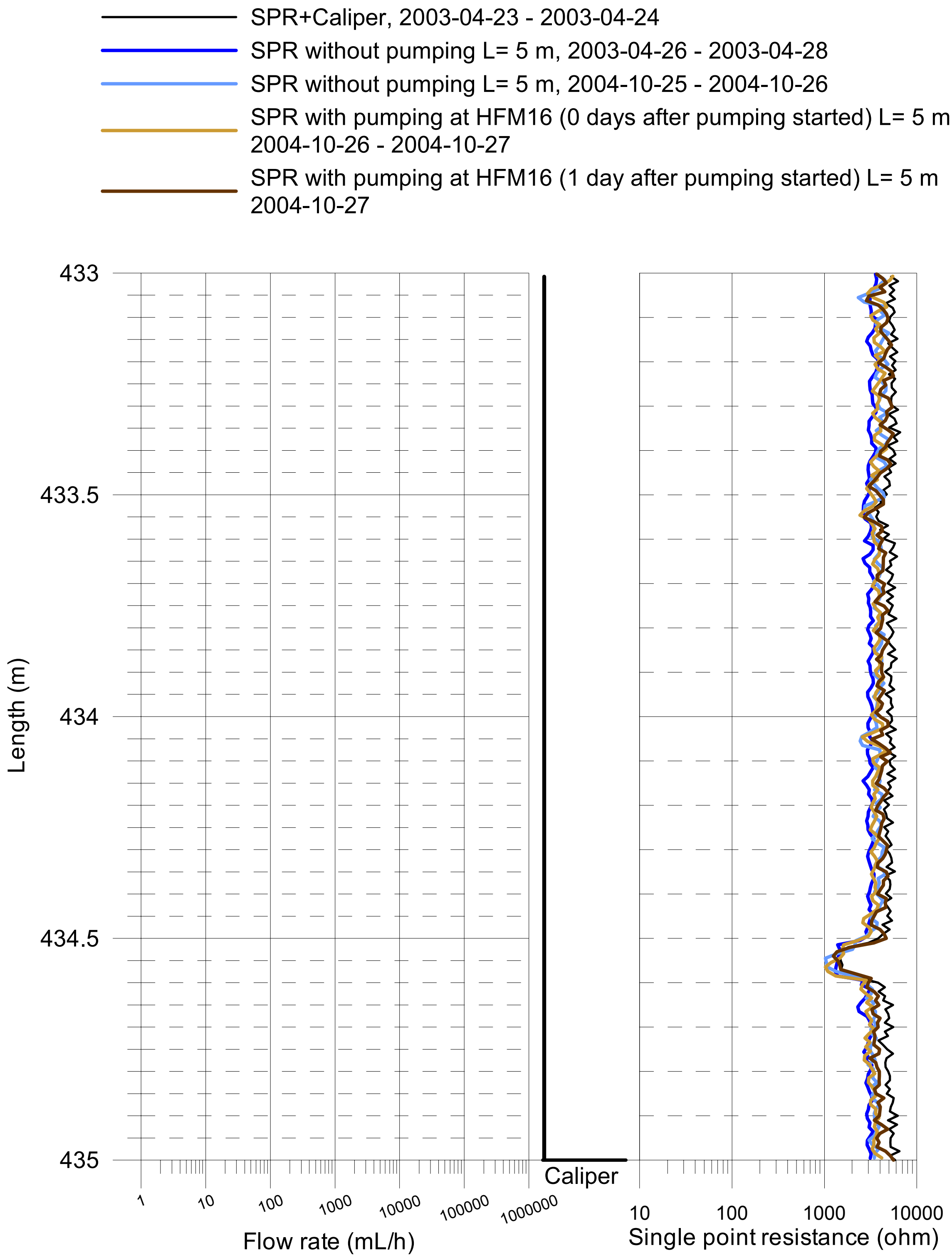
Forsmark, borehole KFM02A
SPR and Caliper results after length correction



Forsmark, borehole KFM02A
SPR and Caliper results after length correction



Forsmark, borehole KFM02A
SPR and Caliper results after length correction



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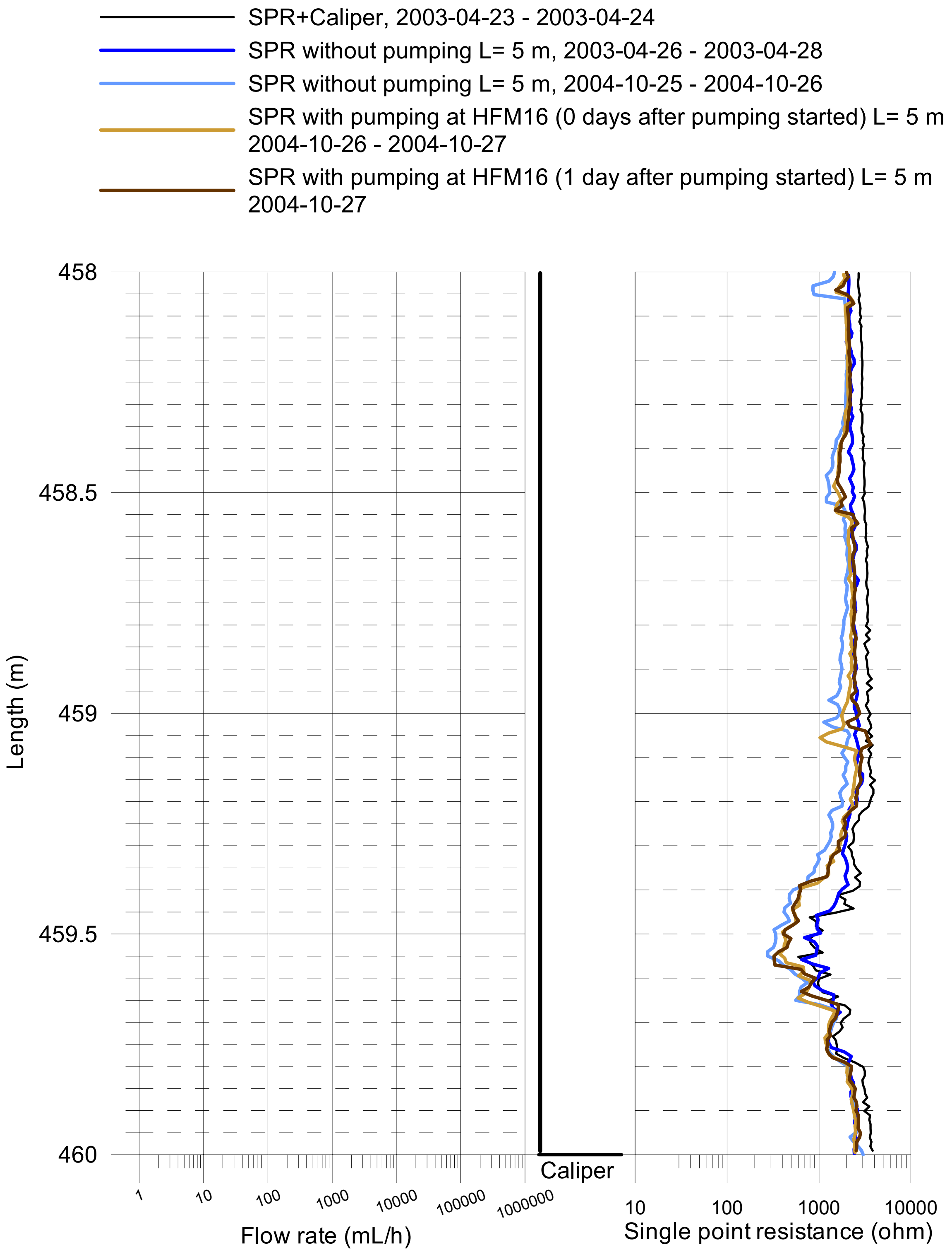
SPR and Caliper results after length correction



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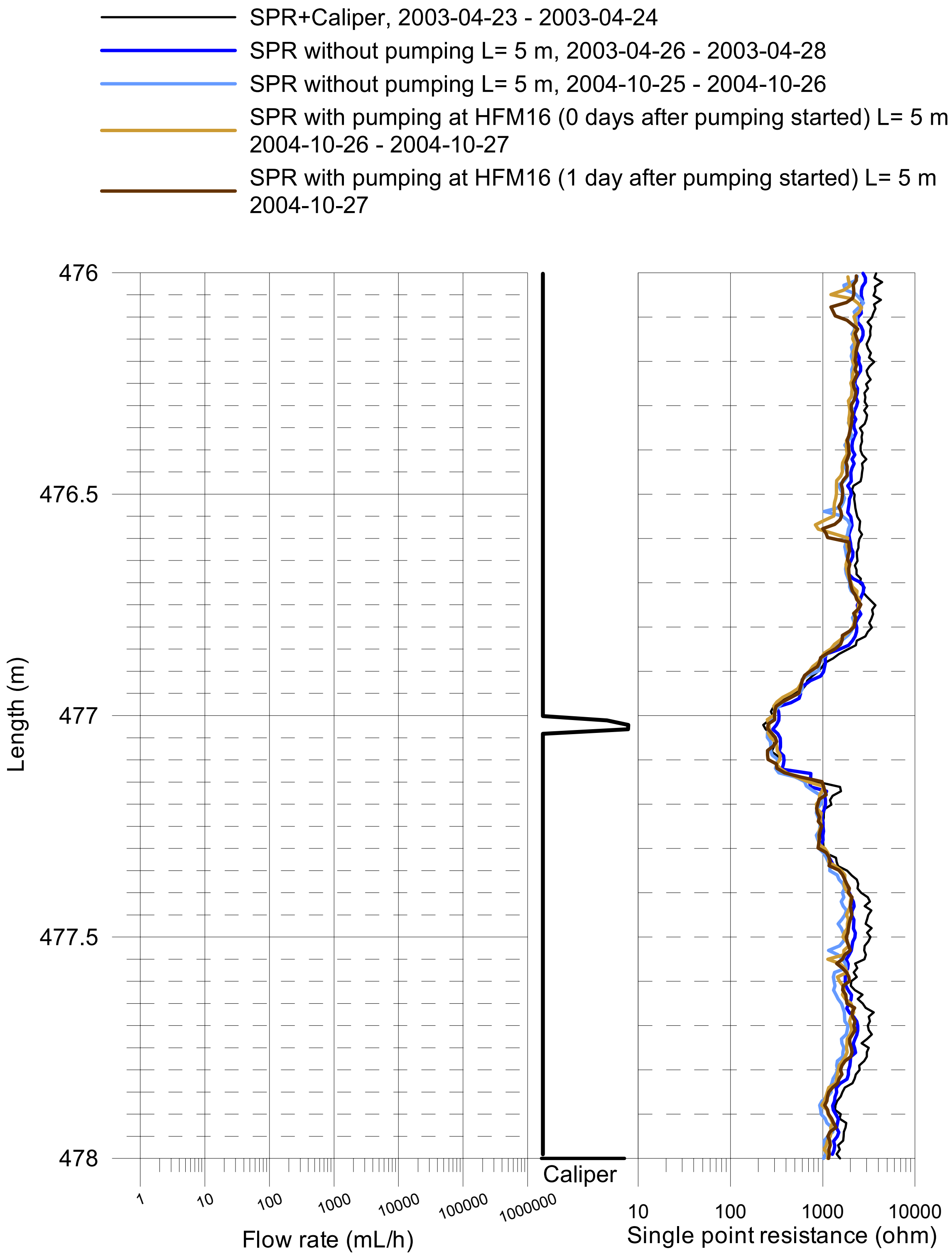
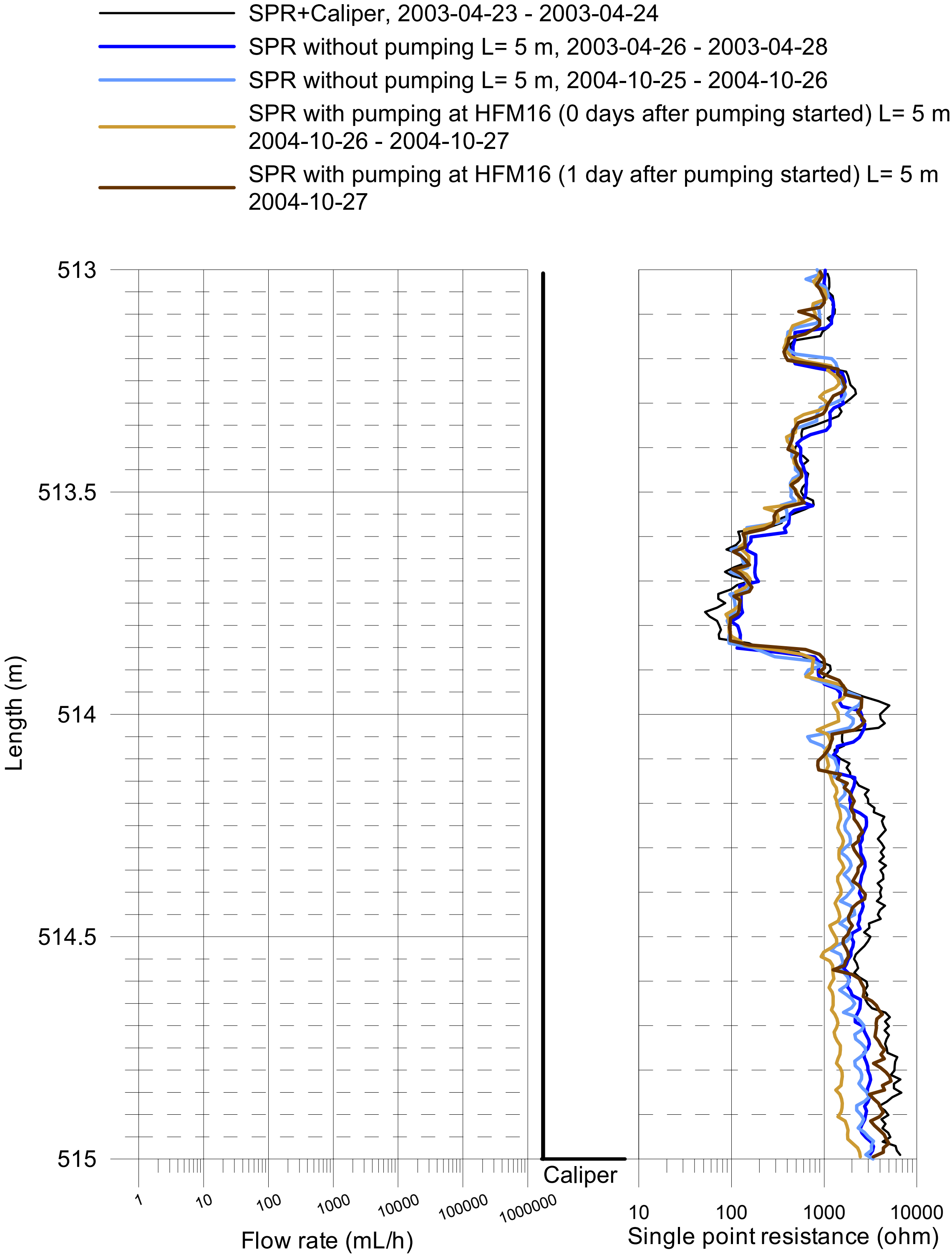
SPR and Caliper results after length correction

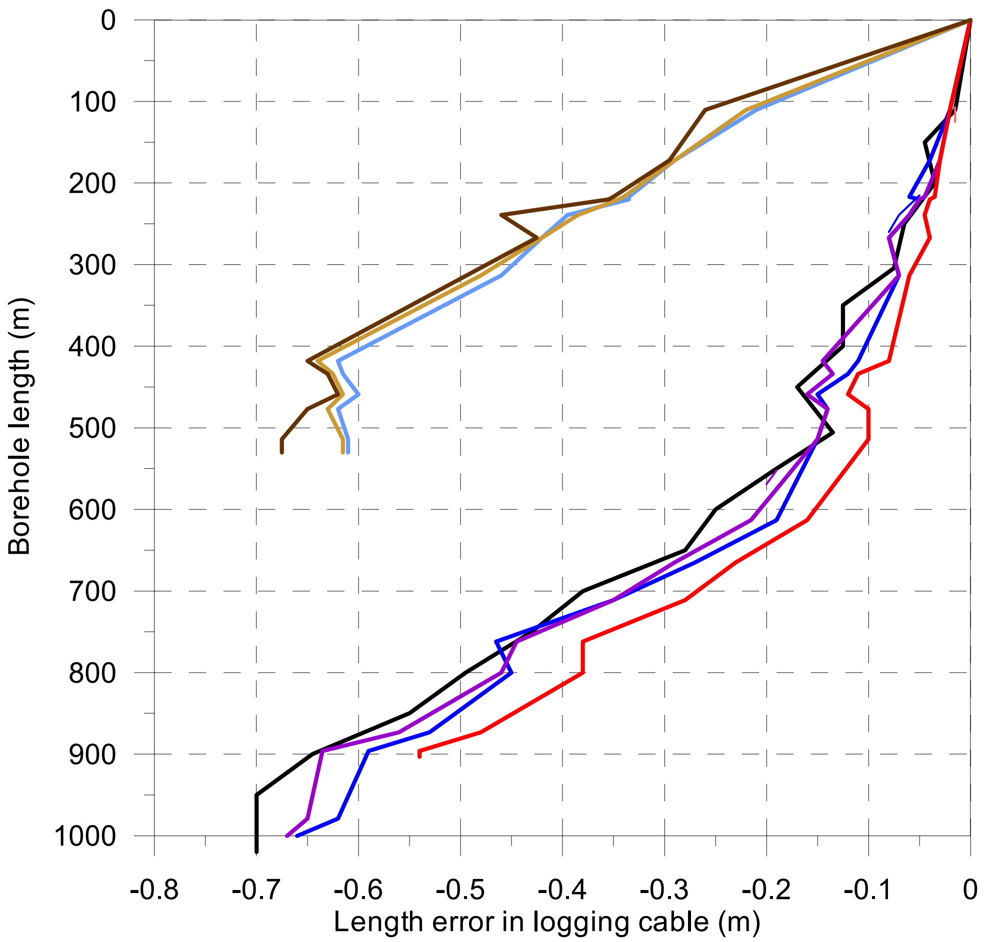


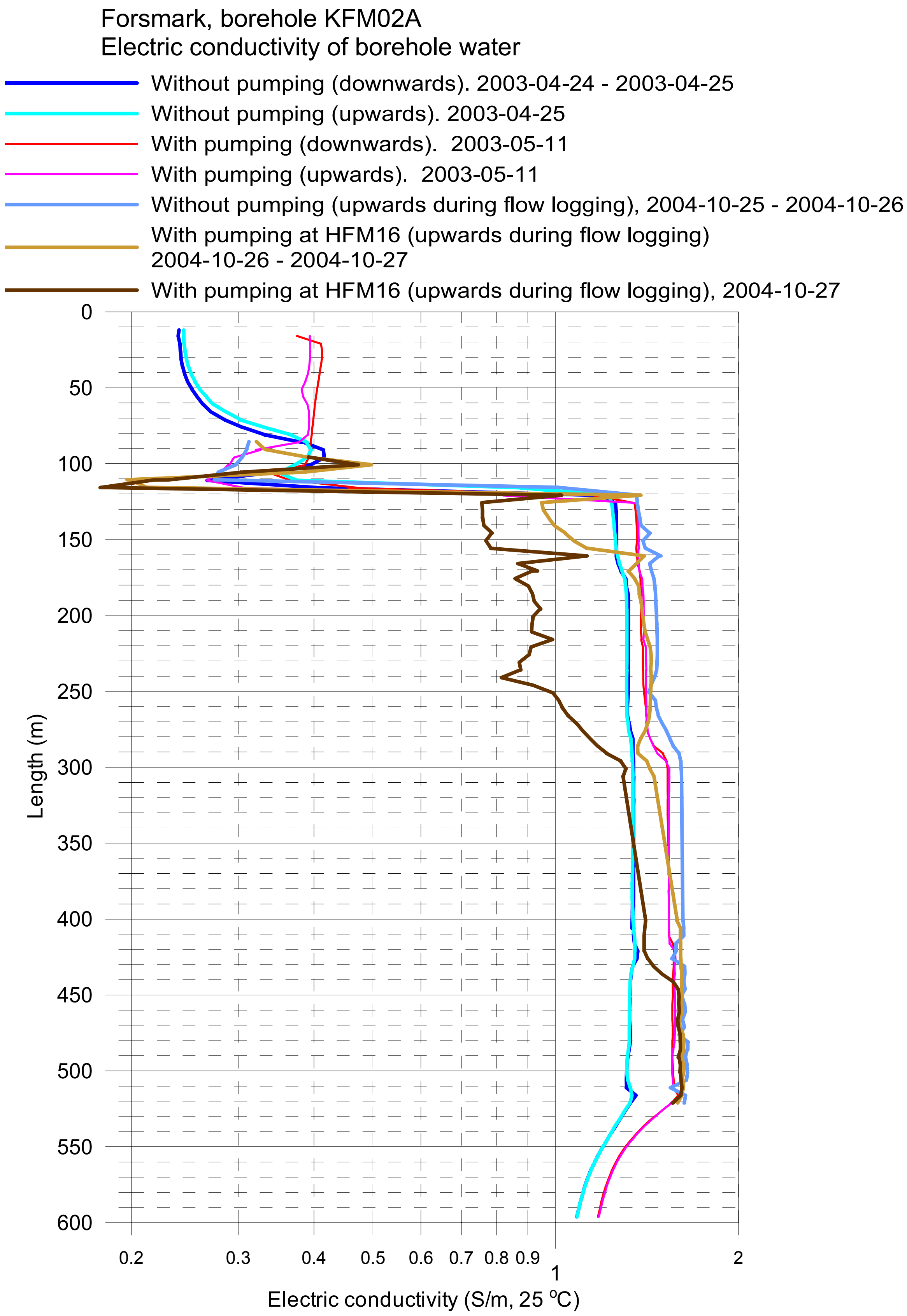
Forsmark, borehole KFM02A
SPR and Caliper results after length correction



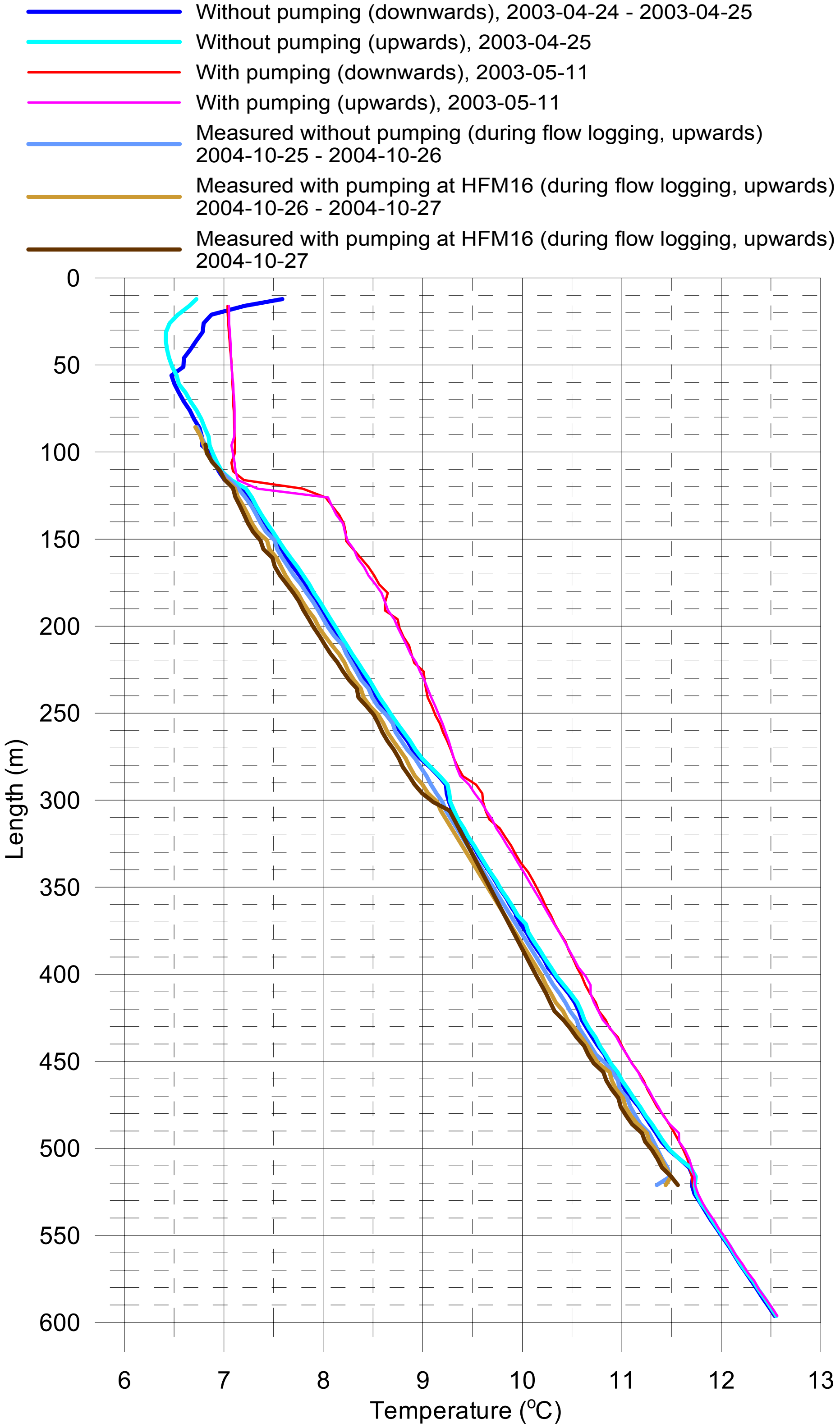
Forsmark, borehole KFM02A
Length correction

- SPR + Caliper, downwards, 2003-04-23 - 2003-04-24
- SPR without pumping, downwards (L= 5 m), 2003-04-26 - 2003-04-28
- SPR without pumping, downwards (L= 5 m), 2003-04-28
- SPR with pumping, downwards (L= 5 m), 2003-05-06 - 2003-05-08
- SPR with pumping, downwards (L= 5 m), 2003-05-08
- SPR with pumping, downwards (L= 1 m), 2003-05-08 - 2003-05-11
- SPR with pumping, downwards (L= 1 m), 2003-05-12
- SPR without pumping, upwards (L= 5 m), 2004-10-25 - 2004-10-26
- SPR with pumping at HFM16, upwards (0 days after pumping started) (L= 5 m), 2004-10-26 - 2004-10-27
- SPR with pumping at HFM16, upwards (1 day after pumping started) (L= 5 m), 2004-10-27

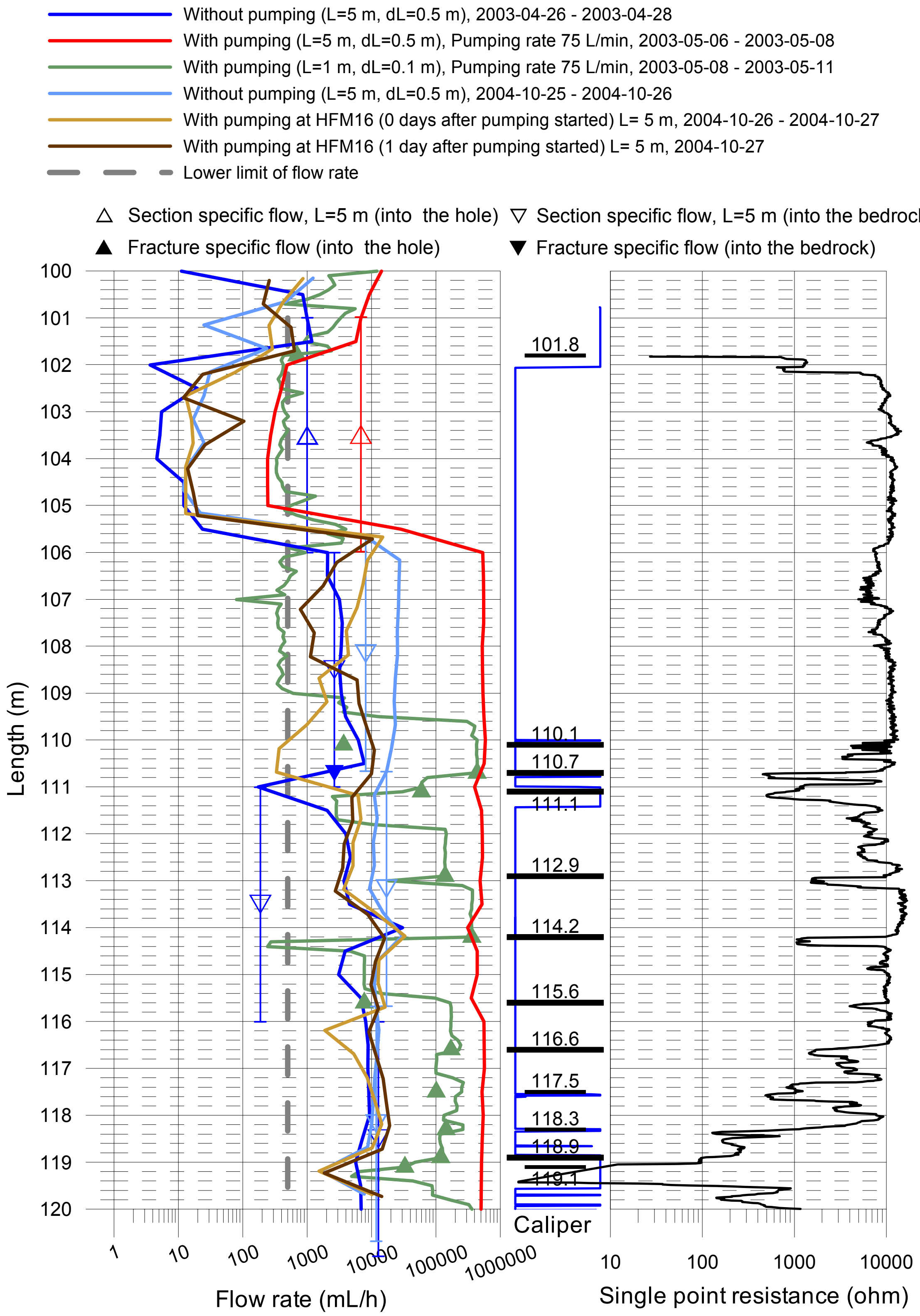



Forsmark, borehole KFM02A
Electric conductivity of borehole water
Without pumping (downwards). 2003-04-24 - 2003-04-25
Without pumping (upwards). 2003-04-25
With pumping (downwards). 2003-05-11
With pumping (upwards). 2003-05-11
Without pumping (upwards during flow logging), 2004-10-25 - 2004-10-26
With pumping at HFM16 (upwards during flow logging) 2004-10-26 - 2004-10-27
With pumping at HFM16 (upwards during flow logging), 2004-10-27
Length (m)
0
50
100
150
200
250
300
350
400
450
500
550
600
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
2
Electric conductivity (S/m, 25 °C)

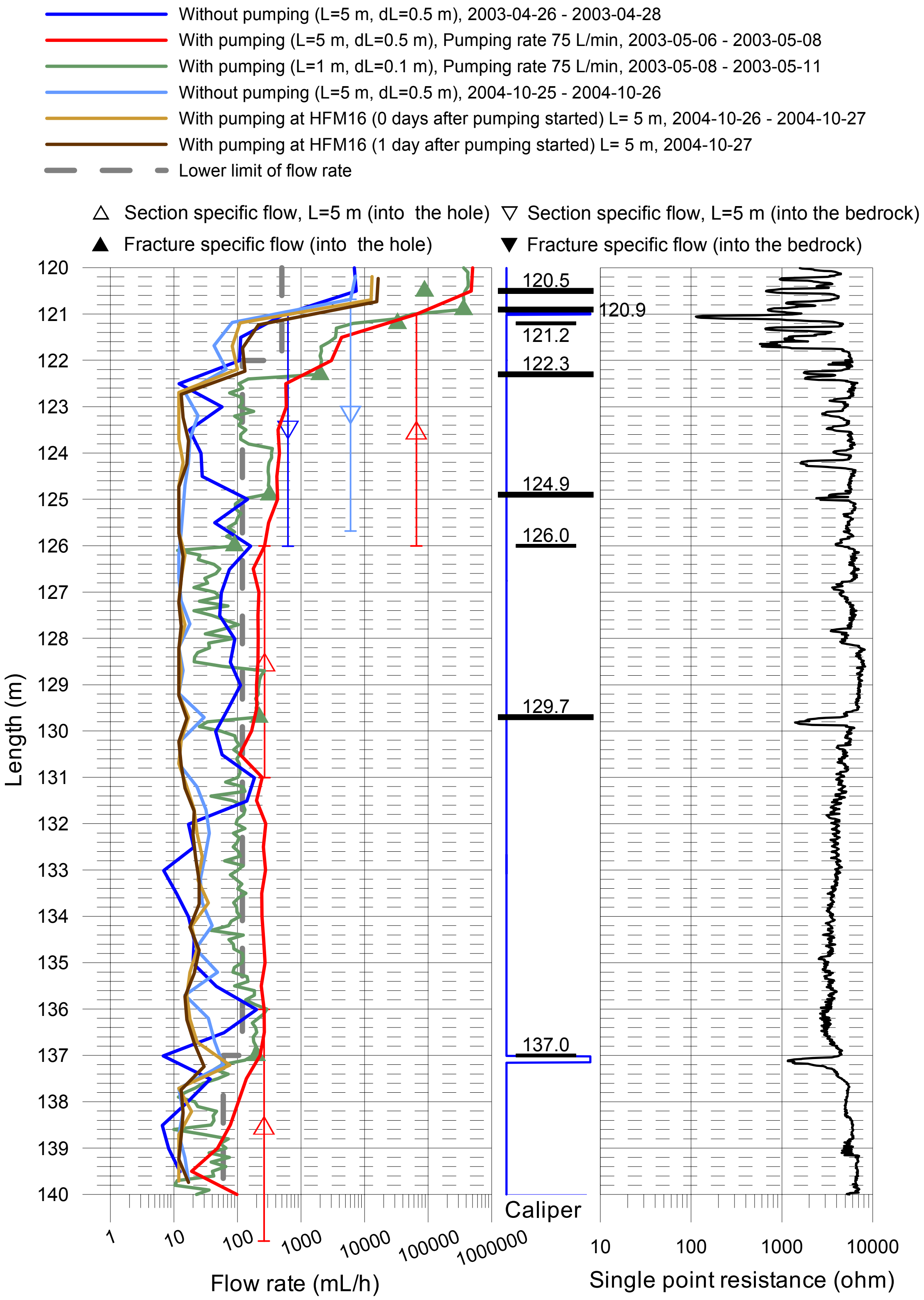
Forsmark, borehole KFM02A
Temperature of borehole water



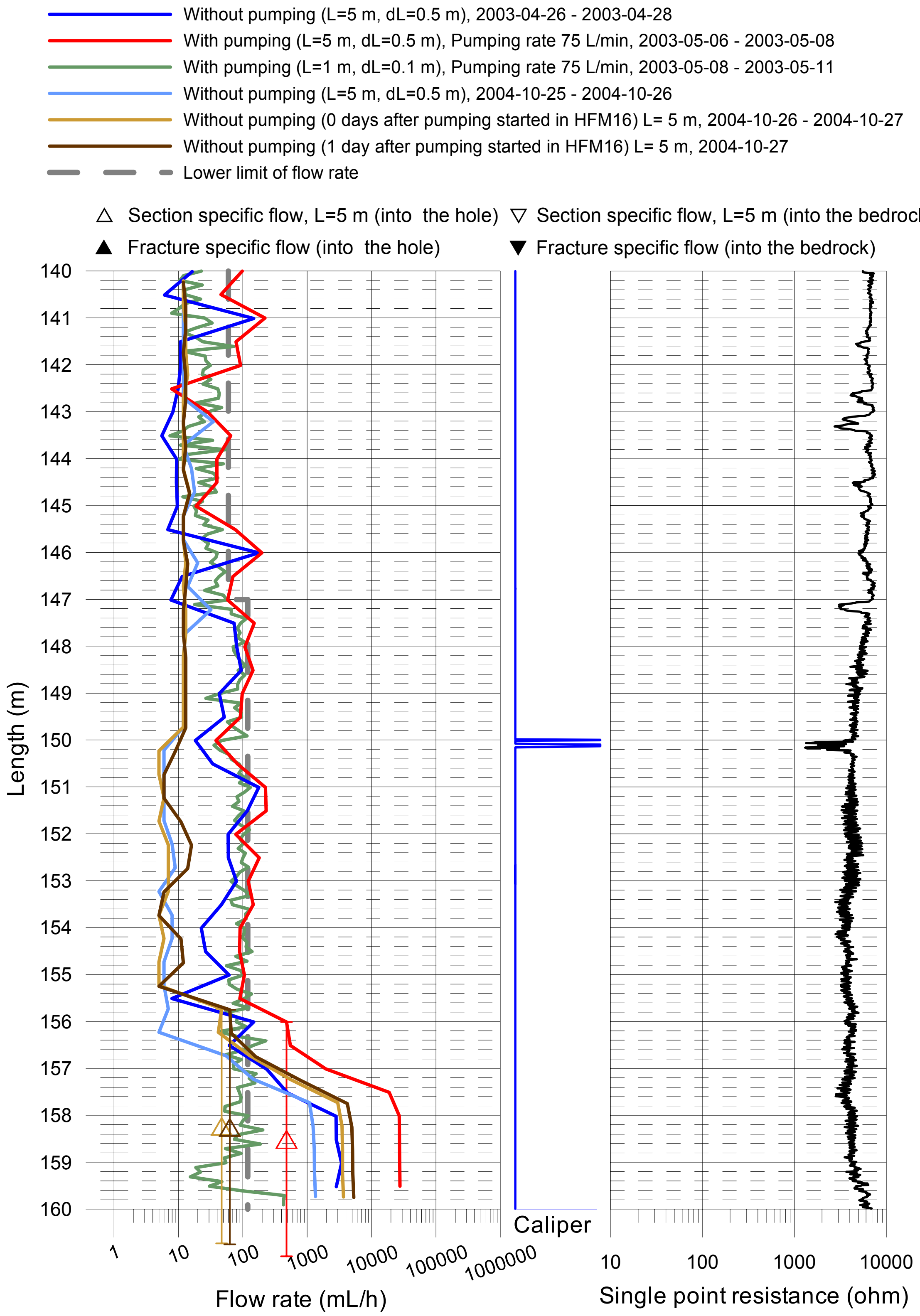
Forsmark, borehole KFM02A
Measured flow rates and single point resistance



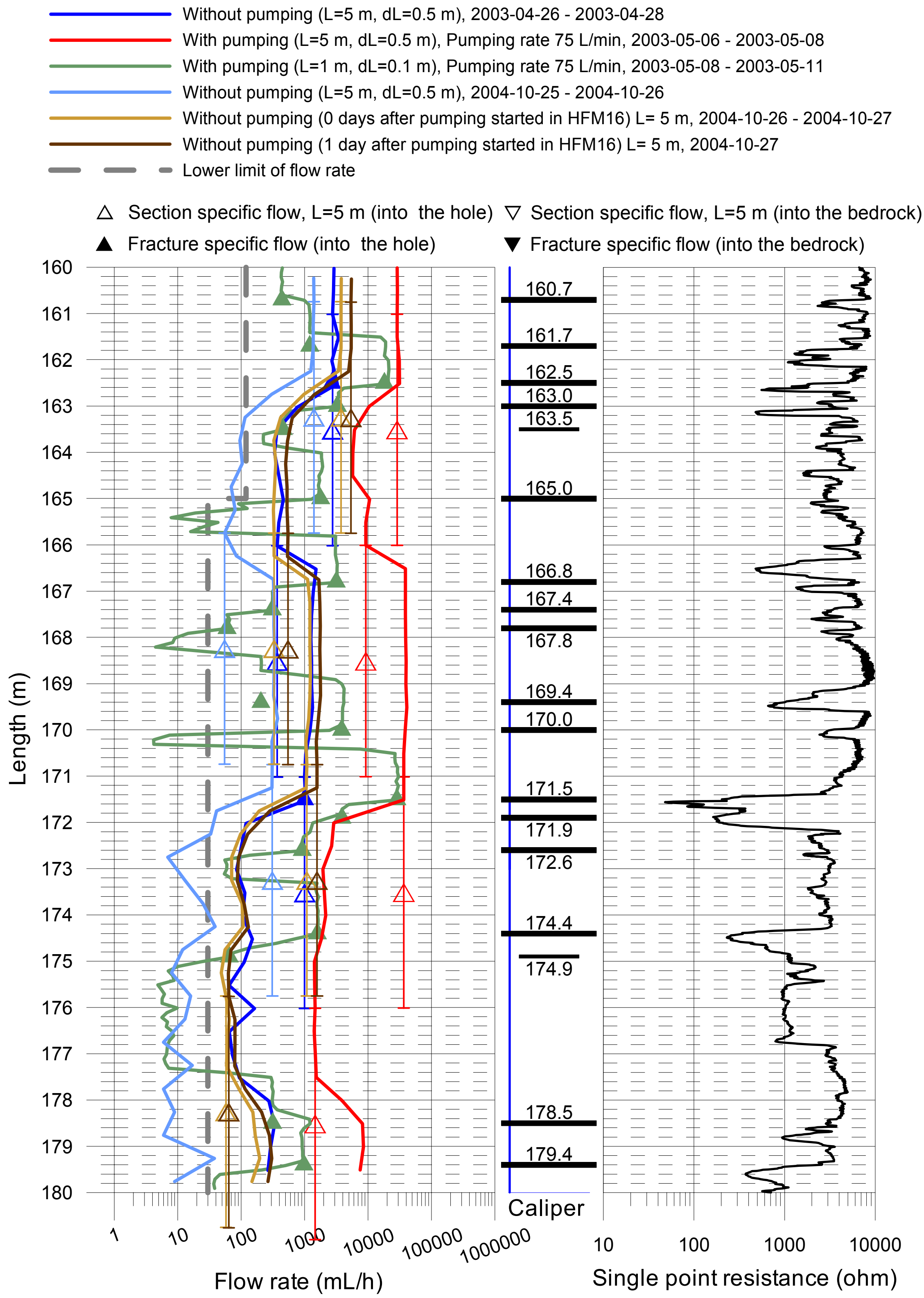
Forsmark, borehole KFM02A
Measured flow rates and single point resistance



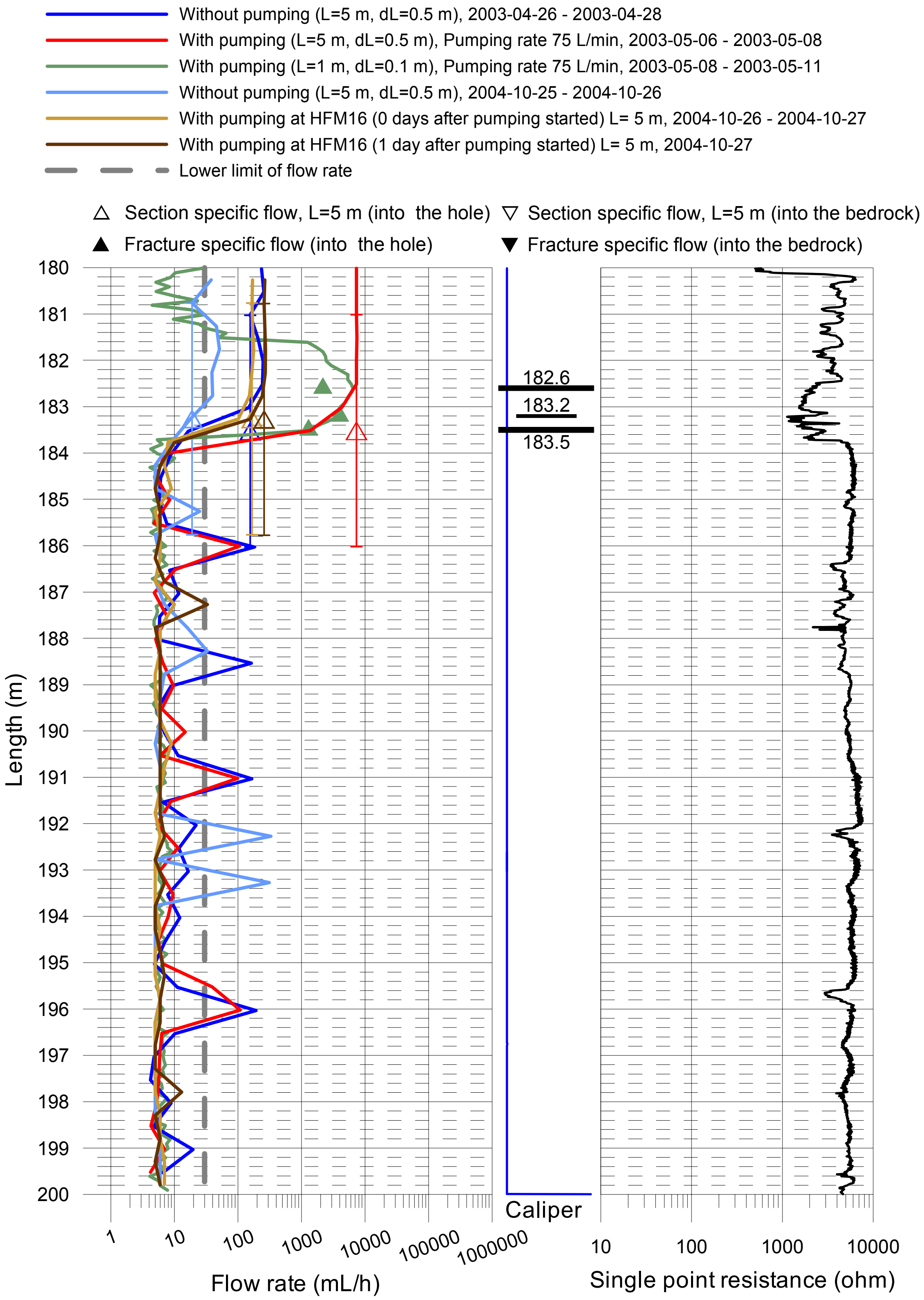
Forsmark, borehole KFM02A
Measured flow rates and single point resistance



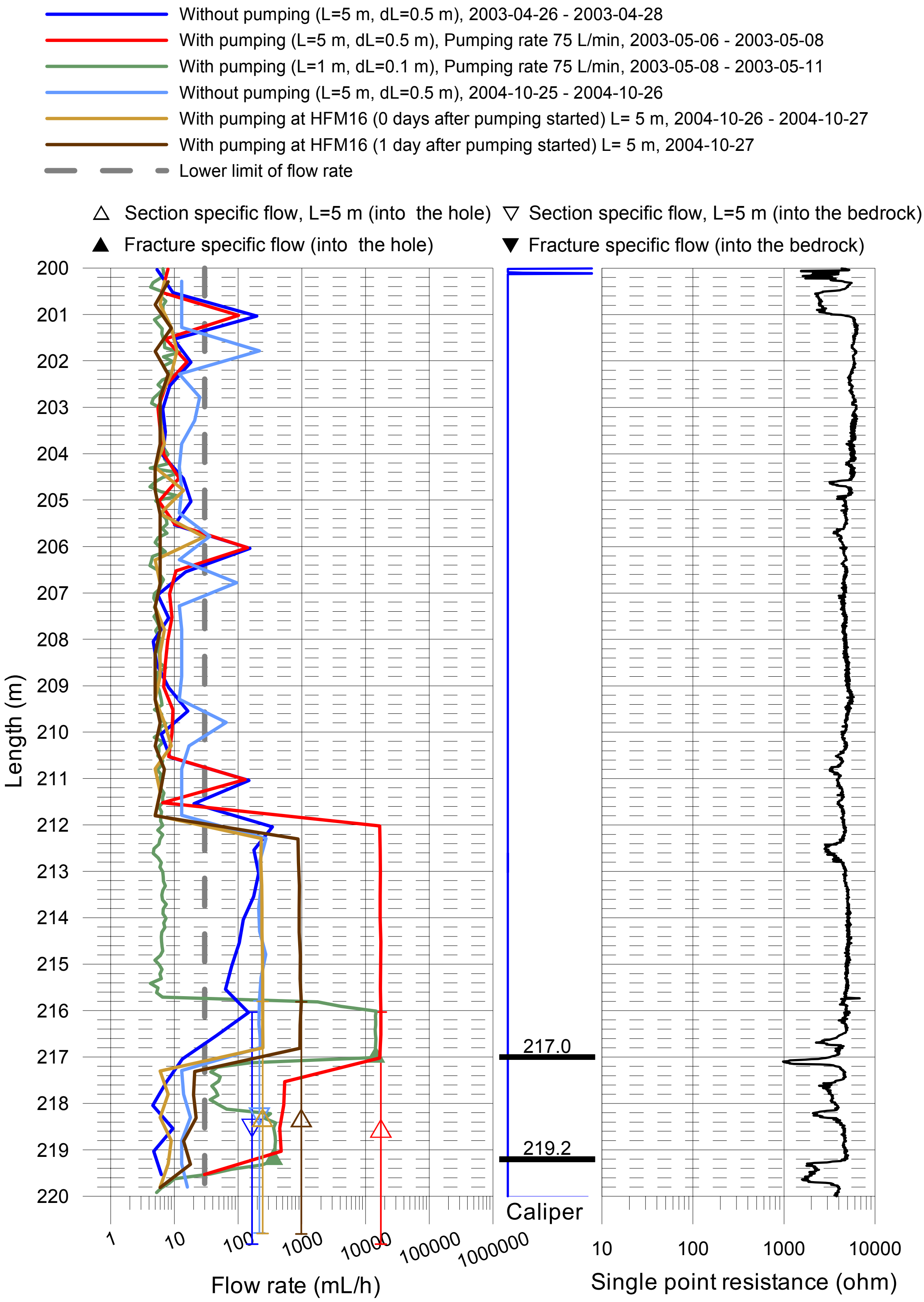
Forsmark, borehole KFM02A
Measured flow rates and single point resistance



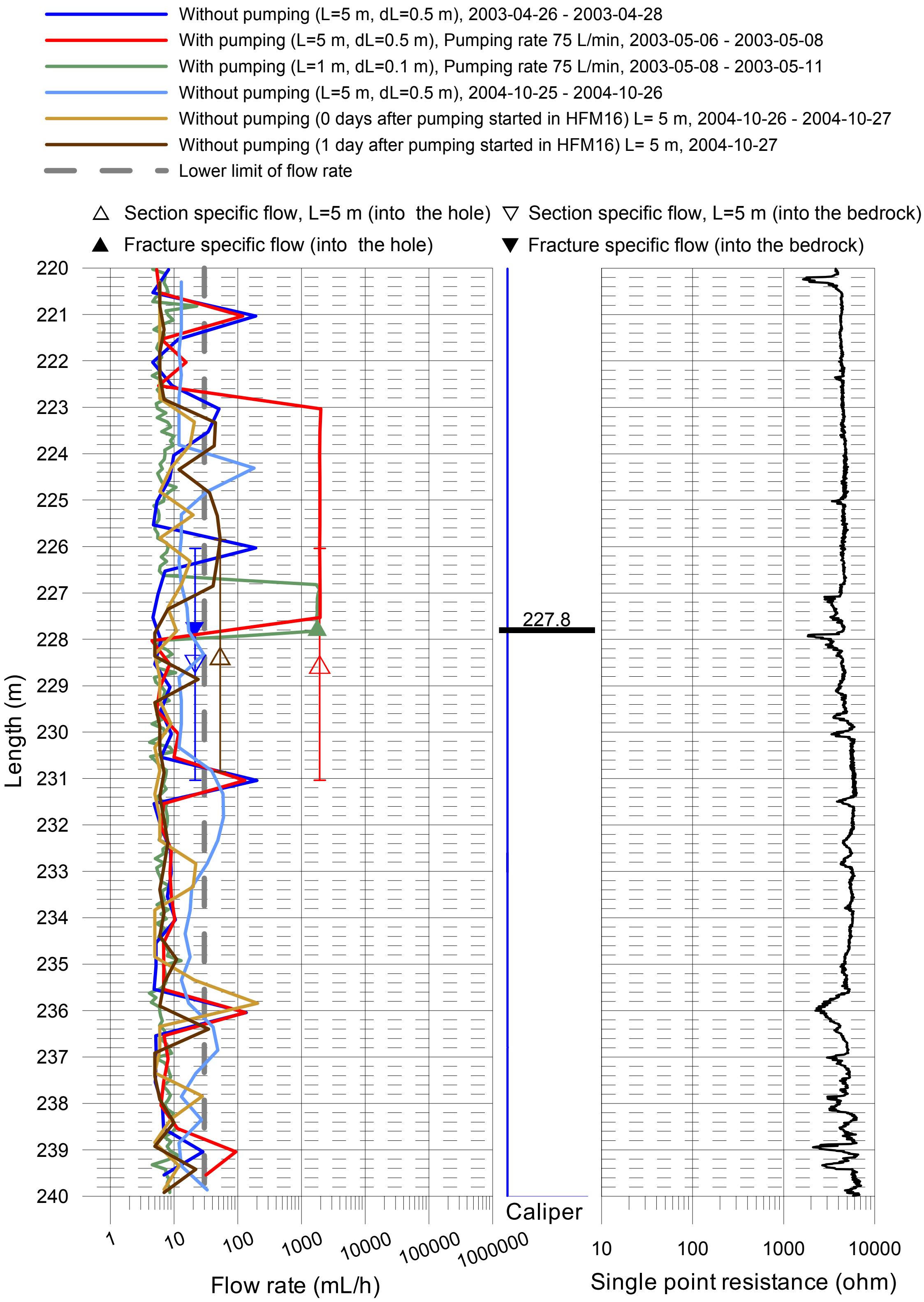
Forsmark, borehole KFM02A
Measured flow rates and single point resistance



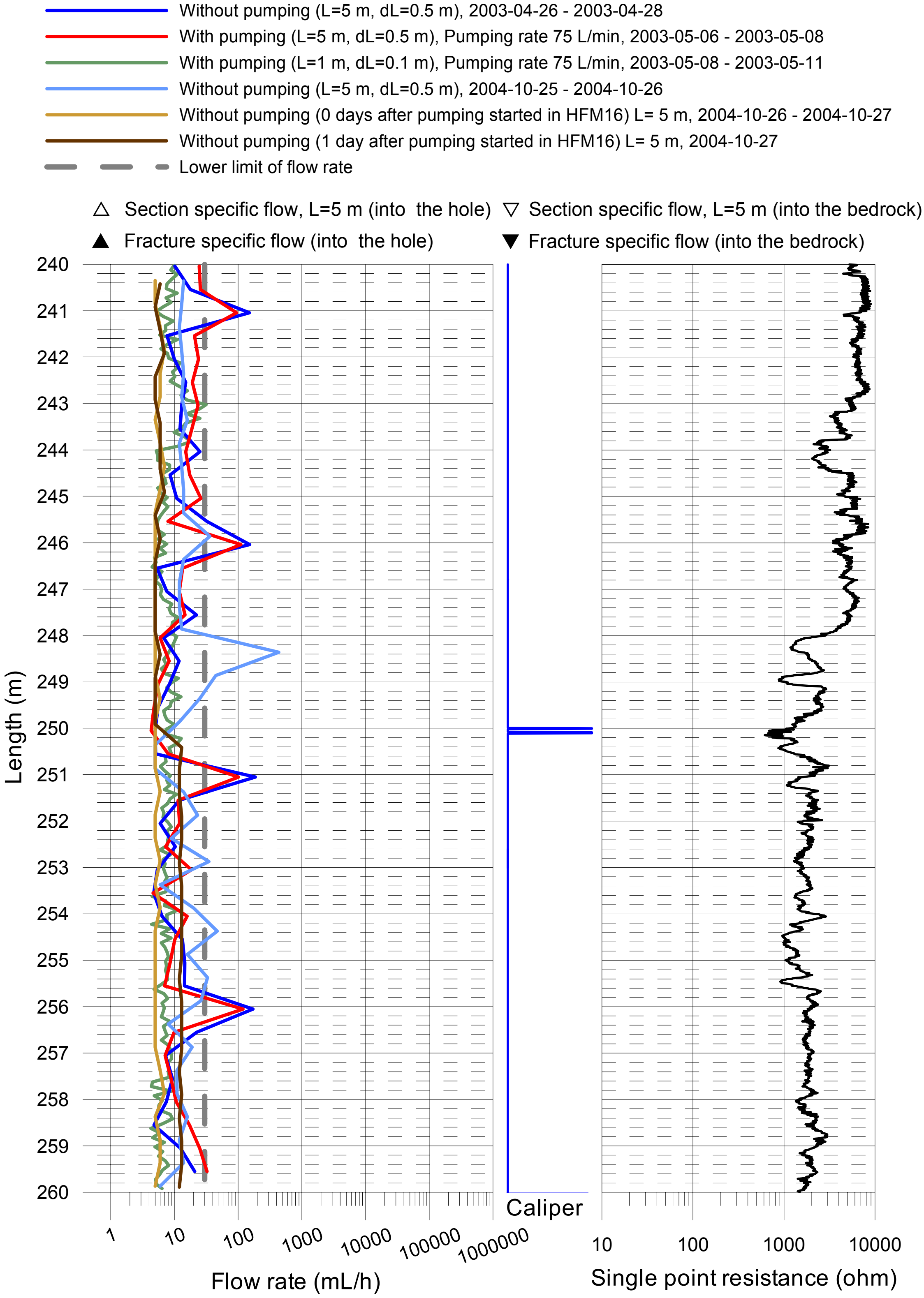
Forsmark, borehole KFM02A
Measured flow rates and single point resistance



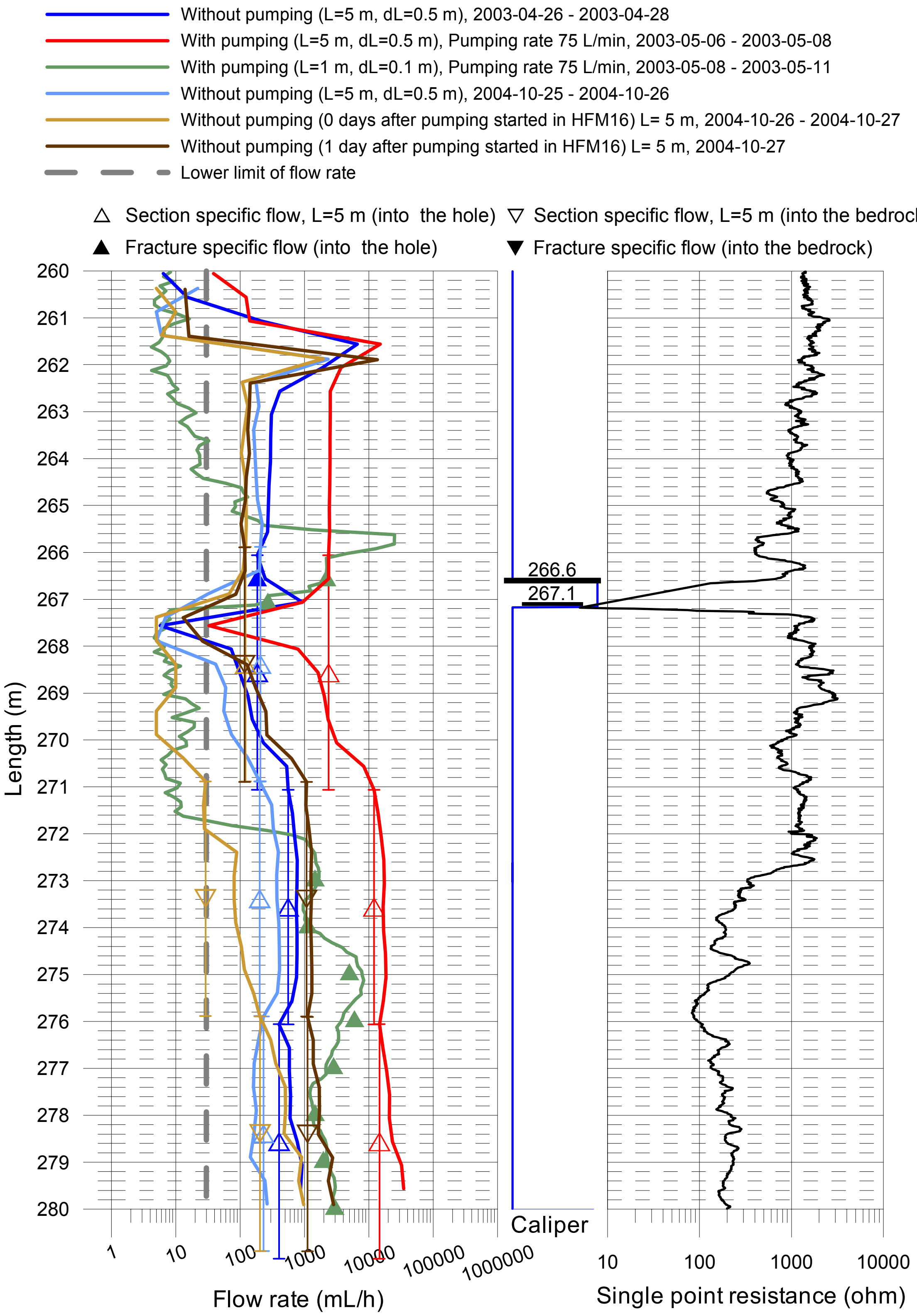
Forsmark, borehole KFM02A
Measured flow rates and single point resistance



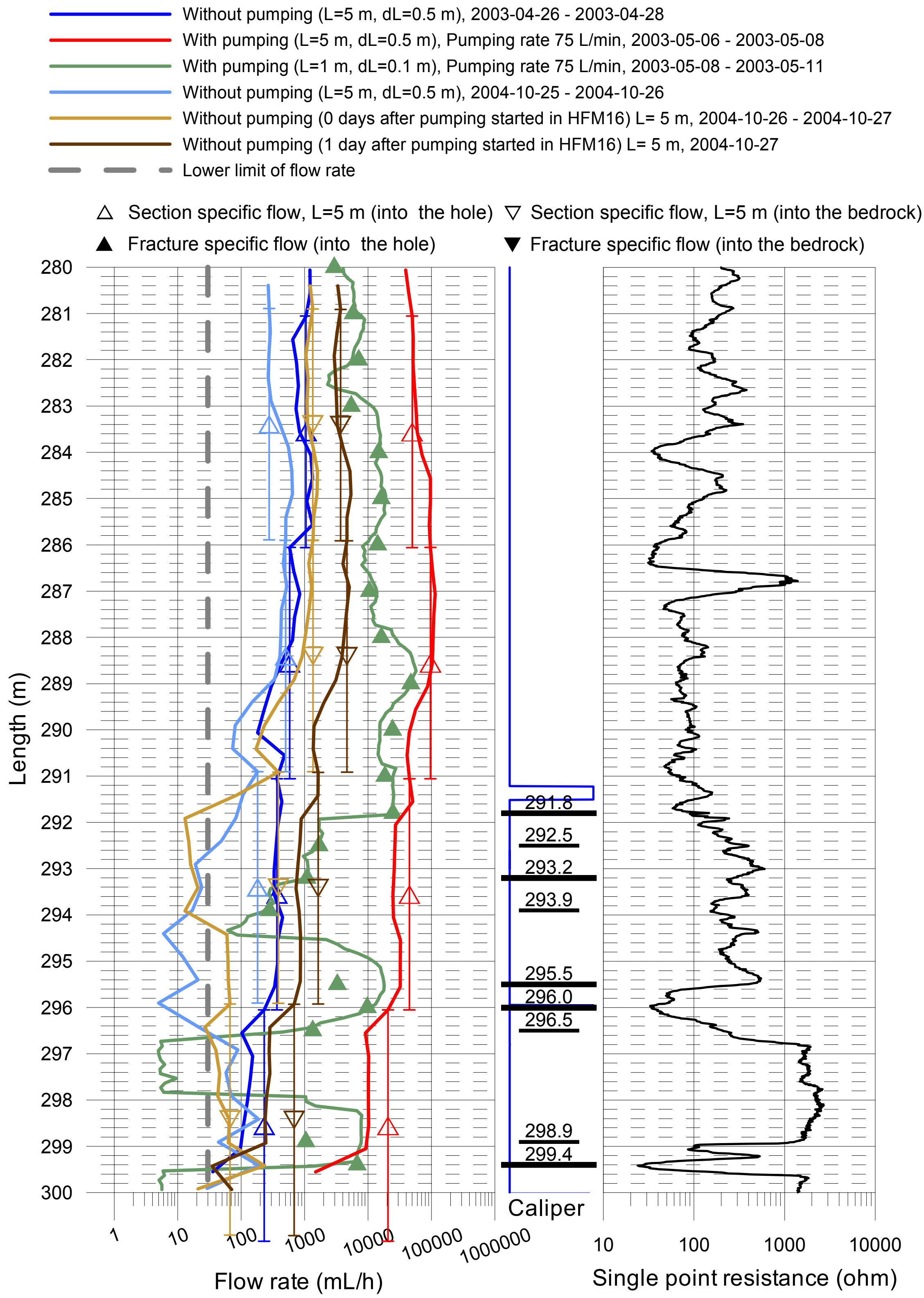
Forsmark, borehole KFM02A
Measured flow rates and single point resistance



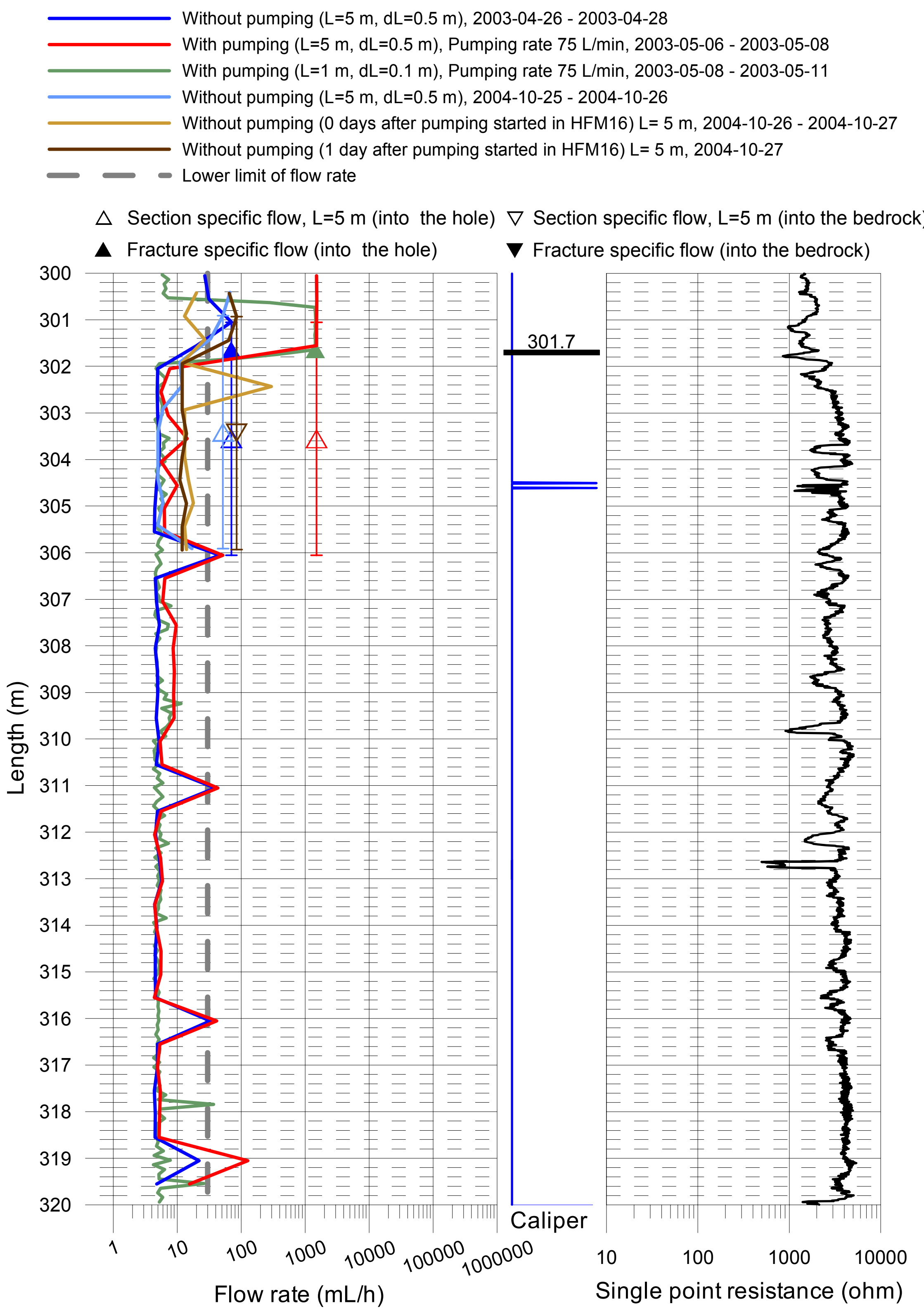
Forsmark, borehole KFM02A
Measured flow rates and single point resistance



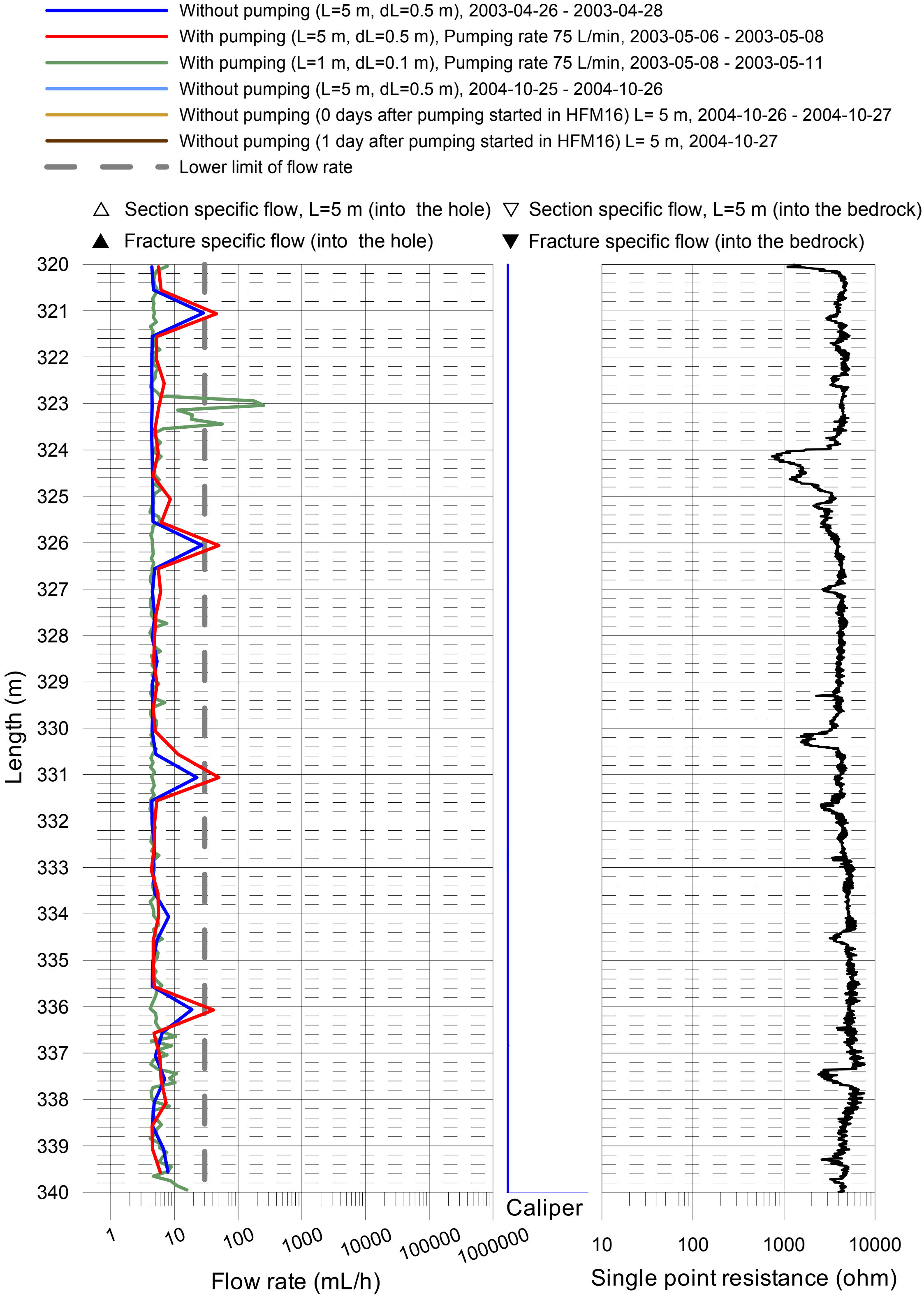
Forsmark, borehole KFM02A
Measured flow rates and single point resistance



Forsmark, borehole KFM02A
Measured flow rates and single point resistance



Forsmark, borehole KFM02A
Measured flow rates and single point resistance



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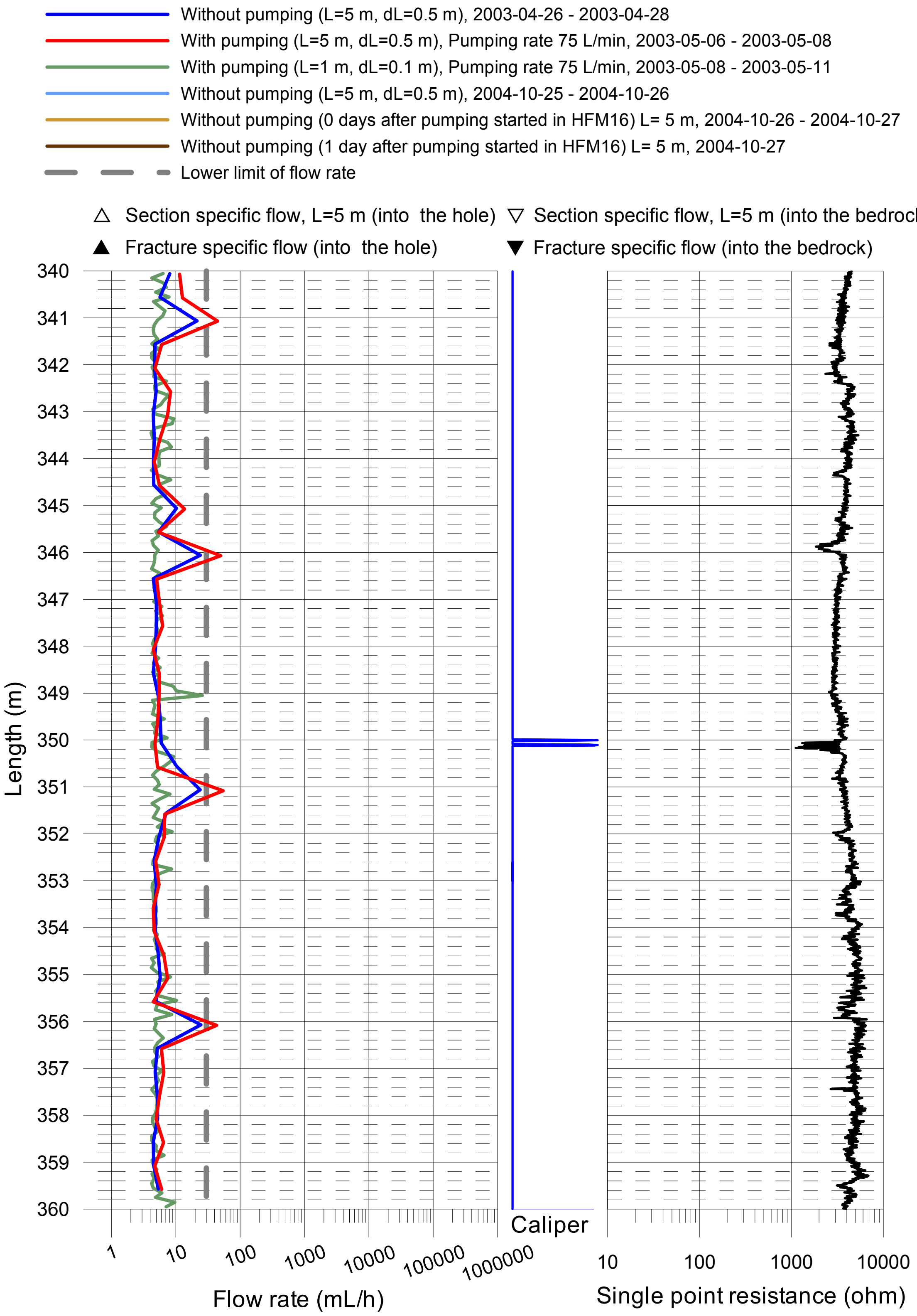
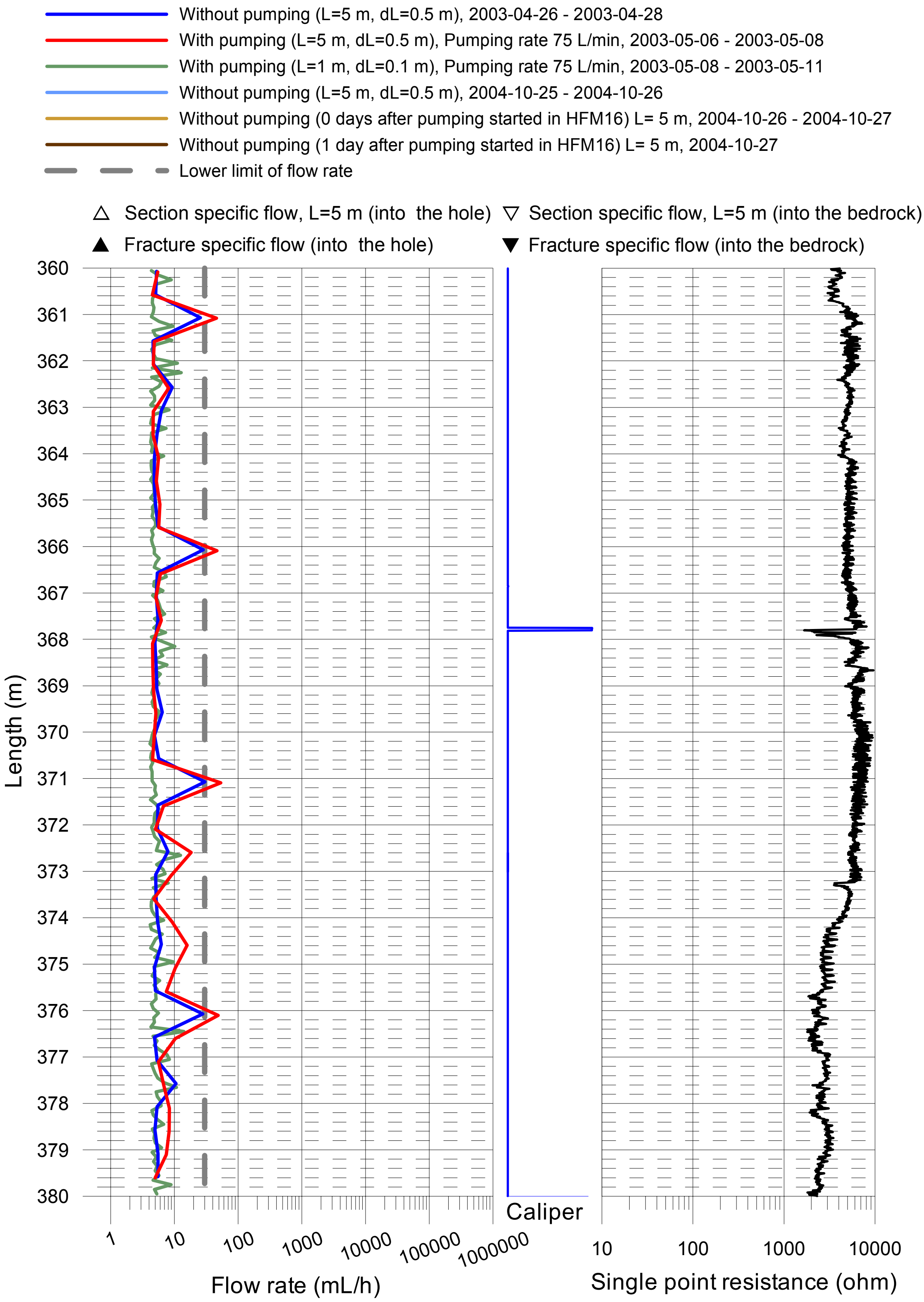
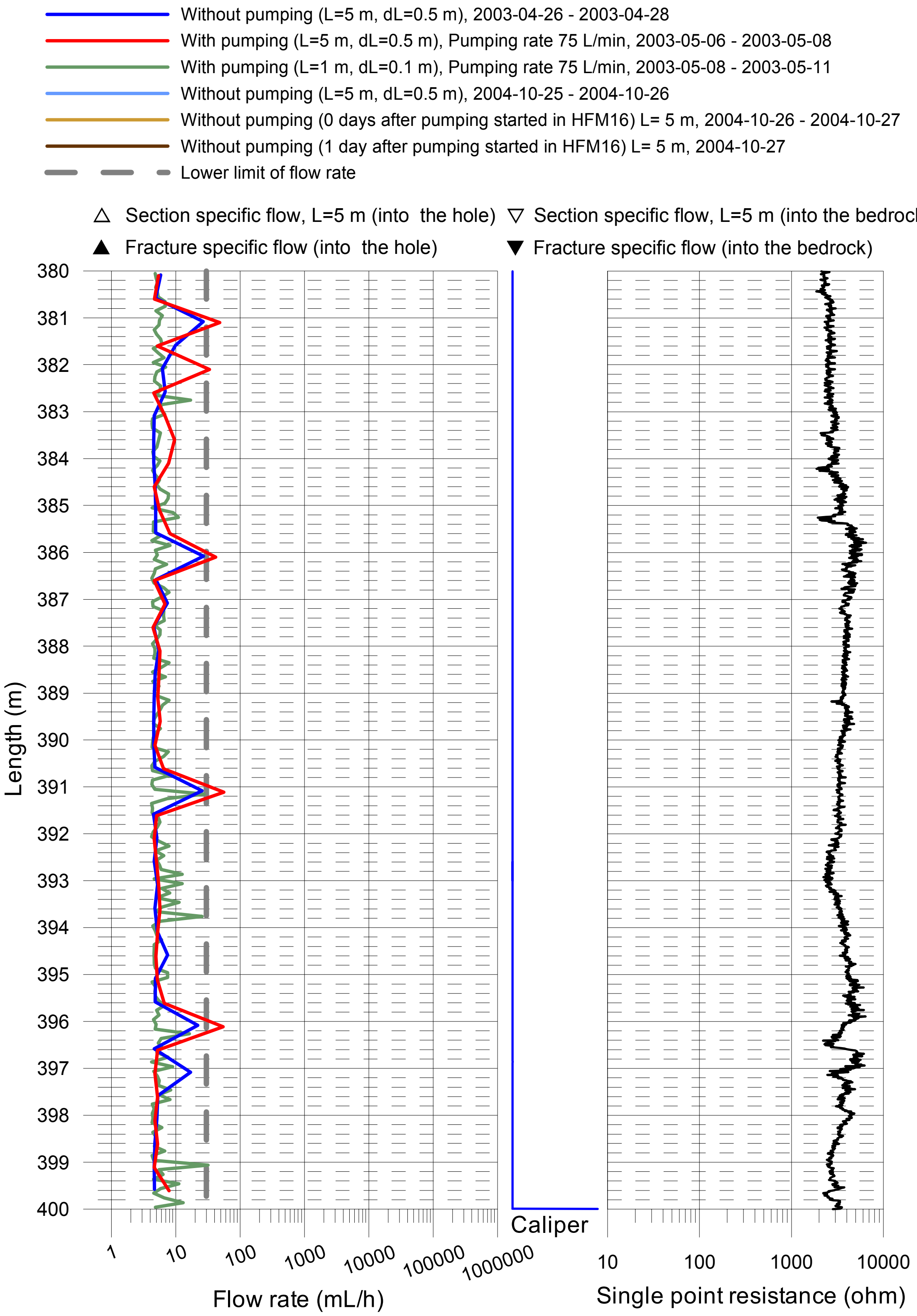
Measured flow rates and single point resistance



Forsmark, borehole KFM02A
Measured flow rates and single point resistance



Forsmark, borehole KFM02A
Measured flow rates and single point resistance



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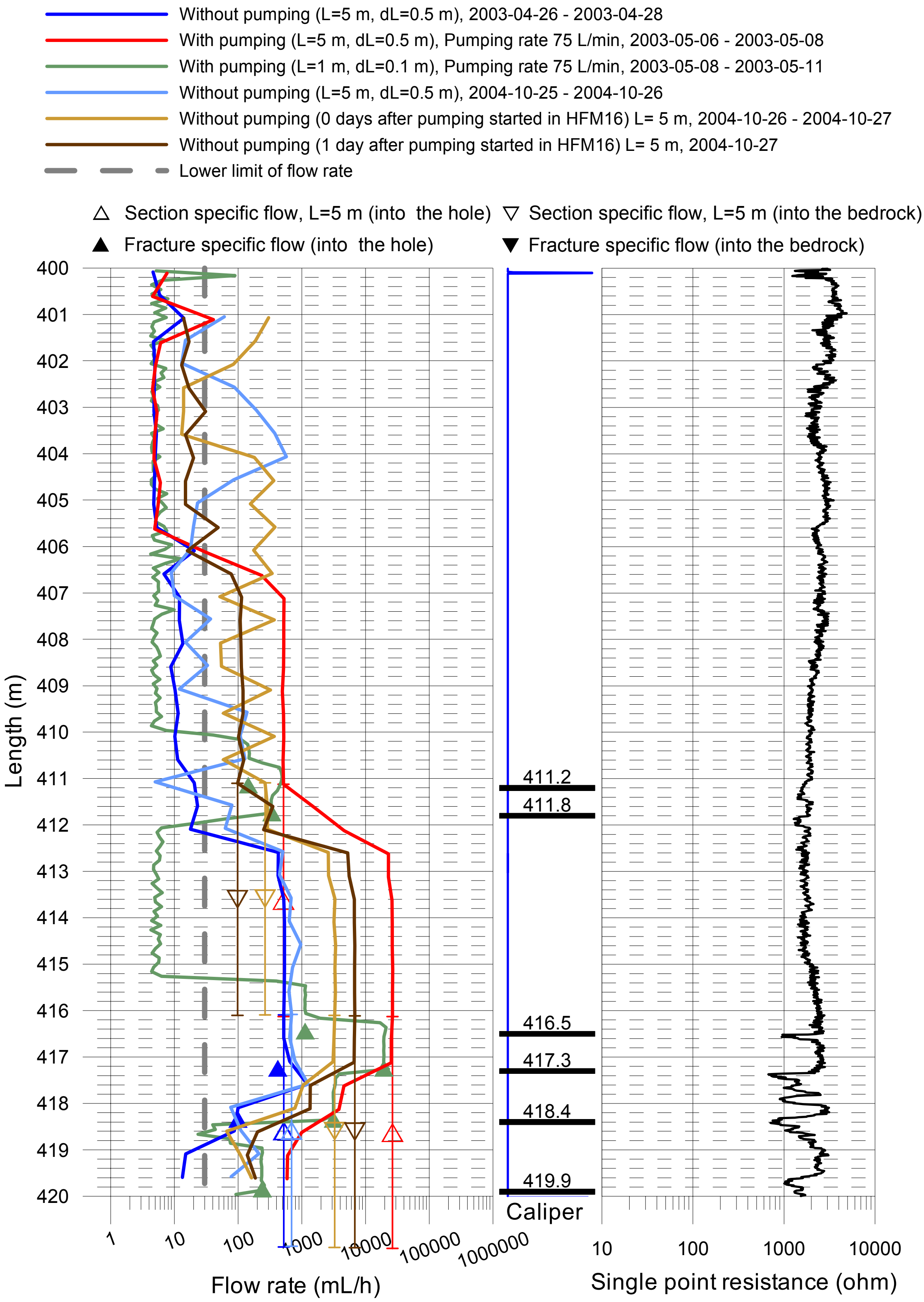
Measured flow rates and single point resistance



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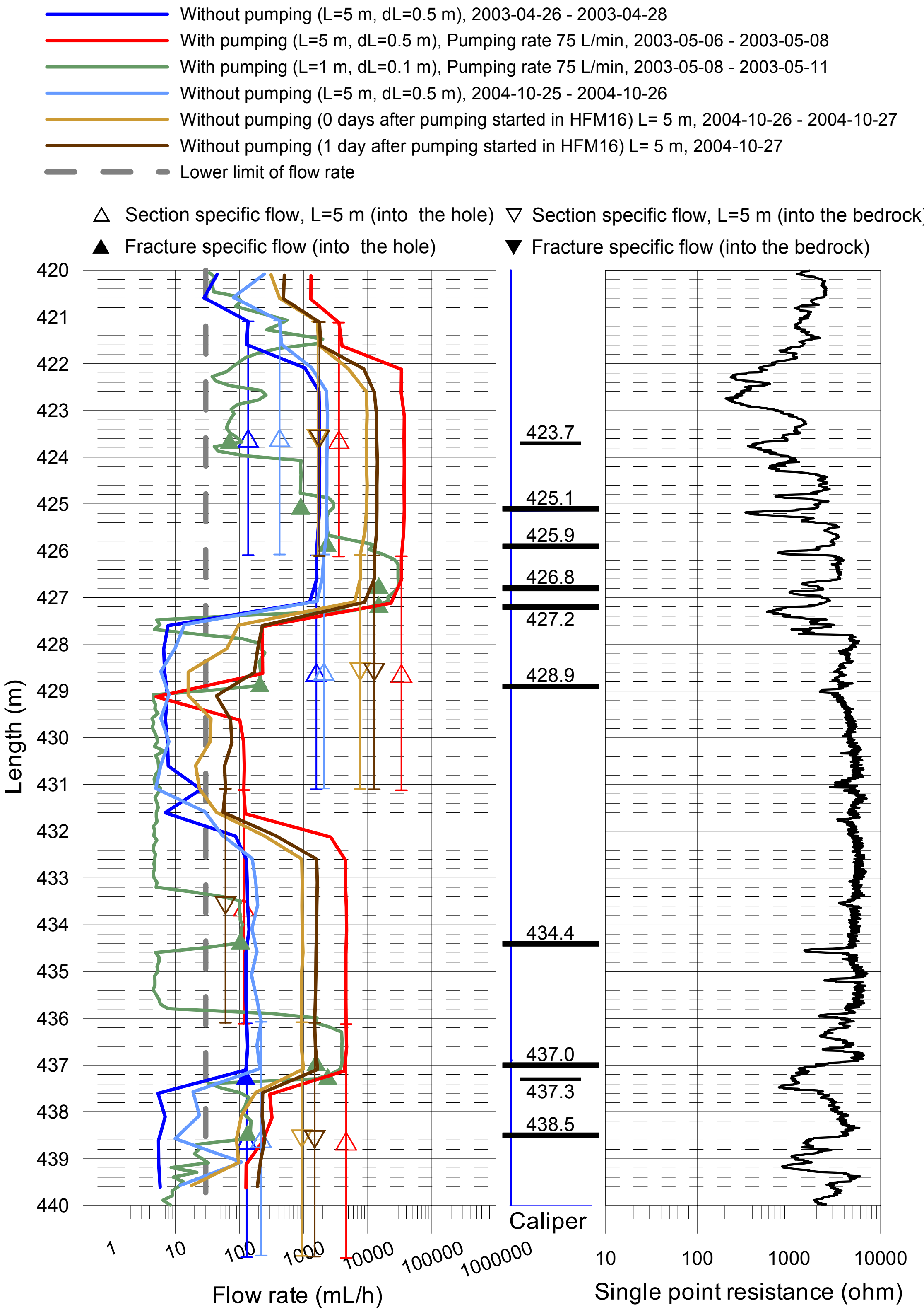
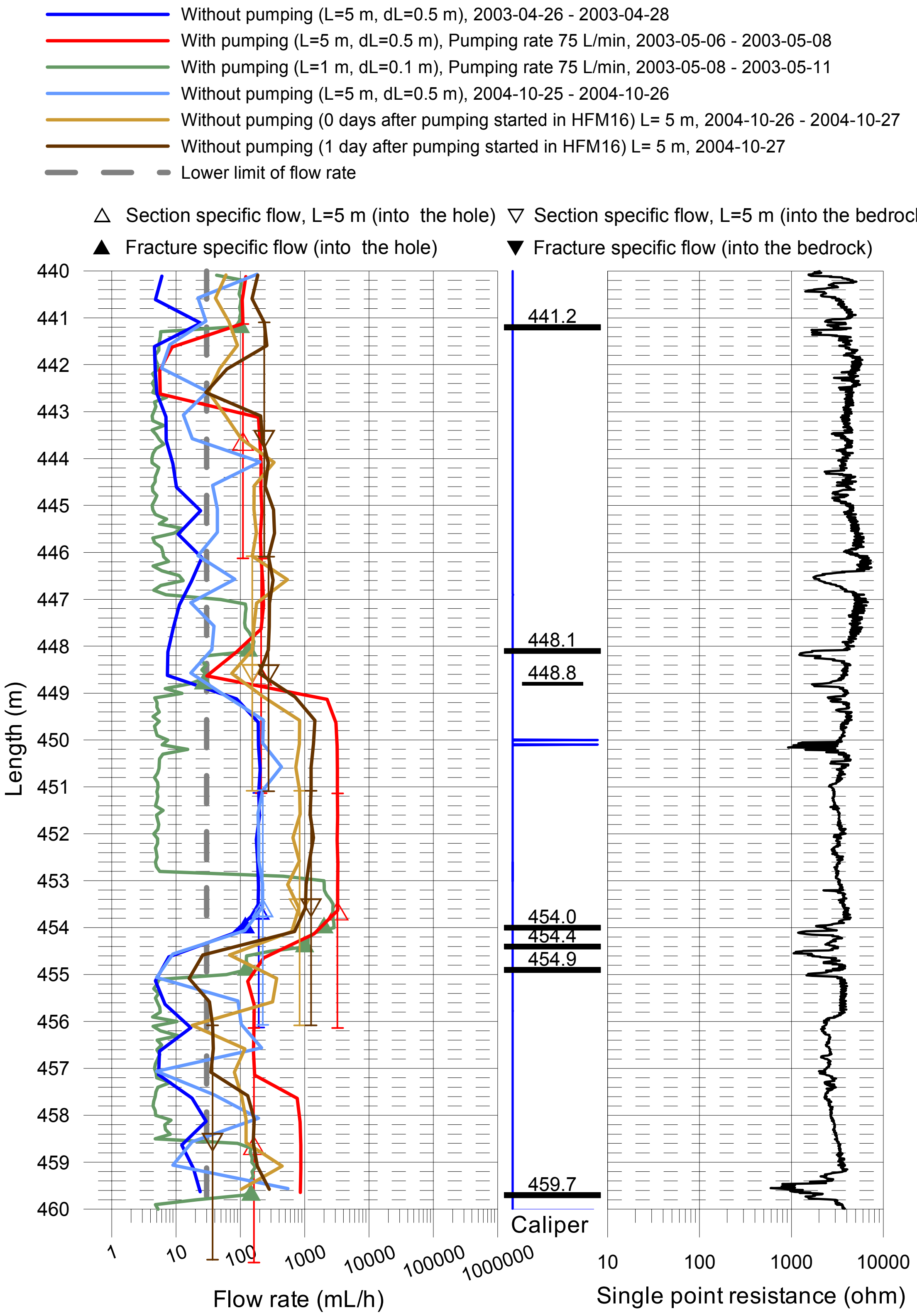
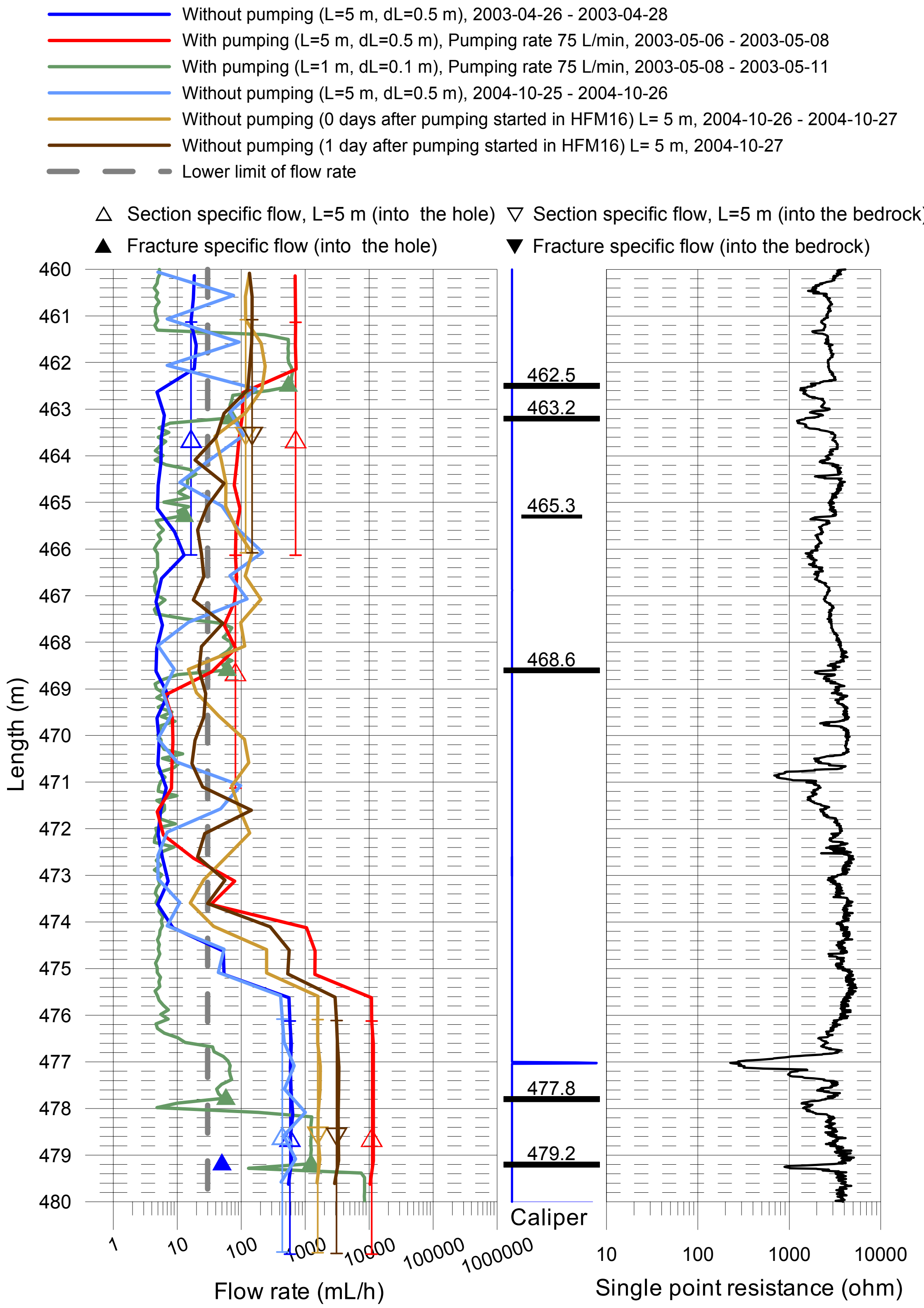
Measured flow rates and single point resistance



Forsmark, borehole KFM02A
Measured flow rates and single point resistance



Forsmark, borehole KFM02A
Measured flow rates and single point resistance



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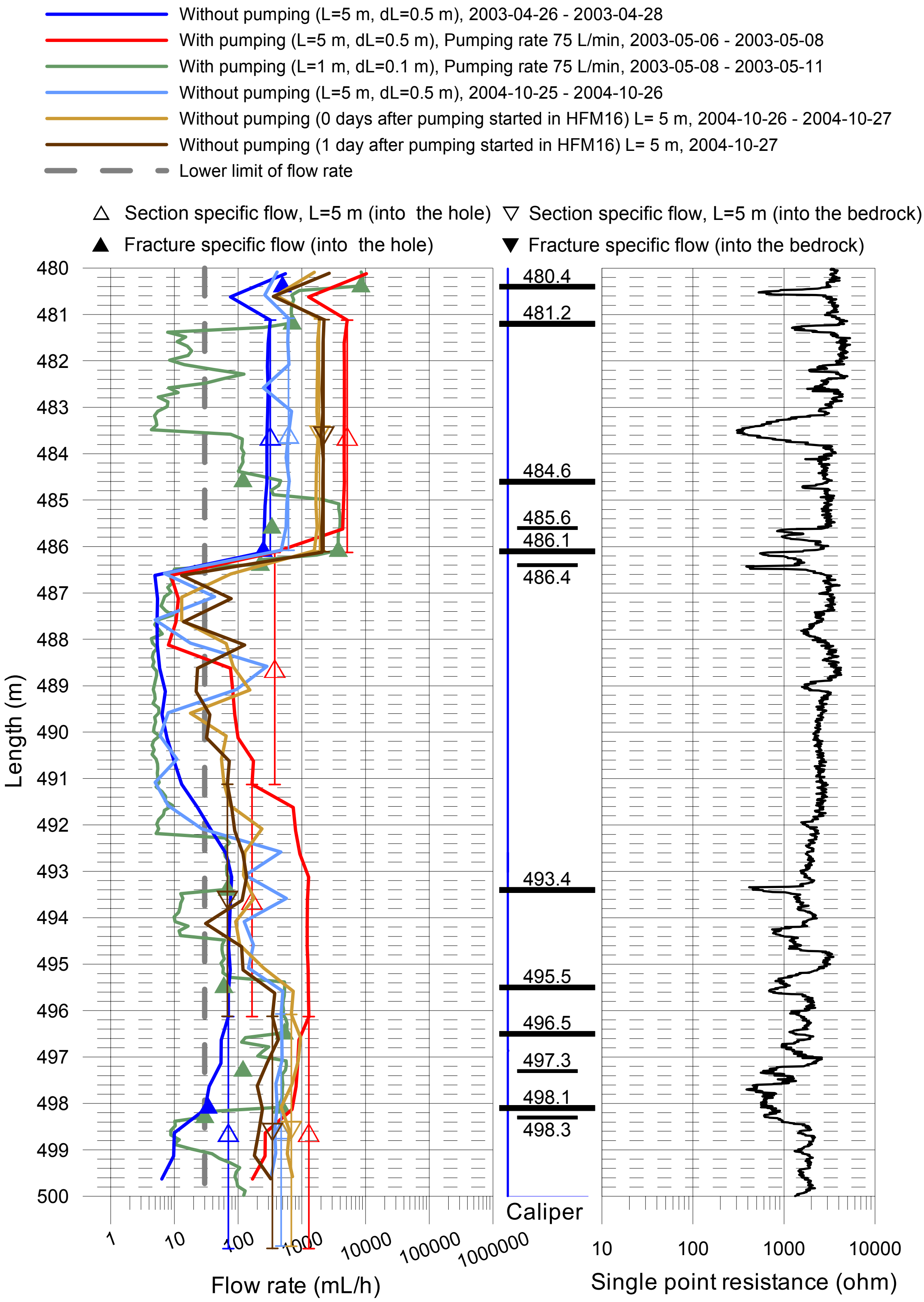
Measured flow rates and single point resistance



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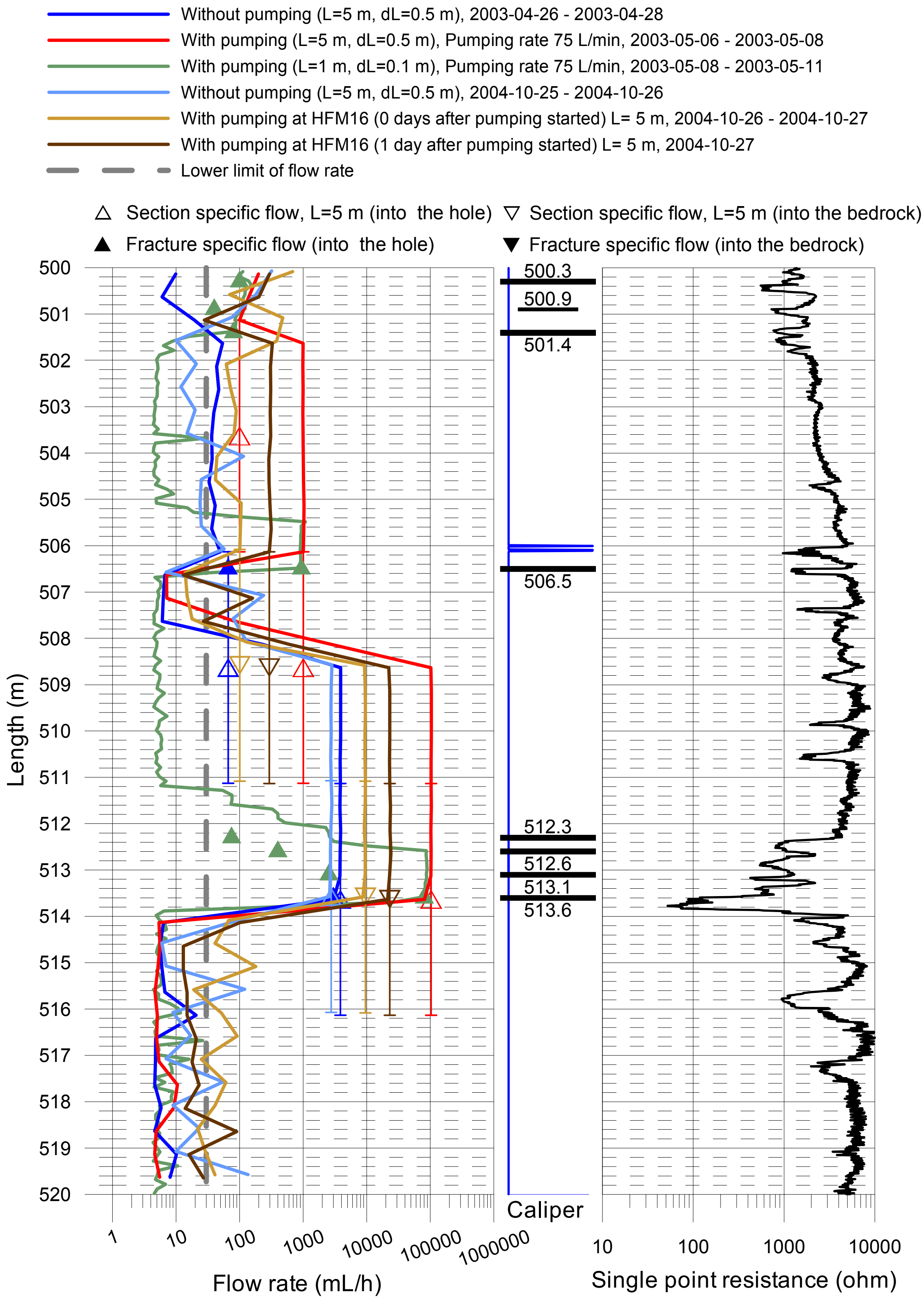
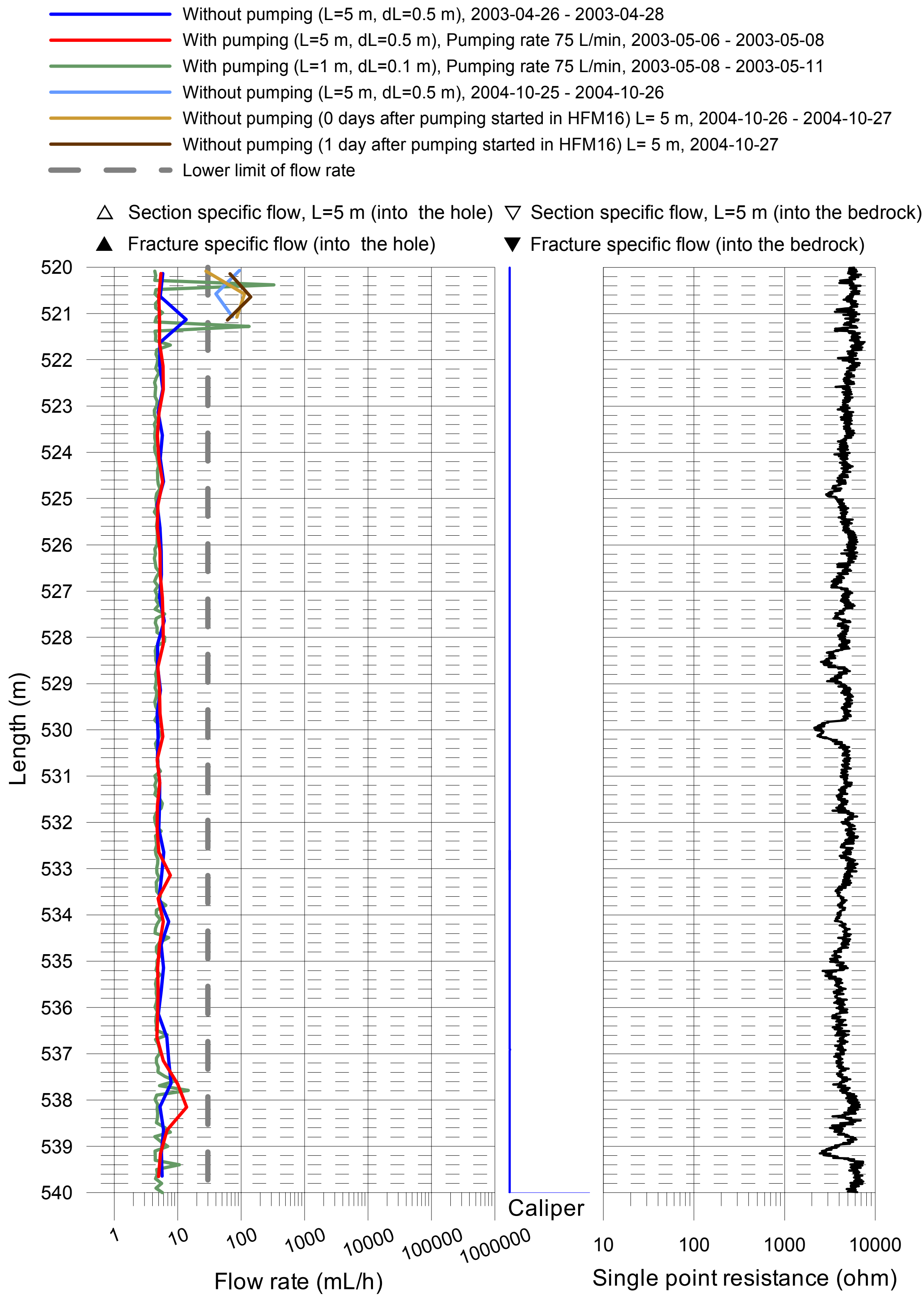
Measured flow rates and single point resistance



Forsmark, borehole KFM02A
Measured flow rates and single point resistance



Explanations.

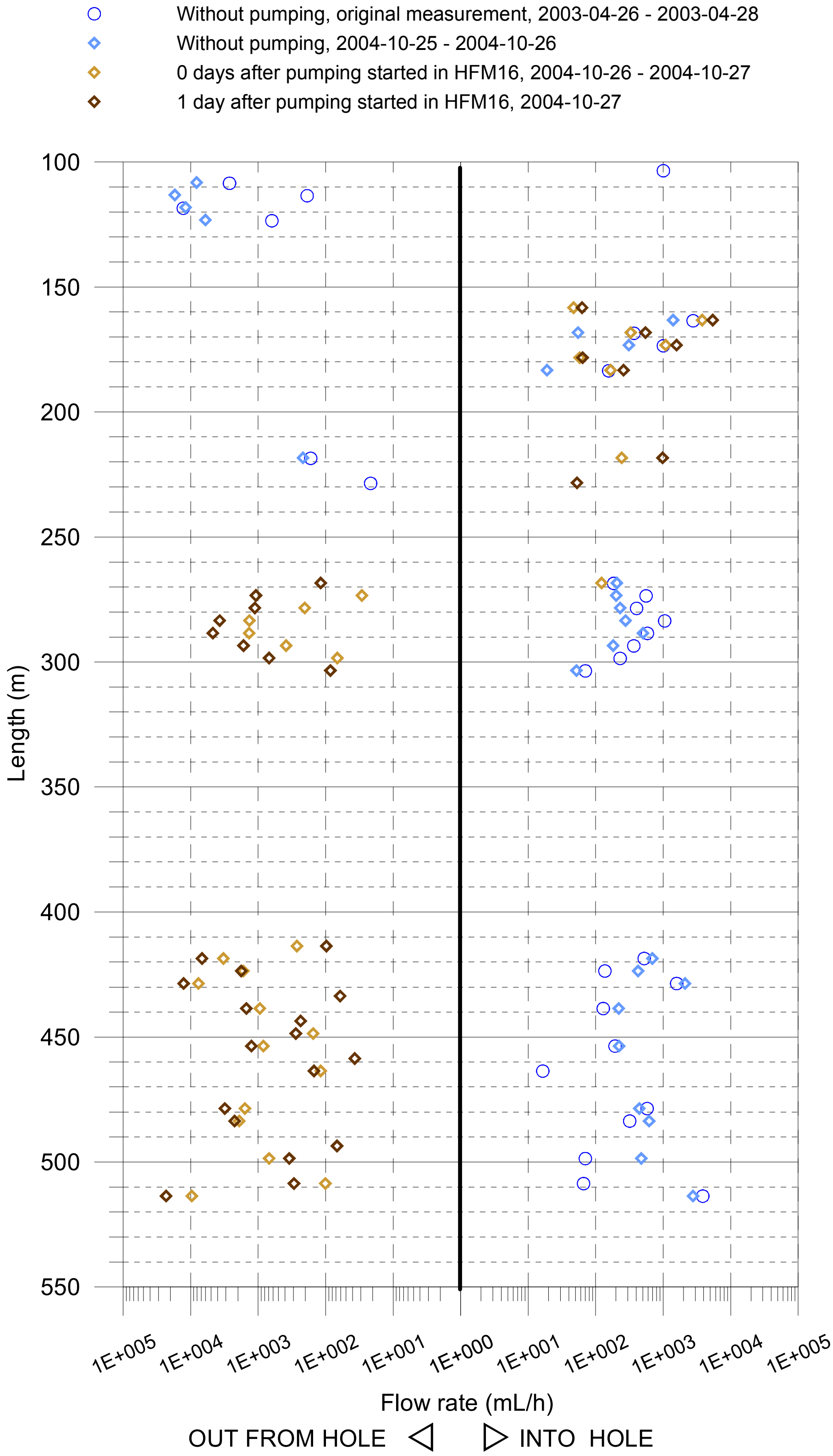
Header	Unit	Explanations
SecUp L	m	Length along the borehole for the upper limit of the test section (based on corrected length L).
SecLow L	m	Length along the borehole for the lower limit of the test section (based on corrected length L).
L	m	Corrected length along borehole based on SKB procedures for length correction.
Lw	m	Section length used in the difference flow logging.
Flow1	mL/h	Measured flow rate through the test section under natural conditions (no pumping).
Flow2	mL/h	Measured flow rate through the test section during pumping in HFM16.
Flow3	mL/h	Measured flow rate through the test section during pumping in HFM16.
Borehole Head1	masl	Initial hydraulic head before pumping in the open borehole in the local co-ordinates system.
Borehole Head2	masl	Hydraulic head in open the borehole during the pumping period in the local co-ordinates system.
Borehole Head3	masl	Hydraulic head in open the borehole during the pumping period in the local co-ordinates system.

Borehole ID	SecUp L(m)	SecLow L(m)	Lw (m)	Flow1 (mL/h)	Borehole Head1 (masl)	Flow2 (mL/h)	Borehole Head2 (masl)	Flow3 (mL/h)	Borehole Head3 (masl)
KFM02A	521.10	526.10	5	–	4.77	–	4.72	–	4.13
KFM02A	516.10	521.10	5	–	4.69	–	4.68	–	4.11
KFM02A	511.09	516.09	5	2,770	4.61	–9,620	4.62	–23,100	4.09
KFM02A	506.09	511.09	5	–	4.62	–101	4.53	–294	4.02
KFM02A	501.09	506.09	5	–	4.56	–	4.52	–	3.92
KFM02A	496.09	501.09	5	475	4.46	–686	4.44	–346	3.90
KFM02A	491.09	496.09	5	–	4.42	–	4.37	–68	3.83
KFM02A	486.10	491.10	5	–	4.37	–	4.33	–	3.75
KFM02A	481.09	486.09	5	623	4.35	–1,910	4.29	–2,230	3.72
KFM02A	476.09	481.09	5	442	4.27	–1,570	4.21	–3,110	3.67
KFM02A	471.08	476.08	5	–	4.19	–	4.12	–	3.58
KFM02A	466.08	471.08	5	–	4.13	–	4.10	–	3.52
KFM02A	461.07	466.07	5	–	4.05	–118	4.02	–149	3.45
KFM02A	456.07	461.07	5	–	4.02	–	3.97	–37	3.41
KFM02A	451.08	456.08	5	223	3.98	–836	3.89	–1,260	3.38
KFM02A	446.08	451.08	5	–	3.93	–153	3.84	–276	3.28
KFM02A	441.08	446.08	5	–	3.88	–	3.79	–235	3.22
KFM02A	436.08	441.08	5	220	3.83	–944	3.74	–1,500	3.18
KFM02A	431.09	436.09	5	–	3.75	–	3.71	–61	3.16
KFM02A	426.09	431.09	5	2,100	3.73	–7,660	3.64	–12,700	3.10
KFM02A	421.10	426.10	5	426	3.69	–1,660	3.59	–1,780	3.04
KFM02A	416.10	421.10	5	695	3.61	–3,270	3.50	–6,800	2.98
KFM02A	411.09	416.09	5	–	3.59	–266	3.43	–98	2.91
KFM02A	406.08	411.08	5	–	3.53	–	3.39	–	2.85

Borehole ID	SecUp L(m)	SecLow L(m)	Lw (m)	Flow1 (mL/h)	Borehole Head1 (masl)	Flow2 (mL/h)	Borehole Head2 (masl)	Flow3 (mL/h)	Borehole Head3 (masl)
KFM02A	401.07	406.07	5	–	3.43	–	3.36	–	2.82
KFM02A	305.93	310.93	5	–	2.46	–	2.38	–	1.94
KFM02A	300.92	305.92	5	52	2.40	–	2.34	–85	1.89
KFM02A	295.92	300.92	5	–	2.37	–67	2.27	–687	1.84
KFM02A	290.91	295.91	5	182	2.26	–386	2.22	–1,650	1.80
KFM02A	285.90	290.90	5	502	2.22	–1,360	2.19	–4,690	1.76
KFM02A	280.90	285.90	5	277	2.18	–1,350	2.09	–3,710	1.68
KFM02A	275.89	280.89	5	231	2.14	–204	2.06	–1,120	1.63
KFM02A	270.88	275.88	5	202	2.10	–29	2.01	–1,080	1.61
KFM02A	265.88	270.88	5	207	2.05	122	1.96	–118	1.58
KFM02A	260.88	265.88	5	–	1.99	–	1.89	–	1.52
KFM02A	255.88	260.88	5	–	1.94	–	1.85	–	1.48
KFM02A	250.88	255.88	5	–	1.89	–	1.80	–	1.43
KFM02A	245.87	250.87	5	–	1.85	–	1.75	–	1.39
KFM02A	240.88	245.88	5	–	1.81	–	1.67	–	1.35
KFM02A	235.86	240.86	5	–	1.76	–	1.64	–	1.31
KFM02A	230.84	235.84	5	–	1.76	–	1.60	–	1.31
KFM02A	225.83	230.83	5	–	1.72	–	1.57	53	1.31
KFM02A	220.81	225.81	5	–	1.64	–	1.48	–	1.20
KFM02A	215.80	220.80	5	–216	1.62	243	1.46	982	1.21
KFM02A	210.79	215.79	5	–	1.59	–	1.41	–	1.18
KFM02A	205.79	210.79	5	–	1.55	–	1.38	–	1.16
KFM02A	200.78	205.78	5	–	1.47	–	1.35	–	1.13
KFM02A	195.78	200.78	5	–	1.42	–	1.32	–	1.11
KFM02A	190.77	195.77	5	–	1.35	–	1.25	–	1.06
KFM02A	185.76	190.76	5	–	1.34	–	1.23	–	1.04
KFM02A	180.76	185.76	5	19	1.32	167	1.17	259	0.98
KFM02A	175.75	180.75	5	–	1.30	58	1.11	64	0.95
KFM02A	170.75	175.75	5	311	1.24	1,090	1.06	1,580	0.95
KFM02A	165.74	170.74	5	55	1.17	331	1.03	549	0.92
KFM02A	160.74	165.74	5	1,410	1.15	3,780	1.03	5,410	0.91
KFM02A	155.74	160.74	5	–	1.13	47	1.01	63	0.87
KFM02A	150.73	155.73	5	–	1.10	–	0.94	–	0.83
KFM02A	145.73	150.73	5	–	1.04	–	0.91	–	0.81
KFM02A	140.72	145.72	5	–	0.95	–	0.85	–	0.75
KFM02A	135.71	140.71	5	–	0.93	–	0.84	–	0.75
KFM02A	130.71	135.71	5	–	0.91	–	0.83	–	0.71
KFM02A	125.71	130.71	5	–	0.89	–	0.79	–	0.67
KFM02A	120.70	125.70	5	–6,040	0.82	*	0.72	*	0.65
KFM02A	115.70	120.70	5	–11,900	0.77	*	0.71	*	0.64
KFM02A	110.69	115.69	5	–17,200	0.76	*	0.72	*	0.66
KFM02A	105.68	110.68	5	–8,160	0.77	*	0.71	*	0.62
KFM02A	100.67	105.67	5	–	0.73	–	0.62	–	0.52

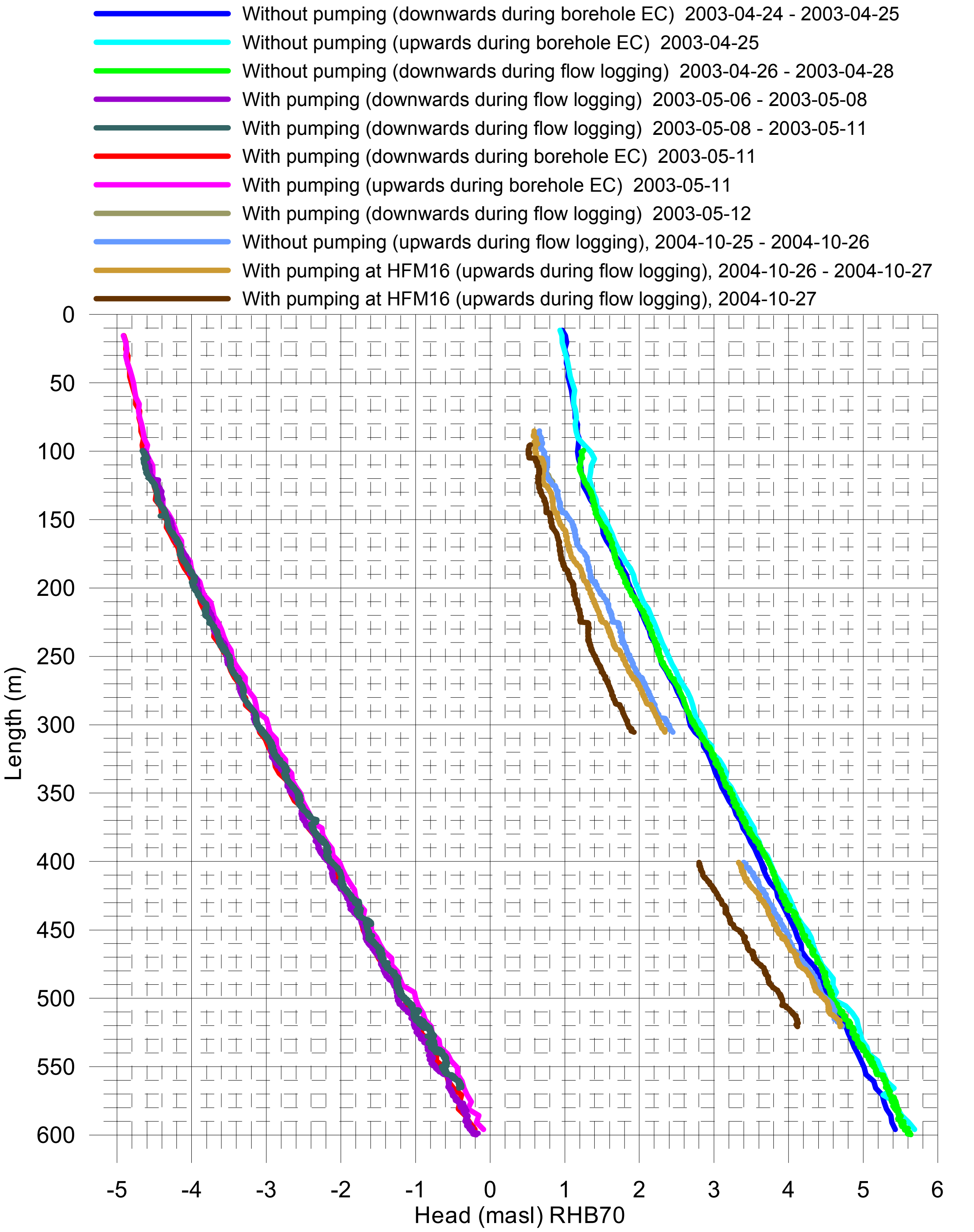
* Flow direction could not be identified

Forsmark, borehole KFM02A
Flow rates of 5 m sections

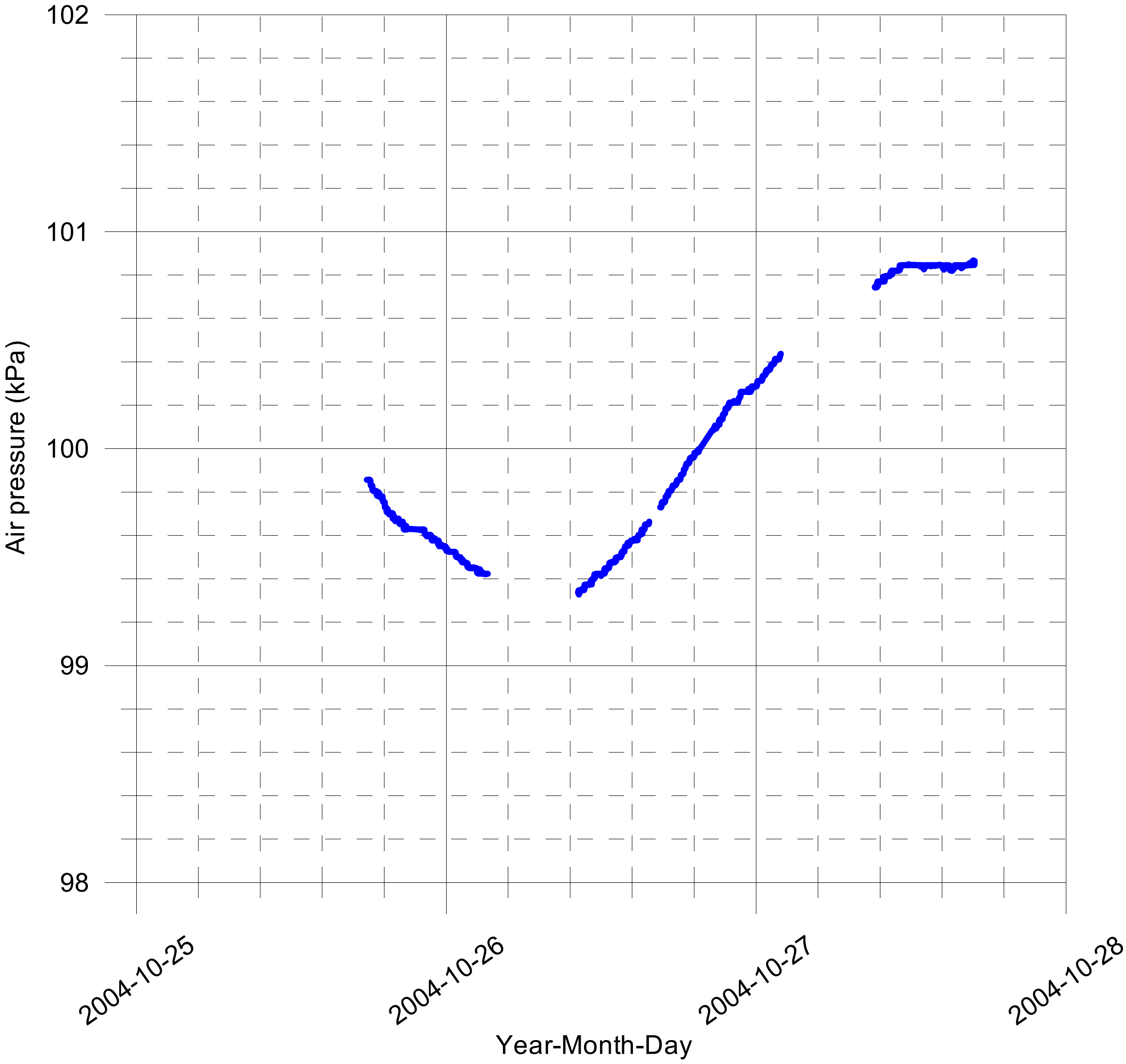


Forsmark, borehole KFM02A
Head in the borehole during flow logging

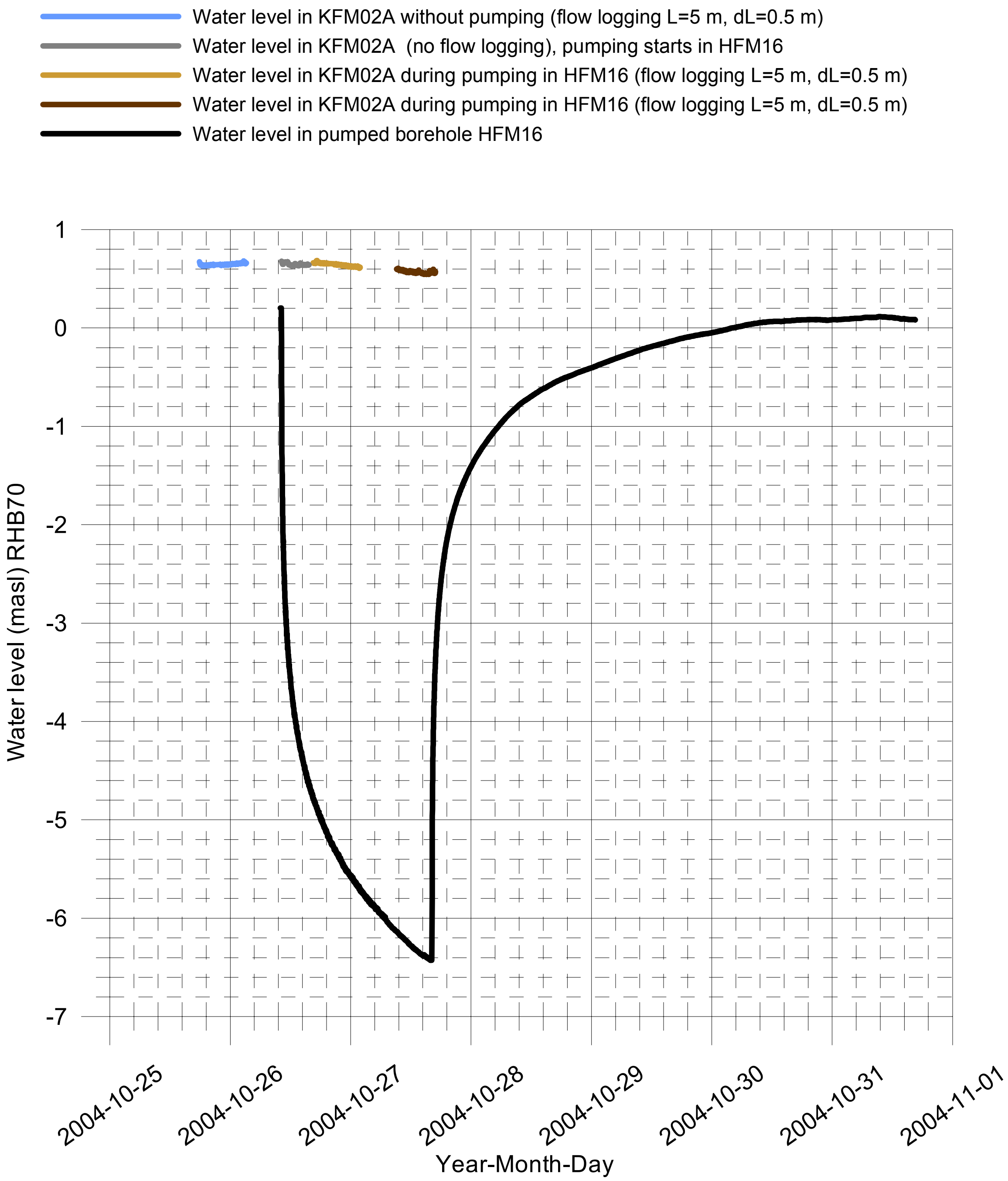
Head(masl)= (Absolute pressure (Pa) - Airpressure (Pa) + Offset) /(1000 kg/m^3 * 9.80065 m/s^2) + Elevation (m)
Offset = 13500 Pa (2460 Pa for the new measurements) (Correction for absolut pressure sensor)



Forsmark, borehole KFM02A
Air pressure during flow logging



Forsmark
boreholes KFM02A and HFM16
Water level in the borehole during flow logging



Forsmark, borehole KFM02A
Flow rates and directions of length interval 105 m - 125 m