P-04-191

Forsmark site investigation

Difference flow logging in borehole KFM05A

Jari Pöllänen, Mikael Sokolnicki, Pekka Rouhiainen
PRG Tec-Oy

September 2004

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

ISSN 1651-4416
SKB P-04-191

Forsmark site investigation

Difference flow logging in borehole KFM05A

Jari Pöllänen, Mikael Sokolnicki, Pekka Rouhiainen
PRG Tec-Oy

September 2004

Keywords: Forsmark, Hydrogeology, Hydraulic tests, Difference flow measurements, AP PF 400-04-29, Field note no Forsmark 311.

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 KFM05A at Forsmark, Sweden, in May and June 2004, using Posiva flow log. The primary aim of the measurements was to determine the position and flow rate of flow yielding fractures in borehole, prior to groundwater sampling.

The flow rate into or out of a 5 m long test section was measured between 110.40–993.94 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 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. The EC-measurements were used to study the occurrence of saline water in the borehole during natural as well as pumped conditions. Finally, EC of the fracture-specific water was measured for a selection of fractures.

Sammanfattning

Differensflödesloggning är en snabb metod för bestämning av transmissivitet och hydraulisk tryckhöjd i borrhålssektioner och sprickor/sprickzoner i kärnborrhål. Denna rapport presenterar huvudprinciperna för metoden och resultat av mätningar utförda i borrhål KFM05A i Forsmark, Sverige, i maj och juni 2004 med Posiva flödesloggningsmetod. Det primära syftet med mätningarna var att bestämma läget och flödet i vattenförande sprickor i borrhål KFM05A före grundvattenprovtagning.

Flödet till eller från en 5 m lång testsektion mättes mellan 110.40–993.94 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 längdmärkerna som frästs in i borrhålsväggen vid noggrant bestämda positioner längs borrhålet. Längdmärkena detekterades med caliper- och punktresistansmätningar med hjälp av sensorer anslutna på flödesloggningssonden.

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

Elektrisk konduktivitet och temperatur på borrhålsvattnet mättes också. EC-mätningarna användes för att studera förekomsten av saltvatten i borrhålet under såväl naturliga som pumpade förhållanden. Slutligen mättes EC på vattnet från ett antal utvalda sprickor.

Contents

1 Introduction

The difference flow logging in the core drilled borehole KFM05A at Forsmark was conducted between May 11–June 2, 2004. KFM05A is the fifth core drilled borehole in the Forsmark candidate area. The borehole is inclined c 60° from the horizontal direction, c 1,000 m long and performed with a telescopic drilling technique. The interval 0–c 100 m is percussion drilled and cased with the inner diameter 200 mm. Section c 100–110 m is reamed to 86 mm and cased with a perforated casing with the inner diameter 77 mm. The interval, c 110–1,000 m, is core drilled with the diameter c 77 mm. The location of borehole KFM05A within the Forsmark area is shown in Figure 1-1.

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 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 KFM05A. The activity is performed within the Forsmak site investigation. The work was carried out in compliance with the SKB internal controlling document AP PF 400-04-29. Data and results were delivered to the SKB site characterization database SICADA with Field note number Forsmark 311.

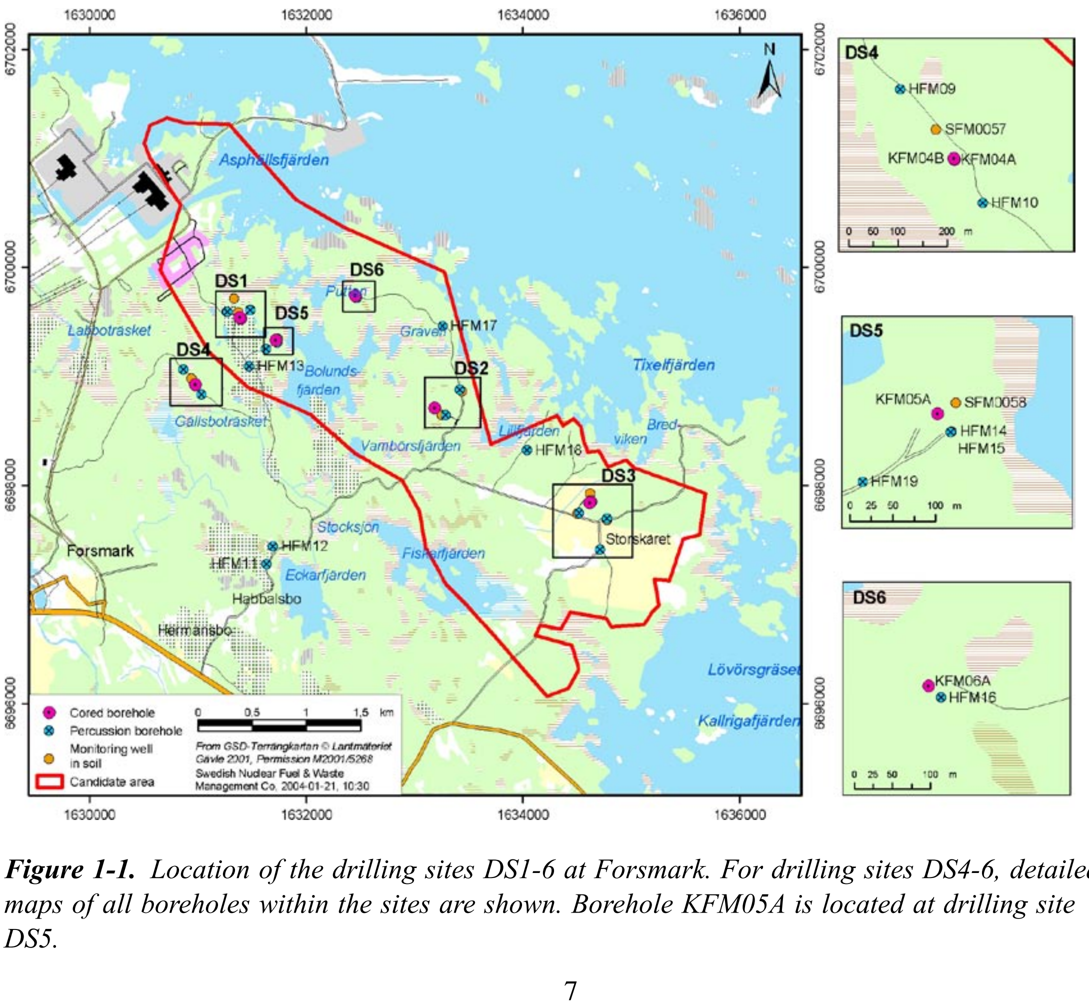


Figure 1-1. Location of the drilling sites DS1-6 at Forsmark. For drilling sites DS4-6, detailed maps of all boreholes within the sites are shown. Borehole KFM05A is located at drilling site DS5.

2 Objective and scope

The main objective of the difference flow logging in KFM05A 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 absolute pressure sensor was used to measure the total pressure along the borehole. These measurements were carried out together 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 length 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 passes 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 applied because it is faster than the thermal pulse method.

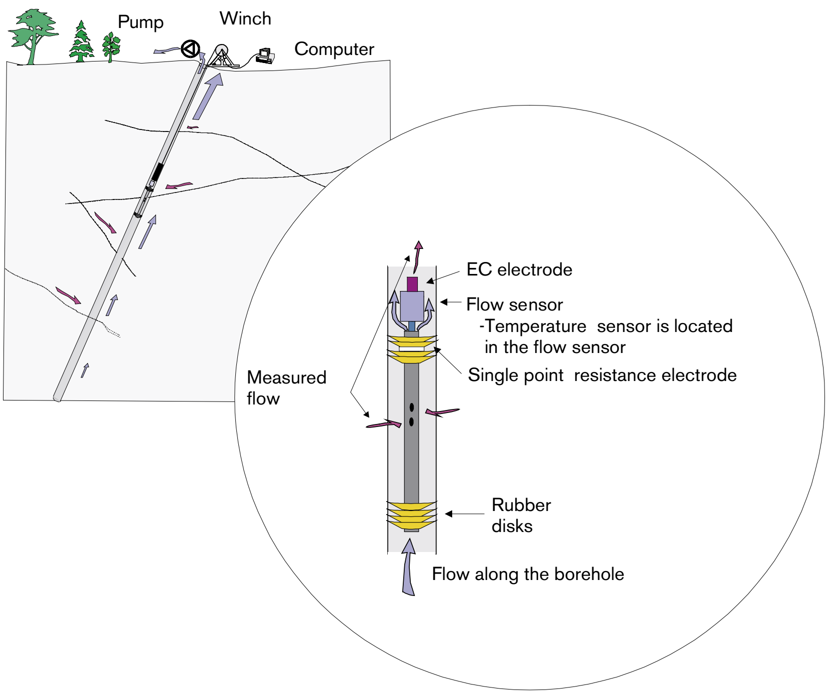


***Figure 3-1.** Schematic presentation of the downhole equipment used in the Difference flowmeter.*

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 the top of the flow sensor, Figure 3-1.
- The single point resistance (SPR) of the borehole wall (grounding resistance), The electrode of the Single point resistance tool is located in between the uppermost rubber disks, see Figure 3-1. This method is used for high resolution depth/length determination of fractures and geological structures.
- The diameter of the borehole (caliper). The caliper tool, combined with SPR, is used for 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 in the flow sensor, Figure 3-1.

All of the above measurements were performed in KFM05A.

The principles of difference flow measurements are described in Figures 3-3 and 3-4. The flow sensor consists of three thermistors, see Figure 3-3a. The central thermistor, A, is used both as a heating element and for the 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.

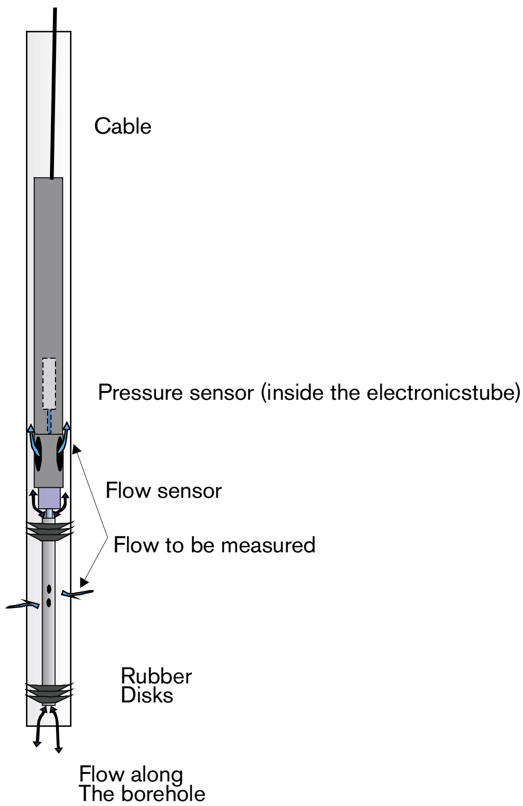


***Figure 3-2.** The absolute pressure sensor is located inside the electronics tube and connected via another tube to the borehole water.*

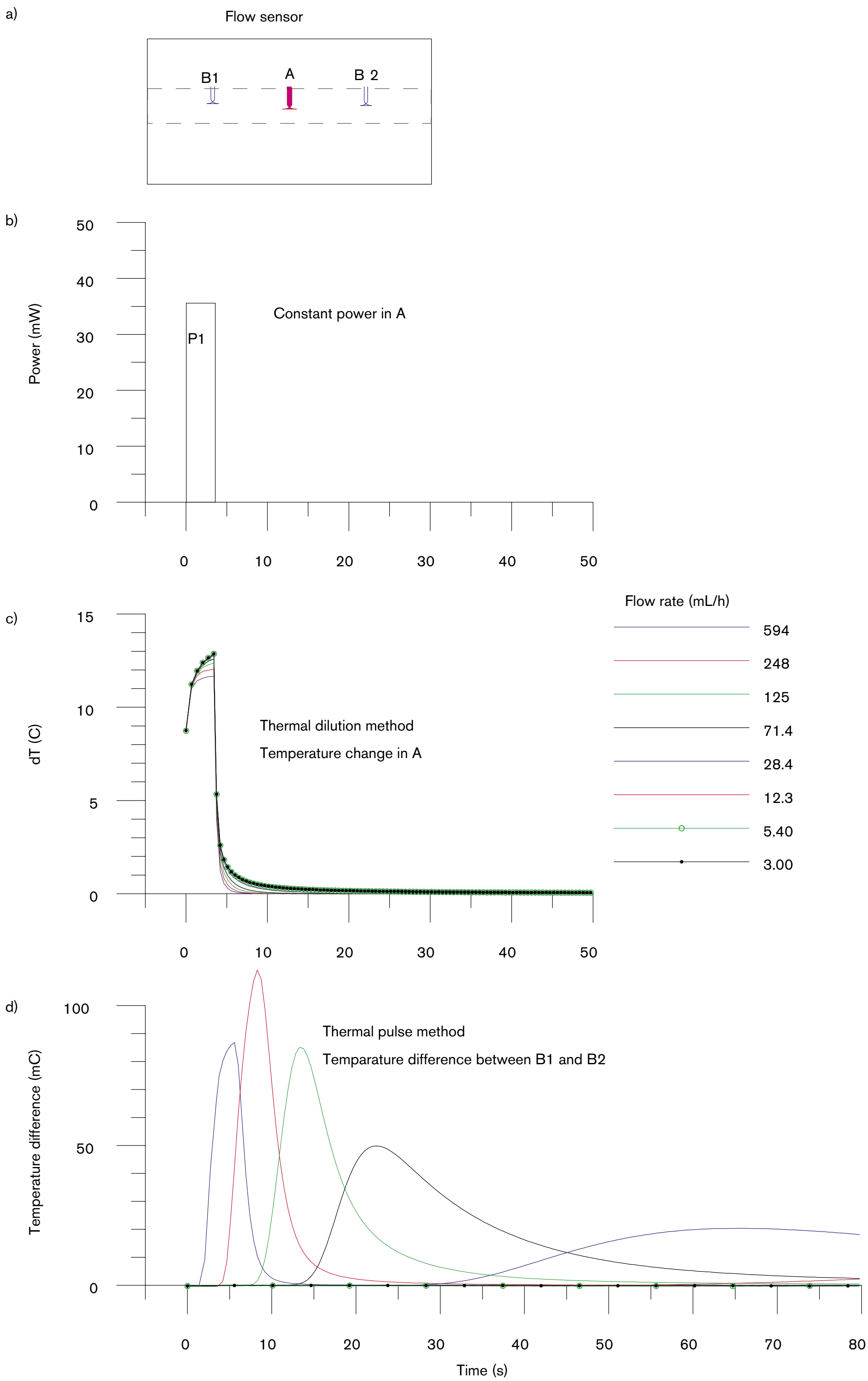


Figure 3-3. *Flow measurement, flow rate < 600 mL/h.*

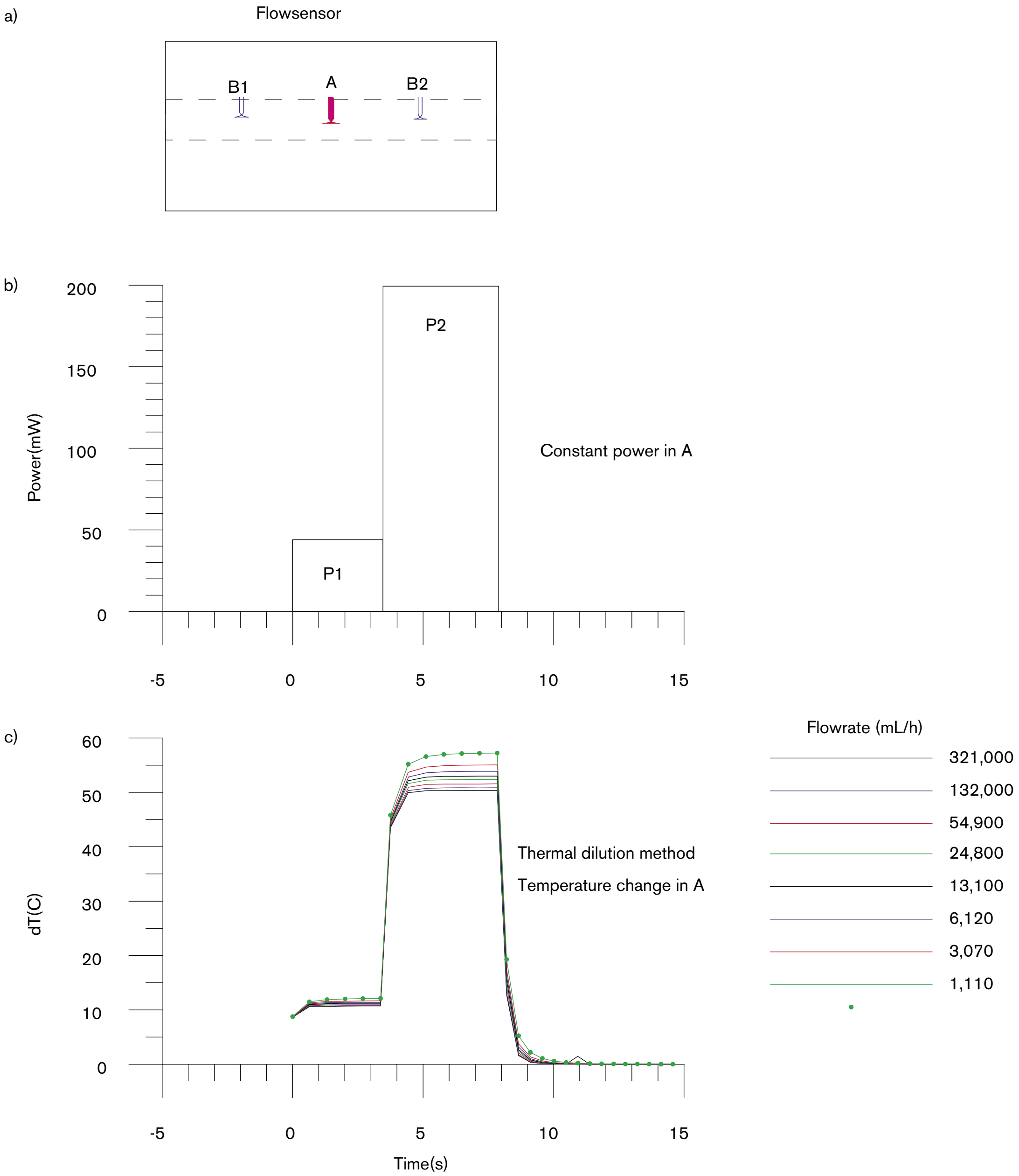


Figure 3-4. *Flow measurement, flow rate > 600 mL/h.*

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.

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

The lower end limits of the thermal dilution and the thermal pulse methods in Table 3-1 are corresponding to the theoretical lowest measurable values. Depending on the borehole conditions, these limits may not always prevail. Examples of disturbing conditions are floating drilling debris 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.

3.2 Interpretation

The interpretation is based on Thiems or Dupuits 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:

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

$$Q_{s2} = T_s \cdot a \cdot (h_s - h_2) \qquad 3\text{-}4$$

where

h_1 and h_2 are the hydraulic heads in the borehole at the test level,

Q_{s1} and Q_{s2} 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:

$h_s = (h_1 - b \cdot h_2)/(1 - b)$ 3-5

$T_s = (1/a)\ (Q_{s1} - Q_{s2})/(h_2 - h_1)$ 3-6

where

$b = Q_{s1}/Q_{s2}$

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).

$h_f = (h_1 - b\ h_2)/(1 - b)$ 3-7

$T_f = (1/a)\ (Q_{f1} - Q_{f2})/(h_2 - h_1)$ 3-8

where

Q_{f1} and Q_{f2} 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 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 c 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 2000.
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 according to Activity Plan AP PF 400-04-29 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 document. 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 KFM05A, 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 flowmeter system uses caliper measurements in combination with single point resistance measurements (SPR) for this purpose, and these measurements were the first to be performed in borehole KFM05A (Item 7 in Table 5-1). These methods also reveal parts of the borehole widened for other reasons (fracture zones, breakouts etc).

The overlapping flow logging (Item 8) was carried out in the borehole interval 100–997 m. The section length was 5 m, and the length increment (step length) 5 m. The measurements were performed during natural (un-pumped) conditions. If the flow rate is below 100 mL/h flow direction cannot be determined using the overlapping flow logging. These length intervals were re-measured using thermal pulse for determination of flow direction.

Pumping was started on May 26. After 26 hours waiting time, the overlapping flow logging (Item 9) was measured in the same interval 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). After that fracture specific EC was measured on water from some selected fractures (Item 11).

Still during pumped conditions, EC of the borehole water (Item 11 extra) was measured. After this, the pump was stopped and the recovery of the groundwater level was monitored (Item 12).

The length interval 106–114 m was re-measured using four different smaller drawdowns, since the flow rate exceeded the measurement limit in this interval. A section length of 1 m and a step length of 0.1 m were used here. (Item 9 extra).

There is a break in measurements between May 12 and 24 because the borehole had to be open for another purpose.

Table 5-1. Flow logging and testing in KFM05A. Activity schedule.

Item	Activity	Explanation	Date
1	Measurements of EC on selected water samples	Some selected water samples were measured in laboratory	2004-05-11
7	Length calibration of the downhole tool	Dummy logging (SKB Caliper and SPR). Logging without the lower rubber discs, no pumping	2004-05-11 2004-05-12
8	Overlapping flow logging	Section length Lw=5 m, Step length dL=0.5 m	2004-05-24 2004-05-26
9	Overlapping flow logging	Section length Lw=5 m. Step length dL=0.5 m at pumping (includes 1 day waiting after beginning of pumping)	2004-05-26 2004-05-29
10	Overlapping flow logging	Section length Lw=1 m. Step length dL=0.1 m, at pumping (only in conductive borehole intervals)	2004-05-29 2004-05-30
11	Fracture-specific EC-measurements in pre-selected fractures	Section length Lw=1 m at pumping (in pre-selected fractures)	2004-05-30 2004-05-31
11 extra	EC-, temp- and Pabs logging of the borehole fluid	Logging without the lower rubber discs, at pumping	2004-05-31
12	Recovery transient	Measurement of water level and absolute pressure in the borehole after stop of pumping	2004-05-31 2004-06-01
9 extra	Combined and overlapping flow logging at different pumpings	Section length Lw=1 m. Step length dL=0.1 m, at four different pumping rates (1.6 L/min, 4.2 L/min, 5.8 L/min, 9.8 L/min)	2004-06-01
11	Continued fracture-specific EC-measurements in pre-selected fractures	Pumping with flow rate 155 L/min	2004-06-01 2004-06-02
12	Demobilisation from the site	Uninstallation of the tool. Packing the trailer. Delivering Daily logs, logging reports and raw data files for SKB	2004-06-02

6 Results

6.1 Length calibration

6.1.1 Caliper and SPR measurements

An 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 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 KFM05A 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. Such marks are milled into the borehole wall at every 50 m in KFM05A (with a few exeptions). 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 7) were initially length corrected in relation to the known length marks, Appendix 1.35 black curve. Corrections between the length marks were obtained for each length mark by linear interpolation.
- The SPR curve of Item 7 was then compared with the SPR curves of Items 8, 9, 10 and 11 to obtain relative length errors of these measurement sequences.
- All SPR curves could then be synchronized, as can be seen in Appendices 1.2–1.34.

The results of the caliper and single point resistance measurements from all measurements in the entire borehole are presented in Appendix 1.1. Ten SPR-curves are plotted together with caliper-data. These measurements correspond to Items 7, 8, 9, 10, and 11 in Table 5-1.

The caliper tool shows low voltages when the borehole diameter is below 77 mm and high voltage when the borehole diameter is above 77 mm.

Zoomed results of caliper and SPR are presented in Appendices 1.2–1.34. The length marks were detected at 120 m, 152 m, 199 m, 252 m, 300 m, 402 m (only the upper one), 606 m, 650 m (only lower one), 800 m (only the upper one) and at 850 m. The length marks were not detected at 352 m, 450 m, 501 m, 550 m, 700 m, 750 m and at 900 m with the caliper tool. In these spots SPR-anomalies were used to make the length correction as accurate as possible. The length corrections were done at 120 m, 152 m, 199 m, 252 m, 300 m, 352 m, 402 m, 450 m, 501 m, 550 m, 606 m, 650 m, 700 m, 800 m and at 850 m. These spots can be seen in the SPR results. However, the 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 aim of the plots in Appendices 1.2–1.34 is to verify the accuracy of the length correction. The curves in these plots represent length corrected results. The same length corrections was applied to the flow- and EC measurements.

The magnitude of length correction along the borehole is presented in Appendix 1.35. 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).

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 can only be seen with a short step length (0.1 m). This 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 7).
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 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.

The length calibration of the borehole EC measurements is not as accurate as of the other measurements, because SPR is not registered during the borehole EC measurements. The length correction of the caliper measurement was applied to the borehole EC measurements, black curve in Appendix 1.35.

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 measured during pumping (after a pumping period of about five days). The measurements were performed in both directions, downwards and upwards, see Appendix 2.1.

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.

6.2.2 EC of fracture-specific water

The flow is always directed 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 identify 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 are commenced 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 borehole length allowing the fracture-specific water to enter the section. The desired 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 exchange 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, waiting times were selected to be much longer than calculated times.

Electric conductivity of fracture-specific water is presented on a time scale, see Appendices 10.1–10.3. 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. The same fracture specific EC measurements are also presented on a zoomed time scale, see Appendices 10.4–10.7.

Borehole lengths at the upper and lower ends of the section, fracture locations as well as the final EC values are listed in Table 6-1.

Table 6-1. Fracture-specific EC.

Upper end of section (m)	Lower end of section (m)	Fractures measured (m)	EC (S/m) at 25°C
108.4	109.4	108.9	1.41
108.7	109.7	108.9	1.26
116.2	117.2	116.5	1.56
123.8	124.8	124.1, 124.4	1.54
175	176	175.6	1.44
264	265	264.4	1.41

6.3 Pressure measurements

The absolute pressure was registered together with the other measurements in Items 8–12 in Table 5-1. The pressure sensor measures the sum of hydrostatic pressure in the borehole and the air pressure. Air pressure was also registered separately, Appendix 9.4. 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 /SKB, 2002/:

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

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 reference point for the measurements (top of casing) (masl) according to the RHB 70 reference system.

An offset of 2.46 kPa is subtracted from all absolute pressure results.

The calculated head results are presented in Appendix 4. Exact z-coordinates are important in the 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 are presented on the same plots as the single point resistance (right hand side) and caliper plot (in the middle), see Appendices 3.1–3.45. Single point resistance usually shows a low resistance value on a fracture where flow is detected. There are also 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 low voltages when the borehole diameter is below 77 mm and high voltages when the borehole diameter exceeds 77 mm.

The flow logging was firstly performed with a 5 m section length and with 0.5 m length increments, see Appendices 3.1–3.45 (red curve with pumping, 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 initially 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. The overlapping flow logging was therefore repeated in the vicinity of identified flow anomalies using a 1 m long test section and 0.1 m length increments.

The upper part of the borehole (106–114 m) was re-measured using four smaller draw-downs. These measurements are discussed in detail in Chapters 6.4.5 and 6.4.6. Pumping rates, heads and flow rates are presented in Appendices 11.1–11.5.

Detected fractures are shown on the caliper scale together 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, if the flow anomalies are overlapping, or if they are unclear because of noise.

6.4.2 Transmissivity and hydraulic head of borehole sections

The entire borehole between 100 m and 997 m was flow logged with a 5 m section length and with 0.5 m length increments. The major part of the flow logging results presented in this report is derived from measurements with the thermal dilution method. However, some length intervals (if the flow rate was below 100 ml/h) were re-measured when the borehole was at rest using the thermal pulse method for determination of flow direction.

The results of the measurements with a 5 m section length are presented in tables, see Appendices 5.1–6.2. Only the results with a 5 m length increments are used. Secup1 and Secup2 presented in Appendices 5.1–5.6 are calculated as the distance along the borehole from the reference level (top of the casing tube) to the upper end of the test section. Secup1 refers to the measurements at natural, i.e. un-pumped conditions, and Secup2 to measurements during pumping. They are not identical, due to a minor difference of the cable stretching between the two sequences. The same flow rates as in Appendix 5 are also plotted in Appendices 3.1–3.45.

Pressure was measured and calculated as described in Chapter 6.3. Borehole Head1 and Borehole Head2 in Appendices 5.1–5.6 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 presented in Appendices 5.1–5.6 (Flow1 and Flow2), 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 is directed from the bedrock into the borehole and vice versa. With the borehole at rest, 7 sections were detected as flow yielding, of which 3 had a flow direction from the borehole into the bedrock (negative flow). During pumping, all 14 detected flows were directed towards the borehole.

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

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 to consider, see Chapter 6.4.4.

Hydraulic head and transmissivity (T_s) 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 (Borehole Head1 and Borehole Head2 in Appendix 5).

The measurable flow range was exceeded at the length of 106.39 m when the borehole was pumped. The results at this depth (last row in Appendix 5.6) are taken from the measurements of the entire borehole, see Chapter 6.4.5, last rows in Tables 6-2 and 6-3.

The sum of detected flows without pumping (Flow1) was –8,218 mL/h. This sum should normally be zero if all the flows in the borehole are correctly measured and 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. One possible reason is the very high transmissivity of the borehole. Minor changes of drawdown can produce high changes of flow rates at the most transmissive locations, see Chapter 6.4.6 and Appendix 11.

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 illustrated for instance in Appendix 3.1. Increase or decrease of the flow anomaly at the fracture location (marked with the lines in Appendix 3) is used for determination of flow rate (filled triangles in Appendix 3).

Since sections with 1 m length were not used at un-pumped conditions, the results for a 5 m section length were used 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. Increase or decrease of the flow anomaly at the fracture location determines the flow rate. The measurement for a 5 m section length at un-pumped conditions are used for the corresponding fracture flow rates. The flow direction is evaluated as well. The results of evaluation are plotted in Appendix 3, blue filled triangle.

The total amount of detected flowing fractures is 27, but only 7 were seen without pumping. These 7 fractures could be used for head estimations and all 27 were used for transmissivity estimations, Appendix 7.1. Transmissivity and hydraulic head of fractures are plotted in Appendix 7.2.

Some fracture-specific results were rated to be "uncertain" results, see Appendix 7.1. 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 them was less than one metre.

The upper part of the borehole (106 m–114 m) was re-measured using four smaller draw-downs. The flow rate was near or above the measurement limit in this interval. The used pumping rates are presented in Appendix 11.1 and the corresponding flow rates in Appendix 11.5. Four different pumping rates were used to check the consistency of the measurement.

The different pumping rates caused only small changes in water level (Appendix 11.3) and in hydraulic head in the borehole (Appendix 11.2). These curves in Appendix 11.2 are measured with the absolute pressure sensor located in the electronics tube of the flowmeter tool. The head in the borehole is measured just above the section. The curve shows a deviation downwards when the section is placed on the high flow structure at about 108.9 m. This anomaly is larger during higher pumping rates. The same phenomenon can be seen in the water level measurements (measured with the superficial pressure sensor), see Appendix 11.3.

The same borehole head curves as in Appendix 11.2 are presented as a function of length using the same colour coding as before (Appendix 11.4). This plot shows the anomalies when the tool enters on the transmissive structure. Since the actual pressure in the borehole at this structure during the corresponding flow measurement could not be determined, transmissivity could not be directly calculated. This situation is discussed in Chapters 6.4.5 and 6.3.6. The transmissivity values at this location (108.9 m) in Appendix 7.1 and 7.2 are taken from analysis of the entire borehole, Tables 6-2 and 6-3, pumping rates 1 and 4.

Fractures at 110.1 m, 111.6 m and 112.6 m were interpreted in six ways using different pairs, see Appendix 11.4. The used head differences were small and the combination with the smallest and highest pumping rates (Pumping rates 1 and 4) is considered to be the most reliable one.

Transmissivity and head of the original measurement (Appendix 7) is plotted for comparison. The deviation in head was large, probably because the groundwater level had not fully recovered after pumping during the extra measurements, see Appendix 9.2.

Fracture-specific transmissivities were compared with transmissivities of borehole sections in Appendix 8. 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.

6.4.4 Theoretical and practical measurement limits of flow rate and transmissivity

The theoretical minimum of measurable flow rate in the overlapping results (thermal dilution method only) is about 30 mL/h.

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

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

1) Rough borehole wall.
2) Solid particles in the borehole water, such as clay or drilling debris.
3) Gas bubbles in water.
4) High flow rate along the borehole.

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

Drilling debris usually increases the noise level. Typically this kind of noise is seen both without pumping and with pumping.

Pumping causes a pressure drop in the borehole water column as well as in water filled fractures near the borehole. This may lead to release of gas from dissolved form to gas bubbles. Some fractures may produce more gas than other. 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 a 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 highly water yielding fractures. Any minor leak at the lower rubber disks is directly measured as an 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. The real flows are registered correctly if they are about ten times larger than the noise. By experience, real flows between 1/10 times the noise and 10 times the noise are summed up with 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 every case.

The noise level was not a serious problem in most parts of borehole KFM05A. The practical minimum level of flow rate is evaluated and presented in Appendices 3.1–3.45 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 KFM05A was 30 mL/h, except at about 720 m and in the bottom of the borehole. Mostly it even 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 many cases there are flow anomalies smaller than 30 mL/h. These fractures are marked with a short line indicating "uncertain".

In some boreholes the upper limit of flow measurement (300,000 mL/h) may be exceeded. Such fractures or structures hardly remain undetected (as the fractures below the lower limit). Highly water yielding fractures can be measured separately at a smaller drawdown. A structure at 108.9 m could not reliably be measured though smaller drawdowns were applied.

The practical minimum of measurable flow rate is also presented in Appendix 5 (Q-lower limit Practical). 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. The theoretical minimum measurable transmissivity can also be evaluated using a Q value of 6 mL/h (minimum theoretical flow rate with the thermal pulse method) instead of Q-lower limit Practical.

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_s-Upper Limit).

All three flow limits are also plotted with the measured flow rates, see Appendix 6.1. Theoretical minimum and maximum values are 6 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, Appendices 7.1 and 7.2. Approximately the same limits would be valid also for these results. The limits for fracture-specific results are however, more difficult to define exactly. For instance, it may be difficult to identify 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 be below 300,000 mL/h.

6.4.5 Estimation of transmissivity of the entire borehole

It's possible to calculate the transmissivity of the entire borehole using pumping rates and corresponding drawdowns or hydraulic heads in the borehole. The pumping rates (Q_1–Q_4) in Table 6-2 are taken from the additional measurements with smaller pumping rate, see Appendix 11.1. The corresponding hydraulic heads are taken from the absolute pressure measurements just below the high-flowing fracture at 108.9 m where the friction caused by the flowmeter is negligible, see Appendices 11.2 and 11.4.

Also the pumping rates and heads of the original measurements (natural state and large drawdown) are presented in Table 6-2. The borehole head values from the additional measurements are taken from the same location, i.e. just below the high-flowing fracture at 108.9 m, see Appendix 11.4. The head values from the ordinary difference flow logging ($h_{natural}$ and h_{pumped}) are derived from Appendix 5.6.

The transmissivity of the entire borehole can be calculated from equation 3-6:

$$T_s = (1/a) * (Q_{s1} – Q_{s2}) / (h_2 – h_1)$$

and the hydraulic head from equation 3-5:

$$h_s = (h_1 – b * h_2) / (1 – b)$$

The results in Table 6-3 are obtained by using the equation 3-6 and 3-5 with different combinations of the measurement pairs in Table 6-2.

The transmissivity of the entire borehole is approximately 1.2E–03 m^2/s. This is the average of the T-values in Table 6.3 obtained from smaller pumpings. The transmissivity can also be calculated from the pumping during the ordinary difference flow logging (T = 4.0E–04 m^2/s, see Table 6-3). The difference between these two outcomes may be explained by turbulence, which leads to increasing flow friction with increasing pumping rate. The conditions in the borehole during the pumping with lower flow rates correspond better with the natural conditions. A drawback with the lower pumping rate is that the head difference is very small, entailing that the borehole head is uncertain.

The sum of transmissivities of all identified fractures, except the highly yielding fracture 108.9 m, is 2.05E–05 m^2/s (Appendix 7.1). The transmissivity of the entire borehole (1.2E–03 m^2/s) is significantly larger than that. Hence, it is plausible to assume that the transmissivity of the highly yielding fracture at 108.9 m is dominant. The estimate of the transmissivity of the fracture at 108.9 m is then 1.2E–03 m^2/s.

Table 6-2. Borehole heads and pumping rates.

h_n	Borehole head (m)	Q_n	Pumping rate Q_n (L/min)
h_1	0.87	Q_1	1.6
h_2	0.84	Q_2	4.2
h_3	0.82	Q_3	5.8
h_4	0.76	Q_4	9.8
$h_{natural}$	1.65	$Q_{natural}$	0
h_{pumped}	–4.60	Q_{pumped}	152

Table 6-3. Calculated hydraulic head and transmissivity of the entire borehole.

Data pair	h (masl)	T (m^2/s)
1 and 2	0.888	1.43E–03
1 and 3	0.893	1.15E–03
1 and 4	0.891	1.23E–03
2 and 3	0.919	8.79E–04
2 and 4	0.900	1.15E–03
3 and 4	0.883	1.32E–03
nat and pump	1.650	4.01E–04

6.4.6 Analysis of the measurements on the fracture at 108.9 m

The total pressure in the borehole was measured with the absolute pressure sensor above the flow sensor, see Figure 6-1. Data were used for calculation of the borehole head. Usually this measurement is sufficient to determine hydraulic head in the borehole within the test section. In normal cases it can be assumed that friction through the flow sensor is negligible. This assumption was not valid when the tool was positioned on the fracture at 108.9 m. The flow sensor itself had an effect both on the measured flow rates and pressures.

An electrical analogy models can be used for interpretation of this kind of situation. When calculating transmissivity, a certain flow geometry always has to be assumed. A cylindrical flow geometry (plate model) is assumed in this report. This, and other possible flow geometries can be converted to equivalent electrical conductance. Conductance can likewise be converted back to transmissivity using certain parameters for each geometry.

Hydraulic head h is analogous to electric voltage U and flow rate Q is analogous to electric current I:

Transmissivity T ⇔ G conductance (=1/Resistance)

Hydraulic head h ⇔ U voltage

Water flow rate Q ⇔ I electric current

The benefit of using an electrical anologue model instead of a hydraulic model is the fact that it converts the hydraulic model to the commonly known circuit theory, which is simple to analyse. The plate model and the equivalent electrical circuit are presented in Figure 6-1a and b.

The electrical model consist of the following parameters:

G1 conductance of flow sensor

G2 conductance of fracture

U1 voltage above the flow sensor

U2 constant voltage corresponding undisturbed hydraulic head far from the borehole

I electric current

An equation pair can be written according to the circuit theory:

$I_1 = (U2 – U1_1) * G$ 6-2

$I_2 = (U2 – U1_2) * G$

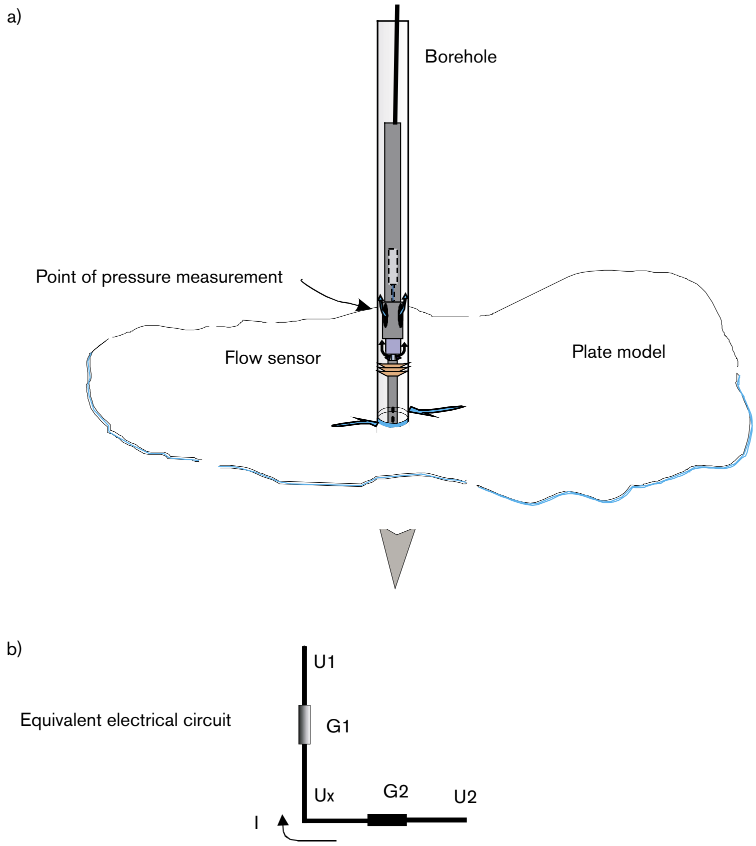


Figure 6-1. *Modelling flow parameters with an equivalent electrical model.*

Table 6-4. Heads and flow rates for conductance calculations.

$U1_n$	Head (m)	I_n	Flow In (mL/h)
$U1_1$	0.82	I_1	40,000
$U1_2$	0.70	I_2	84,000
$U1_3$	0.61	I_3	114,000
$U1_4$	0.39	I_4	174,000

where the total conductance G is:

$$G = (G1 * G2) / (G1 + G2) \qquad 6\text{-}3$$

U2 and G can be deduced from the equations 6-2:

$$U2 = (U1_2 - I_2 / I_1 * U1_1) / (1 - I_2 / I_1) \qquad 6\text{-}4$$

$$G = (I_1 - I_2) / (U1_2 - U1_1) \qquad 6\text{-}5$$

The heads ($U1_1 - U1_4$) in Table 6-4 are taken from Appendix 11.4 and the flow rates ($I_1 - I_4$) from Appendix 11.5. The value for head is the minimum value during flow logging (the measurement section of the tool is above the fracture) and the value for flow rate is the maximum value of flow. Hydraulic head was still changing during the measurement and conditions had not fully reached steady state.

The results in Table 6-5 are obtained using equations 6-4 and 6-5 and the pairs in Table 6-4.

Table 6-5. U2 and total conductance G.

pair	U2 (m)	G (m^2/s)
1 and 2	0.929	1.02E–04
1 and 3	0.934	9.79E–05
1 and 4	0.948	8.66E–05
2 and 3	0.952	9.26E–05
2 and 4	0.989	8.06E–05
3 and 4	1.028	7.58E–05

The conversion between transmissivity T and conductance G can be defined by comparing equations 3-6 and 6-5:

$T = 1/a * G = G/1.011$

The total conductance G is approximately 8.9E–05 m^2/s. This is the average of the G-values in Table 6.5. Since hydraulic head in the section (Ux in Figure 6-1) was unknown, G2 could not be solved. However, the conductance of fracture G2 has to be larger than G. The result G2 > 8.9E–05 m^2/s is in line with the results in Chapter 6.4.5. The transmissivity of the fracture at 108.9 m is thus larger than 8.9E–05 m^2/s.

When the transmissivity of fracture T_f (G2) is taken from the analysis of the previous chapter and the total conductance G from Table 6-5, the conductance of the flow sensor can be calculated. From the equation 6-3:

$G1 = (G * G2) / (G2 – G)$

When G = 8.9E–05 m^2/s and G2 = 1.2E–03 m^2/s, the conductance of the flow sensor G1 is 9.6E–05 m^2/s.

6.1 Groundwater level and pumping rate

The level of the groundwater table in the borehole during the measurement sequences is presented in Appendix 9.2. The borehole was pumped between May 26 and 31 with a drawdown of about 6.4 metres. The borehole was pumped a short time on June 1 with four different very small drawdowns. The water level of this period is presented more accurately in Appendix 11.3. The borehole was also pumped between June 1 and 2 during the measurement of fracture-specific EC. Pumping rate was also recorded, see Appendix 9.1.

The groundwater recovery was measured after the first pumping period, May 26–31, Appendix 9.3. The recovery was measured with two sensors, using the water level sensor (pressure sensor for monitoring water level) and the absolute pressure sensor located in the flowmeter tool at the borehole length of 15.75 m.

Data from the recovery period was utilized to calculate the total borehole transmissivity, see Appendix 12.

7 Summary

In this study, the Posiva Flow Log/Difference Flow method has been applied to determine the location and the flow rate of flowing fractures or structures in borehole KFM05A 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 initially used. The measurements were repeated using a1 m section length with 0.1 m length increments over the flow anomalies.

Length calibration was made using the length marks on the borehole wall. The length marks were detected by the caliper and in the 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 synchronising 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 also measured on water from selected flowing fractures.

The total amount of detected flowing fractures was 27. Transmissivity and hydraulic head were calculated for borehole sections and fractures. The highest transmissivity, detected in a fracture at the borehole length of 108.9 m, was in the range 5–10E–04 m^2/s. High-transmissive fractures were also found at 110.1 m and 111.6 m. Below 264.4 m, no flowing fractures were identified, except for two small fractures at 702.7 m and 720 m.

The results from the difference flow logging in borehole KFM05A are stored in the Sicada database under Field Note No. Forsmark 311. No printouts from the database are presented in this report.

References

Heikkonen J, Heikkinen E, Mäntynen M, 2002. Mathematical modelling of temperature adjustment algorithm for groundwater electrical conductivity on basis of synthetic water sample analysis. Helsinki, Posiva Oy. Working report 2002-10 (in Finnish).

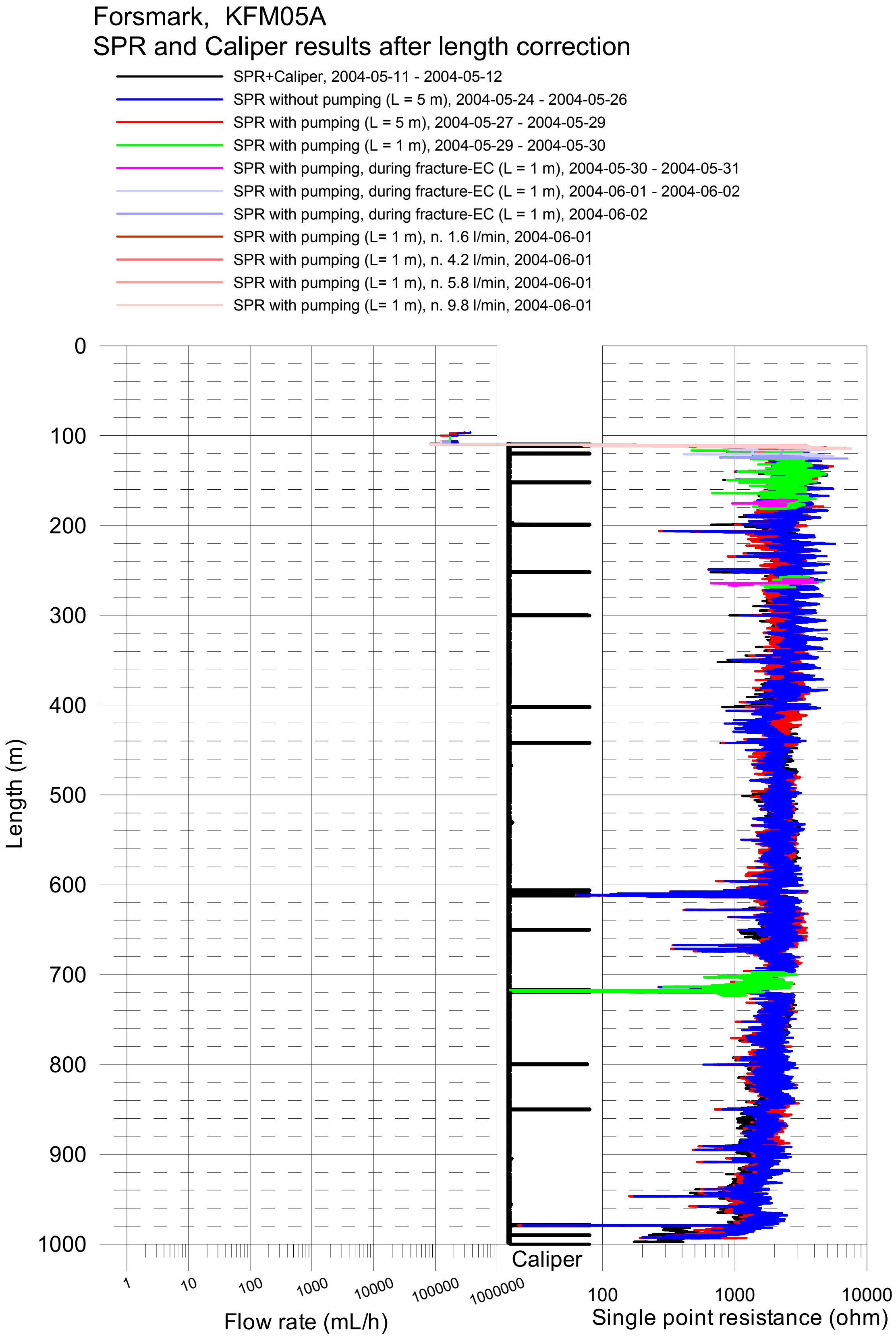
Ludvigson J-E, Hansson K, Rouhiainen P, 2002. Methodology study of Posiva difference flowmeter in borehole KLX02 at Laxemar. SKB R-01-52, Svensk Kärnbränslehantering AB.

Marsily G, 1986. Quantitive Hydrology, Groundwater Hydrology for Engineers. Academic Press, Inc, London.

SKB, 2002. Hantering av primärdata vid platsundersökningar. Rutin SDP-508, version 1.0, Svensk Kärnbränslehantering AB.

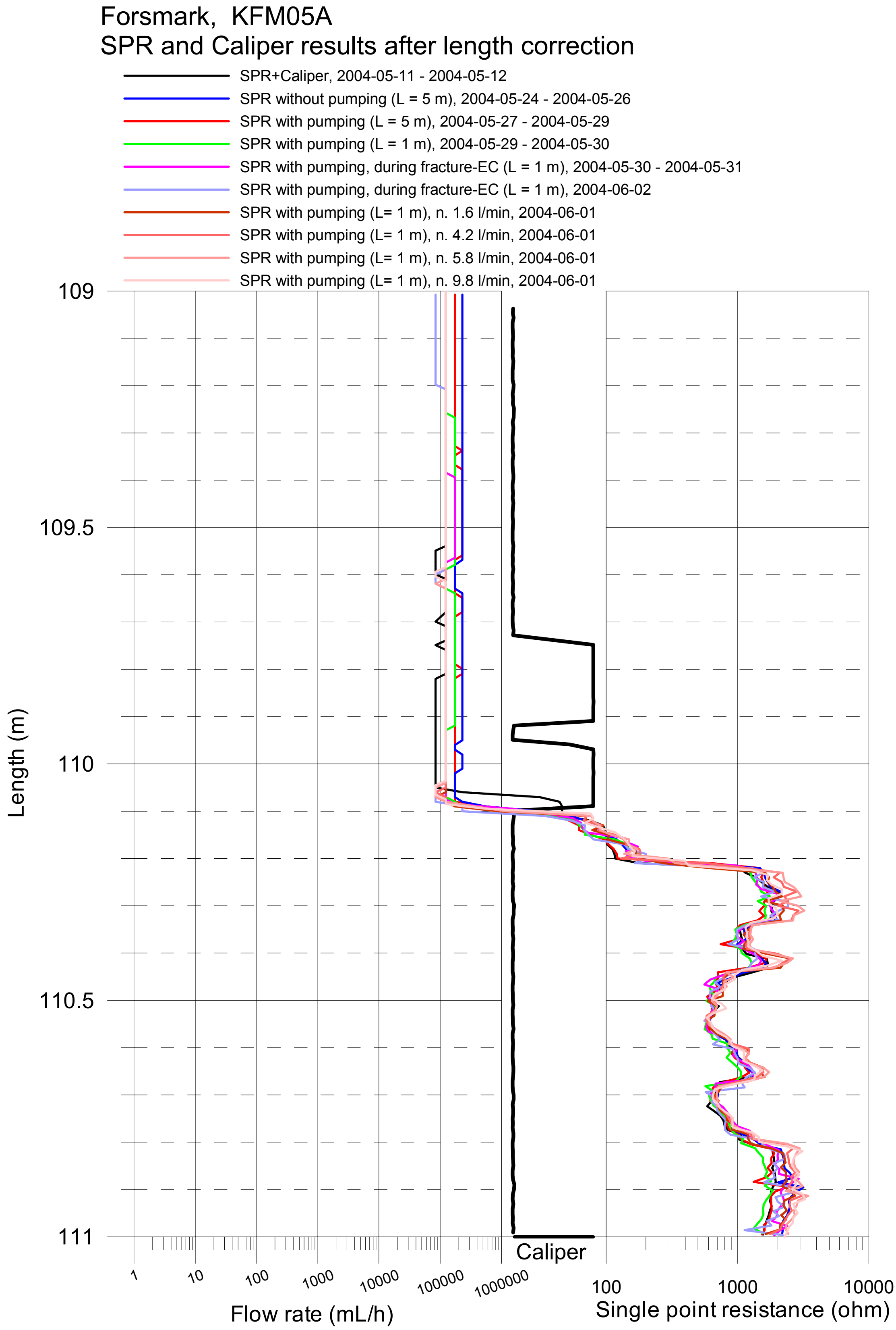
Öhberg A, Rouhiainen P, 2000. Posiva groundwater flow measuring techniques. Helsinki, Posiva Oy. Report POSIVA 2000-12.

Appendices



Forsmark, KFM05A
SPR and Caliper results after length correction
SPR+Caliper, 2004-05-11 - 2004-05-12
SPR without pumping (L = 5 m), 2004-05-24 - 2004-05-26
SPR with pumping (L = 5 m), 2004-05-27 - 2004-05-29
SPR with pumping (L = 1 m), 2004-05-29 - 2004-05-30
SPR with pumping, during fracture-EC (L = 1 m), 2004-05-30 - 2004-05-31
SPR with pumping, during fracture-EC (L = 1 m), 2004-06-01 - 2004-06-02
SPR with pumping, during fracture-EC (L = 1 m), 2004-06-02
SPR with pumping (L= 1 m), n. 1.6 l/min, 2004-06-01
SPR with pumping (L= 1 m), n. 4.2 l/min, 2004-06-01
SPR with pumping (L= 1 m), n. 5.8 l/min, 2004-06-01
SPR with pumping (L= 1 m), n. 9.8 l/min, 2004-06-01
Length (m)
0
100
200
300
400
500
600
700
800
900
1000
Caliper
1
10
100
1000
10000
100000
1000000
Flow rate (mL/h)
100
1000
10000
Single point resistance (ohm)

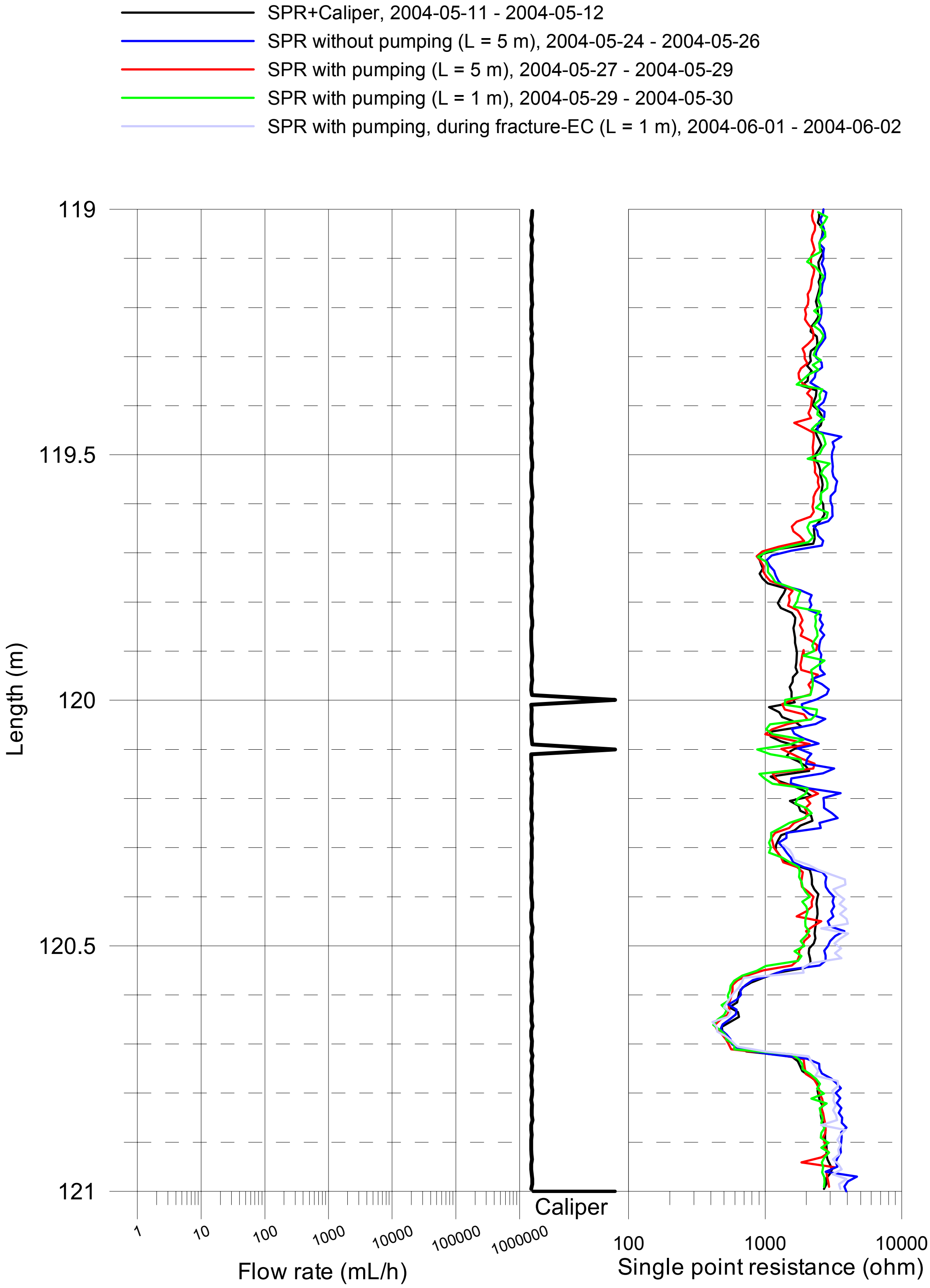
Appendix 1.2



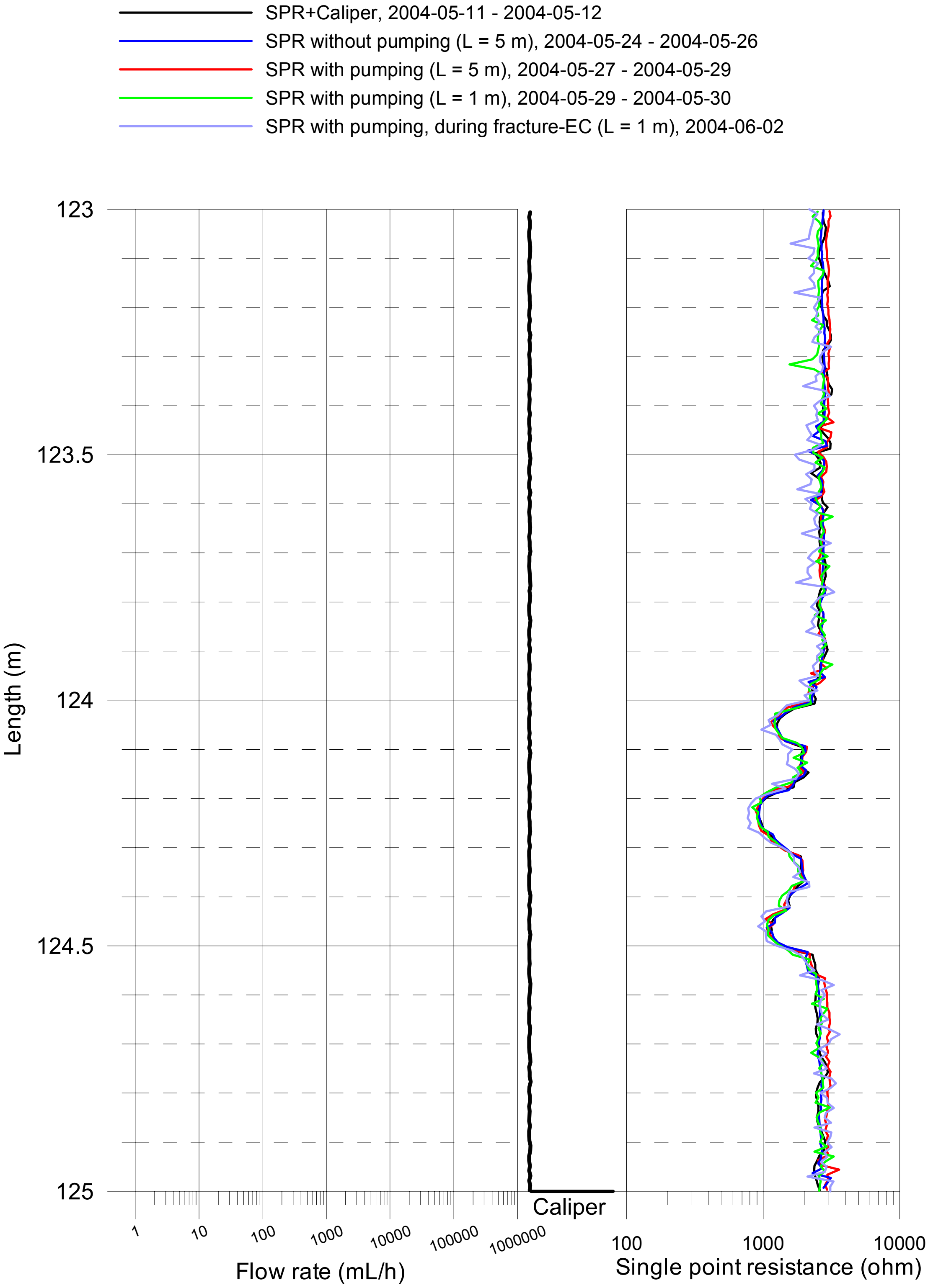
Forsmark, KFM05A
SPR and Caliper results after length correction
SPR+Caliper, 2004-05-11 - 2004-05-12
SPR without pumping (L = 5 m), 2004-05-24 - 2004-05-26
SPR with pumping (L = 5 m), 2004-05-27 - 2004-05-29
SPR with pumping (L = 1 m), 2004-05-29 - 2004-05-30
SPR with pumping, during fracture-EC (L = 1 m), 2004-05-30 - 2004-05-31
SPR with pumping, during fracture-EC (L = 1 m), 2004-06-02
SPR with pumping (L= 1 m), n. 1.6 l/min, 2004-06-01
SPR with pumping (L= 1 m), n. 4.2 l/min, 2004-06-01
SPR with pumping (L= 1 m), n. 5.8 l/min, 2004-06-01
SPR with pumping (L= 1 m), n. 9.8 l/min, 2004-06-01
109
109.5
110
110.5
111
Length (m)
1
10
100
1000
10000
100000
1000000
Flow rate (mL/h)
Caliper
100
1000
10000
Single point resistance (ohm)

Appendix 1.3

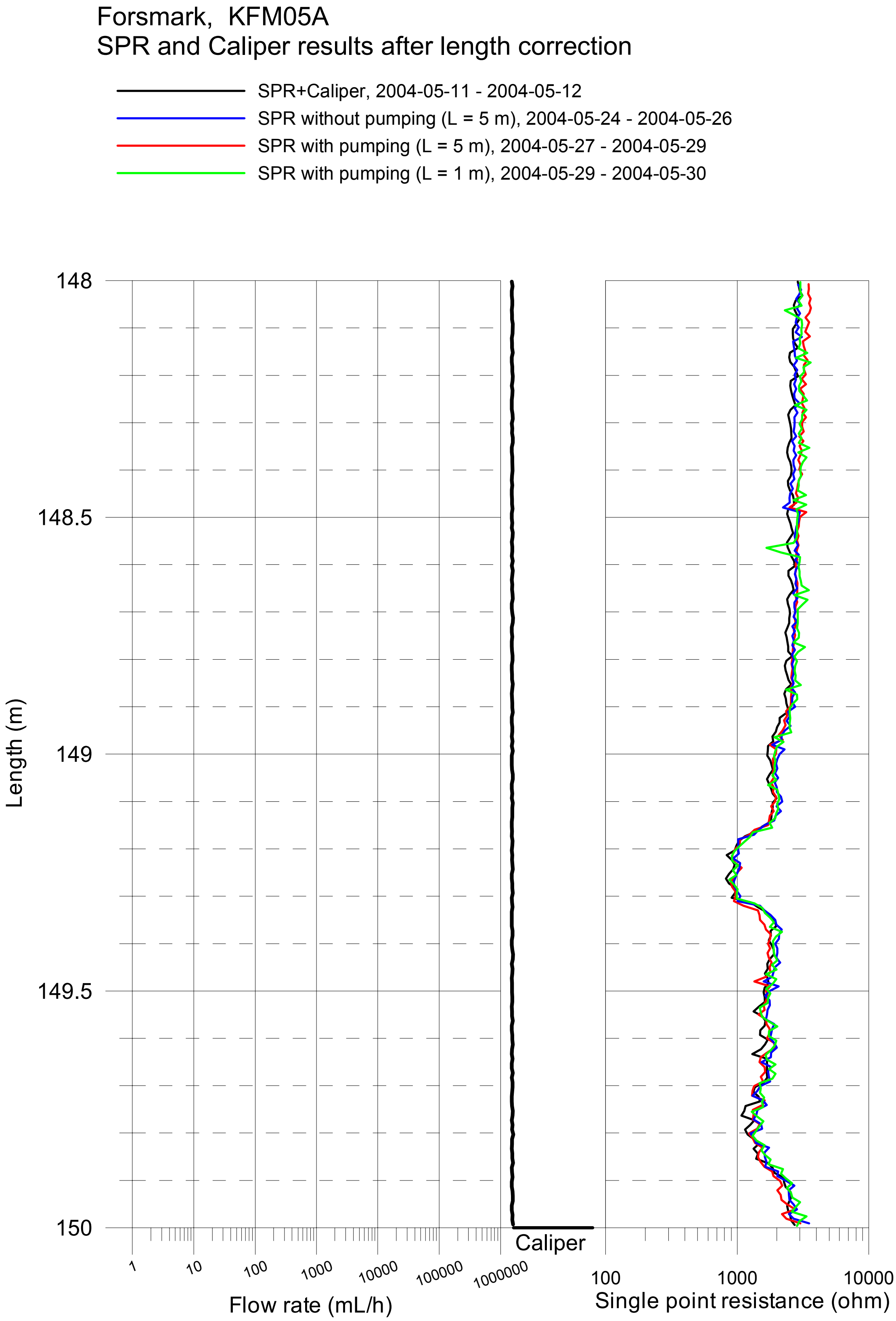
Forsmark, KFM05A
SPR and Caliper results after length correction



Forsmark, KFM05A
SPR and Caliper results after length correction

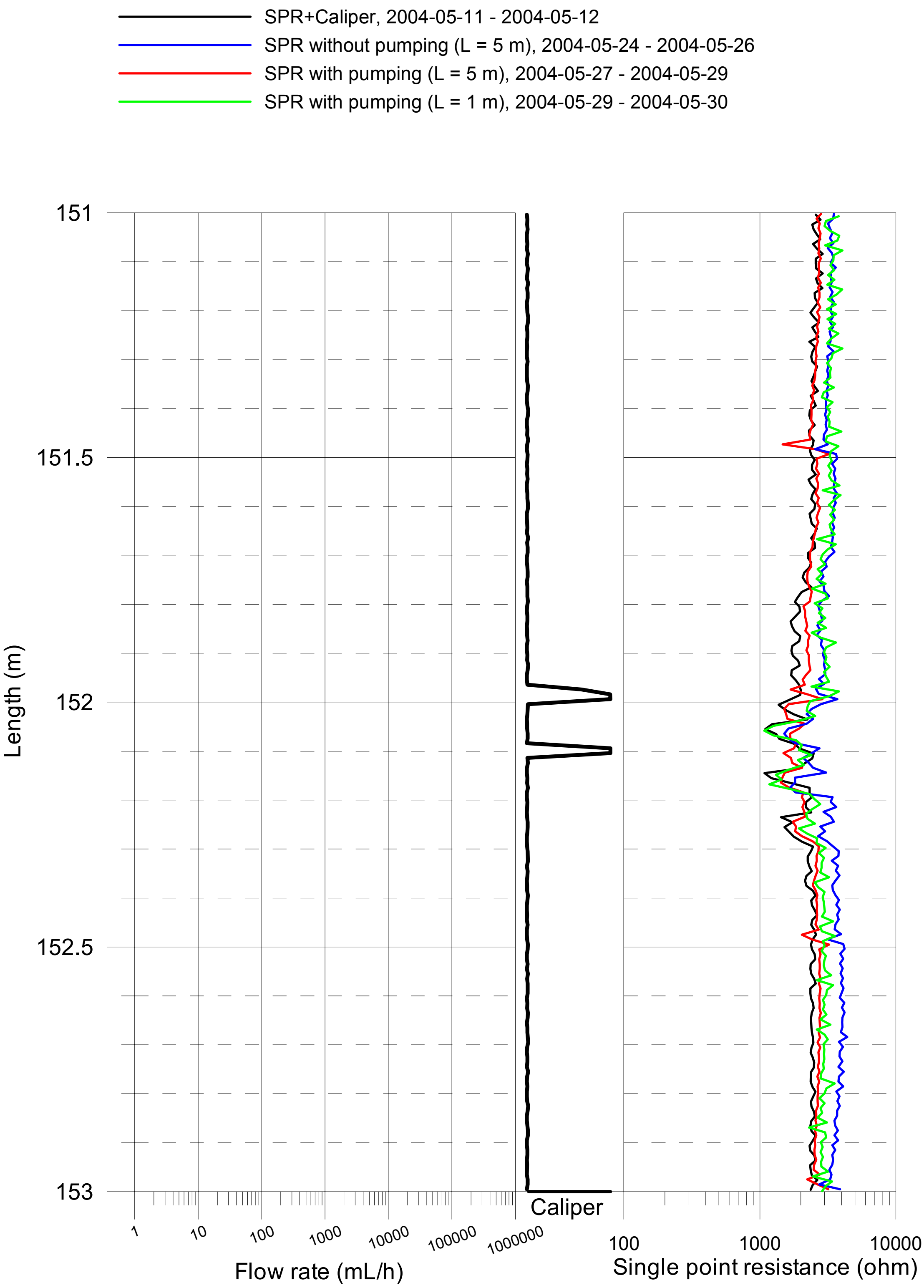


Appendix 1.5

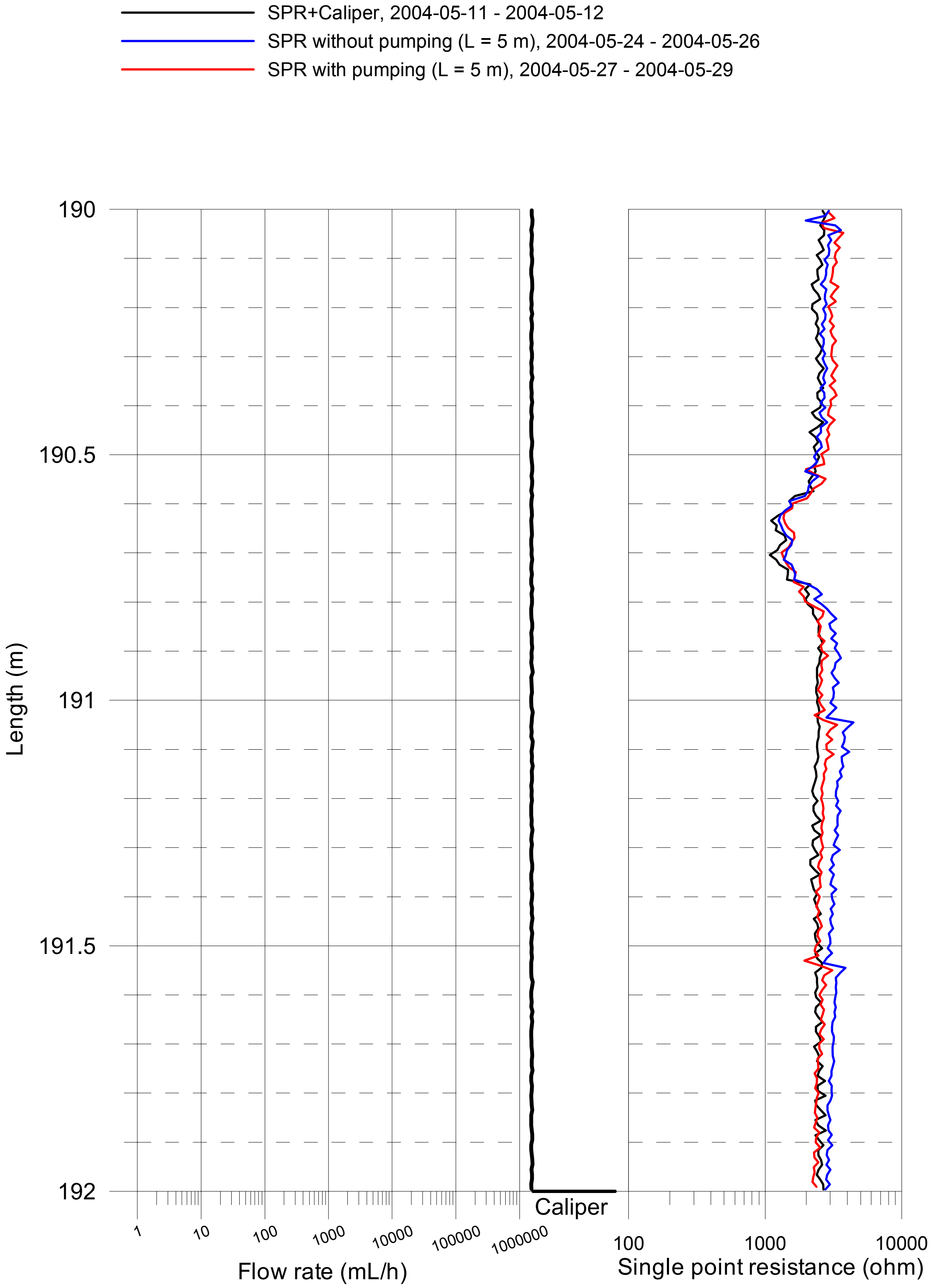


Forsmark, KFM05A
SPR and Caliper results after length correction
SPR+Caliper, 2004-05-11 - 2004-05-12
SPR without pumping (L = 5 m), 2004-05-24 - 2004-05-26
SPR with pumping (L = 5 m), 2004-05-27 - 2004-05-29
SPR with pumping (L = 1 m), 2004-05-29 - 2004-05-30
Length (m)
148
148.5
149
149.5
150
1
10
100
1000
10000
100000
1000000
Flow rate (mL/h)
Caliper
100
1000
10000
Single point resistance (ohm)

Forsmark, KFM05A
SPR and Caliper results after length correction

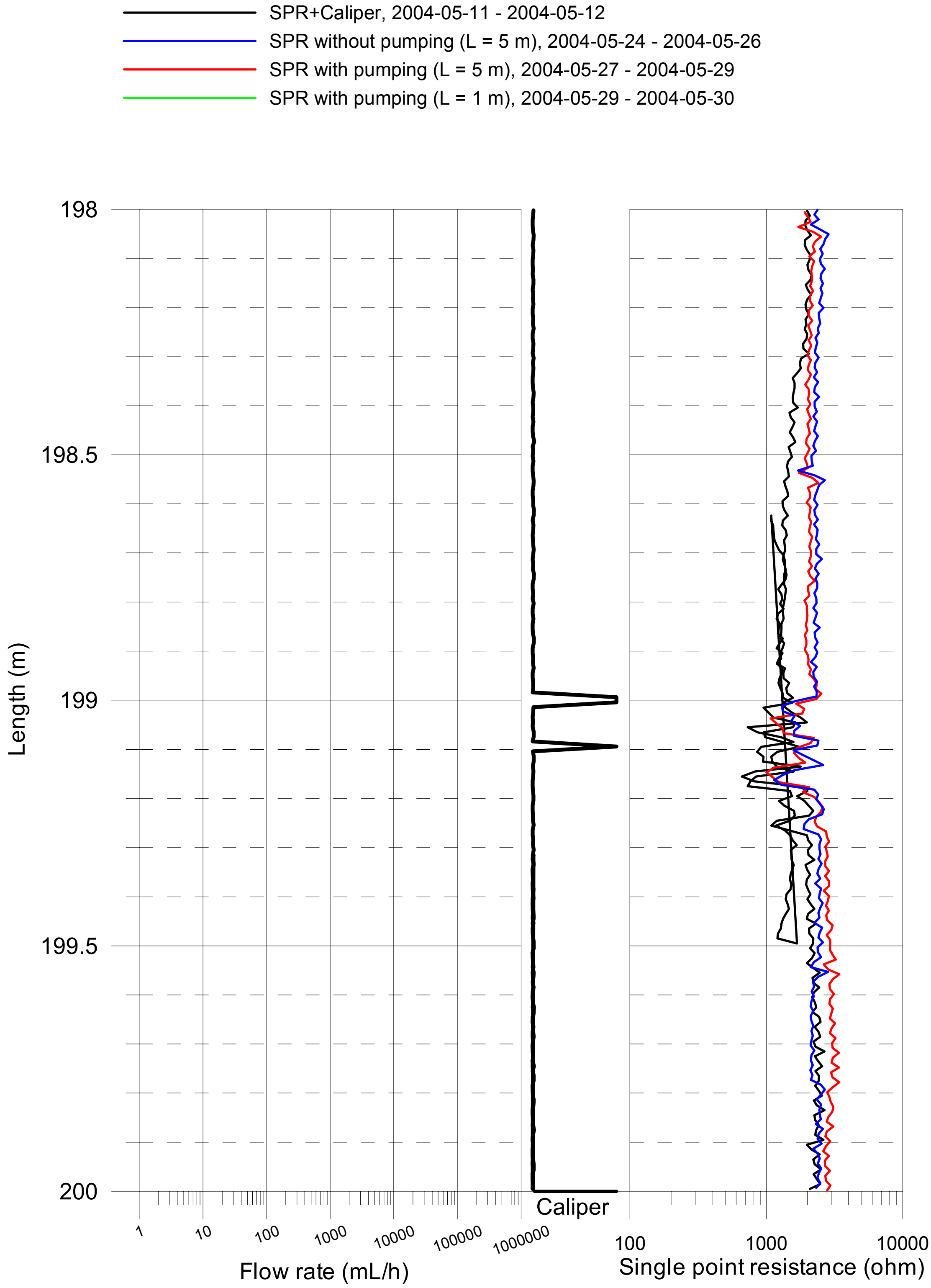


Forsmark, KFM05A
SPR and Caliper results after length correction

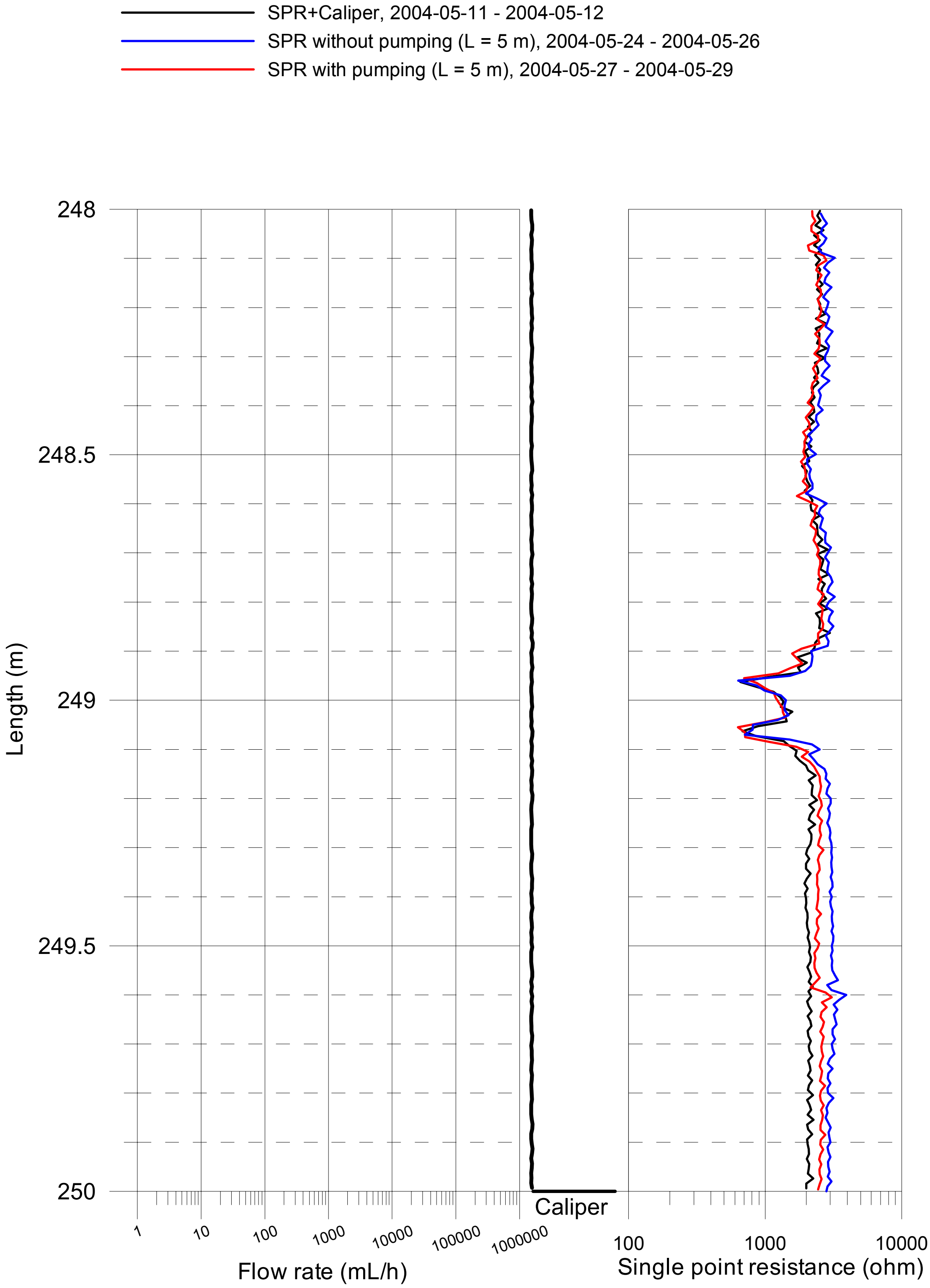


Appendix 1.8

Forsmark, KFM05A
SPR and Caliper results after length correction

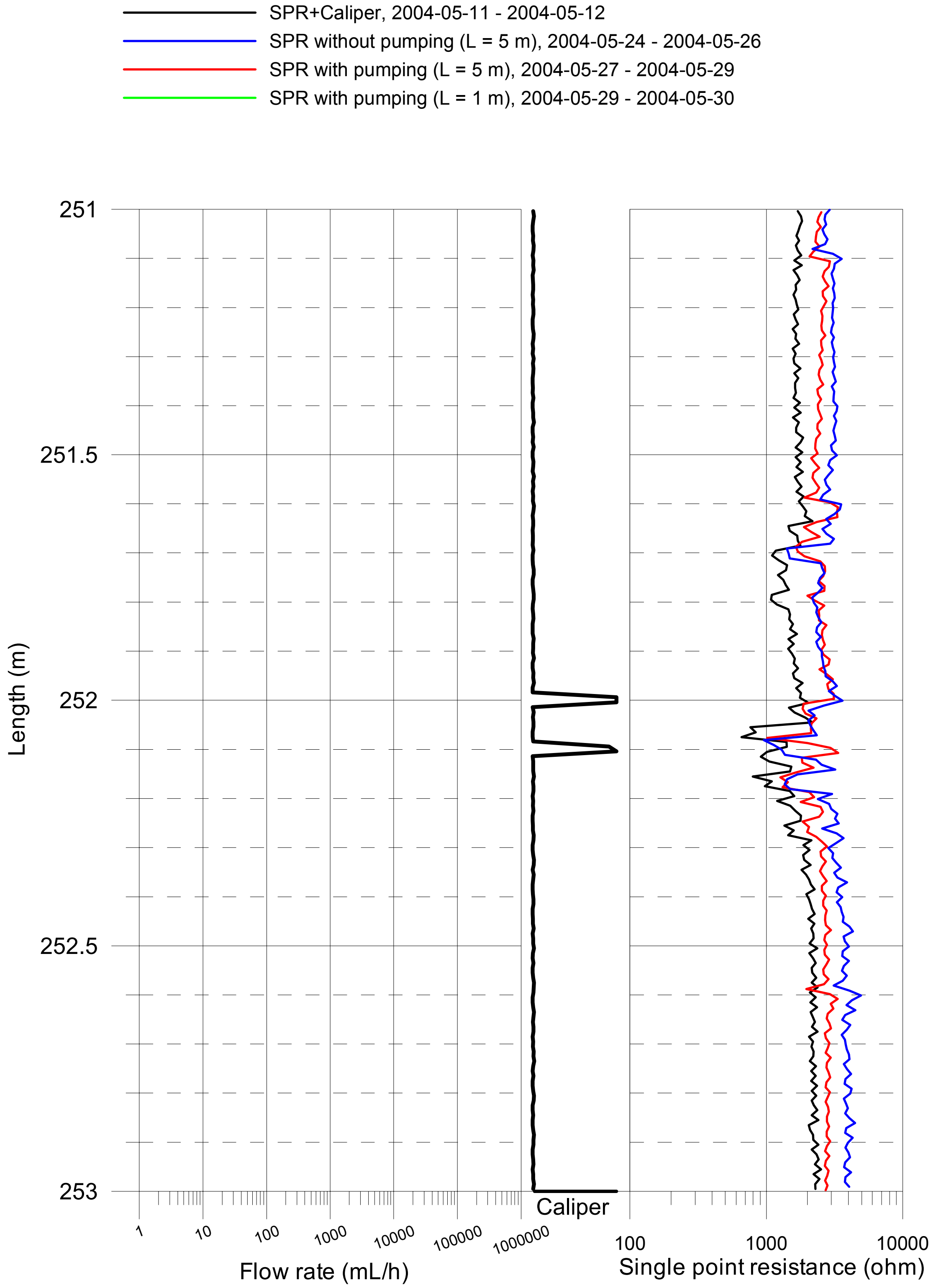


Forsmark, KFM05A
SPR and Caliper results after length correction

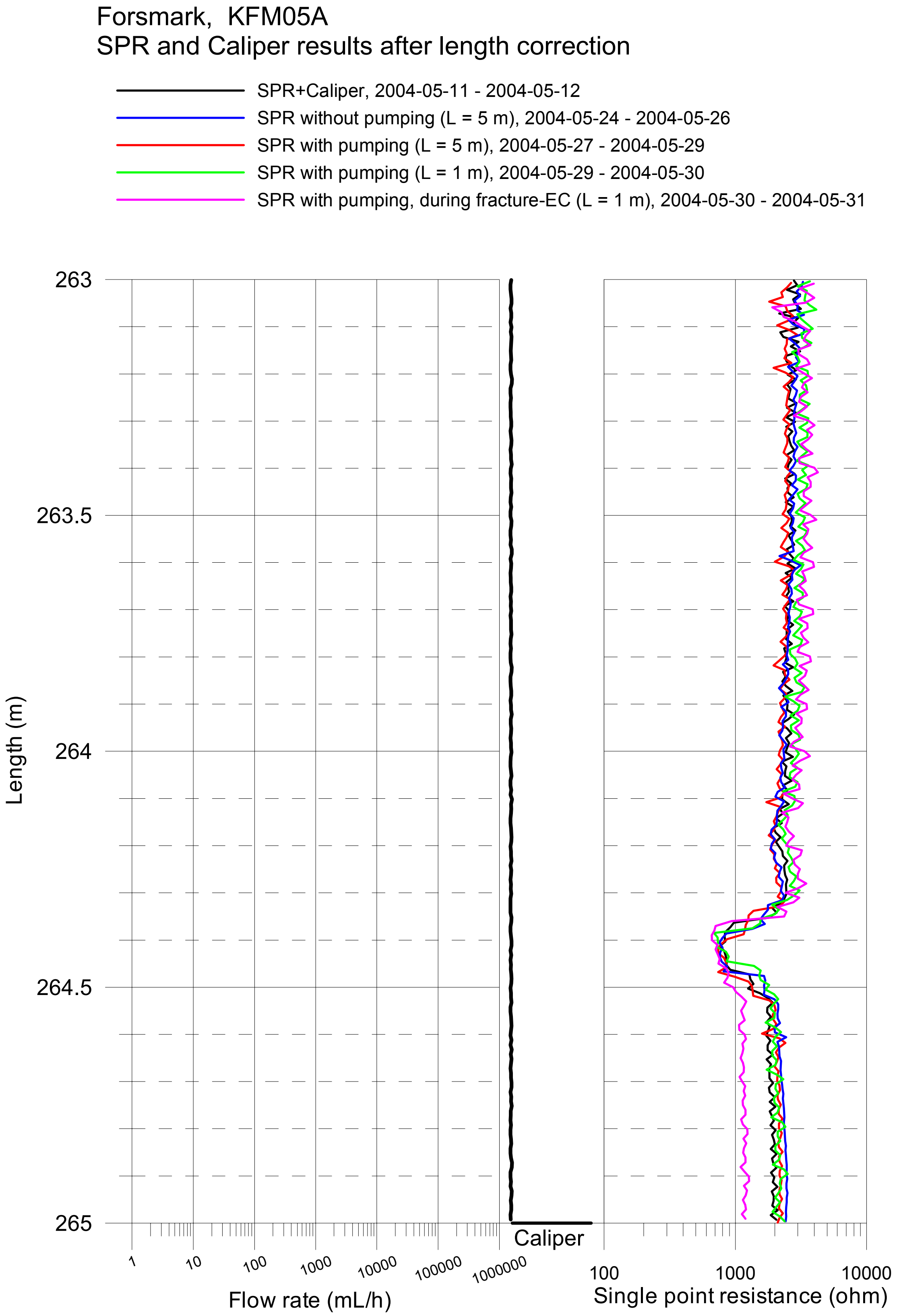


Appendix 1.10

Forsmark, KFM05A
SPR and Caliper results after length correction

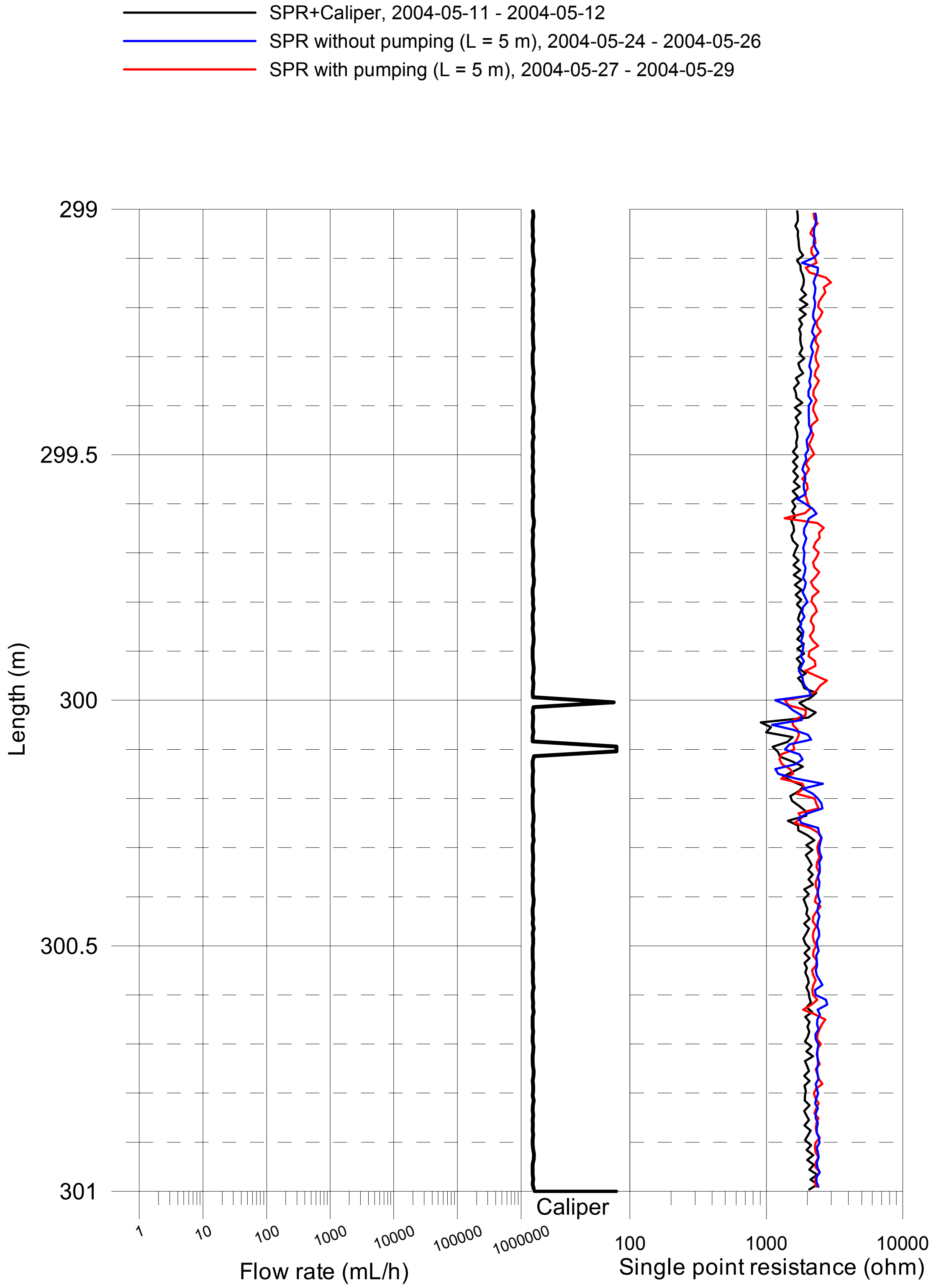


Appendix 1.11



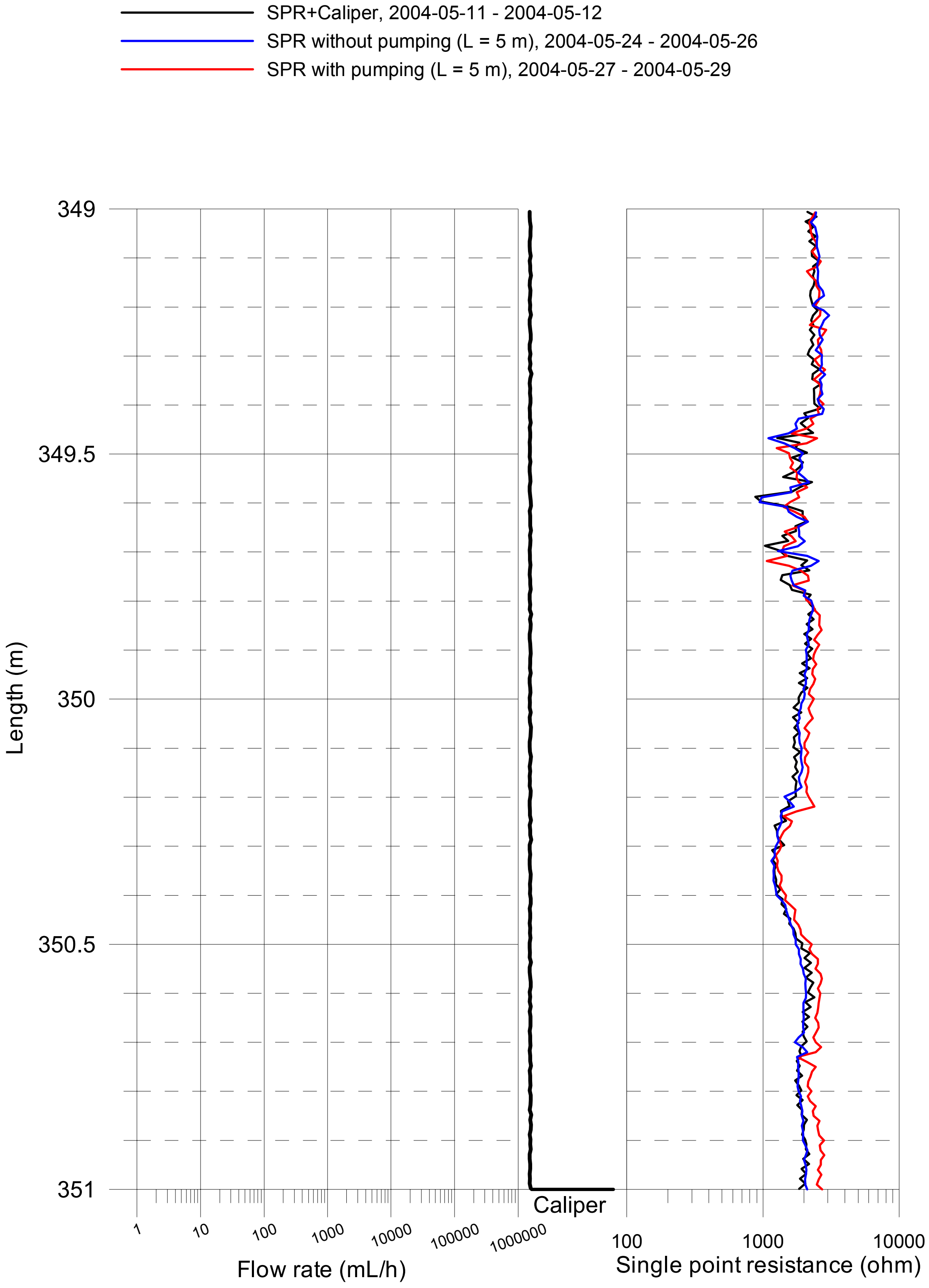
Appendix 1.12

Forsmark, KFM05A
SPR and Caliper results after length correction



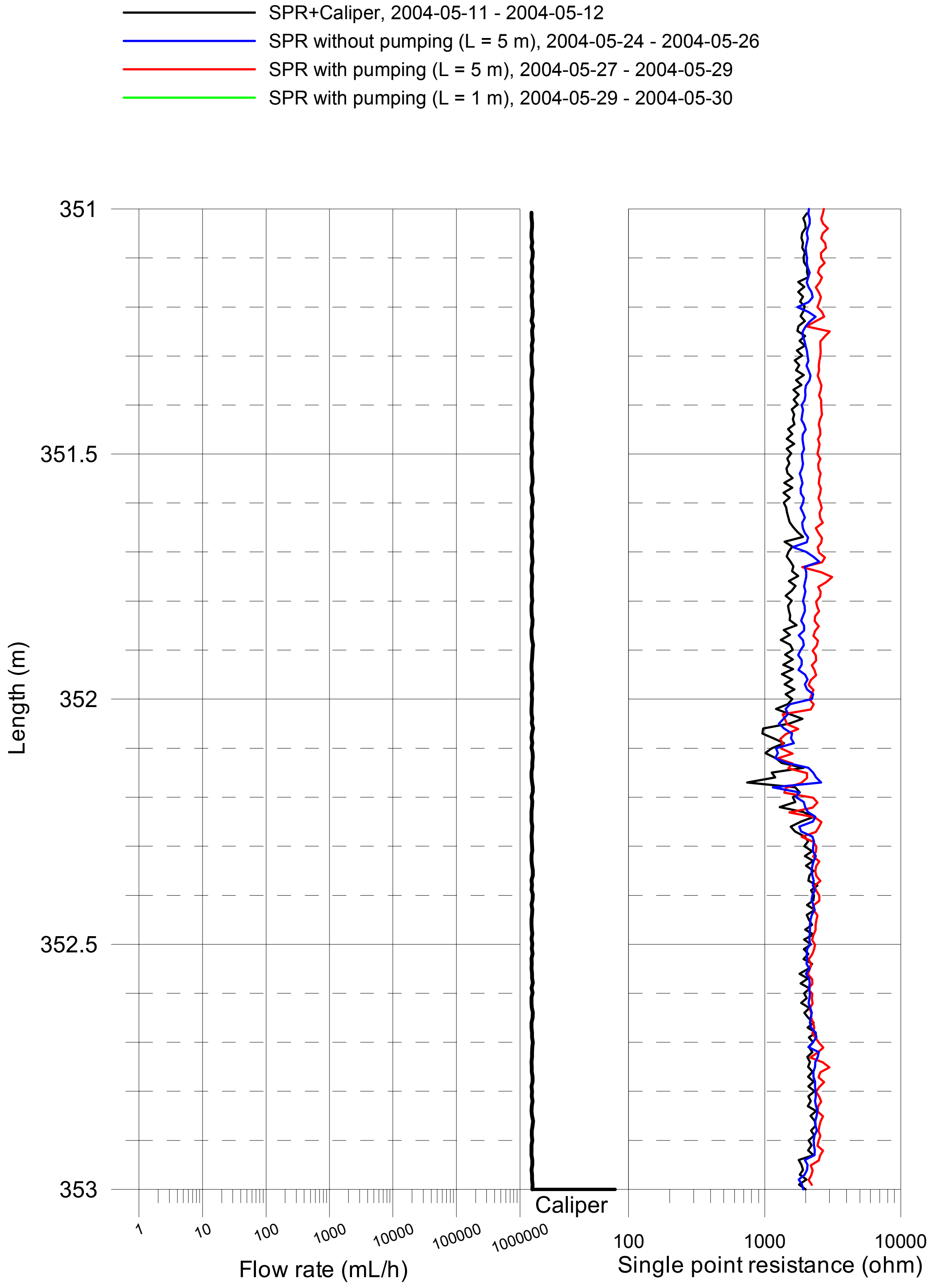
Appendix 1.13

Forsmark, KFM05A
SPR and Caliper results after length correction



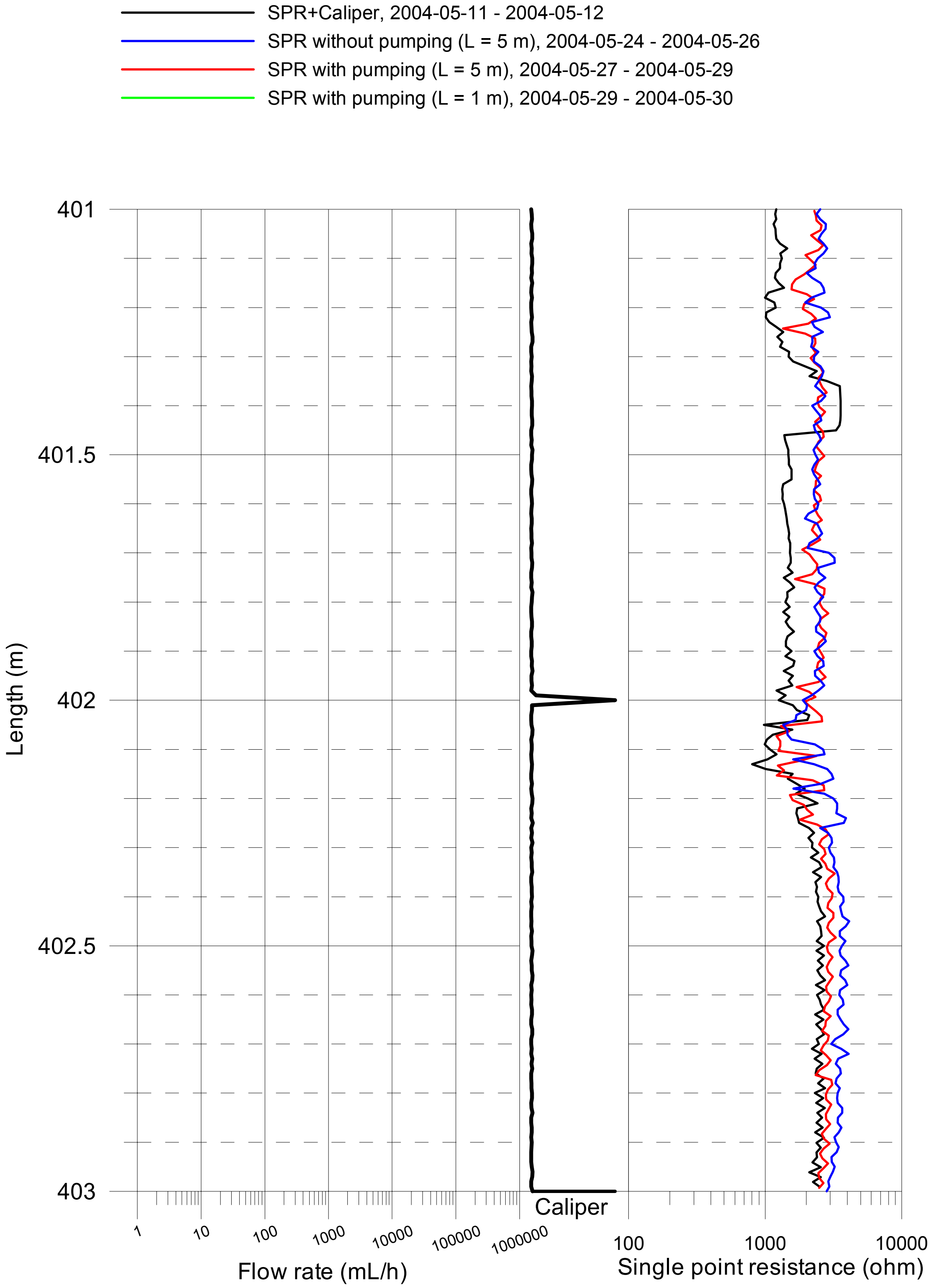
Appendix 1.14

Forsmark, KFM05A
SPR and Caliper results after length correction



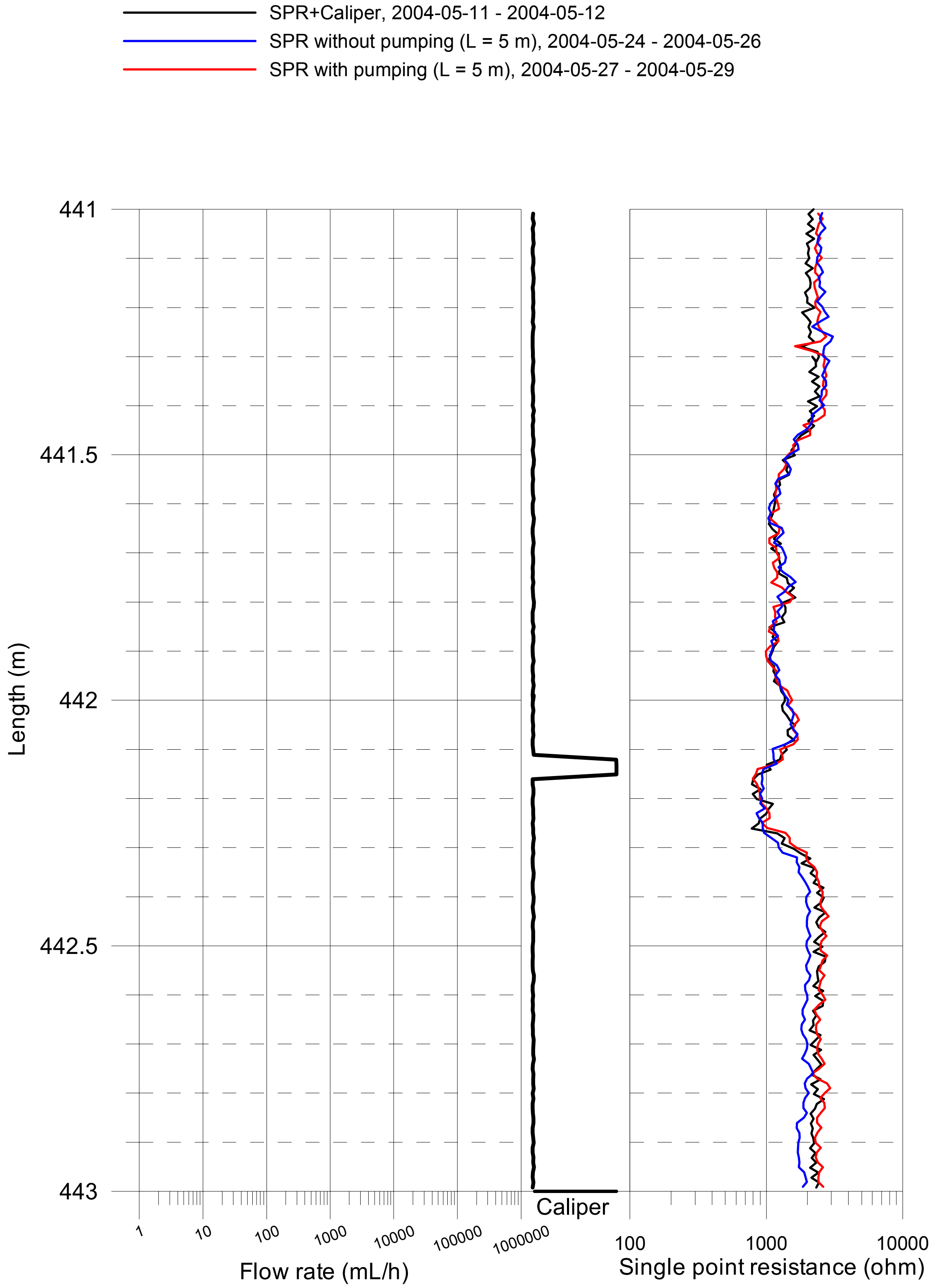
Appendix 1.15

Forsmark, KFM05A
SPR and Caliper results after length correction



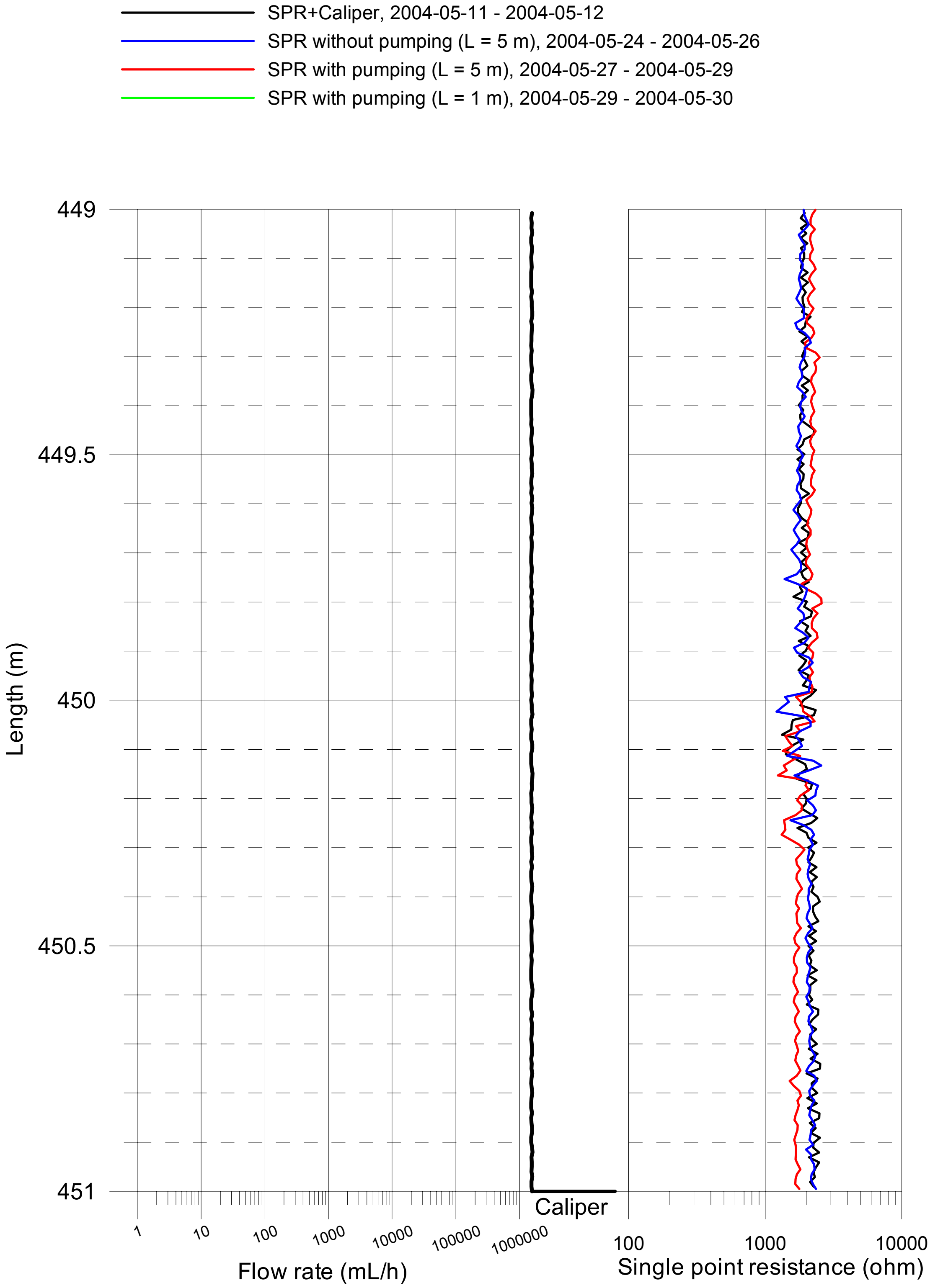
Appendix 1.16

Forsmark, KFM05A
SPR and Caliper results after length correction

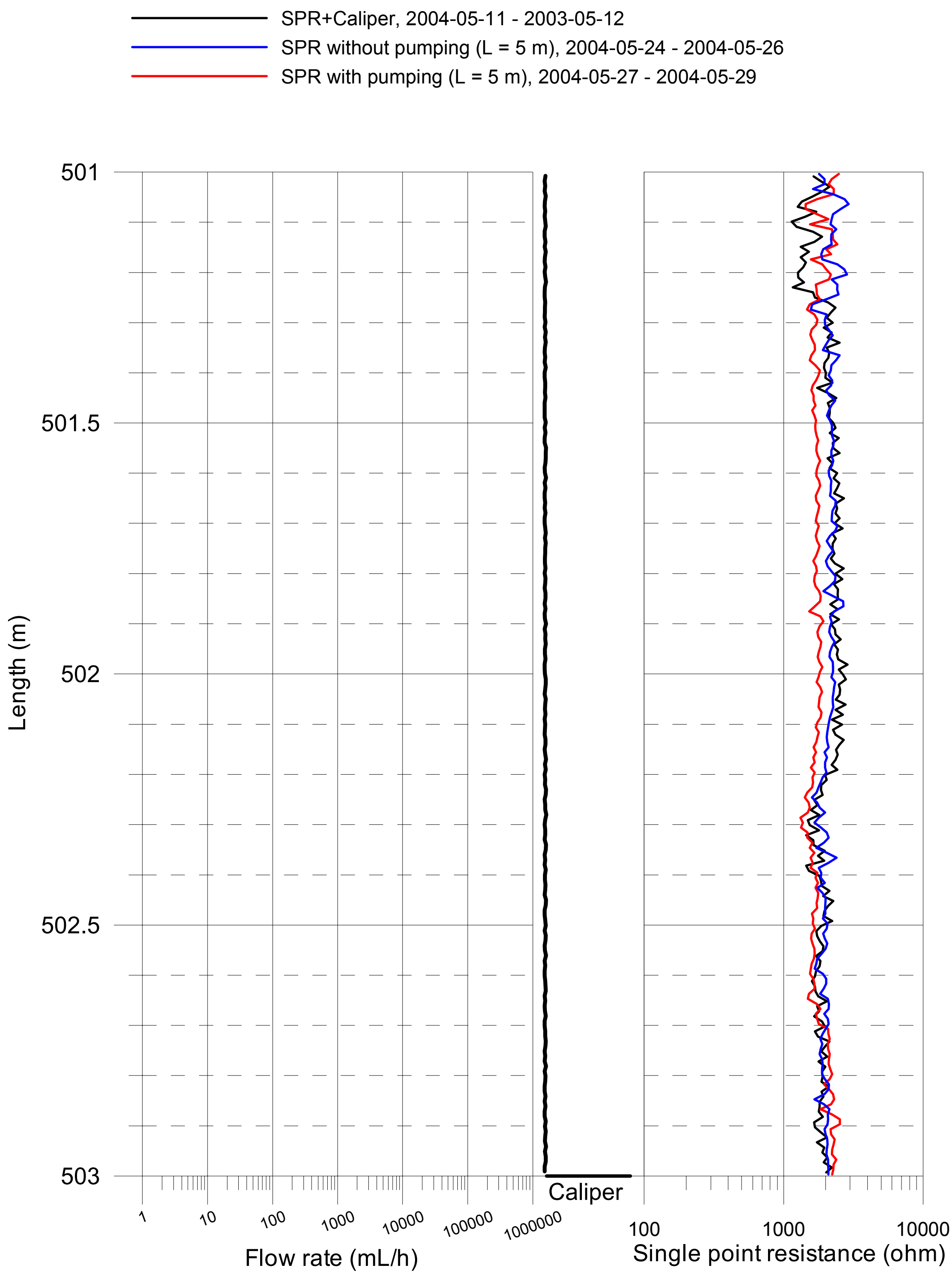


Appendix 1.17

Forsmark, KFM05A
SPR and Caliper results after length correction

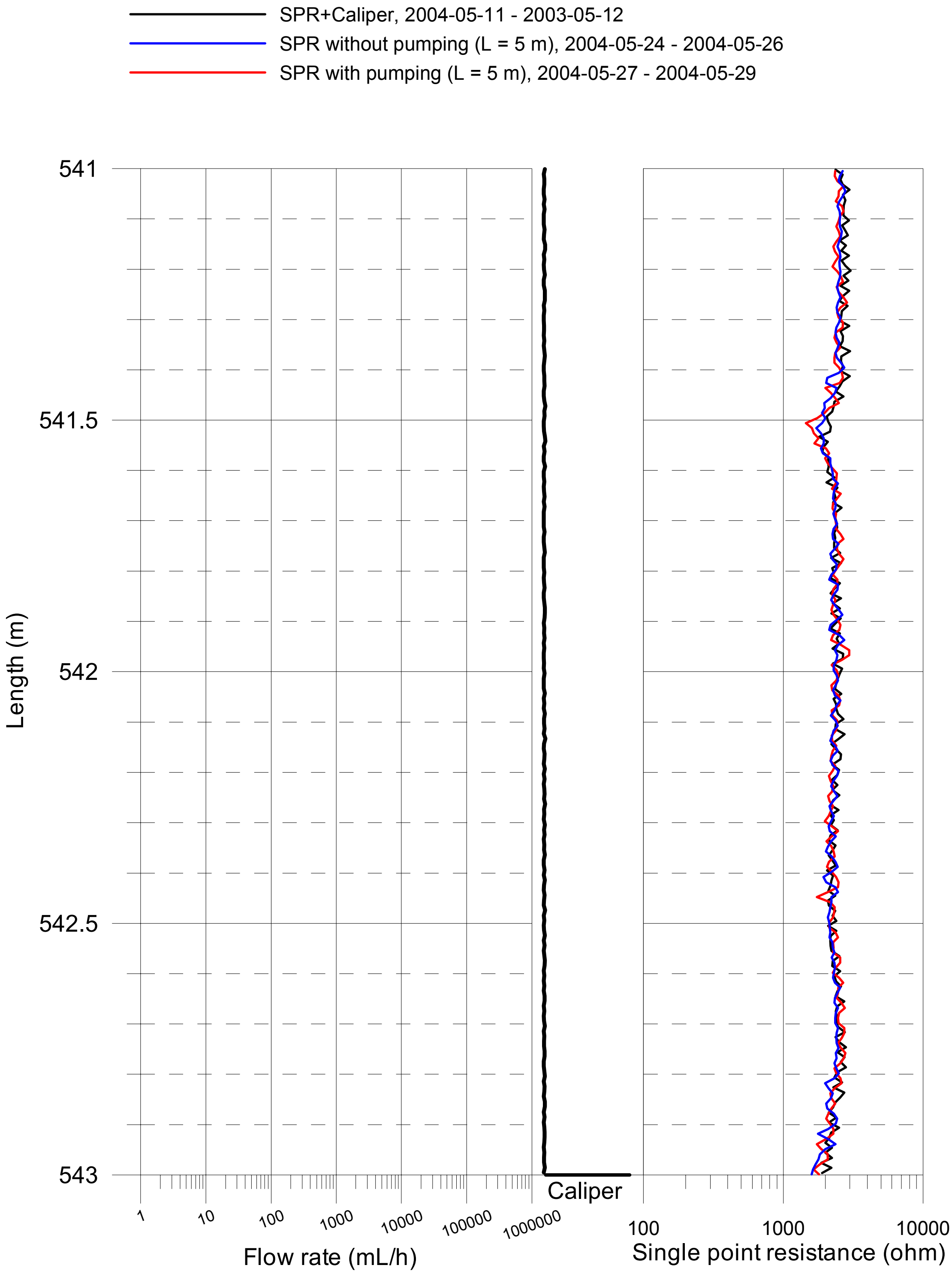


Forsmark, KFM05A
SPR and Caliper results after length correction

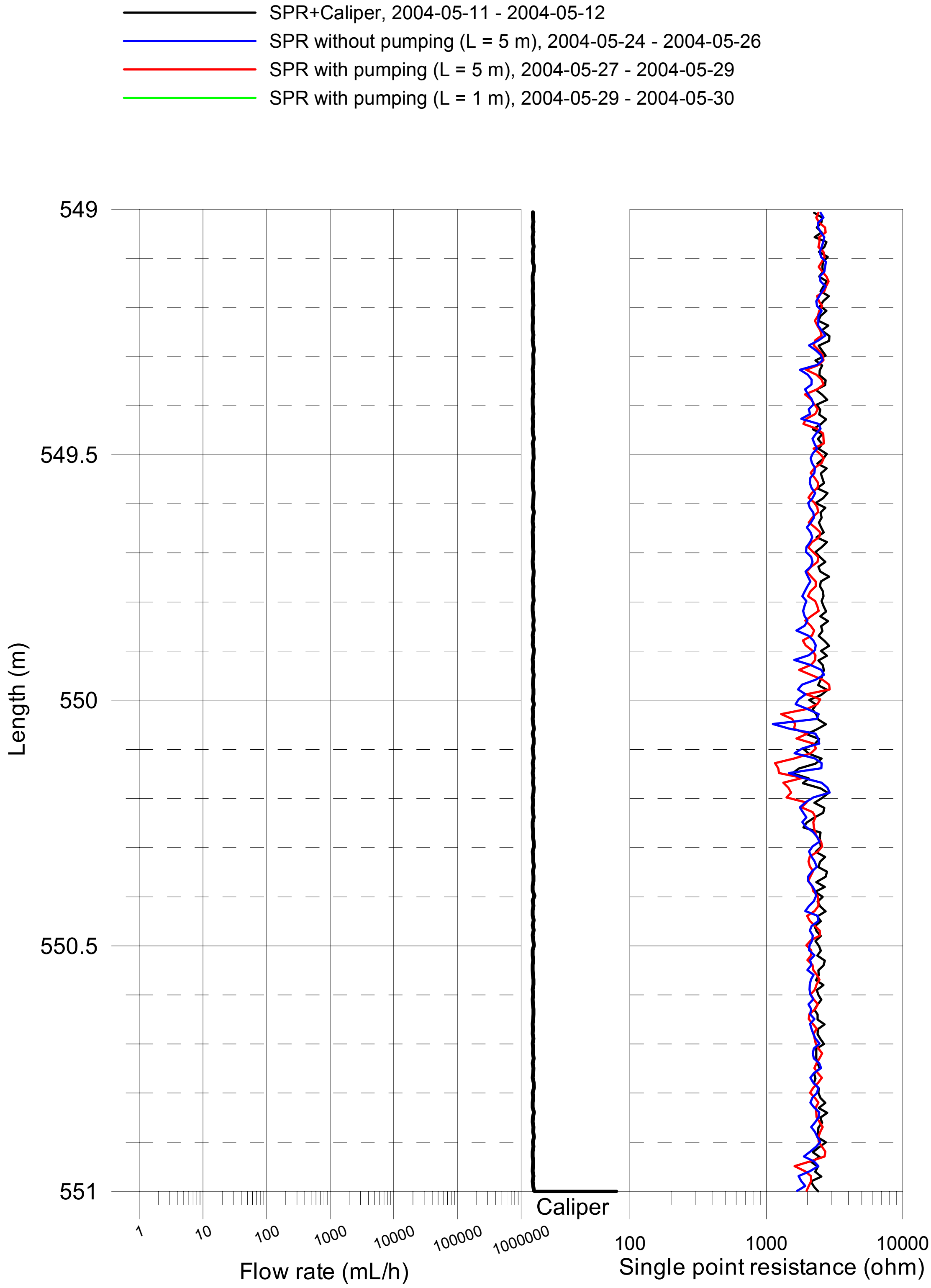


Appendix 1.19

Forsmark, KFM05A
SPR and Caliper results after length correction

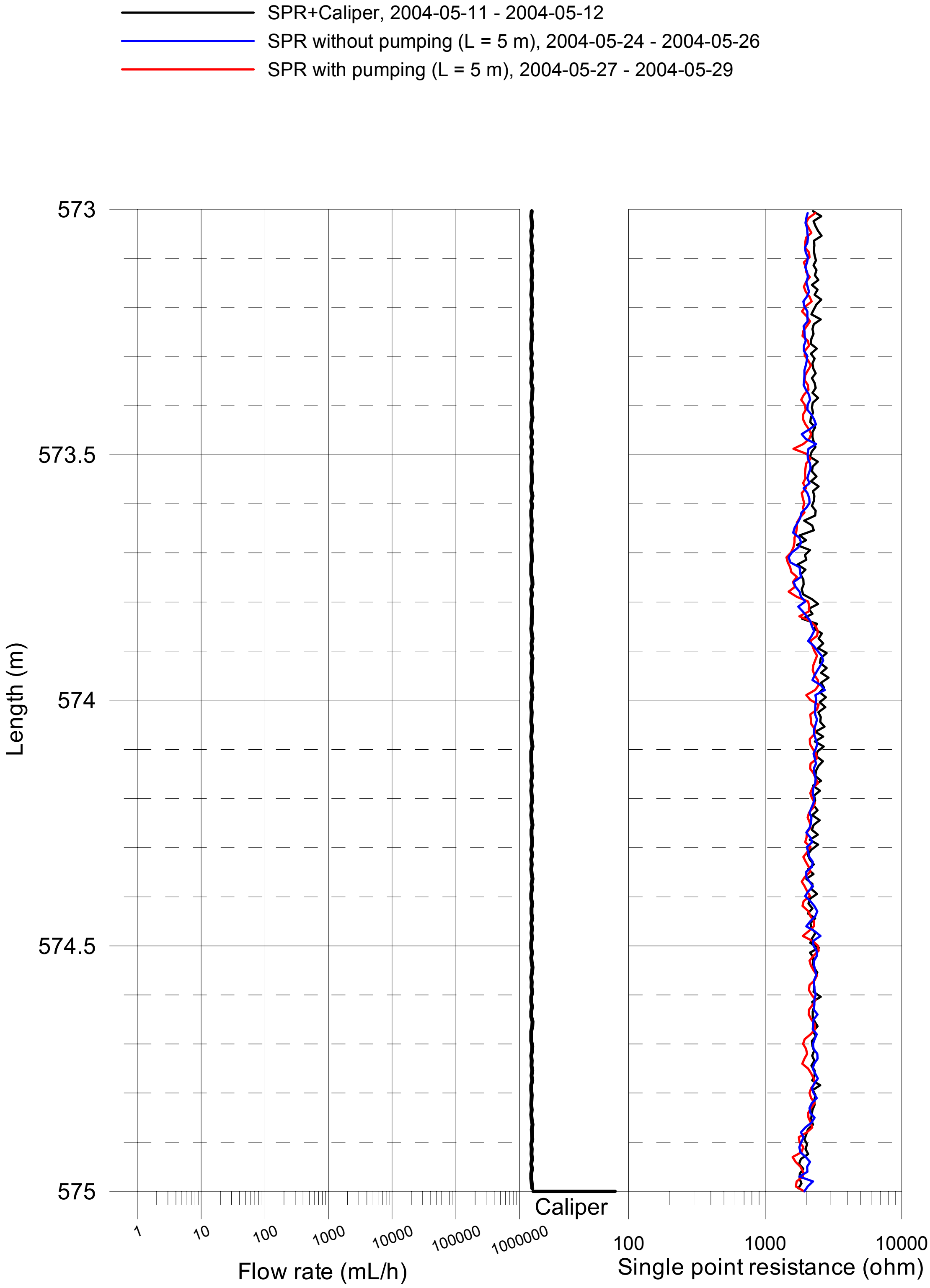


Forsmark, KFM05A
SPR and Caliper results after length correction

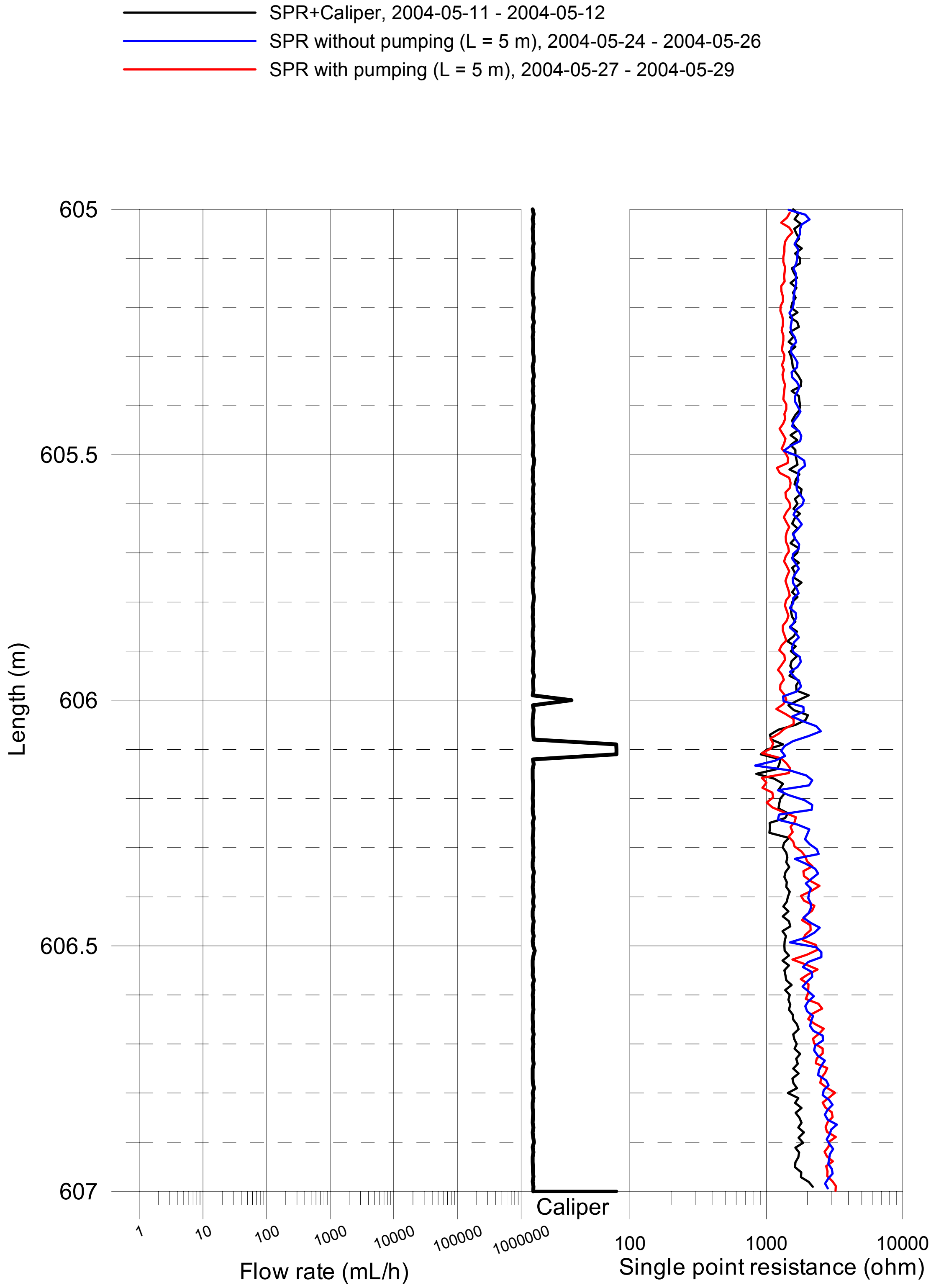


Appendix 1.21

Forsmark, KFM05A
SPR and Caliper results after length correction

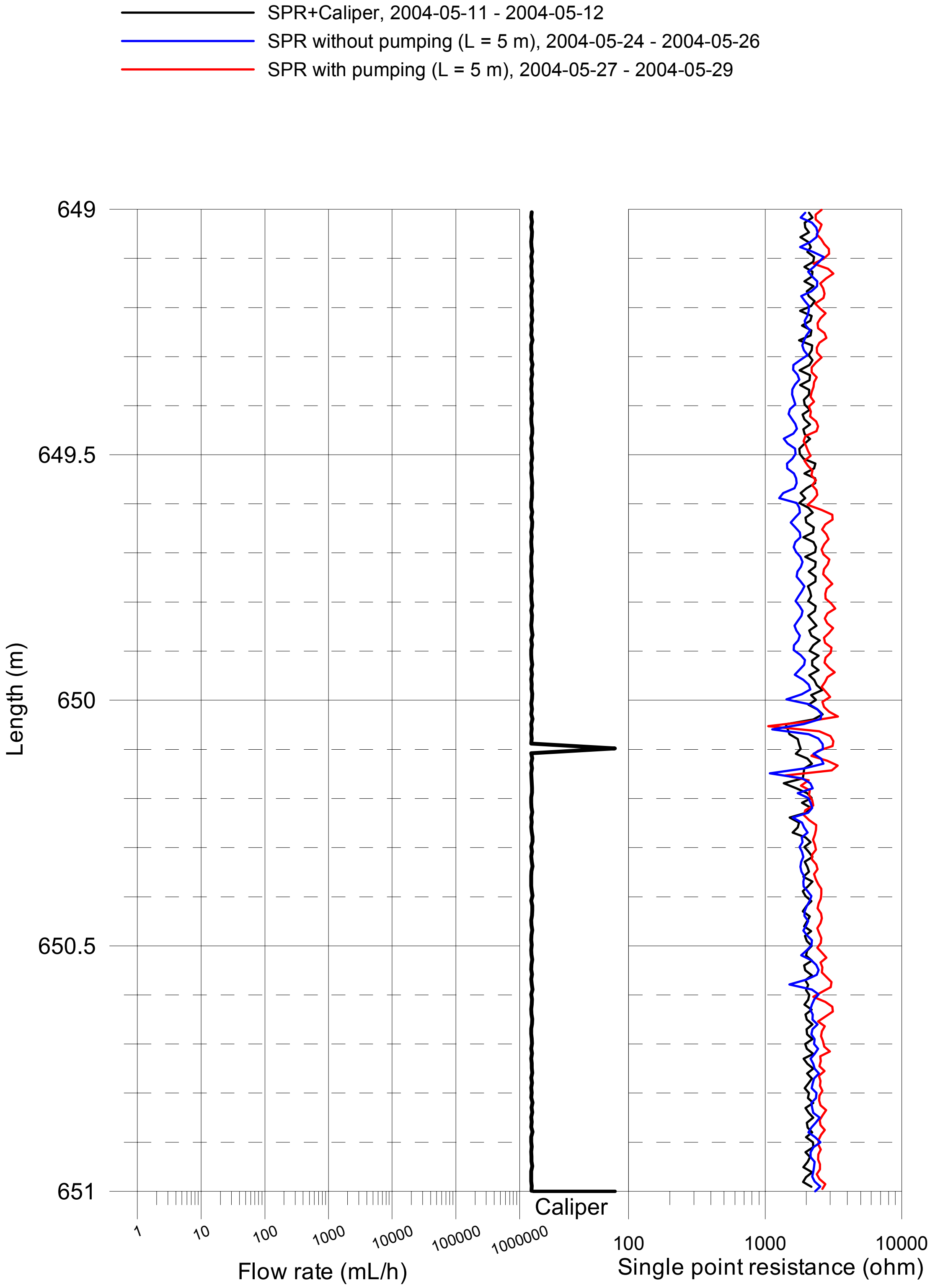


Forsmark, KFM05A
SPR and Caliper results after length correction

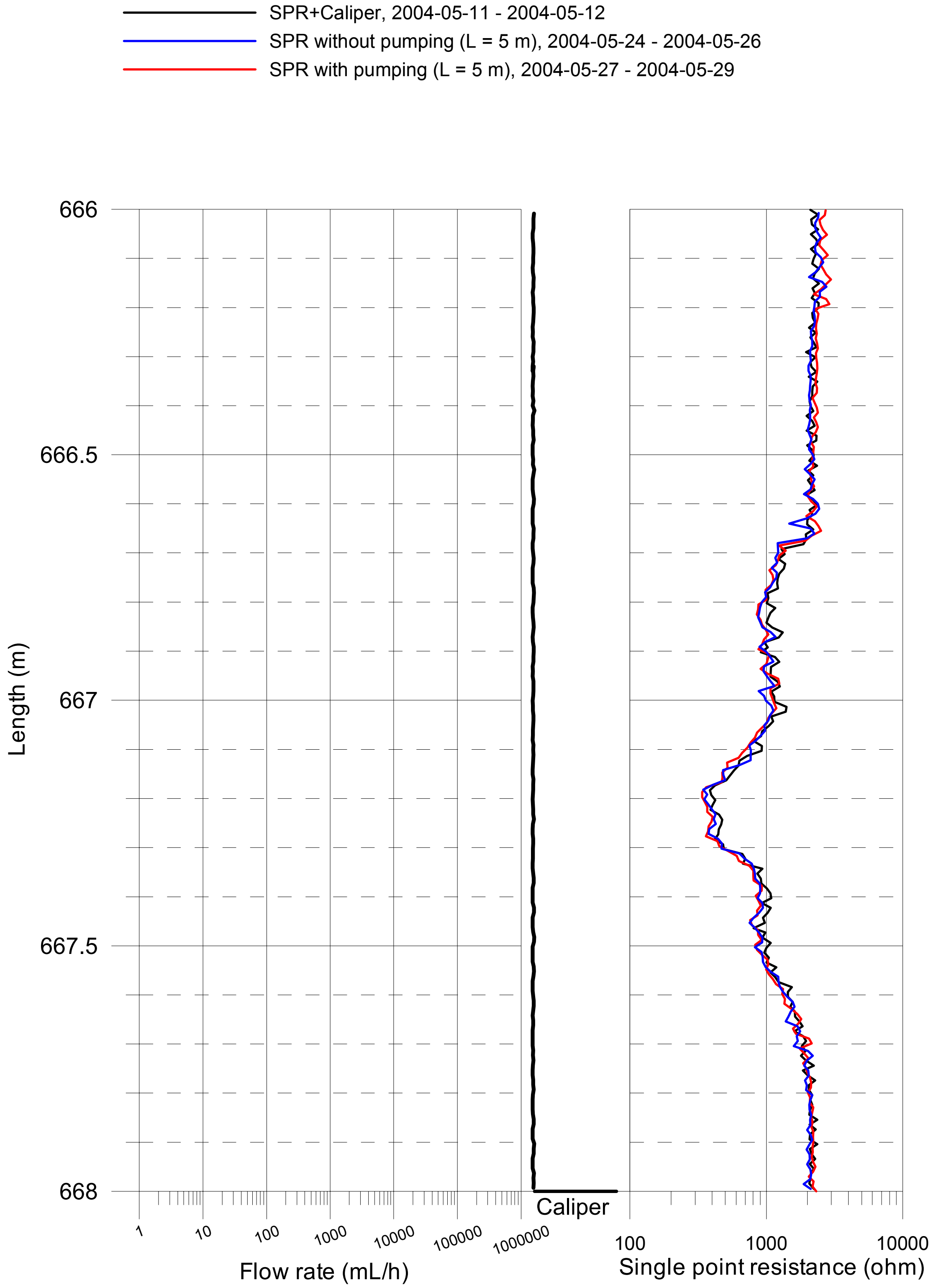


Appendix 1.23

Forsmark, KFM05A
SPR and Caliper results after length correction

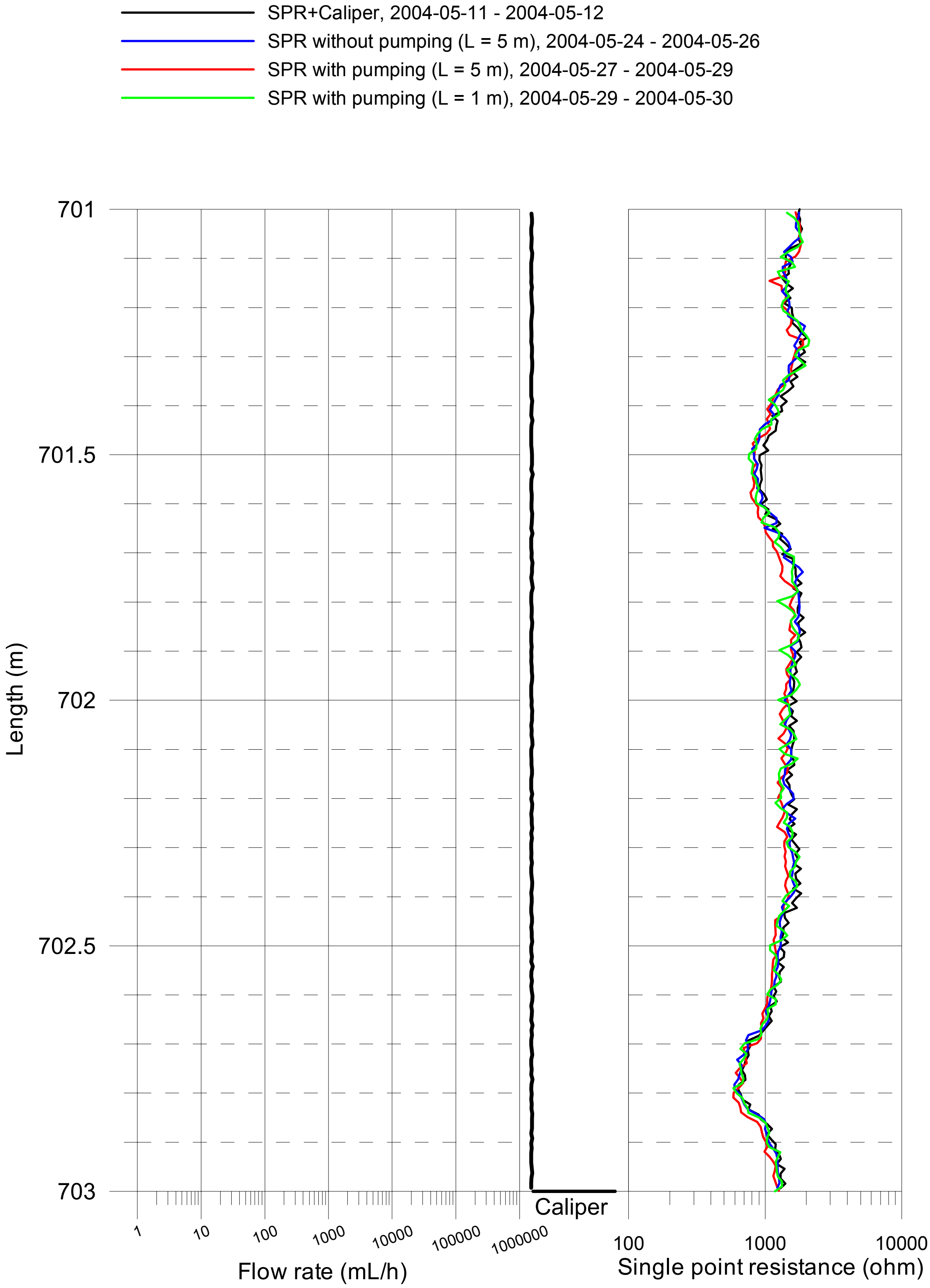


Forsmark, KFM05A
SPR and Caliper results after length correction



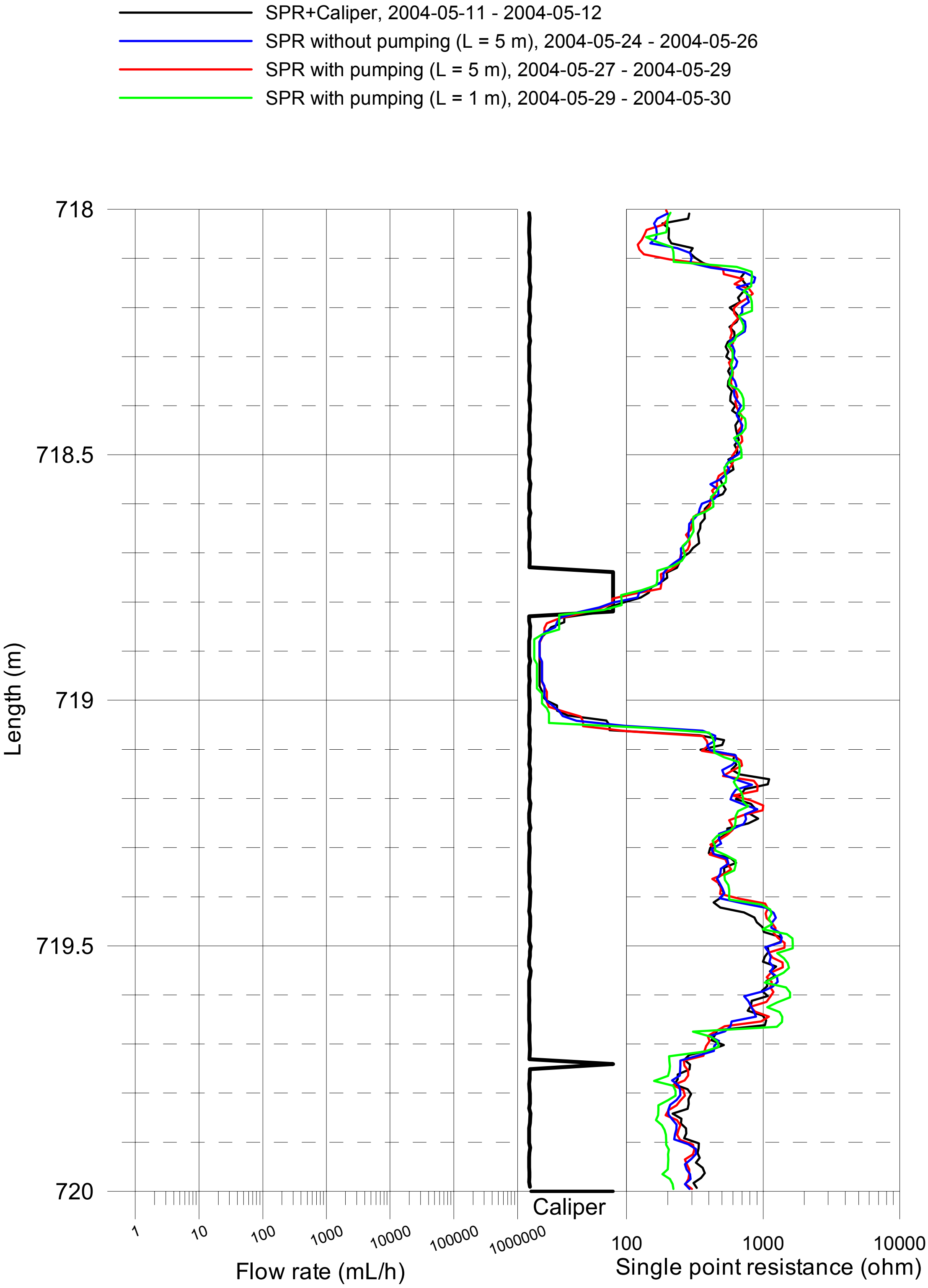
Appendix 1.25

Forsmark, KFM05A
SPR and Caliper results after length correction



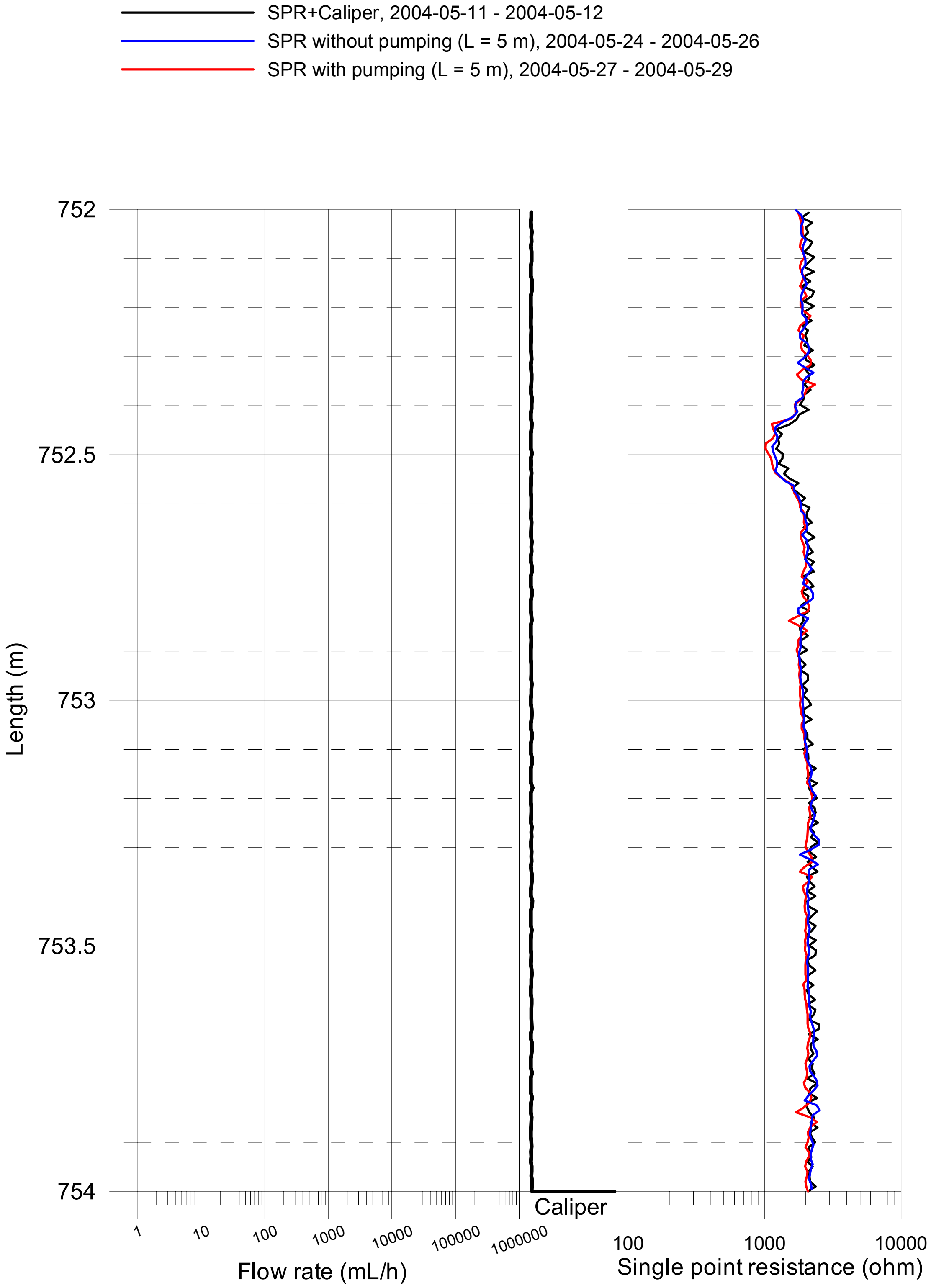
Appendix 1.26

Forsmark, KFM05A
SPR and Caliper results after length correction



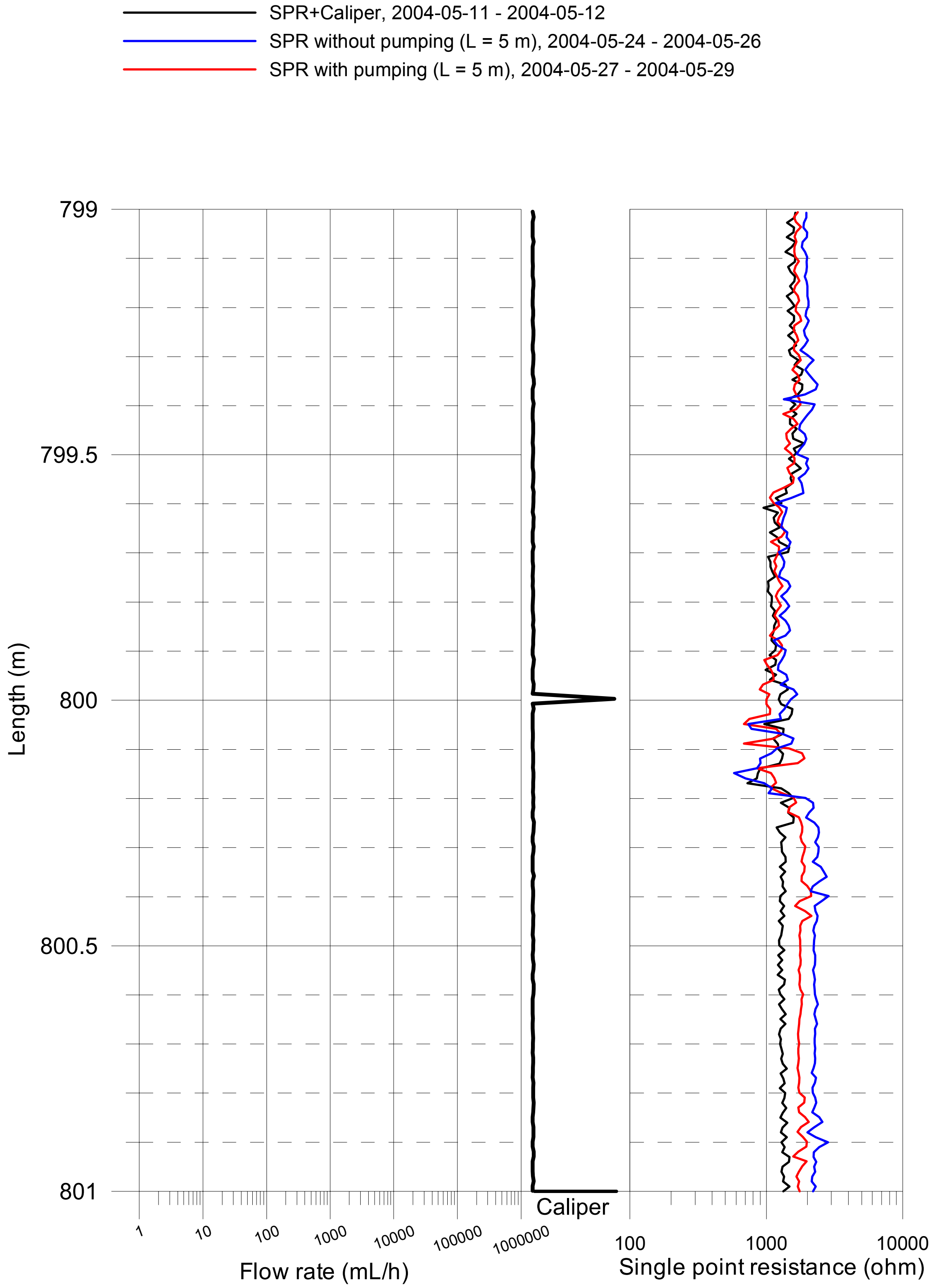
Appendix 1.27

Forsmark, KFM05A
SPR and Caliper results after length correction



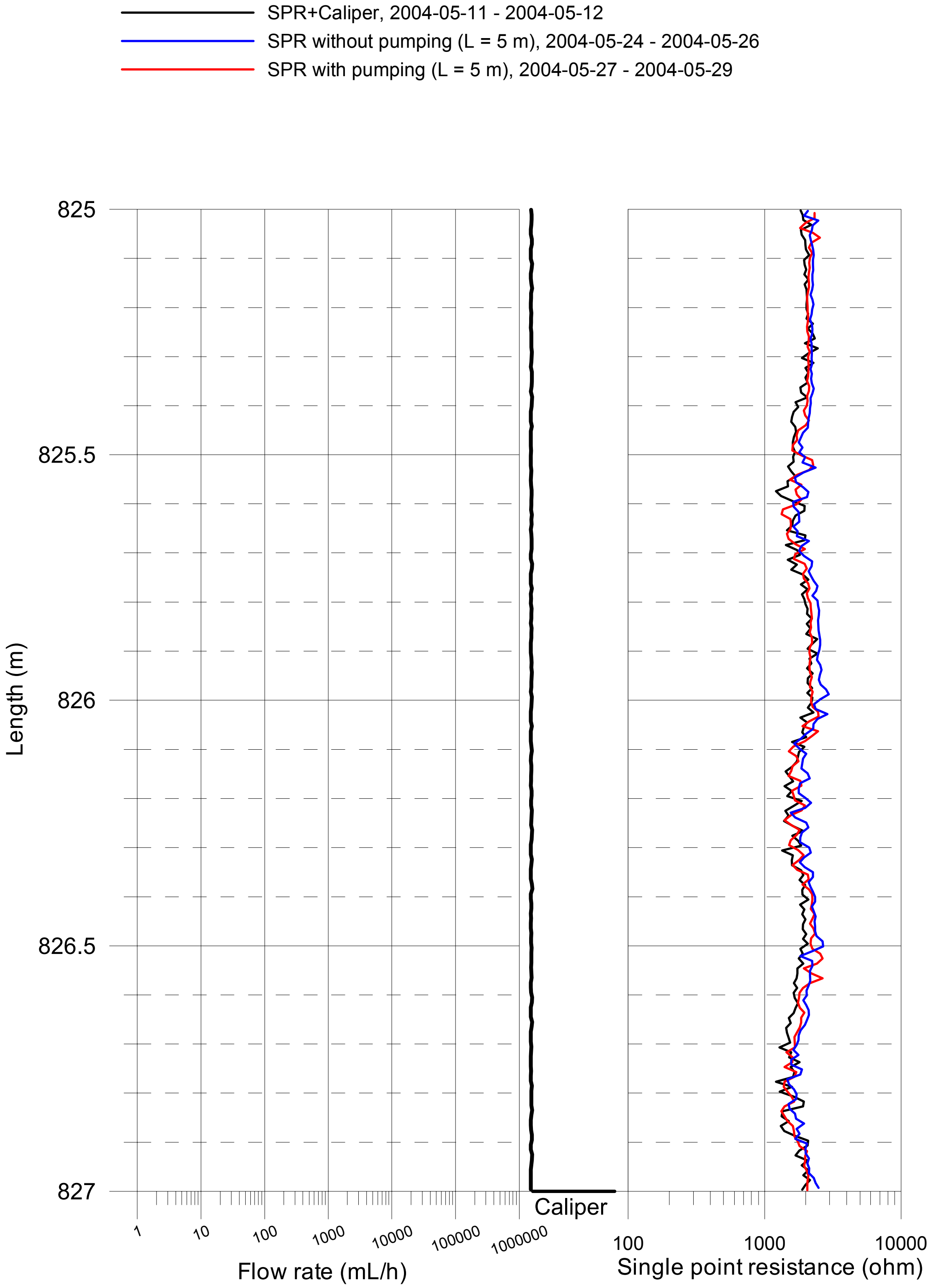
Appendix 1.28

Forsmark, KFM05A
SPR and Caliper results after length correction



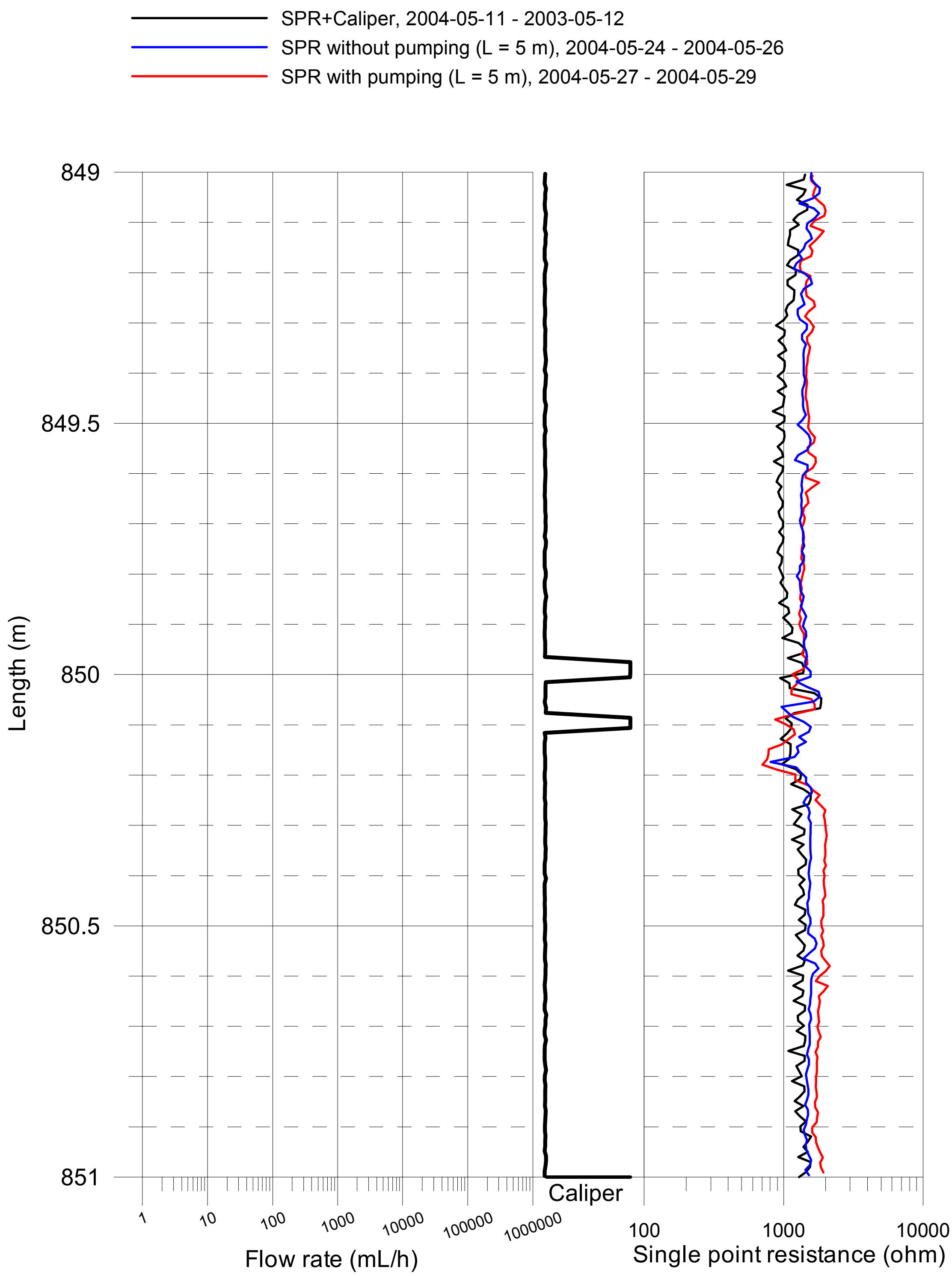
Appendix 1.29

Forsmark, KFM05A
SPR and Caliper results after length correction



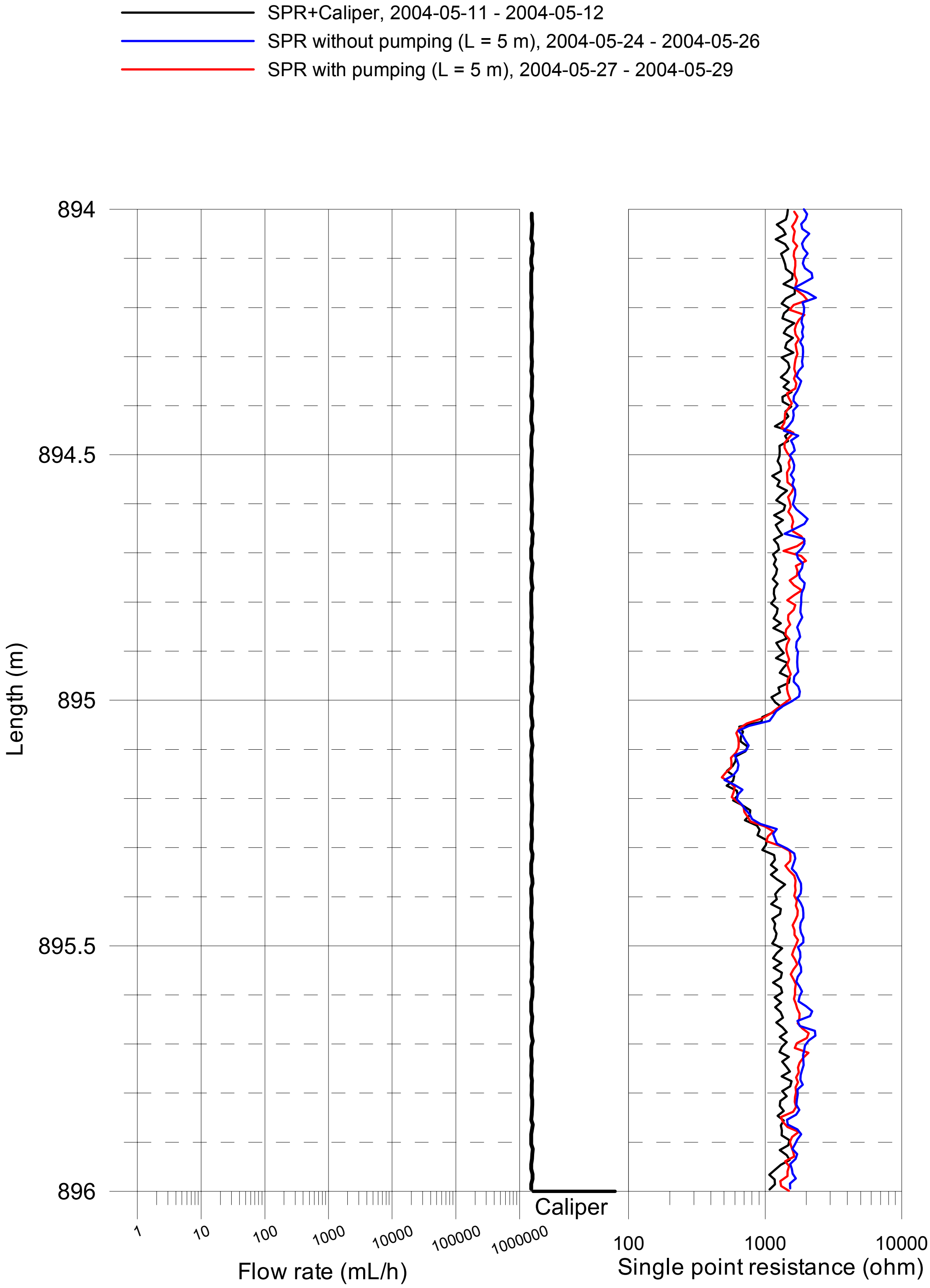
Appendix 1.30

Forsmark, KFM05A
SPR and Caliper results after length correction



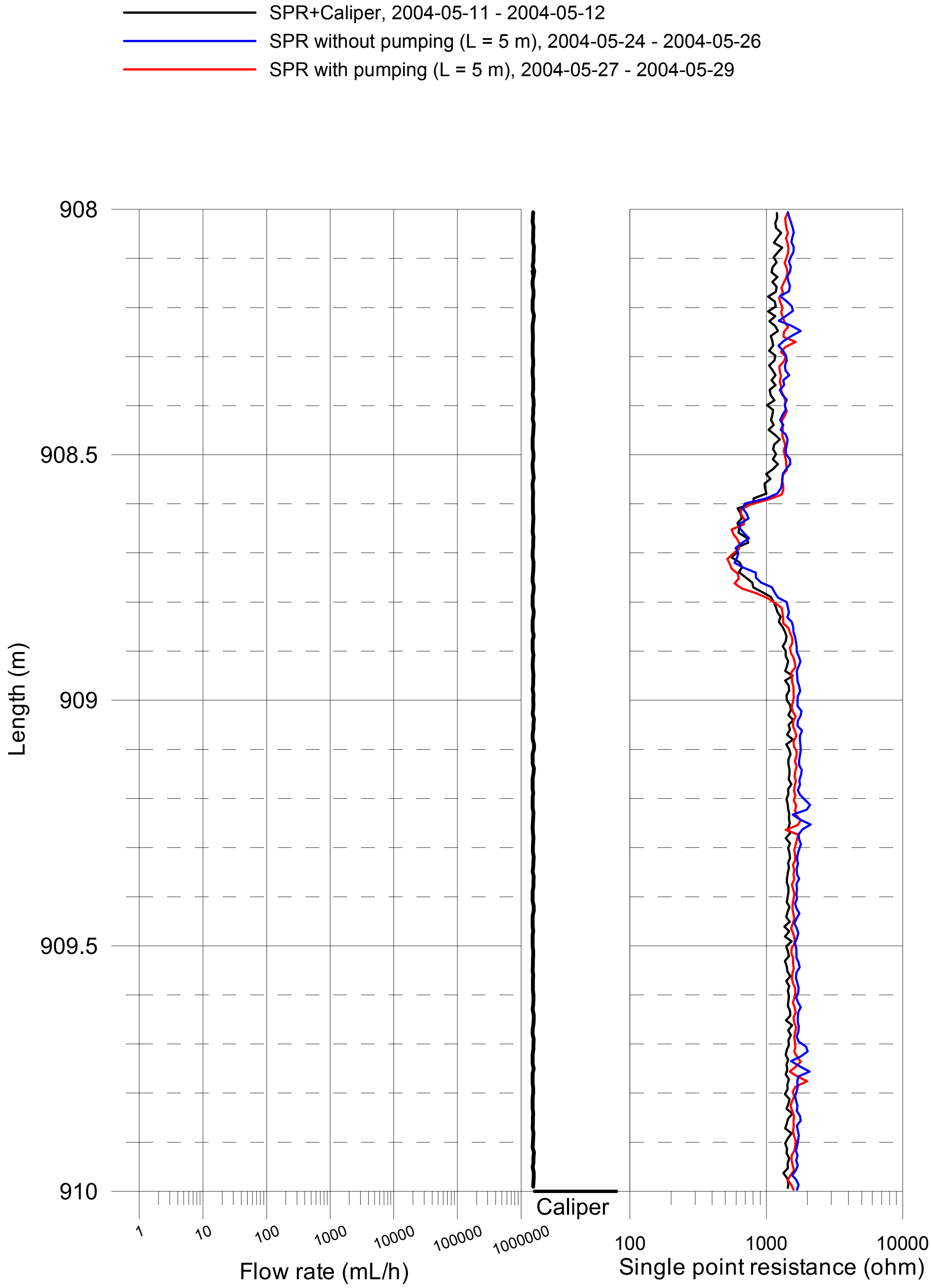
Appendix 1.31

Forsmark, KFM05A
SPR and Caliper results after length correction



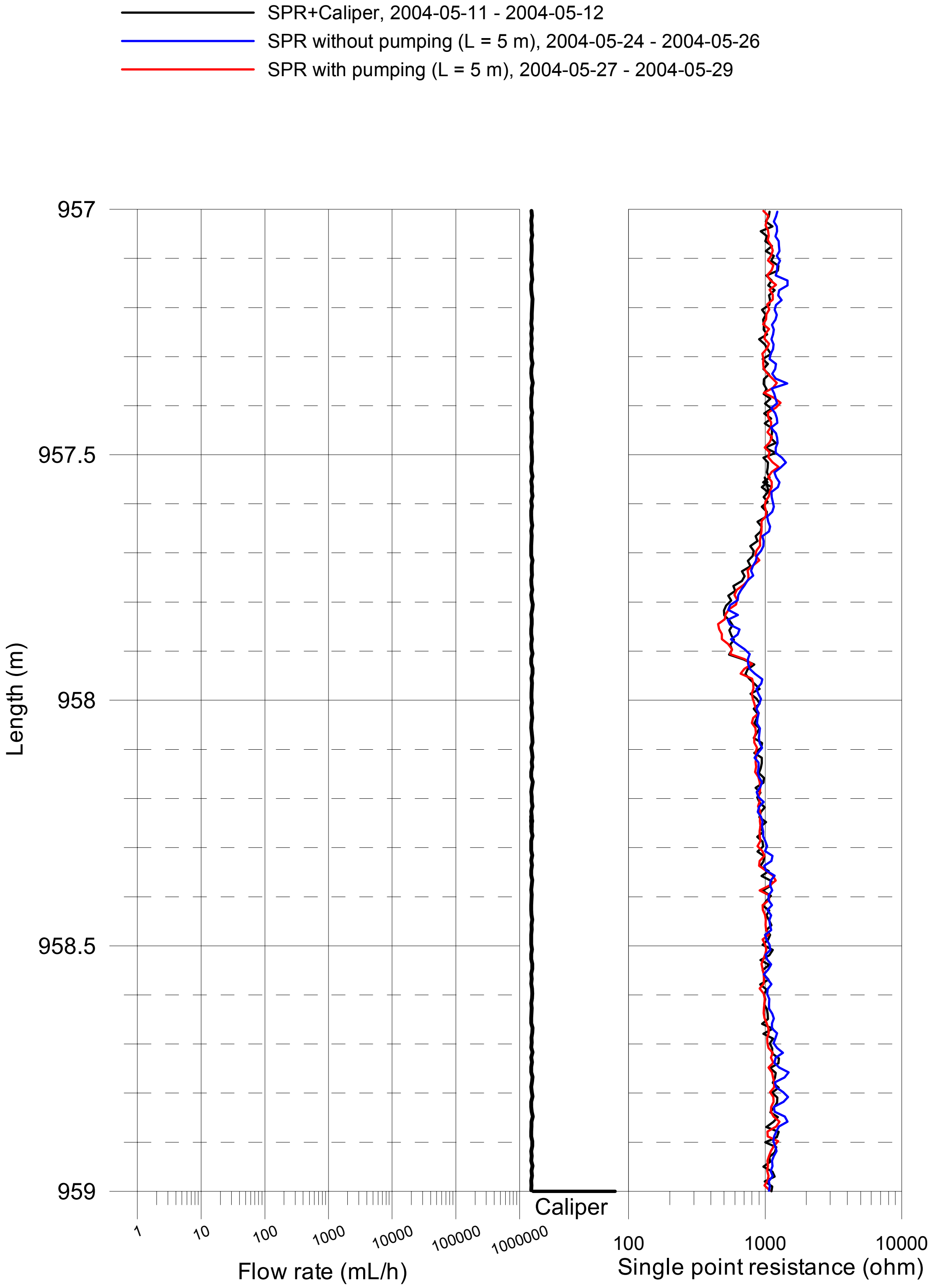
Appendix 1.32

Forsmark, KFM05A
SPR and Caliper results after length correction



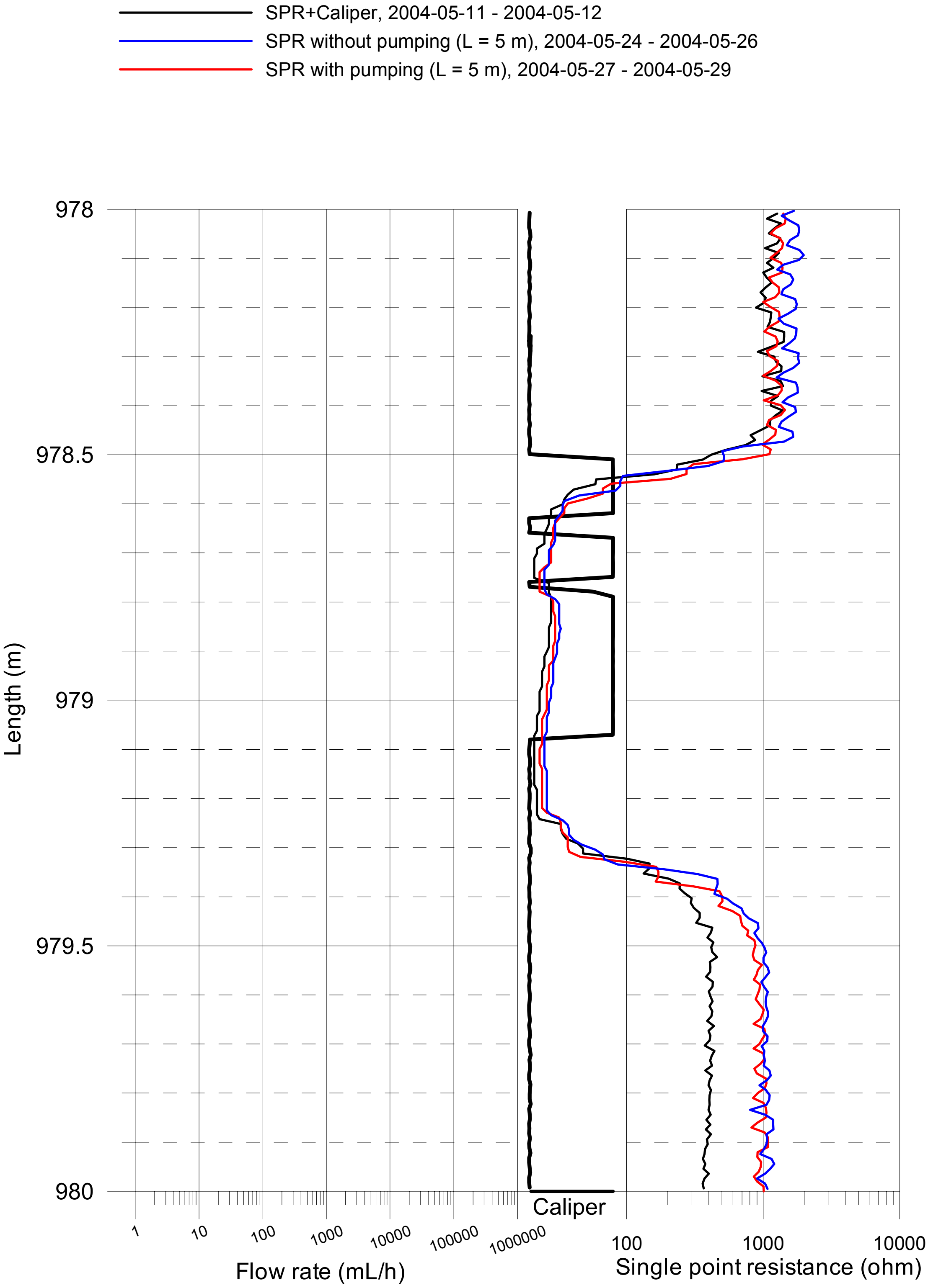
Appendix 1.33

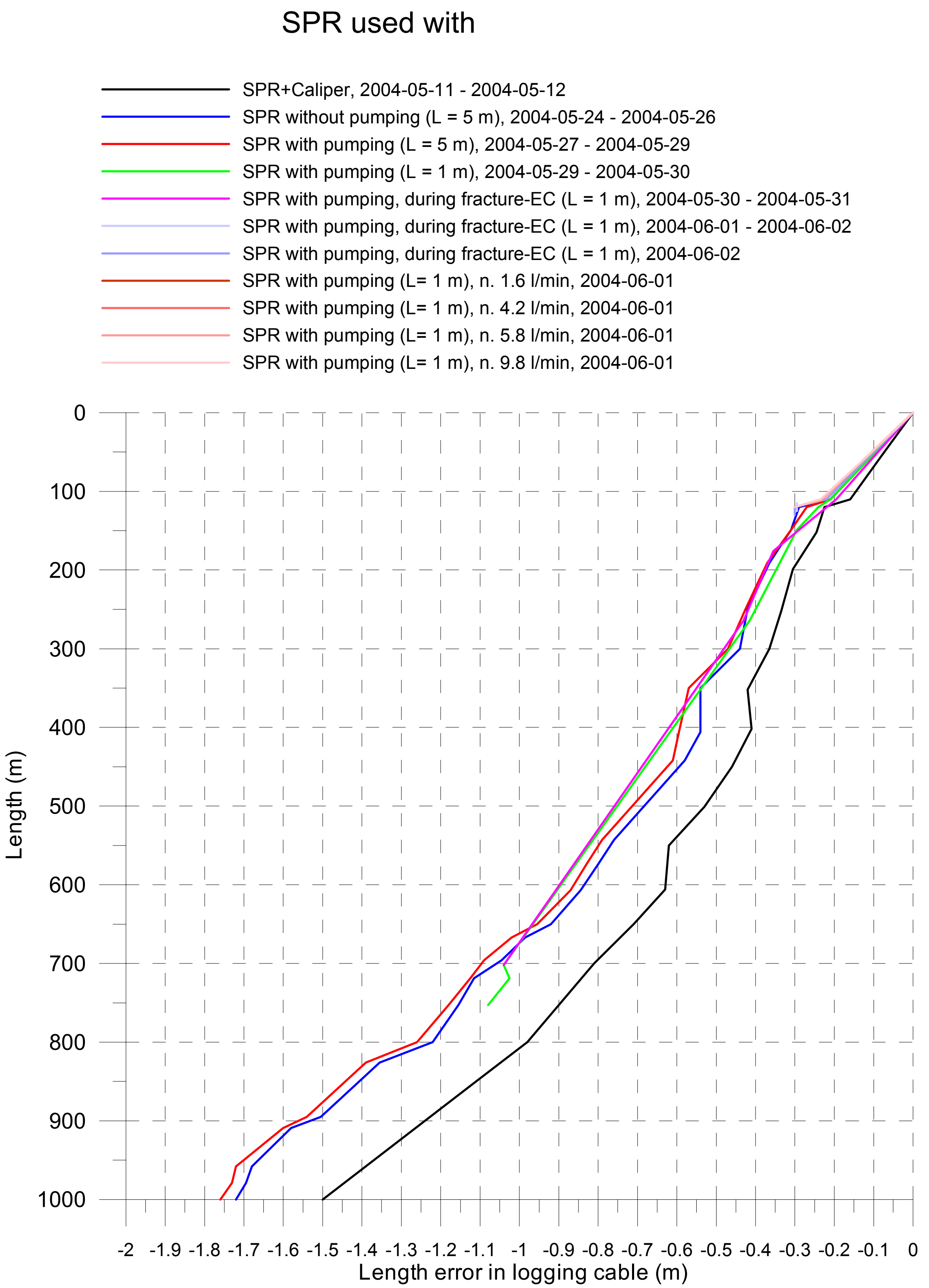
Forsmark, KFM05A
SPR and Caliper results after length correction



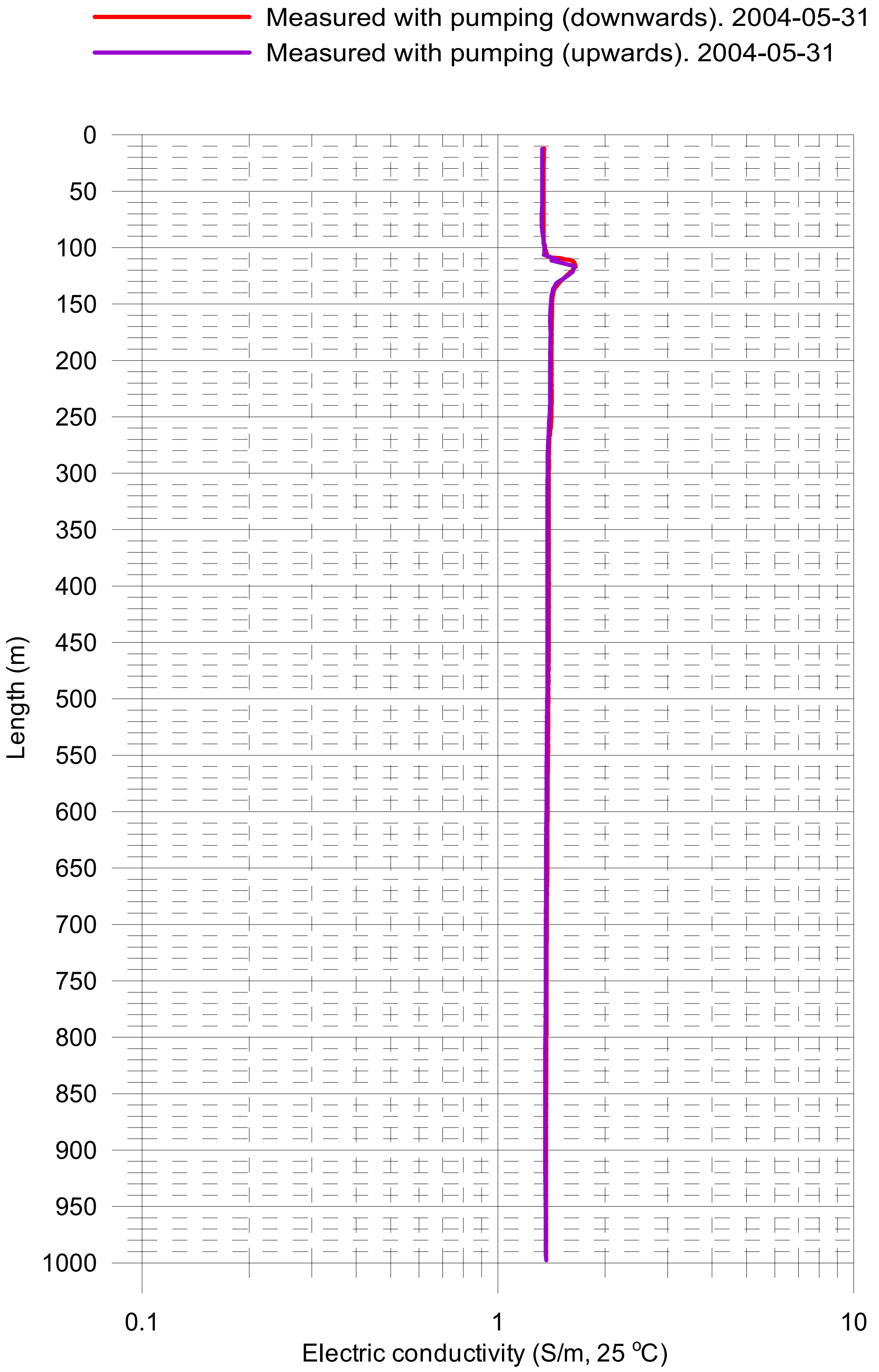
Appendix 1.34

Forsmark, KFM05A
SPR and Caliper results after length correction

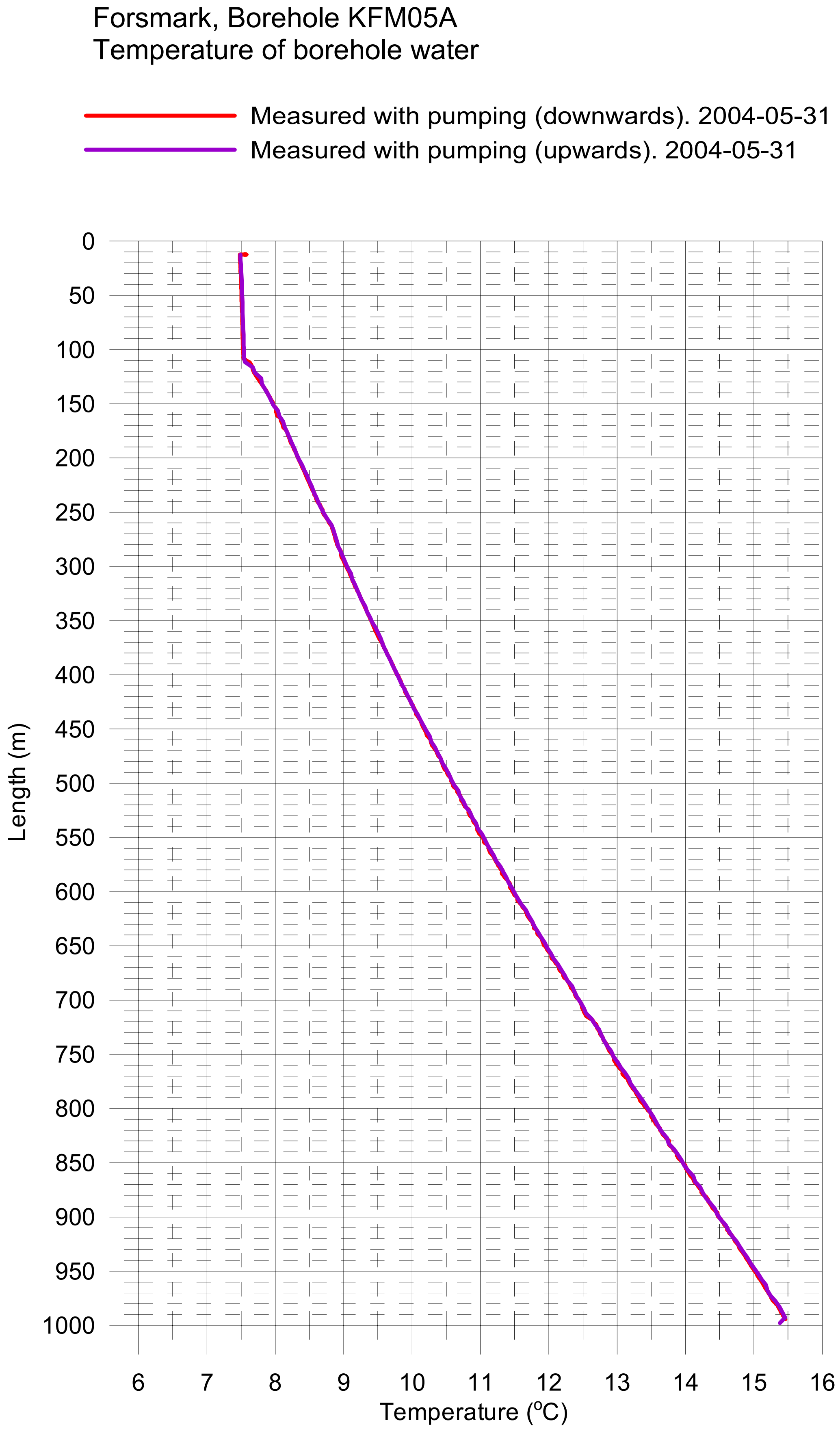



SPR used with
SPR+Caliper, 2004-05-11 - 2004-05-12
SPR without pumping (L = 5 m), 2004-05-24 - 2004-05-26
SPR with pumping (L = 5 m), 2004-05-27 - 2004-05-29
SPR with pumping (L = 1 m), 2004-05-29 - 2004-05-30
SPR with pumping, during fracture-EC (L = 1 m), 2004-05-30 - 2004-05-31
SPR with pumping, during fracture-EC (L = 1 m), 2004-06-01 - 2004-06-02
SPR with pumping, during fracture-EC (L = 1 m), 2004-06-02
SPR with pumping (L= 1 m), n. 1.6 l/min, 2004-06-01
SPR with pumping (L= 1 m), n. 4.2 l/min, 2004-06-01
SPR with pumping (L= 1 m), n. 5.8 l/min, 2004-06-01
SPR with pumping (L= 1 m), n. 9.8 l/min, 2004-06-01
0
100
200
300
400
500
600
700
800
900
1000
Length (m)
-2 -1.9 -1.8 -1.7 -1.6 -1.5 -1.4 -1.3 -1.2 -1.1 -1 -0.9 -0.8 -0.7 -0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0
Length error in logging cable (m)

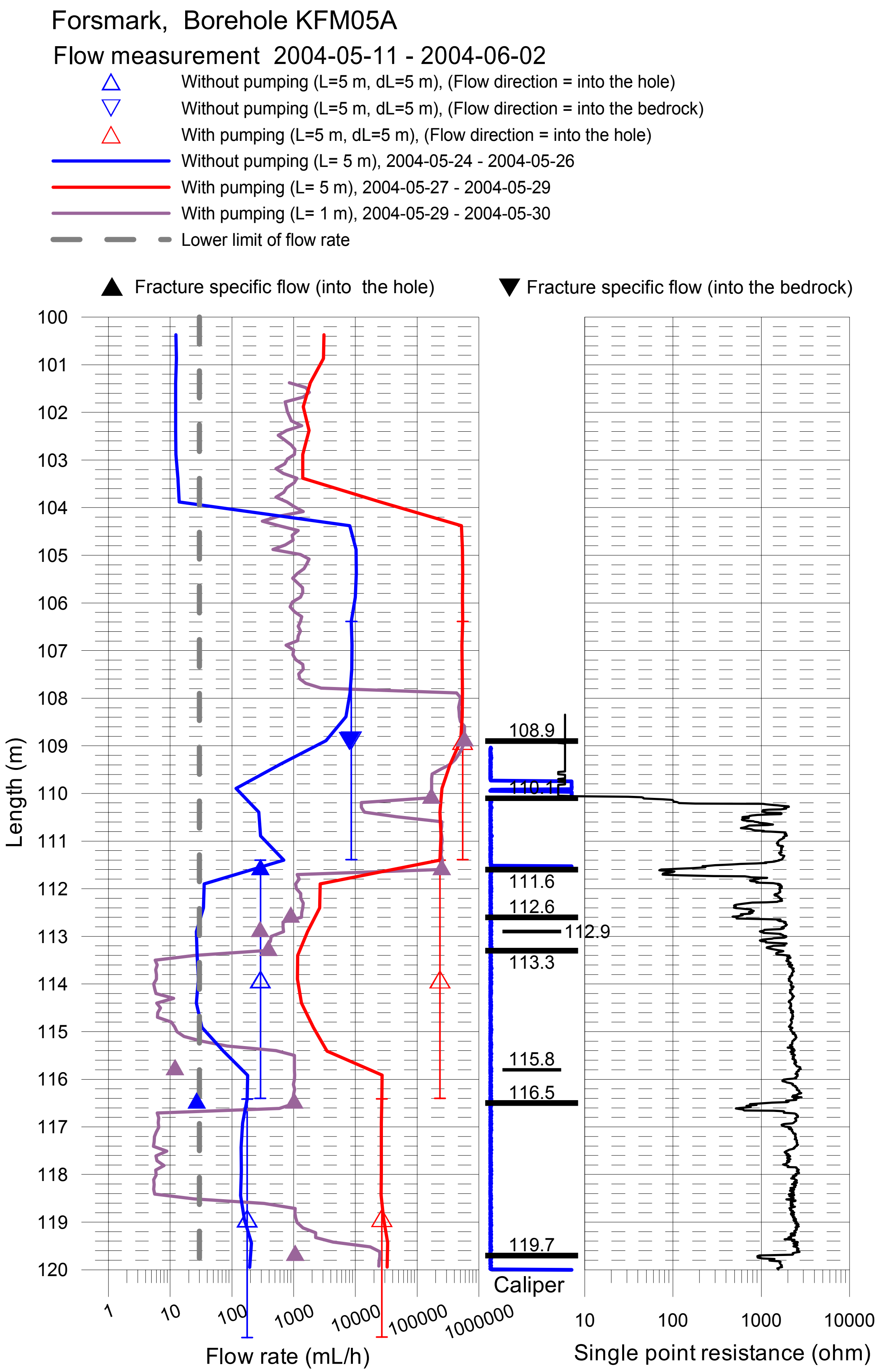
Forsmark, Borehole KFM05A
Electric conductivity of borehole water



Appendix 2.2

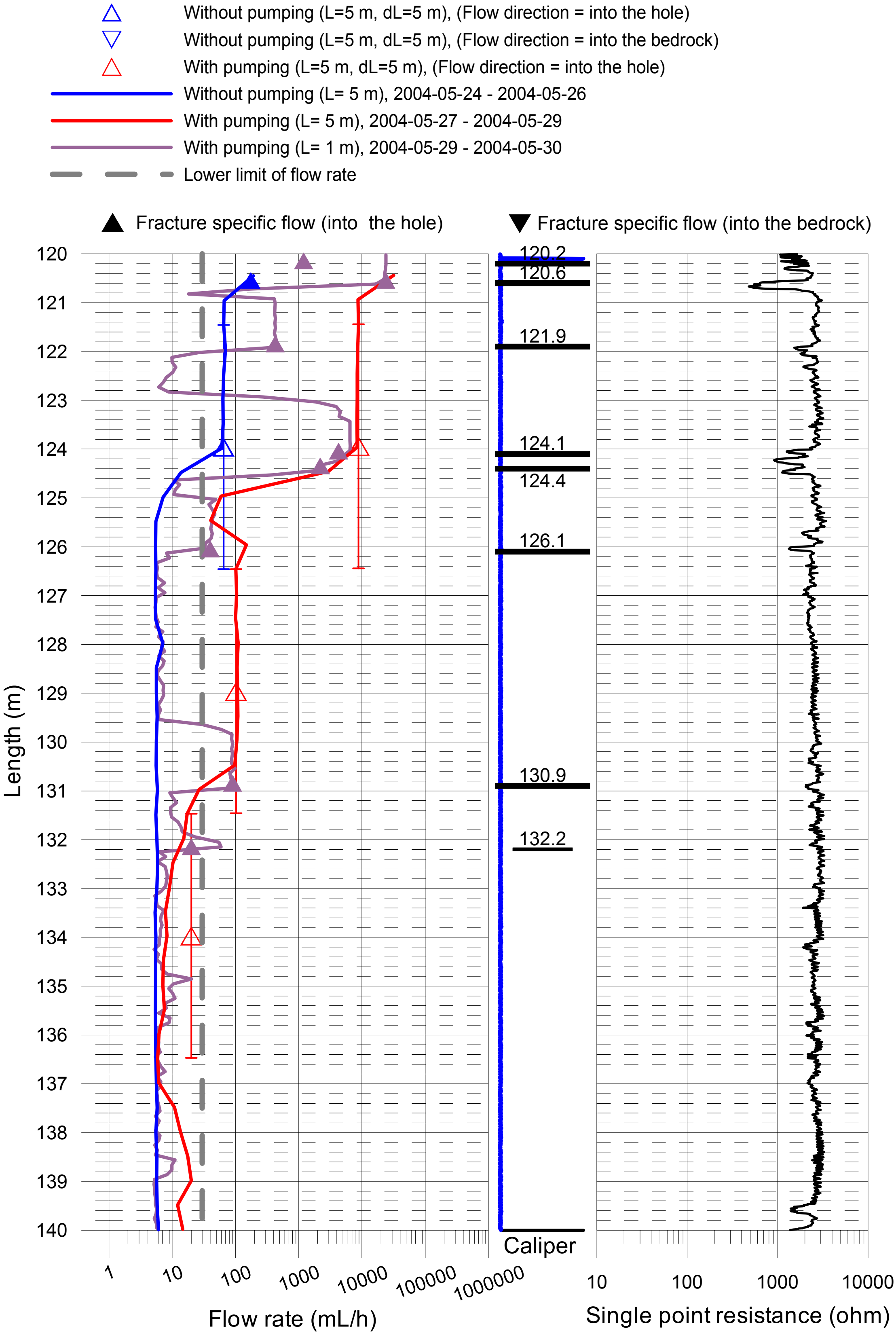


Forsmark, Borehole KFM05A
Temperature of borehole water
Measured with pumping (downwards). 2004-05-31
Measured with pumping (upwards). 2004-05-31
Length (m)
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
6
7
8
9
10
11
12
13
14
15
16
Temperature (°C)

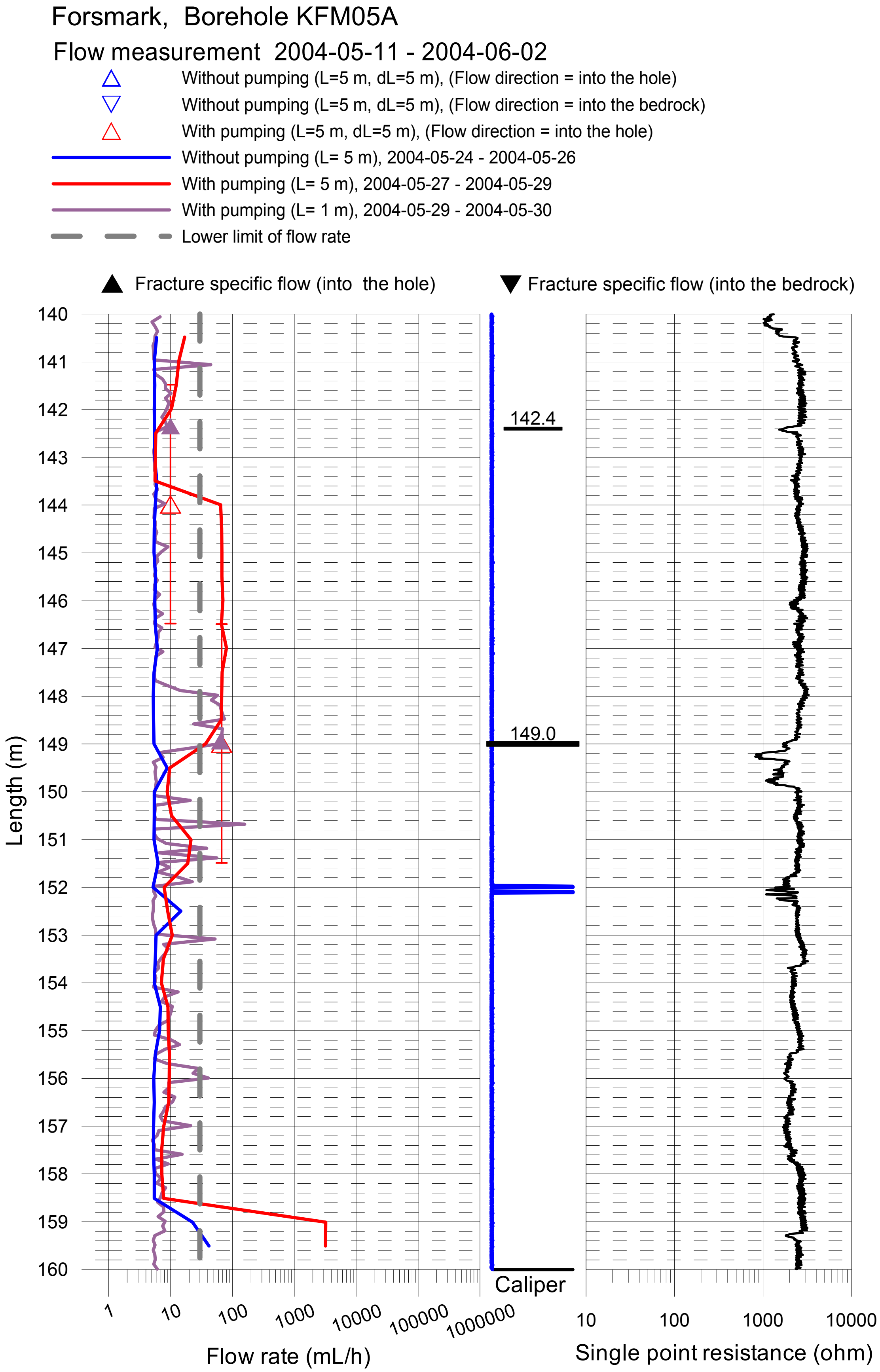

Forsmark, Borehole KFM05A
Flow measurement 2004-05-11 - 2004-06-02
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L= 5 m), 2004-05-24 - 2004-05-26
With pumping (L= 5 m), 2004-05-27 - 2004-05-29
With pumping (L= 1 m), 2004-05-29 - 2004-05-30
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
108.9
110.1
111.6
112.6
112.9
113.3
115.8
116.5
119.7
Caliper
1
10
100
1000
10000
100000
1000000
Flow rate (mL/h)
10
100
1000
10000
Single point resistance (ohm)

Forsmark, Borehole KFM05A

Flow measurement 2004-05-11 - 2004-06-02

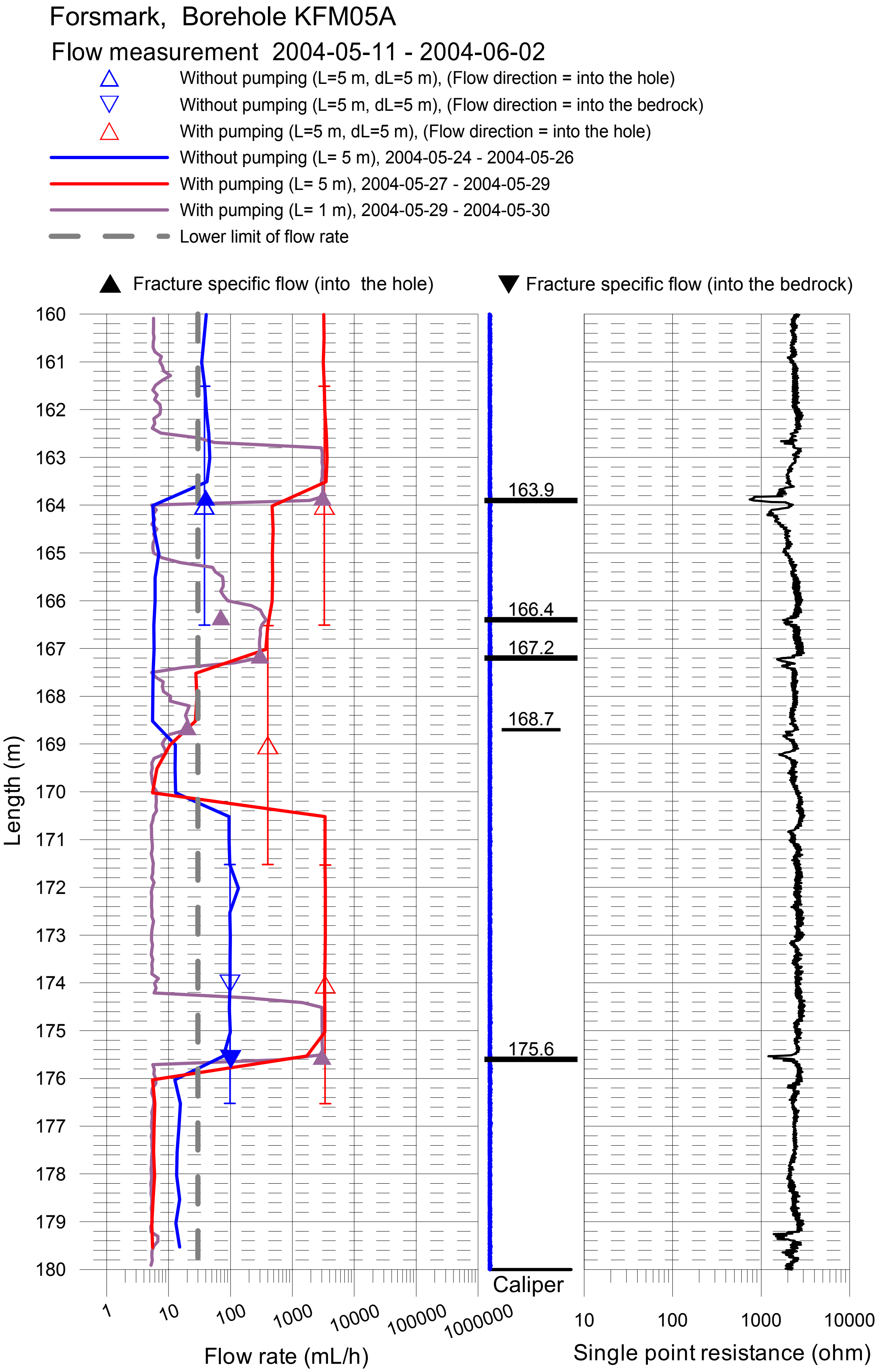


Appendix 3.3



Forsmark, Borehole KFM05A
Flow measurement 2004-05-11 - 2004-06-02
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L= 5 m), 2004-05-24 - 2004-05-26
With pumping (L= 5 m), 2004-05-27 - 2004-05-29
With pumping (L= 1 m), 2004-05-29 - 2004-05-30
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
142.4
149.0
Caliper
1
10
100
1000
10000
100000
1000000
Flow rate (mL/h)
10
100
1000
10000
Single point resistance (ohm)

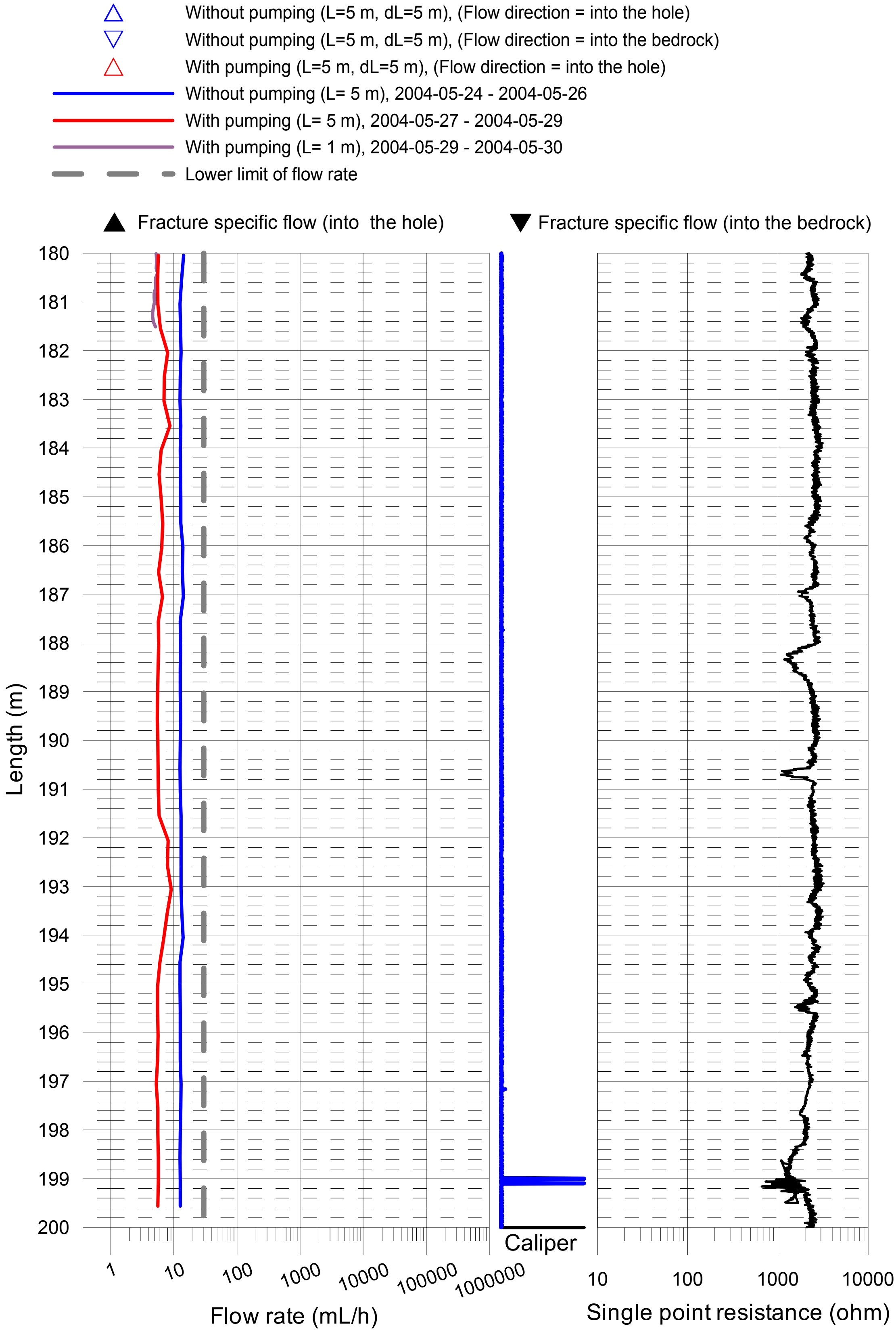
Appendix 3.4



Forsmark, Borehole KFM05A
Flow measurement 2004-05-11 - 2004-06-02
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L= 5 m), 2004-05-24 - 2004-05-26
With pumping (L= 5 m), 2004-05-27 - 2004-05-29
With pumping (L= 1 m), 2004-05-29 - 2004-05-30
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179
180
163.9
166.4
167.2
168.7
175.6
Caliper
1
10
100
1000
10000
100000
1000000
Flow rate (mL/h)
10
100
1000
10000
Single point resistance (ohm)

Forsmark, Borehole KFM05A

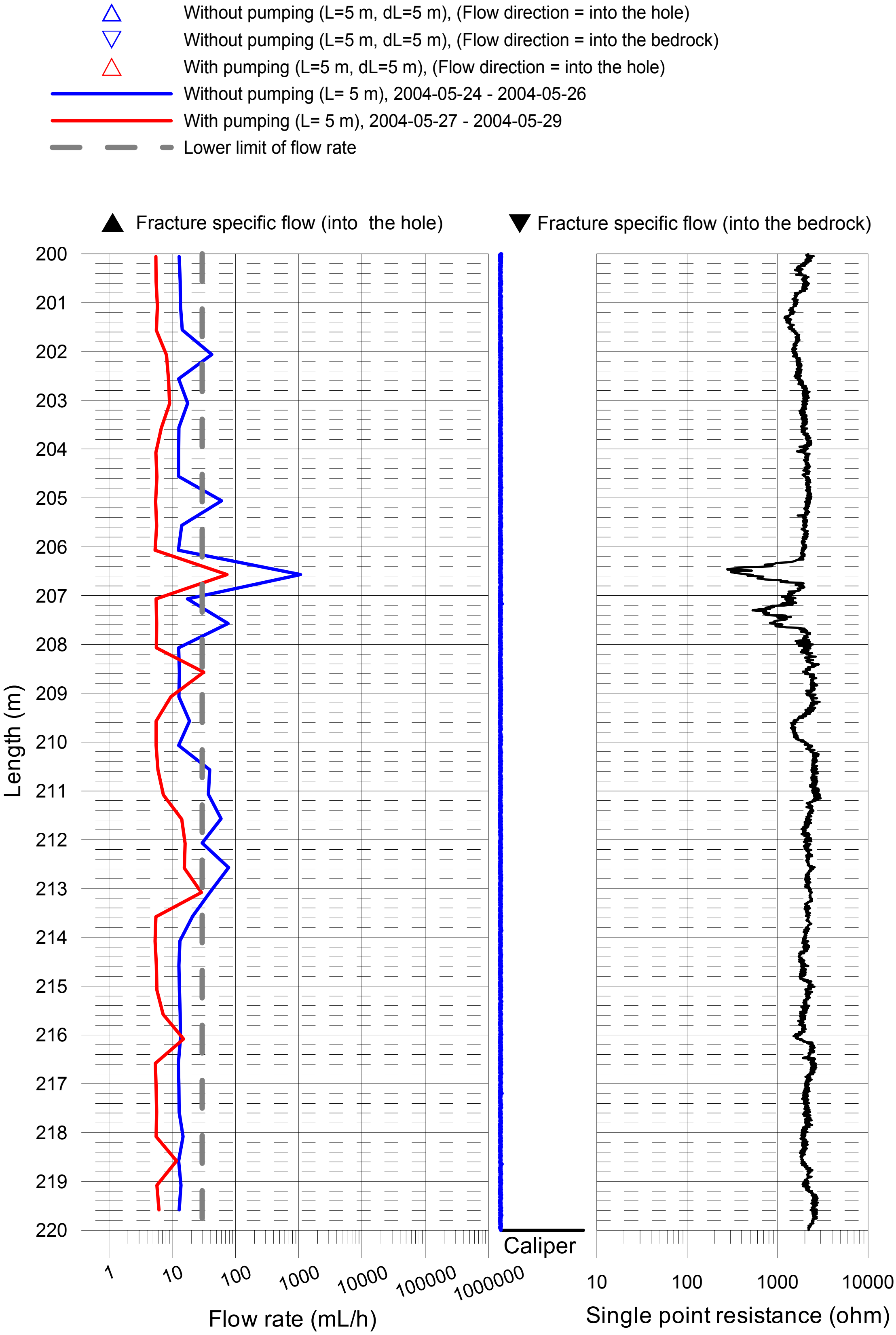
Flow measurement 2004-05-11 - 2004-06-02

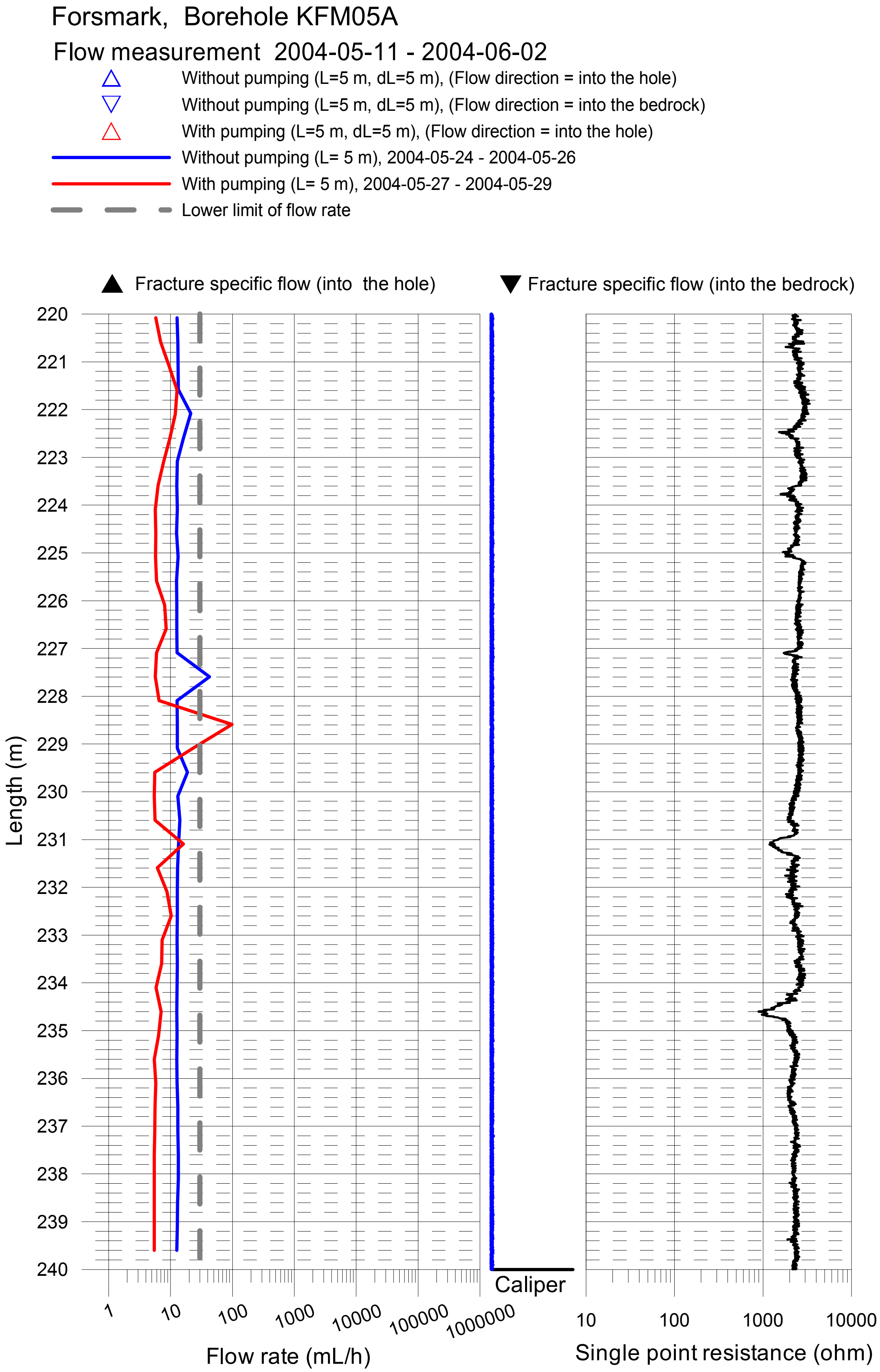


Appendix 3.6

Forsmark, Borehole KFM05A

Flow measurement 2004-05-11 - 2004-06-02

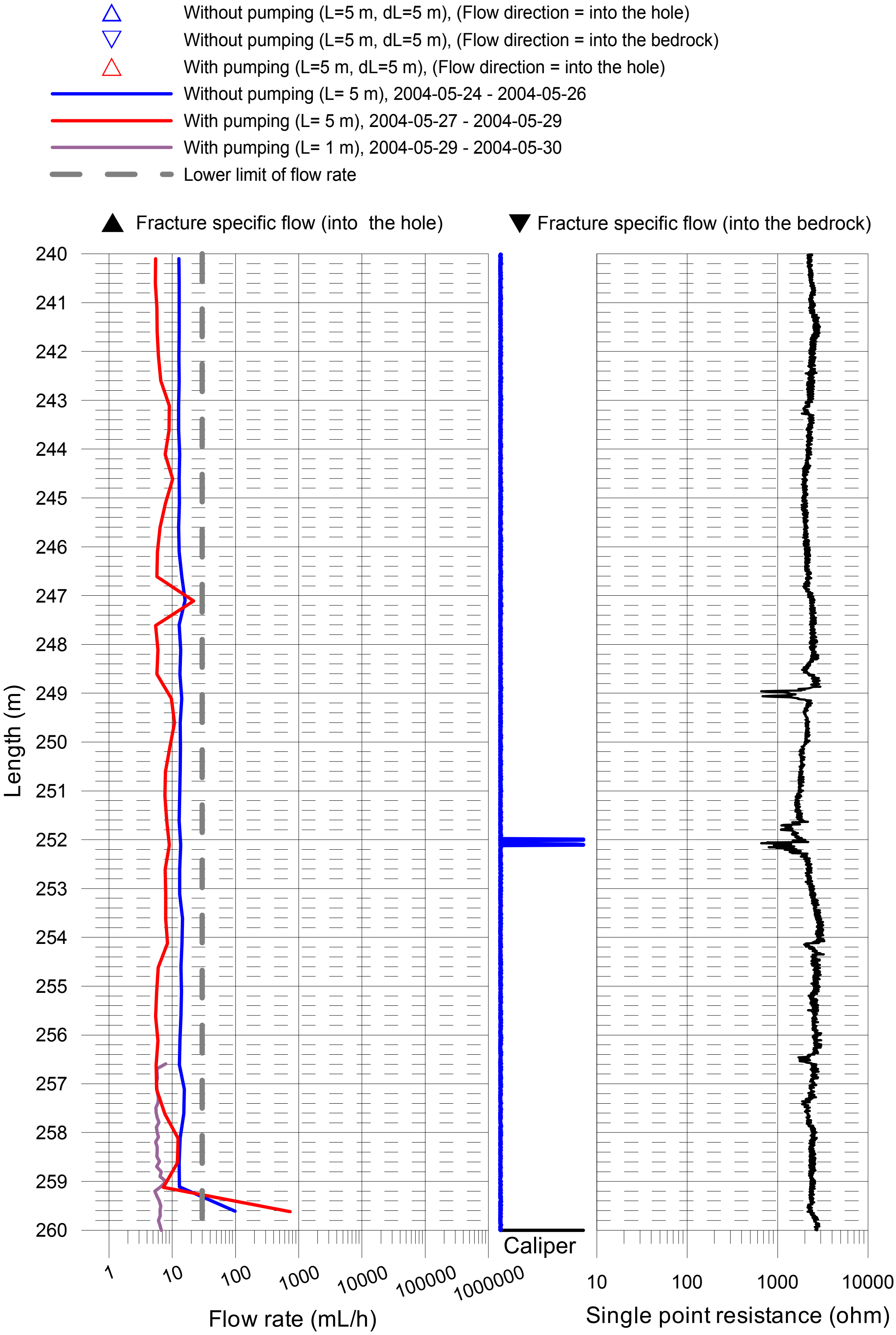



Forsmark, Borehole KFM05A
Flow measurement 2004-05-11 - 2004-06-02
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L= 5 m), 2004-05-24 - 2004-05-26
With pumping (L= 5 m), 2004-05-27 - 2004-05-29
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
220
221
222
223
224
225
226
227
228
229
230
231
232
233
234
235
236
237
238
239
240
1
10
100
1000
10000
100000
1000000
Flow rate (mL/h)
Caliper
10
100
1000
10000
Single point resistance (ohm)

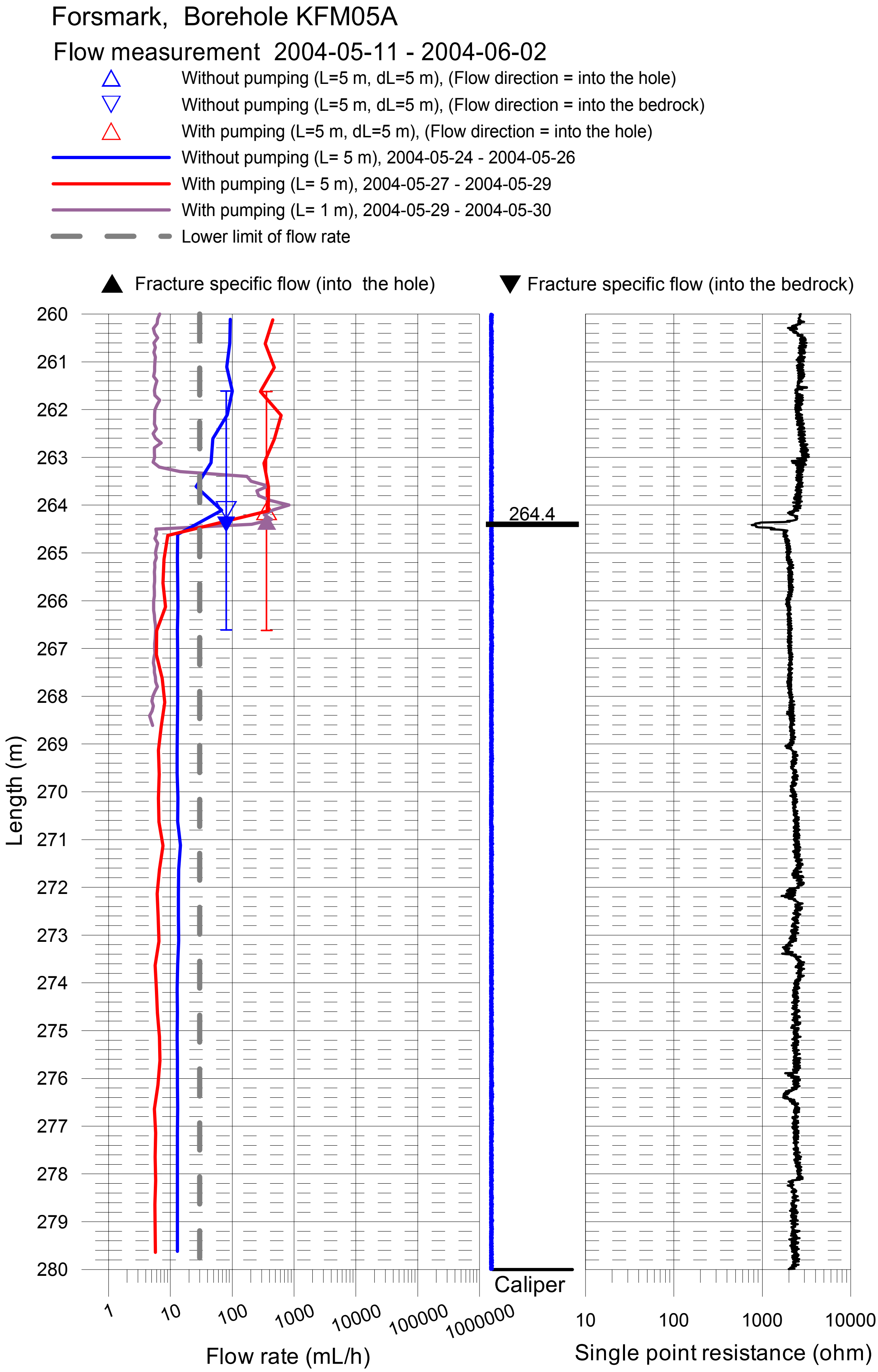
Appendix 3.8

Forsmark, Borehole KFM05A

Flow measurement 2004-05-11 - 2004-06-02



Appendix 3.9

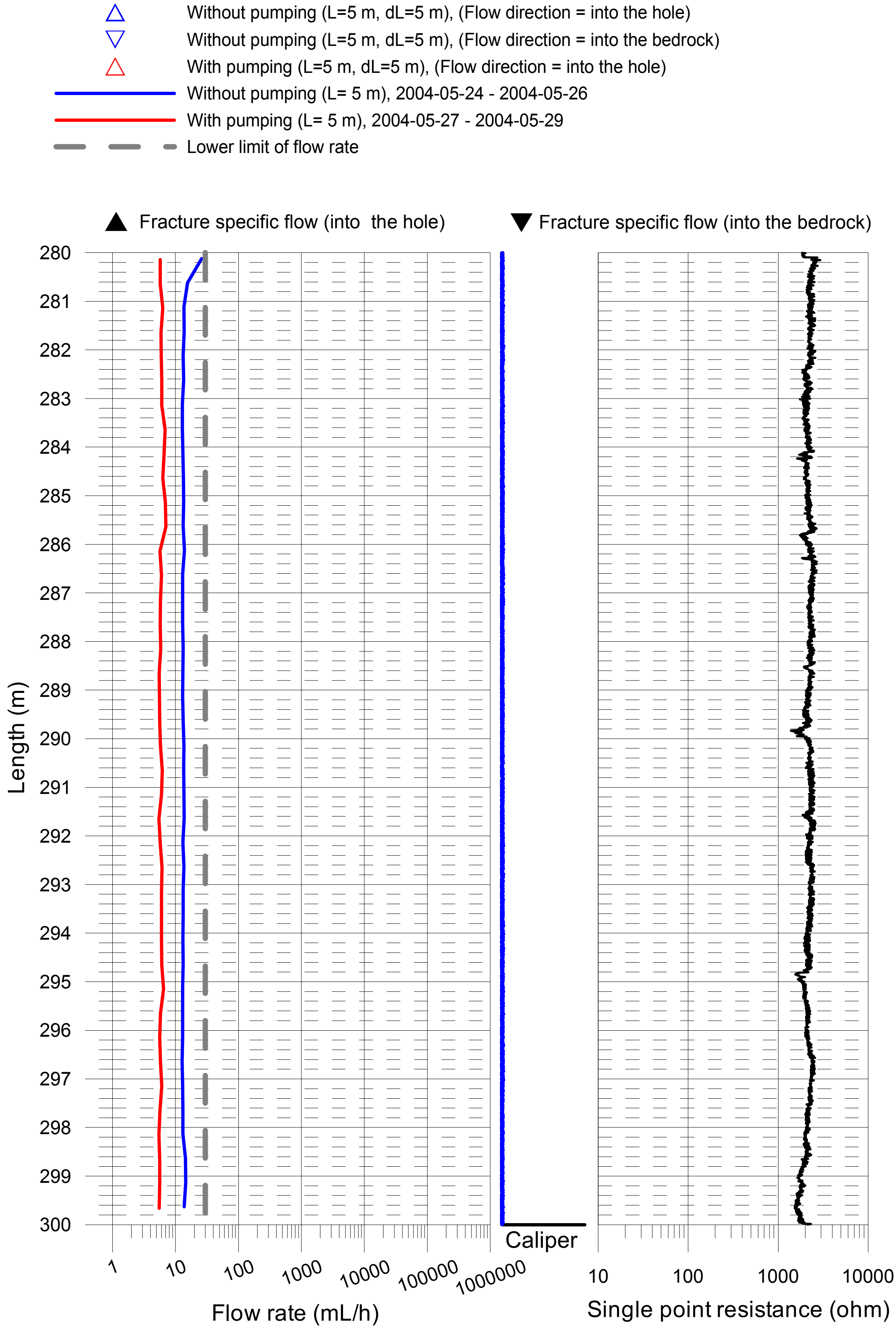


Forsmark, Borehole KFM05A
Flow measurement 2004-05-11 - 2004-06-02
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L= 5 m), 2004-05-24 - 2004-05-26
With pumping (L= 5 m), 2004-05-27 - 2004-05-29
With pumping (L= 1 m), 2004-05-29 - 2004-05-30
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
260
261
262
263
264
265
266
267
268
269
270
271
272
273
274
275
276
277
278
279
280
Length (m)
264.4
Caliper
1
10
100
1000
10000
100000
1000000
Flow rate (mL/h)
10
100
1000
10000
Single point resistance (ohm)

Appendix 3.10

Forsmark, Borehole KFM05A

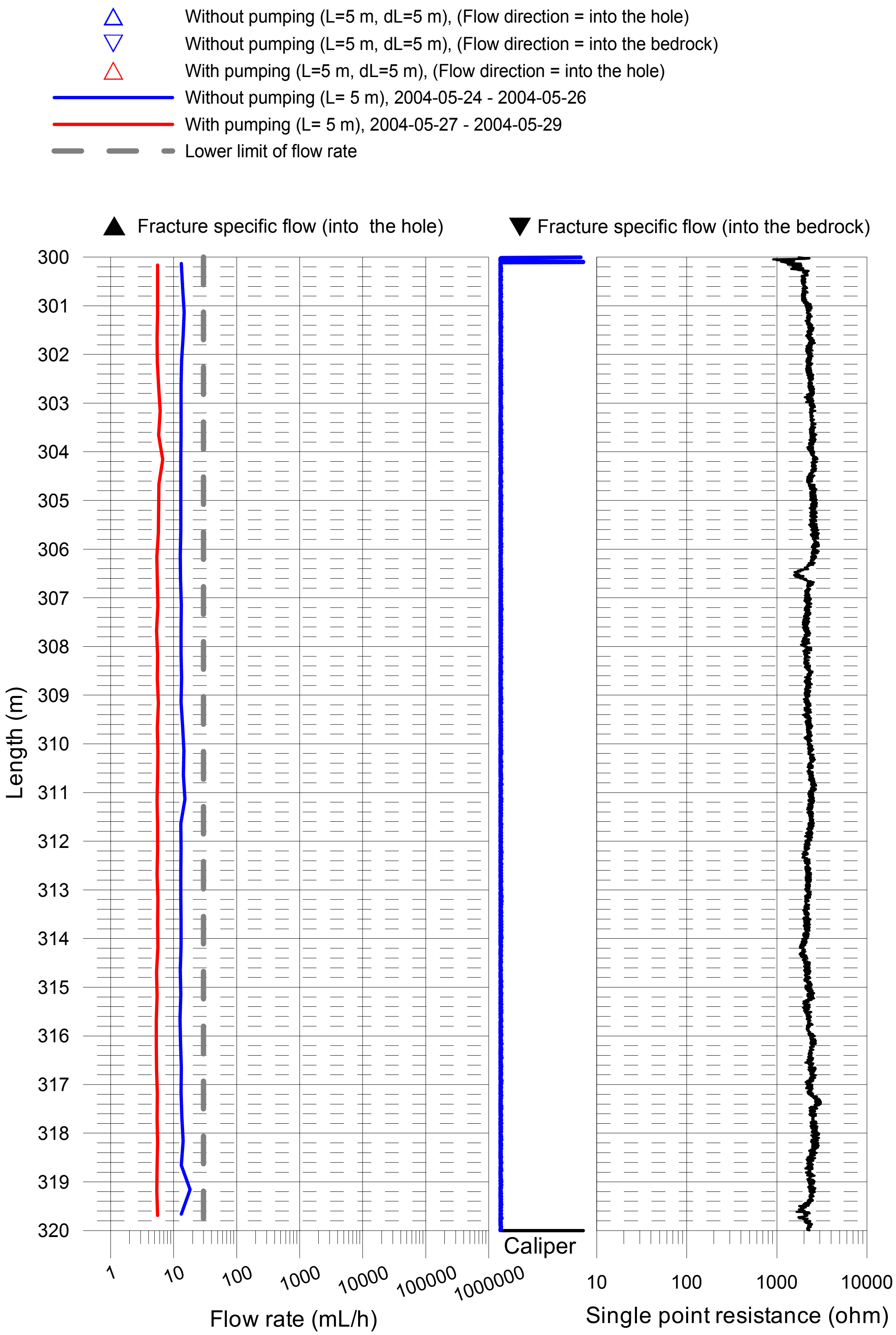
Flow measurement 2004-05-11 - 2004-06-02



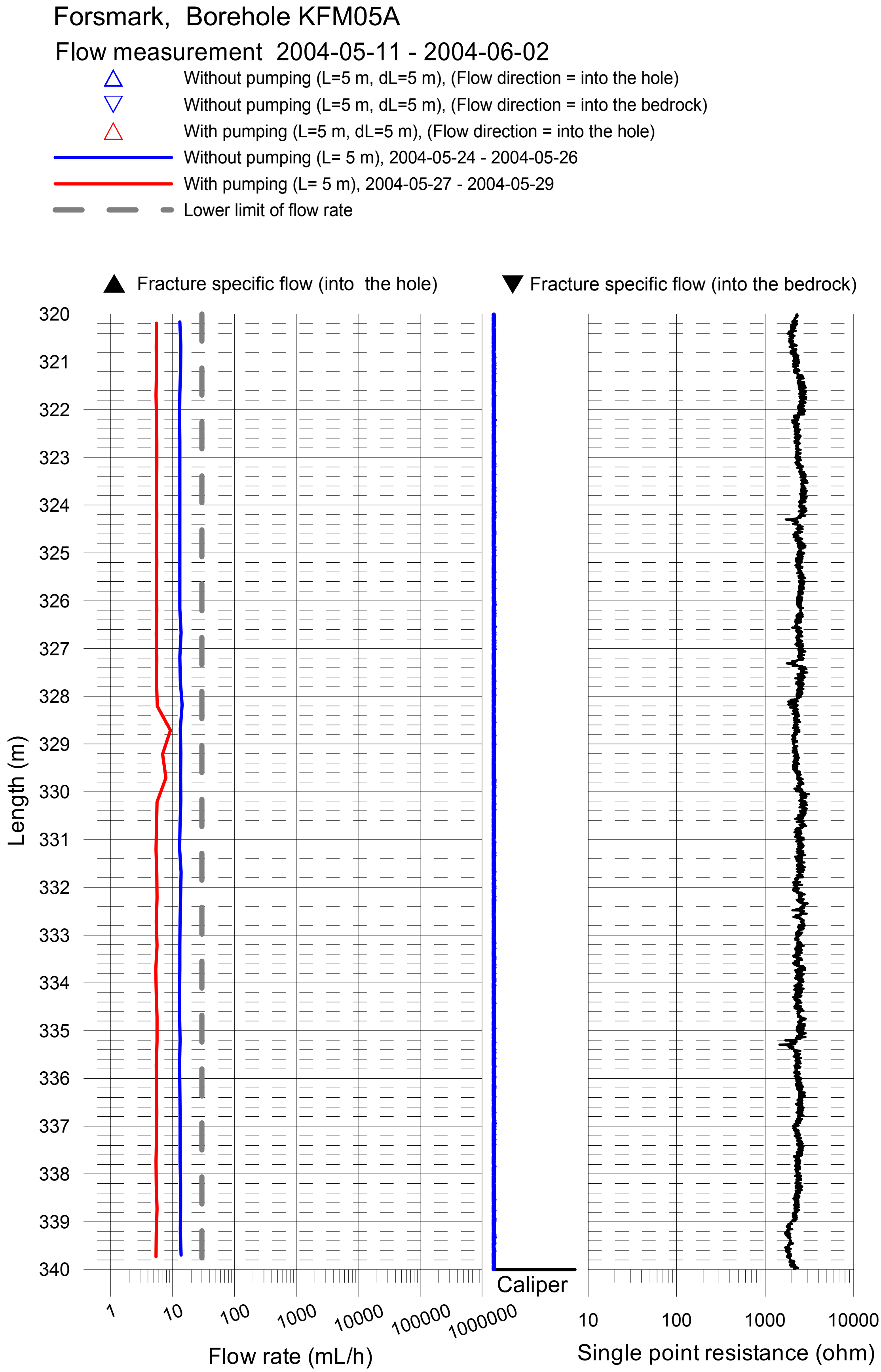
Appendix 3.11

Forsmark, Borehole KFM05A

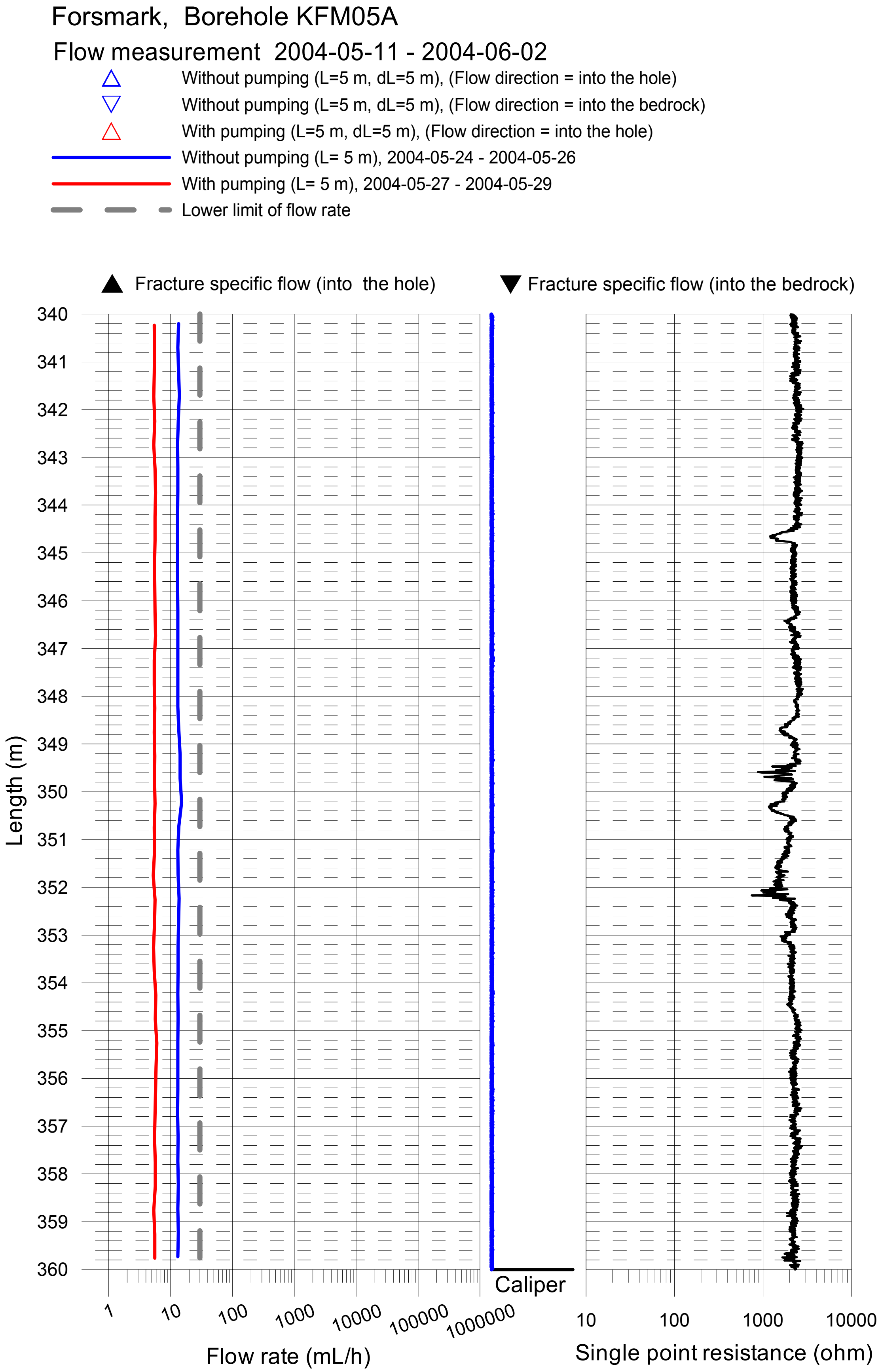
Flow measurement 2004-05-11 - 2004-06-02



Appendix 3.12

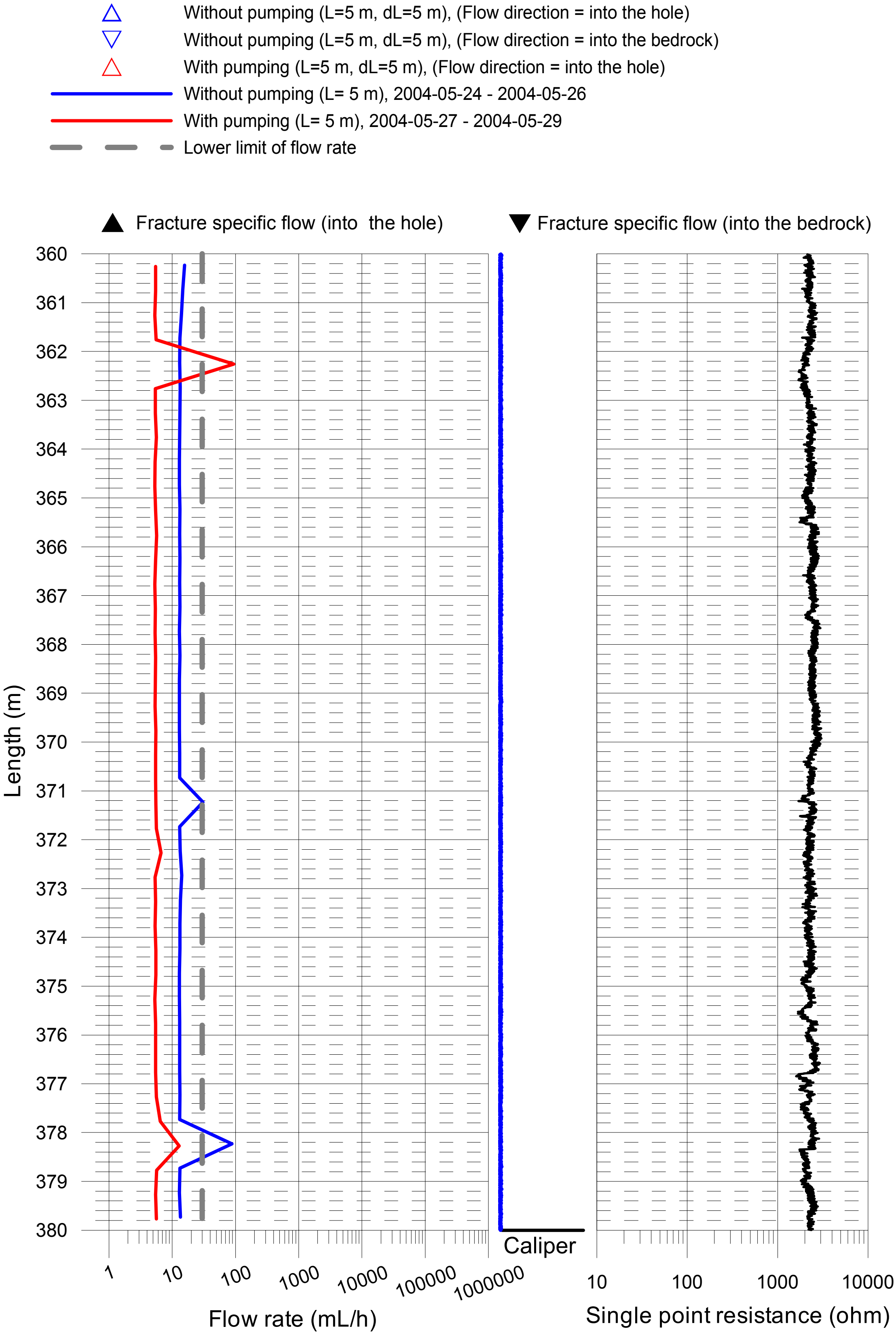


Appendix 3.13

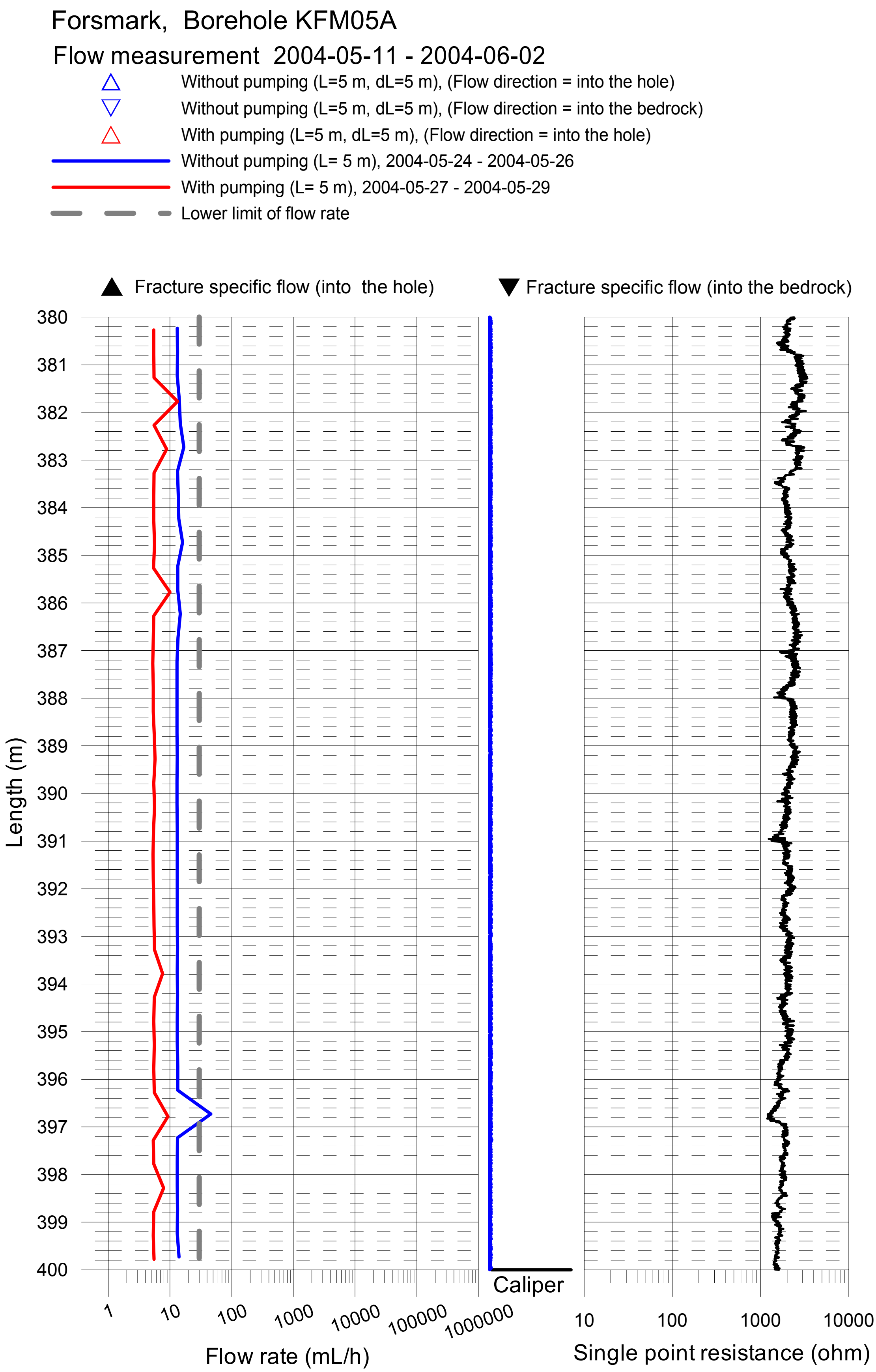


Forsmark, Borehole KFM05A

Flow measurement 2004-05-11 - 2004-06-02



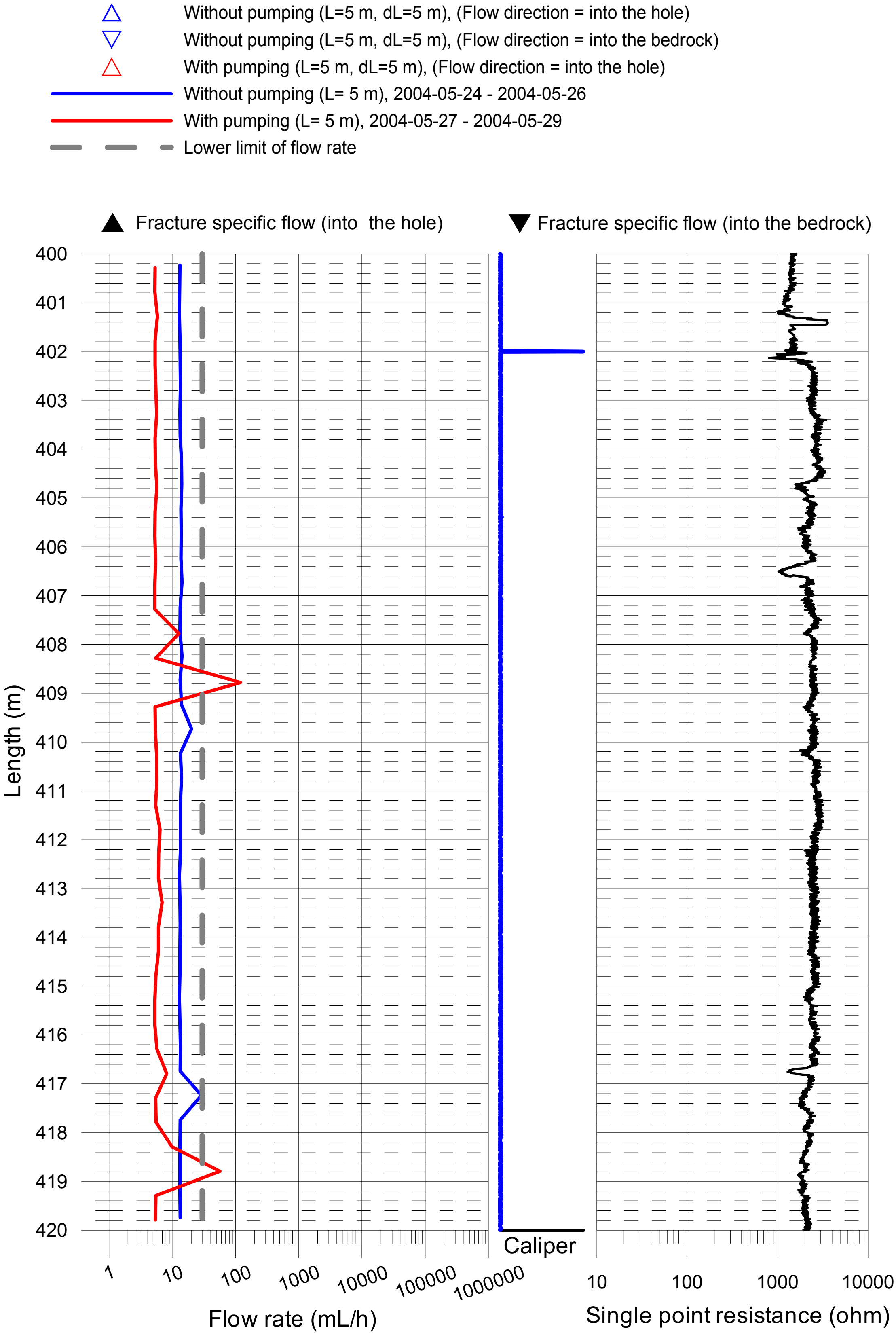
Appendix 3.15

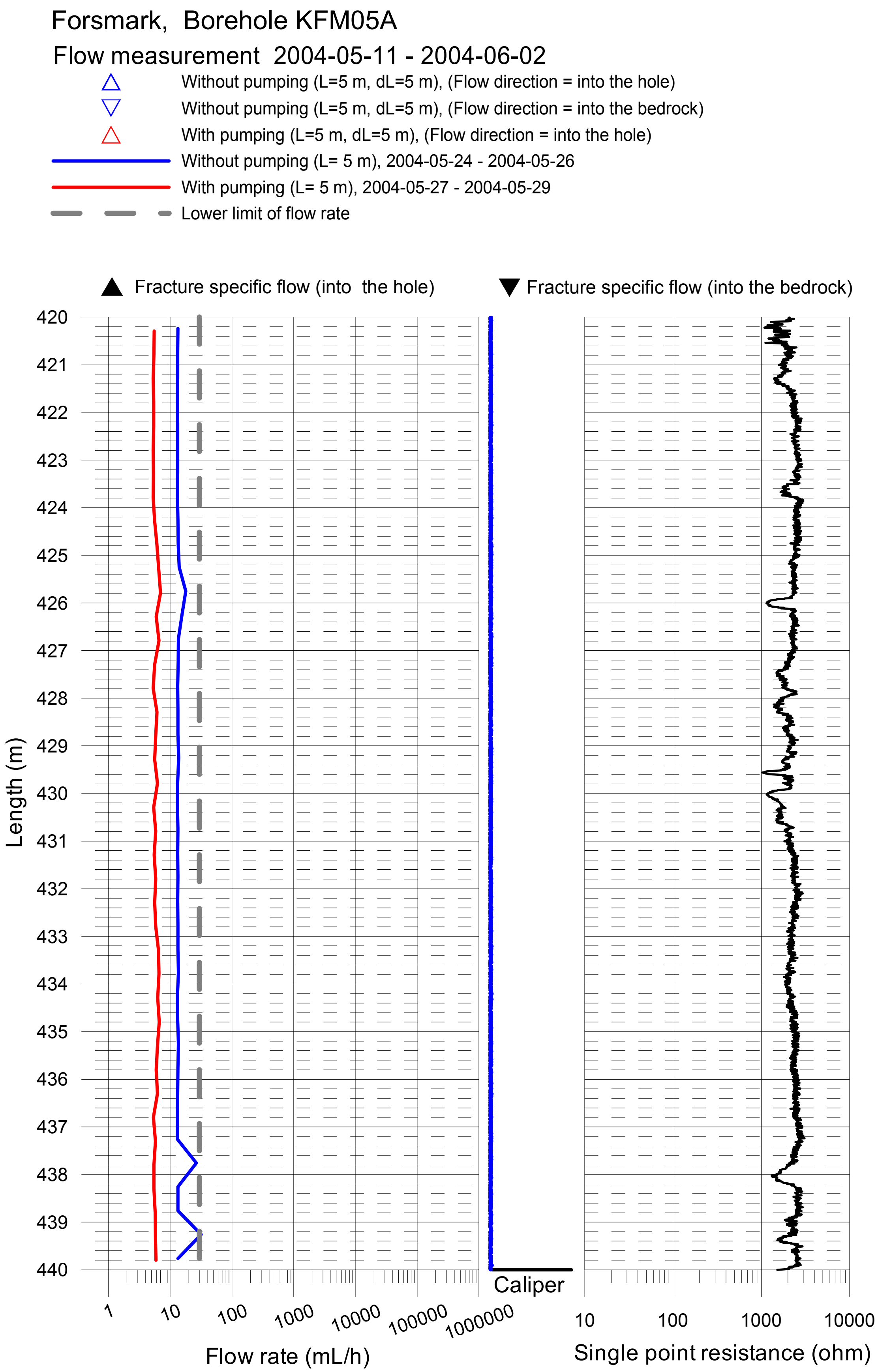


Appendix 3.16

Forsmark, Borehole KFM05A

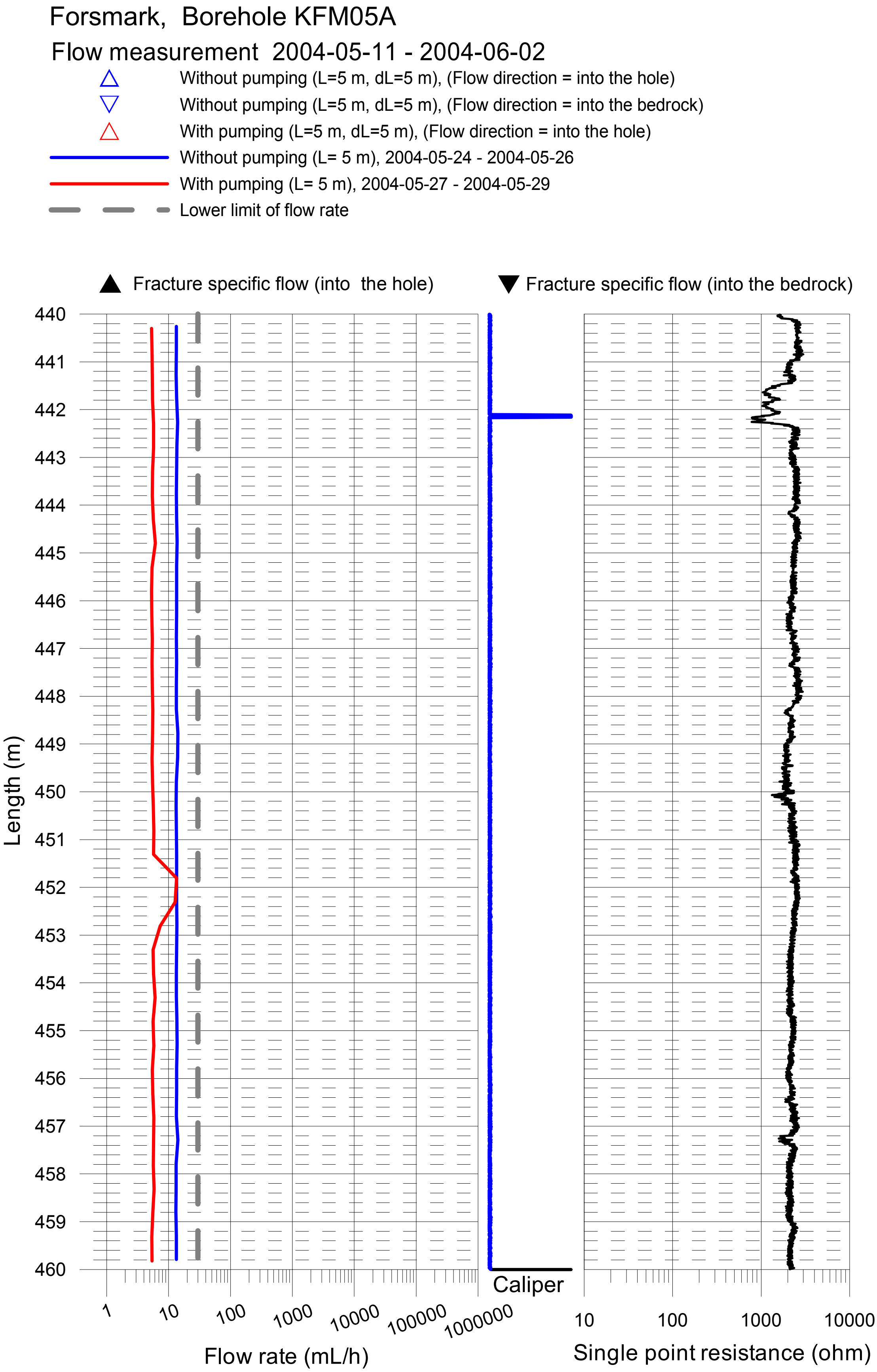
Flow measurement 2004-05-11 - 2004-06-02





Forsmark, Borehole KFM05A
Flow measurement 2004-05-11 - 2004-06-02
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L= 5 m), 2004-05-24 - 2004-05-26
With pumping (L= 5 m), 2004-05-27 - 2004-05-29
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
420
421
422
423
424
425
426
427
428
429
430
431
432
433
434
435
436
437
438
439
440
1
10
100
1000
10000
100000
1000000
Flow rate (mL/h)
Caliper
10
100
1000
10000
Single point resistance (ohm)

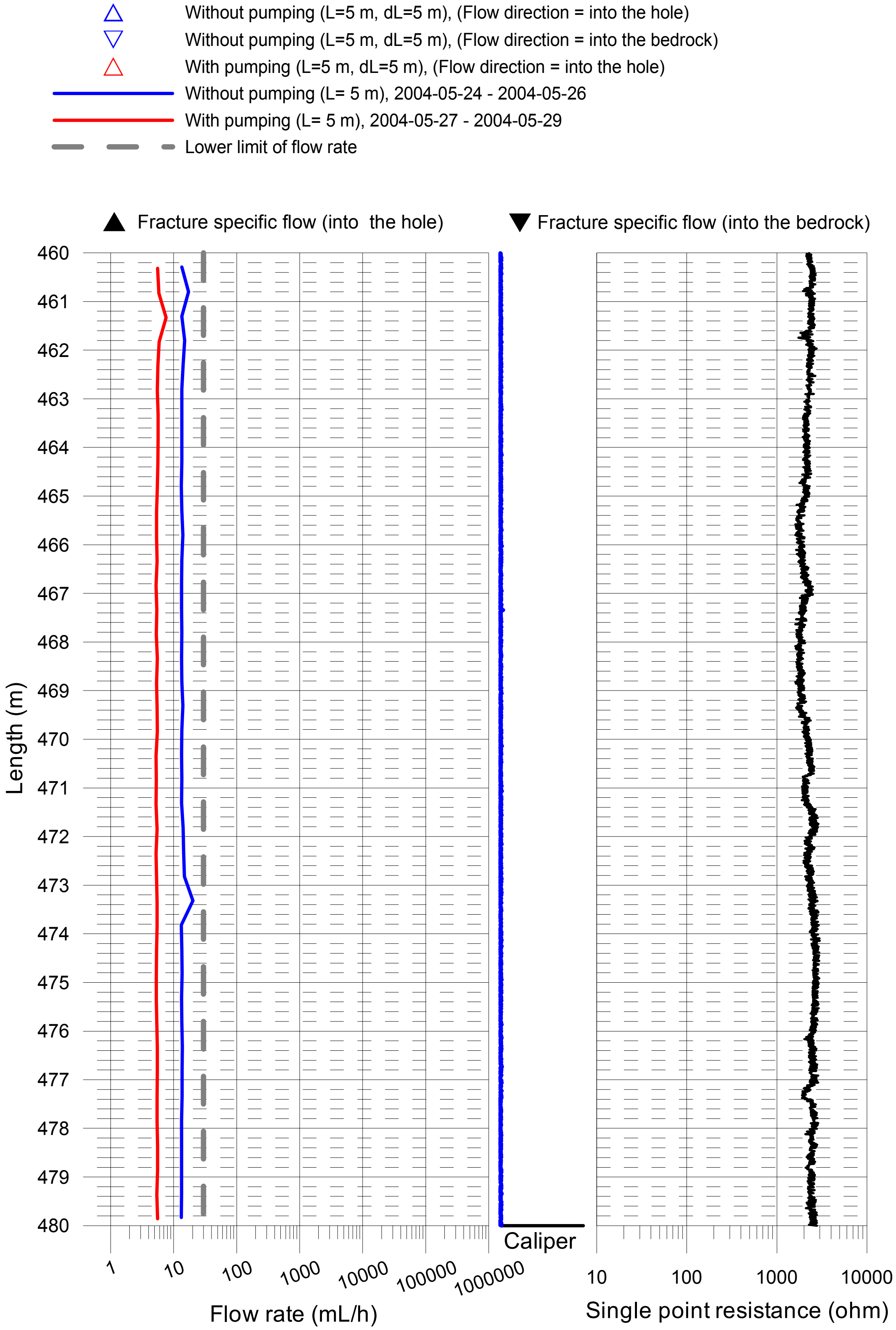
Appendix 3.18



Appendix 3.19

Forsmark, Borehole KFM05A

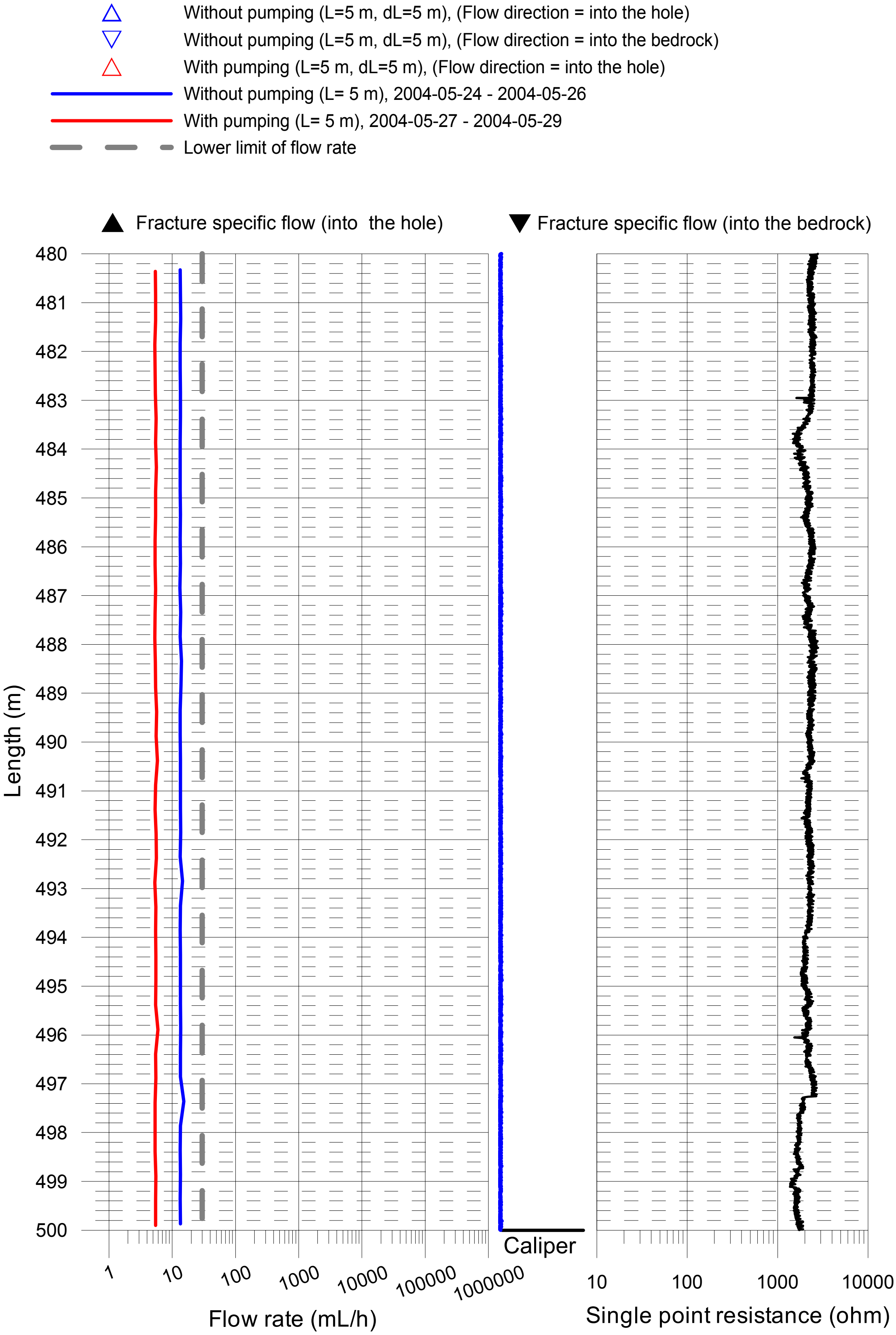
Flow measurement 2004-05-11 - 2004-06-02



Appendix 3.20

Forsmark, Borehole KFM05A

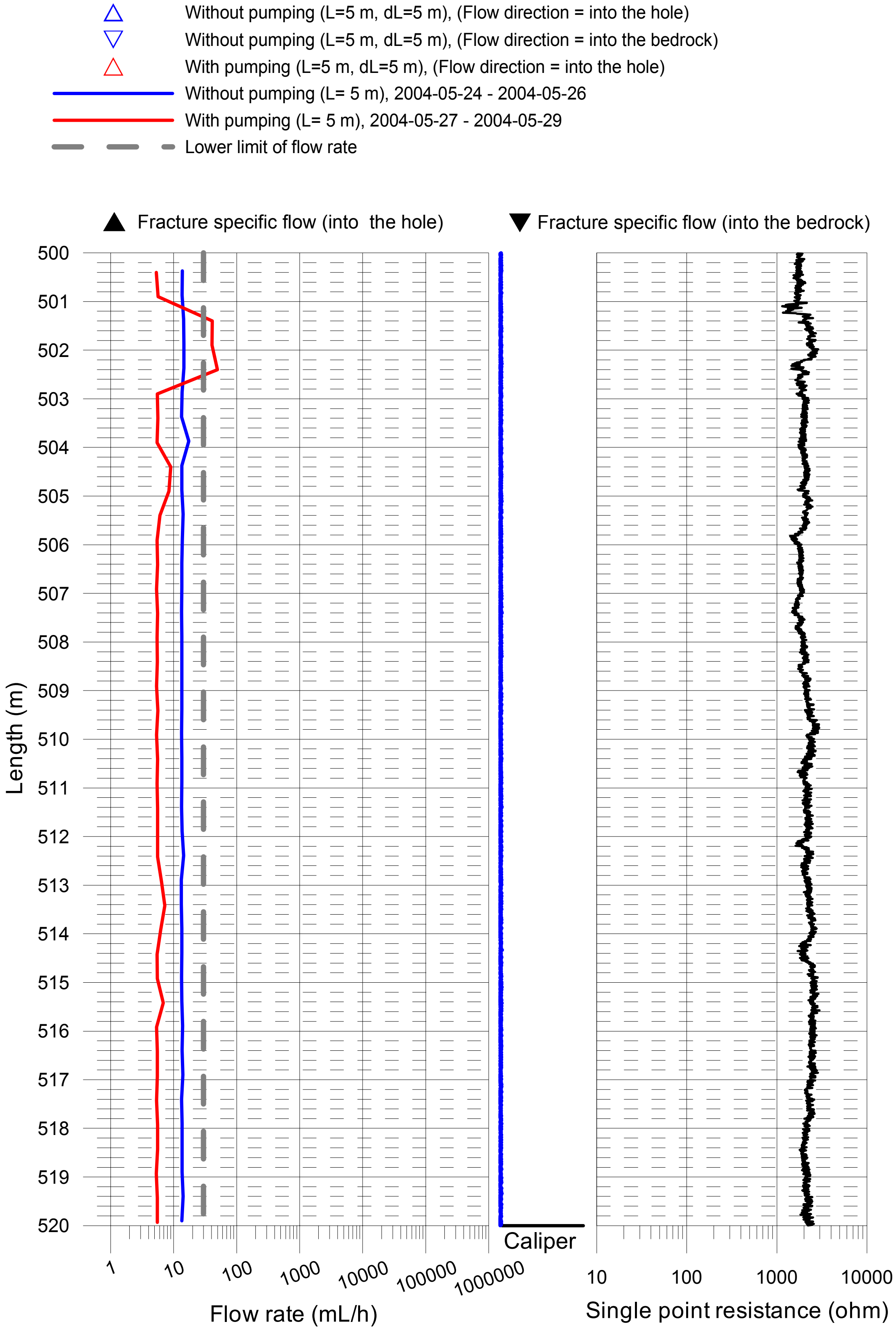
Flow measurement 2004-05-11 - 2004-06-02



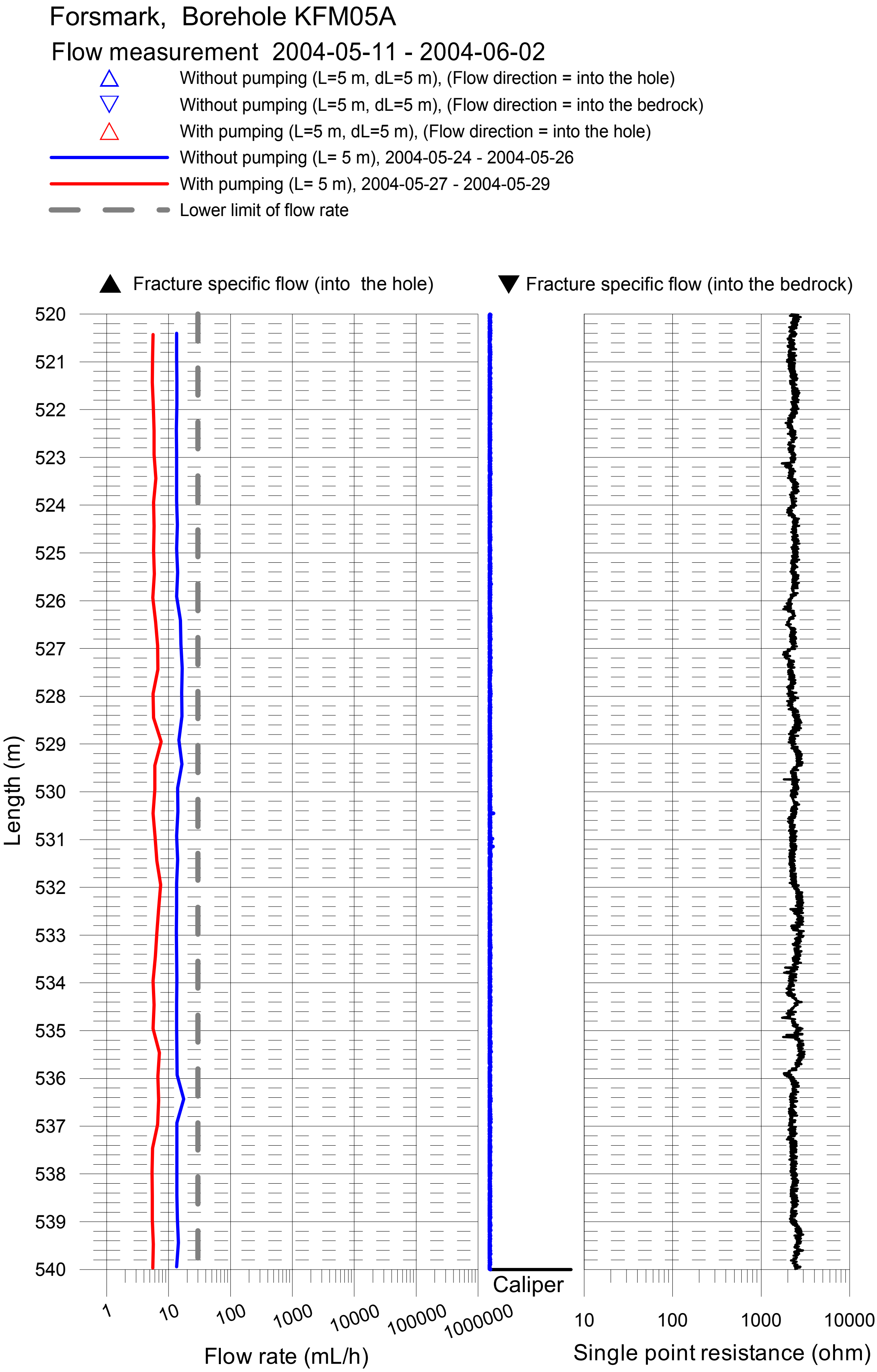
Appendix 3.21

Forsmark, Borehole KFM05A

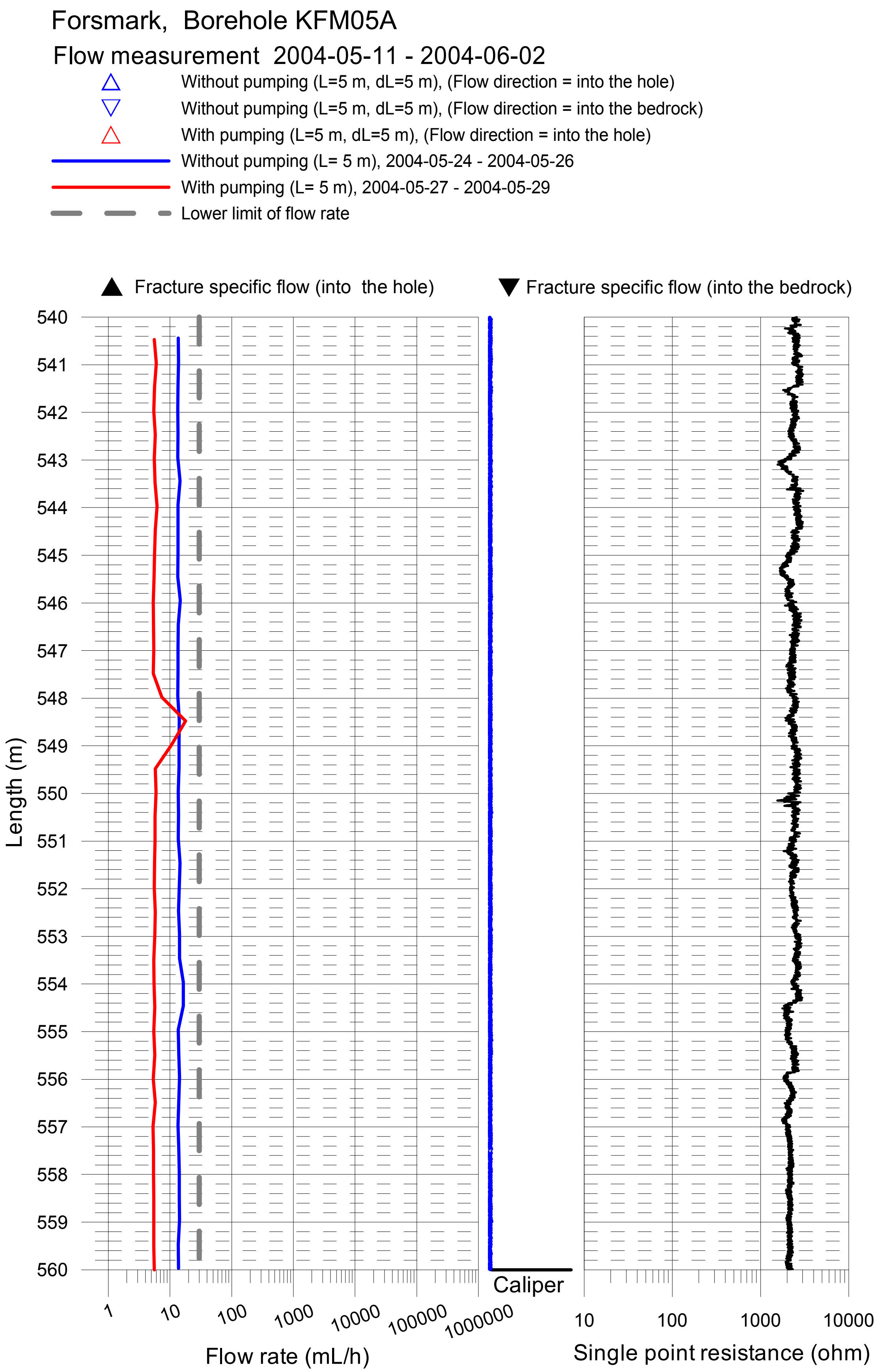
Flow measurement 2004-05-11 - 2004-06-02



Appendix 3.22



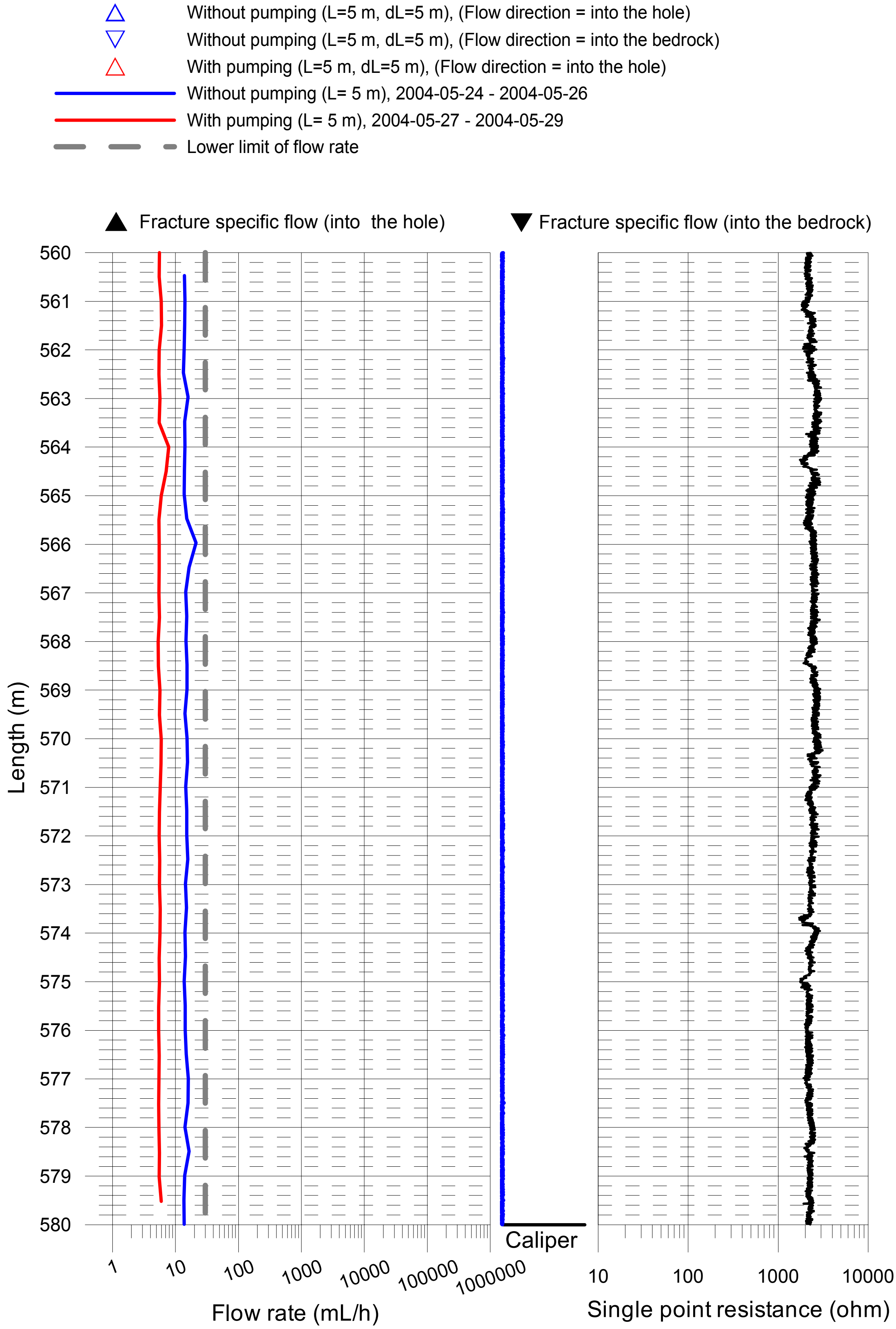
Appendix 3.23



Appendix 3.24

Forsmark, Borehole KFM05A

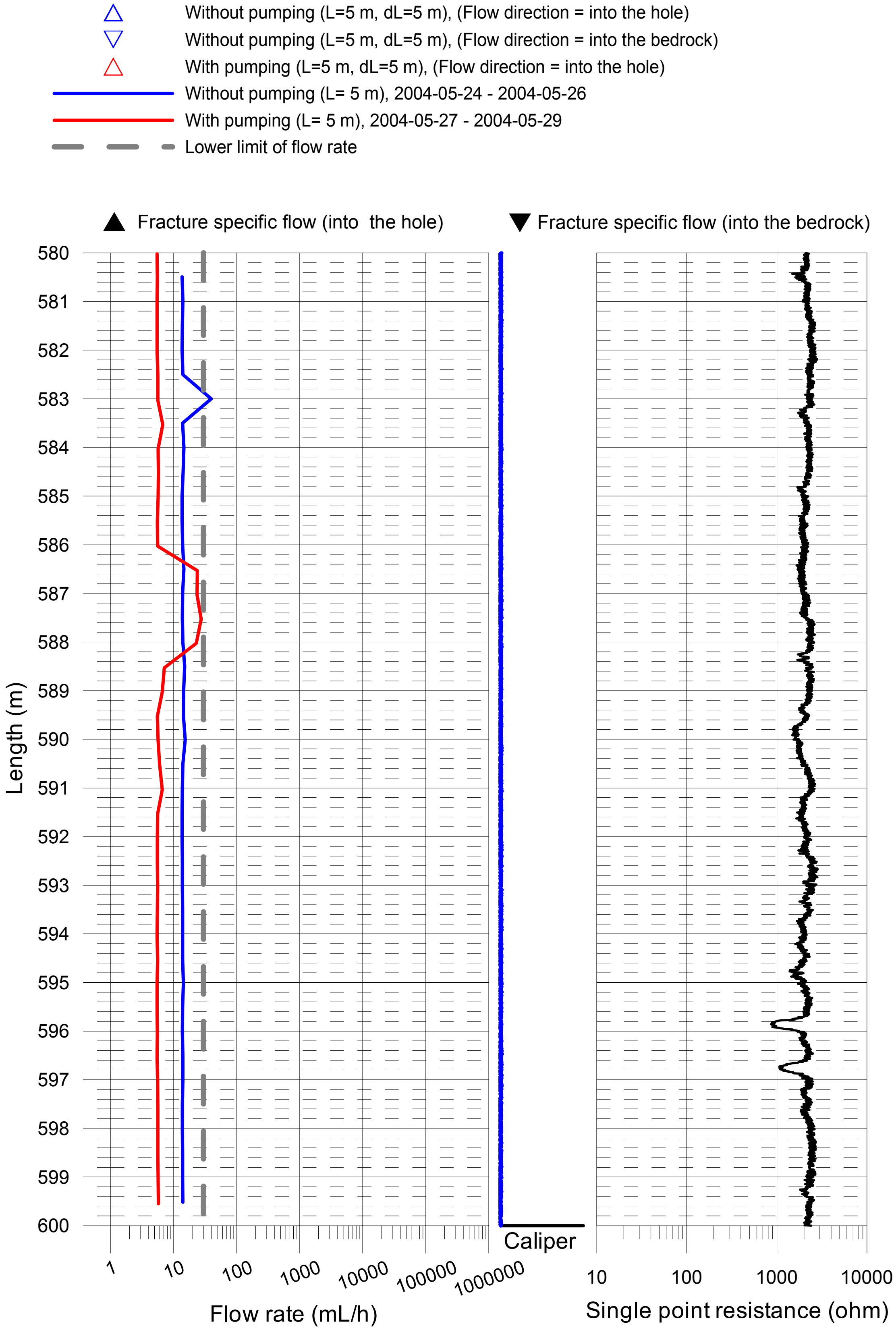
Flow measurement 2004-05-11 - 2004-06-02



Appendix 3.25

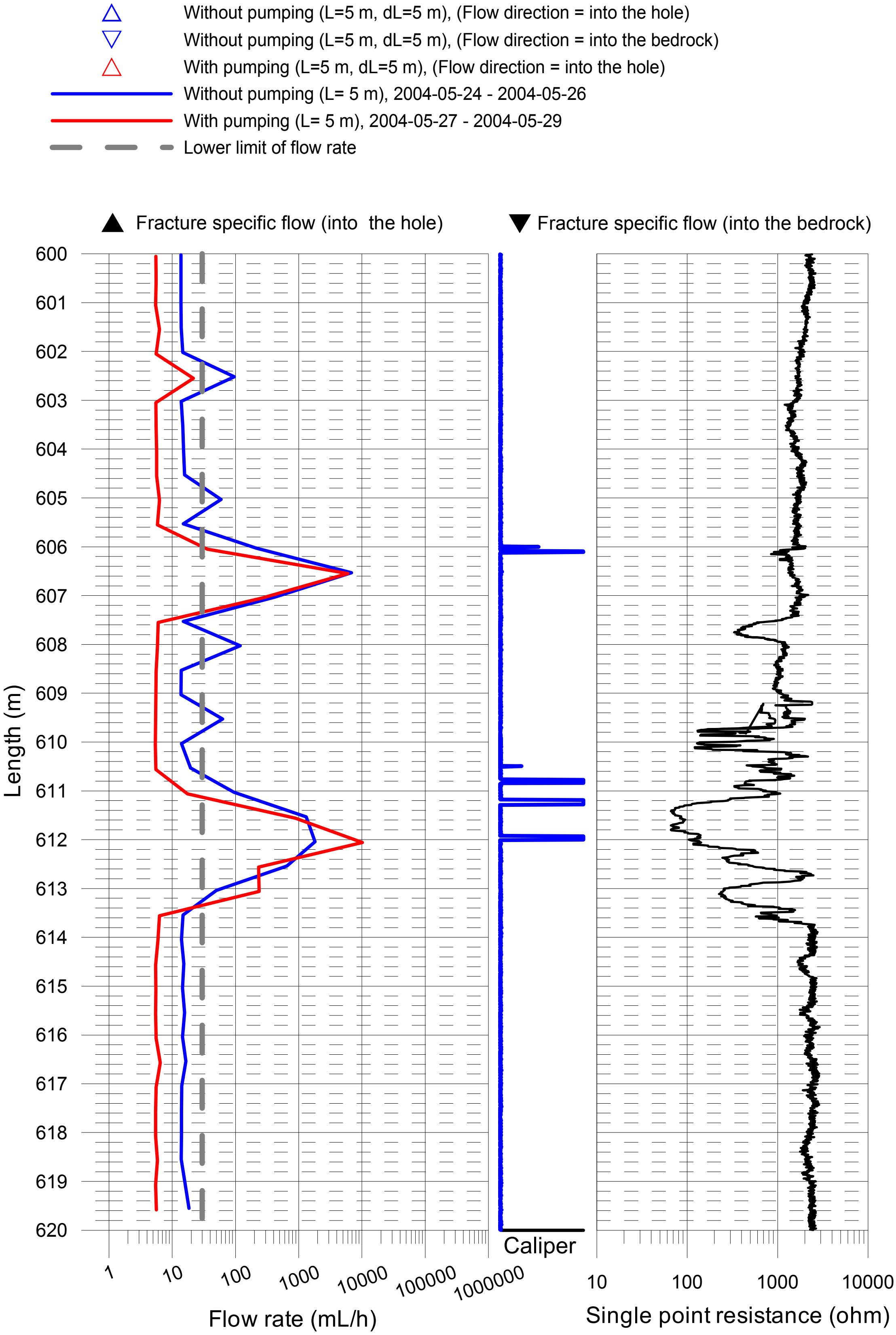
Forsmark, Borehole KFM05A

Flow measurement 2004-05-11 - 2004-06-02



Forsmark, Borehole KFM05A

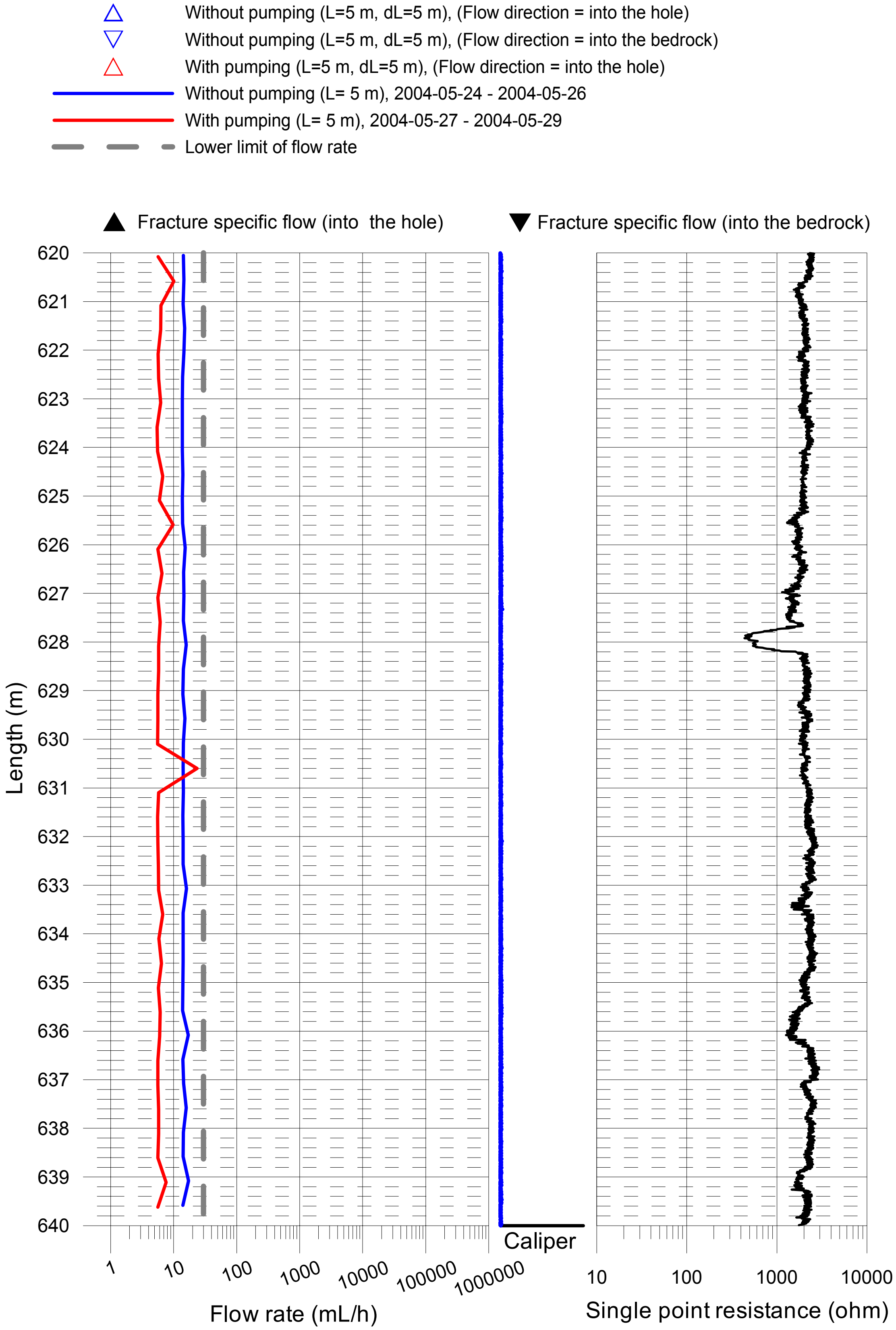
Flow measurement 2004-05-11 - 2004-06-02



Appendix 3.27

Forsmark, Borehole KFM05A

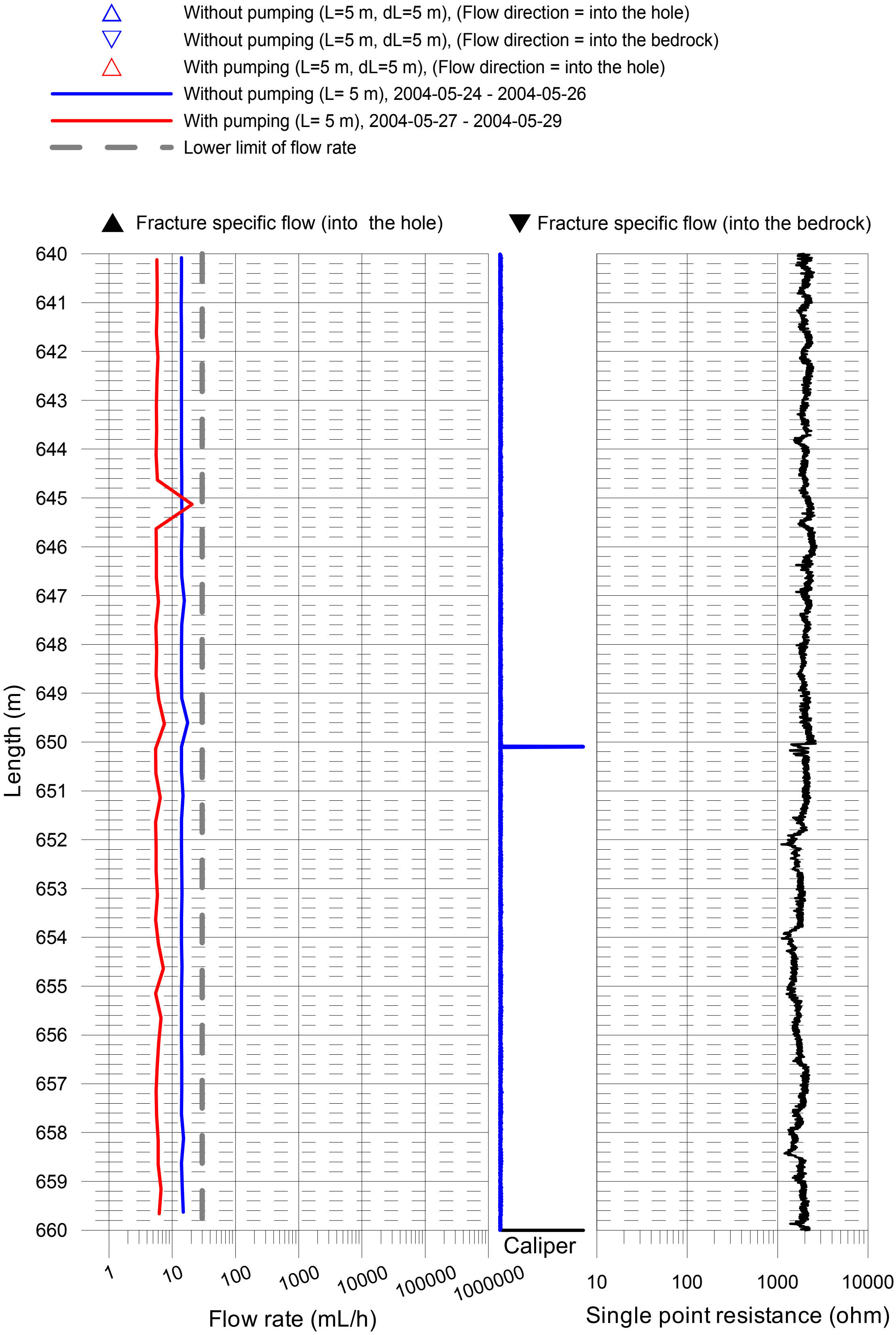
Flow measurement 2004-05-11 - 2004-06-02



Appendix 3.28

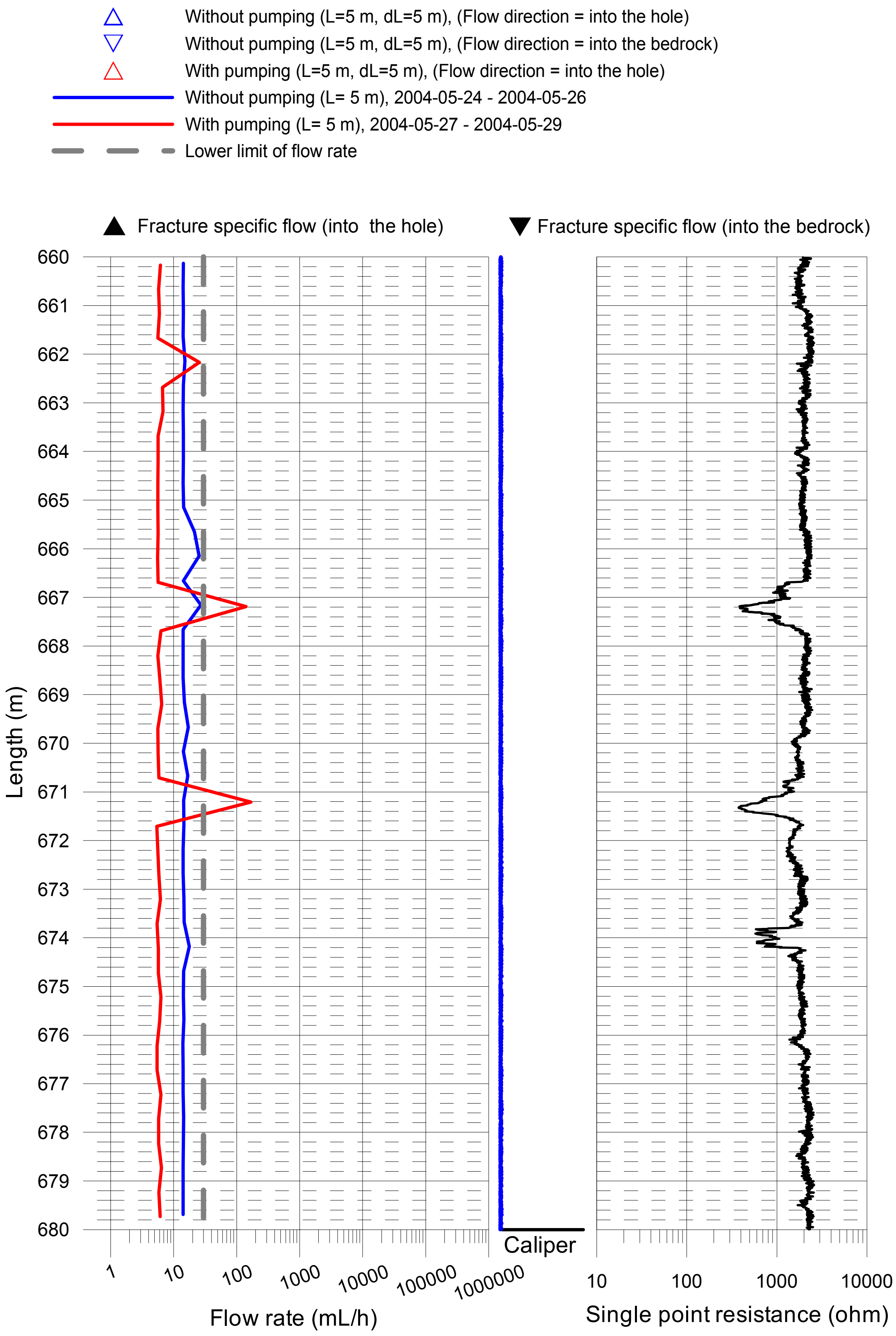
Forsmark, Borehole KFM05A

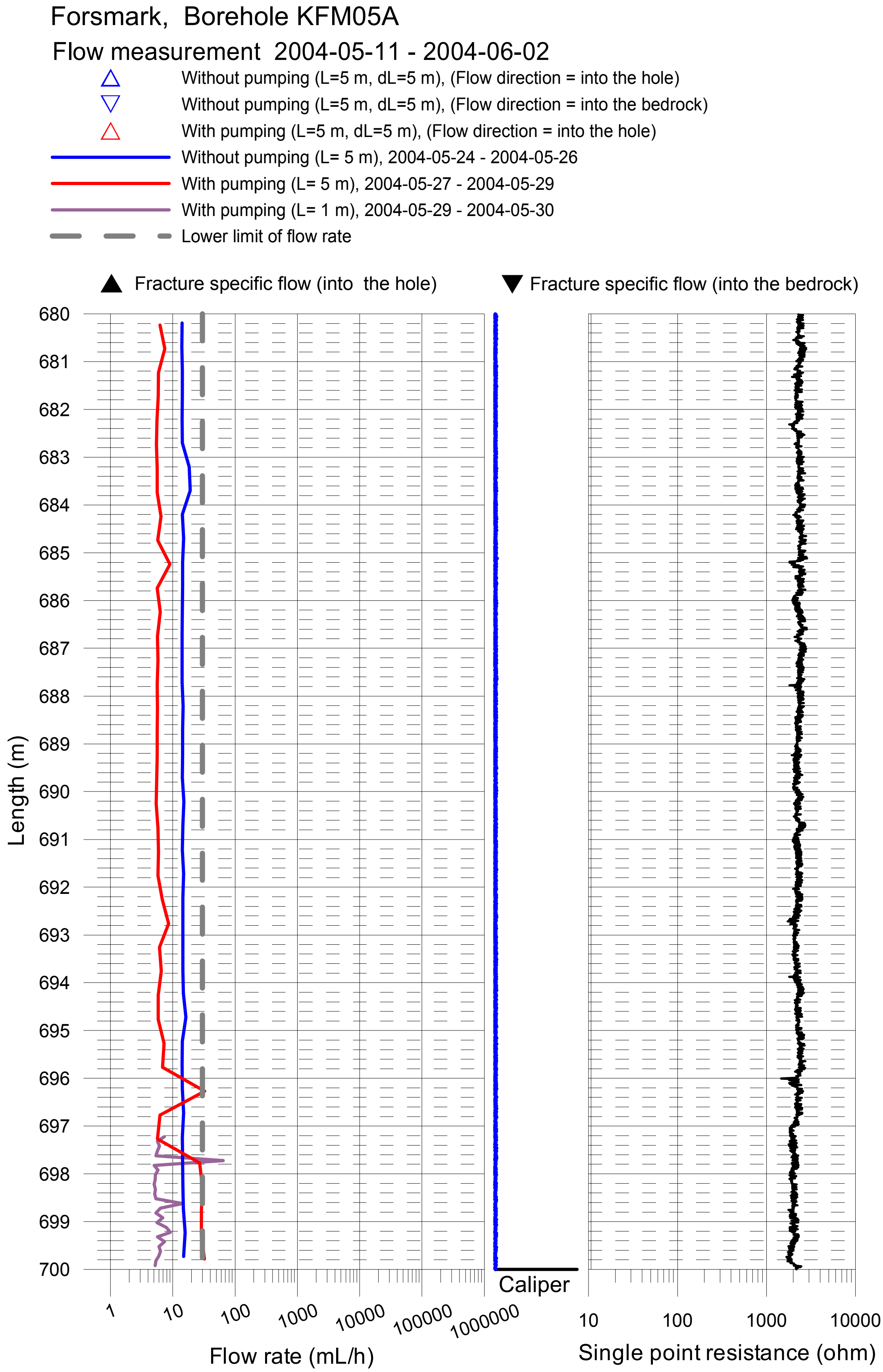
Flow measurement 2004-05-11 - 2004-06-02



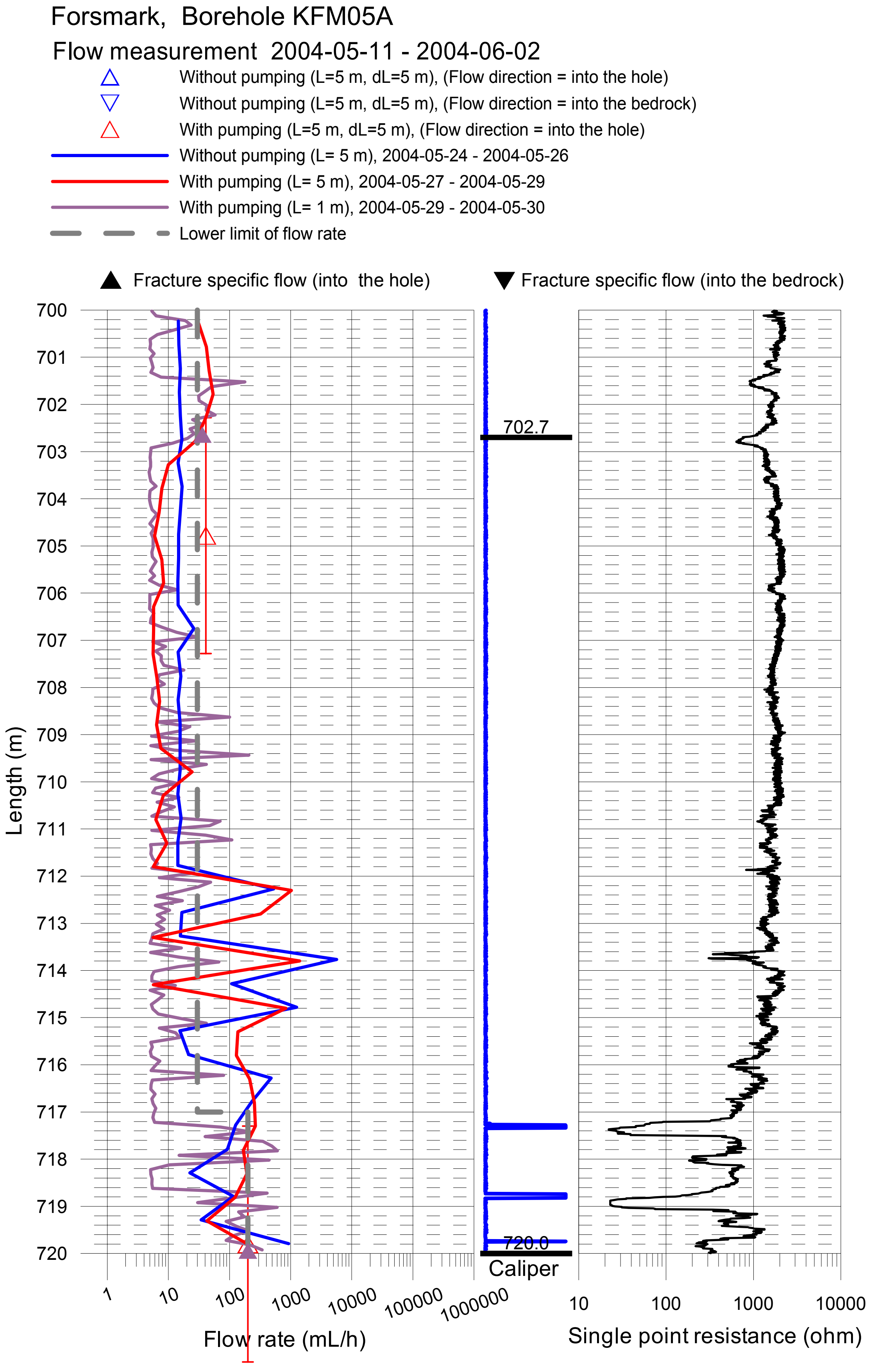
Forsmark, Borehole KFM05A

Flow measurement 2004-05-11 - 2004-06-02

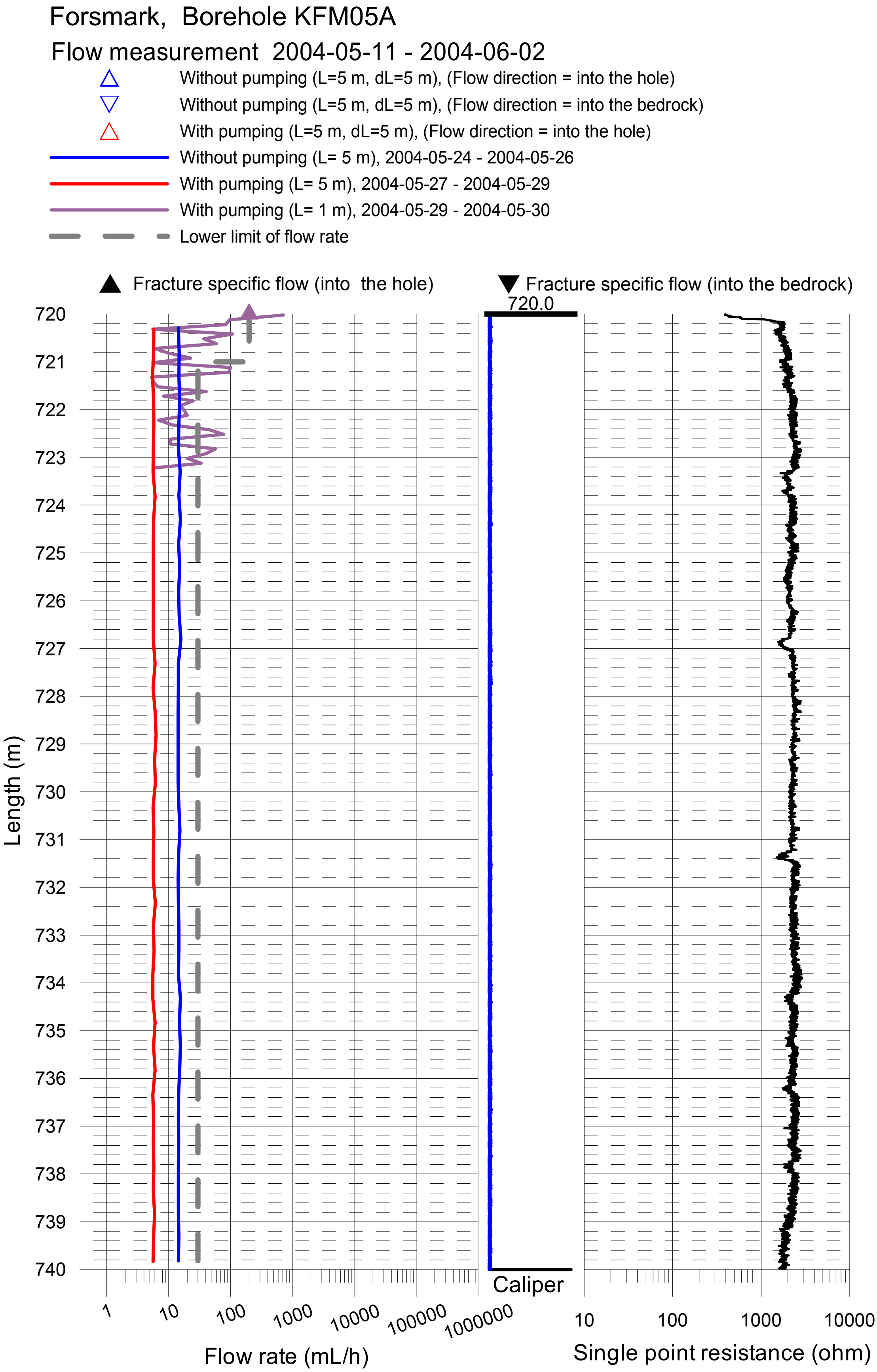



Forsmark, Borehole KFM05A
Flow measurement 2004-05-11 - 2004-06-02
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L= 5 m), 2004-05-24 - 2004-05-26
With pumping (L= 5 m), 2004-05-27 - 2004-05-29
With pumping (L= 1 m), 2004-05-29 - 2004-05-30
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
680
681
682
683
684
685
686
687
688
689
690
691
692
693
694
695
696
697
698
699
700
1
10
100
1000
10000
100000
1000000
Flow rate (mL/h)
Caliper
10
100
1000
10000
Single point resistance (ohm)

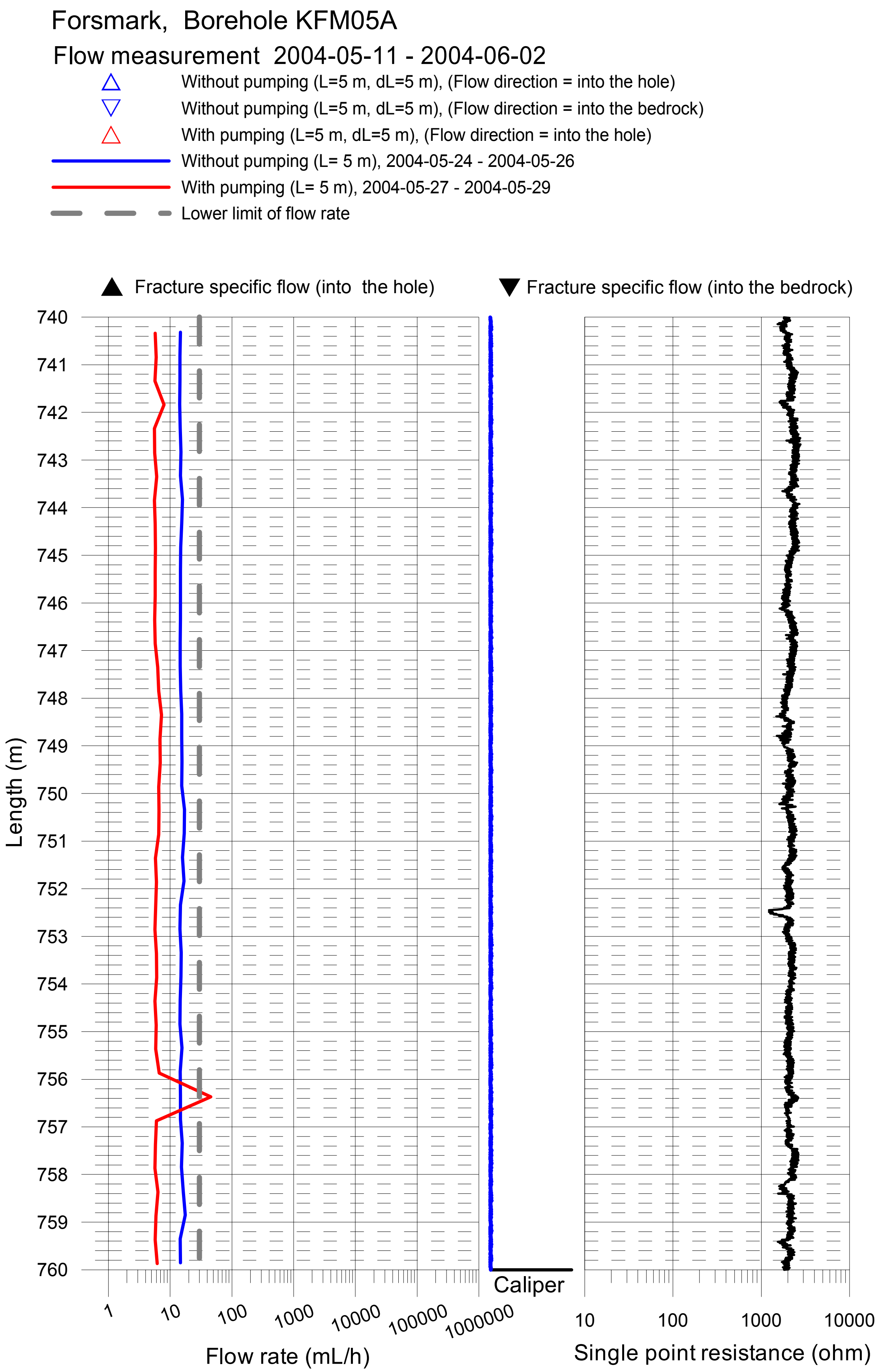
Appendix 3.31



Appendix 3.32



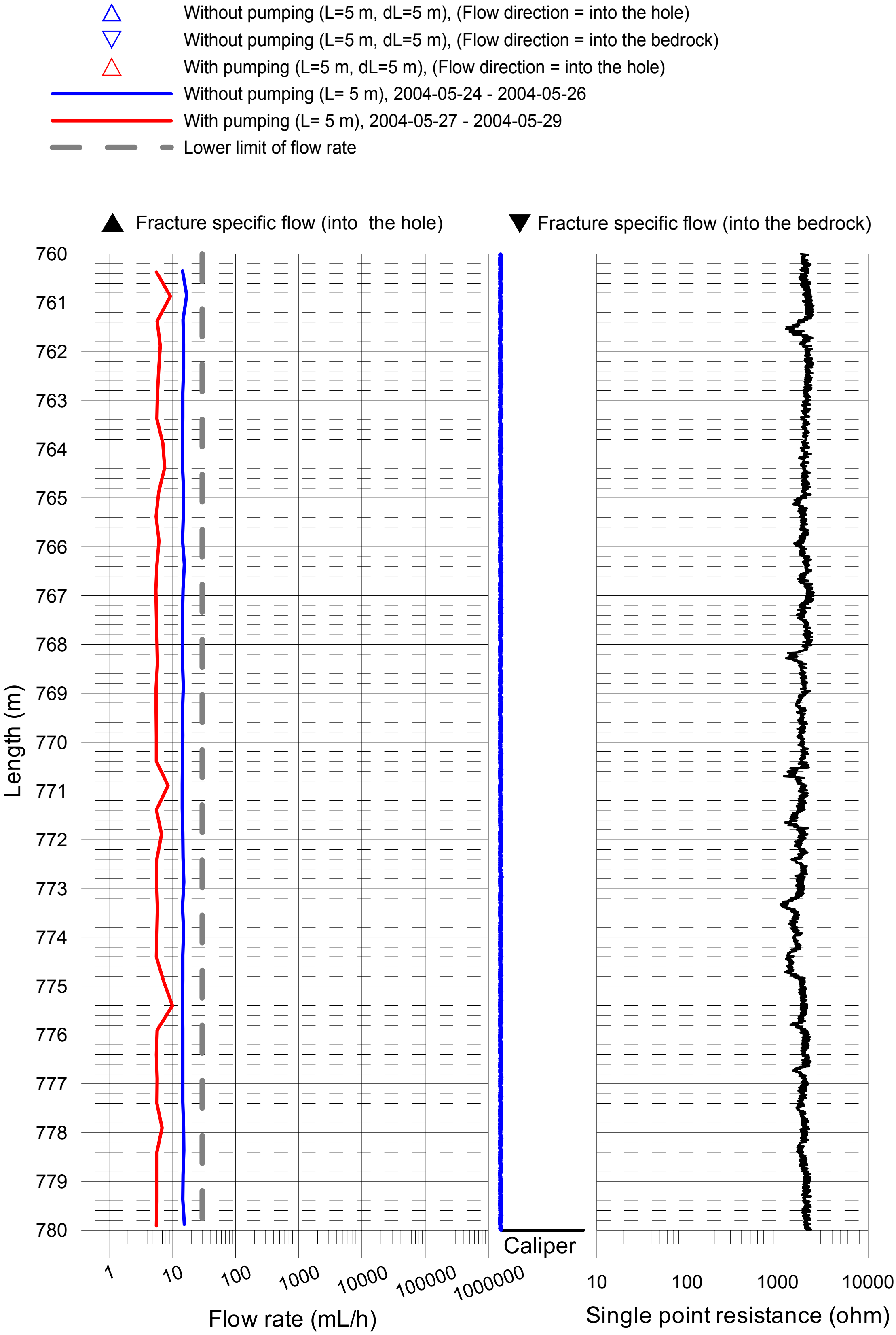
Appendix 3.33



Appendix 3.34

Forsmark, Borehole KFM05A

Flow measurement 2004-05-11 - 2004-06-02

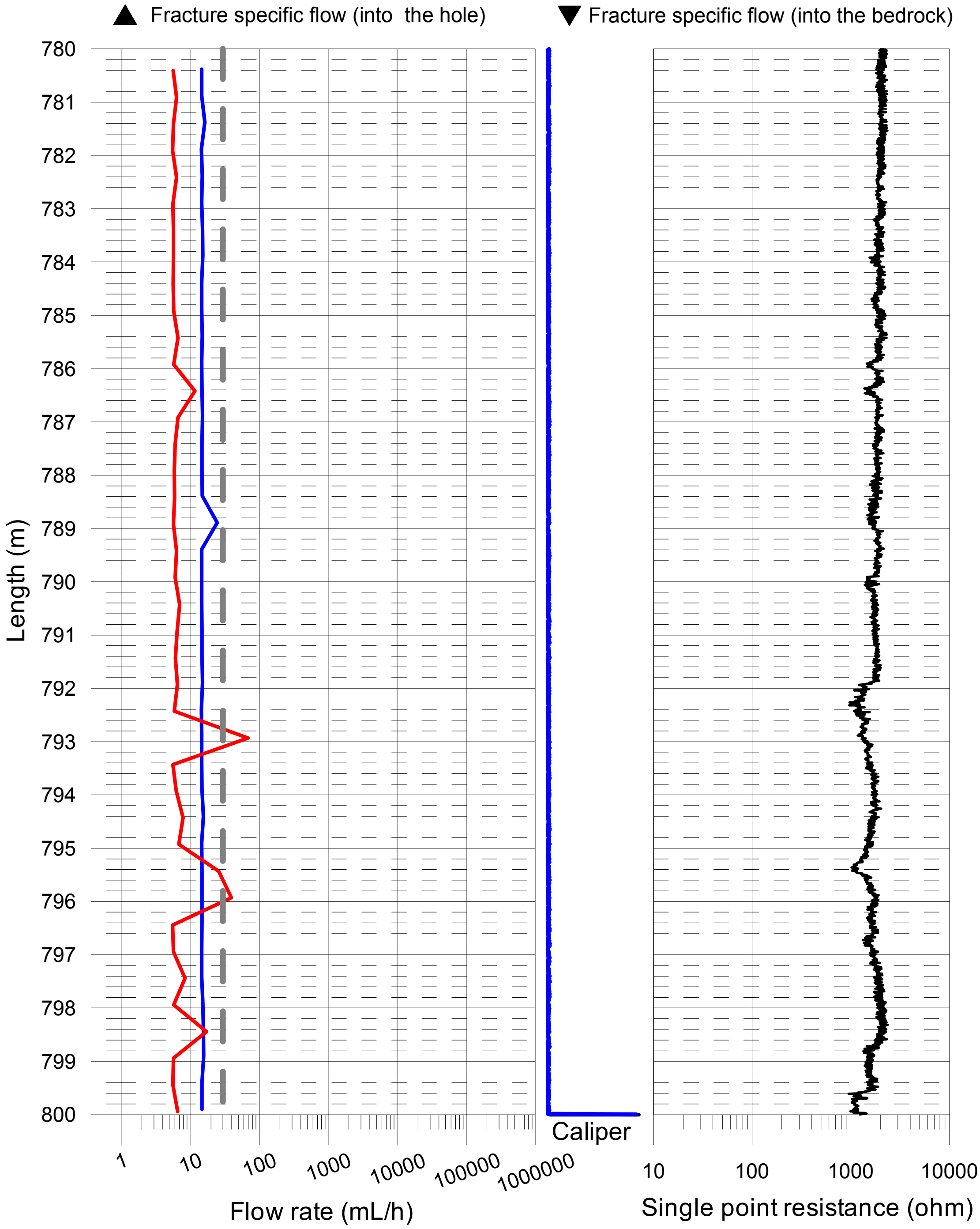


Appendix 3.35

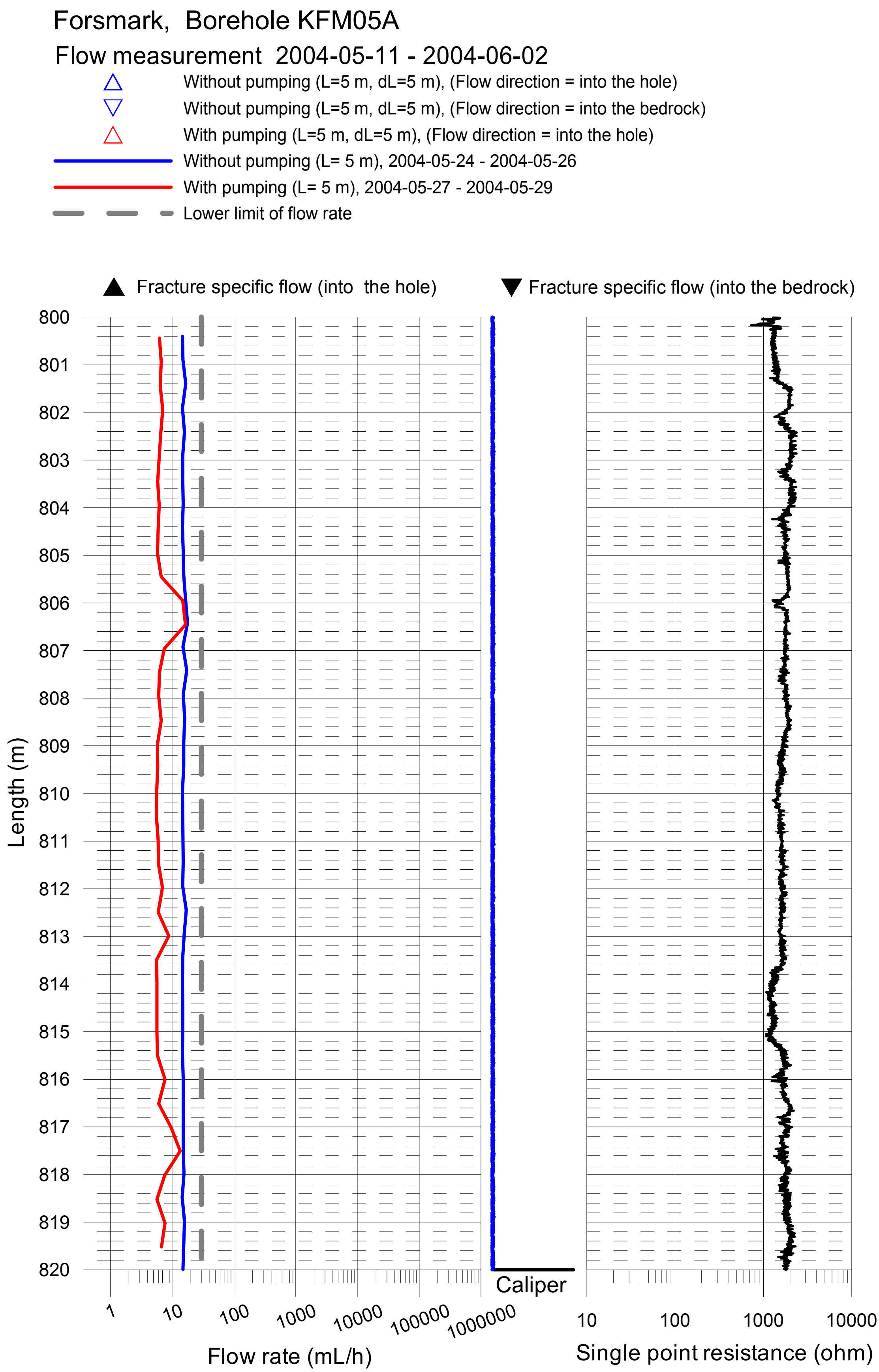
Forsmark, Borehole KFM05A

Flow measurement 2004-05-11 - 2004-06-02

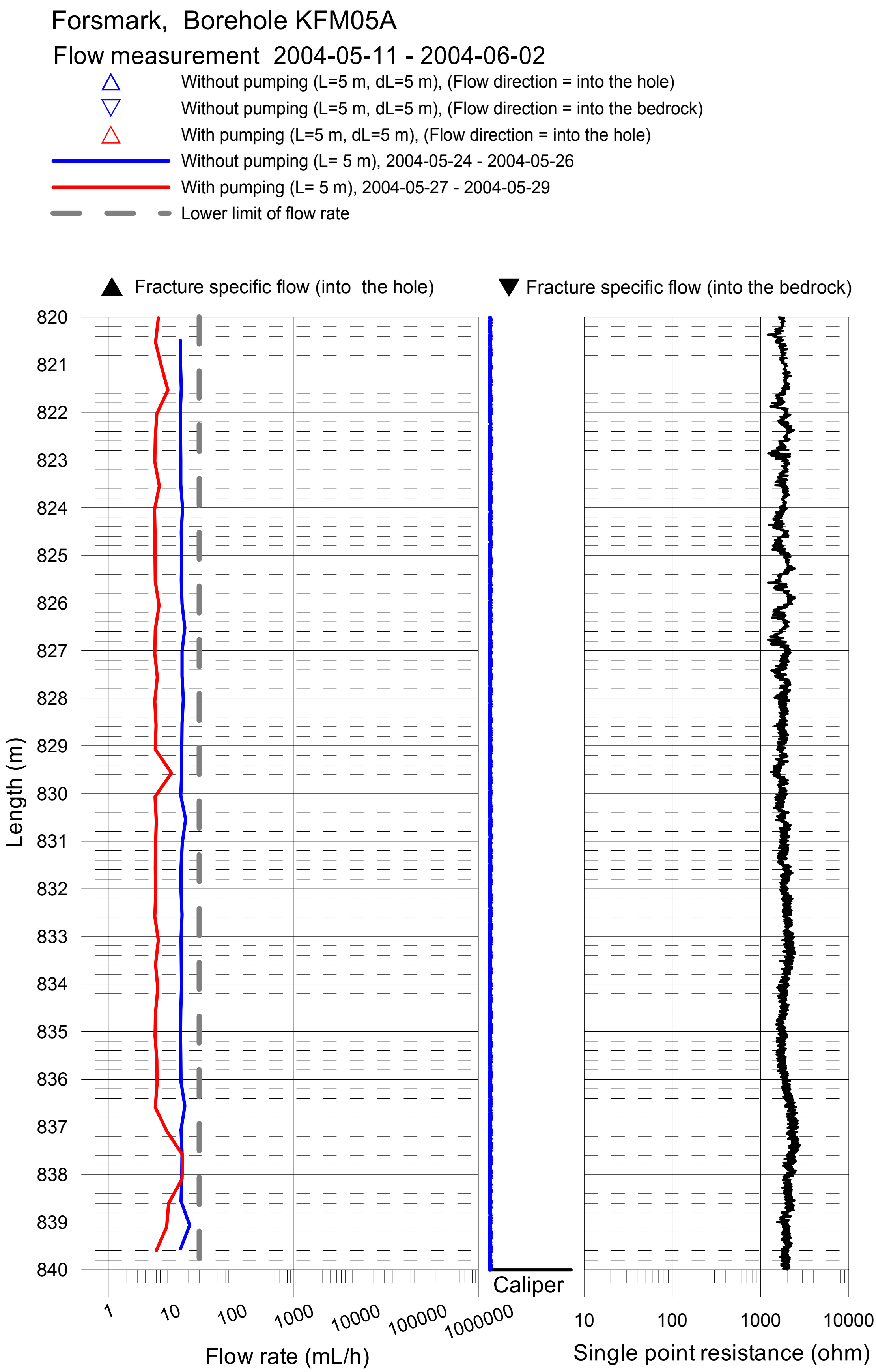
△ Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
▽ Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
△ With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L= 5 m), 2004-05-24 - 2004-05-26
With pumping (L= 5 m), 2004-05-27 - 2004-05-29
Lower limit of flow rate



Appendix 3.36



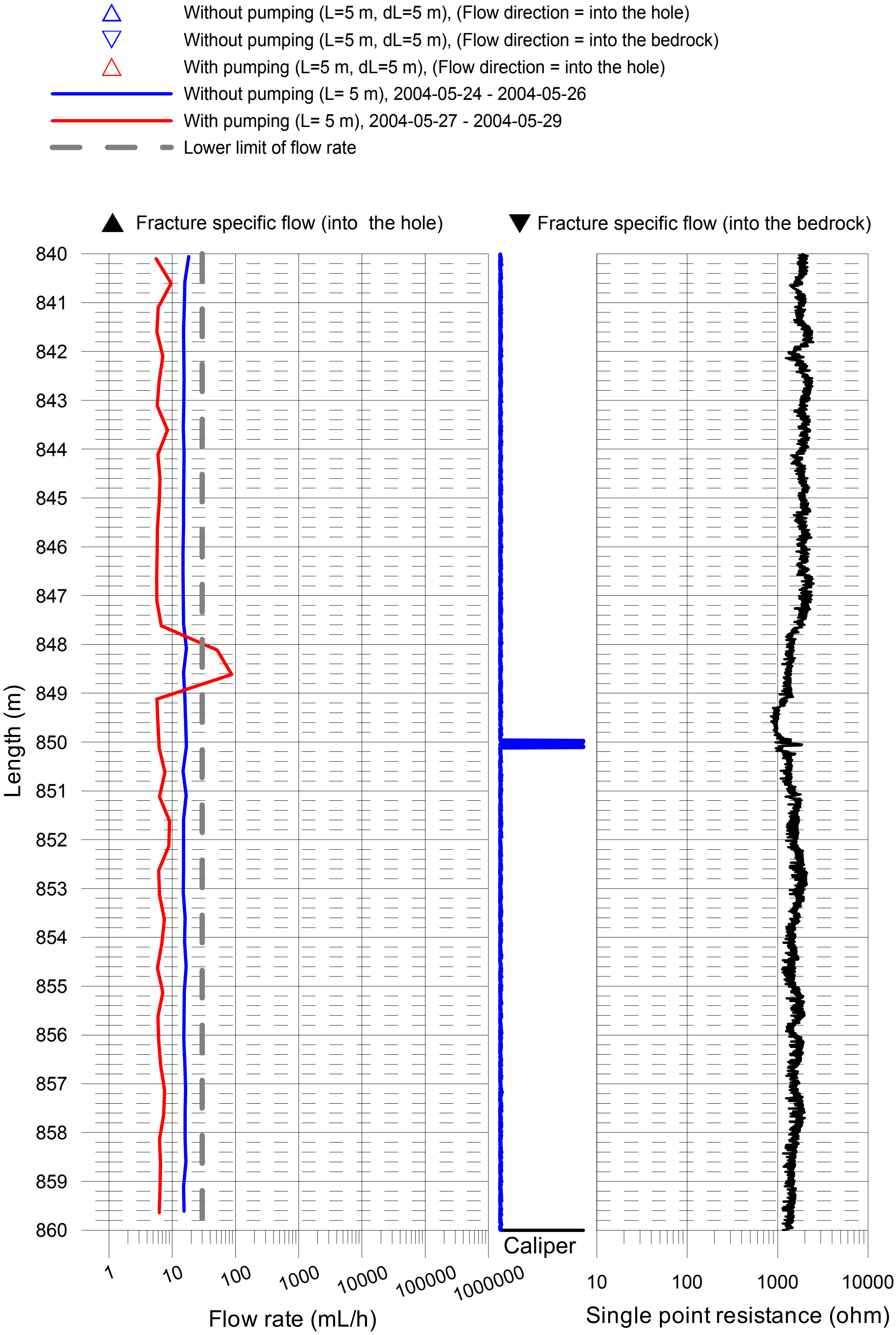
Appendix 3.37



Appendix 3.38

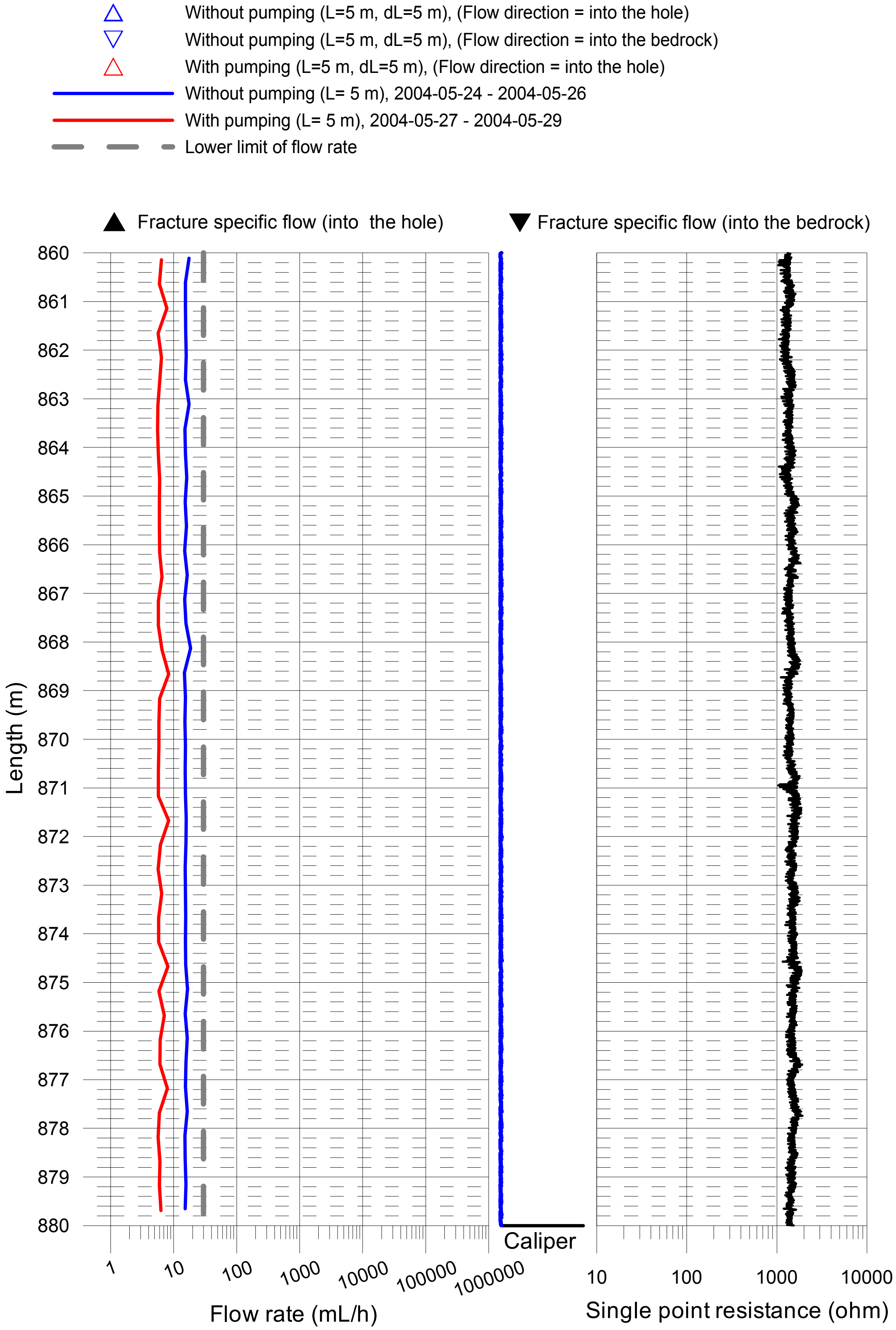
Forsmark, Borehole KFM05A

Flow measurement 2004-05-11 - 2004-06-02

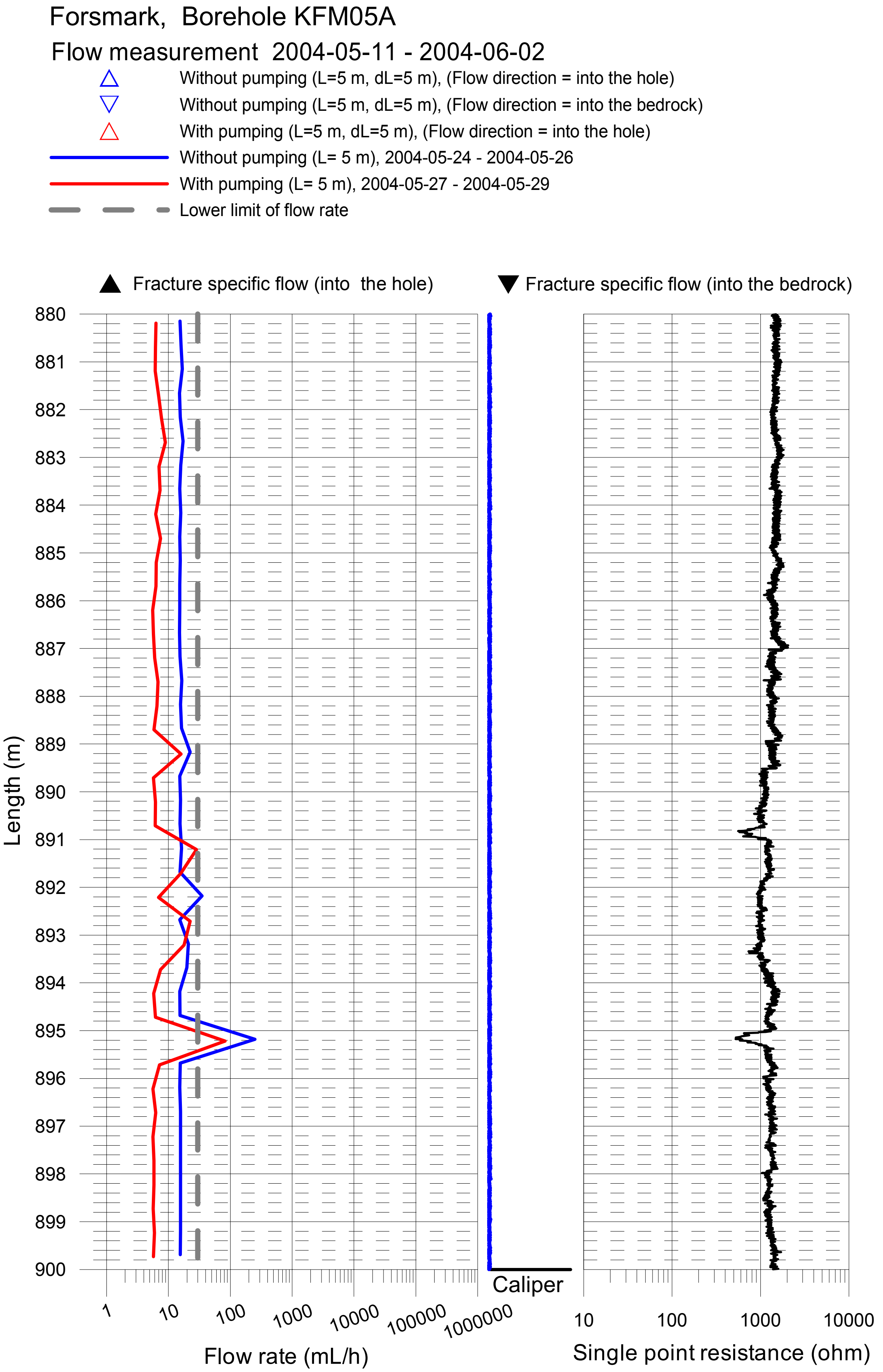


Forsmark, Borehole KFM05A

Flow measurement 2004-05-11 - 2004-06-02



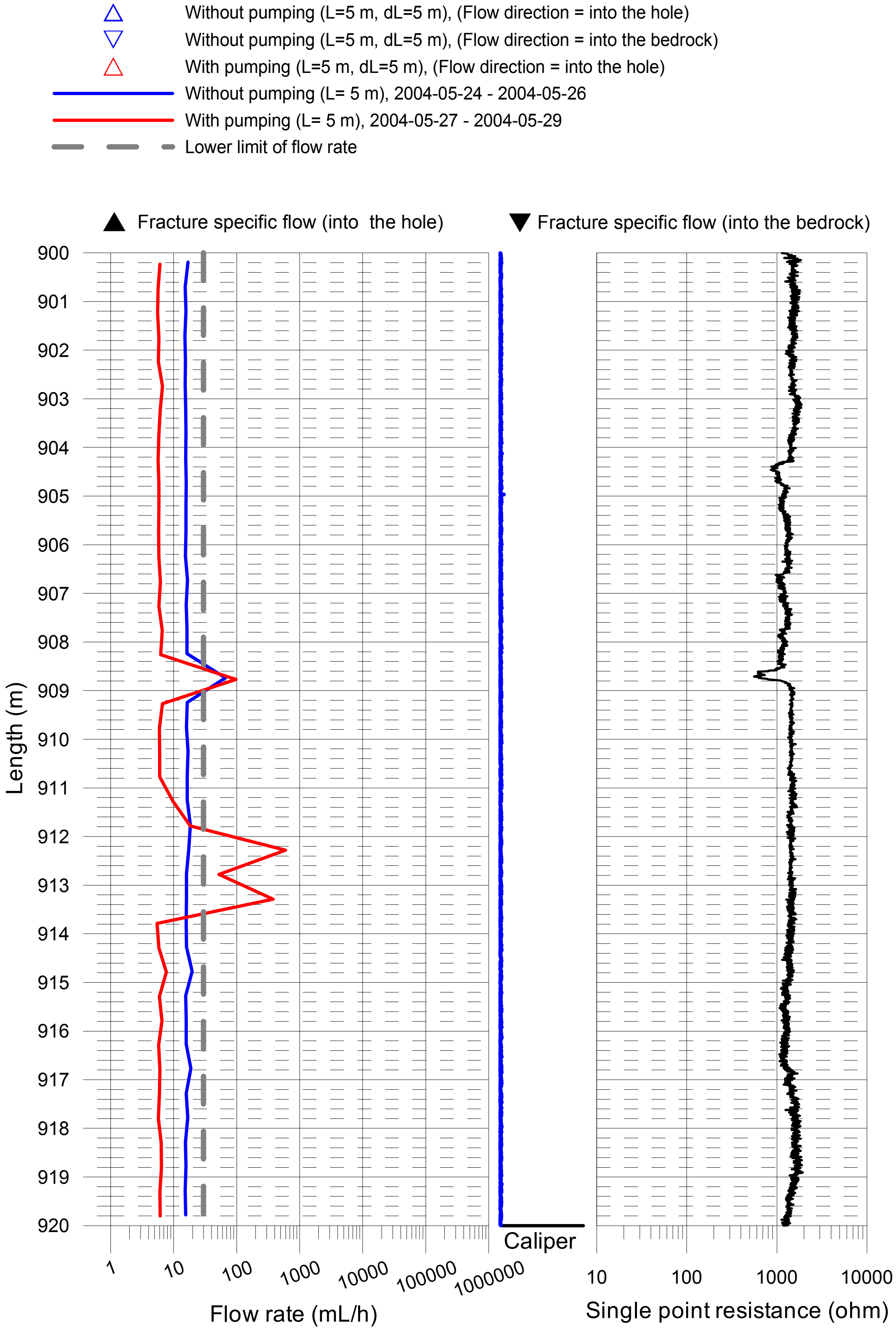
Appendix 3.40



Appendix 3.41

Forsmark, Borehole KFM05A

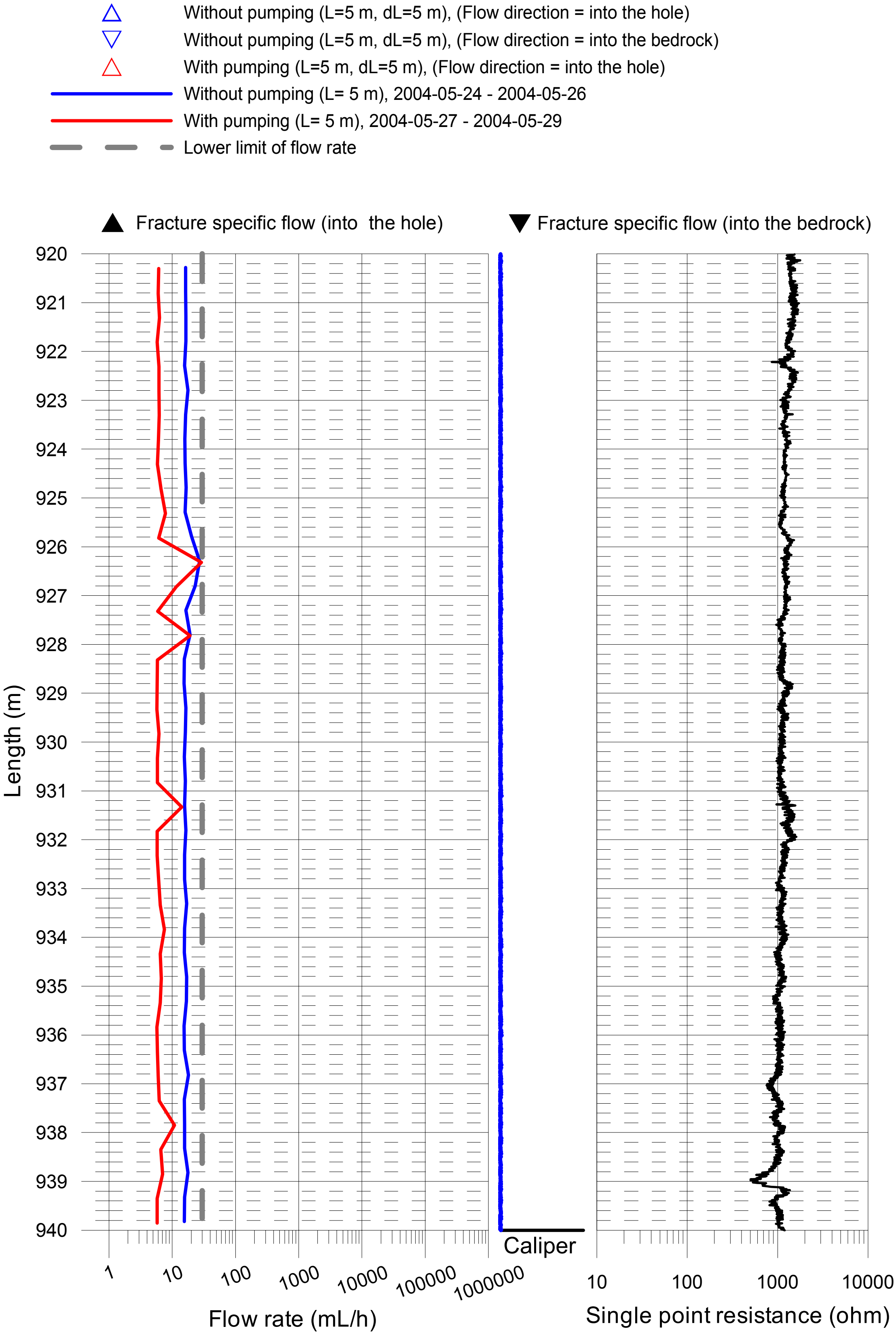
Flow measurement 2004-05-11 - 2004-06-02



Appendix 3.42

Forsmark, Borehole KFM05A

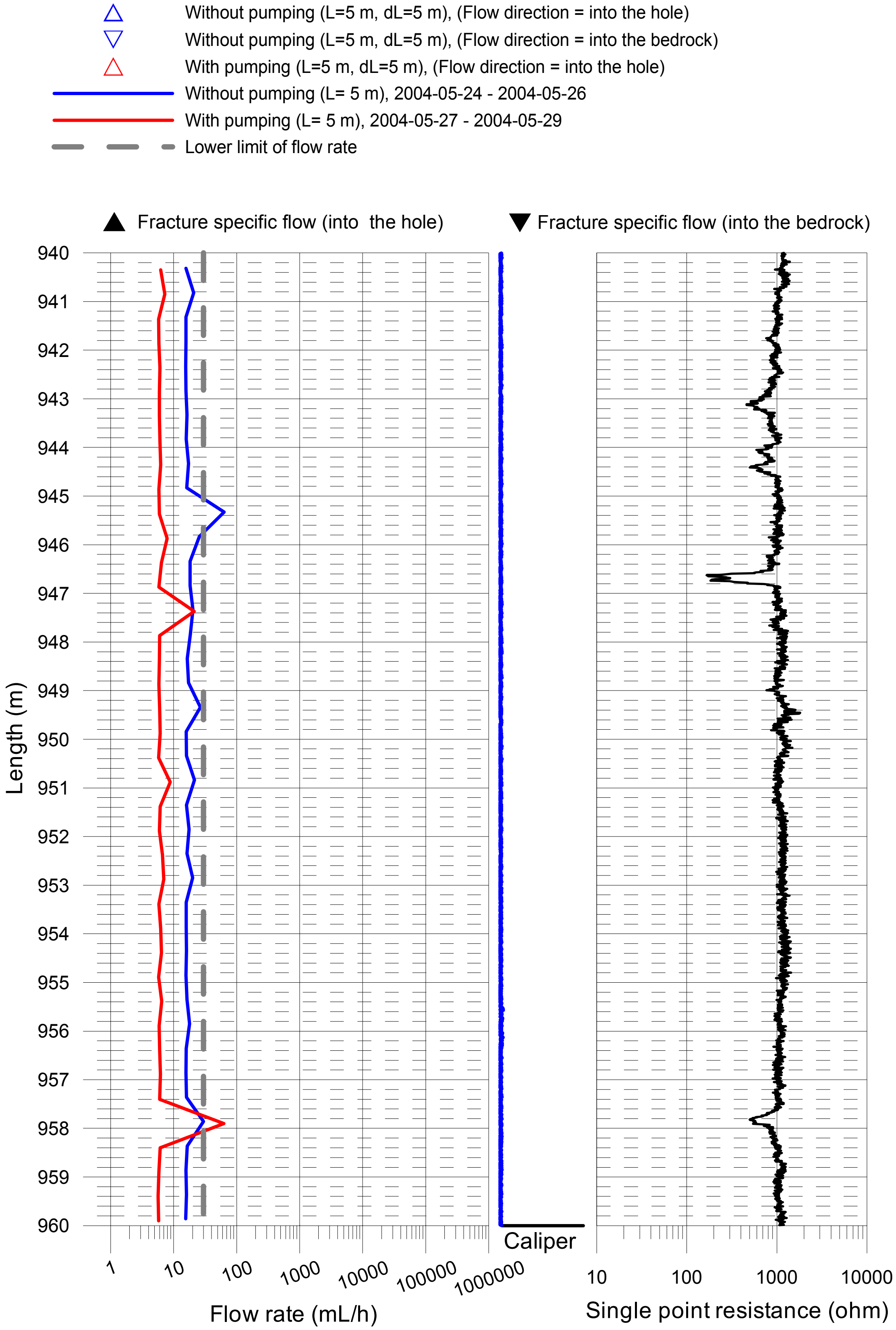
Flow measurement 2004-05-11 - 2004-06-02



Appendix 3.43

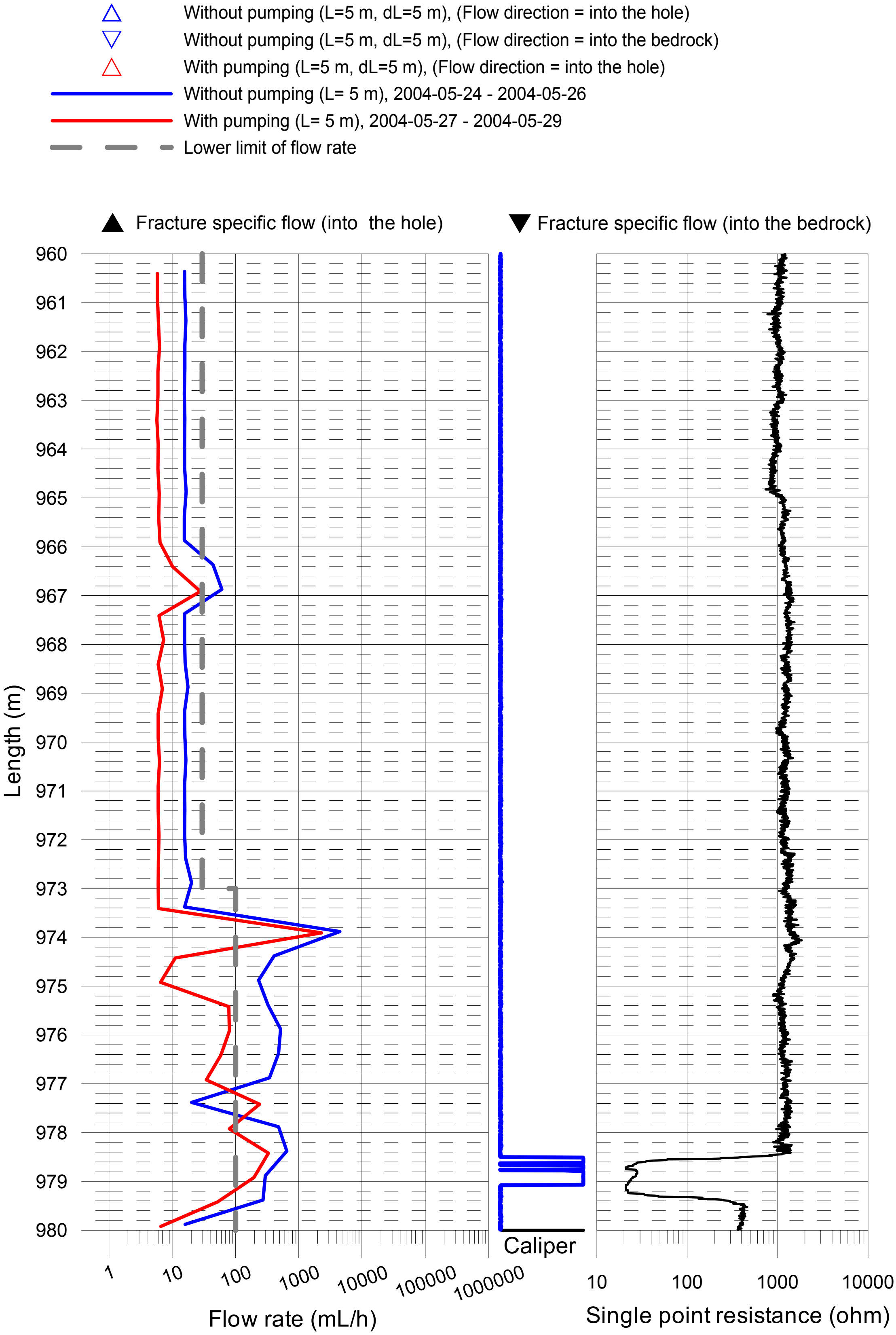
Forsmark, Borehole KFM05A

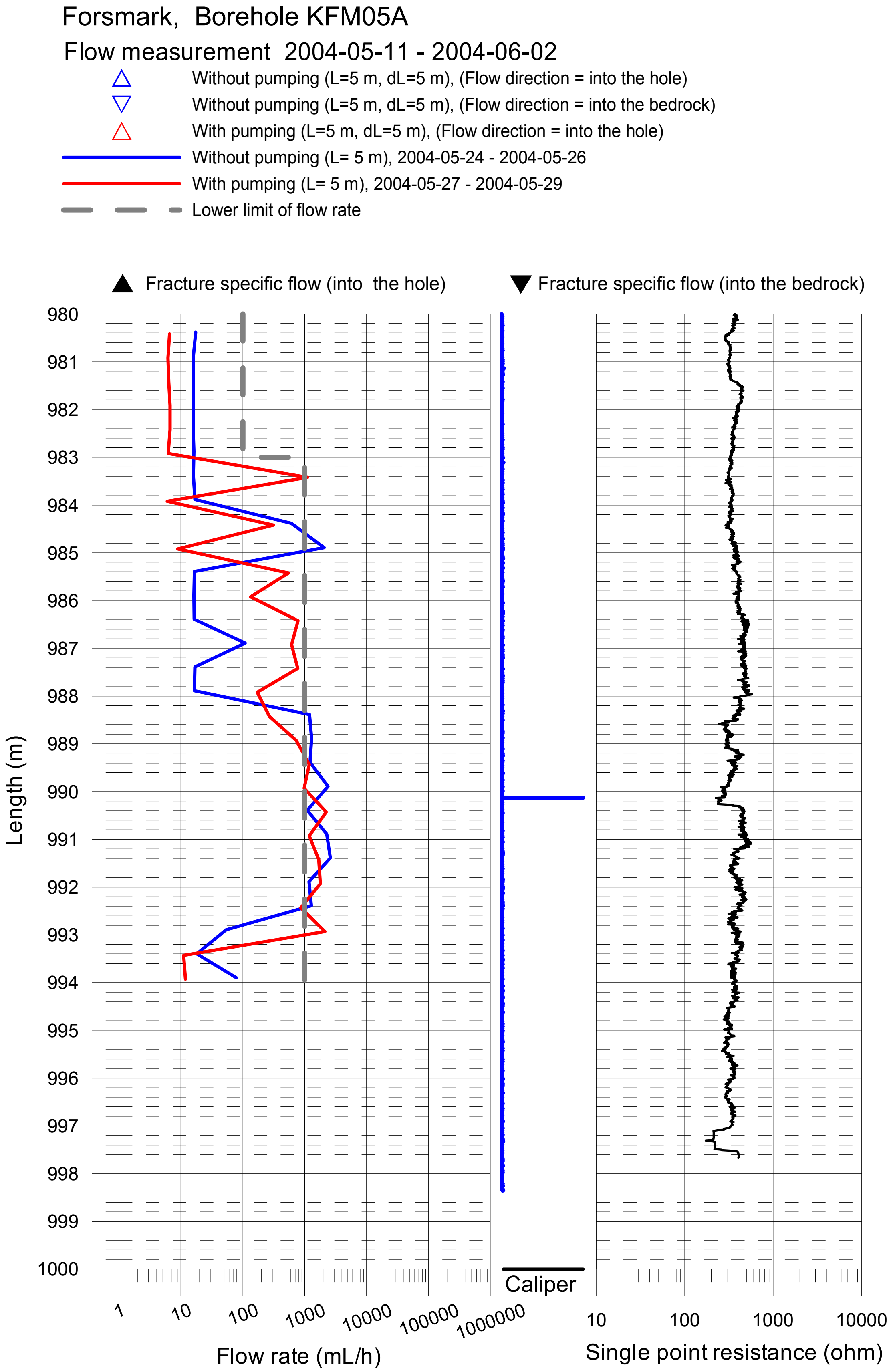
Flow measurement 2004-05-11 - 2004-06-02



Forsmark, Borehole KFM05A

Flow measurement 2004-05-11 - 2004-06-02




Forsmark, Borehole KFM05A
Flow measurement 2004-05-11 - 2004-06-02
Without pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L=5 m, dL=5 m), (Flow direction = into the bedrock)
With pumping (L=5 m, dL=5 m), (Flow direction = into the hole)
Without pumping (L= 5 m), 2004-05-24 - 2004-05-26
With pumping (L= 5 m), 2004-05-27 - 2004-05-29
Lower limit of flow rate
Fracture specific flow (into the hole)
Fracture specific flow (into the bedrock)
Length (m)
980
981
982
983
984
985
986
987
988
989
990
991
992
993
994
995
996
997
998
999
1000
1
10
100
1000
10000
100000
1000000
Flow rate (mL/h)
Caliper
10
100
1000
10000
Single point resistance (ohm)

Appendix 4

Head during flow logging in borehole KFM05A

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)

Appendix 5.1

Secup1 (m)	Borehole Head1 (masl)	Flow1 (mL/h)	Secup2 (m)	Borehole Head2 (masl)	Flow2 (mL/h)	Section Head (masl)	T_s (m2/s)	Q-lower limit Practical (mL/h)	T_s-Lower Limit Theoretical (m2/s)	T_s-Lower Limit Practical (m2/s)	T_s-Upper Limit (m2/s)
987.89	9.64	0	987.92	3.63	0	-	-	1000	2.74E-10	4.57E-08	1.37E-05
982.88	9.62	0	982.92	3.58	0	-	-	1000	2.73E-10	4.55E-08	1.36E-05
977.88	9.57	0	977.92	3.55	0	-	-	100	2.74E-10	4.56E-09	1.37E-05
972.88	9.51	0	972.91	3.44	0	-	-	100	2.72E-10	4.53E-09	1.36E-05
967.87	9.45	0	967.91	3.41	0	-	-	30	2.73E-10	1.36E-09	1.36E-05
962.87	9.39	0	962.91	3.36	0	-	-	30	2.73E-10	1.37E-09	1.37E-05
957.86	9.36	0	957.90	3.32	0	-	-	30	2.73E-10	1.36E-09	1.36E-05
952.85	9.30	0	952.88	3.25	0	-	-	30	2.72E-10	1.36E-09	1.36E-05
947.84	9.25	0	947.87	3.19	0	-	-	30	2.72E-10	1.36E-09	1.36E-05
942.83	9.19	0	942.86	3.15	0	-	-	30	2.73E-10	1.36E-09	1.36E-05
937.82	9.14	0	937.85	3.08	0	-	-	30	2.72E-10	1.36E-09	1.36E-05
932.81	9.09	0	932.84	3.04	0	-	-	30	2.72E-10	1.36E-09	1.36E-05
927.80	9.05	0	927.82	2.99	0	-	-	30	2.72E-10	1.36E-09	1.36E-05
922.79	8.98	0	922.81	2.92	0	-	-	30	2.72E-10	1.36E-09	1.36E-05
917.78	8.94	0	917.80	2.88	0	-	-	30	2.72E-10	1.36E-09	1.36E-05
912.76	8.89	0	912.78	2.80	0	-	-	30	2.71E-10	1.35E-09	1.35E-05
907.73	8.85	0	907.76	2.77	0	-	-	30	2.71E-10	1.36E-09	1.36E-05
902.71	8.79	0	902.74	2.72	0	-	-	30	2.72E-10	1.36E-09	1.36E-05
897.69	8.76	0	897.72	2.68	0	-	-	30	2.71E-10	1.36E-09	1.36E-05
892.68	8.69	0	892.71	2.63	0	-	-	30	2.72E-10	1.36E-09	1.36E-05
887.67	8.65	0	887.70	2.57	0	-	-	30	2.71E-10	1.36E-09	1.36E-05
882.66	8.60	0	882.69	2.49	0	-	-	30	2.70E-10	1.35E-09	1.35E-05
877.65	8.56	0	877.68	2.48	0	-	-	30	2.71E-10	1.36E-09	1.36E-05
872.63	8.53	0	872.67	2.42	0	-	-	30	2.70E-10	1.35E-09	1.35E-05
867.62	8.48	0	867.66	2.40	0	-	-	30	2.71E-10	1.36E-09	1.36E-05
862.61	8.41	0	862.65	2.32	0	-	-	30	2.71E-10	1.35E-09	1.35E-05
857.60	8.37	0	857.64	2.26	0	-	-	30	2.70E-10	1.35E-09	1.35E-05
852.59	8.30	0	852.63	2.20	0	-	-	30	2.70E-10	1.35E-09	1.35E-05

Appendix 5.2

Secup1 (m)	Borehole Head1 (masl)	Flow1 (mL/h)	Secup2 (m)	Borehole Head2 (masl)	Flow2 (mL/h)	Section Head (masl)	T_s (m^2/s)	Q-lower limit Practical (mL/h)	T_s-Lower Limit Theoretical (m^2/s)	T_s-Lower Limit Practical (m^2/s)	T_s-Upper Limit (m^2/s)
847.58	8.26	0	847.62	2.17	0	-	-	30	2.71E-10	1.35E-09	1.35E-05
842.57	8.18	0	842.60	2.08	0	-	-	30	2.70E-10	1.35E-09	1.35E-05
837.56	8.14	0	837.59	2.04	0	-	-	30	2.70E-10	1.35E-09	1.35E-05
832.55	8.08	0	832.58	1.97	0	-	-	30	2.70E-10	1.35E-09	1.35E-05
827.53	8.03	0	827.56	1.92	0	-	-	30	2.70E-10	1.35E-09	1.35E-05
822.50	8.00	0	822.54	1.88	0	-	-	30	2.69E-10	1.35E-09	1.35E-05
817.47	7.97	0	817.51	1.85	0	-	-	30	2.69E-10	1.35E-09	1.35E-05
812.45	7.93	0	812.49	1.79	0	-	-	30	2.68E-10	1.34E-09	1.34E-05
807.42	7.90	0	807.46	1.76	0	-	-	30	2.68E-10	1.34E-09	1.34E-05
802.41	7.84	0	802.45	1.73	0	-	-	30	2.70E-10	1.35E-09	1.35E-05
797.40	7.81	0	797.44	1.69	0	-	-	30	2.69E-10	1.35E-09	1.35E-05
792.39	7.73	0	792.43	1.59	0	-	-	30	2.68E-10	1.34E-09	1.34E-05
787.39	7.70	0	787.42	1.56	0	-	-	30	2.68E-10	1.34E-09	1.34E-05
782.38	7.67	0	782.41	1.51	0	-	-	30	2.68E-10	1.34E-09	1.34E-05
777.37	7.62	0	777.40	1.46	0	-	-	30	2.68E-10	1.34E-09	1.34E-05
772.36	7.56	0	772.39	1.41	0	-	-	30	2.68E-10	1.34E-09	1.34E-05
767.36	7.52	0	767.39	1.37	0	-	-	30	2.68E-10	1.34E-09	1.34E-05
762.35	7.45	0	762.38	1.30	0	-	-	30	2.68E-10	1.34E-09	1.34E-05
757.34	7.40	0	757.37	1.25	0	-	-	30	2.68E-10	1.34E-09	1.34E-05
752.34	7.33	0	752.36	1.16	0	-	-	30	2.67E-10	1.34E-09	1.34E-05
747.33	7.28	0	747.35	1.13	0	-	-	30	2.68E-10	1.34E-09	1.34E-05
742.33	7.25	0	742.34	1.09	0	-	-	30	2.68E-10	1.34E-09	1.34E-05
737.32	7.21	0	737.34	1.06	0	-	-	30	2.68E-10	1.34E-09	1.34E-05
732.31	7.11	0	732.33	0.97	0	-	-	30	2.68E-10	1.34E-09	1.34E-05
727.31	7.08	0	727.32	0.92	0	-	-	30	2.68E-10	1.34E-09	1.34E-05
722.30	7.03	0	722.31	0.85	0	-	-	30	2.67E-10	1.33E-09	1.33E-05
717.28	6.99	0	717.30	0.82	200	-	8.91E-09	200	2.67E-10	8.91E-09	1.34E-05
712.27	6.92	0	712.30	0.77	0	-	-	30	2.68E-10	1.34E-09	1.34E-05
707.25	6.90	0	707.29	0.72	0	-	-	30	2.67E-10	1.33E-09	1.33E-05
702.24	6.89	0	702.28	0.68	41	-	1.81E-09	30	2.65E-10	1.33E-09	1.33E-05

Appendix 5.3

Secup1 (m)	Borehole Head1 (masl)	Flow1 (mL/h)	Secup2 (m)	Borehole Head2 (masl)	Flow2 (mL/h)	Section Head (masl)	T_s (m2/s)	Q-lower limit Practical (mL/h)	T_s-Lower Limit Theoretical (m2/s)	T_s-Lower Limit Practical (m2/s)	T_s-Upper Limit (m2/s)
697.23	6.86	0	697.27	0.63	0	-	-	30	2.65E-10	1.32E-09	1.32E-05
692.22	6.79	0	692.26	0.57	0	-	-	30	2.65E-10	1.33E-09	1.33E-05
687.21	6.74	0	687.25	0.54	0	-	-	30	2.66E-10	1.33E-09	1.33E-05
682.20	6.71	0	682.24	0.51	0	-	-	30	2.66E-10	1.33E-09	1.33E-05
677.19	6.69	0	677.22	0.48	0	-	-	30	2.65E-10	1.33E-09	1.33E-05
672.18	6.63	0	672.21	0.44	0	-	-	30	2.66E-10	1.33E-09	1.33E-05
667.16	6.59	0	667.19	0.40	0	-	-	30	2.66E-10	1.33E-09	1.33E-05
662.14	6.58	0	662.17	0.38	0	-	-	30	2.66E-10	1.33E-09	1.33E-05
657.12	6.55	0	657.15	0.35	0	-	-	30	2.66E-10	1.33E-09	1.33E-05
652.11	6.50	0	652.14	0.28	0	-	-	30	2.65E-10	1.33E-09	1.33E-05
647.10	6.47	0	647.13	0.26	0	-	-	30	2.65E-10	1.33E-09	1.33E-05
642.09	6.42	0	642.12	0.19	0	-	-	30	2.65E-10	1.32E-09	1.32E-05
637.08	6.41	0	637.11	0.17	0	-	-	30	2.64E-10	1.32E-09	1.32E-05
632.07	6.37	0	632.10	0.14	0	-	-	30	2.65E-10	1.32E-09	1.32E-05
627.06	6.35	0	627.09	0.12	0	-	-	30	2.65E-10	1.32E-09	1.32E-05
622.05	6.29	0	622.08	0.06	0	-	-	30	2.65E-10	1.32E-09	1.32E-05
617.04	6.25	0	617.07	0.01	0	-	-	30	2.64E-10	1.32E-09	1.32E-05
612.04	6.20	0	612.06	-0.05	0	-	-	30	2.64E-10	1.32E-09	1.32E-05
607.03	6.13	0	607.05	-0.10	0	-	-	30	2.65E-10	1.32E-09	1.32E-05
602.02	6.05	0	602.05	-0.17	0	-	-	30	2.65E-10	1.33E-09	1.33E-05
597.02	6.01	0	597.04	-0.21	0	-	-	30	2.65E-10	1.33E-09	1.33E-05
592.01	5.99	0	592.04	-0.24	0	-	-	30	2.65E-10	1.32E-09	1.32E-05
587.00	5.94	0	587.03	-0.28	0	-	-	30	2.65E-10	1.33E-09	1.33E-05
581.99	5.87	0	582.02	-0.39	0	-	-	30	2.63E-10	1.32E-09	1.32E-05
576.99	5.81	0	577.02	-0.43	0	-	-	30	2.64E-10	1.32E-09	1.32E-05
571.98	5.76	0	572.01	-0.49	0	-	-	30	2.64E-10	1.32E-09	1.32E-05
566.98	5.70	0	567.01	-0.54	0	-	-	30	2.64E-10	1.32E-09	1.32E-05
561.97	5.65	0	562.00	-0.58	0	-	-	30	2.65E-10	1.32E-09	1.32E-05
556.96	5.61	0	556.99	-0.63	0	-	-	30	2.64E-10	1.32E-09	1.32E-05
551.96	5.53	0	551.99	-0.69	0	-	-	30	2.65E-10	1.33E-09	1.33E-05

Appendix 5.4

Secup1 (m)	Borehole Head1 (masl)	Flow1 (mL/h)	Secup2 (m)	Borehole Head2 (masl)	Flow2 (mL/h)	Section Head (masl)	T_s (m2/s)	Q-lower limit Practical (mL/h)	T_s-Lower Limit Theoretical (m2/s)	T_s-Lower Limit Practical (m2/s)	T_s-Upper Limit (m2/s)
546.95	5.49	0	546.98	-0.74	0	-	-	30	2.65E-10	1.32E-09	1.32E-05
541.94	5.44	0	541.97	-0.78	0	-	-	30	2.65E-10	1.33E-09	1.33E-05
536.93	5.41	0	536.96	-0.82	0	-	-	30	2.65E-10	1.32E-09	1.32E-05
531.92	5.31	0	531.95	-0.85	0	-	-	30	2.68E-10	1.34E-09	1.34E-05
526.91	5.27	0	526.94	-0.89	0	-	-	30	2.68E-10	1.34E-09	1.34E-05
521.90	5.24	0	521.93	-0.94	0	-	-	30	2.67E-10	1.33E-09	1.33E-05
516.90	5.20	0	516.93	-0.97	0	-	-	30	2.67E-10	1.34E-09	1.34E-05
511.89	5.12	0	511.92	-1.11	0	-	-	30	2.65E-10	1.32E-09	1.32E-05
506.88	5.09	0	506.91	-1.15	0	-	-	30	2.64E-10	1.32E-09	1.32E-05
501.87	5.05	0	501.90	-1.21	0	-	-	30	2.63E-10	1.32E-09	1.32E-05
496.86	5.03	0	496.89	-1.25	0	-	-	30	2.62E-10	1.31E-09	1.31E-05
491.85	4.99	0	491.88	-1.34	0	-	-	30	2.60E-10	1.30E-09	1.30E-05
486.84	4.97	0	486.87	-1.38	0	-	-	30	2.60E-10	1.30E-09	1.30E-05
481.83	4.88	0	481.86	-1.42	0	-	-	30	2.62E-10	1.31E-09	1.31E-05
476.82	4.83	0	476.85	-1.47	0	-	-	30	2.62E-10	1.31E-09	1.31E-05
471.82	4.79	0	471.85	-1.53	0	-	-	30	2.61E-10	1.30E-09	1.30E-05
466.81	4.77	0	466.84	-1.58	0	-	-	30	2.60E-10	1.30E-09	1.30E-05
461.80	4.70	0	461.83	-1.64	0	-	-	30	2.60E-10	1.30E-09	1.30E-05
456.79	4.66	0	456.82	-1.68	0	-	-	30	2.60E-10	1.30E-09	1.30E-05
451.78	4.61	0	451.81	-1.71	0	-	-	30	2.61E-10	1.30E-09	1.30E-05
446.77	4.57	0	446.80	-1.76	0	-	-	30	2.60E-10	1.30E-09	1.30E-05
441.76	4.53	0	441.80	-1.79	0	-	-	30	2.61E-10	1.30E-09	1.30E-05
436.76	4.51	0	436.80	-1.82	0	-	-	30	2.60E-10	1.30E-09	1.30E-05
431.75	4.47	0	431.79	-1.87	0	-	-	30	2.60E-10	1.30E-09	1.30E-05
426.75	4.46	0	426.79	-1.91	0	-	-	30	2.59E-10	1.29E-09	1.29E-05
421.74	4.54	0	421.79	-1.98	0	-	-	30	2.53E-10	1.26E-09	1.26E-05
416.74	4.53	0	416.79	-2.03	0	-	-	30	2.51E-10	1.26E-09	1.26E-05
411.73	4.47	0	411.79	-2.07	0	-	-	30	2.52E-10	1.26E-09	1.26E-05
406.73	4.45	0	406.78	-2.11	0	-	-	30	2.51E-10	1.26E-09	1.26E-05
401.73	4.39	0	401.78	-2.15	0	-	-	30	2.52E-10	1.26E-09	1.26E-05

Appendix 5.5

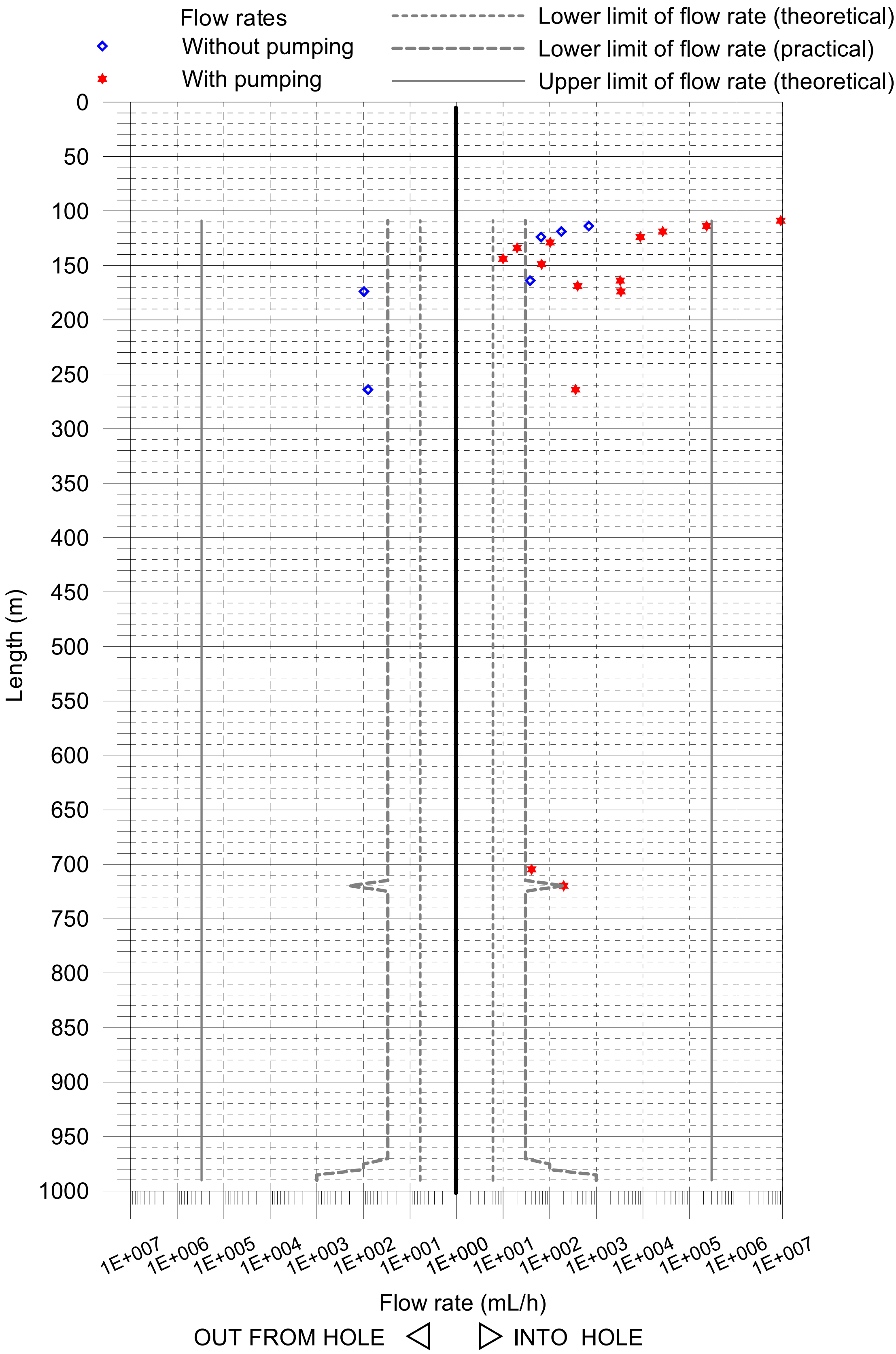
Secup1 (m)	Borehole Head1 (masl)	Flow1 (mL/h)	Secup2 (m)	Borehole Head2 (masl)	Flow2 (mL/h)	Section Head (masl)	T_s (m2/s)	Q-lower limit Practical (mL/h)	T_s-Lower Limit Theoretical (m2/s)	T_s-Lower Limit Practical (m2/s)	T_s-Upper Limit (m2/s)
396.73	4.11	0	396.78	-2.19	0	-	-	30	2.62E-10	1.31E-09	1.31E-05
391.73	4.23	0	391.78	-2.29	0	-	-	30	2.53E-10	1.26E-09	1.26E-05
386.73	4.24	0	386.77	-2.32	0	-	-	30	2.51E-10	1.26E-09	1.26E-05
381.73	4.18	0	381.77	-2.36	0	-	-	30	2.52E-10	1.26E-09	1.26E-05
376.73	3.96	0	376.77	-2.39	0	-	-	30	2.60E-10	1.30E-09	1.30E-05
371.73	4.10	0	371.77	-2.47	0	-	-	30	2.51E-10	1.25E-09	1.25E-05
366.73	3.80	0	366.77	-2.51	0	-	-	30	2.61E-10	1.31E-09	1.31E-05
361.73	3.94	0	361.76	-2.57	0	-	-	30	2.53E-10	1.27E-09	1.27E-05
356.73	3.90	0	356.76	-2.63	0	-	-	30	2.52E-10	1.26E-09	1.26E-05
351.72	3.75	0	351.75	-2.67	0	-	-	30	2.57E-10	1.28E-09	1.28E-05
346.71	3.91	0	346.74	-2.70	0	-	-	30	2.49E-10	1.25E-09	1.25E-05
341.70	3.61	0	341.73	-2.74	0	-	-	30	2.60E-10	1.30E-09	1.30E-05
336.69	3.80	0	336.72	-2.77	0	-	-	30	2.51E-10	1.25E-09	1.25E-05
331.68	3.51	0	331.71	-2.83	0	-	-	30	2.60E-10	1.30E-09	1.30E-05
326.67	3.72	0	326.70	-2.87	0	-	-	30	2.50E-10	1.25E-09	1.25E-05
321.66	3.43	0	321.69	-2.89	0	-	-	30	2.61E-10	1.30E-09	1.30E-05
316.65	3.66	0	316.68	-2.93	0	-	-	30	2.50E-10	1.25E-09	1.25E-05
311.64	3.35	0	311.67	-2.97	0	-	-	30	2.61E-10	1.30E-09	1.30E-05
306.63	3.58	0	306.66	-3.00	0	-	-	30	2.51E-10	1.25E-09	1.25E-05
301.63	3.25	0	301.66	-3.05	0	-	-	30	2.62E-10	1.31E-09	1.31E-05
296.63	3.46	0	296.65	-3.11	0	-	-	30	2.51E-10	1.25E-09	1.25E-05
291.63	3.16	0	291.65	-3.18	0	-	-	30	2.60E-10	1.30E-09	1.30E-05
286.62	3.33	0	286.64	-3.20	0	-	-	30	2.52E-10	1.26E-09	1.26E-05
281.62	3.16	0	281.64	-3.23	0	-	-	30	2.58E-10	1.29E-09	1.29E-05
276.62	3.07	0	276.64	-3.22	0	-	-	30	2.62E-10	1.31E-09	1.31E-05
271.62	3.15	0	271.63	-3.22	0	-	-	30	2.59E-10	1.29E-09	1.29E-05
266.62	2.88	0	266.63	-3.23	0	-	-	30	2.70E-10	1.35E-09	1.35E-05
261.61	3.08	-80	261.62	-3.26	360	1.93	1.91E-08	30	2.60E-10	1.30E-09	1.30E-05
256.61	2.81	0	256.62	-3.26	0	-	-	30	2.72E-10	1.36E-09	1.36E-05
251.61	3.03	0	251.61	-3.53	0	-	-	30	2.51E-10	1.26E-09	1.26E-05

Appendix 5.6

Secup1 (m)	Borehole Head1 (masl)	Flow1 (mL/h)	Secup2 (m)	Borehole Head2 (masl)	Flow2 (mL/h)	Section Head (masl)	T_s (m2/s)	Q-lower limit Practical (mL/h)	T_s-Lower Limit Theoretical (m2/s)	T_s-Lower Limit Practical (m2/s)	T_s-Upper Limit (m2/s)	Comments
246.60	2.81	0	246.61	-3.49	0	-	-	30	2.62E-10	1.31E-09	1.31E-05	
241.60	2.71	0	241.60	-3.42	0	-	-	30	2.69E-10	1.34E-09	1.34E-05	
236.59	2.83	0	236.60	-3.72	0	-	-	30	2.52E-10	1.26E-09	1.26E-05	
231.59	2.56	0	231.59	-3.55	0	-	-	30	2.70E-10	1.35E-09	1.35E-05	
226.58	2.73	0	226.59	-3.80	0	-	-	30	2.52E-10	1.26E-09	1.26E-05	
221.58	2.66	0	221.59	-3.67	0	-	-	30	2.60E-10	1.30E-09	1.30E-05	
216.58	2.42	0	216.58	-3.80	0	-	-	30	2.65E-10	1.33E-09	1.33E-05	
211.57	2.61	0	211.58	-3.75	0	-	-	30	2.59E-10	1.30E-09	1.30E-05	
206.57	2.49	0	206.57	-3.96	0	-	-	30	2.56E-10	1.28E-09	1.28E-05	
201.56	2.28	0	201.57	-3.81	0	-	-	30	2.71E-10	1.35E-09	1.35E-05	
196.56	2.45	0	196.56	-4.06	0	-	-	30	2.53E-10	1.27E-09	1.27E-05	
191.55	2.40	0	191.55	-3.91	0	-	-	30	2.61E-10	1.31E-09	1.31E-05	
186.54	2.14	0	186.55	-4.18	0	-	-	30	2.61E-10	1.30E-09	1.30E-05	
181.54	2.22	0	181.54	-4.01	0	-	-	30	2.65E-10	1.32E-09	1.32E-05	
176.53	2.25	0	176.53	-4.29	0	-	-	30	2.52E-10	1.26E-09	1.26E-05	
171.52	1.97	-98	171.53	-4.12	3388	1.80	1.57E-07	30	2.71E-10	1.35E-09	1.35E-05	
166.52	2.17	0	166.52	-4.39	400	-	1.68E-08	30	2.51E-10	1.26E-09	1.26E-05	
161.51	2.08	38	161.51	-4.20	3278	2.15	1.42E-07	30	2.62E-10	1.31E-09	1.31E-05	
156.50	1.89	0	156.50	-4.36	0	-	-	30	2.64E-10	1.32E-09	1.32E-05	
151.50	2.10	0	151.50	-4.31	0	-	-	30	2.57E-10	1.29E-09	1.29E-05	
146.50	1.88	0	146.49	-4.28	67	-	2.99E-09	30	2.68E-10	1.34E-09	1.34E-05	
141.49	1.84	0	141.48	-4.51	10	-	4.33E-10	30	2.60E-10	1.30E-09	1.30E-05	
136.49	1.98	0	136.48	-4.32	0	-	-	30	2.62E-10	1.31E-09	1.31E-05	
131.49	1.66	0	131.47	-4.66	20	-	8.69E-10	30	2.61E-10	1.30E-09	1.30E-05	
126.48	1.74	0	126.46	-4.50	102	-	4.49E-09	30	2.64E-10	1.32E-09	1.32E-05	
121.46	1.78	65	121.44	-4.62	8821	1.83	3.76E-07	30	2.58E-10	1.29E-09	1.29E-05	
116.42	1.52	177	116.41	-4.72	26766	1.56	1.17E-06	30	2.64E-10	1.32E-09	1.32E-05	
111.40	1.65	290	111.40	-4.60	234249	1.66	1.03E-05	30	2.64E-10	1.32E-09	1.32E-05	
106.39	1.65	0	106.39	-4.60	9120000	-	4.01E-04	30	2.54E-10	1.27E-09	1.27E-05	*

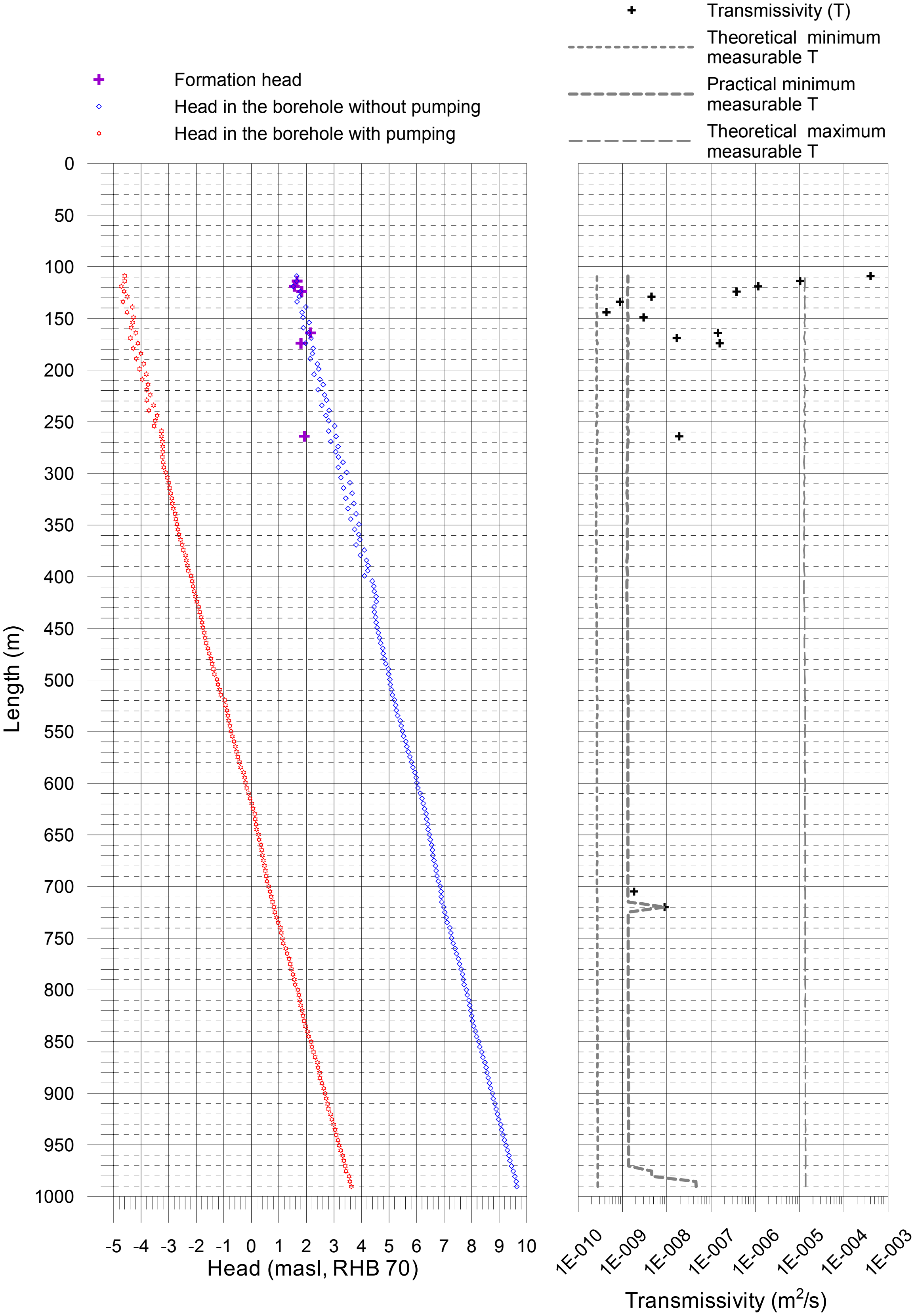
* T_S- Over the upper limit, T_S and head taken from Table 6-3, last row

Forsmark, Borehole KFM05A
Difference flow measurement 2004-05-11 - 2004-06-02
Length of section 5 m, depth increment 5 m



Appendix 6.2

Forsmark, Borehole KFM05A
Difference flow measurement 2004-05-11 - 2004-06-02
Length of section 5 m, length increment 5 m



Appendix 7.1

Length to fracture (m)	Borehole head1 (masl)	Flow1 (mL/h)	Borehole head2 (masl)	Flow2 (mL/h)	T_f (m^2/s)	Fracture head (masl)	Comments		
108.9	0.87	96000	0.76	588000	1.23 E-03	0.89	*	**	***
110.1	1.58	0	-4.62	170000	7.53E-06	-			
111.6	1.46	290	-4.74	250000	1.11E-05	1.47			
112.6	1.48	0	-4.77	900	3.96E-08	-			
112.9	1.51	0	-4.78	285	1.24E-08	-			***
113.3	1.56	0	-4.79	390	1.69E-08	-			
115.8	1.74	0	-4.85	12	5.00E-10	-			***
116.5	1.72	27	-4.8	1020	4.18E-08	1.90			
119.7	1.52	0	-4.58	1060	4.77E-08	-			
120.2	1.54	0	-4.55	1200	5.41E-08	-			
120.6	1.58	175	-4.54	23800	1.06E-06	1.63			
121.9	1.77	0	-4.53	425	1.85E-08	-			
124.1	1.77	0	-4.54	4280	1.86E-07	-			
124.4	1.75	0	-4.55	2200	9.59E-08	-			
126.1	1.6	0	-4.57	40	1.78E-09	-			
130.9	1.86	0	-4.6	90	3.83E-09	-			
132.2	1.8	0	-4.58	20	8.61E-10	-			***
142.4	1.76	0	-4.41	10	4.45E-10	-			***
149.0	1.88	0	-4.26	64	2.86E-09	-			
163.9	2.09	40	-4.34	3070	1.29E-07	2.17			
166.4	1.92	0	-4.4	70	3.04E-09	-			
167.2	1.94	0	-4.39	300	1.30E-08	-			
168.7	2.14	0	-4.29	20	8.55E-10	-			***
175.6	2.03	-101	-4.06	3020	1.41E-07	1.83			
264.4	3.08	-80	-3.42	360	1.86E-08	1.90			
702.7	6.87	0	0.51	36	1.56E-09	-			
720.0	6.99	0	0.62	200	8.63E-09	-	-	-	-

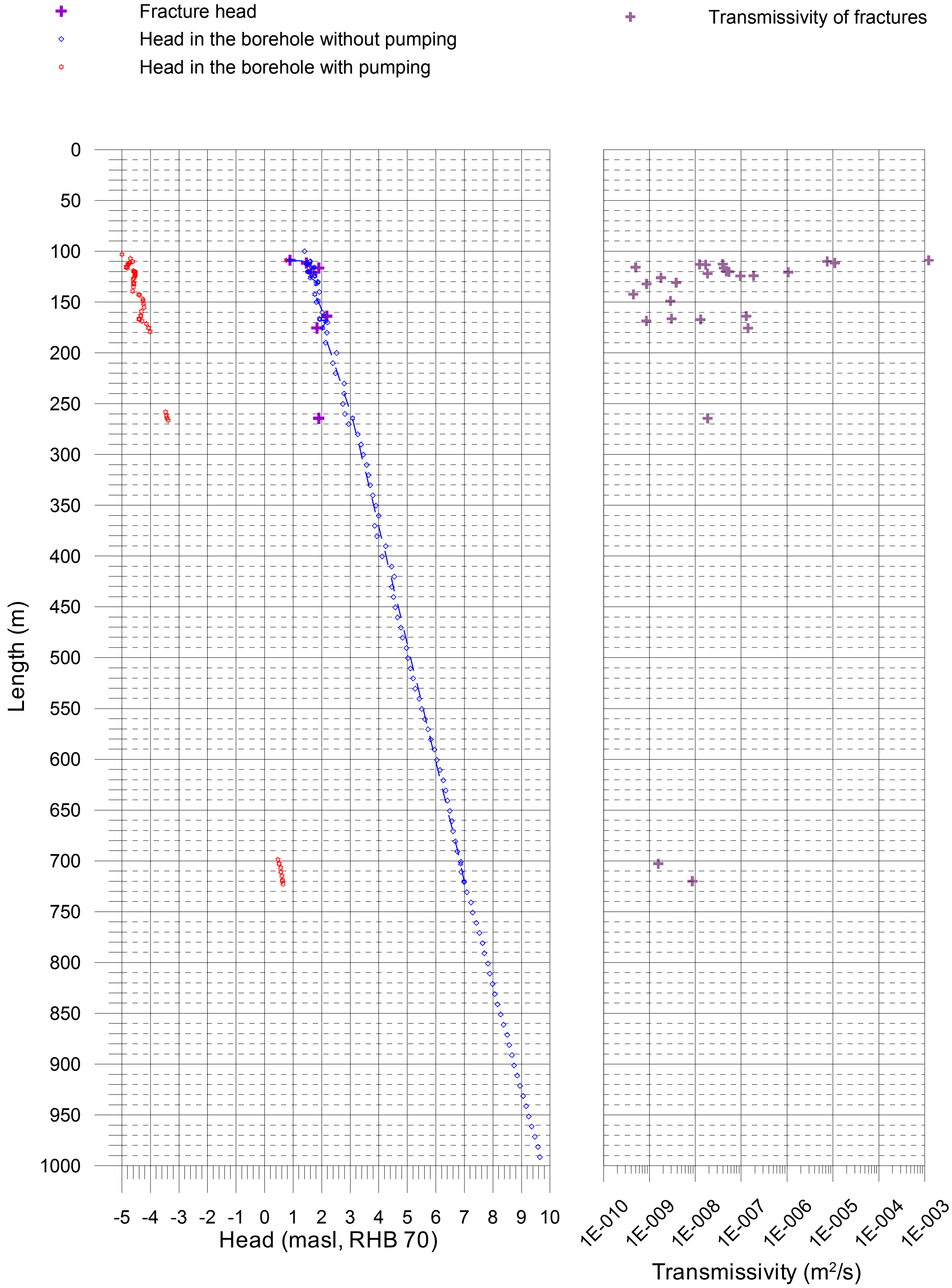
* T_f- Over the upper limit

** T_f and head taken from Table 6-3, pair 1 and 4

*** Uncertain

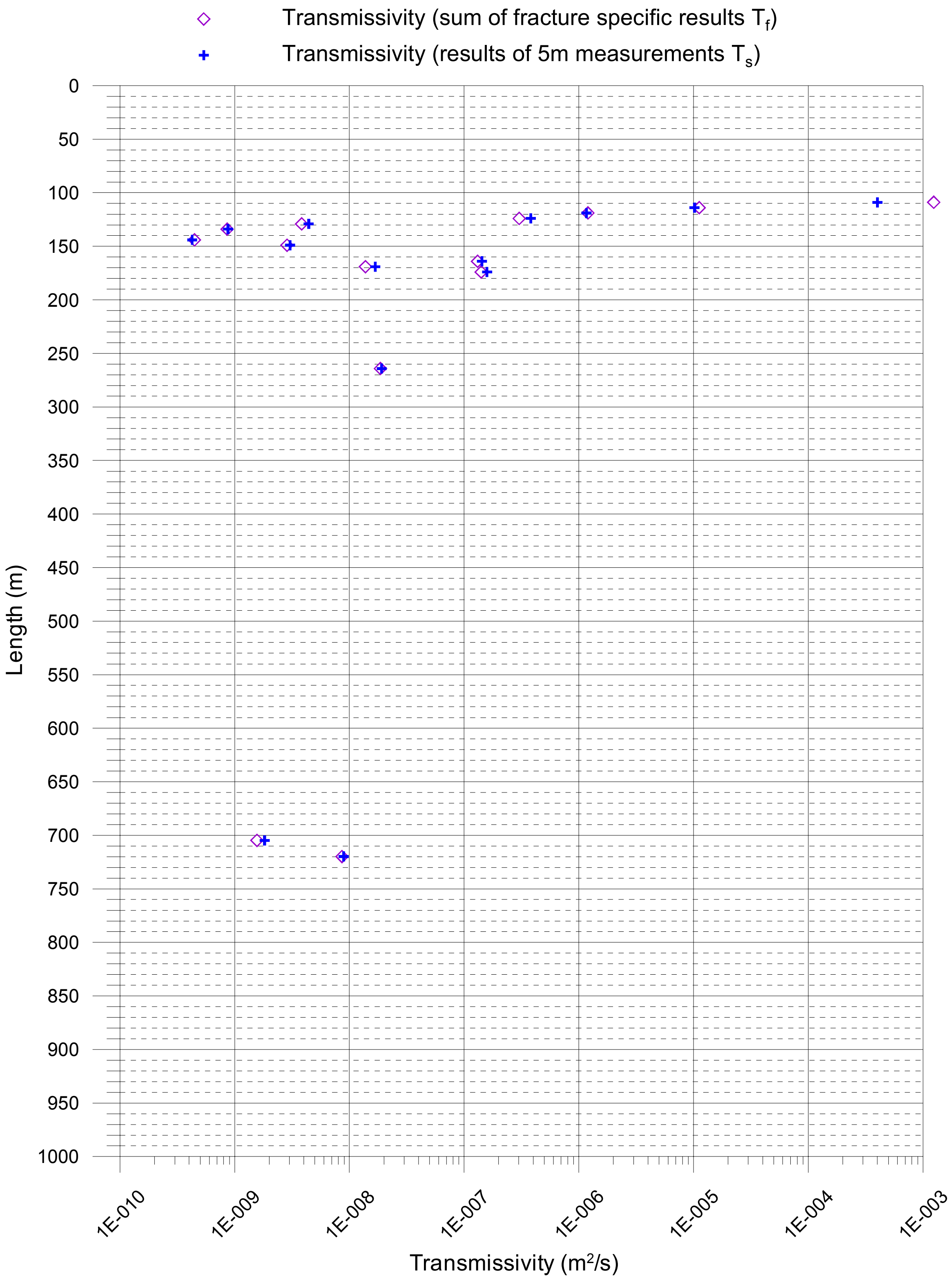
Appendix 7.2

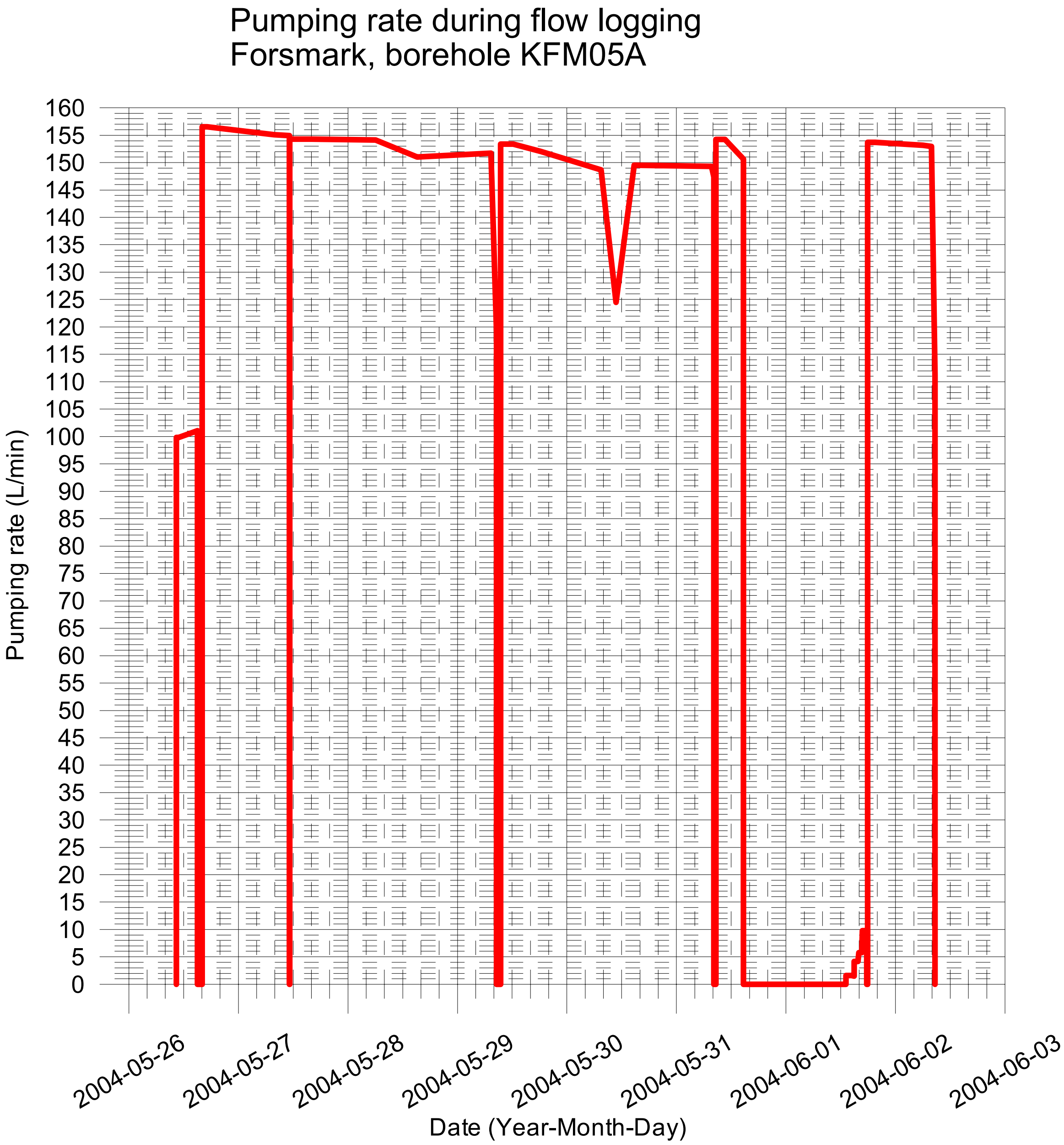
Forsmark, Borehole KFM05A
Difference flow measurement
Fracture-specific results



Appendix 8

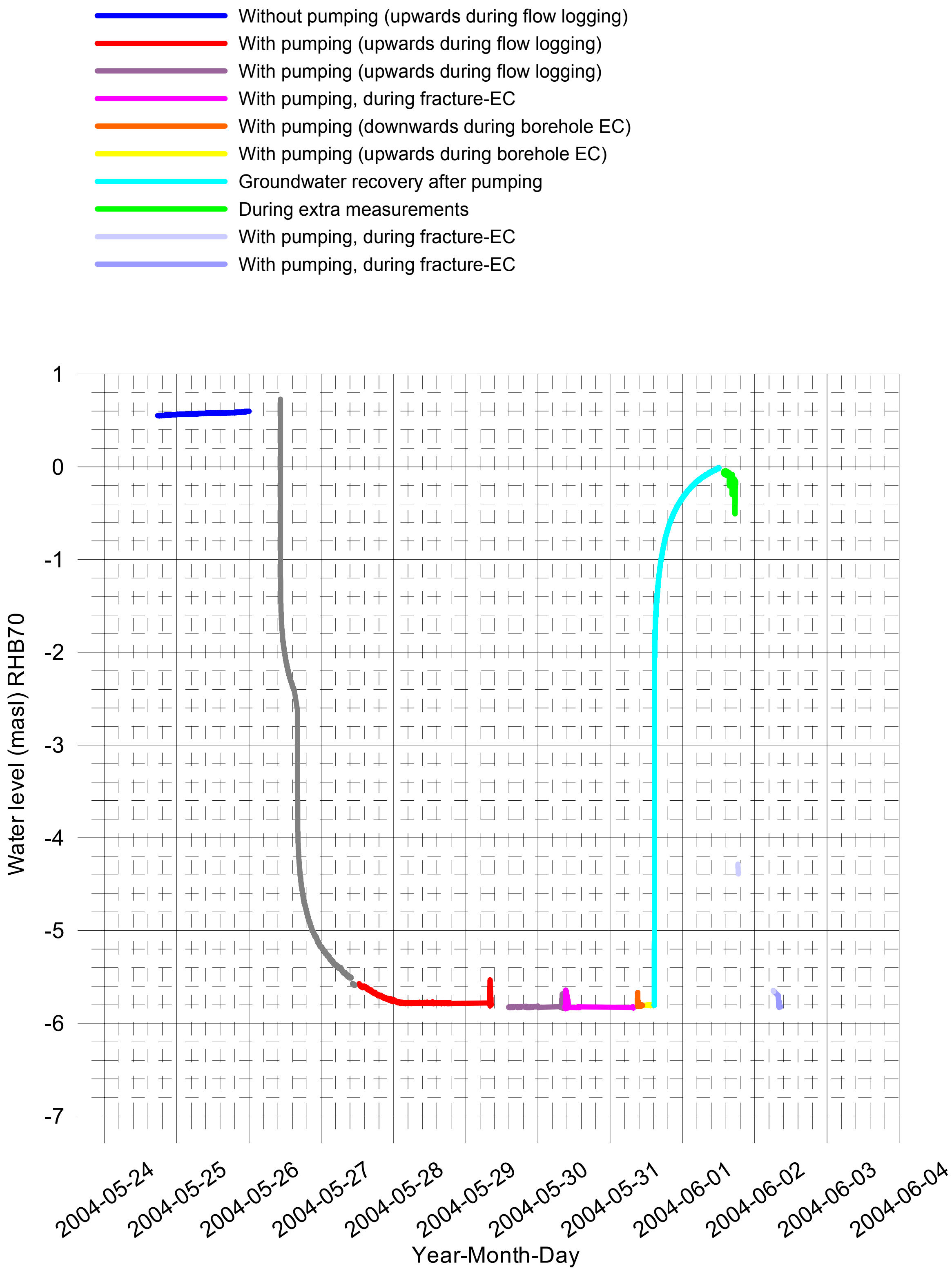
Forsmark, Borehole KFM05A
Comparison of transmissivity of borehole sections (5m) and fracture transmissivities




Pumping rate during flow logging
Forsmark, borehole KFM05A
Pumping rate (L/min)
160
155
150
145
140
135
130
125
120
115
110
105
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
2004-05-26
2004-05-27
2004-05-28
2004-05-29
2004-05-30
2004-05-31
2004-06-01
2004-06-02
2004-06-03
Date (Year-Month-Day)

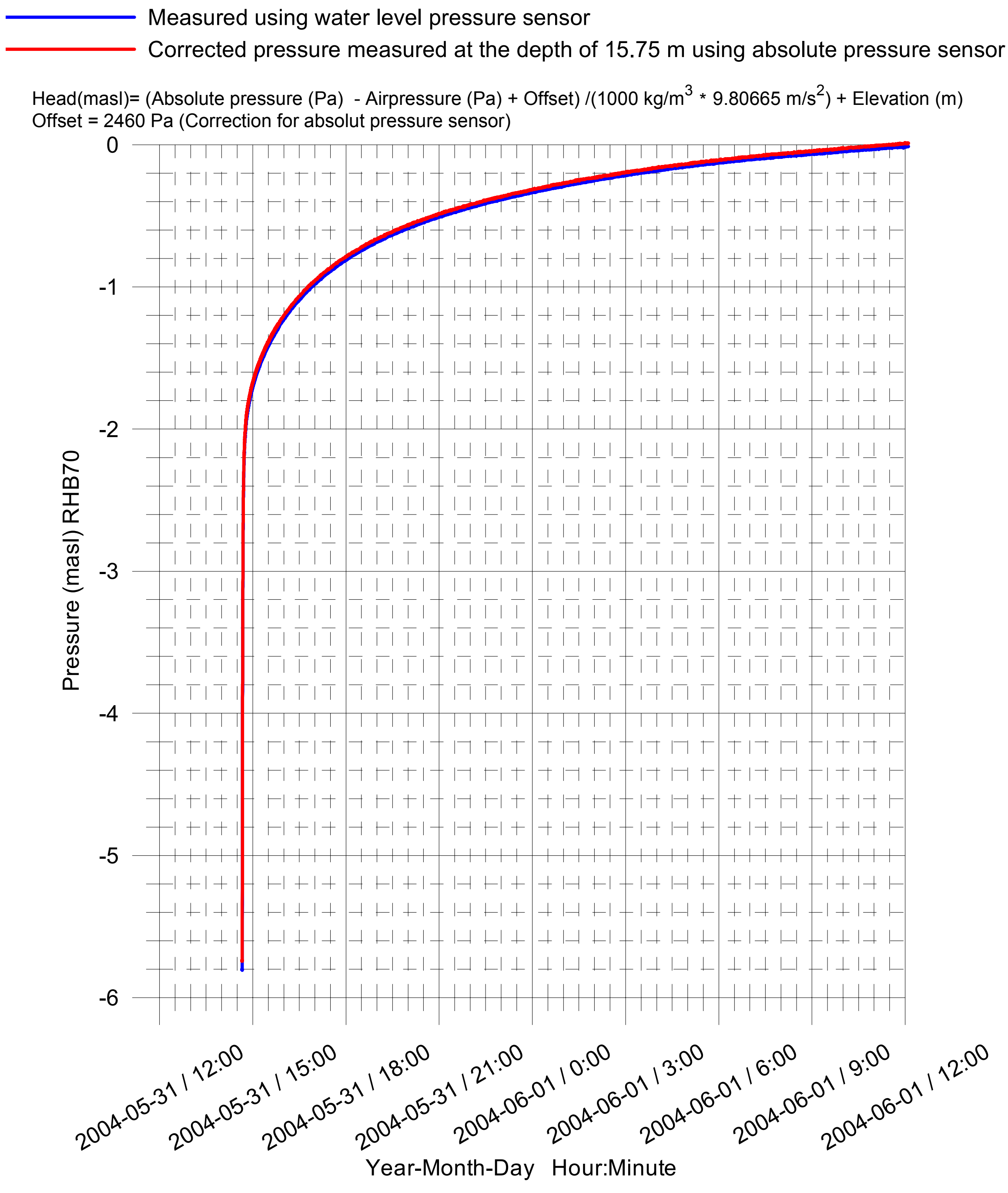
Appendix 9.2

Water level during difference flow logging
Borehole KFM05A, Forsmark

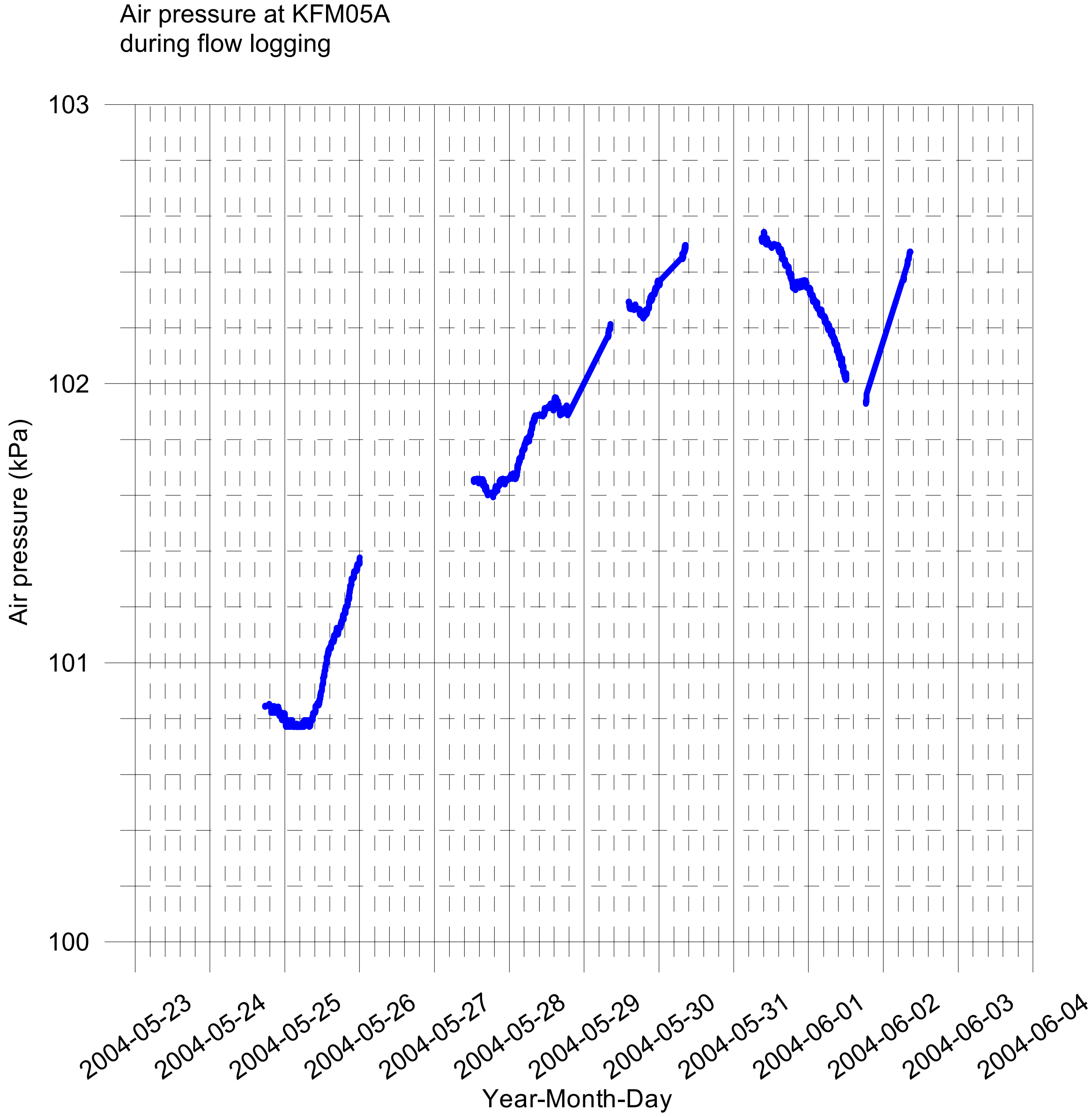


Appendix 9.3

Groundwater recovery after pumping

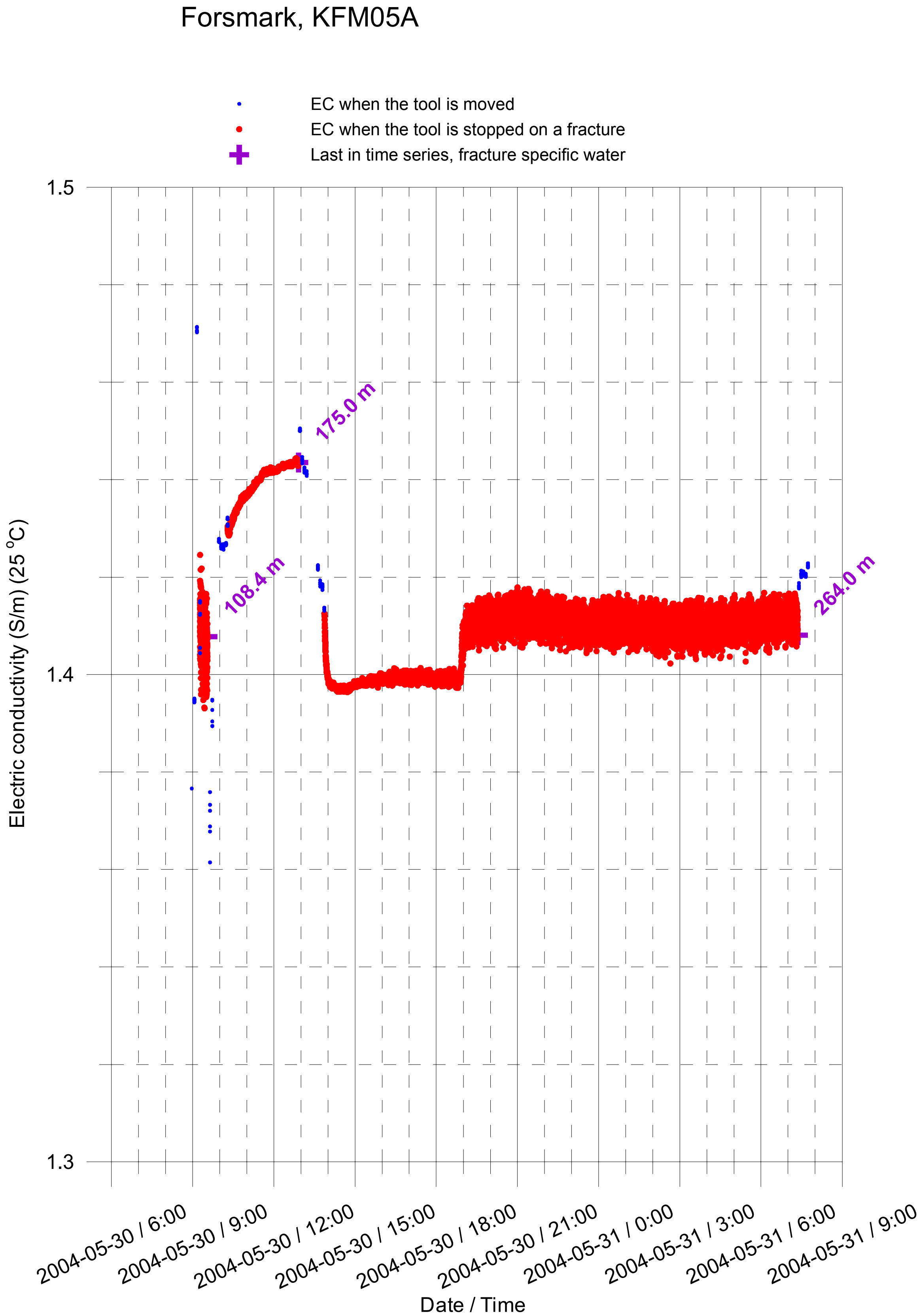


Appendix 9.4



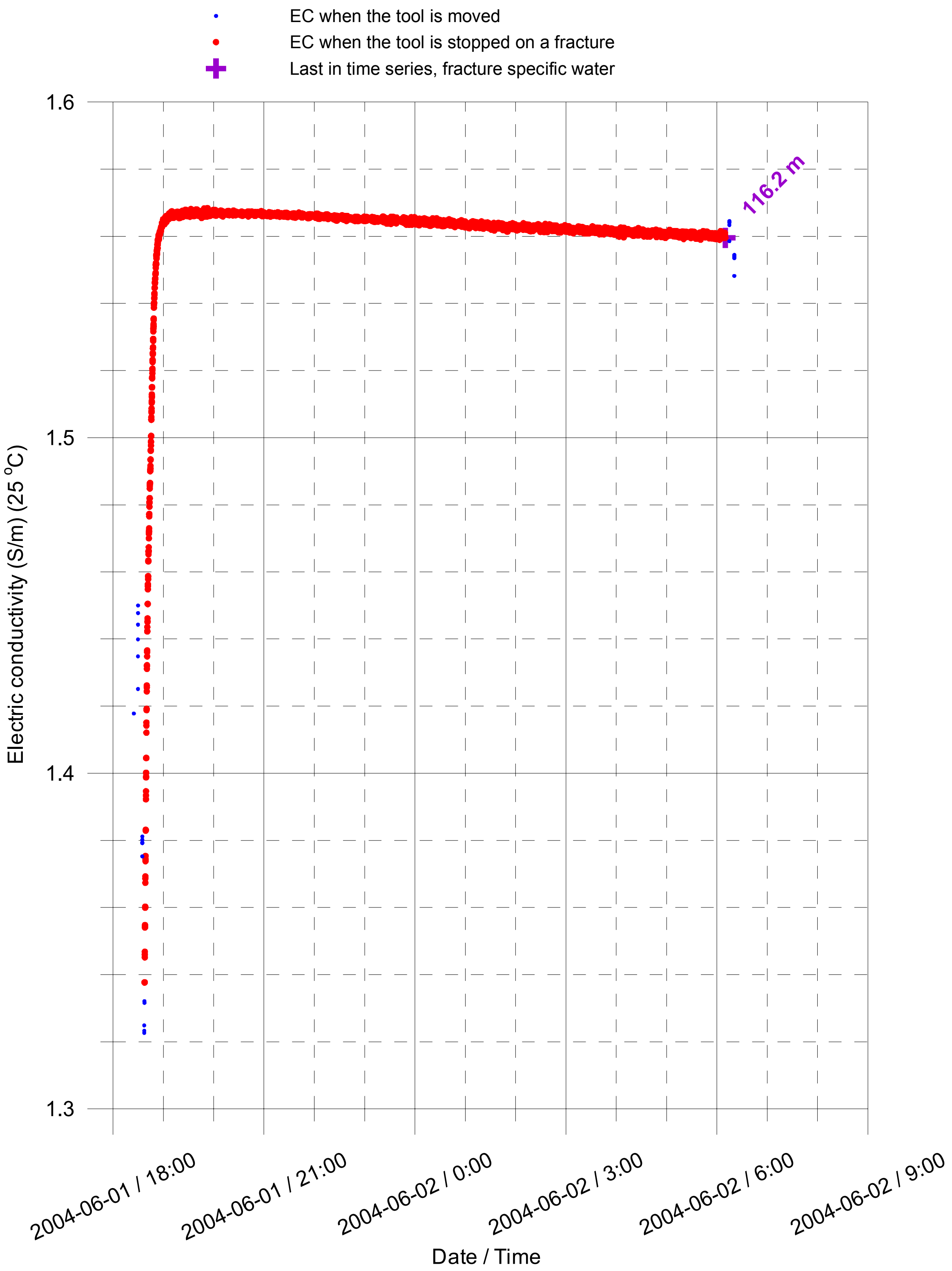
Air pressure at KFM05A
during flow logging
103
102
101
100
Air pressure (kPa)
2004-05-23
2004-05-24
2004-05-25
2004-05-26
2004-05-27
2004-05-28
2004-05-29
2004-05-30
2004-05-31
2004-06-01
2004-06-02
2004-06-03
2004-06-04
Year-Month-Day

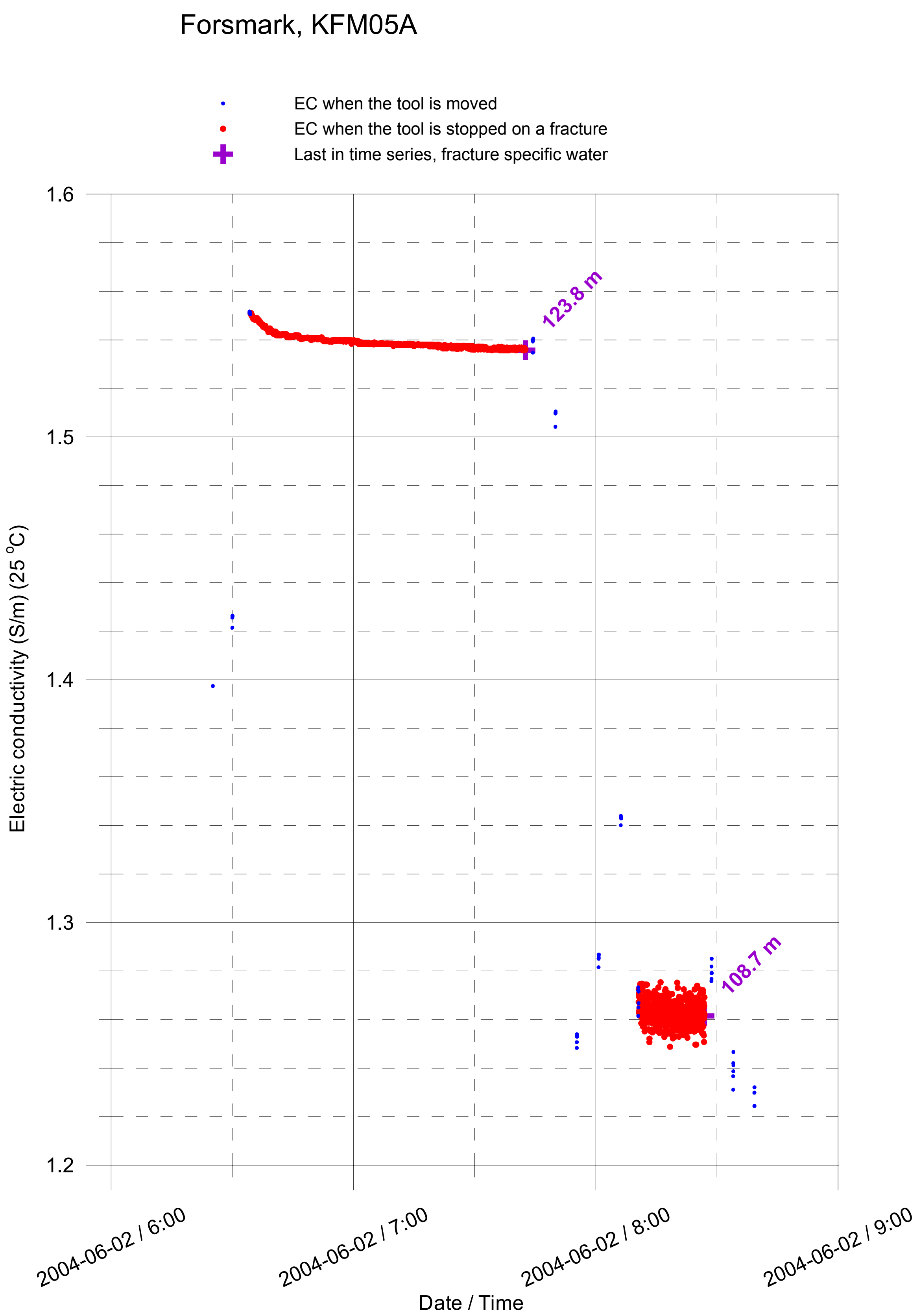
Appendix 10.1



Appendix 10.2

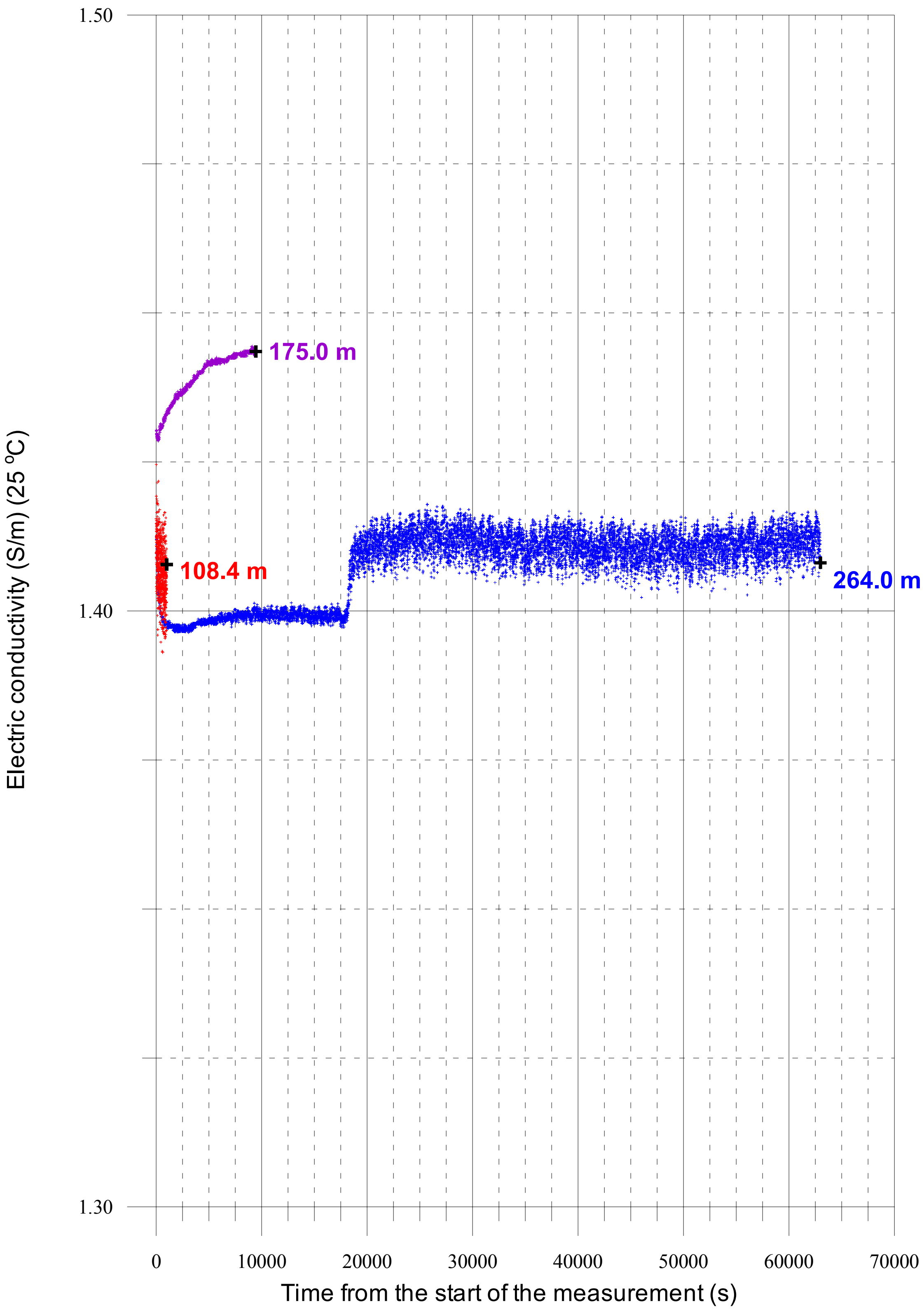
Forsmark, KFM05A



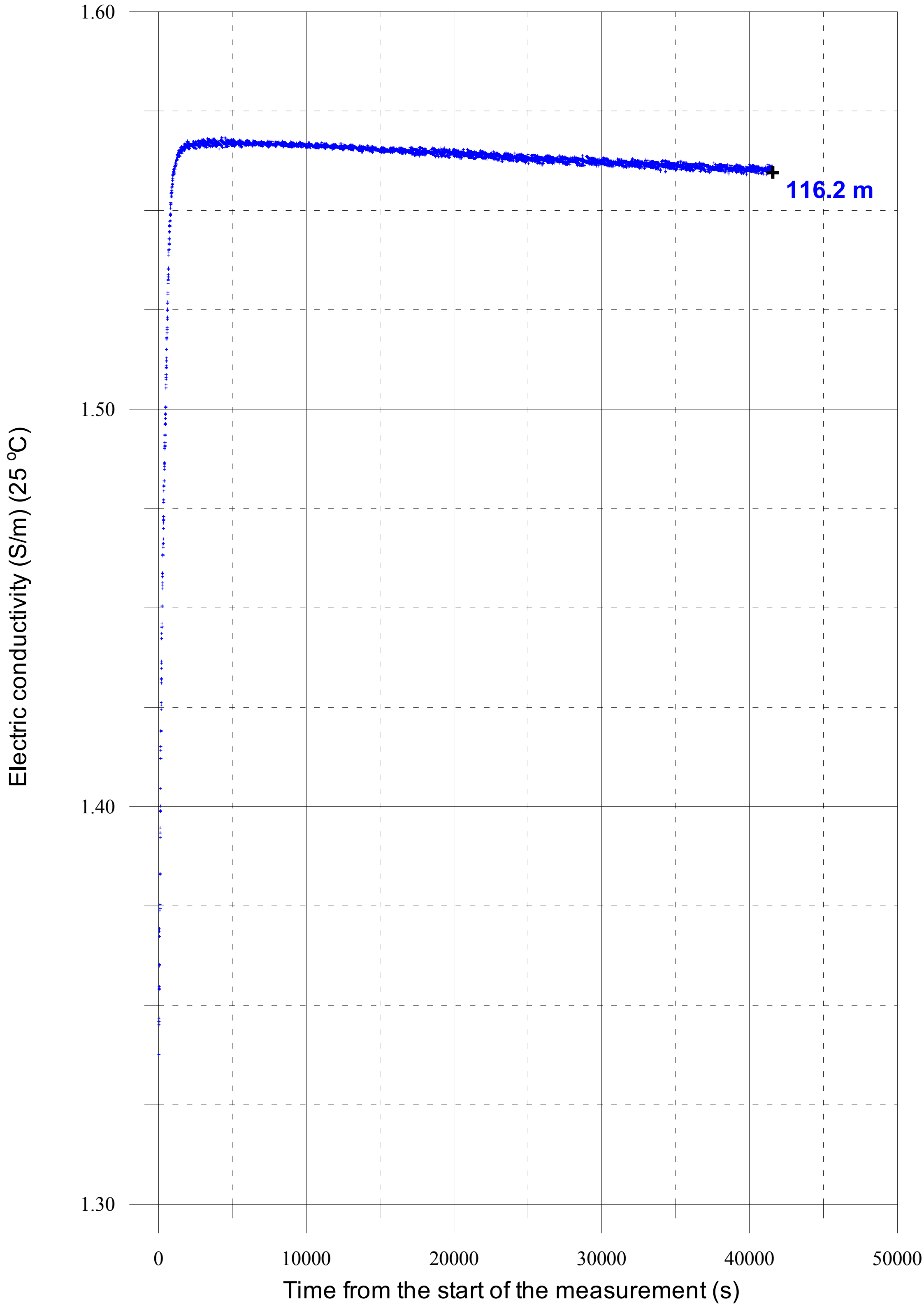


Forsmark, KFM05A
EC when the tool is moved
EC when the tool is stopped on a fracture
Last in time series, fracture specific water
123.8 m
108.7 m
1.6
1.5
1.4
1.3
1.2
Electric conductivity (S/m) (25 °C)
2004-06-02 / 6:00
2004-06-02 / 7:00
2004-06-02 / 8:00
2004-06-02 / 9:00
Date / Time

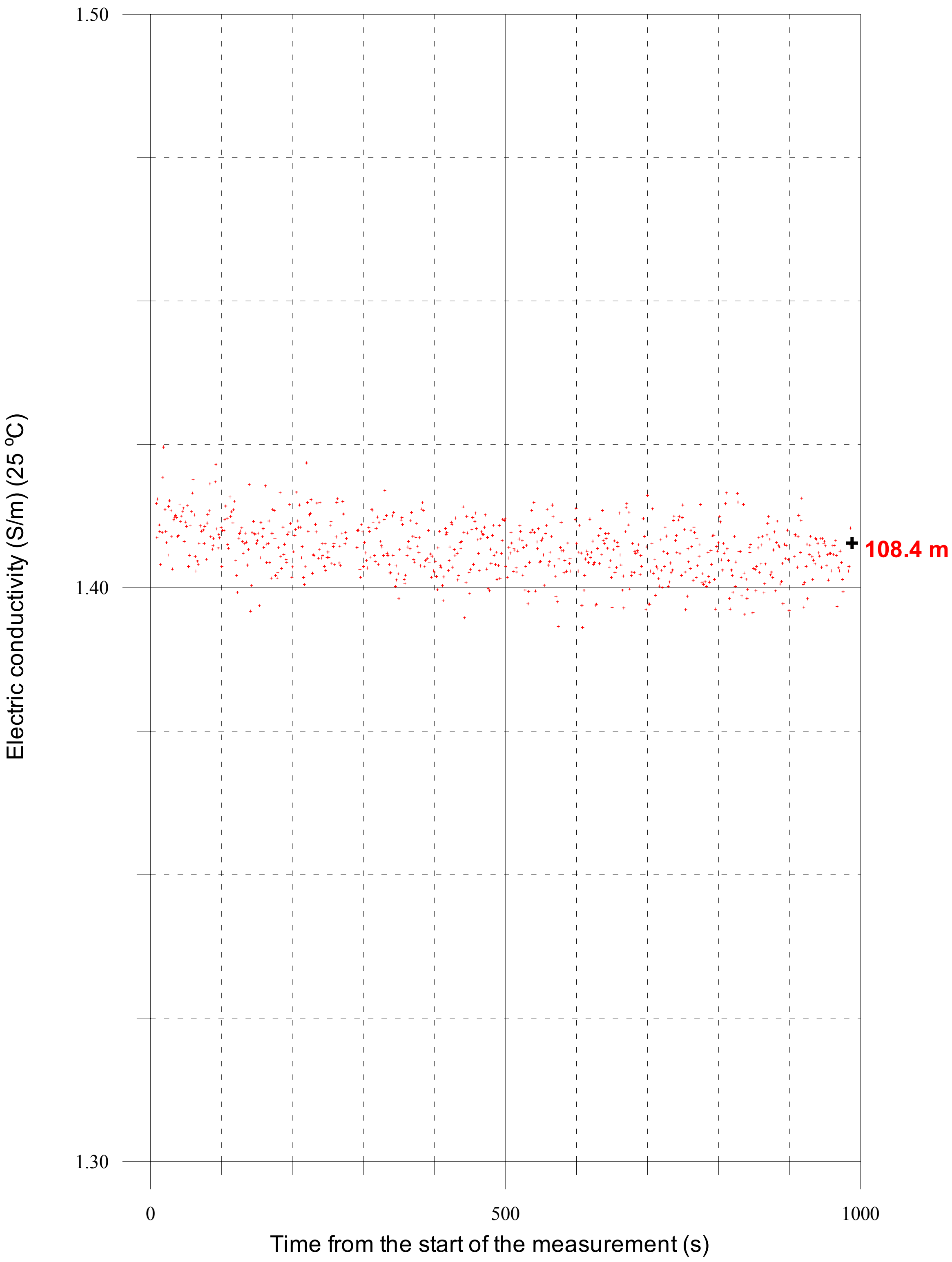
Time series of fracture-specific EC
Forsmark, borehole KFM05A, 2004-05-30 - 2004-05-31



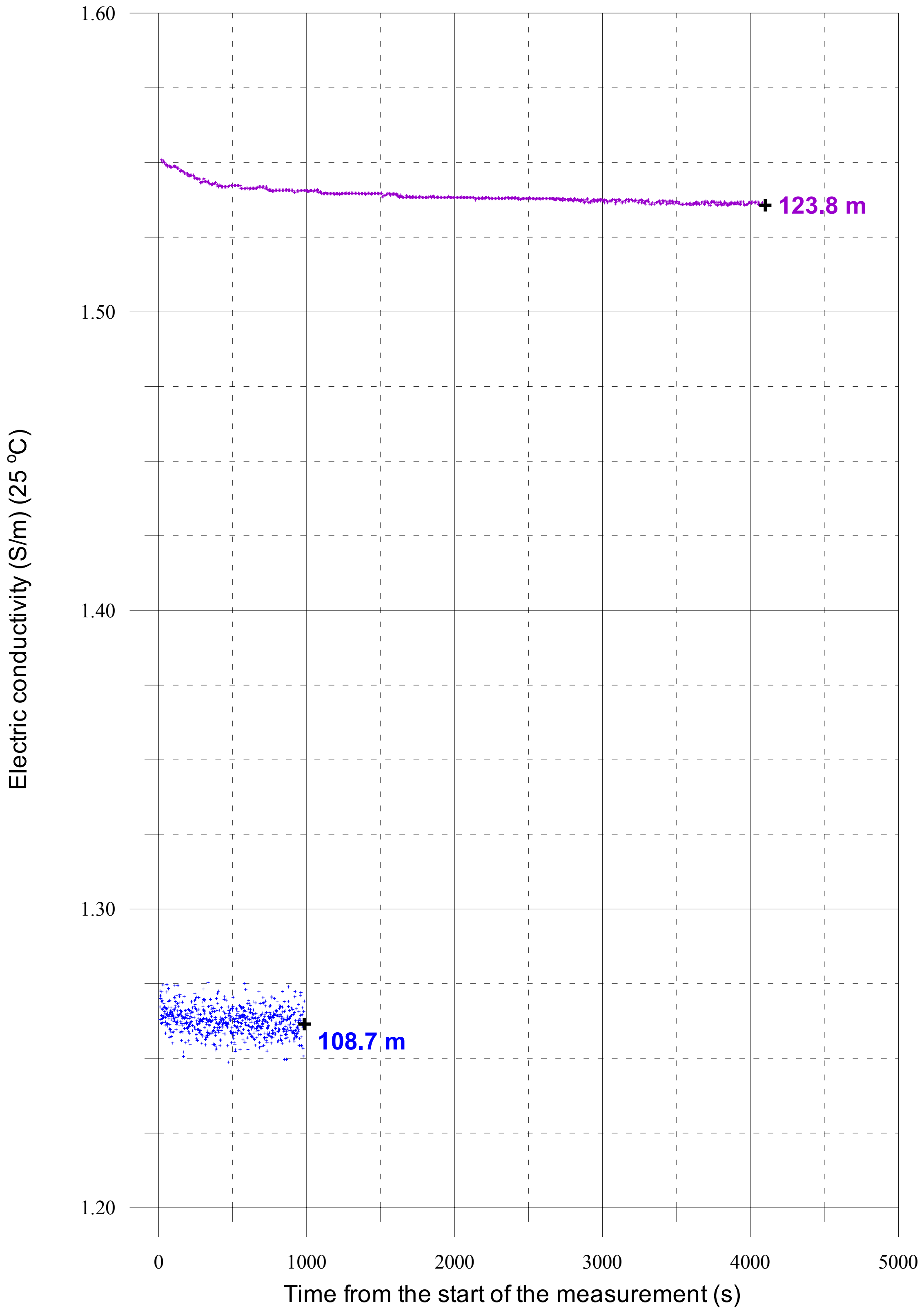
Time series of fracture-specific EC
Forsmark, borehole KFM05A, 2004-06-01 - 2004-06-02



Time series of fracture-specific EC
Forsmark, borehole KFM05A, 2004-05-30 - 2004-05-31

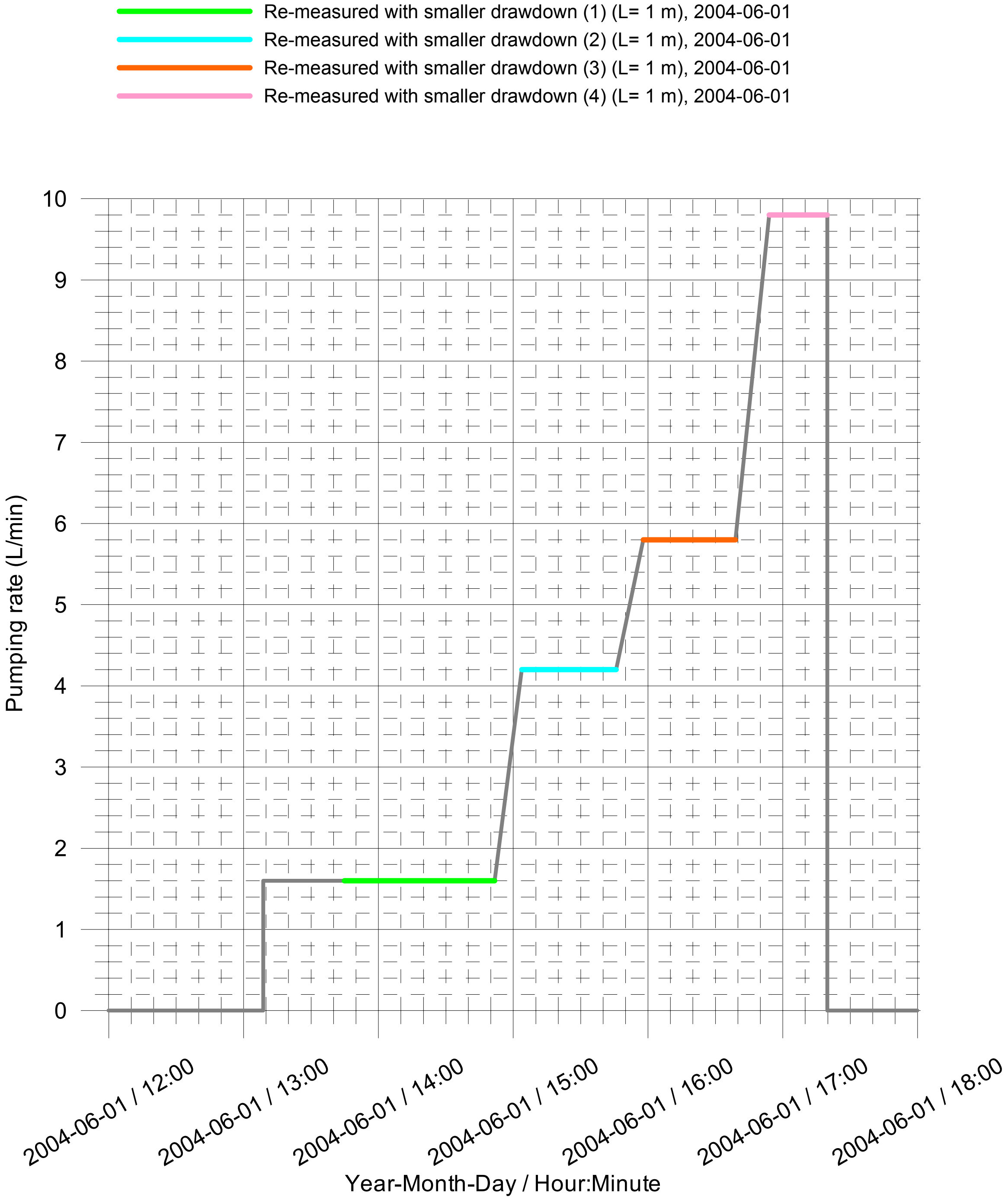


Time series of fracture-specific EC
Forsmark, borehole KFM05A, 2004-06-02



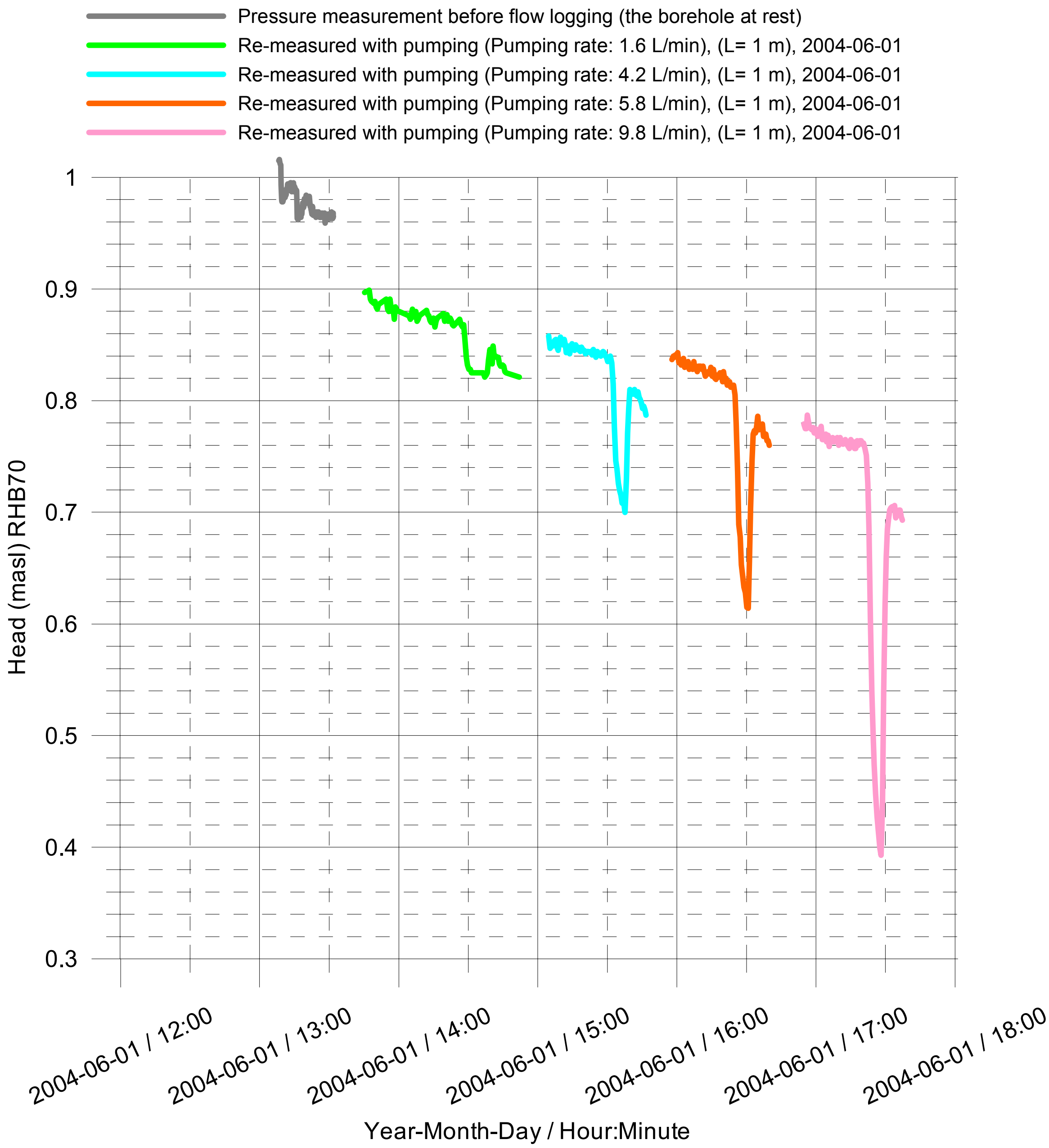
Appendix 11.1

Pumping rate during flow logging
Forsmark, borehole KFM05A
Extra measurements at depth interval 106 m - 114 m



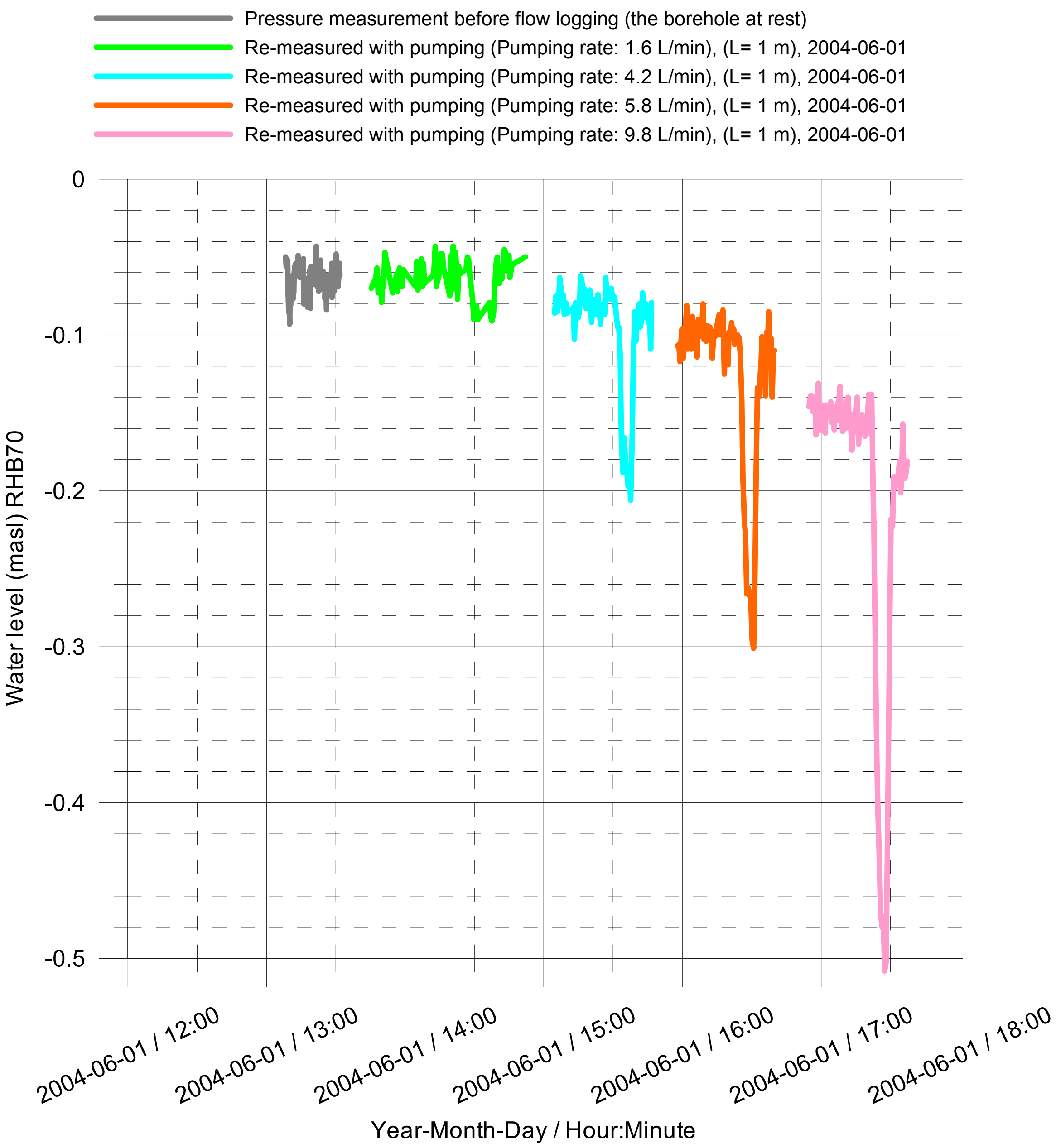
Appendix 11.2

Hydraulic head during difference flow logging
(measured with absolute pressure sensor)
Borehole KFM05A, Forsmark
Extra measurements at depth interval 106 m - 114 m



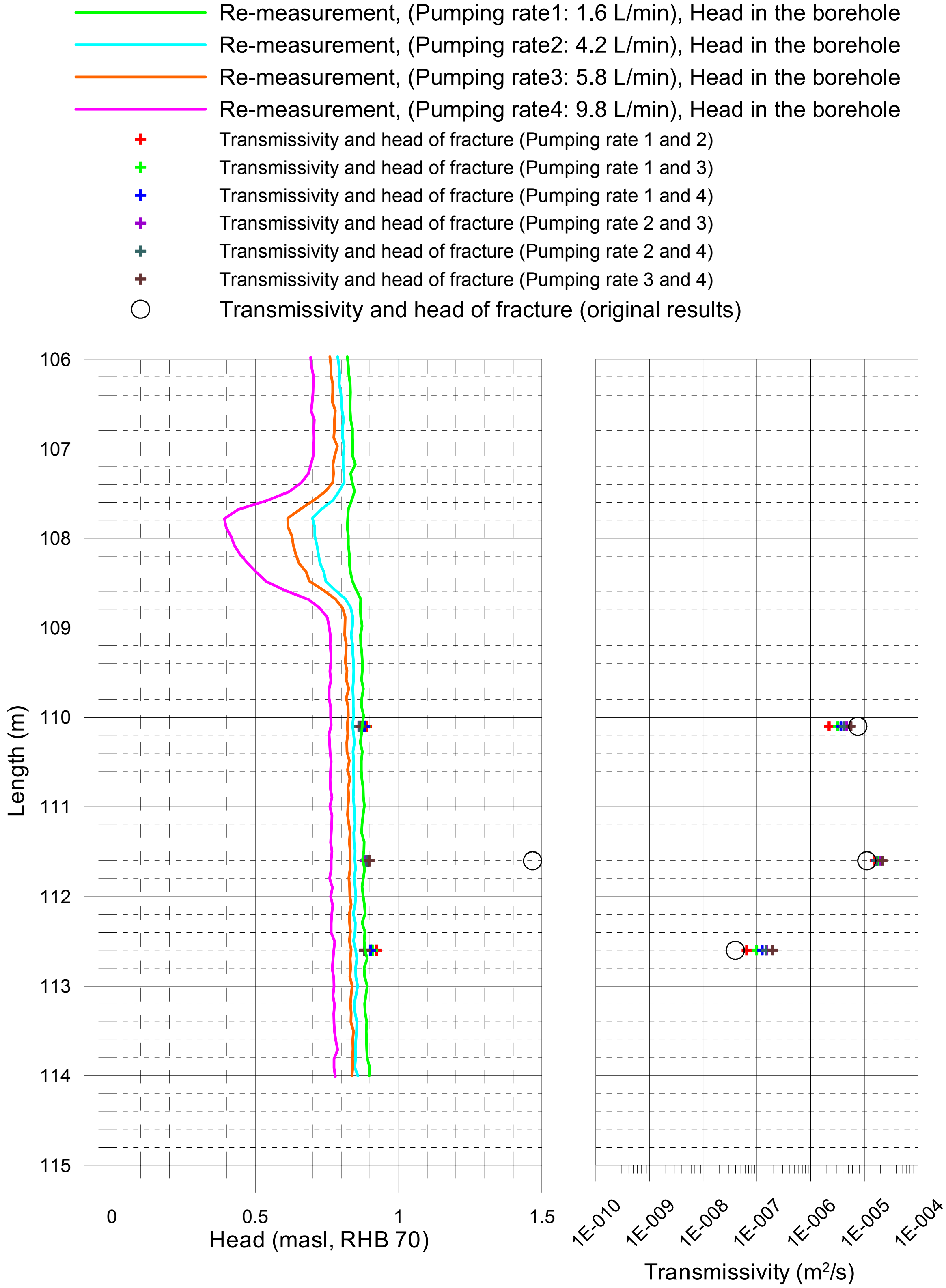
Appendix 11.3

Water level during difference flow logging
(measured with superficial pressure sensor)
Borehole KFM05A, Forsmark
Extra measurements at depth interval 106 m - 114 m



Appendix 11.4

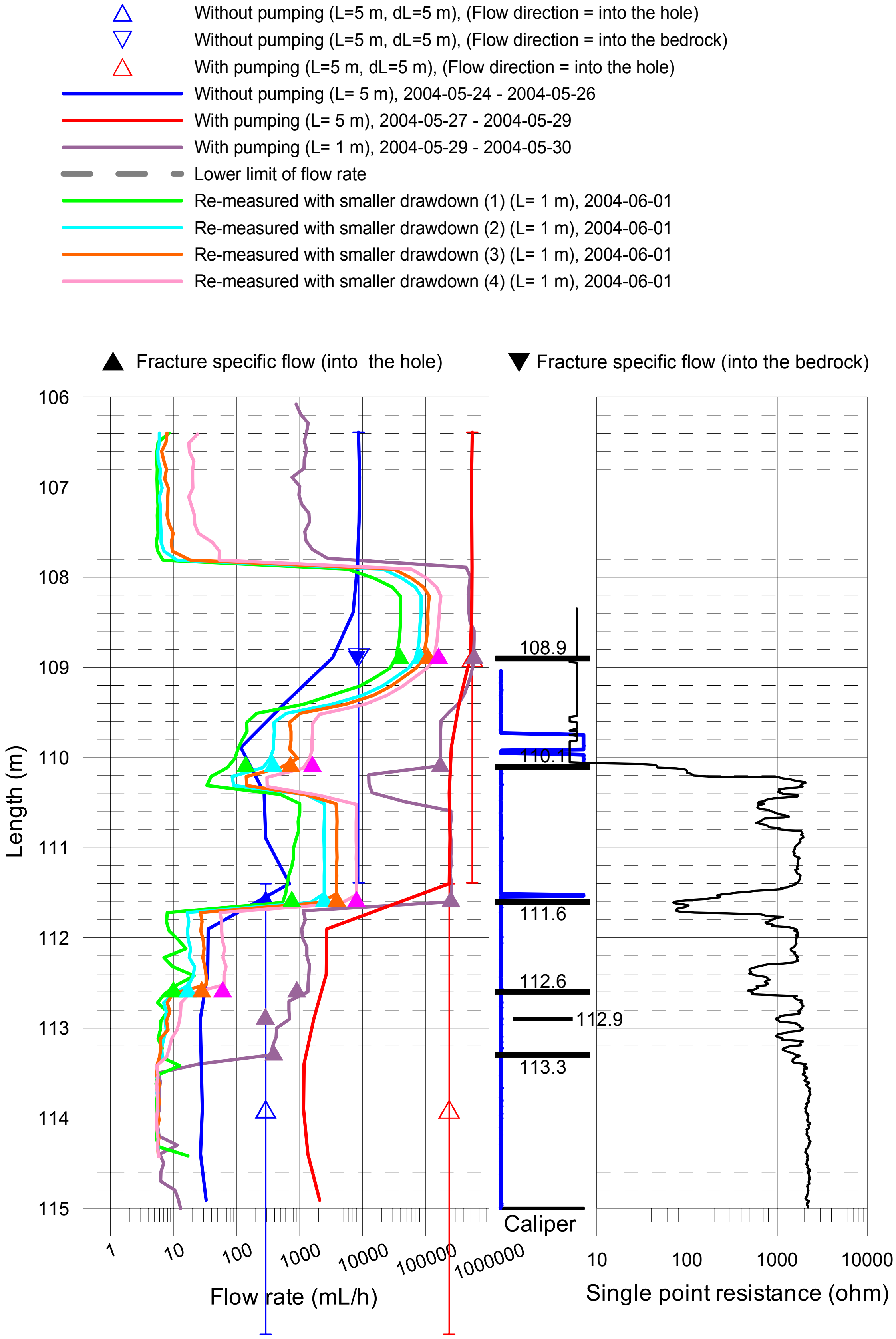
Forsmark, Borehole KFM05A
Difference flow measurement
Fracture-specific results
Extra measurements



Appendix 11.5

Forsmark, Borehole KFM05A

Flow measurement 2004-05-11 - 2004-06-02



Evaluation of pumping test during difference flow logging in borehole KFM05A

Jan-Erik Ludvigson

Geosigma AB

September 2004

Key words: Forsmark, hydrogeology, pumping test, hydraulic parameters, hydraulic transmissivity, hydraulic conductivity, AP PF 400-04-29, Field Note No. Forsmark 311

Appendix 12

Abstract

The flow rate and pressure history during the pumping in conjunction with the standard difference flow logging campaign in borehole KFM05A were used to estimate the total transmissivity of the cored borehole interval (c.109-1003 m) in KFM05A. In addition, possible effects of outer hydraulic boundaries during the pumping test were studied.

Borehole KFM05A was continuously pumped for c. 5 days during the main difference flow logging campaign. After stop of pumping, the recovery of the water level and head in the borehole was recorded during c. 1 day. The pressure recovery and the recovery of the water level were measured by a high-resolution pressure sensor and a superficial pressure transducer, respectively. The pressure recovery in the borehole was evaluated by transient methods for single-hole tests. In addition, an approximate evaluation was made on the pressure drawdown during the first part (c. 24 h) of the flow period when the flow rate was nearly constant. The flow rate was measured by a mechanical water meter during the flow period.

The total transmissivity of the cored borehole interval was calculated from both the recovery period and the first part (c. 24 h) of the flow period. The total transmissivity of the cored borehole KFM05A was calculated to c. $4.5 \cdot 10^{-4}$ m^2/s. According to the difference flow logging, the main inflow to the borehole occurs from the fracture zone at c. 109-112 m. Only two minor conductive fractures were identified below c. 200 m in the borehole.

No significant effects of apparent no-flow hydraulic boundaries could be observed, neither from the flow rate- and pressure histories during the relatively long (c. 5 d) flow period, nor during the recovery period. This fact may indicate that the assumed fracture zone intersecting the borehole at shallow depth has a large lateral extent.

Sammanfattning

Flödet och tryckresponsen under pumpningen i samband med den ordinarie differensflödesloggningen i borrhål KFM05A användes för att beräkna den totala transmissiviteten av den kärnborraden delen (c:a 109-1003 m) i KFM05A. Dessutom studerades förekomsten av eventuella hydrauliska gränser under pumptesten.

Borrhål KFM05A pumpades kontinuerligt under c:a 5 dygn under den ordinarie differensflödesloggningen. Efter avslutad pumpning registrerades återhämtningen av vattennivån och trycket i borrhålet under c:a 1 dygn. Tryckåterhämtningen mättes med en tryckgivare med hög upplösning medan vattenytans återhämtning mättes med en ytligt placerad tryckgivare. Återhämtningen i borrhålet utvärderades med transienta metoder för enhålstester. En approximativ utvärdering gjordes även av avsänkningen under den första delen (c:a 24 h) av flödesperioden då pumpflödet var nästan konstant. Pumpflödet mättes med en mekanisk flödesmätare.

Den totala transmissiviteten av kärnborrhålet, som beräknades dels från återhämtningsperioden och dels från den första delen (c:a 24 h) av flödesperioden. uppgår till c:a $4.5 \cdot 10^{-4}$ m^2/s. Enligt differensflödesloggningen kommer det huvudsakliga inflödet till borrhålet från sprickzonen intervallet 108.85-109.40 m, där ett perforerat foderrör stabiliserar borhålsväggen. Bara två, mindre konduktiva sprickor identifierades under c:a 200 m i borrhålet.

Inga tydliga effekter av skenbara negativa hydrauliska gränser kunde observeras, varken från flödes- och tryckresponsen under den relativt långa (c:a 5 d) flödesperioden eller under återhämtningsperioden. Detta kan tyda på att den förmodade ytliga sprickzonen som skär borrhålet har stor lateral utbredning.

Contents

1 Introduction

From the pumping activity in conjunction with the standard difference flow logging campaign in borehole KFM05A the total transmissivity of the entire, cored borehole interval was estimated. The water level in the open pumping borehole was registered by a superficial pressure sensor during both the flow- and recovery period of the pumping test. In addition, the pressure recovery after pumping was measured by the high-resolution pressure sensor.

The pumping flow rate from the borehole was c. 100 L/min during the first phase of the flow period. After c. 6 h, the flow rate was increased to c. 155 L/min causing a maximum drawdown of the water level of c. 6.5 m. The duration of the pumping period during the standard flow logging was c. 5 d. The subsequent pressure recovery was registered by the high-resolution absolute pressure sensor, whereas the water level in the borehole was registered by the superficial sensor.

The pumping flow rate was registered by a mechanical flow meter during the flow period. The dominating inflow to the borehole occurs in the perforated interval at c. 108.85-109.40 m.

2 Objective

The main purposes of the analysis of the pumping test during difference flow logging in borehole KFM05A were to estimate the total transmissivity of the cored borehole interval (c. 109-1003 m) 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 and other hydraulic tests performed in the borehole.

3 Scope

3.1 Borehole

Selected main technical data for borehole KFM05A are shown in Table 3-1. The borehole, which is c. 1003 m long, is inclined c 60 degrees from the horizontal and performed with a telescopic drilling technique. The borehole is cased to c. 100 m with an inner casing diameter of 0.200 m. Below this casing, there is a c. 10 m long casing with a smaller diameter (0.080 m). This casing is perforated in the interval 108.85-109.40 m at a high-transmissive fracture zone. More detailed borehole data are available from SICADA. The reference point in the borehole is the top of casing (ToC). The reference coordinate system for the X-Y-coordinates is RT90 and RHB70 for the elevation data.

Table 3-1.Selected main technical data of the cored borehole KFM05A. (From SICADA).

Borehole KFM05A							
ID	Elevation of top of casing (ToC) (m.a.s.l.)	Borehole interval from ToC (m)	Casing ID/ Bh-diam. (m)	Inclination-top of bh (from horizontal plane) (º)	Dip-direction-top of borehole (from local N) (º)	Remarks	Drilling finished Date (YYYY-MM-DD)
KFM05A	5.528	0.0-100.02	0.200	-59.804	80.897	Casing ID	2004-05-05
”		100.02-110.00*	0.080			”	
”		110.10-1002.71**	0.077			Open hole	

* casing perforated in the interval 108.85-109.40 m
** uncased cored borehole interval

3.2 Tests performed

During the difference flow logging in borehole KFM05A, continuous pumping of the open borehole was performed during c. 5 days followed by a recovery period of c. 21 h. The registration of the water level and flow rate together with the pressure recovery was performed according to the Activity Plan AP PF 400-04-29 (SKB internal controlling document) and the methodology description for difference flow logging SKB MD 322.010, Version 1.0, (SKB internal controlling document). Pertinent data of the pumping test during difference flow logging in KFM05A are shown in Table 3-2.

Table 3-2. Pertinent data of the pumping test during difference flow logging in borehole KFM05A.

Pumping Bh ID	Pumped interval (open hole) (m)	Test type[1]	Test no	Test start date and time (YYYY-MM-DD tt:mm)	Test stop date and time (YYYY-MM-DD tt:mm)
KFM05A	108.85-1002.71	1B	1	2004-05-26 10:24	2004-06-01 12:06

1) 1B: Pumping test with submersible pump with subsequent recovery

3.3 Equipment check

An equipment check was performed at the site as a simple and fast test to establish the operating status of sensors and other equipment. In addition, calibration constants were implemented and checked.

4 Equipment

4.1 Description of equipment

The pumping test was carried out with the standard equipment in the Posiva difference flow logging system including the following parts:

- submersible pump and connecting hose to the ground surface
- winch and steel wire
- flow rate control valve at the surface
- vessel in the borehole to maintain a constant water level
- superficial pressure transducer (gauge pressure)
- high-resolution absolute pressure sensor (attached to the flow probe)
- pressure sensor for registration of the atmospheric pressure
- data logger
- logging computer

During pumping in KFM05A, the water level in the borehole was at the level of the pump intake. The high-resolution pressure sensor is attached to the flow probe.

4.2 Sensors

Technical specifications of the superficial-and high resolution pressure transducers (P1 and P_{abs}), respectively and of the sensor for registration of the atmospheric pressure are listed in Table 4-1.

Table 4-1. Technical specifications of the pressure sensors used for registration of the barometric pressure, water level and pressure in borehole KFM05A. FS=Full Scale.

Technical specification of pressure sensors*				
Sensor	**Parameter**	**Unit**	**Value/range**	**Comments**
Barometric pressure	Output signal Meas. Range Resolution Accuracy	VDC kPa kPa kPa	0 – 5 80-106 0.01 ±0.03	at +20 °C
Superficial pressure P1 (gauge)	Output signal Meas. Range Resolution Accuracy	mA kPa kPa kPa	4 – 20 0 – 100 0.1 ±1% of FS	
Absolute Pressure P_{abs}	Output signal Meas. Range Resolution Accuracy	digital kPa kPa kPa	 0 – 20000 0.0001% of FS ±0.01% of FS	

* according to the manufacturers

Table 4-2 illustrates the position of equipment which may affect the borehole storage during the pumping test. The position of the pressure sensors (P1 and P_{abs}) together with the (lower) level of the submersible pump vessel is shown. The superficial pressure sensor (P1) was attached to the lower end of the pump. Equipment affecting wellbore storage is given in terms of the outer diameter of the submerged parts. The volume of the submerged pump (~a few dm^3) is in most cases of minor importance regarding wellbore storage and is therefore neglected.

Table 4-2. Position along the borehole (from ToC) of sensors and borehole equipment affecting wellbore storage in the open pumping borehole KFM05A.

Borehole information			Sensors		Equipment affecting wellbore storage (WBS)		
ID	Test interval (m)	Test no	Type	Position (m b. ToC)	Position[1)]	Function	Outer diameter (mm)
KFM05A	108.85-1002.71	1	Pump vessel (lower level) P (P1) P_{abs}	 13.77 13.77 15.75	 In open borehole	Pump hose Pump cable wire Pressure cable	18 11.5 3 8

[1)] Position of equipment that can affect wellbore storage.

5 Execution

5.1 Performance of the test

5.1.1 Test principle

Before the difference flow logging started, the borehole was pumped during c. 1 day in order to obtain as stationary conditions as possible. During the standard flow logging, the water level in the borehole was kept constant during the various flow logging sequences. The pumping period was followed by a pressure recovery period.

5.1.2 Test procedure

The pumping started with a constant flow rate of c. 100 L/min, causing a drawdown of the water level of c. 3 m. After c. 6 h, a submersible pump with higher capacity was installed in order to increase the drawdown. The flow rate was increased to c. 155 L/min and the water level approached a constant drawdown of c. 6.5 m after c. 1 day. The pumping was continued at this drawdown during the standard difference flow logging, cf. Appendix 9.2 in the main report. The total duration of the pumping period was c. 5 d, followed by a recovery period of c. 1 d. The pumped flow was discharged at the ground surface sloping downhill from the pumping borehole. The flow rate was recorded manually c. 5-6 times/day from a mechanical flow meter.

The changes of the water level and pressure were registered by the superficial pressure sensor and the high-resolution pressure sensor, respectively, during both the flow- and recovery period. During the recovery period the absolute pressure sensor was located at c. 15.75 m below top of casing. The sampling frequency was the same for the superficial- and the high-resolution pressure sensor. A higher sampling frequency was used during the recovery period, cf. Table 5-1. The sampling frequency was increased to 1-2 s shortly before stop of pumping to obtain a proper start of the recovery period.

Table 5-1. Sampling frequency for registration of the water level and pressure during the flow- and recovery period of the pumping test in borehole KFM05A.

Time interval (s) from start of pumping	Sampling frequency (s)
0-89 000	c. 30
89 000-252 000	c. 60
252 000-422 000	c. 30
422 000-447 300	c. 6
Time interval (s) from stop of pumping	**Sampling frequency (s)**
0-4165	1-2
4165-77 200	c. 30

5.2 Data handling

A list of the raw data files from the flow- and recovery period is shown in Appendix 12.1. From the pressure versus time data files, relevant drawdown – and recovery files were prepared and plotted in selected diagrams in accordance with the Method Instruction SKB MD 320.004, Version 1.0, Instruktion för analys av injektions- och enhålspumptester (SKB internal controlling document). By the calculation of the pressure drawdown and -recovery from the absolute pressure sensor, the barometric pressure was firstly subtracted from the measured pressure data. However, no such corrections were made on the measured (gauge) pressure data from the superficial 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 a maximum smoothing of the derivative without altering the original shape of the data curve, i.e. the lowest possible step length.

5.3 Analyses and interpretation

The evaluation of the pumping test was mainly made from the pressure recovery period using data from the high-resolution absolute pressure sensor. For comparison, the corresponding data from the superficial sensor were also used. Furthermore, an approximate analysis was made on the first part (c. 24 h) of the flow period, using data from both the superficial- and the absolute pressure sensor. Due to the change to a submersible pump with higher flow capacity, the actual part of the flow period was divided into two phases.

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, preferably in the log-log diagrams. The pressure recovery was plotted versus real time after stop of pumping since both the pressure and flow rate were rather stable at the end of the flow period and the recovery period was fairly short compared to the flow period.

The quantitative, transient interpretation of hydraulic parameters from the pumping borehole (e.g. transmissivity and skin factor) was based on the identified pseudo-radial flow regimes according to the methods described in /1/ and in the instruction mentioned above for constant flow rate tests in an equivalent porous medium using the code AQTESOLV. By the analysis of the flow period a variable flow rate was applied to account for the change in flow rate made by the exchange of submersible pump, cf. Chapter 5.1.2. Finally, a steady-state analysis (Moye's formula) was also made from the flow period.

A brief description of the code AQTESOLV and its application is provided in related pumping test reports from HTHB tests, e.g. /3/.

6 Results

6.1 Nomenclature and symbols

The nomenclature and symbols used for the results of the pumping test are applied according to SKB MD 320.004. Additional symbols used are explained in the text. The nomenclature used in the diagrams prepared by the code AQTESOLV is shown in Appendix 12.2.

6.2 Single-hole pumping test

General test data from the pumping test during the difference flow logging in borehole KFM05A are presented in Table 6-1. As discussed in Section 5.2, the atmospheric pressure was subtracted from the measured data from the absolute pressure sensor by the analysis of the test data whereas no corrections were made on the water level data from the superficial (gauge) sensor in the borehole. The atmospheric pressure during the pumping test and the approximate start and stop of pumping is shown in Figure 6-1.

Since no data from observation boreholes were available, a value on the storativity must be assumed by the calculation of the skin factor. In this case the value $S^*=5\cdot10^{-5}$, obtained from interference tests between HFM01 and HFM02, /2/, was used. A summary of the results of the single-hole pumping test in KFM05A is presented in Table 6-2 and 6-3. Test diagrams are shown in Appendix 12.2.

Table 6-1. General test data from the pumping test in borehole KFM05A.

General test data			
Testtype[1]	Constant flow rate and recovery test		
Test section (open borehole/packed-off section):	open borehole		
Test No	1		
Field crew	J. Pöllänen and P. Heikkinen, PRG Tec-Oy		
Test equipment system	Posiva difference flow logging system		
General comment	Single-hole test		
	Nomen-clature	**Unit**	**Value**
Borehole length	L	m	1002.71
Total casing length	L_c	m	110.00*
Test section- secup	Secup	m	108.85
Test section- seclow	Seclow	m	1002.71
Test section length	L_w	m	893.86
Test section diameter	$2 \cdot r_w$	mm	77.3
Test start (start of pressure registration)		yymmdd hh:mm	2004-05-26 10:24
Packer expanded		yymmdd hh:mm:ss	-
Start of flow period		yymmdd hh:mm:ss	2004-05-26 10:25:14
Stop of flow period		yymmdd hh:mm:ss	2004-05-31 14:39:55
Test stop (stop of pressure registration)		yymmdd hh:mm	2004-06-01 12:06
Total flow time	t_p	min	7455
Total recovery time	t_F	min	1286

*the interval 108.85-109.40 m is perforated

Groundwater level data

Groundwater pressure data in the pumping borehole KFM05A	**Nomen-clature**	**Unit**	**Value (m.a.s.l)**
Water level (from gauge pressure) in borehole before start of flow period	h_i	m	0.73
Water level (from gauge pressure) in borehole before stop of flow period	h_p	m	-5.80
Water level (from gauge pressure) in borehole before stop of recovery period	h_F	m	-0.01
Maximum drawdown in borehole during flow period	s_p	m	6.53

Flow data

Flow data in the pumping borehole KFM05A	**Nomen-clature**	**Unit**	**Value**
Flow rate from test section just before stop of flow period	Q_p	m^3/s	$2.50 \cdot 10^{-3}$
Mean (arithmetic) flow rate during flow period	Q_m	m^3/s	-
Total volume discharged during flow period	V_p	m^3	-

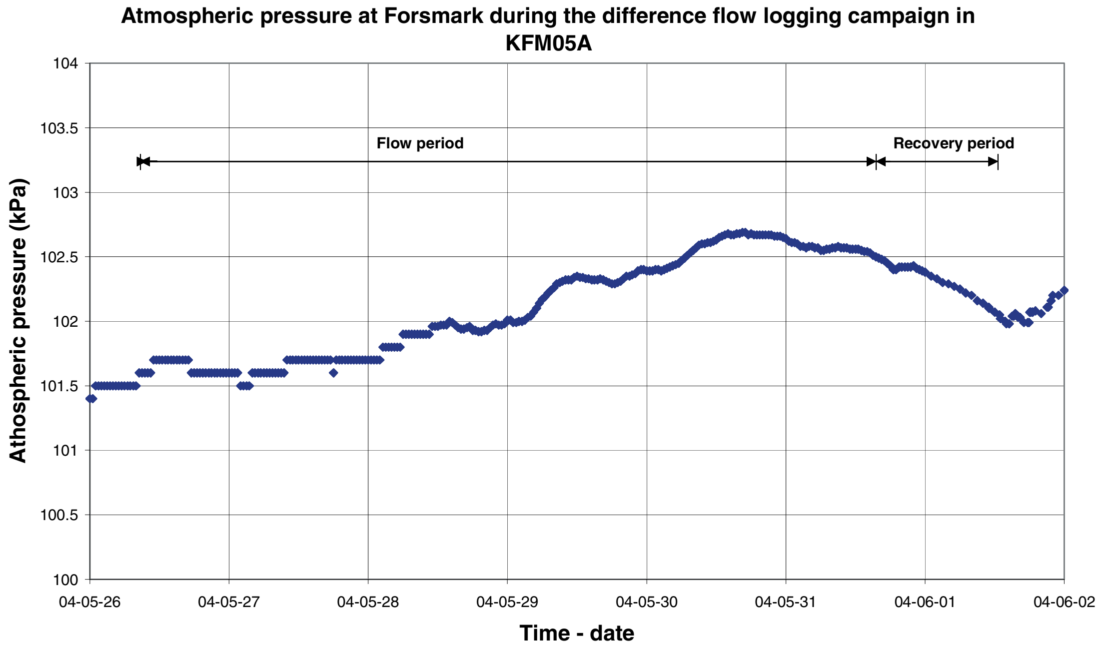


Figure 6-1. *Atmospheric pressure at Forsmark during the pumping test in conjunction with difference flow logging in borehole KFM05A.*

Interpreted flow regimes

Selected test diagrams according to the instruction for analysis of single-hole injection- and pumping tests together with simulated responses are presented in Appendix 12.2. Figure 12.2-1 shows a linear graph of the pressure recovery versus time after stop of pumping, using data from the absolute pressure sensor. Figure 12.2-5 presents a log-log graph of the pressure recovery. The figure shows that wellbore storage effects (WBS) were observed during only the first c. 20 s in the (open) pumping borehole during the recovery period. After a transition period, an early, short pseudo-radial flow regime occurred, followed by a second pseudo-radial flow regime of longer duration during intermediate and late times, as indicated by the pressure derivative. This fact may represent scale effects, i.e. transition from a near-region scale with higher transmissivity to a larger-scale of the investigated bedrock with slightly lower transmissivity at intermediate and late time.

No effects of hydraulic outer boundaries were seen during the recovery period. Although not shown, a very similar pressure response was obtained using water level data from the superficial pressure sensor during the recovery period.

The pressure drawdown (measured by the absolute pressure sensor) during the first phase (c. 24 h) of the flow period is shown in Figures 12.2-2 and -3. As described above, the flow rate was increased after c. 20 000 s which causes the disturbance at this time in the graphs. Due to the limited sampling frequency during the beginning of the flow period, cf. Table 5-1, wellbore storage effects were masked. After the change of flow rate, transition to a late pseudo-radial flow period is indicated by the end of the first phase of the flow period. No evidences of apparent, outer hydraulic boundaries were noticed during this period. The drawdown data from the absolute- and superficial pressure sensors were again very similar during this period.

Interpreted parameters

The transient analyses of the first phase of the flow period and the recovery period, according to the methods described in Section 5-3, based on the identified periods with pseudo-radial flow, are exposed in the corresponding figures in Appendix 12.2. The analyses of both the flow- and recovery period are based on the late pseudo-radial flow regime interpreted. The interpreted parameters from the recovery period are considered as the most representative. The results of the evaluation are presented in Table 6-3 and in the Test Summary Sheets.

6.3 Summary of test data

Test data from the single-hole pumping test in conjunction with difference flow logging in borehole KFM05A are summarized in Table 6-2. The calculated hydraulic parameters are presented in Table 6-3 and in the Test Summary Sheet below. Although the calculated hydraulic parameters represent the entire cored borehole interval 110.10-1002.71 m together with the perforated interval 108.85-109.40 m, they are most likely totally dominated by the fracture zone in the latter interval, where the main inflow to the borehole occurs according to the difference flow logging.

The parameter files of the results from the pumping test for storage in the SICADA data base under Filed Note No. Forsmark 311, are presented in Appendix 12.3 below.

Table 6-2. Summary of test data of the single-hole pumping test during the difference flow logging in the open borehole KFM05A.

Interval (m)	**Test type[1)]**	**h_i (m a s l)**	**h_p (m a s l)**	**h_F (m a s l)**	**Q_p (m^3/s)**	**V_p (m^3)**	**Q_m (m^3/s)**
108.85-1002.71	1B	0.73	-5.80	-0.01	$2.50 \cdot 10^{-3}$	-	-

[1)] 1B: Pumping test-submersible pump followed by a recovery test

Table 6-3. Summary of calculated hydraulic parameters from the pumping test in conjunction with difference flow logging in borehole KFM05A.

Test period	**Time of evaluation**	**Q/s (m^2/s)**	**T_M (m^2/s)**	**T_T (m^2/s)**	**S* (-)**	**ζ (-)**	**C (m^3/Pa)**
Flow period	late	$3.83 \cdot 10^{-4}$	$6.31 \cdot 10^{-4}$	$3.67 \cdot 10^{-4}$	$5 \cdot 10^{-5}$	-4.71	-
recovery	early			$8.62 \cdot 10^{-4}$	$5 \cdot 10^{-5}$	-0.08	$2.78 \cdot 10^{-6}$
recovery	intermediate-late			$4.53 \cdot 10^{-4}$	$5 \cdot 10^{-5}$	-3.98	

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
C = wellbore storage coefficient

6.4 Conclusions

The total, large-scale transmissivity of the interval 108.85-1002.71 m in borehole KFM05A was calculated to c. $4.5 \cdot 10^{-4}$ m^2/s from the recovery period of the pumping test during difference flow logging. As identified from the flow logging, the dominant inflow to the borehole occurs in the perforated interval 108.85-109.40. Thus, the calculated hydraulic parameters of the borehole are likely to represent this interval.

The flow rate and pressure histories during the pumping test indicated no significant effects of outer, apparent no-flow hydraulic boundaries, neither during the rather long (c. 5 days) flow period nor during the recovery period. This fact may indicate that the dominant fracture zone is extensive in the lateral direction.

The calculated transmissivity of the cored borehole interval from the pumping test may be compared with the results of the difference flow logging. The cumulative transmissivity in this interval, both from the flow logging in 5 m sections and the detailed flow logging in 1 m sections, are most likely totally dominated by the fracture zone at 108.85-109.40 m. The total transmissivity of the cored borehole interval was estimated to $4.0 \cdot 10^{-4}$ m^2/s from the ordinary difference flow logging at a drawdown of c 6 m as described in Section 6.4.5 in the main report. From subsequent difference flow logging during pumping of the borehole at very low drawdowns the transmissivity of the cored borehole interval was estimated to $1.2 \cdot 10^{-3}$ m^2/s.
In Table 6-4, the representative total transmissivity T_T of the cored borehole interval in KFM05A from the transient evaluation of the pumping test is shown. In addition, the estimated transmissivity of the corresponding interval from the ordinary difference flow logging and from subsequent flow logging at a series of small drawdowns, respectively (T_D) are shown. The (constant) drawdown (s) in the borehole, at which the difference flow logging measurements were performed, is shown in Table 6-4. The table indicates that the results from the pumping test and difference flow logging are similar, although the latter transmissivity is slightly higher, possibly due to turbulent flow at higher drawdown.

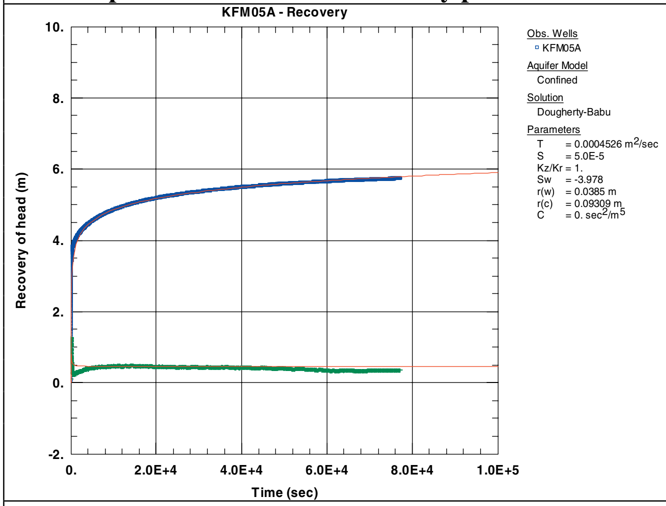
Table 6-4. Comparison of total transmissivity of borehole KFM05A together with the estimated borehole transmissivity from the difference flow logging.

Borehole ID	Test method	Measured interval (m)	T_T (m^2/s)	T_D (m^2/s)	Remarks
KFM05A	Transient pumping test	108.85-1002.71	$4.53 \cdot 10^{-4}$		
	Difference flow logging	106.39-992.89		$4.01 \cdot 10^{-4}$	s=6.25 m
	Difference flow logging	106.39-992.89		$1.23 \cdot 10^{-3}$	s=0.8-0.9 m

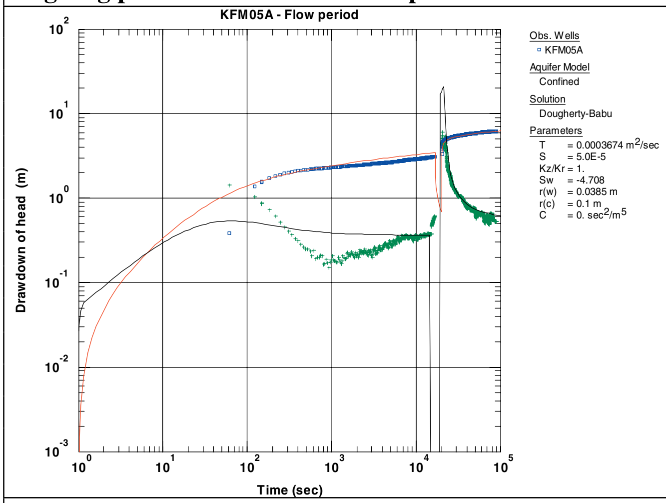
Test Summary Sheet – Pumping borehole KFM05A

Project:	PLU	Test type:	1B
Area:	Forsmark	Test no:	1
Borehole ID:	KFM05A	Test start:	2004-05-26 10:24
Test section (m):	108.85-1002.71	Responsible for test performance:	P. Rouhiainen, PRG-Tec Oy
Section diameter, $2 \cdot r_w$ (m):	0.077	Responsible for test evaluation:	GEOSIGMA AB J-E Ludvigson

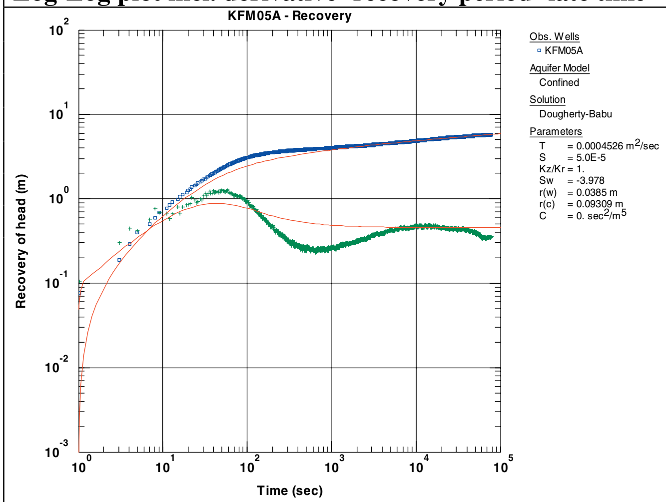
Lin-Lin plot incl. derivative – recovery period-late time



Log-Log plot incl. derivative- flow period-late time



Log-Log plot incl. derivative- recovery period- late time



Flow period		**Recovery period**	
Indata		**Indata**	
h_0 (m.a.s.l.)			
h_i (m.a.s.l.)	0.73		
h_p (m.a.s.l.)	-5.80	h_F (m.a.s.l.)	-0.01
Q_p (m^3/s)	$2.50 \cdot 10^{-3}$		
tp (s)	447 281	t_F (s)	77187
S^*	$5 \cdot 10^{-5}$	S^*	$5 \cdot 10^{-5}$
EC_w (mS/m)	-		
Te_w(gr C)	-		
Derivative fact.	0.1	Derivative fact.	0.1
Results		**Results**	
Q/s (m^2/s)	$3.83 \cdot 10^{-4}$		
T_M (m^2/s)	$6.31 \cdot 10^{-4}$		
Flow regime:	PRF-late	Flow regime:	PRF-late
t_1 (s)	50 000	t_1 (min)	3 000
t_2 (s)	77 000	t_2 (min)	60 000
T_w (m^2/s)	$3.67 \cdot 10^{-4}$	T_w (m^2/s)	$4.53 \cdot 10^{-4}$
S_w (-)	-	S_w (-)	-
K_{sw} (m/s)	-	K_{sw} (m/s)	-
S_{sw} (1/m)	-	S_{sw} (1/m)	-
C (m^3/Pa)	-	C (m^3/Pa)	$2.78 \cdot 10^{-6}$
C_D (-)	-	C_D (-)	-
ξ (-)	-4.71	ξ (-)	-3.98
T_{GRF}(m^2/s)		T_{GRF}(m^2/s)	
S_{GRF}(-)		S_{GRF}(-)	
D_{GRF} (-)		D_{GRF} (-)	

Interpreted formation and well parameters.

Flow regime:	PRF-late	C (m^3/Pa)	$2.78 \cdot 10^{-6}$
t_1 (min)	3 000	C_D (-)	-
t_2 (min)	60 000	ξ (-)	-3.98
T_T (m^2/s)	$4.53 \cdot 10^{-4}$		
S (-)	-		
K_s (m/s)	-		
S_s (1/m)	-		

Comments: After initial wellbore storage- and skin effects, an early, short pseudo-radial flow regime occurred, transiting to another pseudo-radial flow regime during intermediate and late times during the recovery period. By the end of the first phase of the flow period, a transition to a pseudo-radial flow regime was approached. The first phase of the flow period was disturbed by the change of borehole pump.

7 References

1 **Almén K-E, Andersson J-E, Carlsson L, Hansson K, Larsson N-Å, 1986**

Hydraulic testing in crystalline rock. A comparative study of single-hole test methods. Technical Report 86-27, Svensk Kärnbränslehantering AB.

2 **Ludvigson J-E, Jönsson S, 2003**

Forsmark Site Investigation - Hydraulic interference tests. Boreholes HFM01, HFM02 and HFM03. Report P-03-35, Svensk Kärnbränslehantering AB.

3 **Ludvigson J-E, Jönsson S and Hjerne C, 2004**

Forsmark Site Investigation – Pumping tests and flow logging. Boreholes KFM06A (0-100 m) and HFM16. Report P-04-65, Svensk Kärnbränslehantering AB.

8 Appendices

Appendix 12.1: **Test data files**

Appendix 12.2: **Test data diagrams**

Appendix 12.3: **Parameter file to SICADA**

APPENDIX 12.1 – TEST DATA FILES

Bh ID	Test section (m)	Test type[1]	Test start Date, time YYYY-MM-DD tt:mm	Test stop Date, time YYYY-MM-DD tt:mm	Datafile, start Date, time YYYY-MM-DD tt:mm:ss	Datafile, stop Date, time YYYY-MM-DD tt:mm:ss	Data files of raw and primary data	Selected Parameters measured	Comments
KFM05A	108.85-1002.71	1B	2004-05-26 10:24	2004-06-01 12:06	2004-05-26 10:25	2004-06-02 08:40	FOKF5APU13E005T105.DAT	Q	Entire flow period (Item 9-11 in AP)
KFM05A	108.85-1002.71	1B	2004-05-26 10:24	2004-06-01 12:06	2004-05-26 10:24	2004-05-27 09:51	FOKF5AGL17E050D105.CSV	P1, P_{abs}	Flow period Item 9 in AP
KFM05A	108.85-1002.71	1B	2004-05-26 10:24	2004-06-01 12:06	2004-05-27 10:24	2004-05-27 11:07	FOKF5AGL13E050D105.CSV	P1, P_{abs}	Cont. Item 9
KFM05A	108.85-1002.71	1B	2004-05-26 10:24	2004-06-01 12:06	2004-05-27 12:35	2004-05-29 08:25	FOKF5AGW13E050D105.CSV	P1, P_{abs}	Cont. Item 9
KFM05A	108.85-1002.71	1B	2004-05-26 10:24	2004-06-01 12:06	2004-05-29 14:17	2004-05-30 08:38	FOKF5AGW13E010D105.CSV	P1, P_{abs}	Flow period Item 10 in AP
KFM05A	108.85-1002.71	1B	2004-05-26 10:24	2004-06-01 12:06	2004-05-30 08:57	2004-05-31 07:43	FOKF5AGW13G010D105.CSV	P1, P_{abs}	Fracture-EC Item 11 in AP
KFM05A	108.85-1002.71	1B	2004-05-26 10:24	2004-06-01 12:06	2004-05-31 08:58	2004-05-31 10:36	FOKF5APR13D005D205.CSV	P1, P_{abs}	Borehole-EC Item 11 extra
KFM05A	108.85-1002.71	1B	2004-05-26 10:24	2004-06-01 12:06	2004-05-31 10:43	2004-05-31 14:25	FOKF5APR13D005D105.CSV	P1, P_{abs}	Borehole-EC Item 11 extra
KFM05A	108.85-1002.71	1B	2004-05-26 10:24	2004-06-01 12:06	2004-05-31 14:39	2004-06-01 12:06	FOKF5AGL13R005D105.CSV	P1, P_{abs}	Recovery period Item 12

1: 1B: Pumping test-submersible pump

APPENDIX 12.2 TEST DATA DIAGRAMS

Nomenclature used in diagrams from Aqtesolv:

T=transmissivity (m^2/s)

S=storativity (-)

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

S_w=skin factor

r(w)=borehole radius (m)

r(c)= effective casing radius (m)

C= well loss constant (set to 0)

Diagrams

Flow period (lin-lin, log-log and lin-log)

Recovery period (lin-lin, log-log and lin-log)

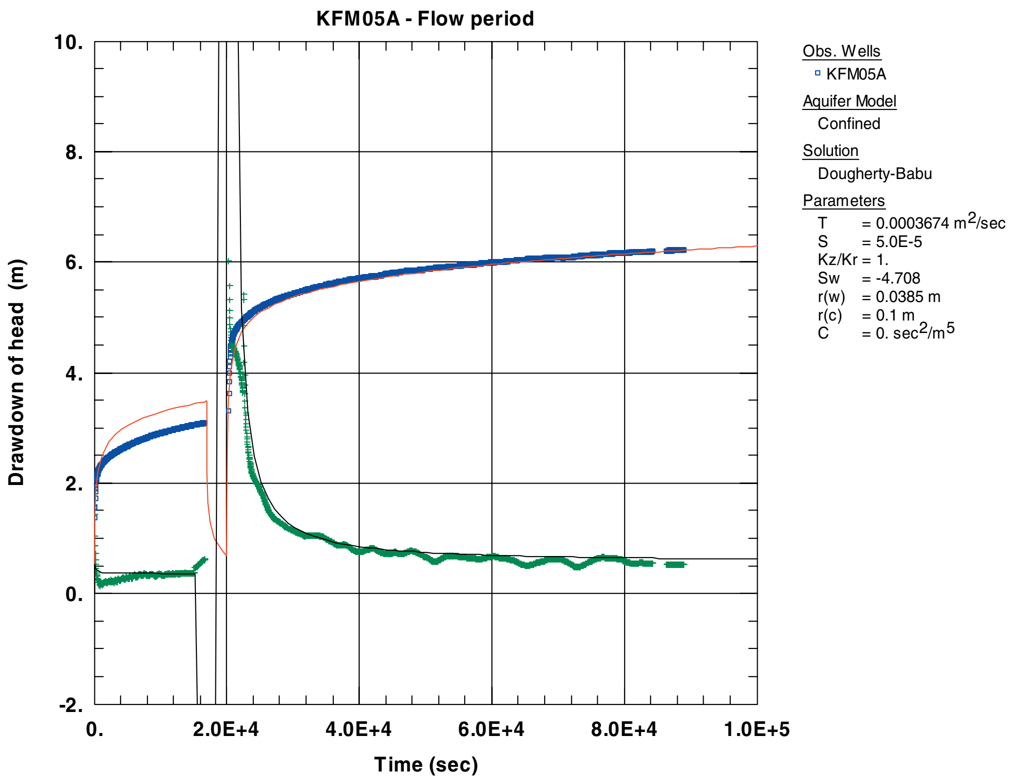


__Figure 12.2-1.__ Linear plot of measured (blue) and simulated (red) pressure drawdown and –derivative (green) versus time during the first phase of the pumping test in conjunction with difference flow logging in borehole KFM05A. The simulation is based on the late-time pressure behavior.

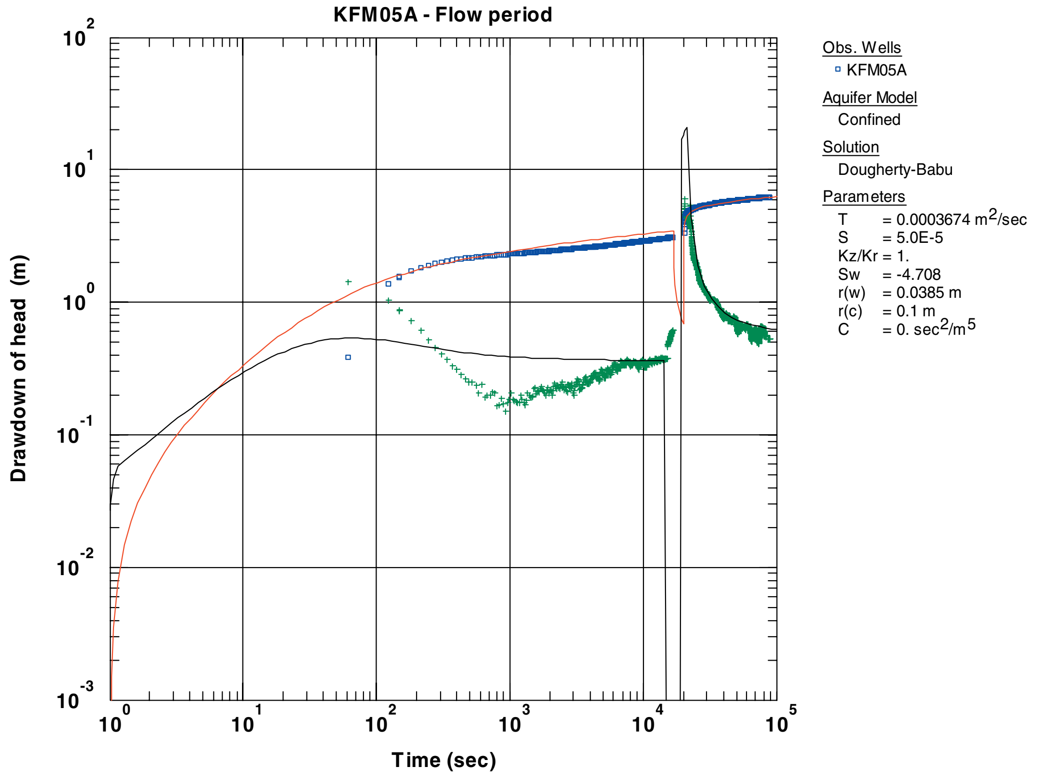


Figure 12.2-2. *Log-log plot of measured (blue) and simulated (red) pressure drawdown and – derivative (green) versus time during the first phase of the flow period of the pumping test in KFM05A. The simulation is based on the late-time pressure behavior.*

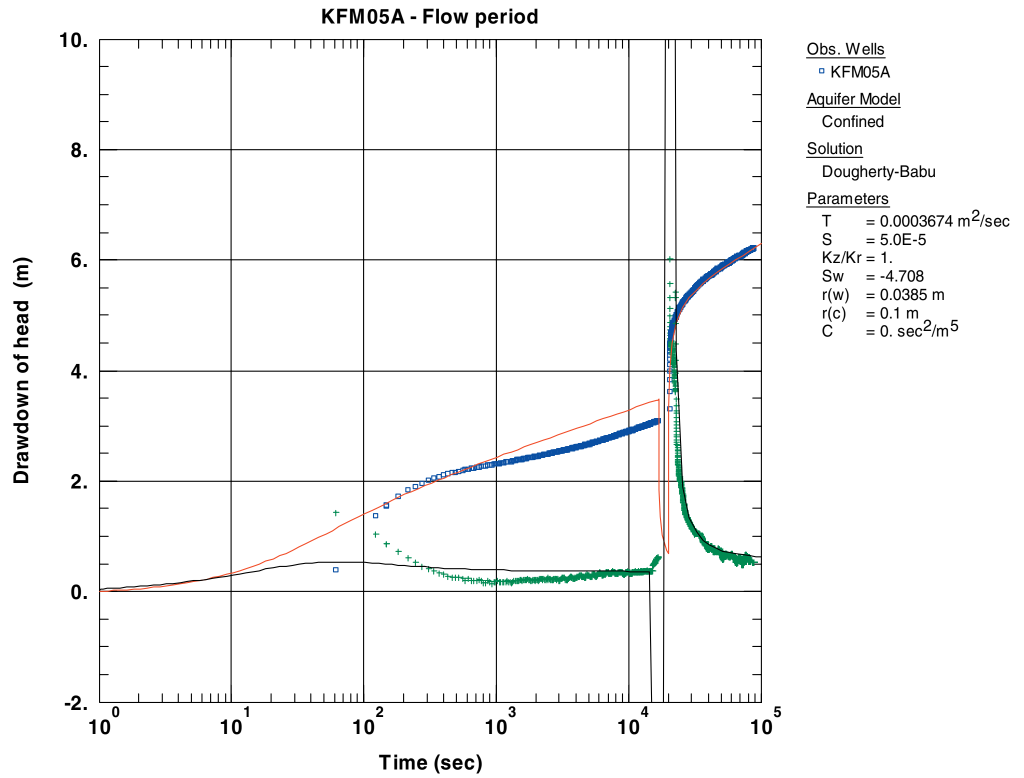


Figure 12.2-3. *Lin-log plot of measured (blue) and simulated (red) pressure drawdown and – derivative (green) versus time during the first phase of the flow period of the pumping test in KFM05A. The simulation is based on the late-time pressure behavior.*

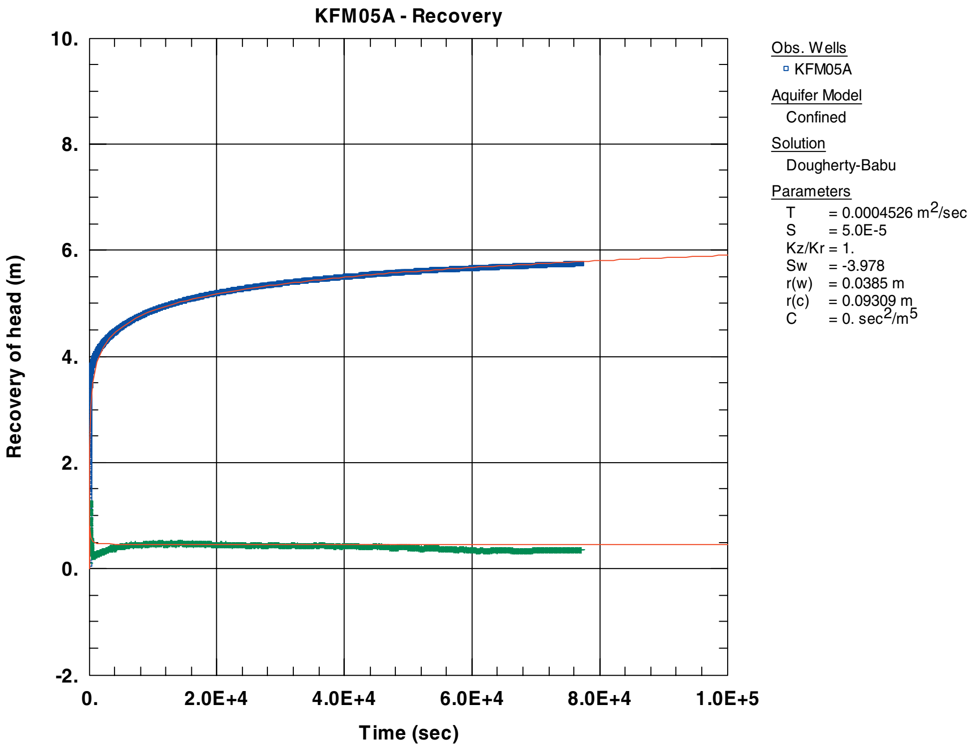


Figure 12.2-4. *Linear plot of measured (blue) and simulated (red) pressure recovery and –derivative (green) versus time during the pumping test in borehole KFM05A. The simulation is based on the late-time pressure behavior.*

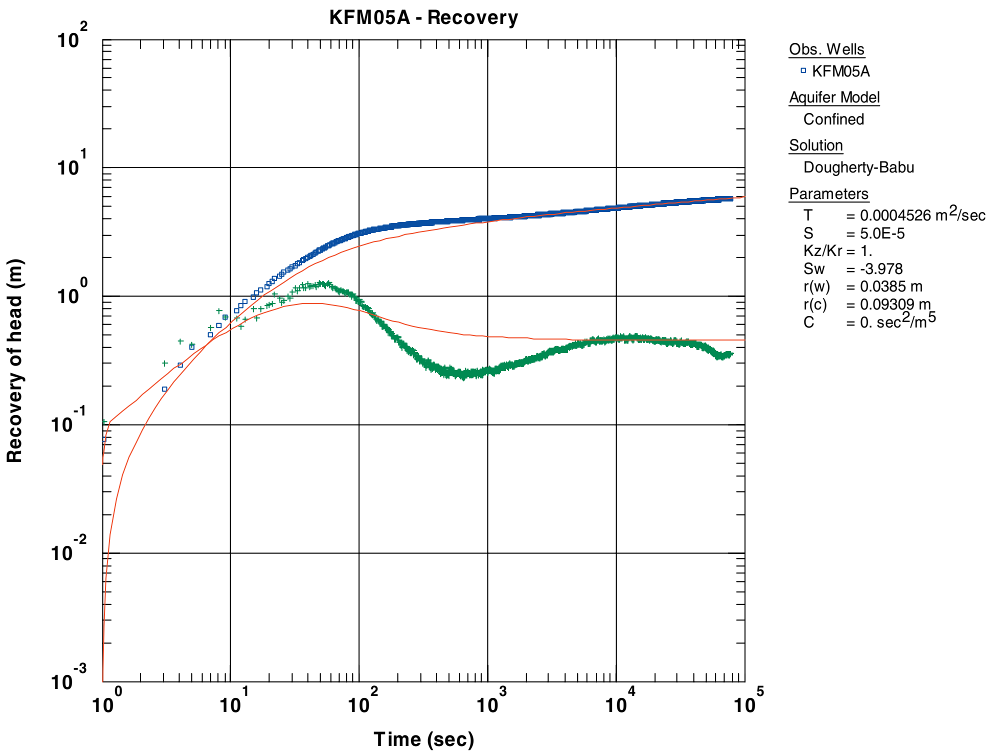


Figure 12.2-5. *Log-log plot of measured (blue) and simulated (red) pressure recovery and –derivative (green) versus time during the pumping test in borehole KFM05A. The simulation is based on the late-time pressure behavior.*

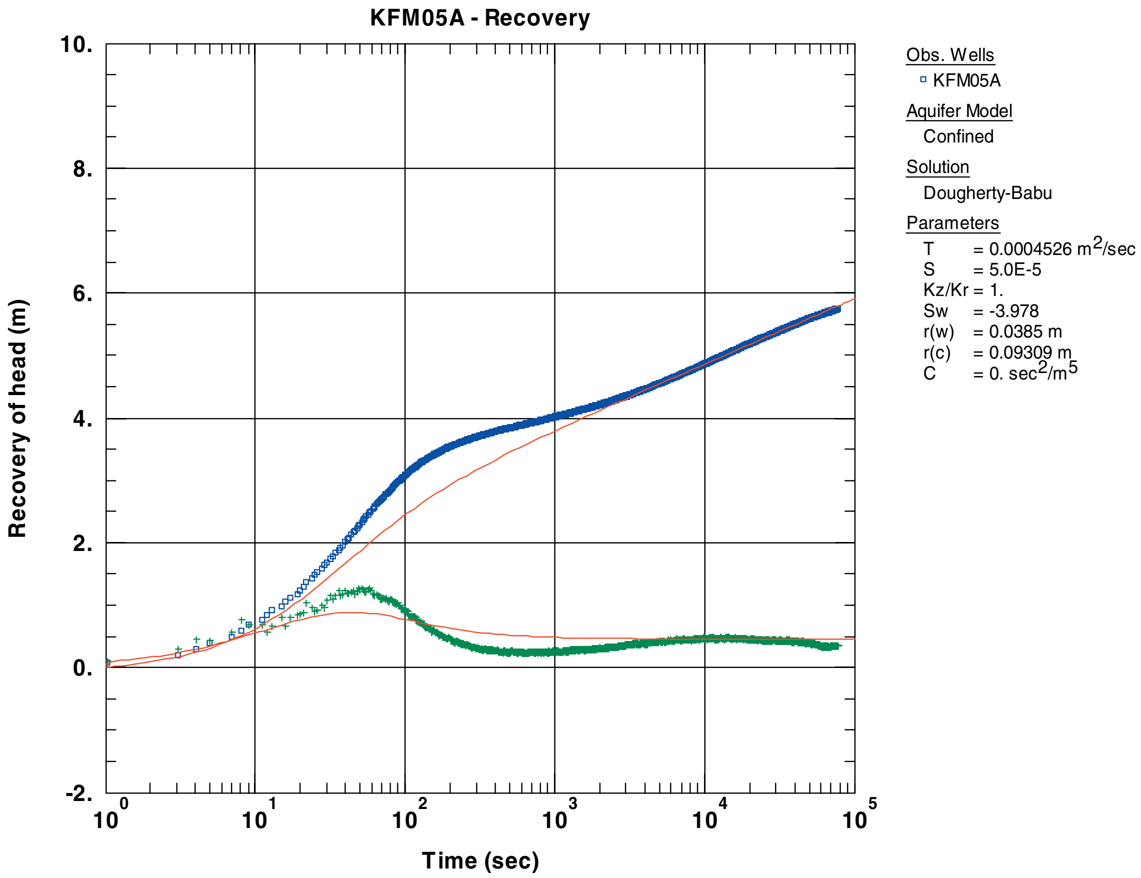


Figure 12.2-6. *Lin-log plot of measured (blue) and simulated (red) pressure recovery and –derivative (green) versus time during the pumping test in borehole KFM05A. The simulation is based on the late-time pressure behavior.*

APPENDIX 12.3 PARAMETER FILE TO SICADA

Result Tables for Single-hole pumping tests

Appendix 12

Parameter file of results from single-hole pumping test in borehole KFM05A during difference flow logging.

SINGLEHOLE TESTS, Pumping and injection, s_hole_test_d; General information

Borehole	Borehole secup (m)	Borehole seclow (m)	Test type (1-7)	Formation type (-)	Date and time for test, start YYYYMMDD hh:mm	Date and time for test, stop YYYYMMDD hh:mm	Date and time of flow/ injection, start YYYYMMDD hh:mm:ss	Date and time of flow/ injection, stop YYYYMMDD hh:mm:ss	Q_p (m**3/s)	Value type-Q_p (-1,0,1)	Q-measl-L (m**3)/s	Q-measl-U (m**3)/s
KFM05A	108.85	1002.71	1B	1	2004-05-26 10:24	2004-06-01 12:06	2004-05-26 10:25	2004-05-31 14:39	2.50E-03	0		

cont.

V_p (m**3)	Q_m (m**3/s)	tp (s)	t_F (s)	h_i (m a sl)	h_p (m a sl)	h_F (m a sl)	p_i (kPa)	p_p (kPa)	p_F (kPa)	Te_w (°C)	EC_w (mS/m)	TDS_w (mg/ L)	TDS_{wm} (mg/ L)	Reference	Comments (-)
		447281	77187	0.73	-5.80	-0.01									

SINGLEHOLE TESTS, Pumping and injection, s_hole_test_ed1; Basic evaluation

Borehole	Borehole secup (m)	Borehole seclow (m)	Date and time for test, start YYYYMMDD hh:mm	Q/s (m^2/ s)	Value type-Q/s (-1, 0, 1)	T_Q (m^2/ s)	T_M (m^2/ s)	b (m)	B (m)	TB (1D) (m^3/ s)	TB-measl-L (1D) (m^3/ s)	TB-measl-U (1D) (m^3/ s)	SB (1D) (m)	SB* (1D) (m)	L_f (1D) (m)	T_T (2D) (m^2/ s)	Value type-T_T (-1, 0, 1)
KFM05A	108.85	1002.71	2004-05-26 10:24	3.83E-04	0		6.31E-04		893.86							4.53E-04	0

cont.

Q/s-measl-L (m^2/ s)	Q/s-measl-U (m^2/ s)	S (2D) (-)	S* (2D) (-)	K´/b´ (2D) (1/s)	K_S (3D) (m/s)	K_S-measl-L (3D) (m/s)	K_S-measl-U (3D) (m/s)	S_S (3D) (1/m)	S_S* (3D) (1/m)	L_p (m)	C (m**3/Pa)	C_D (-)	ξ (2D) (-)	ω (-)	λ (-)	t_1 (s)	t_2 (s)	Comments (-)
2.00E-08	2.00E-03		5.00E-05								2.78E-06		-3.98			3000	60000	

Appendix 12

Header	Unit	Explanation
Borehole		ID for borehole
Borehole secup	m	Length coordinate along the borehole for the upper limit of the test section
Borehole seclow	m	Length coordinate along the borehole for the lower limit of the test section
Test type (1- 7)	(-)	1A: Pumping test - wireline eq., 1B:Pumping test-submersible pump, 1C: Pumpingtest-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,7:Grain size analysis
Date for test start		Date for the start of the pumping or injection test (YYYYMMDD hh:mm)
Start flow / injection		Date and time for the start of the pumping or injection period (YYMMDD hh:mm:ss)
Start flow / injection		Date and time for the end of the pumping or injection period (YYMMDD hh:mm:ss)
Q_m	m^3/s	Arithmetic mean flow rate of the pumping/injection period.
Q_p	m^3/s	Flow rate at the end of the pumping/injection period.
Value type	-	Code for Q_p-value; -1 means Q_p<lower measurement limit, 0 means measured value, 1 means Q_p> upper measurement value of flowrate
Q-measl_L	m^3/s	Estimated lower measurement limit for flow rate
Q-measl_U	m^3/s	Estimated upper measurement limit for flow rate
V_p	m^3	Total volume pumped (positive) or injected (negative) water during the flow period.
t_p	s	Time for the flowing phase of the test
t_F	s	Time for the recovery phase of the test
h_i	m	Initial formation hydraulic head. Measured as water level in open stand pipes from borehole section with reference level in the local coordinates system with z=0 m.
h_p	m	Final hydraulic head at the end of the pumping/injection period. Measured as water level in open stand pipes from borehole section with reference level in the local coordinates system with z=0 m.
h_F	m	Final hydraulic head at the end of the recovery period. Measured as water level in open stand pipes from borehole section with reference level in the local coordinates system with z=0 m.
p_i	kPa	Initial formation pressure.
p_p	kPa	Final pressure at the end of the pumping/injection period.
p_F	kPa	Final pressure at the end of the recovery period.
Te_w	gr C	Fluid temperature in the test section representative for the evaluated parameters
EC_w	mS/m	Electrical conductivity of the fluid in the test section representative for the evaluated parameters
TDS_w	mg/L	Total salinity of the fluid in formation at test section based on EC.
TDS_{wn}	mg/L	Total salinity of the fluid in formation at test section based on water sampling and chemical analysis.
Sec.type,	(-)	Test section (pumping or injection) is labeled 1 and all observation sections are labeled 2
Q/s	m2/s	Specific capacity, based on Qp and s=abs(pi-pp). Only given for test section (label 1) in interference test.
T_Q	m2/s	Steady-state transmissivity based on specific capacity and a function for T=f(Q/s). The function used should be referred in "Comments"
T_M	m2/s	Steady-state transmissivity based on Moye (1967)
b	m	Interpreted formation thickness representative for evaluated T ot TB.
B	m	Interpreted witdth of a formation with evaluated TB
TB	m3/s	1D model for evaluation of formation properties. T=transmissivity, B=width of formation
TB-measl-L	m2/s	Estimated measurement limit for evaluated TB. If estimated TB equals TB-measlim in the table actual TB is considered to be equal or less than TB-measlim
TB-measl-L	m2/s	Estimated measurement limit for evaluated TB. If estimated TB equals TB-measlim in the table actual TB is considered to be equal or greater than TB-measlim
SB	m	1D model for evaluation of formation properties. S= Storativity, B=width of formation
SB*	m	1D model for evaluation of formation properties. Assumed SB. S= Storativity, B=width of formation
L_f	m	1D model for evaluation of Leakage factor
T_T	m2/s	2D model for transient evaluation of formation properties. T=transmissivity

Appendix 12

T-measl-L	m2/s	Estimated measurement limit for evaluated T (TT, TQ, TM). If estimated T equals T-measlim in the table actual T is considered to be equal or less than T-measlim
T-measl-U	m2/s	Estimated measurement limit for evaluated T (TT, TQ, TM). If estimated T equals T-measlim in the table actual T is considered to be equal or grater than T-measlim
S	(-)	2D model for evaluation of formation properties. S= Storativity
S*	(-)	2D model for evaluation of formation properties. Assumed S. S= Storativity
K´/b´	(1/s)	2D model for evaluation of leakage coefficient. K´= hydraulic conductivity in direction of leaking flow for the aquitard, b´= Saturated thickness of aquitard (leaking formation)
K_S	m/s	3D model for evaluation of formation properties. K=Hydraulic conductivity
K_S-measl-L	m/s	Estimated measurement limit for evaluated KS. If estimated KS equals KS-measlim in the table actual KS is considered to be equal or less than KS-measlim
K_S-measl-U	m/s	Estimated measurement limit for evaluated KS. If estimated KS equals KS-measlim in the table actual KS is considered to be equal or greater than KS-measlim
S_S	1/m	3D model for evaluation of formation properties. Ss=Specific Storage
S_S*	1/m	3D model for evaluation of formation properties. Assumed Ss. Ss=Specific Storage
L_p	m	Hydraulic point of appication, based on hydraulic conductivity distribution (if available) or the midpoint of the borehole test section
C	(m3/Pa)	Wellbore storage coefficient
C_D	(-)	Dimensionless wellbore storage coefficient
ξ	(-)	Skin factor
ω	(-)	Storativity ratio
λ	(-)	Interporosity flow coefficient
t_1	s	Estimated start time after pump/injection start OR recovery start, for the period used for the evaluated parameter
t_2	s	Estimated stop time after pump/injection start OR recovery start, for the period used for the evaluated parameter
References		SKB report No for reports describing data and evaluation
Index w		Active borehole or borehole section