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# Forsmark site investigation

# Difference flow logging in borehole KFM01D

Juha Väisäsvaara, Heikki Leppänen, Janne Pekkanen
PRG-Tec Oy

July 2006

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*Keywords:* Forsmark, Hydrogeology, Hydraulic tests, Difference flow measurements, KFM01D, AP PF 400-06-018.

# Foreword

The performance and evaluation of the difference flow logging campaign in borehole KFM01D was made by PRG-Tec Oy.

The evaluation of the pumping test in conjunction with the difference flow logging (Section 6.4.5) was performed by Jan-Erik Ludvigson, Geosigma AB.

# Abstract

Difference flow logging is a swift method for determination of the transmissivity and the hydraulic head in borehole sections and fractures/fracture zones in core drilled boreholes. This report presents the main principles of the methods as well as results of measurements carried out in borehole KFM01D at Forsmark, Sweden, in May and June 2006, using Posiva Flow Log. The Posiva Flow Log is a multipurpose measurement instrument developed by PRG-Tec Oy for the use of Posiva Oy. The primary aim of the measurements was to determine the position and flow rate of flow yielding fractures in borehole KFM01D prior to groundwater sampling.

The flow rates into or out of a 5 m long test section were measured in borehole KFM01D during natural (un-pumped) as well as pumped conditions. The flow measurements were repeated at the location of detected flow anomalies using a 1 m long test section. The device was moved in 0.1 m steps.

Length calibration was made based on length marks milled into the borehole wall at accurately determined positions along the borehole. The length marks were detected by caliper measurements and by single-point resistance measurements using sensors connected to the flow logging tool.

A high-resolution absolute pressure sensor was used to measure the absolute total pressure along the borehole. These measurements were carried out together with the flow measurements.

The electric conductivity (EC) and temperature of the 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. The EC of fracture-specific water was also measured (0.5 m test section) for a selection of fractures.

The total transmissivity of the borehole, calculated with Moye's formula, is $7.2 \cdot 10^{-6}$ $m^2/s$.

# Sammanfattning

Differensflödesloggning är en snabb metod för bestämning av transmissiviteten och hydraulisk tryckhöjd i borrhålssektioner och sprickor/sprickzoner i kärnborrhål. Denna rapport presenterar huvudprinciperna för metoden och resultat av mätningar utförda i borrhål KFM01D i Forsmark, Sverige, i maj och juni 2006 med Posiva flödesloggningsmetod. Posiva Flow Log är ett mångsidigt instrument utvecklat av PRG-Tec Oy för Posiva Oy. Det primära syftet med mätningarna var att bestämma läget av och flödet i vattenförande sprickor i borrhål KFM01D före grundvattenprovtagning.

Flödet till eller från 5 m långa testsektioner mättes i borrhål KFM01D under såväl naturliga (icke-pumpade) som pumpade förhållanden. Flödesmätningarna upprepades vid lägena för de detekterade flödesanomalierna med en 1 m lång testsektion som förflyttades successivt i steg om 0.1 m.

Längdkalibrering gjordes baserad på längdmärkena som frästs in i borrhålsväggen vid noggrant bestämda positioner längs borrhålet. Längdmärkena detekterades med caliper och 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. Även EC på vattnet i ett antal utvalda sprickor mättes (0,5 m lång testsektion).

Borrhålets totala transmissivitet, beräknad enligt Moye's ekvation är $7{,}2 \cdot 10^{-6}$ $m^2/s$

# Contents

# 1 Introduction

The core drilled borehole KFM01D at Forsmark, Sweden was measured using Difference flow logging between May 9 and June 1, 2006. Difference flow logging is a swift method for a multifaceted characterization of a borehole. KFM01D is 800.24 m long and its inclination at the collaring is 54.90° from the horizontal plane. The borehole was drilled using a telescopic drilling technique, where the c 0–90 m interval was percussion drilled and cased and the remaining c 90–800 m interval was core drilled. The diameter of the cased section is 200.0 mm and that of the remaining section 75.8 mm. The location of KFM01D at Forsmark is illustrated in Figure 1-1.

The field work and the subsequent data interpretation were conducted by PRG-Tec Oy. The Posiva Flow Log/Difference flow logging method has previously been employed in Posiva's site characterisation programme in Finland as well as at the Äspö Hard Rock Laboratory at Simpevarp, Sweden. The commissions at the latter site included measurements in the 1,700 m long cored borehole KLX02 at Laxemar together with a methodology study /Ludvigson et al. 2002/.

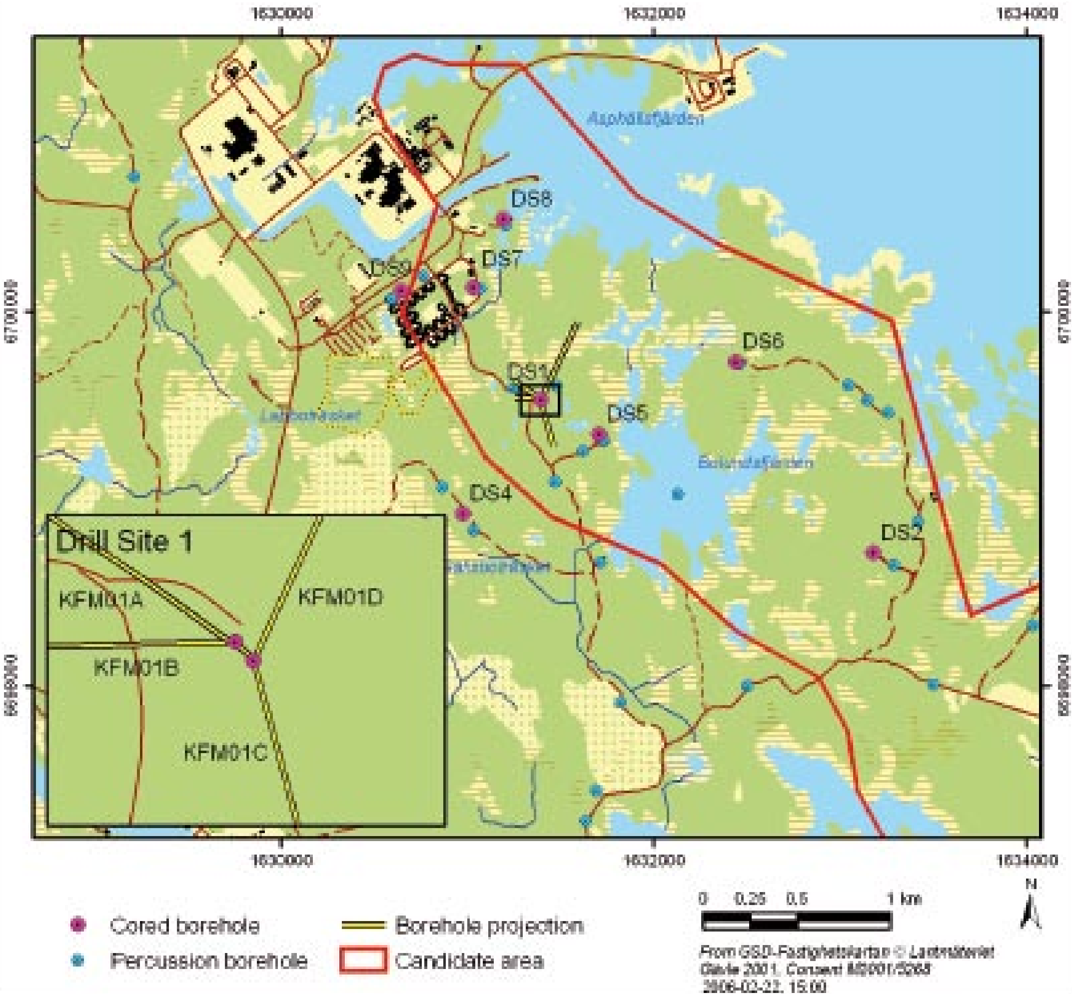


*Figure 1-1. Location of drill site DS1 at Forsmark and detailed maps of all boreholes within the drill site.*

This document reports the results acquired by the Difference flow logging method in the borehole KFM01D. The measurements were carried out as a part of the Forsmark site investigation and in accordance to SKB's internal controlling document AP FP 400-06-018. The controlling documents for performance according to this Activity Plan are listed in Table 1-1. The list of the controlling documents excludes the assignment-specific quality plans. Both the activity plan and the method documents are SKB's internal controlling documents. The measurement data and the results were delivered to the SKB site characterization database SICADA and are traceable by the Activity Plan number.

**Table 1-1. SKB's internal controlling documents for performance of activity.**

| Activity plan | Number | Version |
|---|---|---|
| Difference flow logging in borehole KFM01D | AP PS 400-06-018 | 1.0 |
| **Method documents** | **Number** | **Version** |
| Method description for difference flow logging | SKB MD 322.010 | 1.0 |
| Instruktion för rengöring av borrhålsutrustning och viss markbaserad utrustning | SKB MD 600.004 | 1.0 |
| Instruktion för längdkalibrering vid undersökningar i kärnborrhål | SKB MD 620.010 | 2.0 |
| Instruktion för analys av injektions- och enhålspumptester | SKB MD 320.004 | 1.0 |

# 2 Objective and scope

The main objective of the difference flow logging in KFM01D was to identify water-conductive sections/fractures suitable for subsequent hydrogeochemical 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 difference flow logging, the measurement programme also included supporting measurements, performed to gain a better understanding of the overall hydrogeochemical conditions. These measurements included electric conductivity (EC) and temperature of the borehole fluid as well as the single-point resistance of the borehole wall. The electric conductivity of a number of selected high-transmissive fractures in the borehole was also measured. Furthermore, the recovery of the groundwater level after pumping the borehole was registered and interpreted hydraulically.

A high-resolution pressure sensor was used to measure the absolute pressure along the borehole. These measurements were carried out together with the flow measurements. The results are used for calculation of the hydraulic head along the borehole.

Single-point resistance measurements were also combined with caliper (borehole diameter) measurements to detect depth marks milled into the borehole wall at accurately determined positions. This procedure allowed for the length calibration of all other measurements.

# 3 Principles of measurement and interpretation

## 3.1 Measurements

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

Rubber disks at both ends of the downhole tool are used to isolate the flow in the test section from that in the rest of the borehole, see Figure 3-1. The flow 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, in a sequential mode and an overlapping mode. In the sequential mode, the measurement increment is as long as the section length. It is used for determining the transmissivity and the hydraulic head /Öhberg and Rouhiainen 2000/. In the overlapping mode, the measurement increment is shorter than the section length. It is mostly used to determine the location of hydraulically conductive fractures and to classify them based on their flow rates.

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

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 the detection of the depth/length marks milled into the borehole wall, see Chapter 2. This enables an accurate depth/length calibration of the flow measurements.
- The prevailing water pressure profile in the borehole. The pressure sensor is located inside the electronics tube and connected via another tube to the borehole water, Figure 3-2.
- Temperature of the borehole water. The temperature sensor is placed in the flow sensor, Figure 3-1.

All of the above measurements were performed in KFM01D.

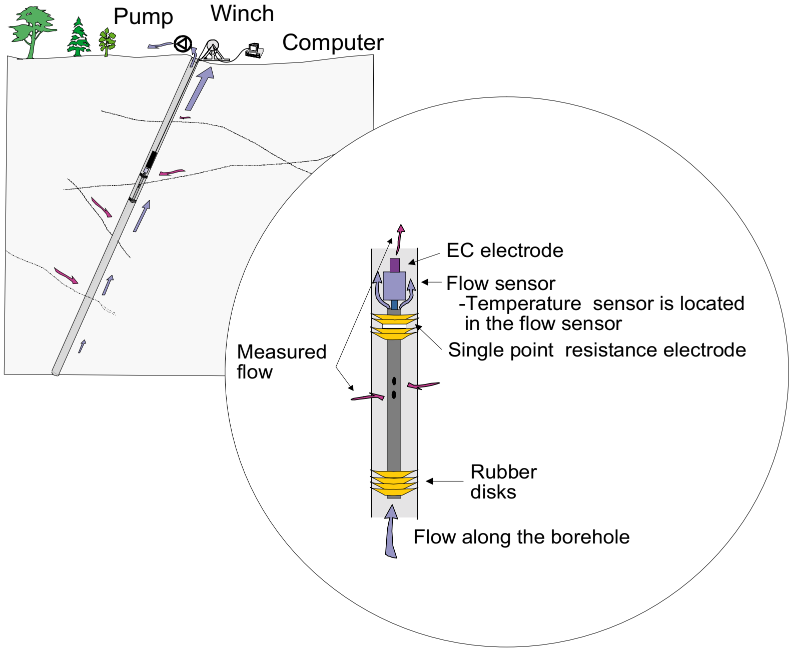


***Figure 3-1.*** *Schematic of the downhole equipment used in the Difference flowmeter.*

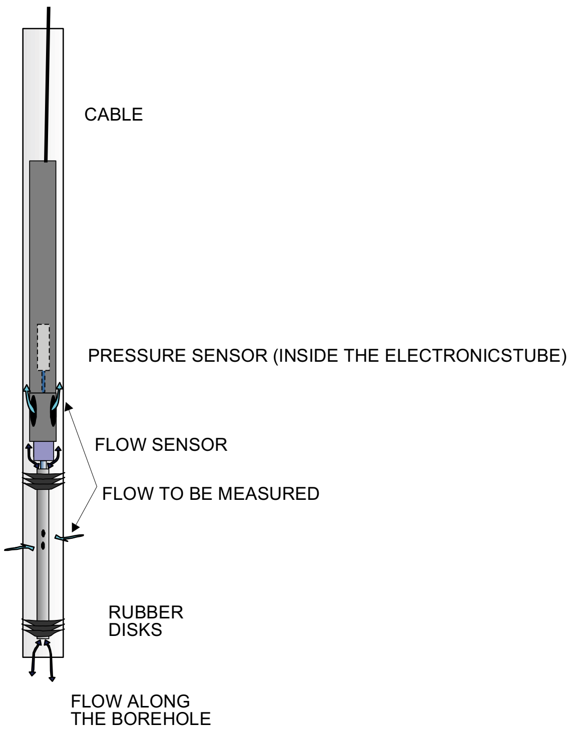


***Figure 3-2.*** *The absolute pressure sensor is located inside the electronics tube and connected through a tube to the borehole water.*

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

Flow rate is measured during constant power ($P_1$) heating (Figure 3-3 b). If the flow rate exceeds 600 mL/h, the constant power heating is increased (to $P_2$), Figure 3-4 b, and the thermal dilution method is applied.

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

The flow is measured when the tool is at rest. After the tool is transferred to a new position, there is a waiting time (the duration of which can be adjusted according to the prevailing circumstances) before the heat pulse (Figure 3-3 b) is applied. 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 measurement range of each method is given in Table 3-1.

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

**Table 3-1. Ranges of flow measurements.**

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

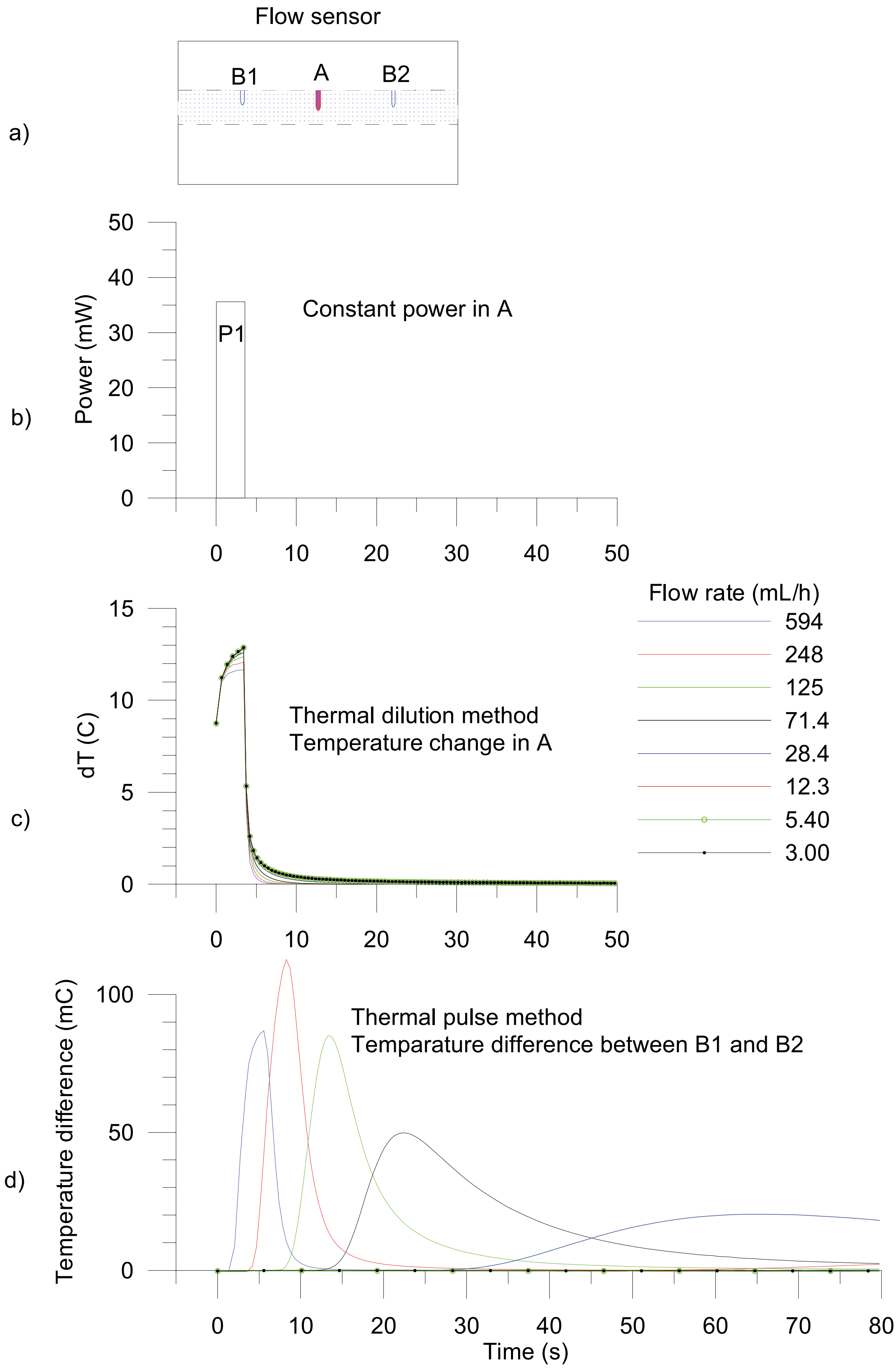


***Figure 3-3.*** *Flow measurement, flow rate < 600 mL/h.*

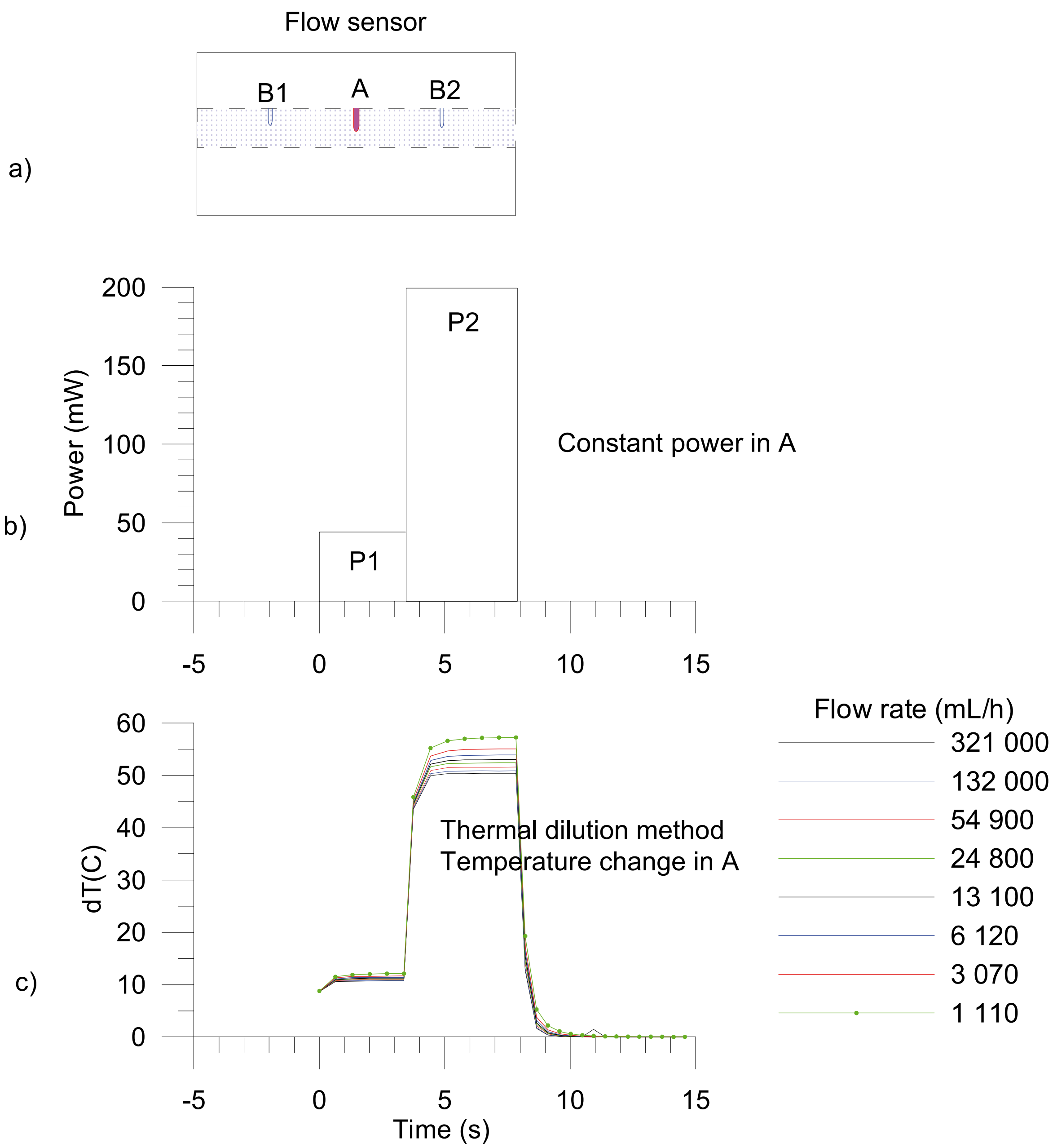


***Figure 3-4.*** *Flow measurement, flow rate > 600 mL/h.*

## 3.2 Interpretation

The interpretation of data is based on Thiems or Dupuits formula that describes a steady state and a two dimensional radial flow into the borehole /Marsily 1986/:

$h_s – h = Q/(T \cdot a)$ 3-1

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

Q is the flow rate into the borehole,

T is the transmissivity of the test section,

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

$a = 2 \cdot \pi / \ln(R/r_0)$ 3-2

where

$r_0$ is the radius of the well and

R is the radius of influence, i.e. the zone inside which the effect of the pumping is felt.

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

$Q_{S0} = T_s \cdot a \cdot (h_s – h_0)$ 3-3

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

where

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

$Q_{s0}$ and $Q_{s1}$ are the measured flow rates in the test section,

$T_s$ is the transmissivity of the test section and

$h_s$ is the undisturbed hydraulic head of the tested zone far from the borehole.

Since, in general, very little is known of the flow geometry, a cylindrical flow without any skin zones is assumed. Cylindrical flow geometry is also justified because the borehole is at a constant head and there are no strong pressure gradients along the borehole, except at its ends.

The radial distance R to the undisturbed hydraulic head $h_S$ is not known and must be assumed. Here a value of 500 is selected for the quotient $R/r_0$.

The hydraulic head and the test section transmissivity can be deduced from the two measurements:

$h_s = (h_0 – b \cdot h_1)/(1-b)$ 3-5

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

where

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

The transmissivity ($T_f$) and hydraulic head ($h_f$) of individual fractures can be calculated provided that the flow rates of individual fractures are known. Similar assumptions as above have to be used (a steady state cylindrical flow regime without skin zones).

$h_f = (h_0 – b\ h_1)/(1-b)$ 3-7

$T_f = (1/a)\ (Q_{f0} – Q_{f1})/(h_1 – h_0)$ 3-8

where

$Q_{f0}$ and $Q_{f1}$ are the flow rates at a fracture and

$h_f$ and $T_f$ are the hydraulic head (far away from borehole) and transmissivity of a fracture, respectively.

Since the actual flow geometry and the skin effects are unknown, transmissivity values should be taken only as an indication of the orders of magnitude. As the calculated hydraulic heads do not depend on geometrical properties but only on the ratio of the flows measured at different heads in the borehole, they should be less sensitive to unknown fracture geometries. A discussion of potential uncertainties in the calculation of transmissivity and hydraulic head is provided in /Ludvigson et al. 2002/.

Transmissivity of the entire borehole can be evaluated in several ways using the data of the pumping phase and of the recovery phase. The assumptions above (cylindrical and steady state flow) leads to Dupuits formula /Marsily 1986/:

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

where

s is drawdown and

Q is the pumping rate at the end of the pumping phase.

In the Moye /Moye 1967/ formula it is assumed the steady state flow is cylindrical near the borehole (to distance r = L/2, where L is the section under test) and spherical further away:

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

where L is length of test section (m), in this case water filled uncased part of the borehole.

The transient recovery phase is evaluated through a Jacob type of analysis following SKB MD 320.004 (SKB internal controlling document) and a T-value is calculated.

# 4 Equipment specifications

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

| | |
|---|---|
| Type of instrument: | Posiva Flow Log/Difference flowmeter. |
| Borehole diameters: | 56 mm, 66 mm and 76–77 mm. |
| Length of test section: | A variable length flow guide is used. |
| Method of flow measurement: | Thermal pulse and/or thermal dilution. |
| Range and accuracy of measurement: | See Table 4-1. |
| Additional measurements: | Temperature, Single point resistance, Electric conductivity of water, Caliper, Water pressure. |
| Winch: | Mount Sopris Wna 10, 0.55 kW, 220V/50Hz. Steel wire cable 1,500 m, four conductors, Gerhard-Owen cable head. |
| Length determination: | Based on the marked cable and on the digital length counter. |
| Logging computer: | PC, Windows XP. |
| Software: | Based on MS Visual Basic. |
| Total power consumption: | 1.5–2.5 kW depending on the pumps. |
| Calibrated: | March 2006. |
| Calibration of cable length: | Using length marks in the borehole. |

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

**Table 4-1. Range and accuracy of sensors.**

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

# 5 Performance

## 5.1 General

The Commission was performed according to Activity Plan AP PF 400-06-018 following the SKB Method Description 322.010, Version 1.0 (Method description for difference flow logging), see Table 1-1. The Activity Plan and the Method Description are both SKB's internal controlling documents. Prior to the measurements, the downhole tools and the measurement cable were disinfected. Time was synchronized to local Swedish time. The activity schedule of the borehole measurements is presented in Table 5-1. The items and activities in Table 5-1 are the same as in the Activity Plan.

Logging cables, wires, and pipe strings are exposed to stretching when lowered into a vertical or sub-vertical borehole. This will introduce a certain error in defining the position of a test tool connected to the end of a logging cable. Immediately after completion of the drilling operations in borehole KFM01D, length marks were milled into the borehole wall at certain intervals to be used for length calibration of various logging tools. By using the known positions of the length marks, logging cables etc can be calibrated in order to obtain an accurate length correction of the testing tool.

Each length mark consists of two 20 mm wide tracks in the borehole wall. The distance between the tracks is 100 mm. The upper track defines a reference level. 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 (Item 9) for this purpose. These methods also reveal parts of the borehole widened for some reason (fracture zones, breakouts etc).

The caliper/SPR-measurements in the measurement schedule were followed by measurements of the electric conductivity (EC) and temperature of the borehole water (Item 10) during natural (un-pumped) conditions.

The combined overlapping/sequential flow logging (Item 12) was carried out in the borehole with a 5 m section length and in 0.5 m length increments (step length). The measurements were performed during natural (un-pumped) conditions. The telescopic part of the borehole was also flow logged (Item 11) to detected possible structural damage.

Pumping was started on May 26, 2006. After c 24 hours waiting time, overlapping flow logging (Item 13) was conducted using the same section and step lengths as before.

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

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

The EC of borehole water (Item 16) was measured while the borehole was still pumped. After this, the pump was stopped and the recovery of the groundwater level was monitored (Item 17). SKB continued with groundwater level monitoring between June 1 and 2.

**Table 5-1. Flow logging and testing in KFM01D. Activity schedule.**

| Item | Activity | Explanation | Date |
|---|---|---|---|
| 8 | Dummy logging | Borehole stability/risk evaluation. | 2006-05-09–2006-05-10, 2006-05-15, 2006-05-23 |
| 9 | Calibration | SKB Caliper and SPR. Logging without the lower rubber disks, no pumping. | 2006-05-10–2006-05-12 |
| 10 | EC- and temp-logging of the borehole fluid | Logging without the lower rubber disks, no pumping. | 2006-05-23–2006-05-24 |
| 11 | Telescopic part of borehole flow logging | Logging without the lower rubber disks, no pumping. | 2006-05-26 |
| 12 | Combined overlapping/ sequential flow logging | Section length $L_w$ = 5 m. Step length dL = 0.5 m. No pumping. | 2006-05-24–2006-05-26 |
| 13 | Overlapping flow logging | Section length $L_w$ = 5 m. Step length dL = 0.5 m, pumping (includes 1 day waiting after the star of pumping). | 2006-05-26–2006-05-28 |
| 14 | Selective overlapping flow logging | Section length $L_w$ = 1 m. Step length dL = 0.1 m, pumping. | 2006-05-28–2006-05-30 |
| 15 | Fracture-specific EC-measurements in pre-selected fractures | Section length $L_w$ = 0.5 m, pumping (measurements in pre-selected fractures). | 2006-05-30–2006-05-31 |
| 16 | EC- and temp-logging of the borehole fluid | Logging without the lower rubber disks, pumping. | 2006-05-31–2006-06-01 |
| 17 | Recovery transient | Measurement of water level and absolute pressure in the borehole after the pumping was stopped. The measurement was continued between 2006-06-01–2006-06-02 by SKB. | 2005-06-01 |

## 5.2 Nonconformities

The measurements were interrupted several times because of data communication errors between the sensor equipment and the measurement computer and because the tool got stuck in the borehole.

Measurements in Items 9, 10, 12, 14 and 16 were often interrupted by data communication errors at night. This prolonged the measurements, but they were still performed within the time limits outlined in the Activity Plan.

The measurement tool also got stuck in the borehole on May 12, 2006. The tool was knocked free with a weight on May 15, 2006. After this the dummy logging was repeated. The dummy tool did not move freely and the measurements were stopped. The measurements were continued on May 23, 2006 with another additional dummy test. After this the measurement program was continued normally.

On May 27 the pump had stopped during the night, but this did not cause any significant delays.

# 6 Results

## 6.1 Length calibration

### 6.1.1 Caliper and SPR measurement

An accurate length scale for the measurements is difficult to achieve in long boreholes. The main cause of inaccuracy is the stretching of the logging cable. The stretching depends on the tension of the cable, the magnitude of which in turn depends, among other things, on the inclination of the borehole and on the friction against the borehole wall. The cable tension is larger when the borehole is measured upwards. The cables, especially new cables, may also stretch out permanently. In KFM01D the stretching of the cable was not high.

Length marks on the borehole wall can be used to minimize the length errors. The length marks are initially detected with the SKB caliper tool. The length scale is first corrected according to the length marks. Single-point resistance is recorded simultaneously with the caliper logging. All flow measurement sequences can then be length corrected by synchronising the SPR results (SPR is recorded during all the measurements) with the original caliper/SPR-measurement.

The procedure of the length correction was the following:

- The caliper/SPR-measurements (Item 9) were initially length corrected in relation to the known length marks, Appendix 1.15, black curve. Corrections between the length marks were obtained by linear interpolation.
- The SPR curve of Item 9 was then compared with the SPR curves of Items 12, 13, 14 and 15 to obtain relative length errors of these measurement sequences.
- All SPR curves could then be synchronized, as can be seen in Appendices 1.2–1.14.

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

Zoomed results of the caliper and SPR data are presented in Appendices 1.2–1.14. The detectability of the length marks is listed in Table 6-1. Every mark was detected at least partly with the caliper tool in the measured interval. They can also be seen in the SPR results. However, the SPR-anomaly is complicated due to the four rubber disks used at the upper end of the section, two at each side of the resistance electrode. When only one length mark was detected, the decision whether it was the lower or the upper mark was made based on the shape of the SPR-anomaly.

The aim of the plots in Appendices 1.2–1.14 is to verify the accuracy of the length correction. The curves in these plots represent length corrected results. The same length corrections were applied to the flow and EC measurements.

The magnitude of length correction along the borehole is presented in Appendix 1.15. The negative values of the error represent the situation where the logging cable has been extended, i.e. the cable is longer than the nominal length marked on it.

**Table 6-1. Detected length marks.**

| Length marks given by SKB (m) | Length marks detected by caliper | Length marks detected by SPR |
|---|---|---|
| 150 | Both | Yes |
| 200 | Both | Yes |
| 250 | Both | Yes |
| 300 | Only Lower | Yes |
| 350 | Both | Yes |
| 400 | Both | Yes |
| 450 | Both | Yes |
| 500 | Both | Yes |
| 550 | Both | Yes |
| 600 | Only Upper | Yes |
| 650 | Both | Yes |
| 700 | Both | Yes |
| 750 | Both | Yes |

### 6.1.2 Estimated error in location of detected fractures

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

1. The point interval in the overlapping mode flow measurements is 0.1 m. This could cause an error of ± 0.05 m.
2. The length of the test section is not exact. The specified section length denotes the distance between the nearest upper and lower rubber disks. Effectively, the section length can be larger. At the upper end of the test section there are four rubber disks. The distance between them is 5 cm. This will cause rounded flow anomalies: a flow may be detected already when a fracture is situated between the upper rubber disks. These phenomena can cause an error of ± 0.05 m when the short step length (0.1 m) is used.
3. Corrections between the length marks can be other than linear. This could cause an error of ± 0.1 m in the caliper/SPR-measurement (Item 9).
4. SPR curves may be imperfectly synchronized. This could cause an error of ± 0.1 m.

In the worst case, the errors from sources 1, 2, 3 and 4 are summed and the total estimated error between the length marks would be ± 0.3 m.

The situation is slightly better near the length marks. In the worst case, the errors from sources 1, 2 and 4 are summed and the total estimated error would be ± 0.2 m.

Knowing the location accurately is important when different measurements are compared, for instance flow logging and borehole TV. In that case the situation may not be as severe as the worst case above, since some of the length errors are systematic and the error is nearly constant in fractures that are close to each other. However, the error from source 1 is random.

Fractures nearly parallel with the borehole may also be problematic. Fracture location may be difficult to define accurately in such cases.

## 6.2 Electric conductivity and temperature

### 6.2.1 Electric conductivity and temperature of borehole water

The electric conductivity of the borehole water was initially measured when the borehole was at rest, i.e. at natural, un-pumped conditions. The measurement was performed downwards, see Appendices 2.1 (logarithmic scale) and 2.2 (linear scale), blue curve.

The EC measurement was repeated during pumping (after a pumping period of about five days), see Appendices 2.1 and 2.2, green curve.

The temperature of the borehole water was measured simultaneously with the EC measurements. The EC values are temperature corrected to 25°C to make them more comparable with other EC measurements /Heikkonen et al. 2002/. The temperature results in Appendix 2.3 have the same length axis as the EC results in Appendices 2.1 and 2.2.

The length calibration of the borehole electric conductivity measurements is not as accurate as in other measurements because single-point resistance is not registered. The length correction of the SPR/caliper-measurement was applied to the borehole EC measurements, black curve in Appendix 1.15.

### 6.2.2 Electric conductivity of fracture-specific water

The flow direction is always from the fractures into the borehole if the borehole is pumped with a sufficiently large drawdown. This enables the determination of electrical conductivity from fracture-specific water. Both electric conductivity and temperature of flowing water from the fractures were measured.

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

The test section in these measurements was 0.5 m long and the tool was moved in 0.05 m steps. The water volume in a half metre long test section is 1.6 L. The results are presented in Appendices 11.1 and 11.2. The blue symbol represents the conductivity value when the tool was moved and the red symbol is used for the set of stationary measurements.

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

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

**Table 6-2. Fracture-specific EC.**

| Upper end of section (m) | Lower end of section (m) | Fractures measured (m) | EC (S/m) at 25°C |
|---|---|---|---|
| 570.8 | 571.3 | 571.17 | 1.20 |
| 431.3 | 431.8 | 431.52 | 1.31 |
| 316.66 | 317.16 | 316.9 | 1.24 |
| 120.6 | 121.1 | 120.9 | 1.18 |

## 6.3 Pressure measurements

The absolute pressure was registered together with the other measurements in Items 11–15 and 17 in Table 5-1. The pressure sensor measures the sum of hydrostatic pressure in the borehole and air pressure. Air pressure was also registered separately, see Appendix 10.2. The hydraulic head along the borehole at natural and pumped conditions is determined in the following way. First, the monitored air pressure at the site is subtracted from the measured absolute pressure by the pressure sensor. The hydraulic head (h) at a certain elevation (z) is calculated according to the following expression /Nordqvist 2001/:

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

where

h is the hydraulic head (m.a.s.l.) according to the RHB 70 reference system,

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

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

$\rho_{fw}$ is the unit density, 1,000 kg/m$^3$

g is the standard gravity, 9.80665 m/s$^2$ and

z is the elevation of measurement (m.a.s.l.) according to the RHB 70 reference system.

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

The calculated head distributions are presented in Appendix 10.1. The exact z-coordinates are important in head calculation. A 10 cm error in the z-coordinate means a 10 cm error in the head.

## 6.4 Flow logging

### 6.4.1 General comments on results

The measuring programme contained several flow logging sequences. They were gathered on the same diagram with single-point resistance (right hand side) and caliper plots (in the middle), see Appendices 3.1–3.36. Single-point resistance is usually lower in value on a fracture where a flow is detected. There are also many other resistance anomalies caused by other fractures and geological features. The electrode of the single-point resistance tool is located within the upper rubber disks. Thus, the locations of the resistance anomalies of leaky fractures coincide with the lower end of the flow anomalies.

The caliper tool outputs a low voltage value when the borehole diameter is below 78 mm and a high voltage value when the borehole diameter exceeds 78 mm.

The flow logging was first performed with a 5 m section length and with 0.5 m length increments, see Appendices 3.1–3.36. 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.

Under natural conditions flow direction may be into the borehole or out from it. The flow direction of small flows (< 100 mL/h) cannot be detected in the normal overlapping mode (thermal dilution method). Therefore the waiting time was longer for the thermal pulse method at every 5 m interval. The thermal pulse method was only used to detect the flow direction, not for the flow rate which would take a longer time to measure. Longer flow direction measurements have to be done during un-pumped conditions.

The test section length determines the width of a flow anomaly of a single fracture. If the distance between flow yielding fractures is less than the section length, the anomalies will overlap, resulting in a stepwise flow data plot. The overlapping flow logging was therefore repeated in the vicinity of identified flow anomalies using a 1 m long test section and 0.1 m length increments.

The positions (borehole length) of the detected fractures are shown on the caliper scale. They are interpreted on the basis of the flow curves and therefore represent flowing fractures. A long line represents the location of a leaky fracture; a short line denotes that the existence of a leaky fracture is uncertain. The short line is used if the flow rate is less than 30 mL/h or the flow anomalies are overlapping or unclear because of noise.

The flow along the borehole was also logged for the telescopic part of the borehole (Item 11). This was done by removing the lower rubber disks and guiding all flow along the borehole through the flow sensor. The location for the measurement was at the intact bedrock just below the telescopic part of the borehole (at 93.52 m). Flow at this point would indicate leaks in the casing tube or just below it. The results are presented in Appendix 10.4. It can be seen from the data that after a short stabilization period the water level remained constant and no significant flow along the borehole was detected.

### 6.4.2 Transmissivity and hydraulic head of borehole sections

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

The results of the measurements with a 5 m section length are presented in tables, see Appendix 5. Only the results with 5 m length increments are used. All borehole sections are shown in Appendices 3.1–3.36. Secup and Seclow in Appendix 5 are the distances along the borehole from the reference level (top of the casing tube) to the upper end of the test section and to the lower end of the test section, respectively. The Secup and Seclow values for the two sequences (measurements at un-pumped and pumped conditions) are not exactly identical, due to a minor difference in the cable stretching. The difference between these two sequences was small. Secup and Seclow given in Appendix 5 are calculated as the average of these two values.

Pressure was measured and calculated as described in Section 6.3. The parameters $h_{0FW}$ and $h_{1FW}$ in Appendix 5 represent heads determined without and with pumping, respectively. The head in the borehole and calculated heads of borehole sections are given in RHB 70 scale.

The flow results in Appendix 5 ($Q_0$ and $Q_1$), representing the flow rates derived from measurements during un-pumped and pumped conditions, are presented side by side to make comparison easier. Flow rates are positive if the flow direction is from the bedrock into the borehole and vice versa. With the borehole at rest, 10 sections were detected as flow yielding, of which 4 had a flow direction from the borehole into the bedrock (negative flow). During pumping, all 19 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.

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

The hydraulic head and transmissivity ($T_D$) of borehole sections can be calculated from flow data using the method described in Chapter 3. The hydraulic head of sections is presented in the plots if none of the two flow values at the same length is equal to zero. Transmissivity is presented if none or just one of the flows is equal to zero, 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 ($h_{0FW}$ and $h_{1FW}$ in Appendix 5).

The sum of detected flows without pumping ($Q_0$) was 4.01E–07 $m^3/s$ (1443 mL/h). This sum should normally be zero if all the flows in the borehole are correctly measured, the borehole is not pumped, the water level is constant, the salinity distribution in the borehole is stabilized and the fractures are at steady state pressure. In this case the sum is fairly close to zero, even though the borehole was not measured below c 791 m.

### 6.4.3 Transmissivity and hydraulic head of fractures

An attempt was made to evaluate the magnitude of fracture-specific flow rates. The results for a 1 m section length and 0.1 m length increments were used for this purpose. The first step in this procedure is to identify the locations of individual flowing fractures and then evaluate their flow rates.

In cases where the fracture distance is less than one metre, it may be difficult to evaluate the flow rate. There are such cases for instance in Appendix 3.3. In these cases a stepwise increase or decrease in the flow data plot equals the flow rate of a specific fracture (filled triangles in the Appendices).

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

The total amount of detected flowing fractures is 34, but only 6 of them could be defined without pumping. These 6 fractures could be used for head estimations and all 34 were used for transmissivity estimations. Transmissivity and hydraulic head of fractures are presented in Appendices 7 and 8.

Some fracture-specific results were classified as "uncertain", see Appendix 7. The basis for this classification was in one of the cases a minor flow rate (< 30 mL/h), but in most of the cases unclear fracture anomalies. The anomalies were unclear because the distance between them was less than one metre or the nature of an anomaly was unclear because of noise.

Fracture-specific transmissivities were compared with transmissivities of borehole sections in Appendix 9. All fracture-specific transmissivities within each 5 m interval were first summed together 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. The decrease of flow as a function of pumping time can be seen in most fractures. The measurements with a 1 m section were carried out about one day later than with a 5 m section during pumping and therefore flow rate and transmissivity are generally smaller during the measurements with a 1 m section. An exception from this is a fracture at 307.4 m where the flow rate with a 1 m section was larger.

### 6.4.4 Theoretical and practical measurements limits of flow and transmissivity

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

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

There are several known reasons for increased noise levels:

1) Rough borehole wall.

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

3) Gas bubbles in water.

4) High flow rate along the borehole.

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

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

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

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

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

The practical minimum of the measurable flow rate is evaluated and presented in Appendices 3.1–3.36 using a grey dashed line (Lower limit of flow rate). The practical minimum level of the measurable flow is always evaluated in pumped conditions since this measurement is the most important for transmissivity calculations. The limit is an approximation. It is evaluated to obtain a limit below which there may be fractures or structures that remain undetected.

The noise level in KFM01D was between 30 and 100 mL/h. In many places anomalies below the theoretical limit of the thermal dilution method (30 mL/h) could be detected. The noise line (grey dashed line) was never drawn below 30 mL/h, because the values of flow rate measured below 30 mL/h are uncertain.

In some boreholes the upper limit of flow measurement (300,000 mL/h) may be exceeded. Such fractures or structures hardly remain undetected (as the fractures below the lower limit). High flow fractures can be measured separately at a smaller drawdown. In KFM01D there was no need for any extra measurements.

The practical minimum of measurable flow rate is also presented in Appendix 5 (Q-lower limit P). It is taken from the plotted curve in Appendix 3 (Lower limit of flow rate). The practical minimum of measurable transmissivity can be evaluated using Q-lower limit and the actual head difference at each measurement location, see Appendix 5 ($T_D$-measl$_{LP}$). The theoretical minimum measurable transmissivity ($T_D$-measl$_{LT}$) is evaluated using a Q value of 30 mL/h (minimum theoretical flow rate with the thermal dilution method). The upper measurement limit of transmissivity can be evaluated using the maximum flow rate (300,000 mL/h) at the actual head difference as above, see Appendix 5 ($T_D$-measl$_U$).

All three flow limits are also plotted with the measured flow rates, see Appendix 6.1. Theoretical minimum and maximum values are 30 mL/h and 300,000 mL/h, respectively.

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

Similar flow and transmissivity limits are not given for the fracture-specific results in Appendix 7. Approximately the same limits would be though valid also for these results. The limits for fracture-specific results are more difficult to define. For instance, it may be difficult to observe a small flow rate near (< 1 m) a high flowing fracture. The situation is similar for the upper flow limit. If there are several high flowing fractures less than one metre apart from each other, the upper flow limit depends on the sum of flows which must be below 300,000 mL/h.

### 6.4.5 Transmissivity of the entire borehole

The flow period of the pumping during difference flow logging and its subsequent recovery period is utilized to evaluate the transmissivity of the entire borehole. This is done with the two steady-state methods together with the transient analysis method described in Chapter 3.

#### *Steady-state analysis*

In Dupuit's formula (Equation 3-9), $R/r_0$ is assumed to be 500, Q was 2.8 L/min and the drawdown s = 10.56 m by the end of the flow period (Appendix 10.2). The transmissivity calculated with Dupuit's formula is $4.4 \cdot 10^{-6}$ m$^2$/s. In Moye's formula (Equation 3-10) the length of the test section L is 708.81 m (91.43–800.24 m) and the borehole diameter $2r_0$ is 0.076 m. The transmissivity calculated with Moye's formula is $7.2 \cdot 10^{-6}$ m$^2$/s.

### *Transient analysis (by J-E Ludvigson, Geosigma AB)*

Transient analysis is done on the recovery period in accordance with the methodology specified in SKB MD 320.004 (SKB internal controlling document). Briefly, it specifies the analysis of the pressure recovery versus Agarwal equivalent time in log-log and semi-log plots together with the derivative. Furthermore, for an assumed storage coefficient S = $9.0 \cdot 10^{-7}$ the recovery period was simulated. The best fit simulation yields a transmissivity T = $1.6 \cdot 10^{-6}$ $m^2/s$ and a skin factor of –7.6.

Figure 6-1 and Figure 6-2 shows the log-log and semi-log plot of the recovery period which was utilised to calculate the transmissivity. The results of the three methods described above are given in Table 6-3.

**Table 6-3. Transmissivity of the entire borehole KFM01D.**

| Method | Transmissivity ($m^2/s$) |
|---|---|
| Dupuit | $4.4 \cdot 10^{-6}$ |
| Moye | $7.2 \cdot 10^{-6}$ |
| Transient | $1.6 \cdot 10^{-6}$ |

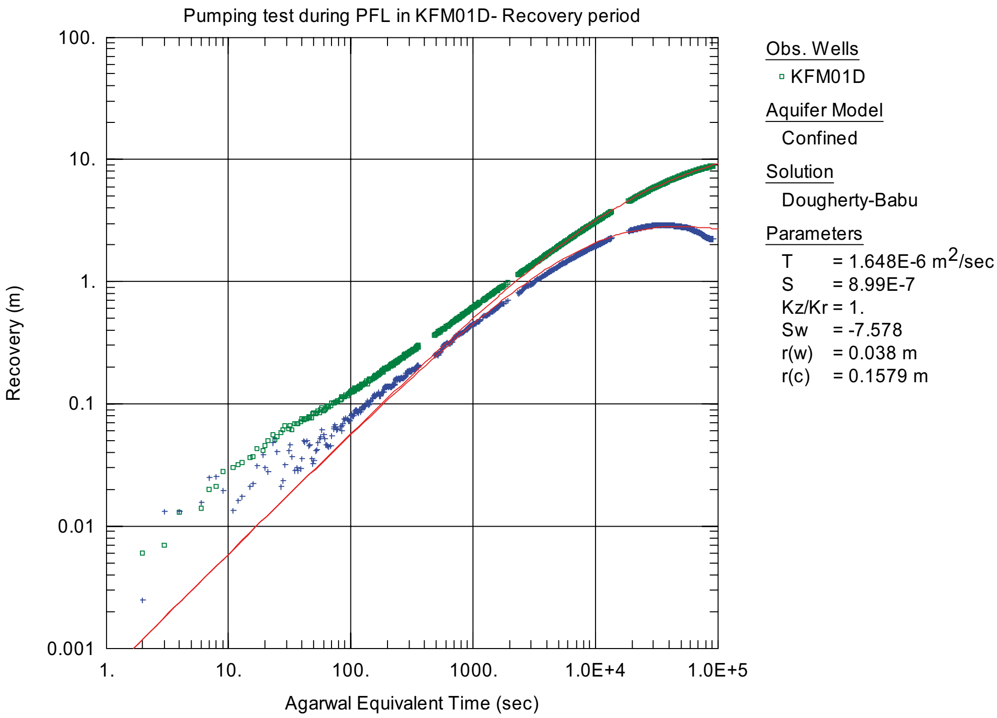


***Figure 6-1.*** *Log-log plot of the pressure recovery in KFM01D showing the measured pressure difference (□) and pressure difference derivative (+) versus Agarwal equivalent time together with simulated best fit curves (–).*

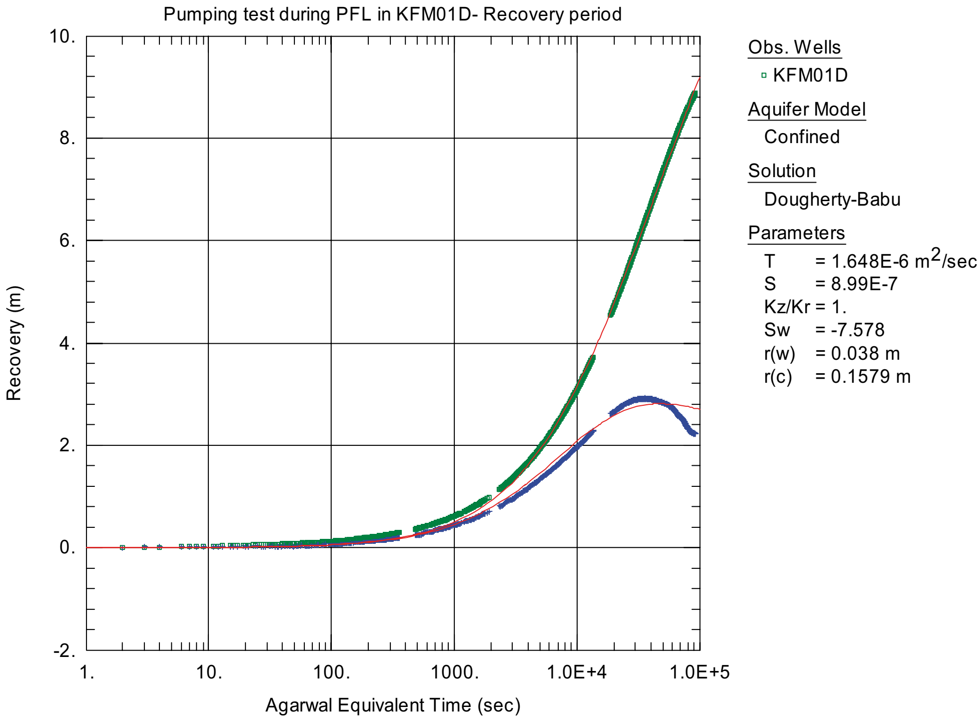


***Figure 6-2.*** *Semi-log plot of the pressure recovery in KFM01D showing the measured pressure difference (□) and pressure difference derivative (+) versus Agarwal equivalent time together with simulated best fit curves (–).*

## 6.5 Groundwater level and pumping rate

The level of the groundwater table in the borehole during the measurement sequences is presented in Appendix 10.2. The borehole was pumped between May 26 and June 1 with a drawdown of about 10.5 metres. The pumping rate was recorded, see Appendix 10.2.

The groundwater recovery was measured after the pumping period, on June 1, Appendix 10.3. The recovery was measured with two sensors, the water level sensor (pressure sensor for monitoring water level) and the absolute pressure sensor located at the borehole length of 33.16 m. Water level monitoring continued by SKB between June 1 and 2, see Appendix 10.2 and 10.3.

# 7 Summary

In this study, the Posiva Flow Log/Difference Flow method has been used to determine the location and flow rate of flowing fractures or structures in borehole KFM01D at Forsmark. Measurements were carried out both when the borehole was at rest and during pumping. A 5 m section length with 0.5 m length increments was used initially. The detected flow anomalies were re-measured with a 1 m section and 0.1 measurement interval.

Length calibration was made using the length marks in the borehole wall. The length marks were detected by caliper and single-point resistance logging. The latter method was also performed simultaneously with the flow measurements, and thus all flow results could be length calibrated by synchronizing the single-point resistance logs.

The distribution of saline water along the borehole was logged by electric conductivity and temperature measurements of the borehole water. In addition, electric conductivity was measured in selected flowing fractures.

The water level in the borehole during pumping and its recovery after the pump was turned off was also measured.

The total amount of detected flowing fractures was 34. Transmissivity and hydraulic head were calculated for borehole sections and fractures above 791 m. The highest fracture transmissivity ($2.3 \cdot 10^{-6}$ $m^2/s$) was detected at the borehole length of 148.0 m. A high-transmissivity fracture was also found at 144.9 m. No flowing fractures were identified below 571.2 m.

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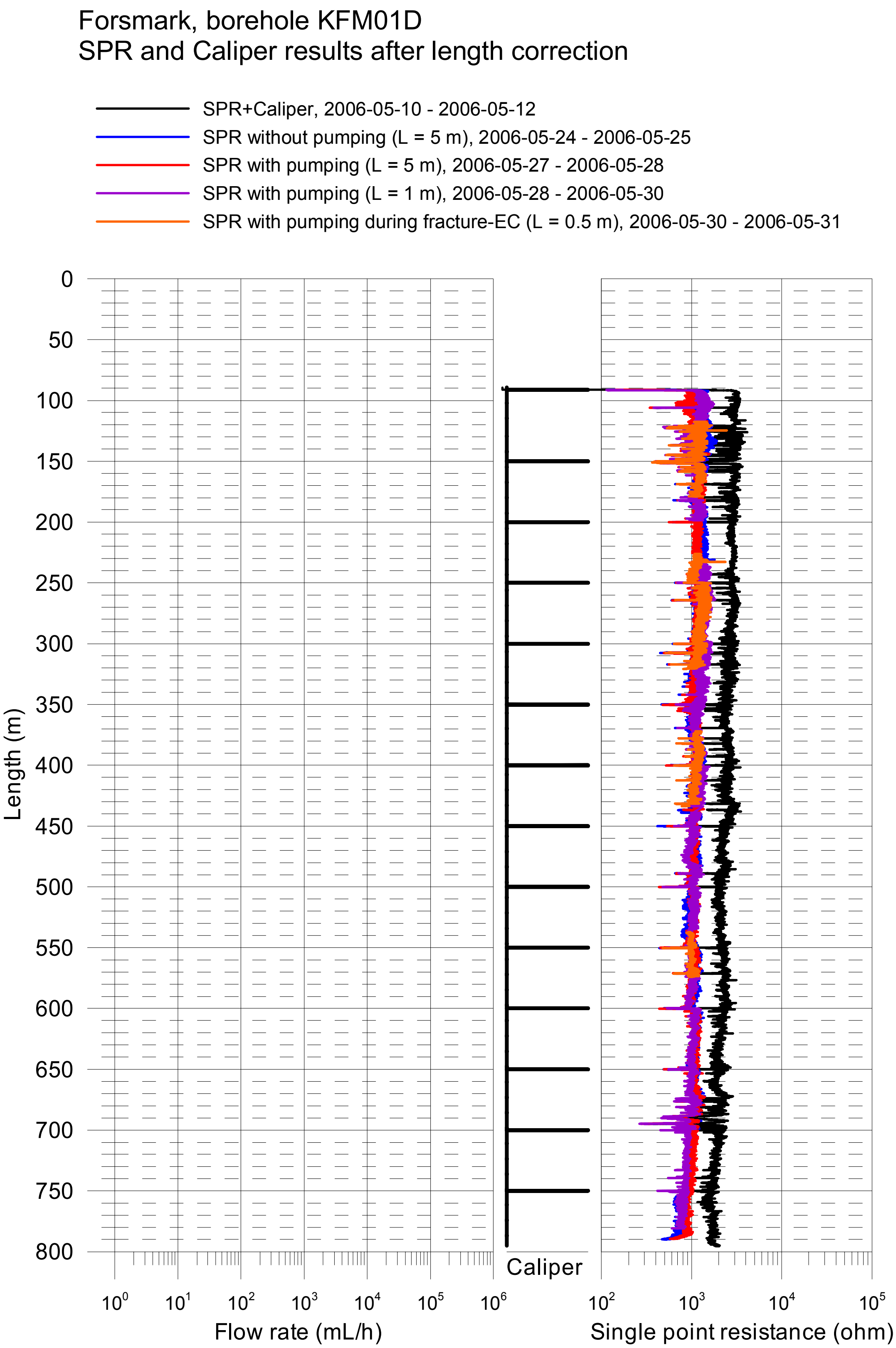
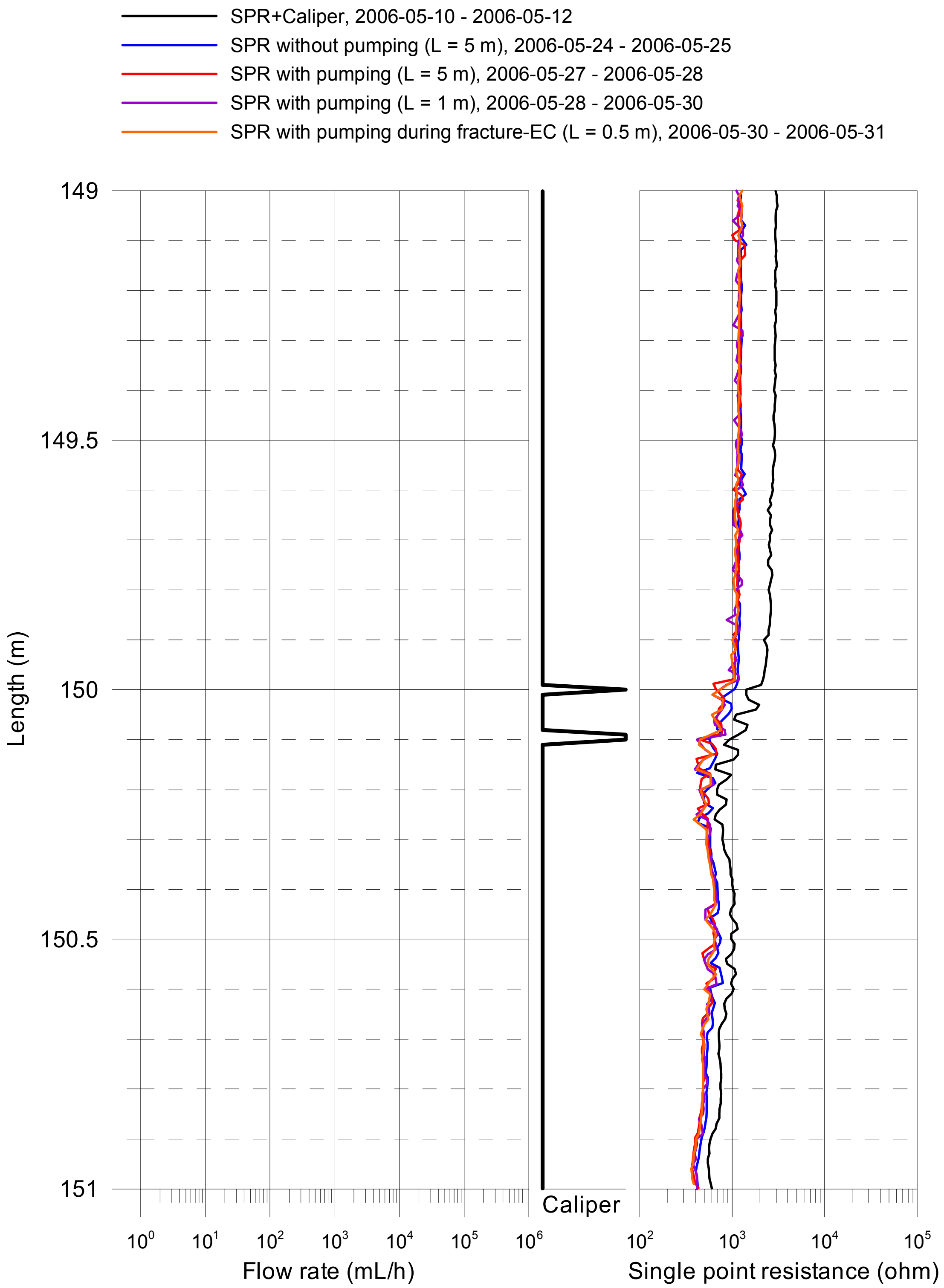
# Appendix 1

## Appendices 1.1–1.14 SPR and Caliper results after length correction

Appendix 1.1



Forsmark, borehole KFM01D
SPR and Caliper results after length correction



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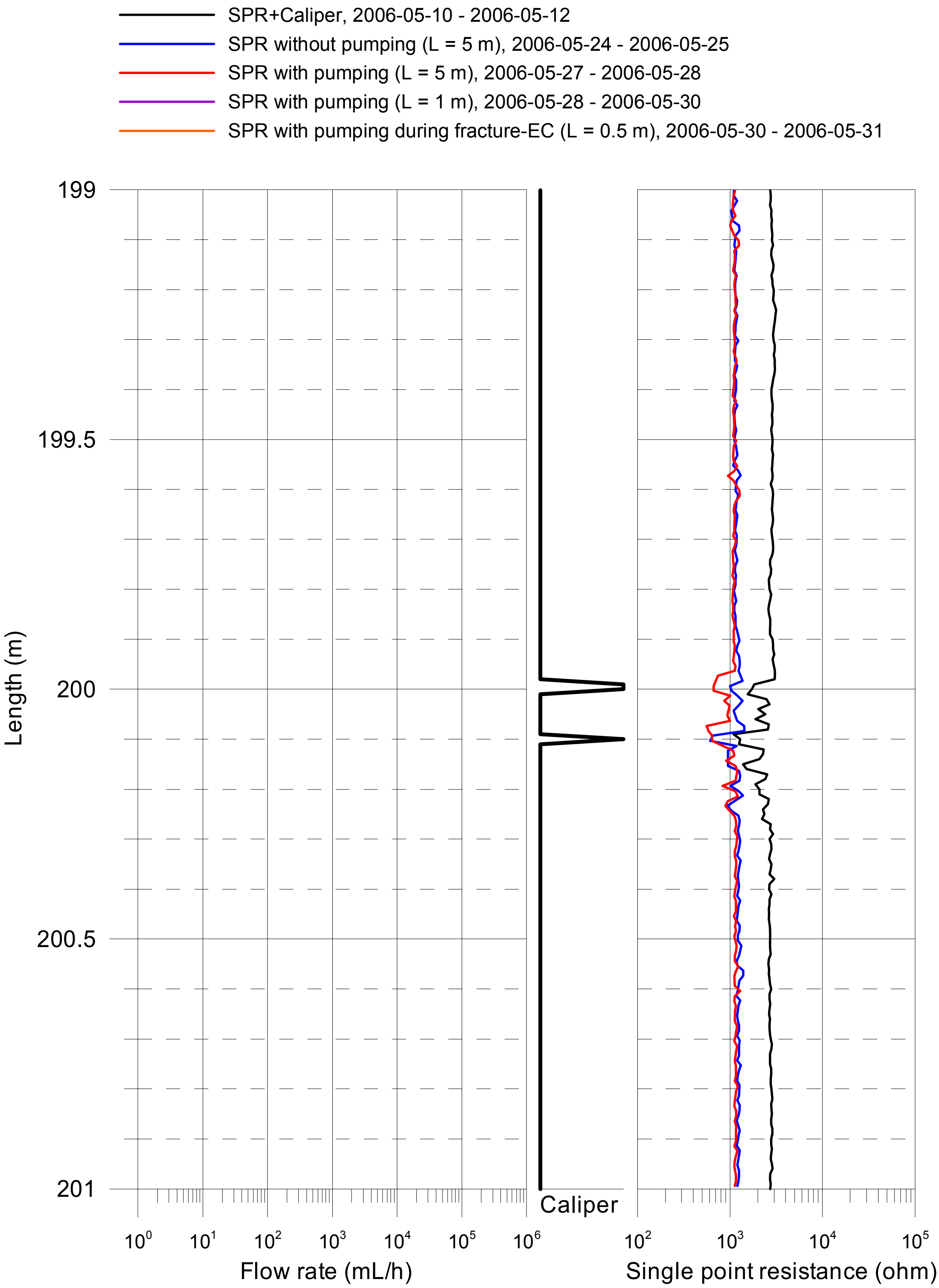
SPR and Caliper results after length correction



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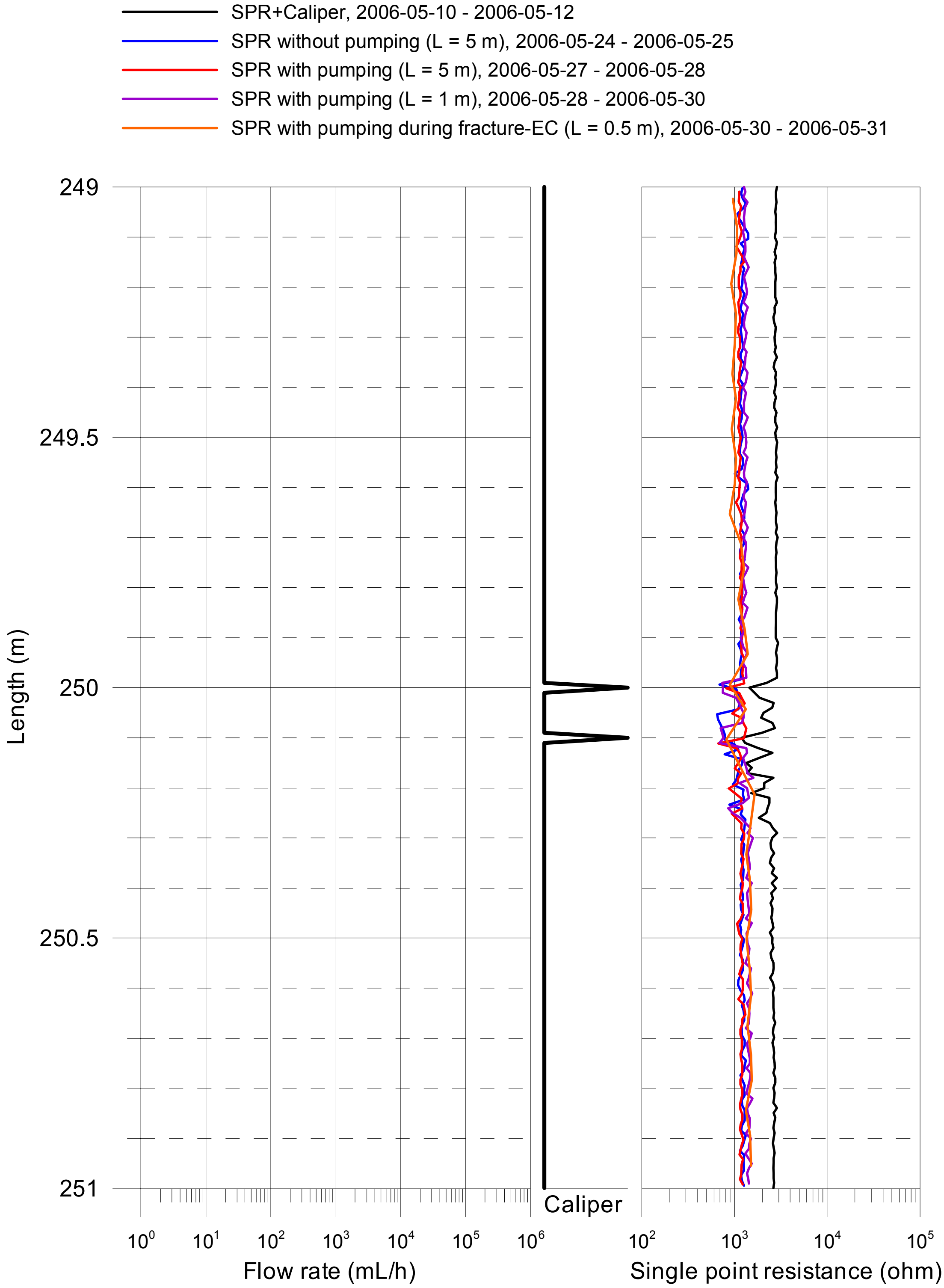
SPR and Caliper results after length correction



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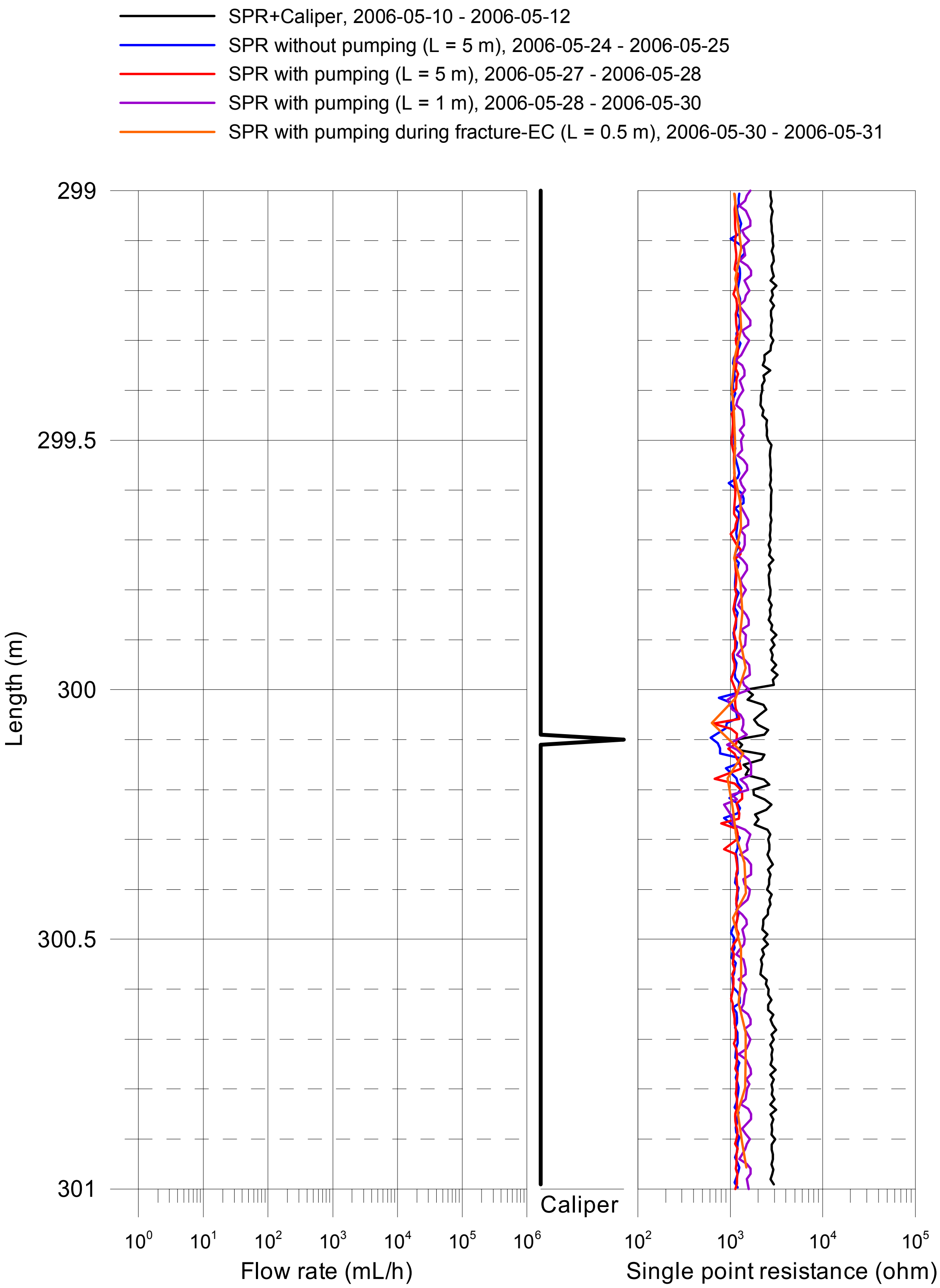

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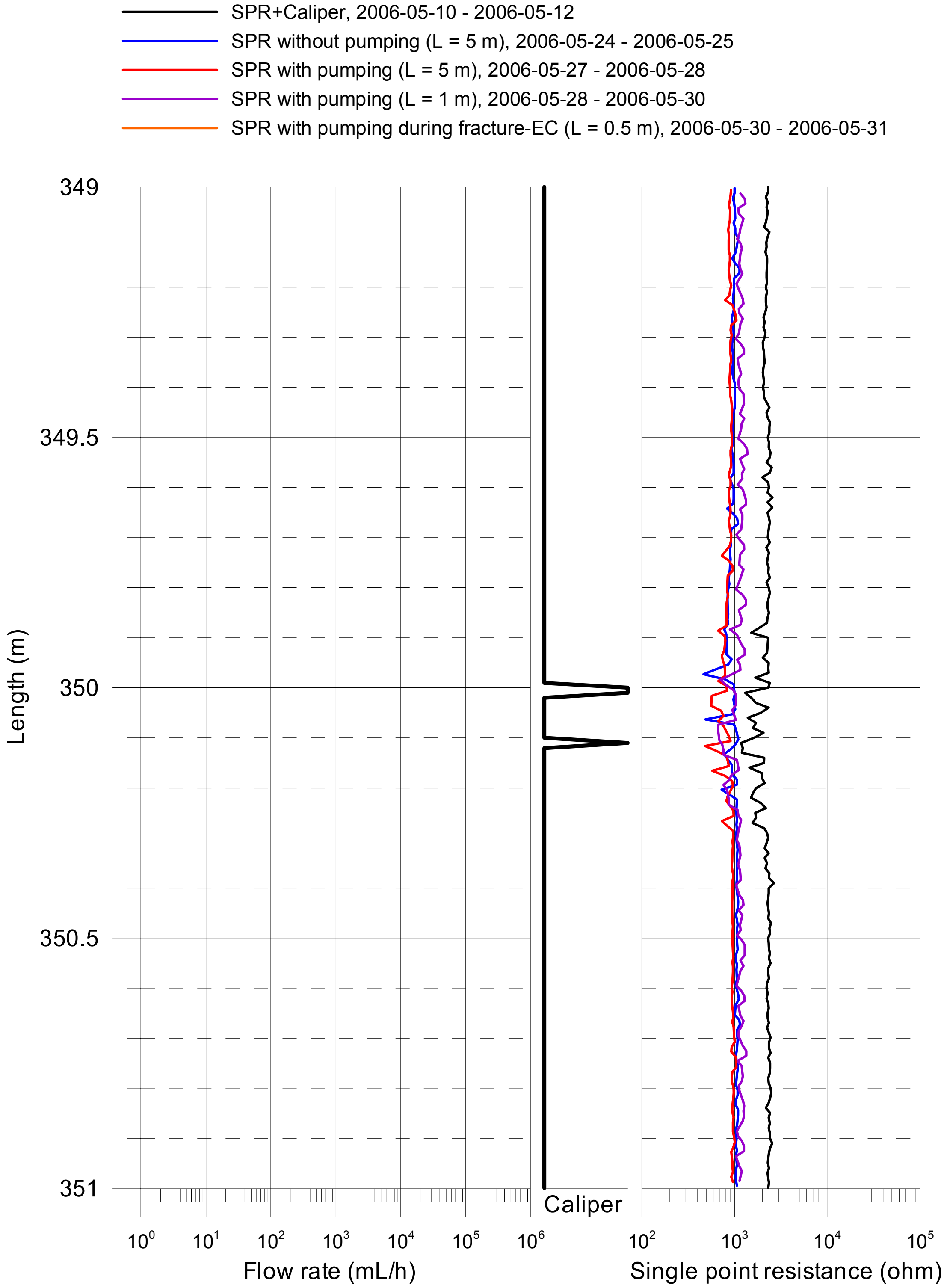
SPR and Caliper results after length correction



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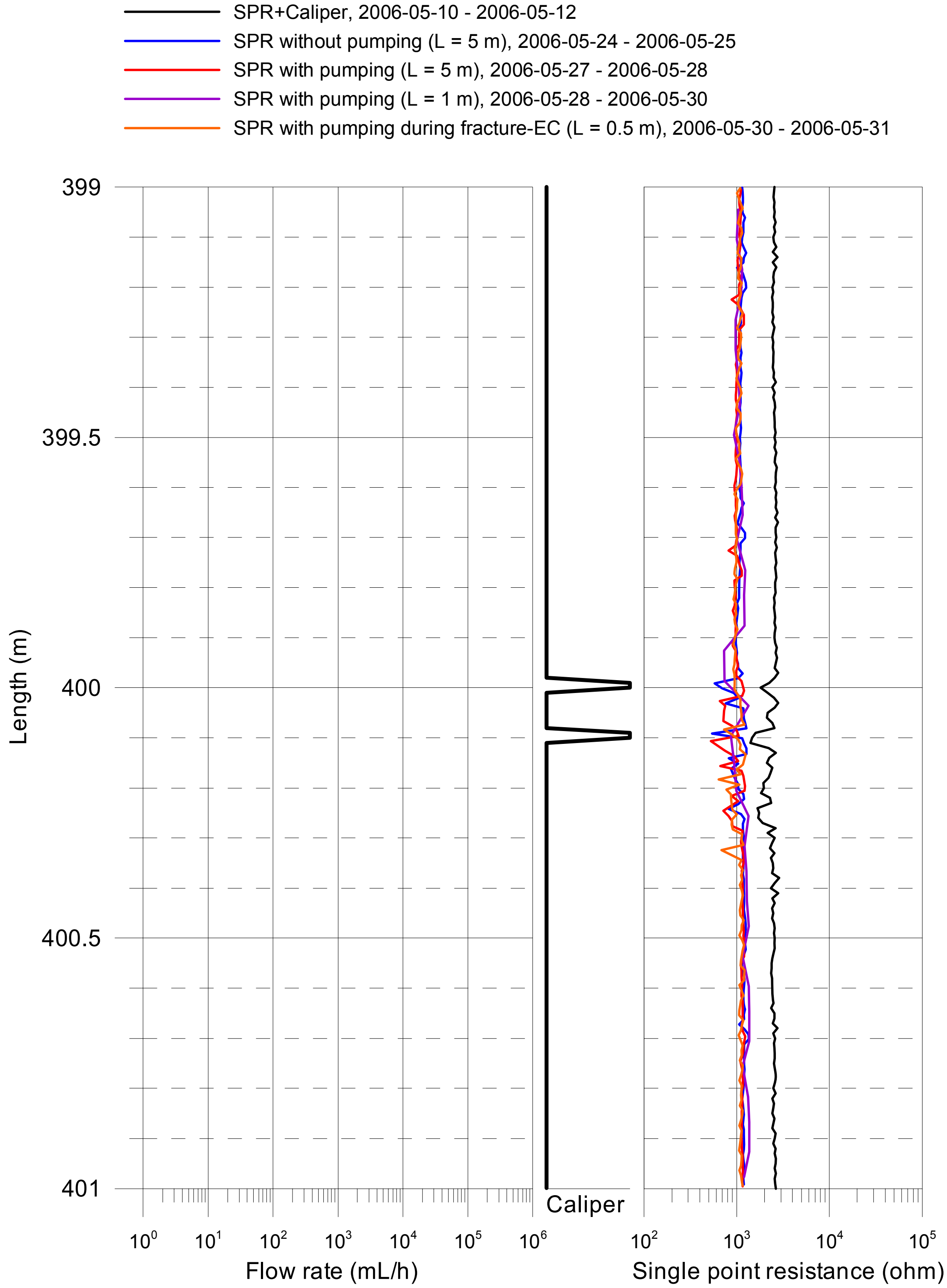

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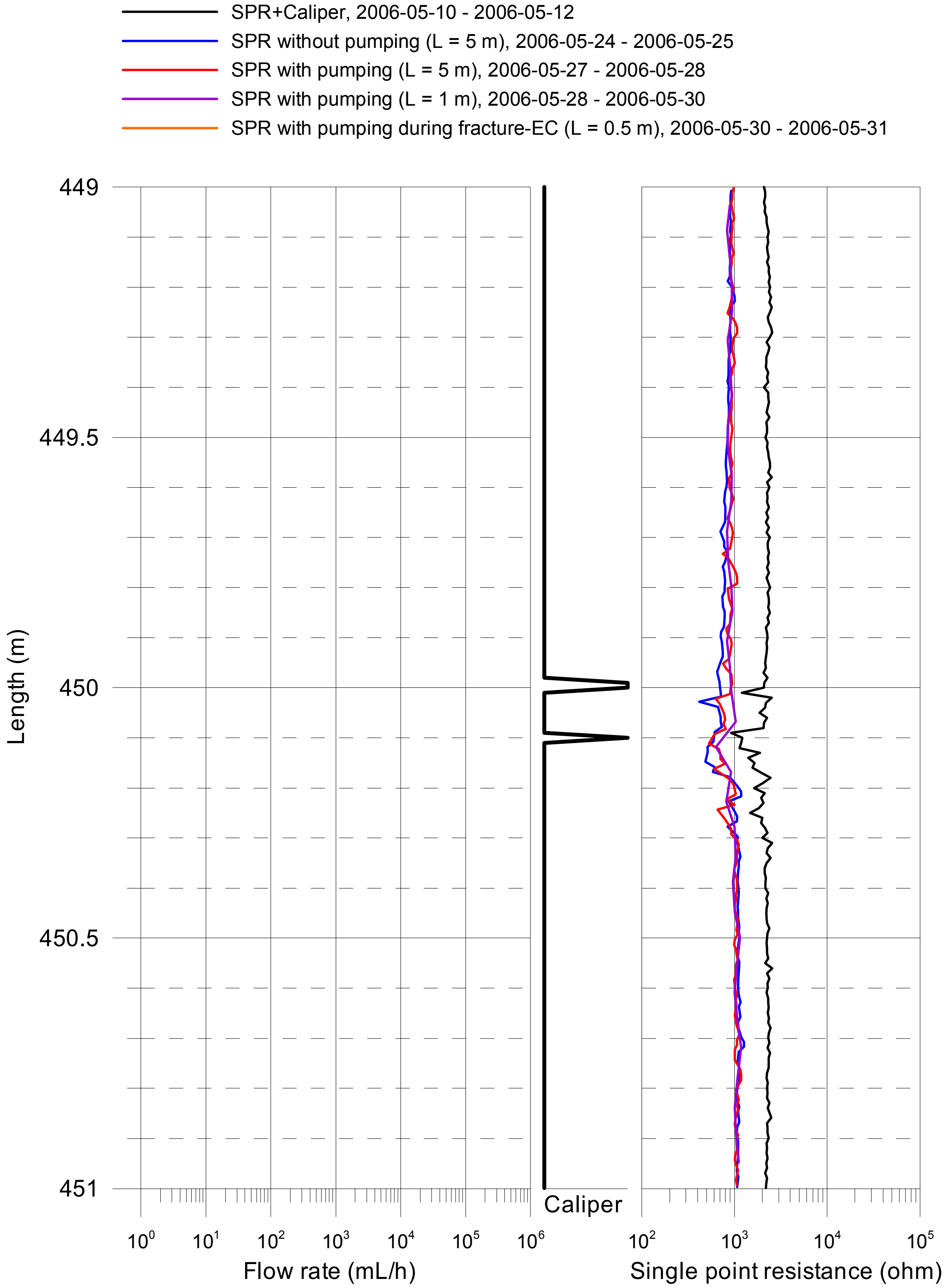
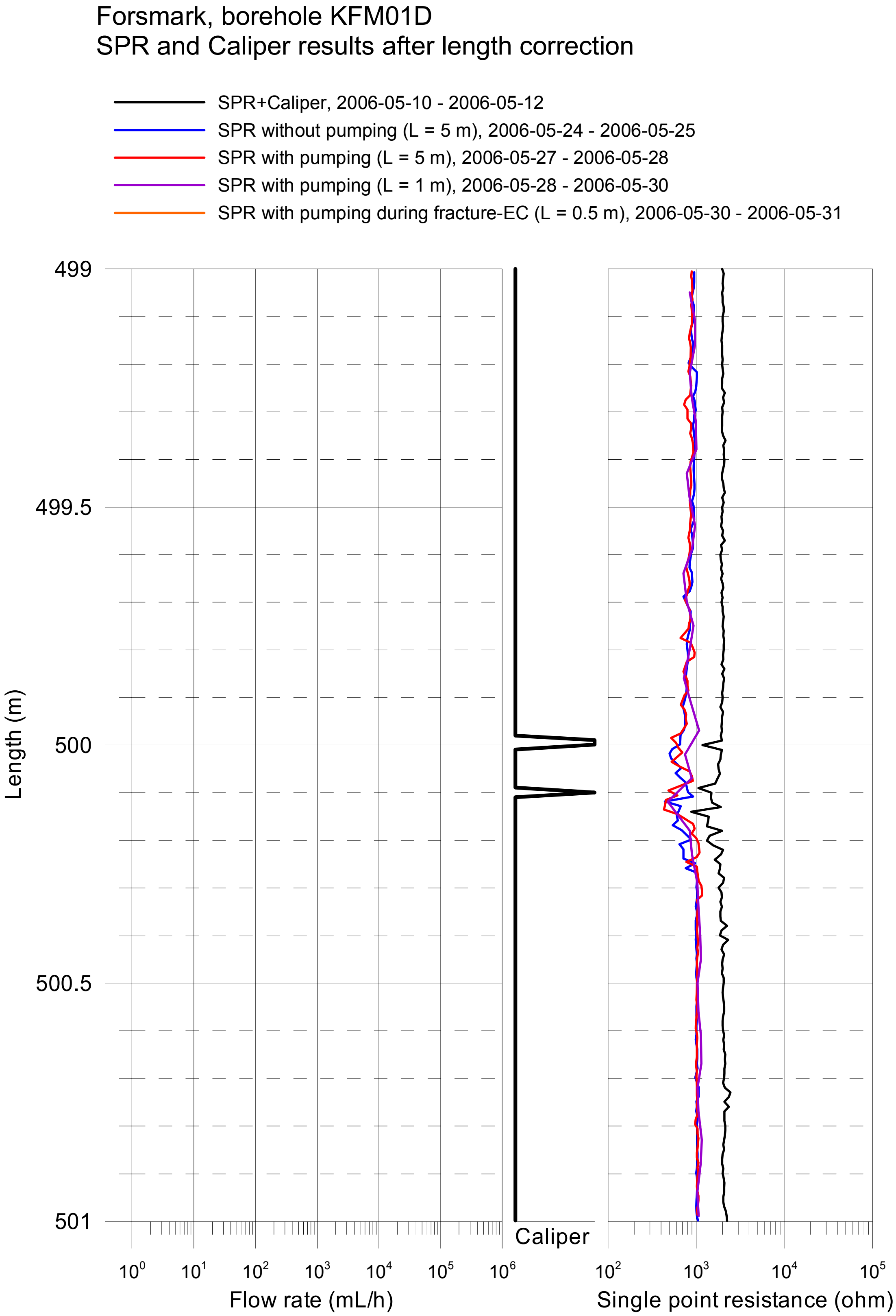
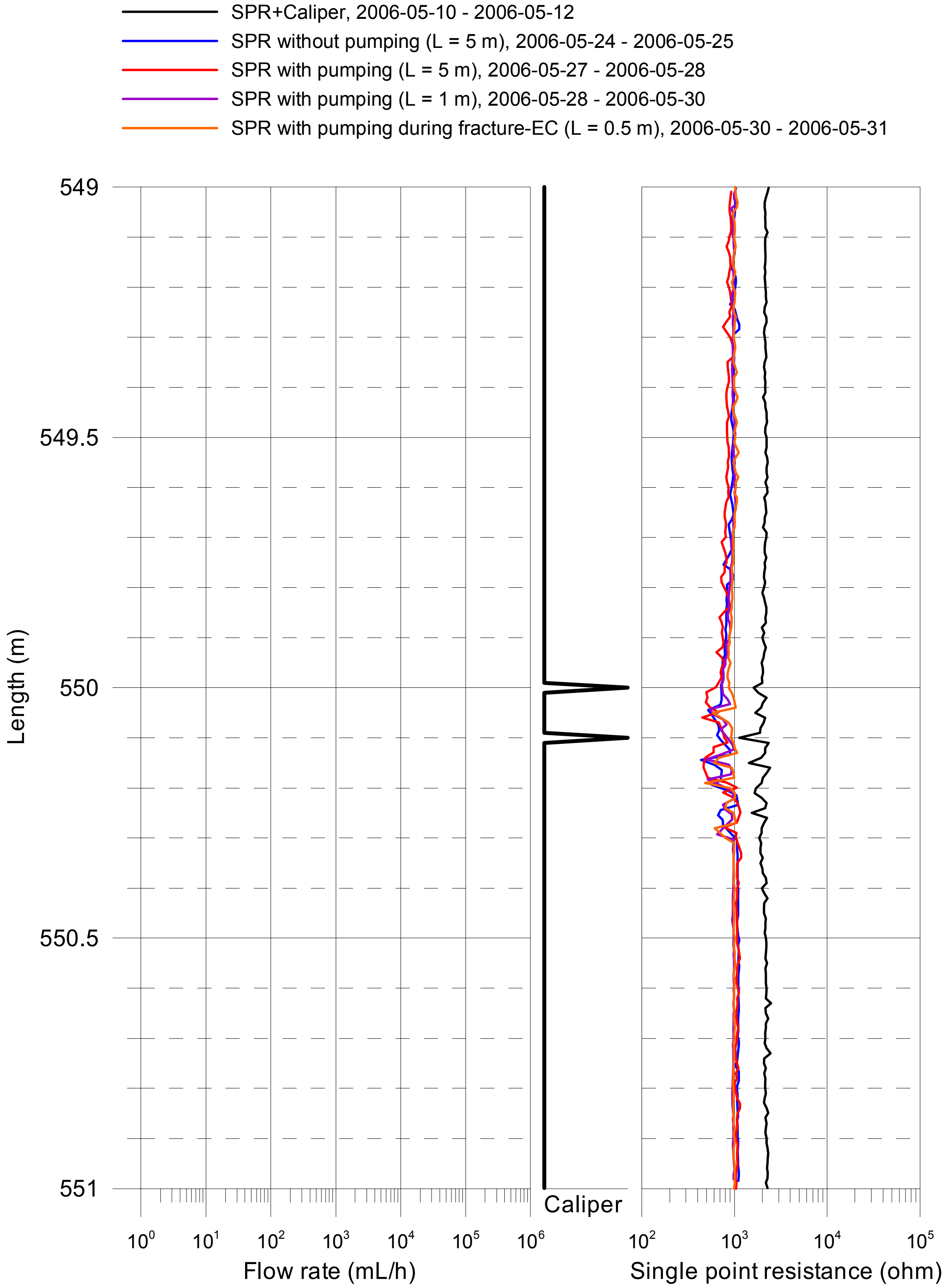
SPR and Caliper results after length correction




Forsmark, borehole KFM01D
SPR and Caliper results after length correction
SPR+Caliper, 2006-05-10 - 2006-05-12
SPR without pumping (L = 5 m), 2006-05-24 - 2006-05-25
SPR with pumping (L = 5 m), 2006-05-27 - 2006-05-28
SPR with pumping (L = 1 m), 2006-05-28 - 2006-05-30
SPR with pumping during fracture-EC (L = 0.5 m), 2006-05-30 - 2006-05-31
Length (m)
499
499.5
500
500.5
501
Caliper
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Flow rate (mL/h)
10^2
10^3
10^4
10^5
Single point resistance (ohm)

Forsmark, borehole KFM01D
SPR and Caliper results after length correction



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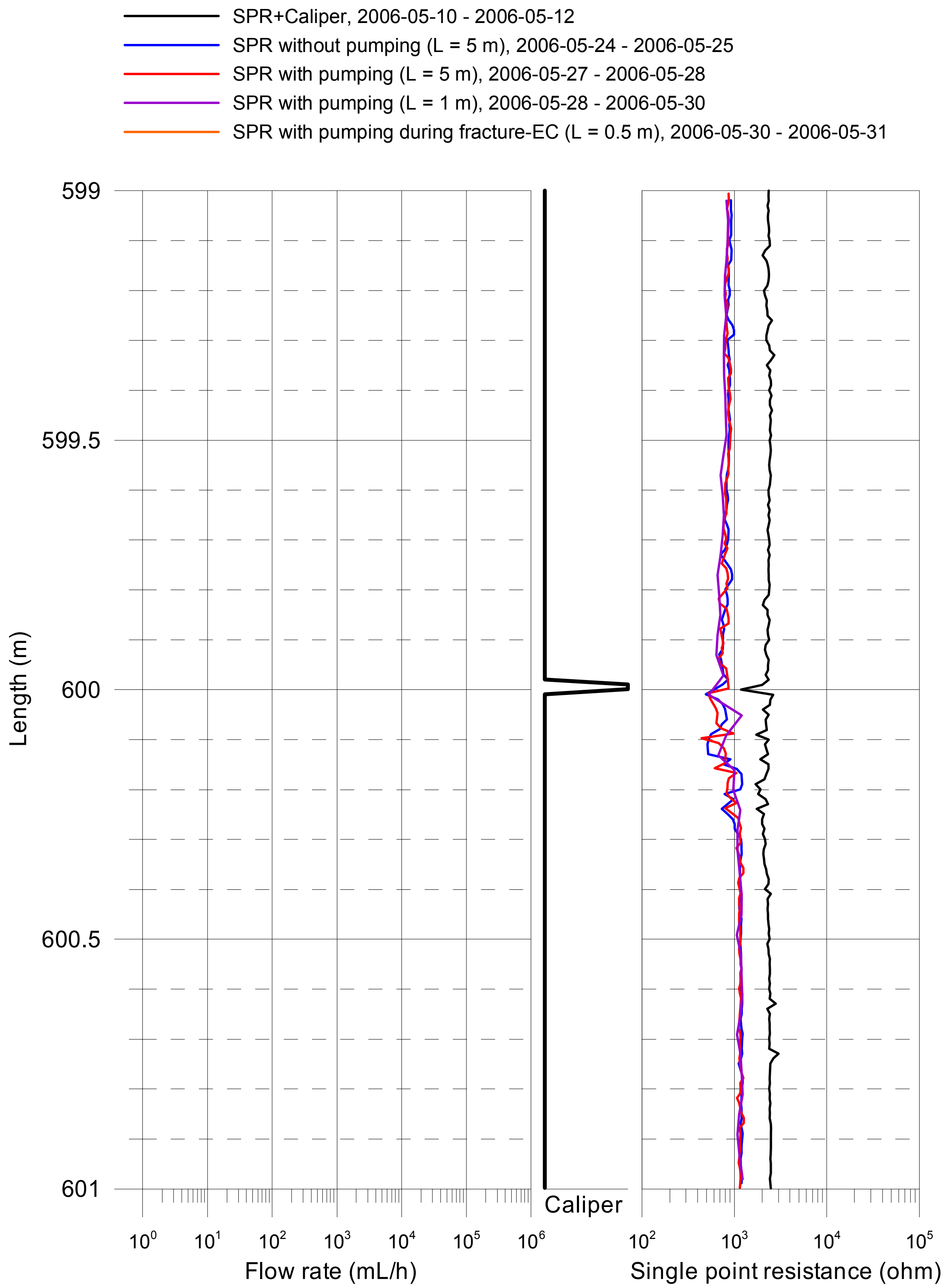
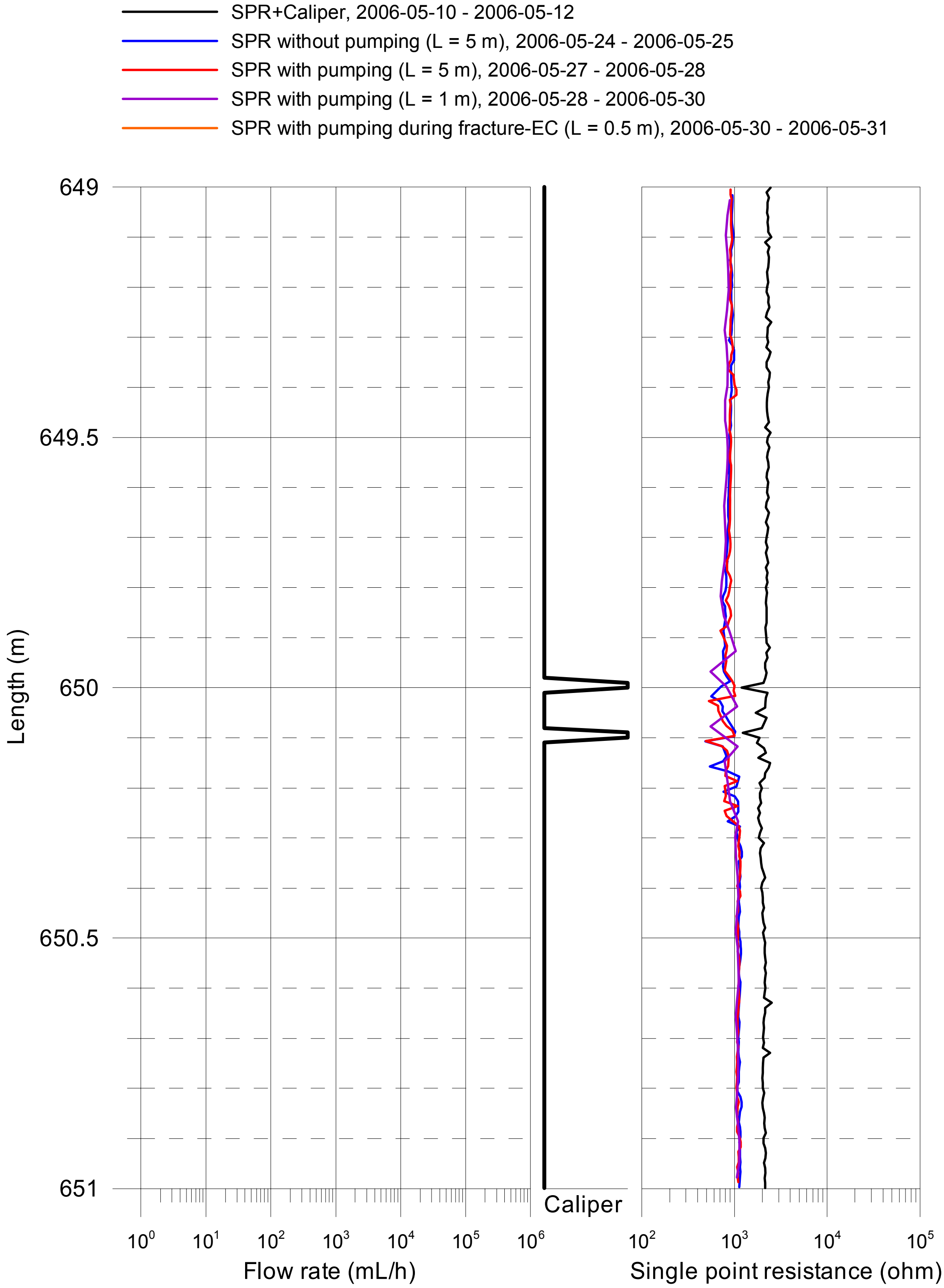
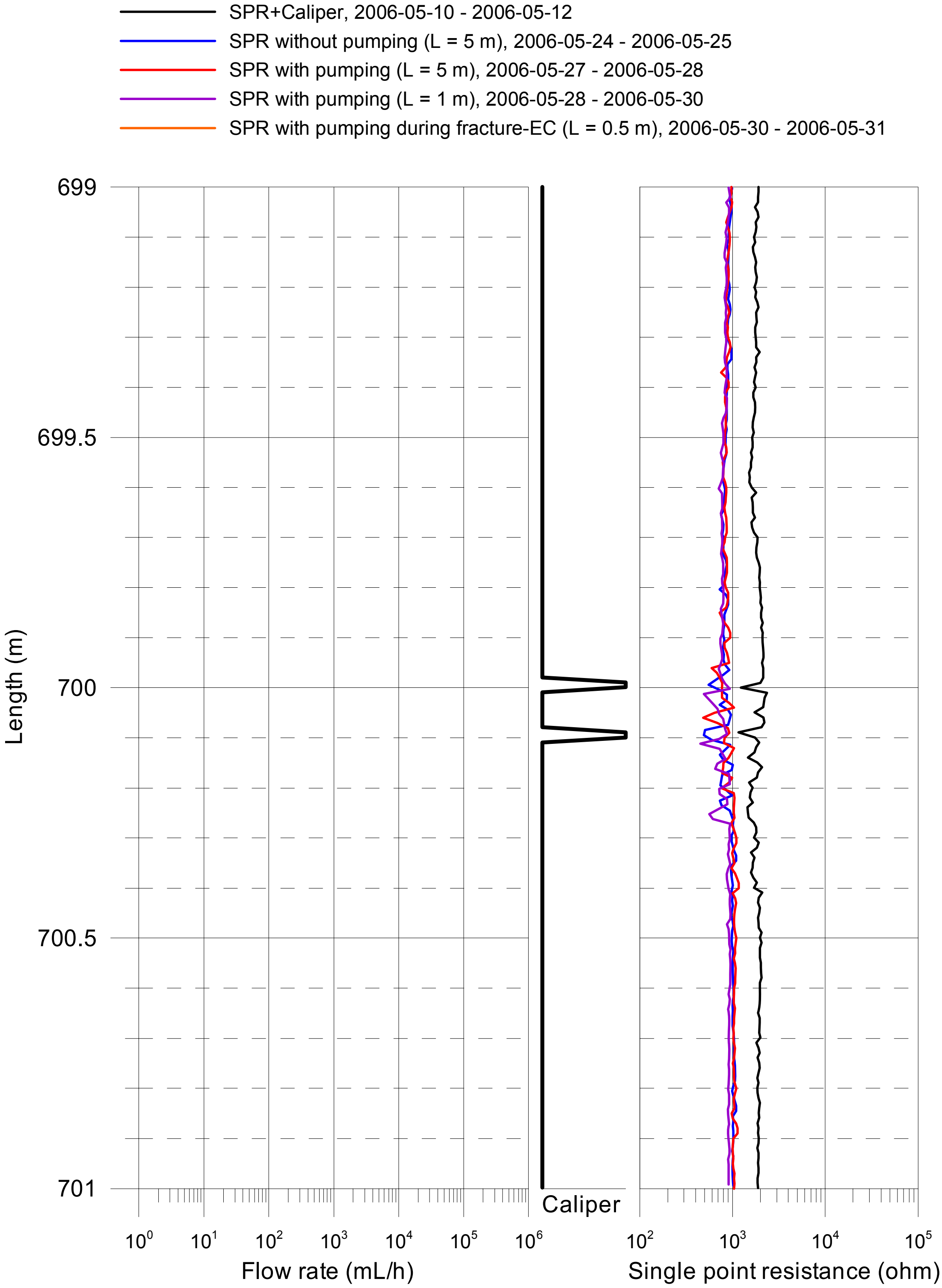
SPR and Caliper results after length correction



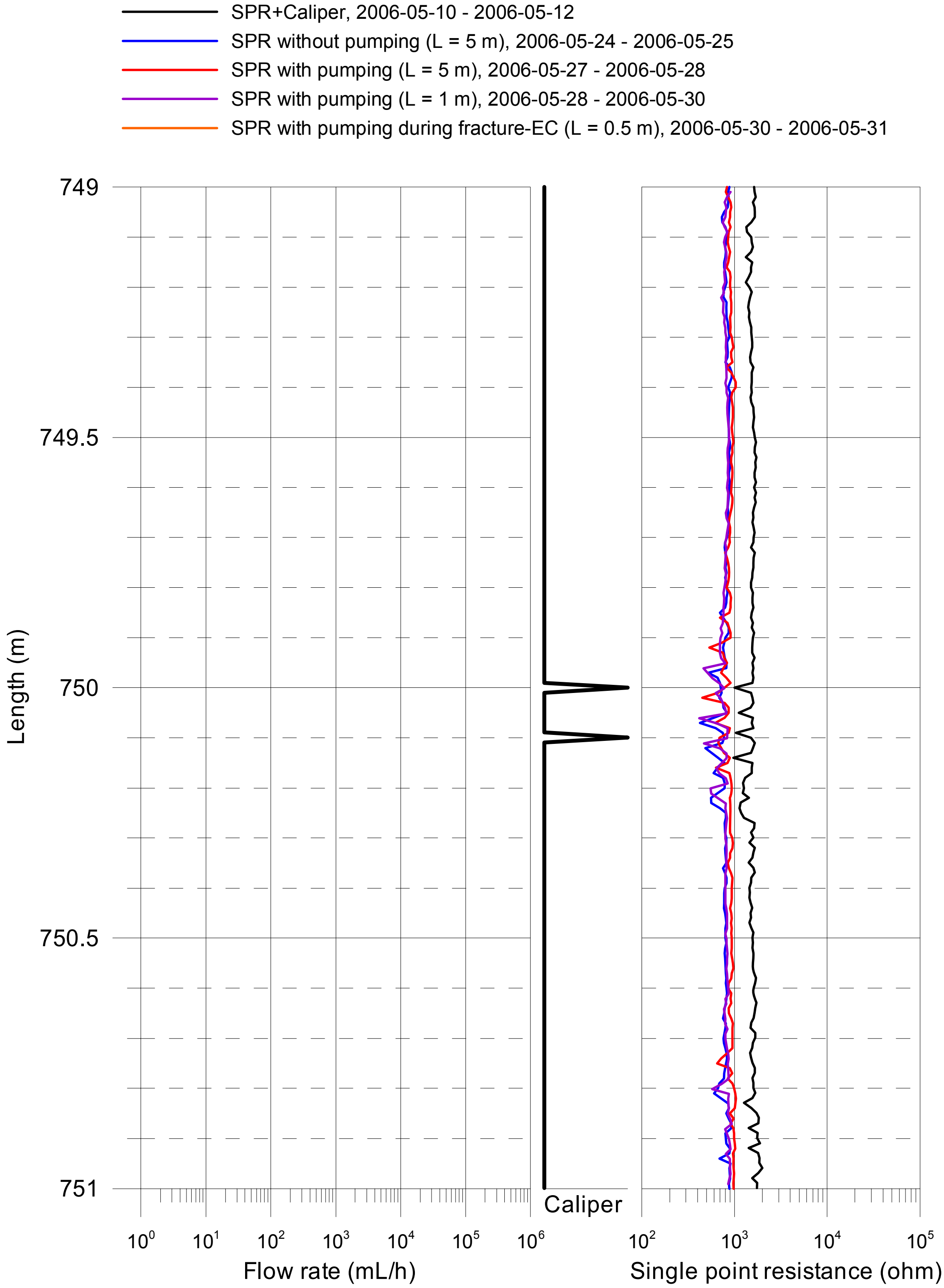
Forsmark, borehole KFM01D
SPR and Caliper results after length correction



Forsmark, borehole KFM01D
SPR and Caliper results after length correction

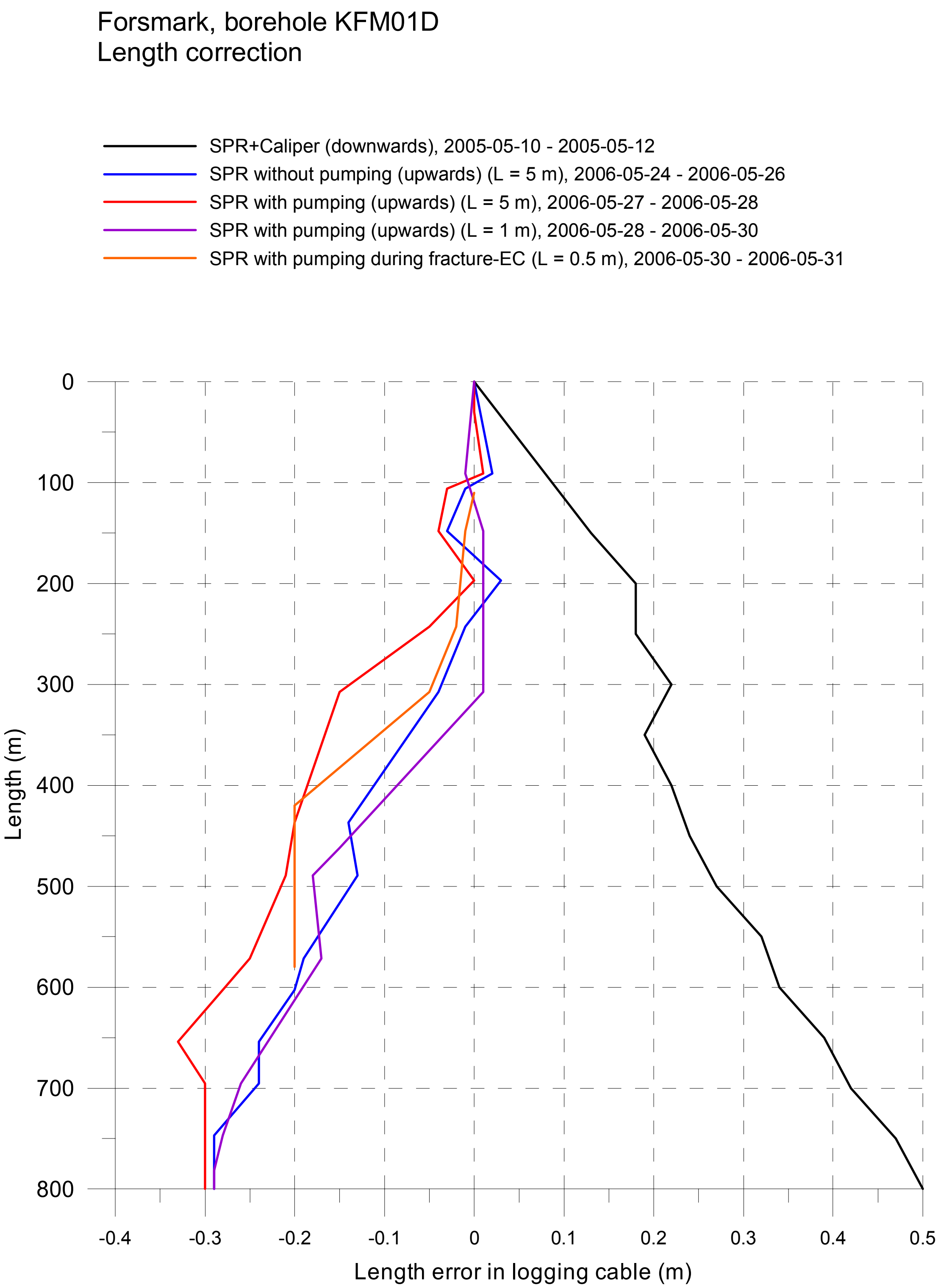


Forsmark, borehole KFM01D
SPR and Caliper results after length correction



## Appendix 1.15 Length correction

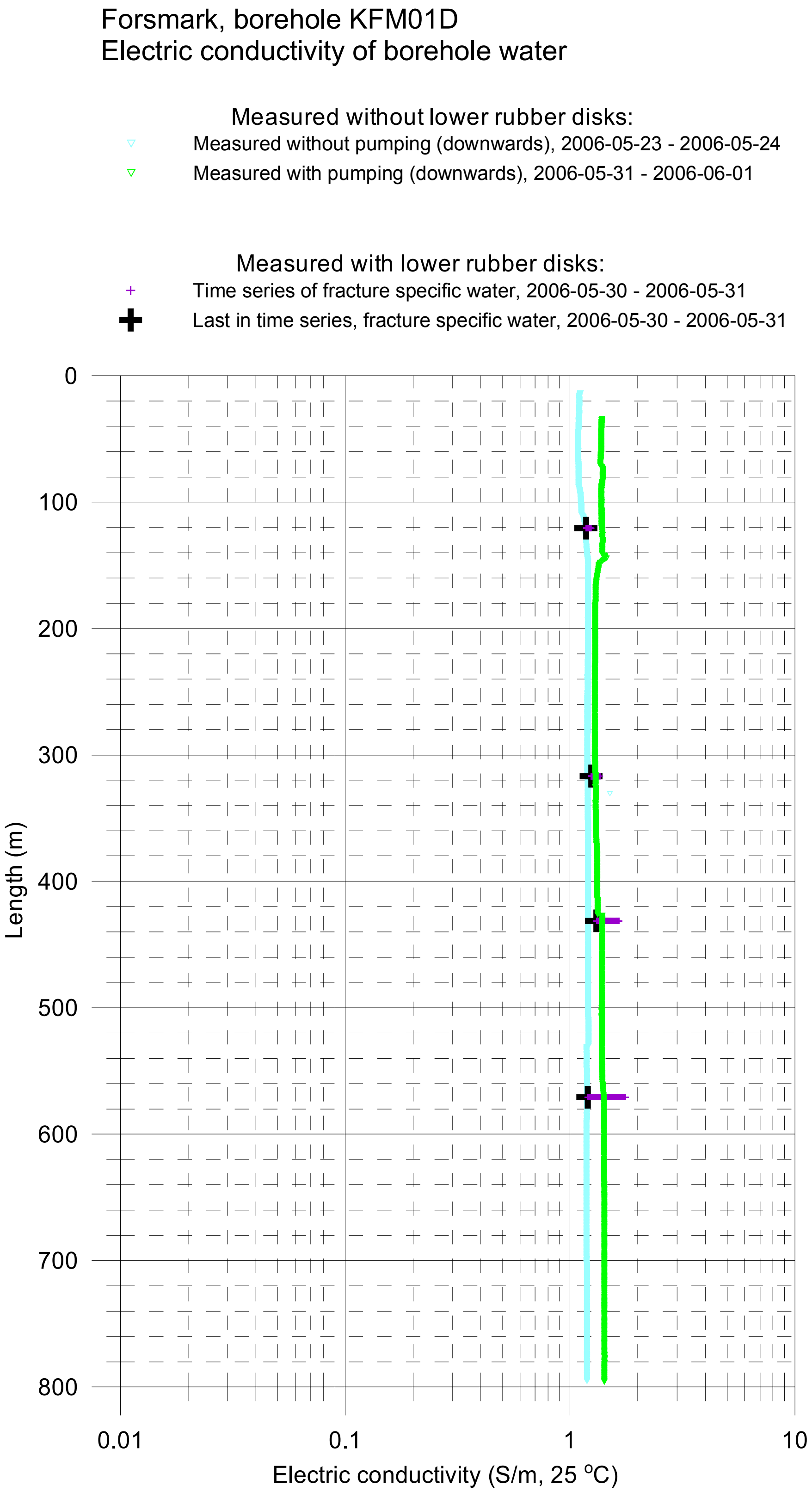




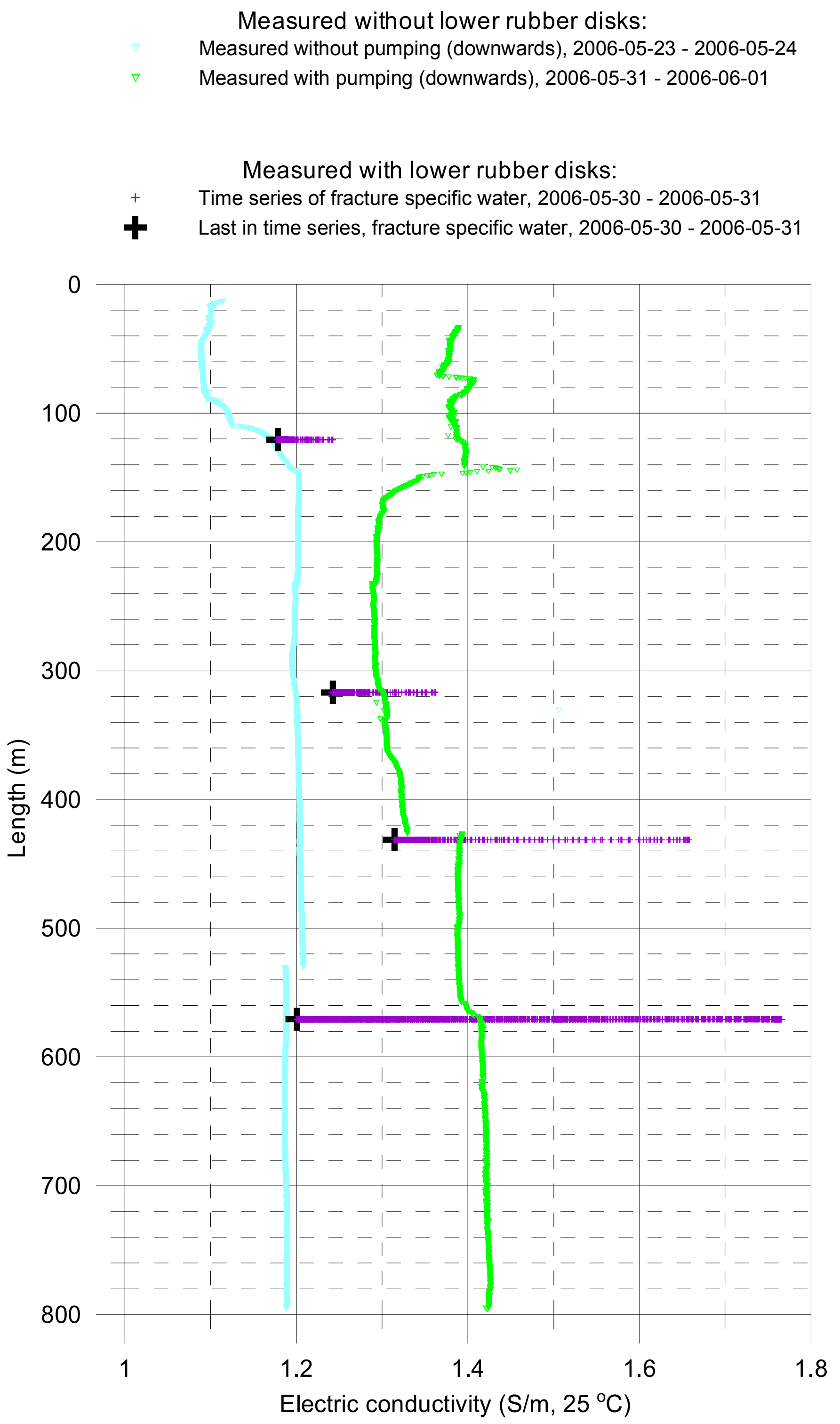
# Appendix 2

## Appendices 2.1–2.2 Electric conductivity of borehole water

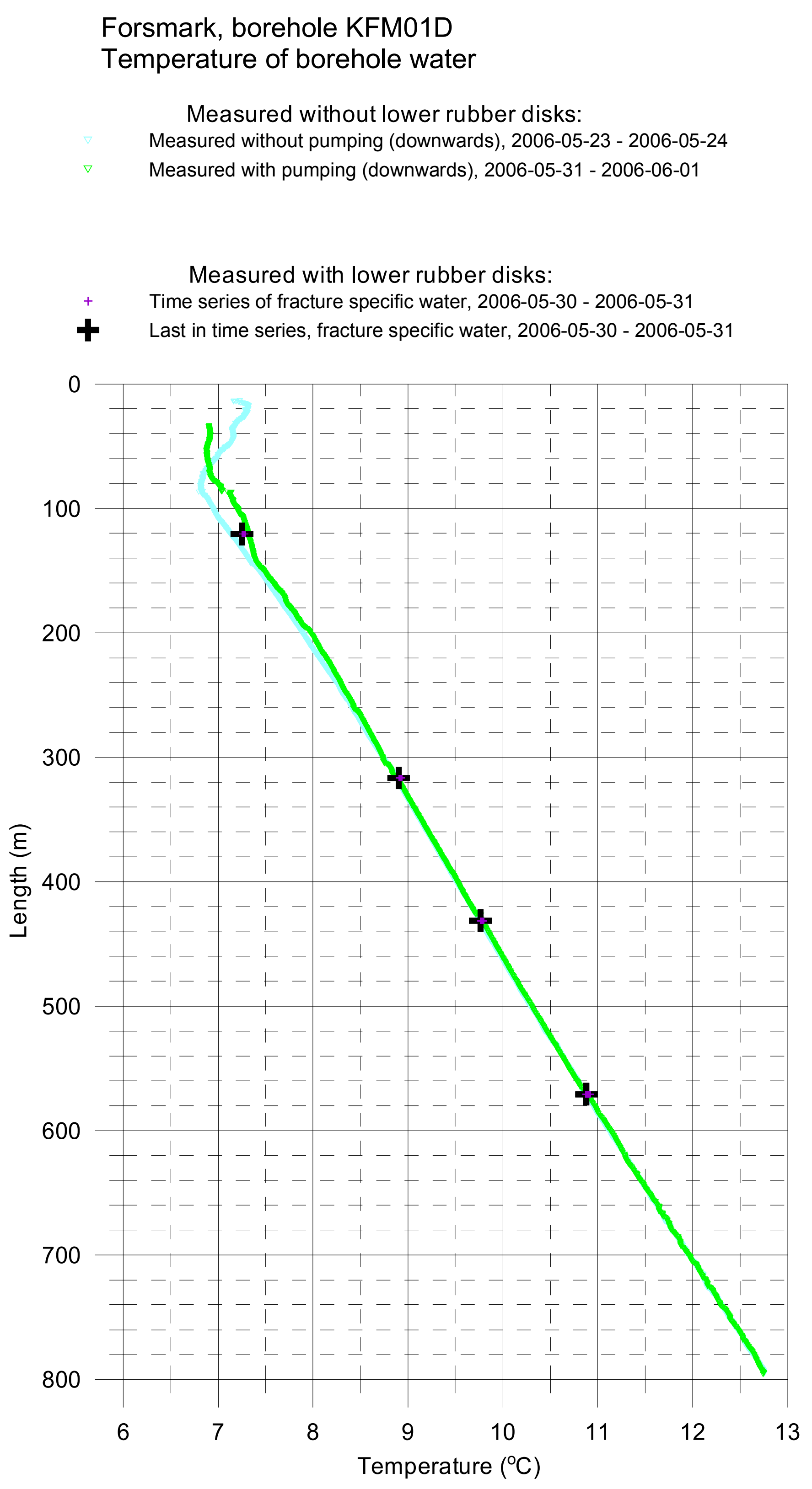
Appendix 2.1



Forsmark, borehole KFM01D
Electric conductivity of borehole water



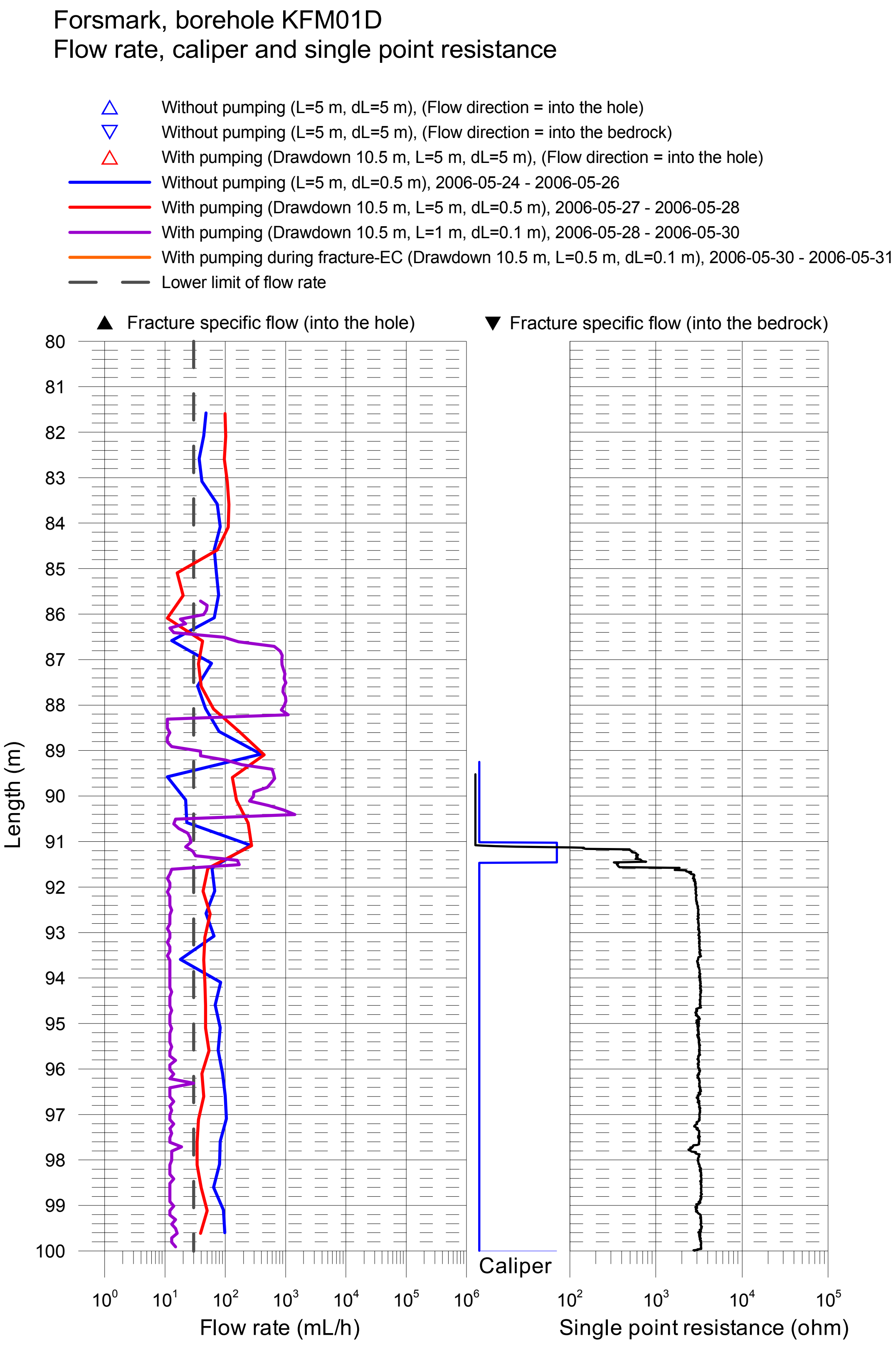
## Appendix 2.3 Temperature of borehole water



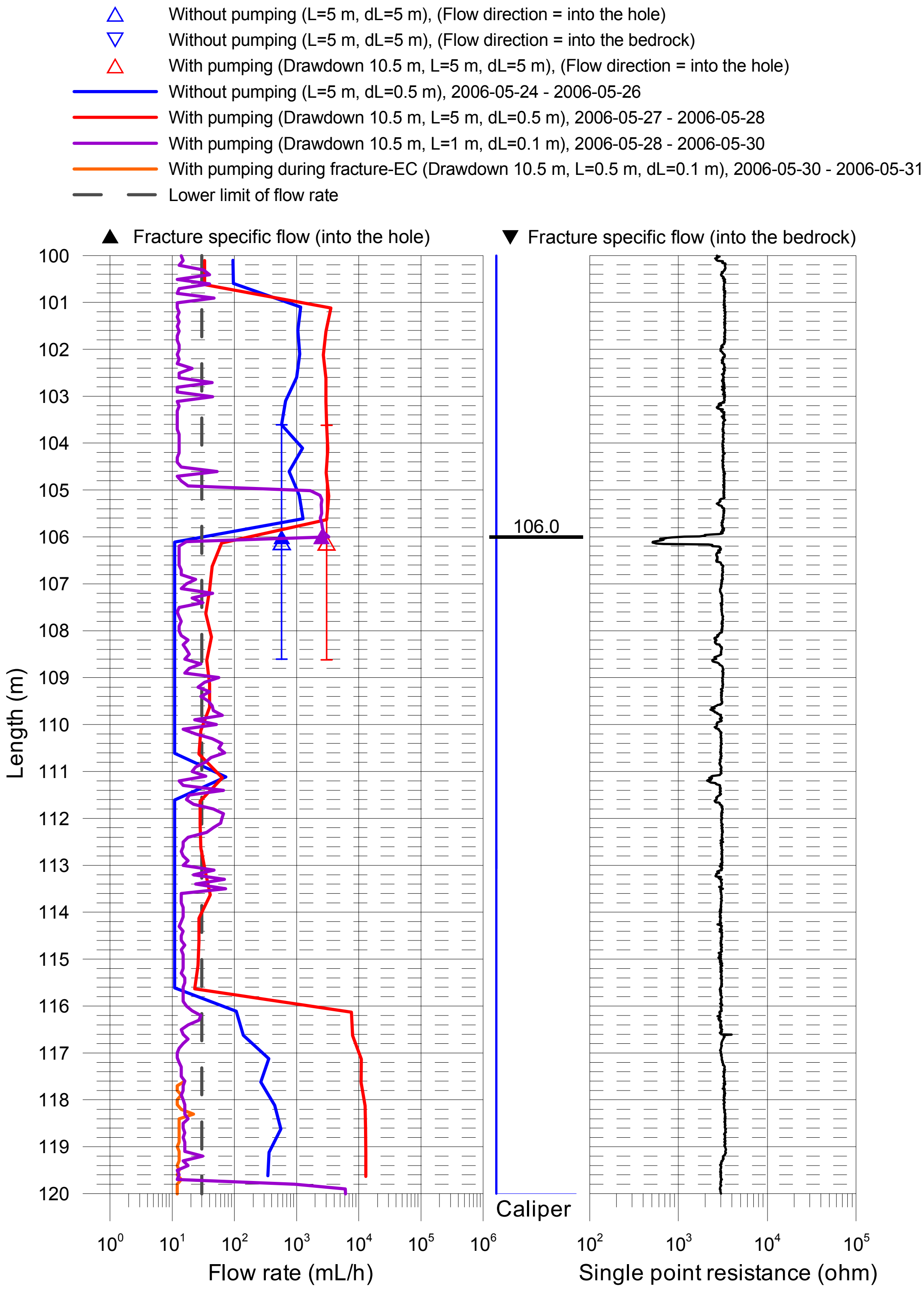
# Appendix 3

## Appendices 3.1–3.36 Flow rate, caliper and single point resistance

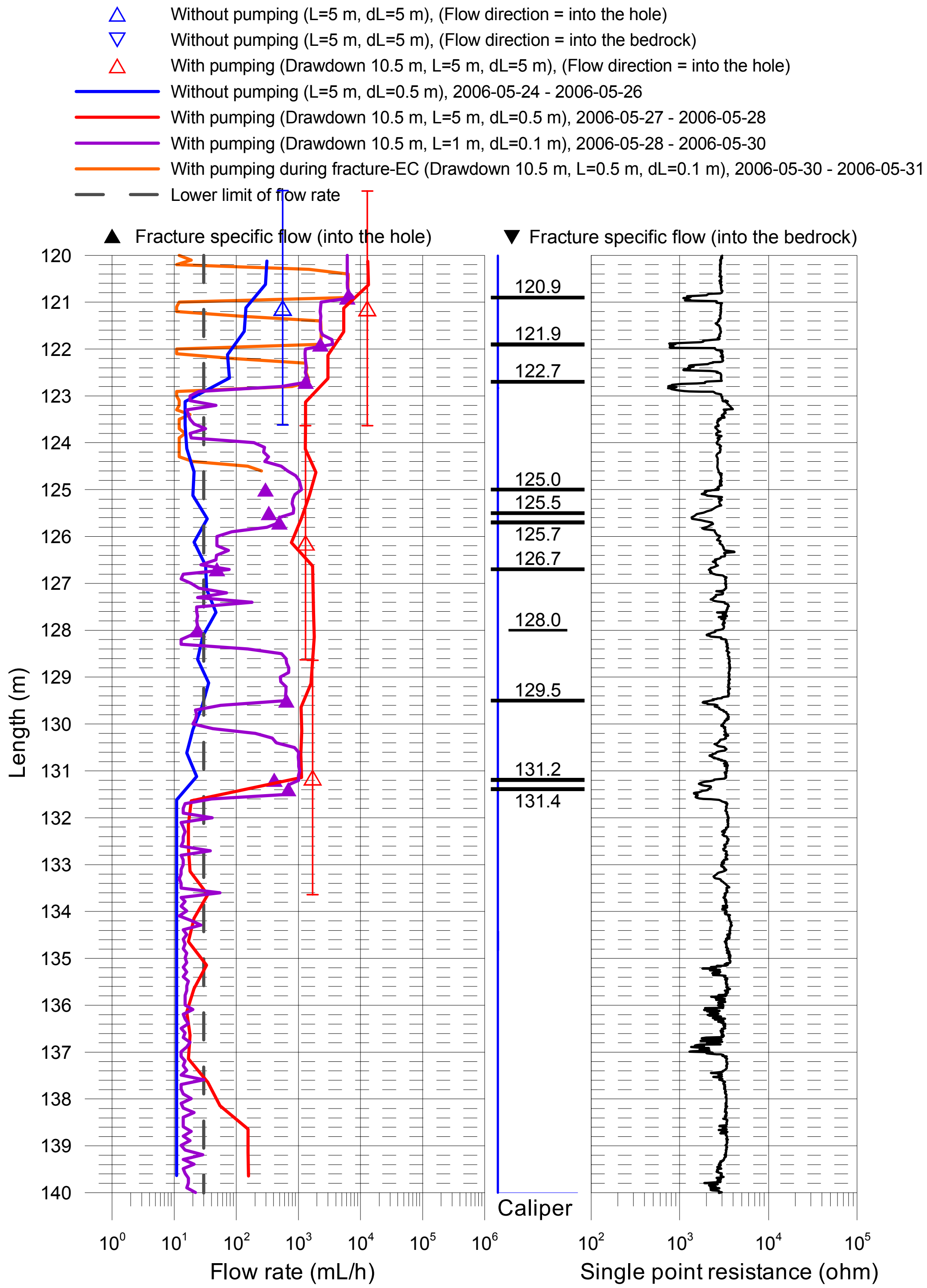
Appendix 3.1



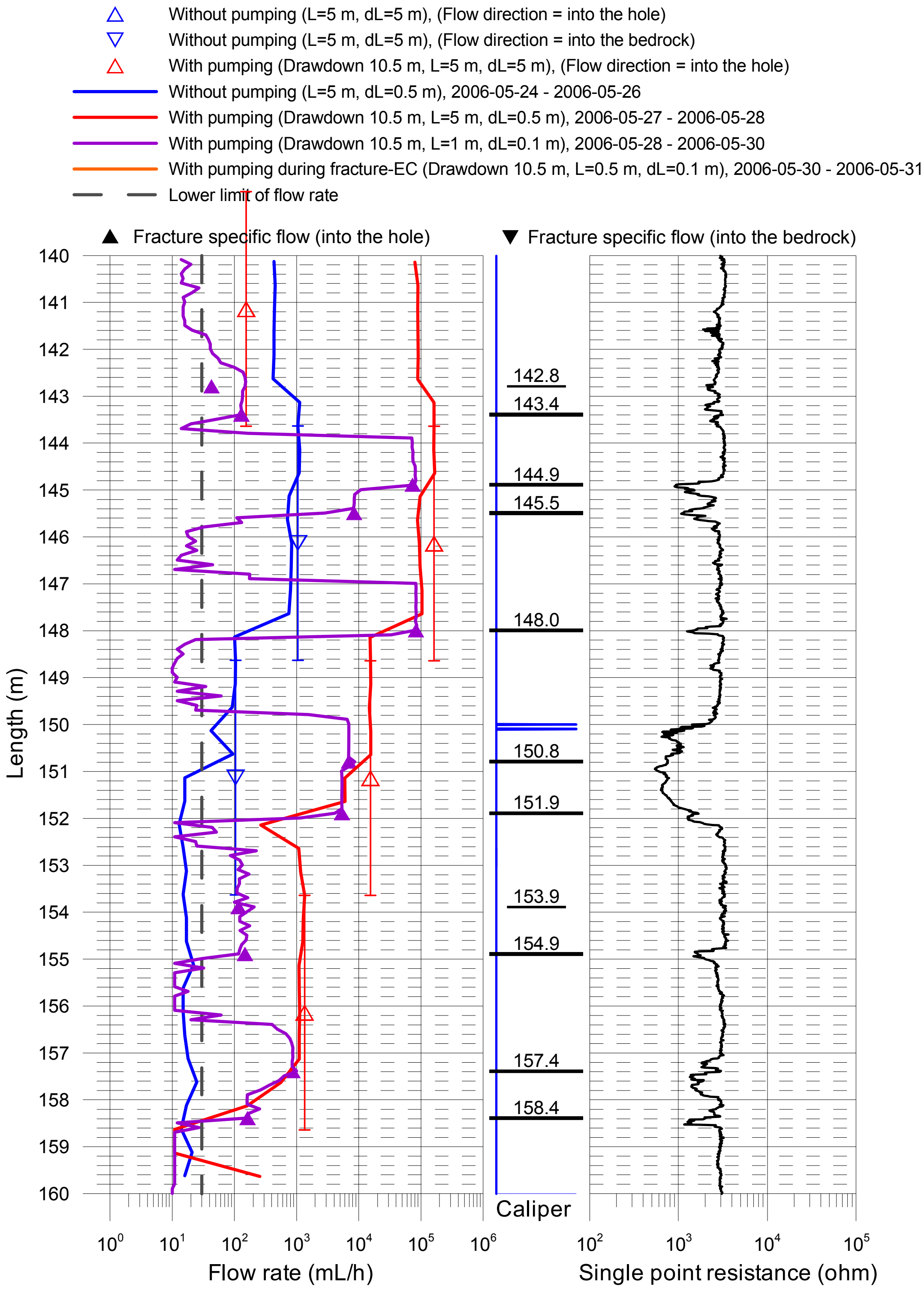
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



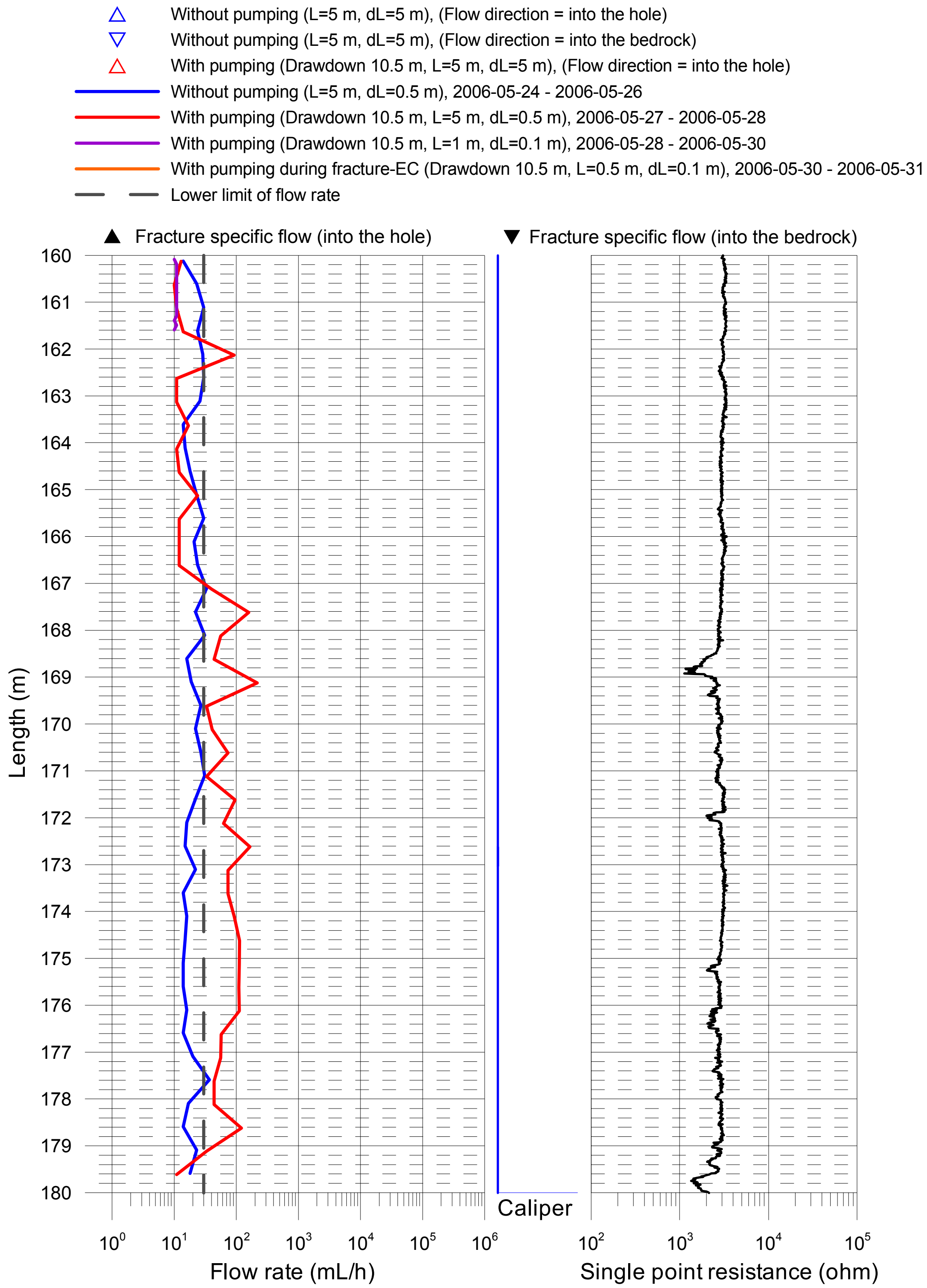
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



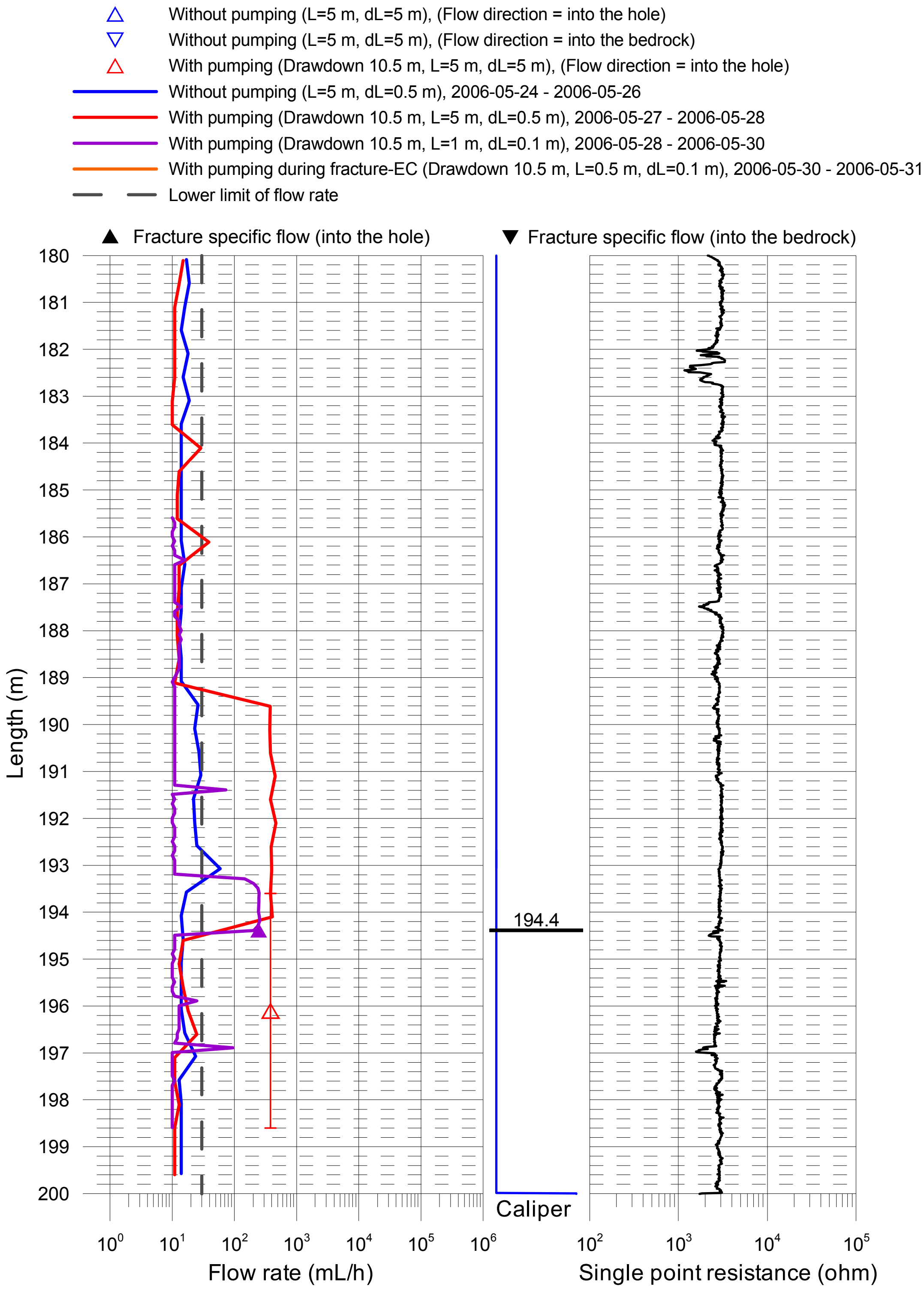
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



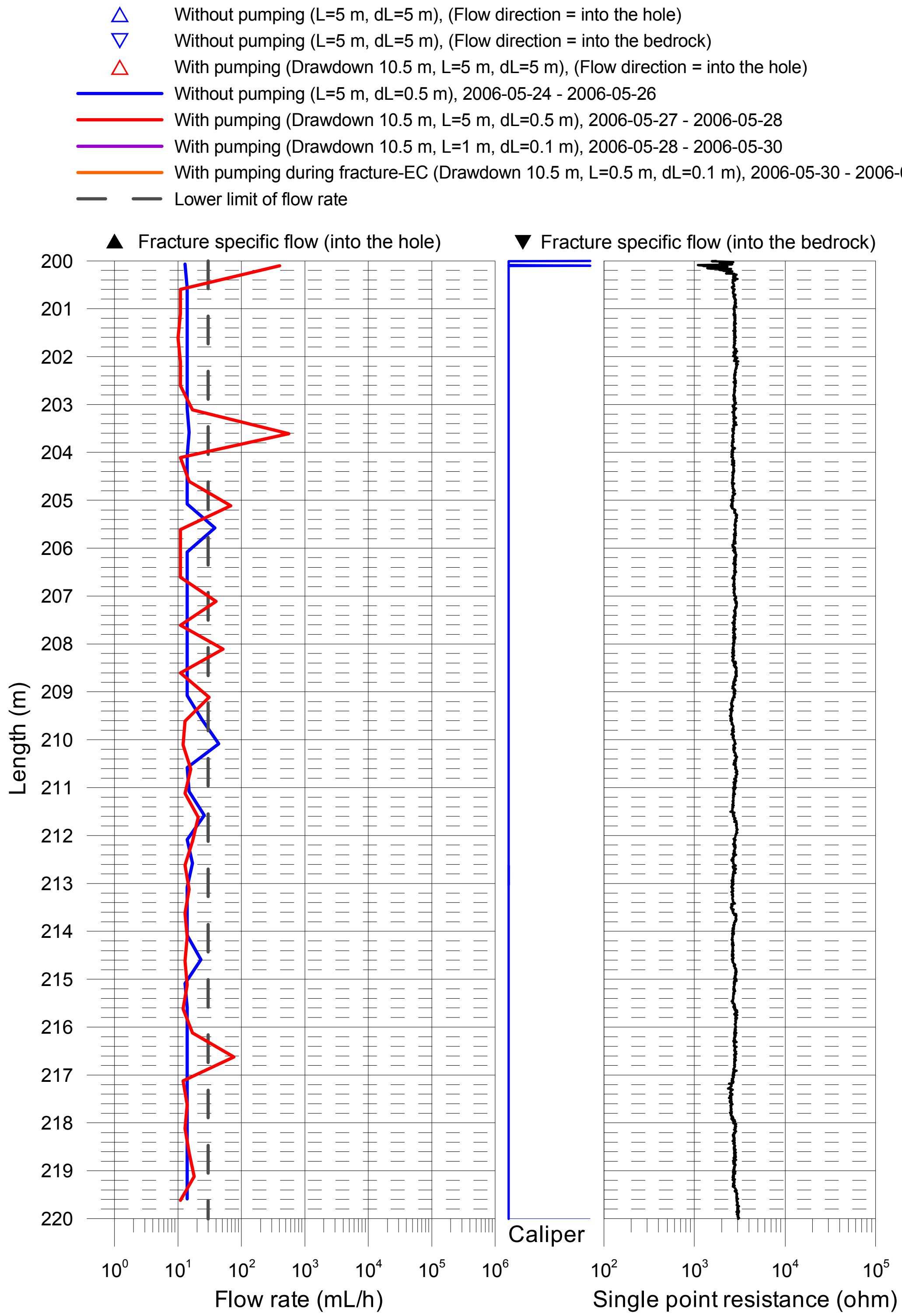
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



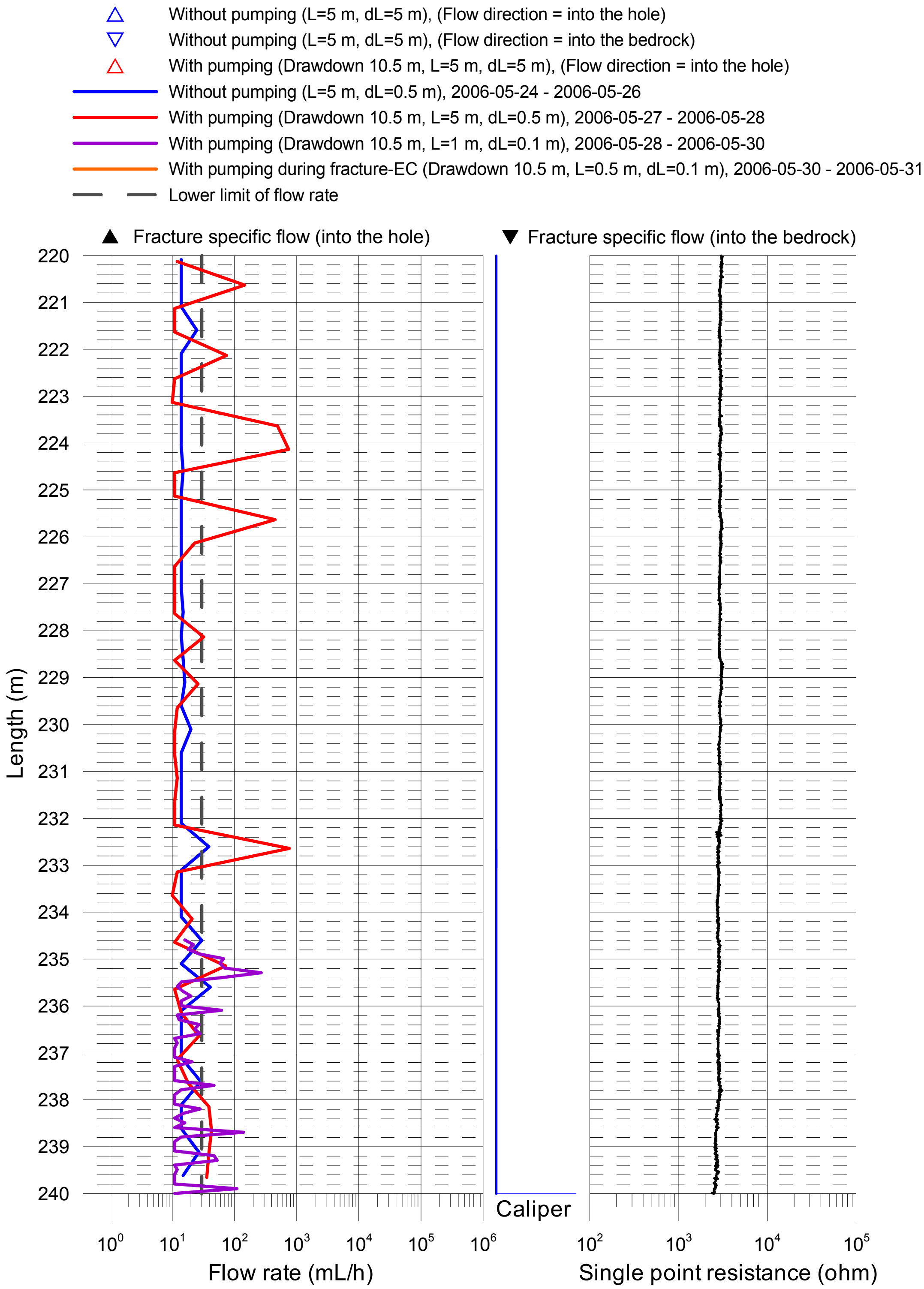
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



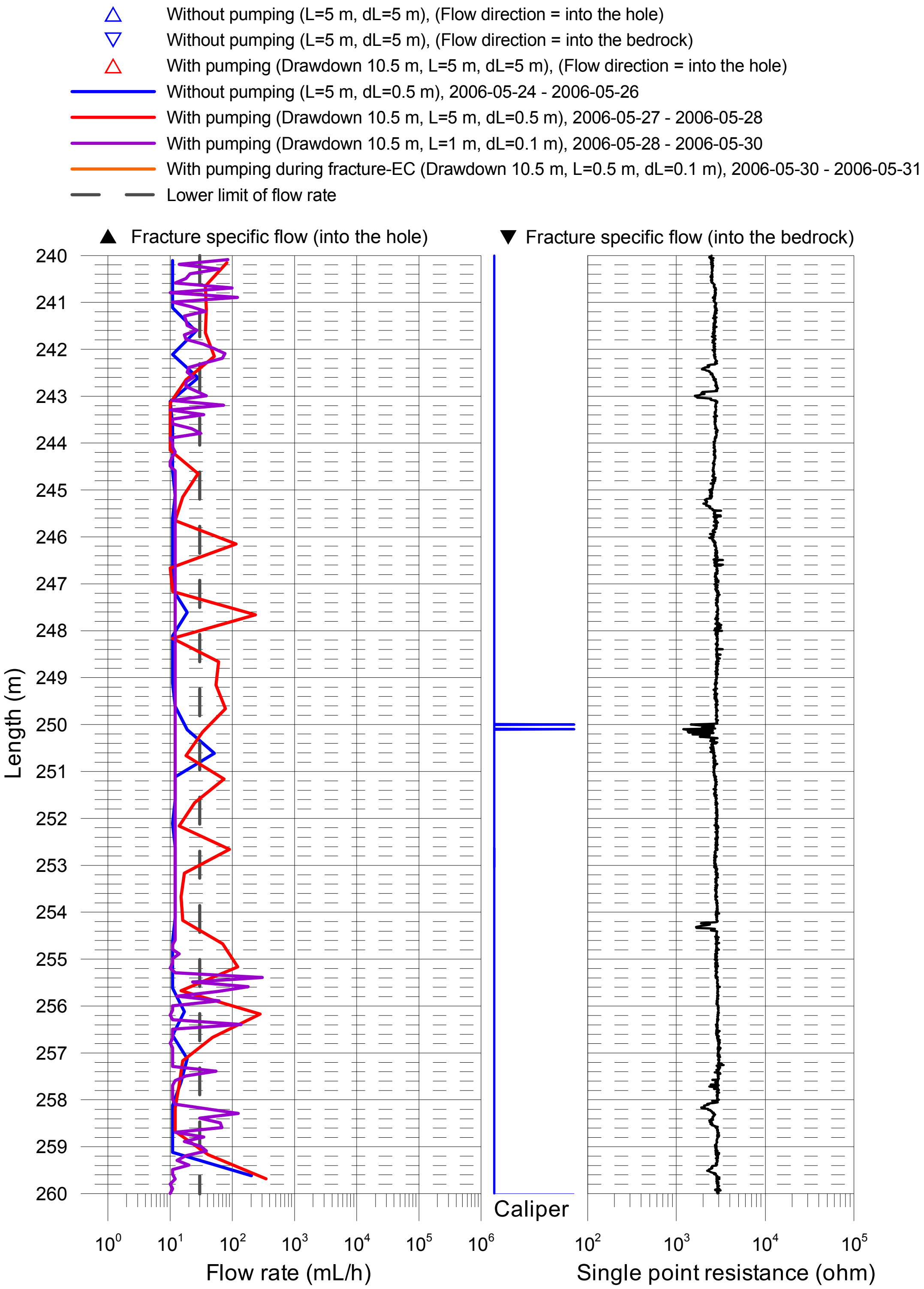
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



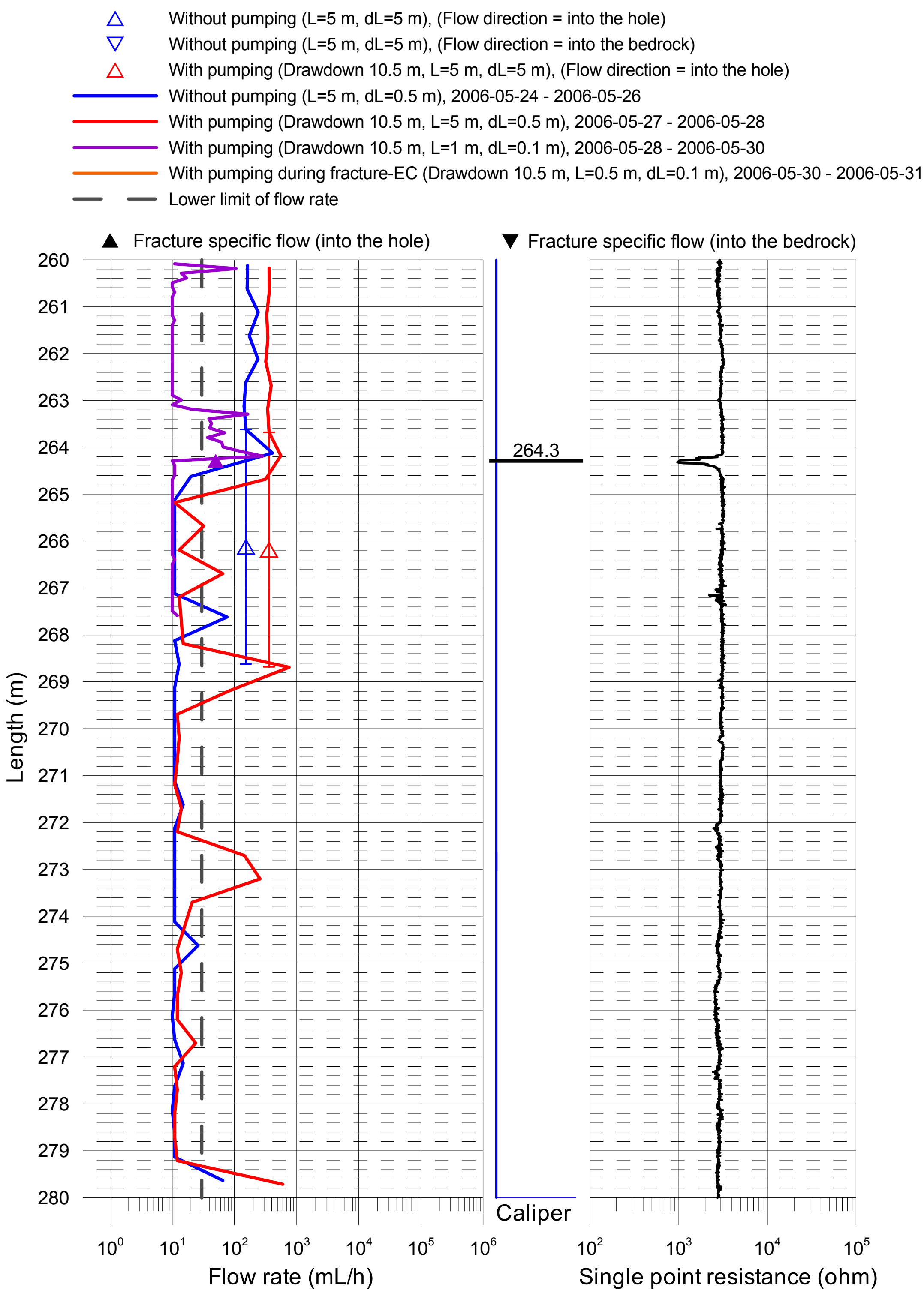
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



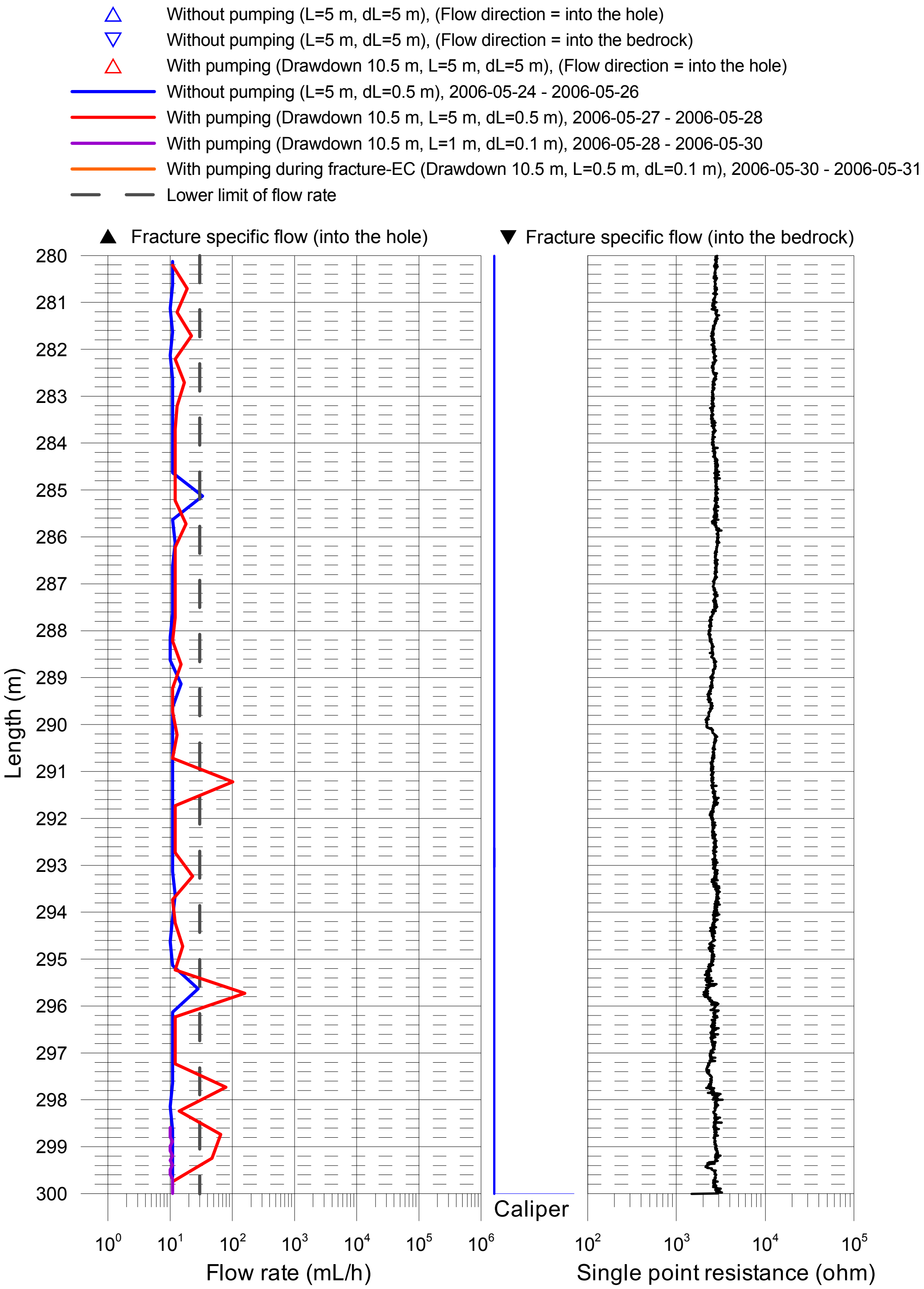
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



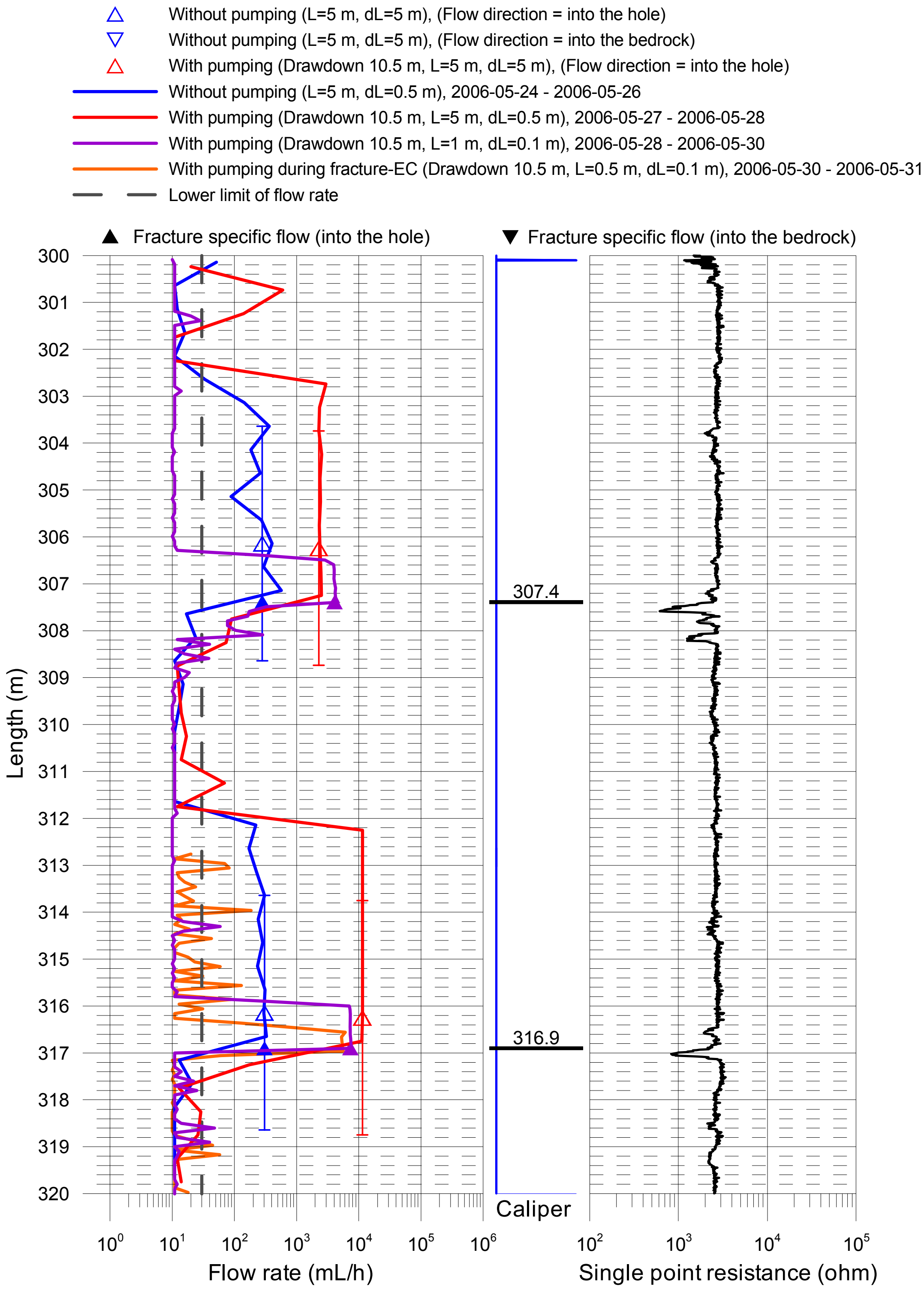
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



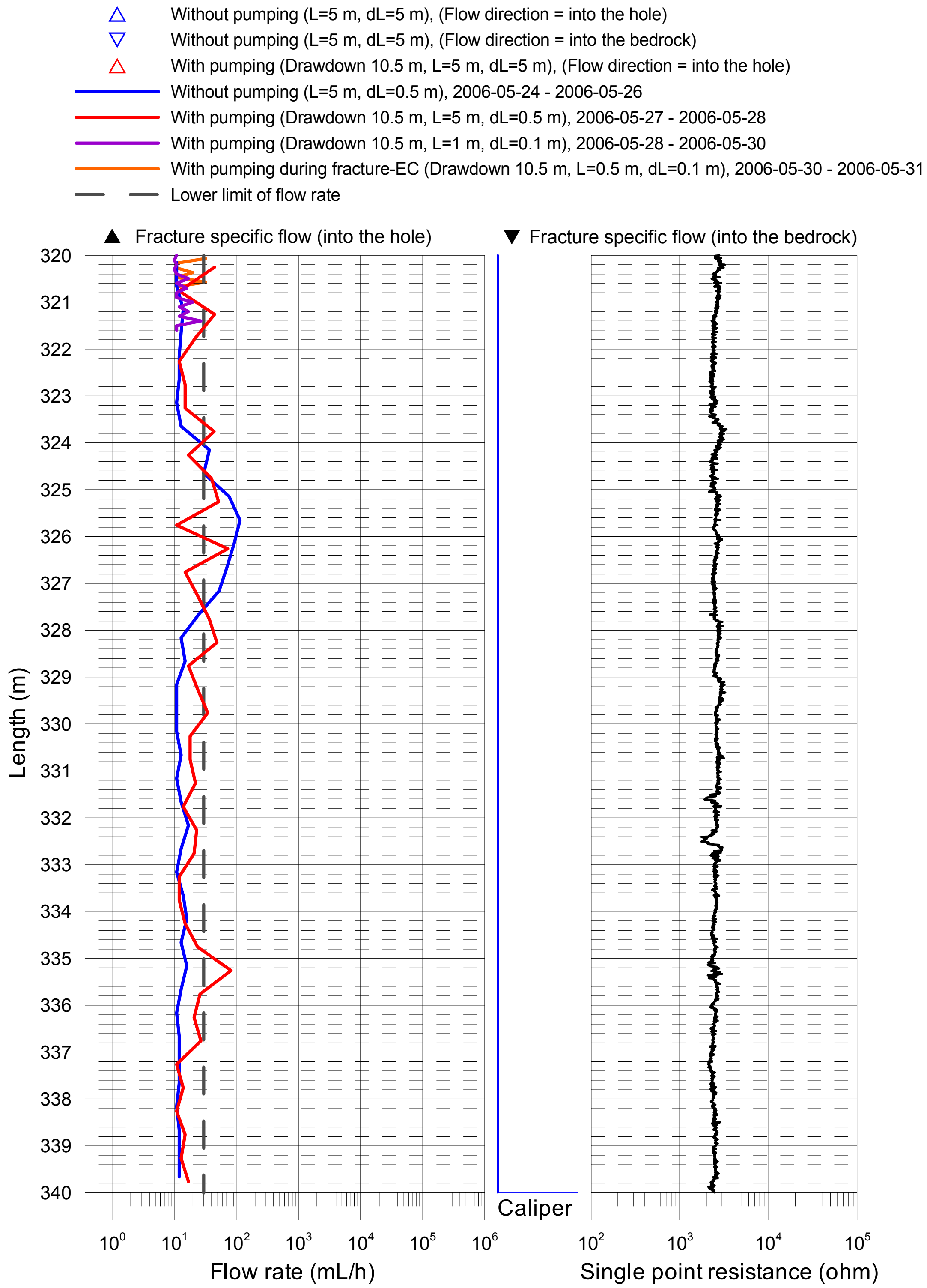
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



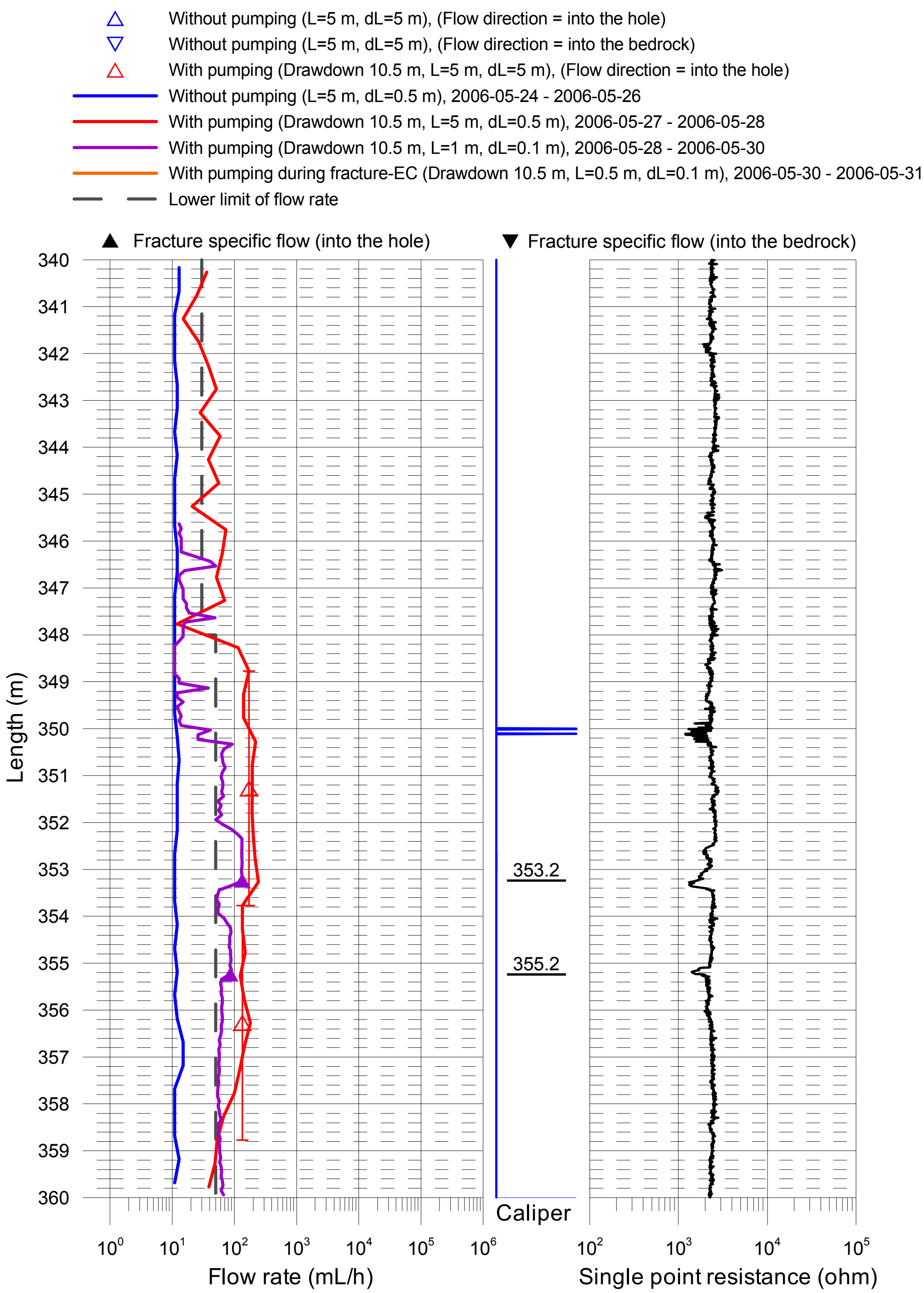
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



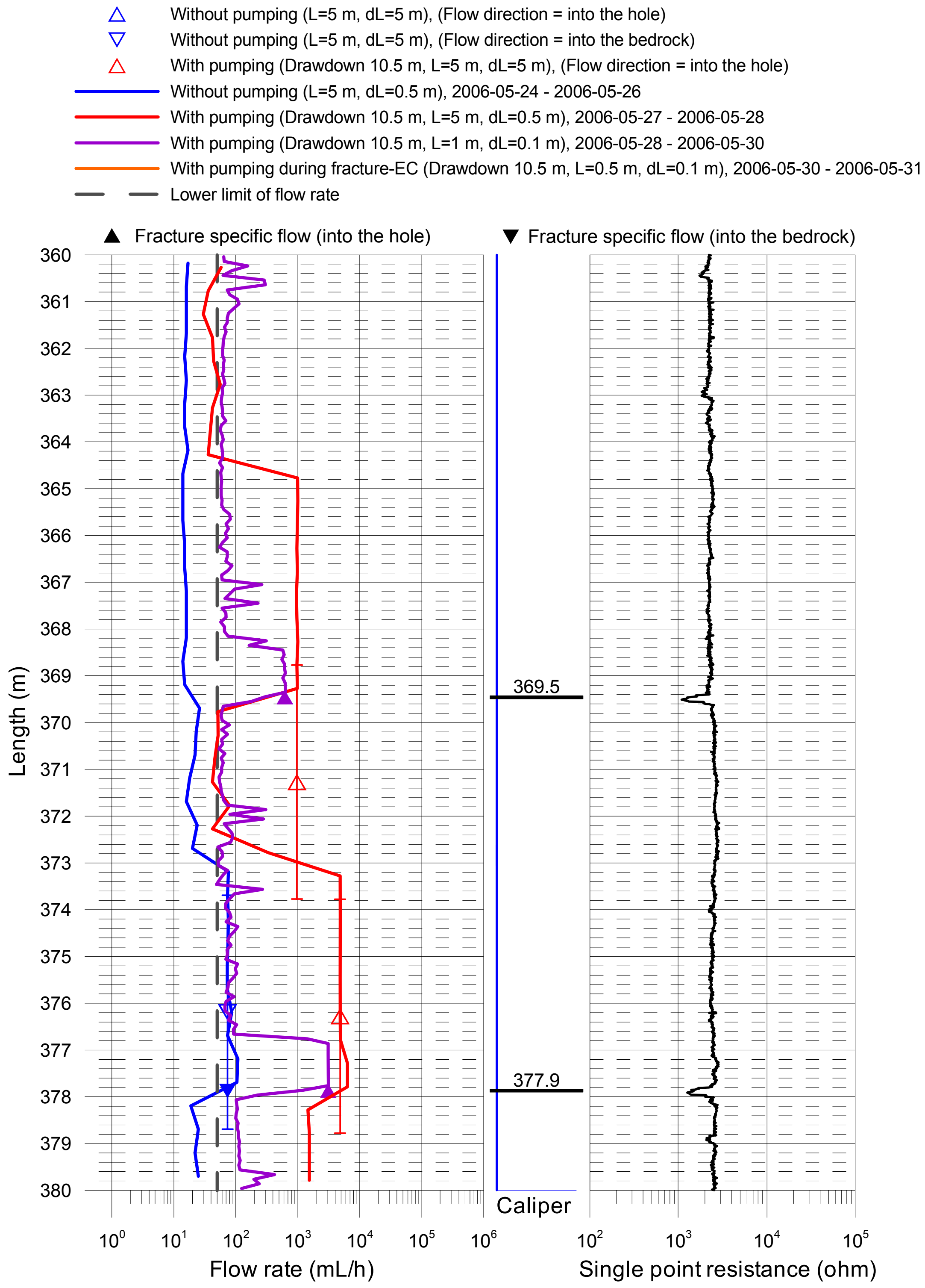
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



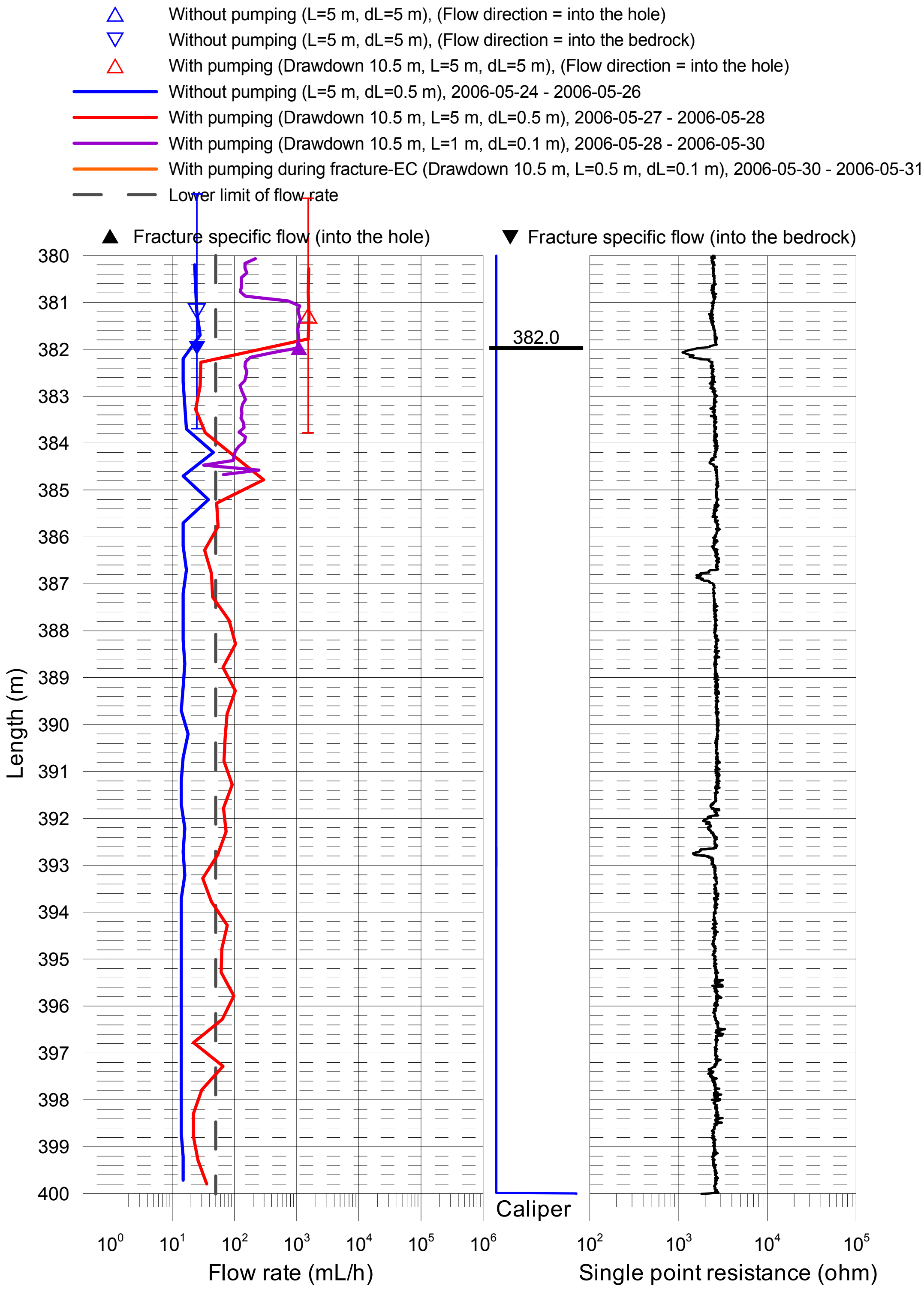
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



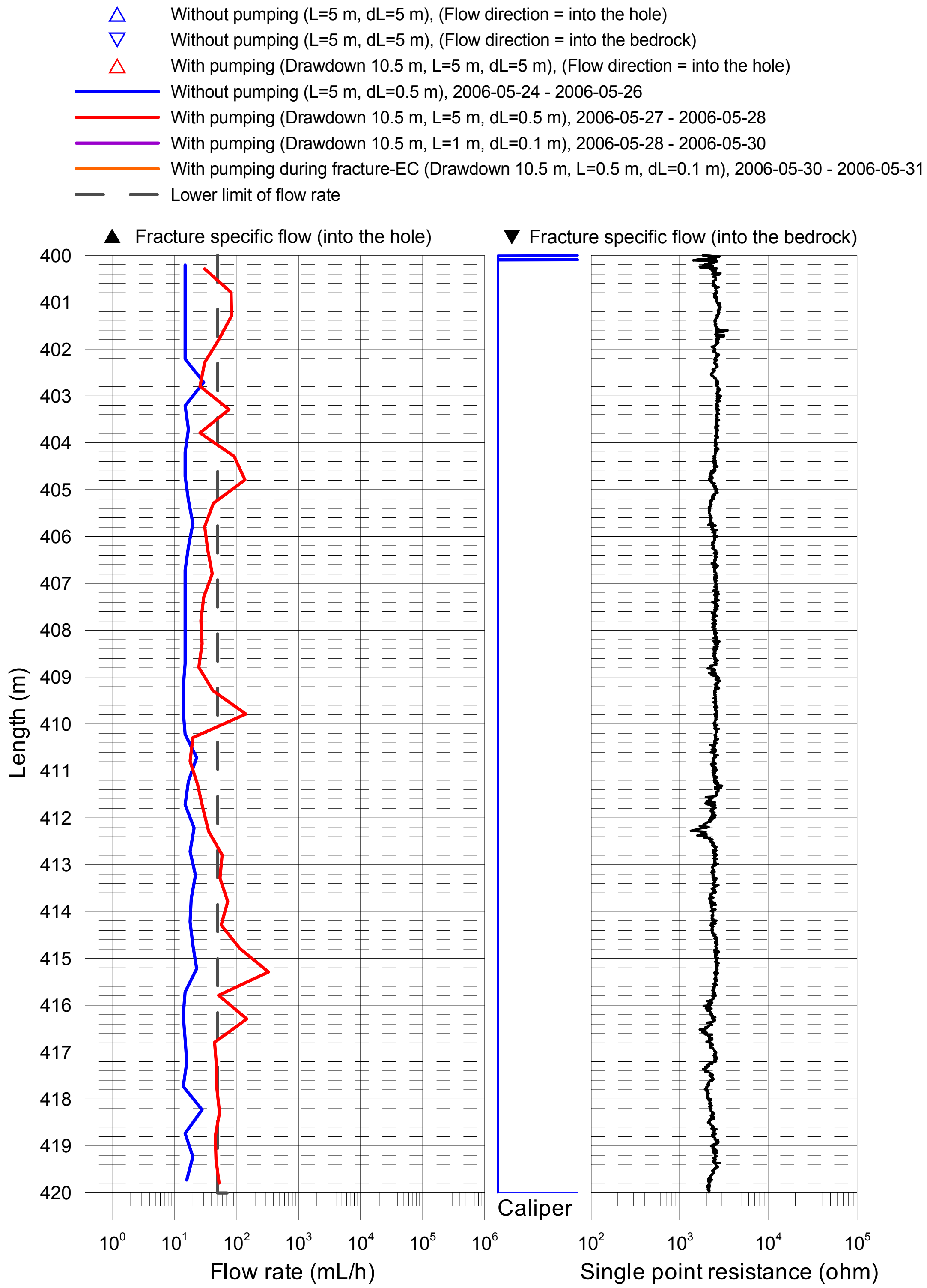
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



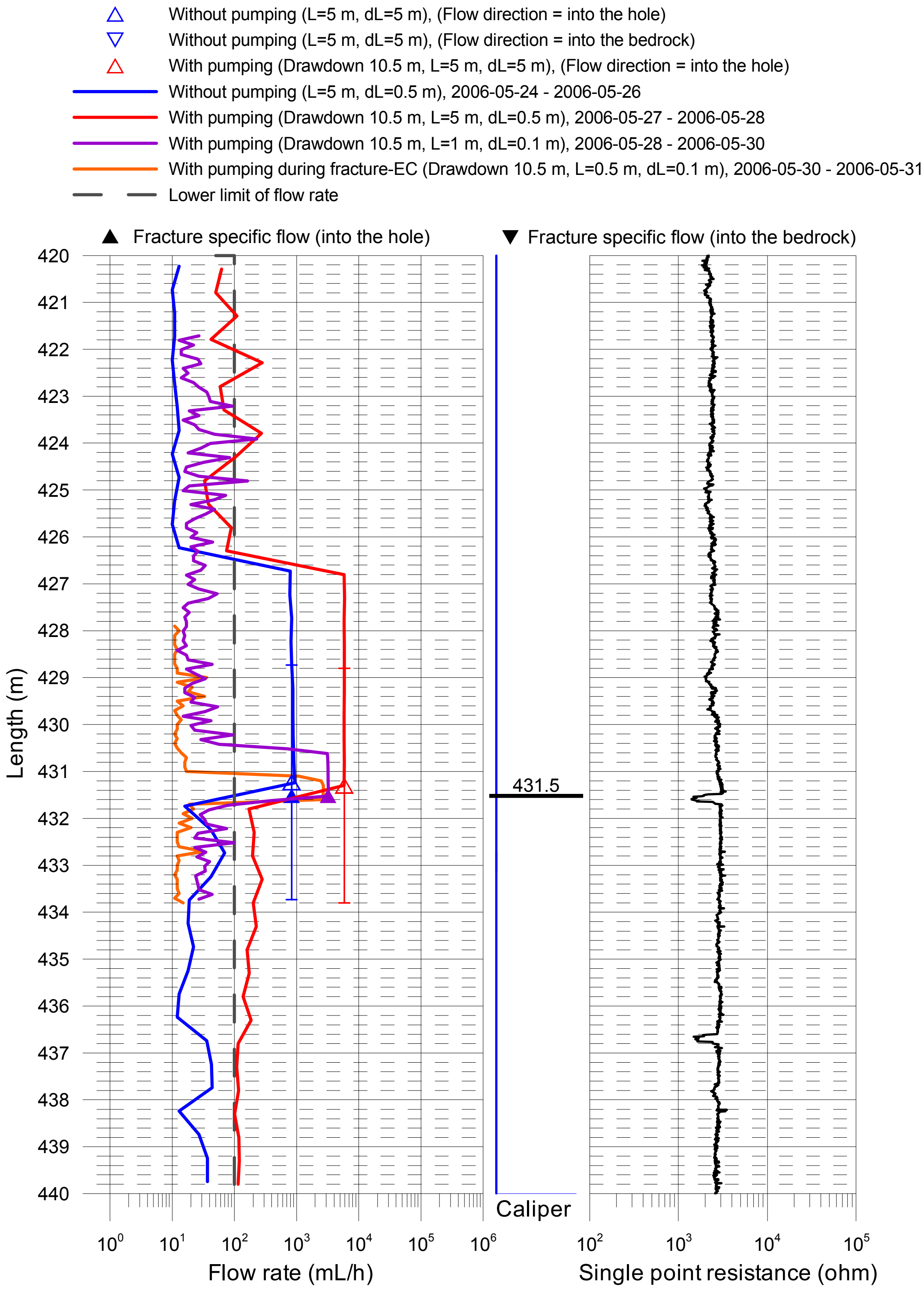
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



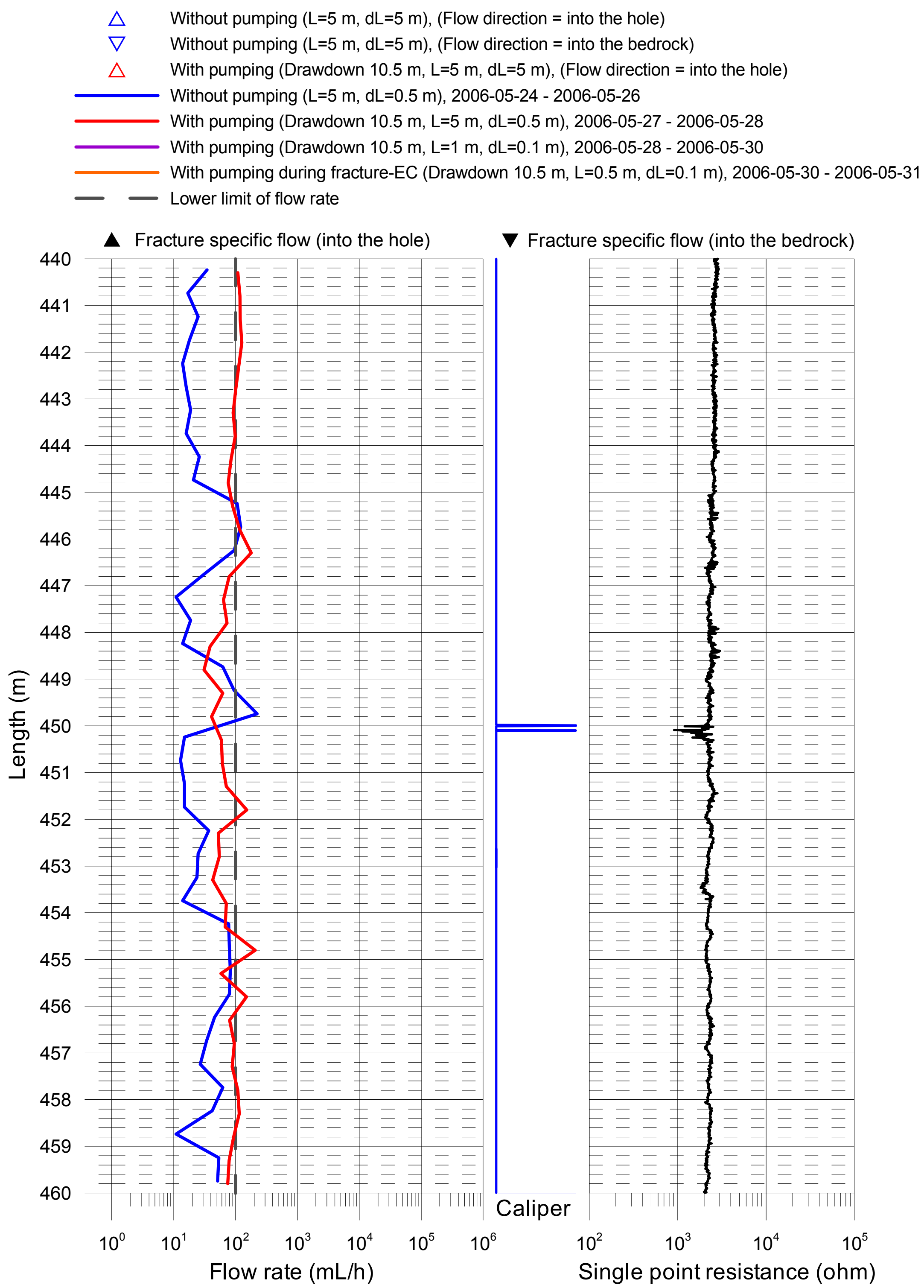
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



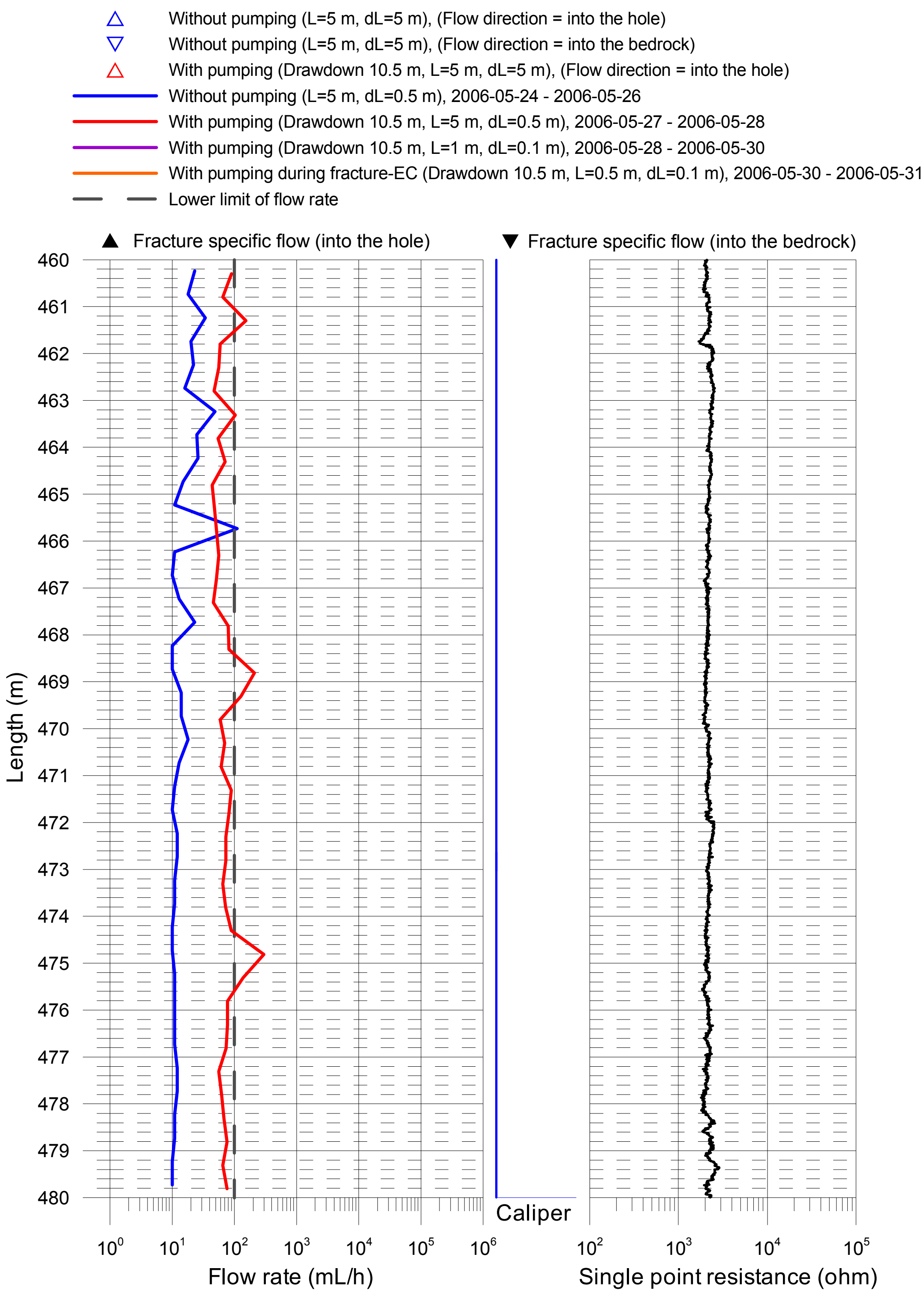
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



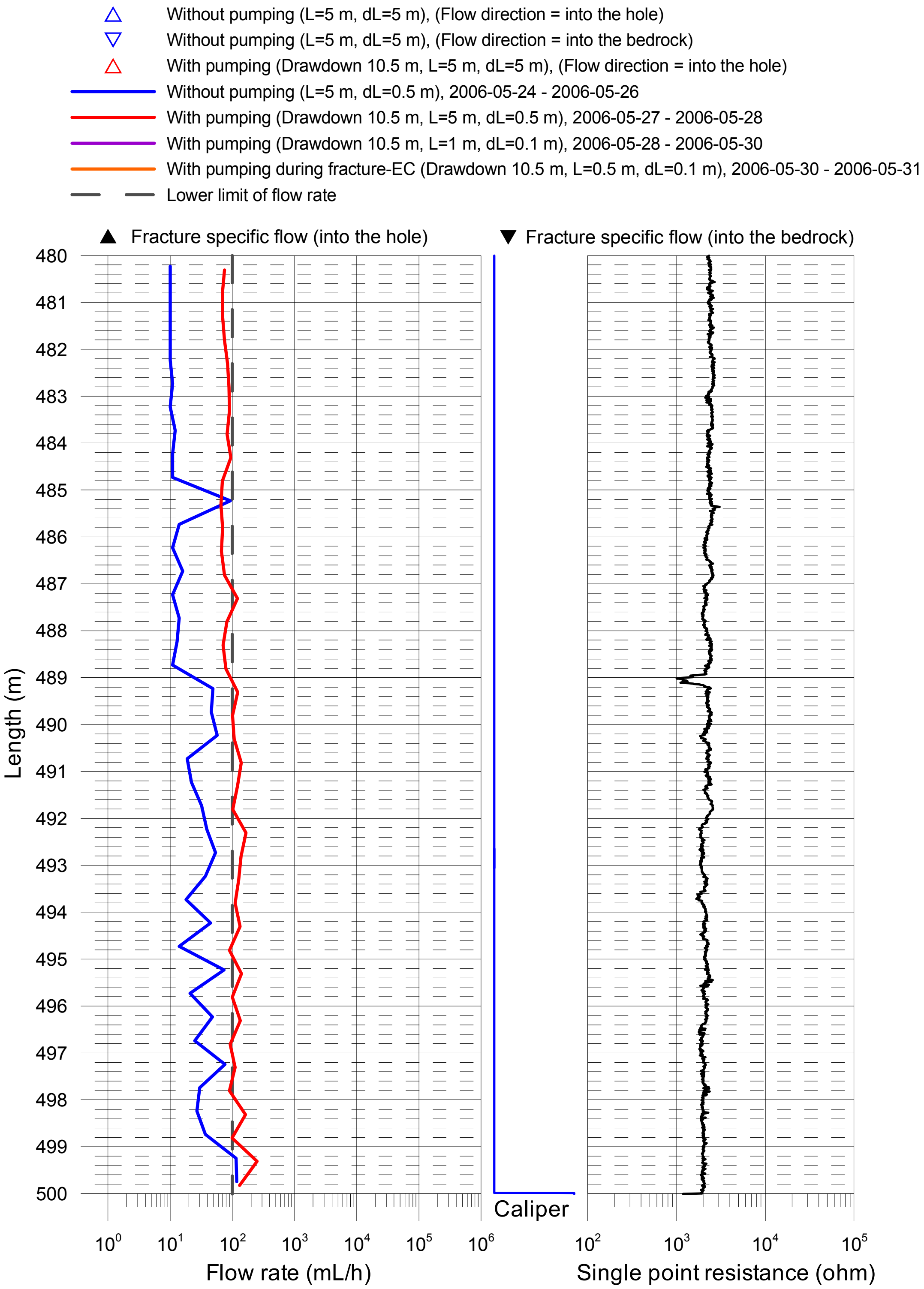
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



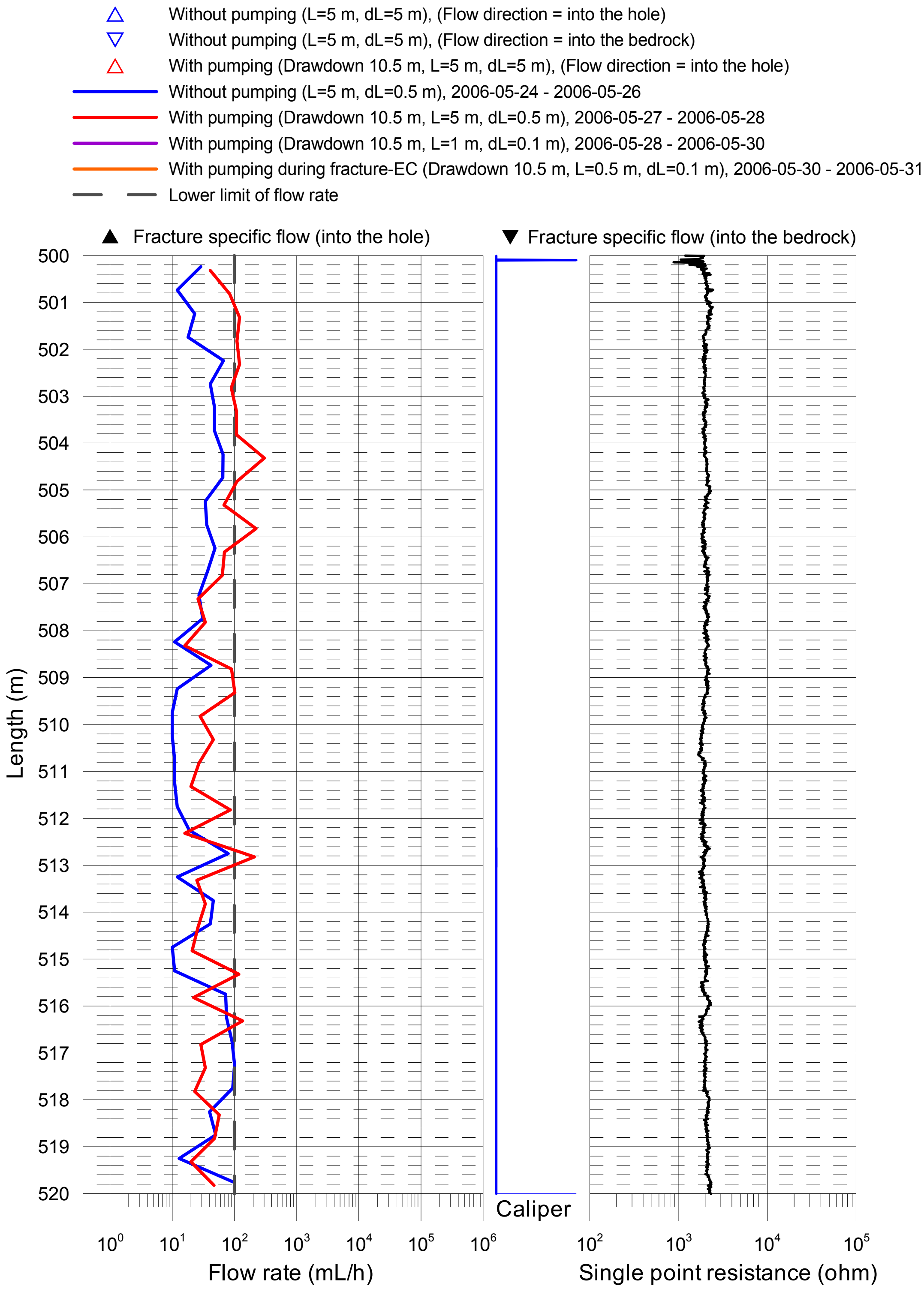
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



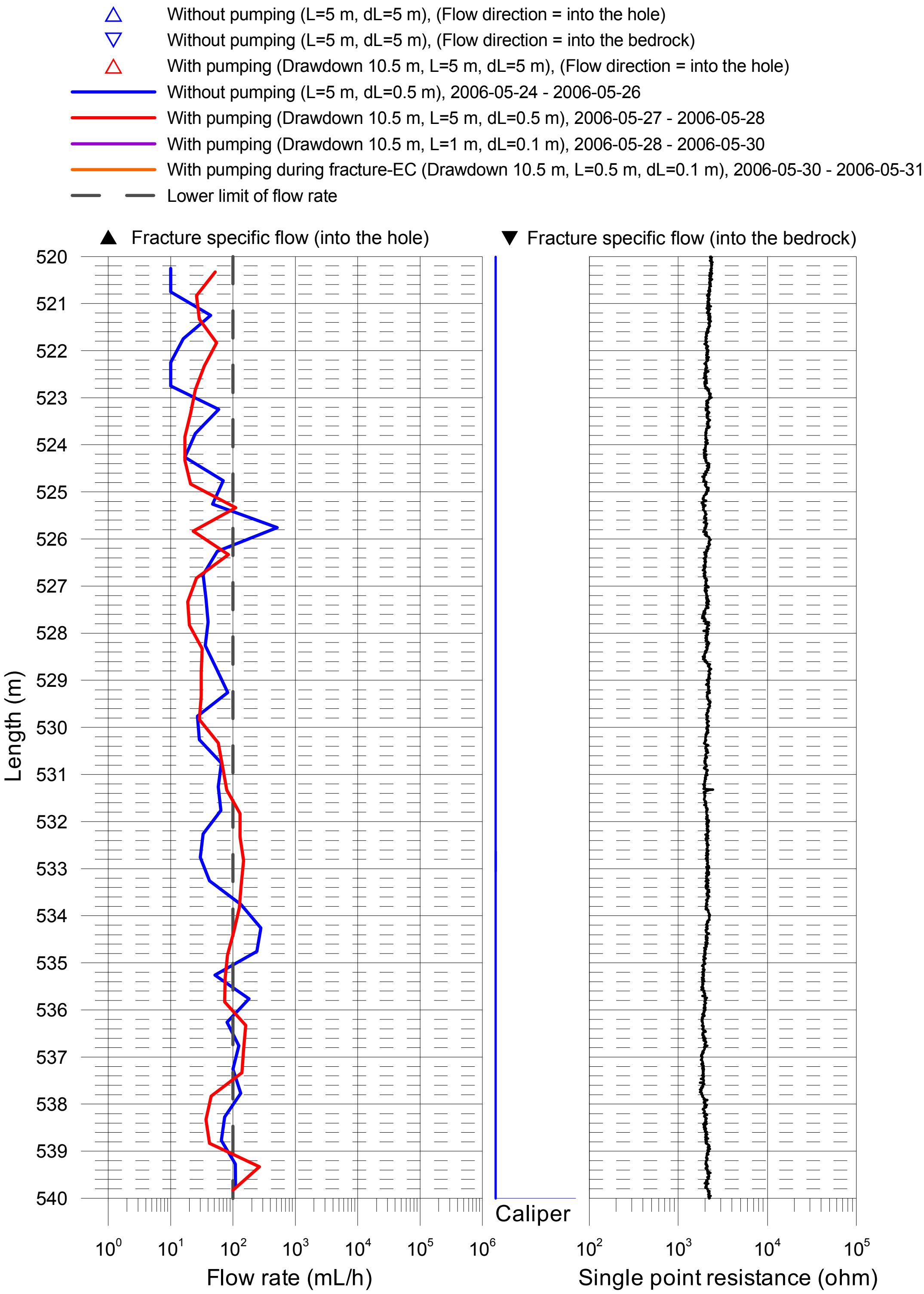
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



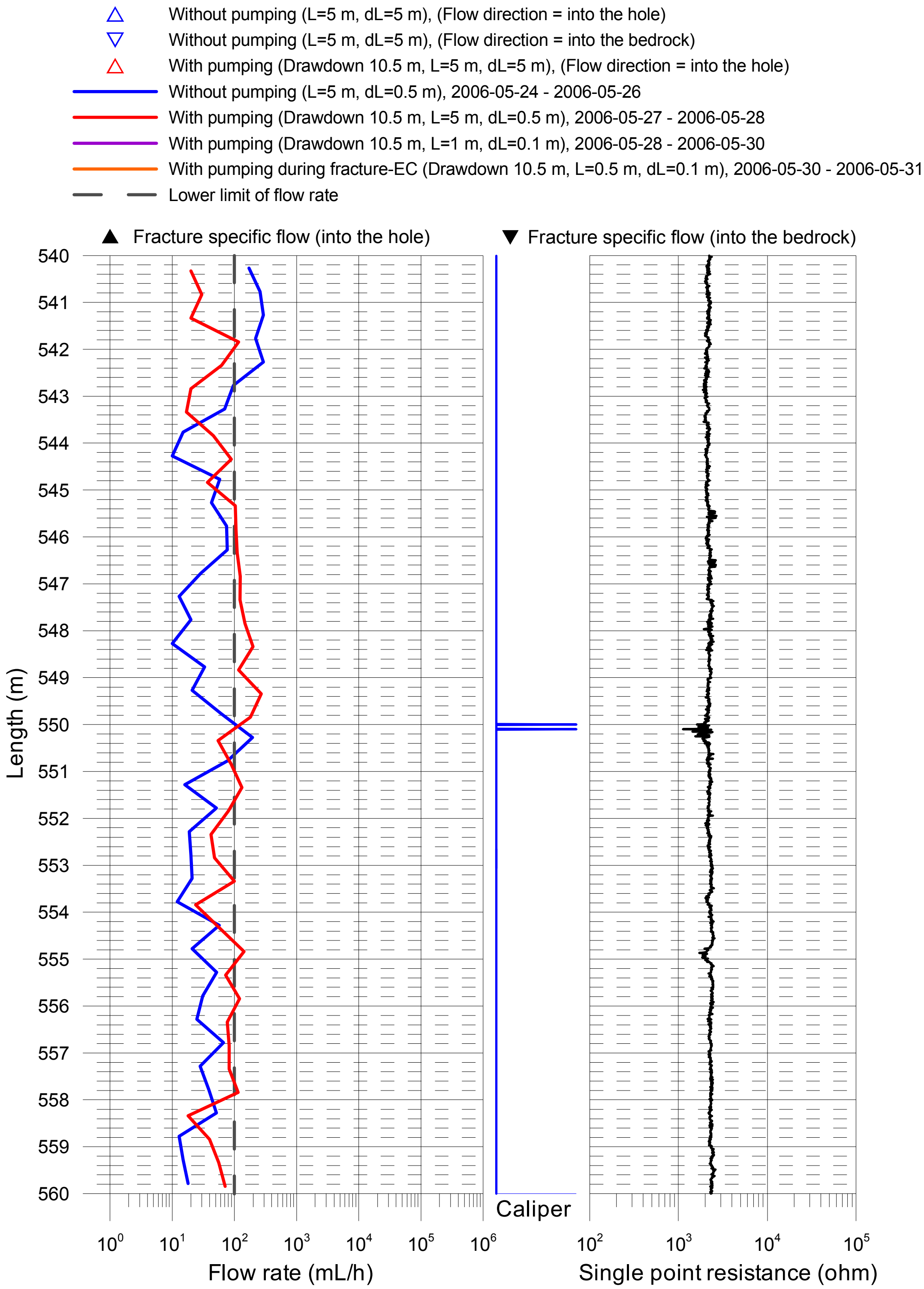
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



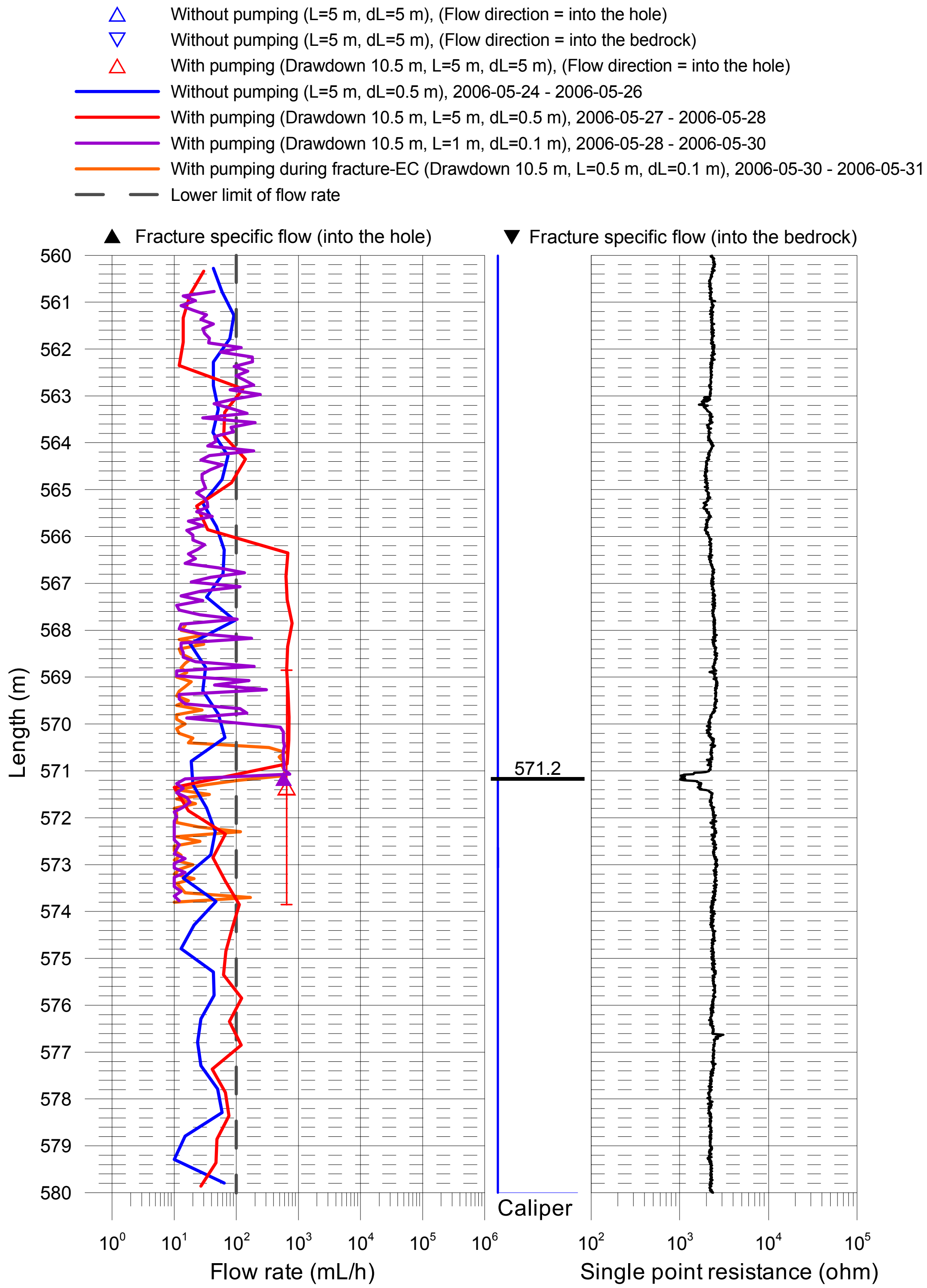
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



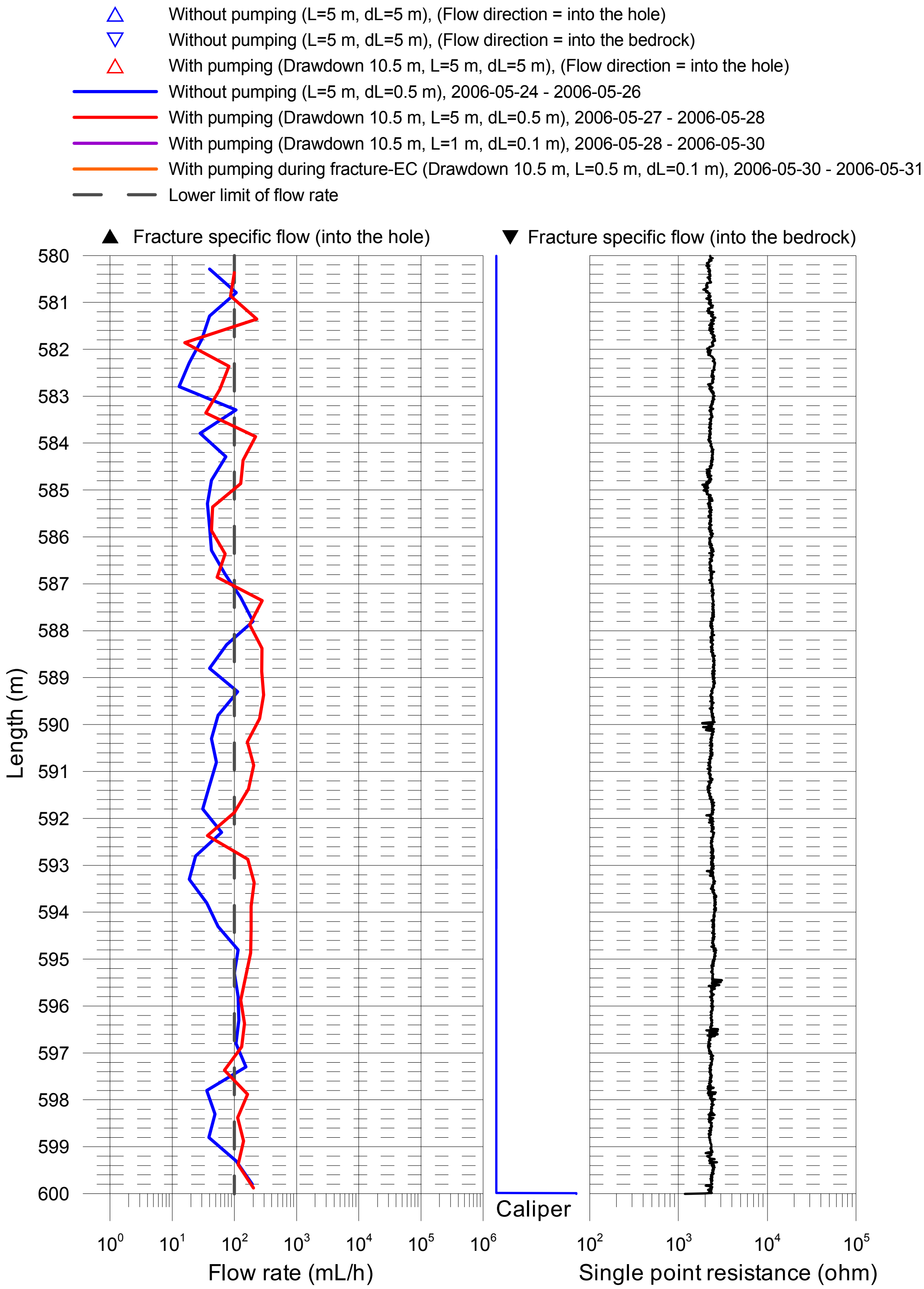
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



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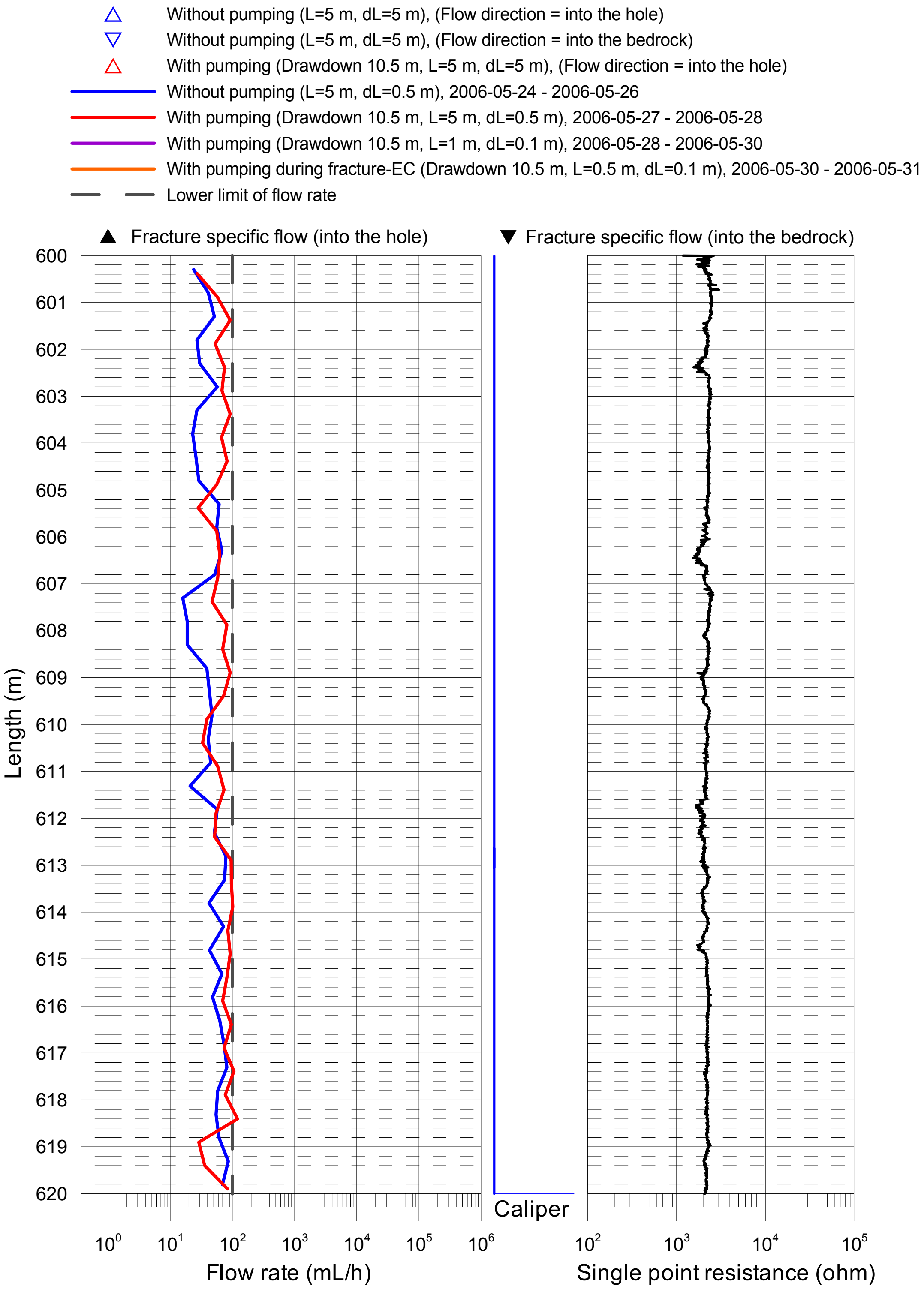
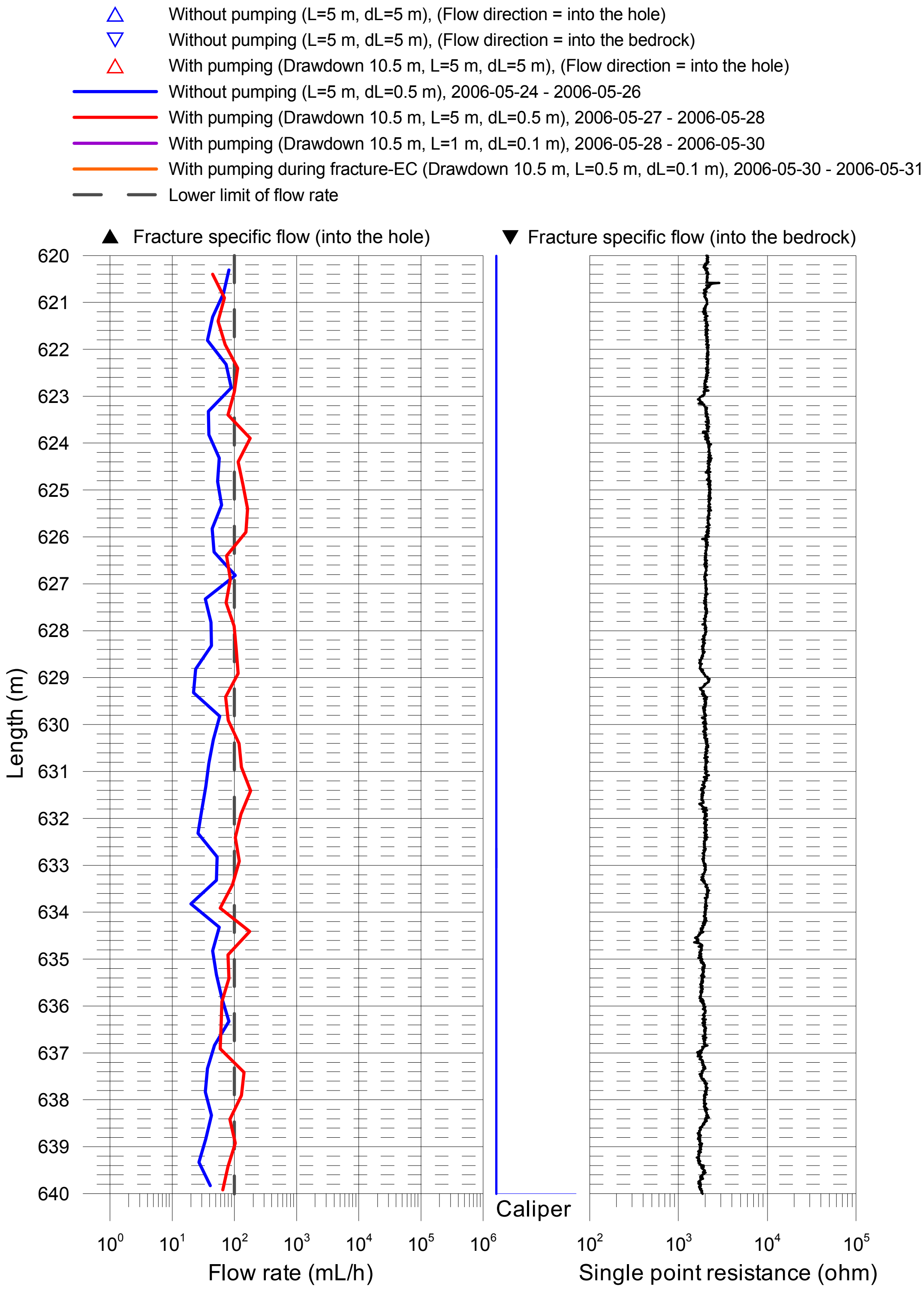
Flow rate, caliper and single point resistance



Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



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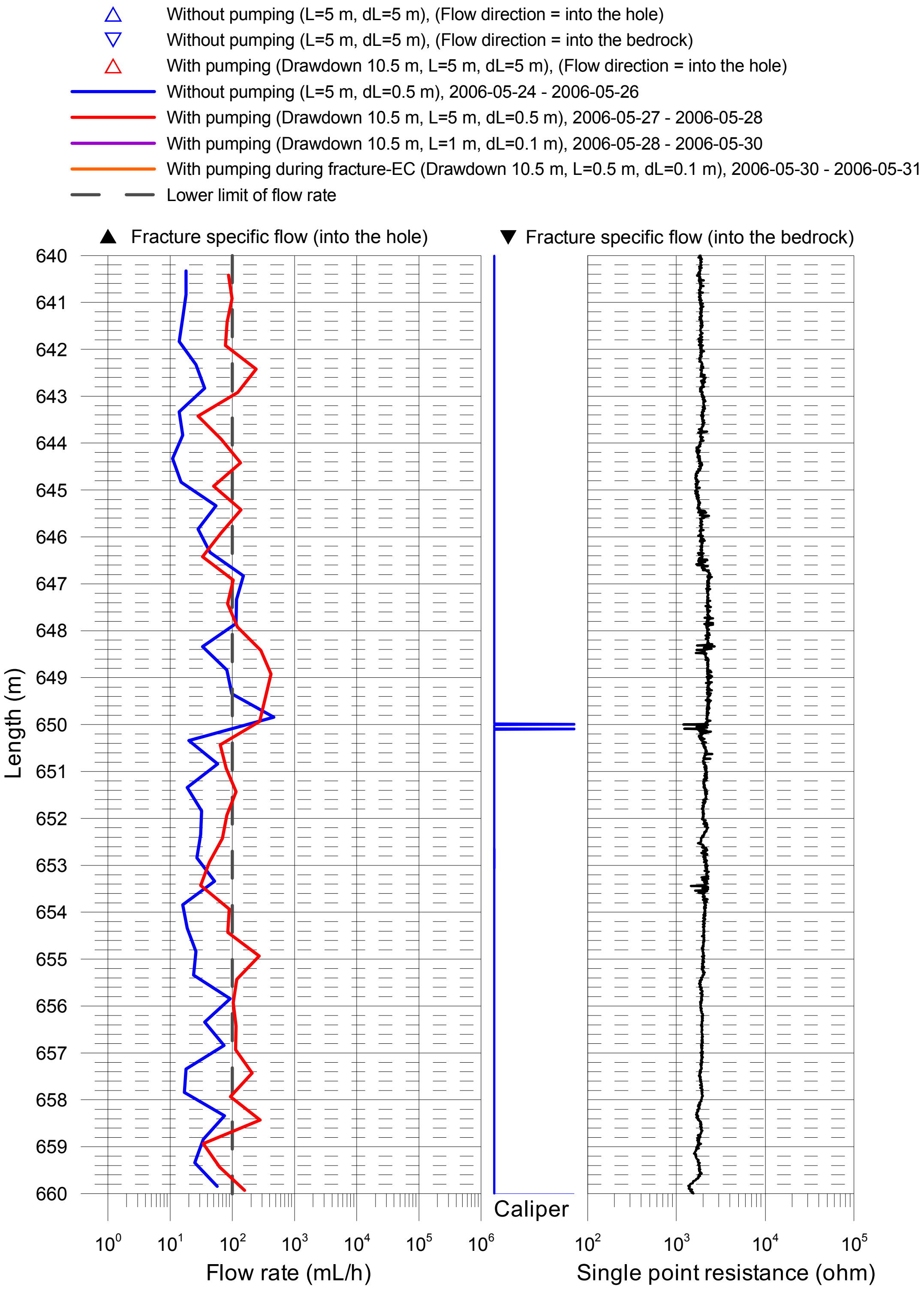
Flow rate, caliper and single point resistance



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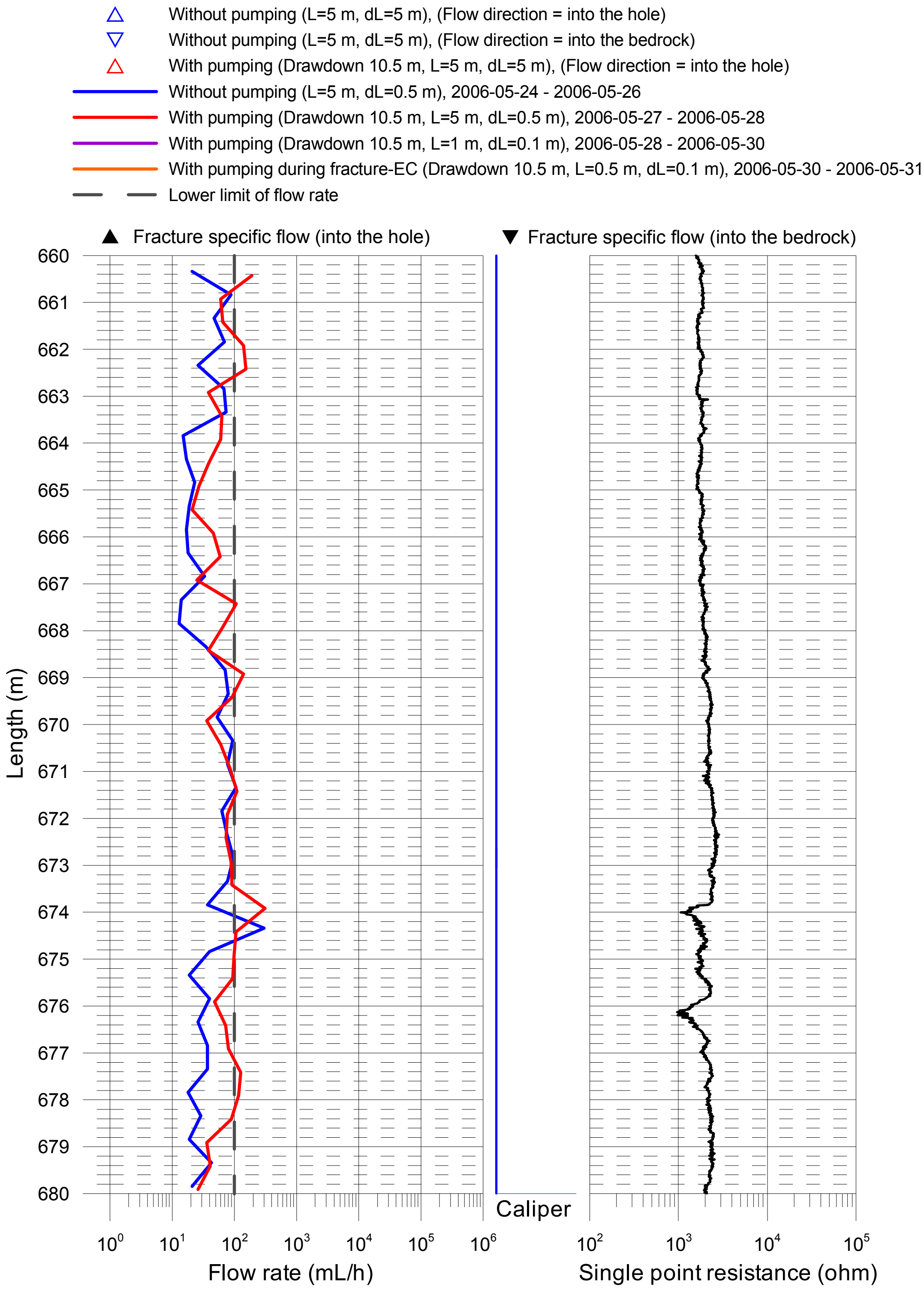
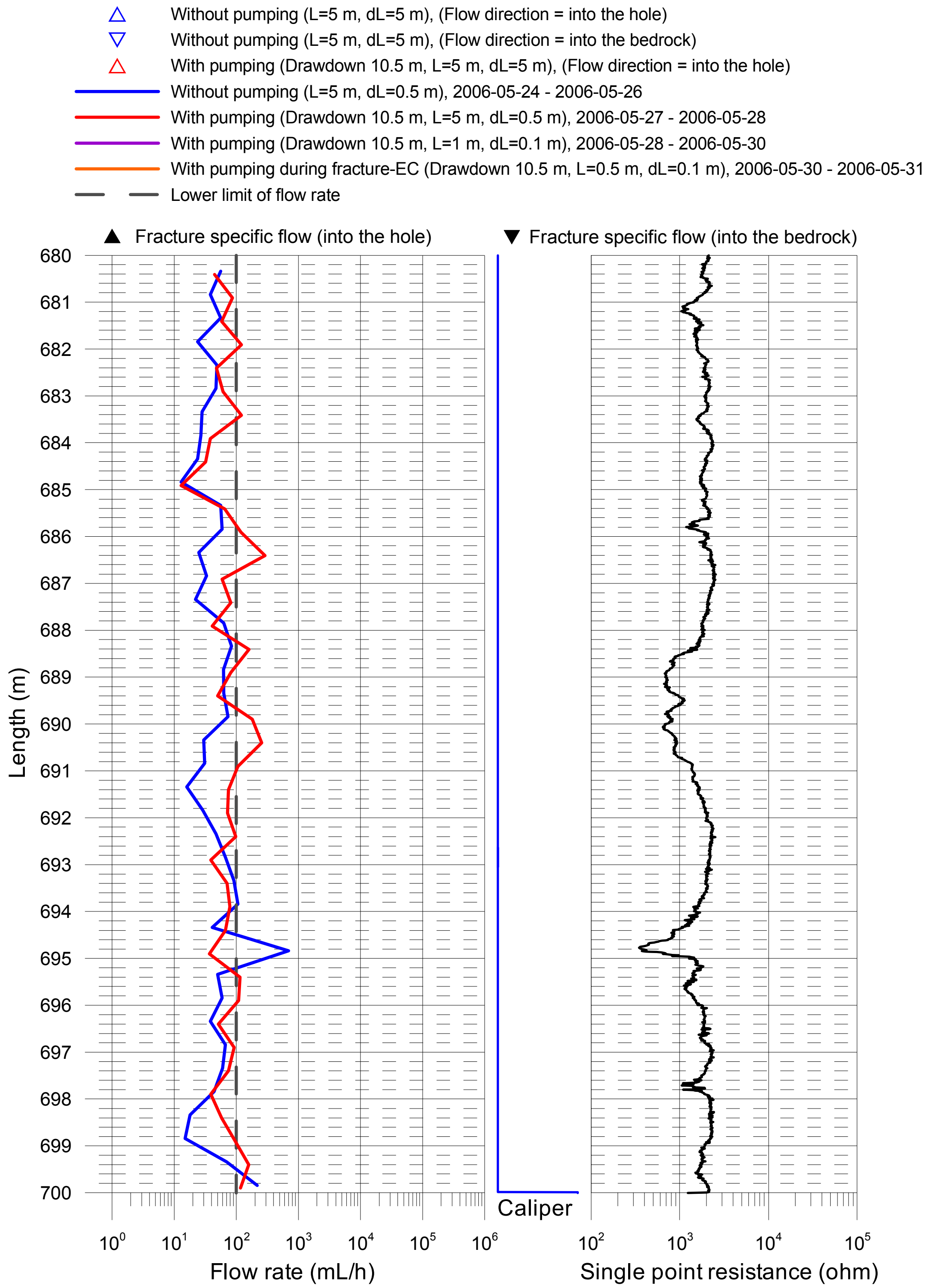
Flow rate, caliper and single point resistance



Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



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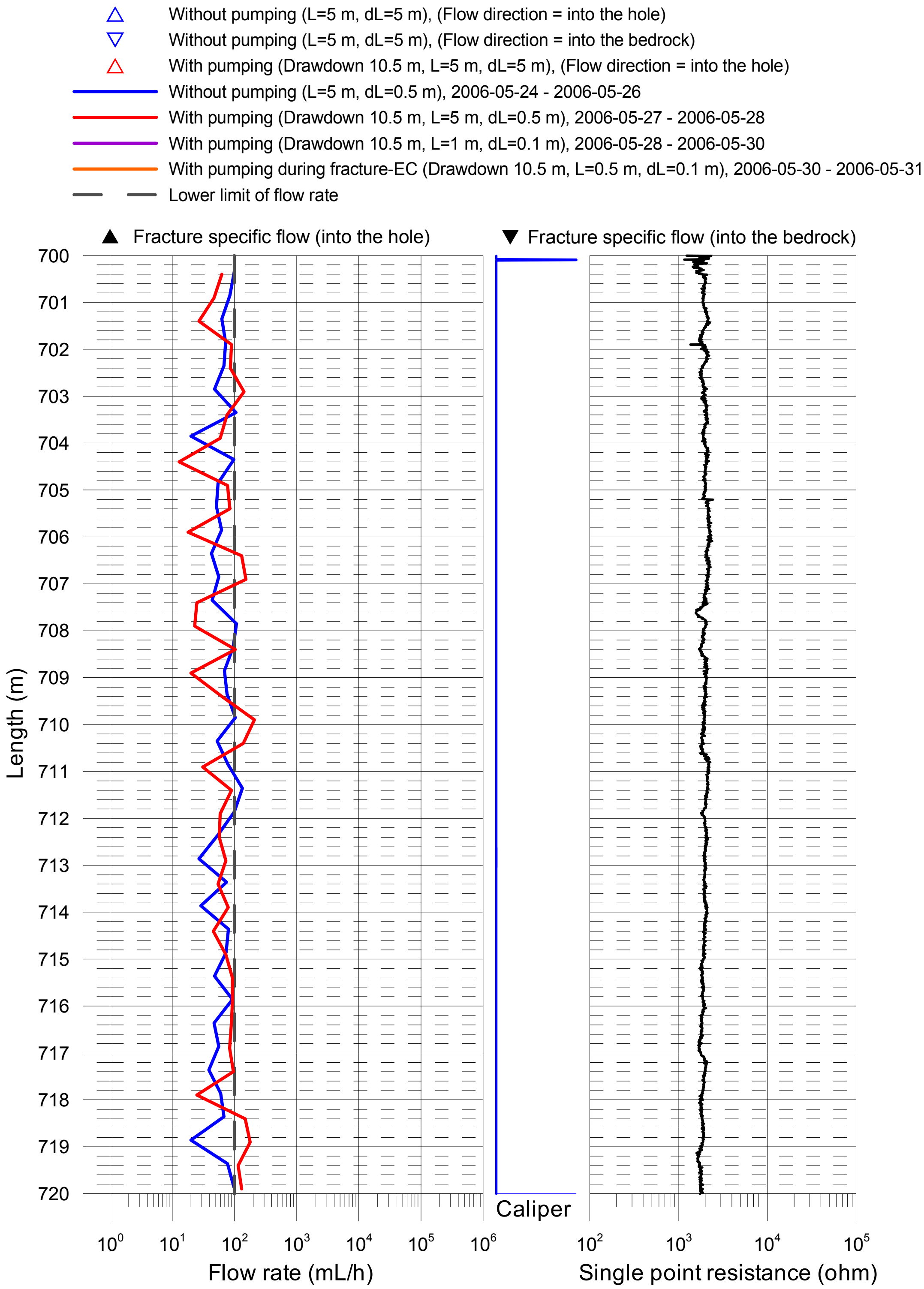
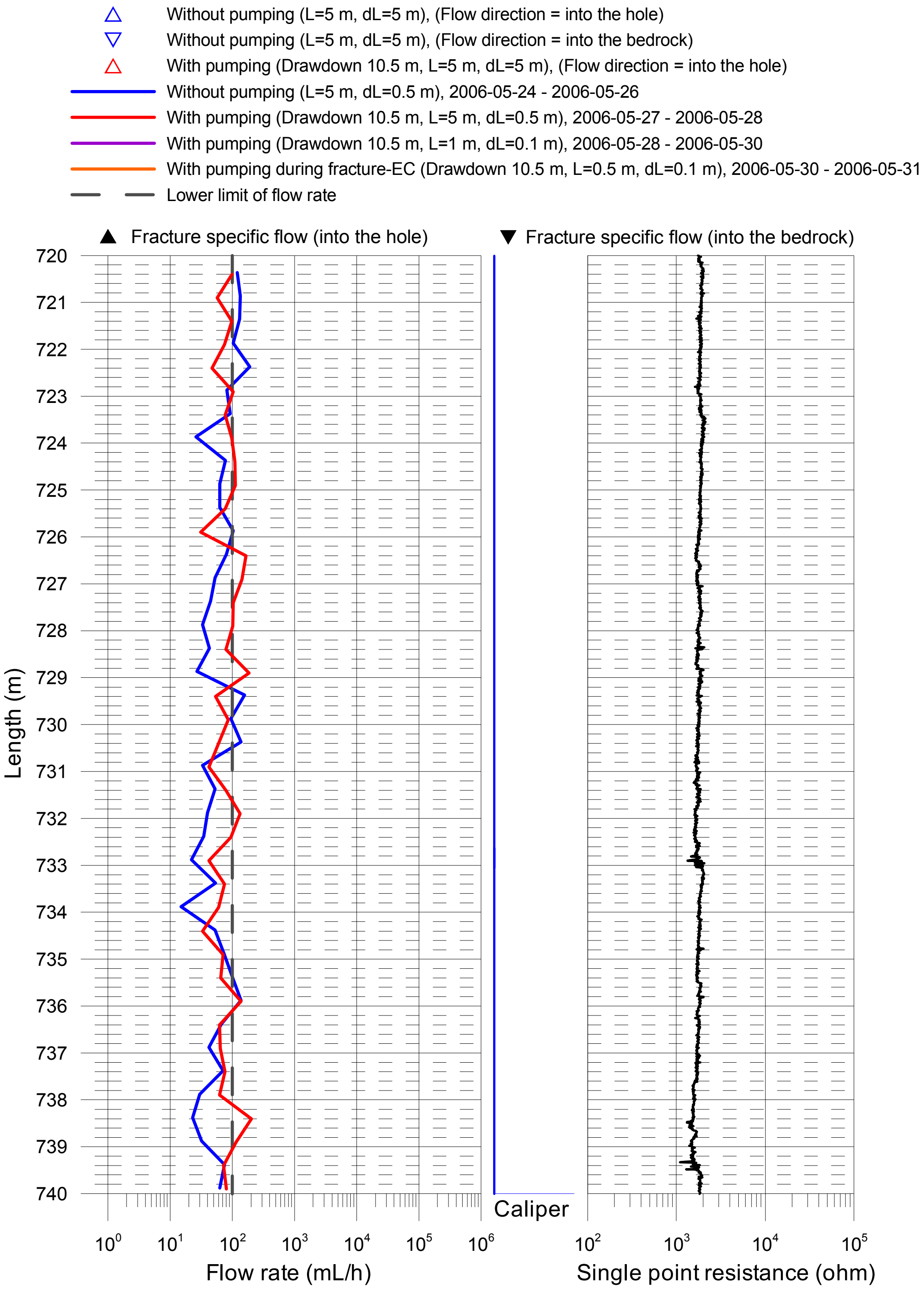
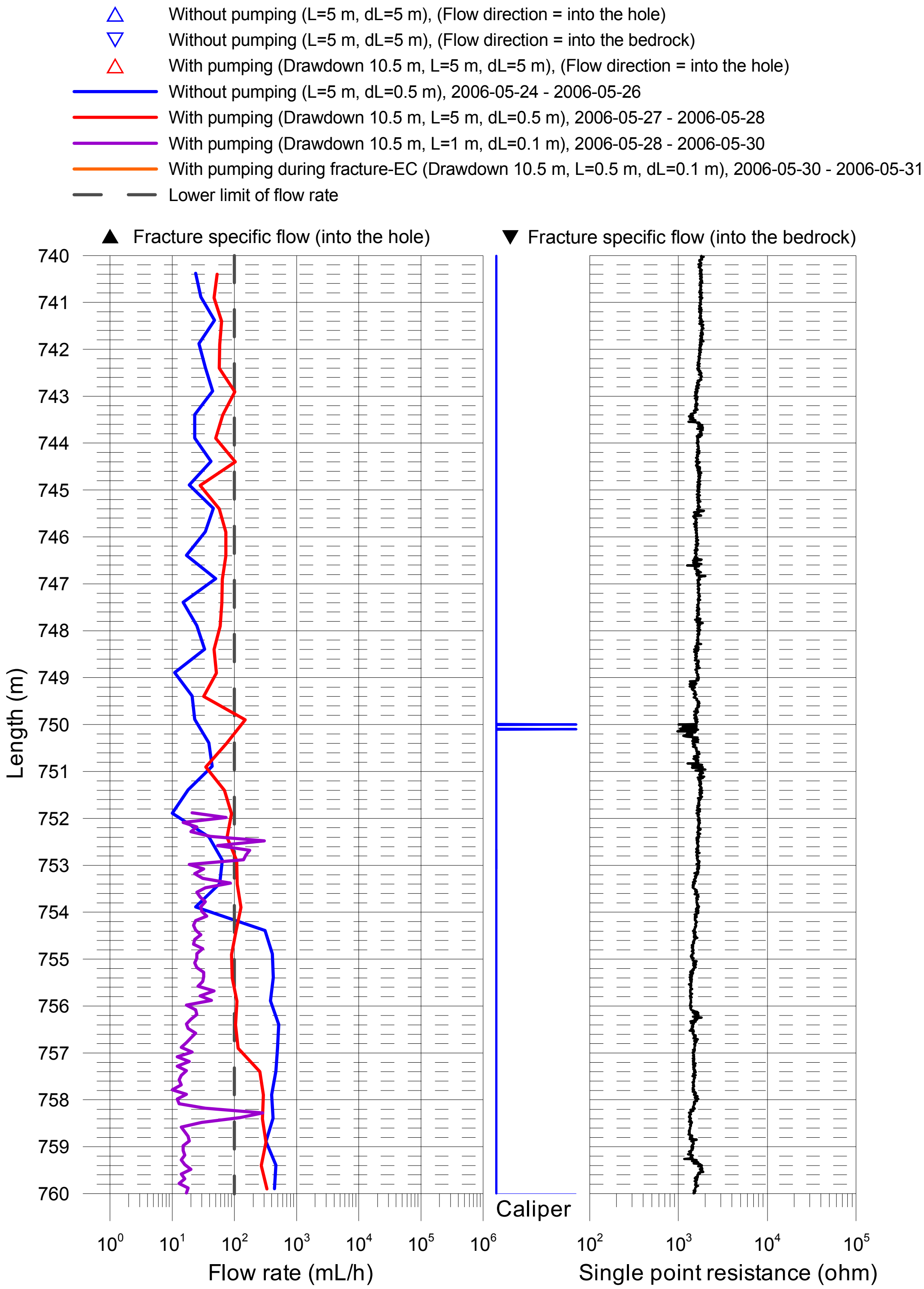
Flow rate, caliper and single point resistance



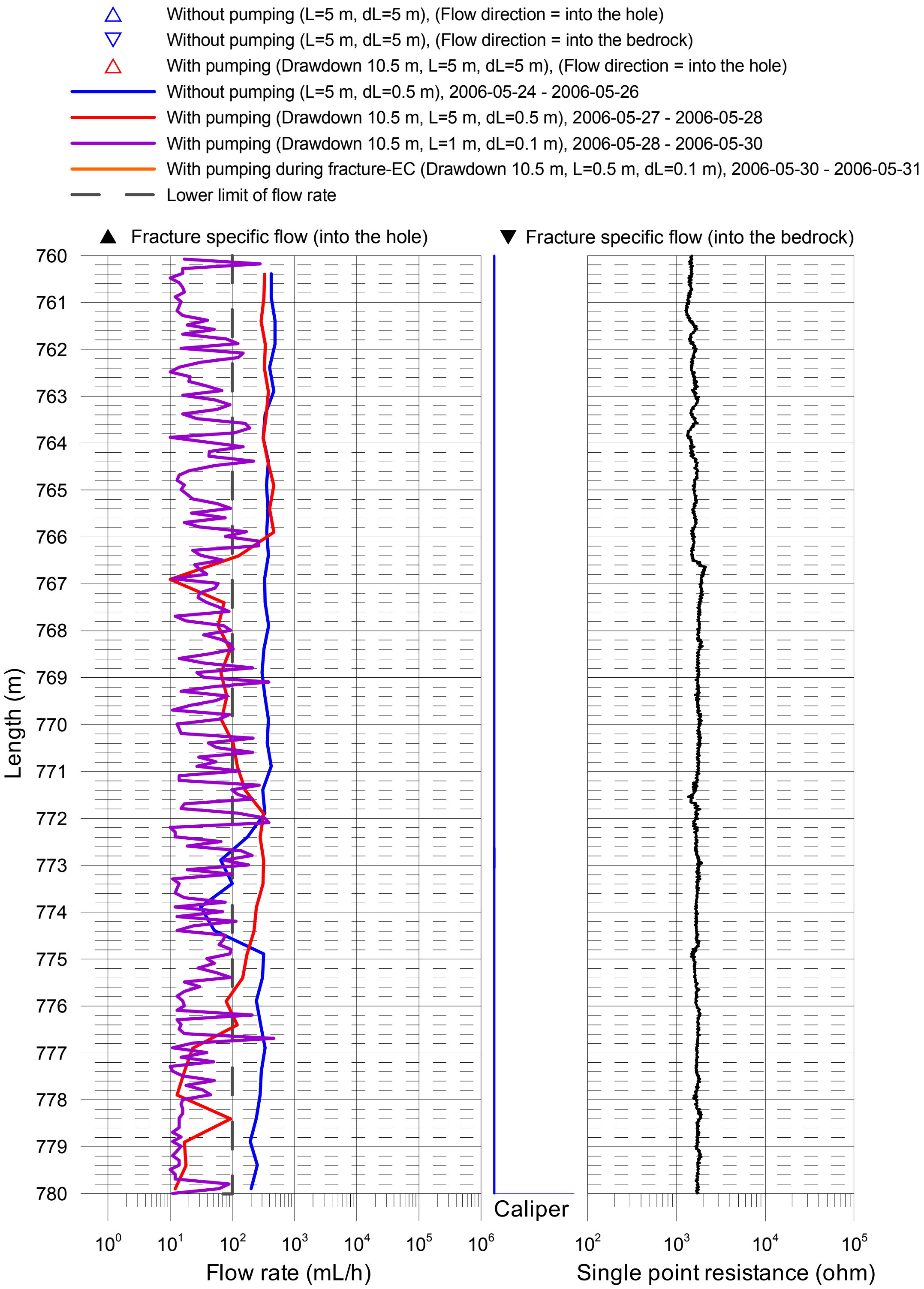
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



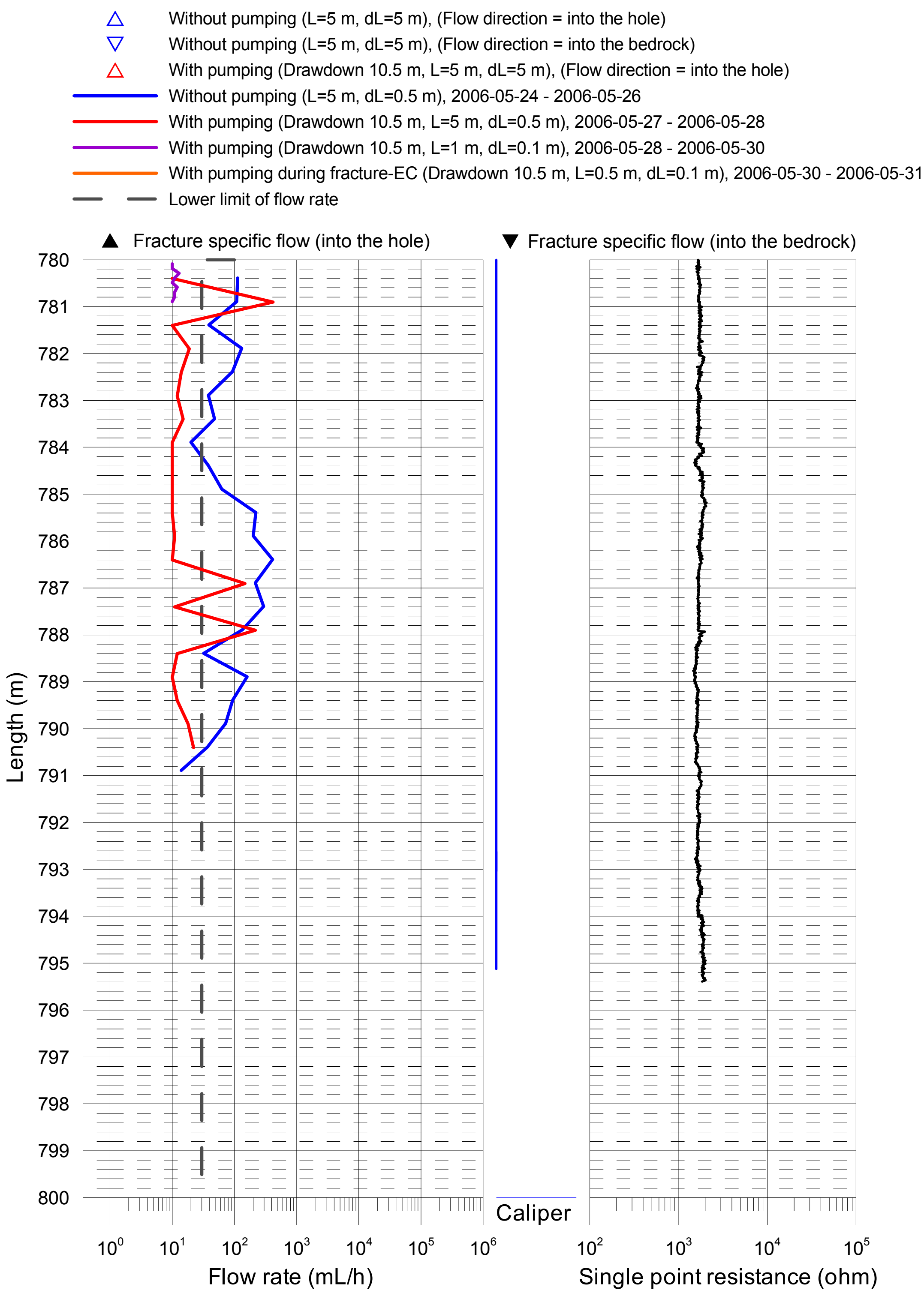
Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



Forsmark, borehole KFM01D
Flow rate, caliper and single point resistance



# Appendix 4

## Explanations for the tables in Appendices 5–6

| Explanations Header | Unit | Explanations |
|---|---|---|
| Borehole | | ID for borehole |
| Secup | m | Length along the borehole for the upper limit of the test section (based on corrected length L) |
| Seclow | m | Length along the borehole for the lower limit of the test section (based on corrected length L) |
| L | m | Corrected length along borehole based on SKB procedures for length correction. |
| Length to flow anom. | m | Length along the borehole to inferred flow anomaly during overlapping flow logging |
| Test type (1–6) | (–) | 1A: Pumping test – wire-line eq. 1B:Pumping test-submersible pump, 1C: Pumping test-airlift pumping, 2: Interference test, 3: Injection test, 4: Slug test, 5A: Difference flow logging -PFL-DIFF-Sequential, 5B: Difference flow logging -PFL-DIFF-Overlapping, 6: Flow logging-Impeller |
| Date of test, start | YY-MM-DD | Date for start of pumping |
| Time of test, start | hh:mm | Time for start of pumping |
| Date of flowl., start . | YY-MM-DD | Date for start of the flow logging |
| Time of flowl., start | hh:mm | Time for start of the flow logging |
| Date of test, stop | YY-MM-DD | Date for stop of the test |
| Time of test, stop | hh:mm | Time for stop of the test |
| $L_w$ | m | Section length used in the difference flow logging |
| dL | m | Step length (increment) used in the difference flow logging |
| $Q_{p1}$ | $m^3/s$ | Flow rate at surface by the end of the first pumping period of the flow logging |
| $Q_{p2}$ | $m^3/s$ | Flow rate at surface by the end of the second pumping period of the flow logging |
| $t_{p1}$ | s | Duration of the first pumping period |
| $t_{p2}$ | s | Duration of the second pumping period |
| $t_{F1}$ | s | Duration of the first recovery period |
| $t_{F2}$ | s | Duration of the second recovery period |
| $h_0$ | m.a.s.l. | Initial hydraulic head before pumping. Elevation of water level in open borehole in the local co-ordinates system with z = 0 m. |
| $h_1$ | m.a.s.l. | Stabilised hydraulic head during the first pumping period. Elevation of water level in open borehole in the local co-ordinates system with z = 0 m. |

**Explanations**

| Header | Unit | Explanations |
|---|---|---|
| $h_2$ | m.a.s.l. | Stabilised hydraulic head during the second pumping period. Elevation of water level in open borehole in the local co-ordinates system with z = 0 m. |
| $s_1$ | m | Drawdown of the water level in the borehole during first pumping period. Difference between the actual hydraulic head and the initial head ($s_1$= $h_1$–$h_0$) |
| $s_2$ | m | Drawdown of the water level in the borehole during second pumping period. Difference between the actual hydraulic head and the initial head ($s_2$ = $h_2$–$h_0$) |
| T | $m^2/s$ | Transmissivity of the entire borehole |
| $Q_0$ | $m^3/s$ | Measured flow rate through the test section or flow anomaly under natural conditions (no pumping) with h = $h_0$ in the open borehole |
| $Q_1$ | $m^3/s$ | Measured flow rate through the test section or flow anomaly during the first pumping period |
| $Q_2$ | $m^3/s$ | Measured flow rate through the test section or flow anomaly during the second pumping period |
| $h_{0FW}$ | m | Corrected initial hydraulic head along the hole due to e.g. varying salinity conditions of the borehole fluid before pumping |
| $h_{1FW}$ | m | Corrected hydraulic head along the hole due to e.g. varying salinity conditions of the borehole fluid during the first pumping period |
| $h_{2FW}$ | m | Corrected hydraulic head along the hole due to e.g. varying salinity conditions of the borehole fluid during the second pumping period |
| $EC_w$ | S/m | Measured electric conductivity of the borehole fluid in the test section during difference flow logging |
| $Te_w$ | ºC | Measured borehole fluid temperature in the test section during difference flow logging |
| $EC_f$ | S/m | Measured fracture-specific electric conductivity of the fluid in flow anomaly during difference flow logging |
| $Te_f$ | ºC | Measured fracture-specific fluid temperature in flow anomaly during difference flow logging |
| $T_D$ | $m^2/s$ | Transmissivity of section or flow anomaly based on 2D model for evaluation of formation properties of the test section based on PFL-DIFF. |
| T-$measl_{LT}$ | $m^2/s$ | Estimated theoretical lower measurement limit for evaluated $T_D$. If the estimated $T_D$ equals $T_D$-measlim, the actual $T_D$ is considered to be equal or less than $T_D$-measlim. |
| T-$measl_{LP}$ | $m^2/s$ | Estimated practical lower measurement limit for evaluated $T_D$. If the estimated $T_D$ equals $T_D$-measlim, the actual $T_D$ is considered to be equal or less than $T_D$-measlim. |
| T-$meas_{lU}$ | $m^2/s$ | Estimated upper measurement limit for evaluated $T_D$. If the estimated $T_D$ equals $T_D$-measlim, the actual $T_D$ is considered to be equal or less than $T_D$-measlim. |
| $h_i$ | m.a.s.l. | Calculated relative, natural freshwater head for test section or flow anomaly (undisturbed conditions) |

# Appendix 5

## Table of transmissivity and head of 5 m sections

**Difference flow logging – Sequential flow logging.**

| Borehole ID | Secup L(m) | Seclow L(m) | $L_w$ (m) | Q0 ($m^3/s$) | h0FW (m.a.s.l.) | Q1 ($m^3/s$) | h1FW (m.a.s.l.) | $T_D$ ($m^2/s$) | hi (m.a.s.l.) | Q-lower limit P (mL/h) | $T_D$-measlLT ($m^2/s$) | $T_D$-measlLP ($m^2/s$) | $T_D$-measlU ($m^2/s$) | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| KFM01D | 83.59 | 88.59 | 5 | – | –0.12 | – | –10.35 | – | – | 30 | 8.10E–10 | 8.10E–10 | 8.10E–06 | |
| KFM01D | 88.59 | 93.59 | 5 | – | –0.04 | – | –10.21 | – | – | 30 | 8.10E–10 | 8.10E–10 | 8.10E–06 | |
| KFM01D | 93.60 | 98.60 | 5 | – | 0.09 | – | –10.13 | – | – | 30 | 8.10E–10 | 8.10E–10 | 8.10E–06 | |
| KFM01D | 98.61 | 103.61 | 5 | – | 0.23 | – | –10.10 | – | – | 30 | 8.00E–10 | 8.00E–10 | 8.00E–06 | |
| KFM01D | 103.62 | 108.62 | 5 | 1.61E–07 | 0.28 | 8.47E–07 | –10.08 | 6.60E–08 | 2.70 | 30 | 8.00E–10 | 8.00E–10 | 8.00E–06 | |
| KFM01D | 108.62 | 113.62 | 5 | – | 0.29 | – | –10.08 | – | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 113.62 | 118.62 | 5 | – | 0.31 | – | –10.07 | – | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 118.63 | 123.63 | 5 | 1.56E–07 | 0.30 | 3.58E–06 | –10.04 | 3.30E–07 | 0.80 | 30 | 8.00E–10 | 8.00E–10 | 8.00E–06 | |
| KFM01D | 123.63 | 128.63 | 5 | – | 0.28 | 3.64E–07 | –9.99 | 3.50E–08 | – | 30 | 8.00E–10 | 8.00E–10 | 8.00E–06 | |
| KFM01D | 128.63 | 133.63 | 5 | – | 0.26 | 4.72E–07 | –9.96 | 4.60E–08 | – | 30 | 8.10E–10 | 8.10E–10 | 8.10E–06 | |
| KFM01D | 133.63 | 138.63 | 5 | – | 0.24 | – | –9.90 | – | – | 30 | 8.10E–10 | 8.10E–10 | 8.10E–06 | |
| KFM01D | 138.64 | 143.64 | 5 | – | 0.29 | 4.31E–08 | –9.85 | 4.20E–09 | – | 30 | 8.10E–10 | 8.10E–10 | 8.10E–06 | |
| KFM01D | 143.64 | 148.64 | 5 | –2.94E–07 | 0.34 | 4.53E–05 | –9.80 | 4.40E–06 | 0.30 | 30 | 8.10E–10 | 8.10E–10 | 8.10E–06 | |
| KFM01D | 148.64 | 153.64 | 5 | –2.92E–08 | 0.40 | 4.28E–06 | –9.75 | 4.20E–07 | 0.30 | 30 | 8.10E–10 | 8.10E–10 | 8.10E–06 | |
| KFM01D | 153.63 | 158.63 | 5 | – | 0.46 | 3.75E–07 | –9.72 | 3.60E–08 | – | 30 | 8.10E–10 | 8.10E–10 | 8.10E–06 | |
| KFM01D | 158.63 | 163.63 | 5 | – | 0.59 | – | –9.67 | – | – | 30 | 8.00E–10 | 8.00E–10 | 8.00E–06 | |
| KFM01D | 163.62 | 168.62 | 5 | – | 0.71 | – | –9.62 | – | – | 30 | 8.00E–10 | 8.00E–10 | 8.00E–06 | |
| KFM01D | 168.61 | 173.61 | 5 | – | 0.83 | – | –9.58 | – | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 173.61 | 178.61 | 5 | – | 0.90 | – | –9.53 | – | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 178.61 | 183.61 | 5 | – | 0.95 | – | –9.49 | – | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 183.60 | 188.60 | 5 | – | 0.94 | – | –9.49 | – | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 188.60 | 193.60 | 5 | – | 0.99 | – | –9.43 | – | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 193.59 | 198.59 | 5 | – | 1.05 | 1.06E–07 | –9.35 | 1.00E–08 | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 198.59 | 203.59 | 5 | – | 1.11 | – | –9.32 | – | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 203.60 | 208.60 | 5 | – | 1.16 | – | –9.28 | – | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 208.60 | 213.60 | 5 | – | 1.22 | – | –9.24 | – | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |

| Borehole ID | Secup L(m) | Seclow L(m) | $L_w$ (m) | Q0 ($m^3/s$) | h0FW (m.a.s.l.) | Q1 ($m^3/s$) | h1FW (m.a.s.l.) | $T_D$ ($m^2/s$) | hi (m.a.s.l.) | Q-lower limit P (mL/h) | $T_D$-measlLT ($m^2/s$) | $T_D$-measlLP ($m^2/s$) | $T_D$-measlU ($m^2/s$) | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| KFM01D | 213.60 | 218.60 | 5 | – | 1.25 | – | –9.19 | – | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 218.61 | 223.61 | 5 | – | 1.30 | – | –9.16 | – | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 223.61 | 228.61 | 5 | – | 1.33 | – | –9.13 | – | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 228.62 | 233.62 | 5 | – | 1.35 | – | –9.09 | – | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 233.62 | 238.62 | 5 | – | 1.41 | – | –9.04 | – | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 238.63 | 243.63 | 5 | – | 1.47 | – | –9.00 | – | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 243.63 | 248.63 | 5 | – | 1.52 | – | –8.96 | – | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 248.64 | 253.64 | 5 | – | 1.57 | – | –8.92 | – | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 253.64 | 258.64 | 5 | – | 1.61 | – | –8.88 | – | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 258.65 | 263.65 | 5 | – | 1.64 | – | –8.85 | – | – | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 263.65 | 268.65 | 5 | 4.25E–08 | 1.71 | 1.00E–07 | –8.79 | 5.40E–09 | 9.50 | 30 | 7.90E–10 | 7.90E–10 | 7.90E–06 | |
| KFM01D | 268.66 | 273.66 | 5 | – | 1.76 | – | –8.76 | – | – | 30 | 7.80E–10 | 7.80E–10 | 7.80E–06 | |
| KFM01D | 273.66 | 278.66 | 5 | – | 1.80 | – | –8.71 | – | – | 30 | 7.80E–10 | 7.80E–10 | 7.80E–06 | |
| KFM01D | 278.67 | 283.67 | 5 | – | 1.86 | – | –8.66 | – | – | 30 | 7.80E–10 | 7.80E–10 | 7.80E–06 | |
| KFM01D | 283.67 | 288.67 | 5 | – | 1.90 | – | –8.64 | – | – | 30 | 7.80E–10 | 7.80E–10 | 7.80E–06 | |
| KFM01D | 288.68 | 293.68 | 5 | – | 1.95 | – | –8.60 | – | – | 30 | 7.80E–10 | 7.80E–10 | 7.80E–06 | |
| KFM01D | 293.68 | 298.68 | 5 | – | 1.98 | – | –8.57 | – | – | 30 | 7.80E–10 | 7.80E–10 | 7.80E–06 | |
| KFM01D | 298.69 | 303.69 | 5 | – | 2.03 | – | –8.51 | – | – | 30 | 7.80E–10 | 7.80E–10 | 7.80E–06 | |
| KFM01D | 303.69 | 308.69 | 5 | 7.83E–08 | 2.09 | 6.31E–07 | –8.42 | 5.20E–08 | 3.60 | 30 | 7.80E–10 | 7.80E–10 | 7.80E–06 | |
| KFM01D | 308.69 | 313.69 | 5 | – | 2.14 | – | –8.42 | – | – | 30 | 7.80E–10 | 7.80E–10 | 7.80E–06 | |
| KFM01D | 313.69 | 318.69 | 5 | 8.44E–08 | 2.21 | 3.17E–06 | –8.38 | 2.90E–07 | 2.50 | 30 | 7.80E–10 | 7.80E–10 | 7.80E–06 | |
| KFM01D | 318.70 | 323.70 | 5 | – | 2.26 | – | –8.29 | – | – | 30 | 7.80E–10 | 7.80E–10 | 7.80E–06 | |
| KFM01D | 323.70 | 328.70 | 5 | – | 2.30 | – | –8.28 | – | – | 30 | 7.80E–10 | 7.80E–10 | 7.80E–06 | |
| KFM01D | 328.71 | 333.71 | 5 | – | 2.36 | – | –8.21 | – | – | 30 | 7.80E–10 | 7.80E–10 | 7.80E–06 | |
| KFM01D | 333.71 | 338.71 | 5 | – | 2.44 | – | –8.16 | – | – | 30 | 7.80E–10 | 7.80E–10 | 7.80E–06 | |
| KFM01D | 338.71 | 343.71 | 5 | – | 2.52 | – | –8.12 | – | – | 30 | 7.70E–10 | 7.70E–10 | 7.70E–06 | |
| KFM01D | 343.72 | 348.72 | 5 | – | 2.57 | – | –8.07 | – | – | 30 | 7.70E–10 | 7.70E–10 | 7.70E–06 | |
| KFM01D | 348.72 | 353.72 | 5 | – | 2.63 | 4.78E–08 | –8.02 | 4.40E–09 | – | 50 | 7.70E–10 | 1.30E–09 | 7.70E–06 | |
| KFM01D | 353.73 | 358.73 | 5 | – | 2.64 | 3.72E–08 | –8.04 | 3.40E–09 | – | 50 | 7.70E–10 | 1.30E–09 | 7.70E–06 | |
| KFM01D | 358.73 | 363.73 | 5 | – | 2.69 | – | –8.03 | – | – | 50 | 7.70E–10 | 1.30E–09 | 7.70E–06 | |
| KFM01D | 363.73 | 368.73 | 5 | – | 2.73 | – | –7.95 | – | – | 50 | 7.70E–10 | 1.30E–09 | 7.70E–06 | |
| KFM01D | 368.73 | 373.73 | 5 | – | 2.77 | 2.70E–07 | –7.88 | 2.50E–08 | – | 50 | 7.70E–10 | 1.30E–09 | 7.70E–06 | |

| Borehole ID | Secup L(m) | Seclow L(m) | $L_w$ (m) | Q0 (m³/s) | h0FW (m.a.s.l.) | Q1 (m³/s) | h1FW (m.a.s.l.) | $T_D$ (m²/s) | hi (m.a.s.l.) | Q-lower limit P (mL/h) | $T_D$-measlLT (m²/s) | $T_D$-measlLP (m²/s) | $T_D$-measlU (m²/s) | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| KFM01D | 373.74 | 378.74 | 5 | –2.06E–08 | 2.83 | 1.34E–06 | –7.84 | 1.30E–07 | 2.70 | 50 | 7.70E–10 | 1.30E–09 | 7.70E–06 | |
| KFM01D | 378.74 | 383.74 | 5 | –6.94E–09 | 2.85 | 4.25E–07 | –7.79 | 4.00E–08 | 2.70 | 50 | 7.70E–10 | 1.30E–09 | 7.70E–06 | |
| KFM01D | 383.74 | 388.74 | 5 | – | 2.89 | – | –7.77 | – | – | 50 | 7.70E–10 | 1.30E–09 | 7.70E–06 | |
| KFM01D | 388.74 | 393.74 | 5 | – | 2.92 | – | –7.71 | – | – | 50 | 7.80E–10 | 1.30E–09 | 7.80E–06 | |
| KFM01D | 393.75 | 398.75 | 5 | – | 2.96 | – | –7.66 | – | – | 50 | 7.80E–10 | 1.30E–09 | 7.80E–06 | |
| KFM01D | 398.75 | 403.75 | 5 | – | 2.99 | – | –7.59 | – | – | 50 | 7.80E–10 | 1.30E–09 | 7.80E–06 | |
| KFM01D | 403.75 | 408.75 | 5 | – | 3.03 | – | –7.47 | – | – | 50 | 7.90E–10 | 1.30E–09 | 7.90E–06 | |
| KFM01D | 408.76 | 413.76 | 5 | – | 3.08 | – | –7.42 | – | – | 50 | 7.90E–10 | 1.30E–09 | 7.90E–06 | |
| KFM01D | 413.76 | 418.76 | 5 | – | 3.17 | – | –7.36 | – | – | 50 | 7.80E–10 | 1.30E–09 | 7.80E–06 | |
| KFM01D | 418.76 | 423.76 | 5 | – | 3.23 | – | –7.30 | – | – | 50 | 7.80E–10 | 1.30E–09 | 7.80E–06 | |
| KFM01D | 423.76 | 428.76 | 5 | – | 3.19 | – | –7.33 | – | – | 100 | 7.80E–10 | 2.60E–09 | 7.80E–06 | |
| KFM01D | 428.77 | 433.77 | 5 | 2.31E–07 | 3.25 | 1.63E–06 | –7.27 | 1.30E–07 | 5.00 | 100 | 7.80E–10 | 2.60E–09 | 7.80E–06 | |
| KFM01D | 433.77 | 438.77 | 5 | – | 3.38 | – | –7.20 | – | – | 100 | 7.80E–10 | 2.60E–09 | 7.80E–06 | |
| KFM01D | 438.77 | 443.77 | 5 | – | 3.32 | – | –7.15 | – | – | 100 | 7.90E–10 | 2.60E–09 | 7.90E–06 | |
| KFM01D | 443.77 | 448.77 | 5 | – | 3.37 | – | –7.08 | – | – | 100 | 7.90E–10 | 2.60E–09 | 7.90E–06 | |
| KFM01D | 448.77 | 453.77 | 5 | – | 3.42 | – | –7.00 | – | – | 100 | 7.90E–10 | 2.60E–09 | 7.90E–06 | |
| KFM01D | 453.77 | 458.77 | 5 | – | 3.48 | – | –6.96 | – | – | 100 | 7.90E–10 | 2.60E–09 | 7.90E–06 | |
| KFM01D | 458.77 | 463.77 | 5 | – | 3.53 | – | –6.89 | – | – | 100 | 7.90E–10 | 2.60E–09 | 7.90E–06 | |
| KFM01D | 463.77 | 468.77 | 5 | – | 3.58 | – | –6.83 | – | – | 100 | 7.90E–10 | 2.60E–09 | 7.90E–06 | |
| KFM01D | 468.77 | 473.77 | 5 | – | 3.64 | – | –6.78 | – | – | 100 | 7.90E–10 | 2.60E–09 | 7.90E–06 | |
| KFM01D | 473.77 | 478.77 | 5 | – | 3.69 | – | –6.72 | – | – | 100 | 7.90E–10 | 2.60E–09 | 7.90E–06 | |
| KFM01D | 478.77 | 483.77 | 5 | – | 3.75 | – | –6.65 | – | – | 100 | 7.90E–10 | 2.60E–09 | 7.90E–06 | |
| KFM01D | 483.77 | 488.77 | 5 | – | 3.79 | – | –6.59 | – | – | 100 | 7.90E–10 | 2.60E–09 | 7.90E–06 | |
| KFM01D | 488.77 | 493.77 | 5 | – | 3.85 | – | –6.52 | – | – | 100 | 7.90E–10 | 2.60E–09 | 7.90E–06 | |
| KFM01D | 493.77 | 498.77 | 5 | – | 3.90 | – | –6.46 | – | – | 100 | 8.00E–10 | 2.70E–09 | 8.00E–06 | |
| KFM01D | 498.78 | 503.78 | 5 | – | 3.95 | – | –6.42 | – | – | 100 | 7.90E–10 | 2.60E–09 | 7.90E–06 | |
| KFM01D | 503.78 | 508.78 | 5 | – | 4.00 | – | –6.35 | – | – | 100 | 8.00E–10 | 2.70E–09 | 8.00E–06 | |
| KFM01D | 508.78 | 513.78 | 5 | – | 4.04 | – | –6.30 | – | – | 100 | 8.00E–10 | 2.70E–09 | 8.00E–06 | |
| KFM01D | 513.79 | 518.79 | 5 | – | 4.10 | – | –6.23 | – | – | 100 | 8.00E–10 | 2.70E–09 | 8.00E–06 | |
| KFM01D | 518.79 | 523.79 | 5 | – | 4.14 | – | –6.18 | – | – | 100 | 8.00E–10 | 2.70E–09 | 8.00E–06 | |
| KFM01D | 523.80 | 528.80 | 5 | – | 4.19 | – | –6.11 | – | – | 100 | 8.00E–10 | 2.70E–09 | 8.00E–06 | |
| KFM01D | 528.80 | 533.80 | 5 | – | 4.25 | – | –6.05 | – | – | 100 | 8.00E–10 | 2.70E–09 | 8.00E–06 | |

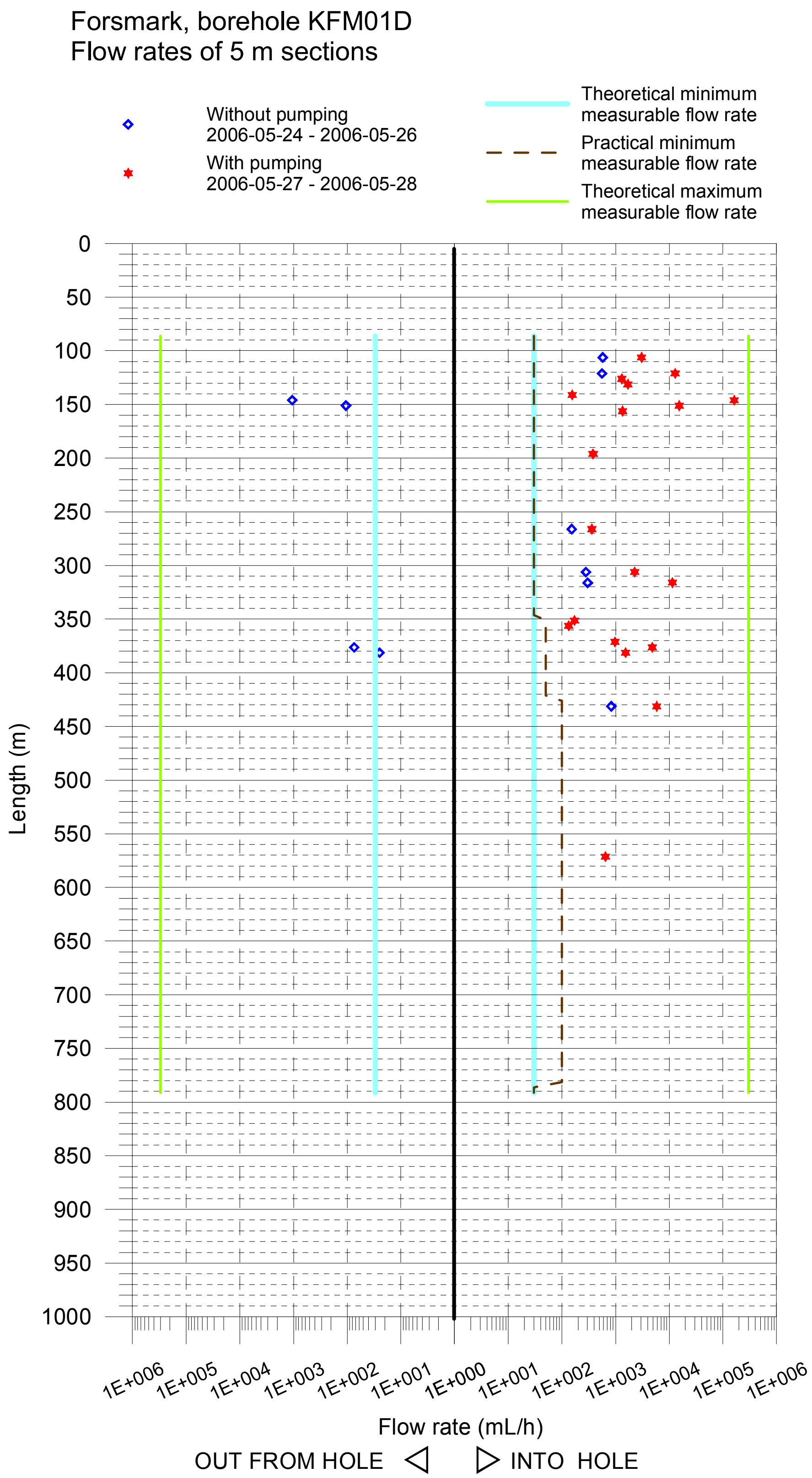
| Borehole ID | Secup L(m) | Seclow L(m) | $L_w$ (m) | Q0 ($m^3/s$) | h0FW (m.a.s.l.) | Q1 ($m^3/s$) | h1FW (m.a.s.l.) | $T_D$ ($m^2/s$) | hi (m.a.s.l.) | Q-lower limit P (mL/h) | $T_D$-measlLT ($m^2/s$) | $T_D$-measlLP ($m^2/s$) | $T_D$-measlU ($m^2/s$) | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| KFM01D | 533.80 | 538.80 | 5 | – | 4.29 | – | –5.99 | – | – | 100 | 8.00E–10 | 2.70E–09 | 8.00E–06 | |
| KFM01D | 538.80 | 543.80 | 5 | – | 4.32 | – | –5.93 | – | – | 100 | 8.00E–10 | 2.70E–09 | 8.00E–06 | |
| KFM01D | 543.81 | 548.81 | 5 | – | 4.35 | – | –5.88 | – | – | 100 | 8.10E–10 | 2.70E–09 | 8.10E–06 | |
| KFM01D | 548.81 | 553.81 | 5 | – | 4.41 | – | –5.80 | – | – | 100 | 8.10E–10 | 2.70E–09 | 8.10E–06 | |
| KFM01D | 553.81 | 558.81 | 5 | – | 4.44 | – | –5.74 | – | – | 100 | 8.10E–10 | 2.70E–09 | 8.10E–06 | |
| KFM01D | 558.81 | 563.81 | 5 | – | 4.49 | – | –5.69 | – | – | 100 | 8.10E–10 | 2.70E–09 | 8.10E–06 | |
| KFM01D | 563.82 | 568.82 | 5 | – | 4.55 | – | –5.62 | – | – | 100 | 8.10E–10 | 2.70E–09 | 8.10E–06 | |
| KFM01D | 568.82 | 573.82 | 5 | – | 4.62 | 1.79E–07 | –5.54 | 1.70E–08 | – | 100 | 8.10E–10 | 2.70E–09 | 8.10E–06 | |
| KFM01D | 573.82 | 578.82 | 5 | – | 4.66 | – | –5.48 | – | – | 100 | 8.10E–10 | 2.70E–09 | 8.10E–06 | |
| KFM01D | 578.83 | 583.83 | 5 | – | 4.72 | – | –5.42 | – | – | 100 | 8.10E–10 | 2.70E–09 | 8.10E–06 | |
| KFM01D | 583.83 | 588.83 | 5 | – | 4.77 | – | –5.36 | – | – | 100 | 8.10E–10 | 2.70E–09 | 8.10E–06 | |
| KFM01D | 588.84 | 593.84 | 5 | – | 4.81 | – | –5.29 | – | – | 100 | 8.20E–10 | 2.70E–09 | 8.20E–06 | |
| KFM01D | 593.84 | 598.84 | 5 | – | 4.89 | – | –5.23 | – | – | 100 | 8.10E–10 | 2.70E–09 | 8.10E–06 | |
| KFM01D | 598.84 | 603.84 | 5 | – | 4.94 | – | –5.17 | – | – | 100 | 8.20E–10 | 2.70E–09 | 8.20E–06 | |
| KFM01D | 603.84 | 608.84 | 5 | – | 5.00 | – | –5.10 | – | – | 100 | 8.20E–10 | 2.70E–09 | 8.20E–06 | |
| KFM01D | 608.85 | 613.85 | 5 | – | 5.07 | – | –5.03 | – | – | 100 | 8.20E–10 | 2.70E–09 | 8.20E–06 | |
| KFM01D | 613.85 | 618.85 | 5 | – | 5.12 | – | –4.96 | – | – | 100 | 8.20E–10 | 2.70E–09 | 8.20E–06 | |
| KFM01D | 618.86 | 623.86 | 5 | – | 5.18 | – | –4.90 | – | – | 100 | 8.20E–10 | 2.70E–09 | 8.20E–06 | |
| KFM01D | 623.86 | 628.86 | 5 | – | 5.23 | – | –4.83 | – | – | 100 | 8.20E–10 | 2.70E–09 | 8.20E–06 | |
| KFM01D | 628.87 | 633.87 | 5 | – | 5.29 | – | –4.77 | – | – | 100 | 8.20E–10 | 2.70E–09 | 8.20E–06 | |
| KFM01D | 633.87 | 638.87 | 5 | – | 5.37 | – | –4.71 | – | – | 100 | 8.20E–10 | 2.70E–09 | 8.20E–06 | |
| KFM01D | 638.88 | 643.88 | 5 | – | 5.44 | – | –4.63 | – | – | 100 | 8.20E–10 | 2.70E–09 | 8.20E–06 | |
| KFM01D | 643.88 | 648.88 | 5 | – | 5.50 | – | –4.58 | – | – | 100 | 8.20E–10 | 2.70E–09 | 8.20E–06 | |
| KFM01D | 648.88 | 653.88 | 5 | – | 5.56 | – | –4.49 | – | – | 100 | 8.20E–10 | 2.70E–09 | 8.20E–06 | |
| KFM01D | 653.89 | 658.89 | 5 | – | 5.60 | – | –4.43 | – | – | 100 | 8.20E–10 | 2.70E–09 | 8.20E–06 | |
| KFM01D | 658.89 | 663.89 | 5 | – | 5.66 | – | –4.37 | – | – | 100 | 8.20E–10 | 2.70E–09 | 8.20E–06 | |
| KFM01D | 663.88 | 668.88 | 5 | – | 5.72 | – | –4.31 | – | – | 100 | 8.20E–10 | 2.70E–09 | 8.20E–06 | |
| KFM01D | 668.88 | 673.88 | 5 | – | 5.77 | – | –4.23 | – | – | 100 | 8.20E–10 | 2.70E–09 | 8.20E–06 | |
| KFM01D | 673.88 | 678.88 | 5 | – | 5.83 | – | –4.15 | – | – | 100 | 8.30E–10 | 2.80E–09 | 8.30E–06 | |
| KFM01D | 678.88 | 683.88 | 5 | – | 5.91 | – | –4.08 | – | – | 100 | 8.30E–10 | 2.80E–09 | 8.30E–06 | |
| KFM01D | 683.88 | 688.88 | 5 | – | 5.97 | – | –4.01 | – | – | 100 | 8.30E–10 | 2.80E–09 | 8.30E–06 | |
| KFM01D | 688.87 | 693.87 | 5 | – | 6.03 | – | –3.93 | – | – | 100 | 8.30E–10 | 2.80E–09 | 8.30E–06 | |

| Borehole ID | Secup L(m) | Seclow L(m) | $L_w$ (m) | Q0 ($m^3/s$) | h0FW (m.a.s.l.) | Q1 ($m^3/s$) | h1FW (m.a.s.l.) | $T_D$ ($m^2/s$) | hi (m.a.s.l.) | Q-lower limit P (mL/h) | $T_D$-measlLT ($m^2/s$) | $T_D$-measlLP ($m^2/s$) | $T_D$-measlU ($m^2/s$) | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| KFM01D | 693.87 | 698.87 | 5 | – | 6.10 | – | –3.84 | – | – | 100 | 8.30E–10 | 2.80E–09 | 8.30E–06 | |
| KFM01D | 698.87 | 703.87 | 5 | – | 6.16 | – | –3.78 | – | – | 100 | 8.30E–10 | 2.80E–09 | 8.30E–06 | |
| KFM01D | 703.88 | 708.88 | 5 | – | 6.22 | – | –3.72 | – | – | 100 | 8.30E–10 | 2.80E–09 | 8.30E–06 | |
| KFM01D | 708.88 | 713.88 | 5 | – | 6.29 | – | –3.64 | – | – | 100 | 8.30E–10 | 2.80E–09 | 8.30E–06 | |
| KFM01D | 713.88 | 718.88 | 5 | – | 6.38 | – | –3.57 | – | – | 100 | 8.30E–10 | 2.80E–09 | 8.30E–06 | |
| KFM01D | 718.88 | 723.88 | 5 | – | 6.43 | – | –3.49 | – | – | 100 | 8.30E–10 | 2.80E–09 | 8.30E–06 | |
| KFM01D | 723.89 | 728.89 | 5 | – | 6.50 | – | –3.43 | – | – | 100 | 8.30E–10 | 2.80E–09 | 8.30E–06 | |
| KFM01D | 728.89 | 733.89 | 5 | – | 6.57 | – | –3.36 | – | – | 100 | 8.30E–10 | 2.80E–09 | 8.30E–06 | |
| KFM01D | 733.89 | 738.89 | 5 | – | 6.63 | – | –3.27 | – | – | 100 | 8.30E–10 | 2.80E–09 | 8.30E–06 | |
| KFM01D | 738.89 | 743.89 | 5 | – | 6.70 | – | –3.19 | – | – | 100 | 8.30E–10 | 2.80E–09 | 8.30E–06 | |
| KFM01D | 743.90 | 748.90 | 5 | – | 6.76 | – | –3.12 | – | – | 100 | 8.30E–10 | 2.80E–09 | 8.30E–06 | |
| KFM01D | 748.90 | 753.90 | 5 | – | 6.84 | – | –3.04 | – | – | 100 | 8.30E–10 | 2.80E–09 | 8.30E–06 | |
| KFM01D | 753.90 | 758.90 | 5 | – | 6.91 | – | –2.97 | – | – | 100 | 8.30E–10 | 2.80E–09 | 8.30E–06 | |
| KFM01D | 758.90 | 763.90 | 5 | – | 6.98 | – | –2.89 | – | – | 100 | 8.40E–10 | 2.80E–09 | 8.40E–06 | |
| KFM01D | 763.90 | 768.90 | 5 | – | 7.05 | – | –2.81 | – | – | 100 | 8.40E–10 | 2.80E–09 | 8.40E–06 | |
| KFM01D | 768.90 | 773.90 | 5 | – | 7.12 | – | –2.74 | – | – | 100 | 8.40E–10 | 2.80E–09 | 8.40E–06 | |
| KFM01D | 773.90 | 778.90 | 5 | – | 7.19 | – | –2.65 | – | – | 100 | 8.40E–10 | 2.80E–09 | 8.40E–06 | |
| KFM01D | 778.90 | 783.90 | 5 | – | 7.28 | – | –2.55 | – | – | 100 | 8.40E–10 | 2.80E–09 | 8.40E–06 | |
| KFM01D | 783.90 | 788.90 | 5 | – | 7.35 | – | –2.49 | – | – | 30 | 8.40E–10 | 8.40E–10 | 8.40E–06 | |
| KFM01D | 788.90 | 793.90 | 5 | – | 6.88 | – | –2.67 | – | – | 30 | 8.60E–10 | 8.60E–10 | 8.60E–06 | |

# Appendix 6

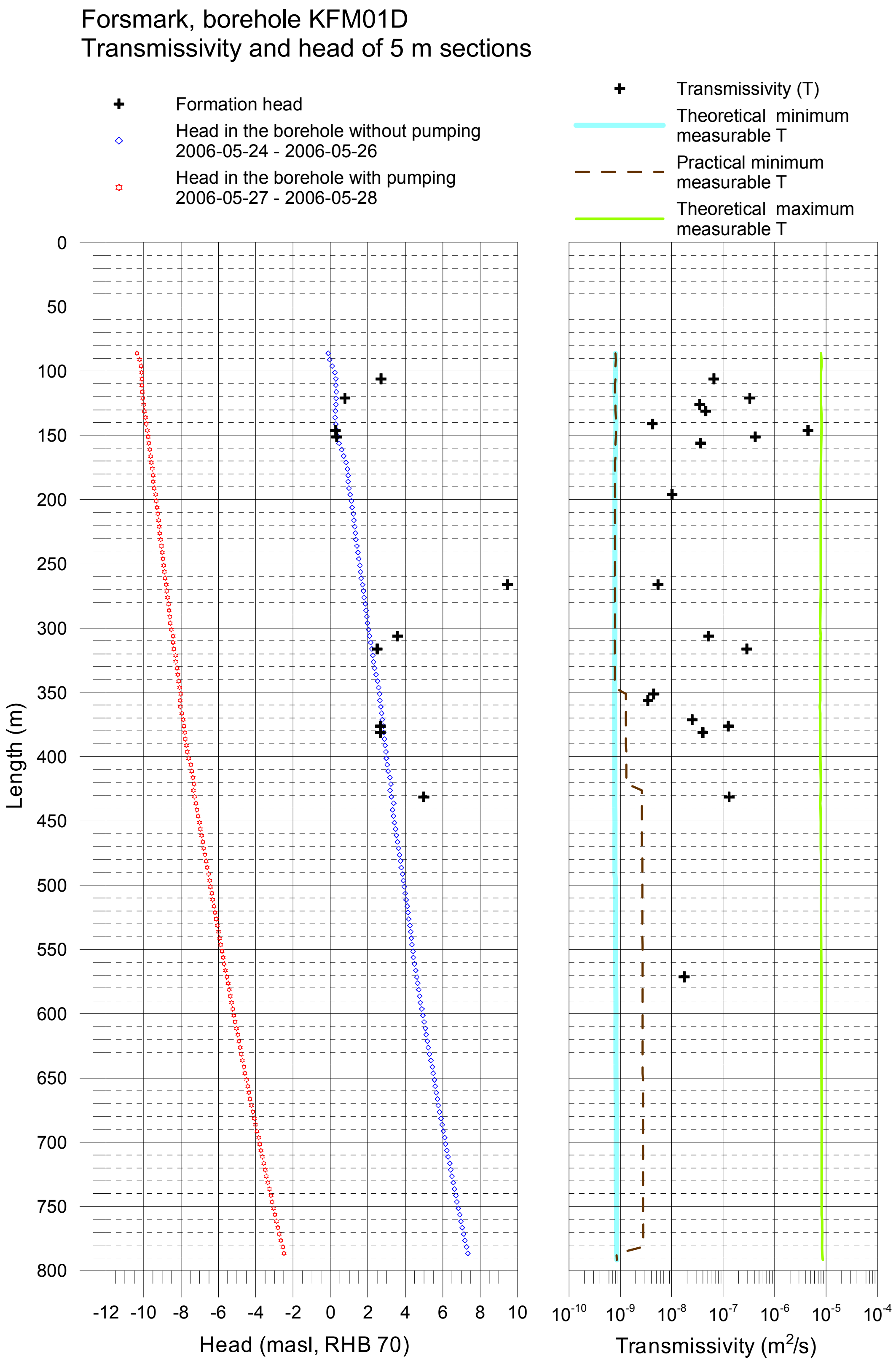
## Appendix 6.1 Flow rates of 5 m sections





## Appendix 6.2 Transmissivity and head of 5 m sections





# Appendix 7

## Table of transmissivity and head of detected fractures

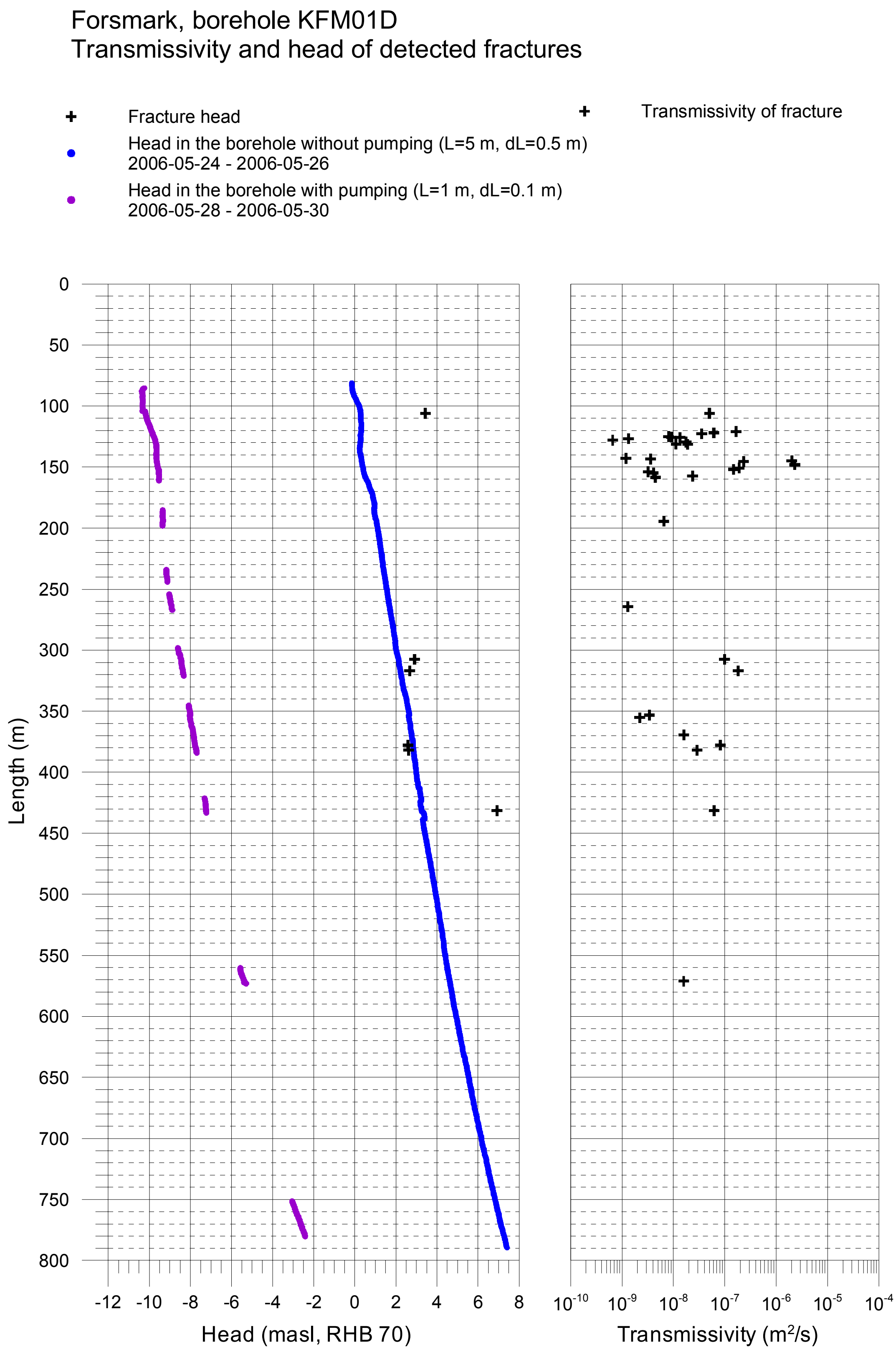
**PFL – Difference flow logging – Inferred flow anomalies from overlapping flow logging.**

| Borehole ID | Length to flow anom. L (m) | $L_w$ (m) | dL (m) | Q0 ($m^3/s$) | h0FW (m.a.s.l.) | Q1 ($m^3/s$) | h1FW (m.a.s.l.) | $T_D$ ($m^2/s$) | hi (m.a.s.l.) | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| KFM01D | 106.0 | 1 | 0.1 | 1.61E–07 | 0.28 | 6.94E–07 | –10.18 | 5.10E–08 | 3.40 | |
| KFM01D | 120.9 | 1 | 0.1 | – | 0.30 | 1.71E–06 | –9.88 | 1.70E–07 | – | |
| KFM01D | 121.9 | 1 | 0.1 | – | 0.30 | 6.28E–07 | –9.86 | 6.10E–08 | – | |
| KFM01D | 122.7 | 1 | 0.1 | – | 0.29 | 3.64E–07 | –9.83 | 3.60E–08 | – | |
| KFM01D | 125.0 | 1 | 0.1 | – | 0.28 | 8.22E–08 | –9.79 | 8.10E–09 | – | |
| KFM01D | 125.5 | 1 | 0.1 | – | 0.28 | 9.33E–08 | –9.77 | 9.20E–09 | – | |
| KFM01D | 125.7 | 1 | 0.1 | – | 0.28 | 1.37E–07 | –9.77 | 1.40E–08 | – | |
| KFM01D | 126.7 | 1 | 0.1 | – | 0.29 | 1.36E–08 | –9.74 | 1.30E–09 | – | |
| KFM01D | 128.0 | 1 | 0.1 | – | 0.29 | 6.67E–09 | –9.71 | 6.60E–10 | – | * |
| KFM01D | 129.5 | 1 | 0.1 | – | 0.26 | 1.79E–07 | –9.70 | 1.80E–08 | – | |
| KFM01D | 131.2 | 1 | 0.1 | – | 0.26 | 1.14E–07 | –9.67 | 1.10E–08 | – | |
| KFM01D | 131.4 | 1 | 0.1 | – | 0.26 | 1.91E–07 | –9.67 | 1.90E–08 | – | |
| KFM01D | 142.8 | 1 | 0.1 | – | 0.31 | 1.19E–08 | –9.65 | 1.20E–09 | – | * |
| KFM01D | 143.4 | 1 | 0.1 | – | 0.31 | 3.61E–08 | –9.65 | 3.60E–09 | – | |
| KFM01D | 144.9 | 1 | 0.1 | – | 0.33 | 2.04E–05 | –9.64 | 2.00E–06 | – | |
| KFM01D | 145.5 | 1 | 0.1 | – | 0.34 | 2.34E–06 | –9.64 | 2.30E–07 | – | |
| KFM01D | 148.0 | 1 | 0.1 | – | 0.36 | 2.32E–05 | –9.61 | 2.30E–06 | – | |
| KFM01D | 150.8 | 1 | 0.1 | – | 0.40 | 1.93E–06 | –9.57 | 1.90E–07 | – | |
| KFM01D | 151.9 | 1 | 0.1 | – | 0.41 | 1.49E–06 | –9.55 | 1.50E–07 | – | |
| KFM01D | 153.9 | 1 | 0.1 | – | 0.43 | 3.25E–08 | –9.53 | 3.20E–09 | – | * |
| KFM01D | 154.9 | 1 | 0.1 | – | 0.44 | 4.11E–08 | –9.55 | 4.10E–09 | – | |
| KFM01D | 157.4 | 1 | 0.1 | – | 0.49 | 2.39E–07 | –9.53 | 2.40E–08 | – | |
| KFM01D | 158.4 | 1 | 0.1 | – | 0.51 | 4.53E–08 | –9.53 | 4.50E–09 | – | |
| KFM01D | 194.4 | 1 | 0.1 | – | 1.05 | 6.86E–08 | –9.34 | 6.50E–09 | – | |
| KFM01D | 264.3 | 1 | 0.1 | – | 1.69 | 1.39E–08 | –8.92 | 1.30E–09 | – | |
| KFM01D | 307.4 | 1 | 0.1 | 7.83E–08 | 2.13 | 1.14E–06 | –8.45 | 9.90E–08 | 2.90 | |
| KFM01D | 316.9 | 1 | 0.1 | 8.44E–08 | 2.21 | 2.04E–06 | –8.37 | 1.80E–07 | 2.70 | |
| KFM01D | 353.2 | 1 | 0.1 | – | 2.66 | 3.69E–08 | –8.02 | 3.40E–09 | – | * |
| KFM01D | 355.2 | 1 | 0.1 | – | 2.63 | 2.39E–08 | –8.03 | 2.20E–09 | – | * |
| KFM01D | 369.5 | 1 | 0.1 | – | 2.76 | 1.72E–07 | –7.86 | 1.60E–08 | – | |
| KFM01D | 377.9 | 1 | 0.1 | –2.06E–08 | 2.84 | 8.61E–07 | –7.78 | 8.20E–08 | 2.60 | |
| KFM01D | 382.0 | 1 | 0.1 | –6.94E–09 | 2.86 | 3.03E–07 | –7.72 | 2.90E–08 | 2.60 | |
| KFM01D | 431.5 | 1 | 0.1 | 2.31E–07 | 3.26 | 8.92E–07 | –7.24 | 6.20E–08 | 6.90 | |
| KFM01D | 571.2 | 1 | 0.1 | – | 4.62 | 1.61E–07 | –5.38 | 1.60E–08 | – | |

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

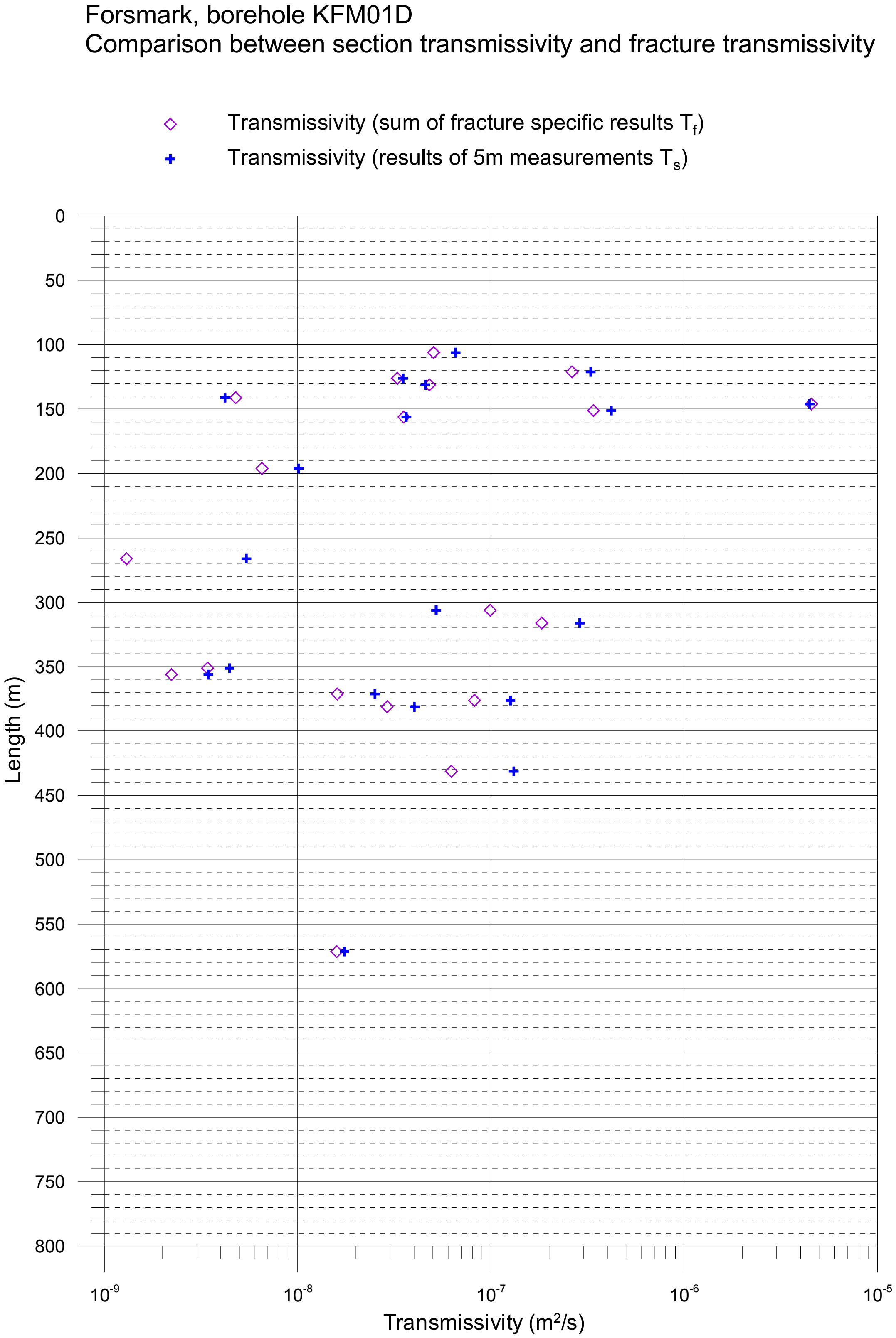
## Transmissivity and head of detected fractures

Appendix 8



# Comparison between section transmissivity and fracture transmissivity

Appendix 9



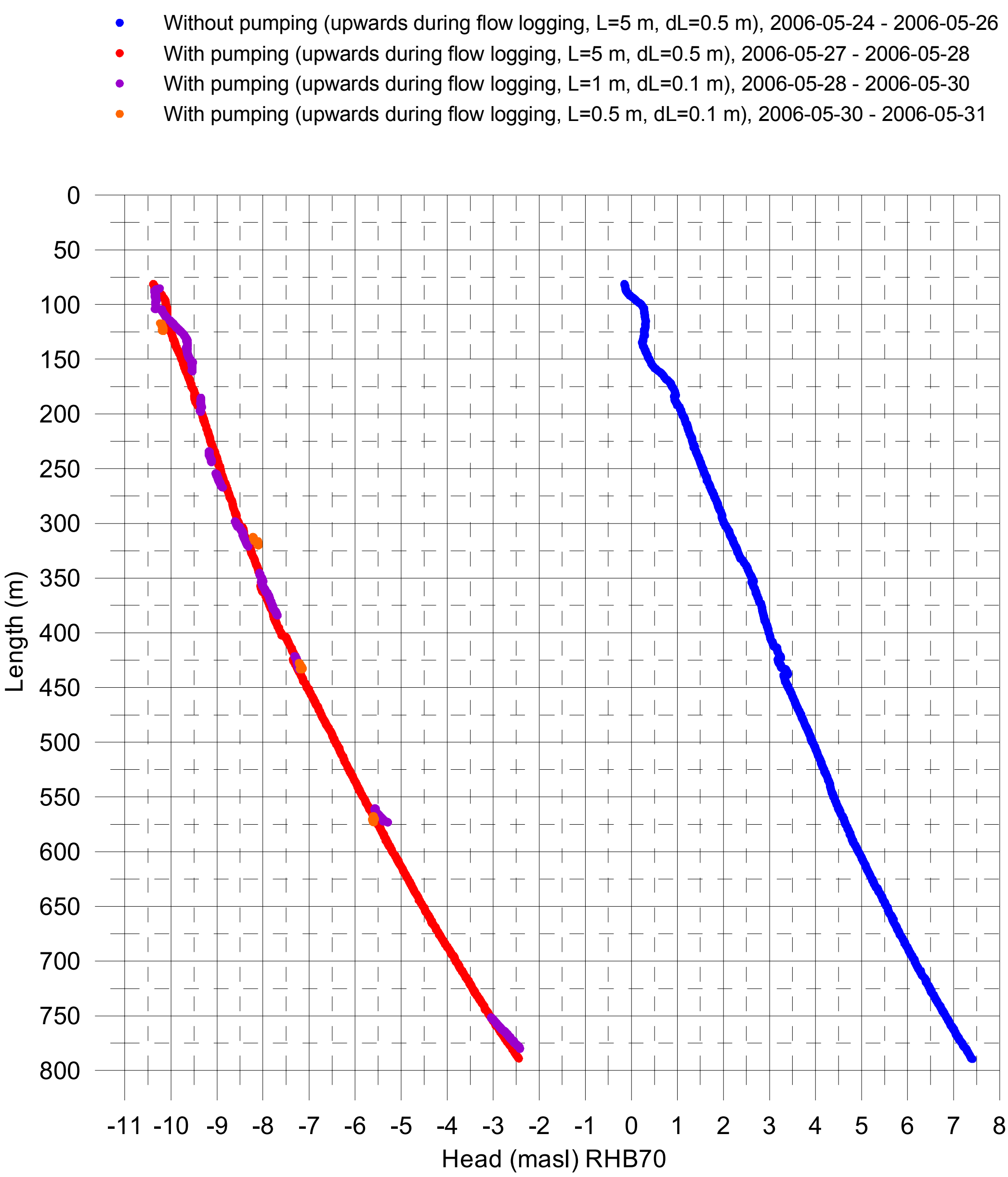
# Appendix 10

## Appendix 10.1 Head in the borehole during flow logging



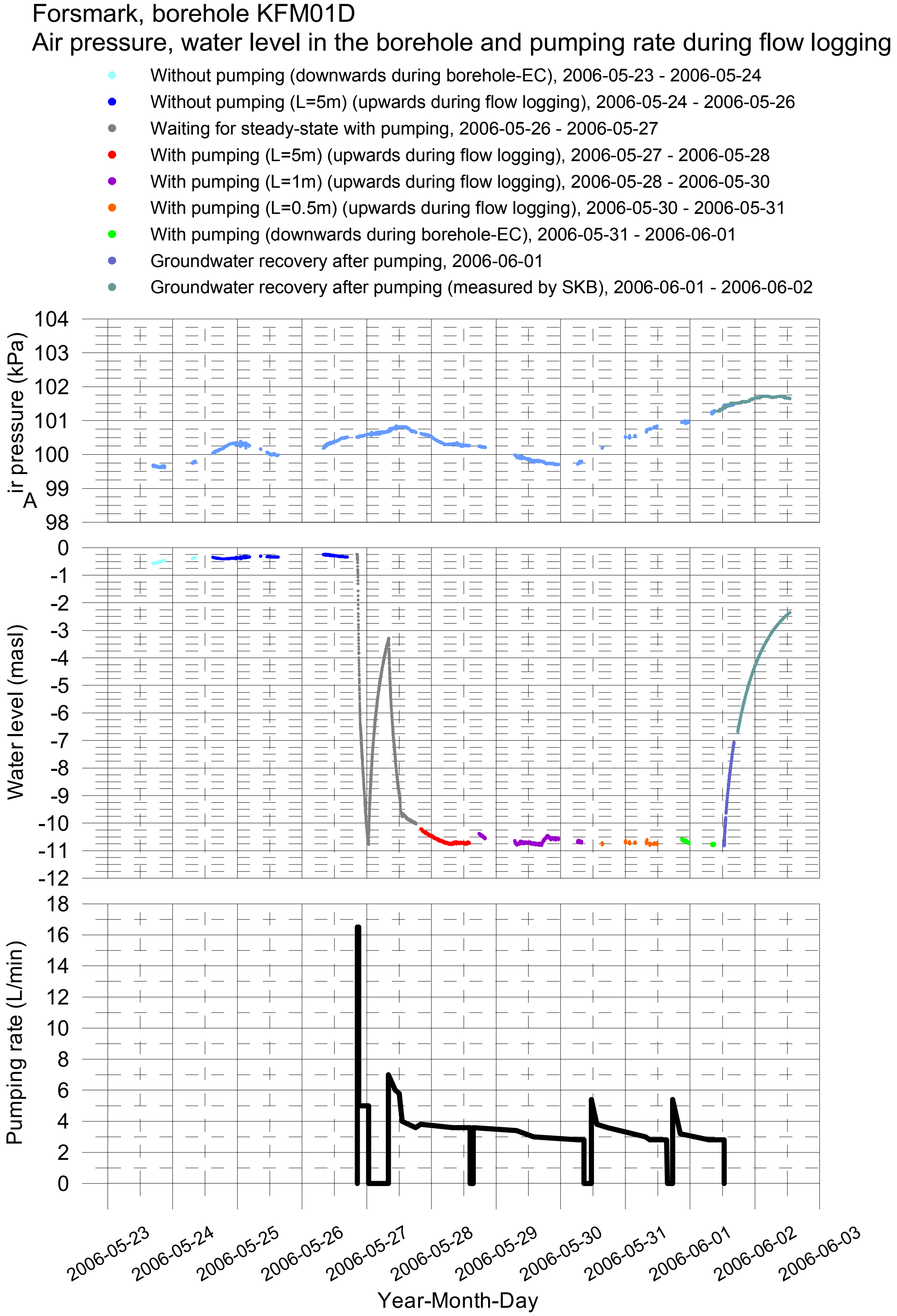
Forsmark, borehole KFM01D
Head in the borehole during flow logging

Head(masl)= (Absolute pressure (Pa) - Airpressure (Pa) + Offset) /(1000 kg/m$^3$ * 9.80665 m/s$^2$) + Elevation (m)
Offset = 2300 Pa (Correction for absolut pressure sensor)



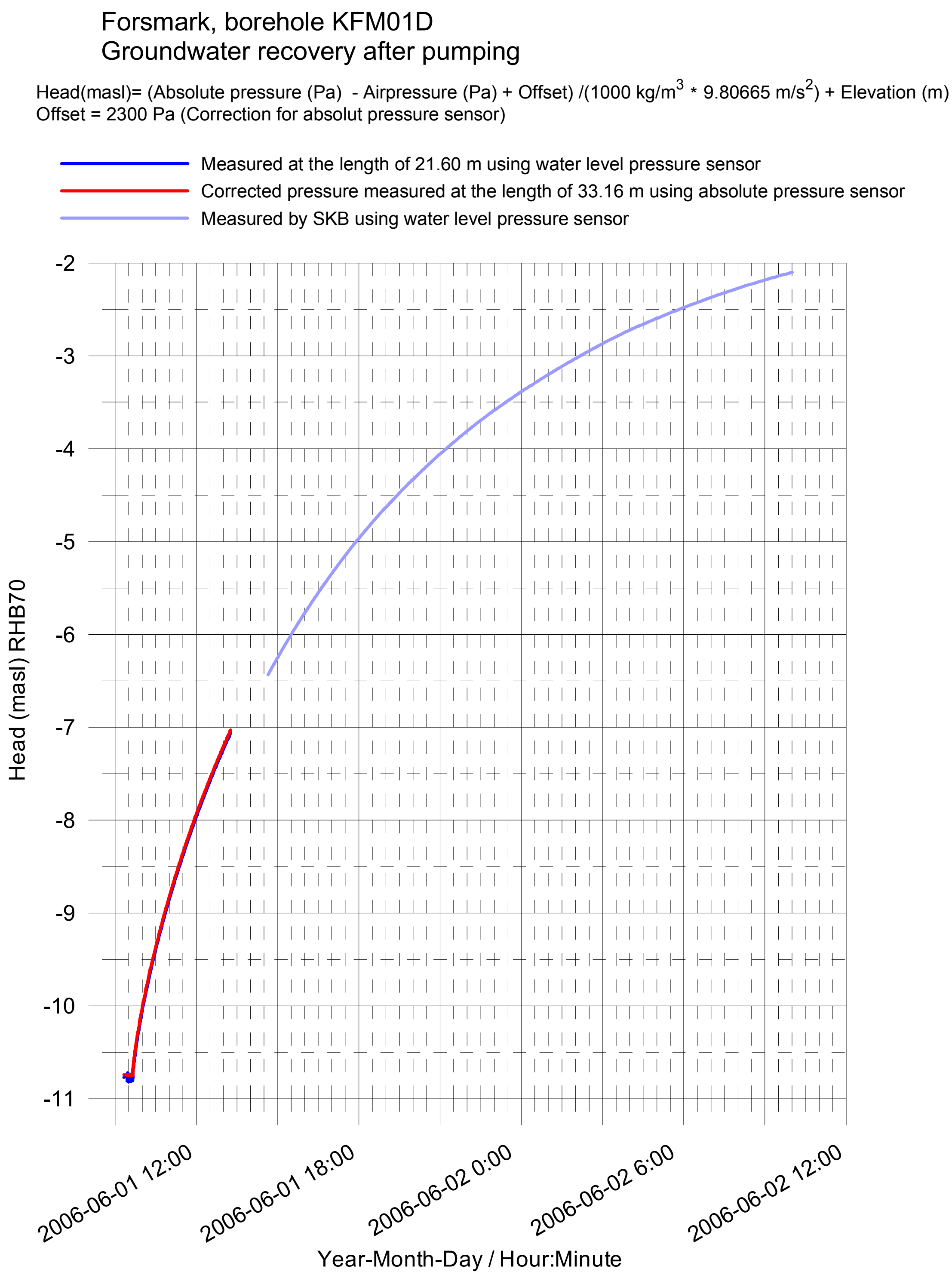
## Appendix 10.2 Air pressure, water level in the borehole and pumping rate during flow logging





## Appendix 10.3 Groundwater recovery after pumping

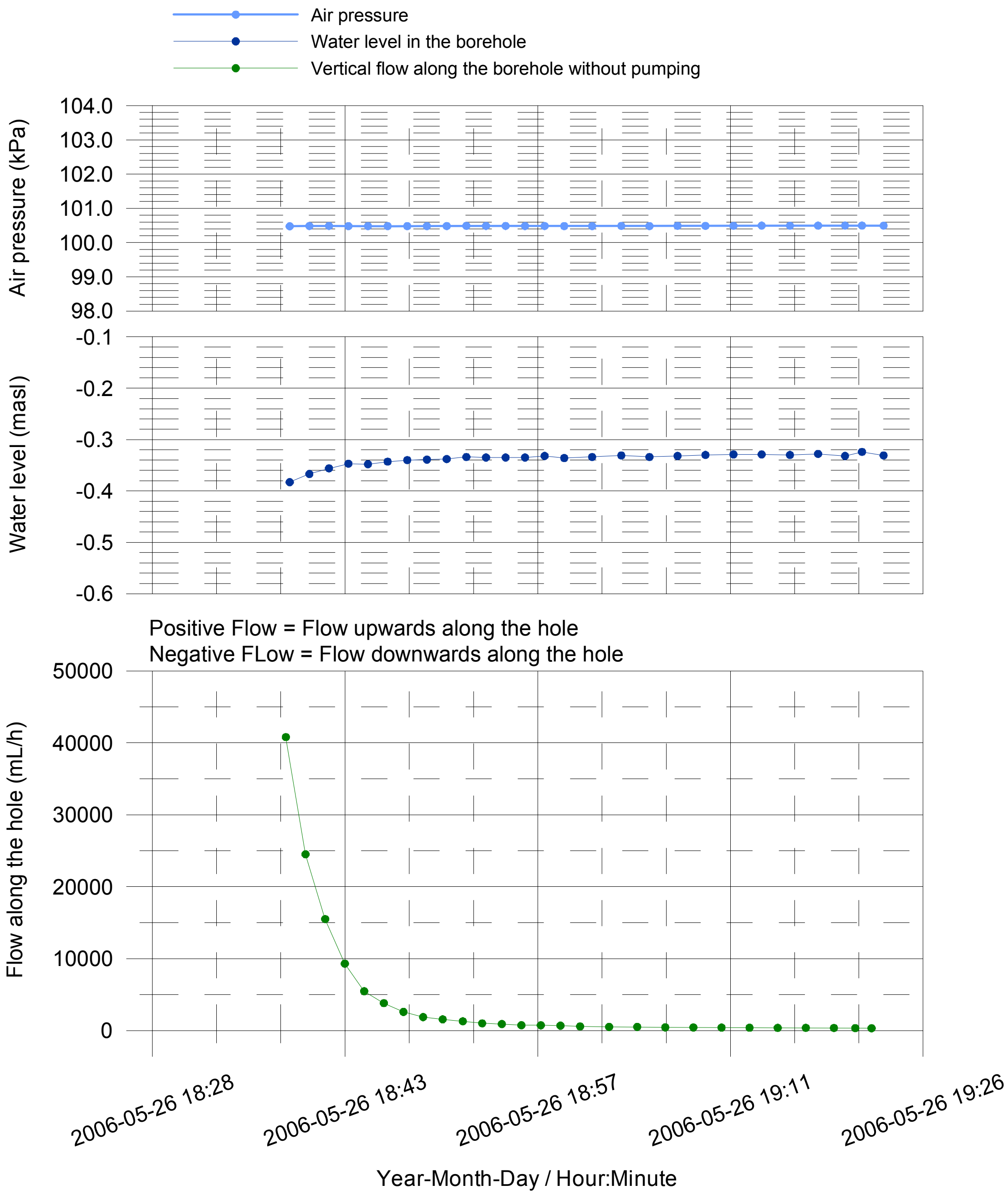




## Appendix 10.4 Vertical flow along the borehole at the length of 93.52 m



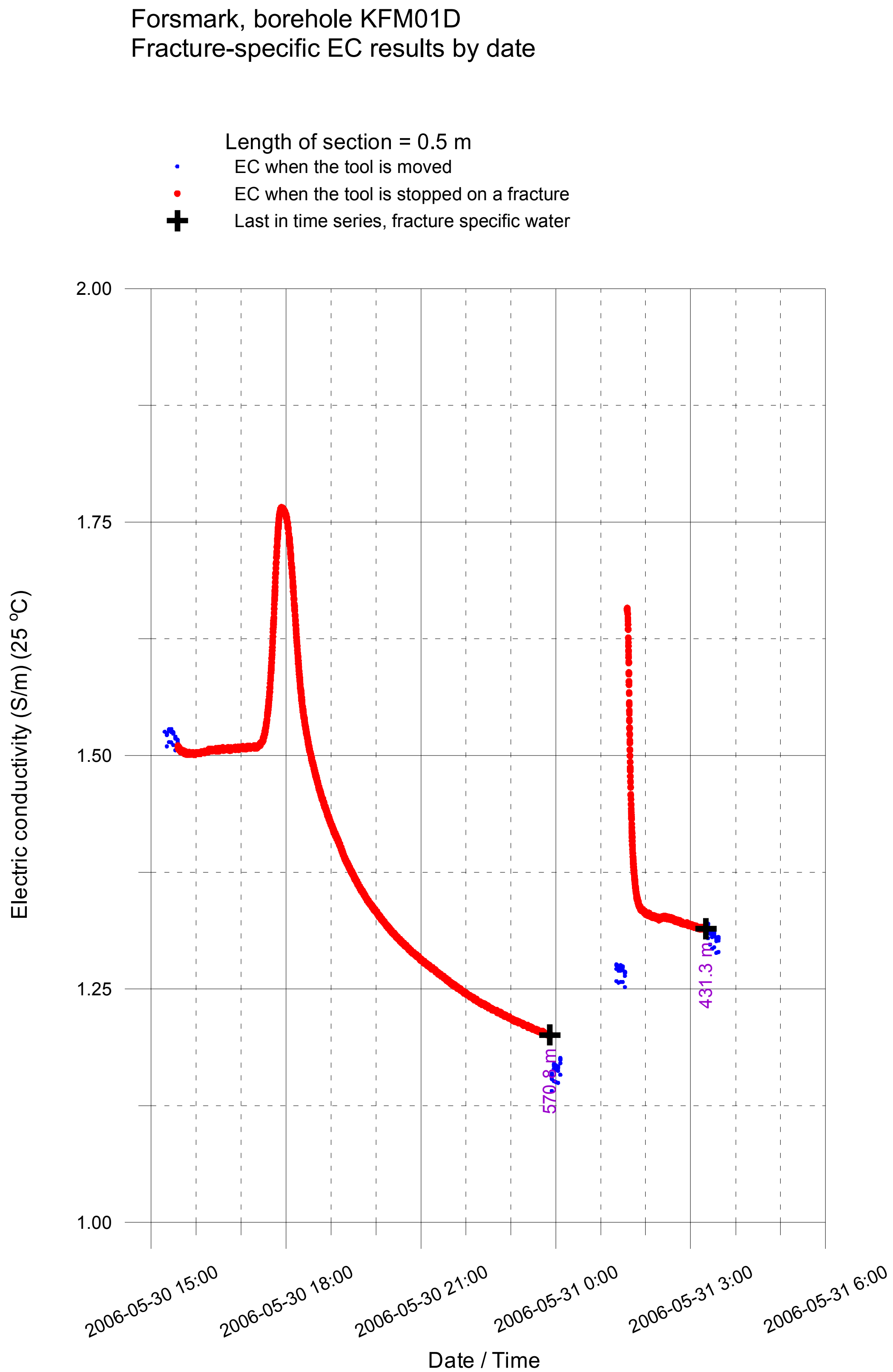
Forsmark, borehole KFM01D
Vertical flow along the borehole at the length of 93.52 m



# Appendix 11

## Appendices 11.1–11.2 Fracture-specific EC results by date

Appendix 11.1



Forsmark, borehole KFM01D
Fracture-specific EC results by date