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Difference flow logging in boreholes KFR119 and KFR121

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Abstract

This report presents the main principles of the methods as well as the results of measurements carried out in boreholes KFR119 and KFR121 at Forsmark area, Sweden, in October and November 2020.

The Posiva Flow Log, Difference Flow Method (PFL DIFF) uses a flowmeter that incorporates a flow guide and can be used for relatively quick determinations of transmissivity and hydraulic head of fractures/fracture zones intersecting boreholes.

The first flow logging measurement was carried out with a 5 m long test section by moving the measurement tool in 0.5 m long increments covering the entire measurable length of a borehole while borehole remained in undisturbed conditions. An additional flow logging during undisturbed conditions with a 1 m long test section and in 0.1 m long increments was conducted, where more detailed information on fracture-specific flows was needed. In KFR121 length intervals ca. 32-110 m, 140–230 m and 260–305 m were measured with a 1 m long test section while in KFR119 the additional measurement was not considered necessary. The flow logging measurement setup with a 5 m long test section and 0.5 m long increments was repeated while water level in the measured borehole was lowered by pumping water out of the borehole. The flow logging measurement in pumped conditions was conducted also using 1 m test section, with 0.1 m long increments.

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

The flow along the borehole was measured below the casing shoe during undisturbed conditions to detect possible leaks between the casing pipe and the bedrock.

Measurements of electrical conductivity (EC) and temperature of borehole water were also conducted. The EC measurements were used to study the occurrence of saline water in the borehole in un-pumped as well as in pumped conditions. The EC of fracture-specific water was measured (using 1 m long test section) at selected fractures.

Recovery of the groundwater level in the boreholes was measured after the pumping of was stopped.

A very high borehole outflow in pumped conditions was measured in KFR119 and the maximum achievable drawdown with available pumping equipment was 1 m. Drawdown of 10 m was used in KFR121. A number of flowing fractures was found in both boreholes. A total of 37 fractures (*0.22 fractures/m*) were detected in KFR119 and 107 fractures (*0.35 fractures/m*) in KFR121. In KFR119 outflow from one measured fracture (*fracture at 11.4 m*) practically exceeded the upper measurement limit even with 1 m drawdown and moving the PFL DIFF tool on the fracture changed the prevailing pressure conditions at the measurement location significantly. This greatly affected the fracture- and section-specific flow and pressure measurements results from the corresponding test section. In KFR121 all of the measured flows were clearly below the upper limit of the flow measurement range.

Sammanfattning

Denna rapport presenterar huvudprinciperna för metoden och resultat av mätningar utförda i borrhål KFR119 och KFR121 i Forsmarksområdet, Sverige, i oktober och november 2020.

Posiva Flow Log, Differensflödesloggning (*PFL DIFF*) är en snabb metod för bestämning av transmissiviteten och hydraulisk tryckhöjd i borrhålssektioner och sprickor/sprickzoner i kärnborrhål.

Flödet till eller från en 5 m lång testsektion (*som successivt förflyttades med 0,5 m*) mättes i borrhålet under såväl naturliga förhållanden som vid pumpning. En ytterligare flödesloggning under ostörda förhållanden, med 1 m testsektion och 0,1 m mätningsmellanrum utfördes, om mer detaljerad information behövdes om sprickspecifika flöden i ett borrhål. Flödesmätningarna upprepades under pumpning med en 1 m lång testsektion som successivt förflyttades i steg om 0,1 m.

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

Mätning av flödet längs borrhålet gjordes nedanför foderröret under naturliga betingelser för att detektera läckage av foderröret.

Elektrisk konduktivitet (*EC*) och temperatur på borrhålsvattnet mättes också. EC-mätningarna användes för att studera förekomsten av saltvatten i borrhålet under såväl naturliga som pumpade förhållanden. EC mättes även i ett antal utvalda sprickor i borrhålet (1 m lång testsektion).

Återhämtningen av grundvattennivån mättes efter att pumpningen i borrhålet avslutats.

I KFR119 mättes mycket högt borrhålsutflöde under pumpade förhållanden och den maximala uppnåeliga neddragningen med tillgänglig pumputrustning var 1 m. I KFR121 uppnåddes en neddragning på 10 m. I båda borrhålen hittades ett antal flödessprickor. 37 sprickor (*0,22 sprickor/m*) hittades i KFR119 och 107 sprickor (*0,35 sprickor/m*) i KFR121. I KFR119 översteg utflödet från en uppmätt spricka (*spricka vid 11,4 m*) praktiskt taget den övre mätgränsen även med 1 m neddragning och en flyttning av PFL DIFF-sonden på sprickan förändrade tryckförhållandena i borrhålet avsevärt. Detta påverkade i hög grad de sprick- och sektionsspecifika flödes- och tryckmätningsresultaten från motsvarande testsektion. I KFR121 var alla uppmätta flöden klart under den övre gränsen av flödes-mätområdet för sonden.

Content

1 Introduction

The core drilled boreholes KFR119 and KFR121 at Forsmark area, Sweden were measured using the Posiva Flow Log, Difference Flow Method (*PFL DIFF*) which provides a swift, multifaceted characterization of a borehole. The measurement campaign was conducted between October 6 and November 3, 2020.

KFR119 is ca 175.6 m long and its inclination at the ground level is ca -80.8 ° from the horizontal plane. Casing pipe in KFR119 is quite short, ca 9 m long, with inner diameter of 77 mm. KFR121 is ca 362.5 m long and its inclination at the ground level is ca -52.5 ° from the horizontal plane. Casing pipe in KFR121 is ca 41.4 m long in total (*including the funnel part and reduction to actual borehole diameter in the bedrock*) with inner diameter of 200 mm. The rest of the boreholes are 75.8 mm in inner diameter. Technical details of the boreholes are presented in Table 1-1.

Table 1-1. Technical details of the measured boreholes (RH 2000 coordinate system).

Borehole ID	Length (m)	Inclination (degrees)	Z coordinate of top of the casing (masl)	Length of casing pipe (m)
KFR119	176.88	-80.79	3.10	9.00
KFR121	362.53	-52.45	2.87	41.32

The locations of measured boreholes at Forsmark are illustrated in Figure 1-1. Borehole number KBH5 is KFR119 and borehole number KBH1 is KFR121.

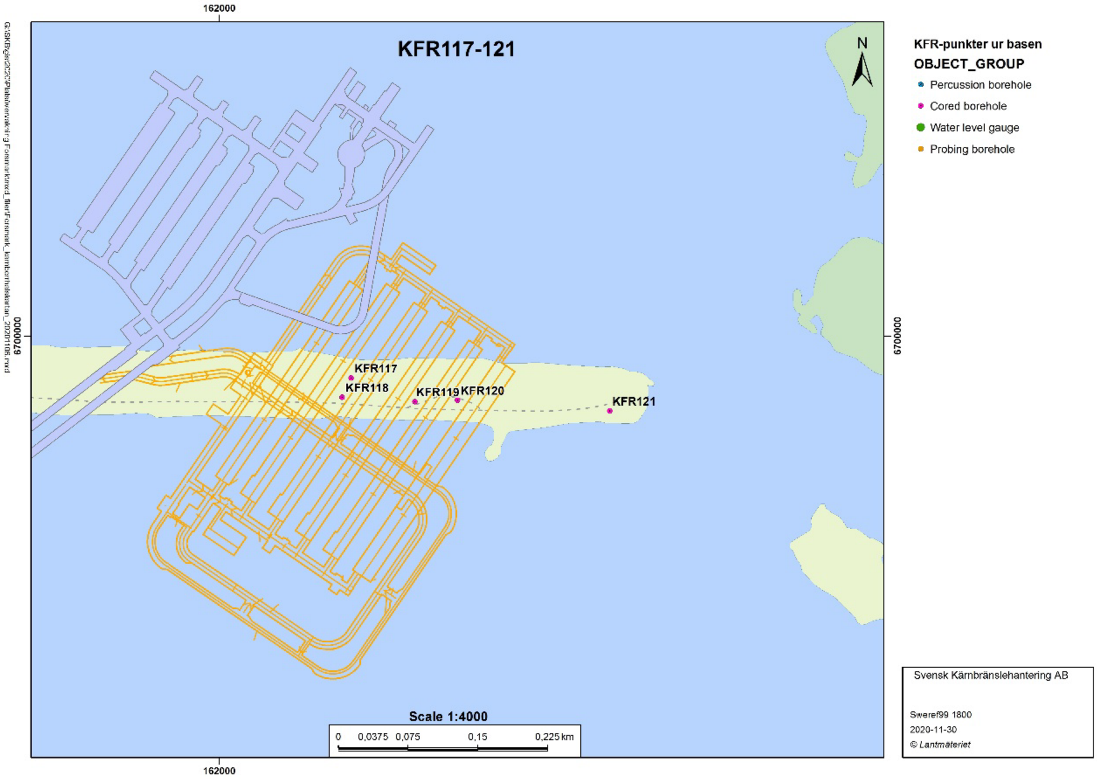

Figure 1-1. Locations of the boreholes in Forsmark (from AP SFK-20-007).

The PFL DIFF measurements were coordinated and led by Posiva Solutions Oy. AFRY Finland Oy acted as a subcontractor in the assignment conducting field work and reporting. The PFL DIFF 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 assignment at the latter site included measurements in the 1700 m long cored borehole KLX02 at Laxemar together with a methodology study (Ludvigson et al. 2002). The PFL DIFF Method has also been employed in SKB’s site characterisation programme at Laxemar and Forsmark.

This document reports the results acquired by using the PFL DIFF Method. The measurements were carried out to investigate hydraulic conditions of bedrock at Forsmark as instructed in SKB's internal controlling document AP SFK-20-007. The controlling documents for performing according to the Activity Plan are listed in Table 1-2. The list of the controlling documents excludes the assignment-specific quality plans. Both the Activity Plan and the Method Descriptions 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 1-2. SKB's internal controlling documents for the activities concerning this report.

Activity Plan	**Number**	**Version**
Difference flow logging in boreholes KFR117 – KFR121	AP SFK-20-007	1.0
Method Descriptions	Number	Version
Method Description for Difference Flow Logging	SKB MD 322.010e	2.0
Instructions for cleaning borehole equipment and certain surface equipment	SKB MD 600.004e	1.0

2 Objectives and scope of the work

The main objective of the PFL DIFF measurements in the boreholes was to identify water-conductive sections/fractures. Secondly, the measurements aimed at a hydro-geological characterisation, which includes the inspection of the prevailing water flow balance in the borehole and the hydraulic properties (*transmissivity and undisturbed hydraulic head*) of the tested sections. Based on the results of these investigations, a more detailed characterisation of flow anomalies along the borehole, e.g. an estimate of the conductive fracture frequency (*CFF*), may be obtained.

Besides difference flow logging, the measurement programme also included supporting measurements, performed in order to gain a better understanding of the overall hydro-geochemical conditions. These measurements included the electrical conductivity (*EC*) and the temperature of the borehole fluid as well as the single-point resistance of the borehole wall. The electrical conductivity of a number of selected fractures (*the electrical conductivity of water in the fractures*) in the boreholes was also measured. Furthermore, the recovery of the groundwater level after pumping period in each borehole was registered.

To measure absolute pressure along a borehole, a high-resolution pressure sensor was used, and pressure measurement was carried out simultaneously with the flow measurements. The results are used for the calculation of the hydraulic head along the borehole.

The flow along the borehole was measured below the casing pipe in undisturbed conditions (*without pumping*) to detect possible leaks from the casing.

3 Principles of measurement and interpretation

3.1 Measurements

Unlike conventional borehole flowmeters, which measure the total cumulative flow rate along a borehole, the PFL DIFF probe measures the flow rate into or out of defined borehole sections during both non-pumped (*"undisturbed"*) and pumped conditions. The advantage that follows from measuring the flow rate in separated sections is improved detection of incremental changes of flow along the borehole. As these flows are generally very small, they can easily be missed when using conventional flowmeters. Technical illustrations of the PFL DIFF probe are presented in Figure 3-1.

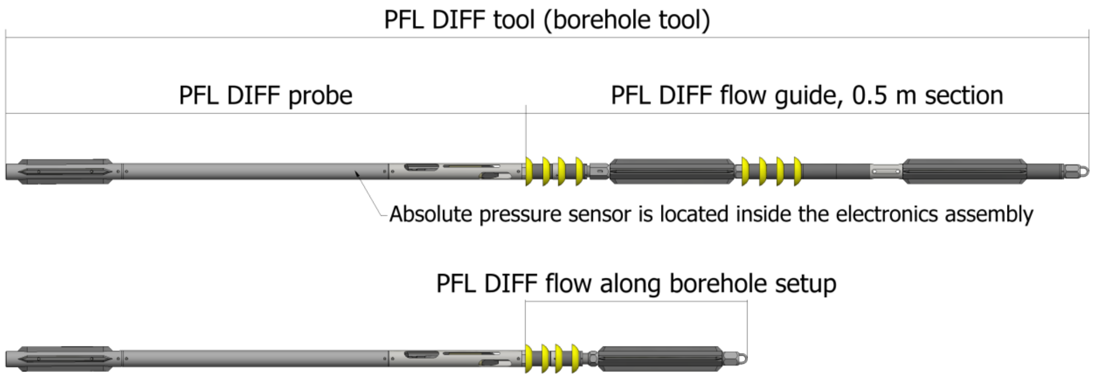

Figure 3-1. Technical illustration of the PFL DIFF probe in different setups.

Rubber sealing disks located at the top and bottom of the PFL DIFF probe are used to separate the flow of water in the test section from the flow in the rest of the borehole, see Figure 3-2. Flow inside the test section is directed through the flow sensor. Flow along the borehole is directed around the test section by means of a bypass pipe and is discharged at either the upper or lower end of the probe. The entire structure is called the flow guide. A schematic illustration representing a cross-section of the PFL DIFF probe's structure is presented in Figure 3-3. It should be noted that, depending on pressure difference between a fracture and a borehole, the direction of the measured flow can be from the bedrock into the borehole as the magenta coloured arrows represent in Figure 3-2 and Figure 3-3, or from the borehole into the bedrock in which case the arrowheads in Figure 3-2 and Figure 3-3 would be inverted. The same applies to flow along the hole as well, as it can go either upwards or downwards depending on the prevailing conditions in a borehole at a certain length.

Generally, two separate measurements with two different section lengths (*e.g. 1 m and 5 m*) are used. The 5 m setup is usually used first to obtain a general picture of the flow anomalies. It is also good for measuring longer (*less than 5 m in length*) fracture zones. The 1 m section setup can distinguish anomalies which are closer to each other. Different section lengths can also confirm that a flow anomaly is real and not caused for instance by leakage of the rubber discs.

In addition to incremental changes in flow, the PFL DIFF probe can also be used to measure:

- The electrical conductivity (*EC*) of both borehole water and fracture-specific water. The electrode used in EC measurements is located at the top of the flow sensor (*Figure 3-2*).
- The single point resistance (*SPR*) of a borehole wall (*grounding resistance*). The SPR electrode is located between the uppermost rubber sealing discs (*Figure 3-2*), and is used for the high-resolution length determination of fractures and geological structures.
- The ambient water pressure profile in a borehole. The pressure transducer is located inside the watertight electronics assembly and is connected to the borehole water through a tube (*Figure 3-1*).

- The temperature of the water in a borehole. The temperature sensor is part of the flow sensor (*Figure 3-2*).

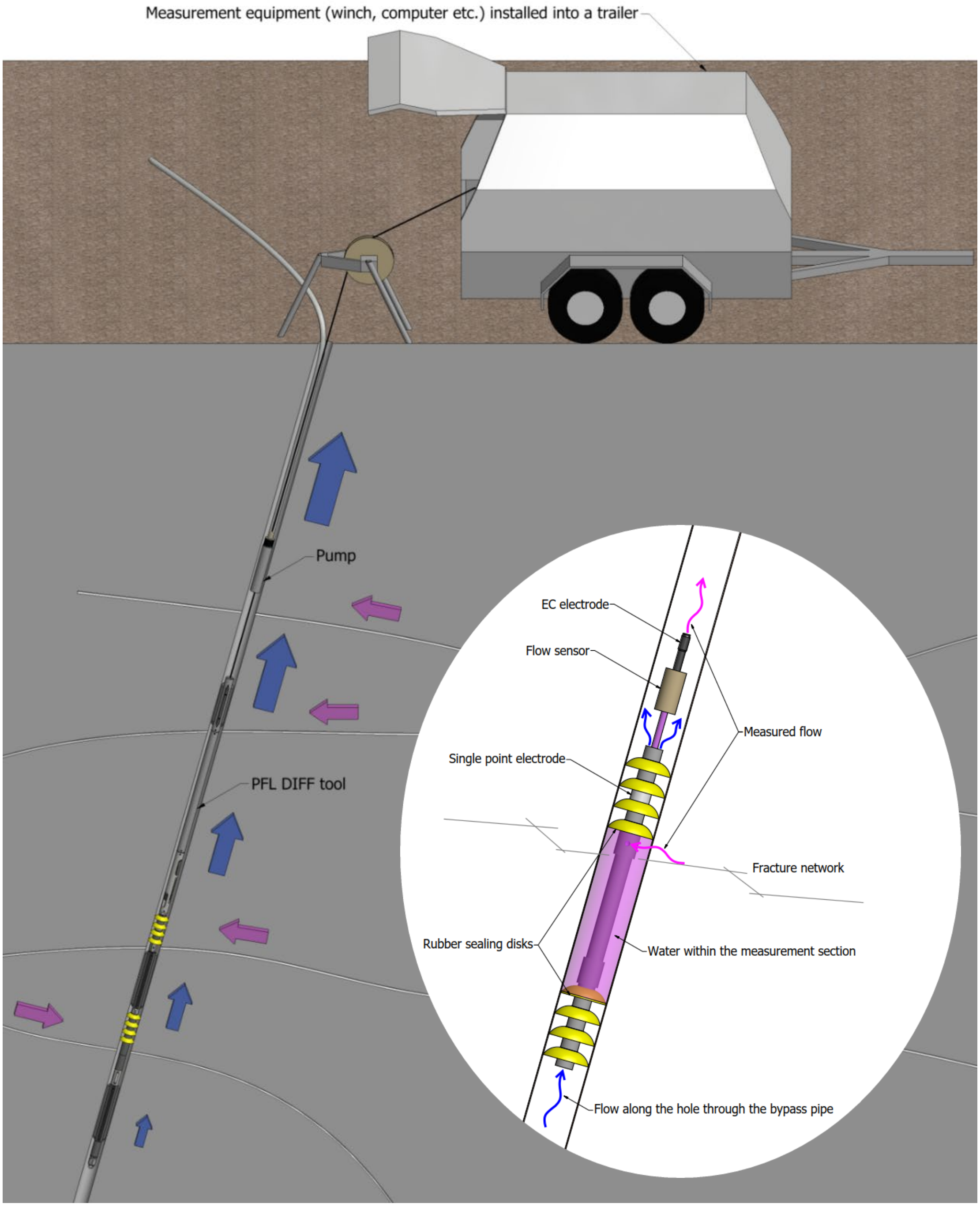

Figure 3-2. Schematic illustration of the probe used in the PFL DIFF.

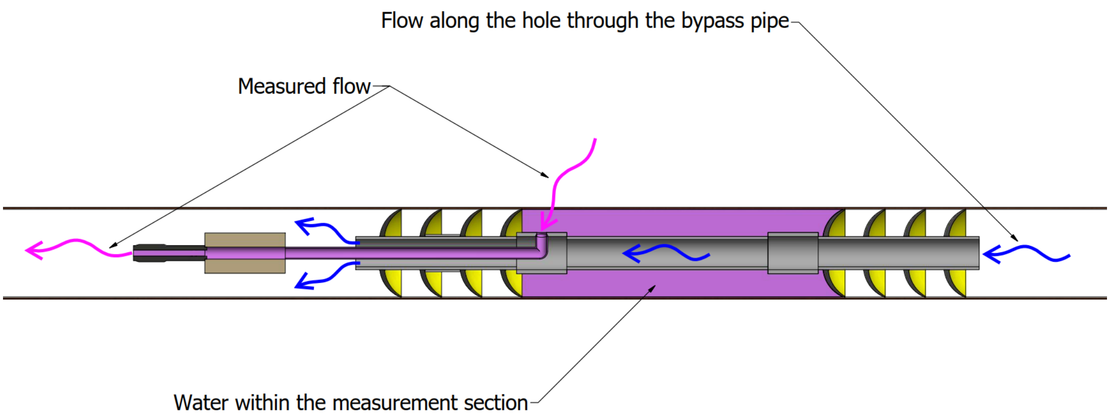

Figure 3-3. The absolute pressure sensor is located inside the electronics assembly and connected to the measurement section through a tube.

The measurement range for flow rate is 30 mL/h – 300 000 mL/h in general. The PFL DIFF probes have been calibrated for flow range from 6 mL/h to 300 000 mL/h in laboratory conditions but usually conditions at field raise the lower limit to ca. 30 mL/h. Therefore, in some cases flow rates below 30 mL/h can be measured. On the other hand, lower limit of 30 mL/h cannot be guaranteed in all borehole conditions. Examples of possible sources for disturbances are drilling debris entrained in the borehole water, bubbles of gas in the water and very high flow rates along the borehole (*some 30 L/min, i.e., 1 800 000 mL/h or more*). In case of significant disturbances, the practical measurement limits are calculated separately for each set of data. Measurement range of 30–300 000 mL/h has been determined based on experience and it is valid in most of cases, but exceptions exist.

3.2 Interpretation

The interpretation of data is based on Thiem's formula, which describes a steady-state and two-dimensional radial flow into the borehole (de Marsily 1986):

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

where

h is the hydraulic head in the borehole (*at borehole radius r_0*),

h_S is the hydraulic head at the radius of influence (*R*),

Q is the flow rate into the borehole,

T is the transmissivity of the test section,

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

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

where

r_0 is the radius of the borehole and

R is the radius of influence, i.e. distance to a constant head boundary.

If measurements of flow rate are carried out using two levels of hydraulic head in a borehole, i.e. undisturbed and pump-induced heads, then the computational value of head when section flow is zero (h_s) and the transmissivity of the borehole sections tested can be calculated. Equation 3-1 can be reformulated in the following two ways:

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

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

where

h_0 and h_1 are the hydraulic heads in the borehole at the test 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 section, i.e. head when the section flow is zero.

In general, since very little is known about the flow geometry, cylindrical flow without skin effect is assumed. The measurements are conducted in steady-state conditions and therefore no skin effect can be assumed, and the calculated transmissivity is determined based on the smallest conductivity in the fracture network where the water flow is coming from or going to. Basically, in case of positive skin the calculated transmissivity represents only the transmissivity close to the borehole and transmissivity of the fracture or fracture network further away from the borehole wall cannot be estimated. Cylindrical flow geometry is justified because the borehole is at a constant head, and no strong pressure gradients along the borehole exist except at its ends.

The radial distance R to the undisturbed hydraulic head h_s is not known and must therefore be assumed. In this case, a value of 500 for the quotient R/r_0 is selected. This corresponds a radius of influence of 19 m when the diameter of the borehole is 76 mm. Assuming a value of 500 implies that $a \approx 1$.

The hydraulic head h_s and the PFL transmissivity $T_{PFL,s}$ in the test section can be deduced from equations 3-5 and 3-6:

$$h_s = \frac{h_0 - bh_1}{1-b} \qquad (3\text{-}5)$$

$$T_{PFL,s} = \frac{1}{a}\frac{Q_{s0} - Q_{s1}}{h_1 - h_0} \qquad (3\text{-}6)$$

where

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

The PFL fracture transmissivity ($T_{PFL,f}$) and fracture hydraulic head (h_f) of individual fractures can be calculated, provided that the flow rates at the individual fractures are known. Similar assumptions to those employed above must be used (*a steady-state cylindrical flow regime without skin zones*).

$$h_f = \frac{h_0 - bh_1}{1-b} \qquad (3\text{-}7)$$

$$T_{PFL,f} = \frac{1}{a}\frac{Q_{f0} - Q_{f1}}{h_1 - h_0} \qquad (3\text{-}8)$$

where

Q_{f0} and Q_{f1} are the flow rates at a fracture and h_f and T_f are the hydraulic head (*head when fracture flow is zero*) and PFL fracture transmissivity of a fracture, respectively.

Since the actual flow geometry and any skin effects cannot be determined for steady-state flow, transmissivity values should only be considered as an indication of the prevailing orders of magnitude. As the calculated hydraulic heads do not depend on geometrical properties but only on the ratio of the flows measured at different heads in the borehole, they should be less sensitive to unknown fracture geometry. However, it is important to recognise that the measured fracture heads are a result of that the open boreholes connect fractures that may not be connected otherwise. A discussion of potential uncertainties in the calculation of transmissivity and hydraulic head can be found in Ludvigson et al. (2002).

The assumed constant radius of influence used in the formula of transmissivity, leads to uncertainty in determination of the transmissivity. The assumption of constant radius of influence (*R=19 m*) leads to definition of PFL transmissivity which is practically ΔQ/Δh, i.e. the specific capacity ($T_{PFL} \approx \Delta Q/\Delta h$). Finally, elevated noise level may affect the flow measurements and decrease the resolution of the flow measurements. This may affect determination of the transmissivity values in low-conducting sections, in which the increased noise level could mask smaller flow anomalies. In this report transmissivity refers to transmissivity calculated by Thiem's formula with above mentioned assumptions unless otherwise stated.

Transmissivity of the entire borehole can be evaluated in several ways using data of the pumping phase. The assumption above (*cylindrical and steady state flow*) leads to Thiems's formula (de Marsily 1986):

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

where

s is drawdown and

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

In the Moye formula (Moye 1967) it is assumed that 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, see the discussion in Chapter 2 of Follin (1992):

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

where

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

4 Equipment specification

With the PFL DIFF Method, the flow of groundwater into or out of a defined borehole section is monitored using a flow guide which employs rubber sealing discs to separate any such flow from the flow of water along the borehole. This flow guide defines the test section being measured without altering the hydraulic head. Groundwater flowing into or out of the test section is guided to the flow sensor, and flow is measured using the thermal pulse and thermal dilution methods. Measured values are transferred to a computer in digital form. The main instruments and features of the equipment are listed in Table 4-1 while the range and accuracy of the sensors used are presented in Table 4-2.

Table 4-1. Equipment and features.

Type of instrument:	PFL DIFF probe
Borehole diameters:	56 mm, 66 mm and 76 mm (or larger).
Length of test section:	The flow guide length can be varied.
Method of flow measurement:	Thermal pulse and thermal dilution.
Range and accuracy of measurement:	See section 3.1.
Additional measurements:	Temperature, Single point resistance, Electrical conductivity of water, Water pressure, Air pressure
Winch:	Mount Sopris 4WNA, 0.55 kW, steel wire cable 1500 m, four conductors, Gearhart-Owen cable head.
Length determination	Based on a digital distance counter at winch.
Logging computer:	PC (Windows 7).
Software	Based on MS Visual Basic.
Total power consumption:	1.5–2.5 kW depending on the type of pump employed.
Calibration of flow probe:	May 2019 (Probe FL14).

Table 4-2. Range and accuracy of sensors.

Sensor	Range	Accuracy
Flow	30–300 000 mL/h	± 10 % curr. value
Temperature (central thermistor)	0–50 °C	0.1 °C
Temperature difference (between outer thermistors)	-2–+2 °C	0.001 °C
Electrical conductivity of water (EC)	0.02–11 S/m	± 5 % curr. value
Single point resistance (SPR)	5–500 000 Ω	± 10 % curr. value
Groundwater level sensor	0–0.1 MPa	± 1 % full-scale
Air pressure sensor	800–1060 hPa	± 5 hPa
Absolute pressure sensor	0–20 MPa	± 0.01 % full-scale

5 Execution of measurements

5.1 General

The work was carried out according to Activity Plan AP SFK-20-007 following the SKB Method Description 322.010e, Version 2.0 (*Method description for Difference Flow Logging; Table 1-2).* Time was synchronised to Swedish normal time (*UTC + 1*). The activity schedules of the borehole-specific measurements are presented in Table 5-1 and Table 5-2. The items and activities in the tables coincide to those presented in the Activity Plan. The planned measurement programme is described below.

The dummy logging (*Item 4*) of the borehole was conducted in order to minimize the risk of the measurement tools getting stuck in the borehole. The dummy probe also collects solid material from the borehole wall. The solid material collected by the dummy is used to evaluate whether it is safe to continue measurements in a borehole with other logging tools. Dummy logging does not completely eliminate the risk of equipment getting stuck but it obviously reduces the risk, as well as provides crucial information on the openness of a borehole.

The electrical conductivity (*EC*) and temperature of borehole water (*Item 5*) during undisturbed conditions were measured before flow logging.

The flow along the borehole (*Item 6*) was measured right below the casing pipe to observe possible leaks from the casing. Measurement was conducted during undisturbed conditions. Casing pipes in the measured boreholes were 77 mm in inner diameter (*the entire casing pipe in KFR119 and the bottom part of the casing pipe in KFR121*), which enabled measurement of flow along a casing pipe similarly as along a borehole. Flow along the lower part of the casing pipe was also measured in both boreholes.

The flow logging during undisturbed conditions (*Item 7*) was carried out in the boreholes with a 5 m long test section and in 0.5 m long increments (*step length*).

An additional flow logging during undisturbed conditions with a 1 m long test section and in 0.1 m long increments (*Item 8*) was conducted, where more detailed information on fracture-specific flows in a borehole was needed, i.e. where individual fracture flows could not be identified using a 5 m long test section. Evaluation over the need for more detailed measurement was based on the results from the initial flow logging (*Item 7*).

The pumping was started after flow loggings in undisturbed conditions were finished. After a minimum of 12 hours of pumping, flow logging with pumping (*Item 9*) was conducted using the same test section and step lengths as in Item 7.

The flow logging in pumped conditions was continued with a 1 m long test section and a 0.1 m step length (*Item 10*).

The EC of borehole water (*Item 11*) was logged while the measured borehole was still pumped.

After the pumping was stopped, the recovery of the groundwater level was monitored (*Item 12*).

Additional measurements carried out during the measurement campaign are listed as extra activities in the tables.

Table 5-1. Flow logging and testing in KFR119. Activity schedule.

Item	Activity	Description	Date
2	Function check of equipment at the site		2020-10-26
3	Synchronization of clocks		2020-10-26
4	Dummy logging	Borehole stability/risk evaluation.	2020-10-26–2020-10-27
5	EC and temperature of borehole water	Logging without the lower rubber discs, no pumping.	2020-10-27
6	Flow along the borehole	Flow along the borehole below the casing pipe (lengths 7.9 m and 9.8 m) without the lower rubber discs, no pumping.	2019-10-28
7	Flow logging without pumping	Section length L_w = 5 m, step length dL = 0.5 m, no pumping.	2020-10-27
9	Flow logging with pumping	Section length L_w = 5 m, step length dL = 0.5 m, with pumping. Drawdown = 1 m.	2020-10-30
10	Flow logging and fracture-EC with pumping	Section length L_w = 1 m, step length dL = 0.1 m, with pumping. Drawdown = 1 m.	2020-10-30–2020-11-02
11	EC and temperature of borehole water with pumping	Logging without the lower rubber discs, with pumping. Drawdown = 1 m.	2020-11-02
12	Transient registration of groundwater recovery	Measurement of groundwater level with absolute pressure sensor in the borehole after the pumping was stopped. The measurement was continued by SKB.	2020-11-02–2020-11-03

Table 5-2. Flow logging and testing in KFR121. Activity schedule.

Item	Activity	Description	Date
1	Cleaning of equipment	According to SKB MD600.004	2020-10-06
2	Function check of equipment at the site		2020-10-06
3	Synchronization of clocks		2020-10-06
4	Dummy logging	Borehole stability/risk evaluation.	2020-10-06–2020-10-08
5	EC and temperature of borehole water	Logging without the lower rubber discs, no pumping.	2020-10-08
6	Flow along the borehole	Flow along the borehole below the casing pipe and at the bottom part of the borehole (lengths 40.6 m, 42.5 m and 342.9 m) without the lower rubber discs, no pumping.	2020-10-13
6 extra 1	Flow along the borehole	Flow along the borehole at length 342.9 m without the lower rubber discs, with pumping.	2020-10-13–2020-10-14
7	Flow logging without pumping	Section length L_w = 5 m, step length dL = 0.5 m, no pumping.	2020-10-09–2020-10-10

Item	Activity	Description	Date
8	Flow logging without pumping	Section length L_w = 1 m, step length dL = 0.1 m, no pumping. Borehole length intervals 31.8–110.3 m, 140.4–230.4 m and 260.4–305.4 m.	2020-10-11–2020-10-12
9	Flow logging with pumping	Section length L_w = 5 m, step length dL = 0.5 m, with pumping. Drawdown = 10 m.	2020-10-14–2020-10-15
10	Flow logging and fracture-EC with pumping	Section length L_w = 1 m, step length dL = 0.1 m, with pumping. Drawdown = 10 m.	2020-10-16–2020-10-21
4	Dummy logging	Additional borehole stability/risk evaluation.	2020-10-22–2020-10-23
11	EC and temperature of borehole water with pumping	Logging without the lower rubber discs, with pumping. Drawdown = 10 m.	2020-10-23
12	Transient registration of groundwater recovery	Measurement of groundwater level with PFL equipment's absolute pressure sensor in the borehole after the pumping was stopped. The measurement was continued by SKB.	2020-10-23–2020-10-26

5.2 Nonconformities

The flow sensor in the PFL DIFF probe is calibrated for flow rates of up to 300 000 mL/h and it is the upper limit that cannot be exceeded. In KFR119 nor in KFR121, this limit was not exceeded. However, even smaller flows (*100 000–300 000 mL/h*) can cause flow friction in the flow sensor, causing a slight pressure rise in the measurement section. Usually flow measurements have been repeated with a smaller drawdown even if the upper limit has not been exceeded, as in these cases actual flow rate for those sections could probably be higher than the measured flow rates. In these measurements high fracture and section flows which caused friction loss in the PFL DIFF probe's flow guide, causing a slight pressure rise, were examined in more detail to make sure that correct head and flow values were used in interpretation (*see Appendices KFR##.11.n*).

Weights and a centralizer attached to the lower end of the PFL DIFF tool, together with other technical limitations of the measurement method, reduce the measurable length of a borehole. The centralizer is ca 0.9 m long and the length required for flipping the sealing discs of the tool prior to starting a measurement is ca 0.2–0.3 m. The number of attached weights depends on the inclination of a borehole, i.e. shallow inclined boreholes requiring more weights than steep inclined ones. In KFR119, two weights were used thus reducing the measurable length of the borehole ca 4 m in total. In KFR121, three weights were used thus reducing the measurable length of the borehole ca 5.4 m in total. Furthermore, it is also possible that there remain fallen rocks and debris at the bottom of a borehole, further limiting the measurable length.

Flow along a borehole was measured just below the casing pipes in order to detect possible leakages between the casing pipe and bedrock as specified in the activity plan. In KFR119 and KFR121 inner diameter of the casing pipes (*the entire casing pipe in KFR119 and the bottom part of the casing pipe in KFR121*) is 77 mm and therefore the rubber sealing disks in the PFL DIFF tool could also seal the casing pipe reliably, thus enabling measuring of flow along the casing pipe as well. Therefore this additional measurement was conducted though it was not included in the activity plan. If the casing pipe diameter is larger the measurement cannot be done.

Nonconformities mentioned above concern both measured boreholes. Borehole-specific nonconformities are summarised below.

5.2.1 KFR119

The Activity plan specified a minimum target drawdown of 5 m during pumping measurements as a drawdown of 5 m was considered sufficient from the data processing point of view. However, the target drawdown of 5 m could not be achieved in borehole KFR119. Despite of a high pumping rate, only 1 m drawdown in the borehole was achieved. The inner diameter of the casing pipe in KFR119 is 77 mm which constrains the physical size of a pump that could be used in the borehole. In this case a Grundfos 3" submersible pump, which has a maximum pumping capacity of ca 60 L/min, was used. Reducing the drawdown from 5 m to 1 m affects the detection of fractures with low transmissivities and it is possible that some of the fractures that could have been detected with 5 m drawdown were not detected with 1 m drawdown. In general, the minimum detectable PFL transmissivity with 1 m drawdown is ca $8.2 \cdot 10^{-9}$ m^2/s (*flow rate of* $8.33 \cdot 10^{-9} m^3/s$). This does not necessarily mean that it would be impossible to detect fractures with lower transmissivities but that most likely fractures with higher transmissivities have been detected.

An additional flow along the borehole measurement was conducted at the length of 7.9 m, in the casing pipe as a complementary measurement to the initial flow along the borehole measurement. The results from this additional time series measurement are presented in Appendix KFR119.2.11. The additional measurement is included in Item 6 presented in Table 5-1.

5.2.2 KFR121

During the initial dummy logging performed in KFR121 on October 6, three weights connected to the dummy probe were lost into the borehole. The reason remains unknown at this time. Further dummy loggings confirmed that the weights were located at the very bottom of the borehole thus further reducing the measurable borehole length ca 4.5 m. Therefore, together with the limitations described in Section 5.2. and a safety clearance left between above mentioned obstruction at the bottom of the borehole, the total unmeasurable length from the bottom of the borehole was ca 11.6 m.

An additional flow along the borehole measurement was conducted at the length of 40.6 m, in the casing pipe, as a supplementary measurement to the initial flow along the borehole measurement. Another additional flow along the borehole measurement was conducted at the length of 342.9 m. The results from those additional time series measurement are presented in Appendices KFR121.2.17 and KFR121.2.19. The two additional measurements performed in un-pumped conditions are included in Item 6 presented in Table 5-2.

To obtain more information regarding the unmeasurable (*see above*) bottom part of the borehole, another flow measurement along the borehole was conducted at the length of 342.5 m. After the initial time series measurement in un-pumped conditions had been finished, another time series measurement was started and pumping was applied with a drawdown of 10 m (Appendix KFR121.2.20). The measurement performed in pumped conditions at 342.5 m is presented as Item 6 extra 1 in Table 5-2.

Length intervals ca 39.8–110.3 m, 140.3–230.3 m and 260.4–305.4 m in KFR121 were flow logged without pumping using a 1 m long test section and 0.1 m increments. The measurement results are labelled as Flow 2 in graphs presented in the appendices. The measurement was conducted to distinguish individual fracture flows from the flow anomalies obtained in Flow 1 measurement (*5 m section length*). The results from Flow 2 measurement replaced Flow 1 measurement results in fracture-specific interpretations at the corresponding length intervals. Flow 2 measurement is presented as Item 8 in Table 5-2. However, as Flow 2 measurement did not cover the entire length of the borehole, Flow 1 measurement was used in such cases where Flow 2 measurement results were not available as well as in cases where Flow 1 results were considered as more representative (*see Section 6.4.3 for details*).

During Flow 3 measurement (*Item 9*), the PFL DIFF tool got stuck in the borehole at the length of ca 318 m. The tool eventually passed through the bad section and the measurement was finished without further difficulties. Due to measurement scheduling, it was decided to continue the flow loggings. The succeeding Flow 4 measurement (*Item 10*) was started above the bad section (*including a safety clearance totalling the entire length of the PFL equipment used*), at ca 309 m.

The unmeasured part below the bad section was planned to be measured separately after an additional dummy logging had been performed to assess the obstruction in the borehole. However, the following dummy logging proved to be unsuccessful as even the dummy probe had difficulties to pass through the bad section. Based on the risk assessment, it was decided not to extend any further measurements below the obstruction. Therefore length interval of ca 309–351 m was left unmeasured in Flow 4 measurement. The results from Flow 3 measurement were used in fracture-specific interpretations in the length interval instead. Furthermore, the obstruction in the borehole limited EC and temperature of borehole water measurement in pumped conditions (*Item 11*) to the length of ca 312 m thus leaving rest of the borehole bottom unmeasured.

6 Results

Measurement results are presented in detail in two appendices, A and B. The table of contents of the appendices is the same for both boreholes and therefore the appendices are referenced by denoting as KFR##.m.n. in which ## denotes the borehole number and m and n are detailing numbers of appendices presenting certain measurement results. At the end of each borehole-specific set of appendices there might be additional plots that are numbered similarly but are borehole-specific plots representing special cases.

6.1 Length calibration

In general, an accurate length scale for the measurements is difficult to achieve in long boreholes. The main cause for inaccuracy is stretching of the logging cable. The stretching depends on the tension applied to the cable during a measurement. The magnitude of stretching in turn depends, among other reasons, on the inclination of the borehole and the roughness (*friction properties*) of the borehole wall. The cable tension is higher when the borehole is measured upwards. The cables, especially new cables, may also stretch out permanently. The cable length marks have been set to a pre-tensioned (*ca. 100 kg*) cable to emulate cable stretching during a measurement. The boreholes KFR119 and KF121 are not very long and therefore cable stretching was not considered a significant issue in this case.

6.1.1 SPR measurement

All flow logging sequences can be length calibrated by synchronising the SPR results (*SPR is recorded during all flow logging measurements, but not during the borehole EC measurements)* with other resistivity measurements. However, in this measurement campaign reference data for SPR was not available. Length determination is therefore based on the length marks on the measurement cable together with the known length of the casing pipes in the measured boreholes (*start of the casing pipe can be observed in the measured SPR data*). In practice, the initial flow logging was set as the reference measurement and subsequent measurements were length matched to it, if needed.

6.1.2 Estimated error in location of detected fractures

Despite the length calibration, as described above, there can still be other contributing errors due to following reasons.

Stretching of the cable is most likely different during a measurement than while the cable length marks have been set (*calibration tension ca. 100 kg*). Based on practical experience, 1000 m of measurement cable stretches ca 3 m when tension is increased from 75 kg to 175 kg. Based on this, the estimated length error in positioning the PFL DIFF tool in a 300 m long borehole while cable tension varies from 50 kg to 150 kg is ±0.45 m at the most.

The point interval in the overlapping mode flow measurements is 0.1 m. This could cause an error of ±0.05 m. This error is random.

The length of the test section is not exact. The specified section length denotes the distance between the nearest upper and lower rubber sealing discs. Effectively, the section length can be longer. At the upper end of the test section there are four rubber sealing discs. The distance between each disc is 5 cm. This will cause rounded flow anomalies as a flow may be detected already when a fracture is situated between the upper rubber sealing discs. This phenomenon can cause an error of ±0.05 m when the short measurement step length (*0.1 m*) is used.

In a worst-case scenario, when the errors from all three sources described above are summed, the total estimated error would be ±0.55 m. Note that the given total error is an estimate based on experience and observations from earlier measurements and does not necessarily realise in all borehole conditions.

Knowing the location accurately is important when different measurement results are compared, for instance flow logging and borehole OPTV. In that case, the situation may not be as severe as the case above, since some of the length errors are systematic and the error is nearly constant in fractures that are close to each other.

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

6.2 Electrical conductivity and temperature

6.2.1 Electrical conductivity and temperature of borehole water

The EC of the borehole water was initially measured when the borehole was at rest, i.e., at undisturbed conditions. The measurement was repeated during pumping (*after a pumping period of ca. four days in KFR119 and ca. ten days in KF121*). Measurements were performed downwards in order to avoid mixing of the borehole water before the measurement. Electrical conductivity measurement results have been presented in Appendices KFR##.1.1 in linear EC scale and in Appendices KFR##1.2 in logarithmic EC scale. In KFR121 in unpumped conditions EC profile had slight change of level at borehole length of ca 140–200 m. Reason for this is unclear as all fracture flows in unpumped conditions at borehole length interval from top of borehole to 250 m are from bedrock into borehole.

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 are presented in Appendices KFR##.1.3.

The length calibration of the borehole EC measurements is not as accurate as in other measurements, because SPR is not registered. The length correction is linear and based on the nearest tape marks on the logging cable at the start and in the end length of the measurement.

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

The flow measurements make it possible to locate the fractures that have been selected for fracture-specific EC measurement. The PFL DIFF tool is deployed so that the fracture to be tested is located within the test section. EC measurement is then started if the measured flow rate is higher than a predetermined limit. The tool is kept positioned over the selected fracture and measurement is continued allowing fracture-specific water to enter the test section. The time required to complete a fracture-specific EC measurement can be calculated automatically from the measured flow rate with the aim being to achieve adequate flushing of the volume of water within the test section. The computer controlling the measurement procedure is programmed to allow the water volume within the test section to be changed ca. three times while the tool remains on a target fracture. The minimum measurement time at a fracture is set to be 18 minutes in order to achieve an adequate amount of measurement data in cases where very high fracture flow rate would otherwise yield even shorter measurement times. After the water volume in the measurement section has changed three times, the time series measurement is stopped and overlapping flow logging is continued.

Target fractures for the fracture-specific EC measurement in KFR119 and KFR121 were selected based on results from flow loggings conducted with a 5 m long section, performed prior to 1 m section measurement. The fracture-specific EC measurements were conducted using a 1 m long test section to minimise the time required to adequately flush the measurement section. Water volume of the 1 m test section is ca 3.6 litres.

Electrical conductivity values for fracture-specific water are presented on a time scale in Appendices A and B, KFR##.10.n. The blue symbol represents the conductivity value when the PFL DIFF tool was moved (*0.1 m increments*) and the red symbol signifies that the tool was stopped on a fracture for fracture-specific EC measurement. For comparison, the fracture-specific EC and temperature results are also plotted with the EC and temperature results of borehole water in Appendices A and B, KFR##.1.1 – KFR##.1.3. The locations of the PFL DIFF tool during the fracture-specific EC measurements are also presented in Appendices A and B, KFR##.2.n.

KFR119

Fracture-specific EC measurement was conducted at 5 fractures in KFR119 which were chosen based on Flow 2 measurement results. Lengths to the upper and lower ends of the test section, fracture locations, fracture-specific flow rates and the final EC values for each measured fracture are listed in Table 6-1.

Table 6-1. KFR119 fracture-specific EC.

Upper end of section (m)	Lower end of section (m)	Measured fracture (m)	Flow (mL/h)	EC (S/m) at 25 °C
10.51	11.51	11.4	110000	0.86
11.31	12.31	11.4 and 11.8	125300*	0.86
22.70	23.70	23.0	44300	0.81
55.09	56.09	55.5	2100	0.86
78.21	79.21	78.6	350	0.87

* Given flow rate is the sum of fractures within the measurement section during the actual measurement (Flow 3).

KFR121

A fracture-specific EC measurement was conducted at 13 fractures in KFR121, most of which were chosen based on Flow 3 measurement results (*some of the fracture-specific measurements were included as extra, as a result of automated measurement process, e.g. due to short distance between a fracture chosen for measurement and another fracture also exceeding the set measurement criteria*). Lengths to the upper and lower ends of the test section, fracture locations, fracture-specific flow rates and the final EC values for each measured fracture are listed in Table 6-2.

Table 6-2. KFR121 fracture-specific EC.

Upper end of section (m)	Lower end of section (m)	Measured fracture (m)	Flow (mL/h)	EC (S/m) at 25 °C
46.16	47.16	46.5	38000	1.04
61.76	62.76	62.0	89600	1.02
77.20	78.20	77.6	5030	1.16
97.56	98.56	97.9	1840	1.00
99.85	100.85	100.6	2100	1.04
100.65	101.65	100.9	3400	1.05
104.34	105.34	104.7	1540	1.10
148.45	149.45	148.8	1280	0.96
153.62	154.62	154.0	883	1.03
173.30	174.30	173.7	1900	1.01
180.98	181.98	181.4	2700	1.10
208.37	209.37	208.7	2380	1.00
273.28	274.28	273.7	480	0.99

6.3 Pressure measurements

Absolute pressure was registered along with the other measurements in Items 6–11. The absolute pressure sensor of the PFL DIFF probe measures the sum of atmospheric pressure and hydrostatic pressure in the borehole. Atmospheric pressure was also registered separately (*Appendices KFR##.9.2*). The hydraulic head along the borehole under undisturbed and pumped conditions can be determined from the measured data. The atmospheric pressure recorded at the site is first subtracted from the measured absolute pressure and the hydraulic head can then be calculated. The hydraulic head (h) at a certain elevation (z) is calculated according to the following expression (Nordqvist 2001):

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

where

h is the hydraulic head in metre above sea level (masl) according to the RH 2000 reference system,

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

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

ρ_{fw} is the unit density, 1000 kg/m^3

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

z is the elevation of measurement (masl) according to the RH 2000 reference system.

Exact z-coordinates are important in hydraulic head calculation as an error in the z-coordinate leads directly to an equal error in the calculated head. The calculated head distributions are presented in Appendices KFR##.9.1.

6.4 Flow logging

6.4.1 General comments on results

The measurement programme contained several flow logging sequences, which are numbered as Flow 1 (*flow flogging without pumping with a 5 m section length, Q_0 in tables*), Flow 2 (*flow logging with pumping with a 5 m section length, Q_1 in section flow table*) and Flow 3 (*flow logging with pumping with a 1 m section length, Q_1 in fracture flow table*). Results from the flow loggings are presented in Appendices KFR##.2.n. The measured SPR is added to the same diagram (*right hand side; Appendices KFR##.2.n*). Any additions or deviations to the preceding are discussed in the following borehole-specific paragraphs. The SPR usually has a lower value over fractures where flow is detected. Many other resistance anomalies result from other fractures and geological features. As the electrode of the SPR sensor is located within the upper rubber sealing discs of the PFL DIFF tool, the locations of resistance anomalies associated with flowing fractures coincide with the lower end of the flow anomalies. The exact position of the SPR electrode is 5 cm higher than upper end of the measurement section (*the lowest rubber disc at the upper end of measurement section*). The reference length for both SPR and flow measurement is distance between borehole 0 m length and upper end of measurement section. This has been considered when processing the data.

The first flow logging was performed with a 5 m long test section and with 0.5 m long increments. The method (*overlapping flow logging*) gives the position of conductive zones along a borehole with a length resolution of 0.5 m.

Under undisturbed conditions (*or if the borehole is not pumped using a sufficient drawdown*) the fracture flow direction may be into the borehole or out from it. The direction of small flows (*<100 mL/h*) cannot be detected in the normal overlapping mode (*thermal dilution method*).

Therefore, the measurement time was set longer (*so that the thermal pulse method could be used*) at every 5 m interval in both (*under undisturbed and pumped conditions*) 5 m section measurements and every 1 m interval in the 1 m section measurement conducted in chosen length intervals under undisturbed conditions.

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

The position (*borehole length*) of the detected fractures is shown on the middle scale in Appendices *KFR##.2.1 – KFR##.2.n*. They are interpreted based on the flow curves and therefore represent flowing fractures. A long line represents the location of a flowing fracture; a short line denotes that the existence of a flowing fracture is uncertain. The short line is used when the flow rate is less than 30 mL/h or if determination of flow rate is uncertain due to overlapping flow anomalies or because of noise (*See Section 6.4.4).*

The coloured triangles show the magnitude and direction (*from borehole into bedrock or from bedrock into borehole*) of the measured flows. The triangles are of the same colour as the corresponding flow curves.

The glossary of terms used in the tables in Appendices KFR##.4 and KFR##.6 are given in Appendices KFR##.3.

KFR119

Results from the vertical flow along the borehole measurements conducted without pumping, alongside with concurrent air pressure and water level measurement results, are presented in Appendices KFR119.2.11 – KFR119.2.12. Two time series measurements were conducted in KFR119, at the borehole lengths of 7.9 m (*in the casing pipe*) and 9.8 m (*below the percussion drilled part of the borehole where the casing pipe is installed*).

Vertical flows measured at the lengths of 7.9 m and 9.8 m fluctuated notably. The reason for the fluctuation is not fully clear. If the highest spike values would be left disregarded, the averaged flow rate measured at the length of 7.9 m would be in the range of ca 1000 mL/h and the flow rate measured at the length of 9.8 m would be in the range of ca 2000 mL/h. However, also the direction of flow varied to some extent during the both measurements rendering the results ultimately inconclusive. Despite the uncertainty over the interpretation of the results, it still can be concluded that the casing pipe or the junction of the bedrock and the casing pipe did not leak notably in un-pumped conditions.

KFR121

Results from the vertical flow along the borehole measurements conducted without and with pumping, alongside with concurrent air pressure and water level measurement results, are presented in Appendices KFR121.2.17 – KFR121.2.20. Three time series measurements without pumping were conducted in KFR121 at the borehole lengths of 40.6 m (*in the casing pipe*), 42.5 m (*just below the percussion drilled part of the borehole where the casing pipe is installed*) and at 342.9 m.

Vertical flow measured at the length of 40.6 m in the casing pipe (*Appendix KFR121.2.17*) had some fluctuation in the flow result. The reason for the fluctuation is not fully clear. Nevertheless, the averaged flow rate would be in the range of ca 400–500 mL/h. Direction of the measured flow was downwards, towards the bottom of the borehole. Based on the result, it is possible that the casing pipe could have had a leak in un-pumped conditions somewhere above the length of 40.6 m.

Vertical flow measured at the length of 42.5 m (*Appendix KFR121.2.18*) had some fluctuation in the flow result but gradually stabilised to ca 23 000 mL/h on average with variation of ca ±5 % between individual measurement points. Direction of the measured flow was downwards, towards the bottom of the borehole. The magnitude of the measured vertical flow rate does not fully coincide with the fracture-specific interpretation in un-pumped conditions (*Flow 1 and Flow 2 measurements*) as the sum of measured fracture flows above 42.5 m was 12 200 mL/h and ca −14 200 mL/h below 42.5 m. However, ambient conditions in the borehole were not exactly the same during the measurements as the difference of groundwater level between the three measurements (*the fracture-specific interpretation in KFR121 is based mainly on Flow 2 measurement and partially on Flow 1 measurement where applicable, as explained in Section 5.2.2*) varied ca 1–12 cm, which could explain some of the difference in flow rates between the measurements.

Vertical flow measured at 342.9 m was made to detect possible hydraulic conductivity present in the unmeasurable lower part of the borehole. The measured vertical flow without pumping stabilised to ca 8 mL/h (*Appendix KFR121.2.19*). Direction of the measured flow was upwards. After a steady-state flow result in un-pumped conditions had been achieved, pumping was started and a drawdown of 10 m was applied. The measured vertical flow in pumped conditions at 342.9 m stabilised to ca 19 mL/h, direction of the measured flow being upwards (*Appendix KFR121.2.20*). The results imply that no significant conductivities remain below the length of 342.9 m (*based on the two measurement results, calculated transmissivity for the bottom part of the borehole would be ca 3.1E-10 m/s^2*).

6.4.2 Transmissivity and hydraulic head of borehole sections

The borehole was flow logged with a 5 m long test section and with 0.5 m long increments in both, undisturbed conditions and during pumping.

The results of the measurements with 5 m section length are presented in tables (*Appendices KFR##.4*). All flowing borehole sections are presented in Appendices KFR##.2.n. Secup and Seclow in Appendices KFR##.4 refer to the distances along the borehole from the reference level (*top of the casing pipe*) 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 in undisturbed conditions and during pumping*) are not exactly identical, due to minor differences in the cable stretching. The differences between these two sequences were minor. Secup and Seclow given in Appendices KFR##.4.n are calculated averages of these two values.

The total conductive fracture frequency (*CFF*) is presented graphically in Appendices KFR##.5.4.

Pressure was measured and hydraulic head calculated as described in Section 6.3. h_{0FW} and h_{1FW} in Appendices KFR##.4 represent heads determined without and with pumping, respectively. The head in the borehole and calculated heads of borehole sections are given in RH 2000 scale.

The flow results in Appendices KFR##.4 (*Q_0 and Q_1*), representing the flow rates derived from measurements during undisturbed conditions and under pumping, are presented side by side to make comparison easier. Flow rates are presented as positive if the measured flow direction was from the bedrock into the borehole and as negative if the direction was from the borehole into the bedrock.

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

The flow data is presented as a plot (*Appendix KFR##.5.1*). The left-hand plot in each diagram represents flow from the borehole into the bedrock for the respective test sections, while the right-hand plot represents flow from the bedrock into the borehole. If flow could not be detected (*zero flow*), no corresponding symbol will be visible on the logarithmic plots in the appendices.

The lower and upper measurement limits of the flow are also presented in the plot (*Appendices KFR##.5.1*) and in the tables (*Appendices KFR##.4*). There are theoretical and practical lower limits of flow (see *Section 6.4.4 for details*).

The hydraulic head and transmissivity (T_{PFL}) of borehole sections can be calculated from the flow data using the method described in Chapter 3. The results are illustrated in Appendices KFR##.5.2. The hydraulic head of sections is presented in the plots if none of the two flow values at the same length was equal to zero. Transmissivity is presented if none or just one of the flows was equal to zero.

The limits of transmissivity are also presented in tables in Appendices KFR##.4 and graphically in Appendices KFR##.5.2. All the presented limit values of transmissivity are based on the actual pressure difference in the borehole (*h_{0FW} and h_{1FW} in Appendices KFR##.4*).

KFR119

The sum of all the detected flows in un-pumped conditions (*Q_0*) was -4.43·10^{-7} m^3/s (*-1595 mL/h*). More flows into the bedrock than into the borehole were detected. This sum should normally be zero if the flows in the borehole are not disturbed by noise or other external factors, the borehole is not pumped, the water level is constant, the salinity distribution in the borehole is stabilised and the fractures remain at steady-state pressure. In this case the measured inflows and outflows were in good balance and well within the given ±10 % accuracy of the flow measurement (*Table 4-2*).

The sum of measured section flows in pumped conditions (*Q_1*) was 5.69·10^{-5} m^3/s (*204 963 mL/h*). Pumping rate during the measurement with 1 m drawdown was ca 60.0 L/min (*3 600 000 mL/h*) on average. Note that the drawdown of 1 m was not sufficient to turn the direction of all section inflows. Flow directions of sections at depth of 102.16m (*Secup*) and below remained into the bedrock.

The pumping rate was notably higher than the sum of measured section flows (*Q_1*). However, in KFR119 the sum of section flows, as such, cannot be compared directly to the pumping rate because the measured flow rates from section at 7.23 m (*Secup*) were enough to cause friction loss in the PFL DIFF probe's flow guide causing a pressure rise in the measurement section while pumping was on. The friction loss also caused momentary fault in the pumping equipment which caused a rise in the borehole groundwater level. Pressure increase of ca 5.3 kPa at the section at 7.23 m (*Secup*) was measured. Therefore, actual flow rate for that section could probably be higher than the measured flow rates.

This section at 7.23 m (*Secup*) length was examined in more detail to make sure what happened during the measurements and what results can be used in interpretation. Flow rate and borehole head were plotted together to see the effect of pressure increase (*Appendix KFR119.11*). It should also be taken into consideration that as the flow logging measurement passes the flowing borehole section relatively quickly; perfect steady-state conditions cannot be reached during normal measurement if a section has significant influence on a borehole flow system. A clear example of the described conditions can be seen at the section 7.23 m (*Secup*) as the measured pumping rate drops dramatically from ca 60 L/min to ca 2 L/min (*see Appendix KFR119.11*) when the PFL DIFF probe remained on the high yielding fractured zone (*within the section were fractures at 9.8 m, 11.4 m and 11.8 m*). As soon as the PFL DIFF probe had passed the high yielding fractured zone, pumping rate normalised to ca 60 L/min. Therefore, it can be assumed that the actual transmissivity value for the section at 7.23 m (*Secup*) would most probably be higher than the one reported here. The occurrences described above could partly explain the off-balance between the sum of section flows and the measured pumping rate.

KFR121

The sum of all detected flows in un-pumped conditions (*Q_0*) was -1.92·10^{-7} m^3/s *(-692 mL/h*). Slightly more flows into the bedrock than into the borehole were detected. This sum should normally be zero if the flows in the borehole are not disturbed by noise or other external factors, the borehole is not pumped, the water level is constant, the salinity distribution in the borehole is stabilised and the fractures remain at steady-state pressure. In this case the measured inflows and outflows were in good balance and well within the given ±10 % accuracy of the flow measurement (*Table 4-2*).

The sum of measured section flows in pumped conditions (*Q_1*) was 1.56·10^{-4} m^3/s (*560 799 mL/h*). Pumping rate during the measurement with 10 m drawdown was ca 18.3 L/min (*1 098 000 mL/h*) on average (*ca 19.0 L/min at the start and ca 17.6 L/min in the end of the measurement*).

The pumping rate was notably higher than the sum of measured section flows (*Q_1*). It should be noted that the measured flow rates from sections at 57.80 m (*Secup*) and 322.94 m (*Secup*) were enough to cause friction loss in the PFL DIFF probe's flow guide causing a pressure rise in the measurement section while pumping was on. Pressure increase of ca 3.3 kPa at the section at 57.80 m (*Secup*) and pressure increase of ca 5.1 kPa at the section at 322.94 m (*Secup*) was measured. Therefore actual flow rates for those sections could probably be higher than the measured flow rates. These section lengths were examined in more detail to make sure that correct head and flow values were used in interpretation. Flow rate and borehole head were plotted together to see the effect of the pressure increase (*Appendices KFR121.11.2 and KFR121.11.4*). Furthermore, a pressure increase concerning the section at 67.82 (*Secup*) is examined in Appendix KFR121.11.3. The increase in borehole head (*ca 4.9 kPa*) was due to a momentary fault in the pumping equipment which caused a rise in the borehole groundwater level. Although there remains some uncertainty regarding the flow and head for the section at 67.82 m (*Secup*) due to the change in borehole ambient conditions, its impact in the interpreted section-specific transmissivity and head is not considered significant. The occurrences described above could partly explain the off-balance. However, the most important contributing factor to the difference between the sum of measured section flows and the measured pumping rate could be that there probably remains a leak in the casing pipe. This assumption is based on the vertical flow measurement result conducted in un-pumped conditions at the borehole length of 40.6 m (*see Section 6.4.1*).

6.4.3 Transmissivity and hydraulic head of fractures

An attempt was made to evaluate the magnitude of fracture-specific flow rates. The first step in this procedure is to identify the locations of individual flowing fractures and then evaluate their flow rates. This is done based on flow logging with 1 m long section in pumped conditions. In cases where the fracture distance is less than one metre, it may be difficult to evaluate the flow rate. In these cases, a stepwise increase or decrease in the flow data plot equals the flow rate of a specific fracture (*colour-filled triangles in Appendices KFR##.2.1 – KFR##.2.n).*

The measurement program included flow logging with a 5 m long section in undisturbed conditions and flow loggings with 1 m and 5 m long sections in pumped conditions. In pumped conditions fracture flows were interpreted based on results from flow logging with 1 m section length. In un-pumped conditions determining flows of individual fractures can be more difficult as measurement section is longer and possibly covers multiple fractures simultaneously. This was taken into consideration during the measurement and, if the fracture flows were difficult to interpret based on the 5 m long section measurement, an additional measurement was conducted with a 1 m long section. These results were used together to interpret flows in un-pumped conditions. If the flow for a specific fracture could not be determined conclusively in un-pumped conditions, the flow rate is denoted by "-" and the value 0 was used in the transmissivity calculation (*Appendices KFR##.6*). The direction of measured flow was evaluated as well. The results of the fracture-specific evaluation are plotted in Appendices KFR##.2.1 – KFR##.2.n, blue filled triangles for undisturbed conditions and purple filled triangles for pumped conditions.

Comparison between fracture-specific transmissivities and section transmissivities is presented in Appendices KFR##.8. All fracture-specific transmissivities within each 5 m interval were first summed together to make them comparable with measurements conducted using a 5 m long measurement section. The results were fairly consistent between the two types of measurements.

In general, decrease of flow as a function of pumping time can sometimes be observed in some fractures (*storage effect*). The 1 m section measurements were carried out after the 5 m section measurements and therefore flow rate and transmissivity could have been lower in the 1 m section measurement results.

KFR119

The total amount of detected fractures was 37, of which 24 were detected also without pumping. Measured length was 166 m, thus there were 0.22 fractures per metre on average. The sum of interpreted fracture flows during pumping of the borehole was $4.88 \cdot 10^{-5}$ m^3/s (*175 633) mL/h*). Pumping rate during the measurement with 1 m drawdown was ca 60 L/min (3 *600 000 mL/h*) on average (*ca 61.6 L/min at the start and ca 58.7 L/min in the end of the measurement*). The pumping rate was notably higher than the sum of measured fracture flows (Q_1) and clearly exceeded the given ±10% accuracy of the flow measurement.

Flow at fracture at 11.4 m caused a pressure rise in the measurement section while pumping was on causing also temporarily malfunctioning on pumping and rising of the water level in borehole. The flow rate of fracture at 11.4 m was too high to measure with PFL DIFF probe. Measured flow rate at this length was high enough to cause friction loss in the PFL DIFF probe's flow guide and therefore actual flow rate for the fracture could probably be higher than the measured flow rate. The magnitude of pressure increase was ca 6.8 kPa at the most which is almost equal to pressure difference caused by pumping of borehole. This length was examined in more detail to make sure what happened during the measurements and what results can be used in interpretation. Flow rate and borehole head were plotted together to see the effect of pressure increase (*Appendix KFR119.11*). The occurrences described above explains most of the off-balance between the sum of fracture flows and the measured pumping rate.

KFR121

The total amount of detected fractures was 107, of which 53 were detected also without pumping. Measured borehole length was ca 310 m, thus there were 0.35 fractures per metre on average. Note that the flow detected at the length of 41.4 m, although most probably being a leak at the joint of casing pipe and the borehole, is presented as a fracture in the results (*see Appendices KFR121.2.1 and KFR121.6.1*). The sum of interpreted fracture flows during pumping of the borehole was $1.44 \cdot 10^{-4}$ m^3/s (*516 927 mL/h*). Pumping rate during the measurement with 10 m drawdown was ca 15.7 L/min (*942 000 mL/h*) on average (*ca 15.5 L/min at the start and ca 15.9 L/min in the end of the measurement*). The pumping rate was significantly higher than the sum of measured fracture flows (Q_1) and the given ±10 % accuracy of the flow measurement (*Table 4-2*) was clearly exceeded.

Flows at fractures at 41.4 m, 46.5 m, 62.0 m and 327.5 caused a pressure rise in the measurement section while pumping was on. Measured flow rates at these lengths were high enough to cause friction loss in the PFL DIFF probe's flow guide and therefore actual flow rates for the four fractures could have probably been higher than the measured flow rates. The magnitude of pressure increase was ca 5.1 kPa at the most. These lengths were examined in more detail to make sure that correct head and flow values were used in the interpretation. Flow rate and borehole head were plotted together to visualise the effect of pressure increase (*Appendices KFR121.11.1 – KFR121.11.2 and KFR121.11.4*). The occurrences described above could partly explain the off-balance noted above. Another contributing factor to the difference between the sum of measured fracture flows and the measured pumping rate could be that there possibly was a leak somewhere in the casing pipe. This assumption is based on the vertical flow measurement result conducted in un-pumped conditions at the borehole length of 40.6 m (*see Section 6.4.1*).

The fracture-specific interpretation in un-pumped conditions for the total of sixteen fractures is based on Flow 1 measurement results. Flow 1 measurement results were used due to being considered more representative or due to inconsistent fracture flow anomalies observed in Flow 2 measurement (*see Appendices KFR121.2.9 and KFR121.2.12 – KFR121.2.13*). Furthermore, Flow 2 measurement did not cover the full length of the borehole as described in Section 5.2.2. Due to the mentioned occurrences, values for fracture flow (Q_0) and hydraulic head (h_{0FW}) in un-pumped conditions for the fractures in question presented in Appendices KFR121.6.1 – KFR121.6.3 are from Flow 1 measurement from the corresponding borehole lengths. For the complete listing of the fractures in question, see Appendices KFR121.6.1 – KFR121.6.3 (*the Comments column*).

The fracture-specific interpretation in pumped conditions for fractures at 197.2 m and 198.2 m is based on Flow 3 measurement results. Flow 3 measurement results were used due to being more representative or due to inconsistent fracture flow anomalies observed in Flow 4 measurement (*see Appendix KFR121.2.8*). Furthermore, Flow 4 measurement was not extended below the length of ca 309 m as described in Section 5.2.2. Therefore fracture-specific interpretation for fractures at 321.9 m, 327.5 m, 334.2 m and 337.0 m is based on Flow 3 measurement results instead (*see Appendix KFR121.2.15*). Values for fracture flow (Q_1) and hydraulic head (h_{1FW}) in pumped conditions presented in Appendices KFR121.6.2 – KFR121.6.3 (*see the Comments column*) for the fractures in question are from Flow 3 measurement from the corresponding borehole lengths.

Note that, when considering the general topography of the area surrounding the measured boreholes, the presented values for fracture head and transmissivity for fracture at 87.0 m (*Appendix KFR121.6.1*) should be considered unrealistic. The reason remains unclear, as the flow logging results from the corresponding borehole length (*Flow 2 and Flow 4 measurements, Appendix KFR121.2.3*) were technically correct and well within the measurement limits, ambient borehole conditions were stable during the flow loggings and interpretation of the results was unambiguous. Even so, the calculation resulted in unrealistic values.

6.4.4 Theoretical and practical measurement limits of flow and transmissivity

The theoretical minimum for measurable flow rate in overlapping measurements is 30 mL/h. In laboratory conditions flow rates as low as 6 mL/h can be measured, but in general 30 mL/h has been considered as the minimum measurable flow rate in actual borehole conditions. In result figures and tables flow rates below 30 mL/h have been presented but these are considered to be less certain than flow rates above 30 mL/h. The upper limit of flow measurement is 300 000 mL/h. Even higher flow rates could be measured by the device but due to small structural dimensions in the PFL DIFF probe's flow sensor, flow friction through the sensor begins to affect the result when flow through the sensor is high. Therefore measurement results can be technically correct, but if the result is affected by the measurement system, then the result does not represent what it should.

In practice, the minimum measurable flow rate may be much higher. Borehole conditions may have an influence on the flow base level (*i.e. noise level*). Noise levels can be evaluated in intervals along the borehole which are lacking flowing fractures and other complicating geological structures. The noise level may vary along a borehole.

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

- Roughness of the borehole wall.
- Solid particles such as clay or drilling debris in the water.
- Gas bubbles entrained in the water.
- High flow rate along the borehole.
- Mixing of waters with different salinity within the test section.

Roughness in the borehole wall always results in high levels of noise, not only in the flow results, but also in the SPR results. The flow curve and SPR curves are typically spiky when the borehole wall is rough.

Drilling debris usually increases noise level. This kind of noise is typical for measurements conducted both, in undisturbed conditions and under pumping.

Pumping results in lower water pressure in the borehole and in fractures located near the borehole. This may lead to the release of dissolved gas and increase the quantity of gas bubbles entrained in the water. Some fractures may produce more gas than others. Sometimes, when the borehole is being measured upwards, increased noise levels are observed just above certain fractures. One of the reasons for this observation is assumed to be gas bubbles.

The effect of a high flow rate along a borehole can often be seen above fractures yielding a high flow and while borehole wall is assumed to be rough. The rubber sealing discs hold the pressure caused by a high flow well, but if there are leakages between the rubber discs and a borehole wall at the same time, high flow along a borehole causes increased noise level.

Another reason for increased noise level could be that, as the PFL DIFF tools passes flowing fractures, there still might be less saline water within the tool's test section originating from other parts of a borehole. When on a flowing fracture, waters with different salinities then mix and therefore might cause high noise level to the flow rate results.

The practical minimum for measurable flow rate is presented in Appendices KFR*##.5.1* by dashed dark grey 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 these measurements was 30 mL/h. In many cases even smaller flows were successfully detected. The noise line (*dark grey dashed line*) is never drawn below 30 mL/h, because the values of flow rate measured below 30 mL/h are always considered as uncertain due to practical limitations of flow measurement (*see Section 3.1 for details*).

The practical minimum for measurable flow rate is also presented in Appendices KFR##.4 (*Q-lower limit P*) and is obtained from the plots in Appendices KFR##.2.1 – KFR##.2.n (*Lower limit of flow rate. Flow rate under 6 mL/h is not plotted*). The practical minimum of transmissivity can be evaluated using Q-lower limit and the actual head difference at each measurement location (*Appendices KFR##.4* T_D*-measl*$_{LP}$). The theoretical minimum for transmissivity (T_D*-measl*$_{LT}$) is evaluated using a Q value of 30 mL/h. The upper limit for transmissivity can be evaluated using the maximum flow rate (*300 000 mL/h*) and the actual head difference as described above (*Appendices KFR##.4* T_D*-measl*$_U$). In cases where upper limit of measured flow rate has been exceeded, flow measurement is repeated with a smaller drawdown to obtain flow rate within the flow measurement limits. Therefore upper limit for transmissivity is never exceeded.

All three flow limits are plotted with the measured flow rates (*Appendices KFR##.5.1*).

The three transmissivity limits are also presented graphically (*Appendices KFR##.5.2*).

Similar flow and transmissivity limits are not provided for the interpreted fracture-specific results as the limits for those are harder to define. The situation is similar for the upper flow limit. If several high-flowing fractures are positioned closer to one another than a distance of 1 m (the shortest test section length used in the measurements), the upper flow limit will depend on the sum of these flows, and must be under 300 000 mL/h.

6.4.5 Sensitivity of transmissivity and the hydraulic head to the errors in flow and pressure measurements

Transmissivity and hydraulic head results have been presented in tables and plots without assuming any errors related to measured values. Nevertheless, possible errors in flow and pressure measurement affect the calculated transmissivity and hydraulic head. Possible error in flow measurement is ±10% of the measured value and ±2 kPa in pressure measurement. Errors in transmissivity and hydraulic head have been evaluated assuming a worst-case combination of errors that can occur within these errors in flow and pressure measurements. The error limits for transmissivity and hydraulic head have been plotted in Appendices KFR##.5.3 and KFR##.7.2.

6.5 Transmissivity of the entire borehole

The transmissivity of the entire borehole was evaluated based on pumping rate and drawdown caused by the pumping during the flow logging. This is done with two steady-state methods described in Chapter 3. The results of the analysis are presented in Table 6-3.

Table 6-3. Evaluated transmissivities for entire boreholes; TM (see Equation 3-10), TT (see Equation 3-9).

Borehole ID	Pumping rate (L/min)	Drawdown (m)	Borehole length (m)	T_M (m²/s)	T_T (m²/s)
KFR119	61.0	1	176.47	$1.41\cdot10^{-3}$	$1.01\cdot10^{-3}$
KFR121	17.0	10	362.53	$4.22\cdot10^{-5}$	$2.80\cdot10^{-5}$

In Thiem's formula (*Equation 3-9*), R/r_0 is assumed to be 500, Q is pumping rate and s is drawdown by the end of the flow period (*Appendices KFR##.9.2*). In the Moye formula (*Equation 3-10*) the borehole length denotes water filled, uncased part of the borehole.

6.6 Groundwater level and pumping rate

The groundwater level in the boreholes during the measurement sequences is presented in Appendices KFR##.9.2. The borehole KFR119 was pumped between October 29 and November 2 with a drawdown of ca. 1 m. The borehole KFR121 was pumped between October 13 and October 23 with a drawdown of ca 10 m.

Note that manually measured pumping rate is presented for KFR121 from the start of the pumping period until October 21 (*Appendix KFR121.9.2, dark grey curve in the corresponding figure*). Manual measurement result is presented due to technical difficulties encountered in the performance of automatic measurement. The problems concerned only measuring of the pumping rate and did not affect performance of the actual pumping equipment or maintaining steady groundwater level in the borehole and therefore did not have any further impact on the representativity of the results. The technical issues were resolved later on and from October 21 onwards, the pumping rate was recorded using an automatic flowmeter for the duration of the rest of the measurements conducted in the borehole (*Appendix KFR121.9.2, black curve in the corresponding figure*).

The groundwater recovery was measured after each pumping period. The PFL equipment remained in the borehole to measure the transient of the water level immediately after pumping was stopped. After registering the initial recovery transient, water level measurement was continued with SKB's water level sensor and the PFL equipment was moved on to next borehole in the measurement program. Water level measurement results during the groundwater recovery are presented in detail in Appendices KFR##.9.3.

7 Summary

In this study, the Posiva Flow Log, Difference Flow Method has been used to determine the locations and flow rates of flowing fractures or structures in boreholes KFR119 and KFR121 located at Forsmark area, Sweden. Measurements were carried out both, when the water level in the borehole was at rest, and during pumping. A 5 m long measurement section with 0.5 m long increments was used initially in un-pumped conditions and again in pumped conditions. The boreholes were measured also with a 1 m long section and 0.1 m long increments in pumped conditions.

In borehole KFR121 selected length intervals were measured also using a 1 m long measurement section and 0.1 m long increments in natural conditions to obtain more detailed information on fracture-specific flows. High flows were also detected in the borehole. High fracture and/or section flows can cause friction loss in the PFL DIFF probe's flow guide, causing a pressure rise inside the measurement section. These cases were examined in more detail to ascertain that correct head and flow values were used in interpretation.

A number of conductive fractures were detected in both boreholes. There were 0.22 fractures per metre in KFR119 on average and 0.35 fractures per metre in KFR121. In general, noise level in the flow measurements was low *(<30 mL/h*) and therefore all flows higher than 30 mL/h were most likely detected.

Possible casing pipe leakages were checked by measuring flow along the borehole just below the casing pipes in undisturbed conditions. The inner diameters of the casing pipes were 77 mm thus enabling the measurement of flow along the casing pipe as well. A possible casing pipe leakage was found in KFR121.

In KFR119 the target drawdown of 5 m was not reached. Despite the high pumping rate of ca 60 L/min only ca 1 m drawdown was achieved. The transmissivity and head of fracture at 11.4 m remain uncertain due to the very high flowrate (too high flow rate to measure with PFL DIFF probe), flow friction in the PFL DIFF probe's flow guide and temporary malfunctioning of the pump. The flow rate of fracture at 11.4 m was too.

In KFR121 a high flow rate was detected at the joint of casing pipe and the borehole. Although it most probably was not a flowing fracture in the bedrock, it has still been considered in fracture- and section-specific tables with added remarks denoting that the flow was possibly from the joint of casing pipe and borehole.

The distribution of saline water along the borehole was logged by electrical conductivity and temperature measurements of the borehole water. Based on the results, water salinity or changes in salinity did not affect the quality of the measurement results.

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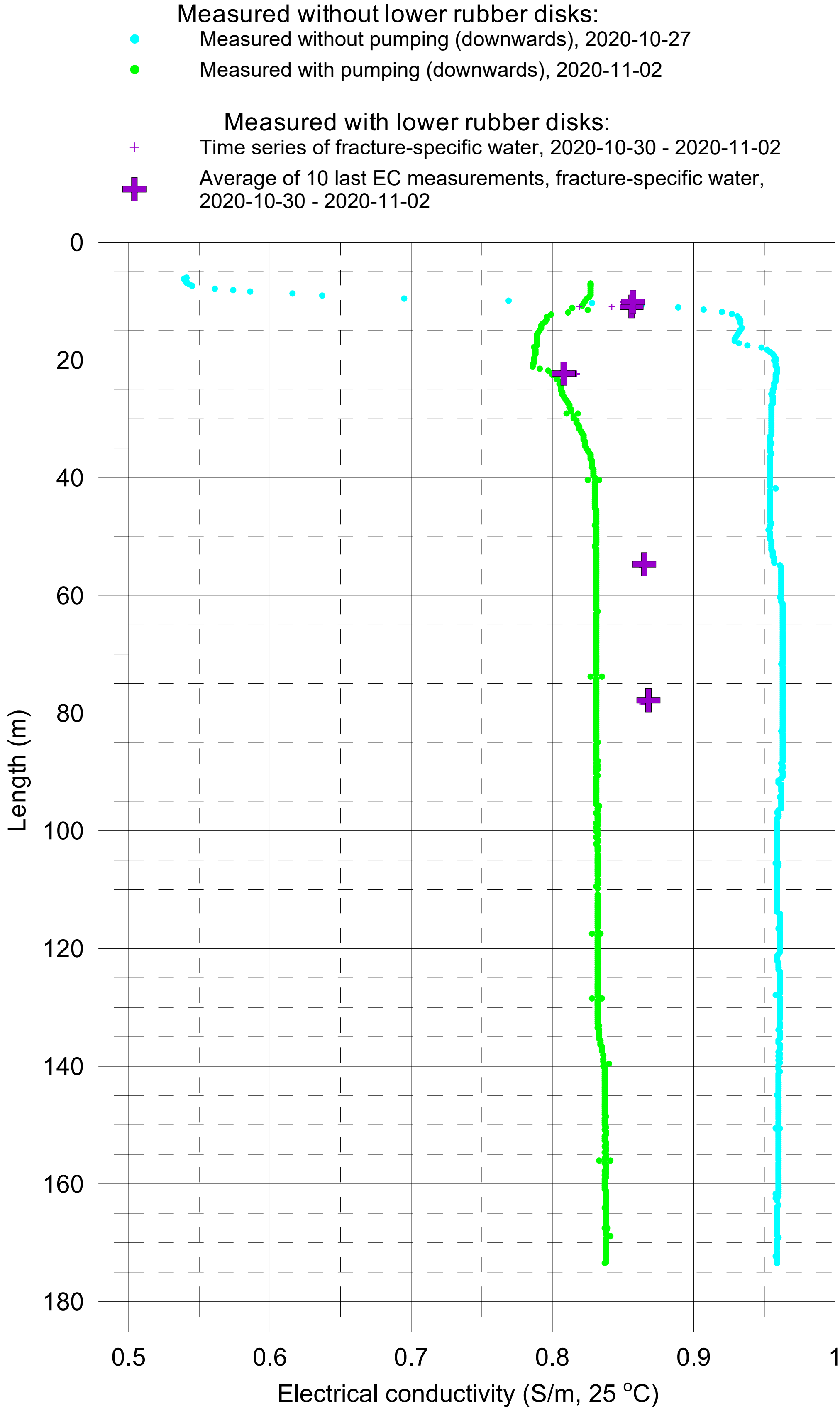
Appendices

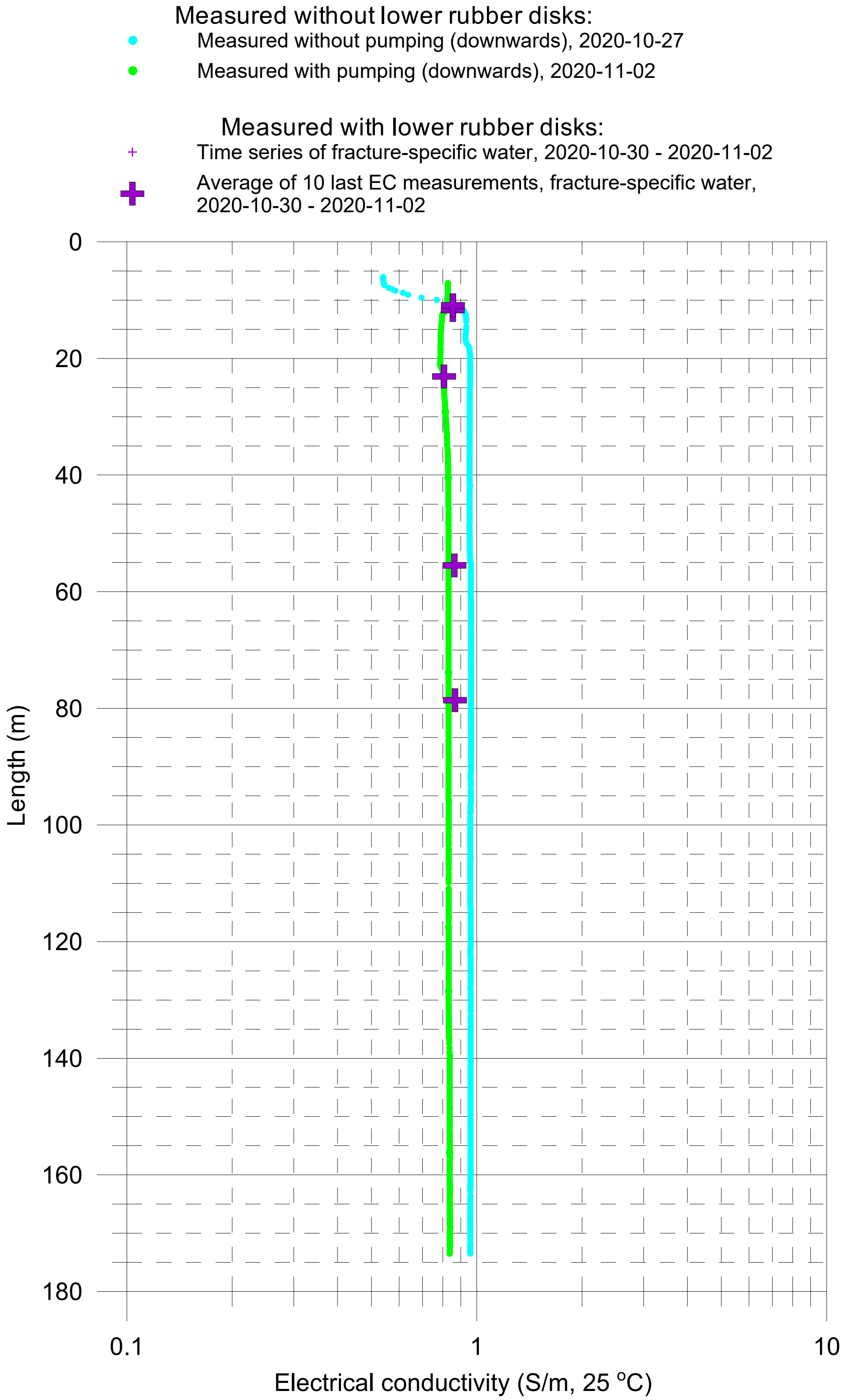
Appendix A

KFR119.1.1 – KFR119.1.2	Electrical conductivity of borehole water
KFR119.1.3	Temperature of borehole water
KFR119.2.1 – KFR119.2.9	Flow rate and single point resistance
KFR119.2.10	Vertical flow along the borehole at 7.9 m
KFR119.2.11	Vertical flow along the borehole at 9.8 m
KFR119.3	Glossary of terms used in the tables in Appendices
KFR121.4.1 – KFR121.4.2	Results of section flows
KFR119.5.1	Plotted flow rates of 5 m sections
KFR119.5.2	Plotted transmissivity and head of 5 m sections
KFR119.5.3	Transmissivity and head of 5 m sections with calculated error limits
KFR119.5.4	Conductive fracture frequency
KFR119.6	Inferred fracture flow anomalies from flow logging
KFR119.7.1	Plotted transmissivity and head of detected fractures
KFR119.7.2	Transmissivity and head of detected fractures with calculated error limits.
KFR119.8	Comparison between section transmissivity and fracture transmissivity
KFR119.9.1	Head in the borehole during flow logging
KFR119.9.2	Air pressure, water level in the borehole and pumping rate during flow logging
KFR119.9.3	Groundwater recovery after pumping
KFR119.10.1 – KFR119.10.3	Fracture-specific EC results by date
KFR119.11	Flow rate, single point resistance and head in the borehole during flow logging

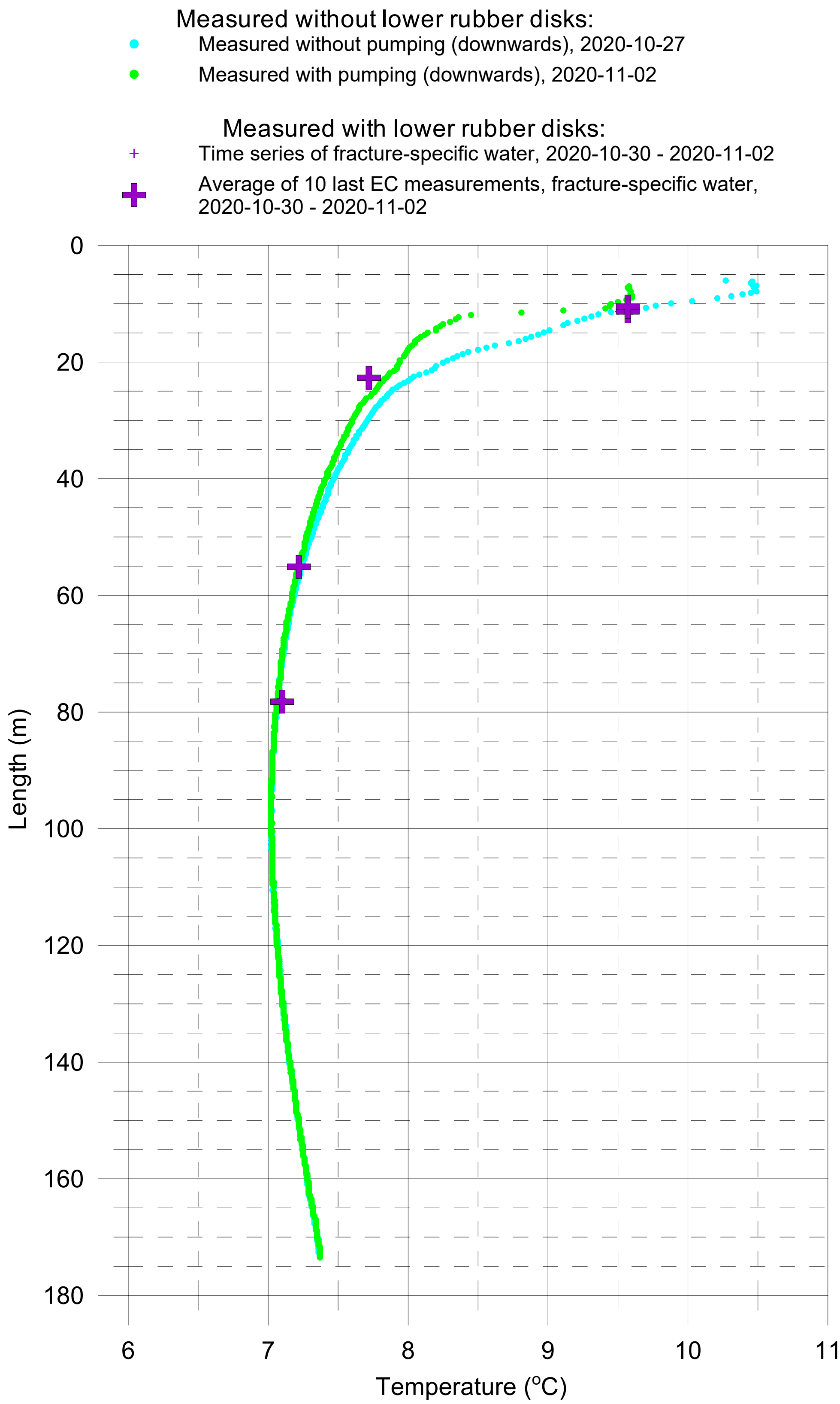
Forsmark, borehole KFR119
Electrical conductivity of borehole water



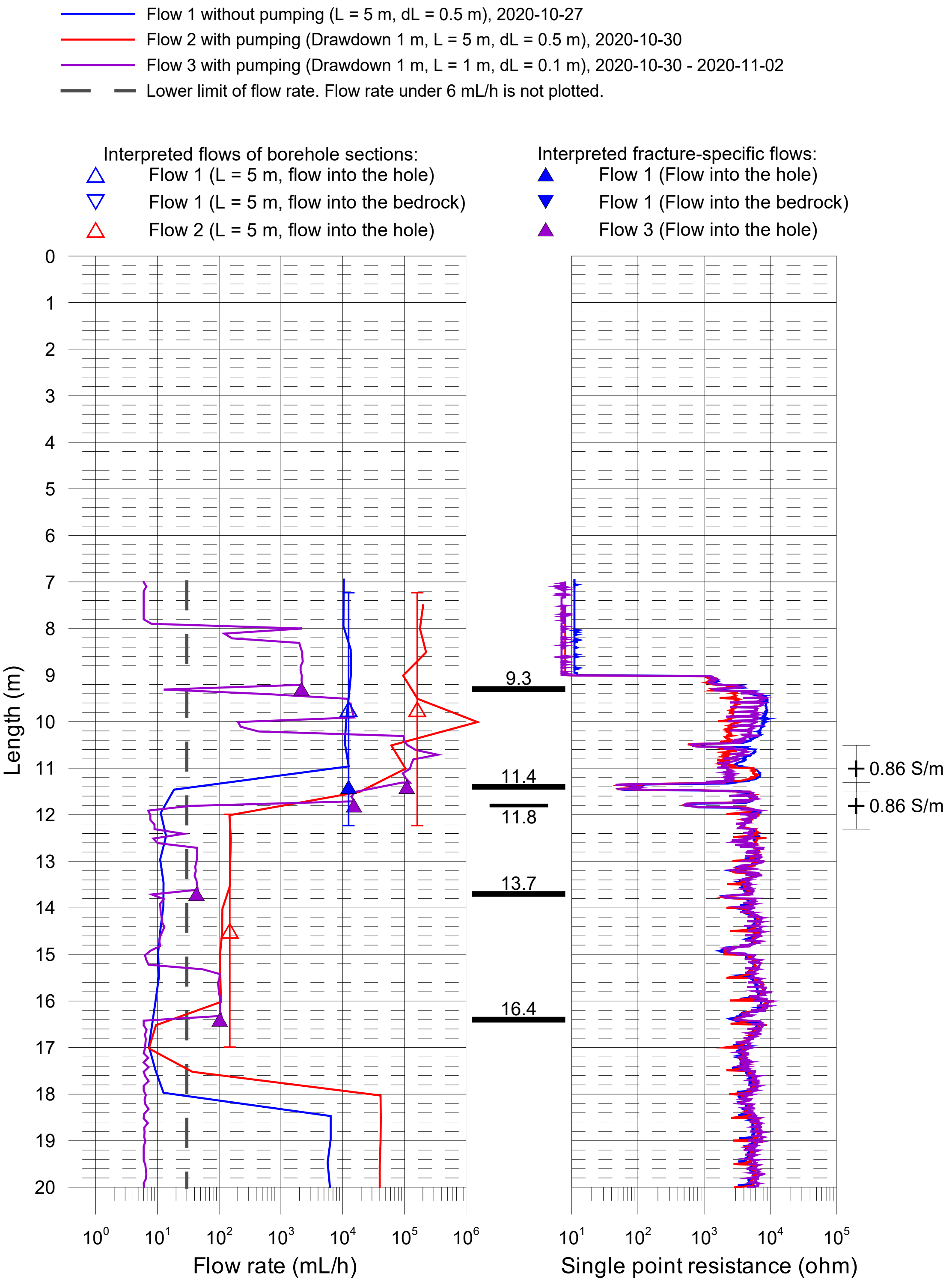
Forsmark, borehole KFR119
Electrical conductivity of borehole water



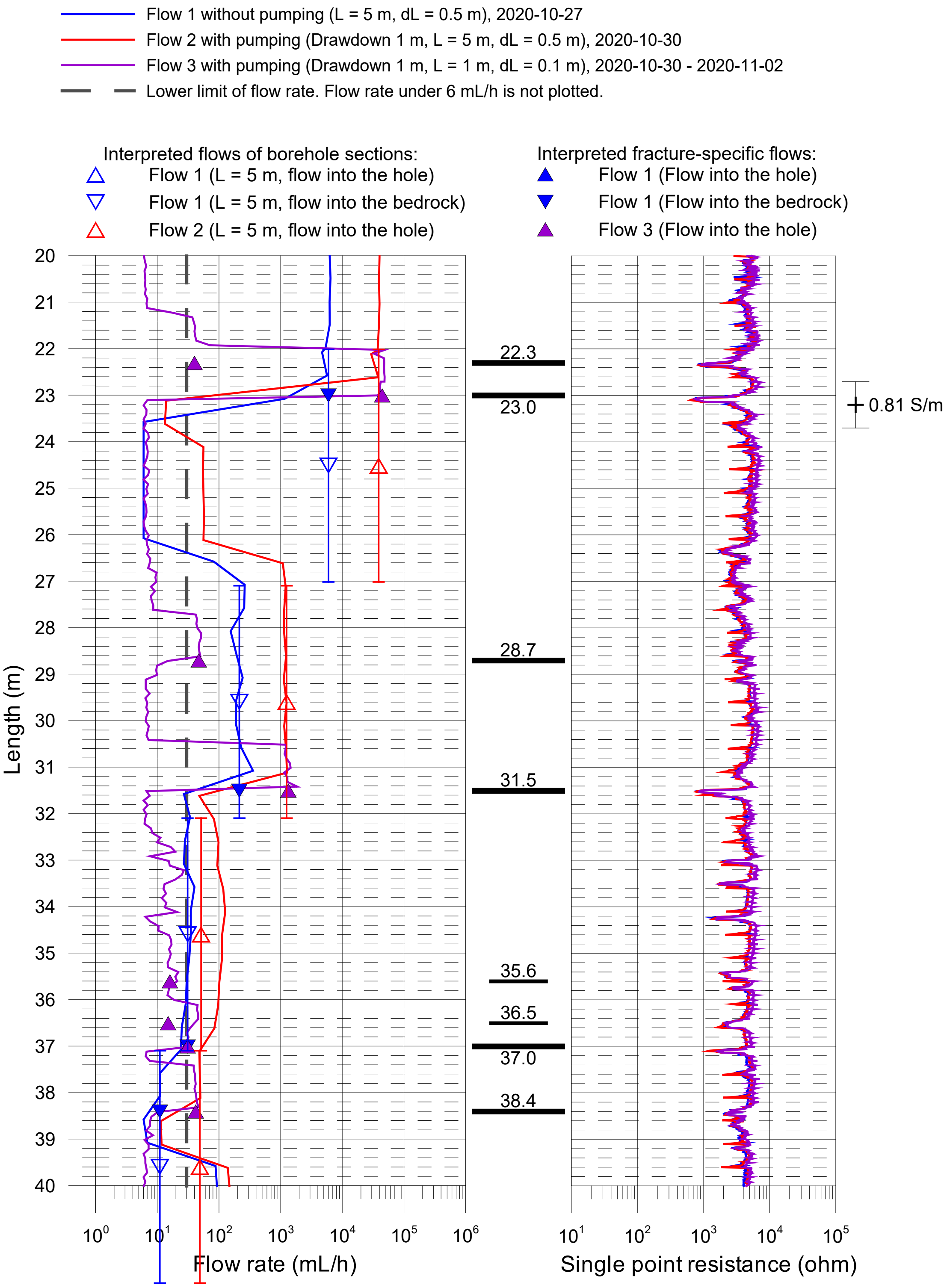
Forsmark, borehole KFR119
Temperature of borehole water



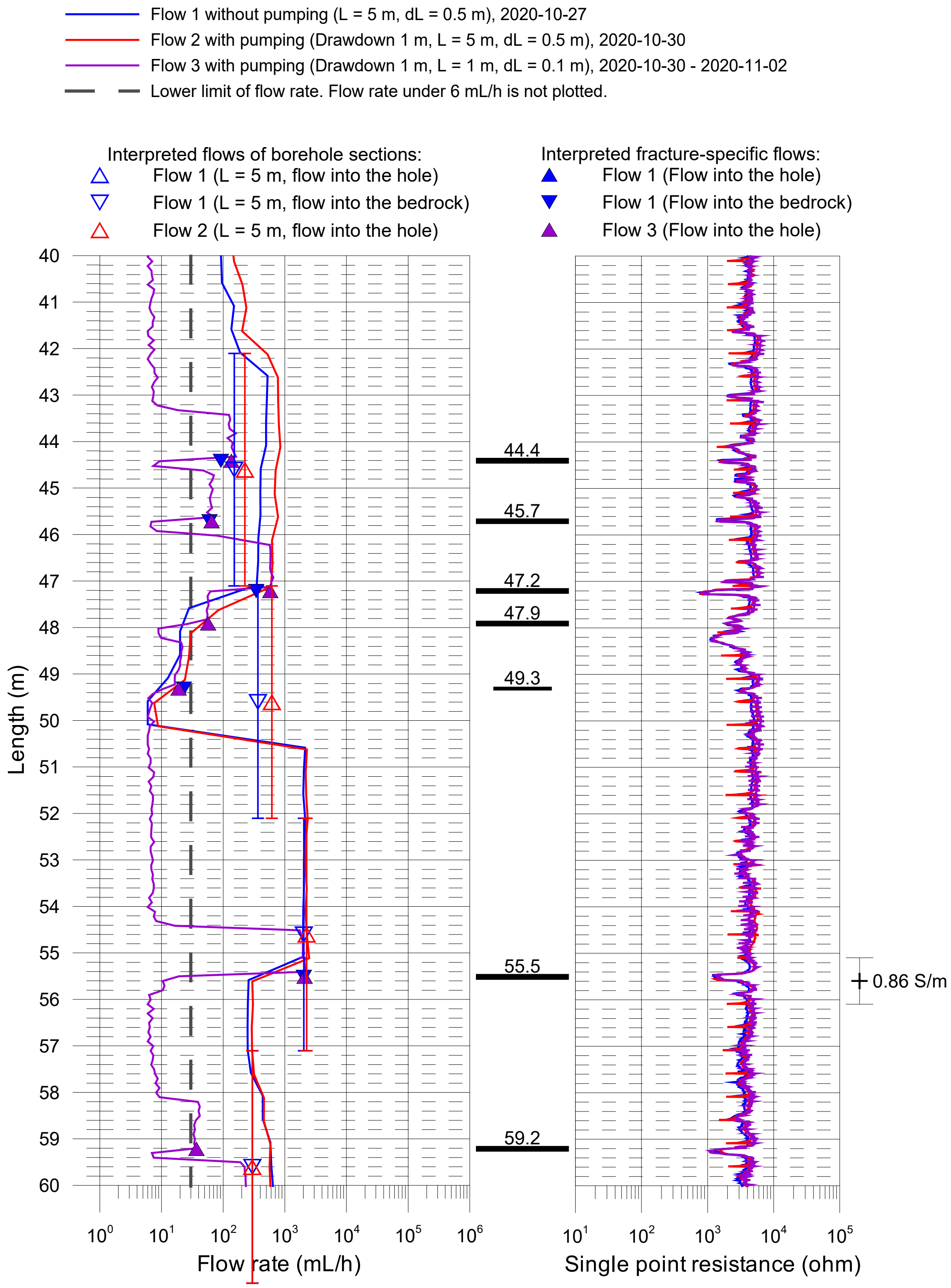
Forsmark, borehole KFR119
Flow rate and single point resistance



Forsmark, borehole KFR119
Flow rate and single point resistance

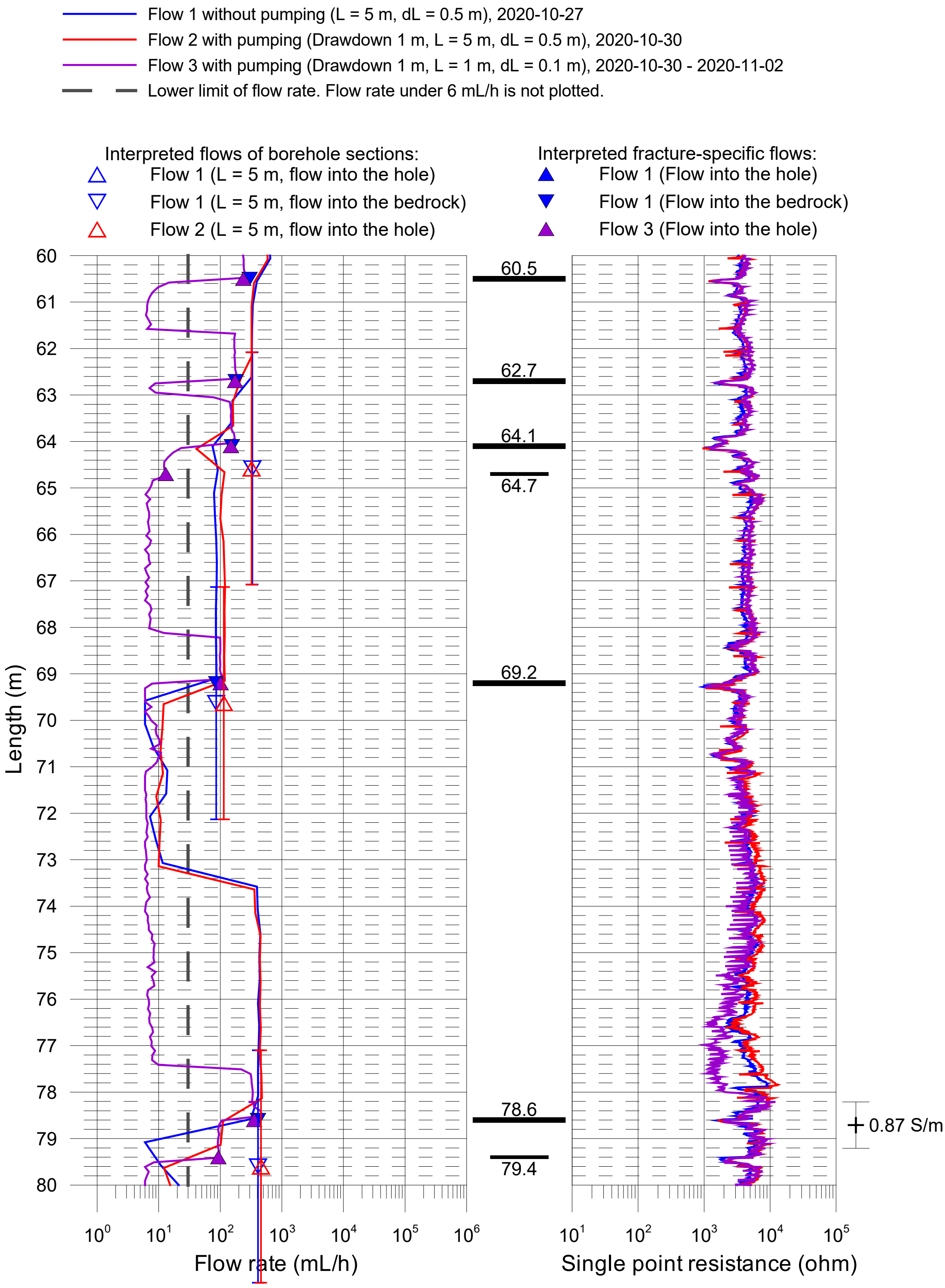


Forsmark, borehole KFR119
Flow rate and single point resistance

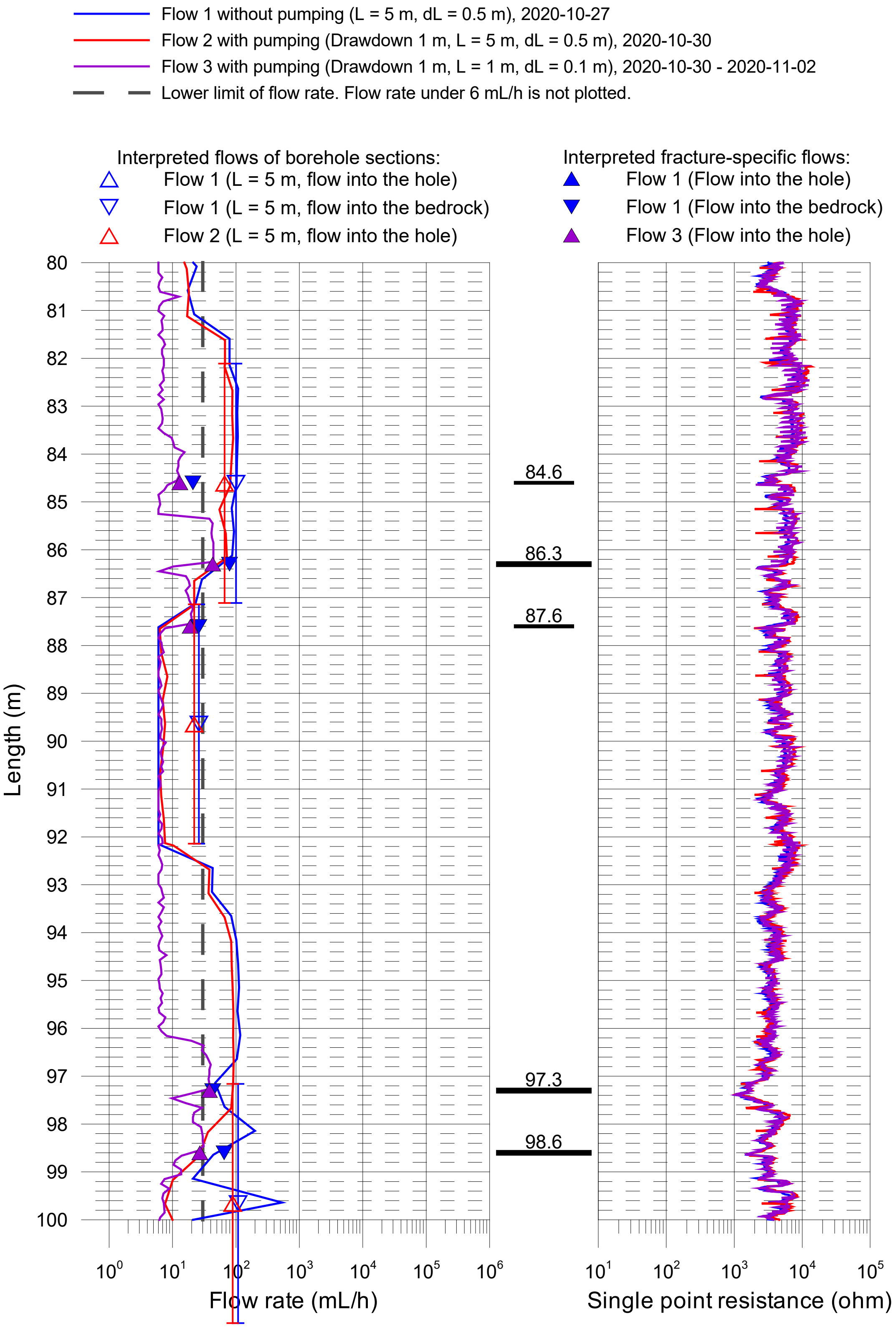


Appendix KFR119.2.4

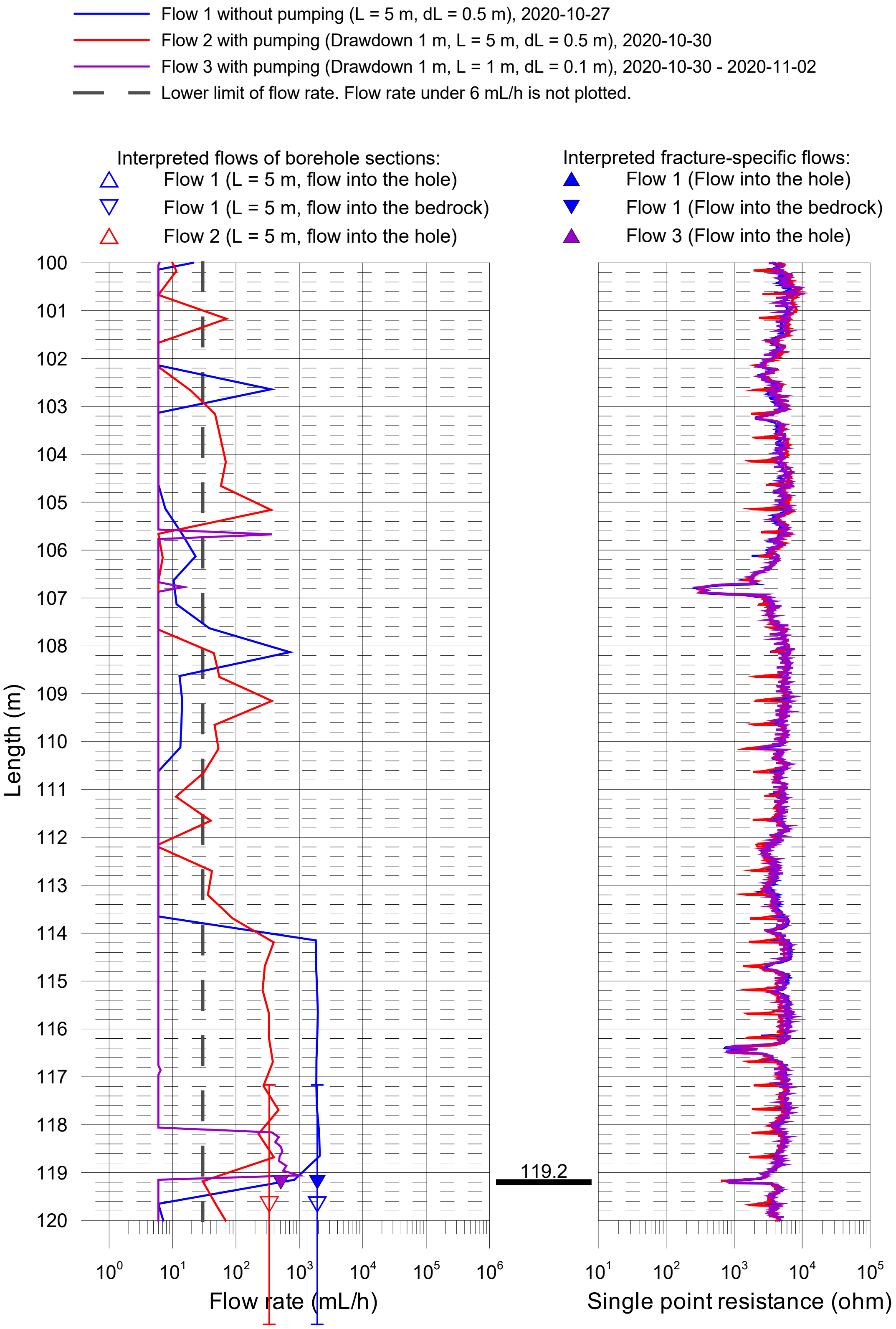
Forsmark, borehole KFR119
Flow rate and single point resistance



Forsmark, borehole KFR119
Flow rate and single point resistance

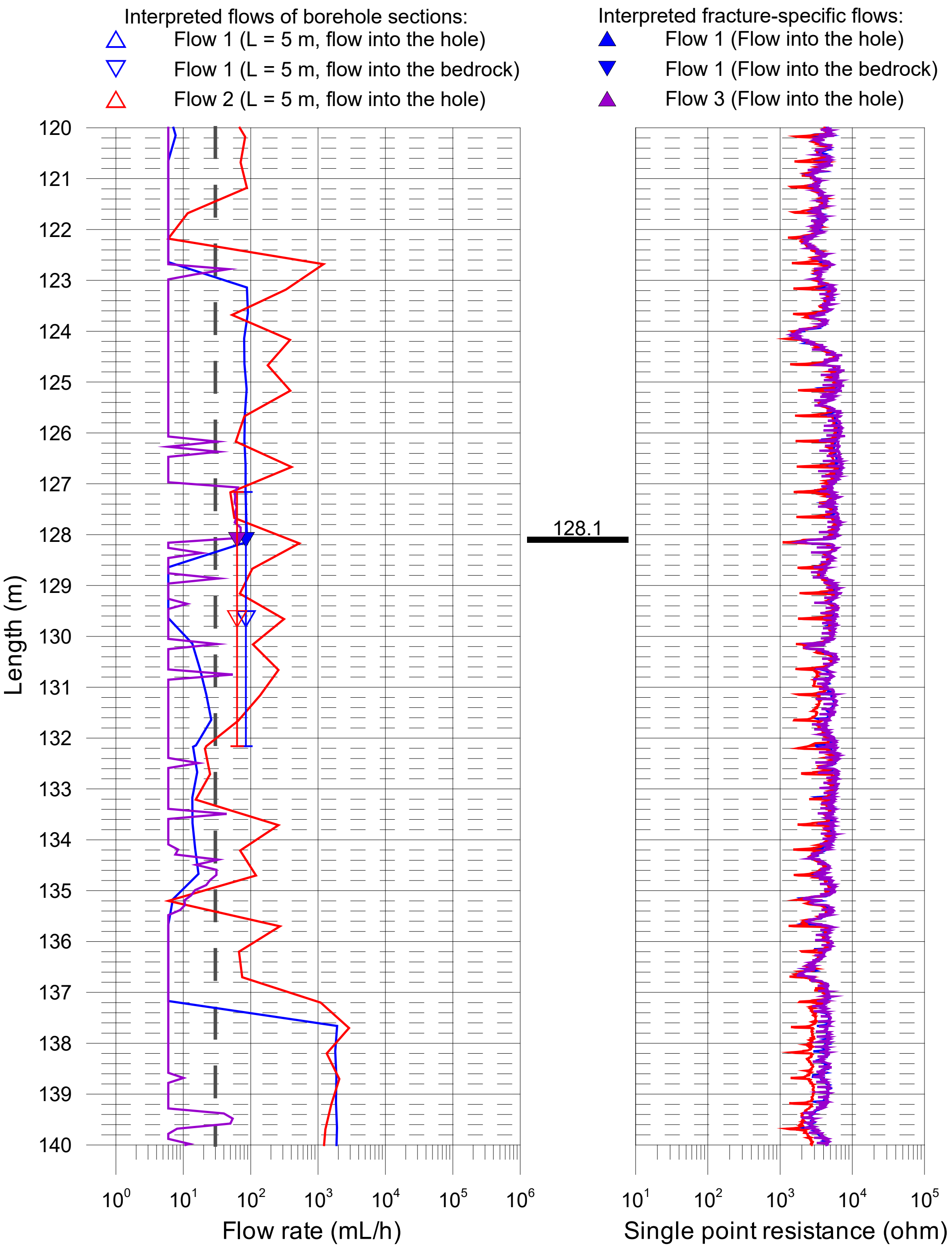


Forsmark, borehole KFR119
Flow rate and single point resistance

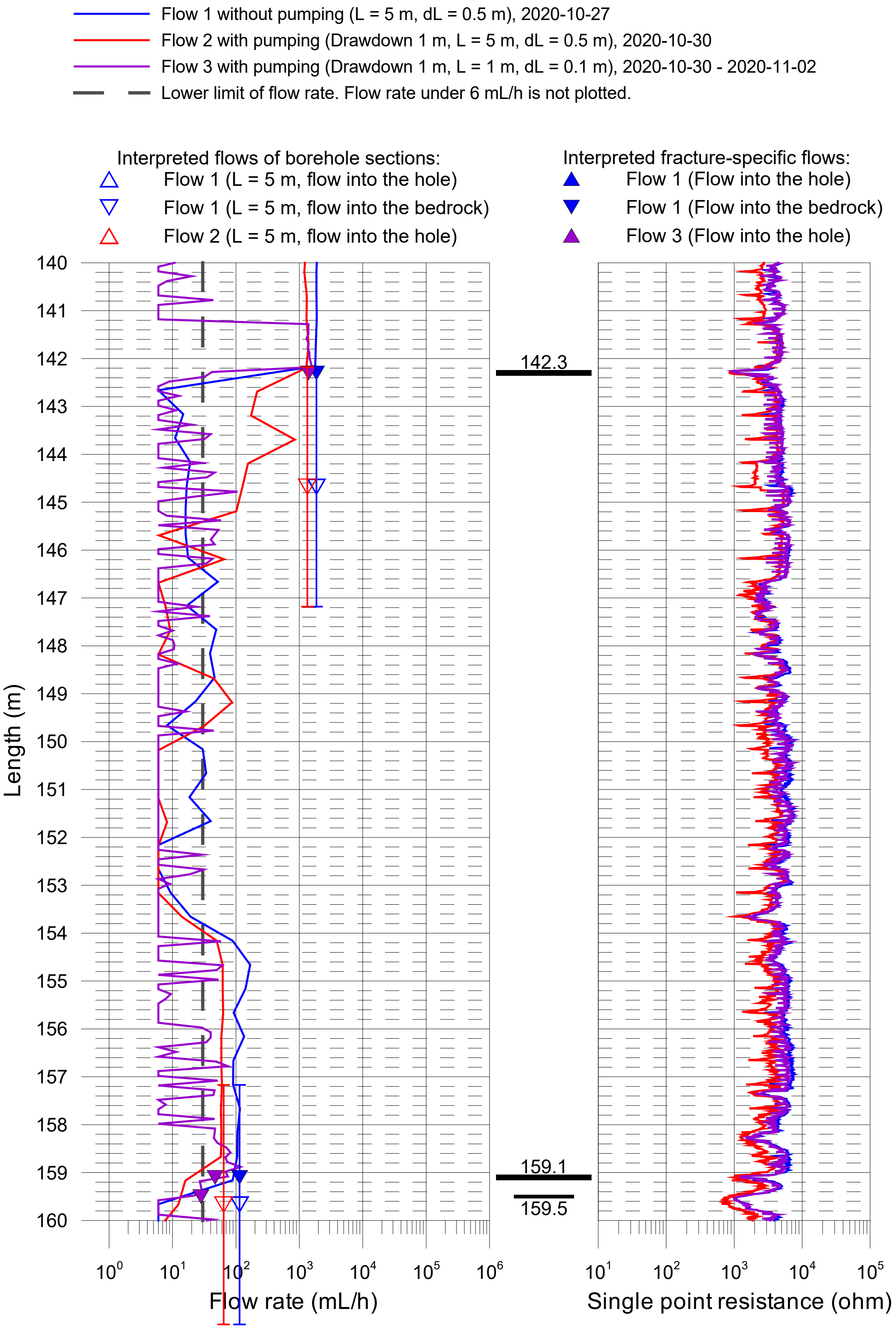


Forsmark, borehole KFR119
Flow rate and single point resistance

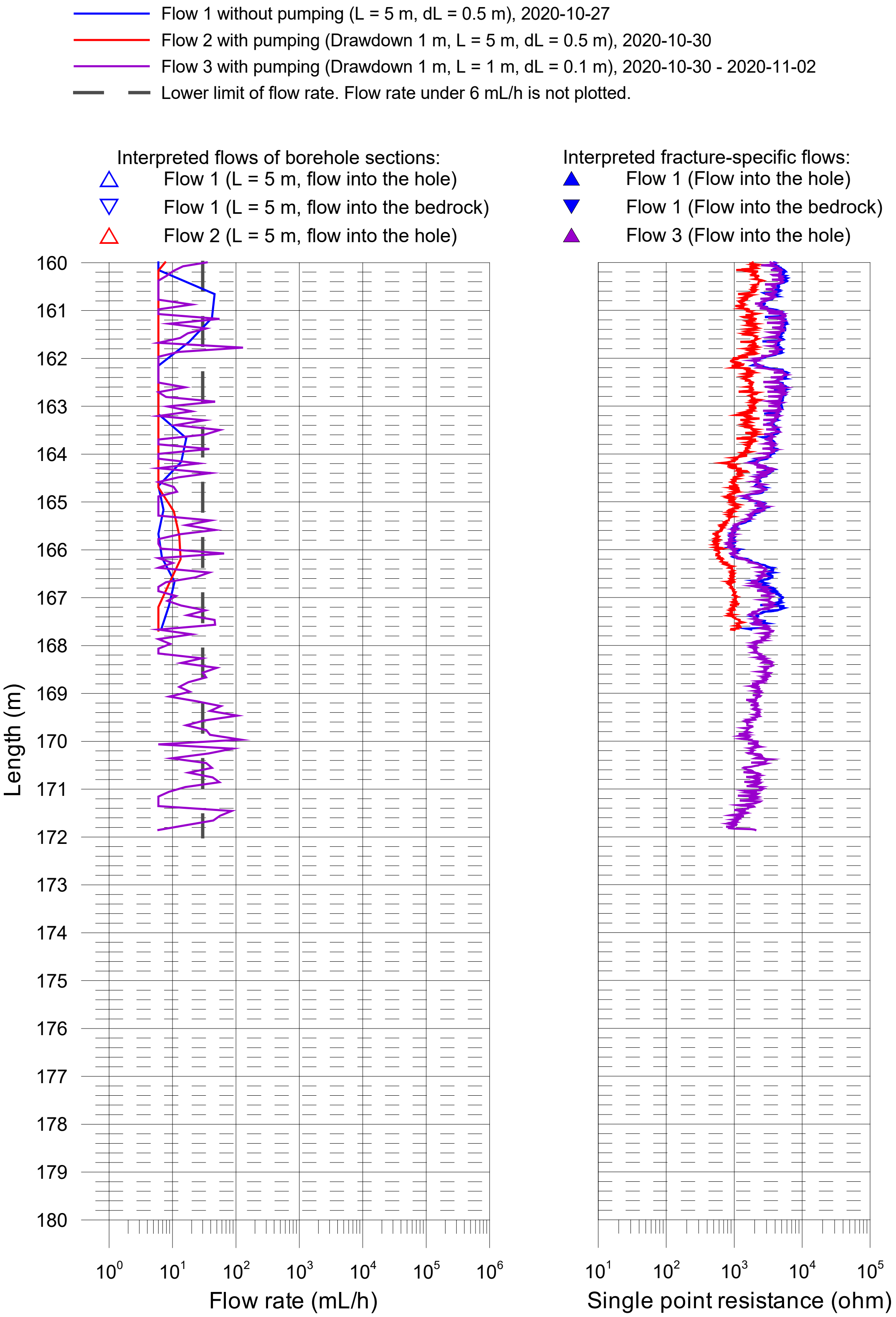
Flow 1 without pumping (L = 5 m, dL = 0.5 m), 2020-10-27
Flow 2 with pumping (Drawdown 1 m, L = 5 m, dL = 0.5 m), 2020-10-30
Flow 3 with pumping (Drawdown 1 m, L = 1 m, dL = 0.1 m), 2020-10-30 - 2020-11-02
Lower limit of flow rate. Flow rate under 6 mL/h is not plotted.



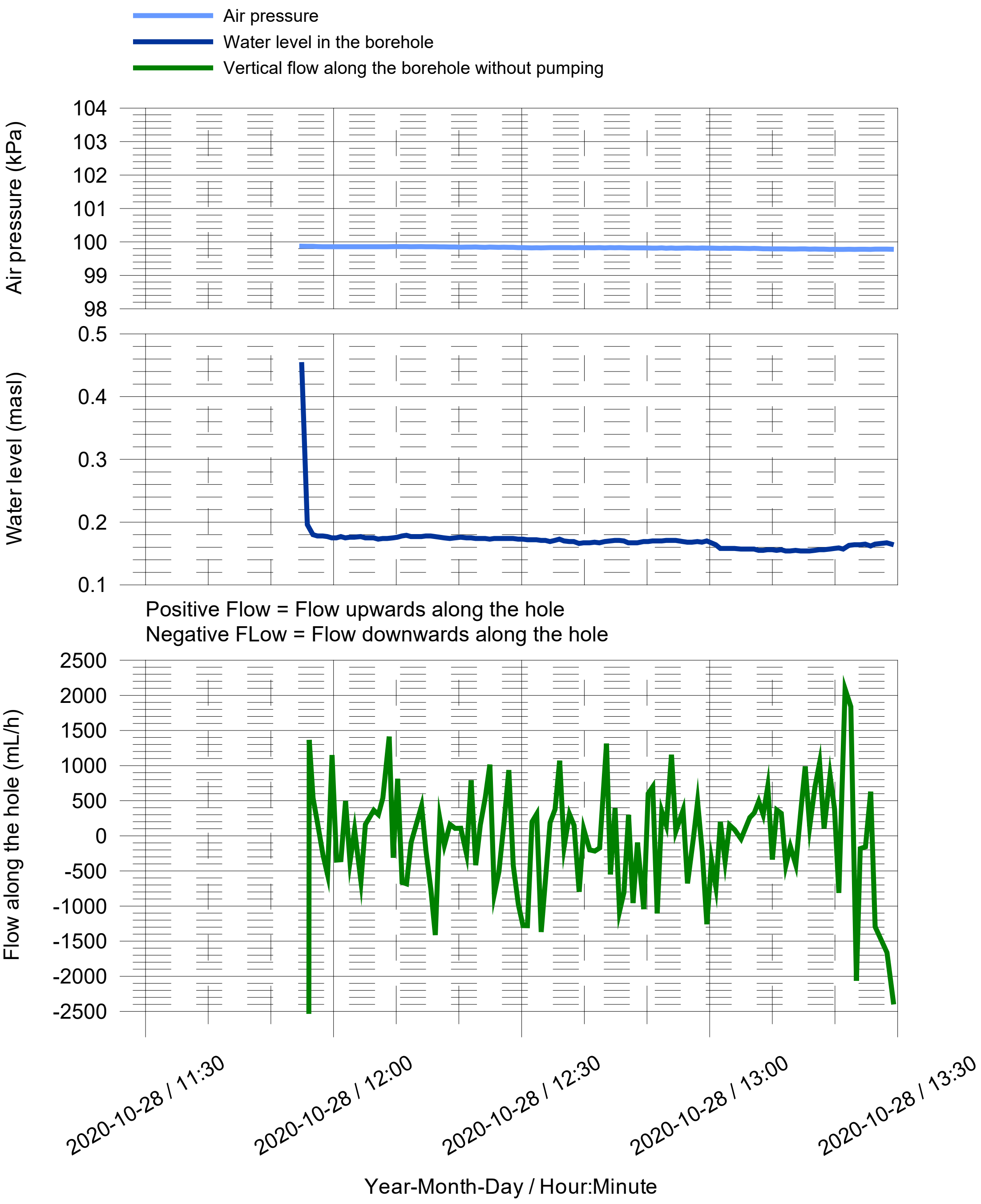
Forsmark, borehole KFR119
Flow rate and single point resistance



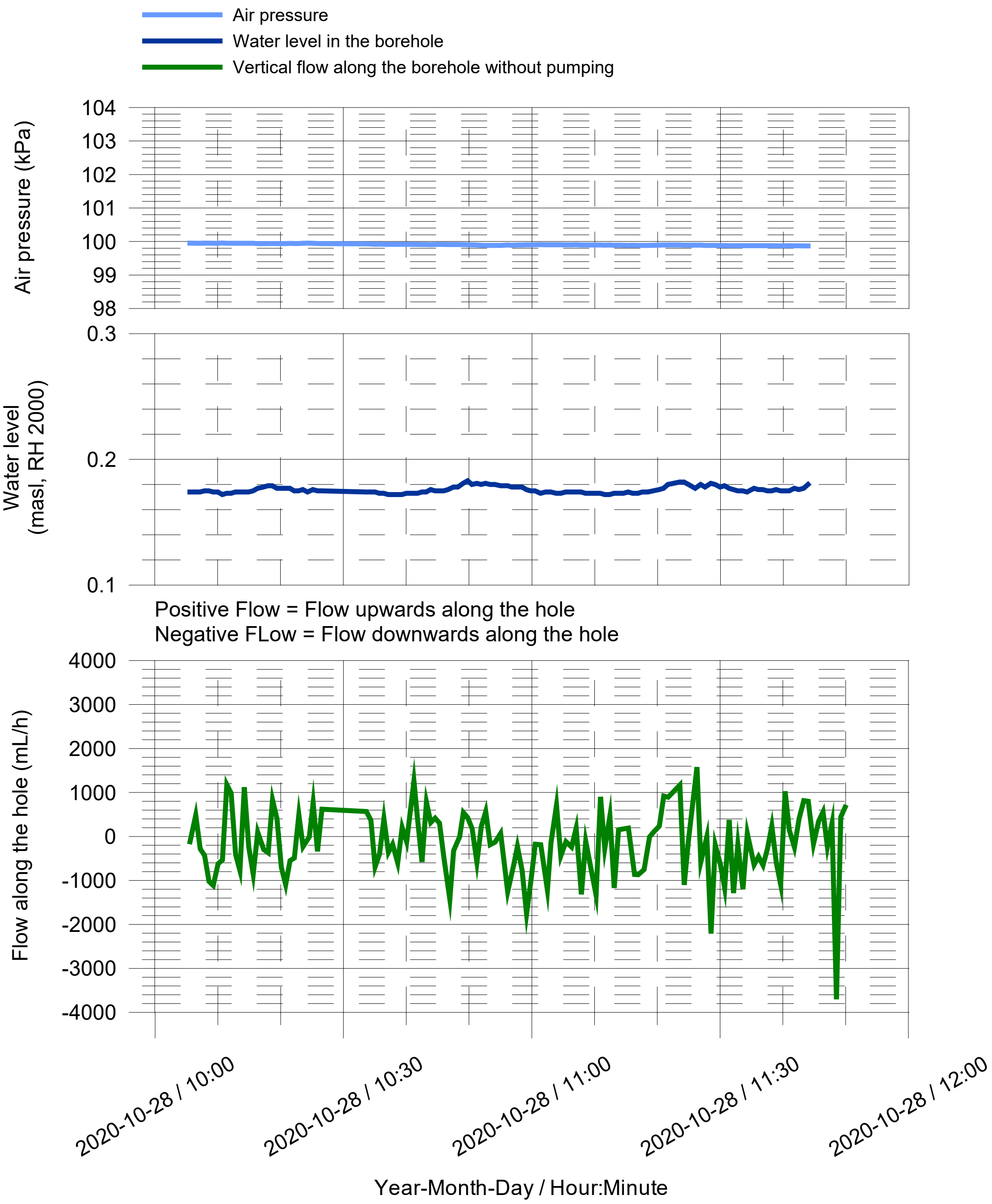
Forsmark, borehole KFR119
Flow rate and single point resistance



Forsmark, borehole KFR119
Vertical flow along the borehole at the length of 7.9 m



Forsmark, borehole KFR119
Vertical flow along the borehole at the length of 9.8 m



Appendix KFR119.3

Glossary of terms used in the tables in Appendices

Header	Unit	Definition
Borehole ID		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)
Length to flow anom.	m	Length along the borehole to inferred flow anomaly during overlapping flow logging
L_w	m	Section length used in the difference flow logging
dL	m	Step length (increment) used in the difference flow logging
Q_0	m^3/s	Measured flow rate through the test section or flow anomaly under natural conditions (no pumping) with h=h0 in the open borehole
Q_1	m^3/s	Measured flow rate through the test section or flow anomaly during the first pumping period
h_{0FW}	masl	Corrected initial hydraulic head along the borehole due to e.g. varying salinity conditions of the borehole fluid before pumping
h_{1FW}	masl	Corrected hydraulic head along the borehole due to e.g. varying salinity conditions of the borehole fluid during the first pumping period
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.
Q-lower limit P	mL/h	Practical lower measurement limit for flow rate.
T-$measl_{LT}$	m^2/s	Estimated theoretical lower measurement limit for evaluated TD. If the estimated TD equals TD-measlim, the actual TD is considered to be equal or less than TD-measlim.
T-$measl_{LP}$	m^2/s	Estimated practical lower measurement limit for evaluated TD. If the estimated TD equals TD-measlim, the actual TD is considered to be equal or less than TD-measlim.
T-$meas_{lU}$	m^2/s	Estimated upper measurement limit for evaluated TD. If the estimated TD equals TD-measlim, the actual TD is considered to be equal or less than TD-measlim.
h_i	masl	Calculated relative, natural freshwater head for test section or flow anomaly (undisturbed conditions)

Appendix KFR119.4.1

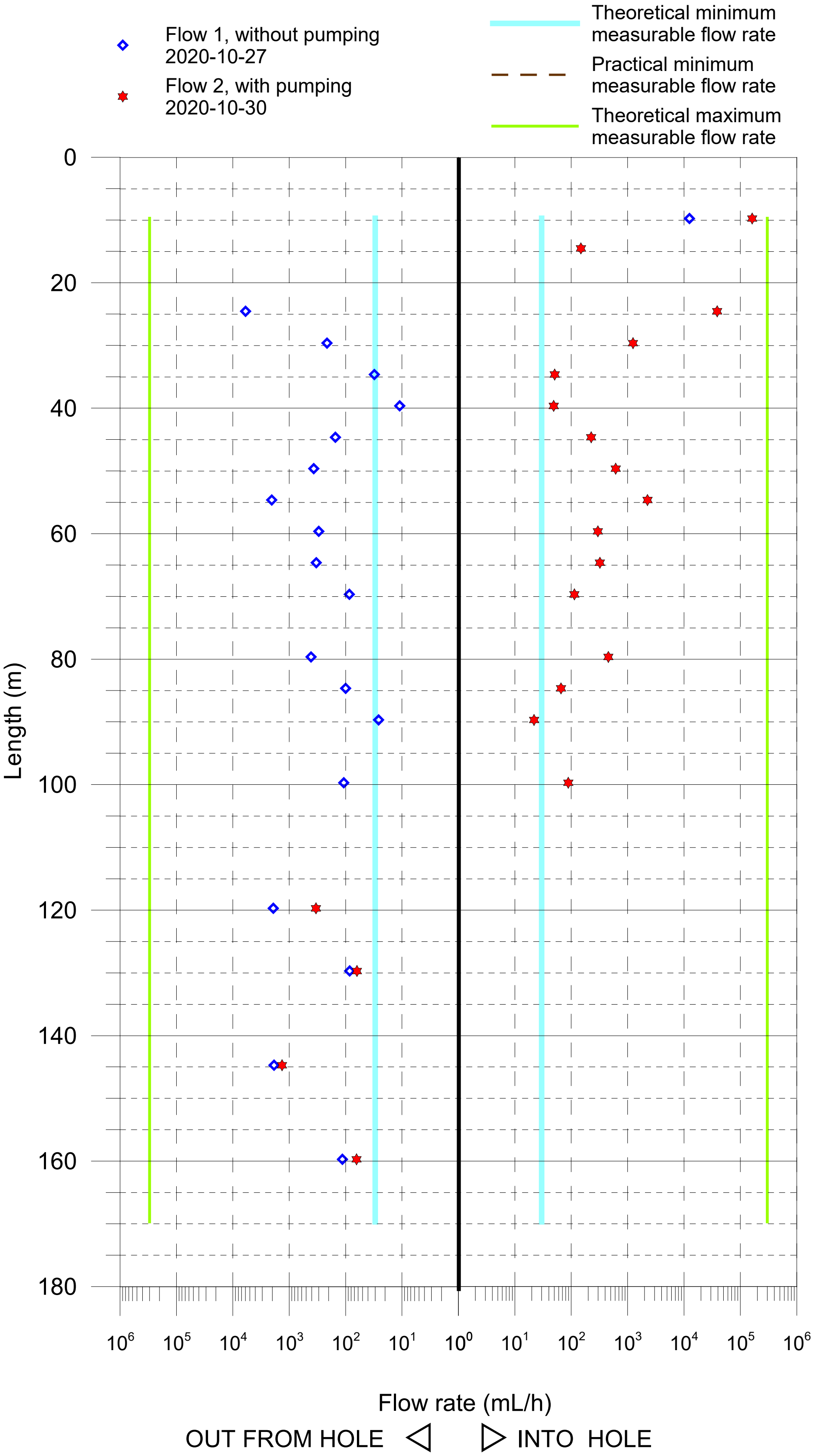
Borehole ID	Secup L(m)	Seclow L(m)	L_w (m)	Q_0 (m^3/s)	h_{0FW} (masl)	Q_1 (m^3/s)	h_{1FW} (masl)	T_D (m^2/s)	h_i (masl)	Q-lower limit P (mL/h)	T_D-measl$_{LT}$ (m^2/s)	T_D - measl$_{LP}$ (m^2/s)	T_D - measl$_U$ (m^2/s)	Comments
KFR119	7.23	12.23	5	3.47E-06	0.57	4.50E-05	0.49	-	-	30	1.0E-07	1.0E-07	9.9E-04	*
KFR119	11.99	16.99	5	-	0.50	4.14E-08	-0.15	6.3E-08	-	30	1.3E-08	1.3E-08	1.3E-04	
KFR119	16.99	21.99	5	-	0.48	-	-0.11	-	-	30	1.4E-08	1.4E-08	1.4E-04	
KFR119	22.01	27.01	5	-1.65E-06	0.52	1.08E-05	-0.15	1.8E-05	0.4	30	1.2E-08	1.2E-08	1.3E-04	
KFR119	27.09	32.09	5	-5.94E-08	0.53	3.46E-07	-0.12	6.2E-07	0.4	30	1.3E-08	1.3E-08	1.3E-04	
KFR119	32.09	37.09	5	-8.61E-09	0.54	1.42E-08	-0.10	3.5E-08	0.3	30	1.3E-08	1.3E-08	1.3E-04	
KFR119	37.09	42.09	5	-3.06E-09	0.54	1.36E-08	-0.07	2.7E-08	0.4	30	1.4E-08	1.4E-08	1.4E-04	
KFR119	42.09	47.09	5	-4.22E-08	0.54	6.28E-08	-0.05	1.8E-07	0.3	30	1.4E-08	1.4E-08	1.4E-04	
KFR119	47.09	52.09	5	-1.02E-07	0.54	1.71E-07	-0.03	4.7E-07	0.3	30	1.5E-08	1.5E-08	1.5E-04	
KFR119	52.09	57.09	5	-5.67E-07	0.57	6.28E-07	-0.01	2.0E-06	0.3	30	1.4E-08	1.4E-08	1.4E-04	
KFR119	57.09	62.09	5	-8.31E-08	0.57	8.25E-08	0.02	3.0E-07	0.3	30	1.5E-08	1.5E-08	1.5E-04	
KFR119	62.08	67.08	5	-9.22E-08	0.63	8.97E-08	0.04	3.1E-07	0.3	30	1.4E-08	1.4E-08	1.4E-04	
KFR119	67.13	72.13	5	-2.39E-08	0.65	3.17E-08	0.06	9.3E-08	0.4	30	1.4E-08	1.4E-08	1.4E-04	
KFR119	72.10	77.10	5	-	0.69	-	0.09	-	-	30	1.4E-08	1.4E-08	1.4E-04	
KFR119	77.10	82.10	5	-1.14E-07	0.72	1.27E-07	0.11	3.9E-07	0.4	30	1.4E-08	1.4E-08	1.4E-04	
KFR119	82.11	87.11	5	-2.78E-08	0.73	1.83E-08	0.15	7.9E-08	0.4	30	1.4E-08	1.4E-08	1.4E-04	
KFR119	87.14	92.14	5	-7.22E-09	0.79	6.11E-09	0.20	2.2E-08	0.5	30	1.4E-08	1.4E-08	1.4E-04	
KFR119	92.12	97.12	5	-	0.79	-	0.23	-	-	30	1.5E-08	1.5E-08	1.5E-04	
KFR119	97.16	102.16	5	-3.00E-08	0.83	2.47E-08	0.26	9.5E-08	0.5	30	1.5E-08	1.5E-08	1.5E-04	
KFR119	102.16	107.16	5	-	0.85	-	0.29	-	-	30	1.5E-08	1.5E-08	1.5E-04	
KFR119	107.15	112.15	5	-	0.88	-	0.30	-	-	30	1.4E-08	1.4E-08	1.4E-04	
KFR119	112.14	117.14	5	-	0.90	-	0.33	-	-	30	1.5E-08	1.5E-08	1.5E-04	
KFR119	117.17	122.17	5	-5.33E-07	0.96	-9.33E-08	0.36	7.3E-07	0.2	30	1.4E-08	1.4E-08	1.4E-04	**
KFR119	122.16	127.16	5	-	1.00	-	0.40	-	-	30	1.4E-08	1.4E-08	1.4E-04	
KFR119	127.16	132.16	5	-2.36E-08	1.03	-1.75E-08	0.44	1.0E-08	-1.3	30	1.4E-08	1.4E-08	1.4E-04	**
KFR119	132.15	137.15	5	-	1.06	-	0.47	-	-	30	1.4E-08	1.4E-08	1.4E-04	
KFR119	137.19	142.19	5	-	1.11	-	0.49	-	-	30	1.3E-08	1.3E-08	1.3E-04	

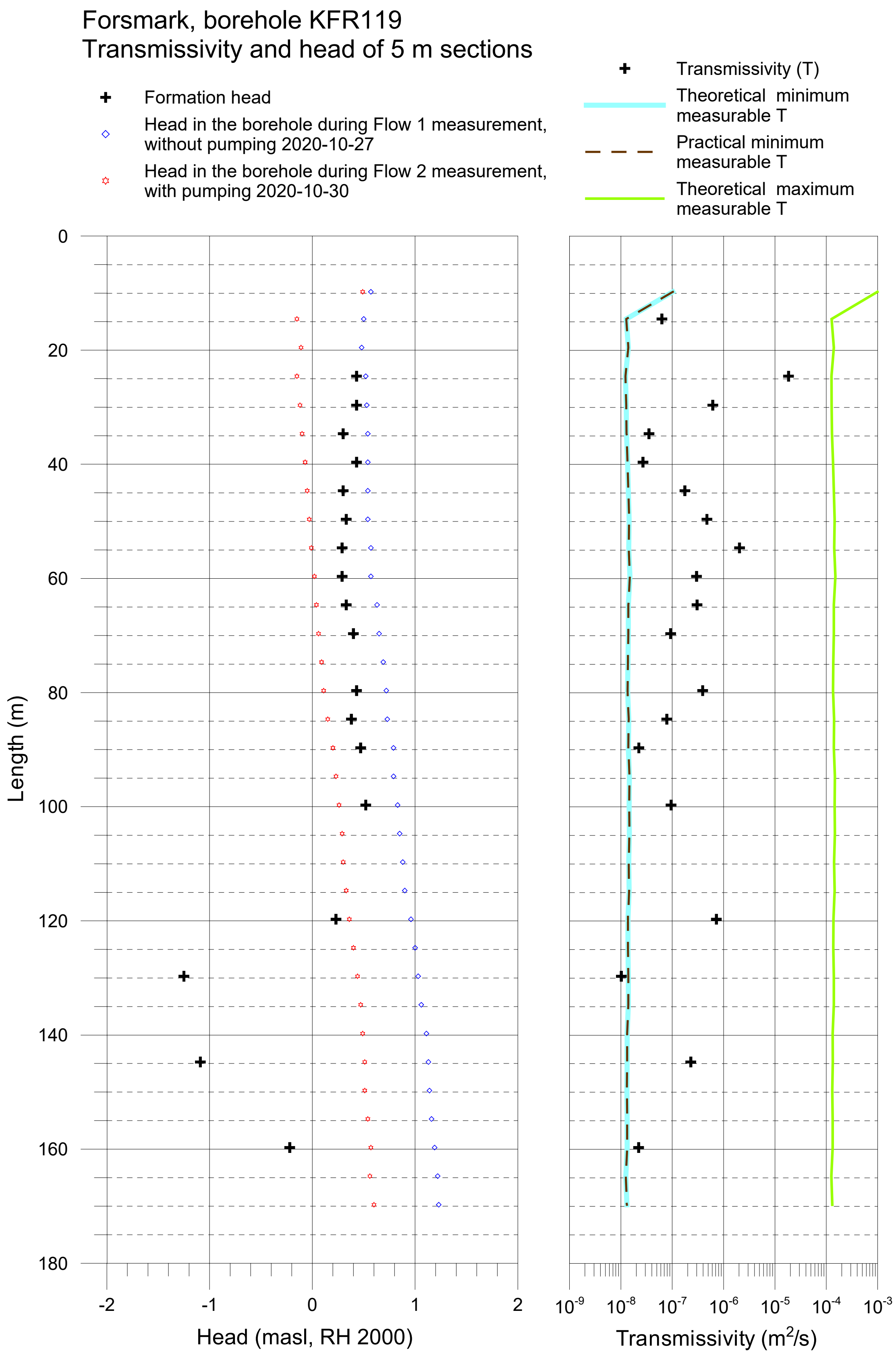
Appendix KFR119.4.2

Borehole ID	Secup L(m)	Seclow L(m)	L_w (m)	Q_0 (m^3/s)	h_{0FW} (masl)	Q_1 (m^3/s)	h_{1FW} (masl)	T_D (m^2/s)	h_i (masl)	Q-lower limit P (mL/h)	T_D-measl$_{LT}$ (m^2/s)	T_D - measl$_{LP}$ (m^2/s)	T_D - measl$_U$ (m^2/s)	Comments
KFR119	142.18	147.18	5	-5.17E-07	1.13	-3.72E-07	0.51	2.3E-07	-1.1	30	1.3E-08	1.3E-08	1.3E-04	**
KFR119	147.17	152.17	5	-	1.14	-	0.51	-	-	30	1.3E-08	1.3E-08	1.3E-04	
KFR119	152.17	157.17	5	-	1.16	-	0.54	-	-	30	1.3E-08	1.3E-08	1.3E-04	
KFR119	157.17	162.17	5	-3.17E-08	1.19	-1.78E-08	0.57	2.2E-08	-0.2	30	1.3E-08	1.3E-08	1.3E-04	**
KFR119	162.17	167.17	5	-	1.22	-	0.56	-	-	30	1.3E-08	1.3E-08	1.3E-04	
KFR119	167.19	172.19	5	-	1.23	-	0.60	-	-	30	1.3E-08	1.3E-08	1.3E-04	

*	In 5 m section measurement with pumping Flow Q_1 (Flow 2) the flow guide caused flow friction at the fracture 11.4 m which caused temporarily decreased pumping rate. Due that the water level rose very close to the 5 m section measurement without pumping Flow Q_0 (Flow 1). Thus transmissivity of the section T_D nor head of the section h_i are not calculated from Flow Q_0 (Flow 1) and Flow Q_1 (Flow 2). Therefore T_D nor h_i is not presented.
**	Due the small drawdown of 1 m the flow direction remained from borehole into the bedrock.

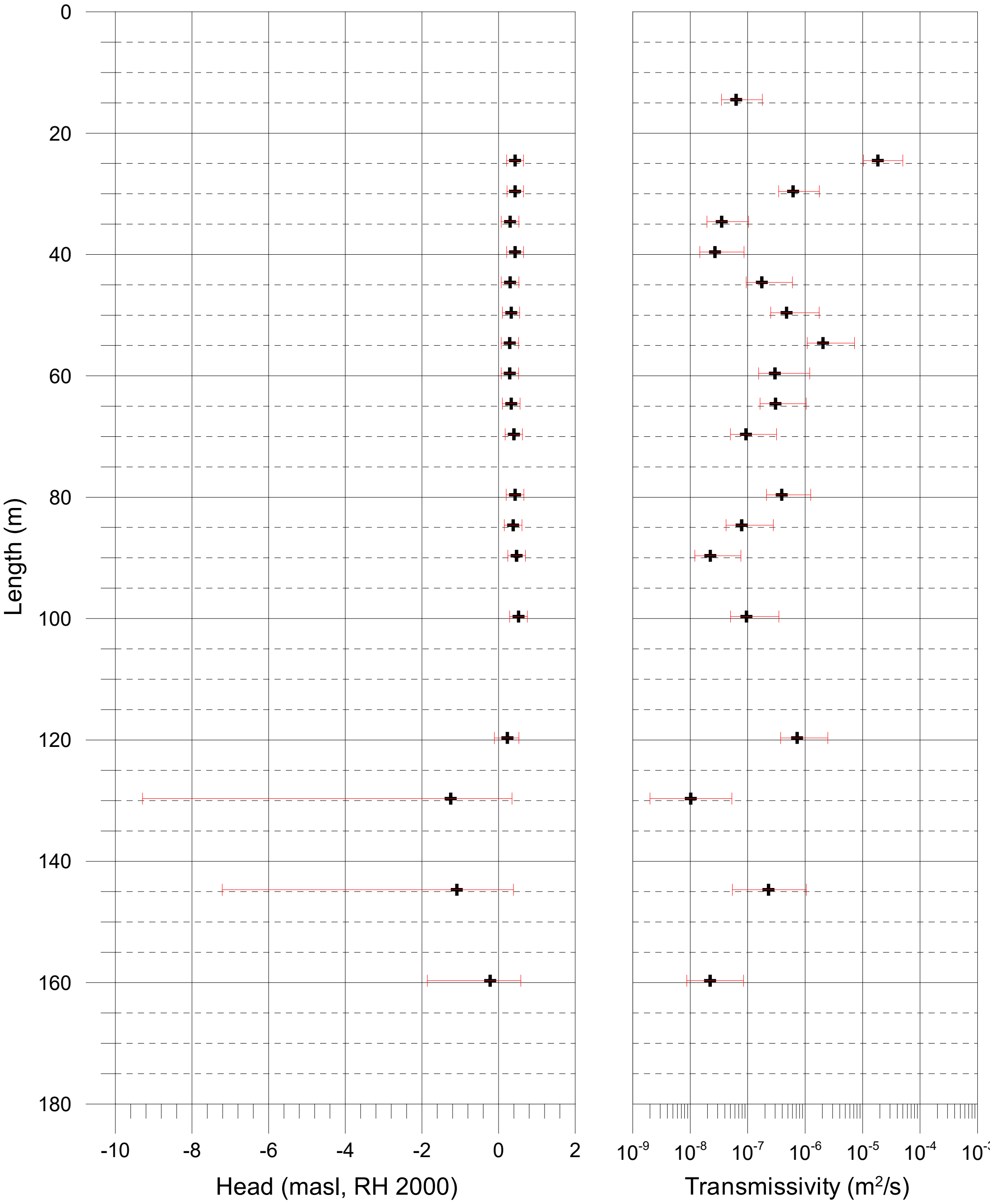
Forsmark, borehole KFR119
Flow rates of 5 m sections




Forsmark, borehole KFR119
Transmissivity and head of 5 m sections
Formation head
Head in the borehole during Flow 1 measurement, without pumping 2020-10-27
Head in the borehole during Flow 2 measurement, with pumping 2020-10-30
Transmissivity (T)
Theoretical minimum measurable T
Practical minimum measurable T
Theoretical maximum measurable T
Length (m)
0
20
40
60
80
100
120
140
160
180
-2
-1
0
1
2
Head (masl, RH 2000)
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
Transmissivity (m^2/s)

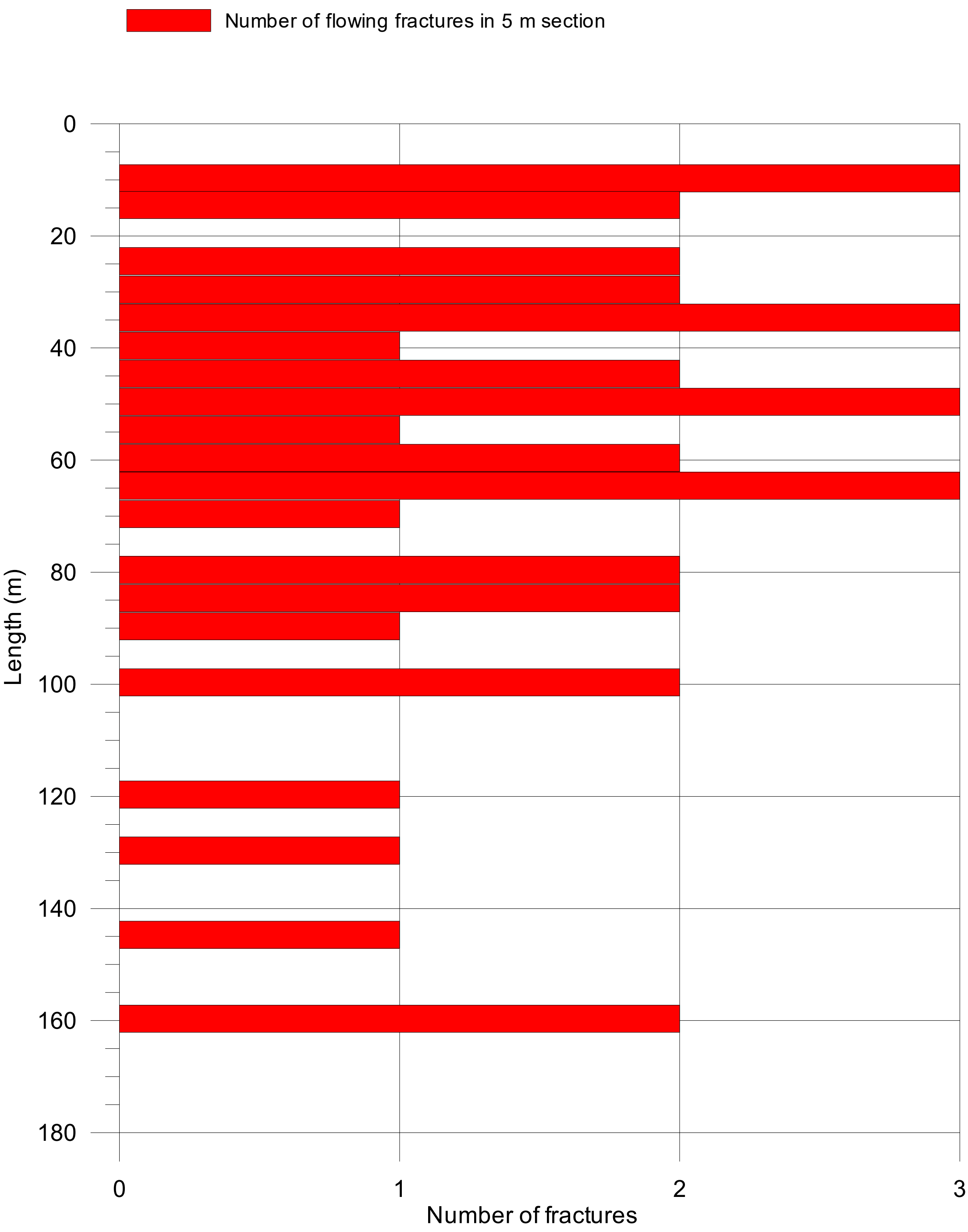
Appendix KFR119.5.3

Forsmark, borehole KFR119
Transmissivity and head of 5 m sections
Error bars assuming ±10% errors in flow rates
and ±0.2 m in head in worst-case combination



Appendix KFR119.5.4

Forsmark, borehole KFR119
Calculation of conductive fracture frequency



Appendix KFR119.6

Inferred fracture flow anomalies from flow logging

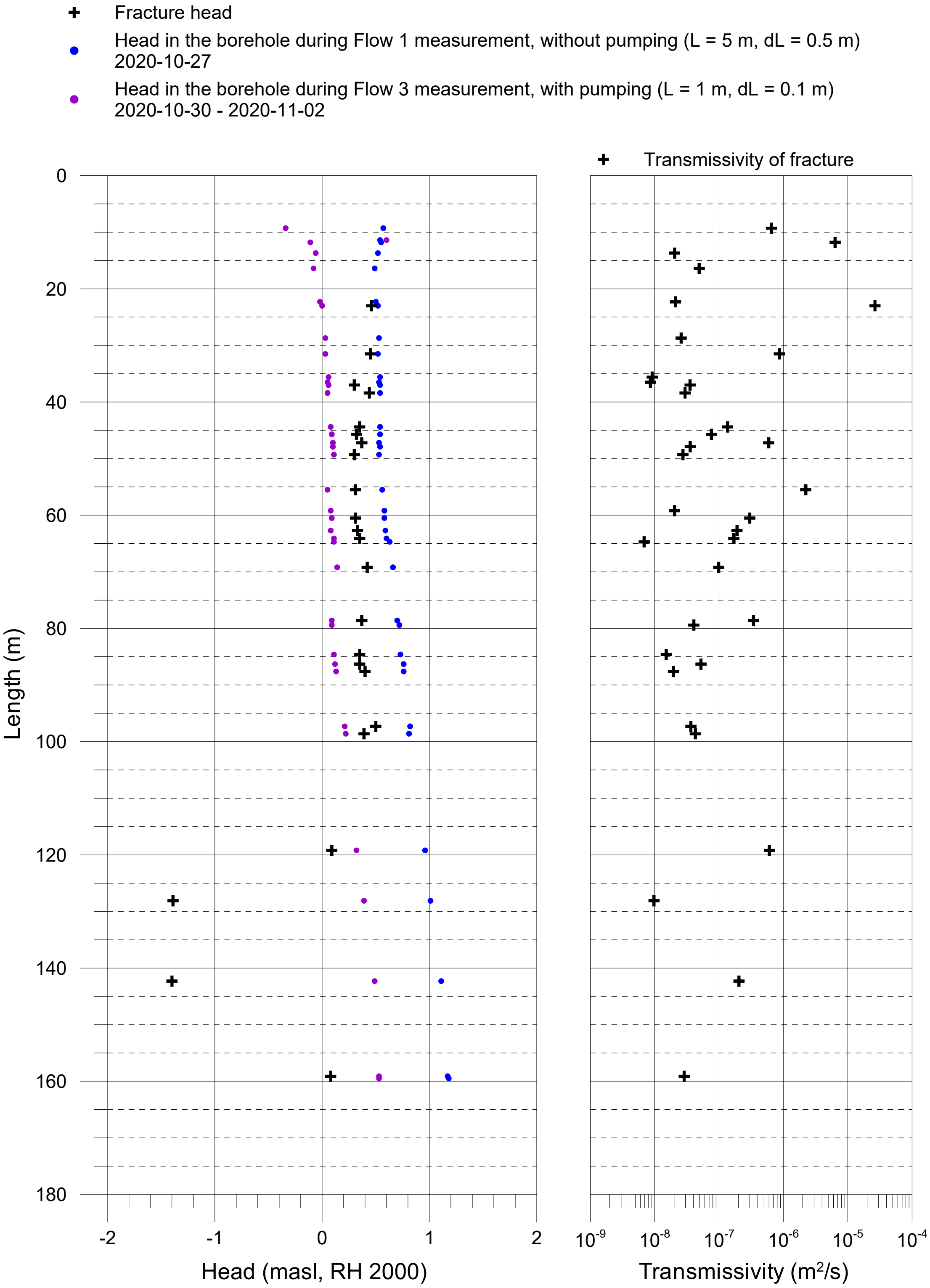
Borehole ID	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_0 (m^3/s)	h_{0FW} (masl)	Q_1 (m^3/s)	h_{1FW} (masl)	T_D (m^2/s)	h_i (masl)	Comments
KFR119	9.3	1	0.1	-	0.57	6.00E-07	-0.34	6.5E-07	-	
KFR119	11.4	1	0.1	3.47E-06	0.54	3.06E-05	0.60	-	-	**,***
KFR119	11.8	1	0.1	-	0.55	4.25E-06	-0.11	6.4E-06	-	*
KFR119	13.7	1	0.1	-	0.52	1.19E-08	-0.06	2.0E-08	-	
KFR119	14.9	1	0.1	-	0.51	3.33E-09	-0.09	5.5E-09	-	*
KFR119	16.4	1	0.1	-	0.49	2.83E-08	-0.08	4.9E-08	-	
KFR119	22.3	1	0.1	-	0.50	1.11E-08	-0.02	2.1E-08	-	
KFR119	23	1	0.1	-1.65E-06	0.52	1.23E-05	0.00	2.7E-05	0.5	
KFR119	28.7	1	0.1	-	0.53	1.31E-08	0.03	2.6E-08	-	
KFR119	31.5	1	0.1	-5.94E-08	0.52	3.69E-07	0.03	8.7E-07	0.5	
KFR119	35.6	1	0.1	-	0.54	4.44E-09	0.06	9.2E-09	-	*
KFR119	36.5	1	0.1	-	0.53	4.17E-09	0.05	8.6E-09	-	*
KFR119	37	1	0.1	-8.61E-09	0.54	8.61E-09	0.06	3.6E-08	0.3	
KFR119	38.4	1	0.1	-3.06E-09	0.54	1.17E-08	0.05	3.0E-08	0.4	
KFR119	44.4	1	0.1	-2.56E-08	0.54	3.78E-08	0.08	1.4E-07	0.4	
KFR119	45.7	1	0.1	-1.67E-08	0.54	1.81E-08	0.09	7.6E-08	0.3	
KFR119	47.2	1	0.1	-9.56E-08	0.53	1.62E-07	0.10	5.9E-07	0.4	
KFR119	47.9	1	0.1	-	0.54	1.58E-08	0.10	3.6E-08	-	
KFR119	49.3	1	0.1	-6.39E-09	0.53	5.28E-09	0.11	2.8E-08	0.3	*
KFR119	55.5	1	0.1	-5.67E-07	0.56	5.83E-07	0.05	2.2E-06	0.3	
KFR119	59.2	1	0.1	-	0.58	1.03E-08	0.08	2.0E-08	-	
KFR119	60.5	1	0.1	-8.31E-08	0.58	6.56E-08	0.09	3.0E-07	0.3	
KFR119	62.7	1	0.1	-4.94E-08	0.59	4.83E-08	0.08	1.9E-07	0.3	
KFR119	64.1	1	0.1	-4.28E-08	0.60	4.14E-08	0.11	1.7E-07	0.4	

Borehole ID	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_0 (m^3/s)	h_{0FW} (masl)	Q_1 (m^3/s)	h_{1FW} (masl)	T_D (m^2/s)	h_i (masl)	Comments
KFR119	64.7	1	0.1	-	0.63	3.61E-09	0.11	6.9E-09	-	*
KFR119	69.2	1	0.1	-2.39E-08	0.66	2.81E-08	0.14	9.9E-08	0.4	
KFR119	78.6	1	0.1	-1.14E-07	0.70	9.83E-08	0.09	3.4E-07	0.4	
KFR119	79.4	1	0.1	-	0.72	2.58E-08	0.09	4.1E-08	-	*
KFR119	84.6	1	0.1	-5.83E-09	0.73	3.61E-09	0.11	1.5E-08	0.4	*
KFR119	86.3	1	0.1	-2.19E-08	0.76	1.19E-08	0.12	5.2E-08	0.4	
KFR119	87.6	1	0.1	-7.22E-09	0.76	5.28E-09	0.13	2.0E-08	0.4	*
KFR119	97.3	1	0.1	-1.19E-08	0.82	1.06E-08	0.21	3.7E-08	0.5	
KFR119	98.6	1	0.1	-1.81E-08	0.81	7.50E-09	0.22	4.3E-08	0.4	
KFR119	119.2	1	0.1	-5.33E-07	0.96	-1.42E-07	0.32	6.1E-07	0.1	
KFR119	128.1	1	0.1	-2.36E-08	1.01	-1.75E-08	0.39	9.8E-09	-1.4	
KFR119	142.3	1	0.1	-5.17E-07	1.11	-3.89E-07	0.49	2.0E-07	-1.4	
KFR119	159.1	1	0.1	-3.17E-08	1.17	-1.31E-08	0.53	2.9E-08	0.1	
KFR119	159.5	1	0.1	-	1.18	-7.78E-09	0.53	-	-	*

*	Uncertain = The flow rate is less than 30 mL/h or the flow anomalies are overlapping or they are unclear because of noise.
**	At the fracture 11.4 m the head value h_{1FW} (Flow 3) increased higher with a 1 m section with pumping than the head value h_{0FW} (Flow 1) with a 5 m section without pumping. This was probably caused by flow friction loss in the PFL DIFF probe's flow guide. Also due to the flow friction loss, the actual flow rate Q_1 would probably be higher than the measured flow rate. The water level in the borehole increased and at the same time pumping rate of the borehole decreased. The flow rate while borehole was pumped was too large to be measured with PFL DIFF equipment. Thus transmissivity of the fracture T_D nor head of the fracture cannot be calculated from Flow Q_0 (Flow 1) and Flow Q_1 (Flow 3). Therefore T_D nor h_i are not presented.

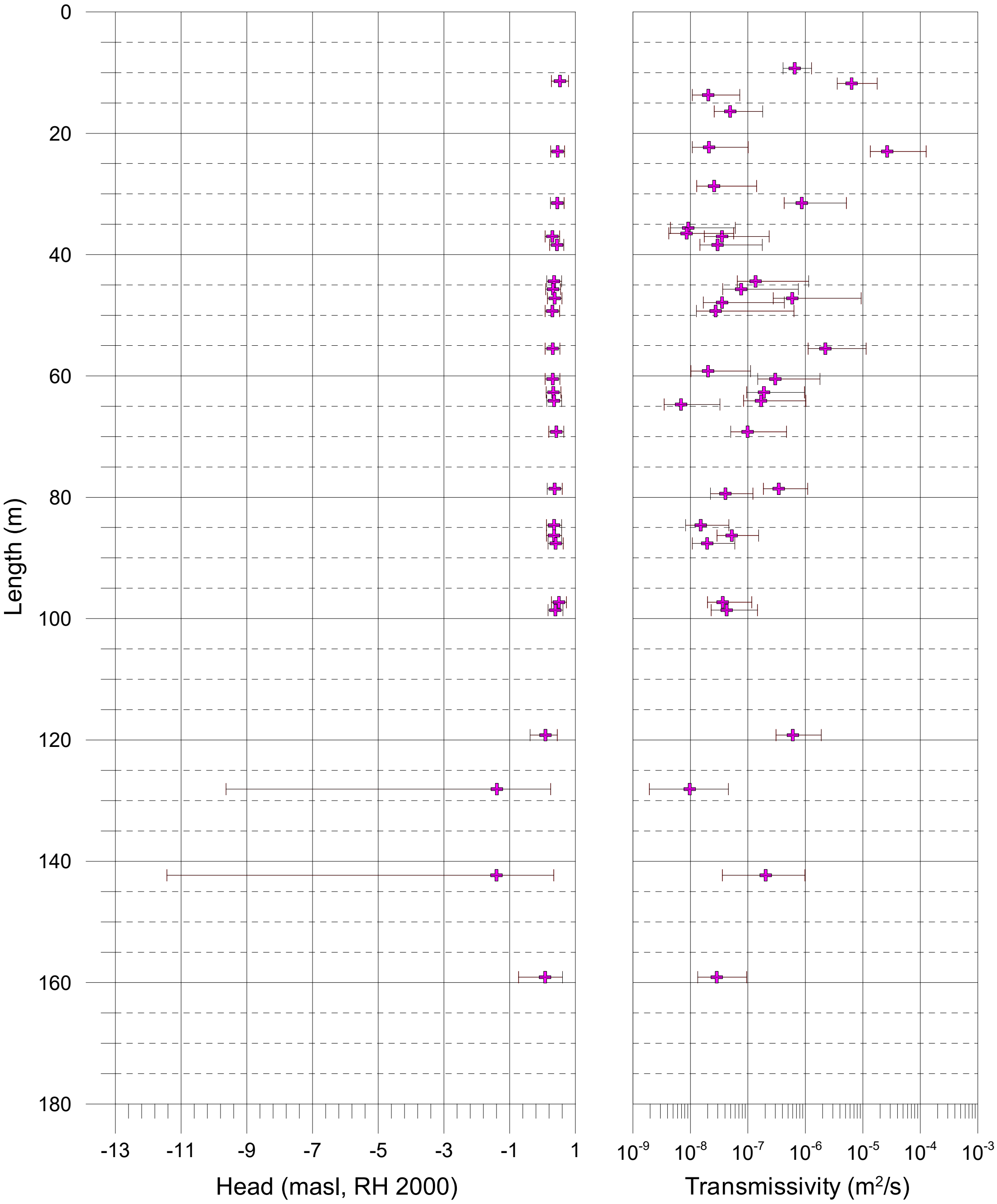
Appendix KFR119.7.1

Forsmark, borehole KFR119
Transmissivity and head of detected fractures

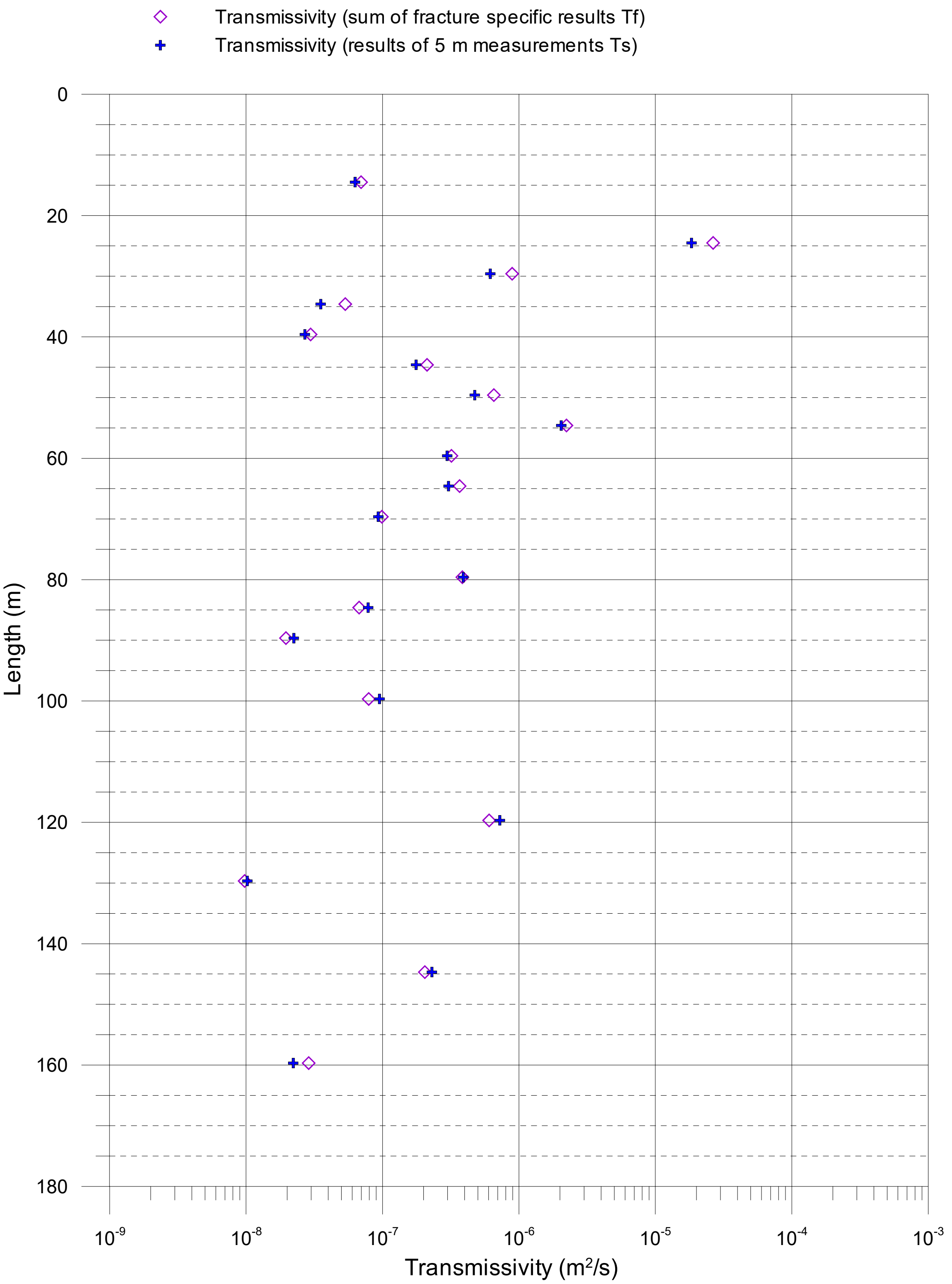


Appendix KFR119.7.2

Forsmark, borehole KFR119
Transmissivity and head of fractures
Error bars assuming ±10% errors in flow rates
and ±0.2 m in head in worst-case combination

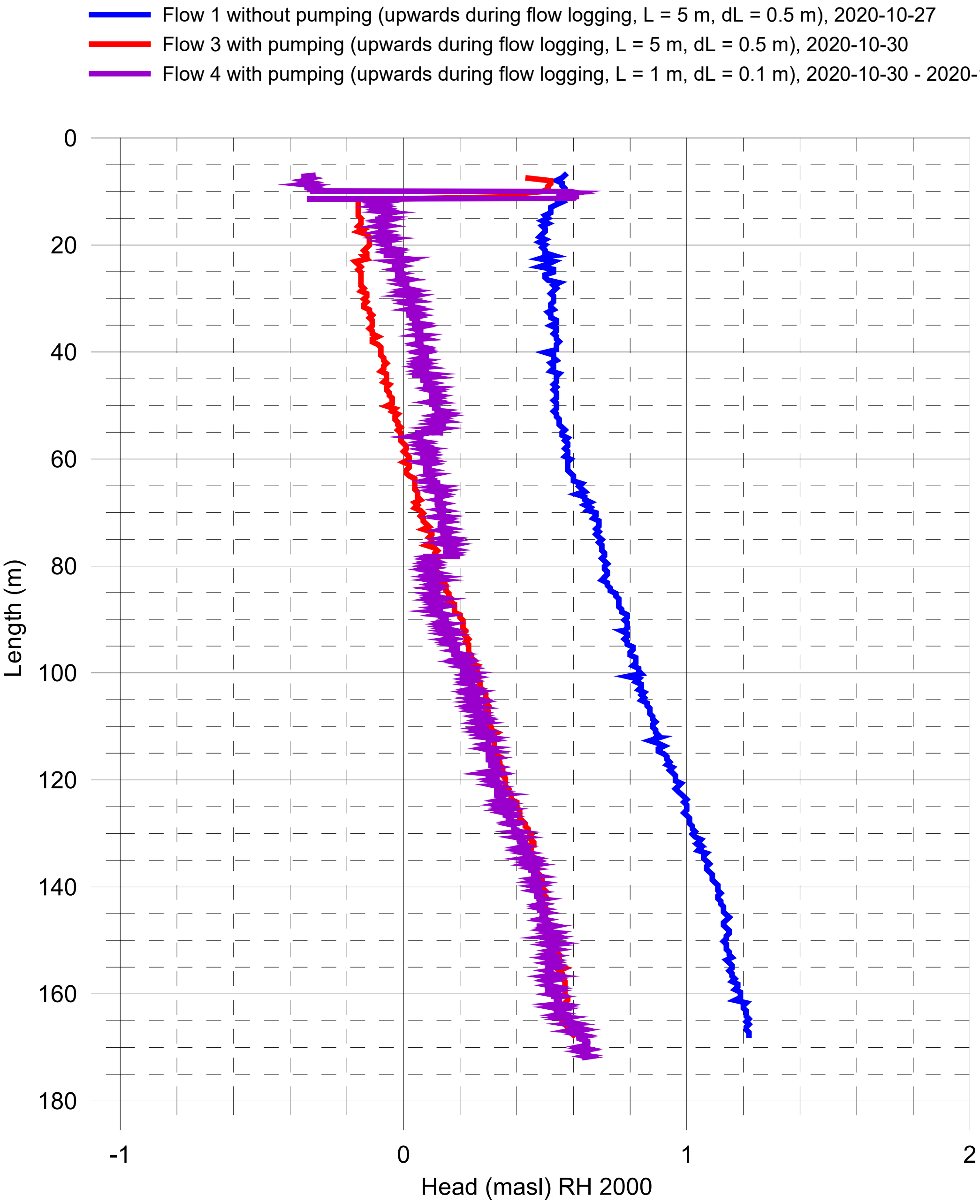


Forsmark, borehole KFR119
Comparison between section transmissivity and fracture transmissivity



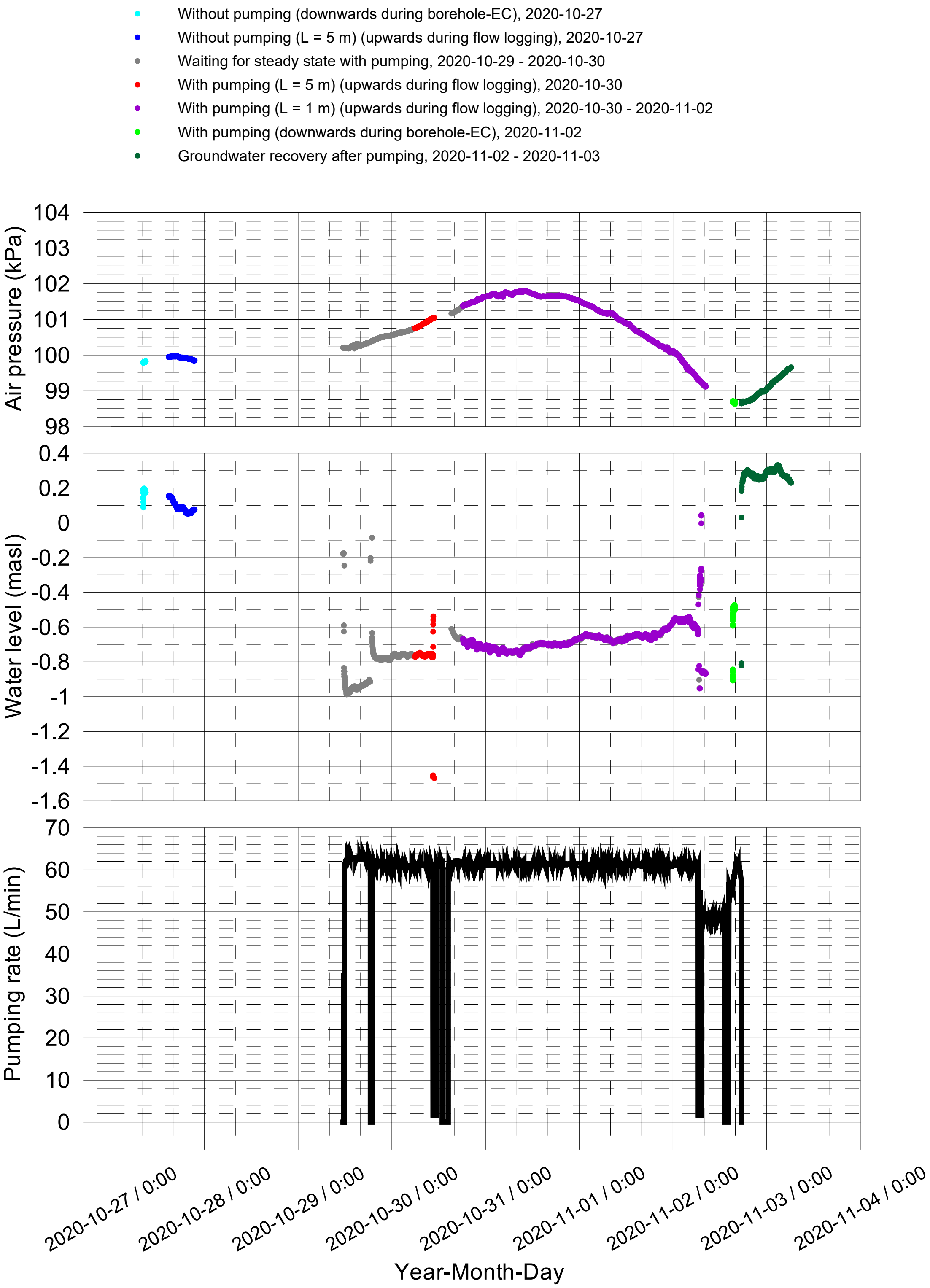
Forsmark, borehole KFR119
Head in the borehole during flow logging

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



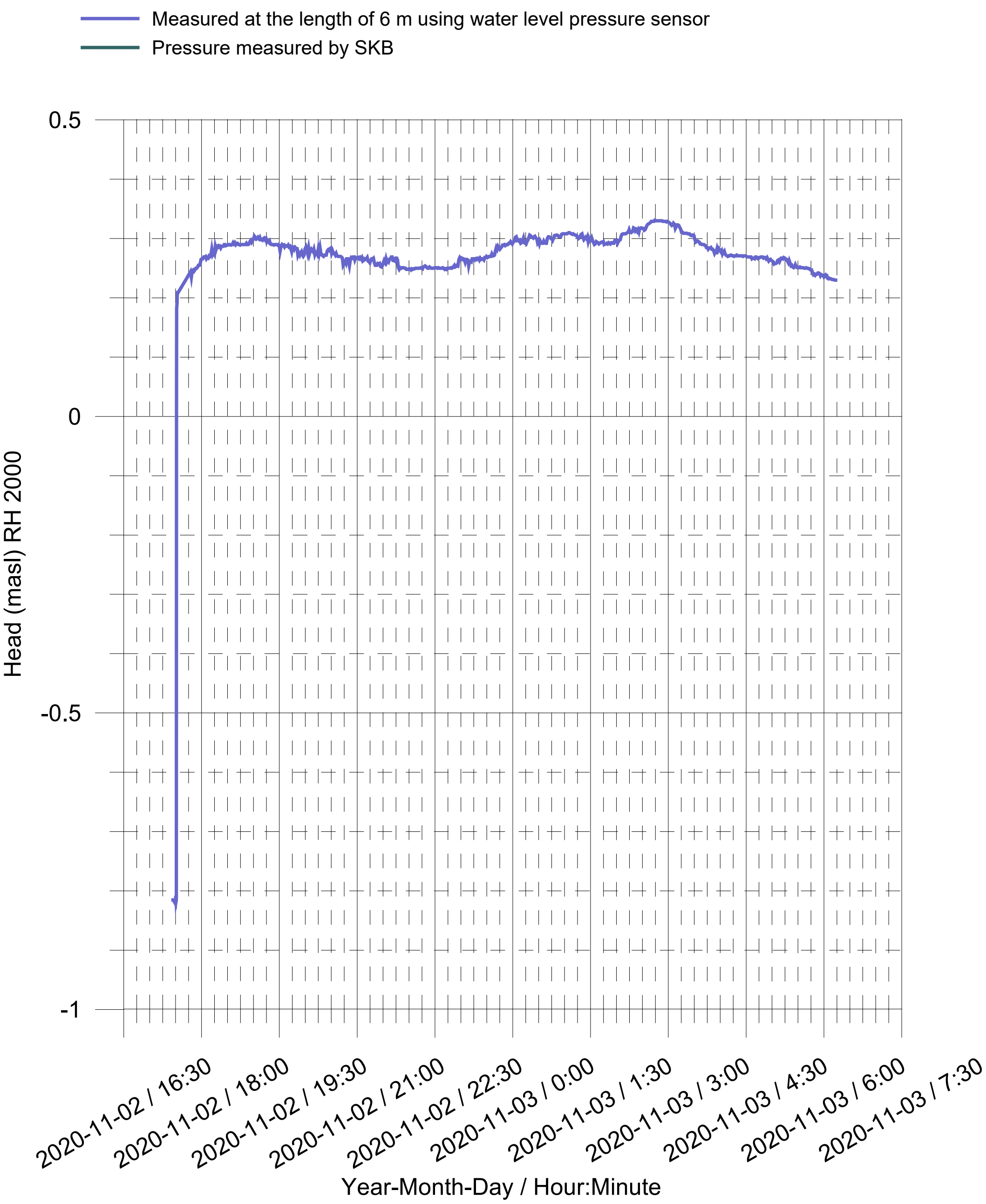
Appendix KFR119.9.2

Forsmark, borehole KFR119
Air pressure, water level in the borehole and pumping rate during flow logging

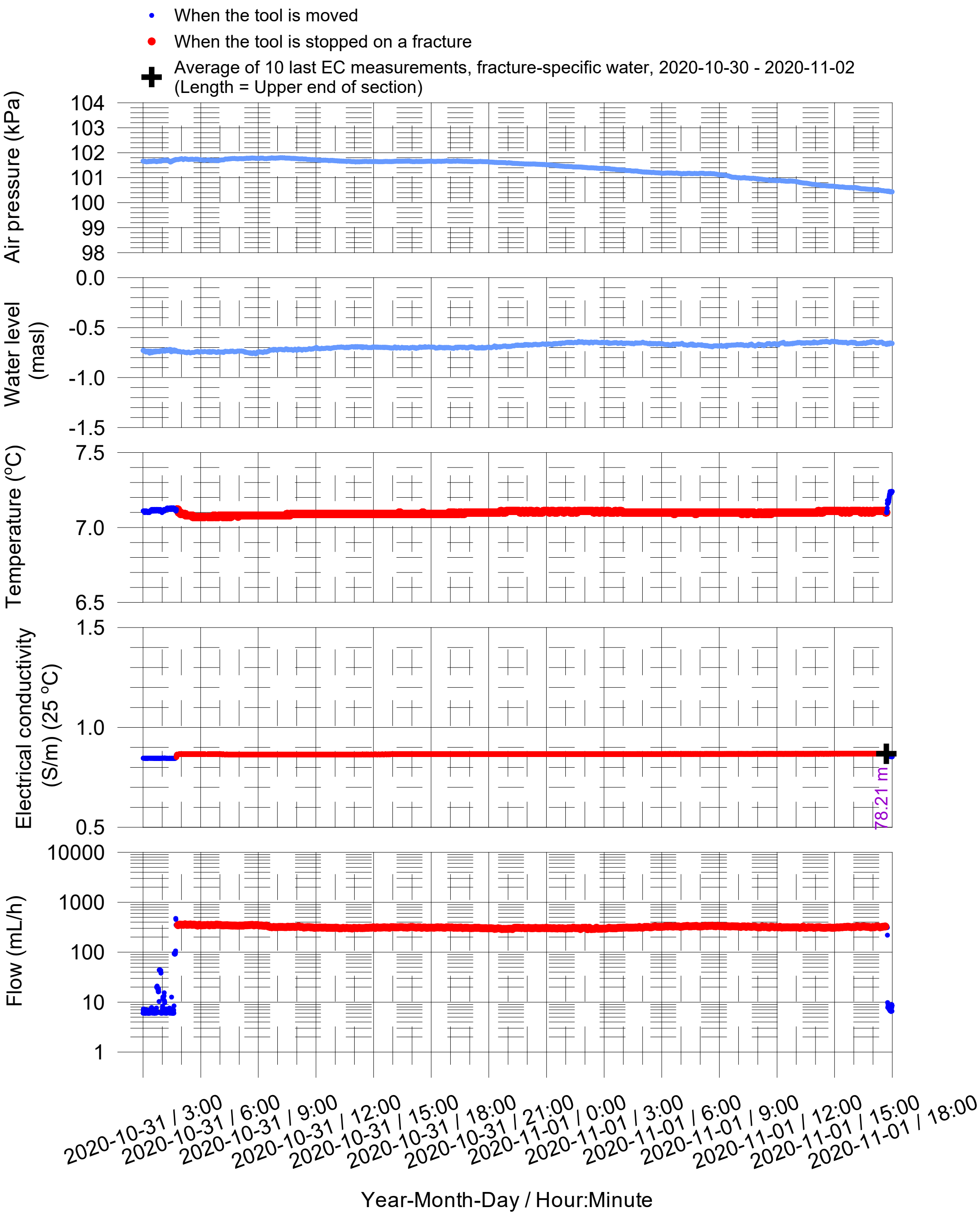


Appendix KFR119.9.3

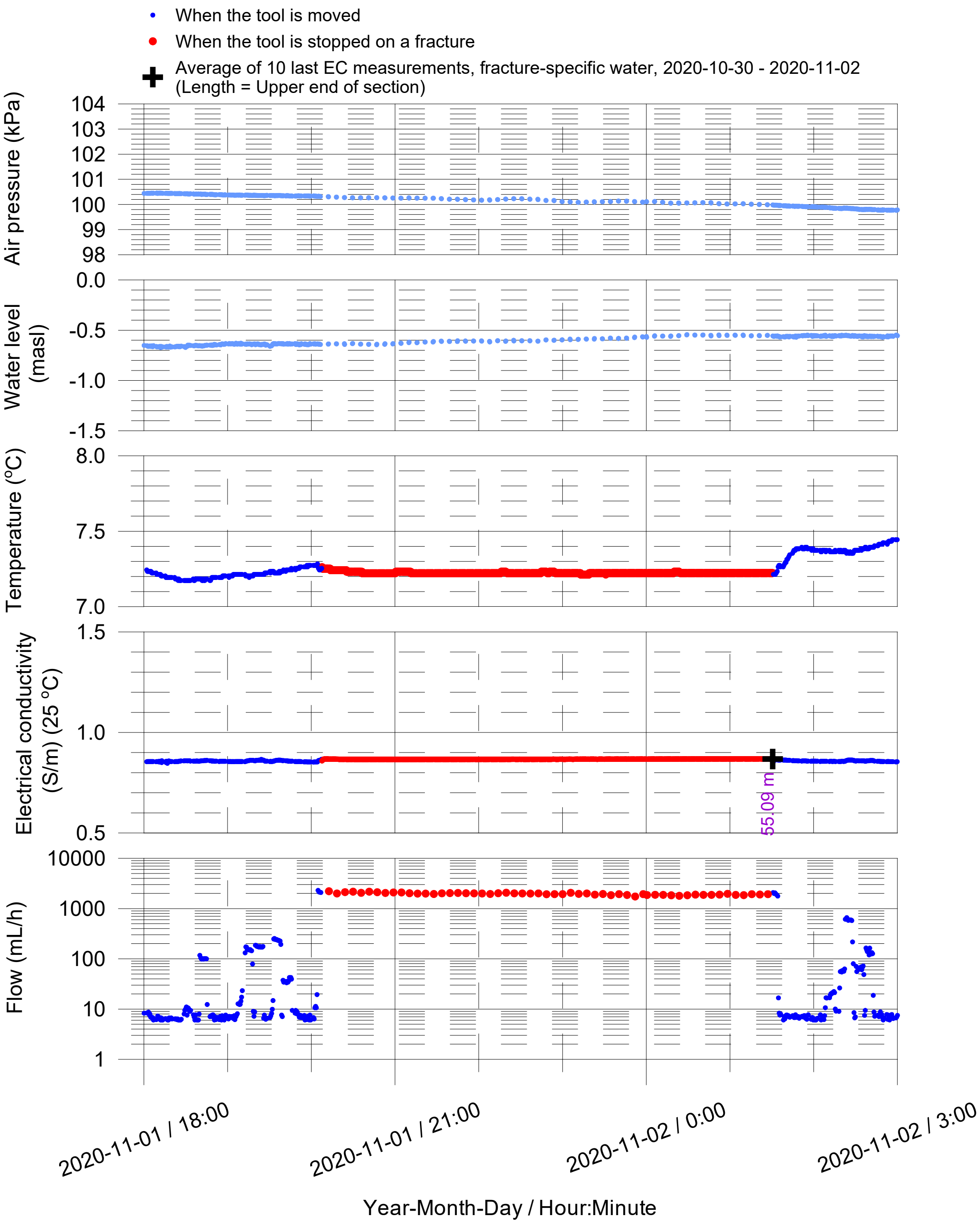
Forsmark, borehole KFR119
Groundwater recovery after pumping



Forsmark, borehole KFR119
Fracture-specific Flow, EC and Temperature results by date
Water level and Air pressure results by date

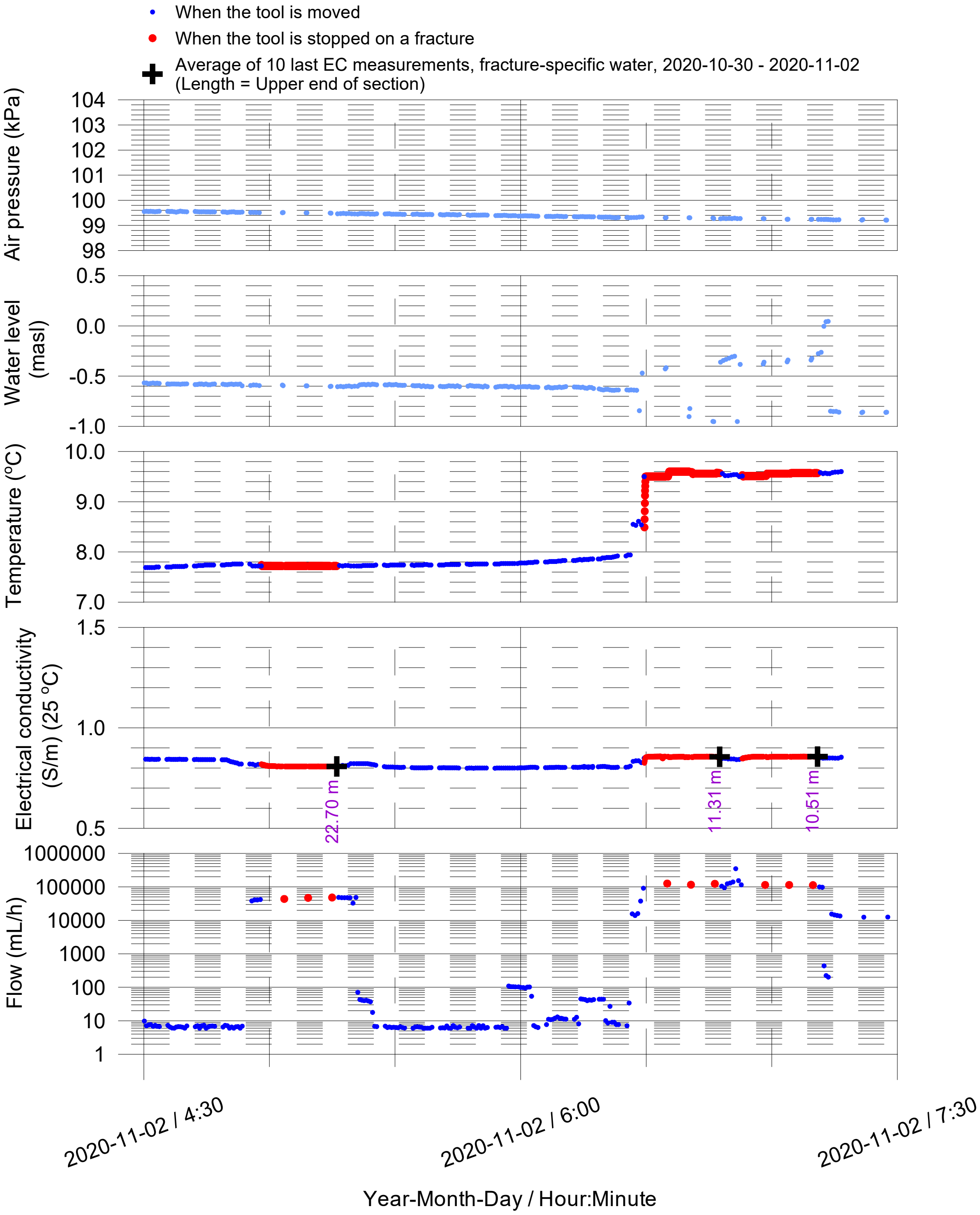


Forsmark, borehole KFR119
Fracture-specific Flow, EC and Temperature results by date
Water level and Air pressure results by date



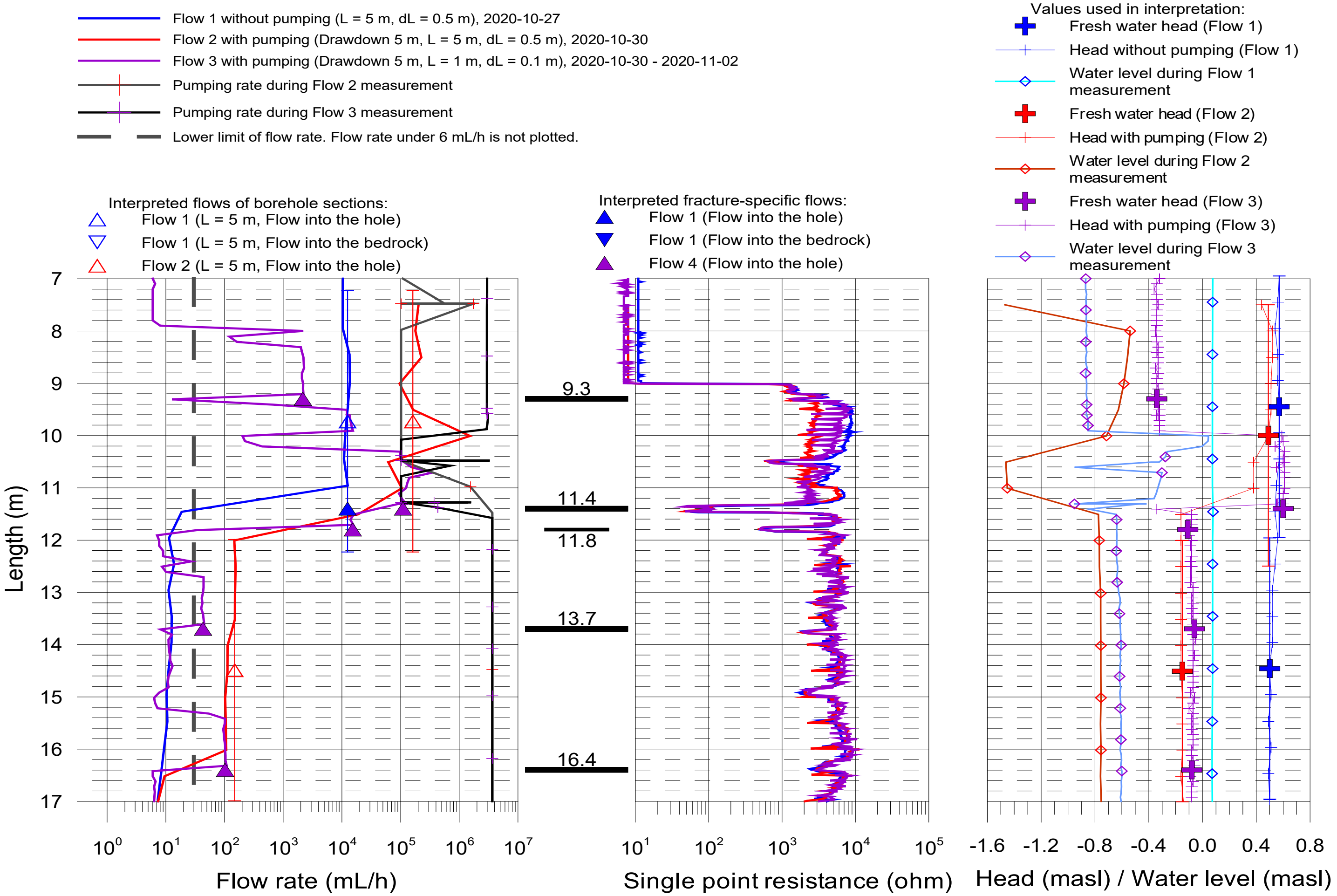
Appendix KFR119.10.3

Forsmark, borehole KFR119
Fracture-specific Flow, EC and Temperature results by date
Water level and Air pressure results by date



Appendix KFR119.11

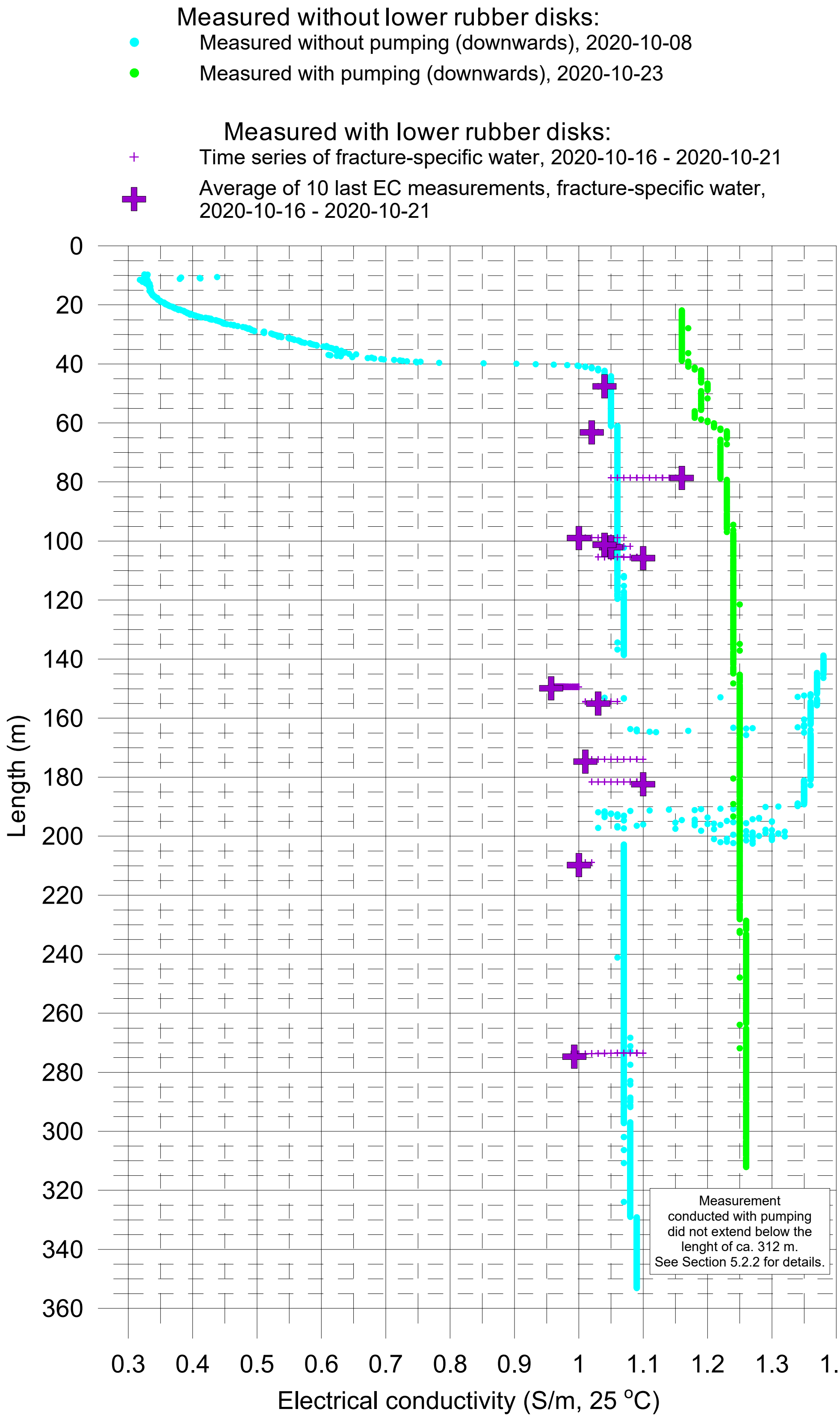
Forsmark, borehole KFR119
Flow rate, single point resistance and head in the borehole during flow logging



Appendix B

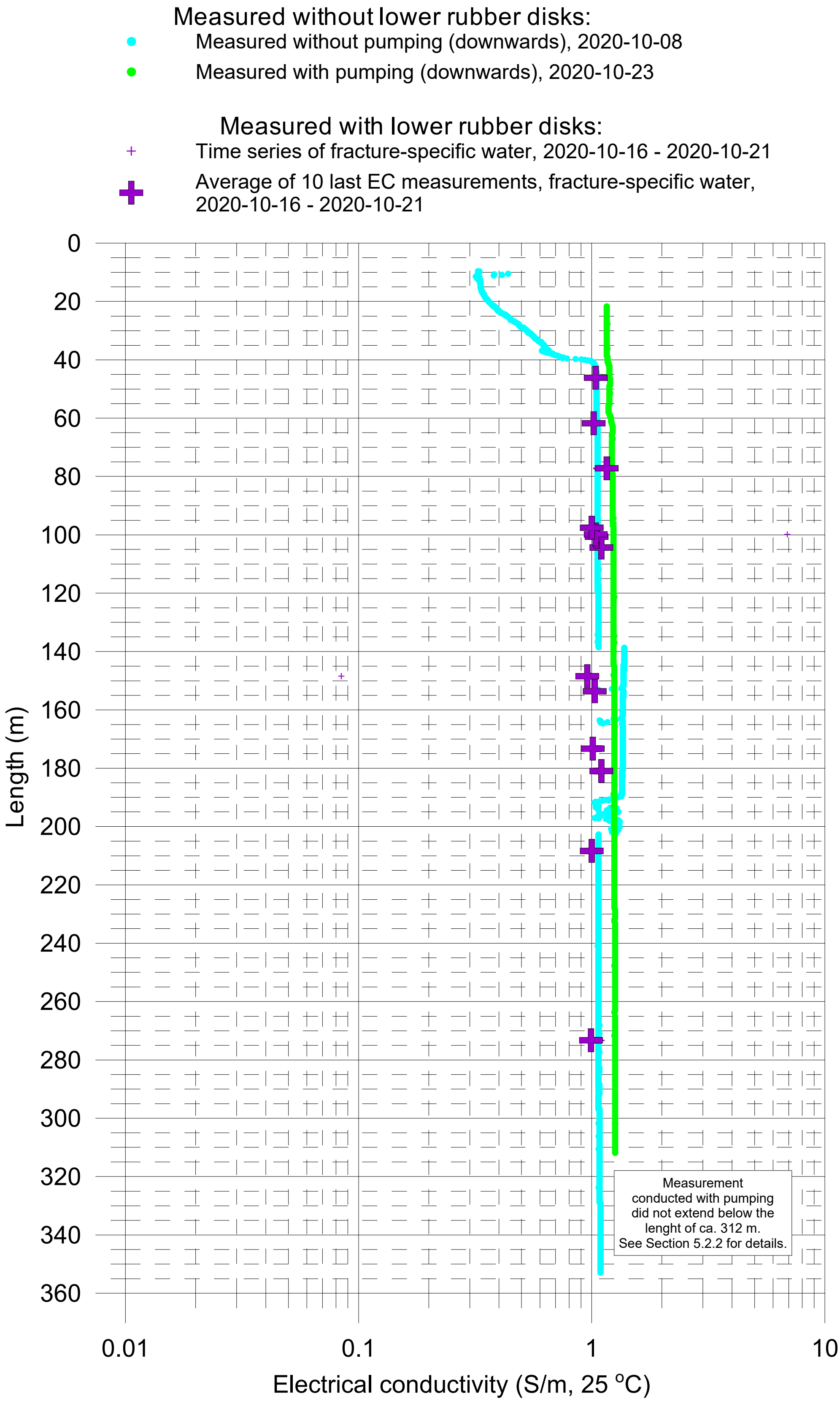
KFR121.1.1 – KFR121.1.2	Electrical conductivity of borehole water
KFR121.1.3	Temperature of borehole water
KFR121.2.1 – KFR121.2.16	Flow rate and single point resistance
KFR121.2.17	Vertical flow along the borehole at 40.6 m
KFR121.2.18	Vertical flow along the borehole at 42.5 m
KFR121.2.19 – KFR121.2.20	Vertical flow along the borehole at 342.9 m
KFR121.3	Glossary of terms used in the tables in Appendices
KFR121.4.1 – KFR121.4.3	Results of section flows
KFR121.5.1	Plotted flow rates of 5 m sections
KFR121.5.2	Plotted transmissivity and head of 5 m sections
KFR121.5.3	Transmissivity and head of 5 m sections with calculated error limits
KFR121.5.4	Conductive fracture frequency
KFR121.6.1 – KFR121.6.3	Inferred fracture flow anomalies from flow logging
KFR121.7.1	Plotted transmissivity and head of detected fractures
KFR121.7.2	Transmissivity and head of detected fractures with calculated error limits.
KFR121.8	Comparison between section transmissivity and fracture transmissivity
KFR121.9.1	Head in the borehole during flow logging
KFR121.9.2	Air pressure, water level in the borehole and pumping rate during flow logging
KFR121.9.3	Groundwater recovery after pumping
KFR121.10.1 – KFR121.10.6	Fracture-specific EC results by date
KFR121.11.1 – KFR121.11.4	Flow rate, single point resistance and head in the borehole during flow logging

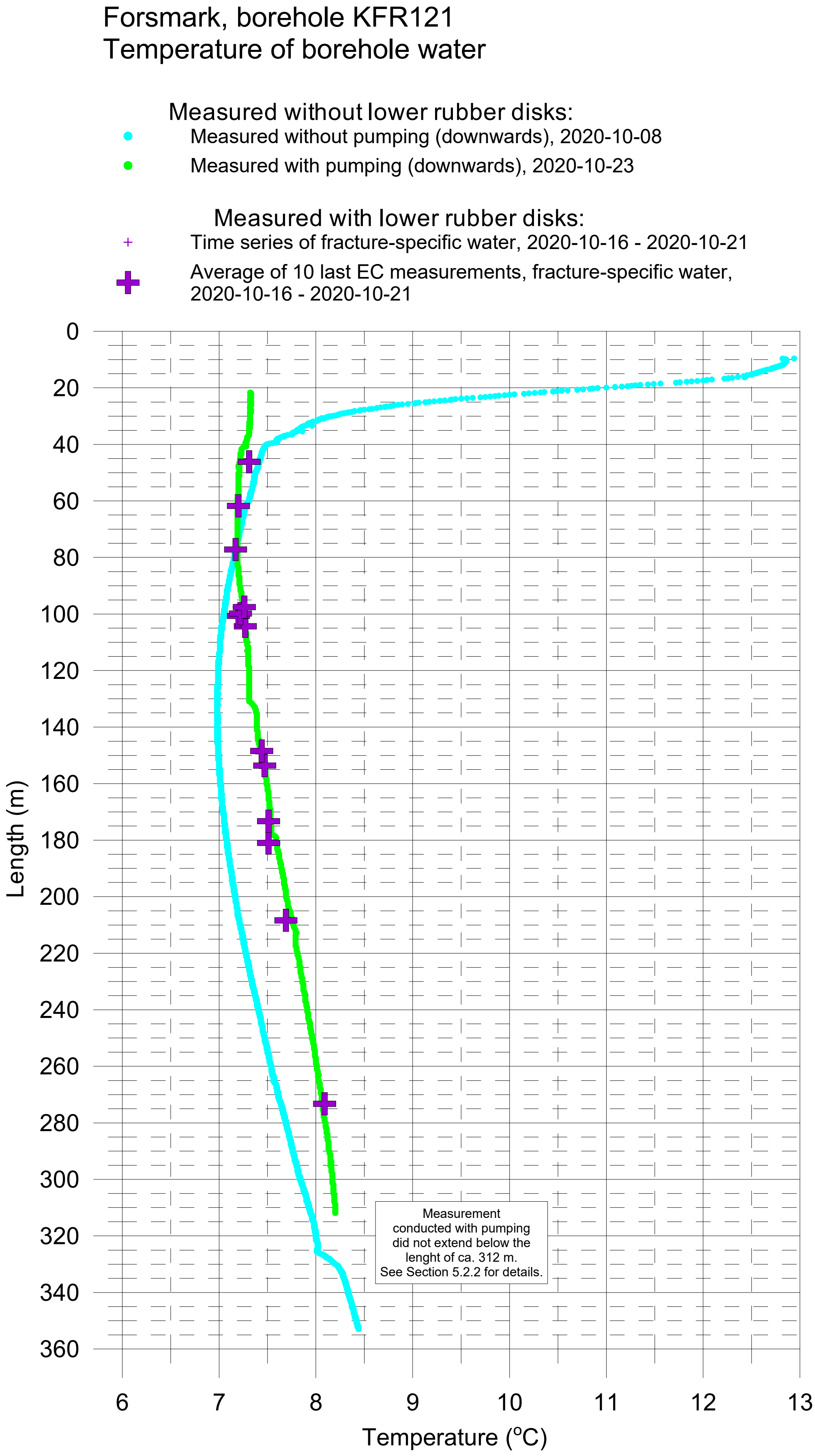
Forsmark, borehole KFR121
Electrical conductivity of borehole water



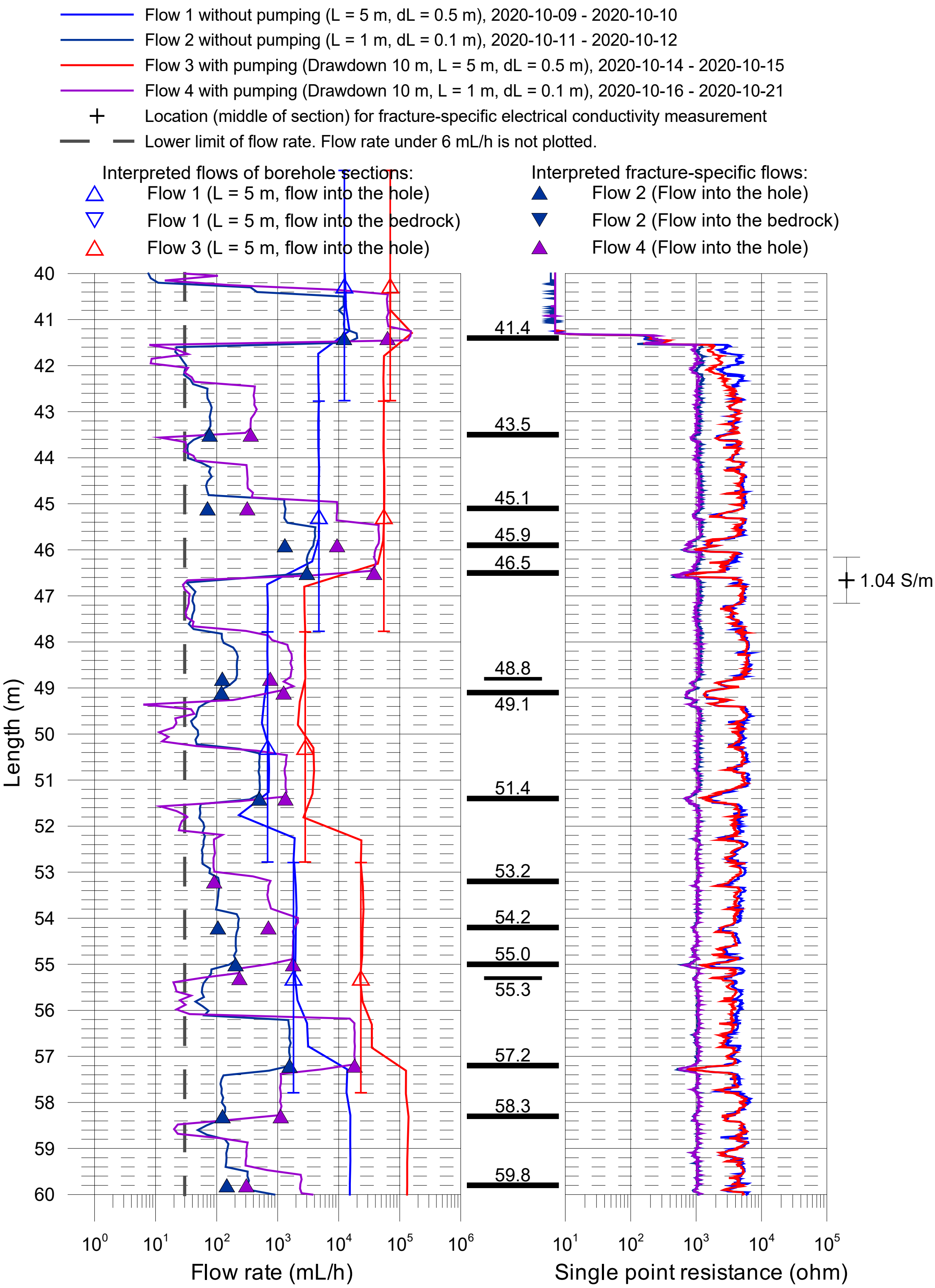
Appendix KFR121.1.2

Forsmark, borehole KFR121
Electrical conductivity of borehole water

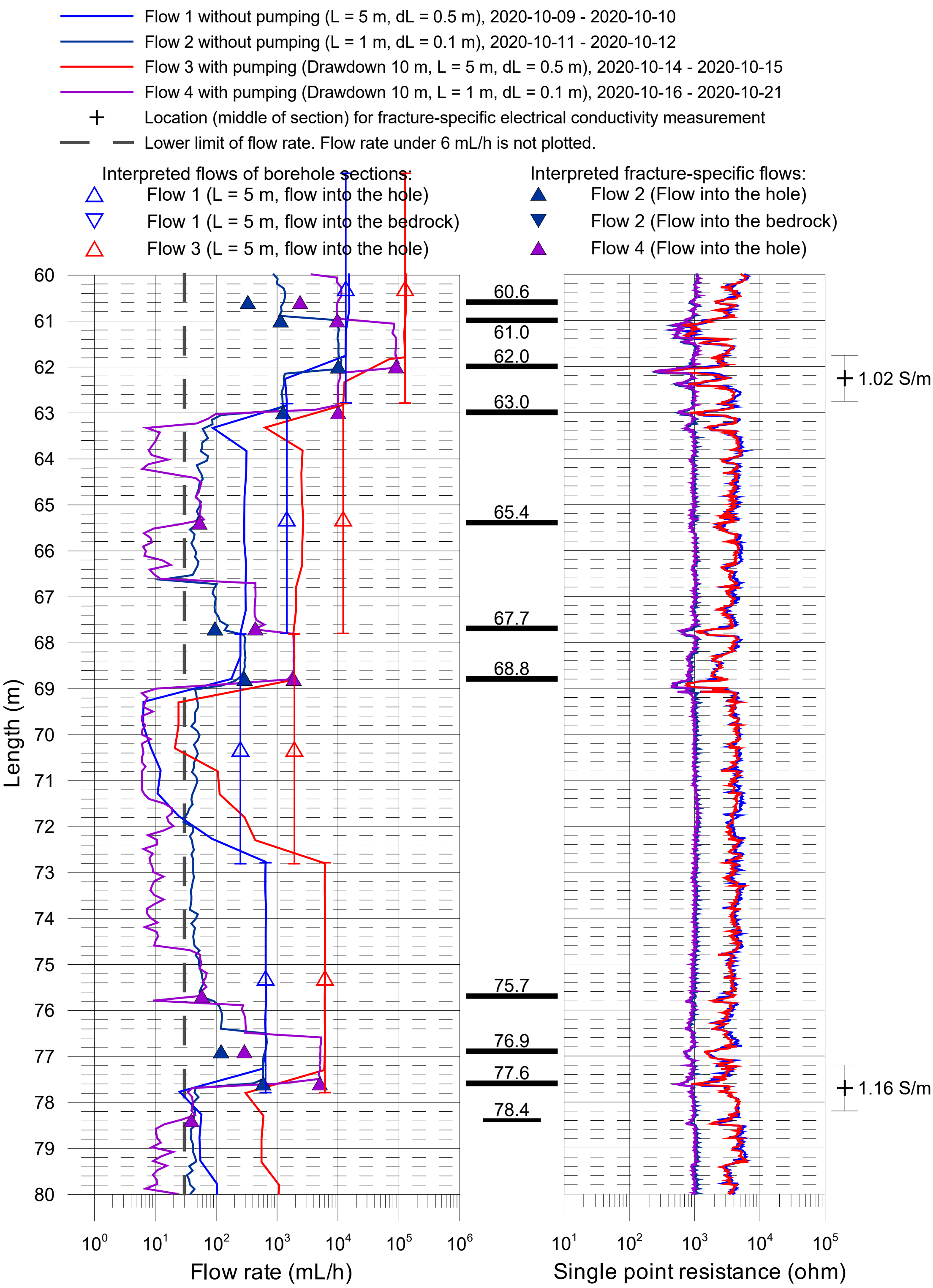



Forsmark, borehole KFR121
Temperature of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2020-10-08
Measured with pumping (downwards), 2020-10-23
Measured with lower rubber disks:
Time series of fracture-specific water, 2020-10-16 - 2020-10-21
Average of 10 last EC measurements, fracture-specific water, 2020-10-16 - 2020-10-21
Length (m)
Temperature (ºC)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
6
7
8
9
10
11
12
13
Measurement conducted with pumping did not extend below the lenght of ca. 312 m. See Section 5.2.2 for details.

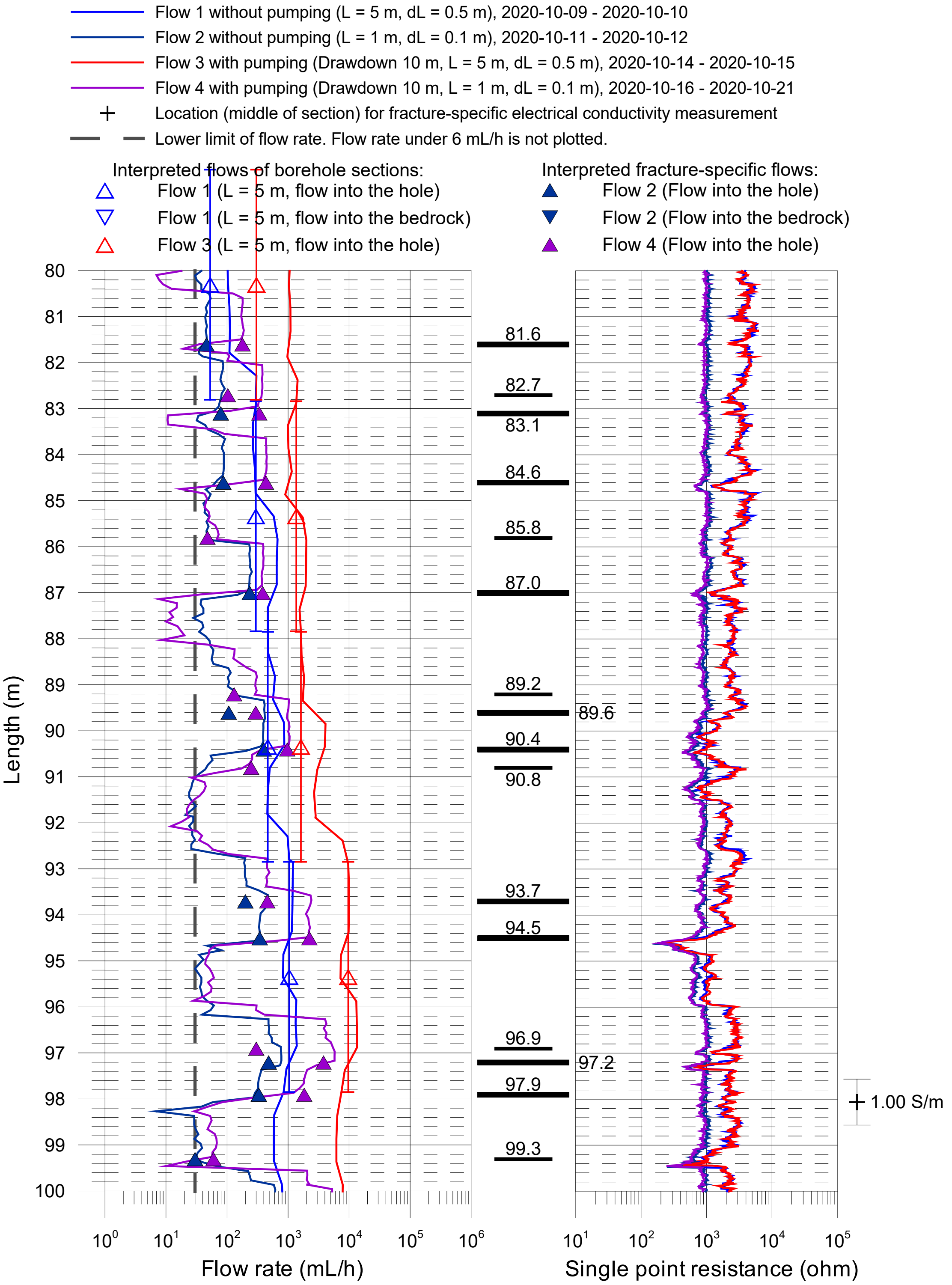
Forsmark, borehole KFR121
Flow rate and single point resistance



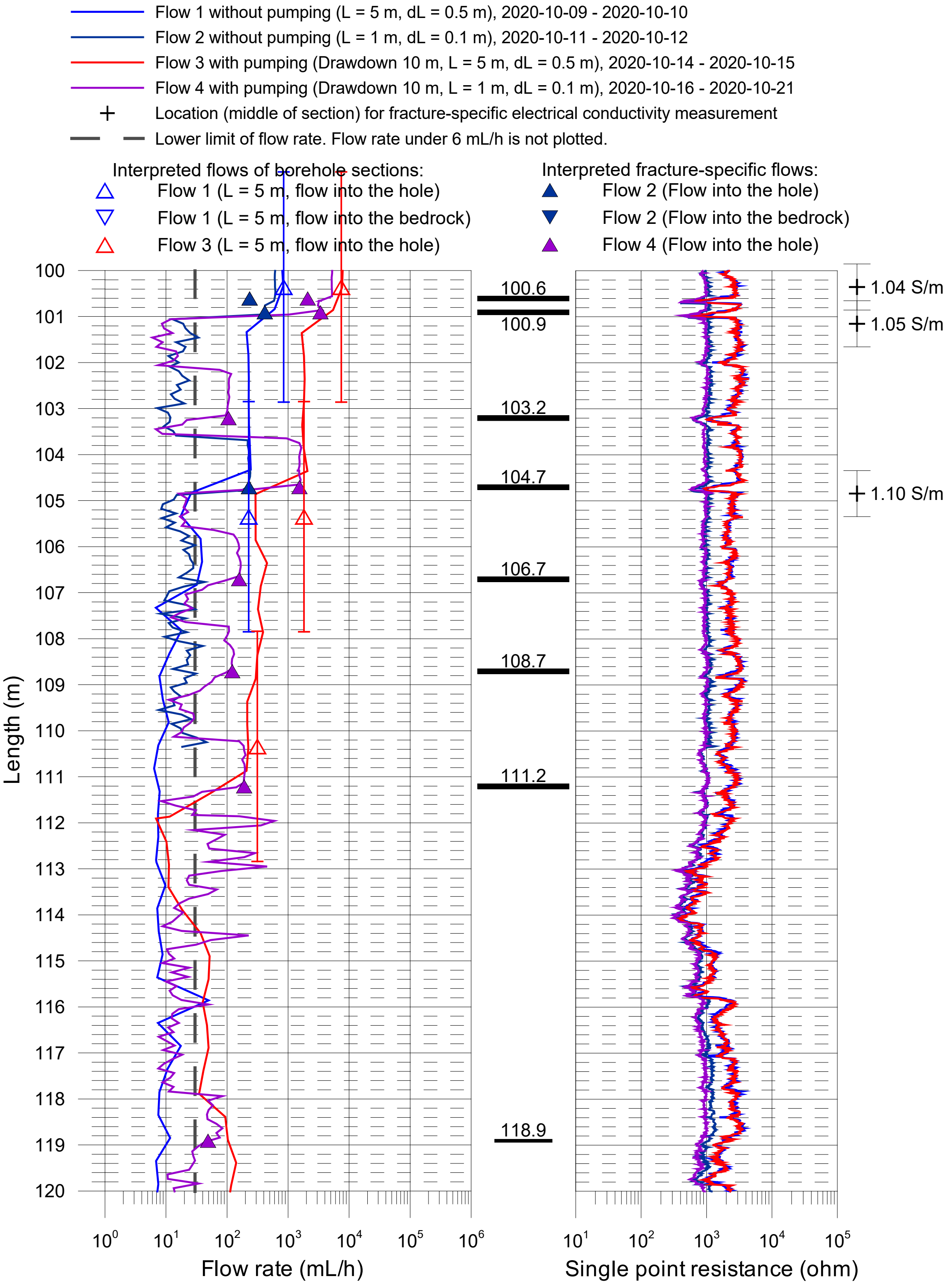
Forsmark, borehole KFR121
Flow rate and single point resistance



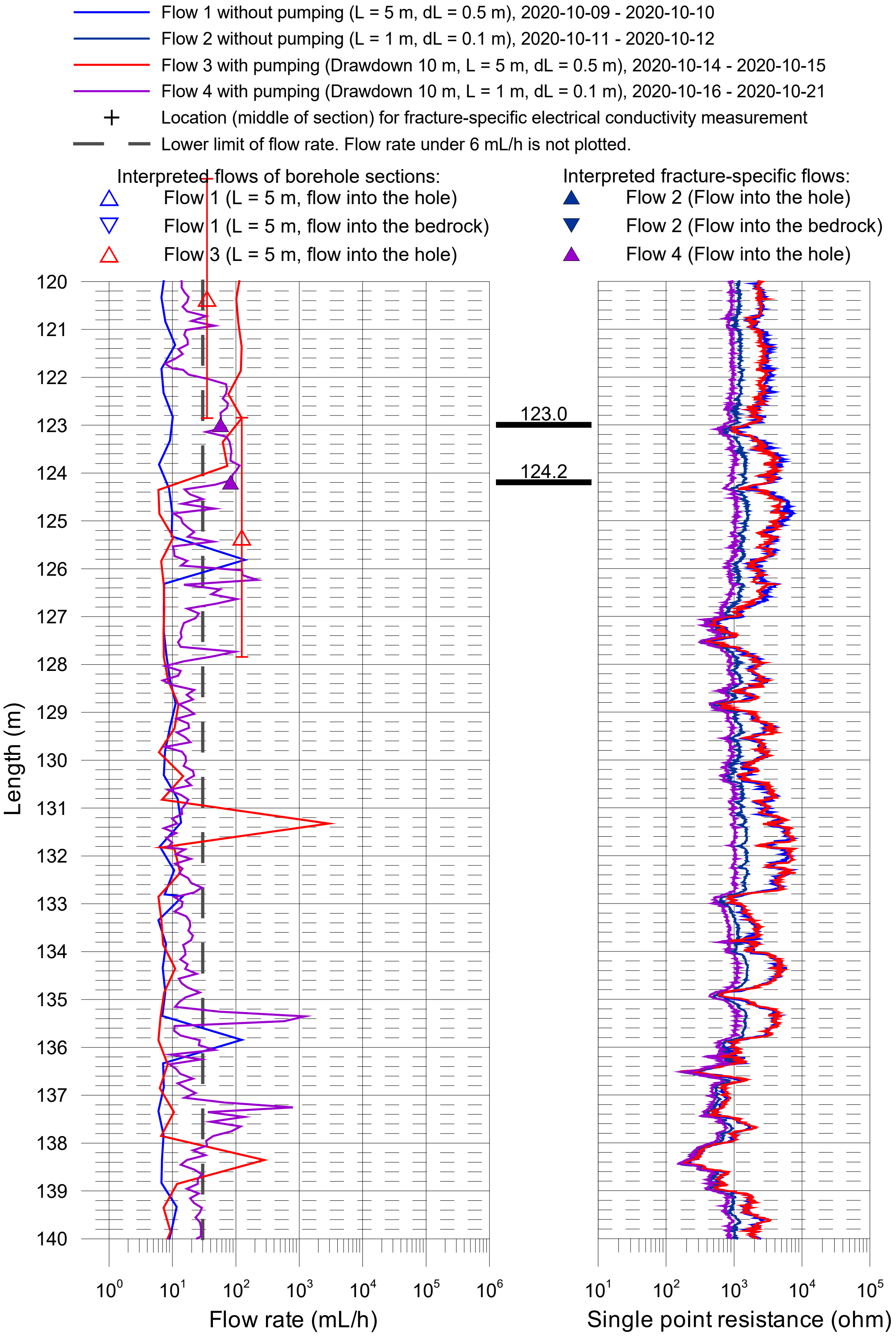
Forsmark, borehole KFR121
Flow rate and single point resistance



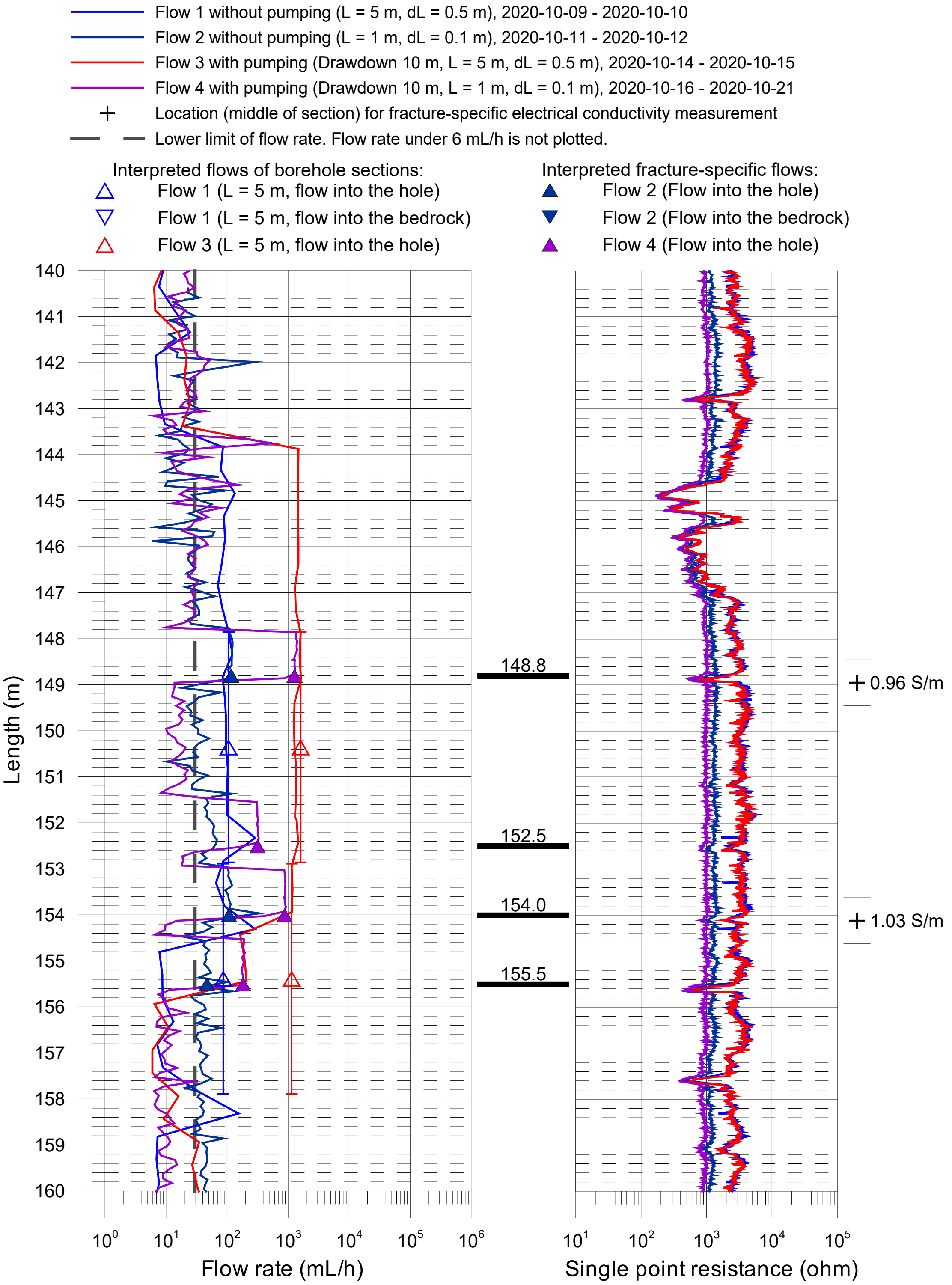
Forsmark, borehole KFR121
Flow rate and single point resistance



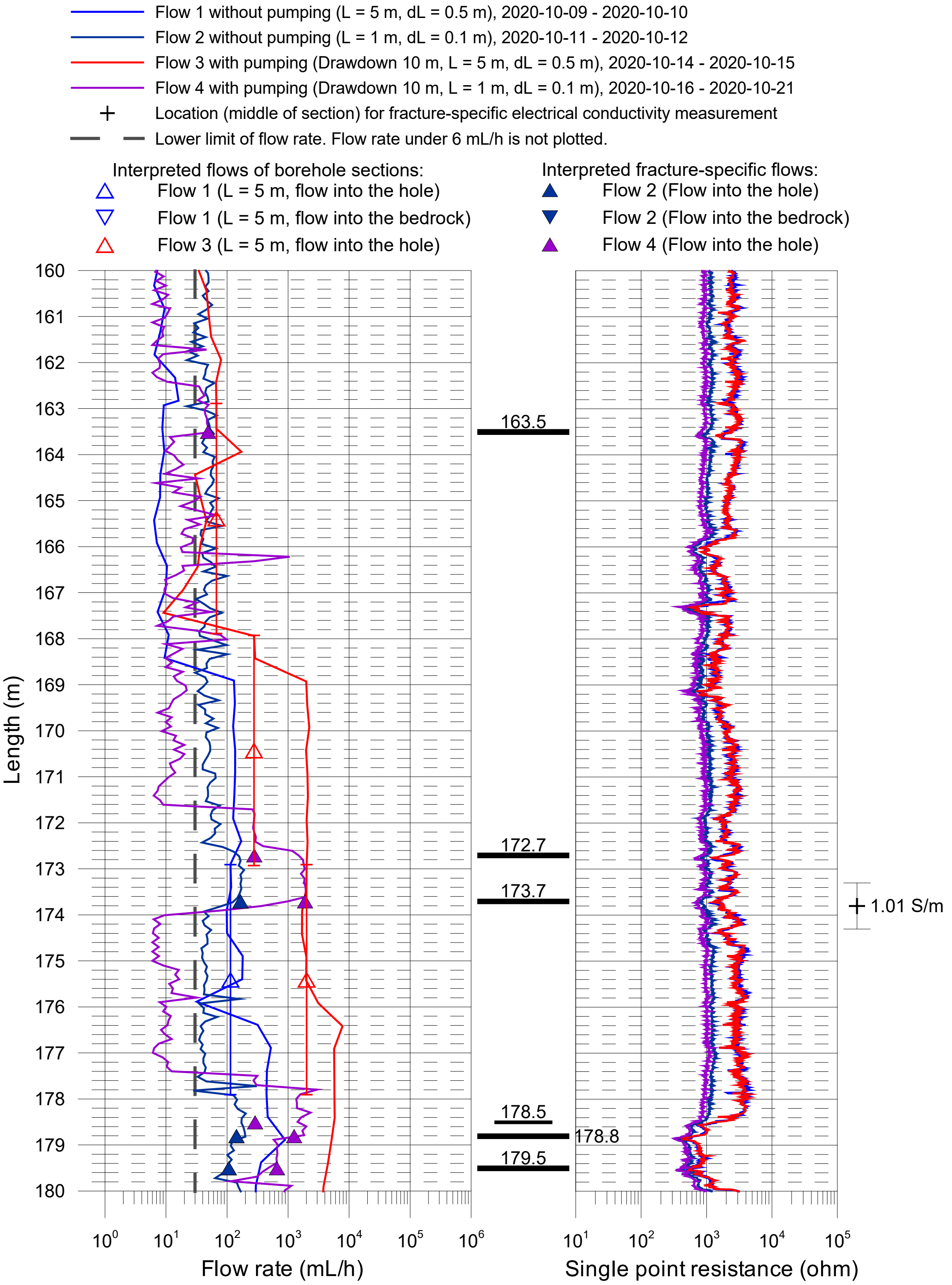
Forsmark, borehole KFR121
Flow rate and single point resistance



Forsmark, borehole KFR121
Flow rate and single point resistance

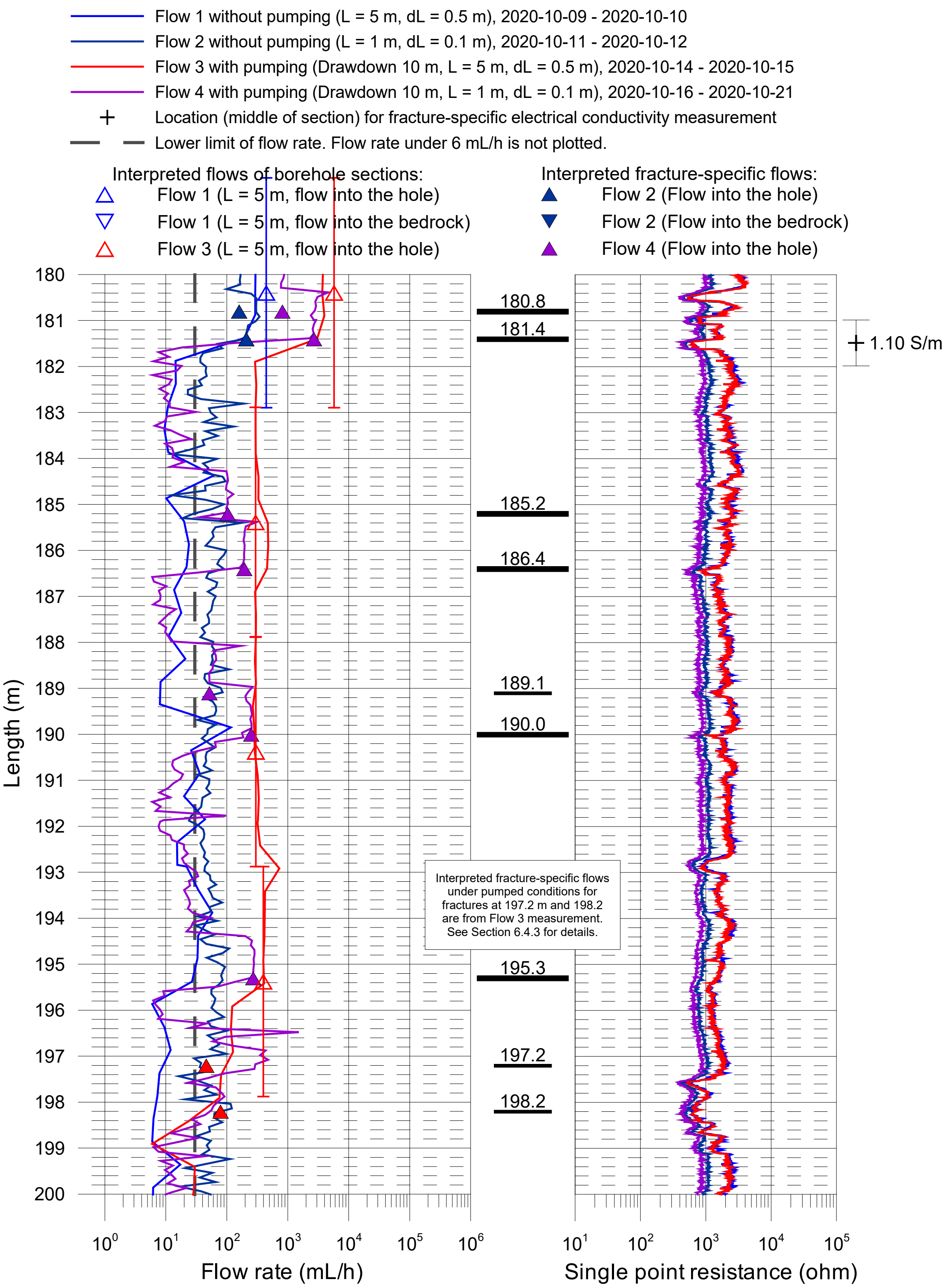


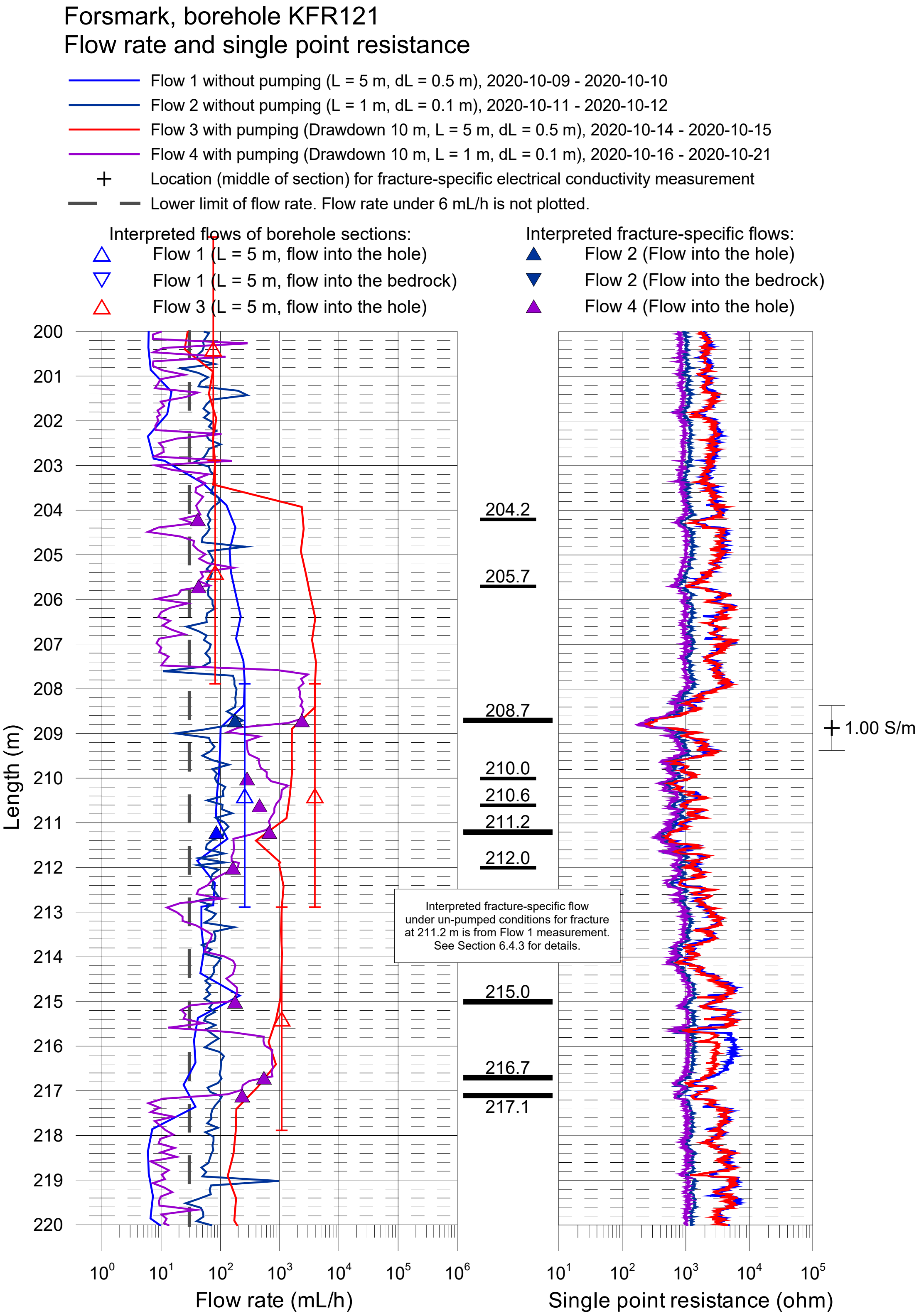
Forsmark, borehole KFR121
Flow rate and single point resistance



Appendix KFR121.2.8

Forsmark, borehole KFR121
Flow rate and single point resistance

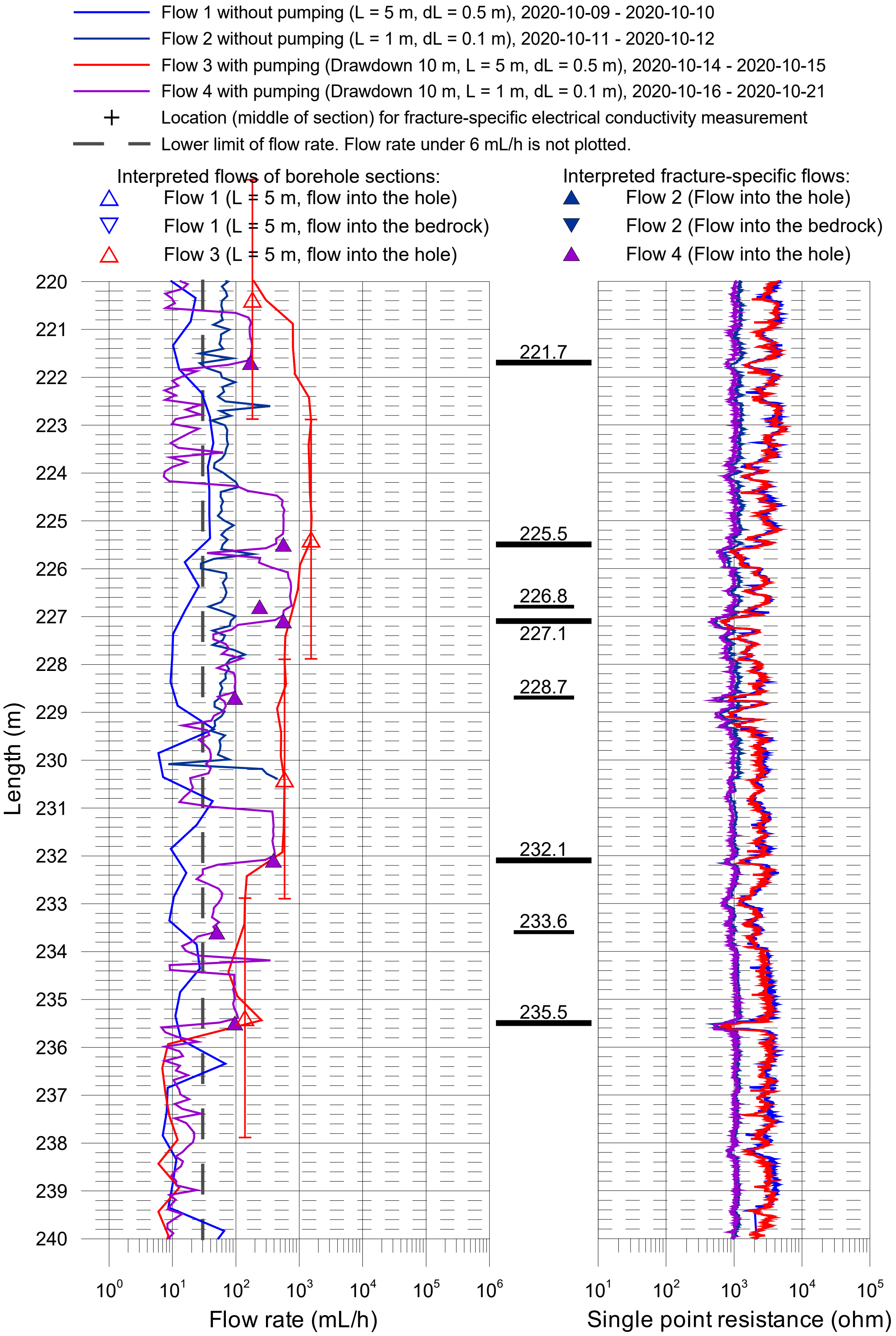




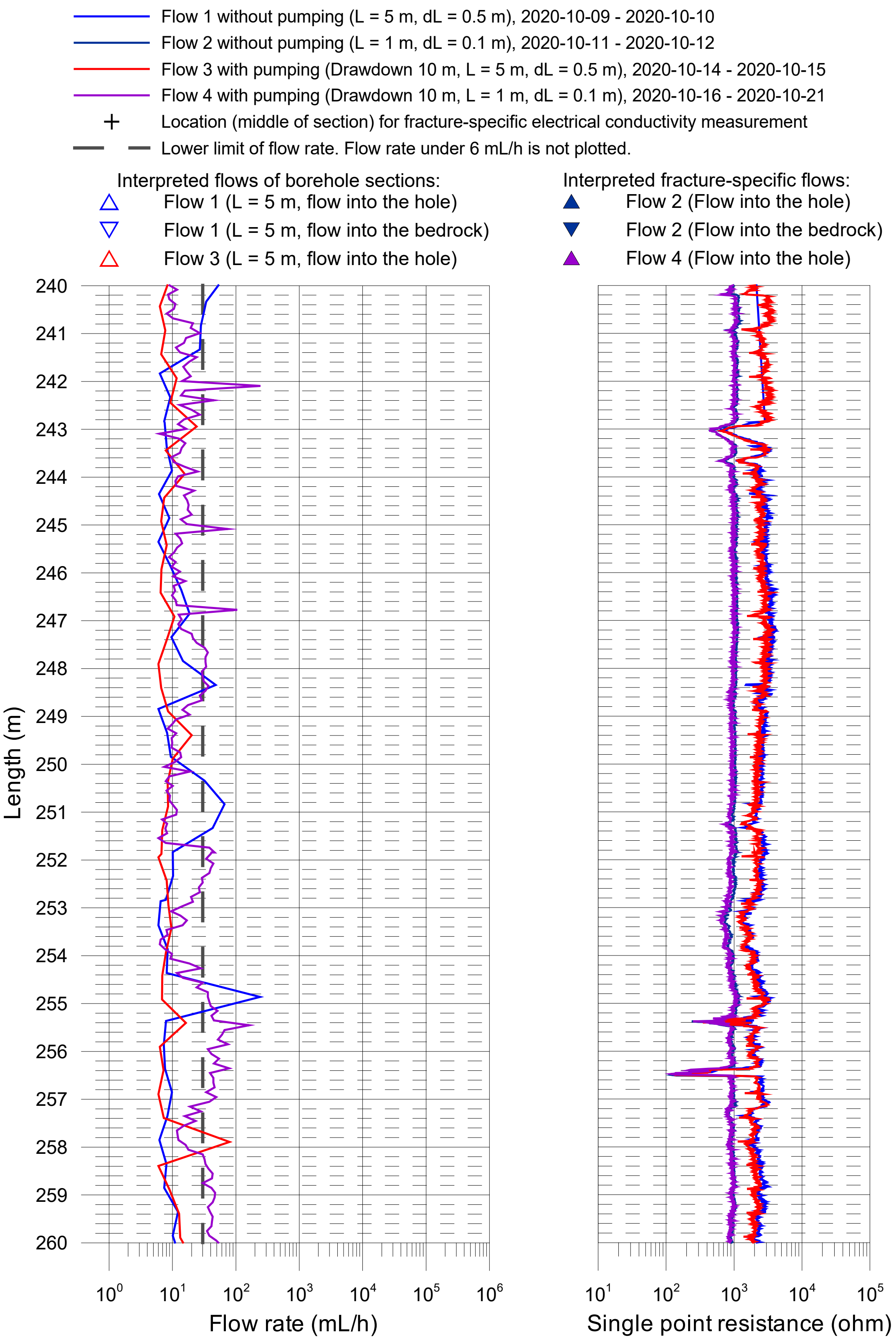
Forsmark, borehole KFR121
Flow rate and single point resistance
Flow 1 without pumping (L = 5 m, dL = 0.5 m), 2020-10-09 - 2020-10-10
Flow 2 without pumping (L = 1 m, dL = 0.1 m), 2020-10-11 - 2020-10-12
Flow 3 with pumping (Drawdown 10 m, L = 5 m, dL = 0.5 m), 2020-10-14 - 2020-10-15
Flow 4 with pumping (Drawdown 10 m, L = 1 m, dL = 0.1 m), 2020-10-16 - 2020-10-21
Location (middle of section) for fracture-specific electrical conductivity measurement
Lower limit of flow rate. Flow rate under 6 mL/h is not plotted.
Interpreted flows of borehole sections:
Flow 1 (L = 5 m, flow into the hole)
Flow 1 (L = 5 m, flow into the bedrock)
Flow 3 (L = 5 m, flow into the hole)
Interpreted fracture-specific flows:
Flow 2 (Flow into the hole)
Flow 2 (Flow into the bedrock)
Flow 4 (Flow into the hole)
Length (m)
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
204.2
205.7
208.7
210.0
210.6
211.2
212.0
215.0
216.7
217.1
Interpreted fracture-specific flow under un-pumped conditions for fracture at 211.2 m is from Flow 1 measurement. See Section 6.4.3 for details.
1.00 S/m
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Flow rate (mL/h)
10^1
10^2
10^3
10^4
10^5
Single point resistance (ohm)

Appendix KFR121.2.10

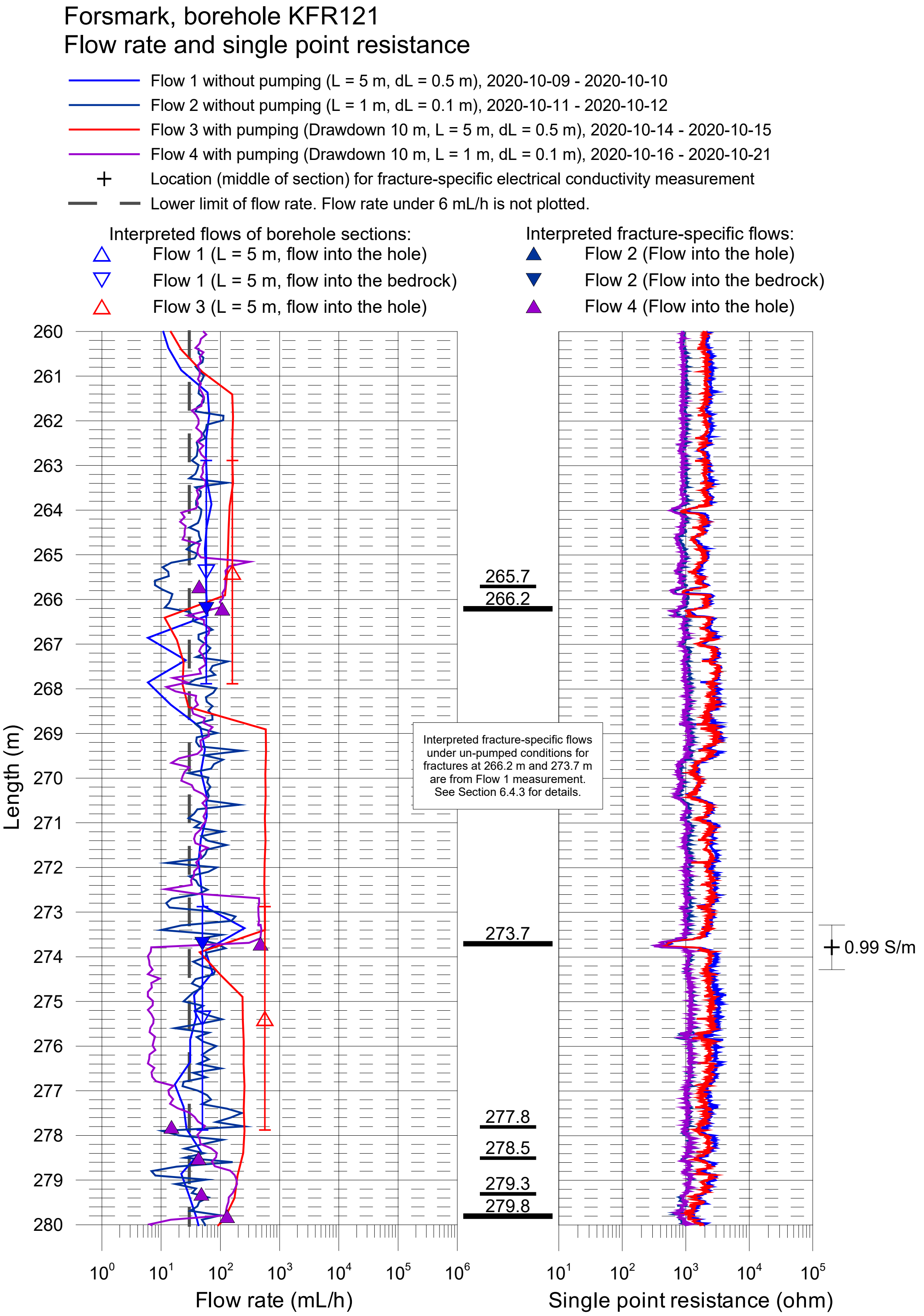
Forsmark, borehole KFR121
Flow rate and single point resistance



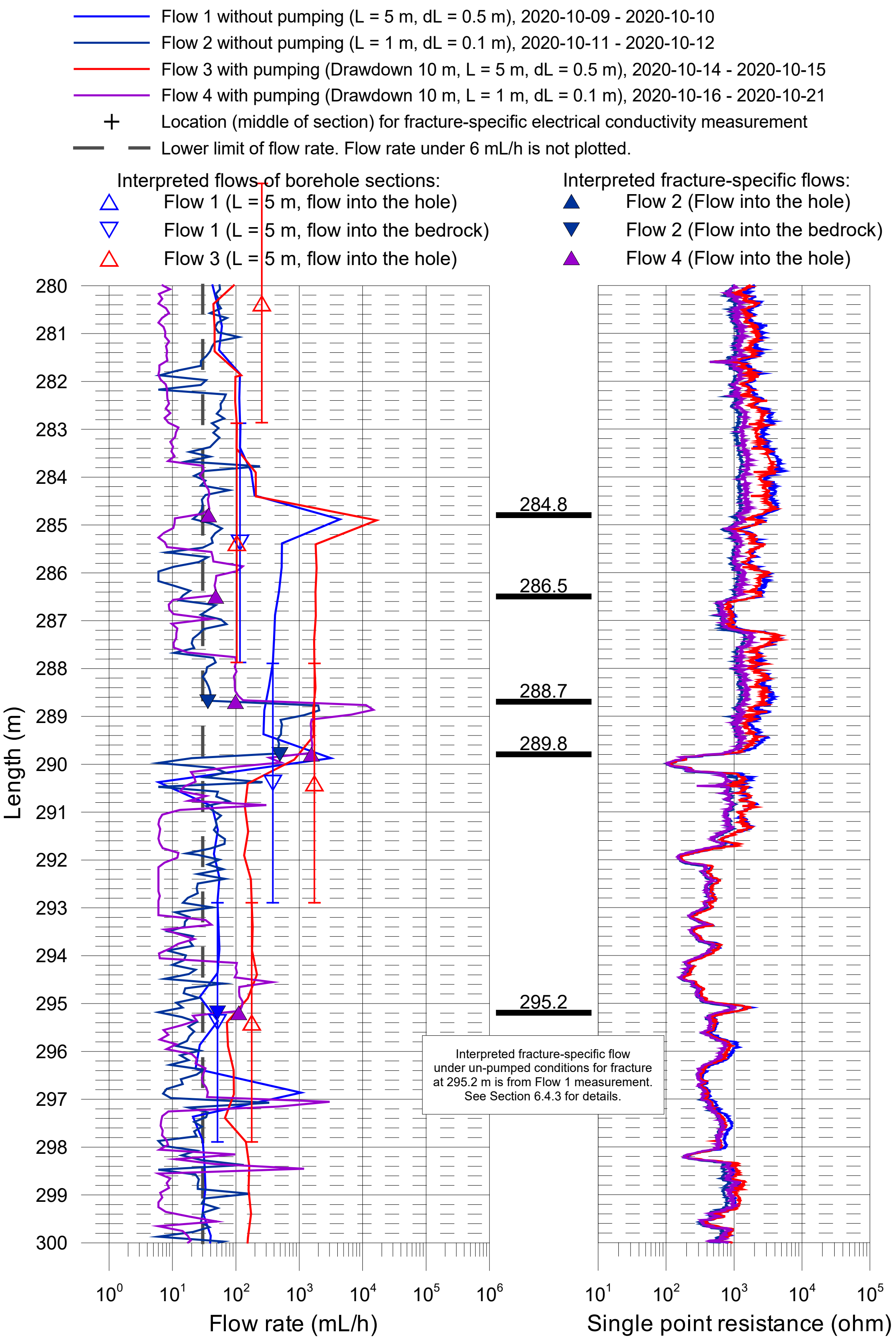
Forsmark, borehole KFR121
Flow rate and single point resistance



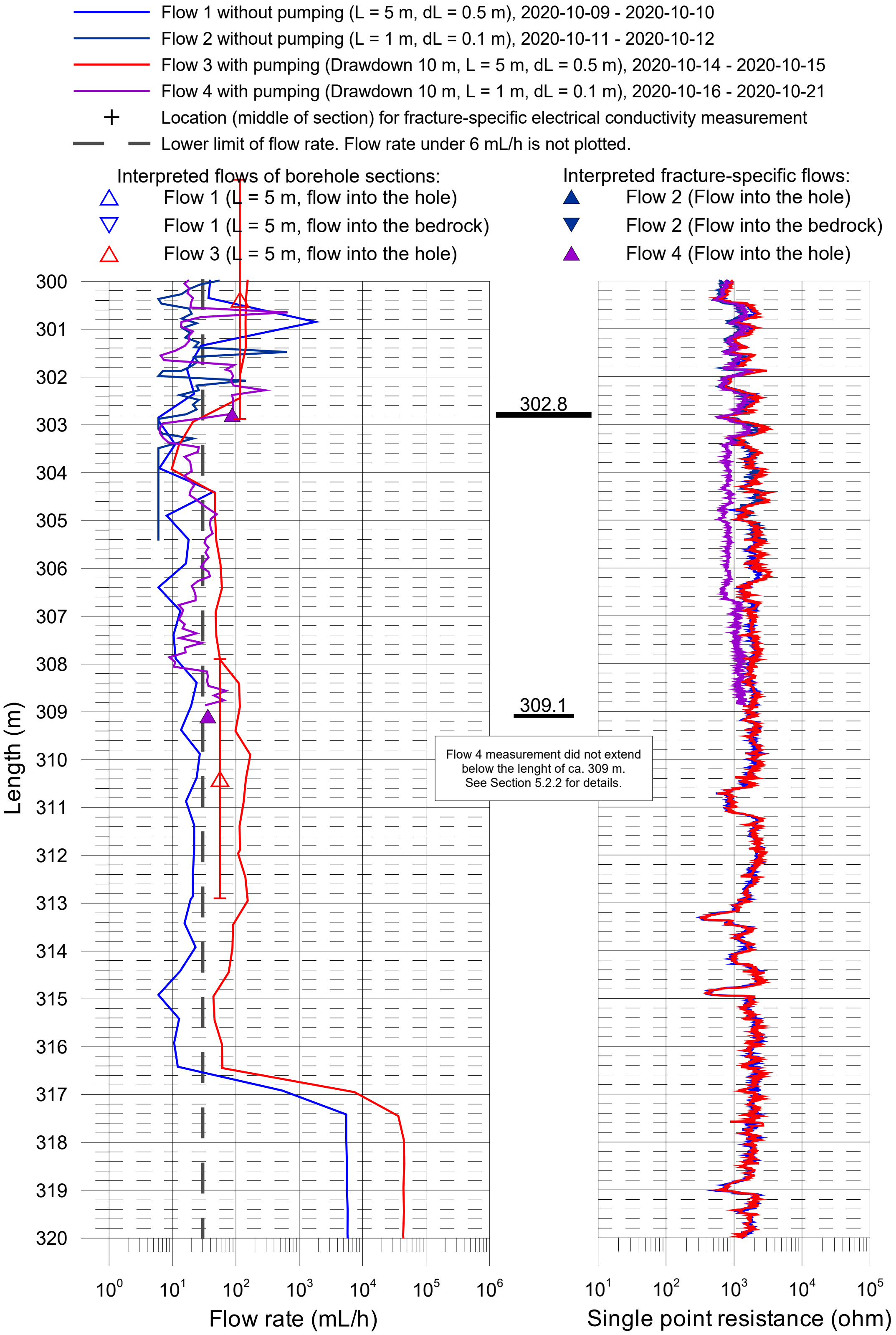
Appendix KFR121.2.12

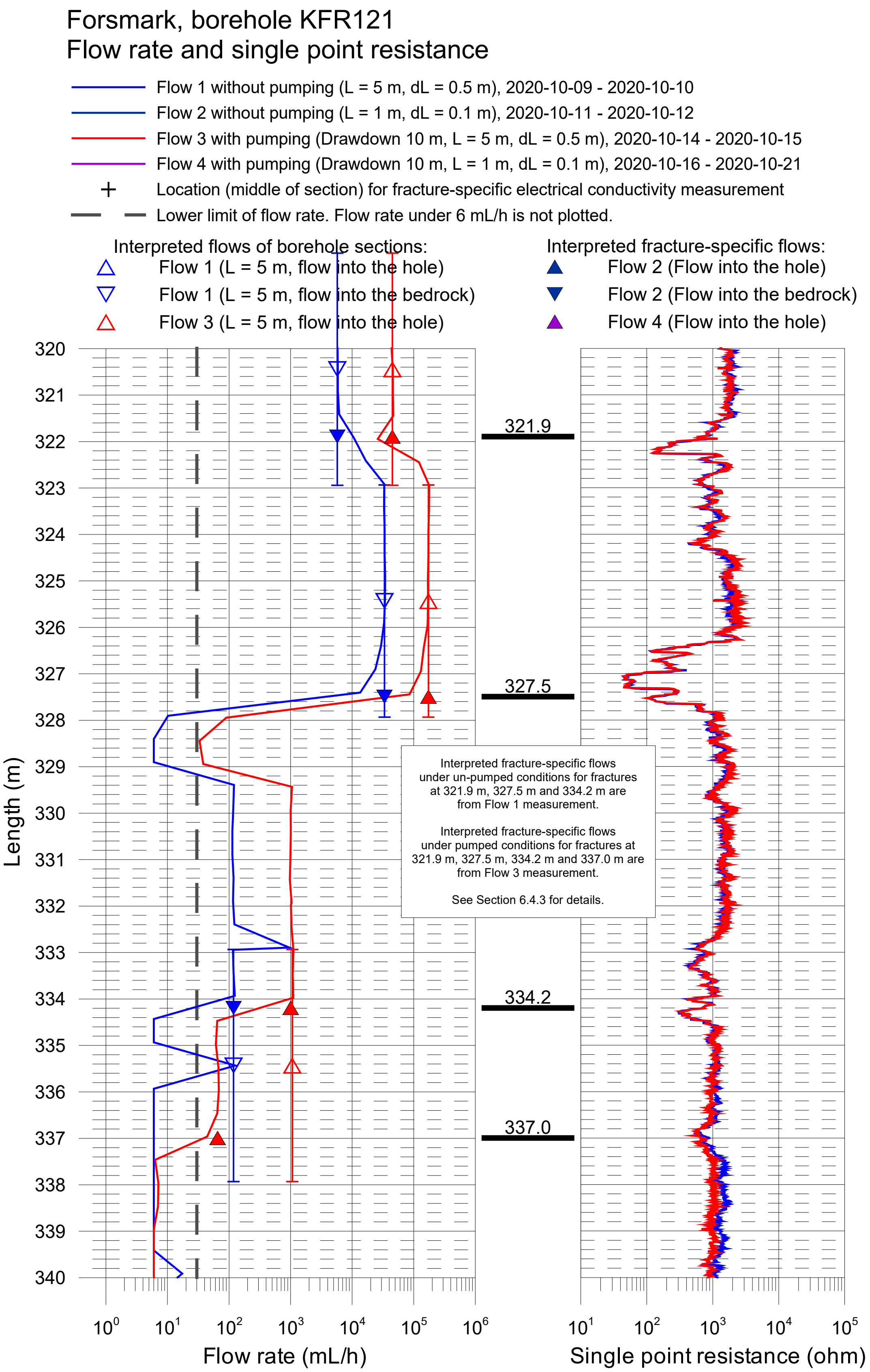


Forsmark, borehole KFR121
Flow rate and single point resistance



Forsmark, borehole KFR121
Flow rate and single point resistance




Forsmark, borehole KFR121
Flow rate and single point resistance
Flow 1 without pumping (L = 5 m, dL = 0.5 m), 2020-10-09 - 2020-10-10
Flow 2 without pumping (L = 1 m, dL = 0.1 m), 2020-10-11 - 2020-10-12
Flow 3 with pumping (Drawdown 10 m, L = 5 m, dL = 0.5 m), 2020-10-14 - 2020-10-15
Flow 4 with pumping (Drawdown 10 m, L = 1 m, dL = 0.1 m), 2020-10-16 - 2020-10-21
Location (middle of section) for fracture-specific electrical conductivity measurement
Lower limit of flow rate. Flow rate under 6 mL/h is not plotted.
Interpreted flows of borehole sections:
Flow 1 (L = 5 m, flow into the hole)
Flow 1 (L = 5 m, flow into the bedrock)
Flow 3 (L = 5 m, flow into the hole)
Interpreted fracture-specific flows:
Flow 2 (Flow into the hole)
Flow 2 (Flow into the bedrock)
Flow 4 (Flow into the hole)
321.9
327.5
334.2
337.0
Interpreted fracture-specific flows under un-pumped conditions for fractures at 321.9 m, 327.5 m and 334.2 m are from Flow 1 measurement.
Interpreted fracture-specific flows under pumped conditions for fractures at 321.9 m, 327.5 m, 334.2 m and 337.0 m are from Flow 3 measurement.
See Section 6.4.3 for details.
Length (m)
320
321
322
323
324
325
326
327
328
329
330
331
332
333
334
335
336
337
338
339
340
10^0 10^1 10^2 10^3 10^4 10^5 10^6
Flow rate (mL/h)
10^1 10^2 10^3 10^4 10^5
Single point resistance (ohm)

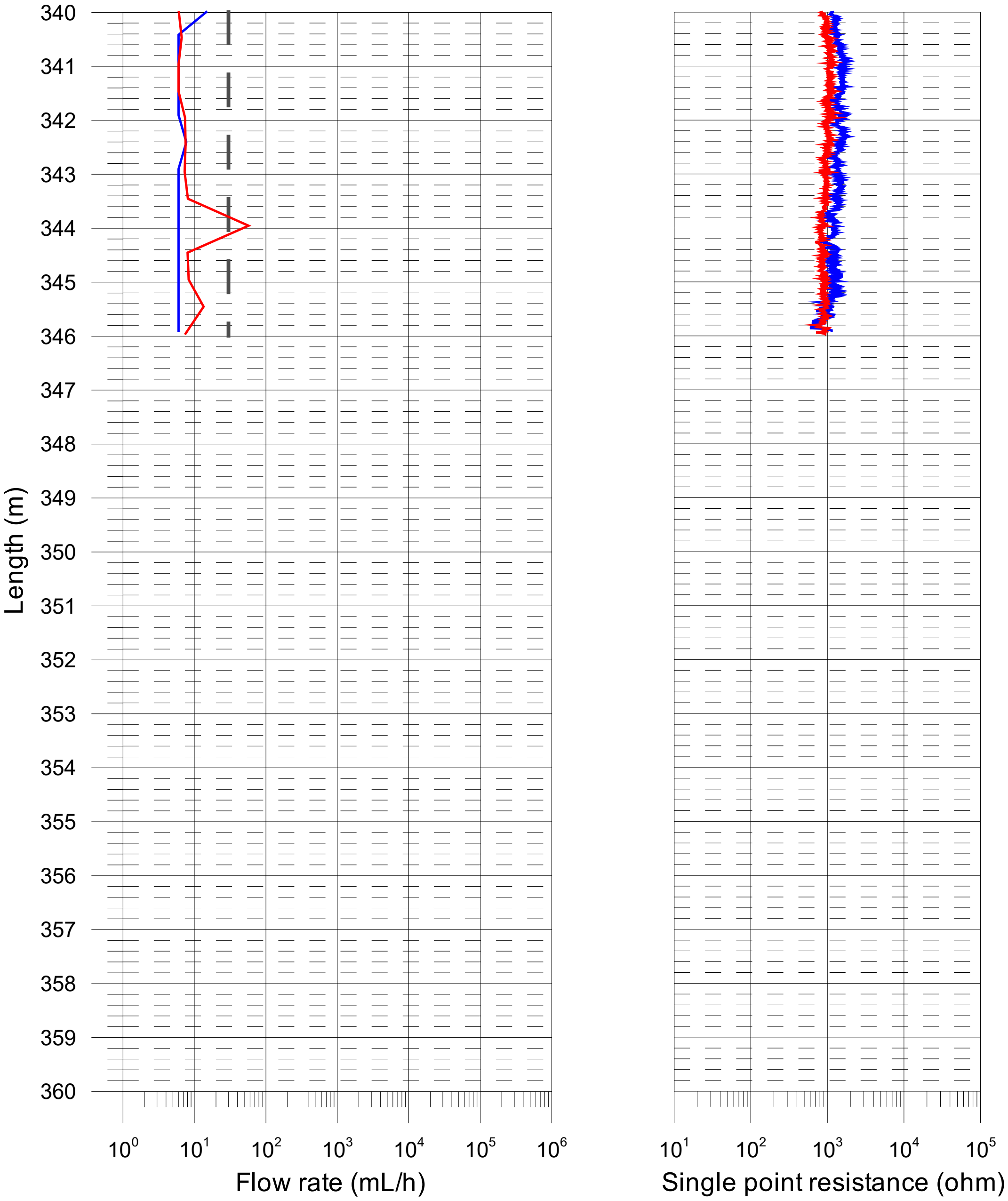
Appendix KFR121.2.16

Forsmark, borehole KFR121
Flow rate and single point resistance

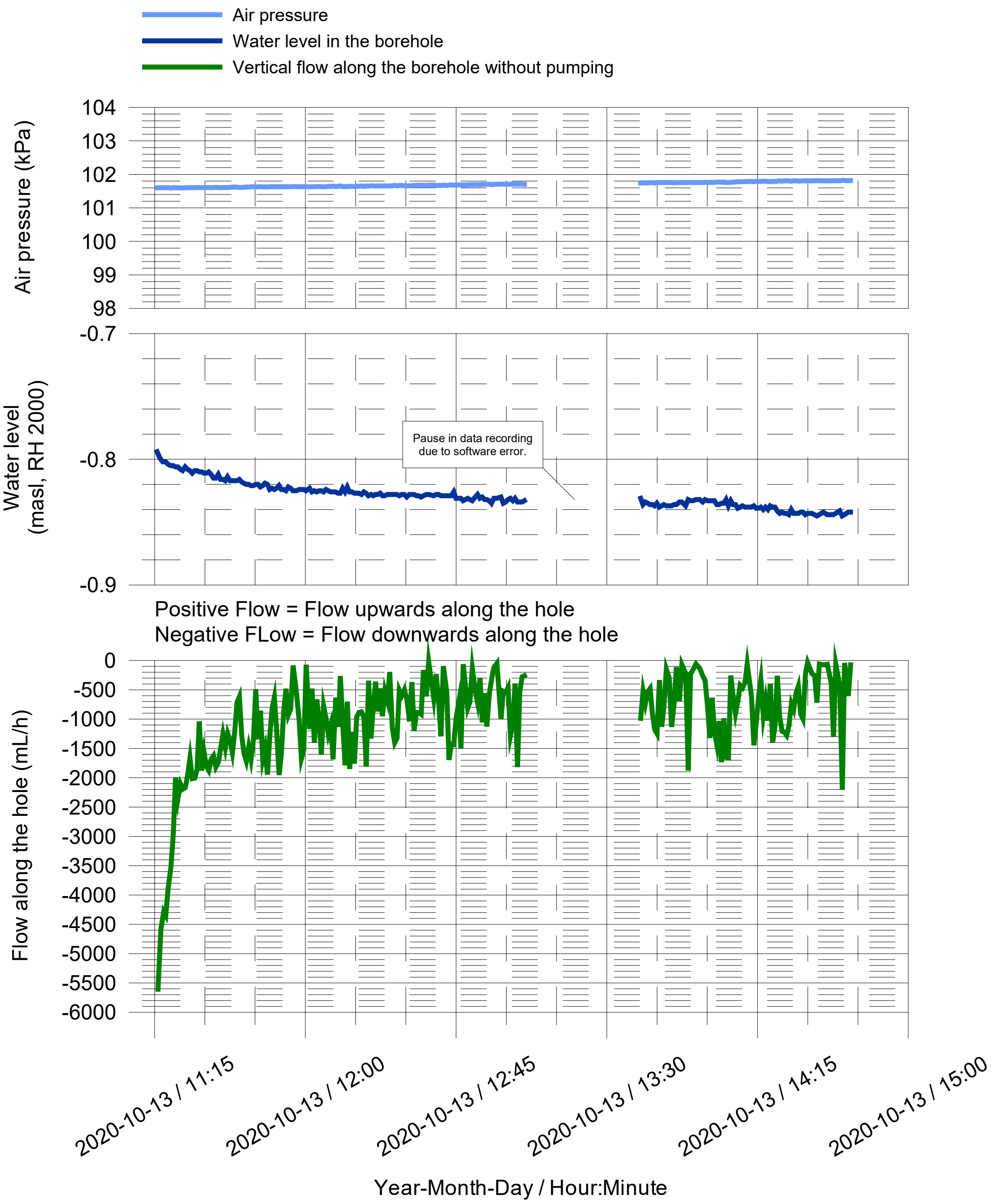
Flow 1 without pumping (L = 5 m, dL = 0.5 m), 2020-10-09 - 2020-10-10
Flow 2 without pumping (L = 1 m, dL = 0.1 m), 2020-10-11 - 2020-10-12
Flow 3 with pumping (Drawdown 10 m, L = 5 m, dL = 0.5 m), 2020-10-14 - 2020-10-15
Flow 4 with pumping (Drawdown 10 m, L = 1 m, dL = 0.1 m), 2020-10-16 - 2020-10-21
+ Location (middle of section) for fracture-specific electrical conductivity measurement
Lower limit of flow rate. Flow rate under 6 mL/h is not plotted.

Interpreted flows of borehole sections:
Flow 1 (L = 5 m, flow into the hole)
Flow 1 (L = 5 m, flow into the bedrock)
Flow 3 (L = 5 m, flow into the hole)

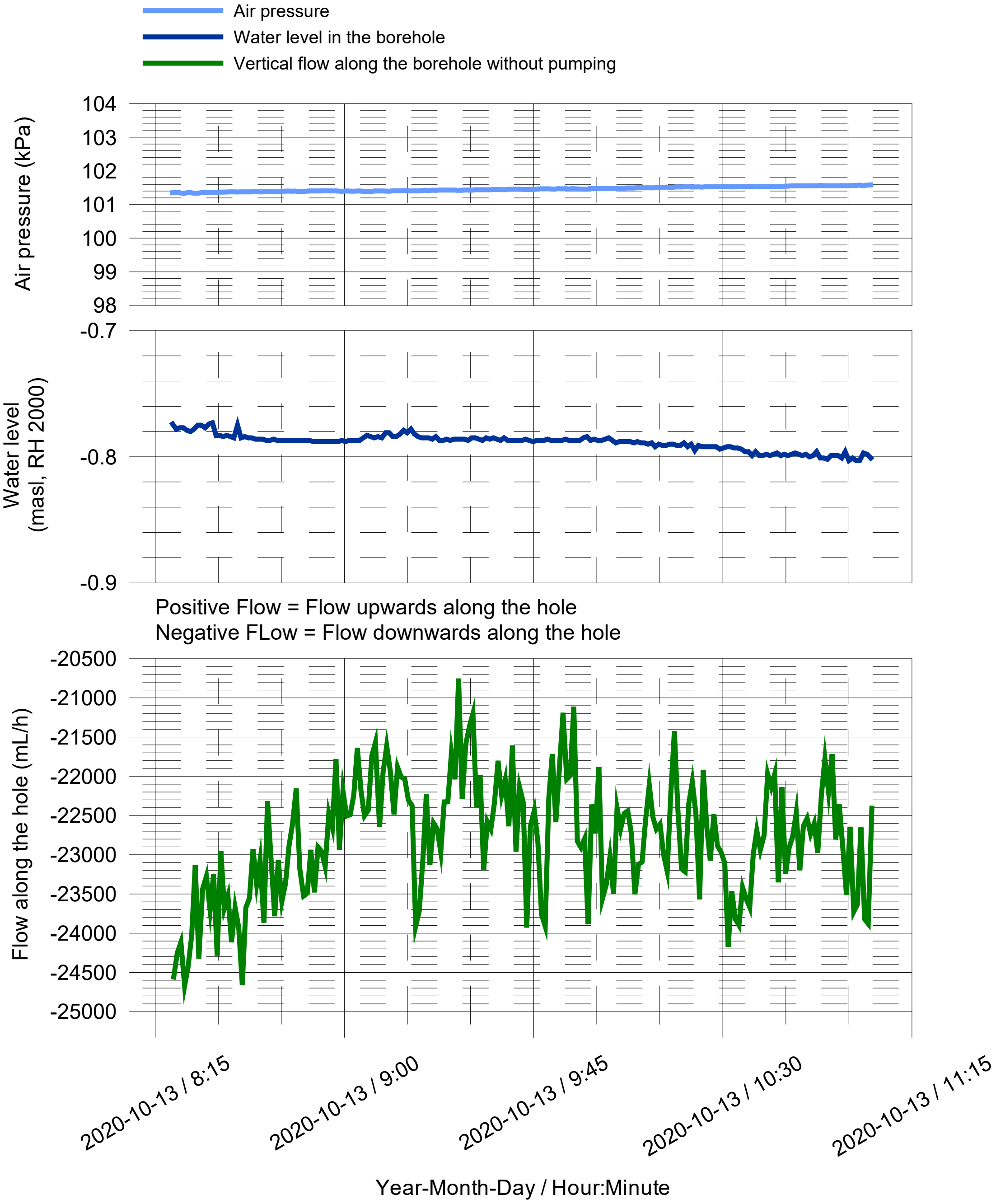
Interpreted fracture-specific flows:
Flow 2 (Flow into the hole)
Flow 2 (Flow into the bedrock)
Flow 4 (Flow into the hole)



Forsmark, borehole KFR121
Vertical flow along the borehole at the length of 40.6 m

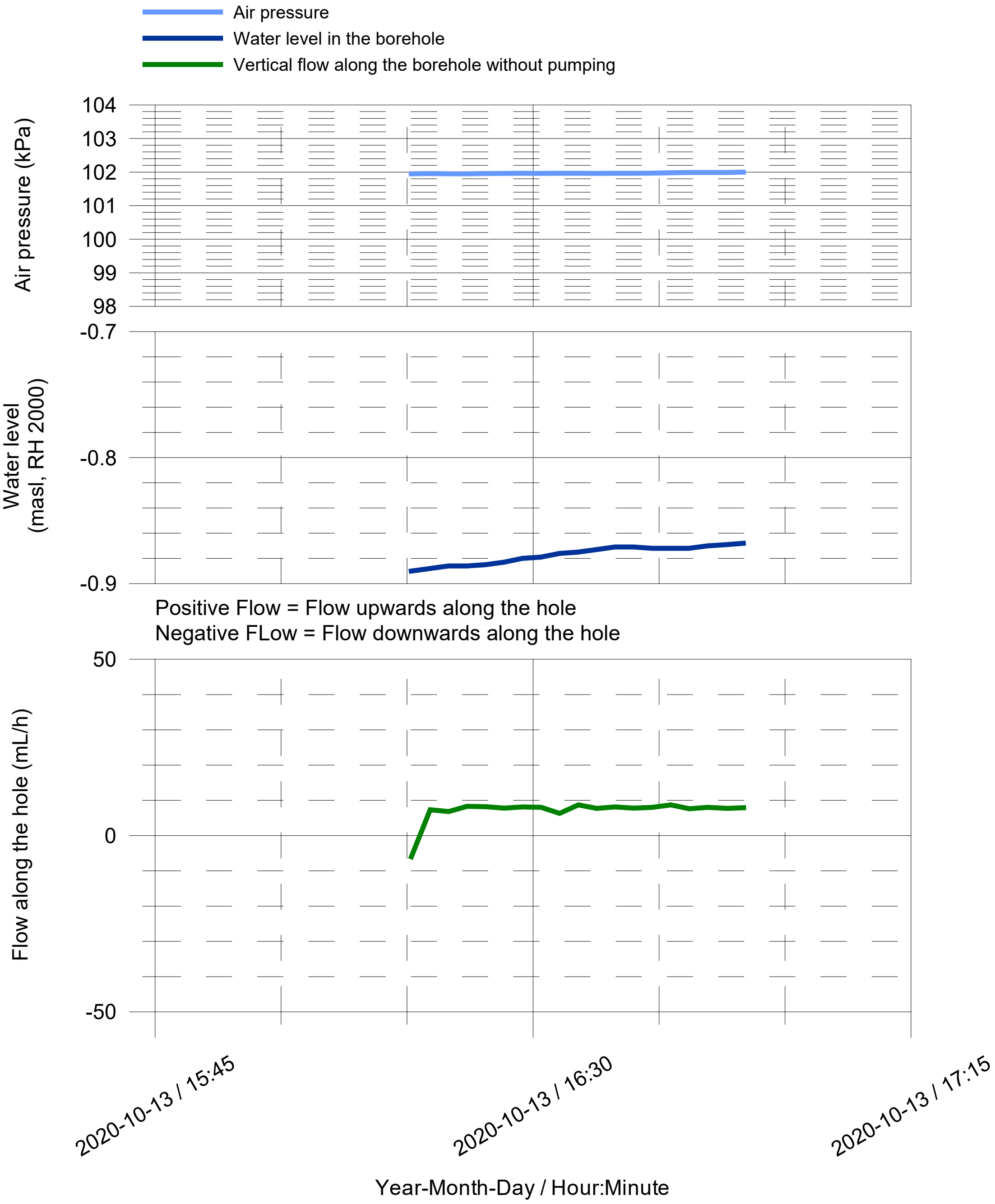


Forsmark, borehole KFR121
Vertical flow along the borehole at the length of 42.5 m



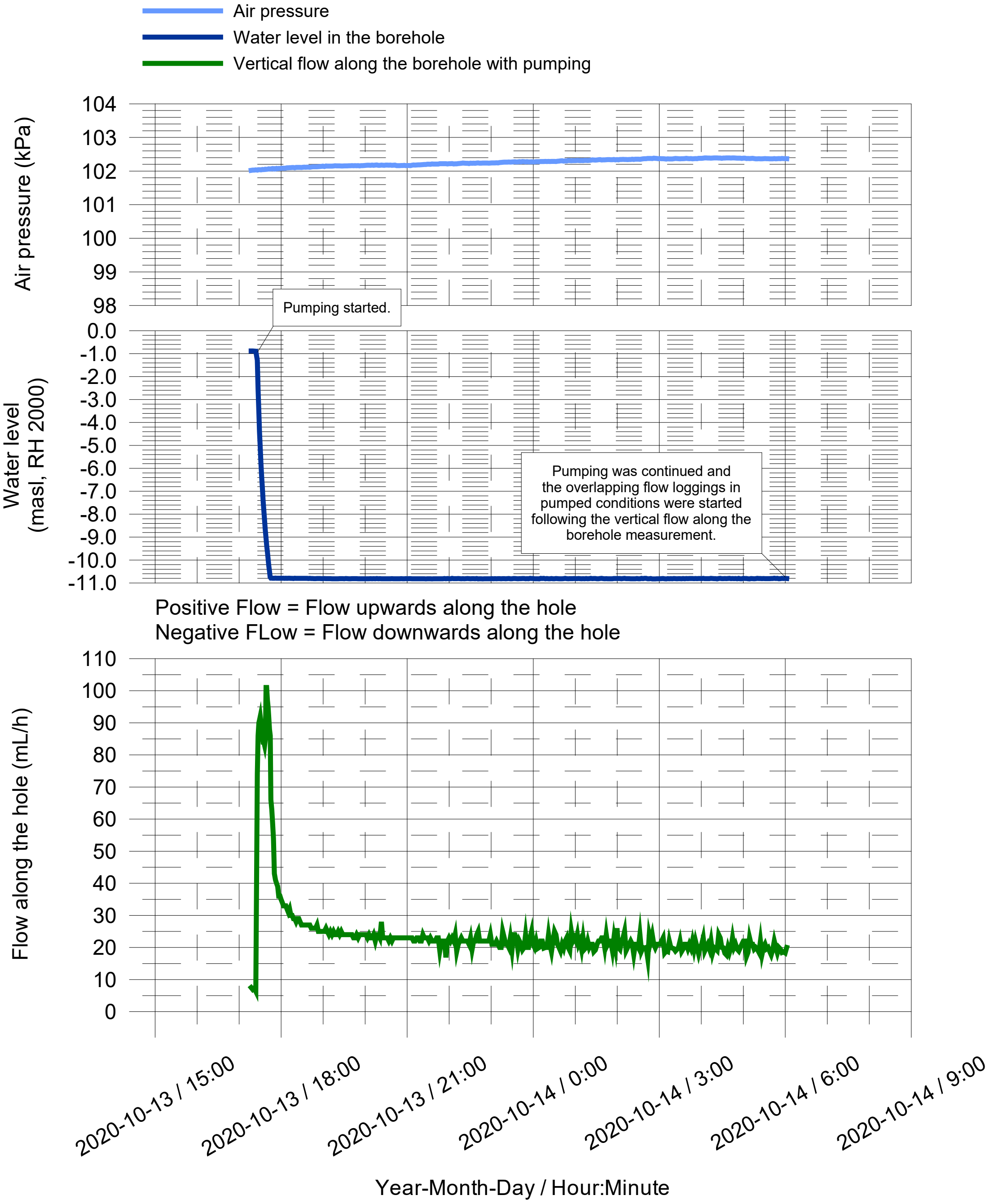
Appendix KFR121.2.19

Forsmark, borehole KFR121
Vertical flow along the borehole at the length of 342.9 m



Appendix KFR121.2.20

Forsmark, borehole KFR121
Vertical flow along the borehole at the length of 342.9 m



Appendix KFR121.3

Glossary of terms used in the tables in Appendices

Header	Unit	Definition
Borehole ID		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)
Length to flow anom.	m	Length along the borehole to inferred flow anomaly during overlapping flow logging
L_w	m	Section length used in the difference flow logging
dL	m	Step length (increment) used in the difference flow logging
Q_0	m^3/s	Measured flow rate through the test section or flow anomaly under natural conditions (no pumping) with h=h0 in the open borehole
Q_1	m^3/s	Measured flow rate through the test section or flow anomaly during the first pumping period
h_{0FW}	masl	Corrected initial hydraulic head along the borehole due to e.g. varying salinity conditions of the borehole fluid before pumping
h_{1FW}	masl	Corrected hydraulic head along the borehole due to e.g. varying salinity conditions of the borehole fluid during the first pumping period
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.
Q-lower limit P	mL/h	Practical lower measurement limit for flow rate.
T-$measl_{LT}$	m^2/s	Estimated theoretical lower measurement limit for evaluated TD. If the estimated TD equals TD-measlim, the actual TD is considered to be equal or less than TD-measlim.
T-$measl_{LP}$	m^2/s	Estimated practical lower measurement limit for evaluated TD. If the estimated TD equals TD-measlim, the actual TD is considered to be equal or less than TD-measlim.
T-$meas_{lU}$	m^2/s	Estimated upper measurement limit for evaluated TD. If the estimated TD equals TD-measlim, the actual TD is considered to be equal or less than TD-measlim.
h_i	masl	Calculated relative, natural freshwater head for test section or flow anomaly (undisturbed conditions)

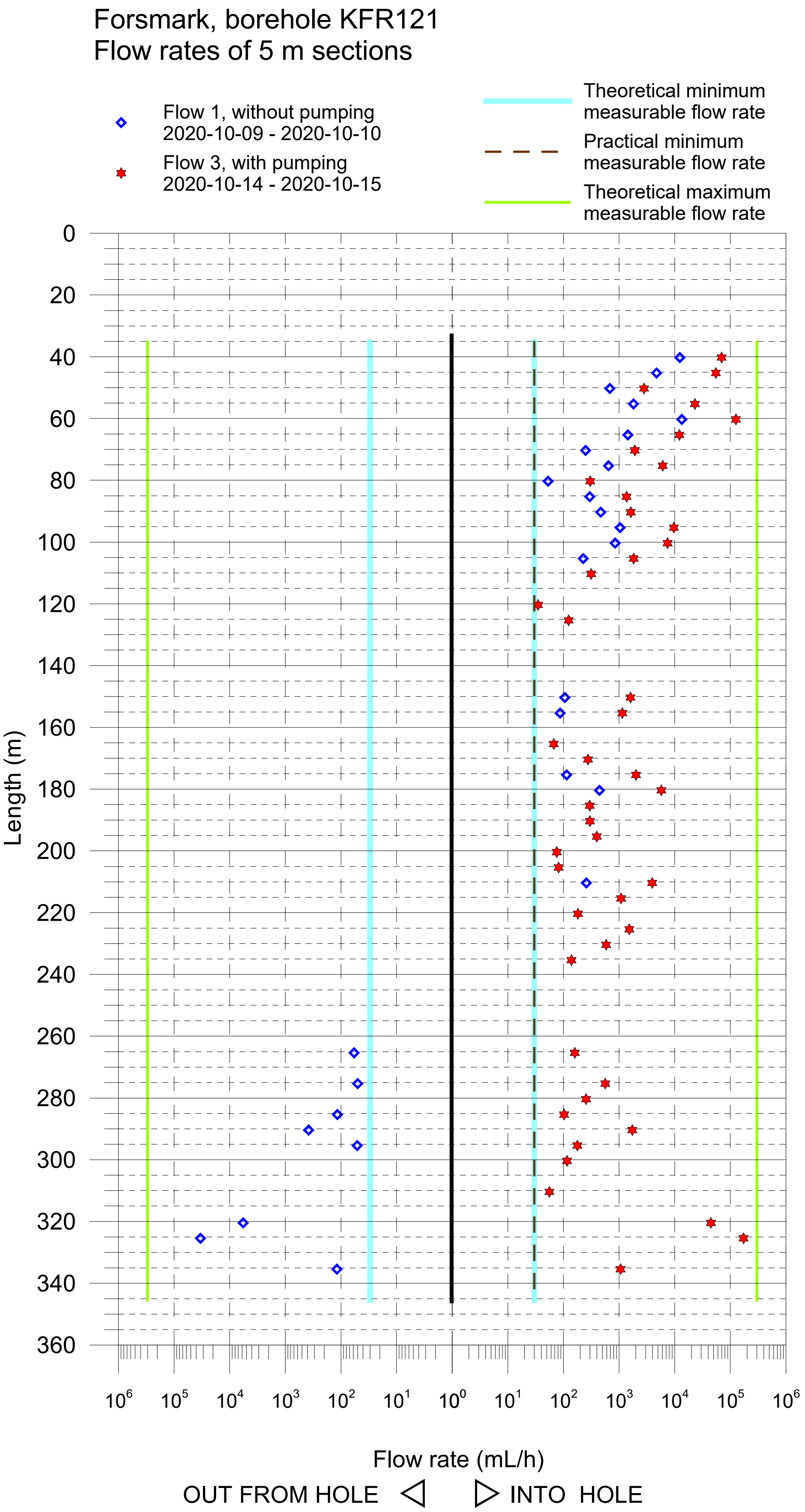
Appendix KFR121.4.1

Results of section flows

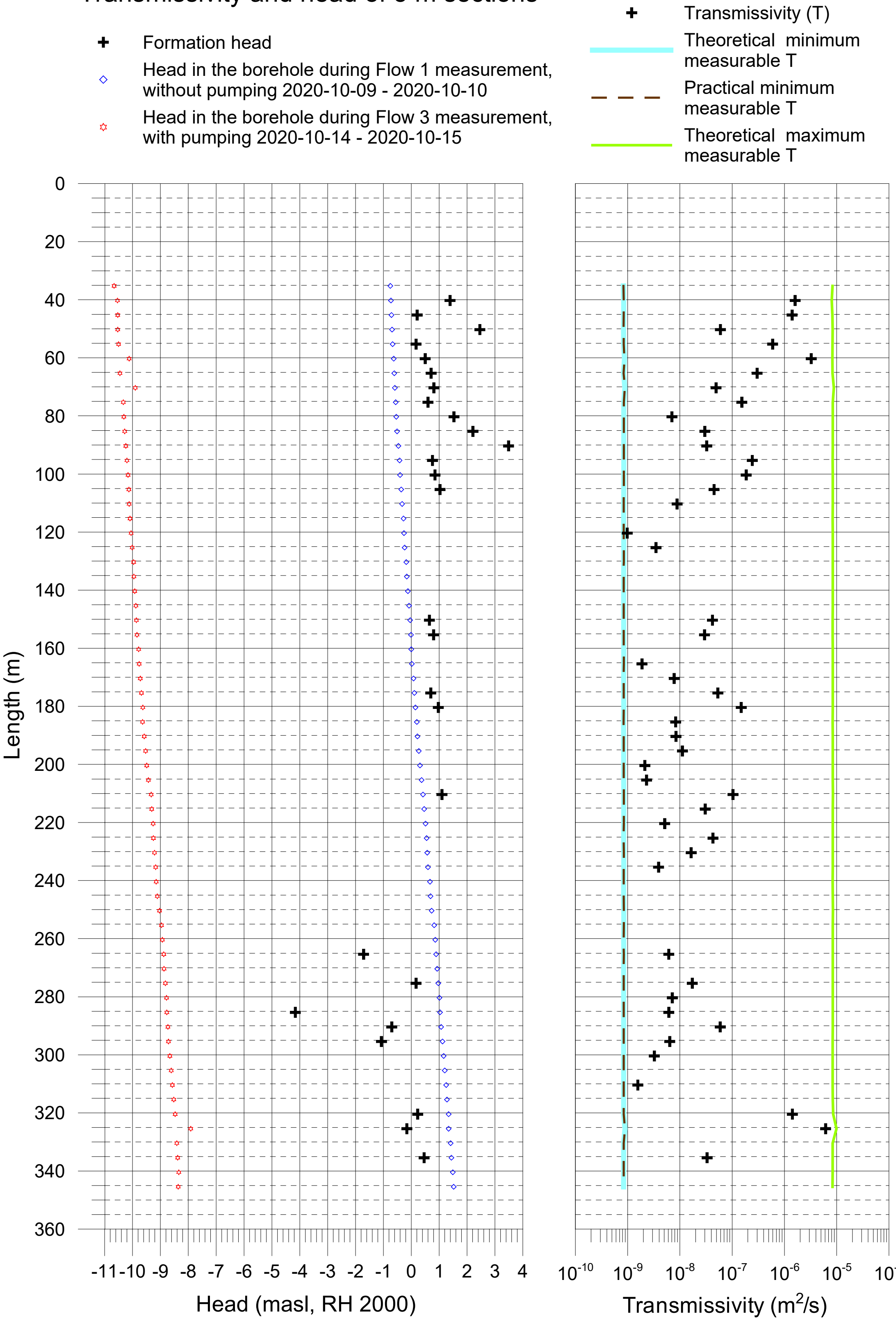
Borehole ID	Secup L(m)	Seclo L(m)	L_w (m)	Q_0 (m^3/s)	h_{0FW} (masl)	Q_1 (m^3/s)	h_{1FW} (masl)	T_D (m^2/s)	h_i (masl)	Q-lower limit P (mL/h)	T_D-measl$_{LT}$ (m^2/s)	T_D - measl$_{LP}$ (m^2/s)	T_D - measl$_U$ (m^2/s)	Comments
KFR121	32.75	37.75	5	-	-0.75	-	-10.66	-	-	30	8.3E-10	8.3E-10	8.3E-06	
KFR121	37.76	42.76	5	3.44E-06	-0.73	1.93E-05	-10.54	1.6E-06	1.4	30	8.4E-10	8.4E-10	8.1E-06	
KFR121	42.77	47.77	5	1.31E-06	-0.71	1.53E-05	-10.53	1.4E-06	0.2	30	8.4E-10	8.4E-10	8.3E-06	
KFR121	47.78	52.78	5	1.90E-07	-0.69	7.83E-07	-10.53	6.0E-08	2.5	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	52.79	57.79	5	5.05E-07	-0.67	6.41E-06	-10.50	5.9E-07	0.2	30	8.4E-10	8.4E-10	8.3E-06	
KFR121	57.80	62.80	5	3.73E-06	-0.63	3.50E-05	-10.12	3.3E-06	0.5	30	8.7E-10	8.7E-10	8.3E-06	
KFR121	62.81	67.81	5	3.99E-07	-0.61	3.38E-06	-10.45	3.0E-07	0.7	30	8.4E-10	8.4E-10	8.3E-06	
KFR121	67.82	72.82	5	6.94E-08	-0.59	5.33E-07	-9.90	4.9E-08	0.8	30	8.9E-10	8.9E-10	8.8E-06	
KFR121	72.80	77.80	5	1.79E-07	-0.56	1.69E-06	-10.33	1.5E-07	0.6	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	77.80	82.80	5	1.47E-08	-0.54	8.42E-08	-10.31	7.0E-09	1.5	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	82.83	87.83	5	8.25E-08	-0.51	3.79E-07	-10.28	3.0E-08	2.2	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	87.84	92.84	5	1.30E-07	-0.46	4.52E-07	-10.24	3.3E-08	3.5	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	92.84	97.84	5	2.90E-07	-0.42	2.69E-06	-10.20	2.4E-07	0.8	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	97.85	102.85	5	2.36E-07	-0.40	2.07E-06	-10.16	1.9E-07	0.9	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	102.84	107.84	5	6.31E-08	-0.36	5.08E-07	-10.13	4.5E-08	1.0	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	107.83	112.83	5	-	-0.33	8.75E-08	-10.12	8.8E-09	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	112.85	117.85	5	-	-0.28	-	-10.09	-	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	117.86	122.86	5	-	-0.26	9.72E-09	-10.05	9.8E-10	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	122.85	127.85	5	-	-0.24	3.44E-08	-10.01	3.5E-09	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	127.84	132.84	5	-	-0.18	-	-9.96	-	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	132.83	137.83	5	-	-0.16	-	-9.95	-	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	137.85	142.85	5	-	-0.12	-	-9.92	-	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	142.85	147.85	5	-	-0.08	-	-9.88	-	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	147.85	152.85	5	2.94E-08	-0.04	4.46E-07	-9.86	4.2E-08	0.7	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	152.88	157.88	5	2.42E-08	-0.01	3.18E-07	-9.84	3.0E-08	0.8	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	157.87	162.87	5	-	0.00	-	-9.78	-	-	30	8.4E-10	8.4E-10	8.4E-06	

Borehole ID	Secup L(m)	Seclo L(m)	L_w (m)	Q_0 (m^3/s)	h_{0FW} (masl)	Q_1 (m^3/s)	h_{1FW} (masl)	T_D (m^2/s)	h_i (masl)	Q-lower limit P (mL/h)	T_D-measl$_{LT}$ (m^2/s)	T_D - measl$_{LP}$ (m^2/s)	T_D - measl$_U$ (m^2/s)	Comments
KFR121	162.88	167.88	5	-	0.02	1.86E-08	-9.76	1.9E-09	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	167.92	172.92	5	-	0.08	7.69E-08	-9.72	7.8E-09	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	172.90	177.90	5	3.17E-08	0.11	5.59E-07	-9.68	5.3E-08	0.7	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	177.89	182.89	5	1.24E-07	0.15	1.60E-06	-9.63	1.5E-07	1.0	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	182.88	187.88	5	-	0.20	8.25E-08	-9.64	8.3E-09	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	187.87	192.87	5	-	0.22	8.33E-08	-9.58	8.4E-09	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	192.87	197.87	5	-	0.27	1.11E-07	-9.53	1.1E-08	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	197.88	202.88	5	-	0.31	2.11E-08	-9.49	2.1E-09	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	202.88	207.88	5	-	0.37	2.28E-08	-9.43	2.3E-09	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	207.88	212.88	5	7.17E-08	0.42	1.10E-06	-9.33	1.0E-07	1.1	30	8.5E-10	8.5E-10	8.4E-06	
KFR121	212.88	217.88	5	-	0.46	3.02E-07	-9.31	3.1E-08	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	217.88	222.88	5	-	0.51	5.06E-08	-9.26	5.1E-09	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	222.89	227.89	5	-	0.55	4.24E-07	-9.25	4.3E-08	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	227.90	232.90	5	-	0.57	1.63E-07	-9.21	1.6E-08	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	232.89	237.89	5	-	0.60	3.86E-08	-9.17	3.9E-09	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	237.90	242.90	5	-	0.67	-	-9.15	-	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	242.89	247.89	5	-	0.69	-	-9.11	-	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	247.88	252.88	5	-	0.73	-	-9.03	-	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	252.89	257.89	5	-	0.82	-	-8.96	-	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	257.88	262.88	5	-	0.86	-	-8.93	-	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	262.88	267.88	5	-1.61E-08	0.89	4.44E-08	-8.88	6.1E-09	-1.7	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	267.88	272.88	5	-	0.93	-	-8.87	-	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	272.87	277.87	5	-1.39E-08	0.97	1.57E-07	-8.82	1.7E-08	0.2	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	277.87	282.87	5	-	1.01	7.08E-08	-8.78	7.2E-09	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	282.88	287.88	5	-3.22E-08	1.03	2.86E-08	-8.77	6.1E-09	-4.2	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	287.90	292.90	5	-1.06E-07	1.07	4.80E-07	-8.73	5.9E-08	-0.7	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	292.90	297.90	5	-1.42E-08	1.12	4.94E-08	-8.71	6.4E-09	-1.1	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	297.89	302.89	5	-	1.16	3.22E-08	-8.66	3.2E-09	-	30	8.4E-10	8.4E-10	8.4E-06	

Borehole ID	Secup L(m)	Seclo L(m)	L_w (m)	Q_0 (m^3/s)	h_{0FW} (masl)	Q_1 (m^3/s)	h_{1FW} (masl)	T_D (m^2/s)	h_i (masl)	Q-lower limit P (mL/h)	T_D-measl$_{LT}$ (m^2/s)	T_D - measl$_{LP}$ (m^2/s)	T_D - measl$_U$ (m^2/s)	Comments
KFR121	302.91	307.91	5	-	1.20	-	-8.61	-	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	307.91	312.91	5	-	1.25	1.56E-08	-8.57	1.6E-09	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	312.91	317.91	5	-	1.28	-	-8.52	-	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	317.95	322.95	5	-1.59E-06	1.34	1.25E-05	-8.47	1.4E-06	0.2	30	8.4E-10	8.4E-10	8.6E-06	
KFR121	322.94	327.94	5	-9.31E-06	1.34	4.81E-05	-7.91	6.1E-06	-0.2	30	8.9E-10	8.9E-10	9.9E-06	
KFR121	327.93	332.93	5	-	1.41	-	-8.41	-	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	332.94	337.94	5	-3.28E-08	1.44	2.96E-07	-8.38	3.3E-08	0.5	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	337.95	342.95	5	-	1.49	-	-8.34	-	-	30	8.4E-10	8.4E-10	8.4E-06	
KFR121	342.94	347.94	5	-	1.52	-	-8.36	-	-	30	8.3E-10	8.3E-10	8.3E-06	

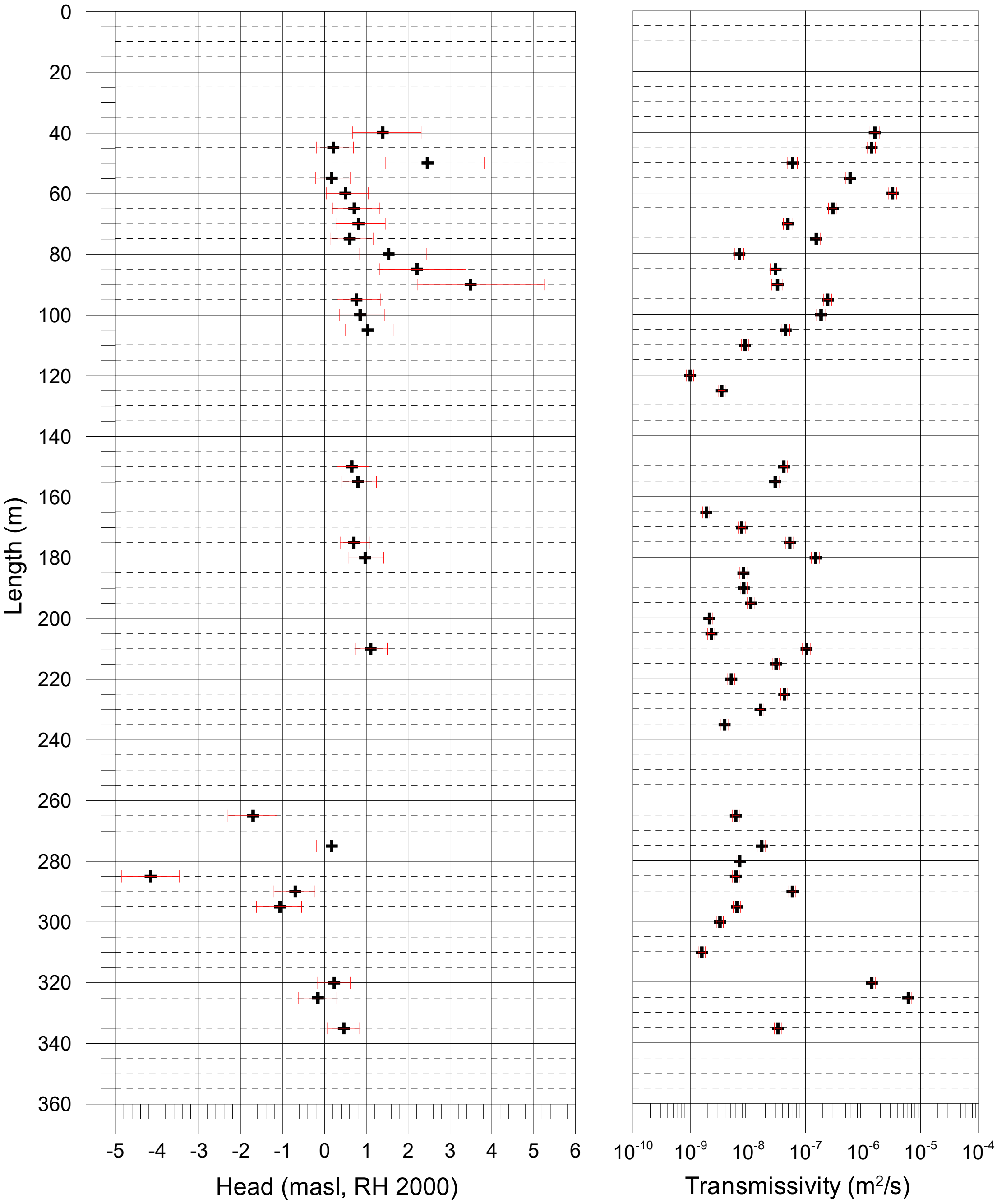

Forsmark, borehole KFR121
Flow rates of 5 m sections
Flow 1, without pumping
2020-10-09 - 2020-10-10
Flow 3, with pumping
2020-10-14 - 2020-10-15
Theoretical minimum measurable flow rate
Practical minimum measurable flow rate
Theoretical maximum measurable flow rate
Length (m)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
10^6 10^5 10^4 10^3 10^2 10^1 10^0 10^1 10^2 10^3 10^4 10^5 10^6
Flow rate (mL/h)
OUT FROM HOLE
INTO HOLE

Forsmark, borehole KFR121
Transmissivity and head of 5 m sections



Appendix KFR121.5.3

Forsmark, borehole KFR121
Transmissivity and head of 5 m sections
Error bars assuming ±10% errors in flow rates
and ±0.2 m in head in worst-case combination



Appendix KFR121.5.4

Forsmark, borehole KFR121
Calculation of conductive fracture frequency

Appendix KFR121.6.1

Inferred fracture flow anomalies from flow logging

Borehole ID	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_0 (m^3/s)	h_{0FW} (masl)	Q_1 (m^3/s)	h_{1FW} (masl)	T_D (m^2/s)	h_i (masl)	Comments
KFR121	41.4	1	0.1	3.39E-06	-0.70	1.76E-05	-10.54	1.4E-06	1.7	**
KFR121	43.5	1	0.1	2.14E-08	-0.69	1.01E-07	-10.67	7.9E-09	2.0	
KFR121	45.1	1	0.1	1.97E-08	-0.68	8.83E-08	-10.66	6.8E-09	2.2	
KFR121	45.9	1	0.1	3.64E-07	-0.69	2.61E-06	-10.66	2.2E-07	0.9	
KFR121	46.5	1	0.1	8.39E-07	-0.67	1.06E-05	-10.60	9.7E-07	0.2	
KFR121	48.8	1	0.1	3.44E-08	-0.66	2.10E-07	-10.65	1.7E-08	1.3	*
KFR121	49.1	1	0.1	3.33E-08	-0.67	3.47E-07	-10.64	3.1E-08	0.4	
KFR121	51.4	1	0.1	1.39E-07	-0.67	3.72E-07	-10.63	2.3E-08	5.3	
KFR121	53.2	1	0.1	-	-0.65	2.53E-08	-10.63	2.5E-09	-	
KFR121	54.2	1	0.1	2.92E-08	-0.65	1.95E-07	-10.61	1.7E-08	1.1	
KFR121	55.0	1	0.1	5.67E-08	-0.65	4.97E-07	-10.60	4.4E-08	0.6	
KFR121	55.3	1	0.1	-	-0.66	6.56E-08	-10.61	6.5E-09	-	*
KFR121	57.2	1	0.1	4.33E-07	-0.65	5.06E-06	-10.58	4.6E-07	0.3	
KFR121	58.3	1	0.1	3.47E-08	-0.62	3.11E-07	-10.59	2.7E-08	0.6	
KFR121	59.8	1	0.1	4.08E-08	-0.62	8.53E-08	-10.58	4.4E-09	8.5	
KFR121	60.6	1	0.1	9.17E-08	-0.61	6.61E-07	-10.56	5.7E-08	1.0	
KFR121	61.0	1	0.1	3.17E-07	-0.62	2.69E-06	-10.55	2.4E-07	0.7	
KFR121	62.0	1	0.1	2.81E-06	-0.61	2.49E-05	-10.32	2.3E-06	0.6	
KFR121	63.0	1	0.1	3.50E-07	-0.59	2.81E-06	-10.54	2.4E-07	0.8	
KFR121	65.4	1	0.1	-	-0.58	1.47E-08	-10.53	1.5E-09	-	
KFR121	67.7	1	0.1	2.64E-08	-0.56	1.22E-07	-10.50	9.5E-09	2.2	
KFR121	68.8	1	0.1	8.14E-08	-0.55	5.19E-07	-10.48	4.4E-08	1.3	
KFR121	75.7	1	0.1	-	-0.51	1.61E-08	-10.43	1.6E-09	-	

Borehole ID	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_0 (m^3/s)	h_{0FW} (masl)	Q_1 (m^3/s)	h_{1FW} (masl)	T_D (m^2/s)	h_i (masl)	Comments
KFR121	76.9	1	0.1	3.33E-08	-0.50	8.06E-08	-10.43	4.7E-09	6.5	
KFR121	77.6	1	0.1	1.64E-07	-0.50	1.40E-06	-10.42	1.2E-07	0.8	
KFR121	78.4	1	0.1	-	-0.49	1.08E-08	-10.42	1.1E-09	-	*
KFR121	81.6	1	0.1	1.28E-08	-0.48	4.97E-08	-10.41	3.7E-09	3.0	
KFR121	82.7	1	0.1	-	-0.47	2.86E-08	-10.40	2.9E-09	-	*
KFR121	83.1	1	0.1	2.19E-08	-0.47	9.42E-08	-10.40	7.2E-09	2.6	
KFR121	84.6	1	0.1	2.42E-08	-0.45	1.21E-07	-10.38	9.7E-09	2.0	
KFR121	85.8	1	0.1	-	-0.45	1.33E-08	-10.37	1.3E-09	-	*
KFR121	87.0	1	0.1	6.56E-08	-0.44	1.07E-07	-10.36	4.1E-09	15.27	***
KFR121	89.2	1	0.1	-	-0.43	3.64E-08	-10.34	3.6E-09	-	*
KFR121	89.6	1	0.1	2.97E-08	-0.42	8.19E-08	-10.33	5.2E-09	5.2	
KFR121	90.4	1	0.1	1.11E-07	-0.43	2.69E-07	-10.33	1.6E-08	6.5	
KFR121	90.8	1	0.1	-	-0.42	6.94E-08	-10.33	6.9E-09	-	*
KFR121	93.7	1	0.1	5.56E-08	-0.41	1.27E-07	-10.31	7.1E-09	7.3	
KFR121	94.5	1	0.1	9.56E-08	-0.40	6.22E-07	-10.29	5.3E-08	1.4	
KFR121	96.9	1	0.1	-	-0.39	8.39E-08	-10.28	8.4E-09	-	*
KFR121	97.2	1	0.1	1.34E-07	-0.39	1.06E-06	-10.27	9.3E-08	1.0	
KFR121	97.9	1	0.1	9.25E-08	-0.39	5.11E-07	-10.25	4.2E-08	1.8	
KFR121	99.3	1	0.1	8.33E-09	-0.37	1.67E-08	-10.25	8.3E-10	9.5	*
KFR121	100.6	1	0.1	6.53E-08	-0.37	5.83E-07	-10.24	5.2E-08	0.9	

Appendix KFR121.6.2

Borehole ID	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_0 (m^3/s)	h_{0FW} (masl)	Q_1 (m^3/s)	h_{1FW} (masl)	T_D (m^2/s)	h_i (masl)	Comments
KFR121	100.9	1	0.1	1.15E-07	-0.35	9.44E-07	-10.25	8.3E-08	1.0	
KFR121	103.2	1	0.1	-	-0.36	2.94E-08	-10.21	3.0E-09	-	
KFR121	104.7	1	0.1	6.36E-08	-0.34	4.28E-07	-10.20	3.7E-08	1.4	
KFR121	106.7	1	0.1	-	-0.32	4.39E-08	-10.20	4.4E-09	-	
KFR121	108.7	1	0.1	-	-0.30	3.39E-08	-10.18	3.4E-09	-	
KFR121	111.2	1	0.1	-	-0.32	5.31E-08	-10.14	5.3E-09	-	#
KFR121	118.9	1	0.1	-	-0.27	1.36E-08	-10.10	1.4E-09	-	*,#
KFR121	123.0	1	0.1	-	-0.27	1.58E-08	-10.09	1.6E-09	-	#
KFR121	124.2	1	0.1	-	-0.25	2.28E-08	-10.08	2.3E-09	-	#
KFR121	148.8	1	0.1	3.25E-08	-0.06	3.56E-07	-9.93	3.2E-08	0.9	
KFR121	152.5	1	0.1	-	-0.03	8.83E-08	-9.89	8.9E-09	-	
KFR121	154.0	1	0.1	3.00E-08	-0.05	2.45E-07	-9.89	2.2E-08	1.3	
KFR121	155.5	1	0.1	1.31E-08	-0.03	5.11E-08	-9.88	3.8E-09	3.4	
KFR121	163.5	1	0.1	-	0.01	1.36E-08	-9.82	1.4E-09	-	
KFR121	172.7	1	0.1	-	0.06	7.75E-08	-9.76	7.8E-09	-	
KFR121	173.7	1	0.1	4.61E-08	0.08	5.28E-07	-9.76	4.8E-08	1.0	
KFR121	178.5	1	0.1	-	0.11	8.03E-08	-9.72	8.1E-09	-	*
KFR121	178.8	1	0.1	3.97E-08	0.12	3.50E-07	-9.71	3.1E-08	1.4	
KFR121	179.5	1	0.1	2.97E-08	0.11	1.84E-07	-9.71	1.6E-08	2.0	
KFR121	180.8	1	0.1	4.44E-08	0.13	2.28E-07	-9.70	1.9E-08	2.5	
KFR121	181.4	1	0.1	5.81E-08	0.12	7.50E-07	-9.70	7.0E-08	0.9	
KFR121	185.2	1	0.1	-	0.18	2.89E-08	-9.66	2.9E-09	-	
KFR121	186.4	1	0.1	-	0.17	5.39E-08	-9.66	5.4E-09	-	
KFR121	189.1	1	0.1	-	0.20	1.44E-08	-9.64	1.5E-09	-	*
KFR121	190.0	1	0.1	-	0.20	7.00E-08	-9.63	7.0E-09	-	

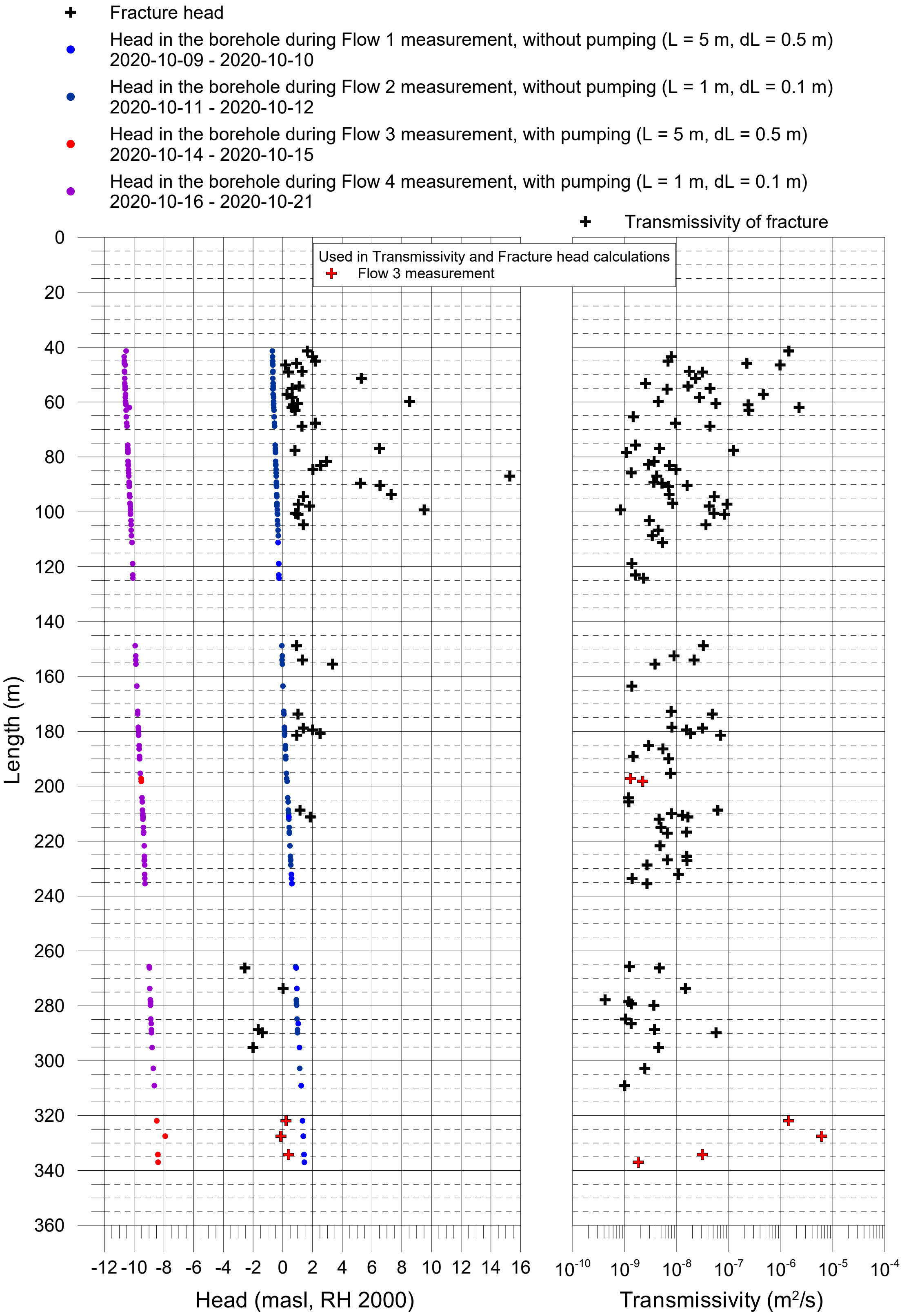
Borehole ID	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_0 (m^3/s)	h_{0FW} (masl)	Q_1 (m^3/s)	h_{1FW} (masl)	T_D (m^2/s)	h_i (masl)	Comments
KFR121	195.3	1	0.1	-	0.24	7.53E-08	-9.59	7.6E-09	-	
KFR121	197.2	5	0.5	-	0.26	1.28E-08	-9.53	1.3E-09	-	*,##
KFR121	198.2	5	0.5	-	0.29	2.19E-08	-9.52	2.2E-09	-	*,##
KFR121	204.2	1	0.1	-	0.33	1.17E-08	-9.47	1.2E-09	-	*
KFR121	205.7	1	0.1	-	0.36	1.19E-08	-9.45	1.2E-09	-	*
KFR121	208.7	1	0.1	4.92E-08	0.37	6.61E-07	-9.44	6.2E-08	1.2	
KFR121	210.0	1	0.1	-	0.39	7.86E-08	-9.41	7.9E-09	-	*
KFR121	210.6	1	0.1	-	0.39	1.28E-07	-9.42	1.3E-08	-	*
KFR121	211.2	1	0.1	2.39E-08	0.41	1.86E-07	-9.40	1.6E-08	1.9	#
KFR121	212.0	1	0.1	-	0.41	4.56E-08	-9.41	4.6E-09	-	*
KFR121	215.0	1	0.1	-	0.43	4.94E-08	-9.38	5.0E-09	-	
KFR121	216.7	1	0.1	-	0.44	1.52E-07	-9.36	1.5E-08	-	
KFR121	217.1	1	0.1	-	0.44	6.53E-08	-9.37	6.6E-09	-	
KFR121	221.7	1	0.1	-	0.48	4.72E-08	-9.32	4.8E-09	-	
KFR121	225.5	1	0.1	-	0.51	1.55E-07	-9.31	1.6E-08	-	
KFR121	226.8	1	0.1	-	0.53	6.56E-08	-9.31	6.6E-09	-	*
KFR121	227.1	1	0.1	-	0.52	1.56E-07	-9.32	1.6E-08	-	
KFR121	228.7	1	0.1	-	0.54	2.67E-08	-9.29	2.7E-09	-	*
KFR121	232.1	1	0.1	-	0.58	1.08E-07	-9.29	1.1E-08	-	#
KFR121	233.6	1	0.1	-	0.59	1.39E-08	-9.28	1.4E-09	-	*,#

Appendix KFR121.6.3

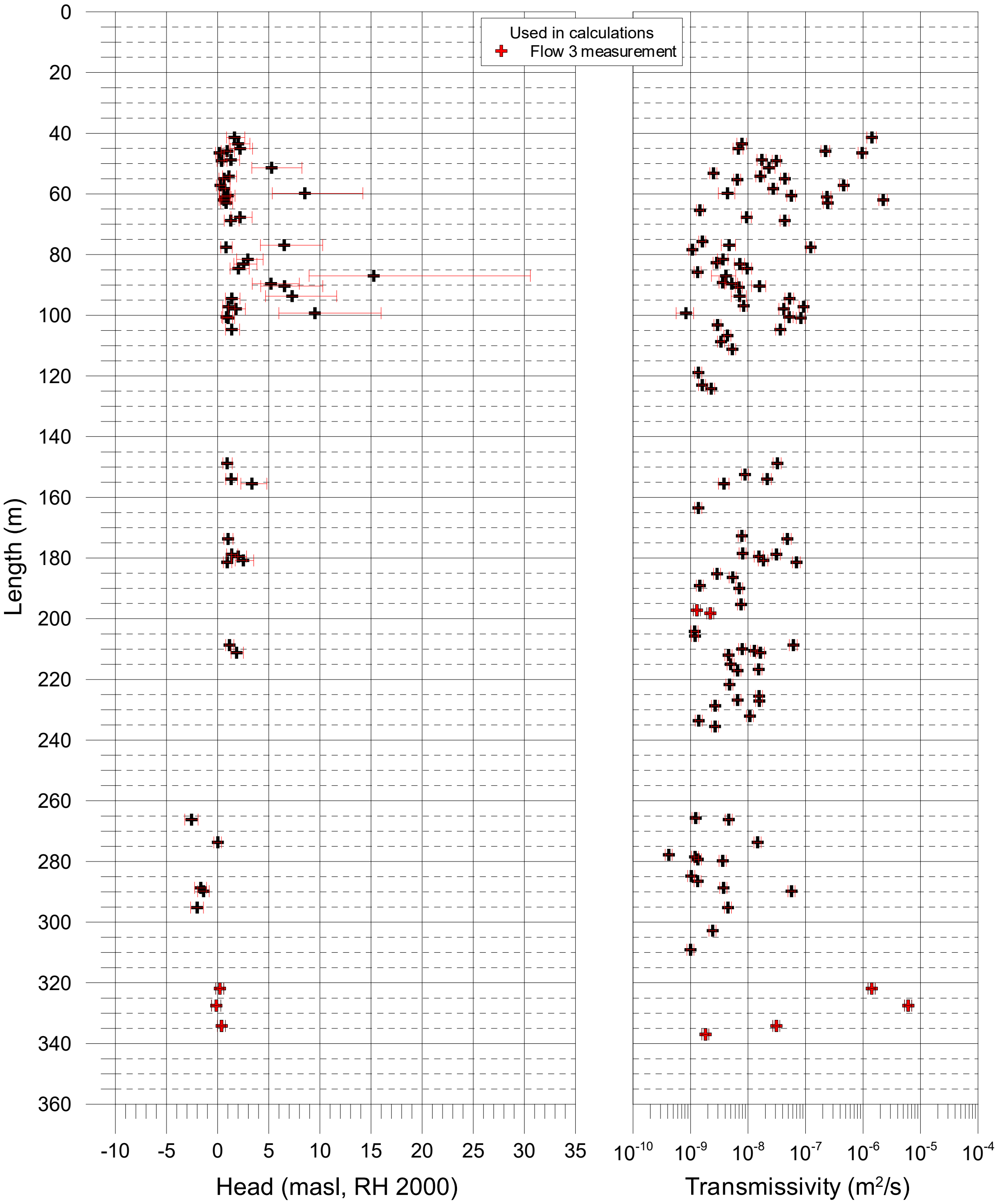
Borehole ID	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_0 (m^3/s)	h_{0FW} (masl)	Q_1 (m^3/s)	h_{1FW} (masl)	T_D (m^2/s)	h_i (masl)	Comments
KFR121	235.5	1	0.1	-	0.61	2.67E-08	-9.27	2.7E-09	-	#
KFR121	265.7	1	0.1	-	0.86	1.22E-08	-8.99	1.2E-09	-	*
KFR121	266.2	1	0.1	-1.61E-08	0.90	3.00E-08	-8.97	4.6E-09	-2.6	#
KFR121	273.7	1	0.1	-1.39E-08	0.95	1.33E-07	-8.95	1.5E-08	0.0	#
KFR121	277.8	1	0.1	-	0.91	4.17E-09	-8.91	4.2E-10	-	*
KFR121	278.5	1	0.1	-	0.92	1.19E-08	-8.89	1.2E-09	-	*
KFR121	279.3	1	0.1	-	0.92	1.33E-08	-8.90	1.3E-09	-	*
KFR121	279.8	1	0.1	-	0.93	3.61E-08	-8.90	3.6E-09	-	
KFR121	284.8	1	0.1	-	0.96	1.03E-08	-8.88	1.0E-09	-	
KFR121	286.5	1	0.1	-	1.04	1.33E-08	-8.85	1.3E-09	-	
KFR121	288.7	1	0.1	-1.00E-08	0.99	2.72E-08	-8.84	3.8E-09	-1.7	
KFR121	289.8	1	0.1	-1.37E-07	0.99	4.31E-07	-8.83	5.7E-08	-1.4	
KFR121	295.2	1	0.1	-1.42E-08	1.12	3.08E-08	-8.79	4.5E-09	-2.0	#
KFR121	302.8	1	0.1	-	1.14	2.42E-08	-8.71	2.4E-09	-	
KFR121	309.1	1	0.1	-	1.24	1.00E-08	-8.64	1.0E-09	-	*,#
KFR121	321.9	5	0.5	-1.59E-06	1.33	1.25E-05	-8.48	1.4E-06	0.2	#,##
KFR121	327.5	5	0.5	-9.31E-06	1.38	4.81E-05	-7.91	6.1E-06	-0.1	#,##
KFR121	334.2	5	0.5	-3.28E-08	1.43	2.78E-07	-8.40	3.1E-08	0.4	#,##
KFR121	337.0	5	0.5	-	1.45	1.81E-08	-8.39	1.8E-09	-	#,##

*	Uncertain = The flow rate is less than 30 mL/h or the flow anomalies are overlapping or they are unclear because of noise.
**	Flow (Q_0 and Q_1) possibly from the joint of casing tube and borehole.
***	Calculation for T_D and h_i resulted in unrealistic figures. See Section 6.4.3 for details.
#	Values for Flow (Q_0) and Head (h_{0FW}) are from Flow 1 measurement.
##	Values for Flow (Q_1) and Head (h_{1FW}) are from Flow 3 measurement.

Forsmark, borehole KFR121
Transmissivity and head of detected fractures

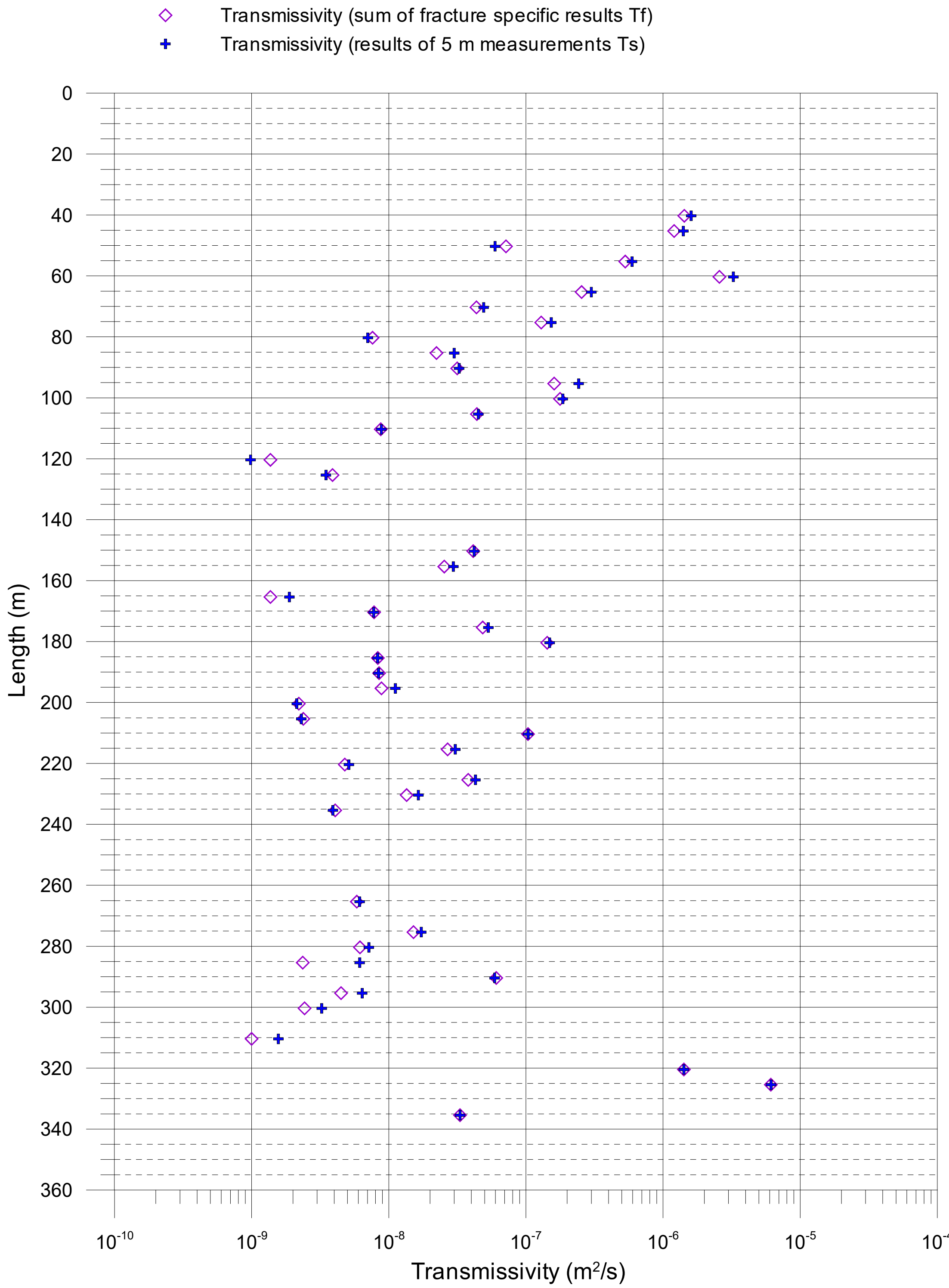


Forsmark, borehole KFR121
Transmissivity and head of fractures
Error bars assuming ±10% errors in flow rates
and ±0.2 m in head in worst-case combination



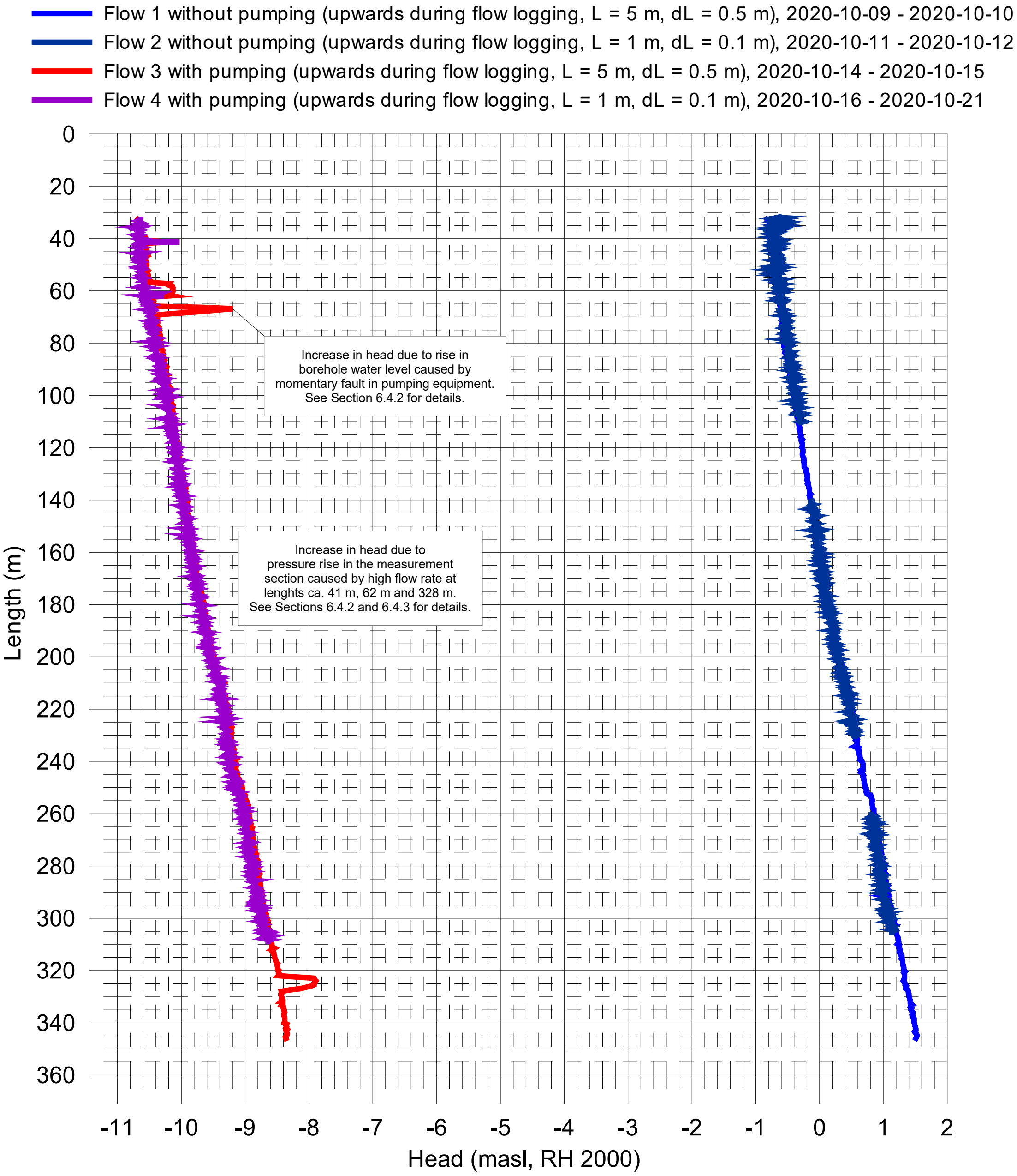
Appendix KFR121.8

Forsmark, borehole KFR121
Comparison between section transmissivity and fracture transmissivity

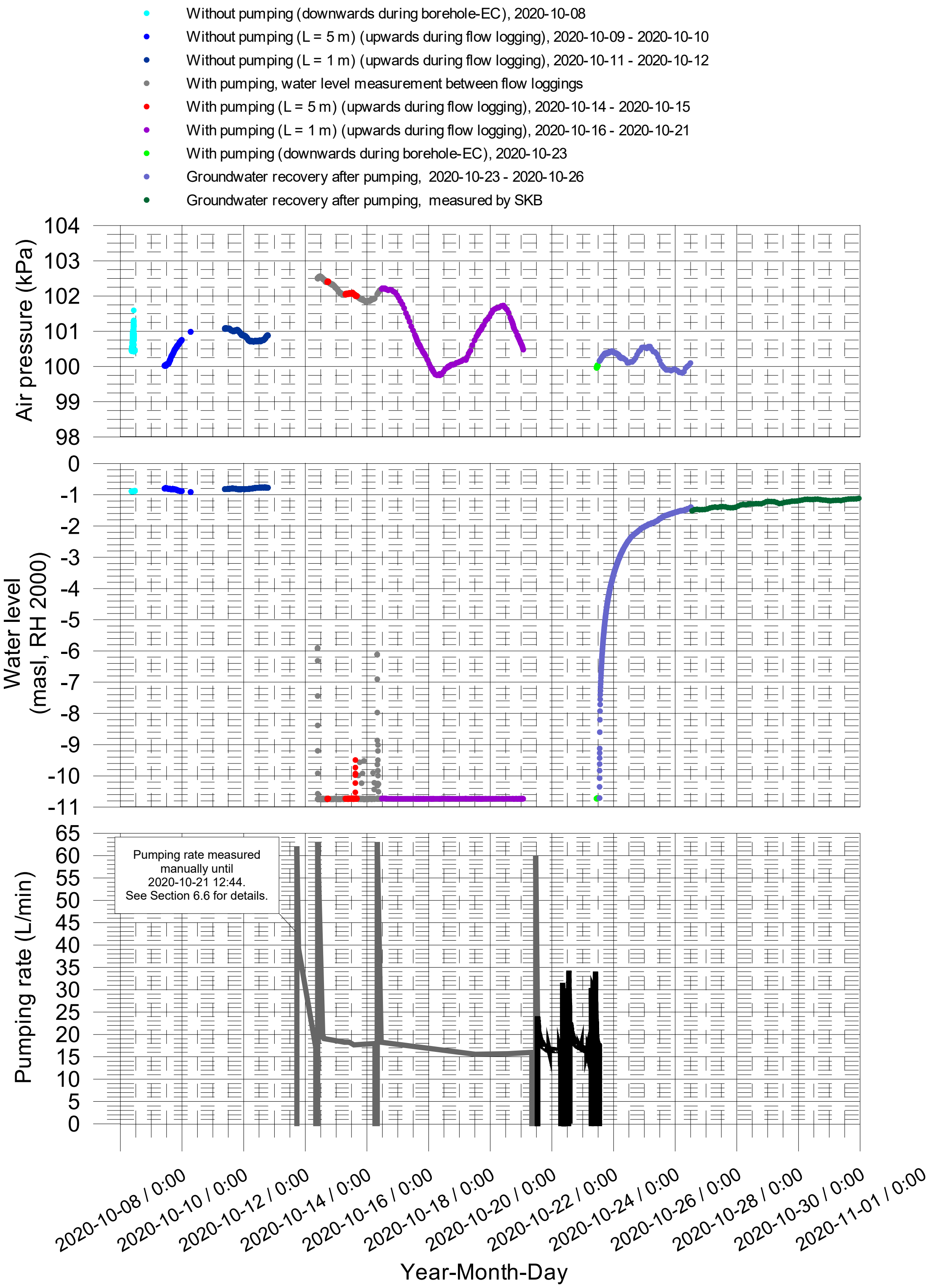


Forsmark, borehole KFR121
Head in the borehole during flow logging

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

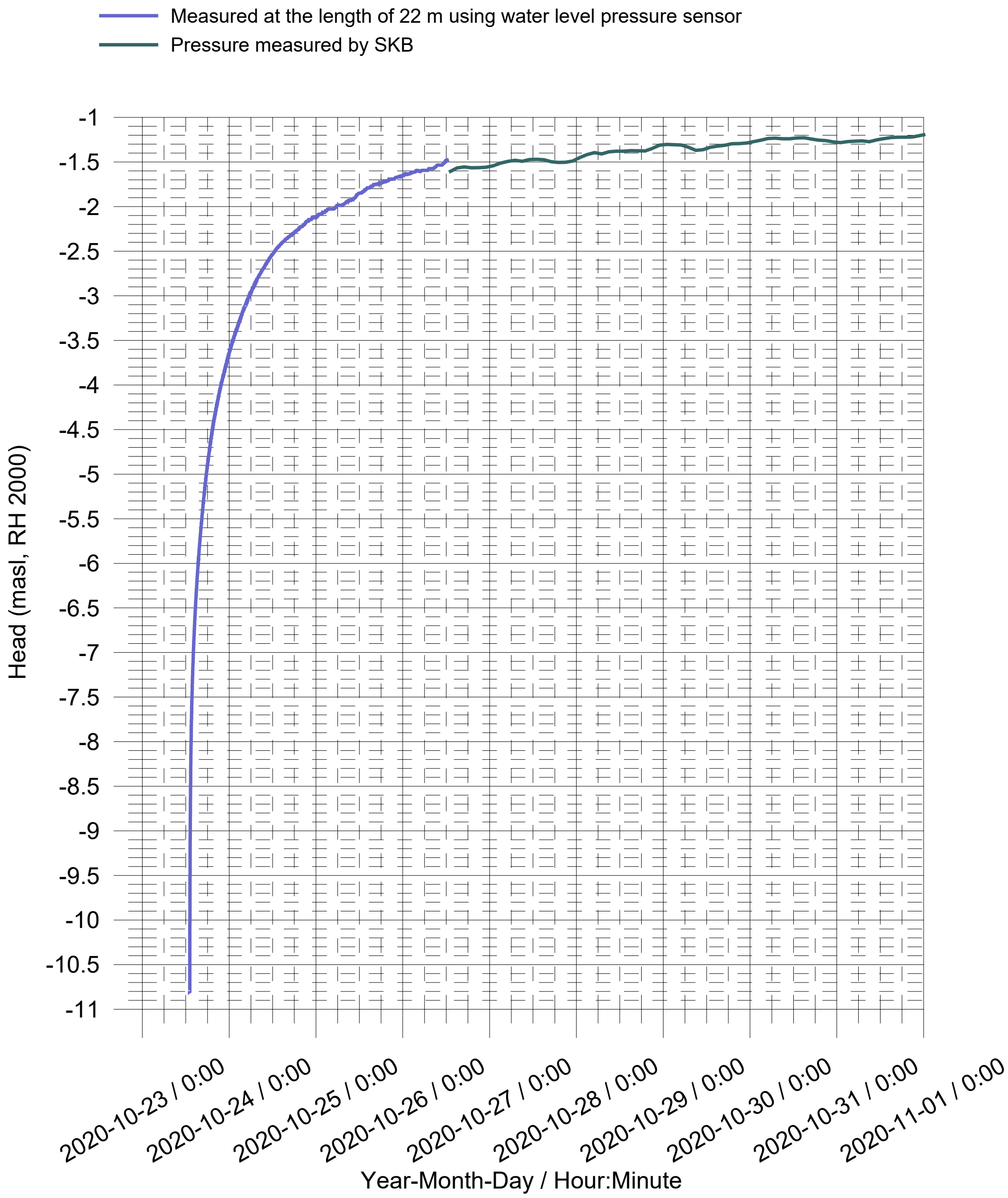


Forsmark, borehole KFR121
Air pressure, water level in the borehole and pumping rate during flow logging

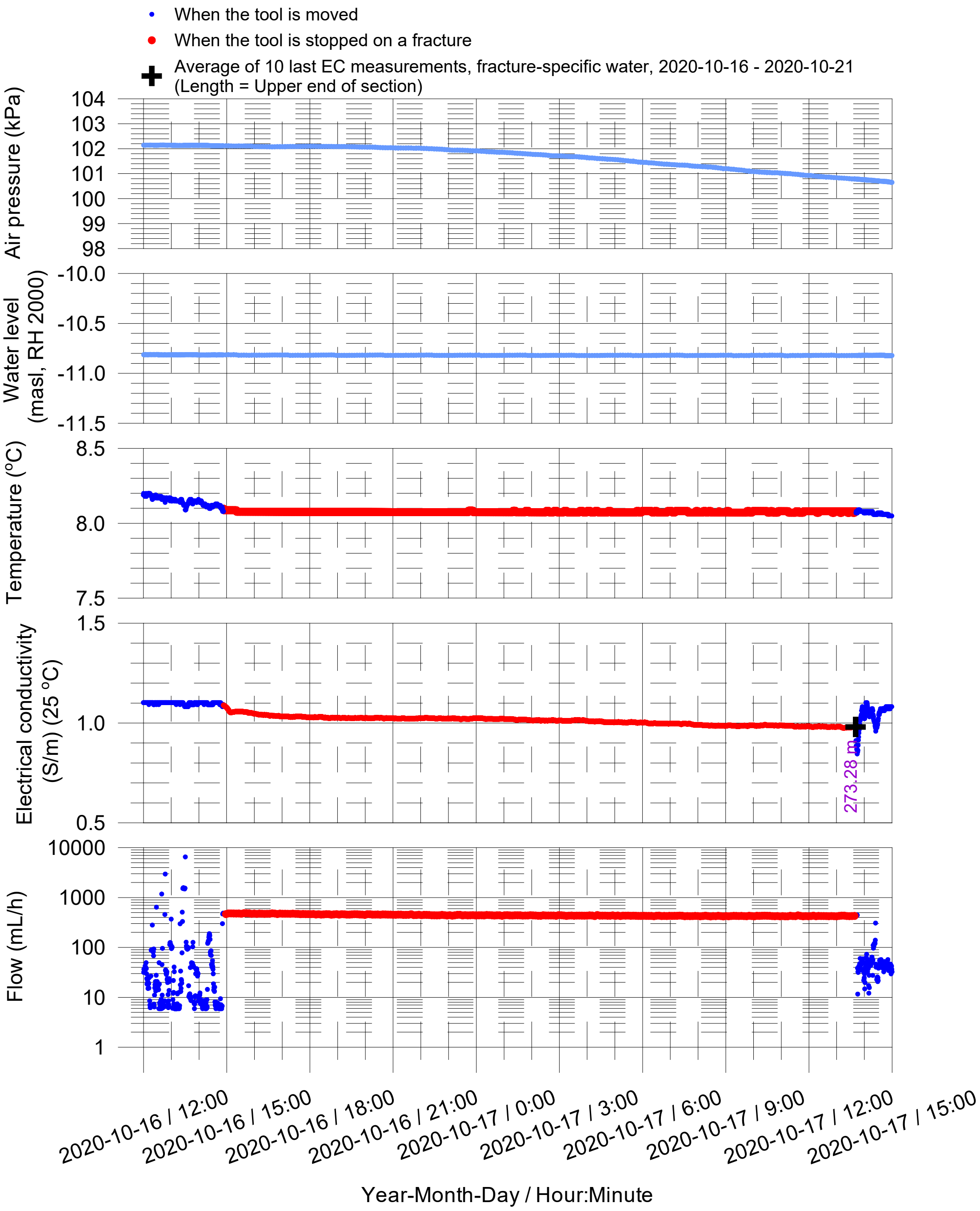


Appendix KFR121.9.3

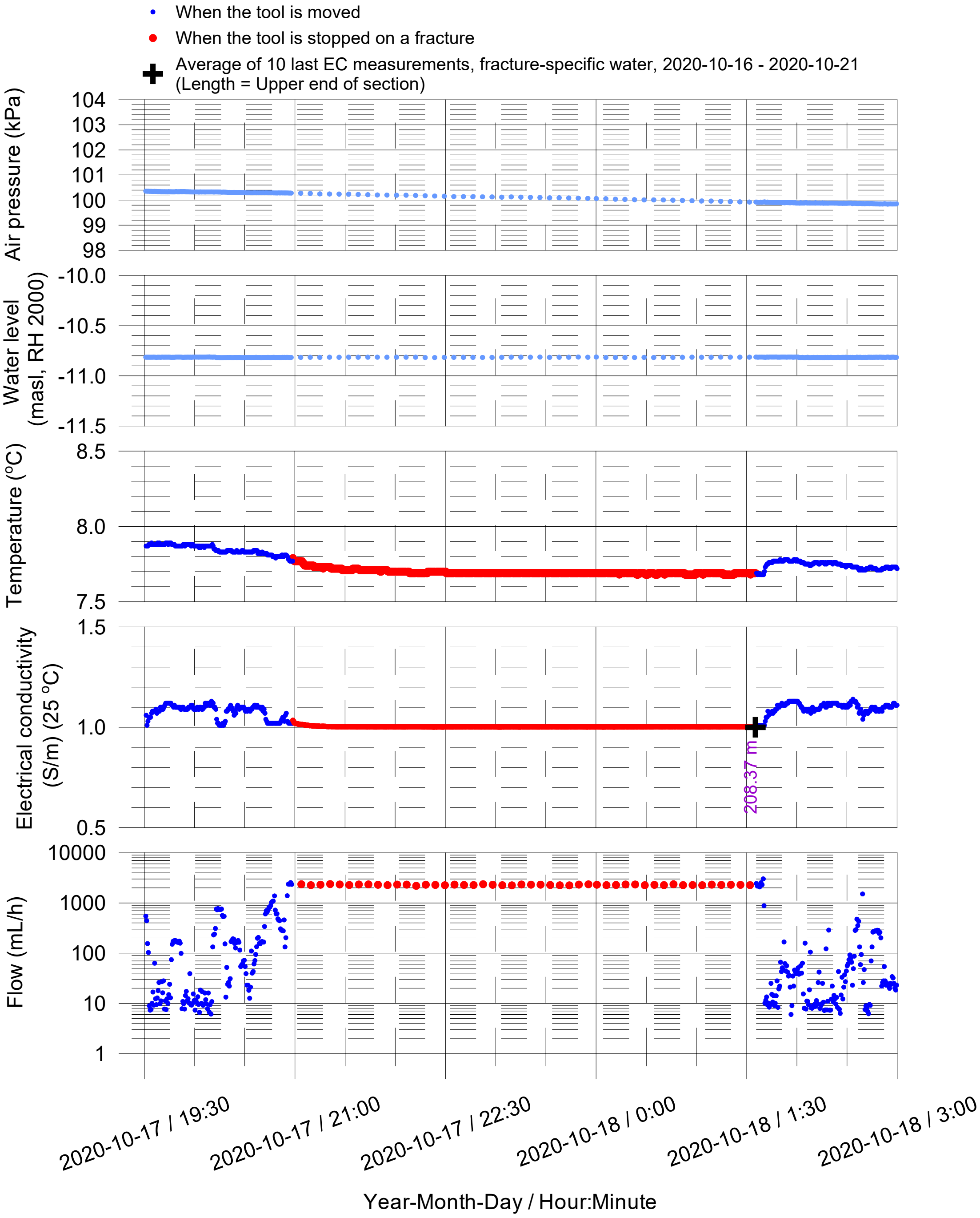
Forsmark, borehole KFR121
Groundwater recovery after pumping



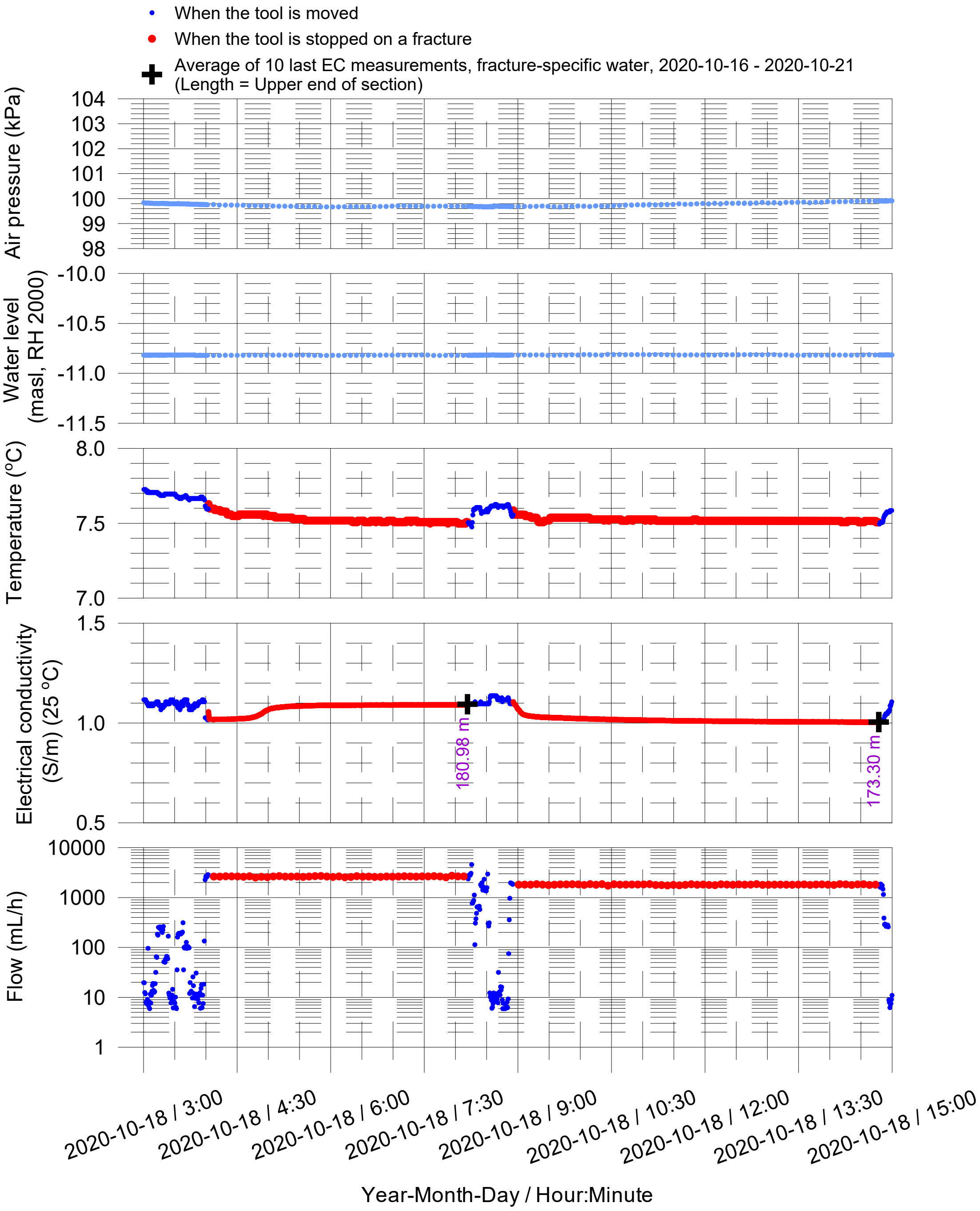
Forsmark, borehole KFR121
Fracture-specific Flow, EC and Temperature results by date
Water level and Air pressure results by date



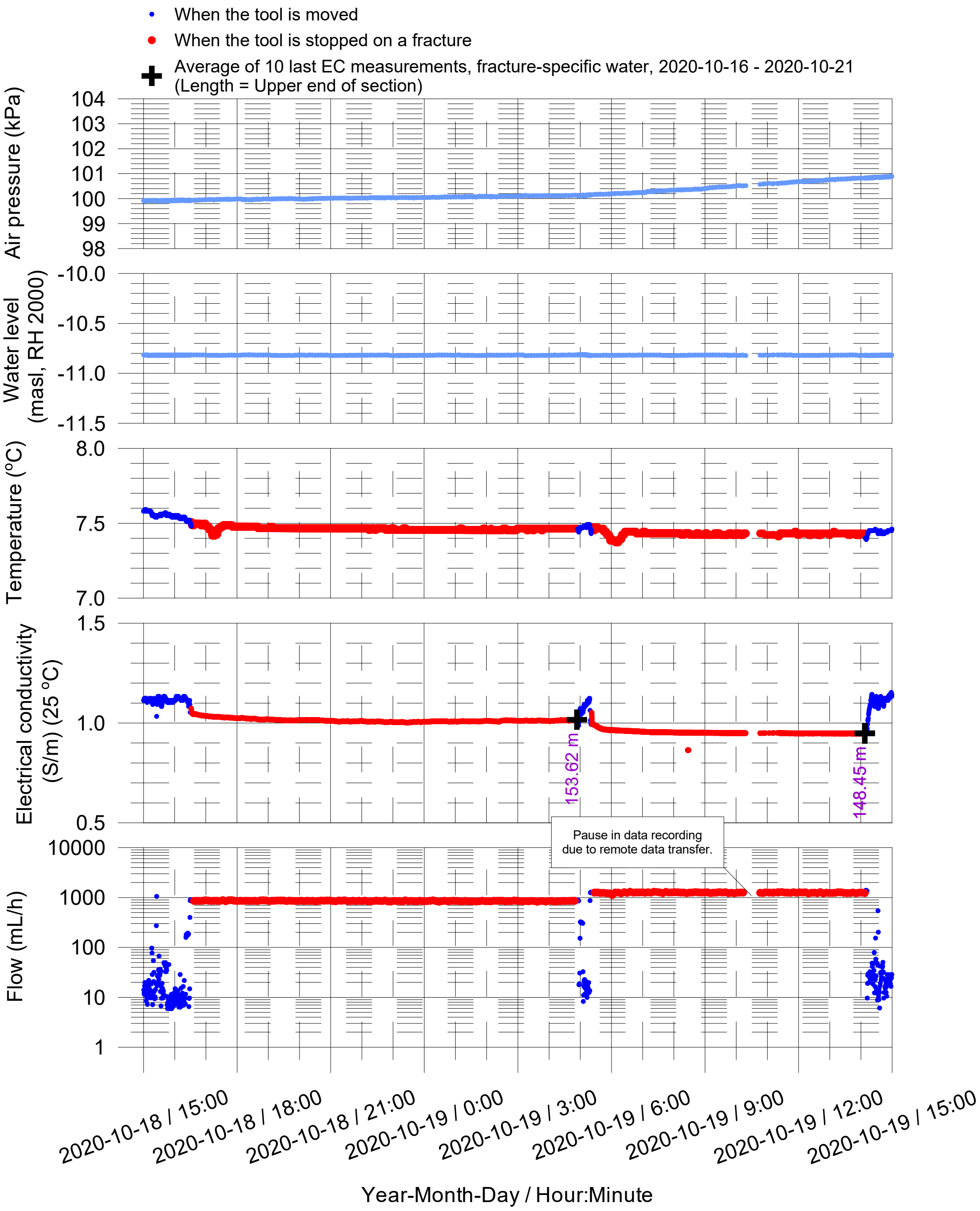
Forsmark, borehole KFR121
Fracture-specific Flow, EC and Temperature results by date
Water level and Air pressure results by date



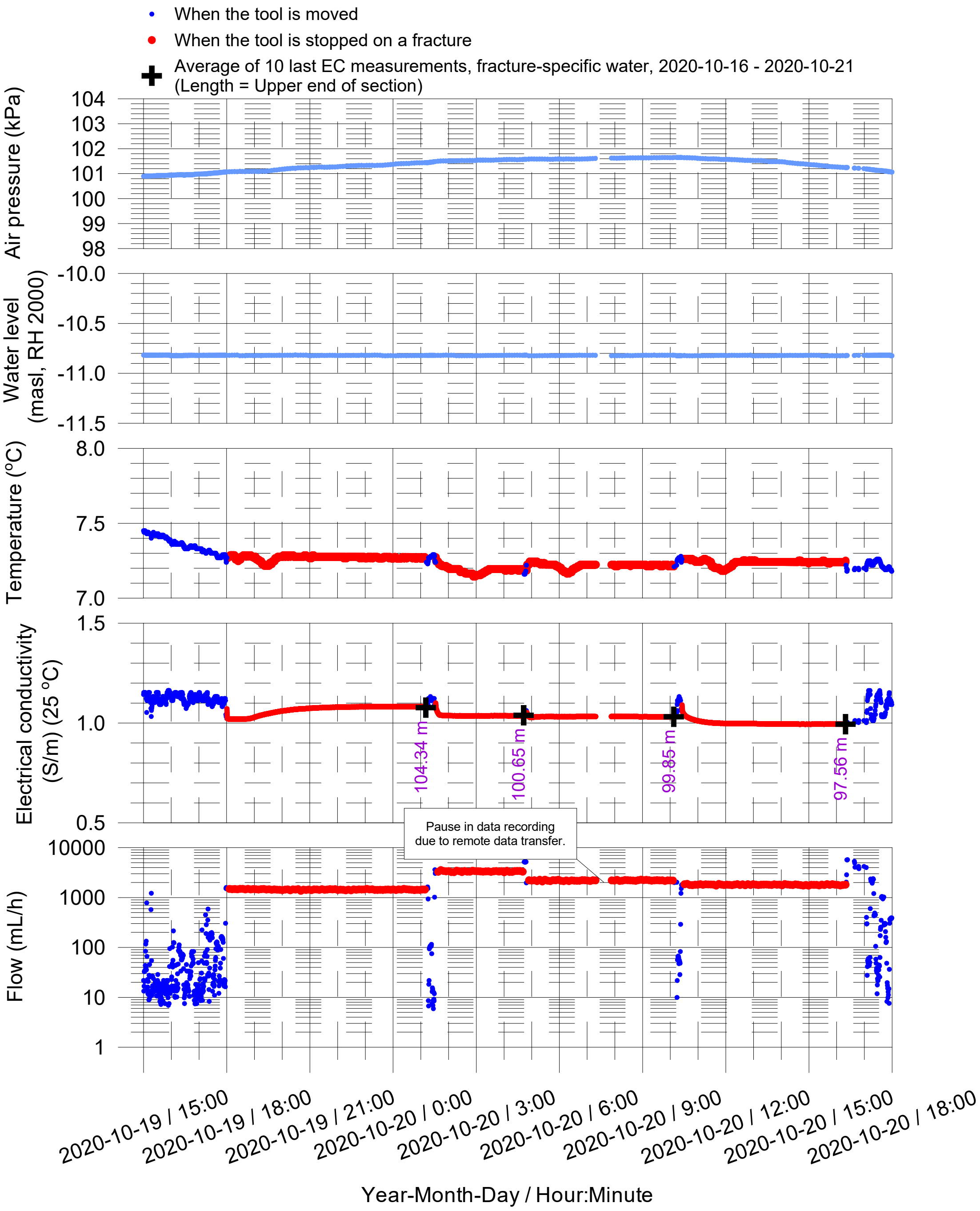
Forsmark, borehole KFR121
Fracture-specific Flow, EC and Temperature results by date
Water level and Air pressure results by date



Forsmark, borehole KFR121
Fracture-specific Flow, EC and Temperature results by date
Water level and Air pressure results by date

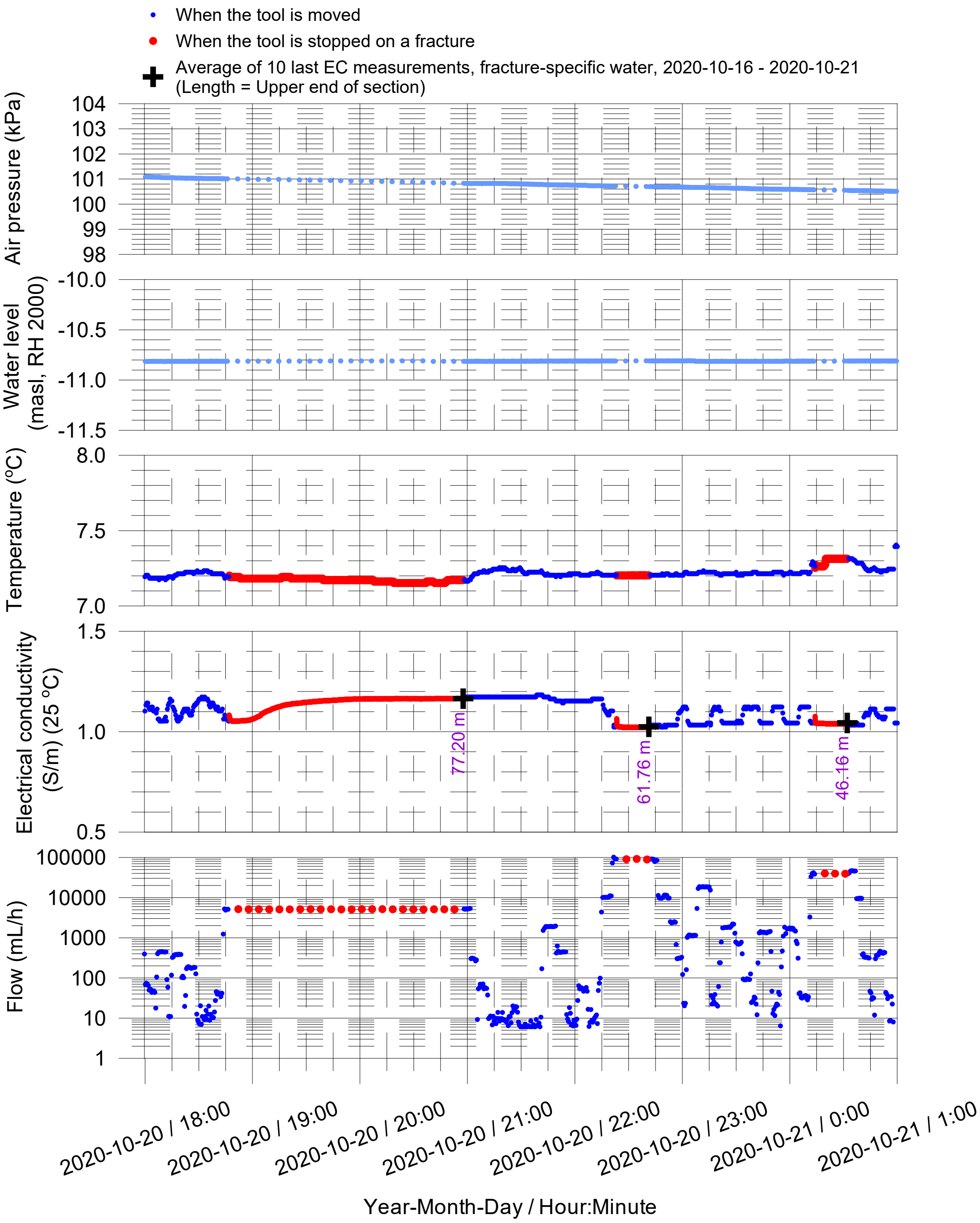


Forsmark, borehole KFR121
Fracture-specific Flow, EC and Temperature results by date
Water level and Air pressure results by date

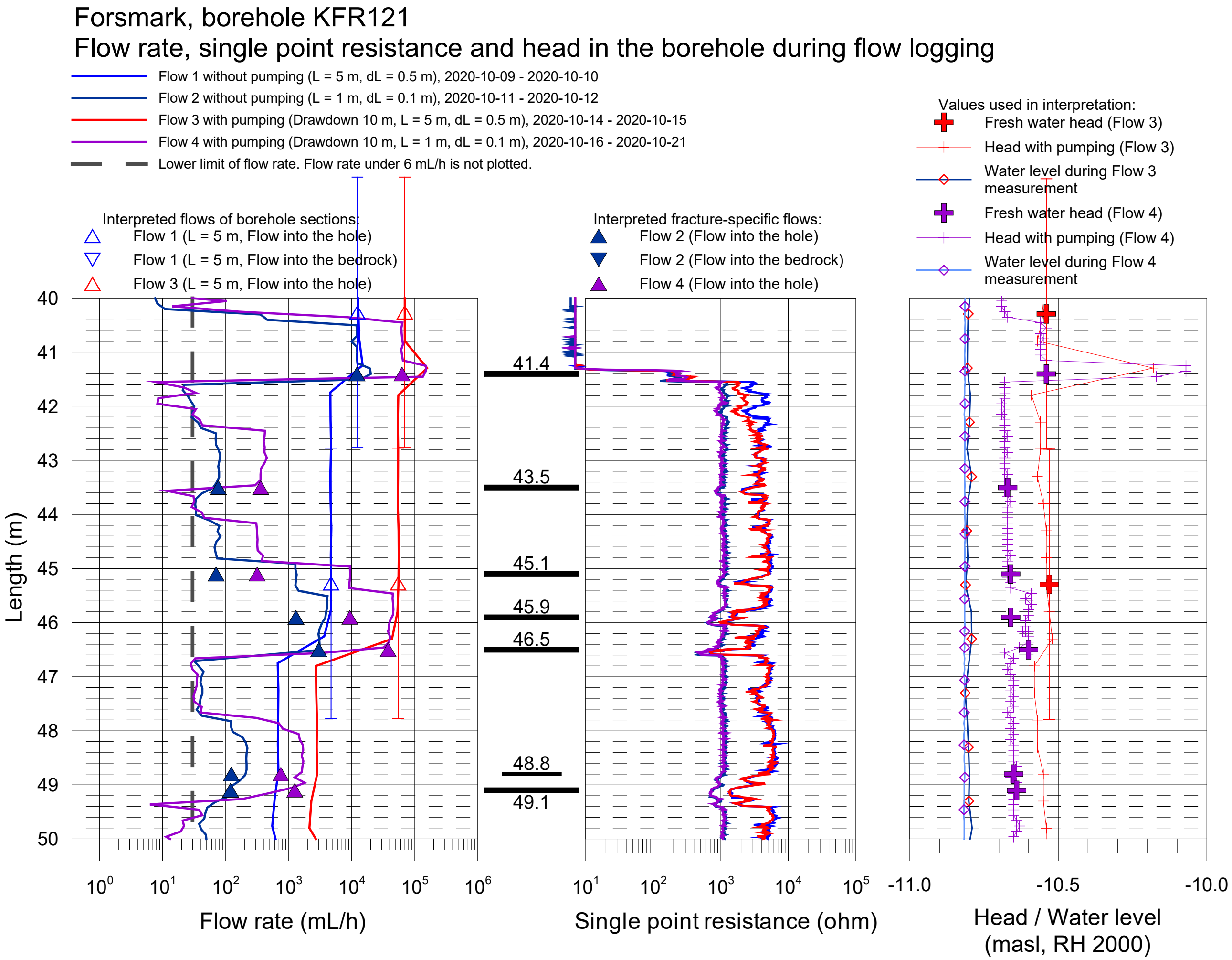


Appendix KFR121.10.6

Forsmark, borehole KFR121
Fracture-specific Flow, EC and Temperature results by date
Water level and Air pressure results by date

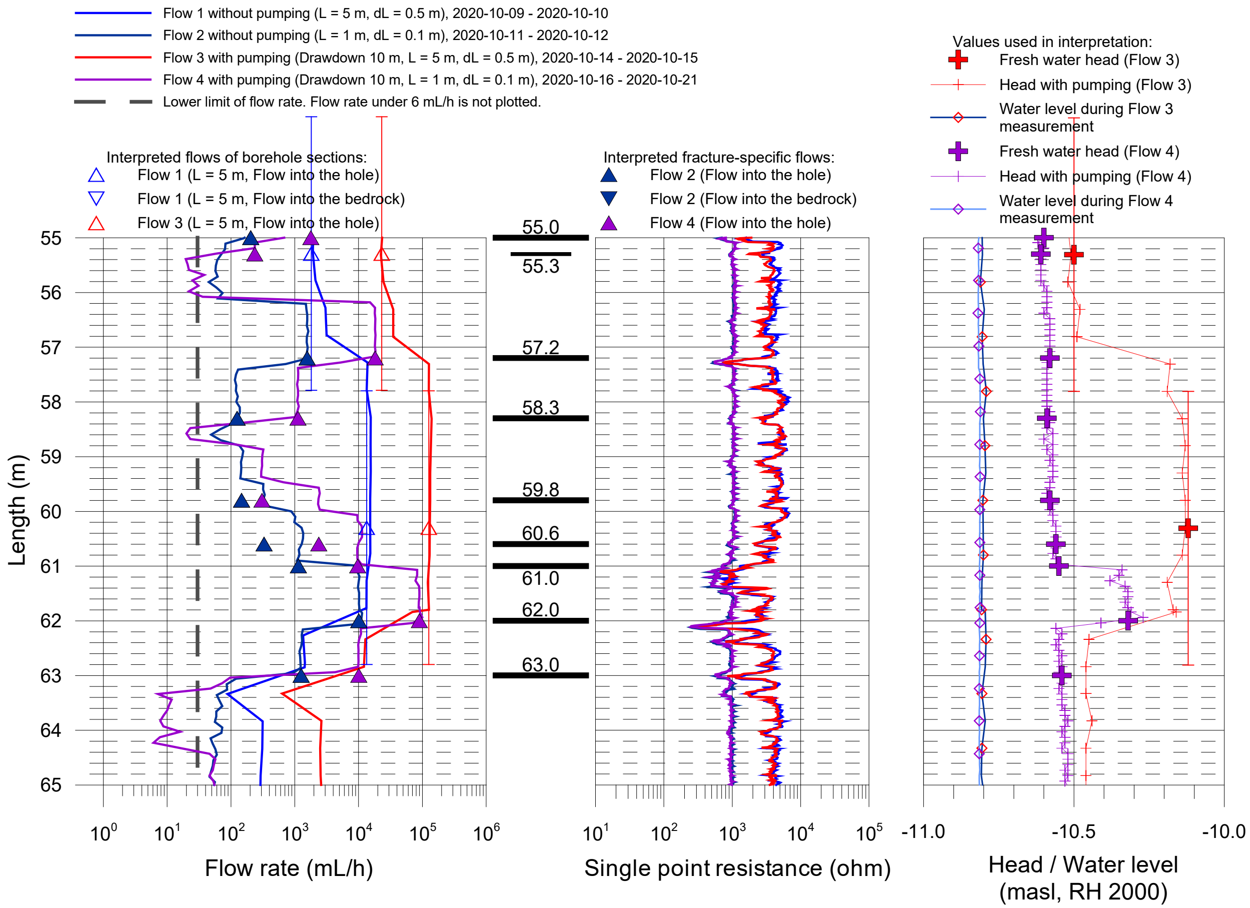


Appendix KFR121.11.1

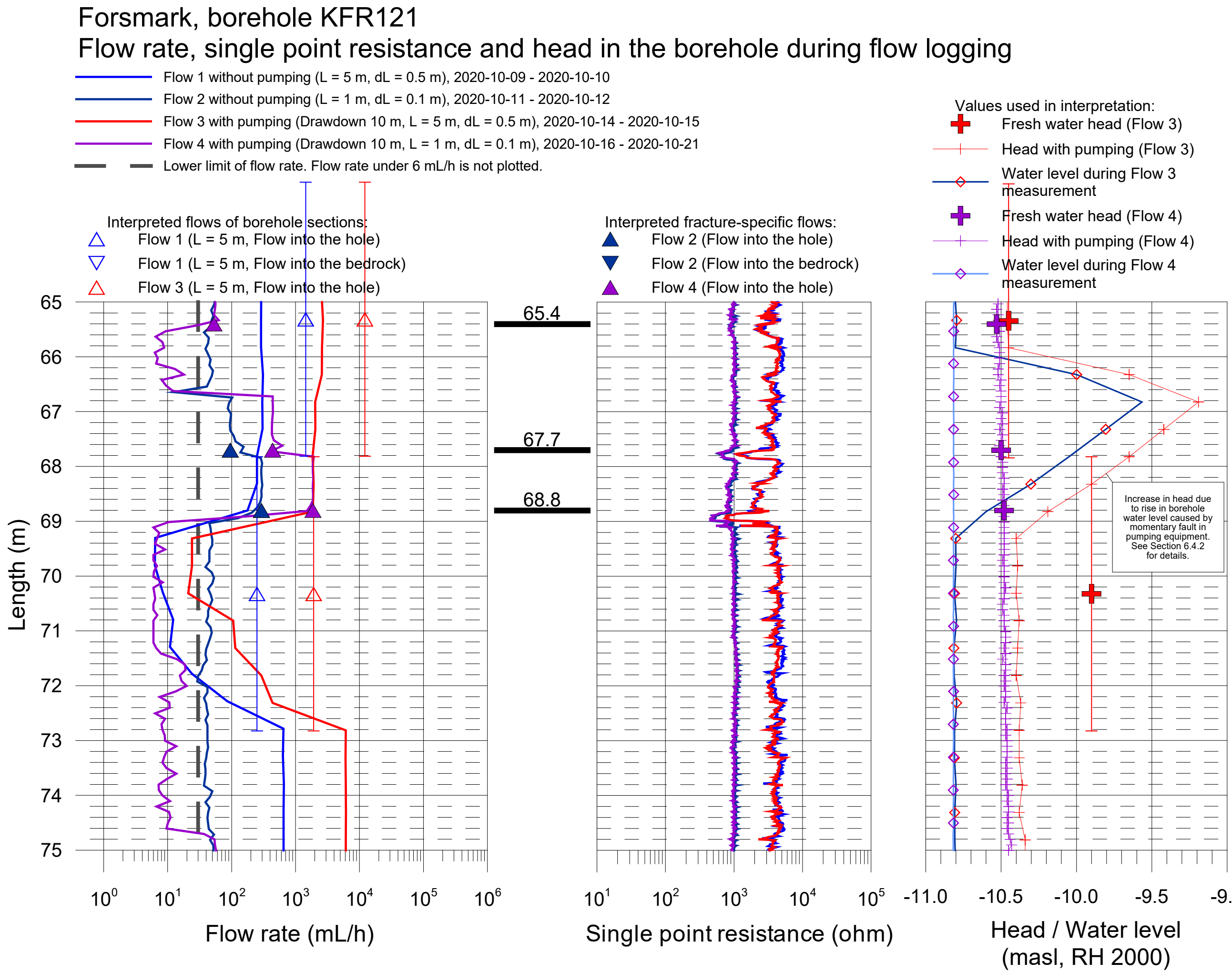


Appendix KFR121.11.2

Forsmark, borehole KFR121
Flow rate, single point resistance and head in the borehole during flow logging



Appendix KFR121.11.3



Appendix KFR121.11.4