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Difference flow logging in boreholes KFR90 and KFR91

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Abstract

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 in fractures/fractured zones in cored boreholes. This report presents the main principles of the method as well as the results of measurements carried out in underground boreholes KFR90 and KFR91 at SFR (the repository for low- and intermediate level radioactive waste) in Forsmark, Sweden, in October 2023.

The flow logging measurements were done with 0.5 m measurement section and by moving the measurement tool in 0.1 m steps. This method was used to flow log the entire measurable parts of the two boreholes. Both boreholes were partially sealed at the collar during the measurements to obtain the desired pressure drawdown in each borehole. Pressure in the borehole was controlled by a valve and a pressure-controlled pump. The flow measurements were carried out at two different pressure drawdowns in the boreholes.

The boreholes were closed using a borehole sealing mechanism, which enables controlling borehole pressure with a measurement cable in the borehole. The outflow from the borehole was measured when the borehole was partially closed during the measurements.

The electrical conductivity (EC) and temperature of borehole water were also measured. The EC measurements were used to study the occurrence of saline water in the boreholes.

Contents

1 Introduction

The cored boreholes KFR90 and KFR91 at Forsmark, Sweden, were measured using the Posiva Flow Log, Difference Flow Method (PFL DIFF) which provides a swift, multifaceted characterization of a borehole. The measurements were conducted between October 12 and November 1, 2023. As illustrated in Figure 1-1 the boreholes are located in one of the access tunnels (Building tunnel) of SFR (the repository for low- and intermediate level radioactive waste).

KFR90 is 450.15 m long, and its reference point is Z = -86.39 m with a -4.5^{o} (*downward*) inclination from the horizontal plane. KFR91 is 340.11 m long, and its reference point is Z = -80.01 m with a -5.22^{o} (downward) inclination from the horizontal plane. All z-coordinates and head values in the borehole and calculated heads in the formation or in fractures are given in the RH 2000 system. The boreholes are cased from length 0 to borehole length 2.37 m in KFR90 and to borehole length 2.34 m in KFR91 (rock surface being the reference level (length 0) for length measurements). The inner diameter of the casing tube is 80 mm in both boreholes. The rest of the boreholes is core drilled with a diameter of ca. 75.8 mm.

This document reports the results acquired with PFL DIFF in boreholes KFR90 and KFR91. Measurements and results presented in this report were undertaken regarding the investigations linked to the planned extension of SFR.

The measurements were carried out in accordance with SKB's internal controlling document AP SFK-23-009. The controlling documents for this Activity Plan are listed in Tabell 1-1. 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 SKB's site characterization database SICADA and are traceable by the Activity Plan number.

Tabell 1-1 SKB's internal controlling documents for the activities concerning this report.

Tableity Plan	**Number**	**Version**
Difference flow logging in boreholes KFR90 and KFR91	AP SFK-23-009	1.0
Method Descriptions	**Number**	**Version**
Method Description for difference flow logging in tunnel boreholes	SKB MD 322.014e	1.0
Instructions for cleaning borehole equipment and certain surface equipment	SKB MD 600.004e	3.0

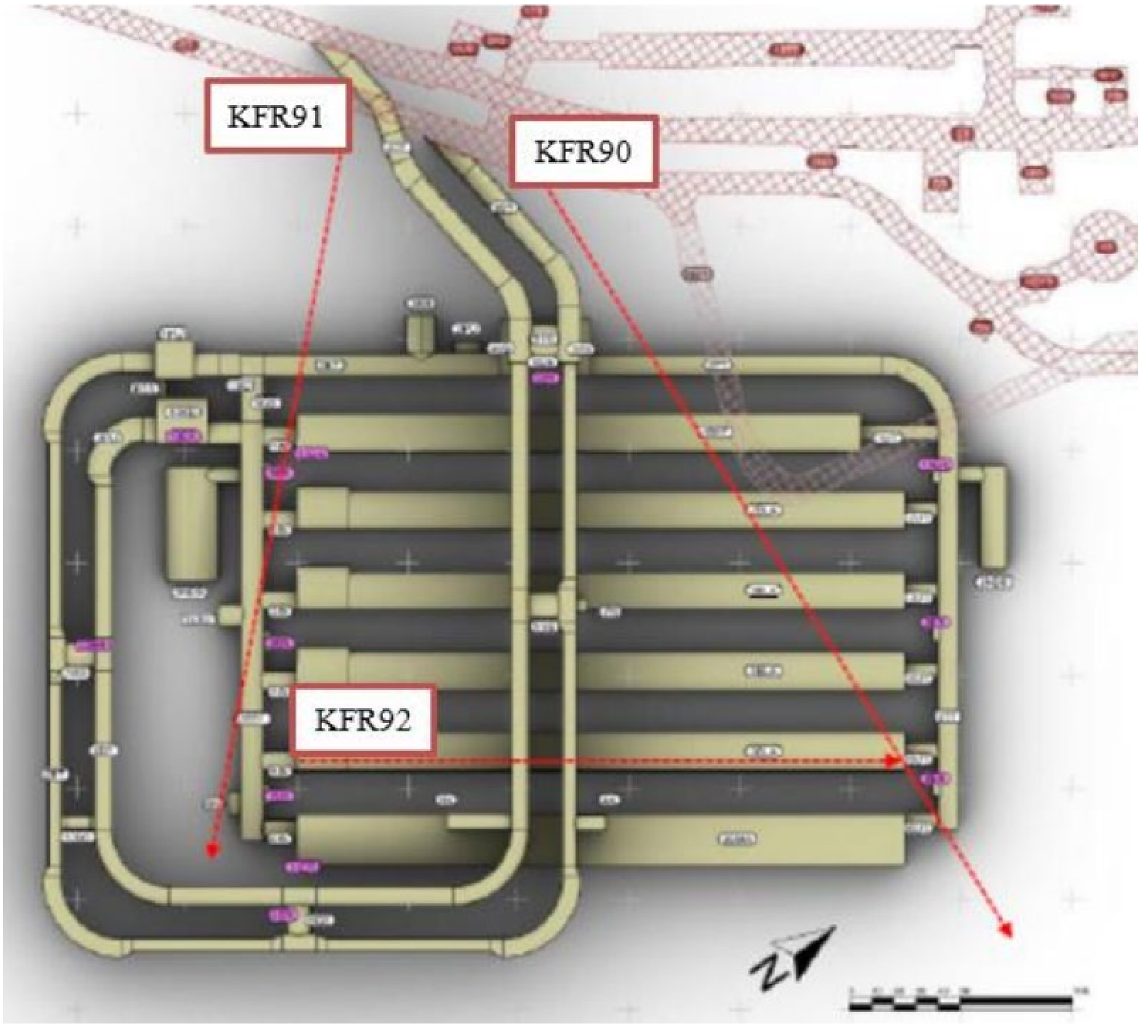

Figure 1-1 Locations and drilling directions of boreholes KFR90 and KFR91 in one of the SFR access tunnels. The hatched area is the existing tunnel system, and the green area is the extended tunnel system to be constructed. KFR92 is a planned borehole.

2 Objective and scope

The main objective of the PFL DIFF measurements in boreholes KFR90 and KFR91 was to characterize the rock with respect to its hydraulic properties, i.e. location of conductive fractures/zones and their transmissivity.

Besides difference flow logging, the measurement programme also included supporting measurements. These included measurements of the electrical conductivity (*EC*) and the temperature of the borehole fluid as well as the single-point resistance (*SPR*) of the borehole wall. The flow measurements and the single-point resistance measurements can be used to locate flowing fractures and for length synchronization with other methods. Furthermore, the flow rate out from the partially closed borehole, at the top of the casing tube, was recorded. This flow contains both non-intended leakages pass the sealing and intended flow through the control valve.

In conjunction with flow measurements, absolute pressure along the borehole was measured with an absolute pressure sensor. The freshwater head along the borehole is derived from the pressure measurements. The flow and pressure measurements in two different pressure conditions are used for calculation of hydraulic head and transmissivity along each borehole.

3 Principles of measurement and interpretation

3.1 Measurements

The employed Posiva Flow Log (PFL) device is developed, owned and operated by Posiva Oy. 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. The advantage that follows from measuring the flow rate in isolated sections is improved detection of individual fracture flows. As these are generally very small, they can easily be missed when using conventional flowmeters. A technical illustration of the PFL DIFF probe is presented in Figure 3-1.

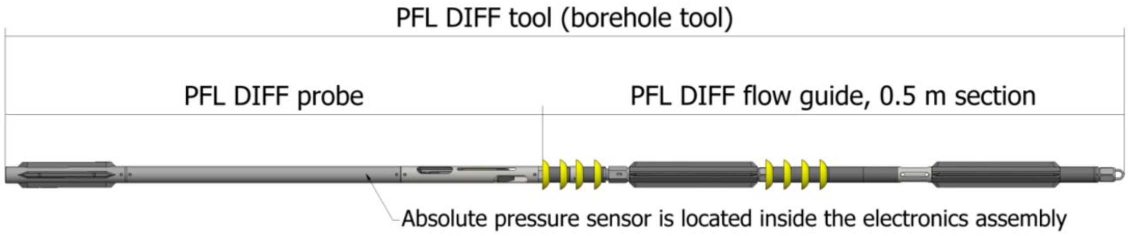

Figure 3-1 *Technical illustration of the PFL DIFF probe with 0.5 m measurement section length.*

Rubber sealing disks located at the top and bottom of the measurement section are used to separate the flow of water in the measurement section from the flow in the rest of the borehole, see Figure 3-3 Flow inside the measurement section is directed through the flow sensor. Flow along the borehole is directed around the measurement 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.

In tunnel boreholes two separate measurement rounds are conducted with two pressure drawdowns Both measurement rounds are conducted with 0.5 m measurement section length and 0.1 m measurement interval. Measurement under larger pressure drawdown is conducted first to detect more flowing fractures. The second measurement run, with a smaller pressure drawdown than that of the first round, can optionally be conducted only at length intervals where flowing fractures were detected in the first round. In general, no additional fractures should be detected during the second measurement run. However, if there are fracture outflows from the borehole to the bedrock this is possible. Therefore, it is generally advised to conduct also the second measurement round in the entire borehole, even though there would be long borehole intervals where fractures were not detected during the first measurement run. In the tests of KFR90 and KFR91, both measurement runs covered the entire boreholes.

For calculation of flow rates into or out of the measurement section, thermistors are monitored to track both the dilution (cooling) of an introduced thermal pulse and its transfer by way of the moving water (Öhberg and Rouhiainen 2000). The flow rates are calculated based on thermal dilution, whereas flow directions are interpreted based on thermal pulse movement. Raw data for both calculations is gathered at each measurement point.

In addition to incremental changes in flow, the PFL DIFF probe can also be used to measure the following:The electrical conductivity (*EC*) of both borehole water and fracture-specific water. The electrode used for EC measurements is located at the top of the flow sensor, see Figure 3-2.

- The single-point resistance (*SPR*) of the borehole wall (*grounding resistance*). The electrode used for SPR measurements is located between the uppermost rubber sealing disks, see Figure 3-2, and is used for the high-resolution length determination of fractures and geological structures.
- The prevailing water-pressure profile in the borehole. Located inside the watertight electronics assembly, the pressure sensor (*transducer*) is connected to the measurement section through a tube.
- The temperature of the water in the borehole. The temperature sensor is part of the flow sensor.

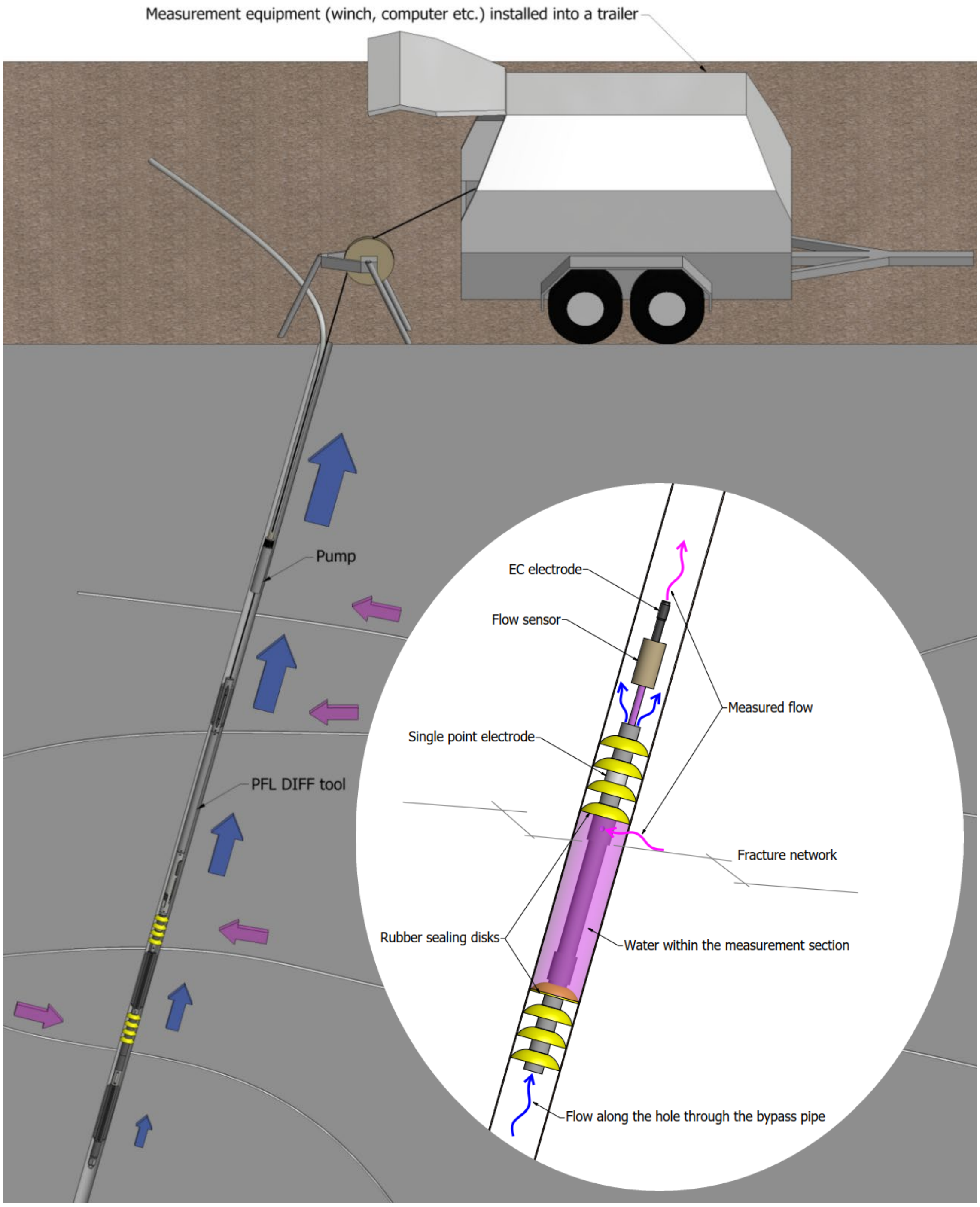

***Figure 3-2** Schematic of the PFL DIFF probe used in a ground-level borehole. In a sub-horizontal tunnel borehole, the probe operation is similar; only the borehole pressure is controlled with a borehole sealing mechanism instead of a submersible pump.*

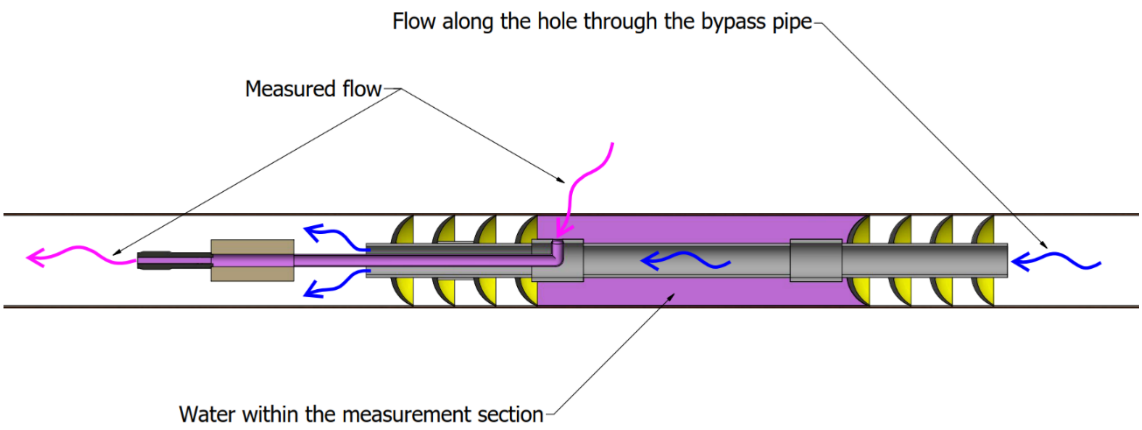

Figure 3-3 *Schematic of a cross-section of the PFL DIFF probe.*

The flow rate measurement range of the flow sensors is 30 –300 000 mL/h. The lower limit of the measurement range is the typical minimum value that can be measured. Depending on conditions in the borehole, these flow limits may not always be valid. Examples of possible disturbances are drilling debris entrained in the borehole water, bubbles of gas in the water and high flow rates (*some 30 L/min, i.e., 1 800 000 mL/h or more*) along the borehole. If the disturbances encountered are significant, practical measurement limits are calculated for each set of data. On the other hand, as low flow values as 6 mL/h (*calibration limit*) can be measured if measurement conditions are perfect.

The length reference point of the PFL DIFF is situated at the upper end of the measurement section.

3.2 Interpretation

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

$$h - h_{r0} = \frac{Q}{T \cdot a} \tag{3-1}$$

where

- h_{r0} is the hydraulic head in the borehole (*at borehole radius r_0*),
- h 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, and
- the constant *a* depends on the assumed flow geometry. For cylindrical flow, the constant *a* is:

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

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) and the transmissivity of the borehole sections tested can be calculated. Equation 3-1 can be reformulated in the following two ways:

$$\boldsymbol{Q_1 = T \cdot a \cdot (h - h_{r0,1})} \tag{3-3}$$

$$\boldsymbol{Q_2 = T \cdot a \cdot (h - h_{r0,2})} \tag{3-4}$$

where

- $h_{r0,1}$ and $h_{r0,2}$ are the hydraulic heads in the borehole at the test levels,
- Q_1 and Q_2 are the measured flow rates in the measurement section,
- T is the transmissivity of the measurement section and
- h 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 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 $R/r_0 = 500$ implies that $a \approx 1$.

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

$$\boldsymbol{h = \frac{h_{r0,1} - bh_{r0,2}}{1 - b}} \tag{3-5}$$

$$\boldsymbol{T_{PFL} = \frac{1}{a}\frac{Q_1 - Q_2}{h_{r0,2} - h_{r0,1}}} \tag{3-6}$$

where

- $b = Q_1/Q_2$
- Q_1 and Q_2 are the flow rates at a given fracture, and
- h and T_{PFL} are the hydraulic head (*far away from borehole*) and transmissivity of the 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 $\Delta Q/\Delta h$, 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-conductive 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 stated otherwise.

4 Equipment specification

In the PFL DIFF Method, the flow of groundwater into or out of a defined borehole section is monitored using a flow guide that employs rubber sealing disks to separate section flow from the flow along the borehole. This flow guide defines the measurement section being measured without altering the hydraulic head. Groundwater flowing into or out of the measurement section is guided to the flow sensor, and flow is measured using the thermal pulse and thermal dilution methods, as described in Chapter 3. 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 (probe ID: PFL5)
Borehole diameters:	56 mm, 66 mm and 76 mm (or larger).
Length of measurement section:	The flow guide length can be varied.
Method of flow measurement:	Thermal pulse and thermal dilution.
Range and accuracy of measurement:	See Table 4-2
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 (see Section 6.1.1).
Logging computer	PC (Windows 7).
Software	PFL software (custom software).
Total power consumption:	1.5–2.5 kW depending on the type of pump employed.
Calibration of flow probe:	February 2023 (Probe ID: PFL5).

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	0.0001 °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

Borehole sealing mechanism (Figure 4-1) was used to maintain the borehole partially closed at the same time when measurement cable was being pulled outwards from the borehole. The borehole sealing mechanism was attached to a flange at the borehole opening. The measurement cable is lead through a seal housing, containing a set of special sealing disks that enable cable movement while preventing uncontrollable flow from the borehole. At the body of the sealing mechanism there are multiple connections and pipes that can be used for necessary auxiliary equipment and functions, e.g., pressure measurements and regulation of borehole outflow.

Figure 4-1 *Borehole sealing mechanism attached to the casing pipe at the opening of the borehole. A cable guide extends onwards from the sealing mechanism.*

Outflow from the borehole was measured with two devices. Controlled borehole outflow was measured with a flow sensor connected to an outflow pipe. The amount of outflow was controlled by a needle valve and pressurization pump that maintained desired pressure in the borehole. Small part of the outflow leaked through the borehole sealing mechanism. This leakage drained into a collecting vessel made from a tarpaulin set up under the sealing mechanism (Figure 4-2). The water was pumped from the collecting vessel with a pump and the flow rate was measured by a special measurement device that collects water and measures the water amount over a long time period (*total flow meter*). Due to this indirect flow rate measurement, it is not possible to present value for outflow rate in high frequency. Furthermore, the nature of the leakage varies as it is larger when the cable is moving and smaller when the cable is still (*i.e. when the PFL DIFF tool is moved in the borehole vs. when the tool is stopped for measurement*).

Figure 4-2 *Tarpaulin gathering water that leaks from the borehole sealing mechanism.*

A pressurization pump was used to maintain desired pressure in the measured borehole. Even though water was not pumped into the borehole, the pressure was controlled with the pump. The controlling unit of the pump measures borehole pressure and adjusts the speed of the pump accordingly.
A needle valve was used to keep the pumping rate at the operating range of the pump (*i.e. it was used as a by-pass valve*). The reported outflow is the actual outflow from the borehole and the pumping does not affect that. A block diagram of the borehole pressure control is presented in Figure 4-3.

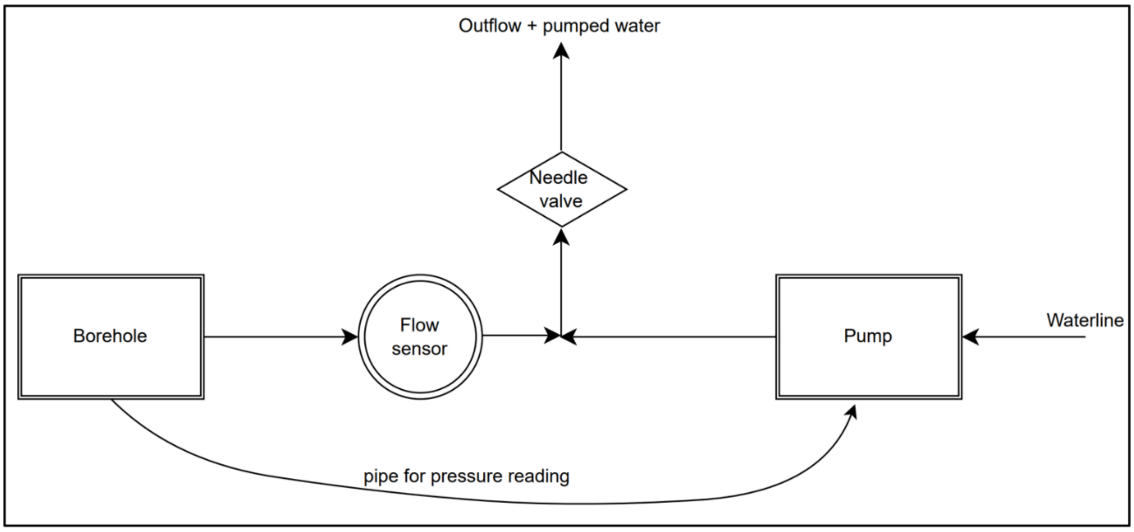

Figure 4-3 *Borehole pressure control during flow logging.*

The PFL DIFF probe was pushed to the bottom of the boreholes with SKB's rod feeding rig (*RFR*). This was the first time to push the probe to a 450 m long (*near*) horizontal borehole. The previously longest borehole this had been done is 350 m in ONKALO, Olkiluoto. Previously used rods had been square shaped 22 mm thick rods with quick connectors, but those have been noticed to be too weak for pushing PFL DIFF probe into long boreholes. SKB provided strong aluminium rods (Figure 4-4) with threaded connections and no problems were encountered while pushing the probe into the boreholes.

Figure 4-4 *Pushing rod with adapter for PFL DIFF probe.*

5 Execution of measurements

5.1 General

The work was performed according to Activity Plan AP SFK-23-009 following the SKB Method Description 322.014e, Version 1.0 (*Method description for difference flow logging in tunnel boreholes*), see Tabell 1-1. The Activity Plan and the Method Description are both SKB's internal controlling documents. Prior to the measurements, the downhole tools and the measurement cable were cleaned. Time was synchronized to prevailing Swedish time (*note that clocks were shifted from summertime to normal time on 29.10.2023 during the measurement campaign*). The activity schedule of the borehole measurements is presented in Table 5-1 And Table 5-2. The items and activities presented in these tables correspond to those presented in the Activity Plan.

The outflow from the partially closed borehole was measured during the PFL DIFF measurements. Leakage through borehole sealing mechanism was gathered on a collecting vessel and pumped into a measurement device. Controlled outflow from borehole was measured with a flow sensor. In the results, controlled outflow and leakage are combined and presented as total outflow from borehole.

The dummy logging (*Item 6*) of the borehole is done prior to the test to minimize the risk that the measurement tools get stuck in the borehole during the test. The dummy also collects solid material from the borehole wall. The solid material in the dummy is used for evaluation whether it is safe to continue with other logging tools. Dummy logging does not completely eliminate the risk of equipment getting stuck but obviously reduces the risk, as well as provides crucial information on the openness of a borehole.

The overlapping flow loggings (*Item 7 and Item 8*) were carried out in the partially closed borehole at two different difference pressure states with 0.5 m section length and employing 0.1 m length increments (*step length*). Different pressure states in the borehole were established by manually controlling the borehole outflow (*with needle valves*) and with a pressure-controlled pump.

The electrical conductivity (*EC*) and temperature of borehole water were measured during flow logging measurements. The measuring arrangements are shown in Figure 5-1.

Table 5-1 Activity schedule for flow logging and testing in KFR90.

Item	Activity	Explanation	Date
2	Mobilisation	Unpacking the trailer. Pressure in closed borehole was 764 kPa (gauge pressure) (information from SKB).	2023-10-09
5	Synchronisation of clocks	Clocks set to Swedish time (UTC+1)	2023-10-10
3	Dummy logging	Borehole stability/risk evaluation.	2023-10-10 – 2023-10-11
4	Function check of equipment at site	Checking functionalities of measurement equipment	2023-10-11
7	Overlapping flow logging – partially closed borehole	Section length Lw=0.5 m. Step length dL=0.1 m. Measurement at borehole length 449.7 m – 2.13 m. Borehole pressure ca. 405 kPa.	2023-10-12 – 2023-10-16
8	Overlapping flow logging – partially closed borehole	Section length Lw=0.5 m. Step length dL=0.1 m. Measurement at borehole length 449.85 m – 2.02 m. Borehole pressure ca. 630 kPa.	2023-10-17 – 2023-10-19
9	Transient registration of borehole drawdown and recovery	Shutting the borehole after measurement is ready and recording the borehole pressure over night.	2023-10-19 – 2023-10-20
	Demobilisation	Packing the trailer and closing the borehole.	2023-10-20

Table 5-2 Activity schedule for flow logging and testing in KFR91.

Item	Activity	Explanation	Date
2	Mobilisation	Moving to KFR91. Unpacking the trailer. Pressure in closed borehole was 691 kPa (gauge pressure) (information from SKB).	2023-10-20
3	Dummy logging	Borehole stability/risk evaluation. The dummy logging was conducted by SKB while testing that push rod rig and rods and strong enough to get probe to bottom of a horizontal borehole.	
7	Overlapping flow logging – partially closed borehole	Section length Lw=0.5 m. Step length dL=0.1 m. Measurement at borehole length 338.9 m – 1.95 m. Borehole pressure ca. 397 kPa.	2023-10-24 – 2023-10-26
8	Overlapping flow logging – partially closed borehole	Section length Lw=0.5 m. Step length dL=0.1 m. Measurement at borehole length 338.9 m – 2.04 m. Borehole pressure ca. 498 kPa	2023-10-27 – 2023-10-29
9	Transient registration of borehole drawdown and recovery	Shutting the borehole after measurement is ready and recording the borehole pressure over night.	2023-10-29 – 2023-10-30
8_extra	Overlapping flow logging – partially closed borehole	Section length Lw=0.5 m. Step length dL=0.1 m. Measurement at fracture 230.7 m due to flow value above measurement limit at ID7. Pressure changed while probe was at the fracture to obtain two flow values within the limits.	2023-10-27 – 2023-10-29
	Demobilisation	Packing the trailer. Closing the borehole.	2023-11-01

Figure 5-1 *Measurement equipment at KFR91.*

5.2 Nonconformities

During the first measurement run in KFR90, the measurement stopped at length of 49.3 m due to winch tension limit. The lower limit was set to 30 kg which was considered as sufficient. Winch lower limit must be set to protect winch in case of malfunction of measurement device. The measurement was restarted next morning, and the rest of the borehole was measured.

The second measurement run in KFR90 was interrupted at length of 257.59 m due to electricity cut off. The cut off happened during lunch break and measurement was restarted.

In KFR91 a fracture at borehole length 230.7 m had flow rate exceeding the upper measurement limit while borehole pressure drawdown was ca. 390 kPa. The measured value was 357 00 mL/h but as the flow channel in PFL DIFF probe causes flow friction at high flows, the actual fracture flow rate was more. This was the only fracture flow exceeding the upper limit and therefore it is possible to estimate flow value based on borehole total outflow and the sum of measured fracture flows from other fractures. Based on these, the actual flow rate at fracture at 230.7 m was ca. 600 000 ml/h at the most.

The fracture flow was remeasured by positioning the probe at the fracture and changing borehole pressure so that two flow values below upper limit could be measured. At first, the pressure was 1 bar below shut-in pressure and 133 000 mL/h flow rate was obtained. Then pressure was dropped 2 bars below shut-in pressure and obtained flow rate was 156 500 mL/h. The obtained transmissivity ($6.37 \cdot 10^{-7}$ m^2/s) was clearly lower than anticipated based on previous measurements and fracture head (42 masl) was unreasonable. Flow rate was monitored over night at both pressure conditions but even still the flow rate was changing. Regardless, smaller flow was increasing and larger flow decreasing so waiting time was unlikely the issue. It is unclear why conflicting results were obtained but the results obtained from measurement runs #1 and #2 are more reasonable even though the flow rate was above measurement limit. This initial value has been reported.

Prior to all measurement runs, a pseudo steady-state conditions were established; waiting long enough so that borehole pressure was stable and total outflow variation was less than ±10% during 10-minute interval (*as described in SKB MD 322.014e*). This is set as an approximate rule of thumb during field operations. However, during the field work it was noticed that it is strongly advisable to wait for borehole stabilization longer than to reach the minimum criteria. Waiting longer affects fracture flow stability, which not only affects to the results but also to the ability to maintain stable pressure conditions in the borehole. At the first measurement run in KFR90, borehole pressure varied more than in the following measurements, and the cause was mainly difficulty to keep stable pressure while borehole outflow was still in transition.

It was physically impossible to measure at the very bottom of the boreholes. The length of the lower rubber disks is about 20 cm and reduces the measured distance. The rubber sealing disks in the device must also be flipped before the measurement begins. This further reduces the measured distance by approximately 0.1 m.

6 Results

6.1 Length calibration

6.1.1 Determination of probe position

An accurate length reference for the measurements is difficult to achieve in long boreholes. The main cause of the inaccuracy is the stretching of the steel logging cable. The amount of stretching depends on the tension on the cable, the magnitude of which in turn depends, among other things, on the inclination of the borehole and the roughness (friction properties) of the borehole wall. The KFR90 and KFR91 boreholes are nearly horizontal, which means that the tension on the measurement cable was relatively low.

The length calibration was made based on borehole casing and length of borehole. The starting length was determined based on push-rod lengths when the probe was at the bottom of the borehole, whereas the ending length was determined based on the borehole casing pipe. The casing pipe was detected by the SPR sensor of the PFL DIFF probe. These starting and ending lengths are assumed to be correct, and all lengths recorded in between them have been processed by applying linear correction based on the start and end corrections. In this case, there are no clear sources of error in the determination of the probe position along the borehole. However, the length corrections of the two measurement runs in each borehole can be evaluated. The length correction described above was applied to the results of both measurement runs and after that SPR anomalies were compared to the corrected length positions. The largest individual length difference was found to be 7 cm, and it is therefore assumed that the error in the probe position at any borehole length is less than 7 cm. The largest error was found in the middle of each borehole, which is reasonable as the starting and ending reference points were fixed. The herein reported lengths from the first measurement run are length corrected as described above, and the following measurement runs are length matched according to the first measurement run.

6.1.2 Estimated error in position of detected fractures

Despite the length correction of the probe as described in Section 6.1.1, there can still be length errors in the positioning of a detected fracture due to the following reasons:

- The point interval in the current overlapping mode flow measurements is 0.1 m. This could cause an error of ±0.05 m.
- The length of the measurement section (in the current case 0.5 m) is not exact. The specified section length denotes the distance between the nearest upper and lower rubber sealing disks. Effectively, the section length can be larger. There are four rubber sealing disks (5 cm apart) at the upper end of the measurement section. In case the rubber disk that is closest to measurement section leak the measurement section effectively is 5 cm longer. This can cause an error of ±0.05 m when a short step length for overlapping measurements (0.1 m) is used.
- Rounded flow anomalies can also occur when the orientation of a fracture is not perpendicular with the borehole. In these cases, the fracture might be in the measurement section on one side of the borehole but out of the section on the other side of the borehole. Fractures nearly parallel with the borehole might be even more problematic to detect, implying that fracture location may be difficult to define accurately in such cases.

In an ideal case, when a fracture is perpendicular to the borehole and the fracture aperture is very small, the total accuracy of the position of the fracture is ca. ±12 cm, which is the sum of the ±7 cm error due to the positioning of the probe and the ±5 cm length interval in overlapping flow logging. There are no length marks that could be detected by SPR sensor in boreholes KFR90 and KFR91.

6.2 Electrical conductivity and temperature

6.2.1 Electrical conductivity and temperature of borehole water

The electrical conductivity of the borehole water (borehole EC) was measured during the flow logging measurements. The measurement was performed upwards, see Appendices 1.1 and 10.1. The boreholes are downwards inclined therefore upwards means towards start of borehole and downwards means towards bottom of the borehole.

When the flow is measured within the measurement sections, the measurement is conducted using both the upper and lower rubber sealing disks. In this case the flow guide carries water with it, which means that thorough flushing at the EC electrode and at the temperature sensor cannot be guaranteed. Therefore, the measured EC and temperature conditions may not fully represent the actual conditions in the borehole.

The temperature of the borehole water was measured simultaneously with the EC and flow measurements (Appendices 1.2 and 10.2). The EC values are corrected for temperature 25 °C to make them comparable with other EC measurements (Heikkonen et al. 2002). Electrical conductivity of water in both boreholes is around 1 S/m. Water temperature in KFR90 was between 7.2 and 8.5 °C and in KFR91 between 7.2 and 7.8 °C, being coldest at the bottom.

6.3 Absolute pressure and outflow measurements

Absolute pressure was registered together with the other measurements of Items 7 and 8. The pressure sensor measures the absolute pressure. The hydraulic head along the borehole is determined in the following way. First, the measured air pressure is subtracted from the measured absolute pressure. 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 fresh water hydraulic head (*m*) according to the RH 2000 reference system,
- p_{abs} is the absolute pressure (*Pa*),
- p_b is the barometric (*air*) pressure (*Pa*),
- ρ_{fw} is the density of fresh water, 1,000 kg/m^3
- g is the acceleration due to gravity, 9.80665 m/s^2 and
- z is the elevation of the upper end of the measurement section (*m*) according to the RH 2000 reference system (*the Swedish national elevation system*).

The calculated head distributions are presented in Appendices 6 and 15. 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 z-coordinates with 3 m borehole length intervals were obtained from SKB and lengths between were interpolated.

Borehole outflow was measured during the measurements. The results are presented in Appendices 7 and 16. Two different drawdowns in the boreholes were achieved by adjusting the pressure with a valve and a pressure-controlled pump.

6.4 Flow logging

6.4.1 General comments on results

The measurement programme comprised two flow logging sequences in both boreholes. The flow results are plotted on the same diagram as measured SPR (single-point resistance, right hand sides), see Appendices 2.1–2.23 and 11.1–11.17. SPR data are usually lower value for a fracture where flow is detected (e.g. length 14.0 m in KFR90). However, it is also possible that a flow anomaly exists without an SPR anomaly (here, anomaly means the distinctive shape of curve in plot based on which interpretations are done), or vice versa. As the SPR electrode is located within the upper rubber sealing disks of the probe, the locations of resistance anomalies associated with conductive fractures coincide with the upper end of the flow anomalies.

The flow logging was performed with a 0.5 m section length using 0.1 m increments. The method (overlapping flow logging) gives the length of conductive zones with a length resolution of 0.1 m.

Determination of the directions of small flows (<100 mL/h) takes more time than determination of flow rate. Therefore, the measurement time was longer at every section length (0.5 m) interval.

The measurement section length determines the width of a flow anomaly of a single fracture as seen in the flow log. If the distance between flowing fractures is less than the measurement section length, the anomalies will overlap, resulting in a stepwise flow data plot (e.g. length interval 283 m–290 m in KFR90). The overlapping flow logging was conducted twice (at two different pressure drawdowns, cf. Table 5-1

The positions (in terms of borehole length) of the detected fractures are shown on the length scale. Fracture locations are interpreted based on the flow curves and therefore represent flowing fractures. A long line represents the location of a conductive fracture; a short line denotes that the existence of a conductive fracture is uncertain. The short line is used if the flow rate is less than 30 mL/h, or the flow anomalies are overlapping or unclear due to noise effects.

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

The glossary of terms used in the tables of Appendices 4.1–4.5 and 13.1–13.3 are given in Appendices 3 and 12.

6.4.2 Hydraulic characteristics of borehole

During the first measurement sequence in KFR90 the borehole pressure varied from 377 kPa to 420 kPa (variation interval 43 kPa) and in the second measurement sequence from 621 kPa to 639 kPa (variation interval 18 kPa), see Appendix 12.2. The shut-in pressure of borehole KFR90 was 764 kPa and the pressure drawdown (calculated from average pressure drawdown) was hence ca. 365 kPa and ca. 134 kPa, respectively. In KFR91 the pressures during the first and second flow logging sequence were from 305 kPa to 309 kPa (deviation of 4 kPa) and from 497 kPa to 501 kPa (deviation of 4 kPa) respectively. The shut-in pressure of the borehole KFR90 was 690 kPa, and the pressure drawdown was hence ca. 383 kPa and ca. 191 kPa, respectively.

Target drawdowns were set to ca. 200 kPa and ca. 500 kPa, but 500 kPa should not be exceeded in any case. The largest pressure deviation during flow loggings was 43 kPa (KFR90 measurement run #1). This represents 12% of the pressure drawdown. The total outflow varied (Appendix 7) so also the fracture flow rates at some fractures must have varied. The fracture flows are measured momentarily (Approximate time when probe passes a fracture is three minutes) therefore it is not possible to estimate how much. After all, the influence of pressure and flow variations on evaluated transmissivity values is most probably small, as pressure changes were slow and the actual pressure and flow values, used in transmissivity calculations, were measured simultaneously.

As described in Section 3.2 (Equation (3-6), two sets of flow measurements are needed for calculation of transmissivity. In this case the borehole was all the time partially closed at a different outflow and pressure state.

The interpreted results of the flow logging measurements are presented in the tables of Appendices 4.1–4.5 and 13.1–13.3. Pressure was measured and calculated as described in Section 6.3. The h_{1FW} and h_{2FW} in Appendices 4.1–4.5 and 13.1–13.3 represent fresh-water heads in the borehole at different pressure states.

The flow rates are presented as positive if the flow direction was from the bedrock into the borehole during the test, and as negative if the direction was from the borehole into the bedrock. In KFR90 fracture flows were from bedrock into the borehole from 19 m borehole length to the bottom of the borehole with the larger drawdown, and from 102 m borehole length to the bottom of the borehole with less drawdown. Closer to the access tunnel, the flow directions were from the borehole into the bedrock. In KFR91 flows from borehole into the bedrock were observed from top of the borehole to 7 m borehole length with larger drawdown, and from the top of the borehole to 34 m borehole length with less drawdown.

The total outflow from borehole KFR90 was ca. 6.5 L/min for larger drawdown and ca. 2.8 L/min for less drawdown. The difference between the drawdowns was about 22 m. The calculated total transmissivity of borehole KFR90 is $2.77 \cdot 10^{-6}$ m^2/s. For borehole KR91, the total outflow was ca. 19 L/min for larger drawdown and ca. 10 L/min for less drawdown. The difference between the two drawdowns was about 20 m. Based on these numbers, the calculated total transmissivity of borehole KFR91 is $7.42 \cdot 10^{-6}$ m^2/s. These transmissivities have been calculated based on outflow differences between two pressure drawdowns with *Eq.* (3-6.

6.4.3 Transmissivity of fractures

The magnitudes of fracture-specific flow rates were evaluated based on flow logging results. The first step in the procedure was to identify the locations of individual flowing fractures and then to evaluate their flow rates. In cases where the distance between fractures is less than the length of the measurement section, it may be difficult to evaluate the flow rate. There are such cases presented in Appendix 2.15 (length 280 m – 290 m). In these cases, a stepwise increase or decrease in the flow data plot equals the flow rate of a specific fracture (filled triangles in the appendices).

The total number of detected flowing fractures was 218 in KFR90 and 125 in KFR91. These fractures were used for transmissivity estimations. The transmissivity of the fractures is presented in Appendices 4.1–4.5, 5.1–5.5, 13.1–13.3 and 14.

Some fracture-specific results were classified to be "uncertain". The basis for this classification is either a small flow rate (<30 mL/h) or unclear definition of the conductive fracture in the flow log. Flow anomalies are considered unclear if their nature is unclear because of noise or if fractures are so close to each other that they are difficult to interpret separately. In these measurements noise level was mostly very low. The flow sensor has been calibrated down to 6 mL/h, so in good borehole conditions it is possible to detect flow values below 30 mL/h. For example, at lengths between 50 m and 60 m in KFR90, three fractures have been detected even though flow rates were below 30 mL/h. For the sake of clarity of the plots, flow rates below 6 mL/h are assigned a value of 6 mL/h.

In KFR90, the largest calculated transmissivities were found at lengths 120 m to 160 m. Transmissivities above 10^{-7} m^2/s were calculated for fractures at lengths 121.7 m, 130.0 m, 135.9 m, 150.8 m and 151.8 m. The highest transmissivity was a fracture at 121.7 m, $3.86 \cdot 10^{-7}$ m^2/s. In KFR91, the highest calculated transmissivities are for fractures at 227.7 m ($1.21 \cdot 10^{-6}$ m^2/s) and 230.7 m ($1.95 \cdot 10^{-6}$ m^2/s), hence larger than 10^{-6} m^2/s. Nine calculated fracture transmissivities were between 10^{-6} m^2/s and 10^{-7} m^2/s.

In KFR90, for the fractures at 12.4 m, 103.8 m, 185.6 m, 251.6 m, 283.5 m, 284.8 m, 285.2 m and 289.4 m, flow changes were illogical (specifically, fracture flow increased) when the borehole pressure was increased (to create less drawdown) for measurement run #2). This led to unrealistic negative transmissivities, which have not been reported. The same occurred with the fracture at length of 290.6 m in KFR91.

The sum of calculated fracture transmissivities in KFR90 is $2.54 \cdot 10^{-6}$ m²/s. This is very close to the estimated total transmissivity of the borehole (*$2.77 \cdot 10^{-6}$ m²/s*). In KFR91 the sum of calculated fracture transmissivities is $6.80 \cdot 10^{-6}$ m²/s. Almost half of this is from the two largest fractures, at 227.7 m and 230.7 m borehole lengths. The sum of transmissivities is less than the estimated total transmissivity of the borehole, which is understandable as the flow at the fracture at 230.7 m borehole length was above the upper measurement limit.

6.4.4 Flow measurement limits and transmissivity range

The typical lower flow rate measurement limit is 30 mL/h. Depending on borehole conditions, the actual lower limit can be lower or higher. The upper flow rate measurement limit is 300 000 mL/h. The flow sensor calibration is valid for even higher flow rates, but the small structural dimensions of the flow channel of the PFL DIFF probe cause flow friction. This implies that measured flow rates exceeding the upper limit do not represent the real flow conditions in borehole.

Borehole conditions that affect the lower limit of flow measurements, i.e. the noise level, are complex and it is not always clear what is the cause for elevated noise level. The effect that can be seen is elevated noise level at flow rate base level (flow value when water is not flowing through the flow sensor). For instance, the measured flow value may stay high between fractures, or the flow rate value may fluctuate a lot. Noise can be due to erroneous flow measurements or by water flow that is caused by rubber disk leakage, not by actual fracture flow.

The following reasons have been identified to cause noise in flow rate value:

- Roughness of the borehole wall.
- Solid particles such as clay or drilling debris in the borehole water.
- Gas bubbles entrained in the borehole water.
- Changes in borehole water salinity.
- High flow rate along the borehole.

Roughness of the borehole wall always results in high levels of noise, not only in the flow measurement results, but also in SPR results. The flow curve and SPR curves are typically spiky when the borehole wall is rough. This is a direct result from rubber disk leakage as the rubber disks don’t seal against the borehole wall.

Drilling debris usually increases noise levels. Good flushing of borehole is advisable between borehole drilling and flow logging.

Pressure of flowing water is reduced when it enters the borehole. This may lead to the release of dissolved gases and increase the quantity of gas bubbles entrained in the water. Some fractures may produce more gases than others. Sometimes, when the borehole is being measured, increased noise levels are observed just after certain fractures. The reason for this is assumed to be gas bubbles.

Another reason for noise level changes after a certain fracture has been passed is that when waters with different salinities mix the density differences might cause water movement that is measured. This causes noise but it is very unlikely that this would cause erroneous fracture interpretation.

The effect of a high flow rate along the borehole can often be seen above high-flowing fractures. Any minor leakage in the seal provided by the lower rubber sealing disks will appear in the measurement as increased levels of noise. Based on tests (Tammisto et al. 2018) the flow along borehole can be very large (ca. 100 L/min) and it does not cause noise if the borehole wall is smooth. However, the combined effects of a rough borehole wall and high flow along the borehole can cause an elevated noise level.

A high level of noise in flow measurements usually masks the “real” flow if the flow is smaller than the noise. Experience indicates that a high noise level (>30 mL/h) can affect the flow rate measurement even if the measured flow is larger than the prevailing noise level. The magnitude of this effect is not fully clear and therefore it can’t be considered in interpretations.

The typical minimum for measurable flow rate is presented in Appendices 2.1–2.23 and 11.1–11.7 using a grey dashed line (Lower limit of flow rate). The minimum level of the measurable flow was evaluated using the flow data obtained from both measurement runs. It is evaluated to obtain a limit below which there may be fractures that remain undetected.

The noise level was in general 30 mL/h in the tests of both boreholes. In some parts of the boreholes even smaller flow values were detected. Nevertheless, the noise line (grey dashed line) is chosen to be no less than 30 mL/h and anomalies below 30 mL/h are considered to be uncertain.

The range of transmissivities that can be calculated is difficult to estimate. Basically, the PFL transmissivity is calculated from flow and pressure difference between two measurement runs. The upper end of the transmissivity range could be obtained from results in which one flow value is 300 000 mL/h and the other is -300 000 mL/h, as this is the largest difference in flow that can be measured. Small pressure differences are equivalent to large transmissivity. With a 20 m difference in drawdown, as obtained in this campaign, transmissivity would be $8.24 \cdot 10^{-6}$ m^2/s. The minimum transmissivity would be obtained from a small flow difference associated with a large drawdown difference. Thus, there is no limit on how small transmissivities can be calculated, as long as both flows are within the measurement range. The more important figure is the transmissivity value of which higher values should not go undetected. With a noise level of 30 mL/h, flow values between -30 mL/h and 30 mL/h are undetected. Therefore transmissivity ($8.24 \cdot 10^{-10}$ m^2/s) calculated based on 60 mL/h flow change and 20 m drawdown (in this campaign) should be detected.

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

The flow measurements are conducted in two pressure conditions to provide data for calculation of fracture- or section-specific transmissivity and head. In theory the two pressure conditions can be any pressures as long as they are not the same. In practise the difference between the pressures must be large enough to cause notable flow differences, but not too large to maintain stable hydraulic conditions around the tested borehole. Creation of notable flow differences is important; if the flow rates are close to equal, even a small error in measured flow value can cause large error in the calculated transmissivity and head. In this measurement campaign ca. 20 m drawdown difference was used.

Figure 6-1 illustrates how the accuracy of flow rate and pressure measurements affects the accuracy of transmissivity and head interpretations. Blue and red dots, representing measurement run 1 and 2 respectively, represent the measured flow and head values. The slope of the black line drawn along through the measurement run 1 and 2 points is inversely proportional to the transmissivity *(Eq.* (3-6). The head of fracture or section (head value at which the flow is zero) is plotted in Figure 6-1with a black cross.

The error in flow rate measurement is within ±10% of the measured value, and the accuracy of absolute pressure sensor ±2 kPa, which corresponds to ±0.2 m error in head. The blue and red lines with arrow endings in Figure 6-1 represent the errors of measured flow and head values (±10% in flow, ±0.2 m in head). The square shape formed from the lines represents the accuracy of the measurements, i.e. the measurement run value should be within the squares when errors are taken into account. The orange line in the figure indicates the maximum transmissivity (T_{max}) and the green line the minimum transmissivity (T_{min}) that is calculated within the error limits. Moreover, the highest fracture head value (h_{max}) is plotted with an orange cross, and the lowest head value (h_{min}) with a green cross.

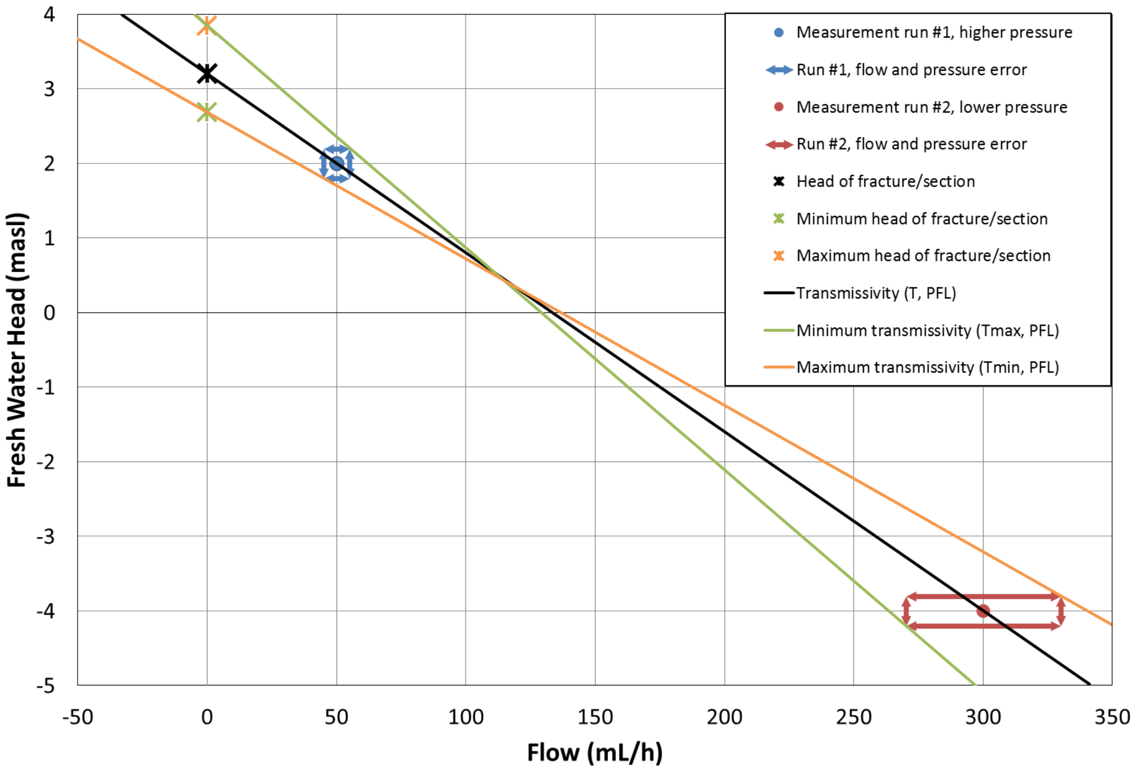

Figure 6-1 *Demonstrative plot how measurement accuracy of flow rate and pressure affects derivation of transmissivity and fracture head.*

Figure 6-1 represents a case in which flow rates in both pressure conditions are positive. It is possible that the flow directions change between measurements or that the flow rate cannot be determined in both pressure conditions. When flow directions are different, the lowest fracture/section head is not necessarily determined by a line representing the largest transmissivity as in Figure 6-1 but the same principles apply. If the flow rate cannot be determined based on both measurements, a zero flow value is used to pair to a flow value that was determined to calculate transmissivity and head. In error calculations, the square determining possible values is formed by estimating what is the highest flow rate that should be detectable based on the measurement. For instance, if the lower flow measurement limit is 30 mL/h the fracture flow rate must be between -30 mL/h and 30 mL/h.

Calculated transmissivity and head values with error limits are presented in Appendices 5.1– 5.5 and 14. If flow values are so close to each other that the measured value added with ±10% uncertainty are overlapping, it is not possible to calculate both error limits.

7 Summary

In this study, the Posiva Flow Log, Difference Flow Method (PFL DIFF) was used to determine the locations and flow rates of flowing fractures or structures in boreholes KFR90 and KFR91, drilled from one of the access tunnels to the SFR repository in Forsmark, Sweden. Measurements were conducted with 0.5 m measurement section length with 0.1 m overlapping steps. The boreholes were partially closed during the measurements. The whole borehole was measured at two different pressure states by adjusting the pressure in the partially closed borehole.

Measurements at two different pressures in the boreholes made it possible to interpret transmissivity and hydraulic head of fractures. The prerequisites for a reliable interpretation are e.g. that the measured flow rates are within measurement limits, and that the ratio of the measured flow rates is large enough for the same borehole lengths. At some fractures flow did not decrease when borehole pressure was increased. For these fractures the transmissivity could not be calculated. In general, ca 20 m drawdown difference should have been enough to cause flow differences.

Length calibration was done by using fixed start (borehole bottom) and stop (casing pipe) lengths. The starting length was fixed by setting the winch length reading based on push rods lengths when the probe was pushed to the bottom of the borehole. Stop length was fixed by setting the winch length based on the lower end of casing pipe, which could be detected with the SPR sensor. All length readings between these points were processed with linear correction.

In borehole KFR90, 218 flow yielding fractures were found. In this borehole, the noise level for flow measurements was low (30 mL/h). The estimated total transmissivity of the borehole is $2.77 \cdot 10^{-6}$ m^2/s (in *Eq.* (3-6 Q_1-Q_2 is total borehole outflow and $h_{r0,2}$-$h_{r0,1}$ is borehole head).
In borehole KFR91, 125 flow anomalies were detected. At one of the fractures (at boreholes length 230.7 m), flow was above the upper flow measurement limit. However, as it was the only flow above the measurement range, the real flow value could be estimated based on borehole total outflow and the sum of flows from the other fractures. An attempt was made to set the borehole pressure so that fracture flow rate would be within measurement range. The flow rate was within measurement range when the drawdown was one and two bars, but the resulted transmissivity and head values were contradictory with previous results. The results obtained for this fracture from the two measurement runs were estimated more reliable and are presented in tables and plots of results.

Electrical conductivity and temperature of the borehole water were also logged during the flow measurements.

For some fractures, the flow rate increased even though the borehole pressure was increased (i.e the drawdown was decreased). This led to unrealistic negative transmissivity values, which have not been presented in the results. The reason for this illogical test result is unclear, but waiting a longer period to achieve steady-state flow conditions in the borehole before starting flow logging may have had improved the quality of the results. In borehole KFR90, flow logging was initiated soon after the pre-defined pseudo steady-state condition (less than ±10% change in borehole outflow for 10 minutes) had been established. However, borehole outflow changed significantly also after the test was initiated. In borehole KFR91, borehole outflow was more constant after flow logging was initiated.

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Appendices

Appendix 1.1	KFR90, Electrical conductivity of borehole water
Appendix 1.2	KFR90, Temperature of borehole water
Appendix 2.1 – 2.23	KFR90, Flow rate and single point resistance
Appendix 3	KFR90, Explanations for the tables in Appendix 4.1 – 4.5
Appendix 4.1 – 4.5	KFR90, Inferred flow anomalies from overlapping flow logging
Appendix 5.1 – 5.5	KFR90, Plotted transmissivity and head of detected fractures
Appendix 6	KFR90, Head in the borehole during flow logging
Appendix 7	KFR90, Borehole pressure and outflow from the borehole
Appendix 8	KFR90, Borehole drawdown recovery
Appendix 9	KFR90, Electrical Calculation of conductive fracture frequency
Appendix 10.1	KFR91, Electrical conductivity of borehole water
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Appendix 14	KFR91, Plotted transmissivity and head of detected fractures
Appendix 15	KFR91, Head in the borehole during flow logging
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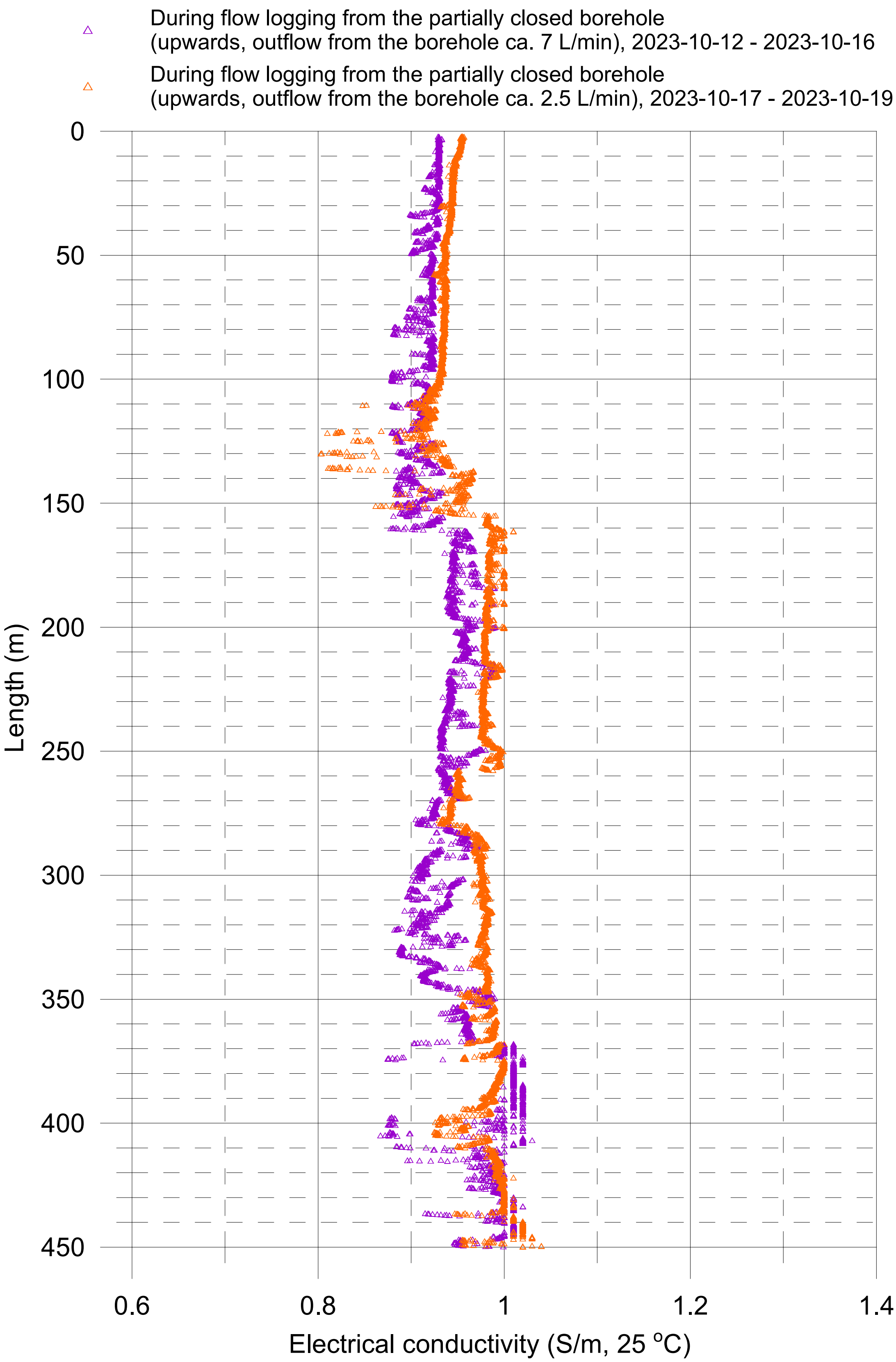
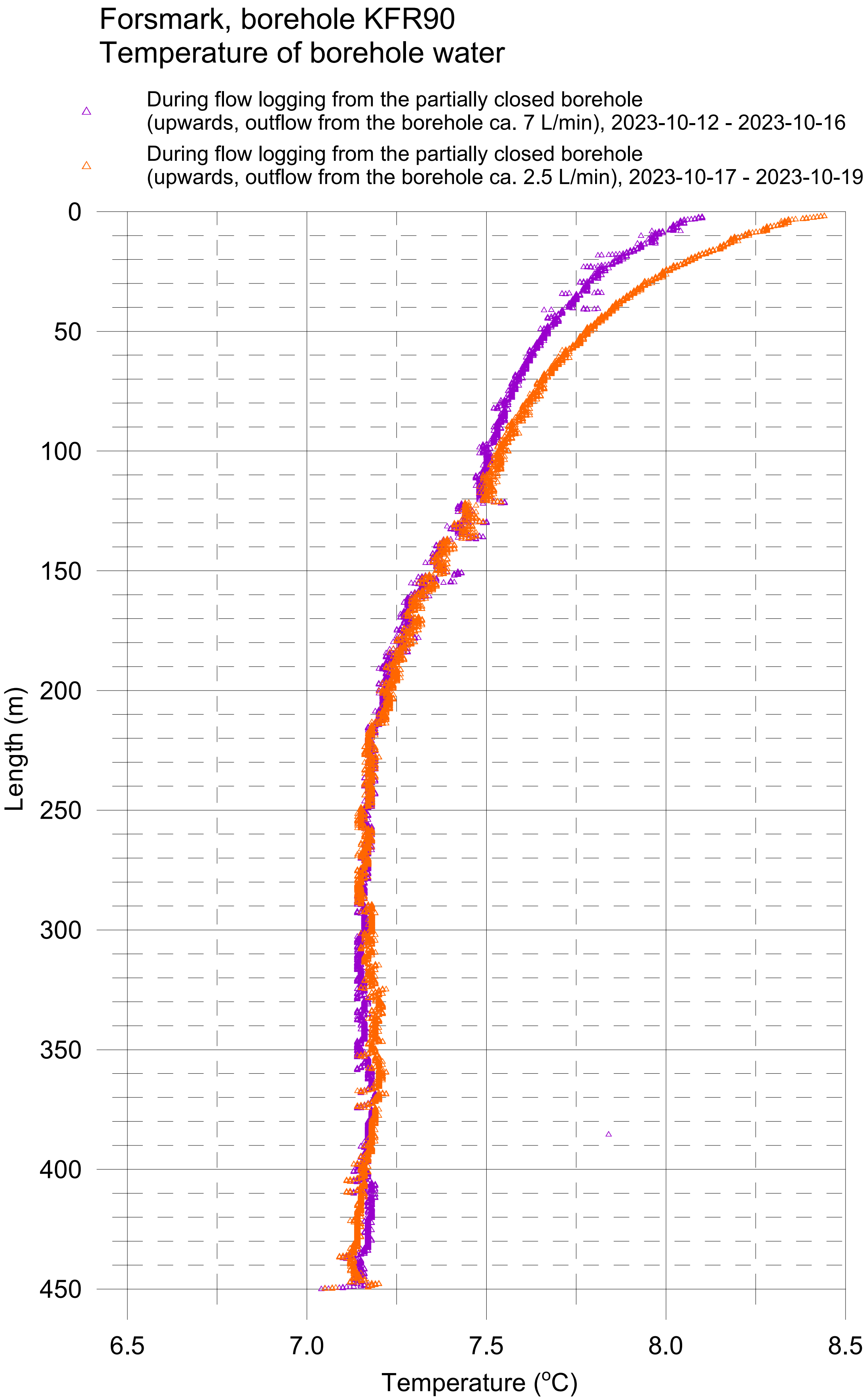
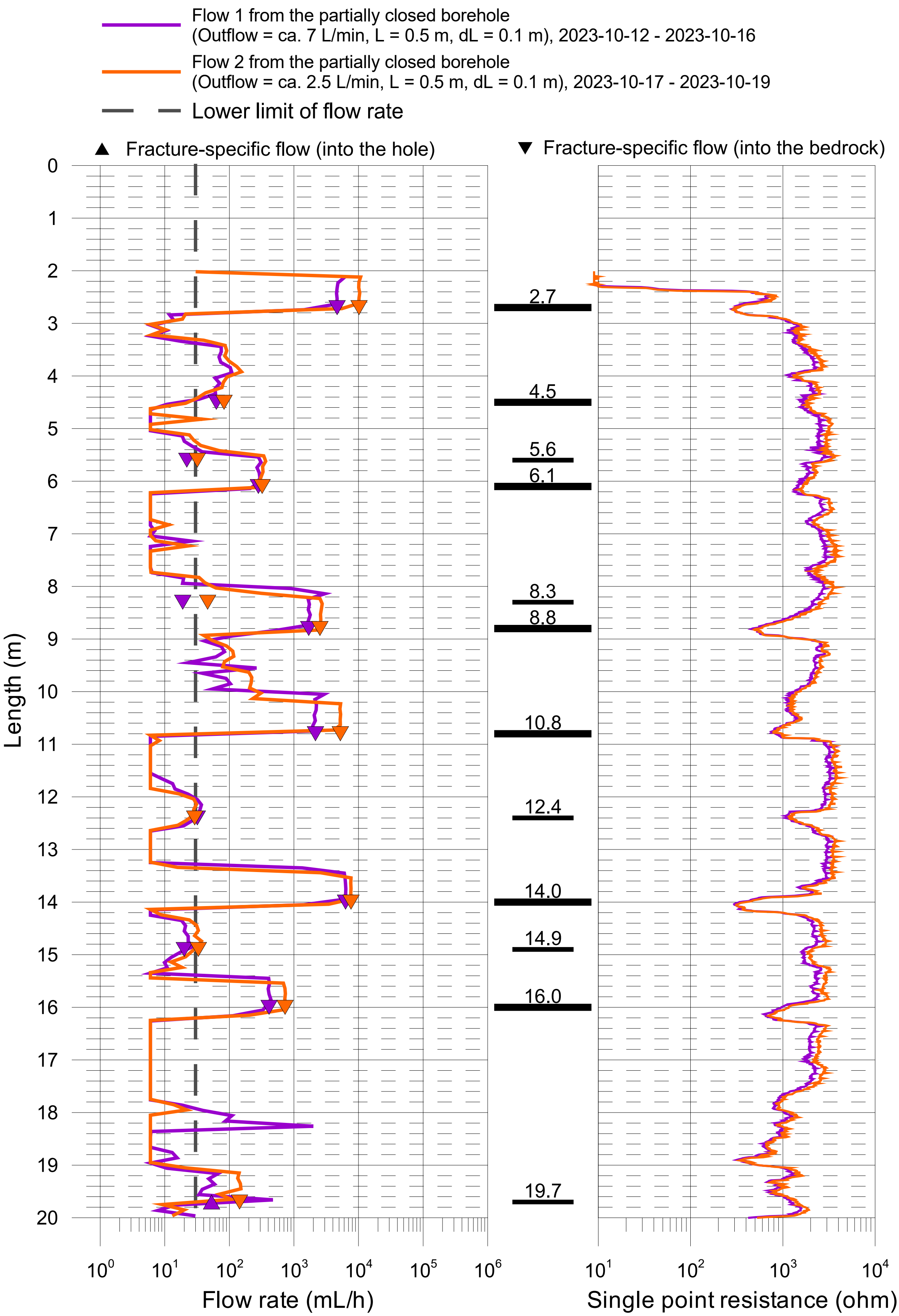
Appendix 17	KFR91, Borehole drawdown recovery
Appendix 18	KFR91, Electrical Calculation of conductive fracture frequency
Appendix 19	KFR91, Borehole pressure, outflow from the borehole, fracture-specific flow and hydraulic head results by date (at fracture at 230.7 m)

Forsmark, borehole KFR90
Electrical conductivity of borehole water

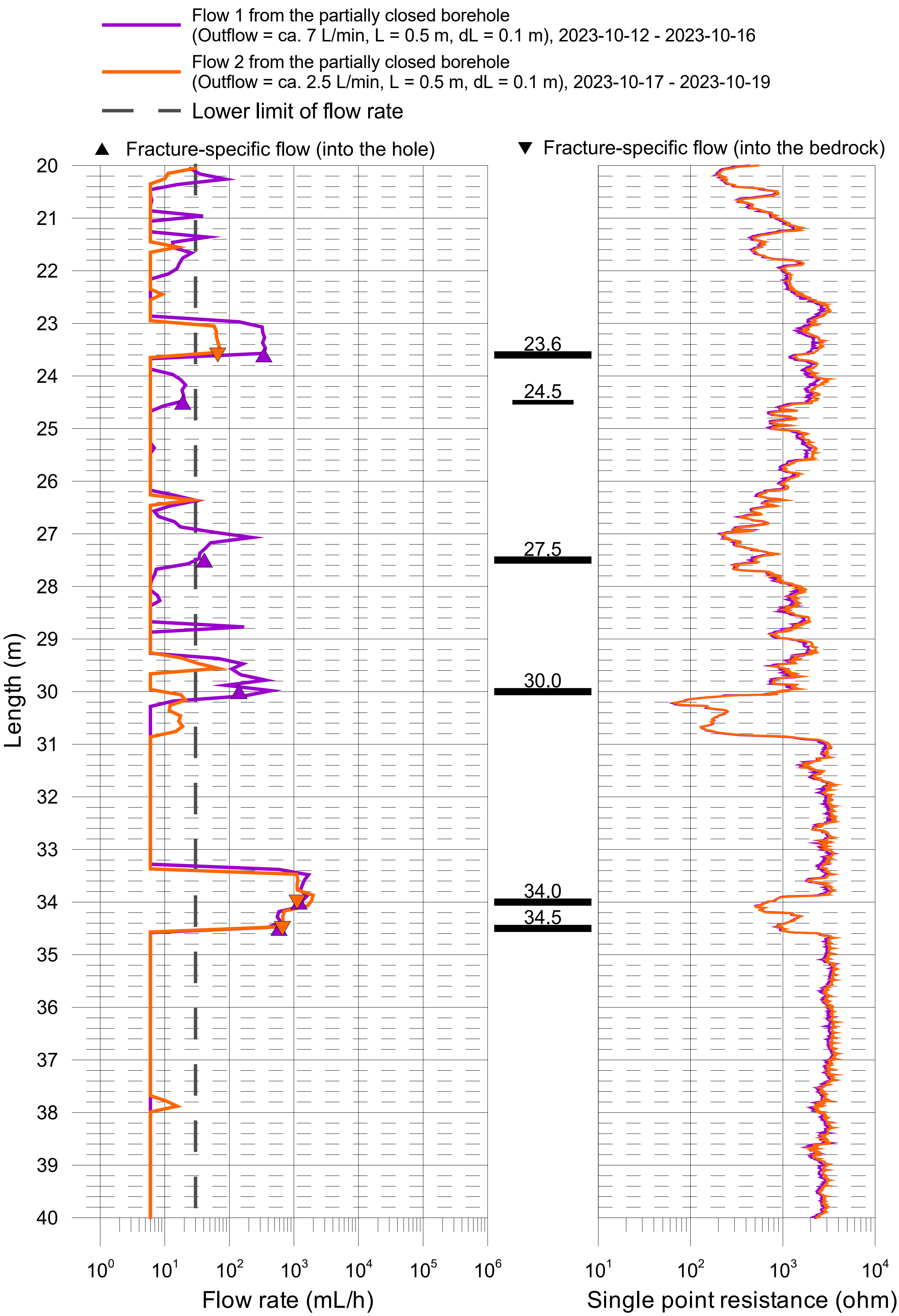


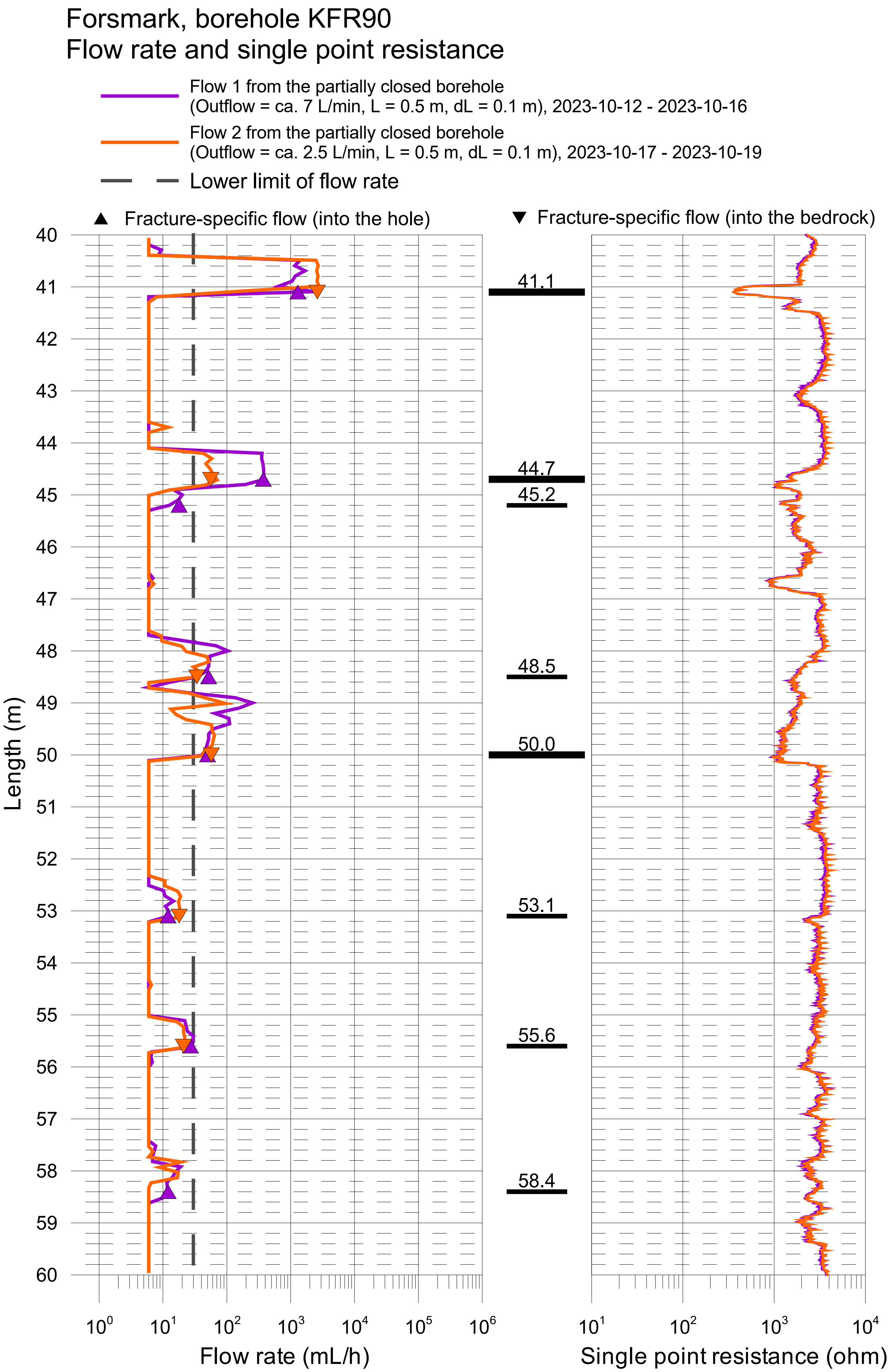

Forsmark, borehole KFR90
Temperature of borehole water
During flow logging from the partially closed borehole
(upwards, outflow from the borehole ca. 7 L/min), 2023-10-12 - 2023-10-16
During flow logging from the partially closed borehole
(upwards, outflow from the borehole ca. 2.5 L/min), 2023-10-17 - 2023-10-19
0
50
100
150
200
250
300
350
400
450
Length (m)
6.5
7.0
7.5
8.0
8.5
Temperature (°C)

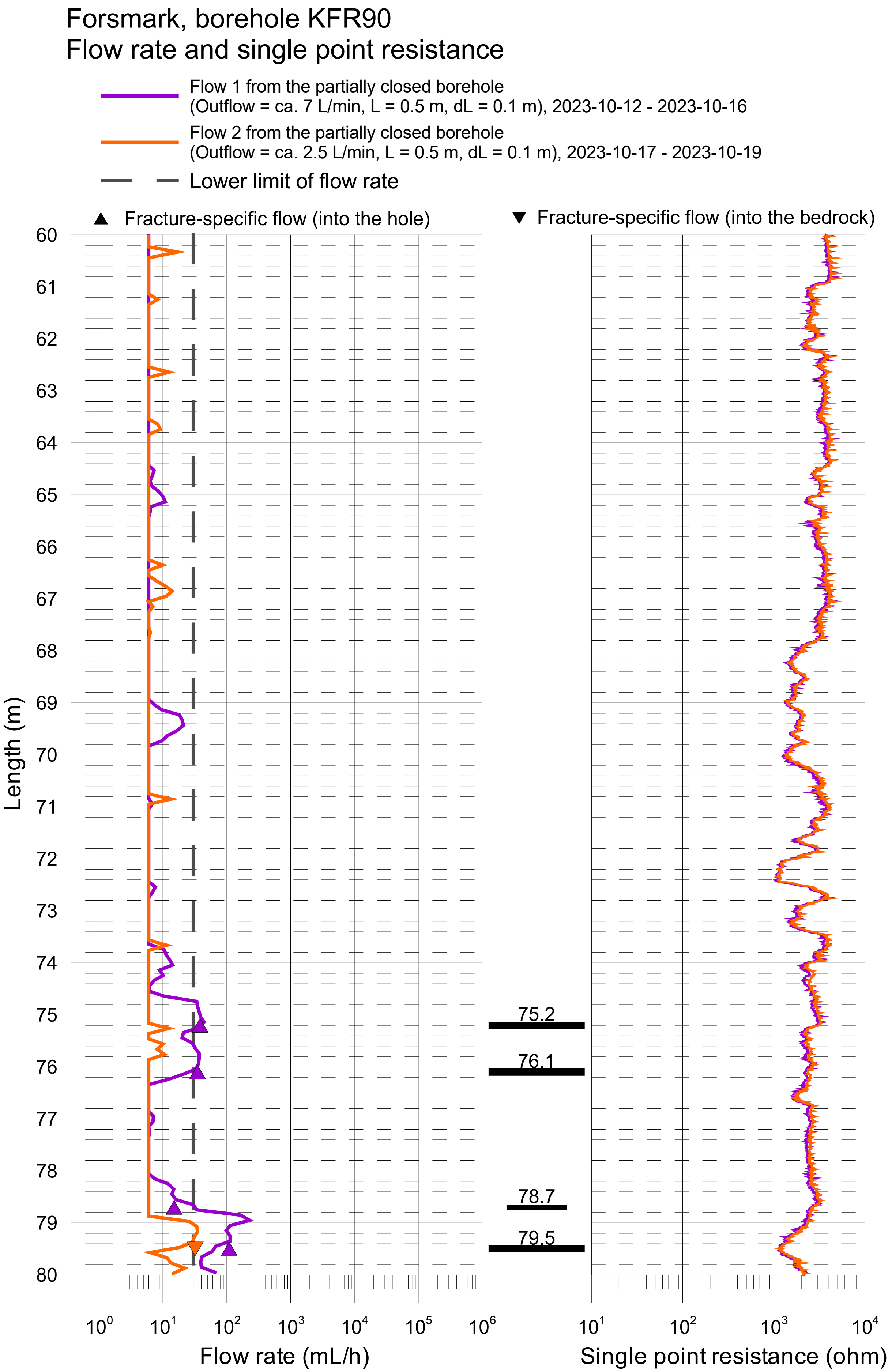
Forsmark, borehole KFR90
Flow rate and single point resistance

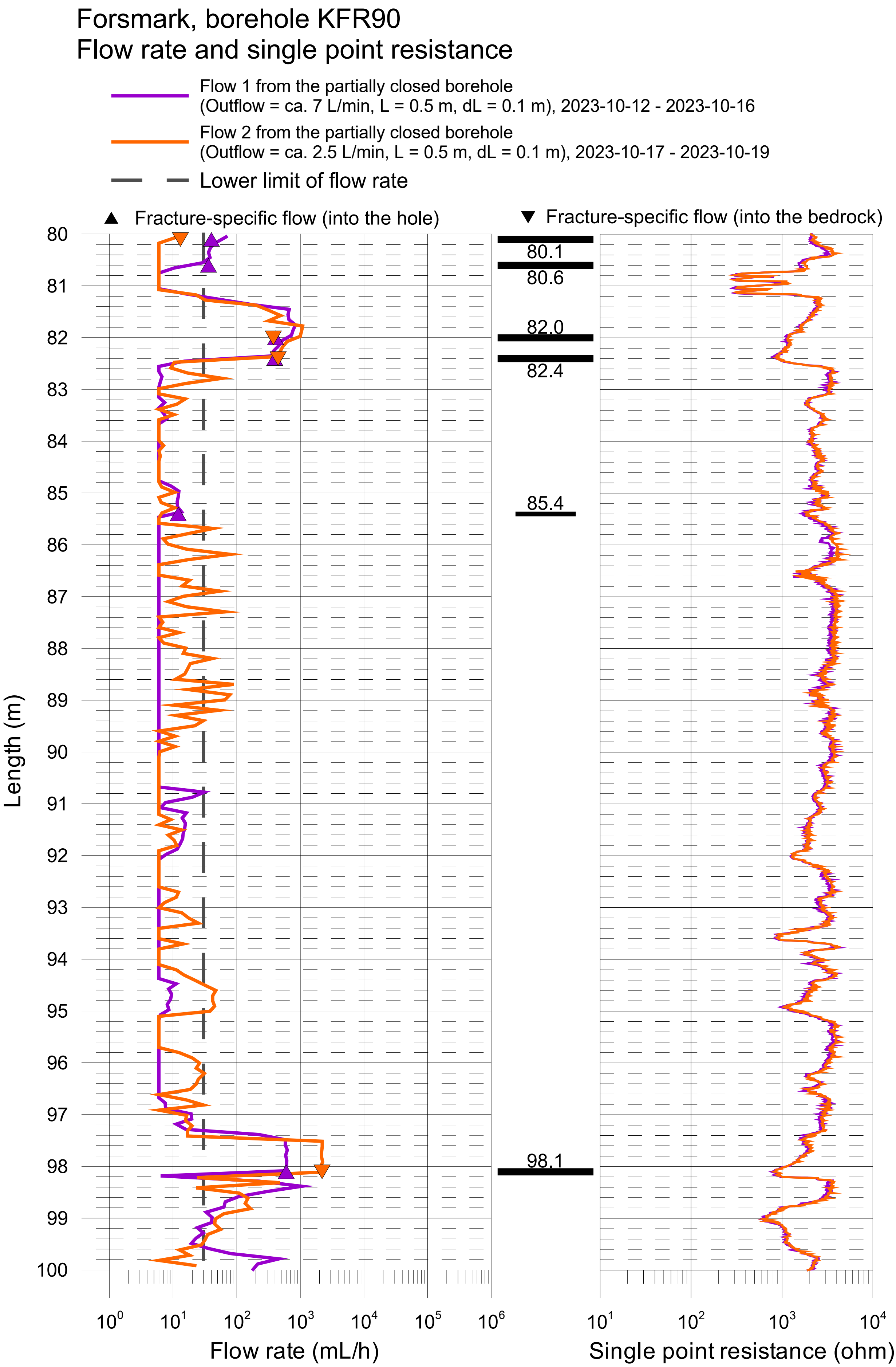


Forsmark, borehole KFR90
Flow rate and single point resistance

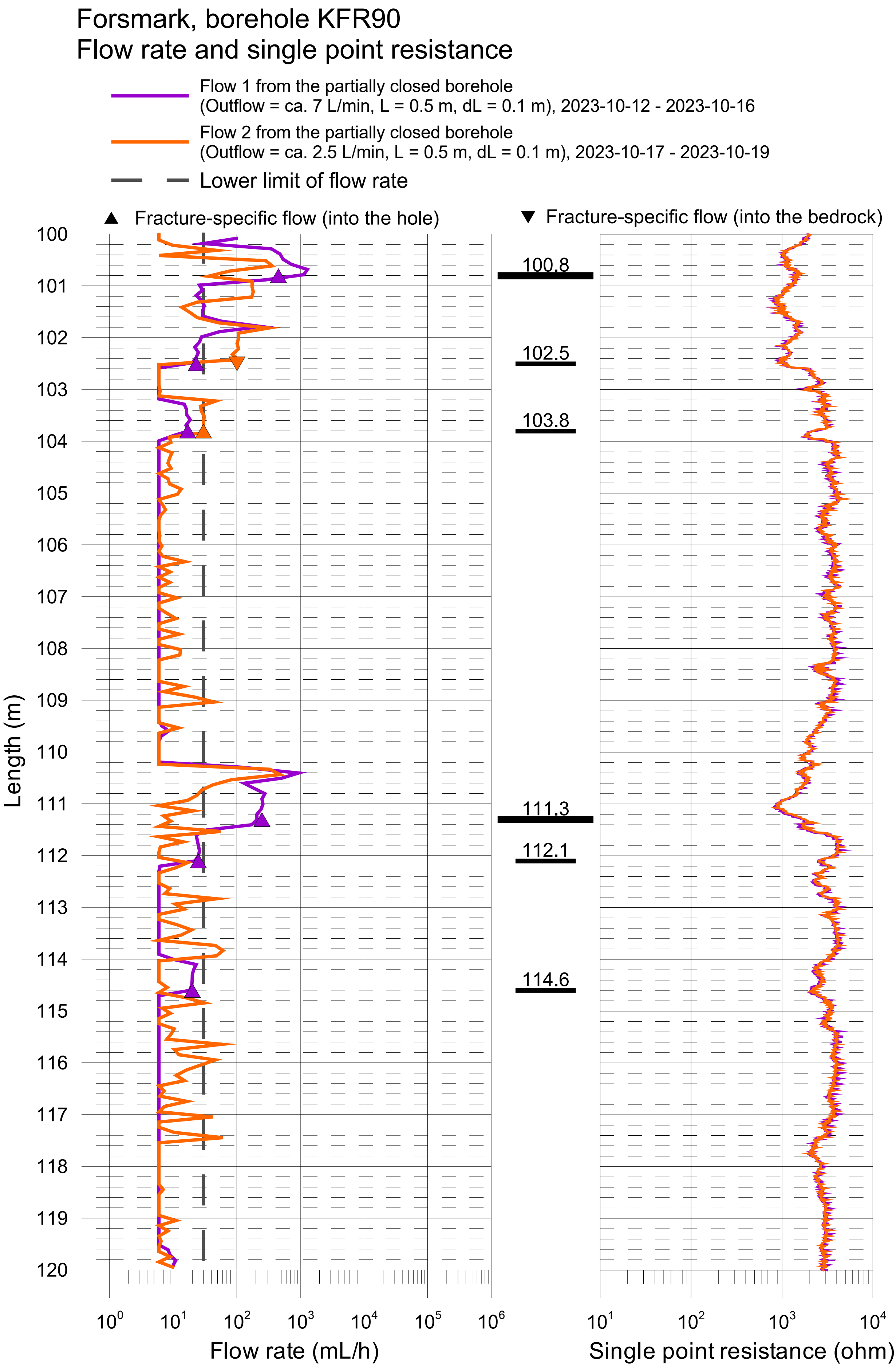



Forsmark, borehole KFR90
Flow rate and single point resistance
Flow 1 from the partially closed borehole
(Outflow = ca. 7 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-12 - 2023-10-16
Flow 2 from the partially closed borehole
(Outflow = ca. 2.5 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-17 - 2023-10-19
Lower limit of flow rate
Fracture-specific flow (into the hole)
Fracture-specific flow (into the bedrock)
Length (m)
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
41.1
44.7
45.2
48.5
50.0
53.1
55.6
58.4
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
Single point resistance (ohm)

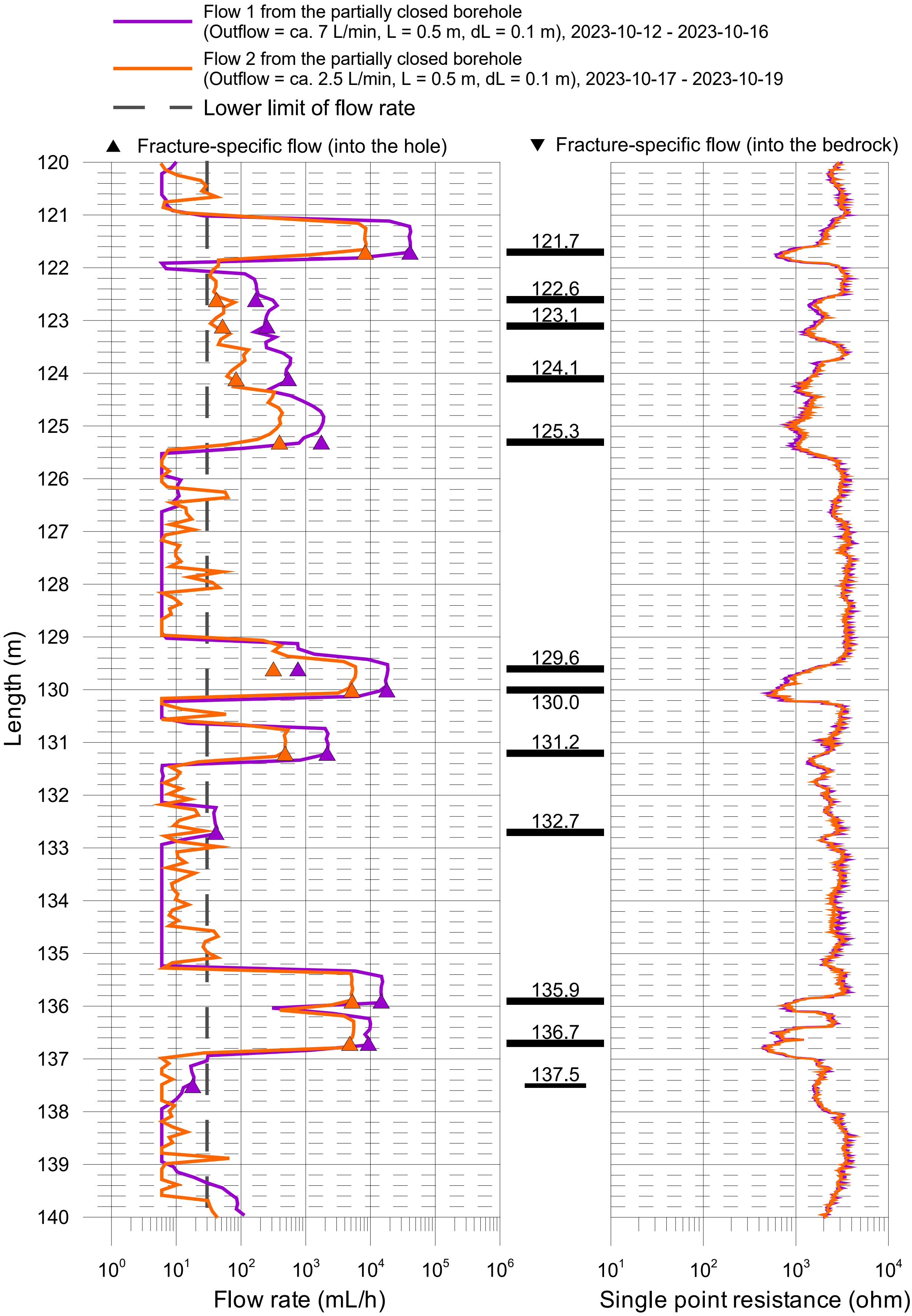

Forsmark, borehole KFR90
Flow rate and single point resistance
Flow 1 from the partially closed borehole
(Outflow = ca. 7 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-12 - 2023-10-16
Flow 2 from the partially closed borehole
(Outflow = ca. 2.5 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-17 - 2023-10-19
Lower limit of flow rate
▲ Fracture-specific flow (into the hole)
▼ Fracture-specific flow (into the bedrock)
Length (m)
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
75.2
76.1
78.7
79.5
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
Single point resistance (ohm)

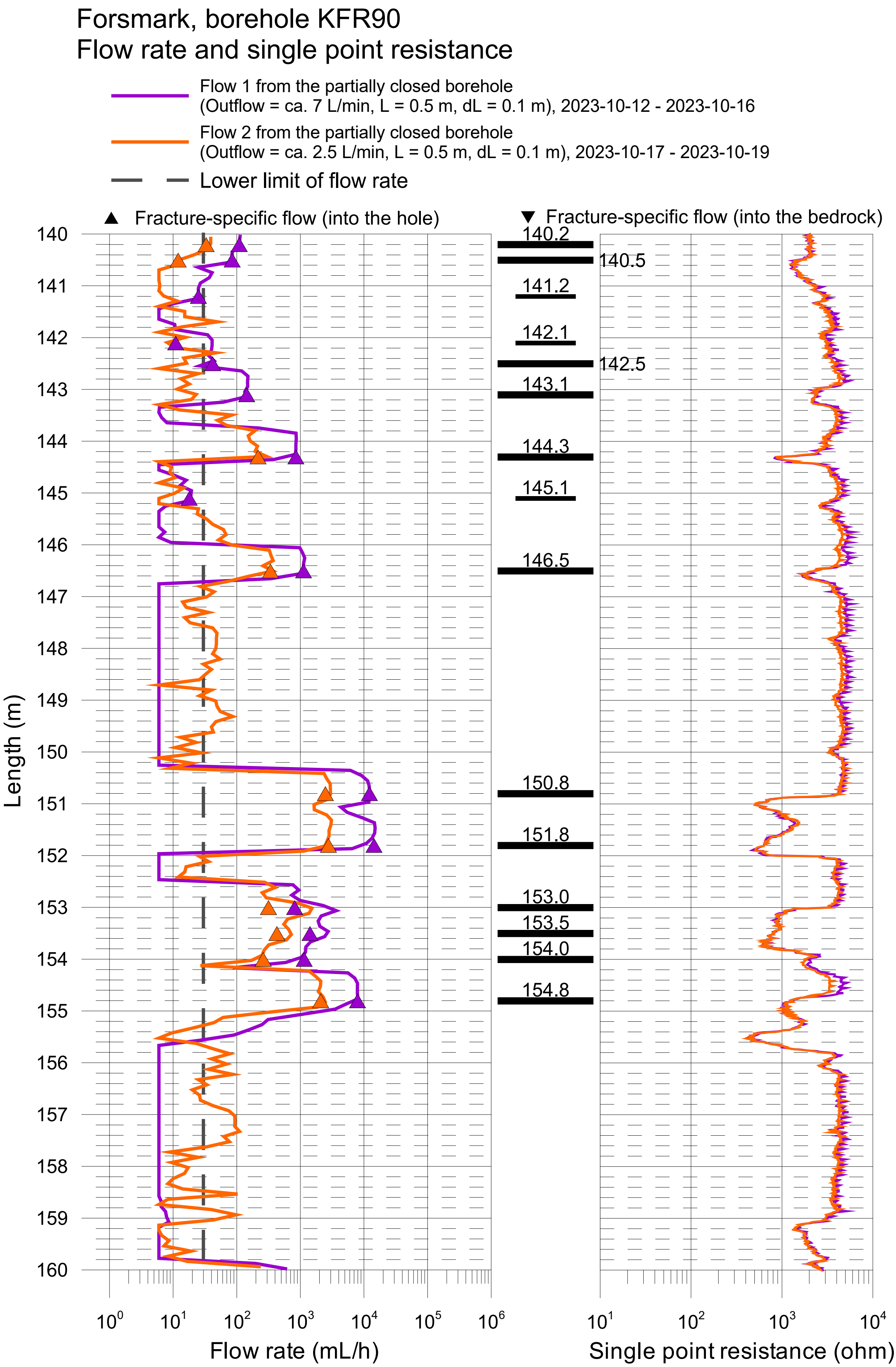


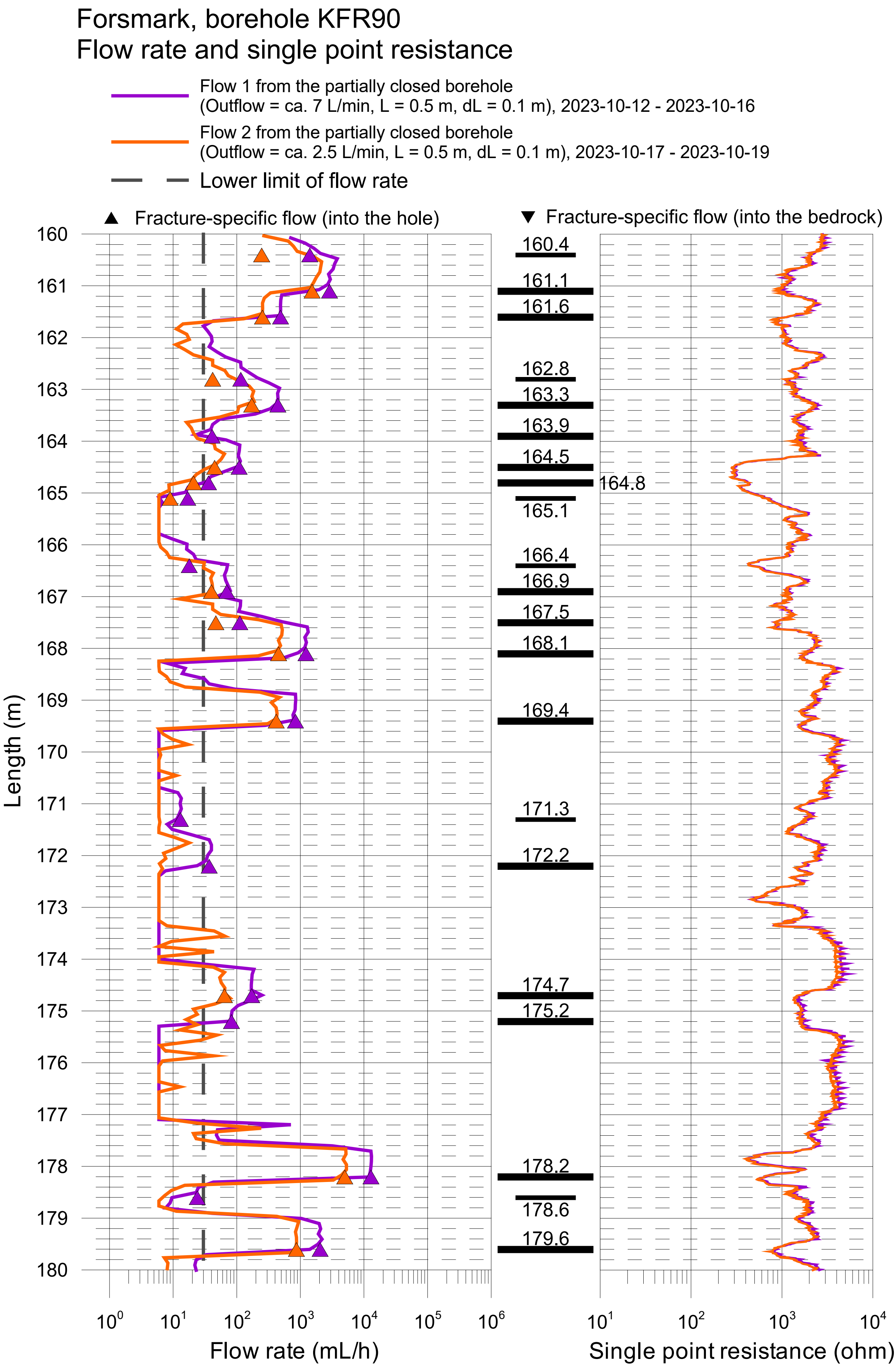
Forsmark, borehole KFR90
Flow rate and single point resistance
Flow 1 from the partially closed borehole
(Outflow = ca. 7 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-12 - 2023-10-16
Flow 2 from the partially closed borehole
(Outflow = ca. 2.5 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-17 - 2023-10-19
Lower limit of flow rate
Fracture-specific flow (into the hole)
Fracture-specific flow (into the bedrock)
Length (m)
80.1
80.6
82.0
82.4
85.4
98.1
Flow rate (mL/h)
Single point resistance (ohm)

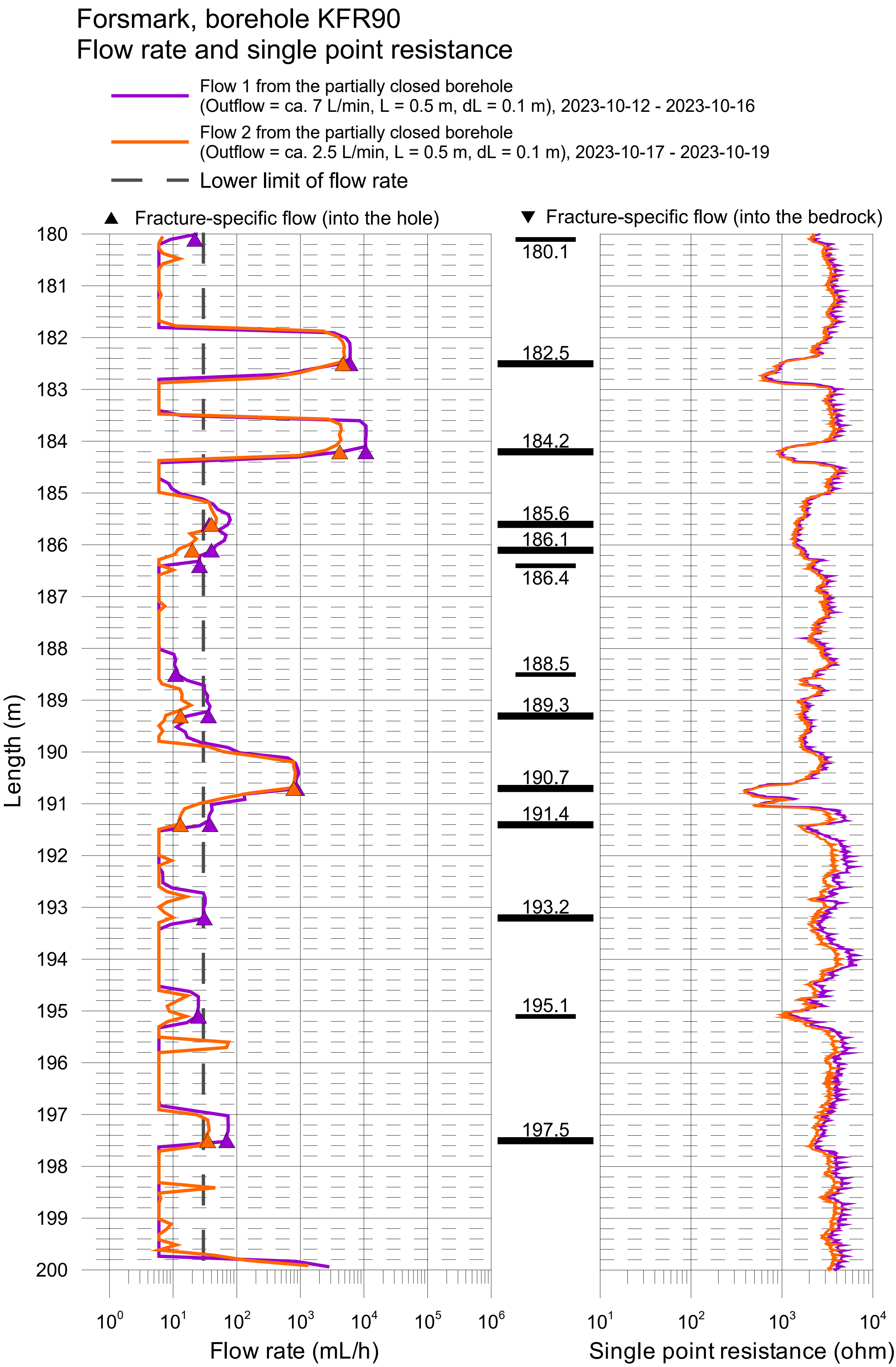

Forsmark, borehole KFR90
Flow rate and single point resistance
Flow 1 from the partially closed borehole
(Outflow = ca. 7 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-12 - 2023-10-16
Flow 2 from the partially closed borehole
(Outflow = ca. 2.5 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-17 - 2023-10-19
Lower limit of flow rate
▲ Fracture-specific flow (into the hole)
▼ Fracture-specific flow (into the bedrock)
Length (m)
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
100.8
102.5
103.8
111.3
112.1
114.6
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
Single point resistance (ohm)

Forsmark, borehole KFR90
Flow rate and single point resistance

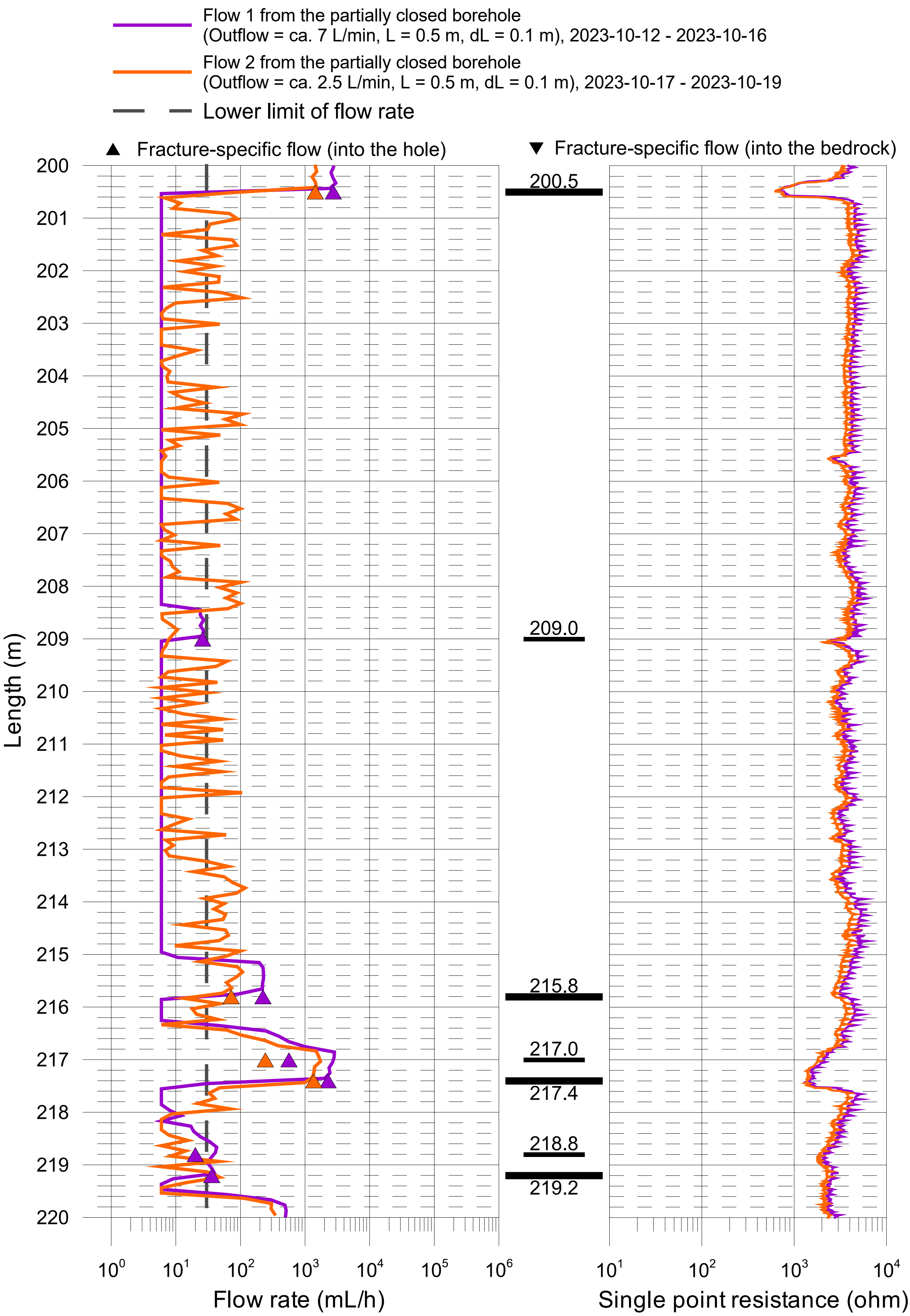


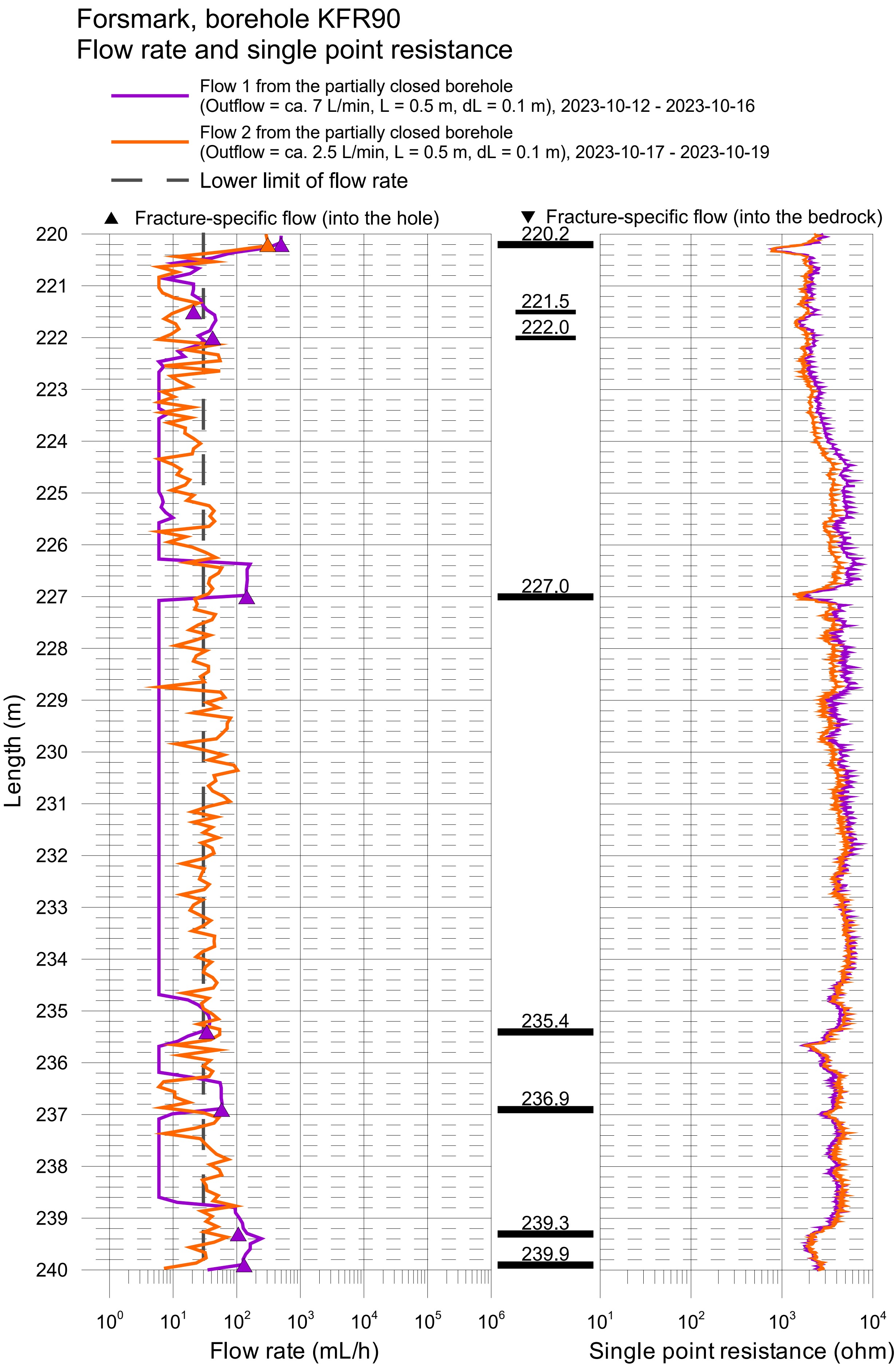

Forsmark, borehole KFR90
Flow rate and single point resistance
Flow 1 from the partially closed borehole
(Outflow = ca. 7 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-12 - 2023-10-16
Flow 2 from the partially closed borehole
(Outflow = ca. 2.5 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-17 - 2023-10-19
Lower limit of flow rate
Fracture-specific flow (into the hole)
Fracture-specific flow (into the bedrock)
140.2
140.5
141.2
142.1
142.5
143.1
144.3
145.1
146.5
150.8
151.8
153.0
153.5
154.0
154.8
Length (m)
Flow rate (mL/h)
Single point resistance (ohm)

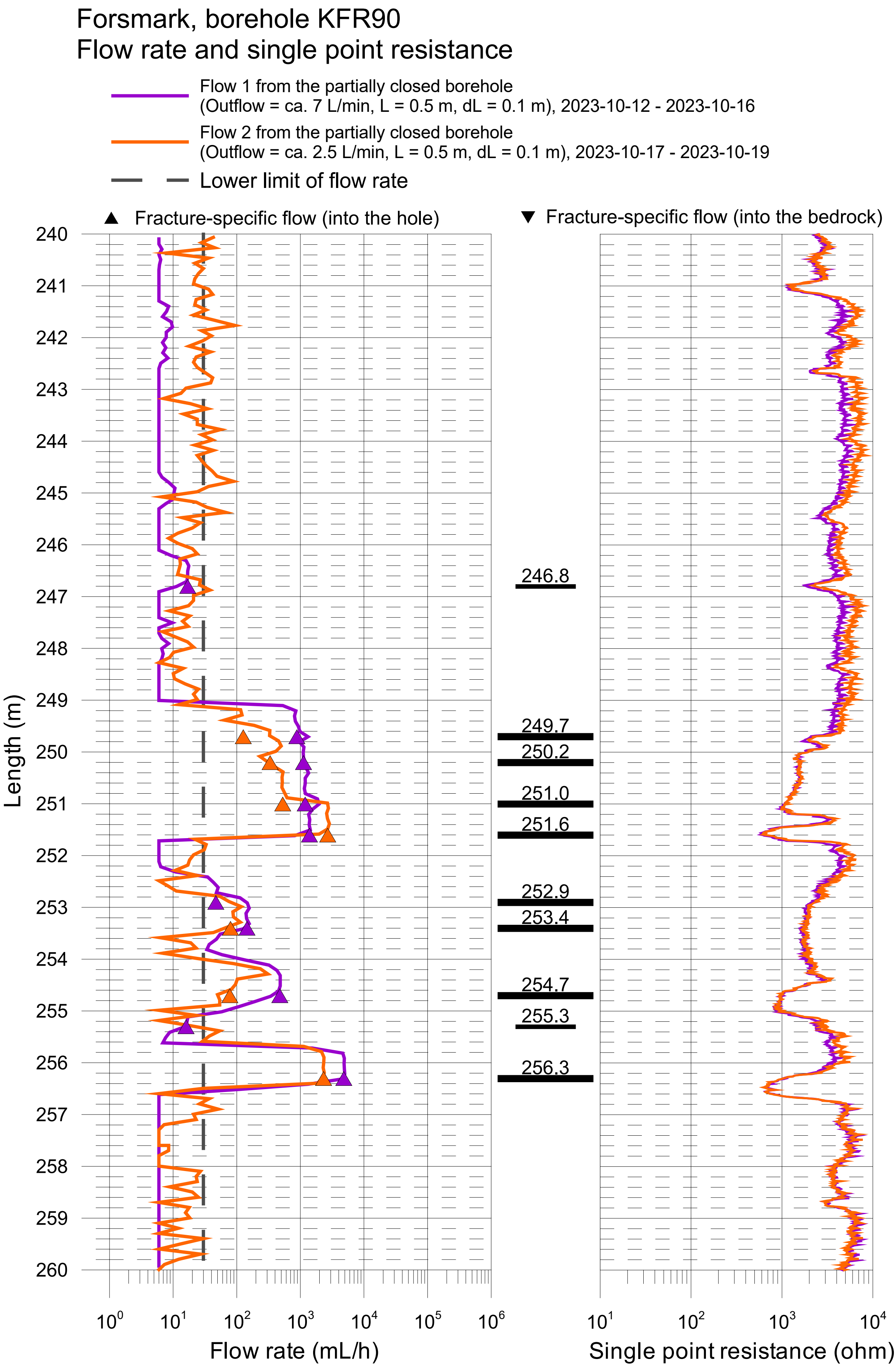

Forsmark, borehole KFR90
Flow rate and single point resistance
Flow 1 from the partially closed borehole
(Outflow = ca. 7 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-12 - 2023-10-16
Flow 2 from the partially closed borehole
(Outflow = ca. 2.5 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-17 - 2023-10-19
Lower limit of flow rate
▲ Fracture-specific flow (into the hole)
▼ Fracture-specific flow (into the bedrock)
Length (m)
160
161
162
163
164
165
166
167
168
169
170
171
172
173
174
175
176
177
178
179
180
160.4
161.1
161.6
162.8
163.3
163.9
164.5
164.8
165.1
166.4
166.9
167.5
168.1
169.4
171.3
172.2
174.7
175.2
178.2
178.6
179.6
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
Single point resistance (ohm)


Forsmark, borehole KFR90
Flow rate and single point resistance
Flow 1 from the partially closed borehole
(Outflow = ca. 7 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-12 - 2023-10-16
Flow 2 from the partially closed borehole
(Outflow = ca. 2.5 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-17 - 2023-10-19
Lower limit of flow rate
▲ Fracture-specific flow (into the hole)
▼ Fracture-specific flow (into the bedrock)
Length (m)
180
181
182
183
184
185
186
187
188
189
190
191
192
193
194
195
196
197
198
199
200
180.1
182.5
184.2
185.6
186.1
186.4
188.5
189.3
190.7
191.4
193.2
195.1
197.5
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
Single point resistance (ohm)

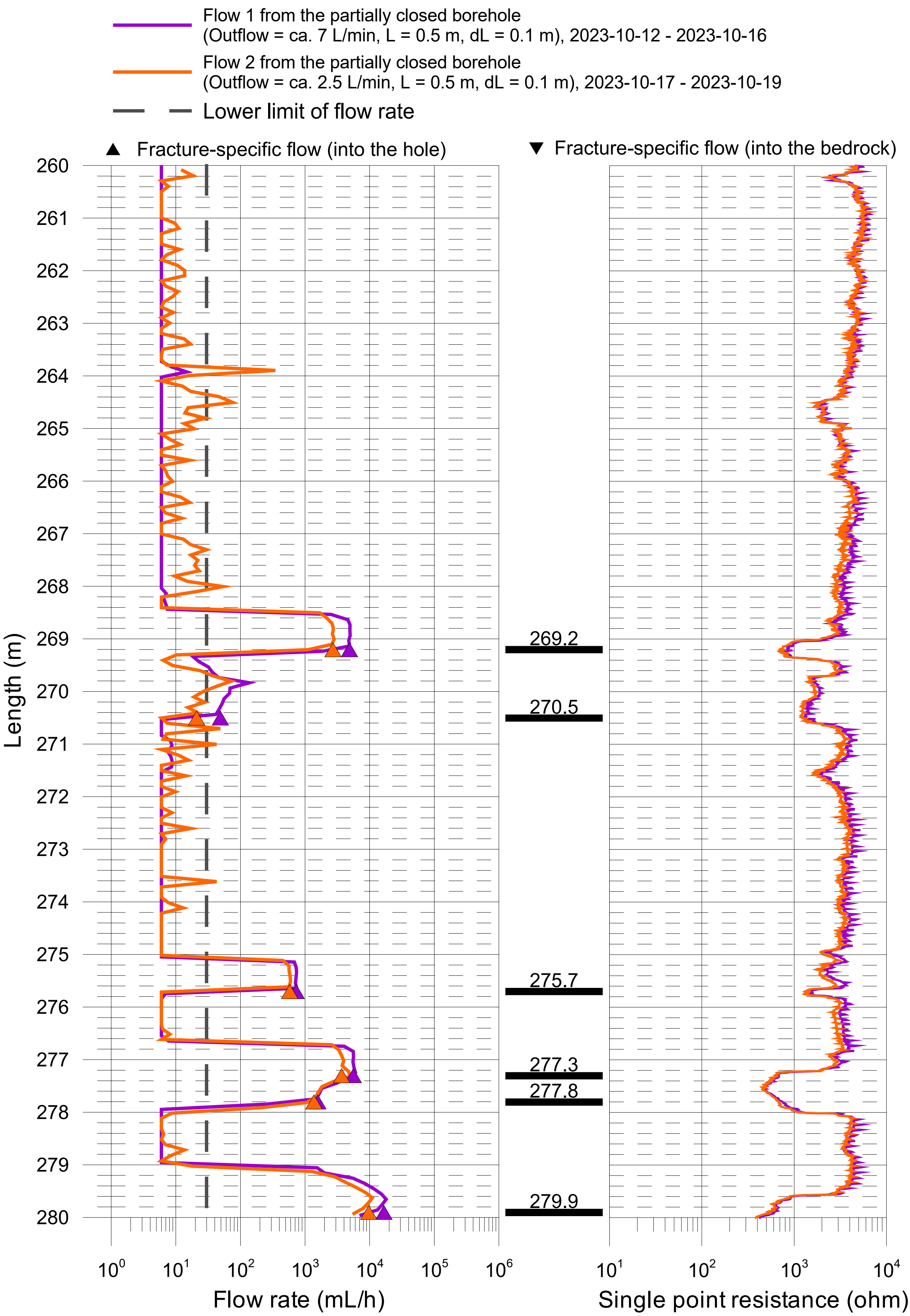
Forsmark, borehole KFR90
Flow rate and single point resistance



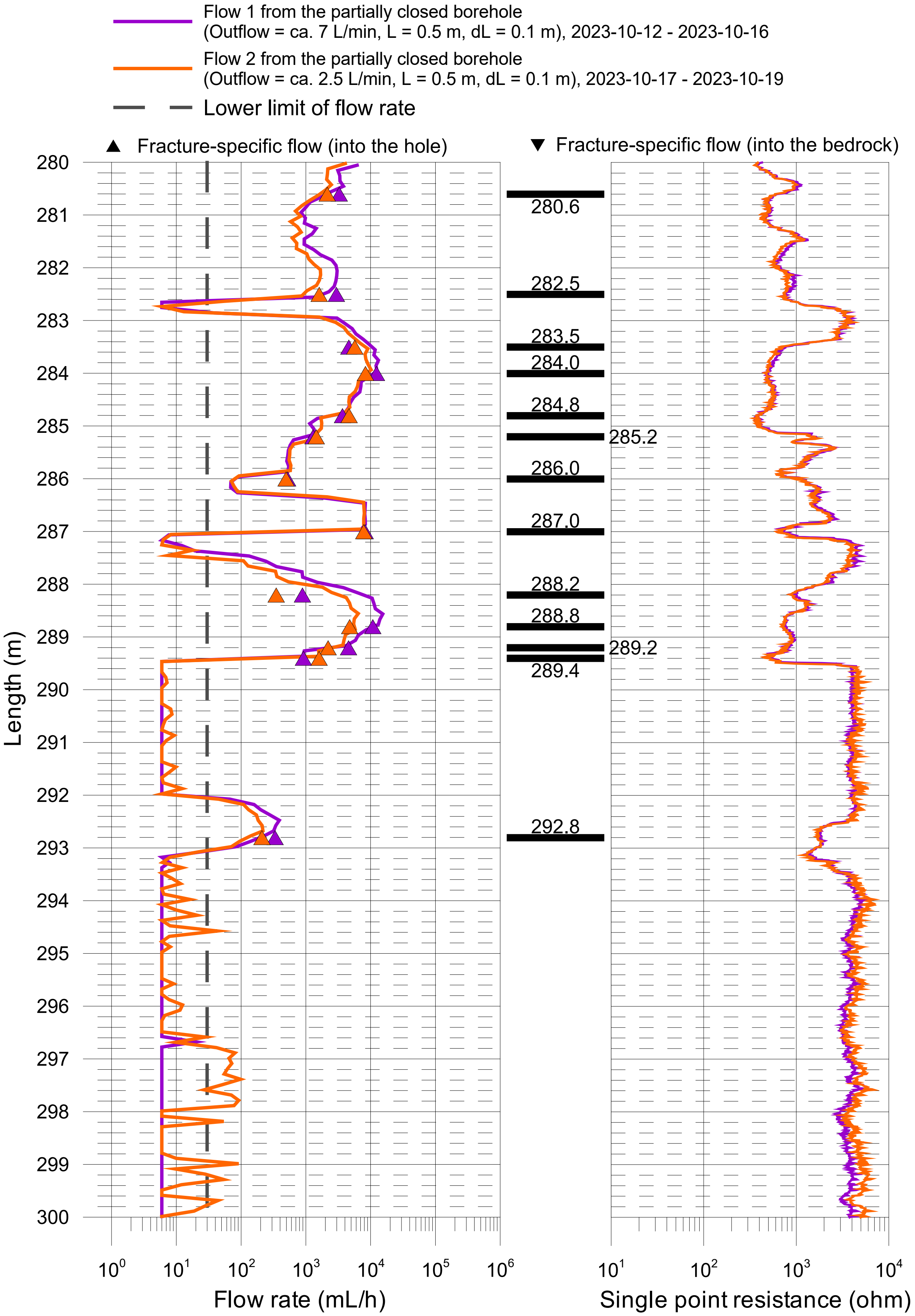

Forsmark, borehole KFR90
Flow rate and single point resistance
Flow 1 from the partially closed borehole
(Outflow = ca. 7 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-12 - 2023-10-16
Flow 2 from the partially closed borehole
(Outflow = ca. 2.5 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-17 - 2023-10-19
Lower limit of flow rate
Fracture-specific flow (into the hole)
Fracture-specific flow (into the bedrock)
Length (m)
220
221
222
223
224
225
226
227
228
229
230
231
232
233
234
235
236
237
238
239
240
220.2
221.5
222.0
227.0
235.4
236.9
239.3
239.9
Flow rate (mL/h)
Single point resistance (ohm)


Forsmark, borehole KFR90
Flow rate and single point resistance
Flow 1 from the partially closed borehole
(Outflow = ca. 7 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-12 - 2023-10-16
Flow 2 from the partially closed borehole
(Outflow = ca. 2.5 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-17 - 2023-10-19
Lower limit of flow rate
▲ Fracture-specific flow (into the hole)
▼ Fracture-specific flow (into the bedrock)
Length (m)
240
241
242
243
244
245
246
247
248
249
250
251
252
253
254
255
256
257
258
259
260
246.8
249.7
250.2
251.0
251.6
252.9
253.4
254.7
255.3
256.3
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
Single point resistance (ohm)

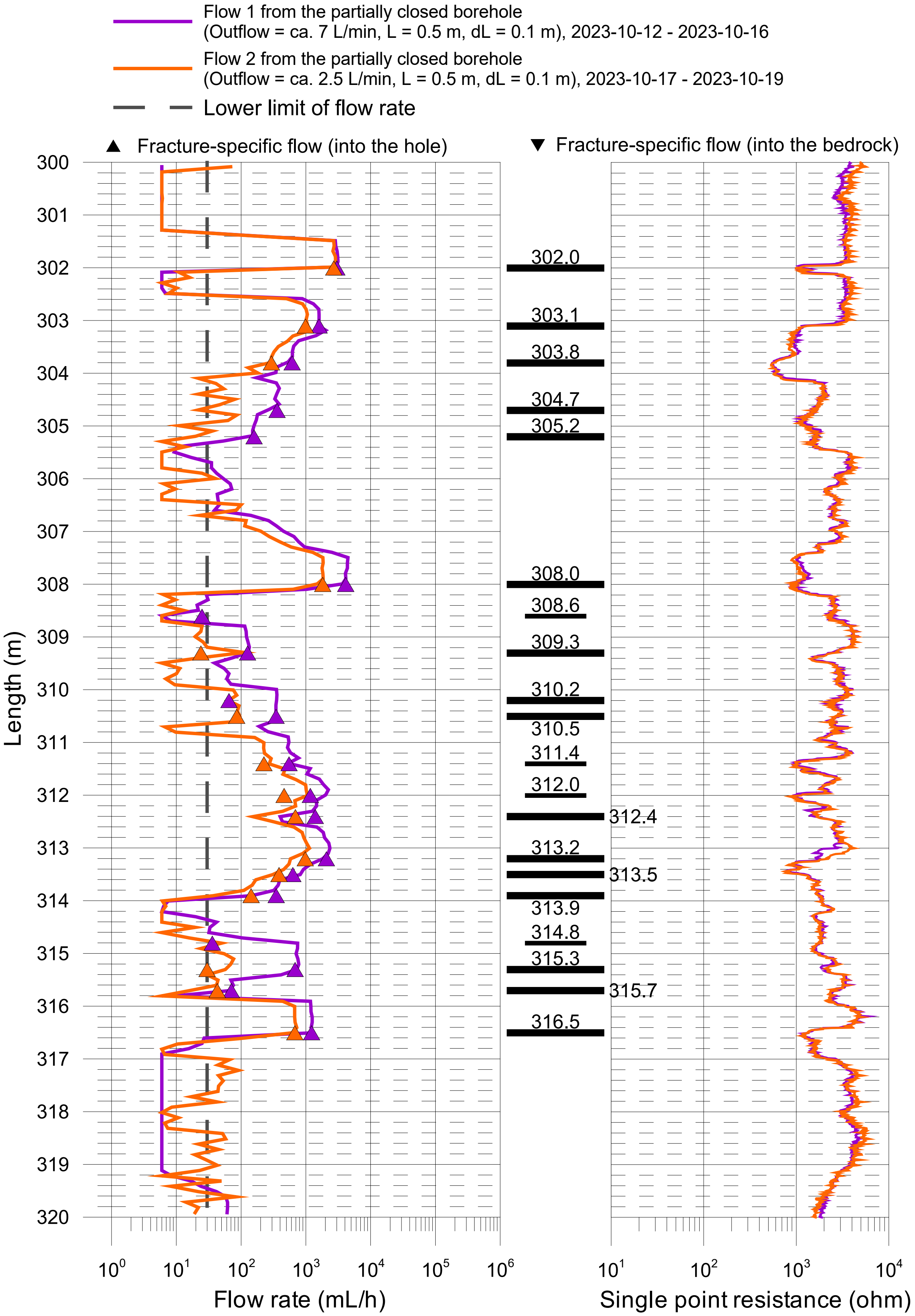
Forsmark, borehole KFR90
Flow rate and single point resistance

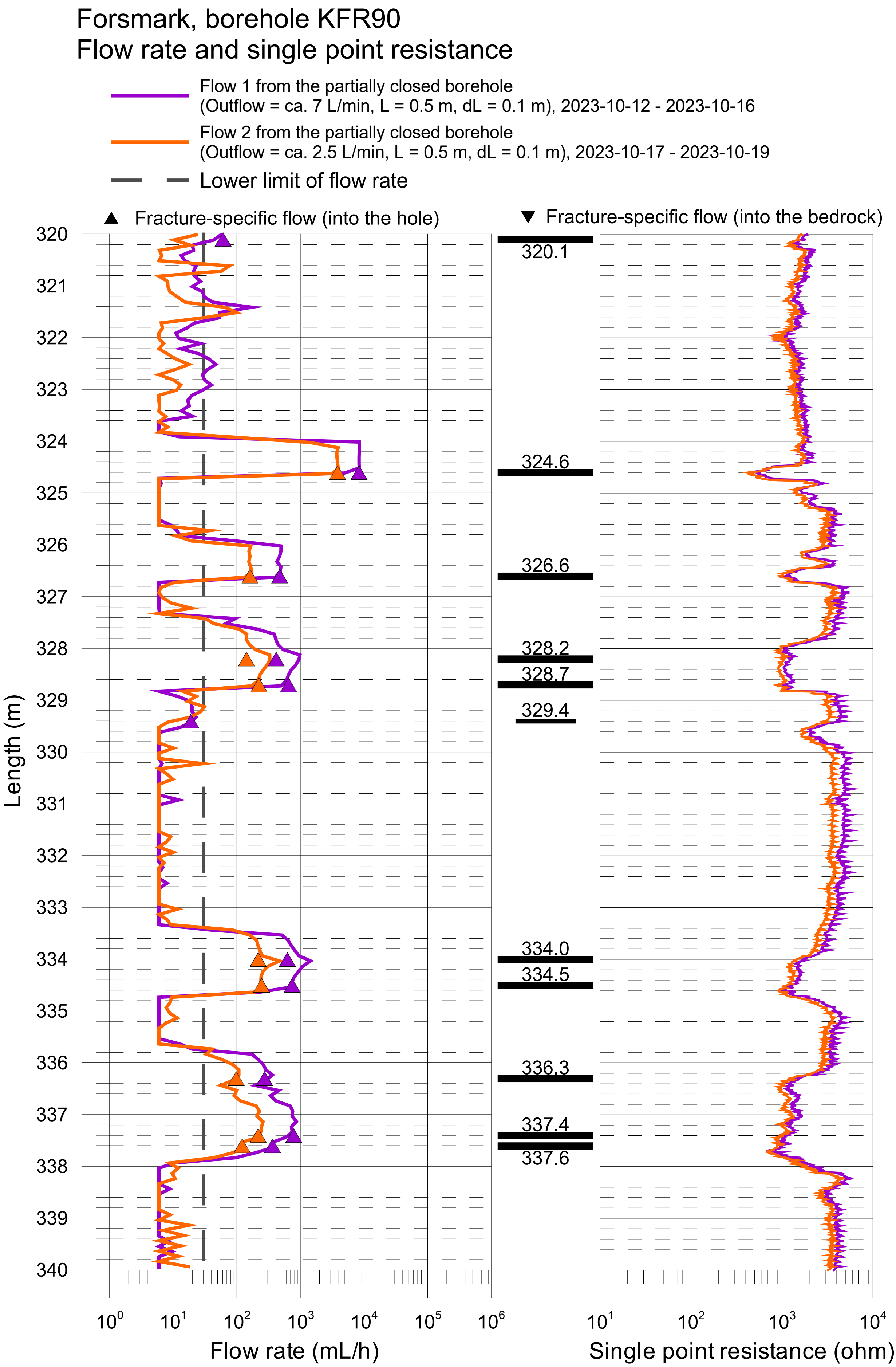


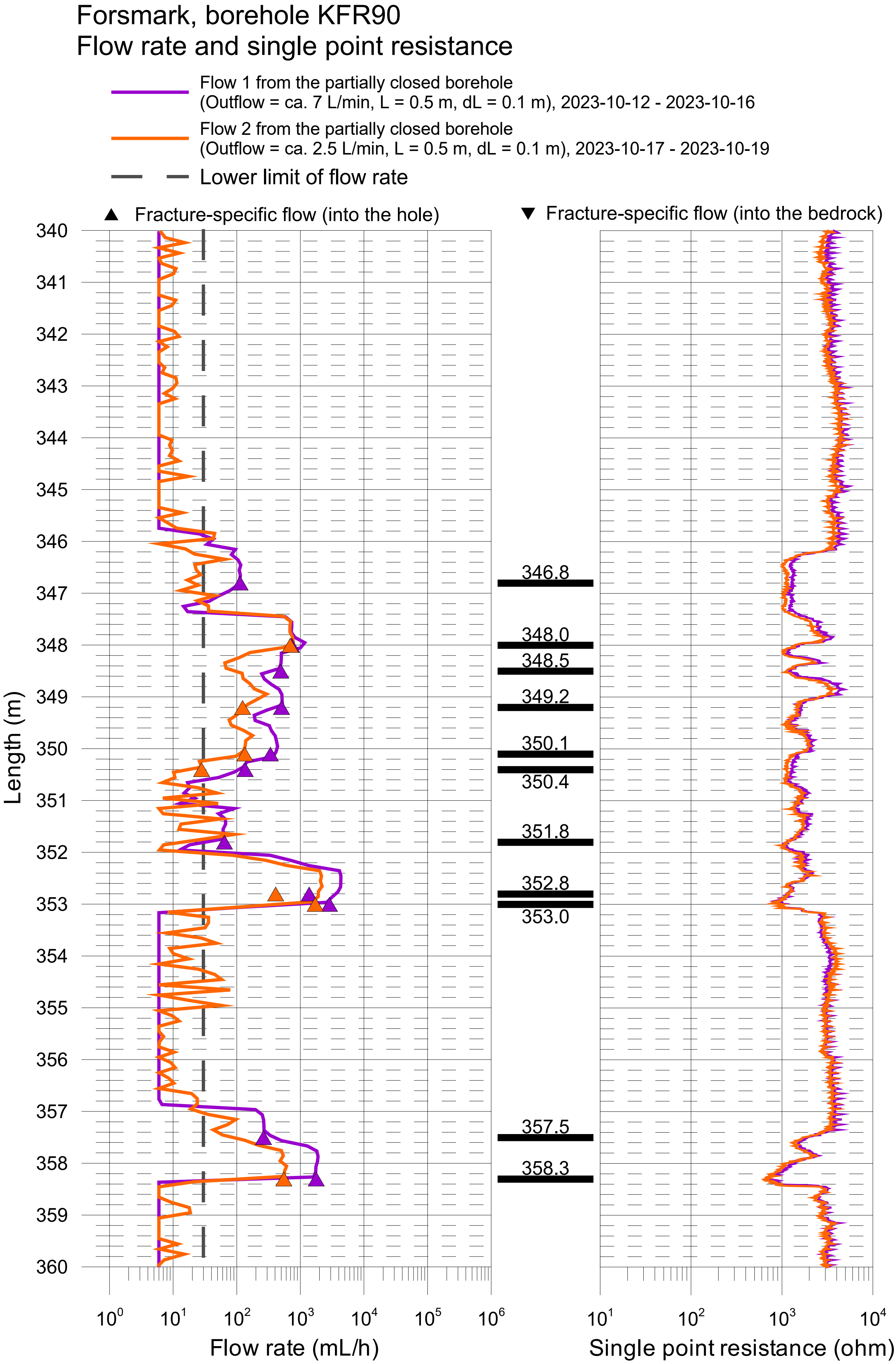
Forsmark, borehole KFR90
Flow rate and single point resistance

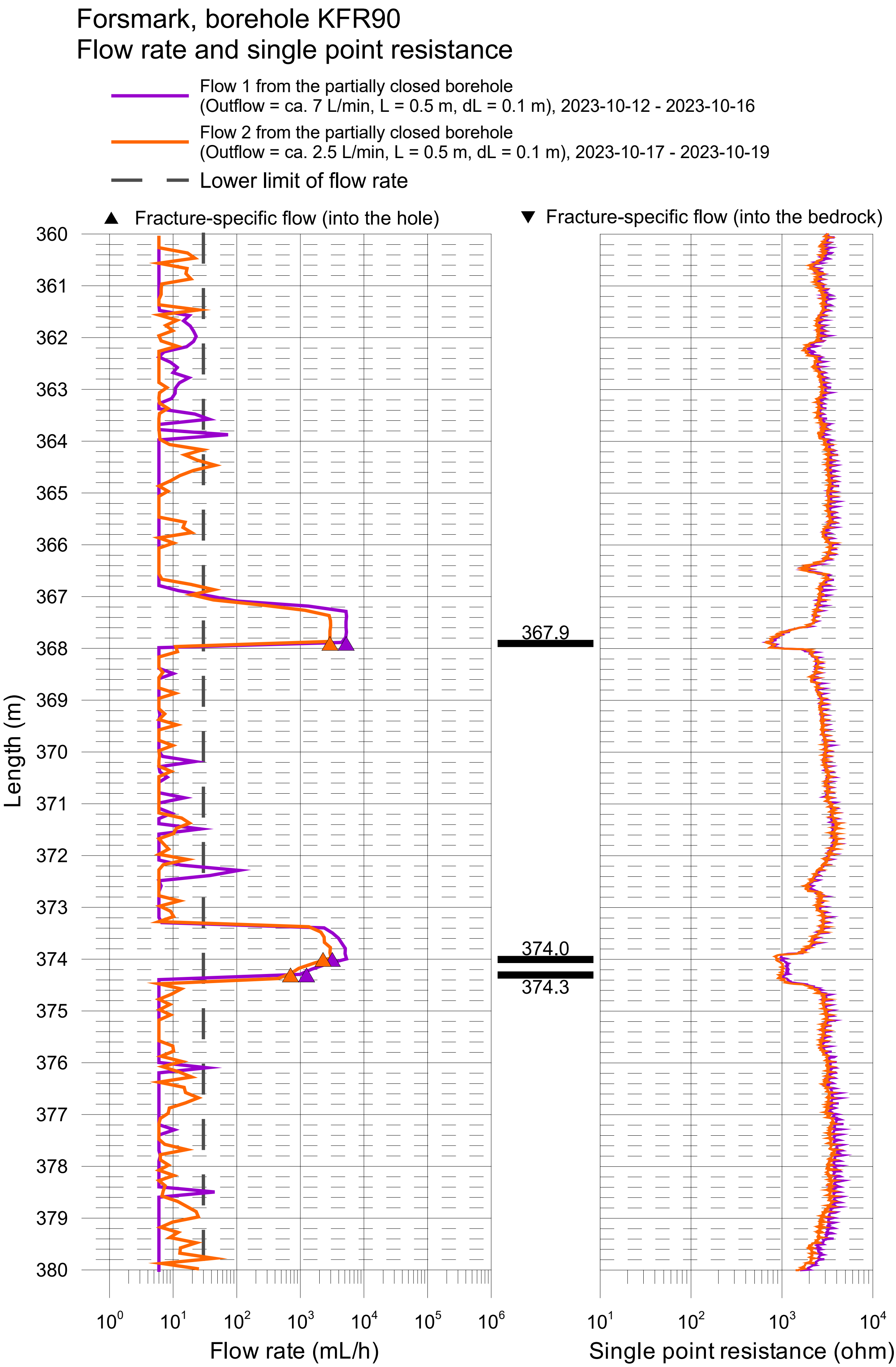


Forsmark, borehole KFR90
Flow rate and single point resistance

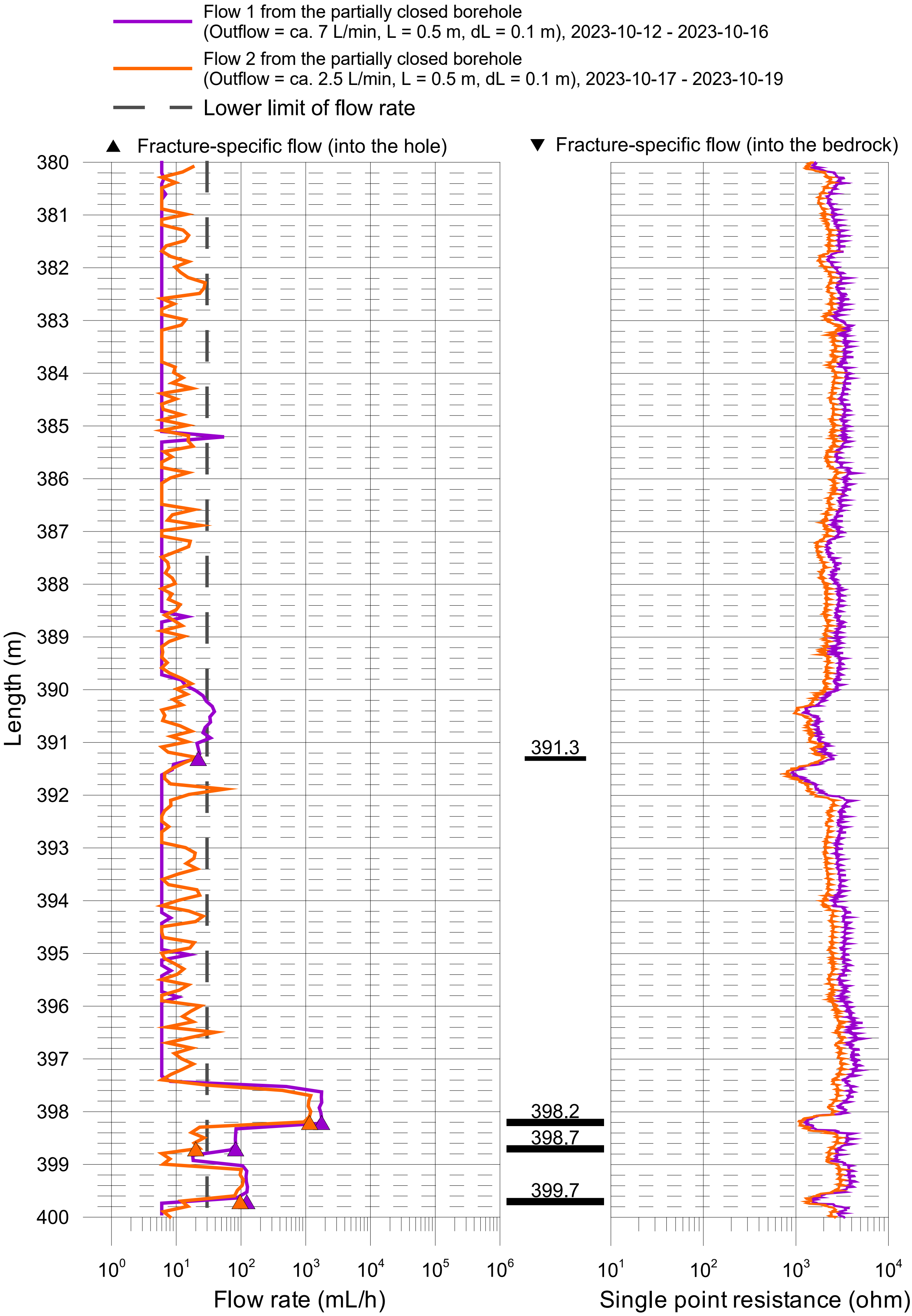



Forsmark, borehole KFR90
Flow rate and single point resistance
Flow 1 from the partially closed borehole
(Outflow = ca. 7 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-12 - 2023-10-16
Flow 2 from the partially closed borehole
(Outflow = ca. 2.5 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-17 - 2023-10-19
Lower limit of flow rate
Fracture-specific flow (into the hole)
Fracture-specific flow (into the bedrock)
Length (m)
320
321
322
323
324
325
326
327
328
329
330
331
332
333
334
335
336
337
338
339
340
320.1
324.6
326.6
328.2
328.7
329.4
334.0
334.5
336.3
337.4
337.6
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
Single point resistance (ohm)

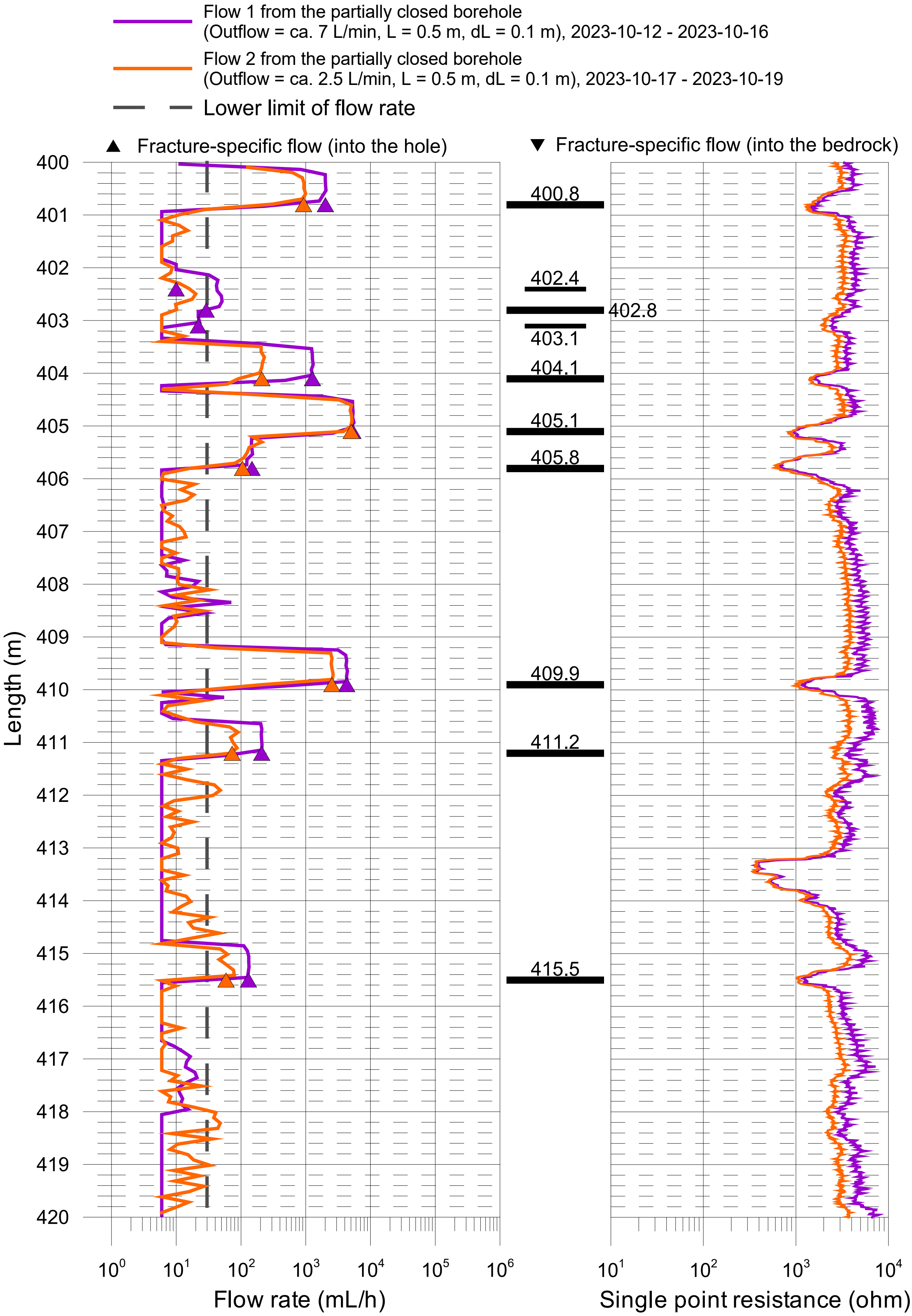

Forsmark, borehole KFR90
Flow rate and single point resistance
Flow 1 from the partially closed borehole
(Outflow = ca. 7 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-12 - 2023-10-16
Flow 2 from the partially closed borehole
(Outflow = ca. 2.5 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-17 - 2023-10-19
Lower limit of flow rate
Fracture-specific flow (into the hole)
Fracture-specific flow (into the bedrock)
Length (m)
340
341
342
343
344
345
346
347
348
349
350
351
352
353
354
355
356
357
358
359
360
346.8
348.0
348.5
349.2
350.1
350.4
351.8
352.8
353.0
357.5
358.3
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
Single point resistance (ohm)


Forsmark, borehole KFR90
Flow rate and single point resistance
Flow 1 from the partially closed borehole
(Outflow = ca. 7 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-12 - 2023-10-16
Flow 2 from the partially closed borehole
(Outflow = ca. 2.5 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-17 - 2023-10-19
Lower limit of flow rate
▲ Fracture-specific flow (into the hole)
▼ Fracture-specific flow (into the bedrock)
Length (m)
360
361
362
363
364
365
366
367
368
369
370
371
372
373
374
375
376
377
378
379
380
367.9
374.0
374.3
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
Single point resistance (ohm)

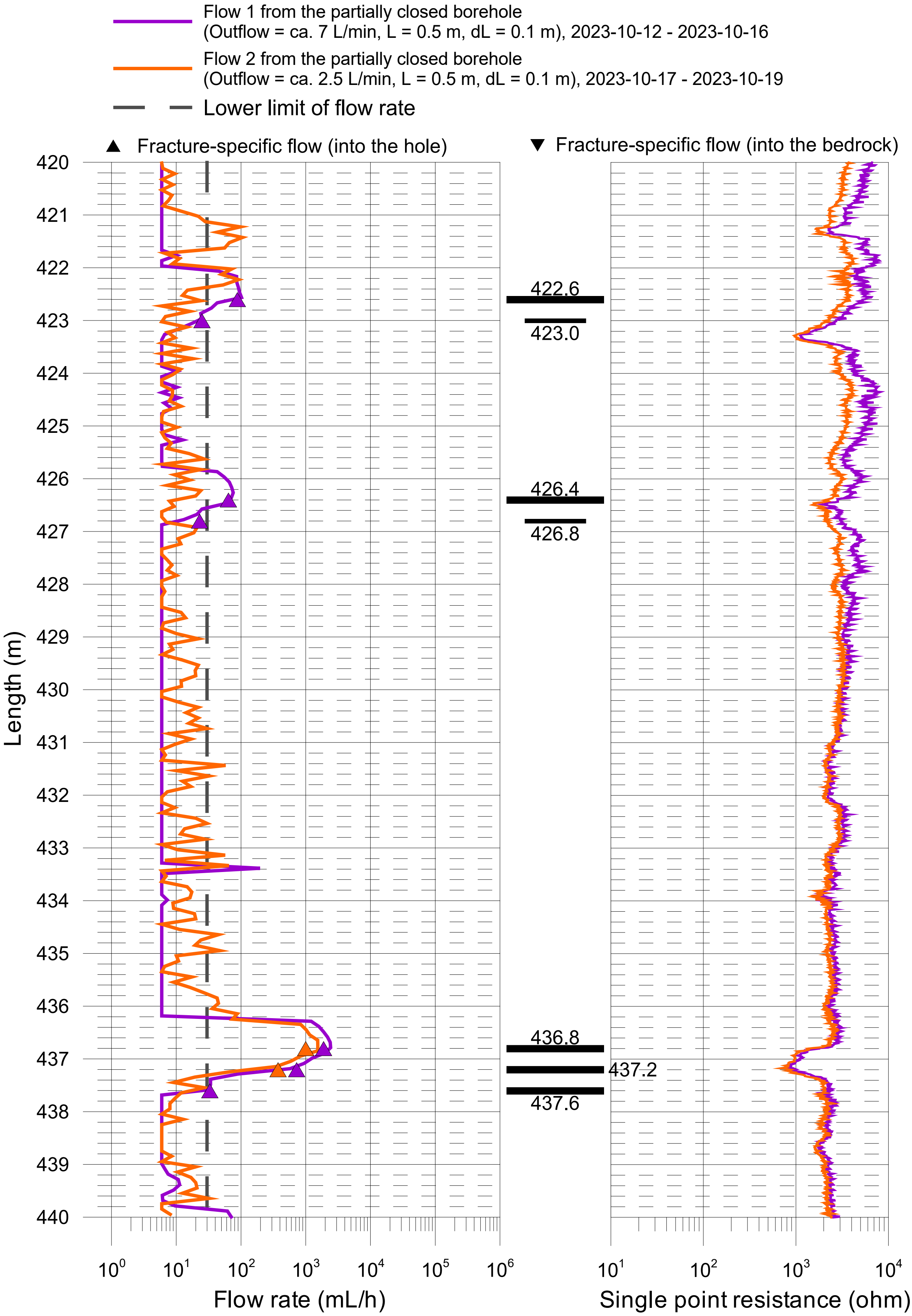
Forsmark, borehole KFR90
Flow rate and single point resistance

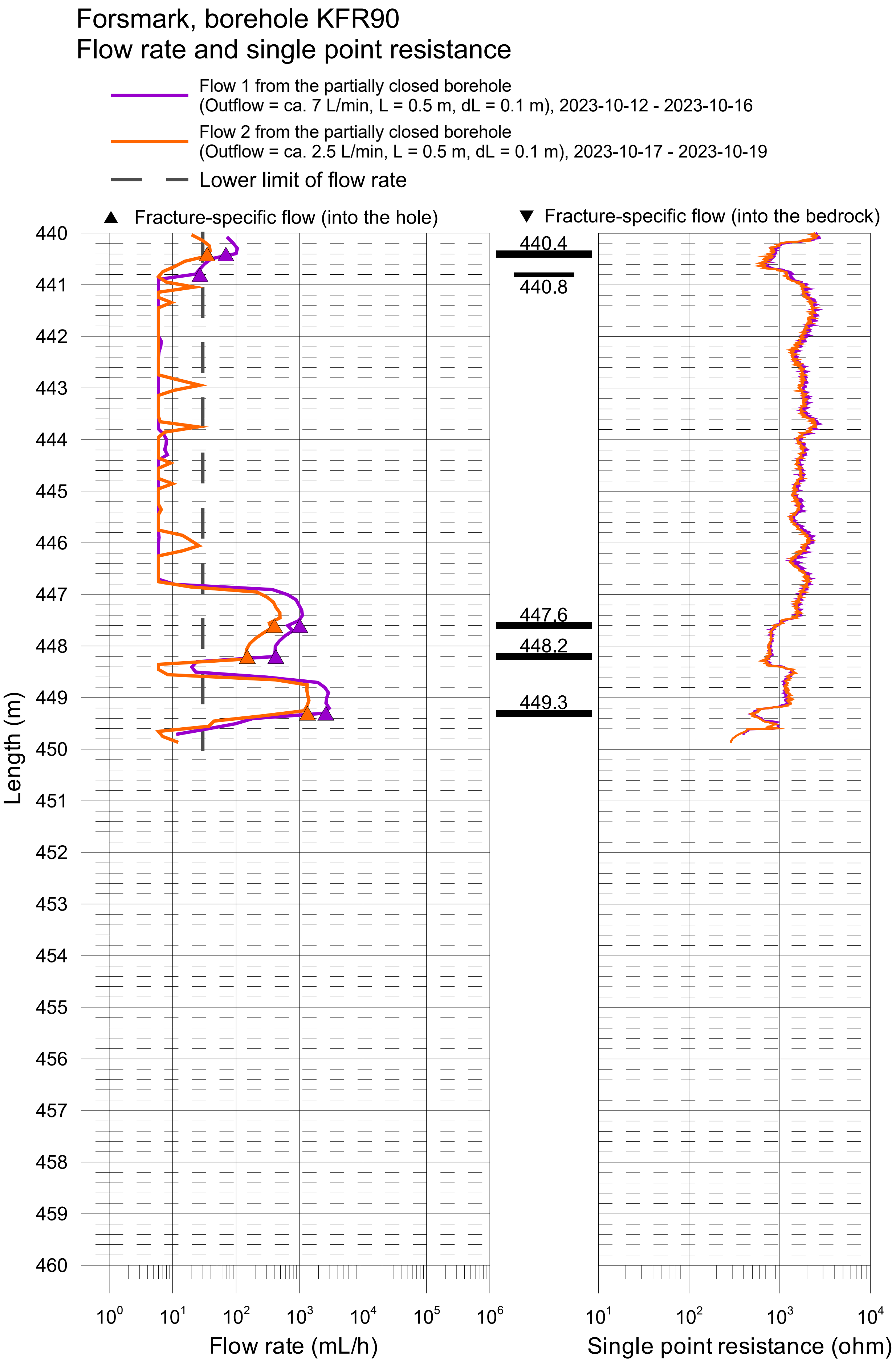


Forsmark, borehole KFR90
Flow rate and single point resistance



Forsmark, borehole KFR90
Flow rate and single point resistance




Forsmark, borehole KFR90
Flow rate and single point resistance
Flow 1 from the partially closed borehole
(Outflow = ca. 7 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-12 - 2023-10-16
Flow 2 from the partially closed borehole
(Outflow = ca. 2.5 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-17 - 2023-10-19
Lower limit of flow rate
Fracture-specific flow (into the hole)
Fracture-specific flow (into the bedrock)
Length (m)
440
441
442
443
444
445
446
447
448
449
450
451
452
453
454
455
456
457
458
459
460
440.4
440.8
447.6
448.2
449.3
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
Single point resistance (ohm)

Glossary of terms used in the tables of Appendices 4.1–4.5

Header	Unit	Explanations
Borehole		ID for borehole
Length to flow anom. L (m)	m	Length along the borehole to inferred flowing fracture 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_1	m^3/s	Measured flow rate through the measurement section during the first pumping period
Q_2	m^3/s	Measured flow rate through the measurement section during the second pumping period
h_{1FW}	m.a.s.l.	Corrected hydraulic head along the hole due to e.g., varying salinity conditions of the borehole fluid during the first pumping period
h_{2FW}	m.a.s.l.	Corrected hydraulic head along the hole due to e.g., varying salinity conditions of the borehole fluid during the second 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.
h_i	m.a.s.l.	Calculated relative, natural freshwater head for measurement section (undisturbed conditions)

Inferred flow anomalies from overlapping flow logging

Borehole	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_1 (m^3/s)	h_{1FW} (masl)	Q_2 (m^3/s)	h_{2FW} (masl)	T_D (m^2/s)	h_i (masl)	Com-ments
KFR90	2.7	0.5	0.1	-1.29E-06	-40.52	-2.83E-06	-18.65	6.96E-08	-58.92	
KFR90	4.5	0.5	0.1	-1.75E-08	-40.51	-2.31E-08	-18.64	2.51E-10	-109.40	
KFR90	5.6	0.5	0.1	-6.11E-09	-40.51	-8.89E-09	-18.62	1.26E-10	-88.67	4
KFR90	6.1	0.5	0.1	-7.81E-08	-40.53	-8.94E-08	-18.63	5.14E-10	-190.63	1
KFR90	8.3	0.5	0.1	-5.28E-09	-40.47	-1.28E-08	-18.64	3.40E-10	-55.83	4
KFR90	8.8	0.5	0.1	-4.69E-07	-40.57	-7.03E-07	-18.65	1.05E-08	-84.67	
KFR90	10.8	0.5	0.1	-6.00E-07	-40.53	-1.45E-06	-18.66	3.86E-08	-55.92	
KFR90	12.4	0.5	0.1	-8.89E-09	-40.52	-8.06E-09	-18.65	-	-	2, 4
KFR90	14.0	0.5	0.1	-1.75E-06	-40.52	-2.13E-06	-18.62	1.72E-08	-141.07	1
KFR90	14.9	0.5	0.1	-5.56E-09	-40.48	-9.17E-09	-18.61	1.63E-10	-74.13	4
KFR90	16.0	0.5	0.1	-1.14E-07	-40.51	-2.02E-07	-18.57	3.97E-09	-68.96	
KFR90	19.7	0.5	0.1	1.47E-08	-40.48	-4.00E-08	-18.62	2.48E-09	-34.60	4
KFR90	23.6	0.5	0.1	9.50E-08	-40.4	-1.83E-08	-18.6	5.14E-09	-22.13	
KFR90	24.5	0.5	0.1	5.28E-09	-40.43	-	-18.58	2.39E-10	-	4
KFR90	27.5	0.5	0.1	1.14E-08	-40.36	-	-18.58	5.17E-10	-	
KFR90	30.0	0.5	0.1	3.92E-08	-40.39	-	-18.58	1.78E-09	-	
KFR90	34.0	0.5	0.1	3.33E-07	-40.3	-3.11E-07	-18.55	2.93E-08	-29.05	
KFR90	34.5	0.5	0.1	1.64E-07	-40.3	-1.84E-07	-18.56	1.58E-08	-30.08	
KFR90	41.1	0.5	0.1	3.61E-07	-40.33	-7.25E-07	-18.48	4.92E-08	-33.07	
KFR90	44.7	0.5	0.1	1.03E-07	-40.32	-1.56E-08	-18.49	5.39E-09	-21.35	
KFR90	45.2	0.5	0.1	5.00E-09	-40.32	-	-18.5	2.27E-10	-	3, 4
KFR90	48.5	0.5	0.1	1.44E-08	-40.41	-9.44E-09	-18.43	1.07E-09	-27.12	4
KFR90	50.0	0.5	0.1	1.39E-08	-41.12	-1.58E-08	-18.37	1.29E-09	-30.49	
KFR90	53.1	0.5	0.1	3.33E-09	-41.16	-5.00E-09	-18.37	3.62E-10	-32.04	4
KFR90	55.6	0.5	0.1	7.50E-09	-41.08	-5.83E-09	-18.37	5.81E-10	-28.31	4
KFR90	58.4	0.5	0.1	3.33E-09	-41.13	-	-18.38	1.45E-10	-	3, 4
KFR90	75.2	0.5	0.1	1.06E-08	-41.14	-	-18.14	4.54E-10	-	3
KFR90	76.1	0.5	0.1	9.72E-09	-41.11	-	-18.11	4.18E-10	-	3
KFR90	78.7	0.5	0.1	4.17E-09	-41.17	-	-18.09	1.79E-10	-	3, 4
KFR90	79.5	0.5	0.1	3.03E-08	-41.18	-8.89E-09	-18.15	1.68E-09	-23.38	
KFR90	80.1	0.5	0.1	1.11E-08	-41.14	-3.61E-09	-18.15	6.33E-10	-23.79	
KFR90	80.6	0.5	0.1	1.00E-08	-41.18	-	-18.17	4.30E-10	-	3
KFR90	82.0	0.5	0.1	1.13E-07	-41.16	-1.04E-07	-18.15	9.36E-09	-29.19	
KFR90	82.4	0.5	0.1	1.10E-07	-41.16	-1.24E-07	-18.15	1.01E-08	-30.36	
KFR90	85.4	0.5	0.1	3.33E-09	-41.2	-	-18.16	1.43E-10	-	3, 4
KFR90	98.1	0.5	0.1	1.66E-07	-41.21	-6.11E-07	-18.2	3.34E-08	-36.29	
KFR90	100.8	0.5	0.1	1.26E-07	-41.24	-	-18.15	5.40E-09	-	3
KFR90	102.5	0.5	0.1	6.39E-09	-41.21	-2.81E-08	-18.15	1.48E-09	-36.93	4
KFR90	103.8	0.5	0.1	4.72E-09	-41.28	8.33E-09	-18.15	-	-	2, 4
KFR90	111.3	0.5	0.1	6.94E-08	-41.24	-	-18.17	2.98E-09	-	3
KFR90	112.1	0.5	0.1	6.94E-09	-41.26	-	-18.17	2.97E-10	-	3, 4
KFR90	114.6	0.5	0.1	5.56E-09	-41.22	-	-18.15	2.38E-10	-	3, 4
KFR90	121.7	0.5	0.1	1.13E-05	-41.28	2.31E-06	-18.17	3.86E-07	-12.26	
KFR90	122.6	0.5	0.1	4.69E-08	-41.31	1.17E-08	-18.21	1.51E-09	-10.57	
KFR90	123.1	0.5	0.1	7.00E-08	-41.29	1.44E-08	-18.21	2.38E-09	-12.21	

Inferred flow anomalies from overlapping flow logging

Borehole	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_1 (m^3/s)	h_{1FW} (masl)	Q_2 (m^3/s)	h_{2FW} (masl)	T_D (m^2/s)	h_i (masl)	Com-ments
KFR90	124.1	0.5	0.1	1.50E-07	-41.3	2.33E-08	-18.22	5.43E-09	-13.97	
KFR90	125.3	0.5	0.1	4.83E-07	-41.26	1.09E-07	-18.19	1.60E-08	-11.46	
KFR90	129.6	0.5	0.1	2.11E-07	-41.24	8.83E-08	-18.17	5.25E-09	-1.53	
KFR90	130.0	0.5	0.1	4.97E-06	-41.26	1.44E-06	-18.18	1.51E-07	-8.76	
KFR90	131.2	0.5	0.1	5.94E-07	-41.25	1.34E-07	-18.16	1.97E-08	-11.47	
KFR90	132.7	0.5	0.1	1.14E-08	-41.3	-	-18.18	4.87E-10	-	3
KFR90	135.9	0.5	0.1	4.08E-06	-41.27	1.46E-06	-18.18	1.13E-07	-5.39	
KFR90	136.7	0.5	0.1	2.58E-06	-41.33	1.34E-06	-18.27	5.35E-08	6.43	
KFR90	137.5	0.5	0.1	5.00E-09	-41.33	-	-18.23	2.14E-10	-	3, 4
KFR90	140.2	0.5	0.1	3.06E-08	-41.33	9.17E-09	-18.23	9.16E-10	-8.33	
KFR90	140.5	0.5	0.1	2.36E-08	-41.35	3.33E-09	-18.22	8.67E-10	-14.42	
KFR90	141.2	0.5	0.1	6.94E-09	-41.29	-	-18.22	2.98E-10	-	3, 4
KFR90	142.1	0.5	0.1	3.06E-09	-41.3	-	-18.22	1.31E-10	-	3, 4
KFR90	142.5	0.5	0.1	1.17E-08	-41.28	-	-18.22	5.00E-10	-	3
KFR90	143.1	0.5	0.1	4.00E-08	-41.3	-	-18.22	1.71E-09	-	3
KFR90	144.3	0.5	0.1	2.37E-07	-41.33	6.03E-08	-18.22	7.56E-09	-10.33	
KFR90	145.1	0.5	0.1	5.00E-09	-41.35	-	-18.21	2.14E-10	-	3, 4
KFR90	146.5	0.5	0.1	3.11E-07	-41.34	9.39E-08	-18.21	9.29E-09	-8.21	
KFR90	150.8	0.5	0.1	3.39E-06	-41.38	6.89E-07	-18.23	1.15E-07	-12.32	
KFR90	151.8	0.5	0.1	4.00E-06	-41.36	7.69E-07	-18.24	1.38E-07	-12.73	
KFR90	153.0	0.5	0.1	2.26E-07	-41.37	8.78E-08	-18.21	5.92E-09	-3.54	
KFR90	153.5	0.5	0.1	3.94E-07	-41.37	1.19E-07	-18.25	1.18E-08	-8.24	
KFR90	154.0	0.5	0.1	3.19E-07	-41.4	7.25E-08	-18.21	1.05E-08	-11.40	
KFR90	154.8	0.5	0.1	2.21E-06	-41.39	5.81E-07	-18.24	6.95E-08	-9.98	
KFR90	160.4	0.5	0.1	3.92E-07	-41.44	6.86E-08	-18.28	1.38E-08	-13.36	4
KFR90	161.1	0.5	0.1	8.00E-07	-41.41	4.25E-07	-18.28	1.60E-08	7.93	
KFR90	161.6	0.5	0.1	1.36E-07	-41.44	7.06E-08	-18.27	2.77E-09	6.88	
KFR90	162.8	0.5	0.1	3.22E-08	-41.42	1.17E-08	-18.25	8.77E-10	-5.10	4
KFR90	163.3	0.5	0.1	1.24E-07	-41.43	4.78E-08	-18.28	3.24E-09	-3.69	
KFR90	163.9	0.5	0.1	1.14E-08	-41.45	-	-18.30	4.87E-10	-	3
KFR90	164.5	0.5	0.1	3.03E-08	-41.44	1.25E-08	-18.26	7.59E-10	-1.96	
KFR90	164.8	0.5	0.1	1.00E-08	-41.45	5.83E-09	-18.26	1.78E-10	14.21	
KFR90	165.1	0.5	0.1	4.72E-09	-41.44	2.50E-09	-18.27	9.49E-11	7.80	4
KFR90	166.4	0.5	0.1	5.00E-09	-41.43	-	-18.24	2.13E-10	-	3, 4
KFR90	166.9	0.5	0.1	1.94E-08	-41.44	1.11E-08	-18.22	3.55E-10	12.74	
KFR90	167.5	0.5	0.1	3.11E-08	-41.47	1.31E-08	-18.27	7.70E-10	-1.49	
KFR90	168.1	0.5	0.1	3.42E-07	-41.45	1.27E-07	-18.23	9.16E-09	-4.55	
KFR90	169.4	0.5	0.1	2.33E-07	-41.47	1.16E-07	-18.29	4.98E-09	4.78	
KFR90	171.3	0.5	0.1	3.61E-09	-41.41	-	-18.26	1.54E-10	-	3, 4
KFR90	172.2	0.5	0.1	1.03E-08	-41.46	-	-18.28	4.39E-10	-	3
KFR90	174.7	0.5	0.1	4.78E-08	-41.47	1.78E-08	-18.27	1.28E-09	-4.52	
KFR90	175.2	0.5	0.1	2.31E-08	-41.46	-	-18.28	9.84E-10	-	3
KFR90	178.2	0.5	0.1	3.58E-06	-41.49	1.39E-06	-18.28	9.35E-08	-3.59	
KFR90	178.6	0.5	0.1	6.67E-09	-41.49	-	-18.29	2.84E-10	-	3, 4
KFR90	179.6	0.5	0.1	5.69E-07	-41.47	2.41E-07	-18.30	1.40E-08	-1.35	

Inferred flow anomalies from overlapping flow logging

Borehole	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_1 (m^3/s)	h_{1FW} (masl)	Q_2 (m^3/s)	h_{2FW} (masl)	T_D (m^2/s)	h_i (masl)	Com-ments
KFR90	180.1	0.5	0.1	6.11E-09	-41.48	-	-18.29	2.61E-10	-	3, 4
KFR90	182.5	0.5	0.1	1.68E-06	-41.5	1.31E-06	-18.3	1.60E-08	62.47	
KFR90	184.2	0.5	0.1	2.97E-06	-41.56	1.16E-06	-18.32	7.71E-08	-3.42	
KFR90	185.6	0.5	0.1	1.03E-08	-41.55	1.11E-08	-18.32	-	-	2
KFR90	186.1	0.5	0.1	1.11E-08	-41.56	5.56E-09	-18.32	2.36E-10	4.92	
KFR90	186.4	0.5	0.1	7.22E-09	-41.58	-	-18.32	3.07E-10	-	3, 4
KFR90	188.5	0.5	0.1	3.06E-09	-41.53	-	-18.34	1.30E-10	-	3, 4
KFR90	189.3	0.5	0.1	1.00E-08	-41.58	3.61E-09	-18.32	2.72E-10	-5.17	
KFR90	190.7	0.5	0.1	2.44E-07	-41.62	2.20E-07	-18.38	1.02E-09	195.37	1
KFR90	191.4	0.5	0.1	1.06E-08	-41.59	3.61E-09	-18.4	2.96E-10	-6.34	
KFR90	193.2	0.5	0.1	8.61E-09	-41.61	-	-18.31	3.66E-10	-	3
KFR90	195.1	0.5	0.1	6.94E-09	-41.78	-	-18.34	2.93E-10	-	3, 4
KFR90	197.5	0.5	0.1	1.94E-08	-41.86	9.72E-09	-18.4	4.10E-10	5.06	
KFR90	200.5	0.5	0.1	7.61E-07	-41.89	4.00E-07	-18.34	1.52E-08	7.75	
KFR90	209.0	0.5	0.1	7.22E-09	-42.04	-	-18.43	3.03E-10	-	3, 4
KFR90	215.8	0.5	0.1	6.22E-08	-42.07	2.00E-08	-18.49	1.77E-09	-7.32	
KFR90	217.0	0.5	0.1	1.56E-07	-42.15	6.78E-08	-18.5	3.71E-09	-0.41	4
KFR90	217.4	0.5	0.1	6.31E-07	-42.13	3.78E-07	-18.53	1.06E-08	16.74	
KFR90	218.8	0.5	0.1	5.56E-09	-42.13	-	-18.5	2.33E-10	-	3, 4
KFR90	219.2	0.5	0.1	1.00E-08	-42.18	-	-18.53	4.18E-10	-	3
KFR90	220.2	0.5	0.1	1.38E-07	-42.19	8.56E-08	-18.49	2.20E-09	19.93	
KFR90	221.5	0.5	0.1	5.83E-09	-42.23	-	-18.51	2.43E-10	-	3, 4
KFR90	222.0	0.5	0.1	1.17E-08	-42.21	-	-18.49	4.86E-10	-	3, 4
KFR90	227.0	0.5	0.1	4.00E-08	-42.26	-	-18.53	1.67E-09	-	3
KFR90	235.4	0.5	0.1	9.44E-09	-41.57	-	-18.46	4.04E-10	-	3
KFR90	236.9	0.5	0.1	1.61E-08	-41.57	-	-18.46	6.90E-10	-	3
KFR90	239.3	0.5	0.1	2.94E-08	-41.54	-	-18.48	1.26E-09	-	3
KFR90	239.9	0.5	0.1	3.64E-08	-41.6	-	-18.45	1.55E-09	-	3
KFR90	246.8	0.5	0.1	4.72E-09	-41.7	-	-18.51	2.01E-10	-	3, 4
KFR90	249.7	0.5	0.1	2.45E-07	-41.79	3.53E-08	-18.86	9.06E-09	-15.01	
KFR90	250.2	0.5	0.1	3.11E-07	-41.79	9.31E-08	-18.84	9.40E-09	-9.05	
KFR90	251.0	0.5	0.1	3.31E-07	-41.78	1.47E-07	-18.86	7.92E-09	-0.52	
KFR90	251.6	0.5	0.1	3.86E-07	-41.79	7.50E-07	-18.97	-	-	2
KFR90	252.9	0.5	0.1	1.31E-08	-41.81	-	-18.86	5.63E-10	-	3
KFR90	253.4	0.5	0.1	4.03E-08	-41.8	2.22E-08	-18.86	7.78E-10	9.37	
KFR90	254.7	0.5	0.1	1.32E-07	-41.84	2.17E-08	-18.8	4.75E-09	-14.28	
KFR90	255.3	0.5	0.1	4.44E-09	-41.85	-	-18.8	1.91E-10	-	3, 4
KFR90	256.3	0.5	0.1	1.34E-06	-41.87	6.44E-07	-18.77	2.99E-08	2.58	
KFR90	269.2	0.5	0.1	1.35E-06	-42.13	7.53E-07	-18.7	2.53E-08	10.70	
KFR90	270.5	0.5	0.1	1.36E-08	-41.79	5.83E-09	-18.57	3.31E-10	-1.16	
KFR90	275.7	0.5	0.1	2.03E-07	-41.69	1.61E-07	-18.83	1.81E-09	68.83	
KFR90	277.3	0.5	0.1	1.55E-06	-41.77	1.02E-06	-18.8	2.27E-08	25.69	
KFR90	277.8	0.5	0.1	4.39E-07	-41.81	3.81E-07	-18.83	2.51E-09	131.09	1
KFR90	279.9	0.5	0.1	4.62E-06	-41.87	2.69E-06	-18.78	8.28E-08	13.36	
KFR90	280.6	0.5	0.1	9.11E-07	-41.88	5.97E-07	-18.8	1.35E-08	25.11	

Inferred flow anomalies from overlapping flow logging

Borehole	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_1 (m^3/s)	h_{1FW} (masl)	Q_2 (m^3/s)	h_{2FW} (masl)	T_D (m^2/s)	h_i (masl)	Com-ments
KFR90	282.5	0.5	0.1	8.25E-07	-41.93	4.47E-07	-18.8	1.62E-08	8.58	
KFR90	283.5	0.5	0.1	1.28E-06	-41.93	1.58E-06	-18.81	-	-	2
KFR90	284.0	0.5	0.1	3.42E-06	-41.95	2.31E-06	-18.8	4.71E-08	29.77	
KFR90	284.8	0.5	0.1	1.03E-06	-41.97	1.29E-06	-18.82	-	-	2
KFR90	285.2	0.5	0.1	3.58E-07	-42.01	4.03E-07	-18.84	-	-	2
KFR90	286.0	0.5	0.1	1.46E-07	-42.04	1.38E-07	-18.81	3.31E-10	392.69	1
KFR90	287.0	0.5	0.1	2.29E-06	-42.12	2.18E-06	-18.82	4.72E-09	437.86	1
KFR90	288.2	0.5	0.1	2.46E-07	-42.18	9.69E-08	-18.83	6.32E-09	-3.65	
KFR90	288.8	0.5	0.1	3.00E-06	-42.25	1.32E-06	-18.83	7.11E-08	-0.47	
KFR90	289.2	0.5	0.1	1.27E-06	-42.22	6.14E-07	-18.87	2.78E-08	3.00	
KFR90	289.4	0.5	0.1	2.56E-07	-42.21	4.44E-07	-18.82	-	-	2
KFR90	292.8	0.5	0.1	9.31E-08	-42.53	5.83E-08	-18.88	1.45E-09	20.85	
KFR90	302.0	0.5	0.1	8.39E-07	-41.86	7.50E-07	-19.2	3.88E-09	171.99	1
KFR90	303.1	0.5	0.1	4.44E-07	-41.84	2.74E-07	-19.19	7.44E-09	17.28	
KFR90	303.8	0.5	0.1	1.71E-07	-41.87	8.17E-08	-19.21	3.88E-09	1.61	
KFR90	304.7	0.5	0.1	1.00E-07	-41.93	-	-19.22	4.36E-09	-	3
KFR90	305.2	0.5	0.1	4.42E-08	-41.96	-	-19.2	1.92E-09	-	3
KFR90	308.0	0.5	0.1	1.15E-06	-41.99	5.08E-07	-19.22	2.79E-08	-1.18	
KFR90	308.6	0.5	0.1	6.94E-09	-42.03	-	-19.23	3.01E-10	-	3, 4
KFR90	309.3	0.5	0.1	3.50E-08	-42.05	6.67E-09	-19.19	1.23E-09	-13.81	
KFR90	310.2	0.5	0.1	1.81E-08	-42.03	-	-19.25	7.84E-10	-	3
KFR90	310.5	0.5	0.1	9.64E-08	-42.04	2.39E-08	-19.22	3.14E-09	-11.70	
KFR90	311.4	0.5	0.1	1.53E-07	-42.09	6.28E-08	-19.22	3.88E-09	-3.22	4
KFR90	312.0	0.5	0.1	1.78E-07	-42.16	1.28E-07	-19.22	2.13E-09	40.32	4
KFR90	312.4	0.5	0.1	3.89E-07	-42.2	1.91E-07	-19.24	8.52E-09	2.95	
KFR90	313.2	0.5	0.1	5.77E-07	-42.16	2.72E-07	-19.2	1.31E-08	1.29	
KFR90	313.5	0.5	0.1	1.75E-07	-42.17	1.07E-07	-19.18	2.90E-09	17.34	
KFR90	313.9	0.5	0.1	9.69E-08	-42.18	3.97E-08	-19.19	2.46E-09	-3.23	
KFR90	314.8	0.5	0.1	1.00E-08	-42.24	-	-19.17	4.29E-10	-	3, 4
KFR90	315.3	0.5	0.1	1.89E-07	-42.28	8.33E-09	-19.17	7.75E-09	-18.11	
KFR90	315.7	0.5	0.1	1.97E-08	-42.31	1.19E-08	-19.14	3.32E-10	16.44	
KFR90	316.5	0.5	0.1	3.42E-07	-42.32	1.88E-07	-19.12	6.56E-09	9.19	
KFR90	320.1	0.5	0.1	1.69E-08	-42.64	-	-18.79	7.03E-10	-	3
KFR90	324.6	0.5	0.1	2.33E-06	-42.44	1.07E-06	-18.69	5.26E-08	1.41	
KFR90	326.6	0.5	0.1	1.32E-07	-42.08	4.50E-08	-18.7	3.67E-09	-6.56	
KFR90	328.2	0.5	0.1	1.16E-07	-42.04	3.97E-08	-18.72	3.22E-09	-6.50	
KFR90	328.7	0.5	0.1	1.81E-07	-42.04	6.22E-08	-18.71	5.05E-09	-6.53	
KFR90	329.4	0.5	0.1	5.28E-09	-41.92	-	-18.64	2.24E-10	-	3, 4
KFR90	334.0	0.5	0.1	1.74E-07	-41.98	6.06E-08	-18.79	4.82E-09	-6.37	
KFR90	334.5	0.5	0.1	2.06E-07	-41.97	6.83E-08	-18.8	5.89E-09	-7.33	
KFR90	336.3	0.5	0.1	7.64E-08	-42	2.72E-08	-18.81	2.10E-09	-5.97	
KFR90	337.4	0.5	0.1	2.20E-07	-42.04	6.03E-08	-18.86	6.80E-09	-10.10	
KFR90	337.6	0.5	0.1	1.02E-07	-42.09	3.39E-08	-18.87	2.89E-09	-7.26	
KFR90	346.8	0.5	0.1	3.14E-08	-42.27	-	-19.05	1.34E-09	-19.05	
KFR90	348.0	0.5	0.1	2.02E-07	-42.27	1.92E-07	-18.98	4.25E-10	428.71	1

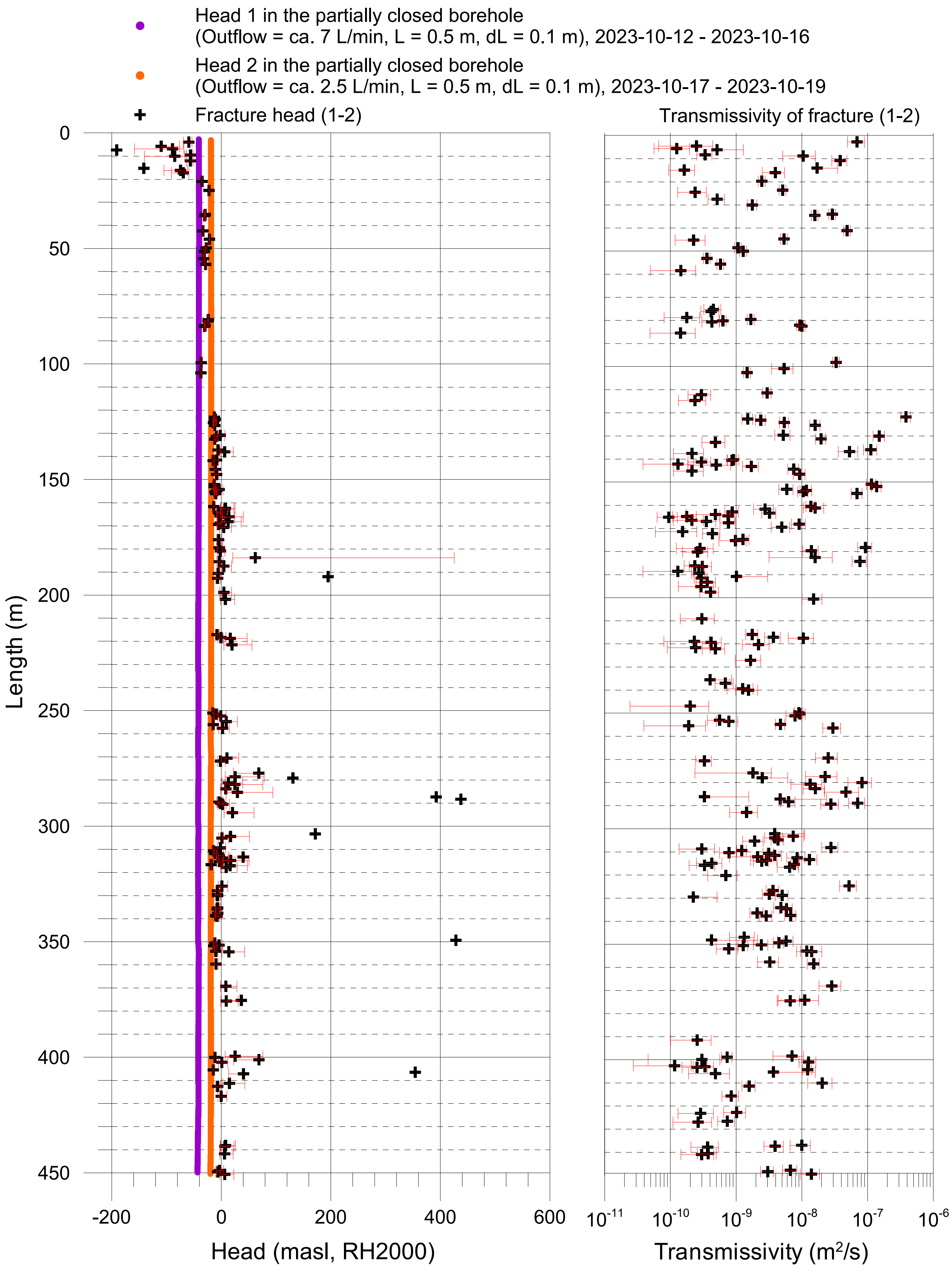
Inferred flow anomalies from overlapping flow logging

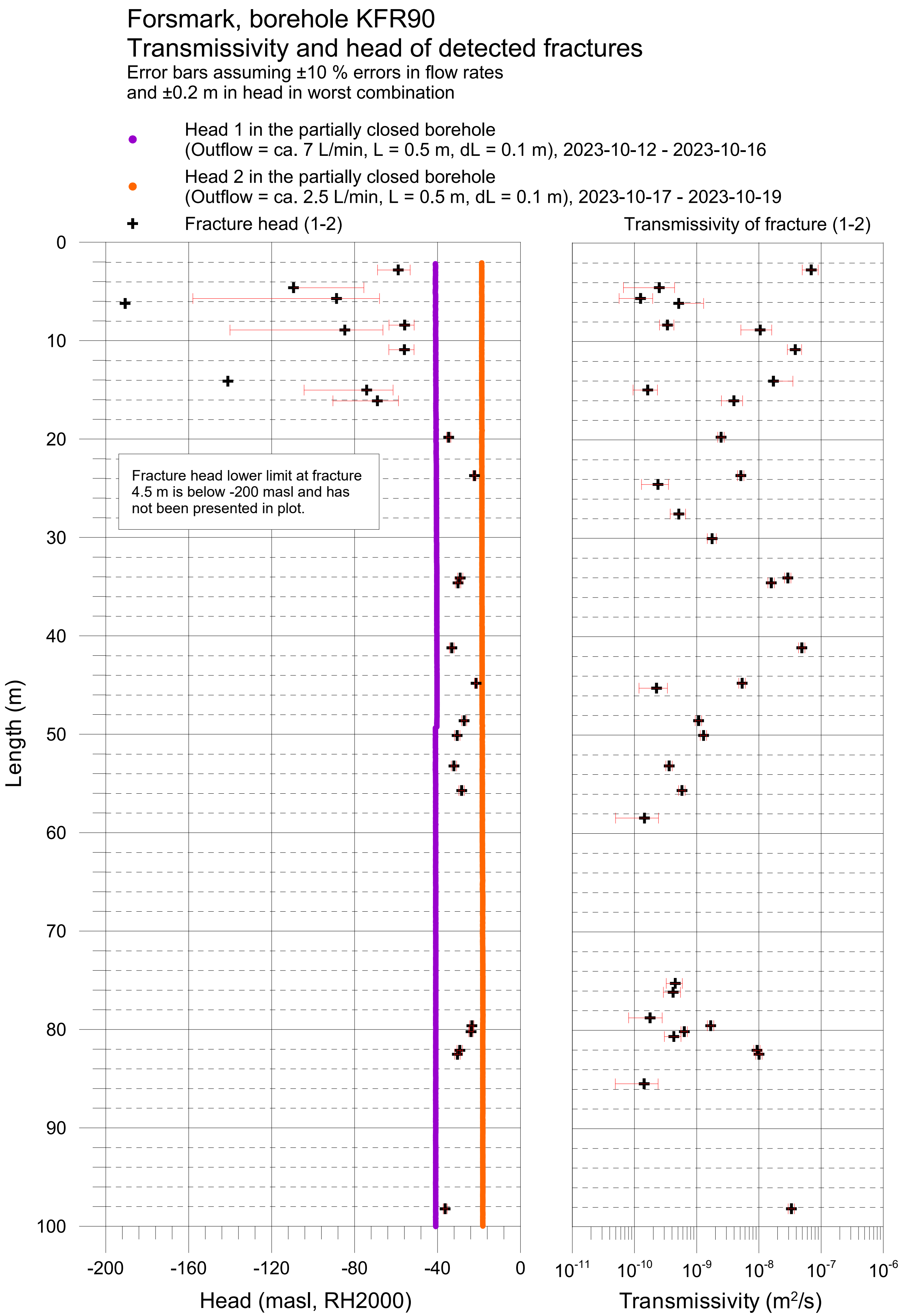
Borehole	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_1 (m^3/s)	h_{1FW} (masl)	Q_2 (m^3/s)	h_{2FW} (masl)	T_D (m^2/s)	h_i (masl)	Com-ments
KFR90	348.5	0.5	0.1	1.37E-07	-42.29	-	-18.98	5.80E-09	-	3
KFR90	349.2	0.5	0.1	1.40E-07	-42.23	3.44E-08	-18.98	4.50E-09	-11.41	
KFR90	350.1	0.5	0.1	9.42E-08	-42.15	3.72E-08	-19.02	2.44E-09	-3.90	
KFR90	350.4	0.5	0.1	3.78E-08	-42.05	7.78E-09	-19.05	1.29E-09	-13.09	
KFR90	351.8	0.5	0.1	1.78E-08	-41.79	-	-19.12	7.76E-10	-	3
KFR90	352.8	0.5	0.1	3.83E-07	-41.43	1.14E-07	-19.13	1.19E-08	-9.72	
KFR90	353.0	0.5	0.1	7.97E-07	-41.39	4.78E-07	-19.14	1.42E-08	14.14	
KFR90	357.5	0.5	0.1	7.31E-08	-41.39	-	-19.26	3.27E-09	-	3
KFR90	358.3	0.5	0.1	4.94E-07	-41.43	1.53E-07	-19.28	1.53E-08	-9.38	
KFR90	367.9	0.5	0.1	1.46E-06	-41.72	8.11E-07	-19.31	2.87E-08	8.65	
KFR90	374.0	0.5	0.1	8.83E-07	-41.71	6.31E-07	-19.2	1.11E-08	36.95	
KFR90	374.3	0.5	0.1	3.47E-07	-41.69	1.95E-07	-19.22	6.70E-09	9.56	
KFR90	391.3	0.5	0.1	6.11E-09	-42.29	-	-18.76	2.57E-10	-	3, 4
KFR90	398.2	0.5	0.1	4.89E-07	-42.34	3.19E-07	-18.8	7.12E-09	25.58	
KFR90	398.7	0.5	0.1	2.31E-08	-42.39	5.56E-09	-18.82	7.34E-10	-11.34	
KFR90	399.7	0.5	0.1	3.42E-08	-42.4	2.69E-08	-18.84	3.03E-10	69.06	
KFR90	400.8	0.5	0.1	5.61E-07	-42.38	2.58E-07	-18.82	1.27E-08	1.28	
KFR90	402.4	0.5	0.1	2.78E-09	-42.4	-	-18.82	1.17E-10	-	3, 4
KFR90	402.8	0.5	0.1	8.06E-09	-42.4	-	-18.8	3.38E-10	-	3
KFR90	403.1	0.5	0.1	6.11E-09	-42.42	-	-18.81	2.56E-10	-	3, 4
KFR90	404.1	0.5	0.1	3.53E-07	-42.44	5.86E-08	-18.82	1.23E-08	-14.11	
KFR90	405.1	0.5	0.1	1.49E-06	-42.46	1.40E-06	-18.81	3.72E-09	354.42	1
KFR90	405.8	0.5	0.1	4.11E-08	-42.45	2.94E-08	-18.8	4.88E-10	40.89	
KFR90	409.9	0.5	0.1	1.20E-06	-42.53	7.06E-07	-18.85	2.05E-08	15.13	
KFR90	411.2	0.5	0.1	5.81E-08	-42.38	2.03E-08	-18.85	1.59E-09	-6.22	
KFR90	415.5	0.5	0.1	3.64E-08	-42.17	1.64E-08	-18.84	8.48E-10	0.28	
KFR90	422.6	0.5	0.1	2.44E-08	-42.49	-	-18.85	1.02E-09	-	3
KFR90	423.0	0.5	0.1	6.94E-09	-42.54	-	-18.83	2.90E-10	-	3, 4
KFR90	426.4	0.5	0.1	1.78E-08	-42.76	-	-18.93	7.38E-10	-	3
KFR90	426.8	0.5	0.1	6.39E-09	-42.76	-	-18.97	2.66E-10	-	3, 4
KFR90	436.8	0.5	0.1	5.25E-07	-43.52	2.78E-07	-19.15	1.00E-08	8.23	
KFR90	437.2	0.5	0.1	2.01E-07	-43.55	1.04E-07	-19.14	3.94E-09	6.94	
KFR90	437.6	0.5	0.1	9.17E-09	-43.61	-	-19.15	3.71E-10	-	3
KFR90	440.4	0.5	0.1	1.92E-08	-43.82	9.72E-09	-19.13	3.78E-10	6.29	
KFR90	440.8	0.5	0.1	7.50E-09	-43.84	-	-19.12	3.00E-10	-	3, 4
KFR90	447.6	0.5	0.1	2.81E-07	-44.2	1.12E-07	-19.5	6.74E-09	-3.03	
KFR90	448.2	0.5	0.1	1.18E-07	-44.2	4.17E-08	-19.51	3.05E-09	-5.99	
KFR90	449.3	0.5	0.1	7.22E-07	-44.21	3.72E-07	-19.6	1.41E-08	6.57	

1) Flow change is smaller than measurement uncertainty.
2) Flow results lead to unrealistic negative transmissivity.
3) Flow was not detected during measurement run #2.
4) Uncertain = The flow rate is less than 30 mL/h or the flow anomalies are overlapping or they are unclear because of noise.

Forsmark, borehole KFR90
Transmissivity and head of detected fractures

Error bars assuming ±10 % errors in flow rates
and ±0.2 m in head in worst combination

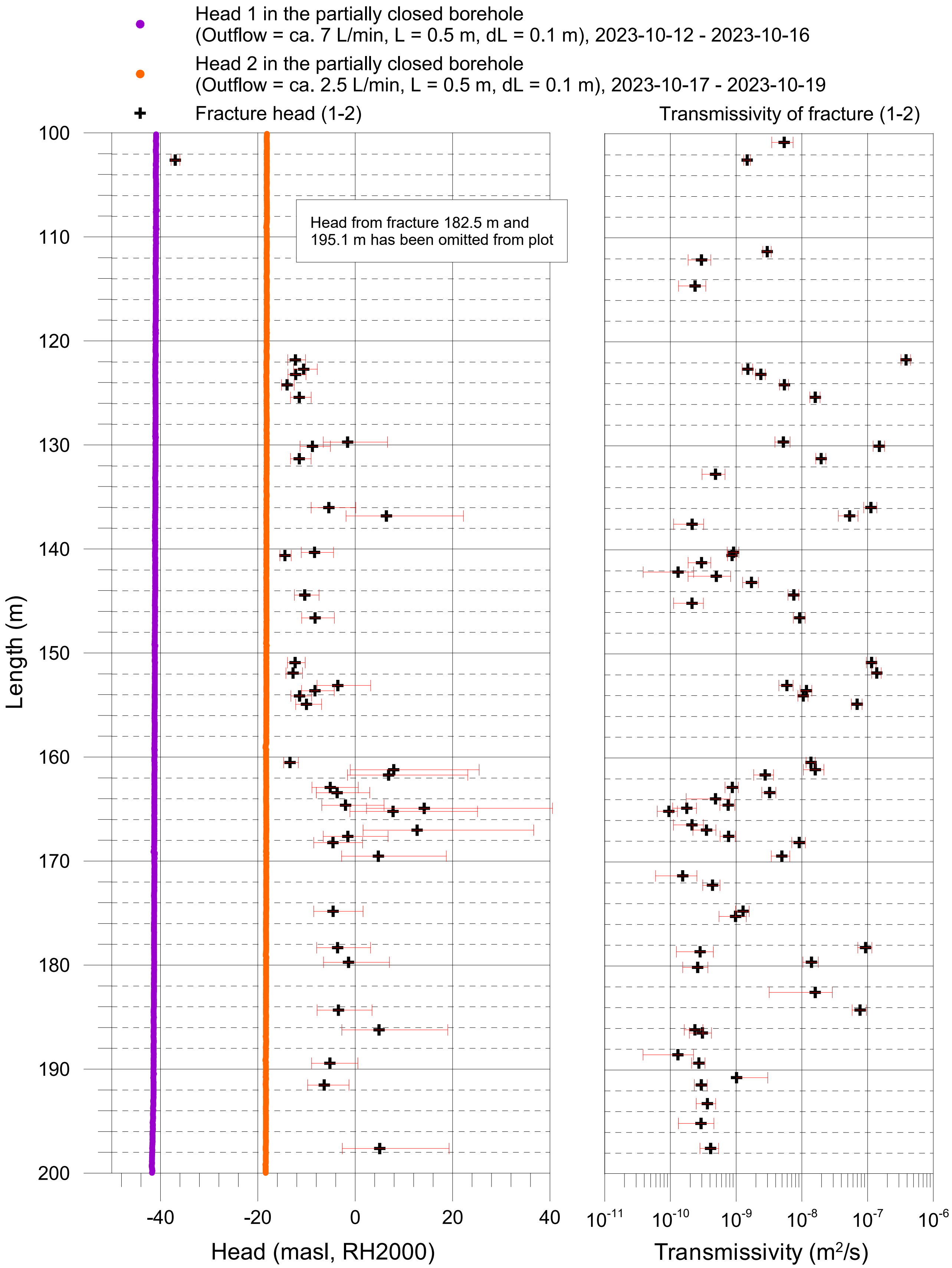


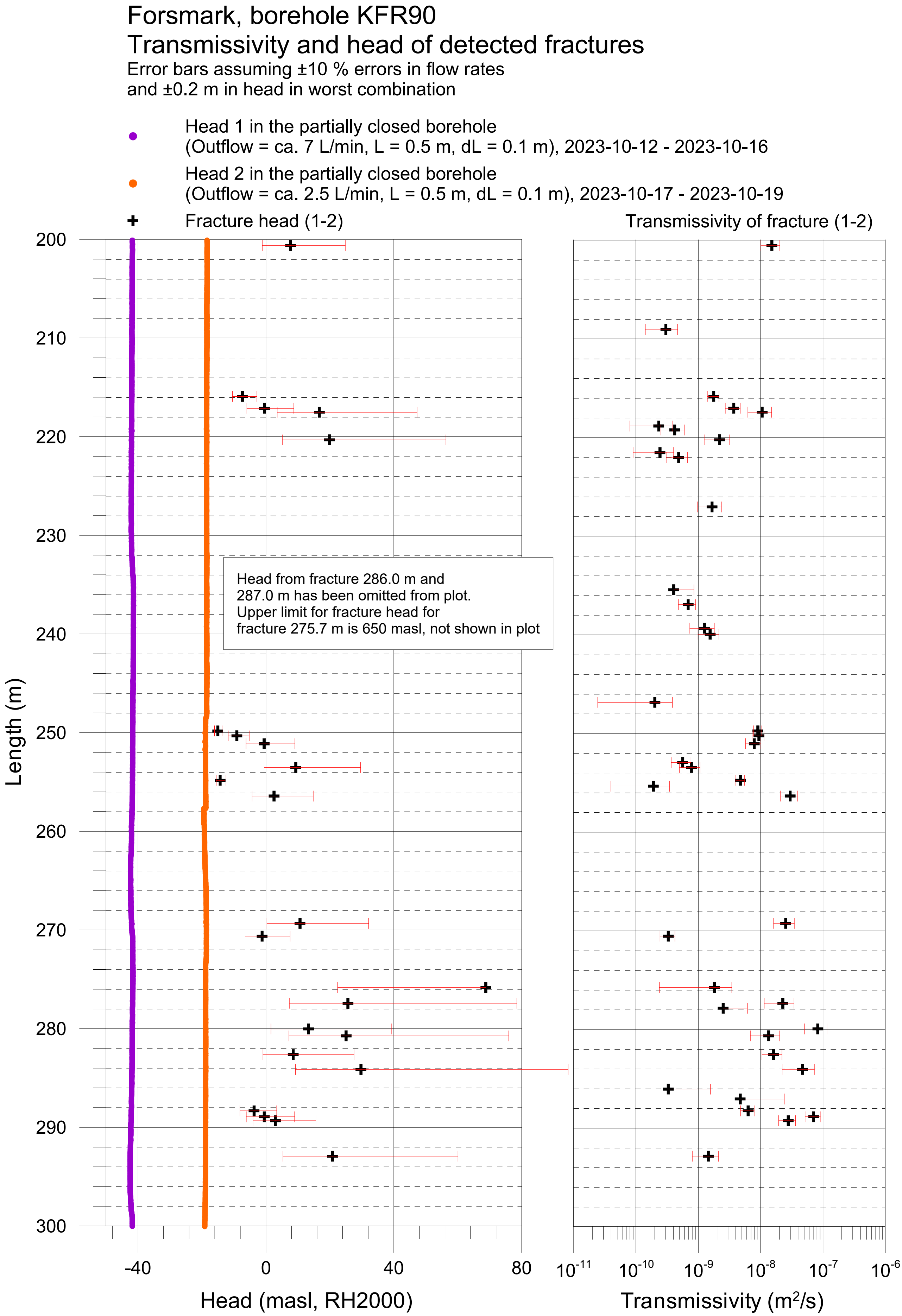

Forsmark, borehole KFR90
Transmissivity and head of detected fractures
Error bars assuming ±10 % errors in flow rates
and ±0.2 m in head in worst combination
Head 1 in the partially closed borehole
(Outflow = ca. 7 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-12 - 2023-10-16
Head 2 in the partially closed borehole
(Outflow = ca. 2.5 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-17 - 2023-10-19
Fracture head (1-2)
Transmissivity of fracture (1-2)
Fracture head lower limit at fracture 4.5 m is below -200 masl and has not been presented in plot.
Length (m)
Head (masl, RH2000)
Transmissivity (m²/s)

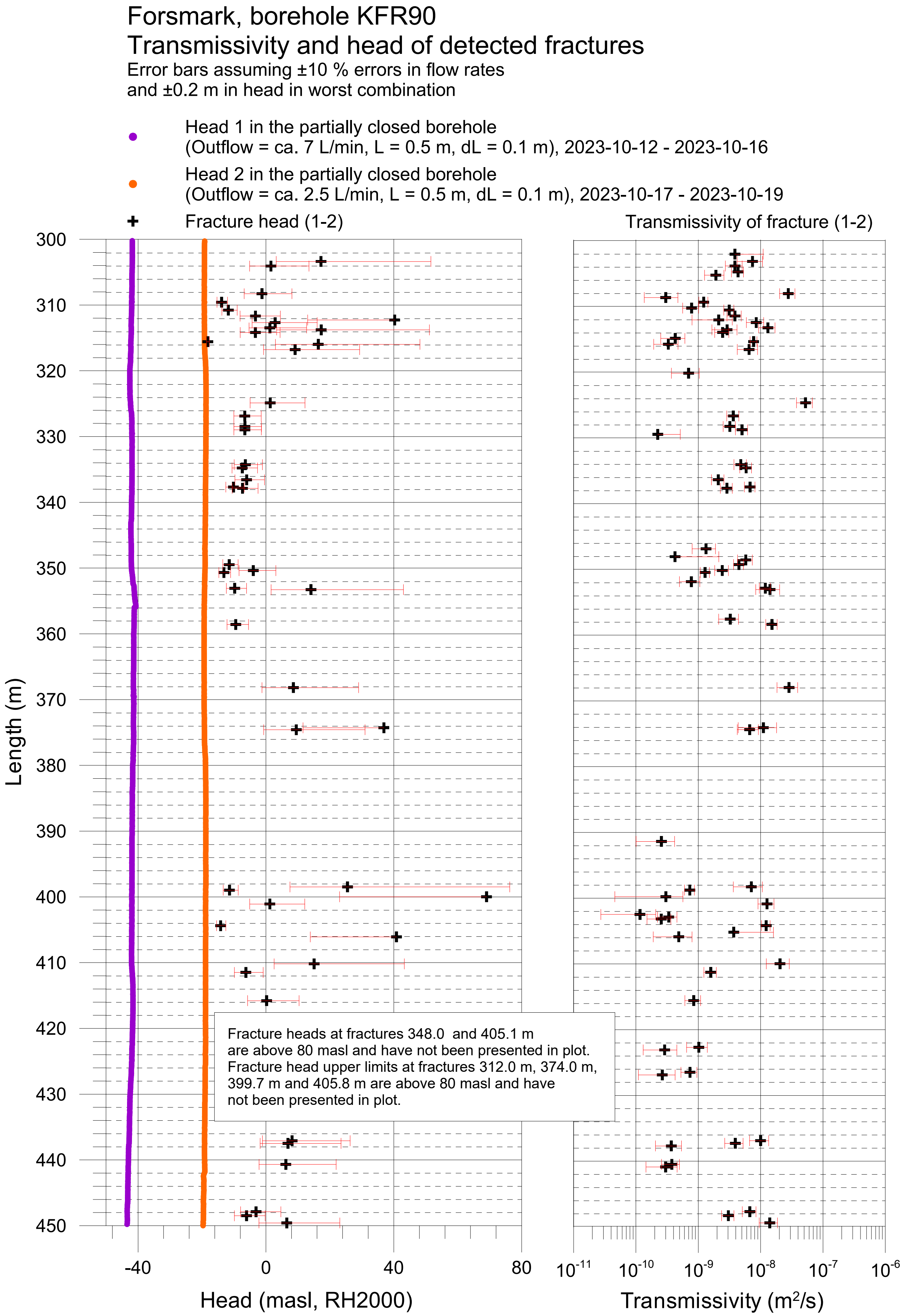
Forsmark, borehole KFR90

Transmissivity and head of detected fractures

Error bars assuming ±10 % errors in flow rates
and ±0.2 m in head in worst combination



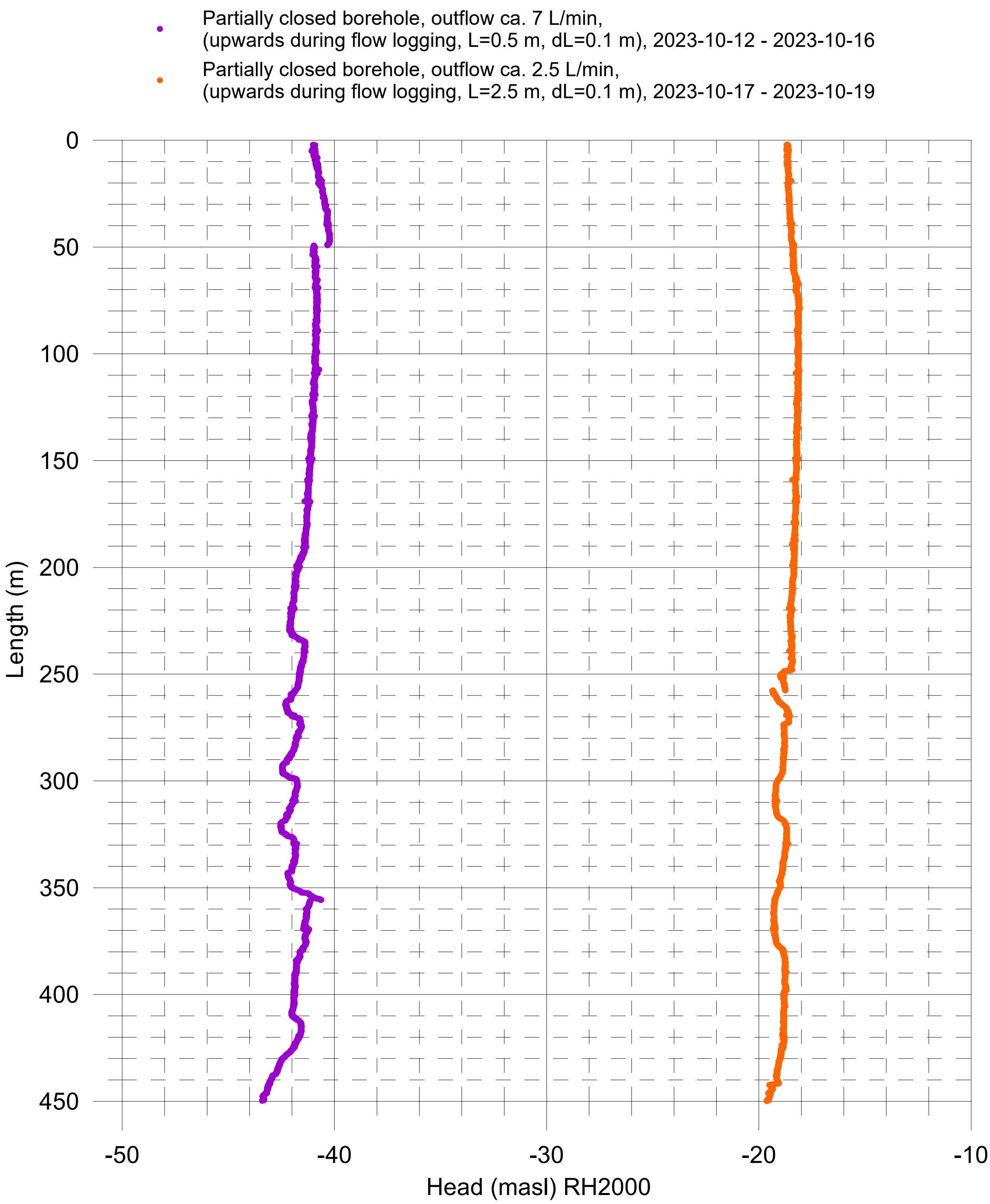

Forsmark, borehole KFR90
Transmissivity and head of detected fractures
Error bars assuming ±10 % errors in flow rates
and ±0.2 m in head in worst combination
Head 1 in the partially closed borehole
(Outflow = ca. 7 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-12 - 2023-10-16
Head 2 in the partially closed borehole
(Outflow = ca. 2.5 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-17 - 2023-10-19
Fracture head (1-2)
Transmissivity of fracture (1-2)
Head from fracture 286.0 m and
287.0 m has been omitted from plot.
Upper limit for fracture head for
fracture 275.7 m is 650 masl, not shown in plot
Length (m)
200
210
220
230
240
250
260
270
280
290
300
-40
0
40
80
Head (masl, RH2000)
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
Transmissivity (m^2/s)



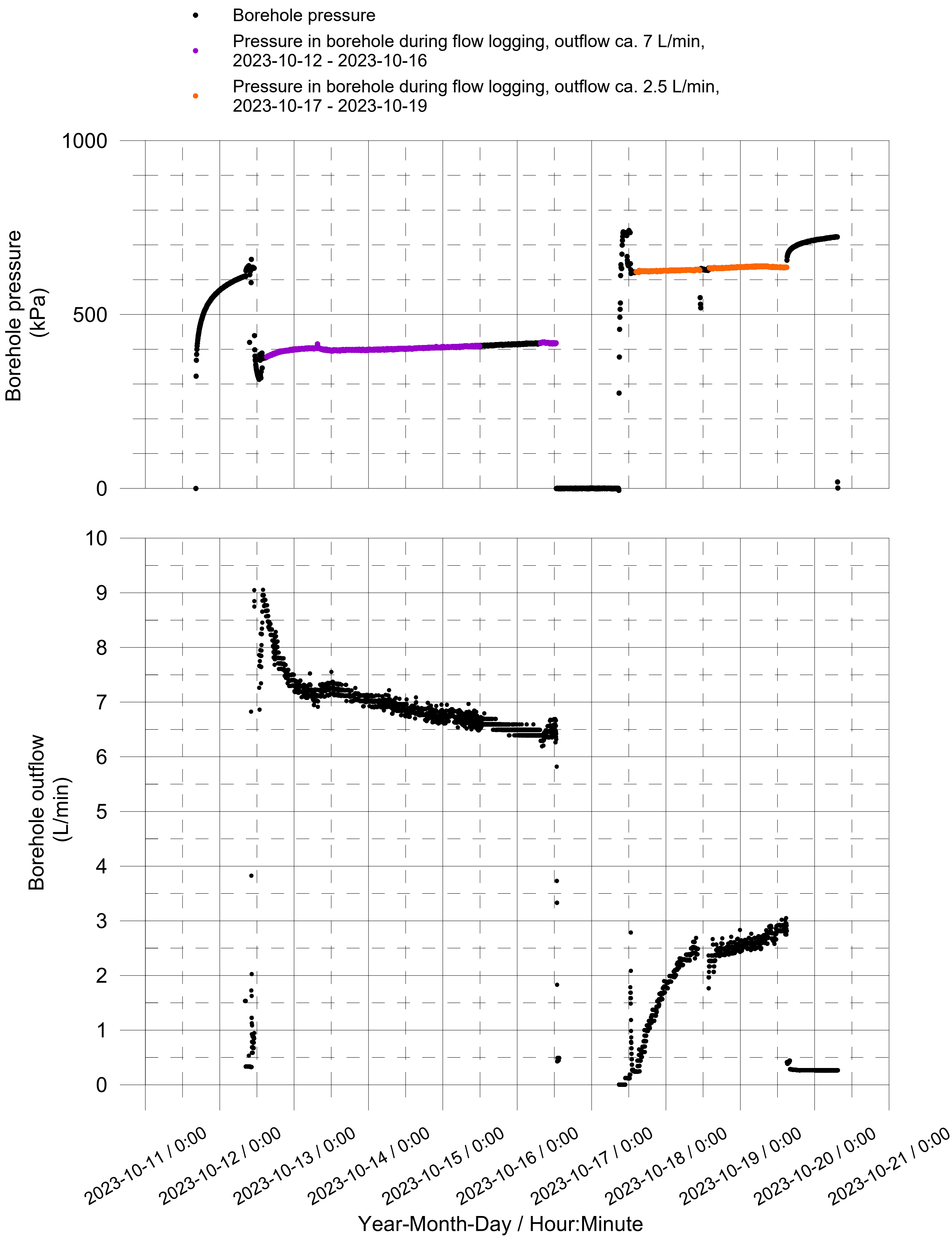
Forsmark, borehole KFR90
Transmissivity and head of detected fractures
Error bars assuming ±10 % errors in flow rates
and ±0.2 m in head in worst combination
Head 1 in the partially closed borehole
(Outflow = ca. 7 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-12 - 2023-10-16
Head 2 in the partially closed borehole
(Outflow = ca. 2.5 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-17 - 2023-10-19
Fracture head (1-2)
Transmissivity of fracture (1-2)
Length (m)
Head (masl, RH2000)
Transmissivity (m²/s)
Fracture heads at fractures 348.0 and 405.1 m
are above 80 masl and have not been presented in plot.
Fracture head upper limits at fractures 312.0 m, 374.0 m,
399.7 m and 405.8 m are above 80 masl and have
not been presented in plot.

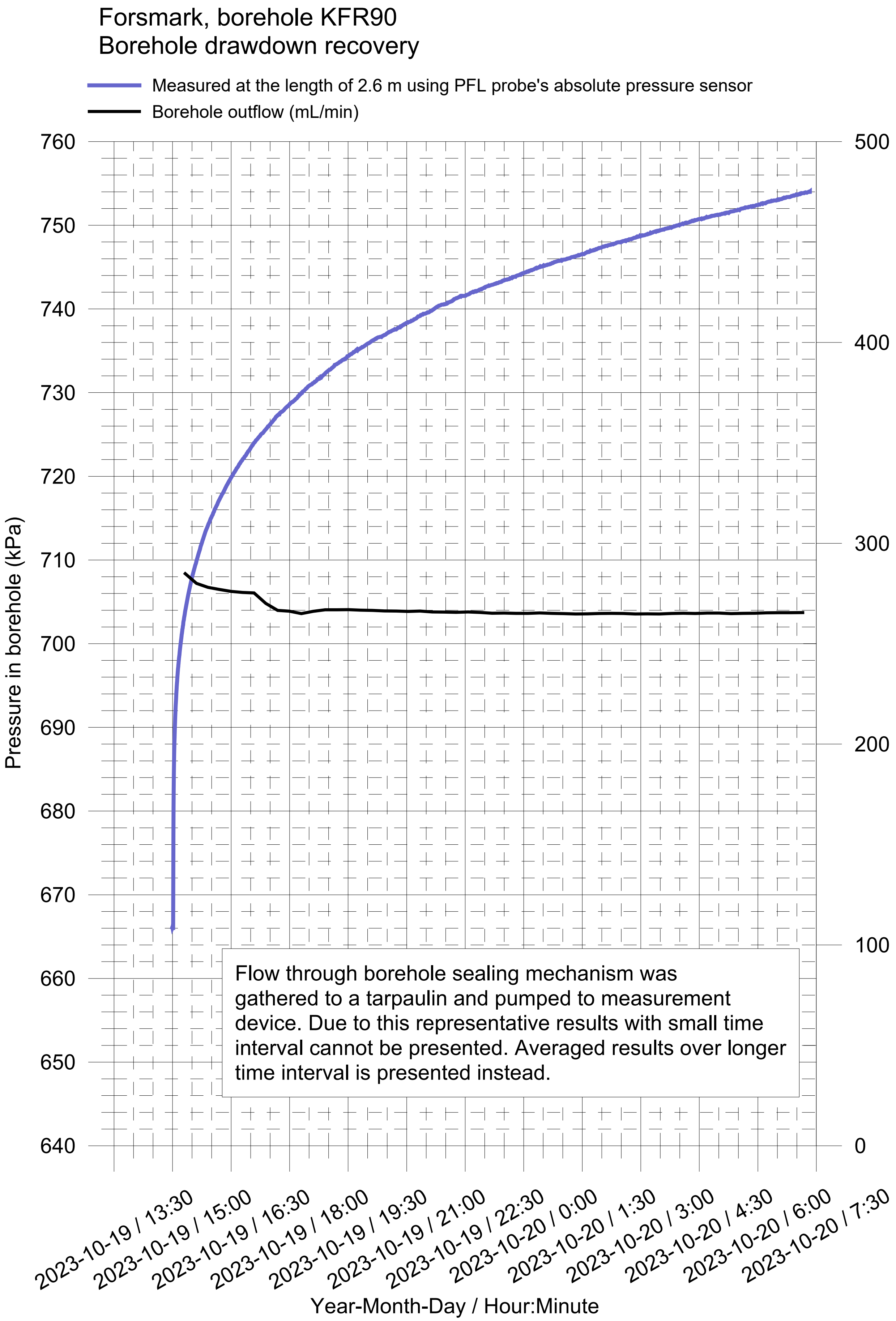
Forsmark, borehole KFR90
Head in the borehole during flow logging

Head (masl) = (Absolute pressure (Pa) - Airpressure (Pa) + Offset) / (1000 kg/m^3 * 9.80665 m/s^2) + Elevation (m)
Offset = 2600 Pa (Correction for absolute pressure sensor)

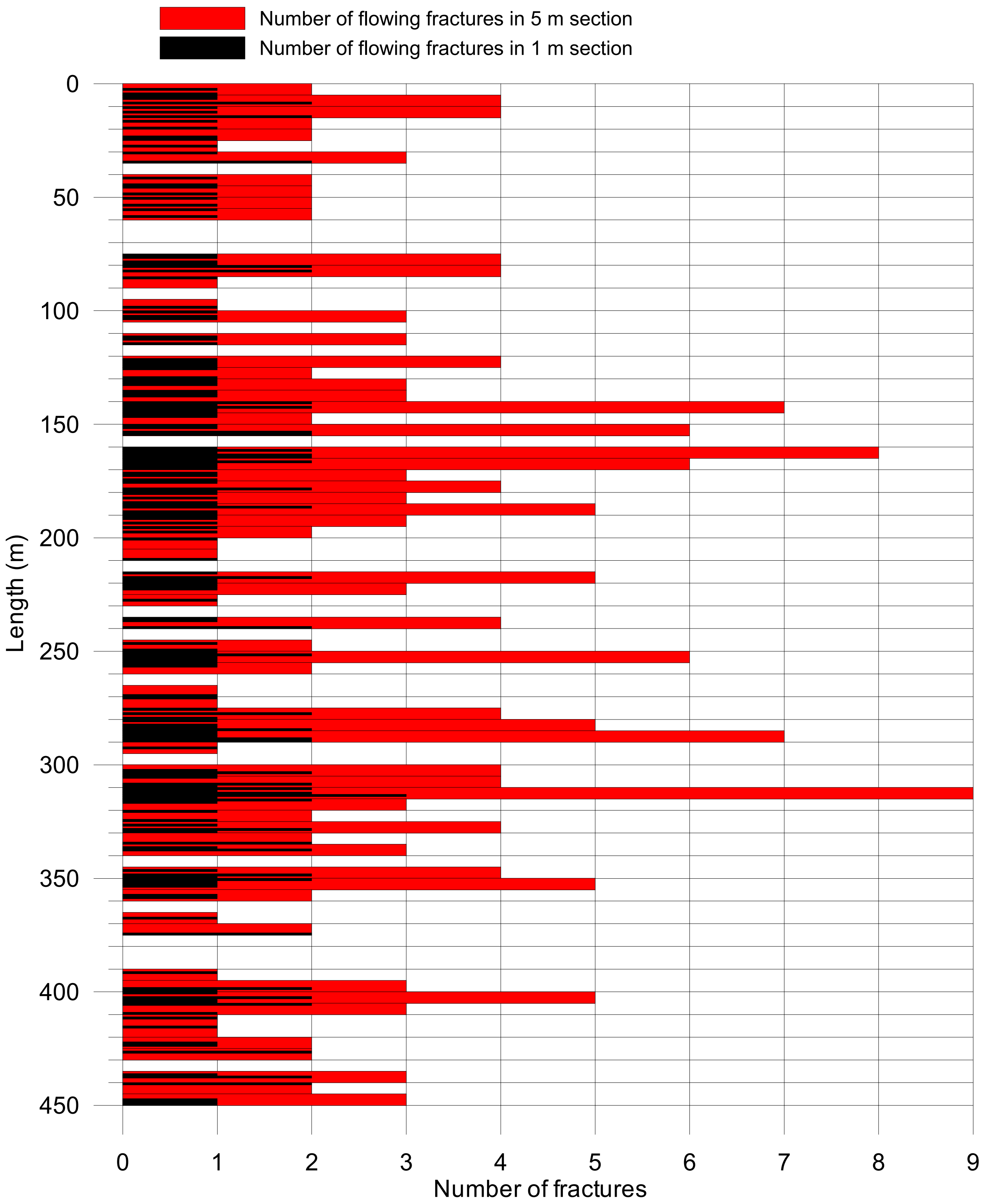


Forsmark, borehole KFR90
Borehole pressure (gauge pressure) and outflow from the borehole

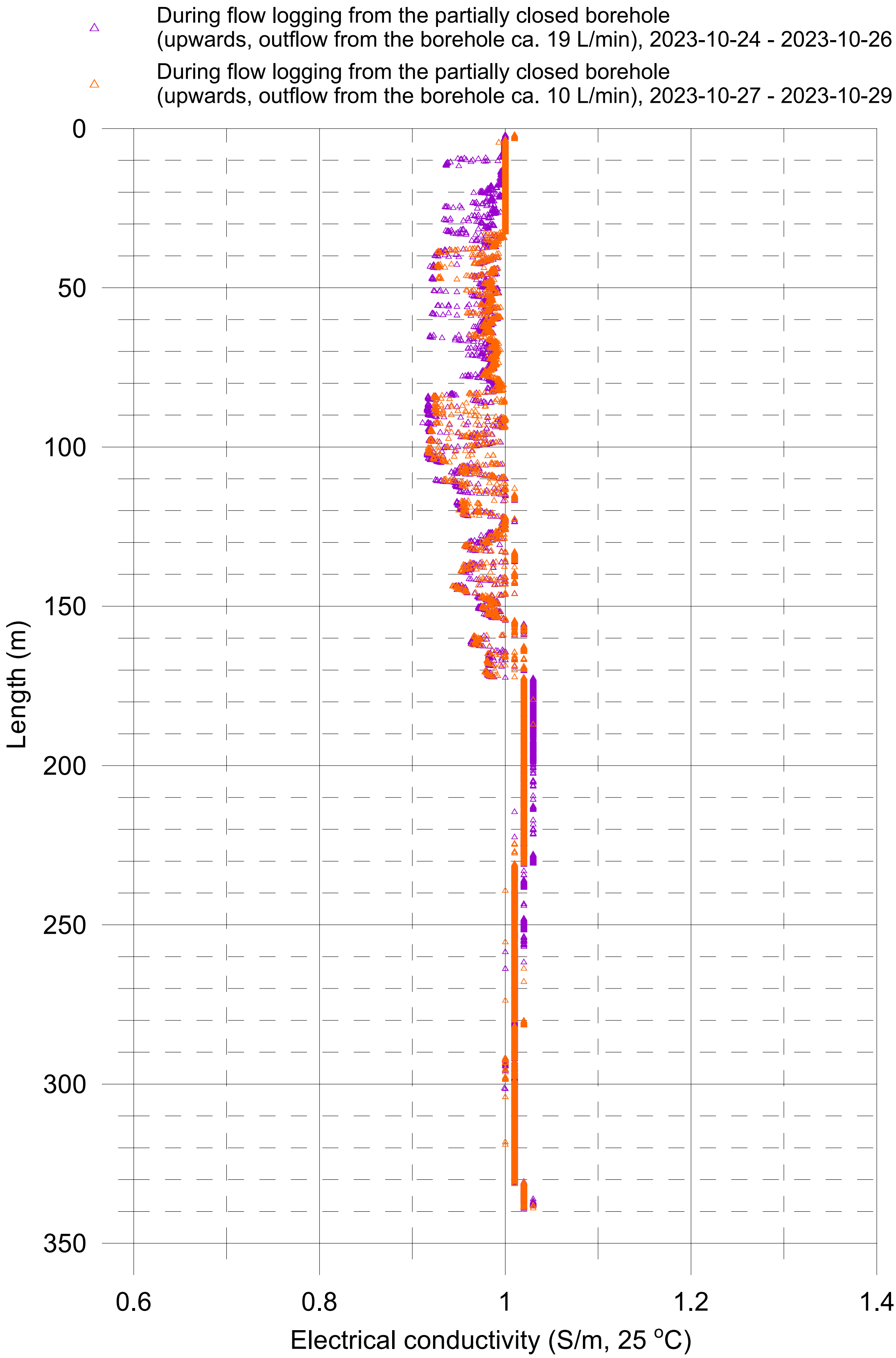


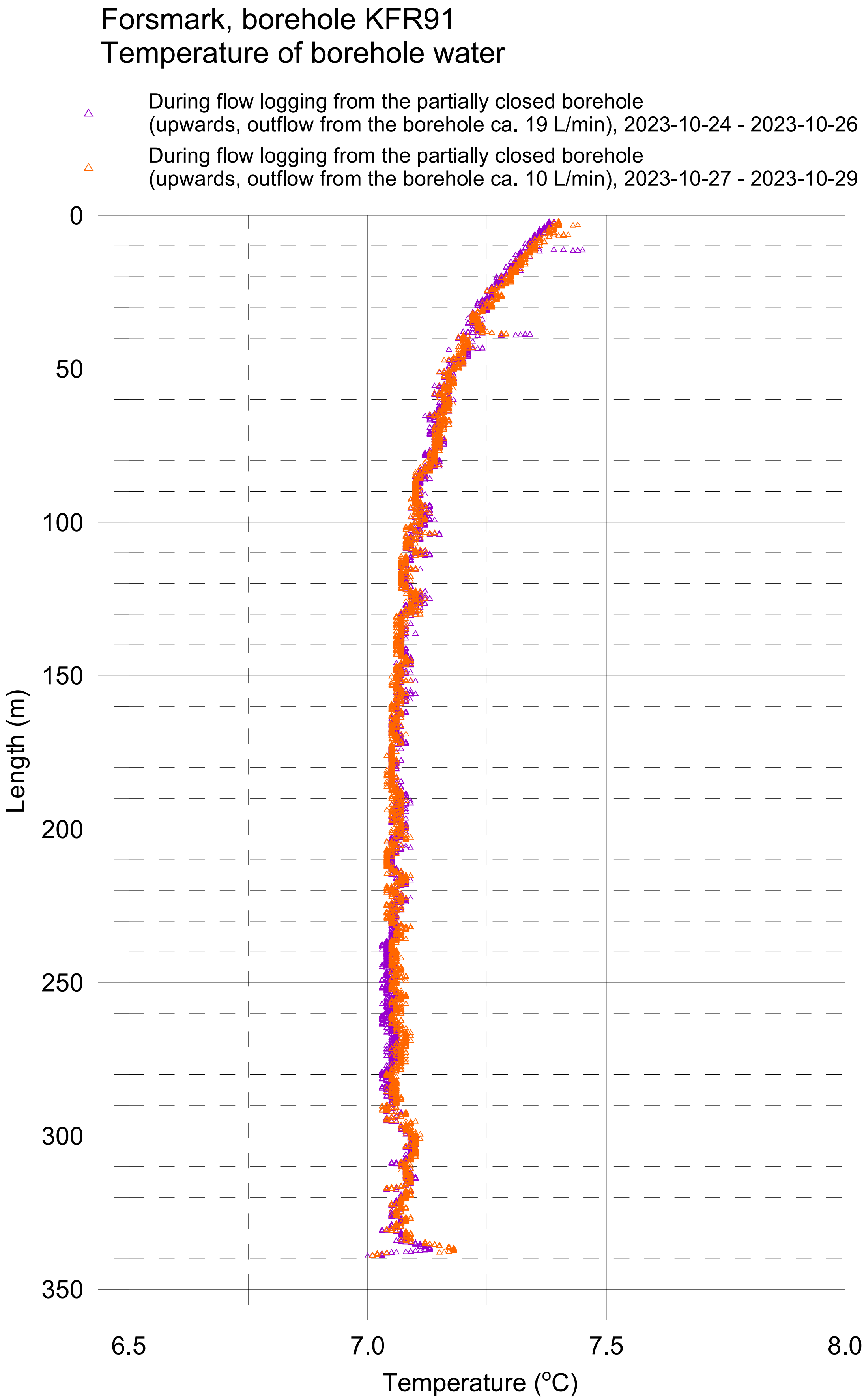

Forsmark, borehole KFR90
Borehole drawdown recovery
Measured at the length of 2.6 m using PFL probe's absolute pressure sensor
Borehole outflow (mL/min)
Pressure in borehole (kPa)
Borehole outflow (mL/min)
760
750
740
730
720
710
700
690
680
670
660
650
640
500
400
300
200
100
0
Flow through borehole sealing mechanism was gathered to a tarpaulin and pumped to measurement device. Due to this representative results with small time interval cannot be presented. Averaged results over longer time interval is presented instead.
2023-10-19 / 13:30
2023-10-19 / 15:00
2023-10-19 / 16:30
2023-10-19 / 18:00
2023-10-19 / 19:30
2023-10-19 / 21:00
2023-10-19 / 22:30
2023-10-20 / 0:00
2023-10-20 / 1:30
2023-10-20 / 3:00
2023-10-20 / 4:30
2023-10-20 / 6:00
2023-10-20 / 7:30
Year-Month-Day / Hour:Minute

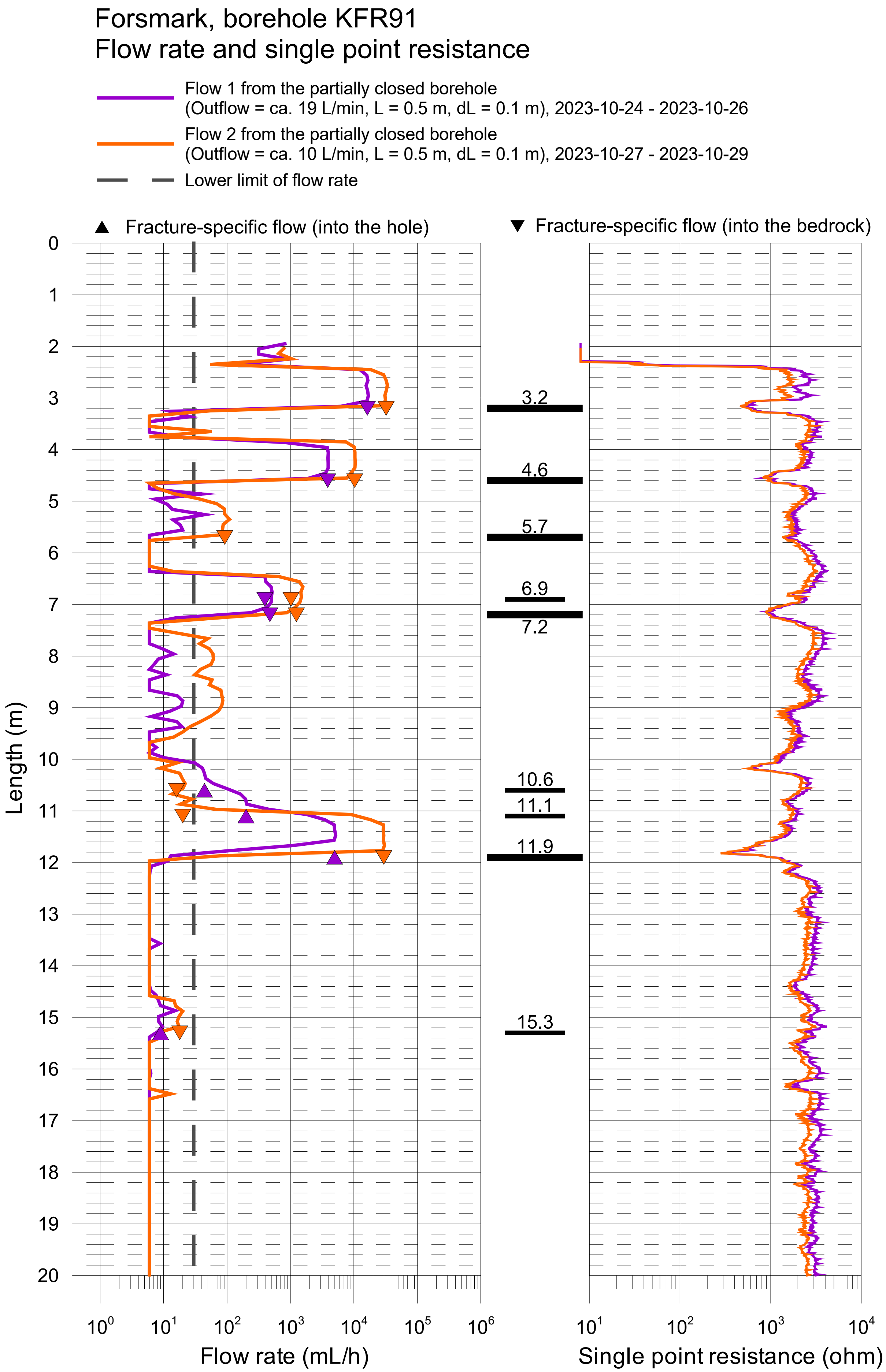
Forsmark, borehole KFR90
Calculation of conductive fracture frequency



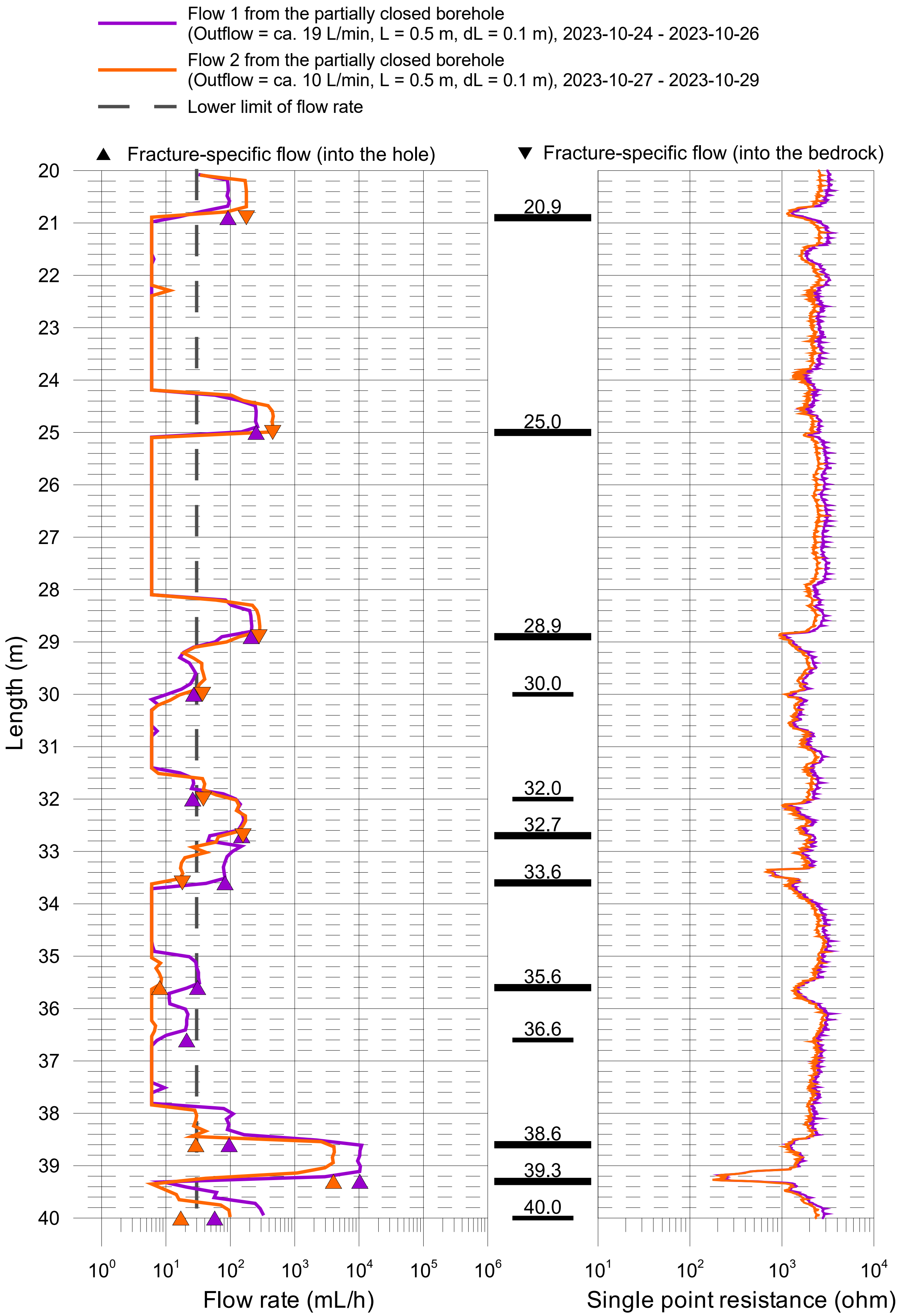
Forsmark, borehole KFR91
Electrical conductivity of borehole water



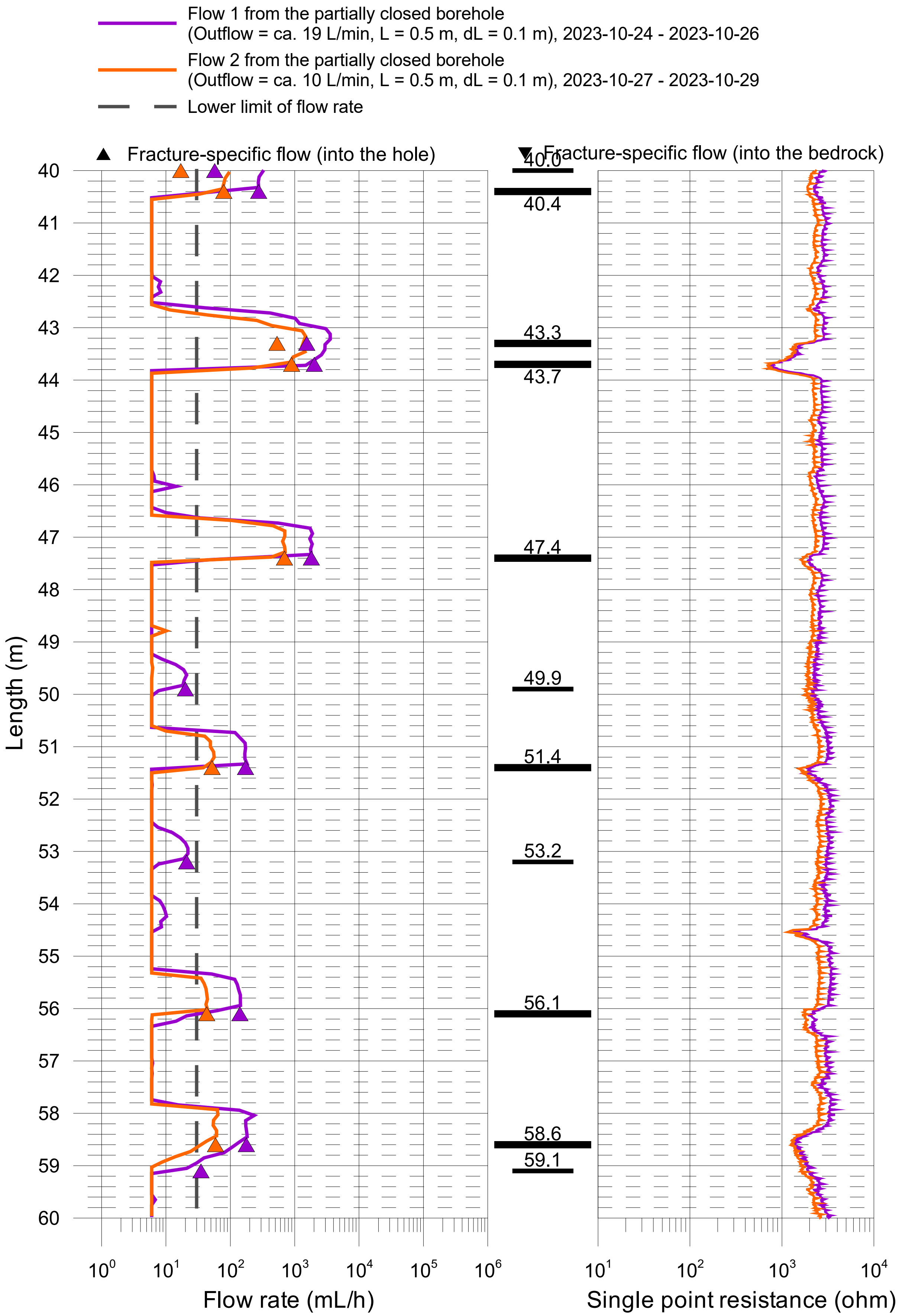

Forsmark, borehole KFR91
Temperature of borehole water
During flow logging from the partially closed borehole
(upwards, outflow from the borehole ca. 19 L/min), 2023-10-24 - 2023-10-26
During flow logging from the partially closed borehole
(upwards, outflow from the borehole ca. 10 L/min), 2023-10-27 - 2023-10-29
0
50
100
150
200
250
300
350
Length (m)
6.5
7.0
7.5
8.0
Temperature (°C)

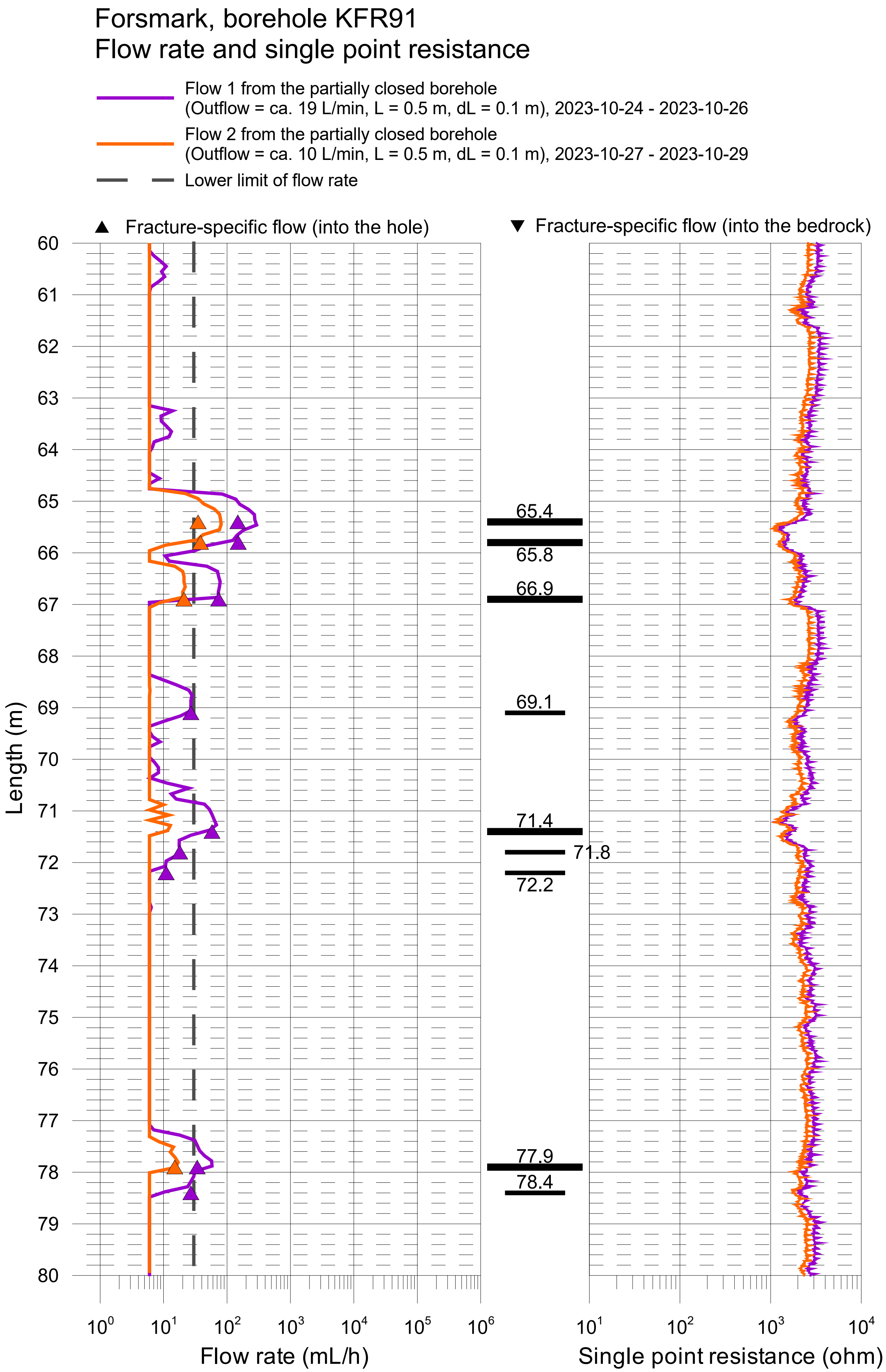

Forsmark, borehole KFR91
Flow rate and single point resistance
Flow 1 from the partially closed borehole
(Outflow = ca. 19 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-24 - 2023-10-26
Flow 2 from the partially closed borehole
(Outflow = ca. 10 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-27 - 2023-10-29
Lower limit of flow rate
Fracture-specific flow (into the hole)
Fracture-specific flow (into the bedrock)
Length (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
3.2
4.6
5.7
6.9
7.2
10.6
11.1
11.9
15.3
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
Single point resistance (ohm)

Forsmark, borehole KFR91
Flow rate and single point resistance

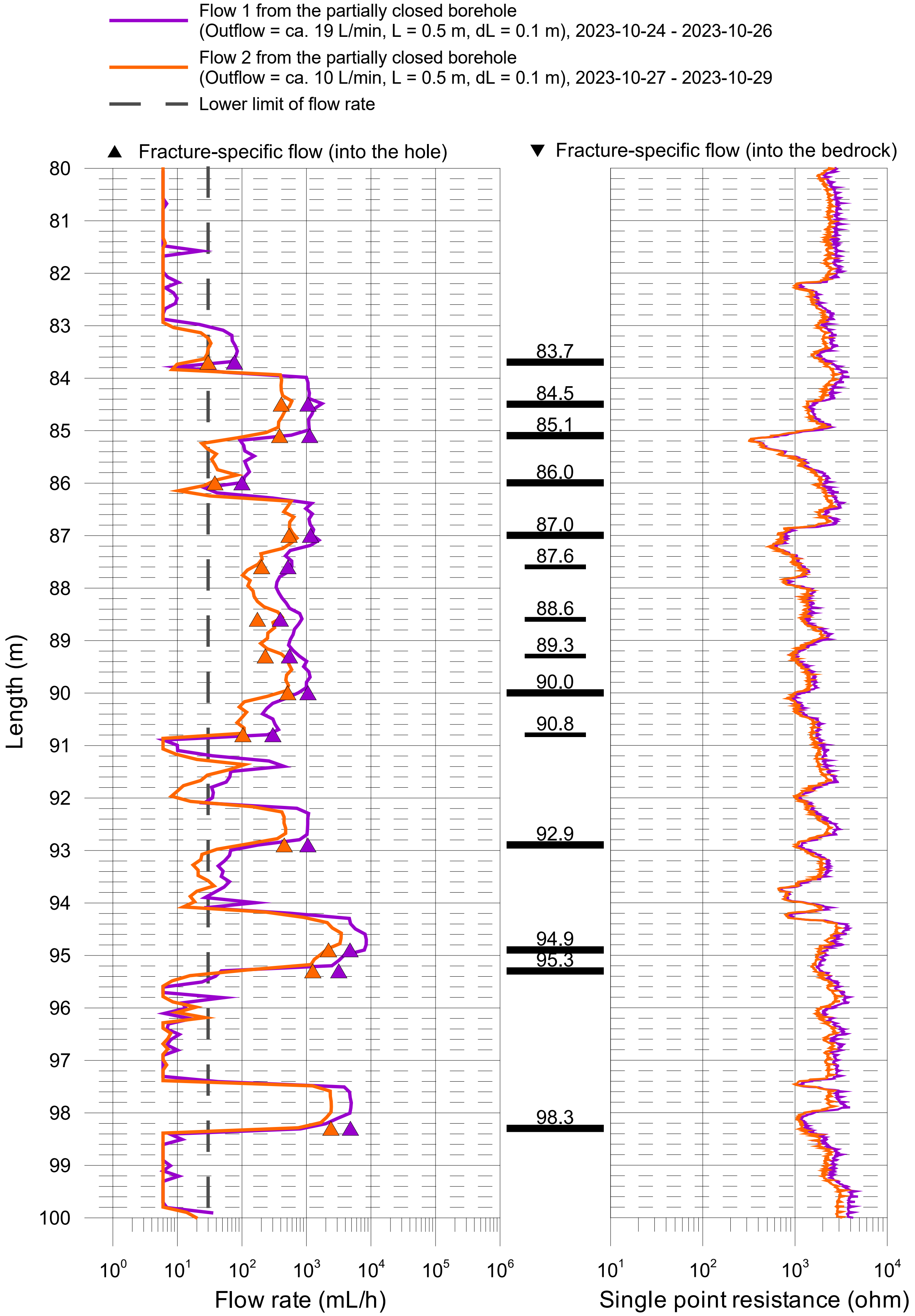


Forsmark, borehole KFR91
Flow rate and single point resistance

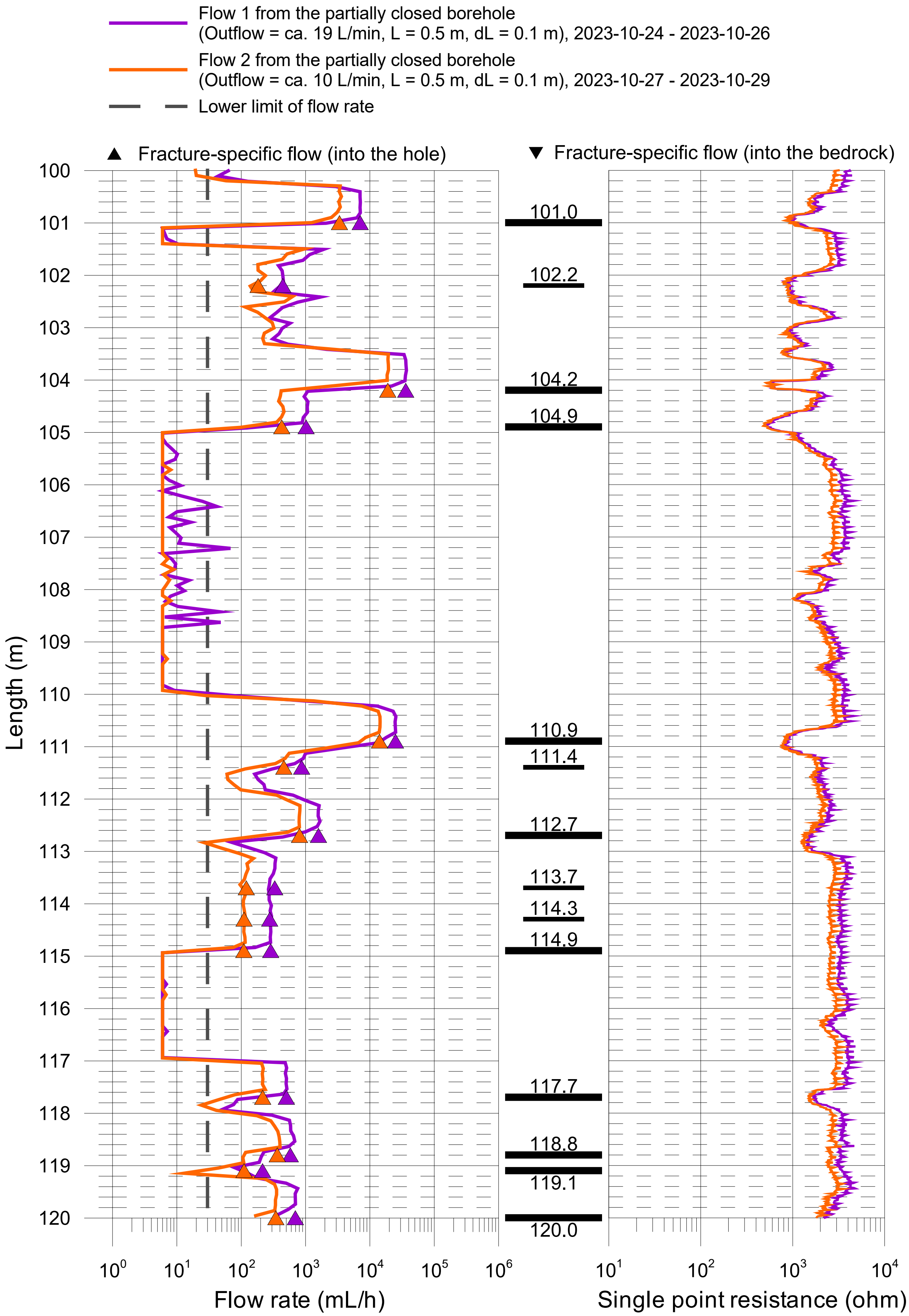



Forsmark, borehole KFR91
Flow rate and single point resistance
Flow 1 from the partially closed borehole
(Outflow = ca. 19 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-24 - 2023-10-26
Flow 2 from the partially closed borehole
(Outflow = ca. 10 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-27 - 2023-10-29
Lower limit of flow rate
Fracture-specific flow (into the hole)
Fracture-specific flow (into the bedrock)
Length (m)
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
65.4
65.8
66.9
69.1
71.4
71.8
72.2
77.9
78.4
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
Single point resistance (ohm)

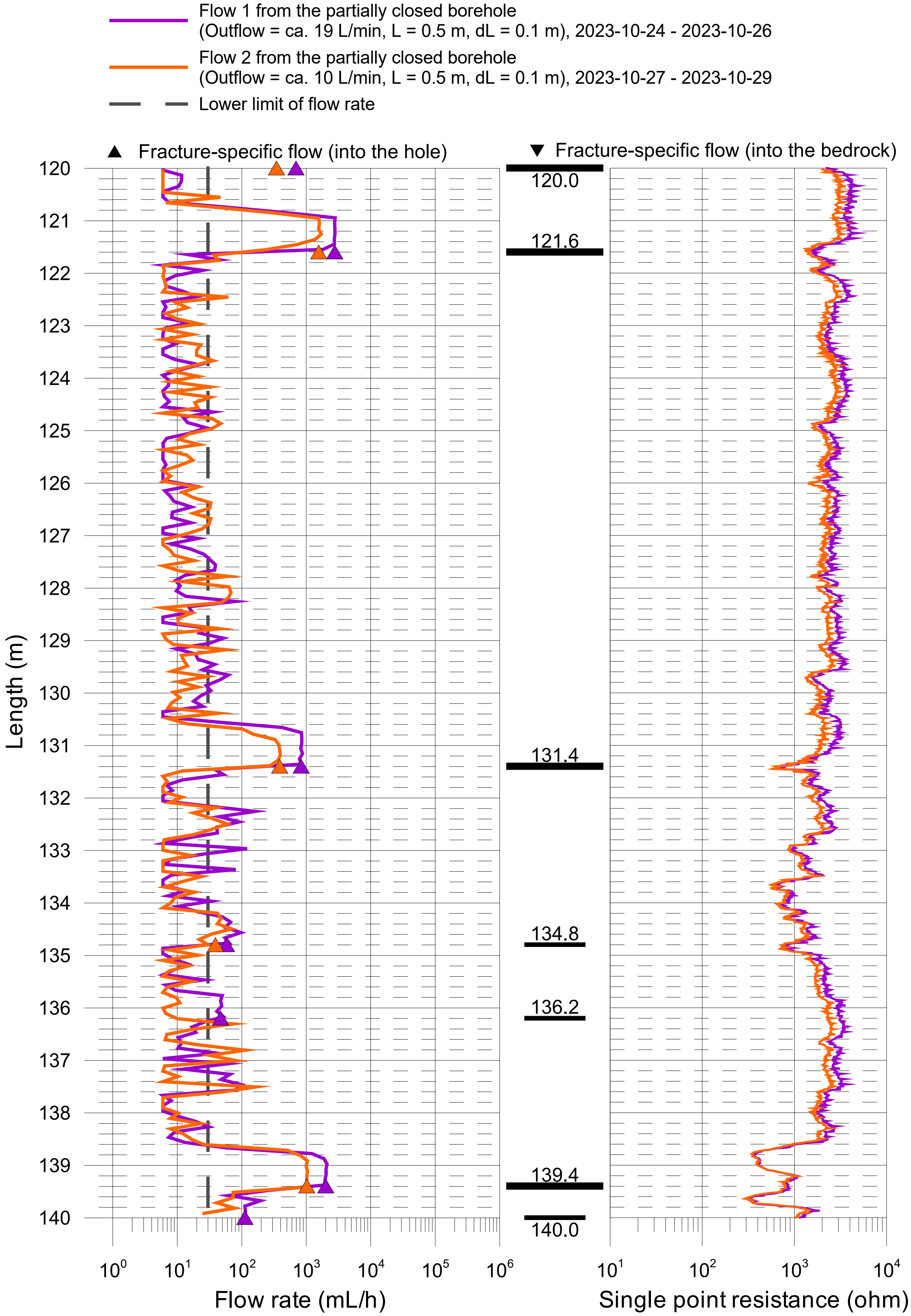
Forsmark, borehole KFR91
Flow rate and single point resistance



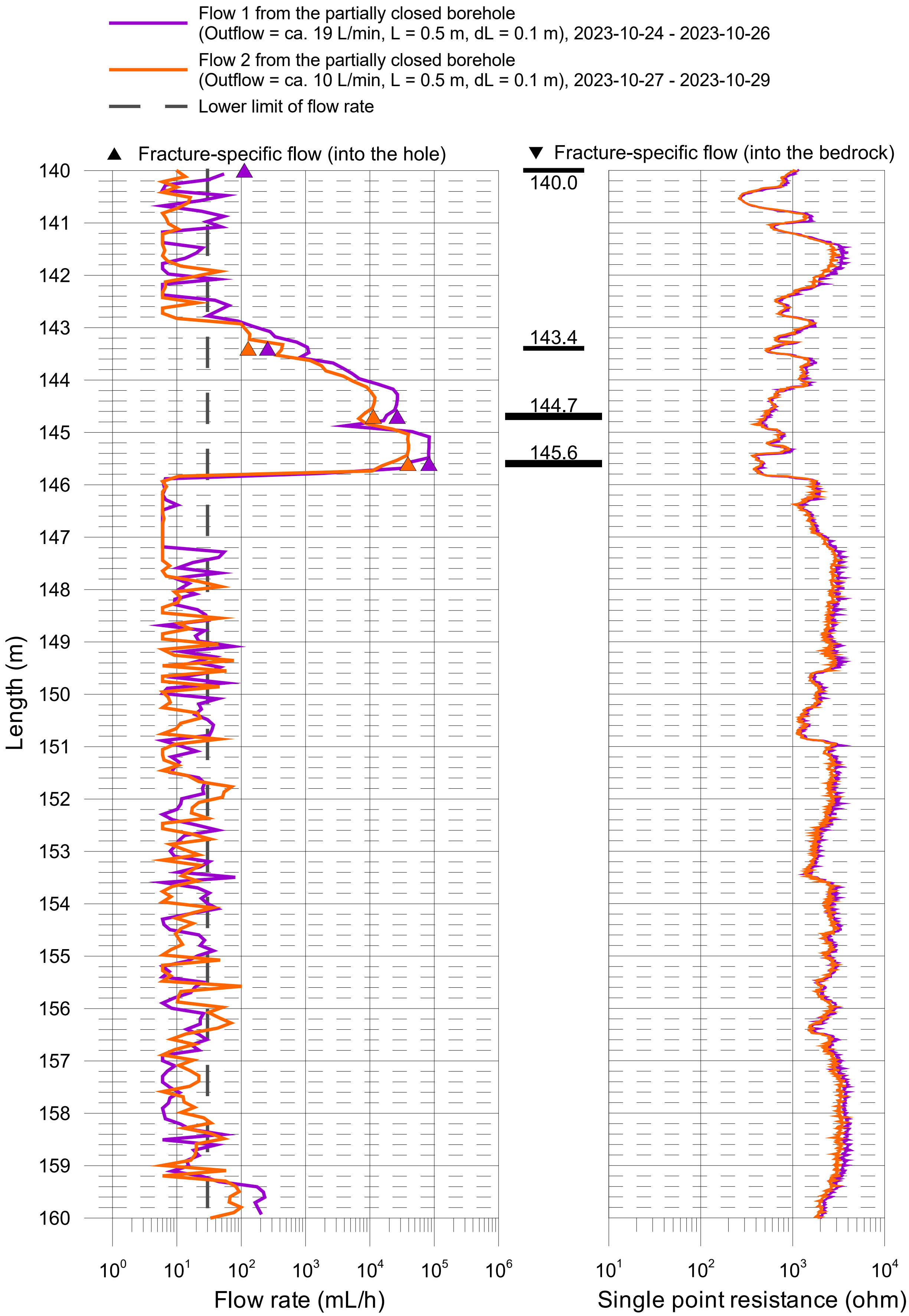
Forsmark, borehole KFR91
Flow rate and single point resistance



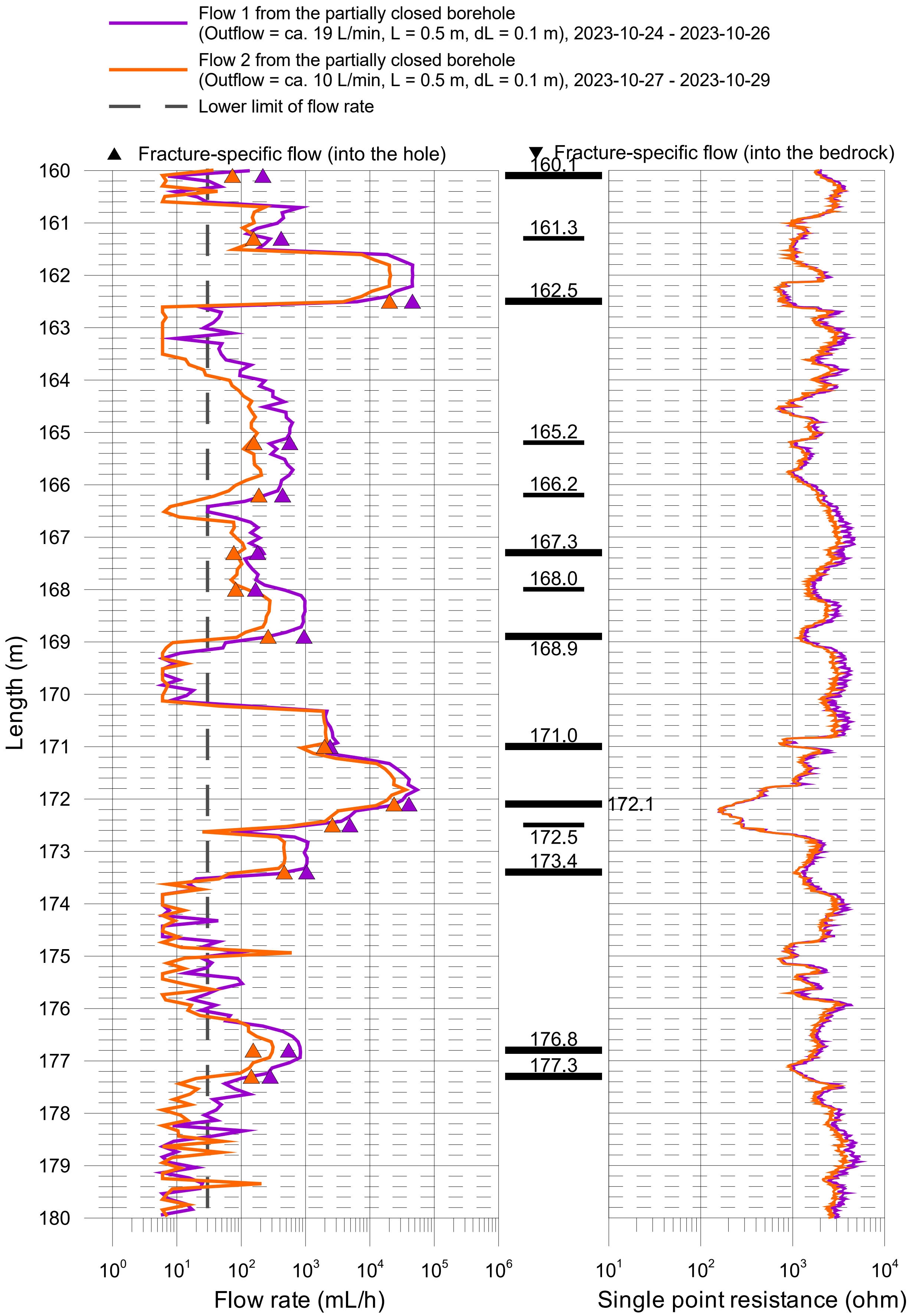
Forsmark, borehole KFR91
Flow rate and single point resistance



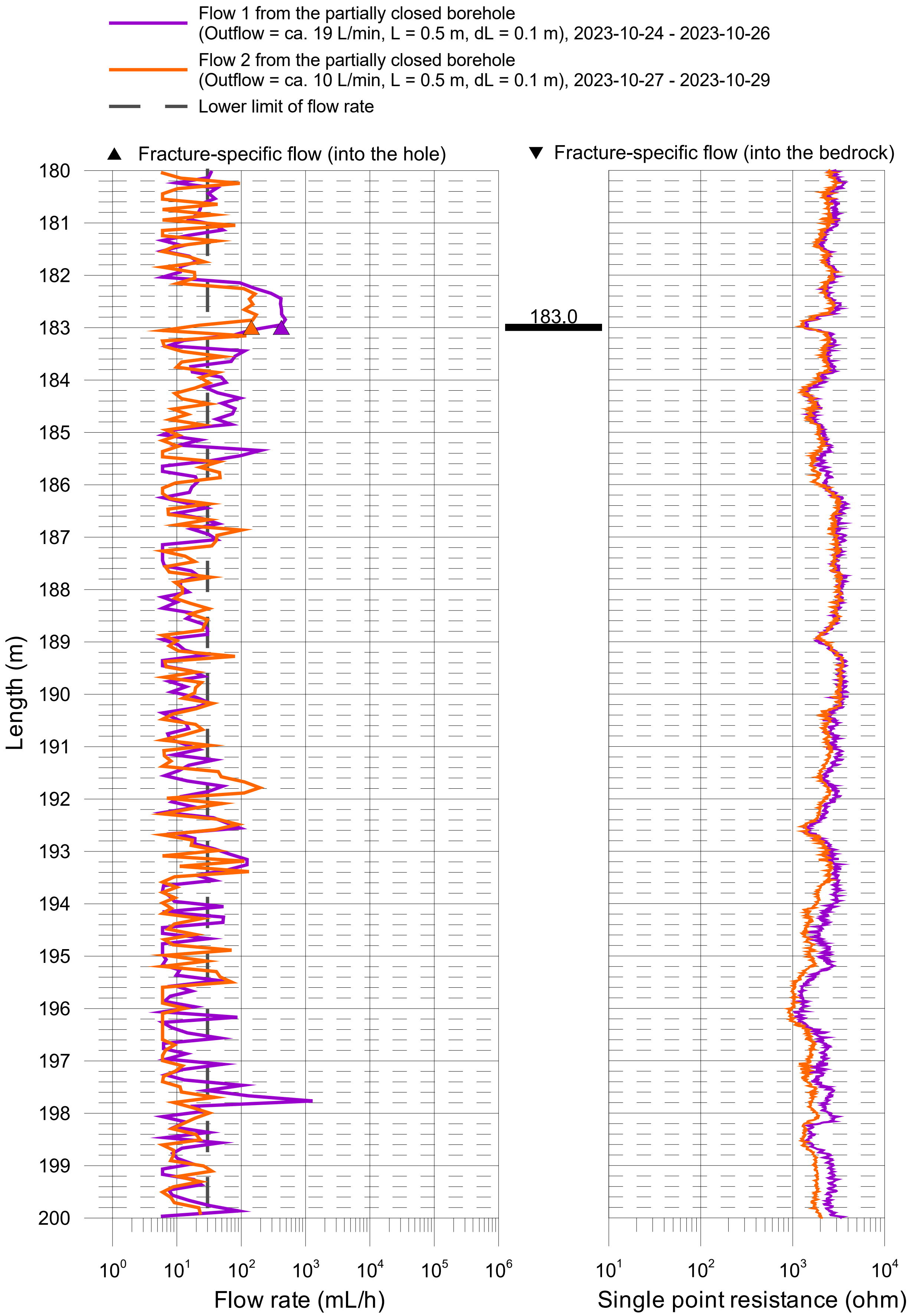
Forsmark, borehole KFR91
Flow rate and single point resistance



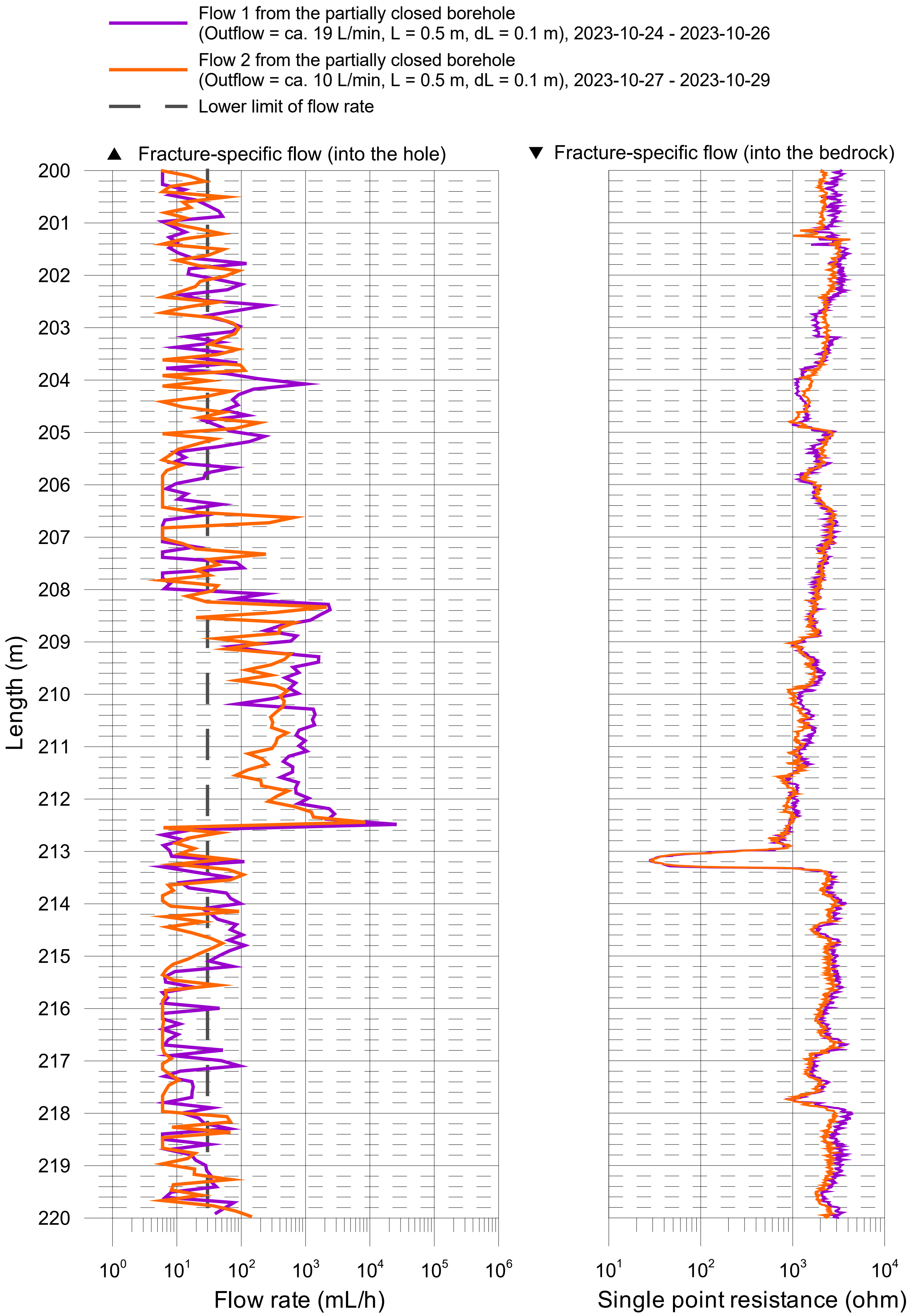
Forsmark, borehole KFR91
Flow rate and single point resistance



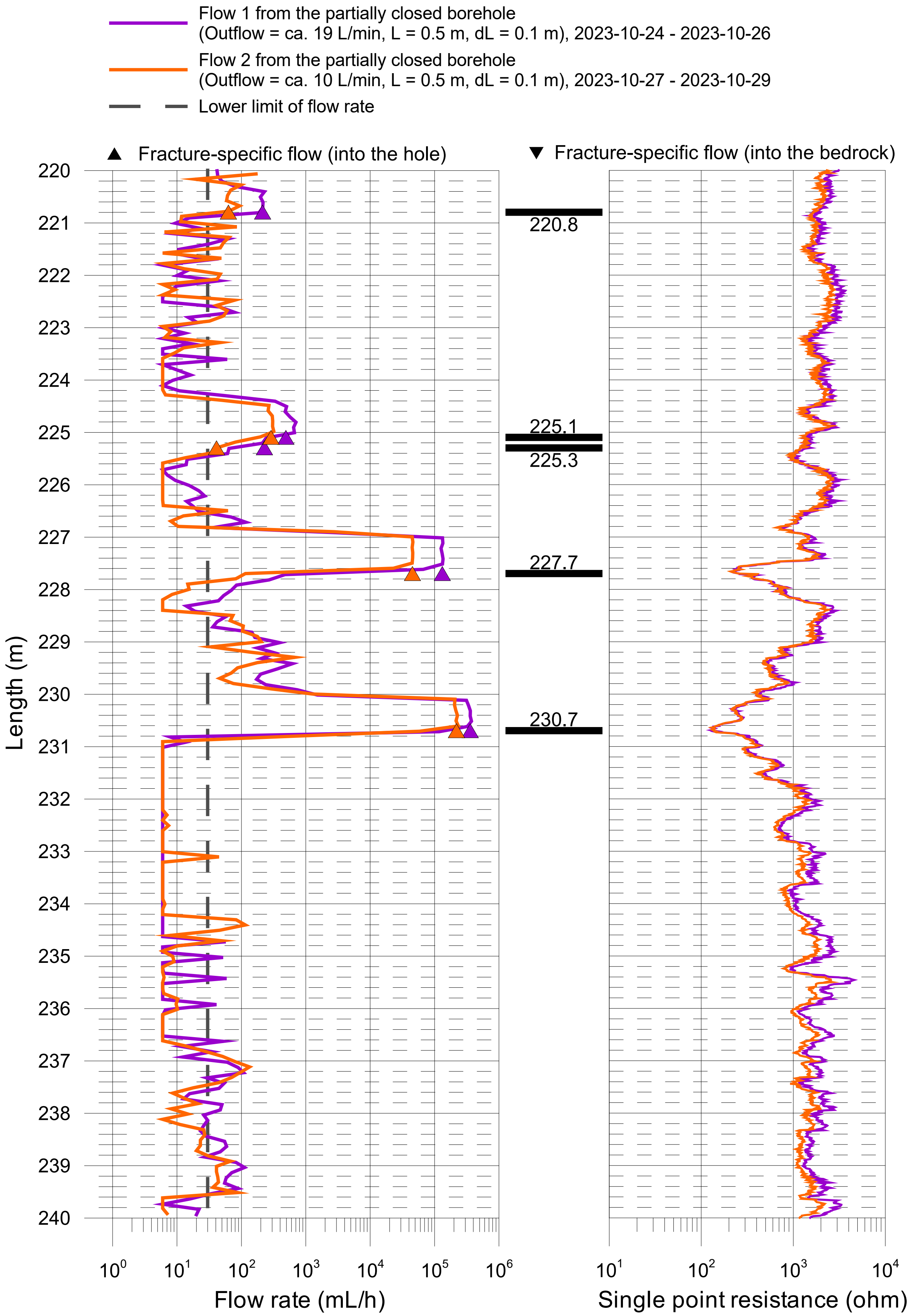
Forsmark, borehole KFR91
Flow rate and single point resistance



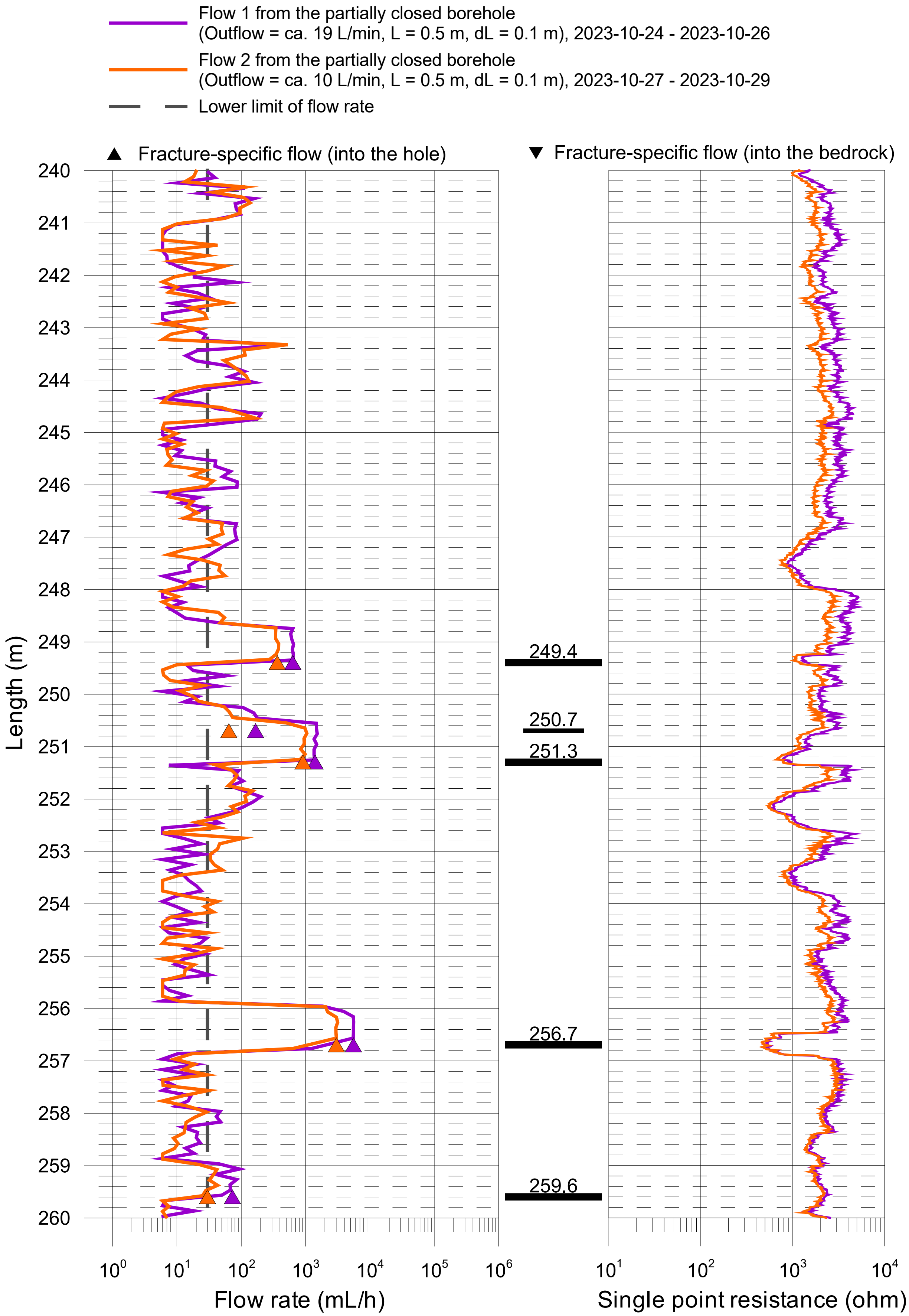
Forsmark, borehole KFR91
Flow rate and single point resistance



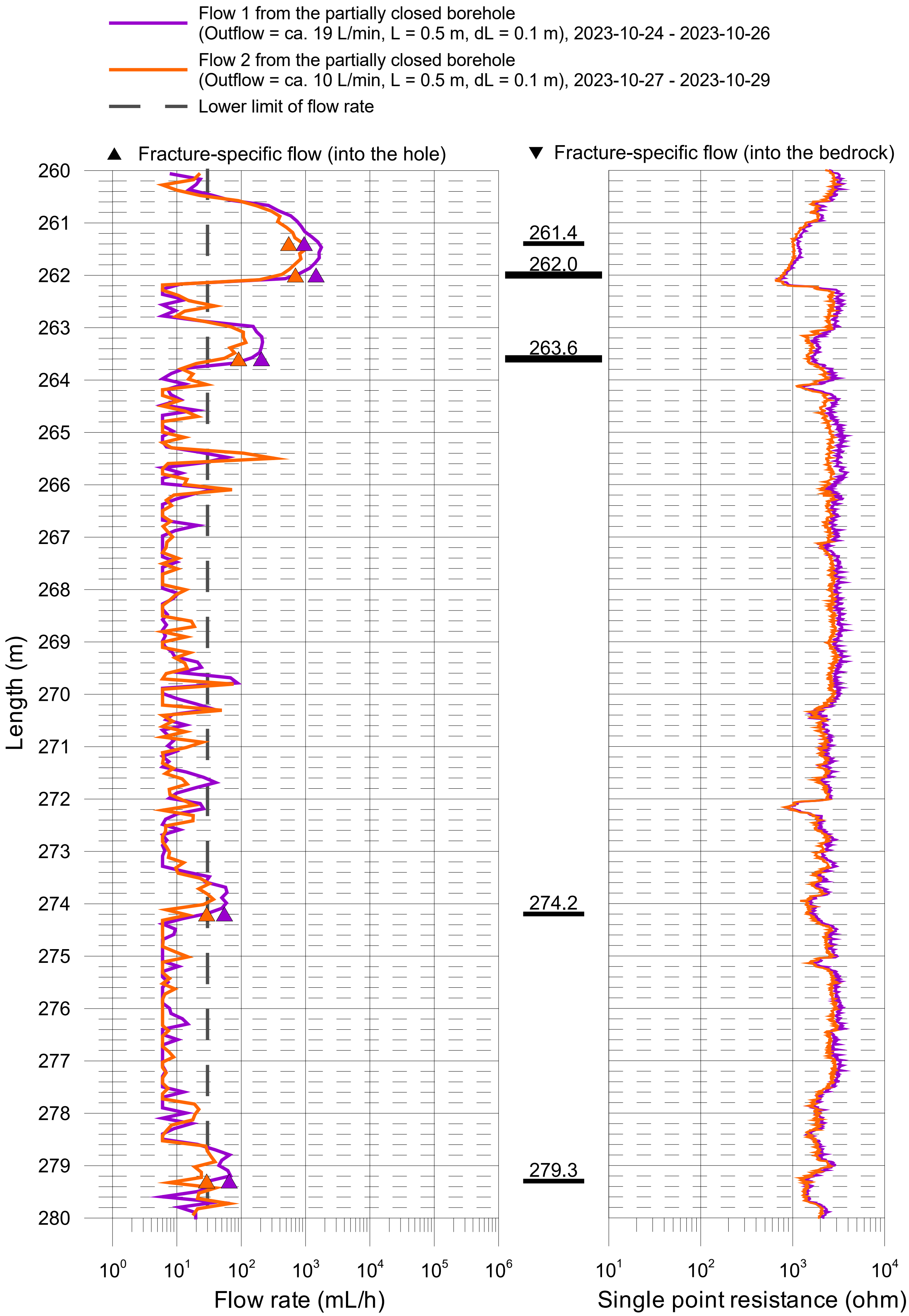
Forsmark, borehole KFR91
Flow rate and single point resistance



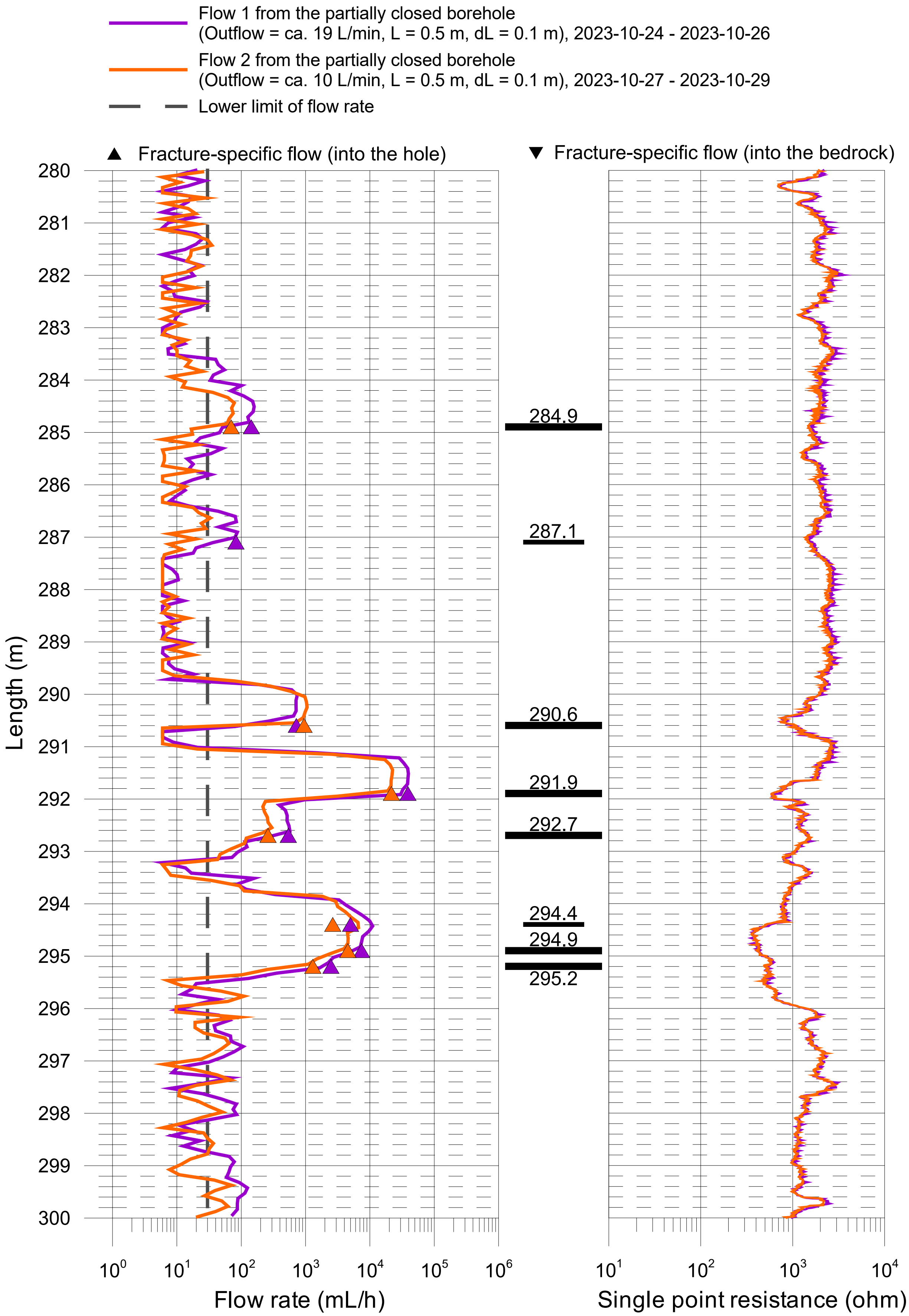
Forsmark, borehole KFR91
Flow rate and single point resistance



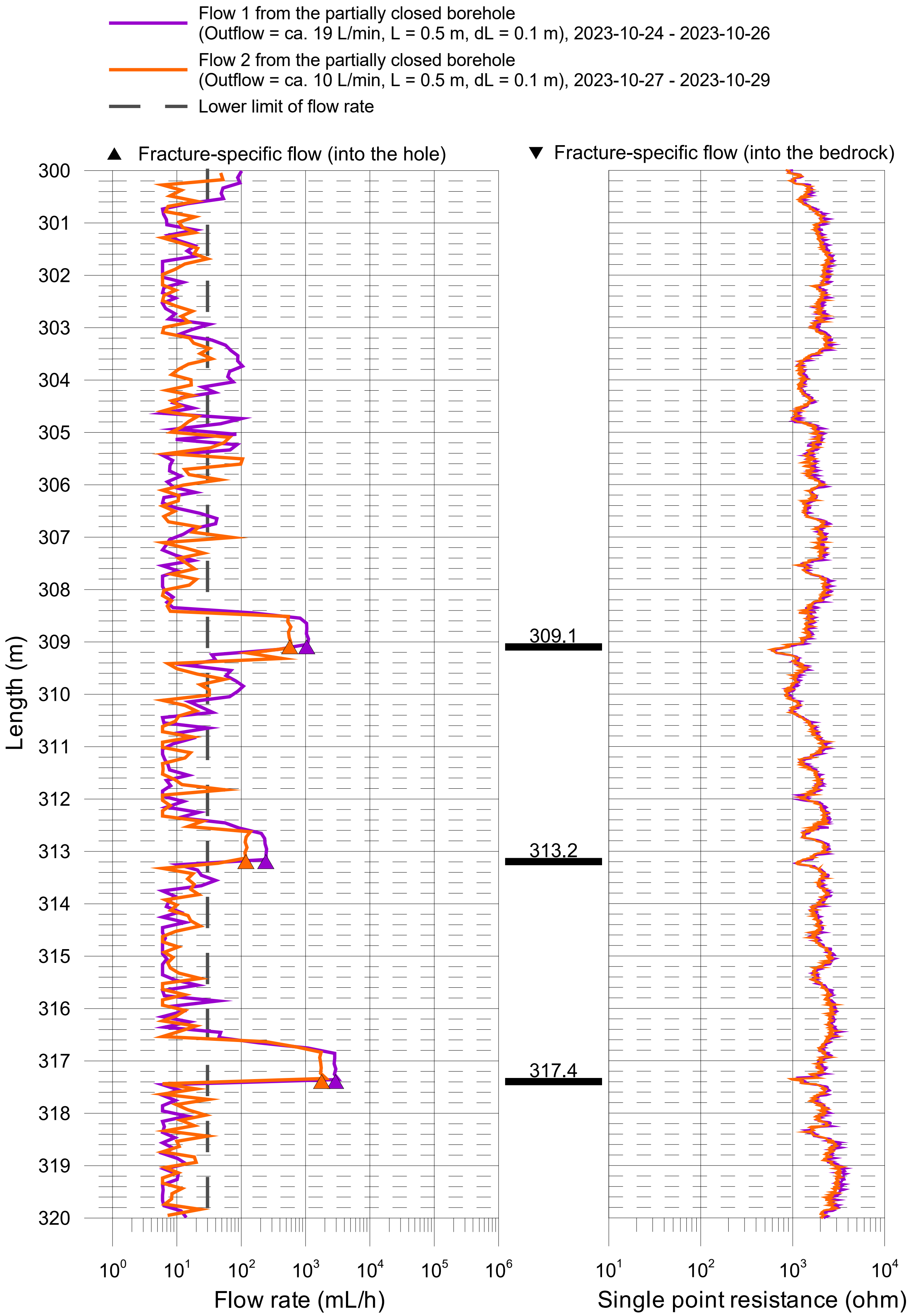
Forsmark, borehole KFR91
Flow rate and single point resistance

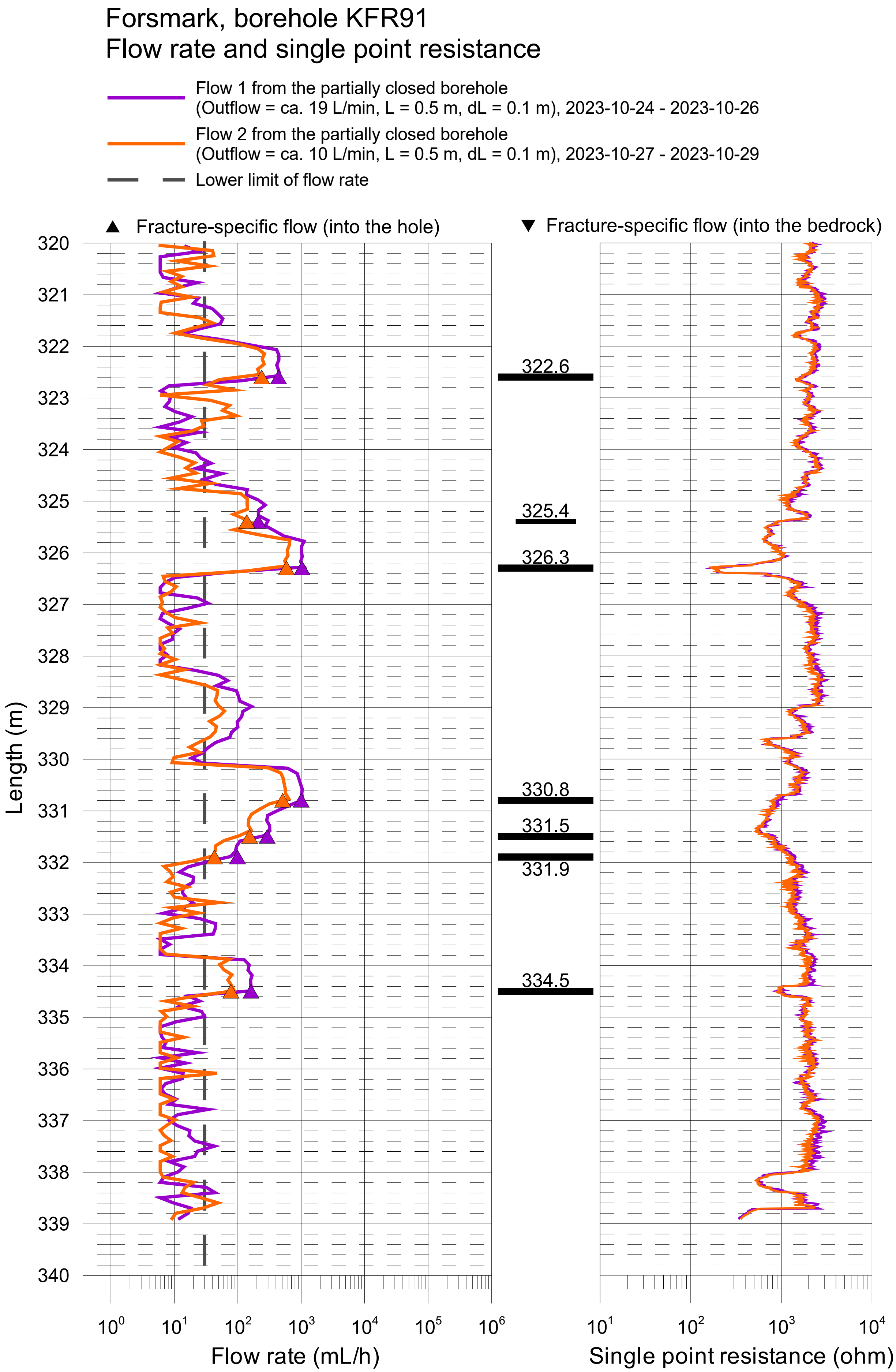


Forsmark, borehole KFR91
Flow rate and single point resistance



Forsmark, borehole KFR91
Flow rate and single point resistance




Forsmark, borehole KFR91
Flow rate and single point resistance
Flow 1 from the partially closed borehole
(Outflow = ca. 19 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-24 - 2023-10-26
Flow 2 from the partially closed borehole
(Outflow = ca. 10 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-27 - 2023-10-29
Lower limit of flow rate
▲ Fracture-specific flow (into the hole)
▼ Fracture-specific flow (into the bedrock)
Length (m)
320
321
322
323
324
325
326
327
328
329
330
331
332
333
334
335
336
337
338
339
340
322.6
325.4
326.3
330.8
331.5
331.9
334.5
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
Single point resistance (ohm)

Glossary of terms used in the tables in Appendices 13.1 – 13.3

Header	Unit	Explanations
Borehole		ID for borehole
Length to flow anom. L (m)	m	Length along the borehole to inferred flowing fracture 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_1	m^3/s	Measured flow rate through the measurement section during the first pumping period
Q_2	m^3/s	Measured flow rate through the measurement section during the second pumping period
h_{1FW}	m.a.s.l.	Corrected hydraulic head along the hole due to e.g., varying salinity conditions of the borehole fluid during the first pumping period
h_{2FW}	m.a.s.l.	Corrected hydraulic head along the hole due to e.g., varying salinity conditions of the borehole fluid during the second 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.
h_i	m.a.s.l.	Calculated relative, natural freshwater head for measurement section (undisturbed conditions)

Inferred flow anomalies from overlapping flow logging

Borehole	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_1 (m^3/s)	h_{1FW} (masl)	Q_2 (m^3/s)	h_{2FW} (masl)	T_D (m^2/s)	h_i (masl)	Com-ments
KFR91	3.2	0.5	0.1	-4.53E-06	-45.64	-8.94E-06	-26.02	2.23E-07	-65.75	
KFR91	4.6	0.5	0.1	-1.07E-06	-45.65	-2.86E-06	-26.10	9.05E-08	-57.37	
KFR91	5.7	0.5	0.1	-	-45.59	-2.56E-08	-26.04	1.29E-09	-	3
KFR91	6.9	0.5	0.1	-1.10E-07	-45.63	-2.83E-07	-26.03	8.75E-09	-58.07	4
KFR91	7.2	0.5	0.1	-1.32E-07	-45.64	-3.44E-07	-26.02	1.07E-08	-57.78	
KFR91	10.6	0.5	0.1	1.22E-08	-45.67	-4.44E-09	-26.09	8.42E-10	-31.31	4
KFR91	11.1	0.5	0.1	5.56E-08	-45.68	-5.56E-09	-26.01	3.07E-09	-27.80	4
KFR91	11.9	0.5	0.1	1.38E-06	-45.65	-8.22E-06	-26.01	4.84E-07	-42.82	
KFR91	15.3	0.5	0.1	2.50E-09	-45.72	-5.00E-09	-26.03	3.77E-10	-39.16	4
KFR91	20.9	0.5	0.1	2.56E-08	-45.76	-4.92E-08	-26.11	3.76E-09	-39.04	
KFR91	25.0	0.5	0.1	7.00E-08	-45.76	-1.26E-07	-26.08	9.87E-09	-38.75	
KFR91	28.9	0.5	0.1	5.89E-08	-45.79	-7.72E-08	-26.08	6.83E-09	-37.26	
KFR91	30.0	0.5	0.1	7.50E-09	-45.8	-1.03E-08	-26.08	8.92E-10	-37.48	4
KFR91	32.0	0.5	0.1	7.22E-09	-45.80	-1.06E-08	-26.08	8.92E-10	-37.79	4
KFR91	32.7	0.5	0.1	4.17E-08	-45.81	-4.36E-08	-26.06	4.27E-09	-36.16	
KFR91	33.6	0.5	0.1	2.31E-08	-45.83	-5.00E-09	-26.09	1.41E-09	-29.61	
KFR91	35.6	0.5	0.1	8.61E-09	-45.80	2.22E-09	-26.12	3.21E-10	-19.27	
KFR91	36.6	0.5	0.1	5.83E-09	-45.80	-	-26.06	2.92E-10	-	2, 4
KFR91	38.6	0.5	0.1	2.67E-08	-45.77	8.06E-09	-26.02	9.32E-10	-17.47	
KFR91	39.3	0.5	0.1	2.86E-06	-45.76	1.11E-06	-26.01	8.76E-08	-13.47	
KFR91	40.0	0.5	0.1	1.58E-08	-45.80	4.72E-09	-26.08	5.57E-10	-17.70	4
KFR91	40.4	0.5	0.1	7.67E-08	-45.80	2.19E-08	-26.07	2.74E-09	-18.16	
KFR91	43.3	0.5	0.1	4.28E-07	-45.79	1.48E-07	-26.12	1.41E-08	-15.77	
KFR91	43.7	0.5	0.1	5.61E-07	-45.80	2.49E-07	-26.08	1.56E-08	-10.33	
KFR91	47.4	0.5	0.1	5.03E-07	-45.79	1.92E-07	-26.14	1.56E-08	-13.98	
KFR91	49.9	0.5	0.1	5.56E-09	-45.76	-	-26.11	2.80E-10	-	2, 4
KFR91	51.4	0.5	0.1	4.78E-08	-45.79	1.44E-08	-26.13	1.68E-09	-17.61	
KFR91	53.2	0.5	0.1	5.83E-09	-45.77	-	-26.09	2.93E-10	-	2, 4
KFR91	56.1	0.5	0.1	3.92E-08	-45.77	1.19E-08	-26.06	1.37E-09	-17.41	
KFR91	58.6	0.5	0.1	4.92E-08	-45.78	1.64E-08	-26.07	1.64E-09	-16.22	
KFR91	59.1	0.5	0.1	9.72E-09	-45.79	-	-26.07	4.88E-10	-	2, 4
KFR91	65.4	0.5	0.1	4.11E-08	-45.80	9.72E-09	-26.05	1.57E-09	-19.93	
KFR91	65.8	0.5	0.1	4.17E-08	-45.76	1.06E-08	-26.02	1.56E-09	-19.32	
KFR91	66.9	0.5	0.1	2.06E-08	-45.78	5.83E-09	-26.03	7.37E-10	-18.20	
KFR91	69.1	0.5	0.1	7.50E-09	-45.78	-	-26.04	3.76E-10	-	2, 4
KFR91	71.4	0.5	0.1	1.61E-08	-45.79	-	-26.07	8.08E-10	-	2
KFR91	71.8	0.5	0.1	5.00E-09	-45.79	-	-26.07	2.51E-10	-	2, 4
KFR91	72.2	0.5	0.1	3.06E-09	-45.79	-	-26.06	1.53E-10	-	2, 4
KFR91	77.9	0.5	0.1	9.44E-09	-45.82	4.17E-09	-26.09	2.65E-10	-10.51	
KFR91	78.4	0.5	0.1	7.50E-09	-45.81	-	-26.12	3.77E-10	-	2, 4
KFR91	83.7	0.5	0.1	2.14E-08	-45.89	8.33E-09	-26.15	6.54E-10	-13.55	
KFR91	84.5	0.5	0.1	2.94E-07	-45.88	1.13E-07	-26.15	9.08E-09	-13.80	
KFR91	85.1	0.5	0.1	3.11E-07	-45.89	1.07E-07	-26.17	1.02E-08	-15.84	
KFR91	86.0	0.5	0.1	2.78E-08	-45.90	1.06E-08	-26.18	8.64E-10	-14.09	
KFR91	87.0	0.5	0.1	3.22E-07	-45.94	1.49E-07	-26.24	8.67E-09	-9.20	

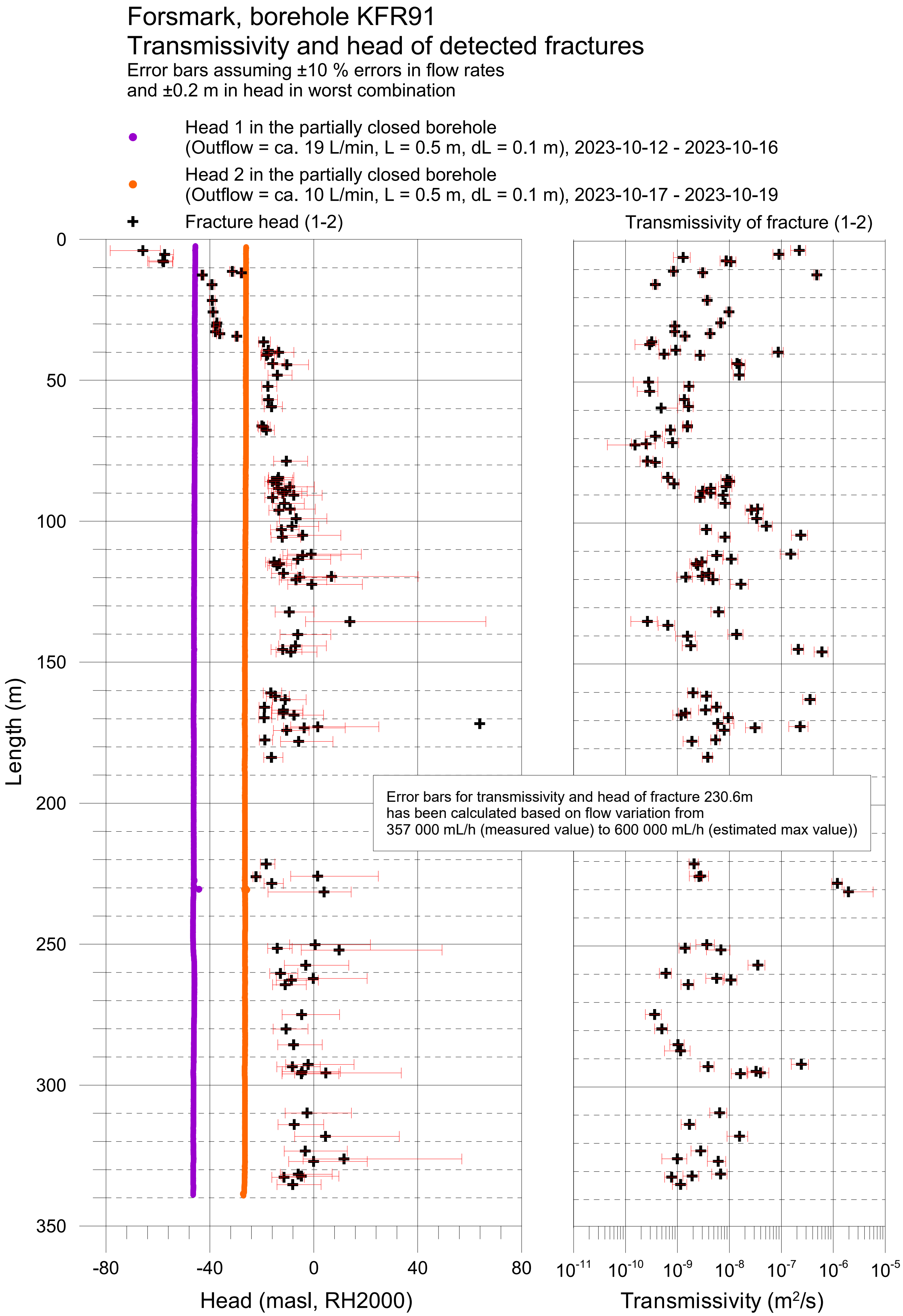
Inferred flow anomalies from overlapping flow logging

Borehole	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_1 (m^3/s)	h_{1FW} (masl)	Q_2 (m^3/s)	h_{2FW} (masl)	T_D (m^2/s)	h_i (masl)	Comments
KFR91	87.6	0.5	0.1	1.44E-07	-45.97	5.61E-08	-26.26	4.39E-09	-13.62	4
KFR91	88.6	0.5	0.1	1.09E-07	-45.94	4.83E-08	-26.26	3.07E-09	-10.69	4
KFR91	89.3	0.5	0.1	1.51E-07	-45.94	6.39E-08	-26.22	4.39E-09	-11.82	4
KFR91	90.0	0.5	0.1	2.94E-07	-45.93	1.43E-07	-26.22	7.61E-09	-7.67	
KFR91	90.8	0.5	0.1	8.36E-08	-45.9	2.89E-08	-26.21	2.75E-09	-15.82	4
KFR91	92.9	0.5	0.1	2.92E-07	-45.91	1.26E-07	-26.21	8.33E-09	-11.26	
KFR91	94.9	0.5	0.1	1.31E-06	-45.93	6.11E-07	-26.21	3.51E-08	-8.99	
KFR91	95.3	0.5	0.1	8.81E-07	-45.91	3.47E-07	-26.22	2.68E-08	-13.40	
KFR91	98.3	0.5	0.1	1.34E-06	-45.91	6.64E-07	-26.20	3.37E-08	-6.73	
KFR91	101.0	0.5	0.1	1.96E-06	-45.94	9.33E-07	-26.24	5.16E-08	-8.35	
KFR91	102.2	0.5	0.1	1.23E-07	-45.97	5.08E-08	-26.25	3.64E-09	-12.42	4
KFR91	104.2	0.5	0.1	1.00E-05	-45.98	5.28E-06	-26.28	2.37E-07	-4.26	
KFR91	104.9	0.5	0.1	2.83E-07	-46.00	1.19E-07	-26.28	8.26E-09	-12.08	
KFR91	110.9	0.5	0.1	6.94E-06	-46.03	3.92E-06	-26.37	1.52E-07	-0.94	
KFR91	111.4	0.5	0.1	2.41E-07	-46.02	1.28E-07	-26.35	5.71E-09	-4.28	4
KFR91	112.7	0.5	0.1	4.42E-07	-46.01	2.24E-07	-26.34	1.10E-08	-6.12	
KFR91	113.7	0.5	0.1	9.25E-08	-45.99	3.33E-08	-26.33	2.98E-09	-15.25	4
KFR91	114.3	0.5	0.1	7.69E-08	-46.05	3.08E-08	-26.33	2.31E-09	-13.14	4
KFR91	114.9	0.5	0.1	7.97E-08	-46.04	3.06E-08	-26.36	2.47E-09	-14.13	
KFR91	117.7	0.5	0.1	1.40E-07	-46.05	6.00E-08	-26.41	4.01E-09	-11.63	
KFR91	118.8	0.5	0.1	1.61E-07	-46.04	1.01E-07	-26.36	3.00E-09	6.87	
KFR91	119.1	0.5	0.1	5.97E-08	-46.04	3.08E-08	-26.36	1.45E-09	-5.36	
KFR91	120.0	0.5	0.1	1.93E-07	-46.07	9.58E-08	-26.33	4.86E-09	-6.82	
KFR91	121.6	0.5	0.1	7.67E-07	-46.07	4.33E-07	-26.37	1.67E-08	-0.76	
KFR91	131.4	0.5	0.1	2.32E-07	-46.1	1.08E-07	-26.42	6.24E-09	-9.38	
KFR91	134.8	0.5	0.1	1.61E-08	-46.09	1.08E-08	-26.43	2.66E-10	13.92	4
KFR91	136.2	0.5	0.1	1.31E-08	-46.12	-	-26.46	6.57E-10	-	2, 4
KFR91	139.4	0.5	0.1	5.58E-07	-46.13	2.83E-07	-26.43	1.38E-08	-6.13	
KFR91	140.0	0.5	0.1	3.11E-08	-46.12	-	-26.43	1.56E-09	-	2, 4
KFR91	143.4	0.5	0.1	7.14E-08	-46.13	3.56E-08	-26.50	1.81E-09	-7.02	4
KFR91	144.7	0.5	0.1	7.36E-06	-46.13	3.14E-06	-26.50	2.13E-07	-11.91	
KFR91	145.6	0.5	0.1	2.29E-05	-46.09	1.09E-05	-26.45	6.09E-07	-8.80	
KFR91	160.1	0.5	0.1	6.03E-08	-46.18	2.03E-08	-26.50	2.01E-09	-16.52	
KFR91	161.3	0.5	0.1	1.16E-07	-46.19	4.33E-08	-26.48	3.65E-09	-14.74	4
KFR91	162.5	0.5	0.1	1.28E-05	-46.19	5.61E-06	-26.48	3.58E-07	-10.99	
KFR91	165.2	0.5	0.1	1.58E-07	-46.24	4.36E-08	-26.49	5.70E-09	-18.93	4
KFR91	166.2	0.5	0.1	1.22E-07	-46.25	5.22E-08	-26.47	3.49E-09	-11.65	4
KFR91	167.3	0.5	0.1	5.00E-08	-46.27	2.14E-08	-26.50	1.43E-09	-11.72	
KFR91	168.0	0.5	0.1	4.64E-08	-46.28	2.28E-08	-26.57	1.18E-09	-7.56	4
KFR91	168.9	0.5	0.1	2.63E-07	-46.27	7.28E-08	-26.56	9.56E-09	-19.03	
KFR91	171.0	0.5	0.1	6.67E-07	-46.29	5.47E-07	-26.54	5.98E-09	63.94	1
KFR91	172.1	0.5	0.1	1.12E-05	-46.25	6.60E-06	-26.54	2.32E-07	1.60	
KFR91	172.5	0.5	0.1	1.35E-06	-46.26	7.25E-07	-26.53	3.13E-08	-3.64	4
KFR91	173.4	0.5	0.1	2.89E-07	-46.20	1.30E-07	-26.51	7.98E-09	-10.40	
KFR91	176.8	0.5	0.1	1.51E-07	-46.18	4.25E-08	-26.48	5.47E-09	-18.79	

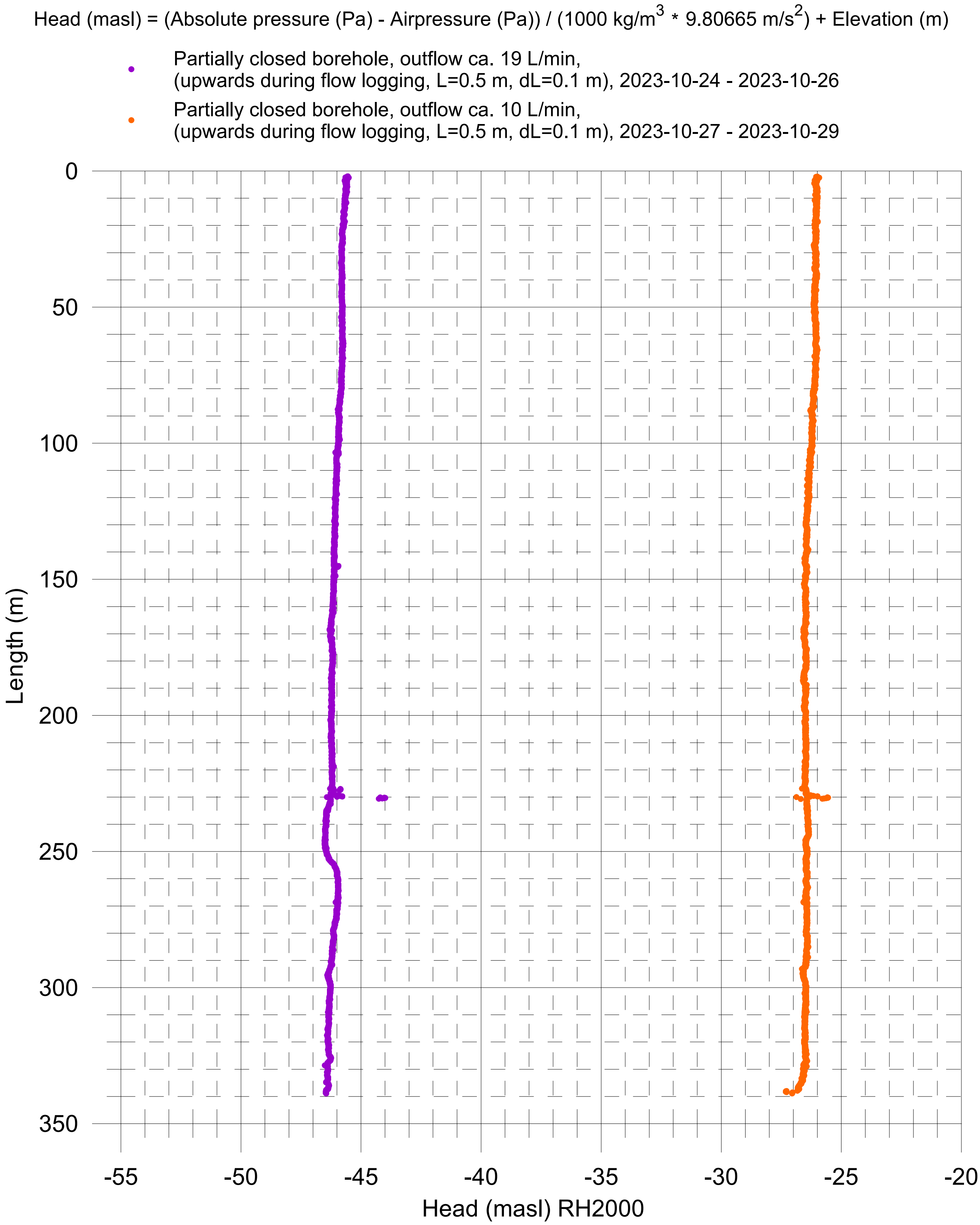
Inferred flow anomalies from overlapping flow logging

Borehole	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_1 (m^3/s)	h_{1FW} (masl)	Q_2 (m^3/s)	h_{2FW} (masl)	T_D (m^2/s)	h_i (masl)	Com-ments
KFR91	177.3	0.5	0.1	7.81E-08	-46.17	4.00E-08	-26.48	1.91E-09	-5.78	
KFR91	183.0	0.5	0.1	1.17E-07	-46.23	4.00E-08	-26.50	3.86E-09	-16.24	
KFR91	220.8	0.5	0.1	5.94E-08	-46.23	1.75E-08	-26.48	2.10E-09	-18.24	
KFR91	225.1	0.5	0.1	1.36E-07	-46.20	8.00E-08	-26.52	2.82E-09	1.54	
KFR91	225.3	0.5	0.1	6.33E-08	-46.20	1.14E-08	-26.51	2.61E-09	-22.19	
KFR91	227.7	0.5	0.1	3.67E-05	-46.19	1.26E-05	-26.47	1.21E-06	-16.13	
KFR91	230.7	0.5	0.1	9.92E-05	-45.88	6.08E-05	-26.60	1.97E-06	4.00	
KFR91	249.4	0.5	0.1	1.76E-07	-46.48	1.01E-07	-26.46	3.69E-09	0.56	
KFR91	250.7	0.5	0.1	4.64E-08	-46.43	1.78E-08	-26.43	1.41E-09	-14.00	4
KFR91	251.3	0.5	0.1	3.92E-07	-46.39	2.53E-07	-26.43	6.90E-09	9.78	
KFR91	256.7	0.5	0.1	1.54E-06	-46.02	8.39E-07	-26.48	3.54E-08	-3.06	
KFR91	259.6	0.5	0.1	2.03E-08	-45.97	8.33E-09	-26.43	6.05E-10	-12.80	
KFR91	261.4	0.5	0.1	2.65E-07	-45.97	1.52E-07	-26.45	5.71E-09	-0.15	4
KFR91	262.0	0.5	0.1	4.06E-07	-45.95	1.94E-07	-26.46	1.07E-08	-8.56	
KFR91	263.6	0.5	0.1	5.72E-08	-45.95	2.53E-08	-26.42	1.62E-09	-10.97	
KFR91	274.2	0.5	0.1	1.53E-08	-46.03	8.06E-09	-26.46	3.65E-10	-4.63	4
KFR91	279.3	0.5	0.1	1.81E-08	-46.16	8.06E-09	-26.48	5.03E-10	-10.63	4
KFR91	284.9	0.5	0.1	4.00E-08	-46.18	1.94E-08	-26.42	1.03E-09	-7.73	
KFR91	287.1	0.5	0.1	2.31E-08	-46.21	-	-26.44	1.15E-09	-	2, 4
KFR91	290.6	0.5	0.1	2.00E-07	-46.25	2.62E-07	-26.46	-	-	5
KFR91	291.9	0.5	0.1	1.09E-05	-46.24	6.00E-06	-26.5	2.44E-07	-2.14	
KFR91	292.7	0.5	0.1	1.50E-07	-46.28	7.25E-08	-26.56	3.90E-09	-8.18	
KFR91	294.4	0.5	0.1	1.39E-06	-46.35	7.33E-07	-26.59	3.28E-08	-4.49	4
KFR91	294.9	0.5	0.1	2.06E-06	-46.37	1.26E-06	-26.6	3.99E-08	4.67	
KFR91	295.2	0.5	0.1	6.89E-07	-46.38	3.61E-07	-26.56	1.64E-08	-4.72	
KFR91	309.1	0.5	0.1	2.89E-07	-46.36	1.58E-07	-26.52	6.52E-09	-2.55	
KFR91	313.2	0.5	0.1	6.69E-08	-46.34	3.28E-08	-26.51	1.70E-09	-7.49	
KFR91	317.4	0.5	0.1	8.11E-07	-46.40	4.94E-07	-26.51	1.57E-08	4.55	
KFR91	322.6	0.5	0.1	1.23E-07	-46.36	6.61E-08	-26.51	2.81E-09	-3.24	
KFR91	325.4	0.5	0.1	5.86E-08	-46.27	3.86E-08	-26.50	1.00E-09	11.67	4
KFR91	326.3	0.5	0.1	2.86E-07	-46.27	1.64E-07	-26.47	6.12E-09	-0.03	
KFR91	330.8	0.5	0.1	2.78E-07	-46.39	1.42E-07	-26.57	6.79E-09	-5.94	
KFR91	331.5	0.5	0.1	8.11E-08	-46.41	4.25E-08	-26.57	1.92E-09	-4.73	
KFR91	331.9	0.5	0.1	2.75E-08	-46.41	1.19E-08	-26.61	7.77E-10	-11.41	
KFR91	334.5	0.5	0.1	4.47E-08	-46.43	2.17E-08	-26.65	1.15E-09	-8.06	

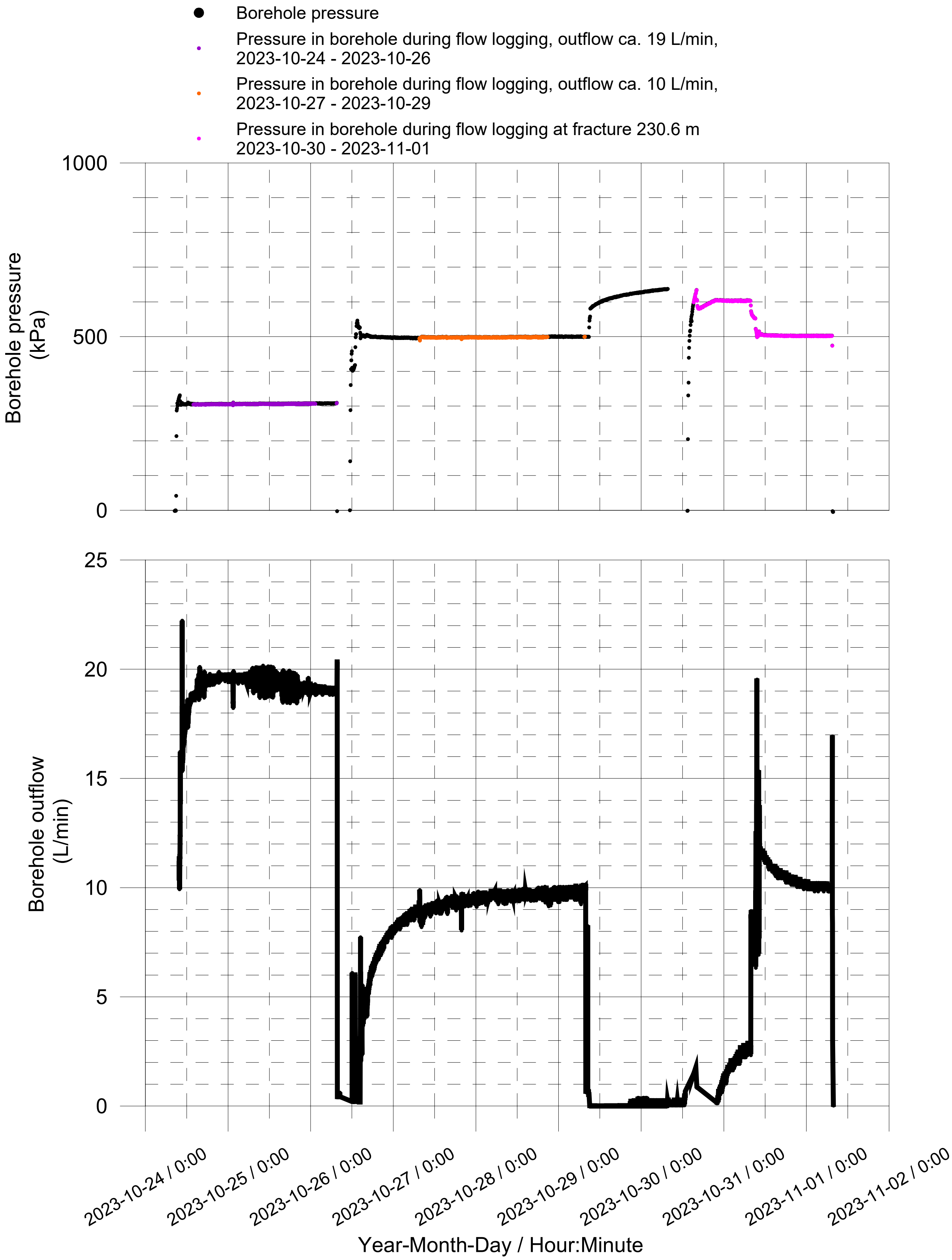
1) Flow change is smaller than measurement uncertainty.
2) Flow was not detected during measurement run #2.
3) Flow was not detected during measurement run #1.
4) Uncertain = The flow rate is less than 30 mL/h or the flow anomalies are overlapping or they are unclear because of noise.
5) Flow results lead to unrealistic negative transmissivity.

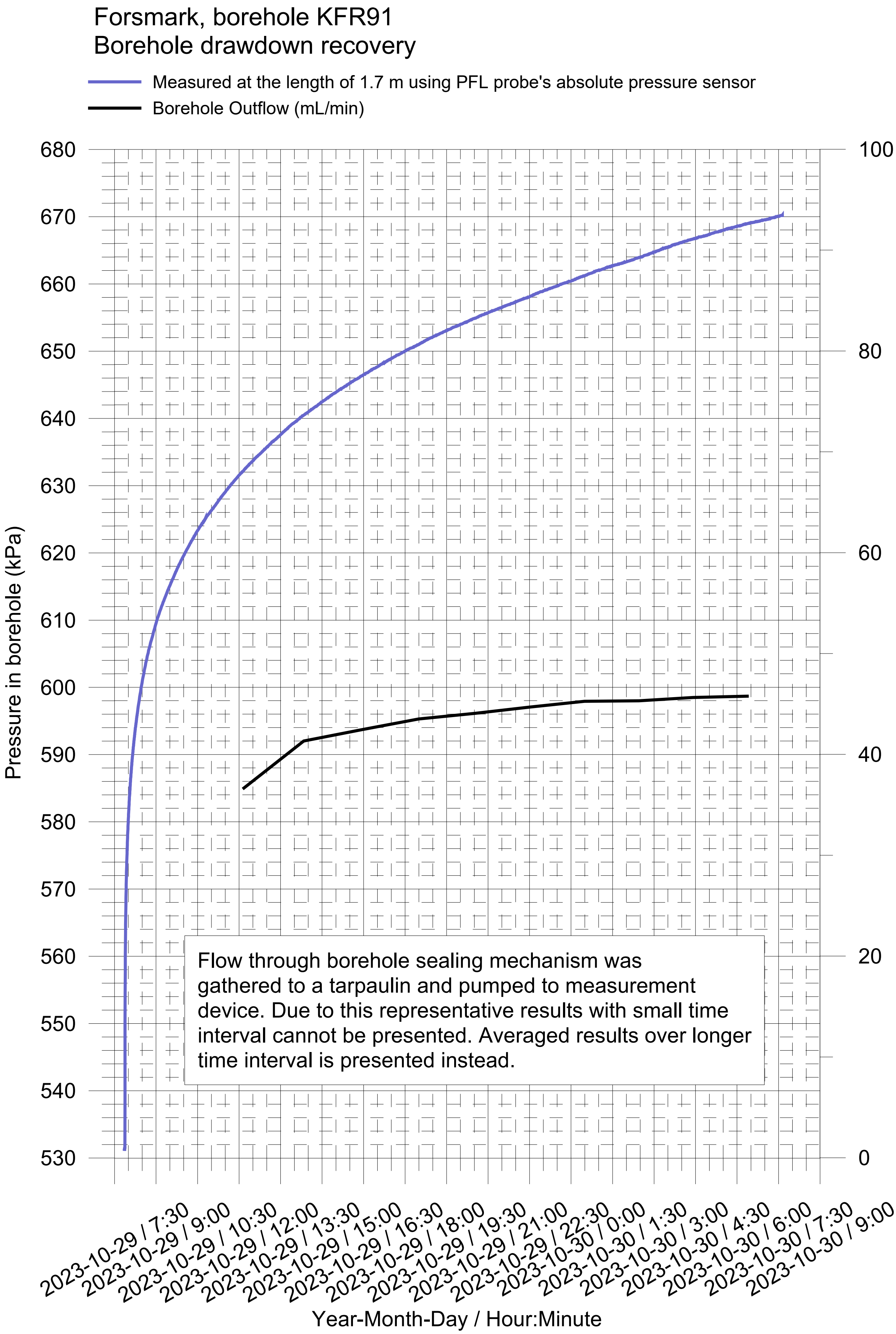

Forsmark, borehole KFR91
Transmissivity and head of detected fractures
Error bars assuming ±10 % errors in flow rates
and ±0.2 m in head in worst combination
Head 1 in the partially closed borehole
(Outflow = ca. 19 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-12 - 2023-10-16
Head 2 in the partially closed borehole
(Outflow = ca. 10 L/min, L = 0.5 m, dL = 0.1 m), 2023-10-17 - 2023-10-19
Fracture head (1-2)
Transmissivity of fracture (1-2)
Error bars for transmissivity and head of fracture 230.6m
has been calculated based on flow variation from
357 000 mL/h (measured value) to 600 000 mL/h (estimated max value))
Length (m)
Head (masl, RH2000)
Transmissivity (m²/s)
0
50
100
150
200
250
300
350
-80
-40
0
40
80
10⁻¹¹
10⁻¹⁰
10⁻⁹
10⁻⁸
10⁻⁷
10⁻⁶
10⁻⁵

Forsmark, borehole KFR91
Head in the borehole during flow logging



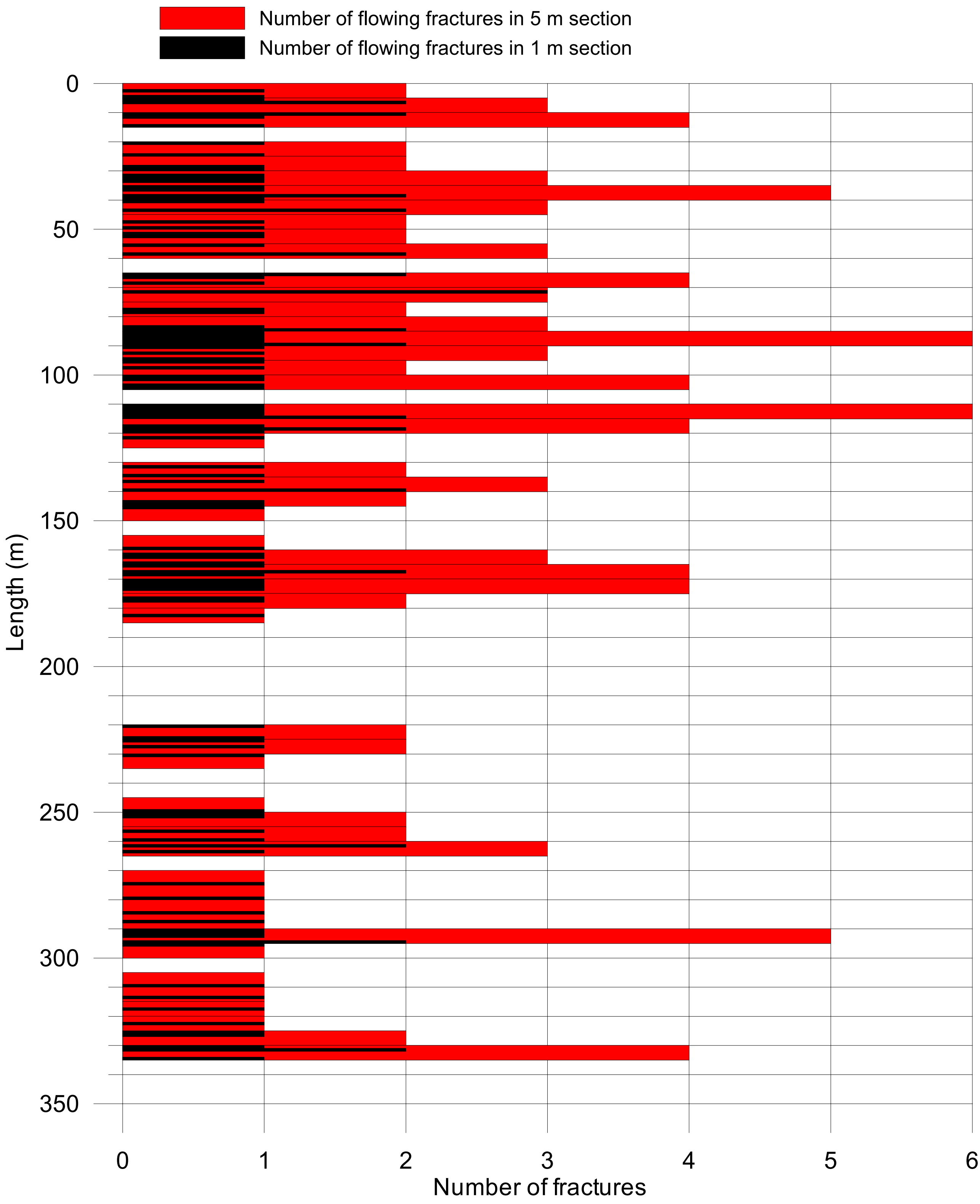
Forsmark, borehole KFR91
Borehole pressure and outflow from the borehole





Forsmark, borehole KFR91
Borehole drawdown recovery
Measured at the length of 1.7 m using PFL probe's absolute pressure sensor
Borehole Outflow (mL/min)
Pressure in borehole (kPa)
680
670
660
650
640
630
620
610
600
590
580
570
560
550
540
530
Borehole outflow (mL/min)
100
80
60
40
20
0
Flow through borehole sealing mechanism was gathered to a tarpaulin and pumped to measurement device. Due to this representative results with small time interval cannot be presented. Averaged results over longer time interval is presented instead.
2023-10-29 / 7:30
2023-10-29 / 9:00
2023-10-29 / 10:30
2023-10-29 / 12:00
2023-10-29 / 13:30
2023-10-29 / 15:00
2023-10-29 / 16:30
2023-10-29 / 18:00
2023-10-29 / 19:30
2023-10-29 / 21:00
2023-10-29 / 22:30
2023-10-30 / 0:00
2023-10-30 / 1:30
2023-10-30 / 3:00
2023-10-30 / 4:30
2023-10-30 / 6:00
2023-10-30 / 7:30
2023-10-30 / 9:00
Year-Month-Day / Hour:Minute

Forsmark, borehole KFR91
Calculation of conductive fracture frequency



Forsmark, borehole KFR91
Borehole pressure, outflow from the borehole, fracture-specific flow and hydraulic head results by date (at fracture at 230.7 m)