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Äspö Hard Rock Laboratory

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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 hydraulic conductivity and hydraulic head in fractures/fractured zones in cored boreholes. This report presents the main principles of the methods as well as the results of measurements carried out in an underground borehole KA3007A01 at the Äspö Hard Rock Laboratory, Sweden, in June 2011.

The flow logging measurement was done with a 1 m test section by moving the measurement tool in 0.1 m steps. This method was used to flow log the entire measurable part of the borehole. The borehole was open during the measurement.

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 borehole.

The outflow from the borehole was measured during the time the borehole was open for measurements.

Sammanfattning

Posiva Flow Log, Differensflödesloggning (PFL DIFF) är en snabb metod för bestämning av transmissiviteten och hydraulisk tryckhöjd i borrhålssektioner och sprickor/sprickzoner i kärnborrhål. Denna rapport presenterar huvudprinciperna för metoden och resultat av mätningar utförda i borrhål KA3007A01 inom Äspö Hard Rock Laboratoriet, Sverige, i juni 2011.

Flödesmätningarna gjordes med en 1 m lång testsektion som förflyttades successivt i steg om 0.1 m i den mätbara delen av borrhålet. Borrhålet var öppet under mätningarna.

Elektrisk konduktivitet (EC) och temperatur på borrhålsvattnet mättes också. EC-mätningarna användes för att studera förekomsten av saltvatten i borrhålet.

Utflödet från borrhålet mättes under tiden detta var öppet för mätningarna.

Contents

1 Introduction

The core drilled borehole KA3007A1 at Äspö, Sweden was 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 June 16 and 17, 2011. The borehole is located in the Äspö tunnel at the Äspö Hard Rock Laboratory (HRL).

KA3007A1 is 227.76 m long and its inclination at its reference point at –400.61 masl is –14.7° from the horizontal plane. The borehole interval 0 m–2.54 m is cased and its inner diameter is 80 mm. Diameter between interval 2.54 m–3.04 m is 116 mm. The interval between 3.04 m and 227.76 m is core drilled with a diameter of c 76 mm. The borehole interval 0 m–146.50 m is grouted.

The location of KA3007A01 at the Äspö tunnel is illustrated in Figure 1-1.

The field work and the subsequent data interpretation were conducted by Pöyry Finland Oy. PFL DIFF has previously been employed in Posiva's site characterisation programme in Finland as well as at the Äspö HRL, Sweden. The commissions at the latter site included measurements in the 1,700 m long cored borehole KLX02 at Laxemar together with a methodology study (Ludvigson et al. 2002). PFL DIFF has also been employed in SKB's site characterisation programme at Laxemar and Forsmark.

This document reports the results acquired by PFL DIFF in borehole KA3007A01. Measurements and results presented in this report were undertaken in the framework of the project TDUP002 towards extending the tunnel system at the Äspö Hard Rock Laboratory (HRL). The measurements were carried out in accordance to SKB's internal controlling document AP TD TDUP002-11-006. The controlling documents for performing according to this Activity Plan are listed in Table 1-1. The list of the controlling documents excludes the assignment-specific quality plans. Both the Activity Plan and the Method Descriptions are SKB's internal controlling documents. The measurement data and the results were delivered to the SKB site characterization database SICADA and are traceable by the Activity Plan number.

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

Activity Plan	Number	Version
Difference flow logging in borehole KA2051A01 and KA3007A01	AP TD TDUP002-11-006	1.0

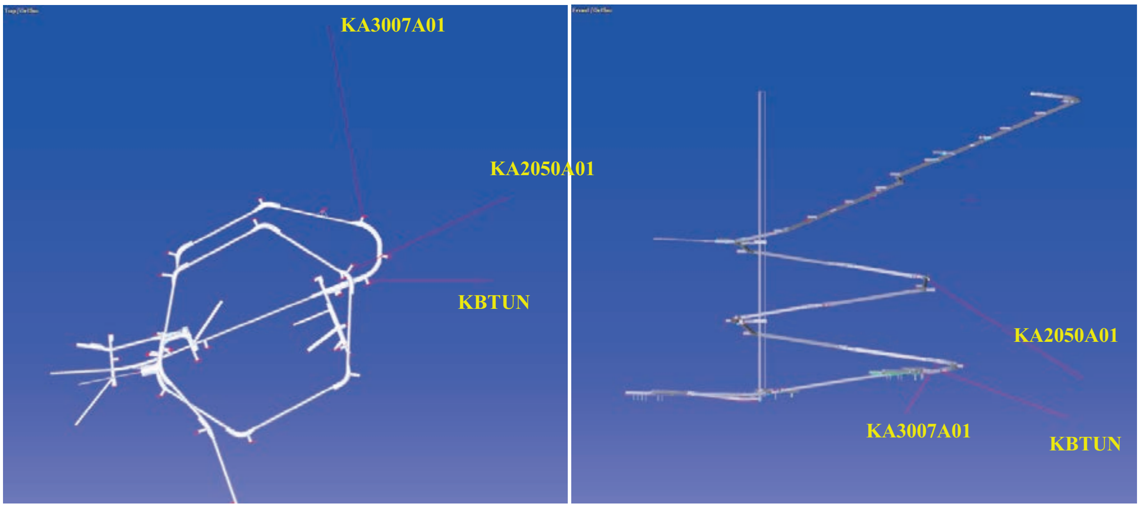

Figure 1-1. *Tentative location of boreholes KA2051A01, KA3007A01 and KBTUN in the Äspö tunnel.*

2 Objective and scope

The main objective of the PFL DIFF measurements in KA3007A01 was to identify water-conductive fractures suitable for subsequent hydro-geochemical characterisation. Secondly, the measurements aimed at a hydrogeological characterisation, which includes the estimates of the transmissivity of tested sections and detected fractures. Based on the results of these investigations, a more detailed characterisation of flow anomalies along the borehole, e.g. an estimate of the conductive fracture frequency (CFF), may be obtained.

Besides difference flow logging, the measurement programme also included supporting measurements, performed in order to gain a better understanding of the overall hydrogeochemical conditions. These measurements included the electrical conductivity (EC) and the temperature of the borehole fluid as well as the single-point resistance of the borehole wall. The flow measurement and the single-point resistance measurement were used to locate flowing fractures. Furthermore, the flow rate out from the open borehole was recorded.

3 Principles of measurement and interpretation

3.1 Measurements

Unlike conventional borehole flowmeters which measure the total cumulative flow rate along a borehole, 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 incremental changes of flow along the borehole. As these are generally very small, they can easily be missed when using conventional flowmeters.

Rubber sealing disks located at the top and bottom of the probe are used to isolate the flow of water in the test section from the flow in the rest of the borehole, see Figure 3-1. Flow inside the test section is directed through the flow sensor. Flow along the borehole is directed around the test section by means of a bypass pipe and is discharged at either the upper or lower end of the probe. The entire structure is called the flow guide.

Generally two separate measurements with two different section lengths (e.g. 5 m and 1 m) are used. The 5 m setup is usually used first to obtain a general picture of the flow anomalies. It is also good for measuring larger (less than 5 m in length) fractured zones. The 1 m section setup can separate anomalies which are close to each other. There are also many other advantages to using different section lengths.

Flow rates into or out of the test section are monitored using thermistors, which track both the dilution (cooling) of a thermal pulse and its transfer by the moving water (Öhberg and Rouhiainen, 2000, pp 11–13). The thermal dilution method is used in measuring flow rates because it is faster than the thermal pulse method, and the latter is used only to determine flow direction within a given time frame. Both methods are used simultaneously at each measurement location.

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

- The electrical conductivity (EC) of both borehole water and fracture-specific water. The electrode used in EC measurements is located at the top of the flow sensor, see Figure 3-1.
- 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 3-1, and is used for the high-resolution depth 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 borehole water through a tube, see Figure 3-2. Water pressure measurement is not important in nearly horizontal boreholes as in KA3007A01.
- The temperature of the water in the borehole. The temperature sensor is part of the flow sensor, see Figure 3-1.

The principles behind PFL DIFF flow measurements are shown in Figure 3-3. The flow sensor consists of three thermistors (Figure 3-3 a). The central thermistor, A, is used both as a heating element and to register temperature changes (Figures 3-3 b and c). The side thermistors, B1 and B2, serve as detectors of the moving thermal pulse caused by the heating of A.

Flow rate is measured by monitoring heat transients after constant power heating in thermistor A. The measurement begins by constant power (P_1) heating. After the power is cut off the flow rate is measured by monitoring transient thermal dilution (Figure 3-3 c). If the measured flow rate exceeds a certain limit, another constant power heating (P_2) period is started after which the flow rate is re-measured from the following heat transient.

Flows are measured when the probe is at rest. After transferring the probe to a new position, a waiting period (which can be adjusted according to the prevailing circumstances) is allowed to elapse before the heat pulse (Figure 3-3 b) is applied. The measurement period after the constant-power thermal pulse (normally 100 s each time the probe has moved a distance equal to the test section length and 10 s in every other location) can also be adjusted. The longer (100 s) measurement time is used to allow the direction of even the smallest measurable flows to be visible.

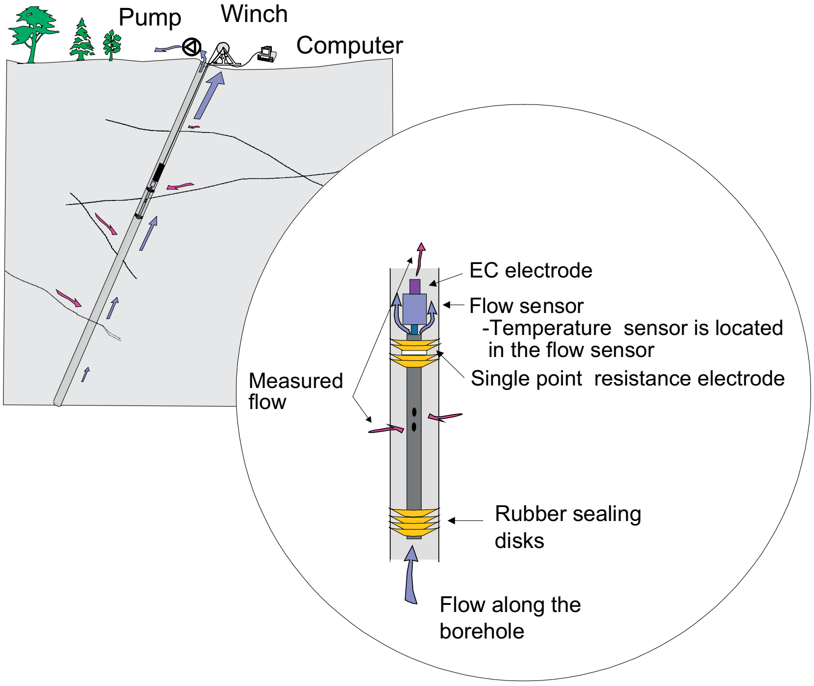

Figure 3-1. Schematic of the probe used in the PFL DIFF.

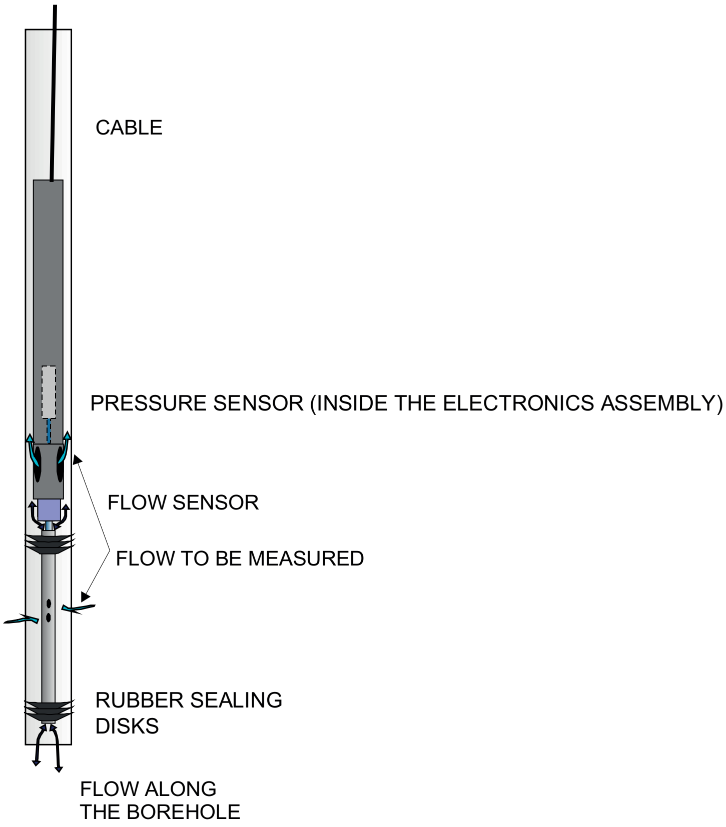

Figure 3-2. The absolute pressure sensor is located inside the electronics assembly and connected to the borehole water through a tube.

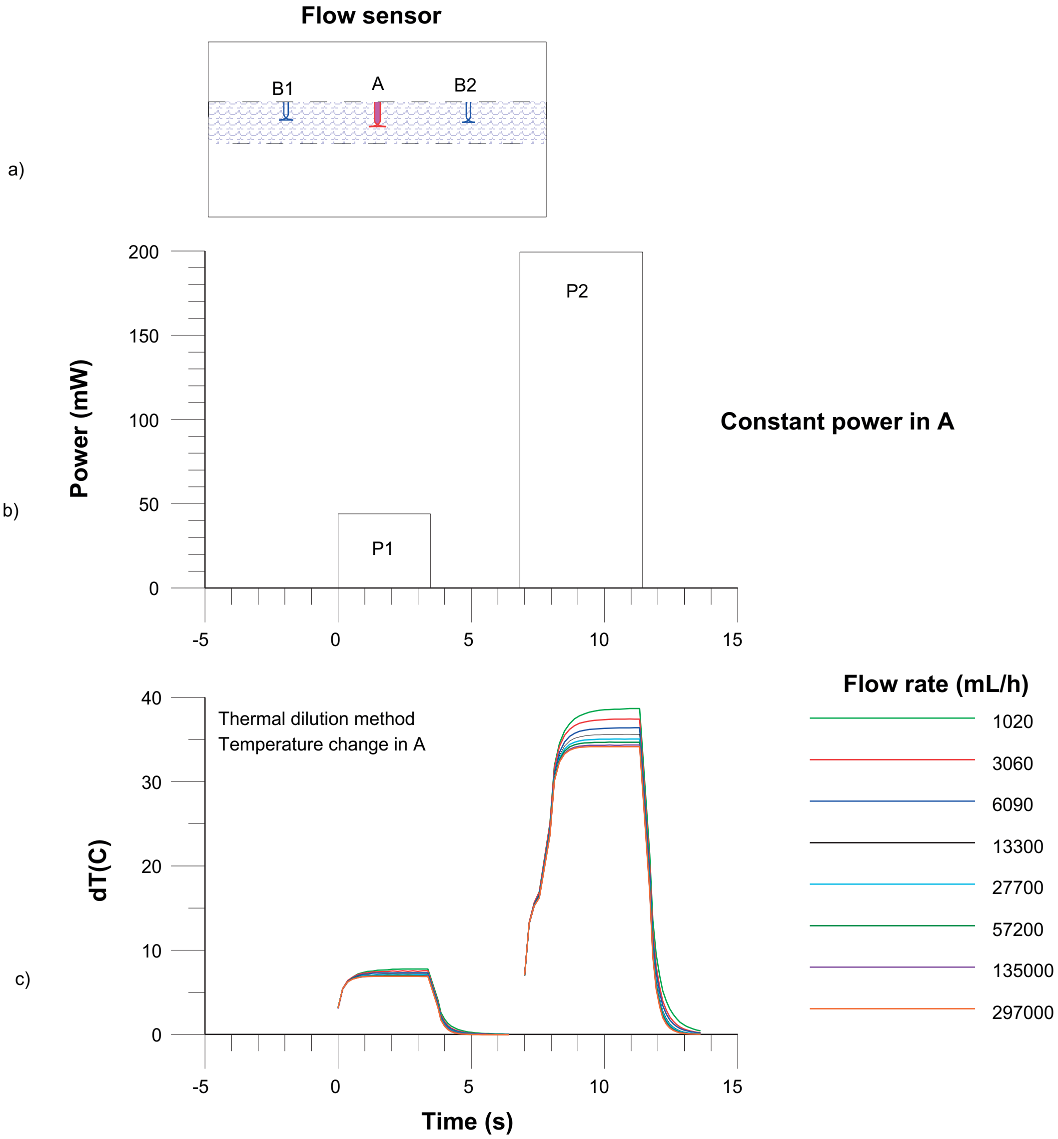

Figure 3-3. *Flow rate measurement.*

The flow rate measurement range is 30 mL/h–300,000 mL/h. The lower limit of measurement for the thermal dilution method is the theoretical lowest measurable value. Depending on conditions in the borehole, these flow limits may not always prevail. 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, limits on practical measurements are calculated for each set of data.

The device depth reference point in the PFL DIFF is situated at the upper end of the test section.

3.2 Interpretation

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

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

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

Q is the flow rate into the borehole,
T is the transmissivity of the test section,

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

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

where

r_0 is the radius of the well and

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

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

$Q_{S0} = T_S \cdot a \cdot (h_S - h_0)$ 3-3

$Q_{S1} = T_S \cdot a \cdot (h_S - h_1)$ 3-4

where

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

Q_{S0} and Q_{S1} are the measured flow rates in the test section,

T_S is the transmissivity of the test section and

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

In general, since very little is known about the flow geometry, cylindrical flow without skin zones is assumed. Cylindrical flow geometry is also justified because the borehole is at a constant head, and no strong pressure gradients along the borehole exist except at its ends.

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

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

$h_S = (h_0 - b \cdot h_1)/(1 - b)$ 3-5

$T_S = (1/a)\ (Q_{S0} - Q_{S1})/(h_1 - h_0)$ 3-6

where

$b = Q_{S0}/Q_{S1}$

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

$h_f = (h_0 - b \cdot h_1)/(1 - b)$ 3-7

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

where

Q_{f0} and Q_{f1} are the flow rates at a fracture and h_f and T_f are the hydraulic head (far away from borehole) and transmissivity of a fracture, respectively.

Since the actual flow geometry and any skin effects are unknown, 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. A discussion of potential uncertainties in the calculation of transmissivity and hydraulic head can be found in Ludvigson et al. (2002).

4 Equipment specification

In the PFL DIFF method, the flow of groundwater into or out of a borehole section is monitored using a flow guide which employs rubber sealing disks to isolate any such flow from the flow of water along the borehole. This flow guide defines the test section being measured without altering the hydraulic head. Groundwater flowing into or out of the test section is guided to the flow sensor, and flow is measured using the thermal pulse and thermal dilution methods. Measured values are transferred to a computer in digital form.

Type of instrument:	PFL DIFF probe
Borehole diameters:	56 mm, 66 mm and 76 mm (or larger)
Length of test section:	The flow guide length can be varied
Method of flow measurement:	Thermal pulse and thermal dilution.
Range and accuracy of measurement:	See Table 4-1.
Additional measurements:	Temperature, Single point resistance, Electrical conductivity of water, Water pressure
Winch:	Mount Sopris Wna 10, 0.55 kW, conductors, Gerhard-Owen cable head.
Depth determination	Based on a digital distance counter.
Logging computer:	PC (Windows 7)
Software	Based on MS Visual Basic
Total power consumption:	1.5–2.5 kW depending on the type of pump employed
Calibration of flow probe:	May 2011 (Probe PFL12)

The range and accuracy of the sensors used is shown in Table 4-1.

Table 4-1. 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	800–1,060 hPa	± 5 hPa
Absolute pressure sensor	0–20 MPa	± 0.01% full-scale

5 Execution of measurements

5.1 General

The work commission was performed according to Activity Plan AP TD TDUP002-11-006 following the SKB Method Description 322.011e, Version 2.0 (Method description for Difference Flow Logging), see Table 1-1. The Activity Plan and the Method Description are both SKB's internal controlling documents. Prior to the measurements, the downhole tools and the measurement cable were disinfected. Time was synchronized to local Swedish time, UTC +2 (Central European Summer Time). The activity schedule of the borehole measurements is presented in Table 5-1. The items and activities in Table 5-1 are the same as in the Activity Plan.

Logging cables, wires, and pipe strings are exposed to stretching when lowered into a vertical or subvertical borehole. This will introduce a certain error in defining the position of a test tool connected to the end of a logging cable. A linear length calibration was made based on the cable counter and on length marks marked into the measurement cable.

The outflow from the open borehole was measured during the measurements.

The dummy logging (Item 7) of the borehole is done in order to assure that the measurement tools do not get stuck in the borehole. 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.

The overlapping flow logging (Item 8) was carried out in the open borehole with a 1 m section length and in 0.1 m length increments (step length). After the measurement the borehole was closed.

The electrical conductivity (EC) and temperature of borehole water (Item 8) were measured during flow logging measurement.

5.2 Nonconformities

The flow rate was over the measurement limit (300,000 mL/h) at fractures 16.8 m, 21.3 m, 22.3 m, 23.3 m, 30.3 m and 216.4 m. The borehole was measured only when it was open because the limited measurement program was in use. In order to get the flow rates into the measurement limit, the borehole should be partially closed to reduce the outflow.

The high outflow (c 170–180 L/min) from the borehole pushed the PFL DIFF probe towards the tunnel which caused shorter flow anomalies than 1 meter to the results (see e.g. Appendix 3.2 fracture 30.3 m).

Between borehole's casing tube and core drilled part was 0.5 m long wider section. The dummy probe went without problems through it. Before the measurements the PFL probe was pushed over the wider part of the borehole. The probe got stuck in the bad section when it was tried to pull back.

Table 5-1. Flow logging and testing in KA3007A01. Activity schedule.

Item	Activity	Explanation	Date
7	Dummy logging	Borehole stability/risk evaluation over the bad section c 0–6 m.	2011-06-15
2	Mobilisation at site	Unpacking the trailer.	2011-06-16
7	Dummy logging	Borehole stability/risk evaluation.	2011-06-16
8	Overlapping flow logging – open borehole	Section length L_w=1 m. Step length dL=0.1 m.	2011-06-16 – 2011-06-17
–	Closing of the borehole	–	2011-06-17
10	Demobilisation	Packing the trailer.	2011-06-18

Due to safety reasons upper part of the borehole between 0 m–7.69 m was not measured. After the measurements the probe went over the bad section by way of a manufactured tool.

It was not physically possible to measure approximately 11.35 m of the bottom of the borehole. There were drilling rods stuck at the bottom of the borehole which made it impossible to measure from the bottom. There is also a centralizer in the measurement device, which reduces the measured distance by c 0.85 m. The rubber sealing disks in the device must also be flipped before the measurement begins. This reduces the measured distance for approximately 0.1 m.

6 Results

6.1 Length calibration

6.1.1 SPR measurement

An accurate length scale for the measurements is difficult to achieve in long boreholes. The main cause of inaccuracy is the stretching of the logging cable. The stretching depends on the tension 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 cable tension is larger when the borehole is measured upwards. The cables, especially new cables, may also stretch out permanently.

A linear length calibration was made based on the cable counter and on the length marks marked on the measurement cable. At the end of the borehole measurement length was adjusted using cable length marks. Length corrected single point resistance curve is plotted in Appendix 1.

6.1.2 Estimated error in location of detected fractures

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

1. The point interval in the overlapping mode flow measurements is 0.1 m. This could cause an error of ± 0.05 m.
2. The length of the test section is not exact. The specified section length denotes the distance between the nearest upper and lower rubber sealing disks. Effectively, the section length can be larger. At the upper end of the test section there are four rubber sealing disks. The distance between them is 5 cm. This will cause rounded flow anomalies: a flow may be detected already when a fracture is situated between the upper rubber sealing disks. These phenomena can cause an error of ± 0.05 m when the short step length (0.1 m) is used.
3. The cable stretches under tension. When the probe is lifted upwards at c 1,000 m the tension can be c 175 kg. When it is lowered at the same length, the tension can be c 75 kg. This difference could cause a depth difference of c 3 m between the measurements at depth of c 1,000 m. The tension values here are estimates and can vary greatly depending on the device setup and hole properties.
4. The total error in the worst case can be estimated. With a 0.1 m point interval the error would be:

$E = 0.05\ \text{m} + 0.05\ \text{m} + d \cdot 0.002$

where E is the total estimated error and d is the length of the probe shown by the cable counter of the winch. Note that this is only a rough estimate and it is subject to change. It should also be noted that this is only one way of estimating the error. Experience has shown that when holes with length marks have been measured the error has been approximately 1 m at the length of c 1,000 m.

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

6.2 Electrical conductivity and temperature

6.2.1 Electrical conductivity and temperature of borehole water

The electrical conductivity of the borehole water (borehole EC) was measured during the flow logging measurements. The measurement was performed upwards, see Appendices 2.1 (linear scale) and 2.2 (logarithmic scale).

Borehole EC profile was relatively constant during measurement, average value about 0.8 S/m. At interval 60 m–140 m EC value varied between 0.8 S/m and 1.1 S/m.

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

6.3 Pressure and outflow measurements

No absolute pressure measurements were conducted during this measurement campaign because the borehole is nearly horizontal. Absolute pressure measurement is carried out because the density of the borehole fluid is not exactly constant. In deep vertical boreholes absolute pressure varies not only by depth but also by the density of the water column above the point of measurement. In horizontal boreholes the latter effect is insignificant.

Borehole outflow was measured manually during the measurements. The results are shown in Appendix 7. After the measurements the borehole was closed.

6.4 Flow logging

6.4.1 General comments on results

The measuring programme contained one flow logging sequence. The results were plotted on the same diagram with single-point resistance (right hand side), see Appendices 3.1–3.11. SPR has a lower value on a fracture where flow is detected. Many other resistance anomalies result from other fractures and geological features. As the electrode of the SPR tool is located within the upper rubber sealing disks of the probe, the locations of resistance anomalies associated with leaky fractures coincide with the lower end of the flow anomalies.

The flow logging was performed with a 1 m section length and with 0.1 m length increments. The method (overlapping flow logging) gives the length and the thickness of conductive zones with a length resolution of 0.1 m.

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

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

The coloured triangles show the magnitude and direction of the measured flows. The triangles have the same colour than the corresponding curves.

The interval between 0 m and 146.50 m is not representative as properties of the rock because of grouting.

6.4.2 Transmissivity of borehole sections

Two sets of flow measurements are needed for calculation of transmissivity as described in Section 3, Equation 3-6. The head in the borehole h_1 corresponds the situation in a pumped borehole. In this case the borehole is freely flowing into the tunnel and h_1 is the water level at the top of the borehole (–400.66 m in RHB 70 scale). The unpumped condition when the hydraulic head in the borehole would be h_0 could be the case when the borehole is closed. In that case h_0 would be closer to the sea level, i.e. $h_0 \sim 0$. For technical reasons and for the tight time schedule, flow rates were measured neither in the closed borehole nor in partially closed borehole.

The assumptions for calculation of transmissivity are $(h_1–h_0) \sim h_1$ and $(Q_{S0}–Q_{S1}) \sim –Q_{S1}$ in Equation 3-6.

The two assumptions made above would mean that the hydraulic head of all fractures crossed by the borehole is nearly zero, i.e. they are hydraulically well connected to the ground surface but not to the tunnel. In such case there would be no internal flows in the closed borehole.

It is clear that the assumptions made above do not hold and the calculated transmissivities are only rough estimates. Typically the assumptions hold better for fractures or sections far away from the tunnel. The transmissivity values are too small for fractures or sections that are well hydraulically connected to the tunnel. There is even a risk that some of such transmissive fractures remained undetected.

The results of the flow logging measurement with a 1 m section length are presented in tables, see Appendices 5.1–5.2. In Appendices 5.1–5.2 h_{0FW} was assumed to be zero and h_{1FW} is the hydraulic head of the borehole for the flow measurement with the 1 m section length (–400.66 m in RHB 70 scale). The explanations to the table in Appendices 5.1–5.2 are given in Appendix 4.

The flow rates are positive if the flow direction is from the bedrock into the borehole and vice versa. 84 fractures were detected as flow yielding in the 1 m section length measurement. All of the flows were positive.

Since in this case there was only one measurement, the hydraulic head of the sections could not be calculated. The transmissivity results of the detected fractures are illustrated in Appendix 6.

The sum of all the detected flows (Q_1) was $8.9 \cdot 10^{-4}$ m^3/s (53 L/min). The outflow from the borehole was approximately 170 L/min – 180 L/min during the measurement. These values should normally be equal. In this measurement there were 6 flowing fractures over the measurement limit (300,000 mL/h). The flow rates of these fractures can be much higher than the measured ones. Also it was not possible to measure the upper part of the borehole and all the way from the bottom, and it is possible that there are flows in these sections.

6.4.3 Transmissivity of fractures

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

In cases where the fracture distance is less than one metre, it may be difficult to evaluate the flow rate. There are such cases for instance in Appendix 3.8. 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 amount of detected flowing fractures was 84. These fractures were used for transmissivity estimations. Transmissivity of fractures is presented in Appendices 5.1–5-2 and 6.

Some fracture-specific results were classified to be “uncertain.” The basis for this classification is either a minor flow rate (< 30 mL/h) or unclear fracture anomalies. Anomalies are considered unclear if the distance between them is less than 1 m or their nature is unclear because of noise.

6.4.4 Theoretical and practical measurement limits of flow and transmissivity

The theoretical minimum for measurable flow rate is some 30 mL/h. The upper limit of flow measurement is 300,000 mL/h. As these upper and lower limits are determined by flow calibration, it is assumed that flows can be reliably detected between the upper and lower theoretical limits in favorable borehole conditions.

In practice, the minimum measurable flow rate may be much higher. Borehole conditions may have an influence on the flow base level (i.e. noise level). Noise levels can be evaluated in intervals along the borehole where there are no flowing fractures or other complicating structures, and may vary along a borehole.

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

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

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

Drilling debris usually increases noise levels. This kind of noise is typical for both natural (un-pumped) and pumped conditions.

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

The effect of a high flow rate along the borehole can often be seen above fractures with a high flow. Any minor leakage in the seal provided by the lower rubber sealing disks will appear in the measurement as increased levels of noise.

A high level of noise in a flow will mask the "real" flow if this is smaller than the noise. Real flows are registered correctly if they are about ten times larger than the noise but are totally invisible if they are some ten times smaller than the noise. Experience indicates that real flows between one-tenth of the noise level and 10 times the noise level are summed with the noise. Noise levels could therefore be subtracted from measured flows to get real flows. This correction has not yet been carried out because the cases to which it is applicable are unclear.

The practical minimum for measurable flow rate is presented in Appendices 3.1–3.11 using a grey dashed line (Lower limit of flow rate). The practical minimum level of the measurable flow was evaluated using the flow data obtained in the 1 m section length measurements. The limit is an approximation. It is evaluated to obtain a limit below which there may be fractures or structures that remain undetected.

The noise level varied between 100 mL/h and 1,000 mL/h. It is possible to detect the existence of flow anomalies below the theoretical limit of the thermal dilution method (30 mL/h). The noise line (grey dashed line) was never drawn below 30 mL/h, because the values of flow rate measured below 30 mL/h are uncertain.

In some boreholes the upper limit of flow measurement (300,000 mL/h) may be exceeded. Such fractures or structures hardly remain undetected (as the fractures below the lower limit). There were 6 such fractures detected during this campaign. If several high-flowing fractures are positioned closer to one another than a distance of 1 m, the upper flow limit will depend on the sum of these flows, and this must be below 300,000 mL/h.

7 Summary

In this study, the Posiva Flow Log, Difference Flow Method has been used to determine the location and flow rate of flowing fractures or structures in borehole KA3007A01 in Äspö HRL, Sweden. A 1 m section length with 0.1 m length increments was used. The borehole was open during the flow measurements.

Length calibration was made linearly by the cable counter and the cable's length marks. The single point resistance was measured simultaneously with the flow measurements.

The distribution of saline water along the borehole was logged during flow measurement by electrical conductivity and temperature measurements of the borehole water.

The outflow from the borehole was measured before and during the flow logging measurements. The borehole was closed after the measurements.

The total amount of detected flowing fractures was 84. Transmissivity was calculated for measured borehole fractures. The calculated transmissivities are rough estimates because the measurements were carried out in only one pressure condition and because the limit of measurement was exceeded at some fractures.

References

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de Marsily G, 1986. Quantitative hydrogeology: groundwater hydrology for engineers. London: Academic Press.

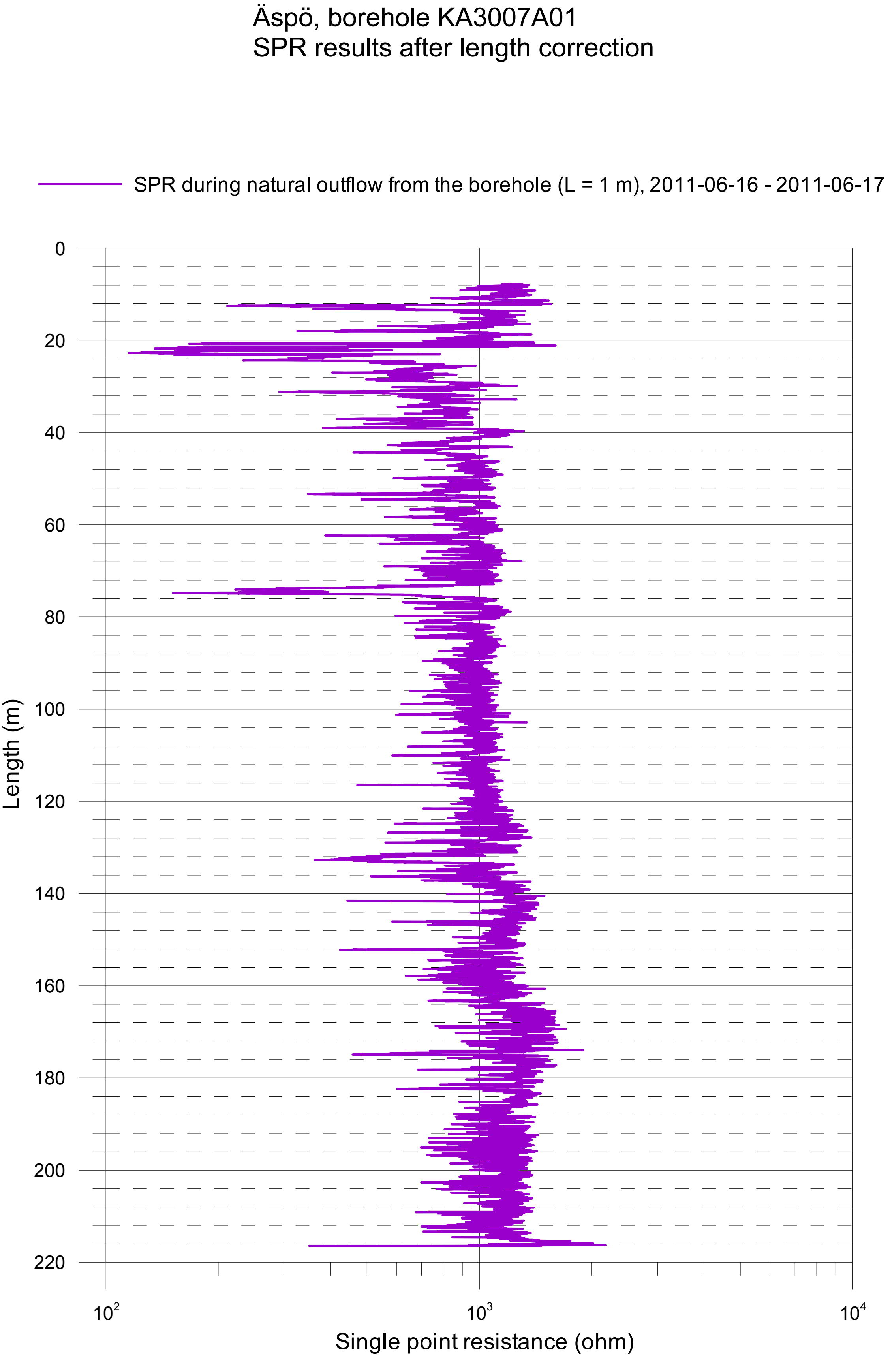
Heikkonen J, Heikkinen E, Mäntynen M, 2002. Pohjaveden sähkönjohtavuuden lämpötilakorjauksen matemaattinen mallinnus synteettisten vesinäytteiden mittauksista (Mathematical modelling of temperature adjustment algorithm for groundwater electrical conductivity on basis of synthetic water sample analysis). Posiva Työraportti 2002-10, Posiva Oy, Finland. (In Finnish.)

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

Öhberg A, Rouhiainen P, 2000. Posiva groundwater flow measuring techniques. Posiva 2000-12, Posiva Oy, Finland.

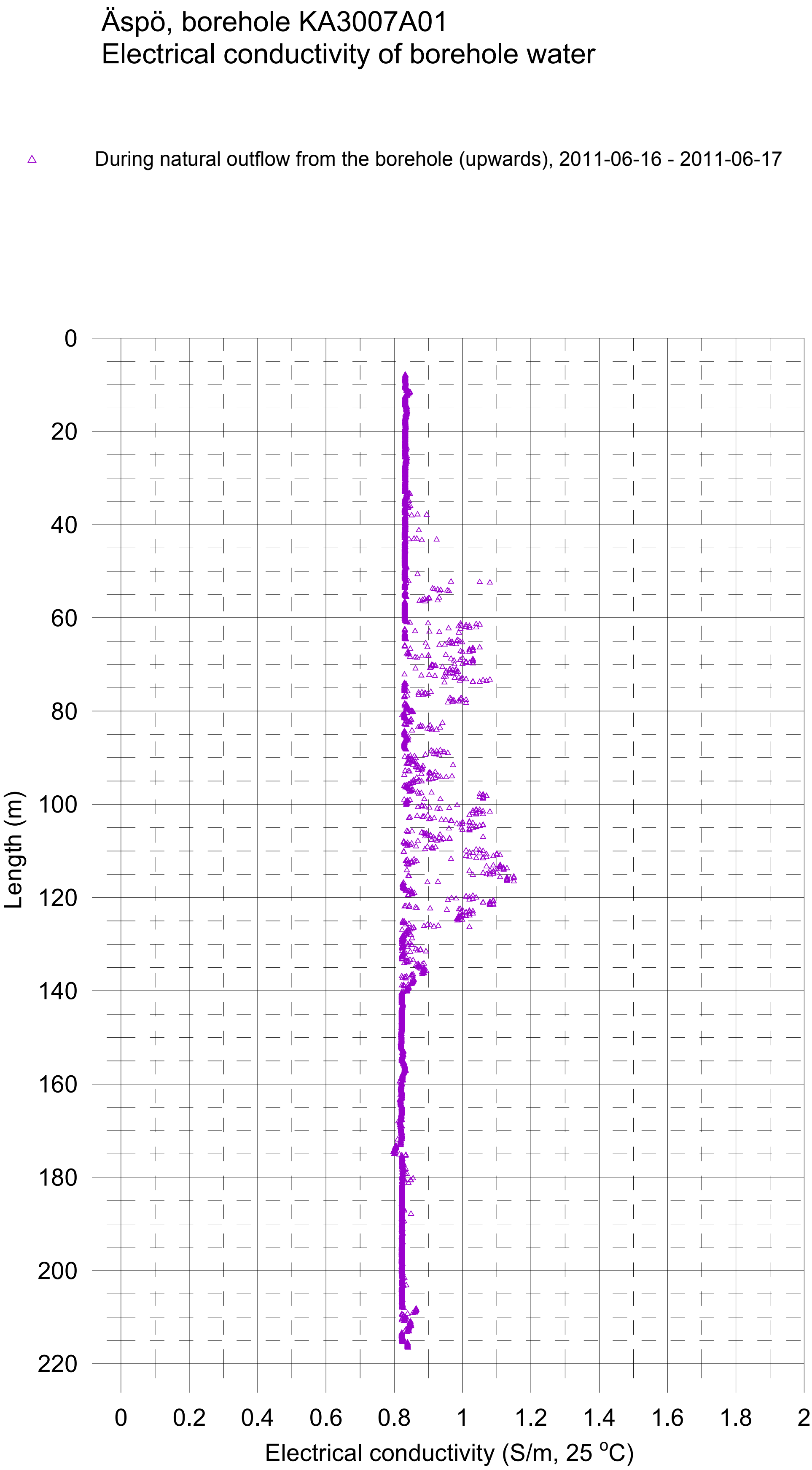
Appendix 1

SPR results after length correction

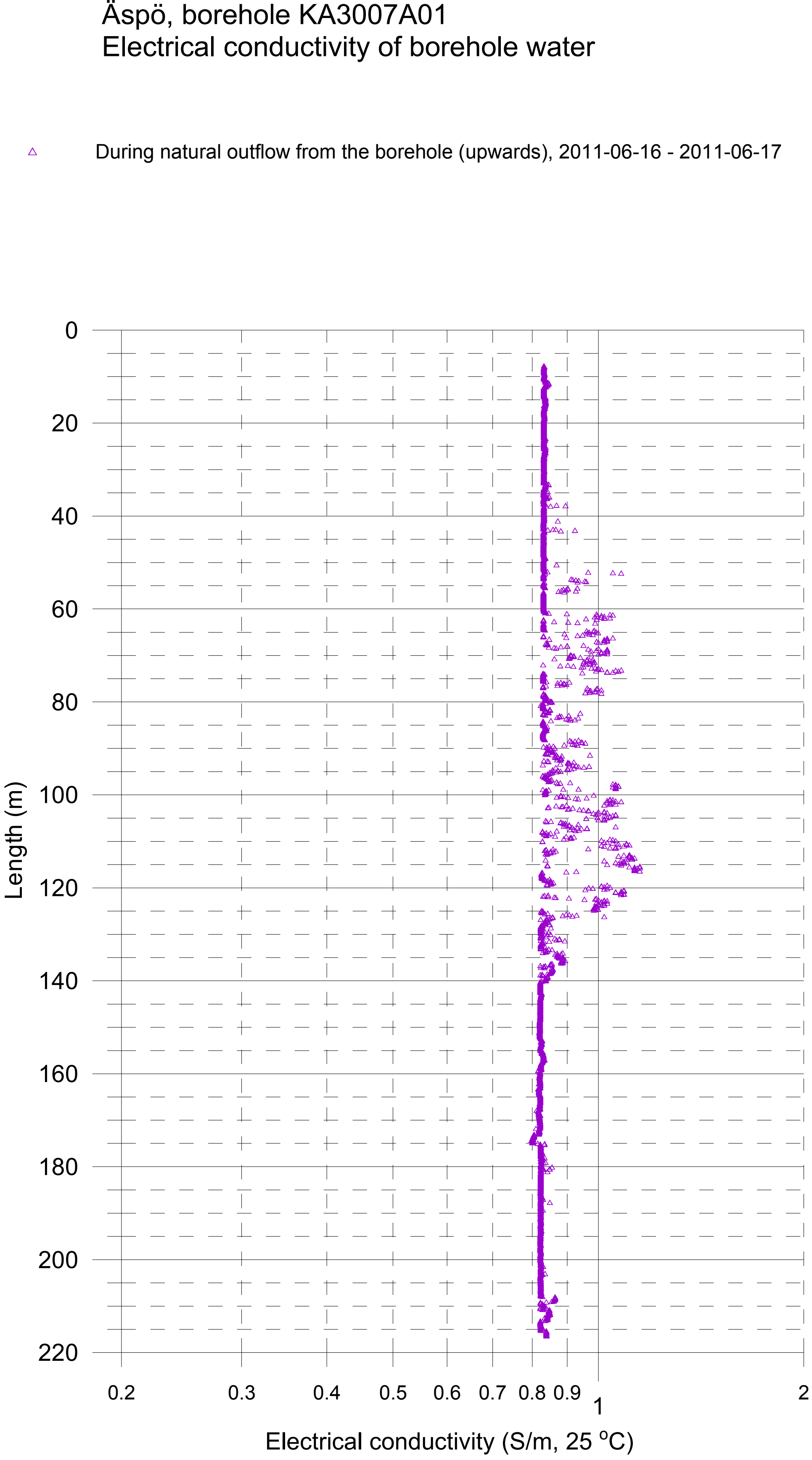


Appendix 2.1

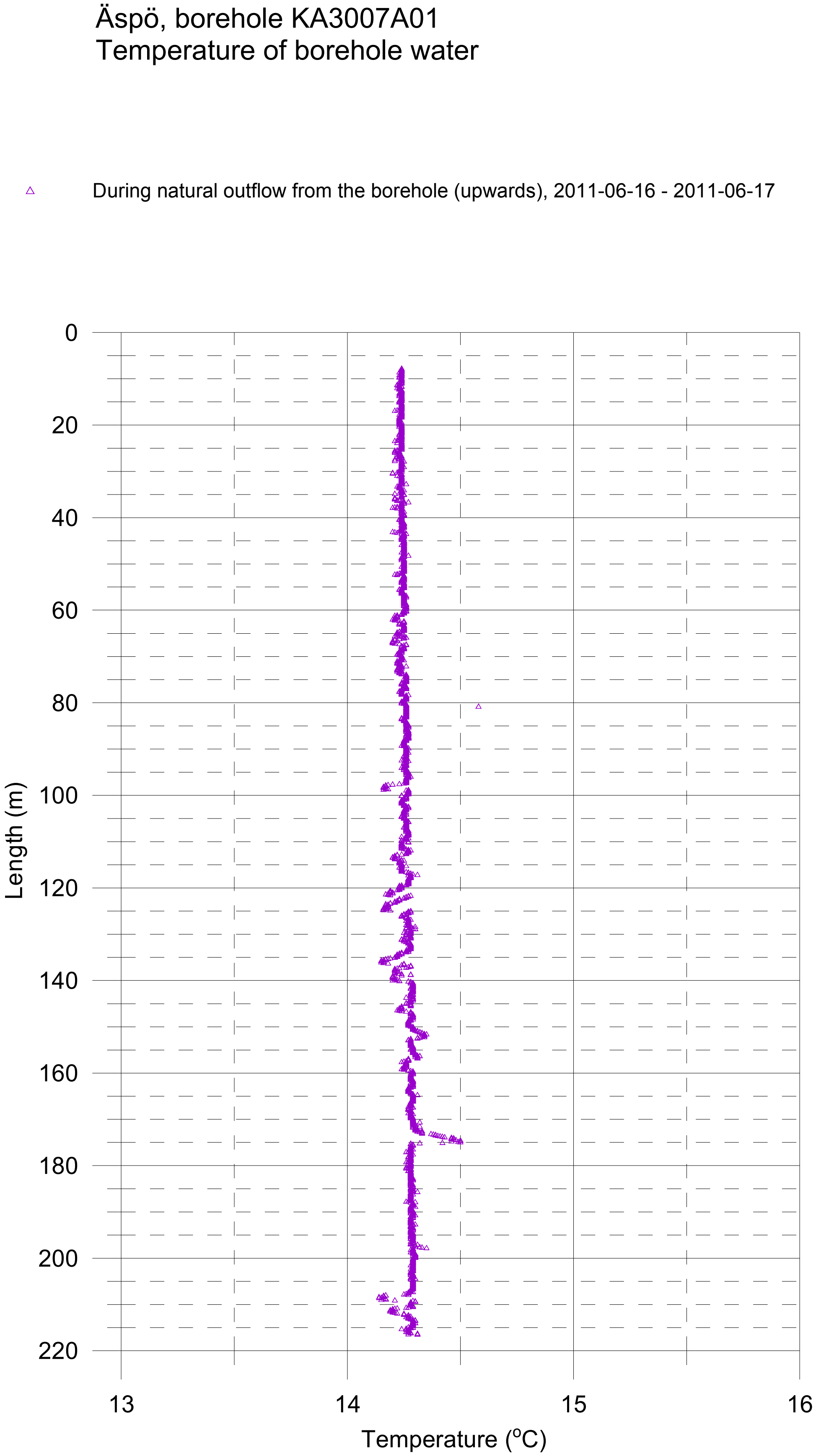
Electrical conductivity of borehole water



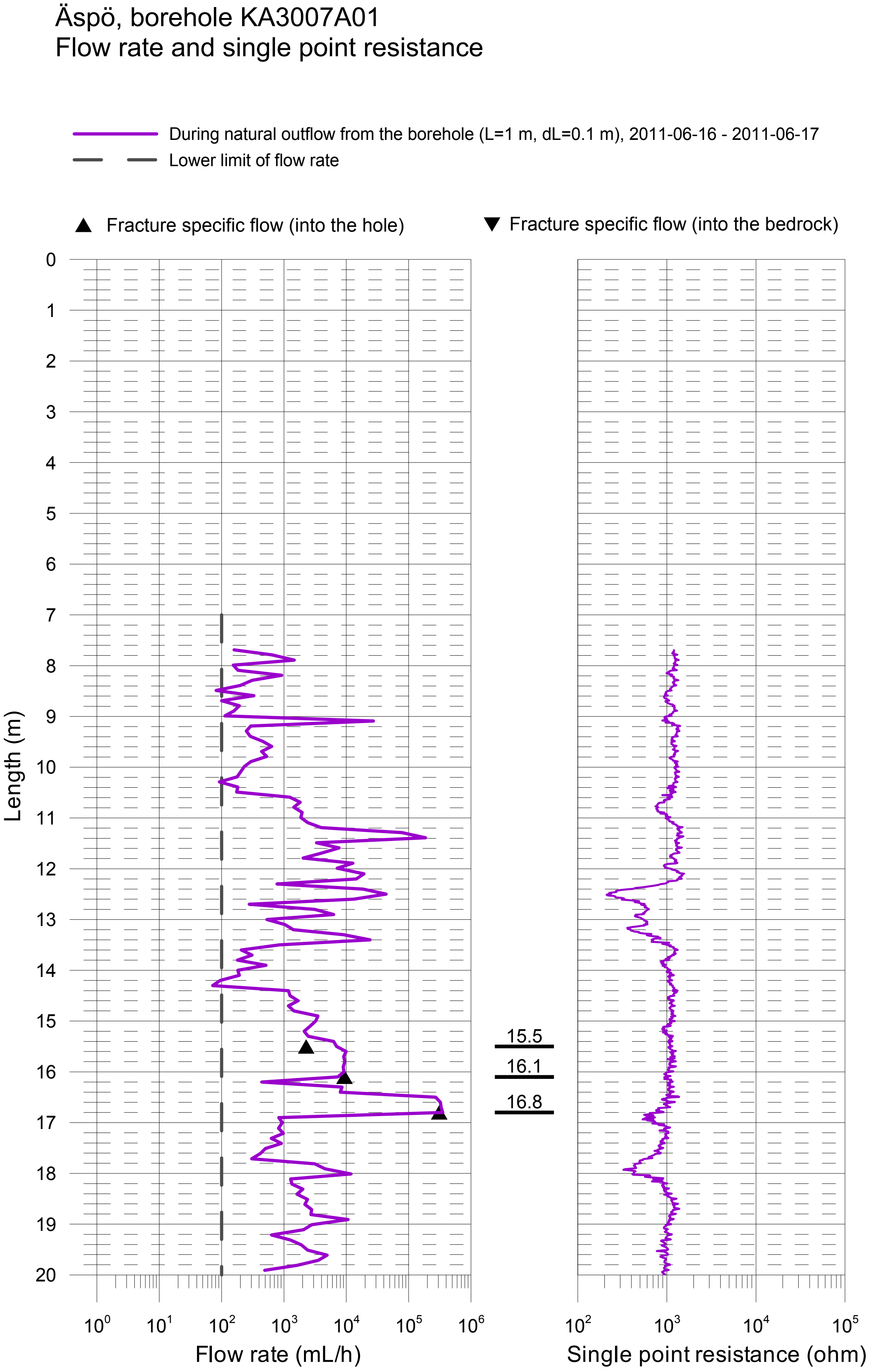
Electrical conductivity of borehole water



Temperature of borehole water



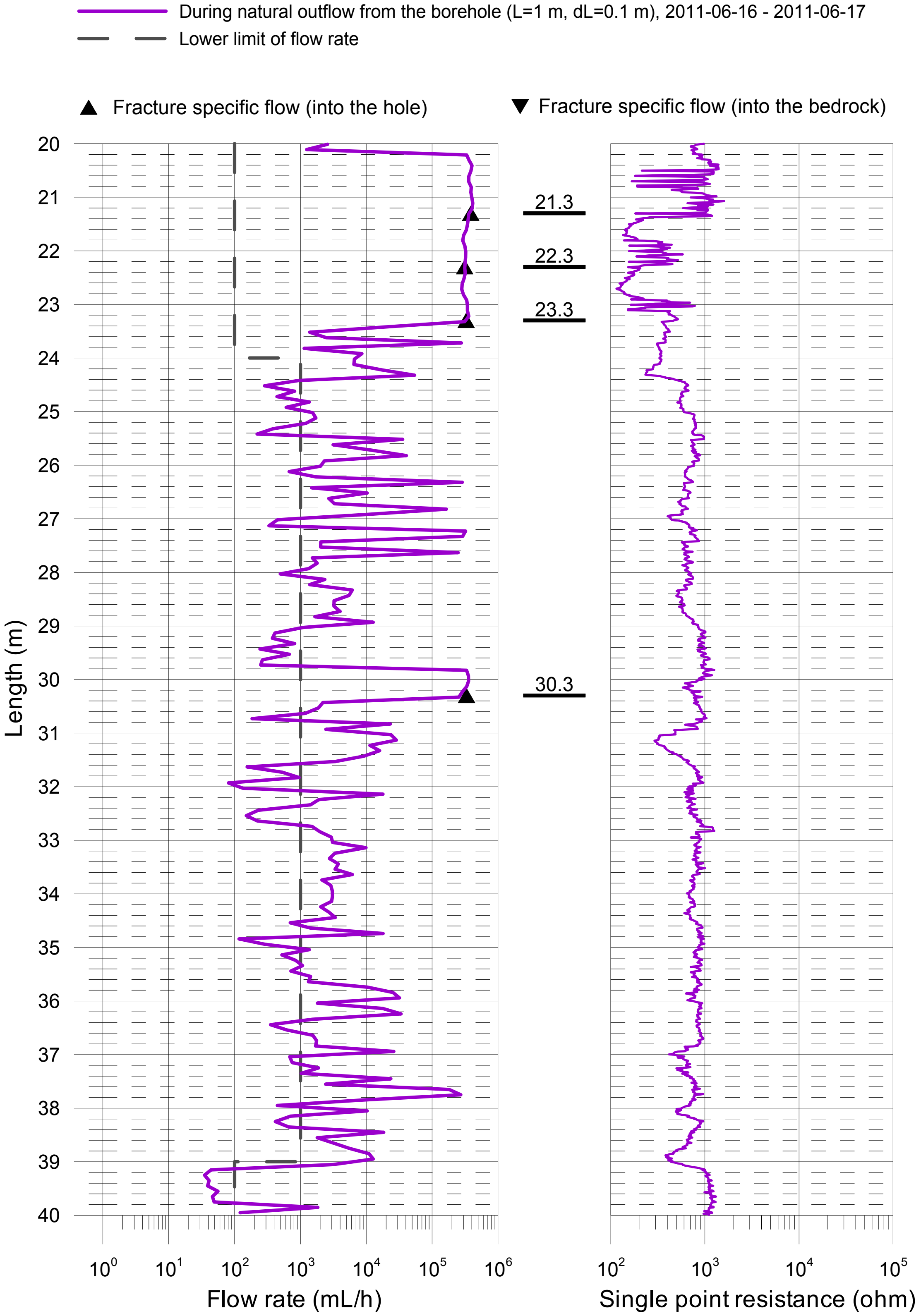
Flow rate and single point resistance



Appendix 3.2

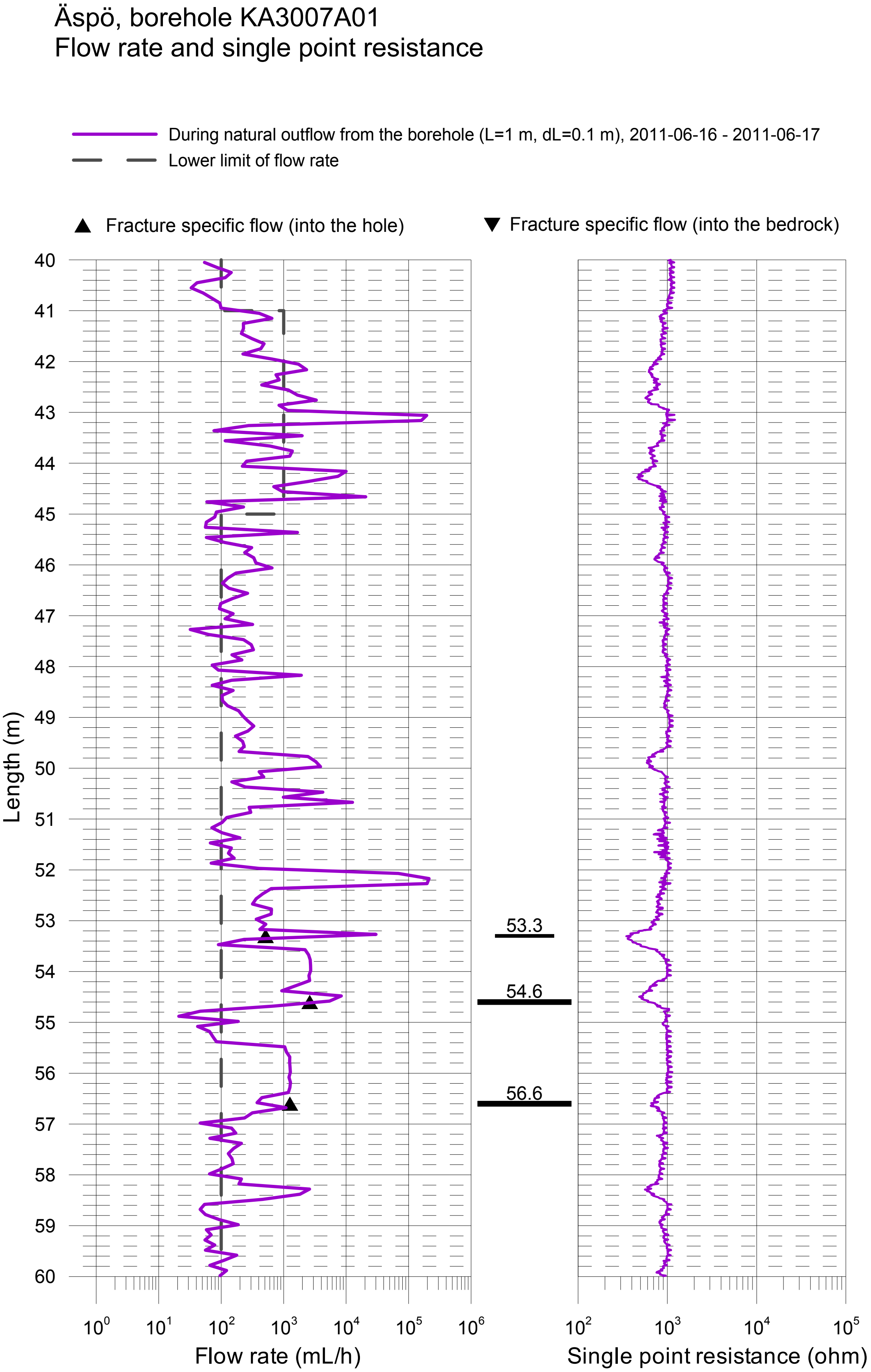
Flow rate and single point resistance

Äspö, borehole KA3007A01
Flow rate and single point resistance



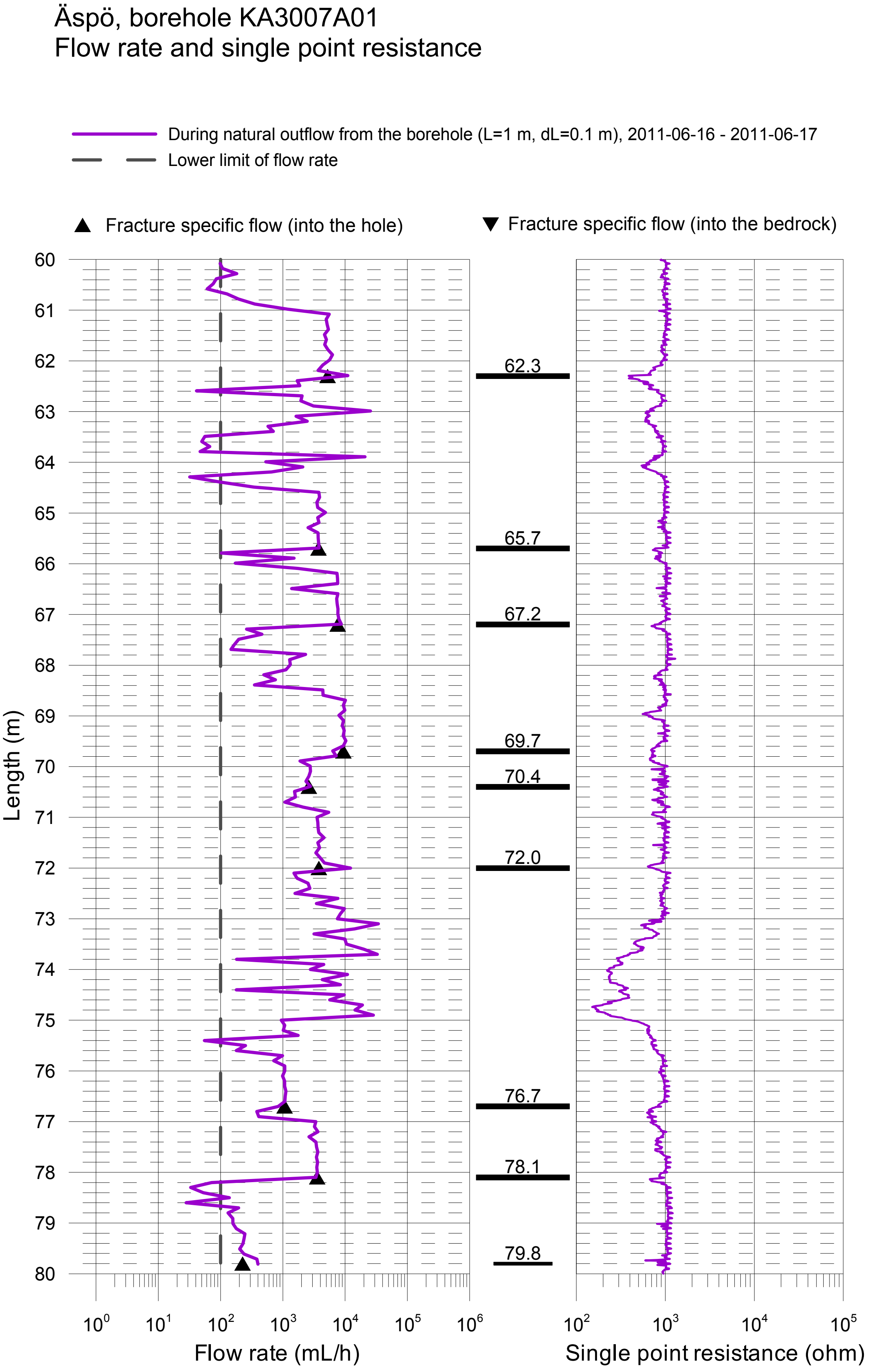
Appendix 3.3

Flow rate and single point resistance

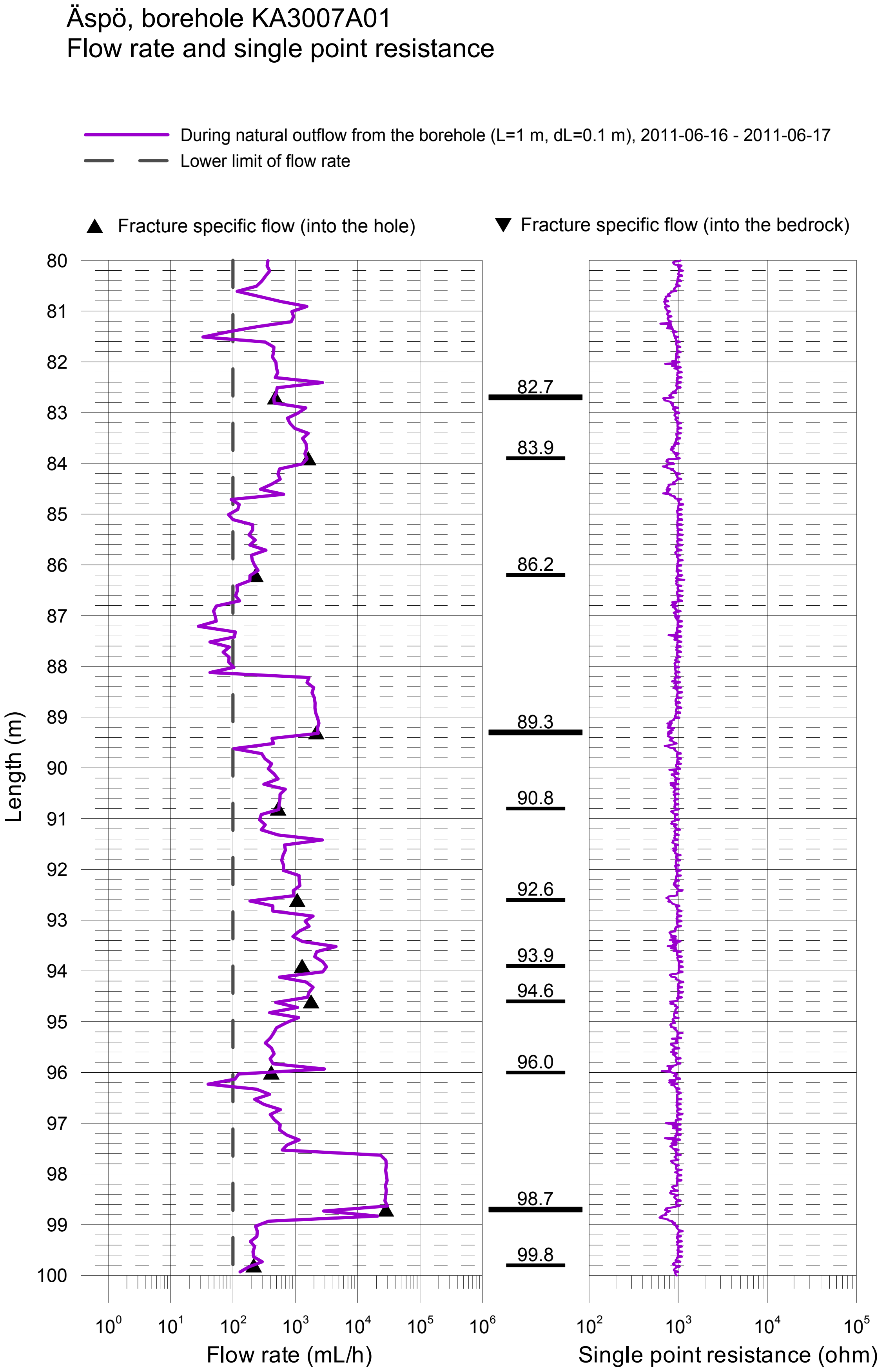


Appendix 3.4

Flow rate and single point resistance

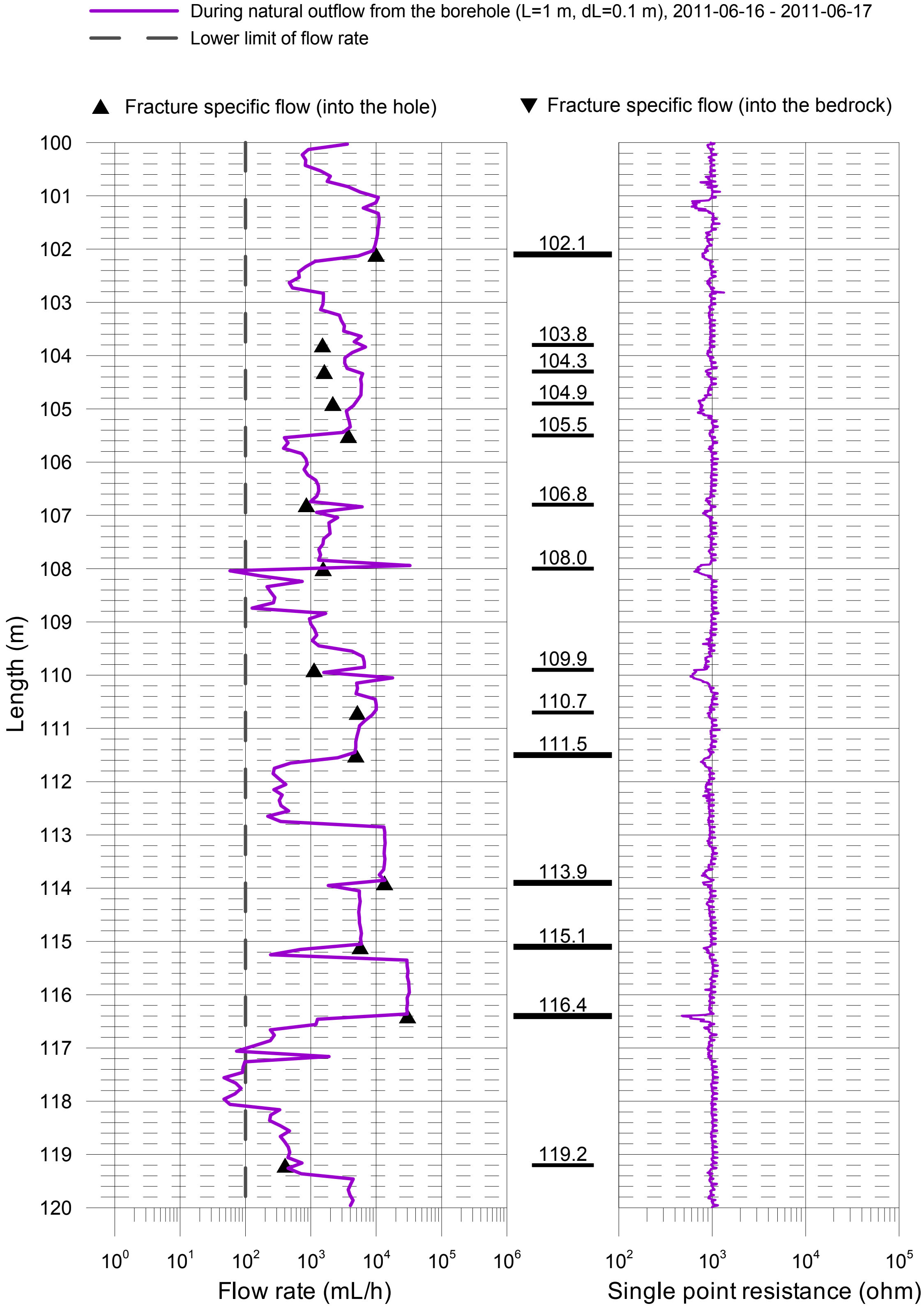


Flow rate and single point resistance



Flow rate and single point resistance

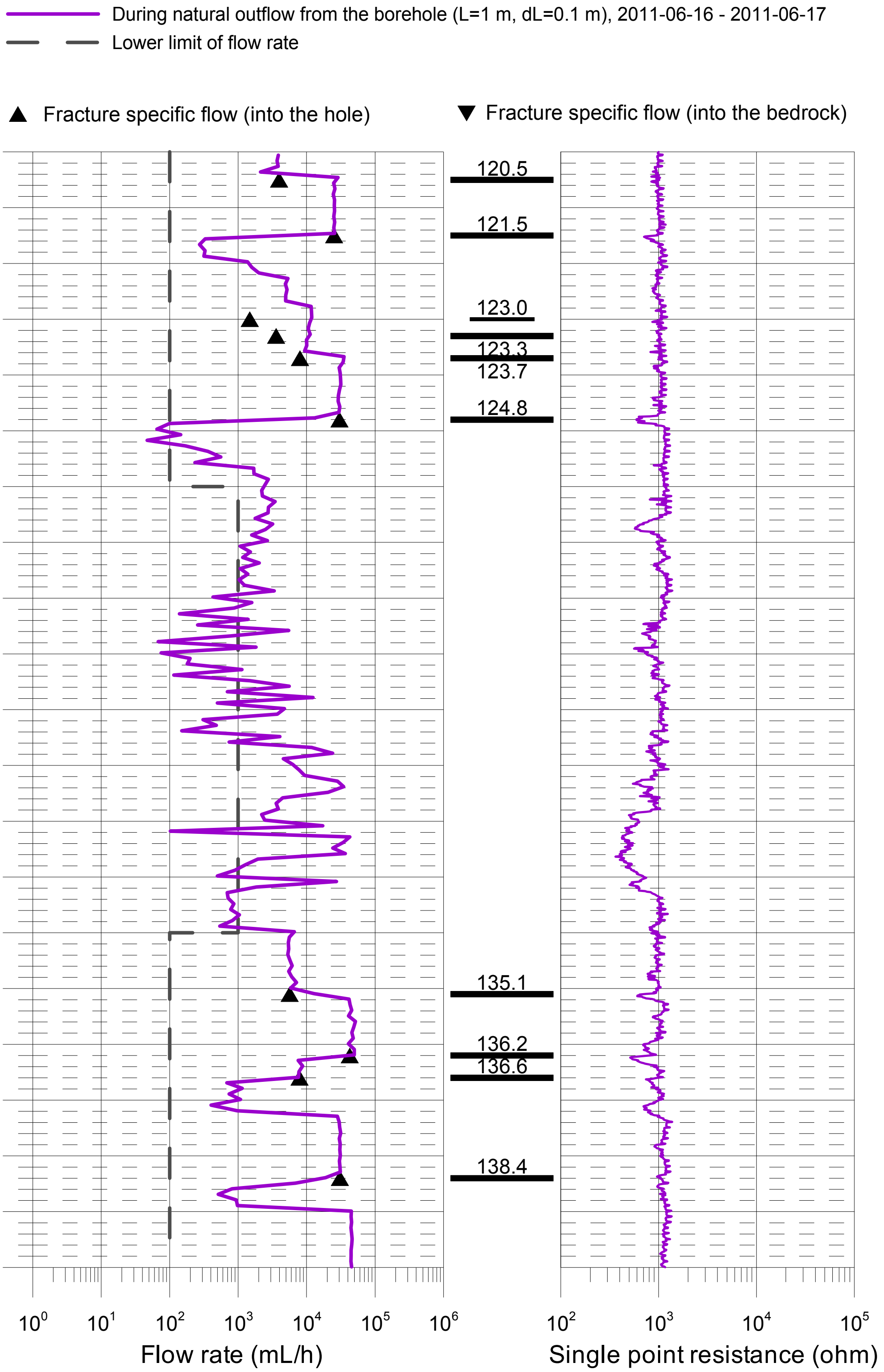
Äspö, borehole KA3007A01
Flow rate and single point resistance



Appendix 3.7

Flow rate and single point resistance

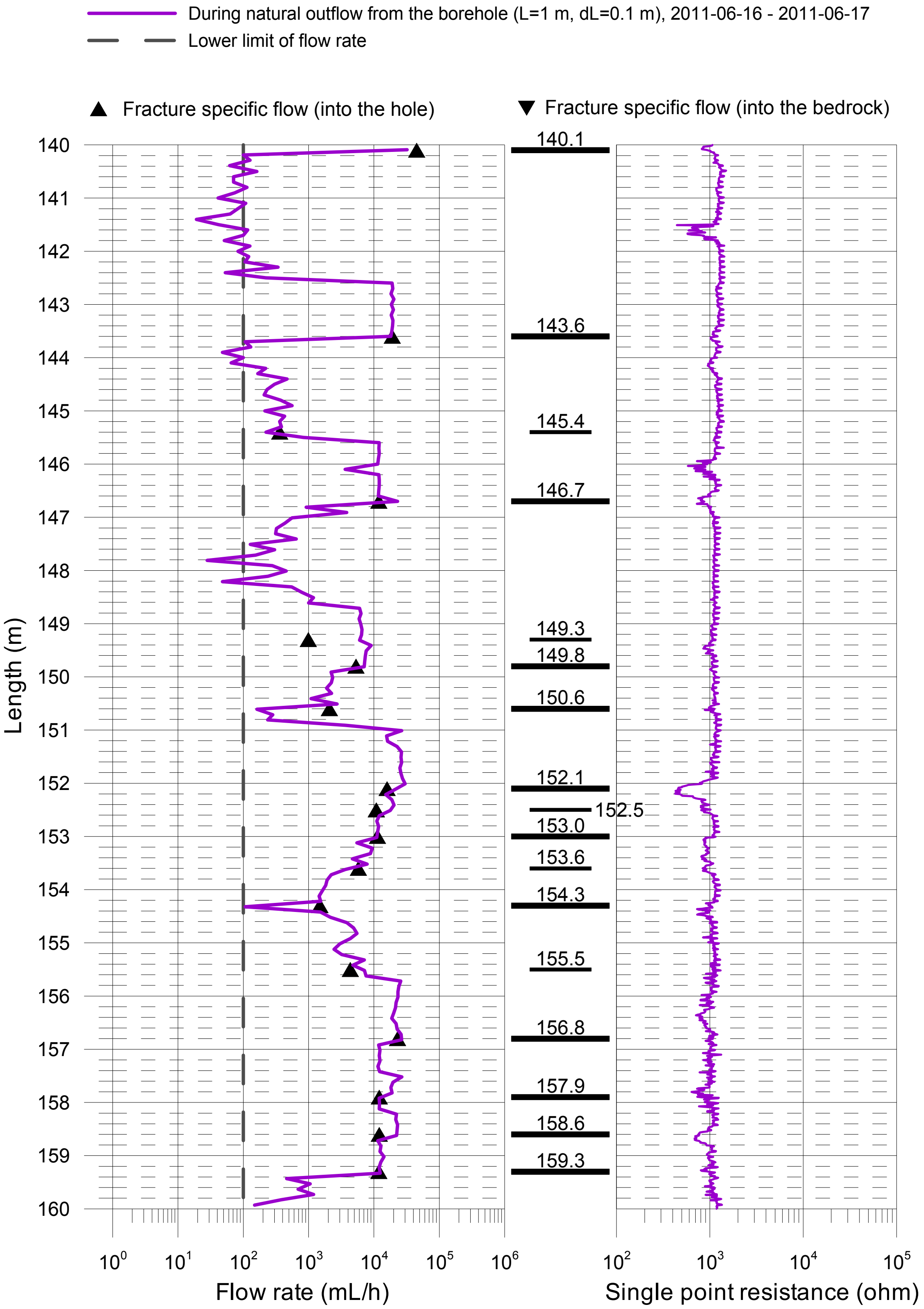
Äspö, borehole KA3007A01
Flow rate and single point resistance



Appendix 3.8

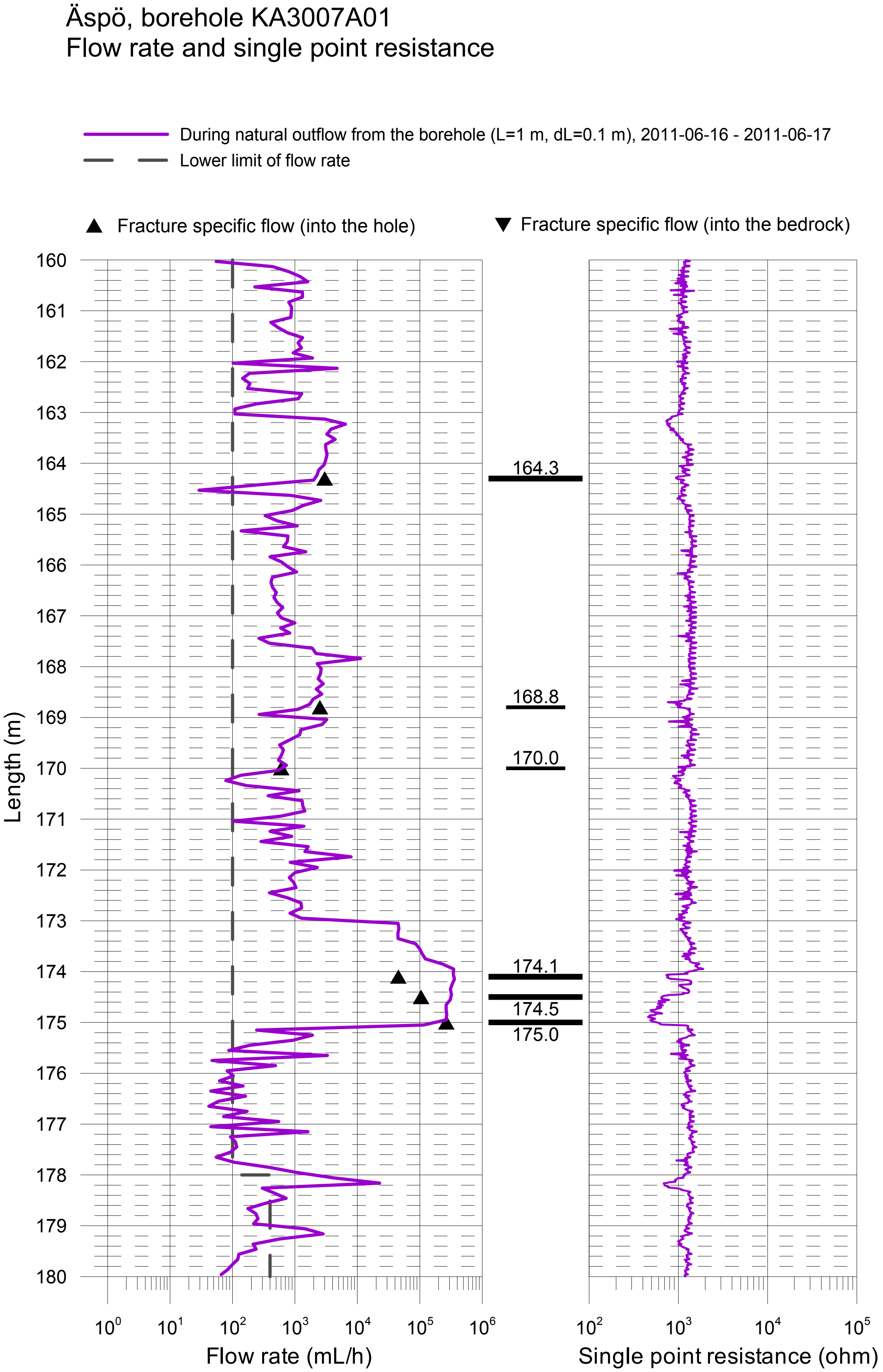
Flow rate and single point resistance

Äspö, borehole KA3007A01
Flow rate and single point resistance

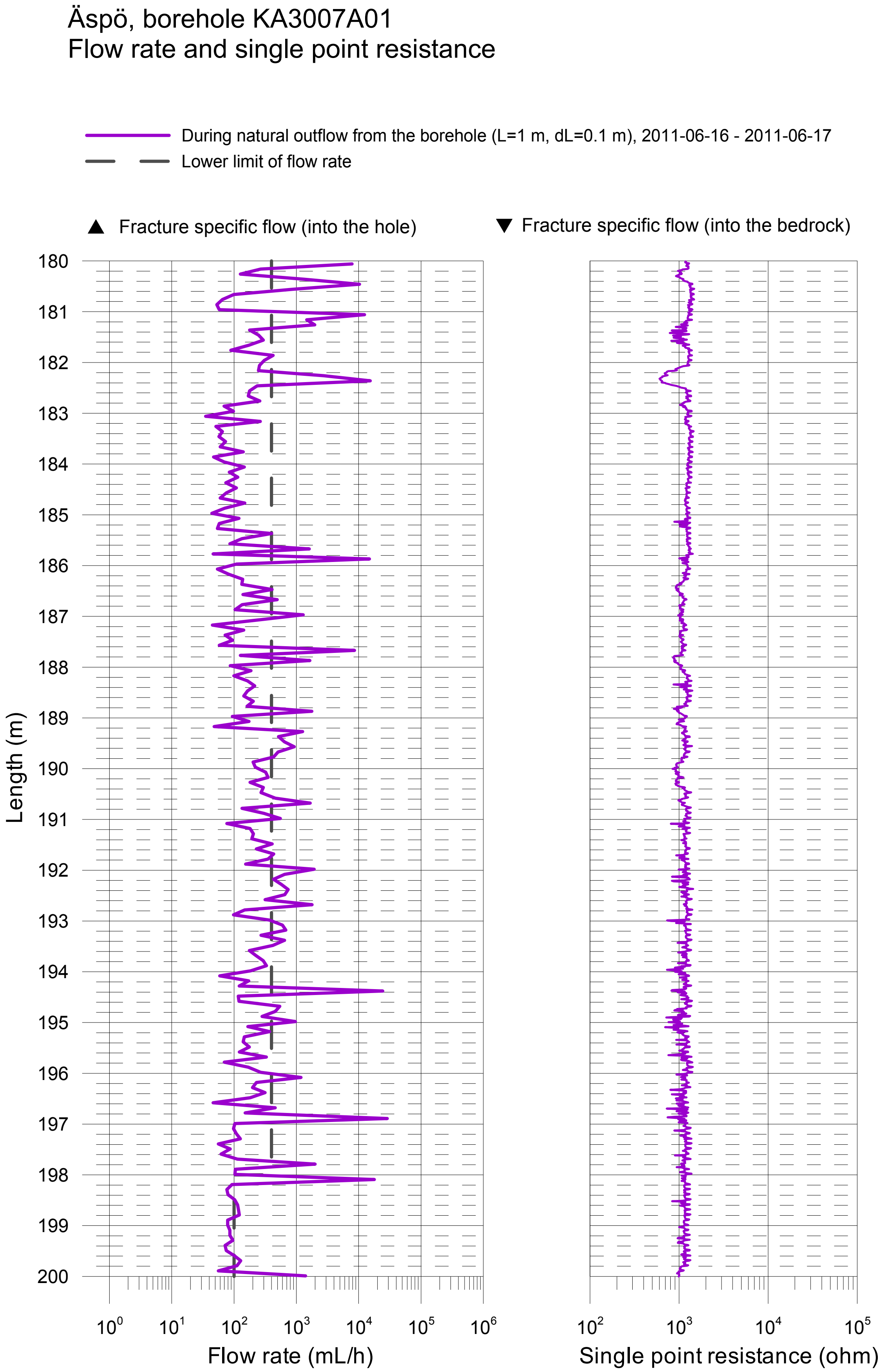


Appendix 3.9

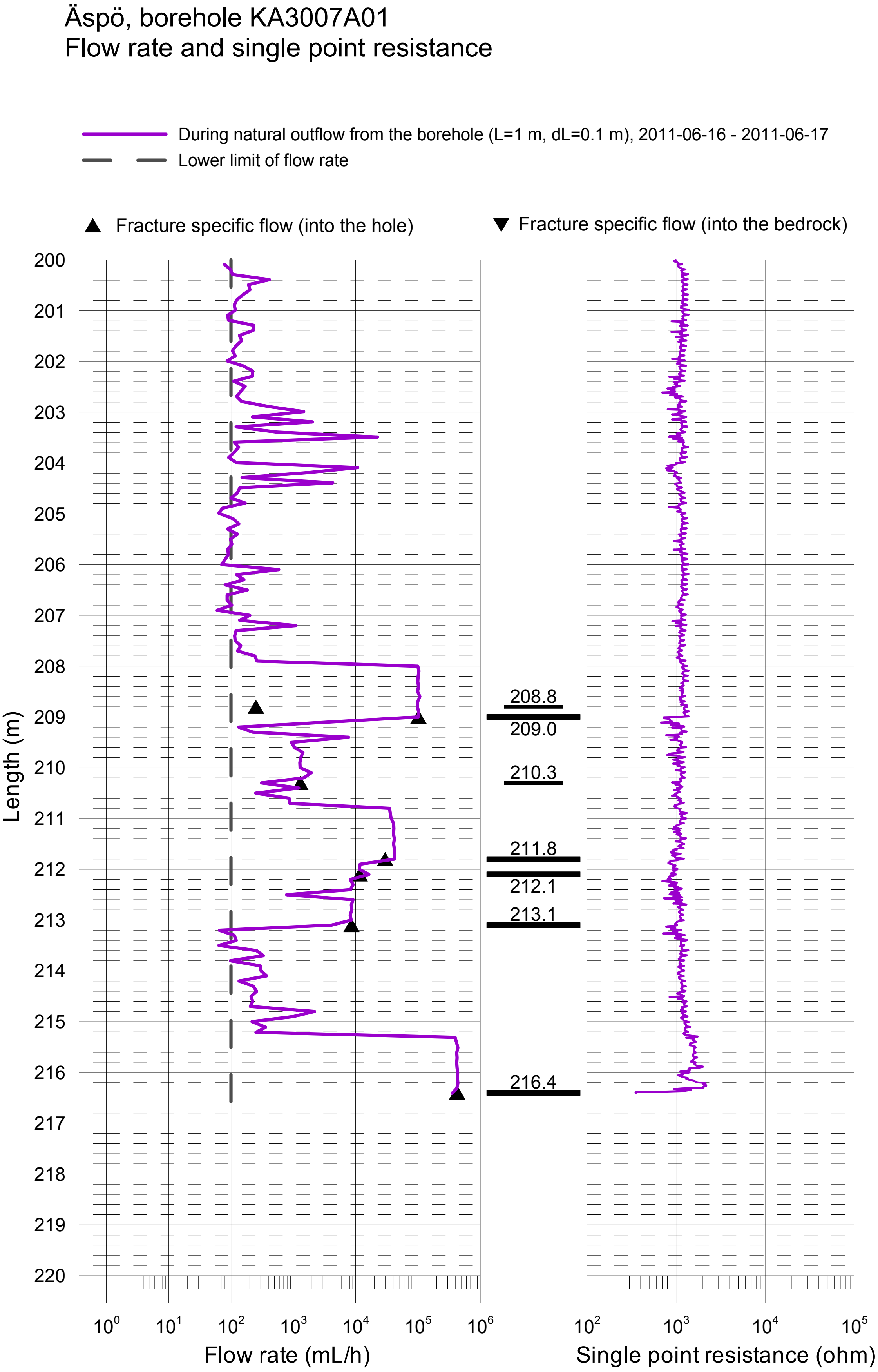
Flow rate and single point resistance



Flow rate and single point resistance



Flow rate and single point resistance



Appendix 4

Explanations for the tables

Explanations

Header	Unit	Explanations
Borehole		ID for borehole
Secup	m	Length along the borehole for the upper limit of the test section (based on corrected length L)
Seclow	m	Length along the borehole for the lower limit of the test section (based on corrected length L)
L	m	Corrected length along borehole based on SKB procedures for length correction.
Length to flow anom.	m	Length along the borehole to inferred flow anomaly during overlapping flow logging
Test type (1–6)	(–)	1A: Pumping test – wire-line eq. 1B:Pumping test-submersible pump, 1C: Pumping test-airlift pumping, 2: Interference test, 3: Injection test, 4: Slug test, 5A: Difference flow logging – PFL-DIFF-Sequential, 5B: Difference flow logging – PFL-DIFF-Overlapping, 6: Flow logging-Impeller
Date of test, start	YY-MM-DD	Date for start of pumping
Time of test, start	hh:mm	Time for start of pumping
Date of flowl., start .	YY-MM-DD	Date for start of the flow logging
Time of flowl., start	hh:mm	Time for start of the flow logging
Date of test, stop	YY-MM-DD	Date for stop of the test
Time of test, stop	hh:mm	Time for stop of the test
L_w	m	Section length used in the difference flow logging
dL	m	Step length (increment) used in the difference flow logging
Q_{p1}	m^3/s	Flow rate at surface by the end of the first pumping period of the flow logging
Q_{p2}	m^3/s	Flow rate at surface by the end of the second pumping period of the flow logging
t_{p1}	s	Duration of the first pumping period
t_{p2}	s	Duration of the second pumping period
t_{F1}	s	Duration of the first recovery period
t_{F2}	s	Duration of the second recovery period
h_0	m.a.s.l.	Initial hydraulic head before pumping. Elevation of water level in open borehole in the local co-ordinates system with z=0 m.
h_1	m.a.s.l.	Stabilized hydraulic head during the first pumping period. Elevation of water level in open borehole in the local co-ordinates system with z=0 m.
h_2	m.a.s.l.	Stabilized hydraulic head during the second pumping period. Elevation of water level in open borehole in the local co-ordinates system with z=0 m.
s_1	m	Drawdown of the water level in the borehole during first pumping period. Difference between the actual hydraulic head and the initial head ($s_1= h_1–h_0$)
s_2	m	Drawdown of the water level in the borehole during second pumping period. Difference between the actual hydraulic head and the initial head ($s_2=h_2–h_0$)
T	m^2/s	Transmissivity of the entire borehole
Q_0	m^3/s	Measured flow rate through the test section or flow anomaly under natural conditions (no pumping) with $h=h_0$ in the open borehole

Header	Unit	Explanations
Q_1	m^3/s	Measured flow rate through the test section or flow anomaly during the first pumping period
Q_2	m^3/s	Measured flow rate through the test section or flow anomaly during the second pumping period
h_{0FW}	m.a.s.l.	Corrected initial hydraulic head along the hole due to e.g. varying salinity conditions of the borehole fluid before pumping
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
EC_w	S/m	Measured electrical conductivity of the borehole fluid in the test section during difference flow logging
Te_w	°C	Measured borehole fluid temperature in the test section during difference flow logging
EC_f	S/m	Measured fracture-specific electrical conductivity of the fluid in flow anomaly during difference flow logging
Te_f	°C	Measured fracture-specific fluid temperature in flow anomaly during difference flow logging
T_D	m^2/s	Transmissivity of section or flow anomaly based on 2D model for evaluation of formation properties of the test section based on PFL-DIFF.
T-$measl_{LT}$	m^2/s	Estimated theoretical lower measurement limit for evaluated T_D. If the estimated T_D equals T_D-measlim, the actual T_D is considered to be equal or less than T_D-measlim.
T-$measl_{LP}$	m^2/s	Estimated practical lower measurement limit for evaluated T_D. If the estimated T_D equals T_D-measlim, the actual T_D is considered to be equal or less than T_D-measlim.
T-$meas_{lU}$	m^2/s	Estimated upper measurement limit for evaluated T_D. If the estimated T_D equals T_D-measlim, the actual T_D is considered to be equal or less than T_D-measlim.
h_i	m.a.s.l.	Calculated relative, natural freshwater head for test section or flow anomaly (undisturbed conditions)

Inferred flow anomalies from overlapping flow logging

Borehole ID	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_0 (m^3/s)	h_{0FW} (masl)	Q_1 (m^3/s)	h_{1FW} (masl)	T_D (m^2/s)	h_i (masl)	Comments
KA3007A01	15.5	1	0.1	–	0.00	6.33E-07	–400.66	1.6E-09	–	*
KA3007A01	16.1	1	0.1	–	0.00	2.59E-06	–400.66	6.4E-09	–	*
KA3007A01	16.8	1	0.1	–	0.00	8.58E-05	–400.66	2.1E-07	–	*,**
KA3007A01	21.3	1	0.1	–	0.00	1.07E-04	–400.66	2.7E-07	–	*,**
KA3007A01	22.3	1	0.1	–	0.00	8.67E-05	–400.66	2.1E-07	–	*,**
KA3007A01	23.3	1	0.1	–	0.00	9.11E-05	–400.66	2.3E-07	–	*,**
KA3007A01	30.3	1	0.1	–	0.00	9.28E-05	–400.66	2.3E-07	–	*,**
KA3007A01	53.3	1	0.1	–	0.00	1.43E-07	–400.66	3.5E-10	–	*
KA3007A01	54.6	1	0.1	–	0.00	7.28E-07	–400.66	1.8E-09	–	
KA3007A01	56.6	1	0.1	–	0.00	3.50E-07	–400.66	8.6E-10	–	
KA3007A01	62.3	1	0.1	–	0.00	1.45E-06	–400.66	3.6E-09	–	
KA3007A01	65.7	1	0.1	–	0.00	1.04E-06	–400.66	2.6E-09	–	
KA3007A01	67.2	1	0.1	–	0.00	2.11E-06	–400.66	5.2E-09	–	
KA3007A01	69.7	1	0.1	–	0.00	2.60E-06	–400.66	6.4E-09	–	
KA3007A01	70.4	1	0.1	–	0.00	7.28E-07	–400.66	1.8E-09	–	
KA3007A01	72.0	1	0.1	–	0.00	1.05E-06	–400.66	2.6E-09	–	
KA3007A01	76.7	1	0.1	–	0.00	2.97E-07	–400.66	7.3E-10	–	
KA3007A01	78.1	1	0.1	–	0.00	9.86E-07	–400.66	2.4E-09	–	
KA3007A01	79.8	1	0.1	–	0.00	6.28E-08	–400.66	1.6E-10	–	*
KA3007A01	82.7	1	0.1	–	0.00	1.33E-07	–400.66	3.3E-10	–	
KA3007A01	83.9	1	0.1	–	0.00	4.50E-07	–400.66	1.1E-09	–	*
KA3007A01	86.2	1	0.1	–	0.00	6.39E-08	–400.66	1.6E-10	–	*
KA3007A01	89.3	1	0.1	–	0.00	6.06E-07	–400.66	1.5E-09	–	
KA3007A01	90.8	1	0.1	–	0.00	1.48E-07	–400.66	3.7E-10	–	*
KA3007A01	92.6	1	0.1	–	0.00	3.00E-07	–400.66	7.4E-10	–	*
KA3007A01	93.9	1	0.1	–	0.00	3.58E-07	–400.66	8.9E-10	–	*
KA3007A01	94.6	1	0.1	–	0.00	5.00E-07	–400.66	1.2E-09	–	*
KA3007A01	96.0	1	0.1	–	0.00	1.15E-07	–400.66	2.8E-10	–	*
KA3007A01	98.7	1	0.1	–	0.00	7.92E-06	–400.66	2.0E-08	–	
KA3007A01	99.8	1	0.1	–	0.00	6.00E-08	–400.66	1.5E-10	–	*
KA3007A01	102.1	1	0.1	–	0.00	2.77E-06	–400.66	6.8E-09	–	
KA3007A01	103.8	1	0.1	–	0.00	4.19E-07	–400.66	1.0E-09	–	*
KA3007A01	104.3	1	0.1	–	0.00	4.47E-07	–400.66	1.1E-09	–	*
KA3007A01	104.9	1	0.1	–	0.00	6.06E-07	–400.66	1.5E-09	–	*
KA3007A01	105.5	1	0.1	–	0.00	1.04E-06	–400.66	2.6E-09	–	*
KA3007A01	106.8	1	0.1	–	0.00	2.38E-07	–400.66	5.9E-10	–	*
KA3007A01	108.0	1	0.1	–	0.00	4.31E-07	–400.66	1.1E-09	–	*
KA3007A01	109.9	1	0.1	–	0.00	3.11E-07	–400.66	7.7E-10	–	*
KA3007A01	110.7	1	0.1	–	0.00	1.43E-06	–400.66	3.5E-09	–	*
KA3007A01	111.5	1	0.1	–	0.00	1.36E-06	–400.66	3.4E-09	–	
KA3007A01	113.9	1	0.1	–	0.00	3.72E-06	–400.66	9.2E-09	–	
KA3007A01	115.1	1	0.1	–	0.00	1.58E-06	–400.66	3.9E-09	–	
KA3007A01	116.4	1	0.1	–	0.00	8.42E-06	–400.66	2.1E-08	–	
KA3007A01	119.2	1	0.1	–	0.00	1.13E-07	–400.66	2.8E-10	–	*
KA3007A01	120.5	1	0.1	–	0.00	1.10E-06	–400.66	2.7E-09	–	
KA3007A01	121.5	1	0.1	–	0.00	7.03E-06	–400.66	1.7E-08	–	
KA3007A01	123.0	1	0.1	–	0.00	4.11E-07	–400.66	1.0E-09	–	*
KA3007A01	123.3	1	0.1	–	0.00	9.97E-07	–400.66	2.5E-09	–	
KA3007A01	123.7	1	0.1	–	0.00	2.22E-06	–400.66	5.5E-09	–	
KA3007A01	124.8	1	0.1	–	0.00	8.42E-06	–400.66	2.1E-08	–	

Inferred flow anomalies from overlapping flow logging

Borehole ID	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_0 (m^3/s)	h_{0FW} (masl)	Q_1 (m^3/s)	h_{1FW} (masl)	T_D (m^2/s)	h_i (masl)	Comments
KA3007A01	135.1	1	0.1	–	0.00	1.57E-06	–400.66	3.9E-09	–	
KA3007A01	136.2	1	0.1	–	0.00	1.19E-05	–400.66	2.9E-08	–	
KA3007A01	136.6	1	0.1	–	0.00	2.20E-06	–400.66	5.4E-09	–	
KA3007A01	138.4	1	0.1	–	0.00	8.53E-06	–400.66	2.1E-08	–	
KA3007A01	140.1	1	0.1	–	0.00	1.25E-05	–400.66	3.1E-08	–	
KA3007A01	143.6	1	0.1	–	0.00	5.31E-06	–400.66	1.3E-08	–	
KA3007A01	145.4	1	0.1	–	0.00	1.00E-07	–400.66	2.5E-10	–	*
KA3007A01	146.7	1	0.1	–	0.00	3.31E-06	–400.66	8.2E-09	–	
KA3007A01	149.3	1	0.1	–	0.00	2.75E-07	–400.66	6.8E-10	–	*
KA3007A01	149.8	1	0.1	–	0.00	1.48E-06	–400.66	3.7E-09	–	
KA3007A01	150.6	1	0.1	–	0.00	5.78E-07	–400.66	1.4E-09	–	
KA3007A01	152.1	1	0.1	–	0.00	4.42E-06	–400.66	1.1E-08	–	
KA3007A01	152.5	1	0.1	–	0.00	3.03E-06	–400.66	7.5E-09	–	*
KA3007A01	153.0	1	0.1	–	0.00	3.14E-06	–400.66	7.8E-09	–	
KA3007A01	153.6	1	0.1	–	0.00	1.60E-06	–400.66	4.0E-09	–	*
KA3007A01	154.3	1	0.1	–	0.00	4.14E-07	–400.66	1.0E-09	–	
KA3007A01	155.5	1	0.1	–	0.00	1.21E-06	–400.66	3.0E-09	–	*
KA3007A01	156.8	1	0.1	–	0.00	6.36E-06	–400.66	1.6E-08	–	
KA3007A01	157.9	1	0.1	–	0.00	3.36E-06	–400.66	8.3E-09	–	
KA3007A01	158.6	1	0.1	–	0.00	3.36E-06	–400.66	8.3E-09	–	
KA3007A01	159.3	1	0.1	–	0.00	3.31E-06	–400.66	8.2E-09	–	
KA3007A01	164.3	1	0.1	–	0.00	8.31E-07	–400.66	2.1E-09	–	
KA3007A01	168.8	1	0.1	–	0.00	7.00E-07	–400.66	1.7E-09	–	*
KA3007A01	170.0	1	0.1	–	0.00	1.68E-07	–400.66	4.1E-10	–	*
KA3007A01	174.1	1	0.1	–	0.00	1.26E-05	–400.66	3.1E-08	–	
KA3007A01	174.5	1	0.1	–	0.00	2.92E-05	–400.66	7.2E-08	–	
KA3007A01	175.0	1	0.1	–	0.00	7.39E-05	–400.66	1.8E-07	–	
KA3007A01	208.8	1	0.1	–	0.00	7.00E-08	–400.66	1.7E-10	–	*
KA3007A01	209.0	1	0.1	–	0.00	2.83E-05	–400.66	7.0E-08	–	
KA3007A01	210.3	1	0.1	–	0.00	3.61E-07	–400.66	8.9E-10	–	*
KA3007A01	211.8	1	0.1	–	0.00	8.28E-06	–400.66	2.0E-08	–	
KA3007A01	212.1	1	0.1	–	0.00	3.22E-06	–400.66	8.0E-09	–	
KA3007A01	213.1	1	0.1	–	0.00	2.39E-06	–400.66	5.9E-09	–	
KA3007A01	216.4	1	0.1	–	0.00	1.18E-04	–400.66	2.9E-07	–	**

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

** Upper limit of the flow rate exceeded. Flow rate and transmissivity are probably larger than the specified value.

Q_0 was not measured. It was assumed to be zero.

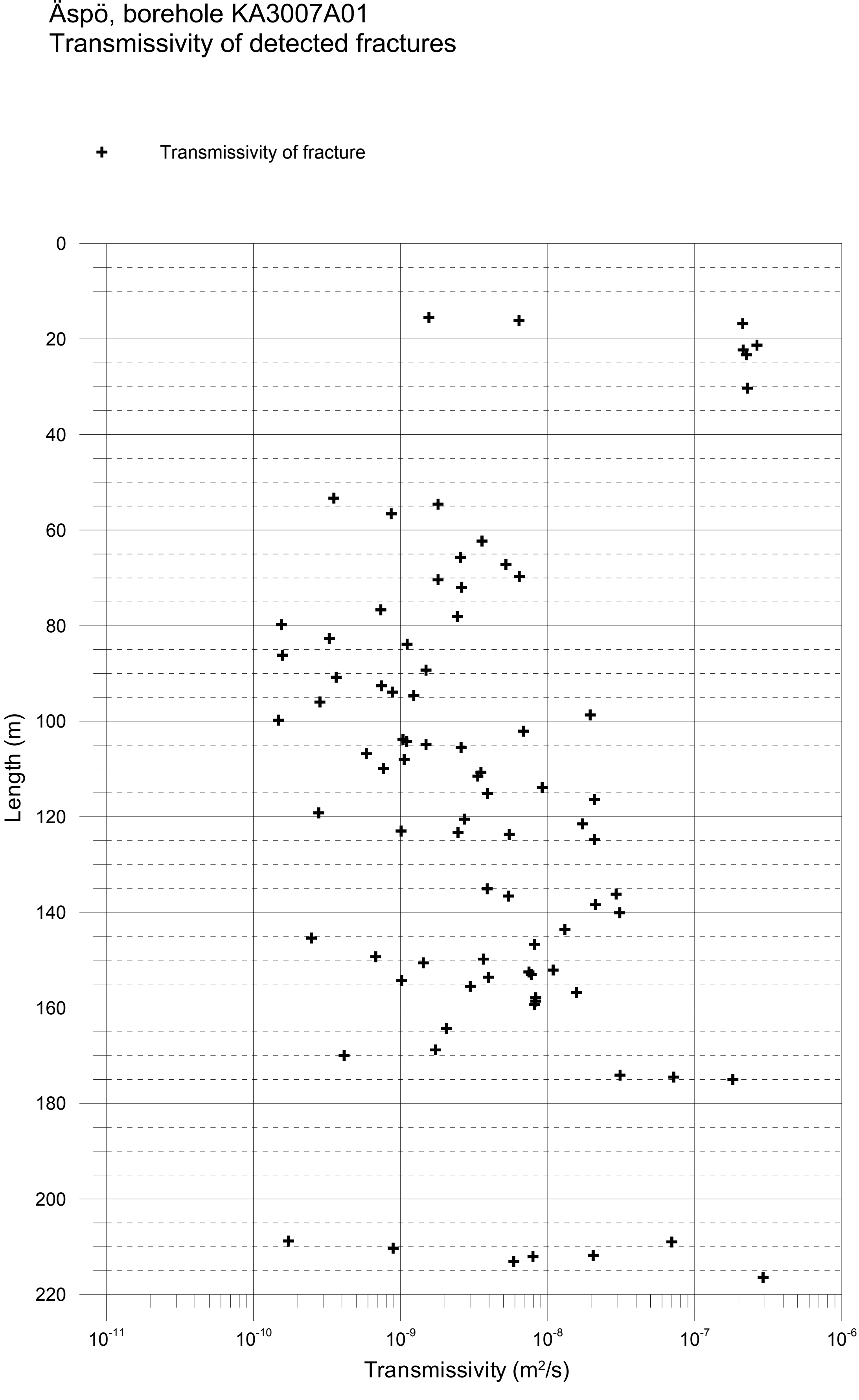
h_{0FW} was assumed to be zero (sea level).

h_{1FW} was same as the elevation of top of the casing tube.

Because of these assumptions the value of T_D is a rough estimate.

Appendix 6

Transmissivity and head of detected fractures



Appendix 7

Outflow from the borehole