P-12-11

Site investigation Äspö Hard Rock Laboratory

Difference flow logging in boreholes KO0011A01, KO0014G01, KO0015G01, KO0016G01, KO0017G01, KO0017G02, KO0017G03 and KO0017G04

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January 2015

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ISSN 1651-4416
SKB P-12-11
ID 1377334

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Keywords: Simpevarp, Hydrogeology, Hydraulic tests, PFL, Posiva Flow Log, AP TD PRAS1004-11-045 BRIE, Äspö Hard Rock Laboratory.

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 underground boreholes KO0011A01, KO0014G01, KO0015G01, KO0016G01 and KO0017G01–KO0017G04 at the Äspö Hard Rock Laboratory at Simpevarp, Sweden, in June 2011.

The flow along the borehole measurements were done by moving the measurement tool in 0.1 m steps. This method was used to flow log the entire measurable part of the boreholes. The measured borehole was open during the measurements and the surrounding boreholes were closed.

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.

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 KO0011A01, KO0014G01, KO0015G01, KO0016G01 and KO0017G01–KO0017G04 inom Äspö Hard Rock Laboratoriet i Simpevarp, Sverige, i juni 2011.

Flödet längs hålet mättes med PFL DIFF som förflyttades successivt i steg om 0.1 m i den mätbara delen av borrhålet. Borrhålet var öppet och andra borrhålen i närheten var stängda under mätningarna.

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

Contents

1 Introduction

The core drilled boreholes KO0011A01, KO0014G01, KO0015G01, KO0016G01 and KO0017G01–KO0017G04 at Simpevarp, Sweden were measured using the Posiva Flow Log, Difference Flow Method (PFL DIFF) which provides a swift, multifaceted characterization of a borehole. The measurements described in this report are part of the SKB's project PRAS1004-11-045 BRIE. Measurements were conducted between June 9 and 10, 2011. The boreholes are located in the Äspö tunnel at the Äspö Hard Rock Laboratory (HRL).

Technical information of the boreholes is presented in Table 1-1. Boreholes are core drilled with a diameter of c 76 mm. The locations of boreholes at the Äspö tunnel are illustrated in Figure 1-1 and Figure 1-2.

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 at Simpevarp, Sweden.

This document reports the results acquired by PFL DIFF in boreholes KO0011A01, KO0014G01, KO0015G01, KO0016G01 and KO0017G01–KO0017G04. 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. Technical information of the boreholes.

Borehole ID	Length (m)	Reference point Z (masl)	Inclination (degrees)
KO0011A01	c 10	–415.901	–0.1154
KO0014G01	3.00	–417.312	–89.6886
KO0015G01	3.03	–417.106	–89.2649
KO0016G01	c 3.50	–417.201	–89.6056
KO0017G01	2.97	–417.231	–89.3979
KO0017G02	c 3.50	–417.364	–89.5656
KO0017G03	c 3.50	–417.205	–89.2155
KO0017G04	c 3.50	–417.373	–89.4791

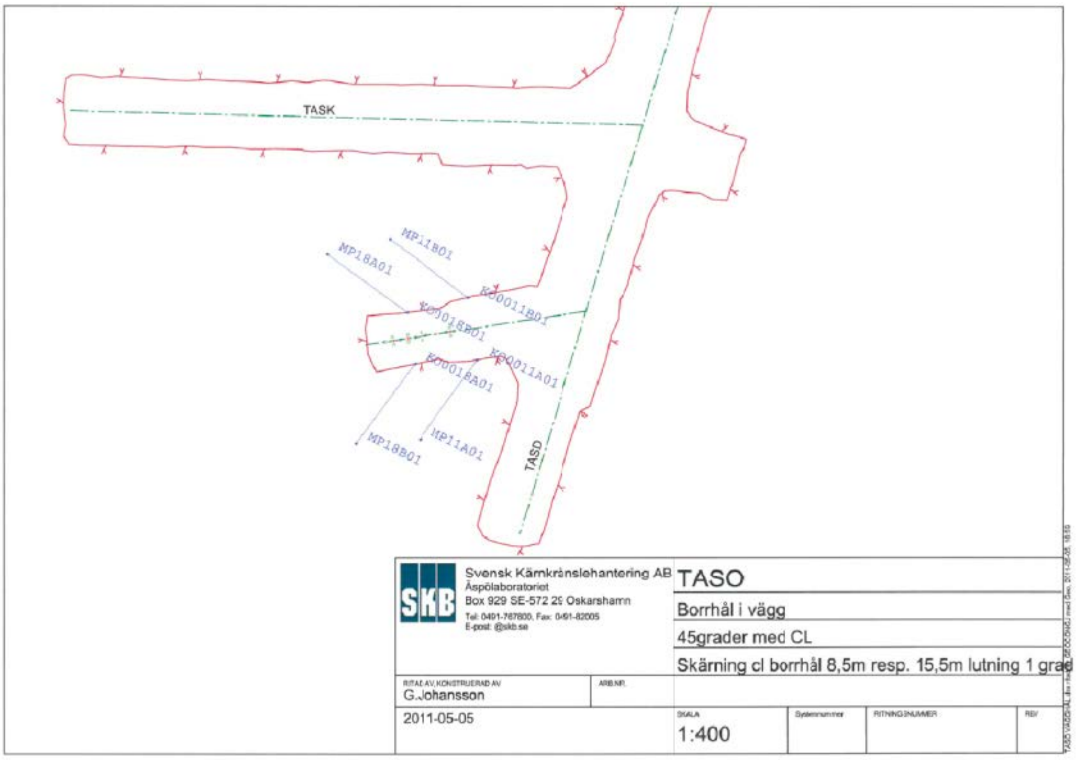


Figure 1-1. *The location of measured borehole KO0011A01 on the tunnel wall in the Äspö tunnel.*

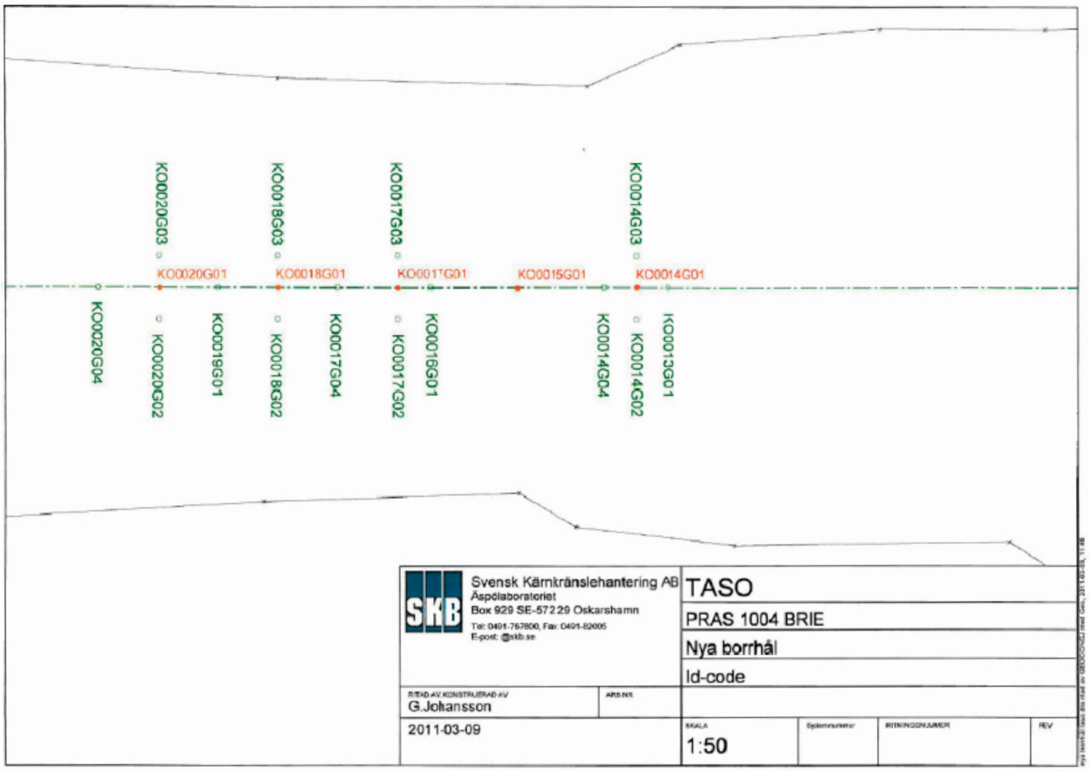


Figure 1-2. *The location of measured boreholes KO0014G01, KO0015G01, KO0016G01 and KO0017G01–KO0017G04 on tunnel floor in the Äspö tunnel.*

2 Objective and scope

The main objective of the PFL DIFF measurements in the boreholes was to identify water-conductive fractures and estimate the transmissivity of fractures. Besides 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.

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.

In spite of the proven benefit of the DIFF geometry it was not used in this study. The flow probe was connected to a flow guide for flow along the borehole, i.e. the measuring geometry was conventional. Many conductive fractures were not expected in these short boreholes and it was also important the measure the bottom of the boreholes. A short interval at the bottom remains unmeasured with the DIFF flow guide.

Flow rates 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 needed in very short or in nearly horizontal boreholes.
- 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.

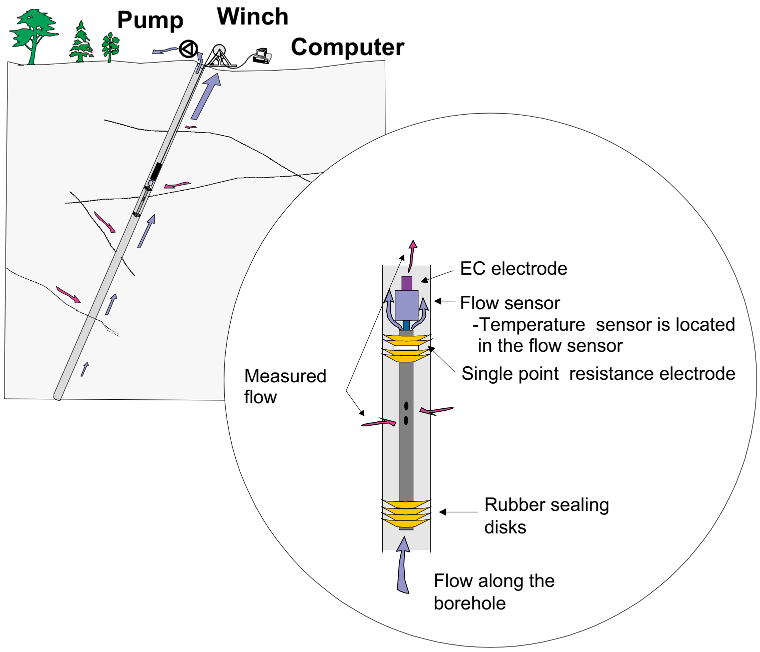


Figure 3-1. *Schematic of the probe used in the PFL DIFF.*

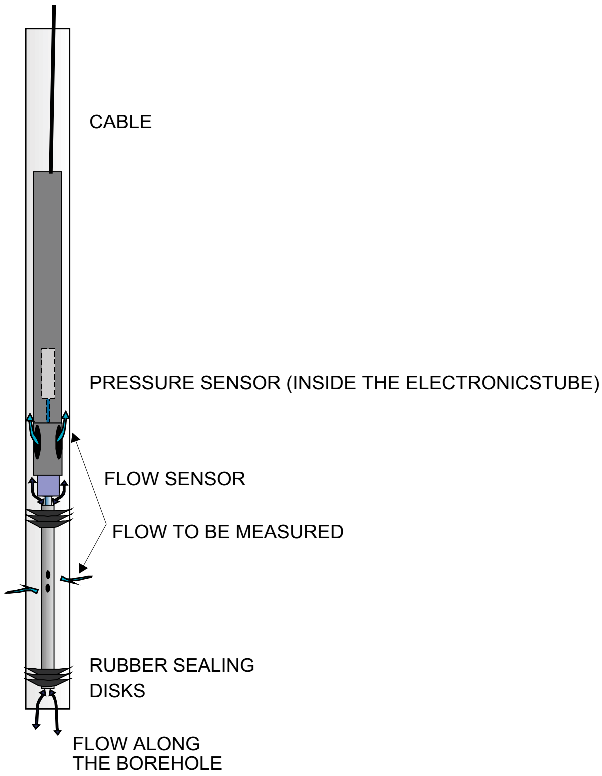


Figure 3-2. *The absolute pressure sensor is located inside the electronics assembly and connected to the borehole water through a tube.*

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.

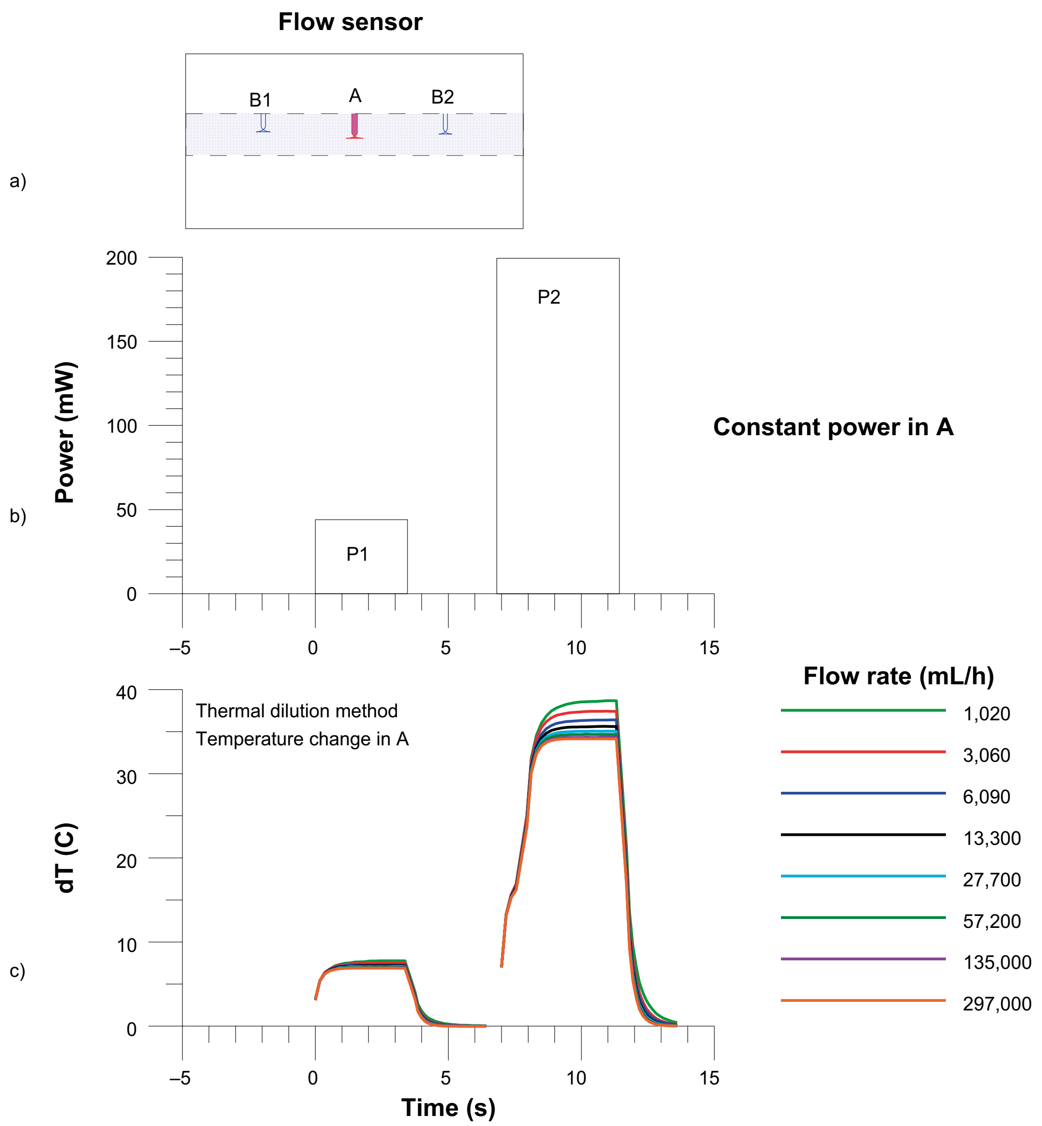


Figure 3-3. *Flow rate measurement.*

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:

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

where

r_0 is the radius of the well and

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

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

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

where

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

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

T_S is the transmissivity of the test section and

h_S is the undisturbed hydraulic head of the 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:

$$h_S = (h_0 - b \cdot h_1)/(1 - b) \quad (3\text{-}5)$$

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

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).

$$h_f = (h_0 - b \cdot h_1)/(1 - b) \quad (3\text{-}7)$$

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

where

Q_{f0} and Q_{f1} are the flow rates at a fracture and h_f and T_f are the hydraulic head (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 PRAS1004-11-045 BRIE – Phase 2 following the SKB Method Description 322.010e, Version 2.0 (Method description for Difference Flow Logging). 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 sub-vertical borehole. This will introduce a certain error in defining the position of a test tool connected to the end of a logging cable.

The dummy logging (Item 8) 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.

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

Item	Activity	Explanation	Date
3	Mobilisation at site	Unpacking the trailer.	2011-06-09
8	Dummy logging in KO0017G01	Borehole stability/risk evaluation.	2011-06-09
9	Flow along the borehole KO0017G01 – open borehole	Step length dL = 0.1 m.	2011-06-09
8	Dummy logging in KO0017G04	Borehole stability/risk evaluation.	2011-06-09
9	Flow along the borehole KO0017G04 – open borehole	Step length dL = 0.1 m.	2011-06-09
8	Dummy logging in KO0014G01	Borehole stability/risk evaluation.	2011-06-09
9	Flow along the borehole KO0014G01 – open borehole	Step length dL = 0.1 m.	2011-06-09
9	Flow along the borehole KO0017G01 – open borehole	Step length dL = 0.1 m. All section packers deflated except those at the surface.	2011-06-09
8	Dummy logging in KO0011A01	Borehole stability/risk evaluation.	2011-06-09
9	Flow along the borehole KO0011A01 – open borehole	Step length dL = 0.1 m.	2011-06-09
8	Dummy logging in KO0017G03	Borehole stability/risk evaluation.	2011-06-10
9	Flow along the borehole KO0017G03 – open borehole	Step length dL = 0.1 m.	2011-06-10
8	Dummy logging in KO0016G01	Borehole stability/risk evaluation.	2011-06-10
9	Flow along the borehole KO0016G01 – open borehole	Step length dL = 0.1 m.	2011-06-10
8	Dummy logging in KO0017G02	Borehole stability/risk evaluation.	2011-06-10
9	Flow along the borehole KO0017G02 – open borehole	Step length dL = 0.1 m.	2011-06-10
8	Dummy logging in KO0015G01	Borehole stability/risk evaluation.	2011-06-10
9	Flow along the borehole KO0015G01 – open borehole	Step length dL = 0.1 m.	2011-06-10
10	Demobilisation	Packing the trailer.	2011-06-10

The flow along the borehole (Item 9) was carried out in the open borehole with in 0.1 m length increments (step length). Surrounding boreholes were closed with packers by SKB personnel based on the Activity Plan. The measurement location with measurement setup can be seen in Figure 5-1.

The electrical conductivity (EC) and temperature of borehole water (Item 9) were measured during flow logging measurements.

5.2 Nonconformities

The upper part of the boreholes could not be measured because the PFL DIFF probe's thermistors must be under water during measurements. The minimum measuring distance is about 0.45 m from the water level. In borehole KO0011A01 a section of about 4.2 m from the top of the hole could not be measured because the borehole is nearly horizontal.

Flow logging measurements were carried out only in open boreholes. The accurate calculation of transmissivity requires two sets of measurements at different pressure stages. Boreholes could not be closed due to technical reasons. Closing the borehole requires casing tube and closing mechanism for flow logging cable. In this case mechanism would have been built specifically for these measurements and for the given time schedule it was not possible.

Figure 5-1. *The location of the measured boreholes and the measurement trailer in the Äspö TASO-tunnel.*

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.

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:
5. $E = 0.05\ m + 0.05\ m + d \cdot 0.002$
6. 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.

Length corrections were not made in this measurement campaign because the boreholes are such short (less than 10 meters). Instead the length was checked with the top of the borehole.

6.2 Electrical conductivity and temperature

The electrical conductivity of the borehole water (borehole EC) was measured during the flow logging measurements. These results don't represent groundwater in the bedrock because the boreholes were filled with water from the HRL's water line. The measurements were performed upwards, see Appendices KO0011A01.1, KO0014G01.1, KO0015G01.1, KO0016G01.1, KO0017G01.1, KO0017G02.1, KO0017G03.1 and KO0017G04.1.

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 Appendices KO0011A01.2, KO0014G01.2, KO0015G01.2, KO0016G01.2, KO0017G01.2, KO0017G02.2, KO0017G03.2 and KO0017G04.2 have the same length axis as the EC plots.

6.3 Pressure measurements

No absolute pressure measurements were conducted during this measurement campaign. 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 short and in horizontal boreholes the latter effect is insignificant.

6.4 Flow logging

6.4.1 General comments on results

The measuring programme contained one flow logging sequence in each borehole. The results were plotted on the same diagram with single-point resistance (right hand side), see Appendices KO0011A01.3, KO0014G01.3, KO0015G01.3, KO0016G01.3, KO0017G01.3, KO0017G02.3, KO0017G03.3 and KO0017G04.3. 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 along the borehole measurements were performed with 0.1 m length increments. The method (flow along the borehole logging) gives the length and the thickness of conductive zones with a length resolution of 0.1 m.

KO0011A01 and KO0014G01 were the only boreholes where water yielding fractures were found.

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.

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. Head h_1 in the borehole corresponds the situation in a pumped borehole. In this case the boreholes are freely flowing into the tunnel and h_1 is the water level at the top of the borehole (Z). 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. $h_0 \sim 0$.

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 along the borehole measurement are presented in tables, see Table 6-1 and Appendices KO0011A01.4 and KO0014G01.4. In these Appendices h_{0FW} is assumed to be zero and h_{1FW} is the hydraulic head of the borehole for the flow measurement (–415.90 m in KO0011A01 and –417.31 m in KO0014G01). Explanations to the tables in Appendices KO0011A01.4 and KO0014G01.4 are given in Appendix 1.

The flow rates are positive if the flow direction is from the bedrock into the borehole and vice versa. Two fractures were detected as flow yielding in the borehole KO0011A01 and one in the borehole KO0014G01. 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 Appendices KO0011A01.5 and KO0014G01.5.

The sum of all the detected flows (Q_1) in KO0011A01 was $2.0 \cdot 10^{-6}$ m^3/s (120 mL/min) and in KO0014G01 $1.1 \cdot 10^{-8}$ m^3/s (0.67 mL/min). The outflow from the boreholes could not be measured without a packer.

6.4.3 Transmissivity of fractures

An attempt was made to evaluate the magnitude of fracture-specific flow rates. The results for flow along the borehole measurement with 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.

The total amount of detected flowing fractures was two in the borehole KO0011A01 and one in the borehole KO0014G01. These fractures were used for transmissivity estimations. Transmissivity of fractures is presented in Table 6-1 and in Appendices KO0011A01.4, KO0011A01.5, KO0014G01.4 and KO0014G01.5.

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 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 about 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.

Table 6-1. Inferred flow anomalies from flow logging.

Borehole ID	Length to flow anom. L (m)	Q_0 (m^3/s)	h_{0FW} (masl)	Q_1 (m^3/s)	h_{1FW} (masl)	T_D (m^2/s)	h_i (masl)	Q_{min} (m^3/s)	Comments
KO0011A01	4.4	–	0.00	2.00E–06	–415.90	4.8E–09	–	8.33E–09	
KO0011A01	5.4	–	0.00	2.14E–08	–415.90	5.1E–11	–	8.33E–09	
KO0014G01	1.1	–	0.00	1.11E–08	–417.31	2.6E–11	–	8.33E–09	*

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

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.

Flowing water in tunnel boreholes 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 practical minimum for measurable flow rate is presented in Table 6-1 and in Appendices KO0011A01.3, KO0014G01.3, KO0015G01.3, KO0016G01.3, KO0017G01.3, KO0017G02.3, KO0017G03.3 and KO0017G04.3 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 flow along the borehole 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 was 30 mL/h in each hole. 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 none of such fractures detected during this campaign. If several high-flowing fractures are found, 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 boreholes KO0011A01, KO0014G01, KO0015G01, KO0016G01 and KO0017G01–KO0017G04 in the Äspö HRL, at Simpevarp, Sweden. A flow along the borehole was measured with 0.1 m length increments. The boreholes were open during the flow measurements while surrounding boreholes were closed with packers by SKB's personnel.

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

The total amount of detected flowing fractures was three. Transmissivity was calculated for the measured borehole fractures. The calculated transmissivities are rough estimates because the measurements were carried out in only one pressure condition.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.se/publications.

de Marsily G, 1986. Quantitative hydrogeology: groundwater hydrology for engineers. Orlando, FL: 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 Working Report 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

Explanations for the tables in Appendices KO0011A01.4 and KO0014G01.4

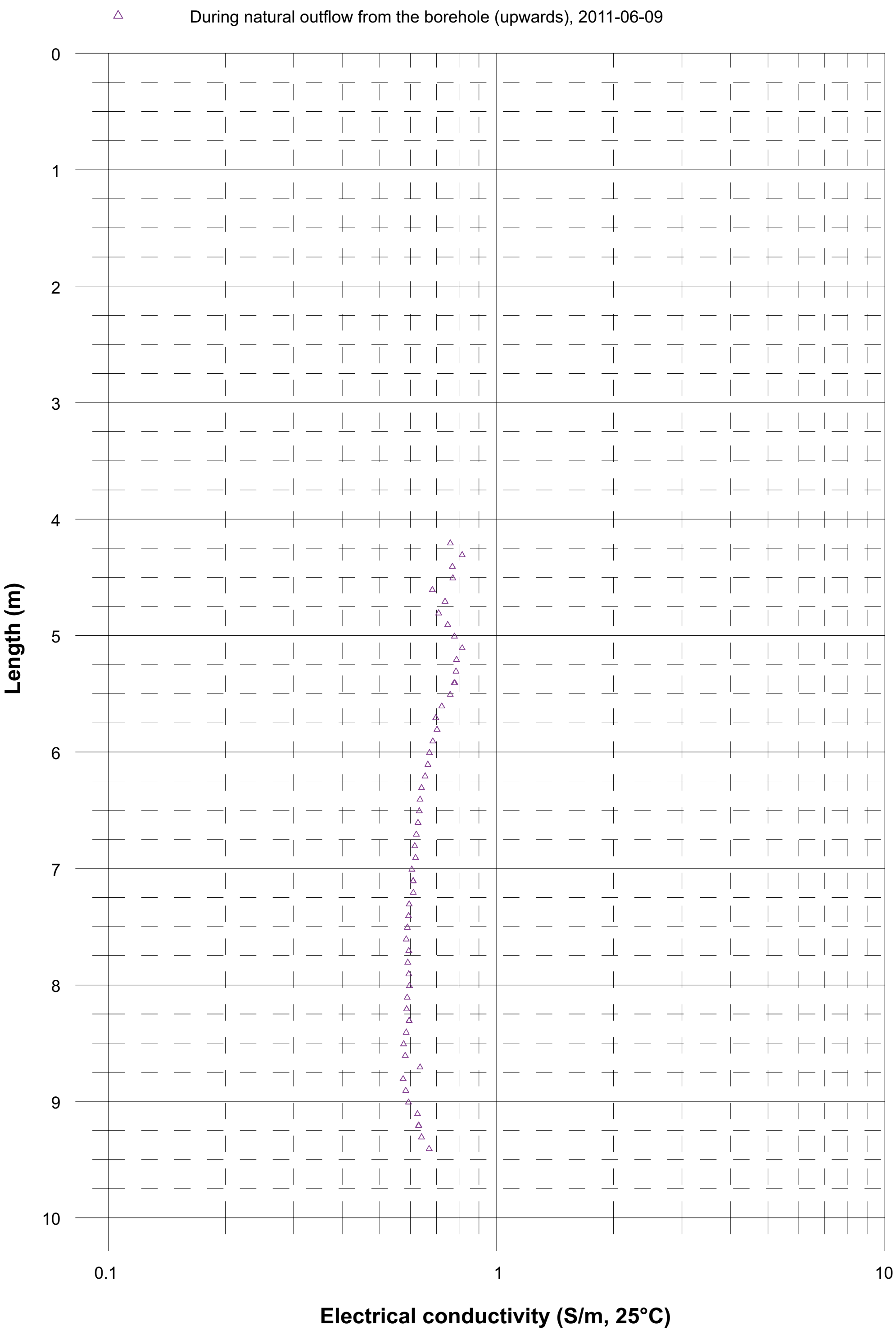
Header	Unit	Explanations
Borehole		ID for borehole
Secup	m	Length along the borehole for the upper limit of the test section (based on corrected length L)
Seclow	m	Length along the borehole for the lower limit of the test section (based on corrected length L)
L	m	Corrected length along borehole based 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
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

Header	Unit	Explanations
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.
$T\text{-measl}_{LT}$	m^2/s	Estimated theoretical lower measurement limit for evaluated TD. If the estimated TD equals TD-measlim, the actual TD is considered to be equal or less than TD-measlim.
$T\text{-measl}_{LP}$	m^2/s	Estimated practical lower measurement limit for evaluated TD. If the estimated TD equals TD-measlim, the actual TD is considered to be equal or less than TD-measlim.
$T\text{-meas}_{lU}$	m^2/s	Estimated upper measurement limit for evaluated TD. If the estimated TD equals TD-measlim, the actual TD is considered to be equal or less than TD-measlim.
h_i	m.a.s.l.	Calculated relative, natural freshwater head for test section or flow anomaly (undisturbed conditions)

Appendix KO0011A01.1

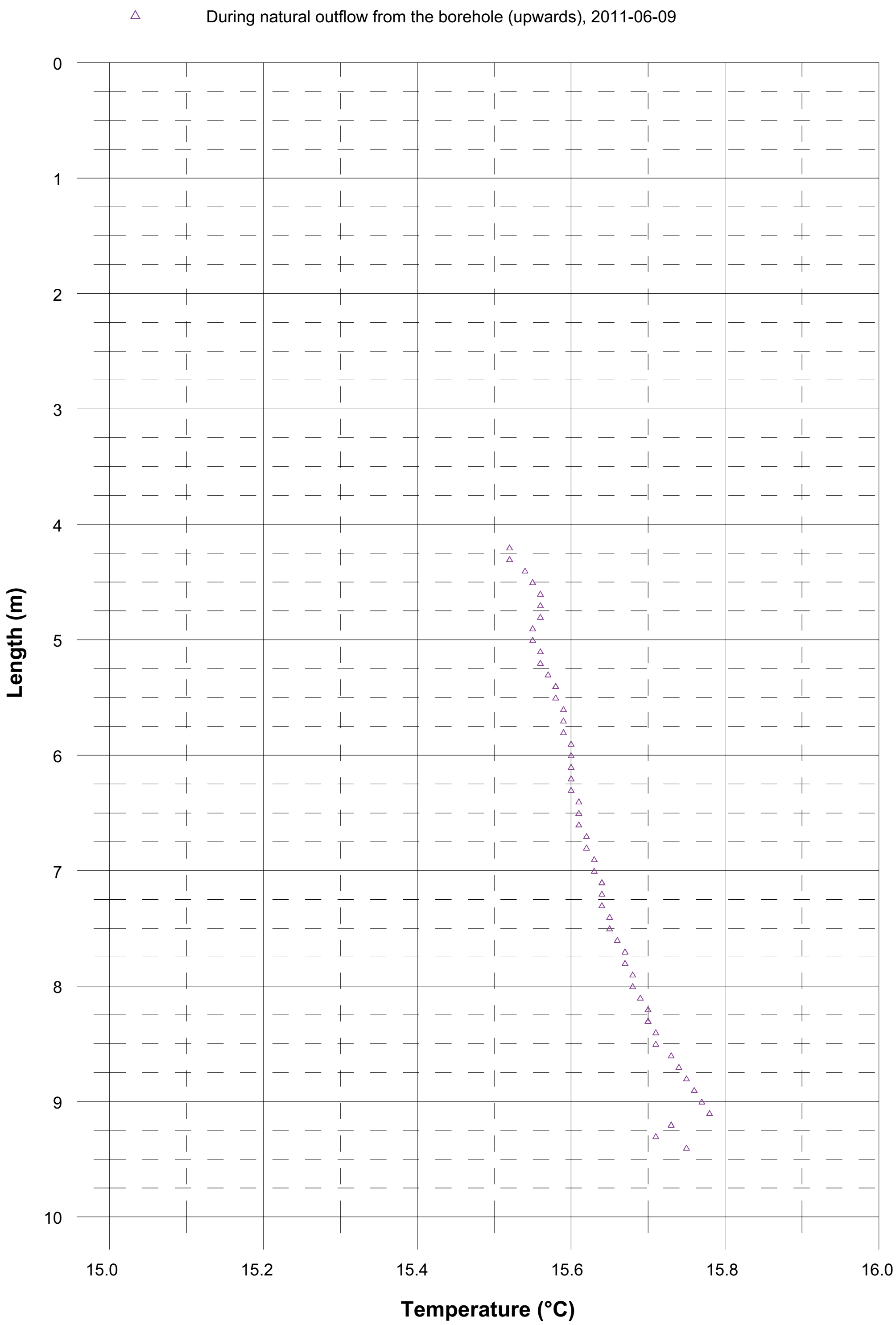
Äspö, borehole KO0011A01

Electrical conductivity of borehole water



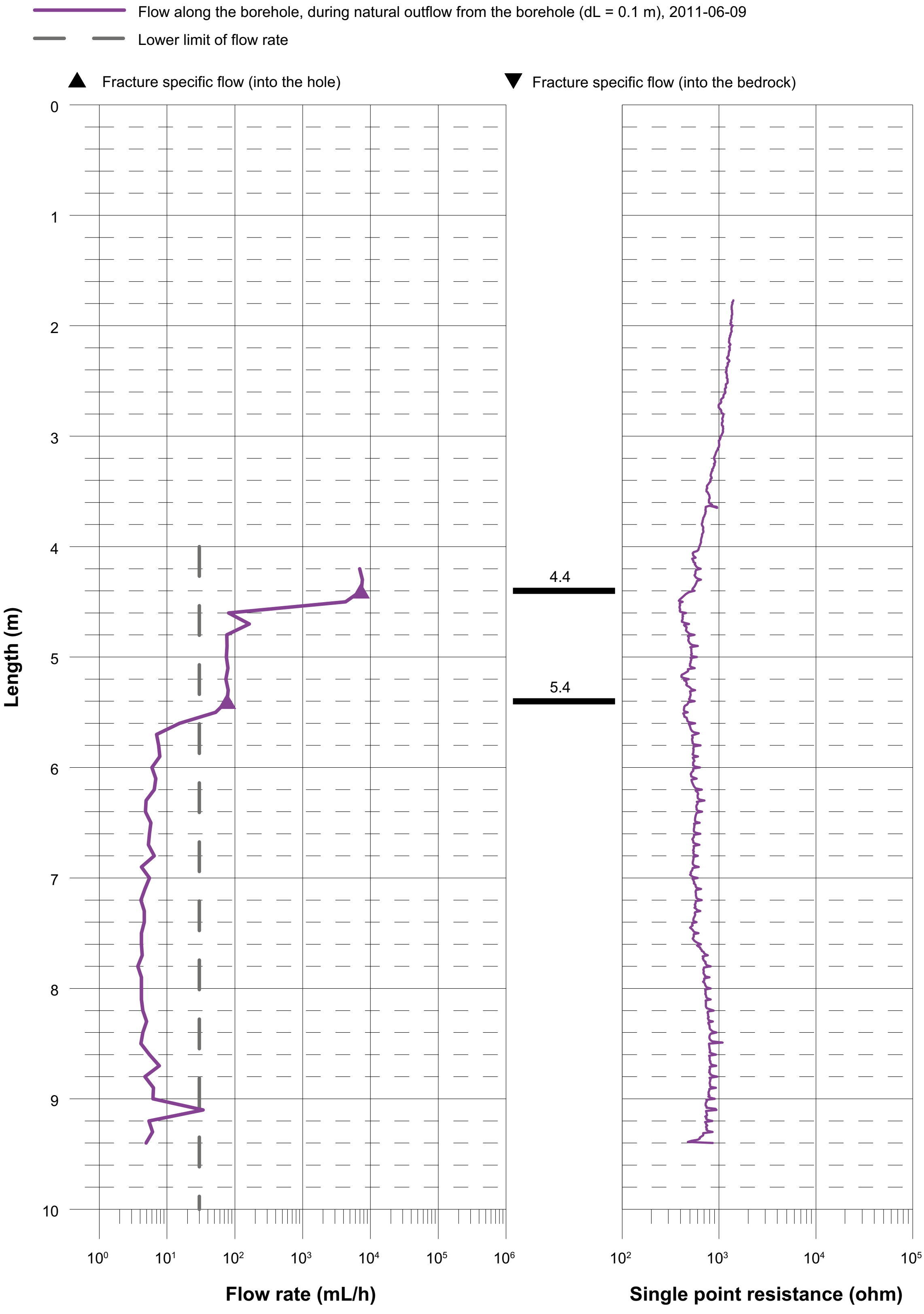
Äspö, borehole KO0011A01

Temperature of borehole water



Äspö, borehole KO0011A01

Flow rate and single point resistance



Appendix KO0011A01.4

Inferred flow anomalies from flow logging

Borehole ID	Length to flow anom. L (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
KO0011A01	4.4	0.1	–	0.00	2.00E–06	–415.90	4.8E–09	–	
KO0011A01	5.4	0.1	–	0.00	2.14E–08	–415.90	5.1E–11	–	

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

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

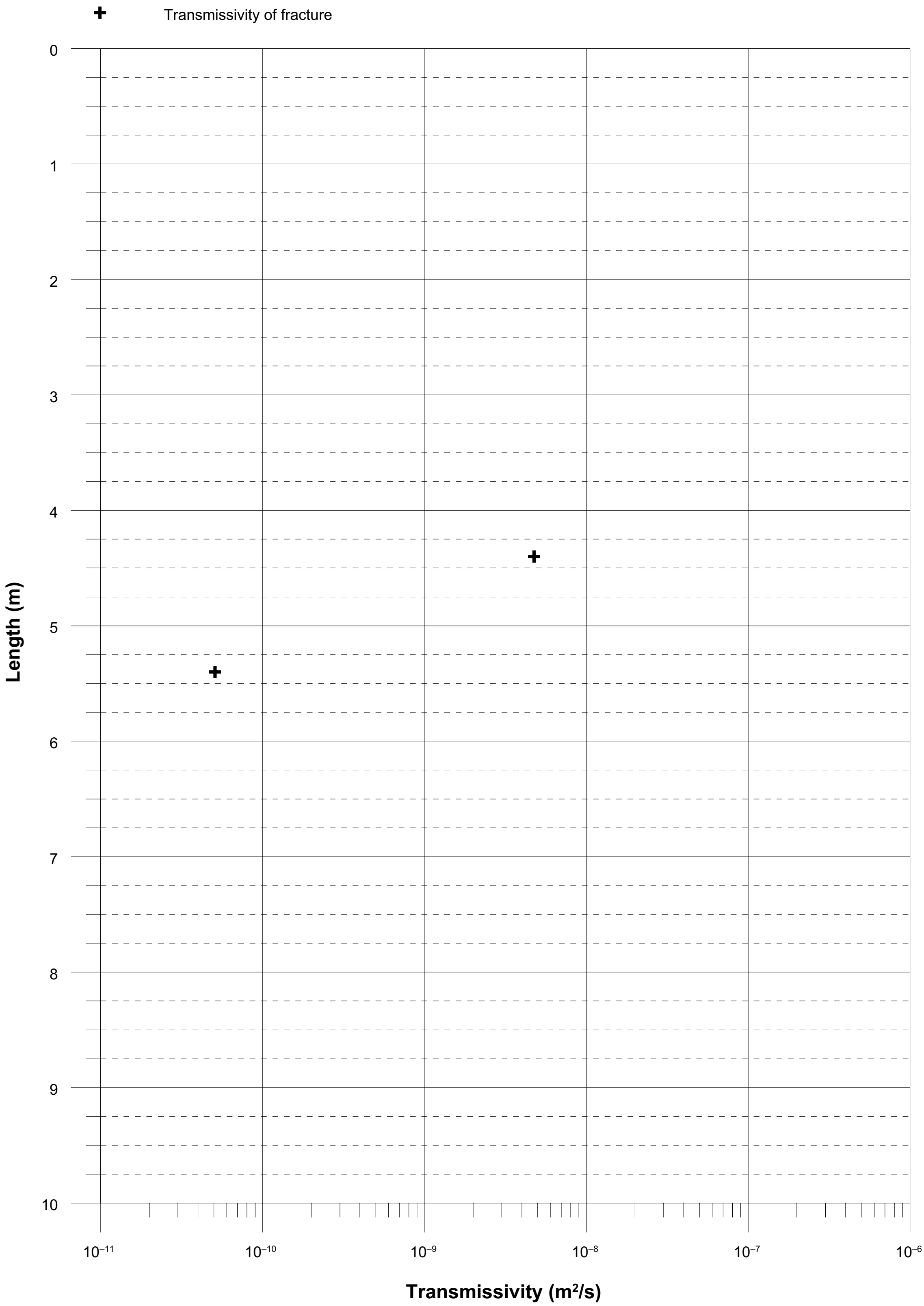
h_{0FW} was assumed to be zero (sea level).

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

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

Äspö, borehole KO0011A01

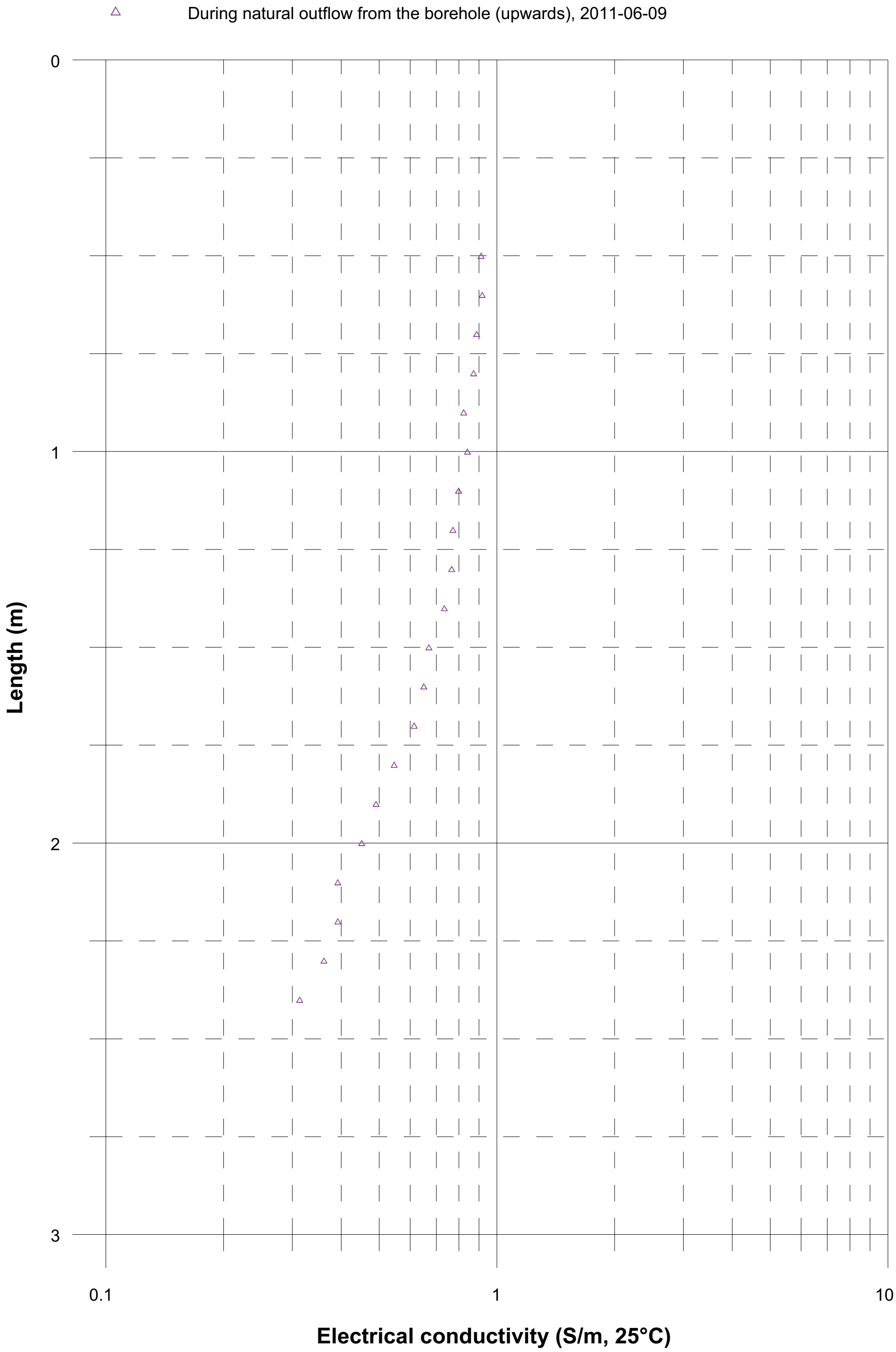
Plotted transmissivity of detected fractures



Appendix KO0014G01.1

Äspö, borehole KO0014G01

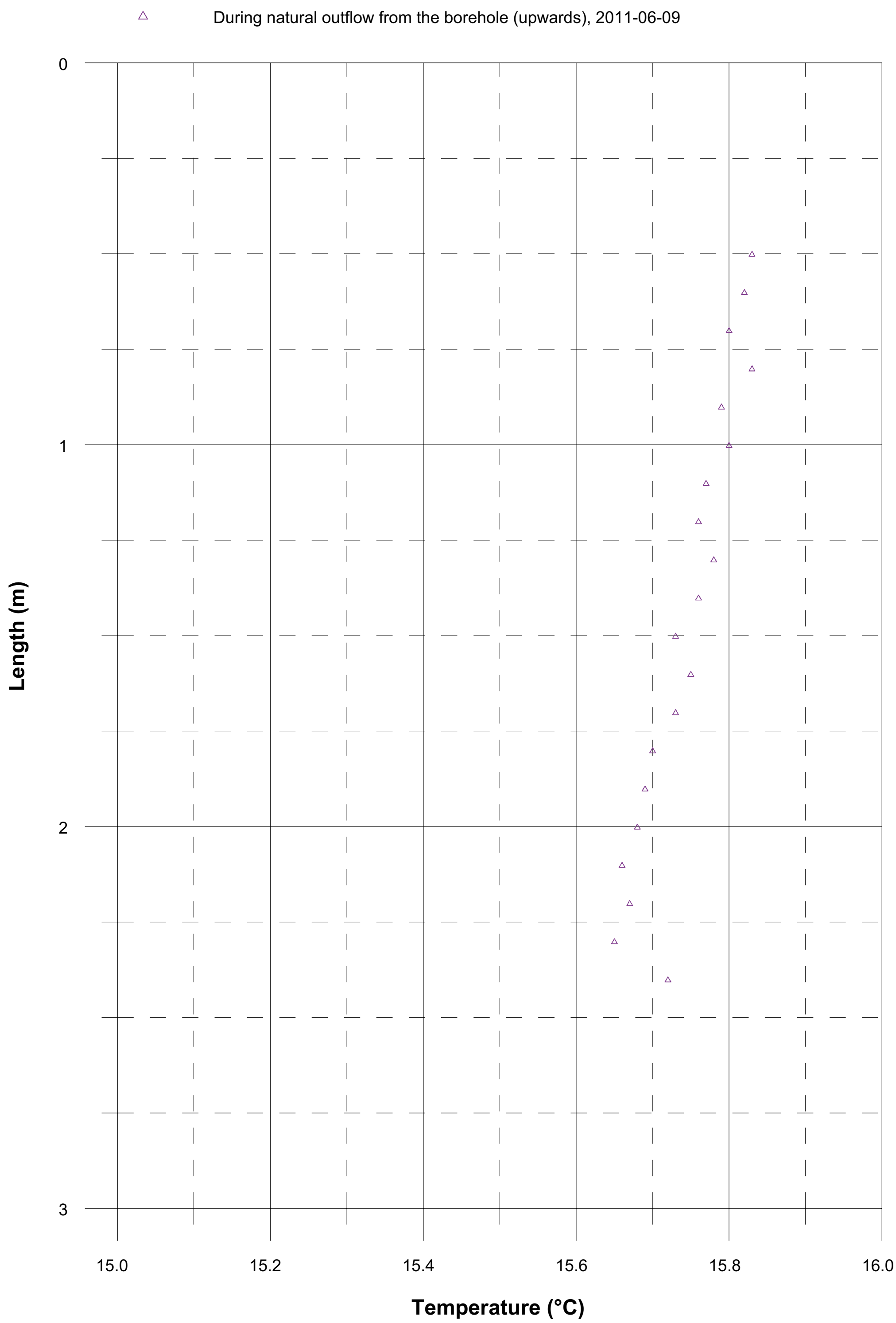
Electrical conductivity of borehole water



Appendix KO0014G01.2

Äspö, borehole KO0014G01

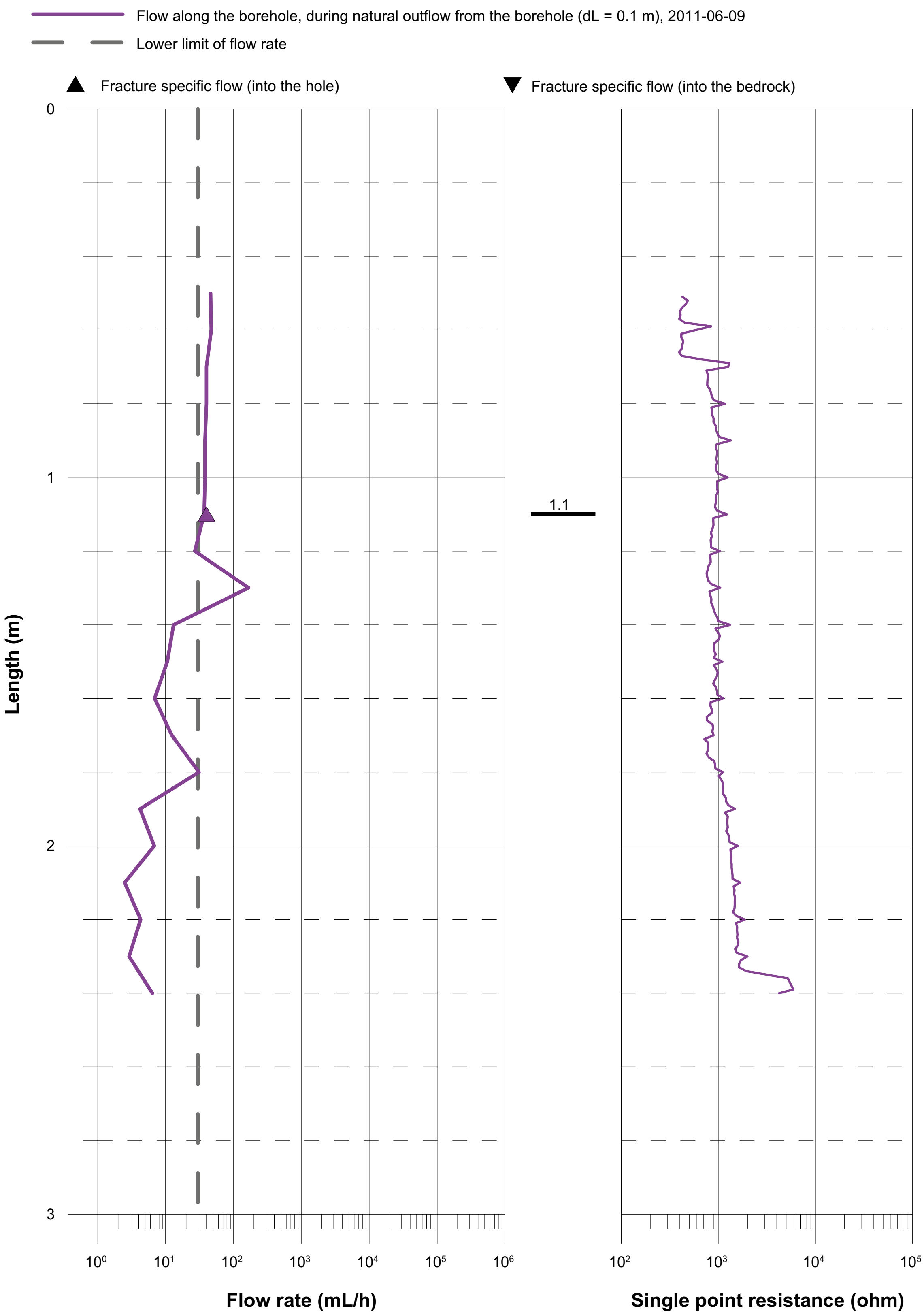
Temperature of borehole water



Appendix KO0014G01.3

Äspö, borehole KO0014G01

Flow rate and single point resistance



Appendix KO0014G01.4

Inferred flow anomalies from flow logging

Borehole ID	Length to flow anom. L (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
KO0014G01	1.1	0.1	–	0.00	1.11E–08	–417.31	2.6E–11	–	*

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

Q0 was not measured. It was assumed to be zero.

h0FW was assumed to be zero (sea level).

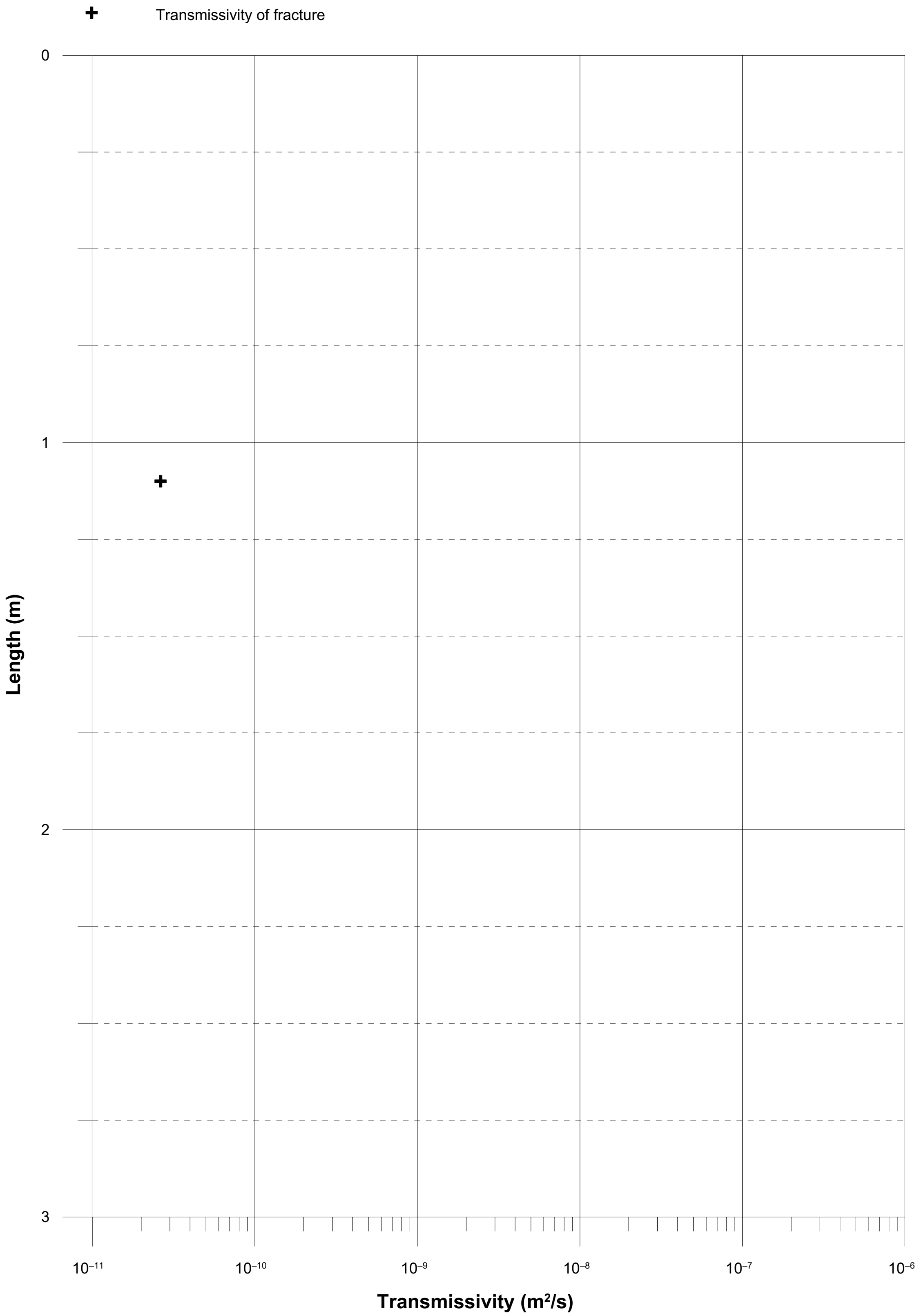
h1FW was same as the elevation of top of the casing tube.

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

Appendix KO0014G01.5

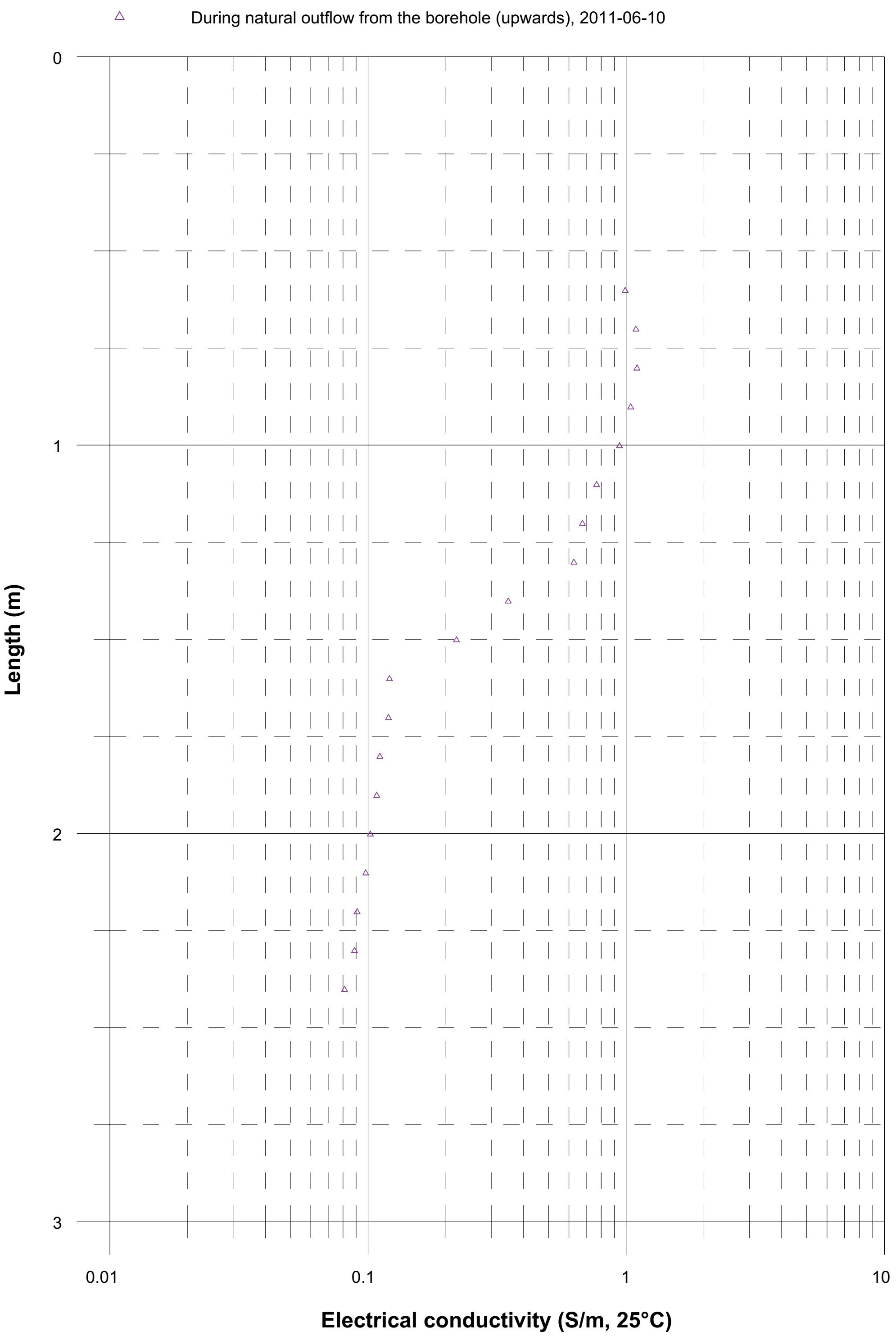
Äspö, borehole KO0014G01

Plotted transmissivity of detected fractures



Äspö, borehole KO0015G01

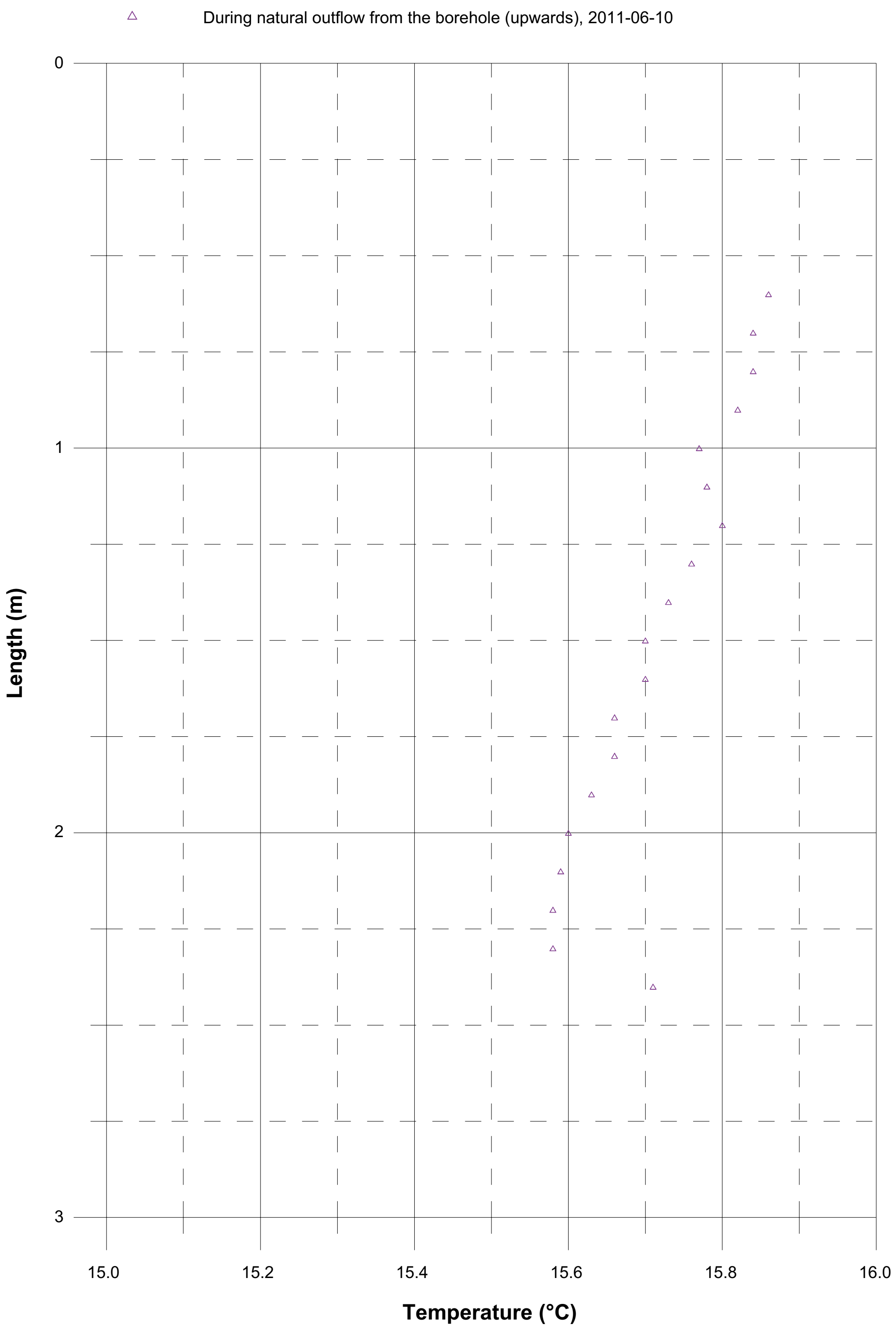
Electrical conductivity of borehole water



Appendix KO0015G01.2

Äspö, borehole KO0015G01

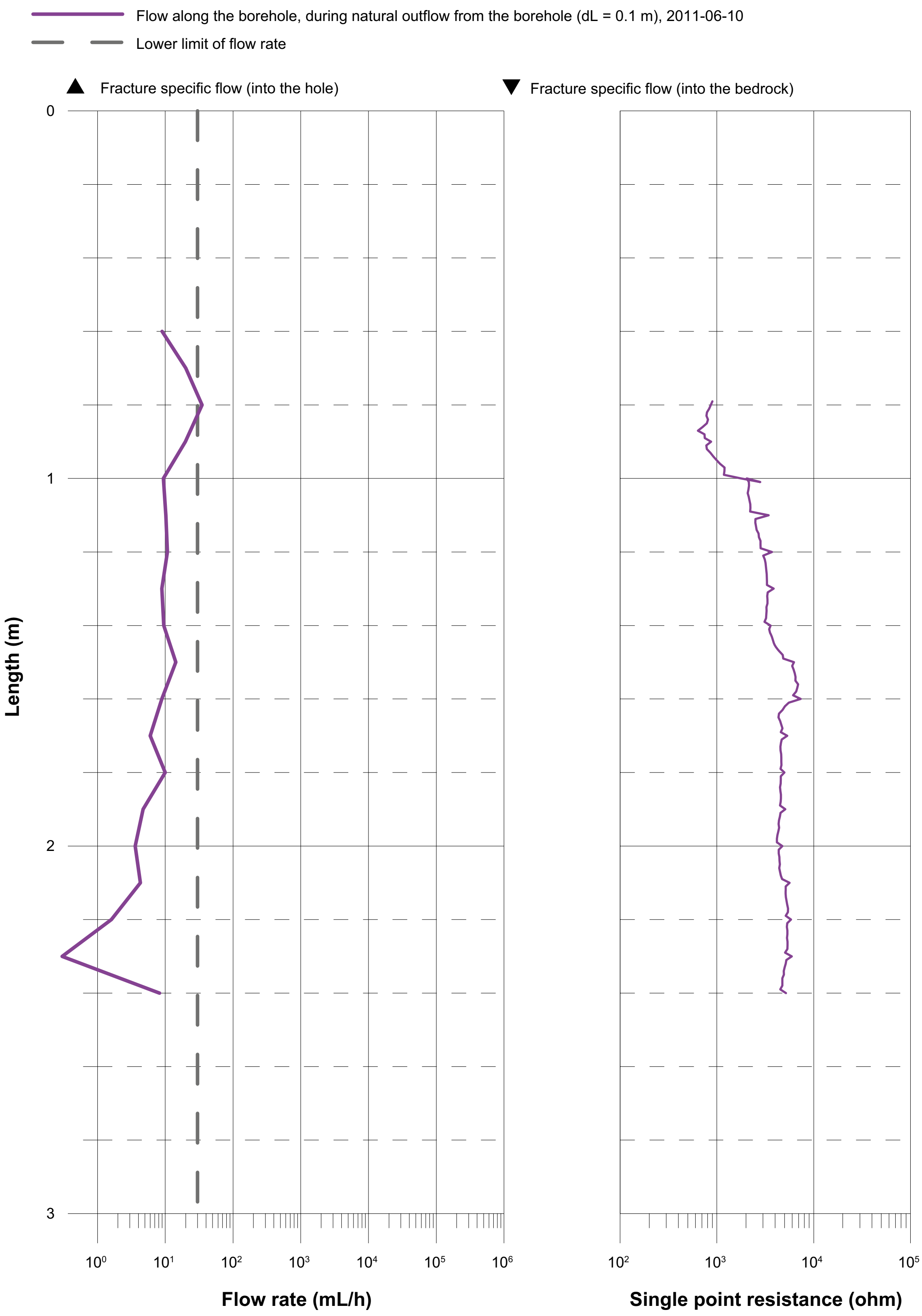
Temperature of borehole water



Appendix KO0015G01.3

Äspö, borehole KO0015G01

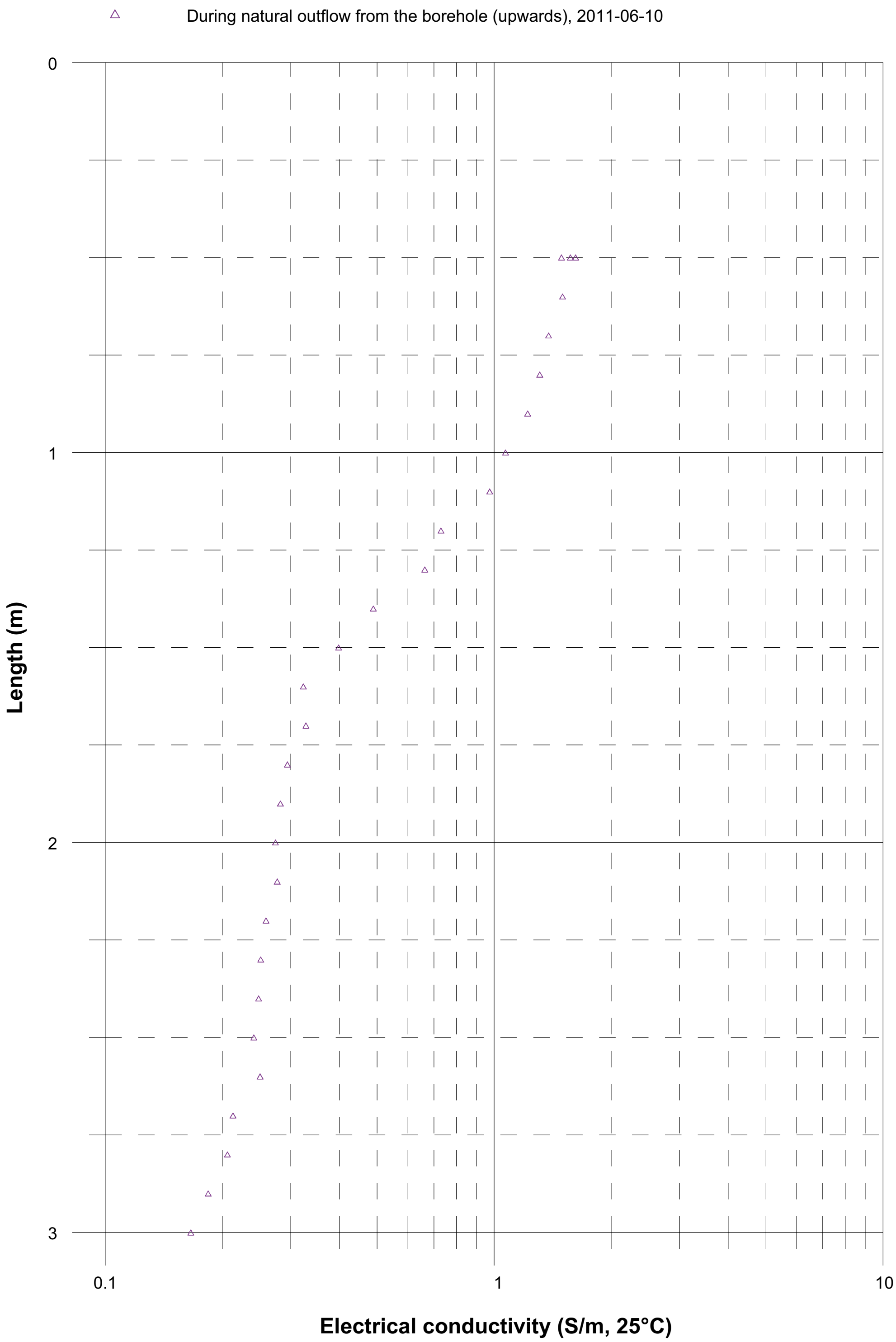
Flow rate and single point resistance



Appendix KO0016G01.1

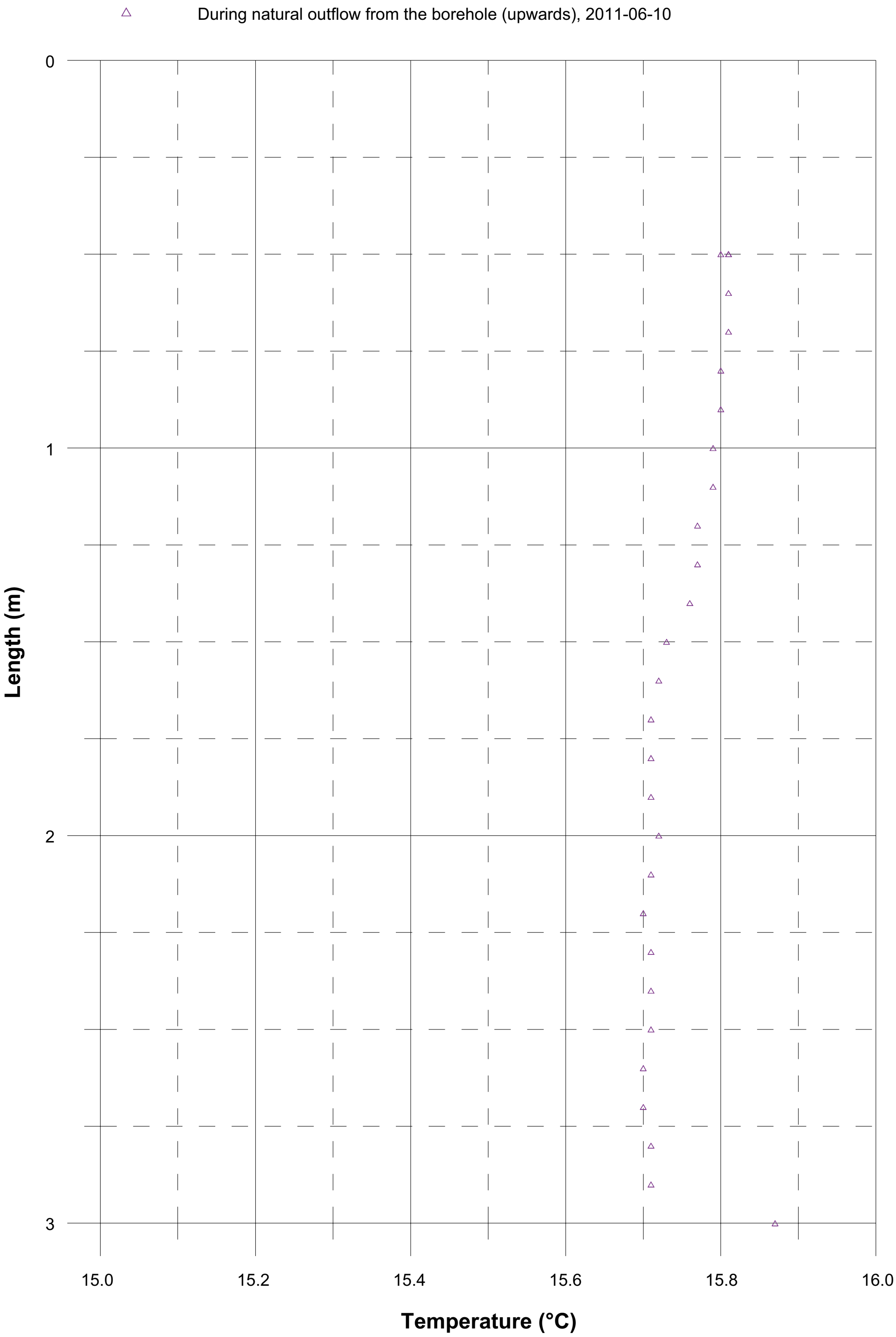
Äspö, borehole KO0016G01

Electrical conductivity of borehole water



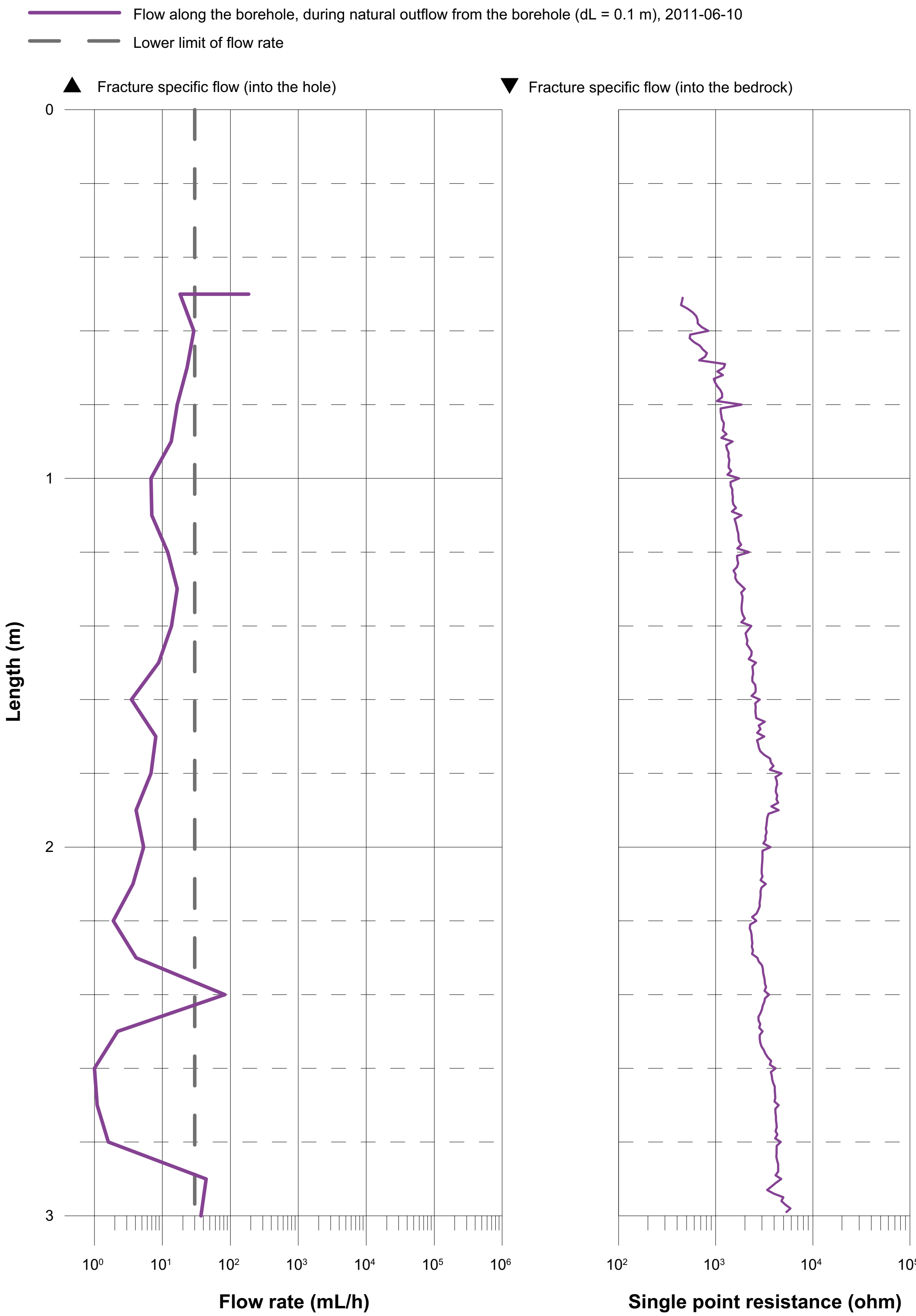
Äspö, borehole KO0016G01

Temperature of borehole water



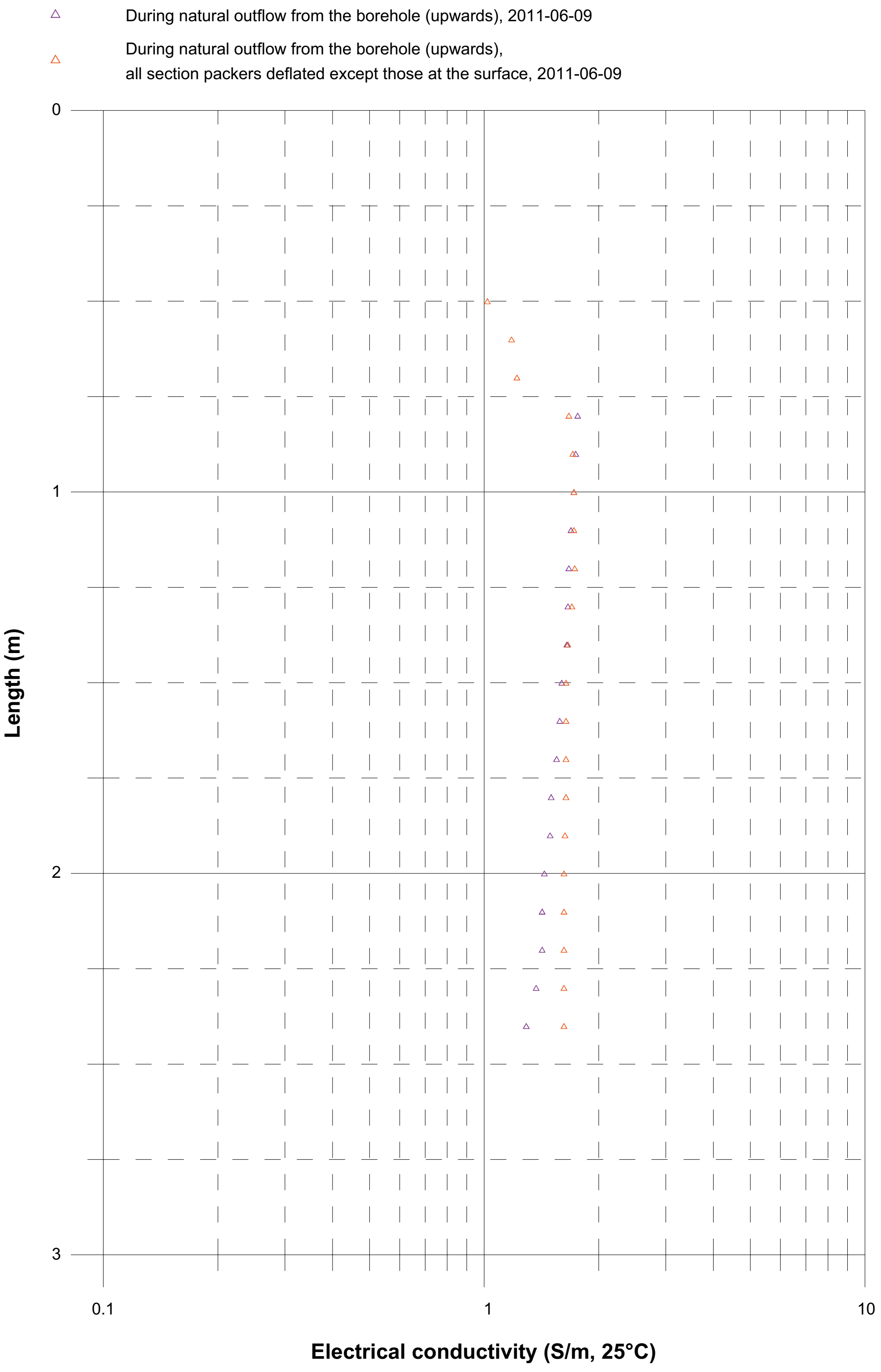
Äspö, borehole KO0016G01

Flow rate and single point resistance



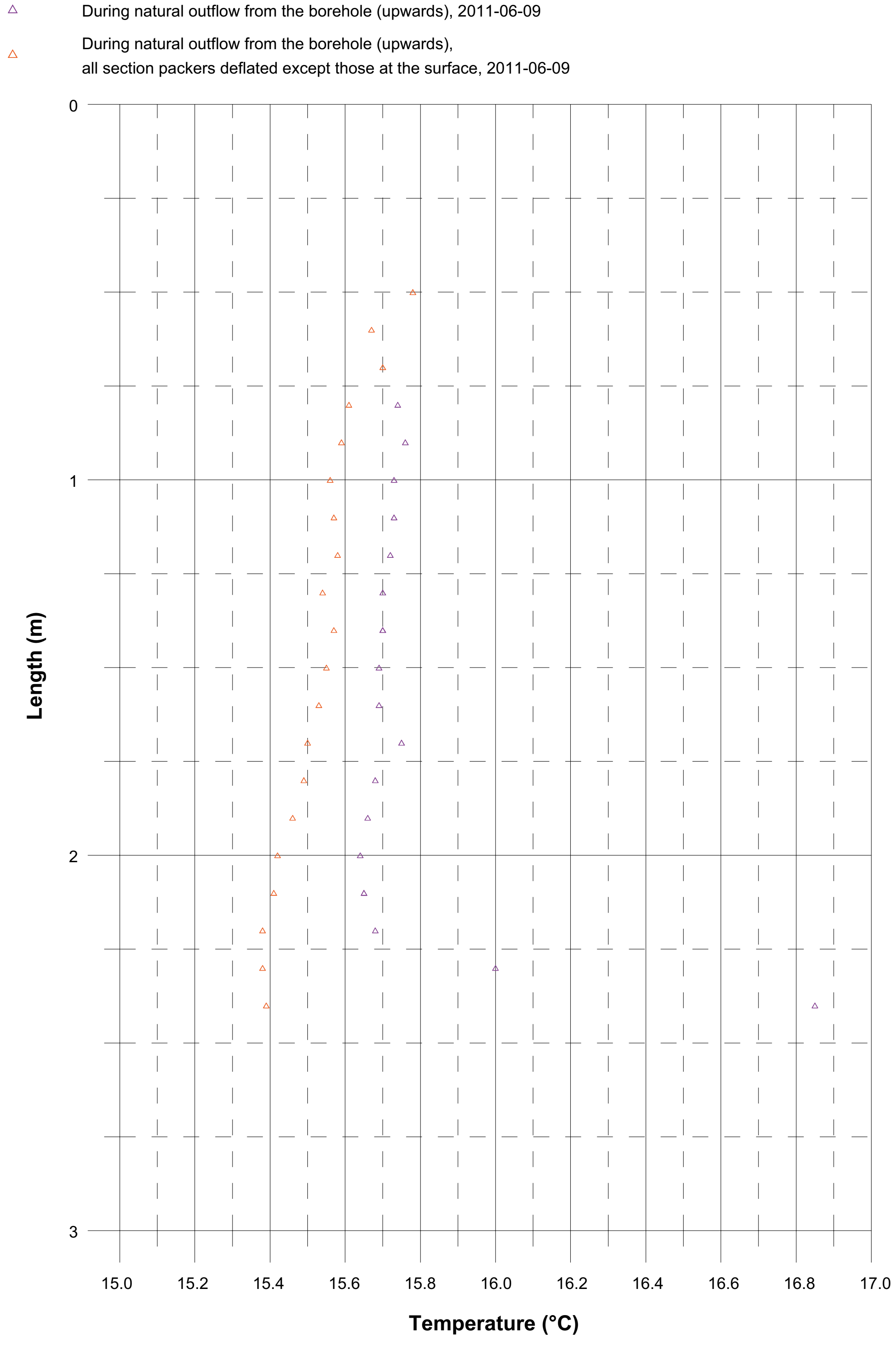
Äspö, borehole KO0017G01

Electrical conductivity of borehole water



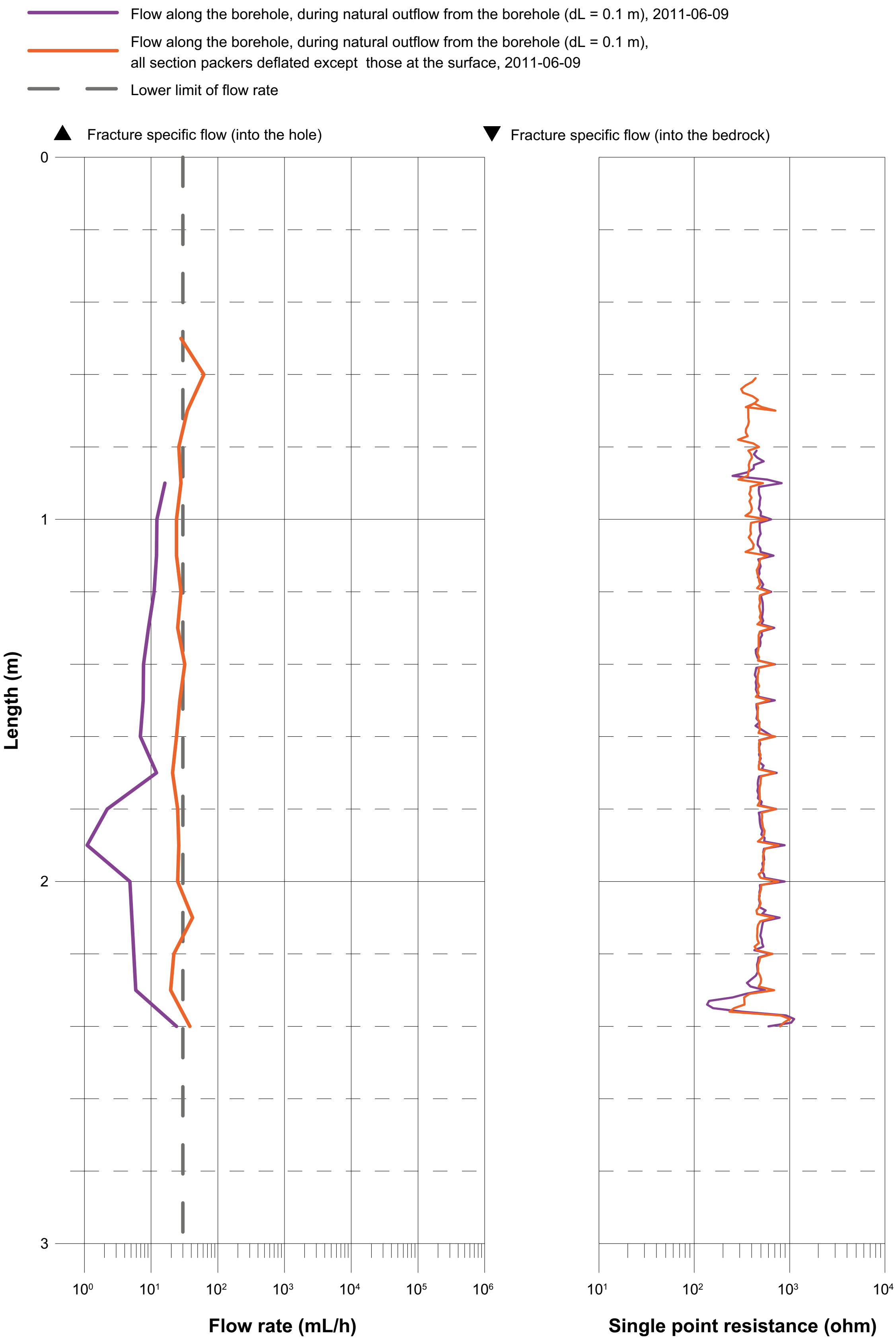
Äspö, borehole KO0017G01

Temperature of borehole water



Äspö, borehole KO0017G01

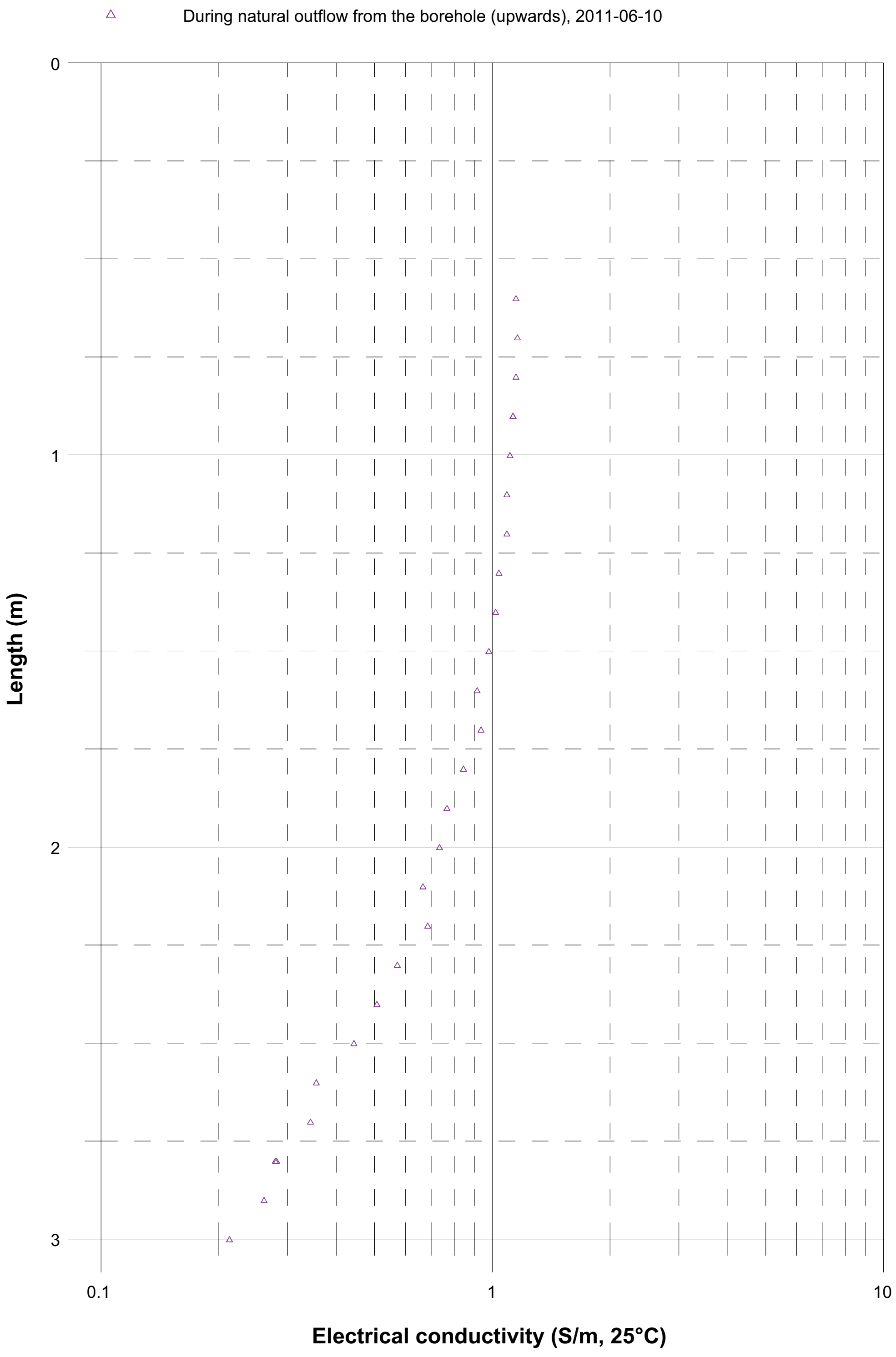
Flow rate and single point resistance



Appendix KO0017G02.1

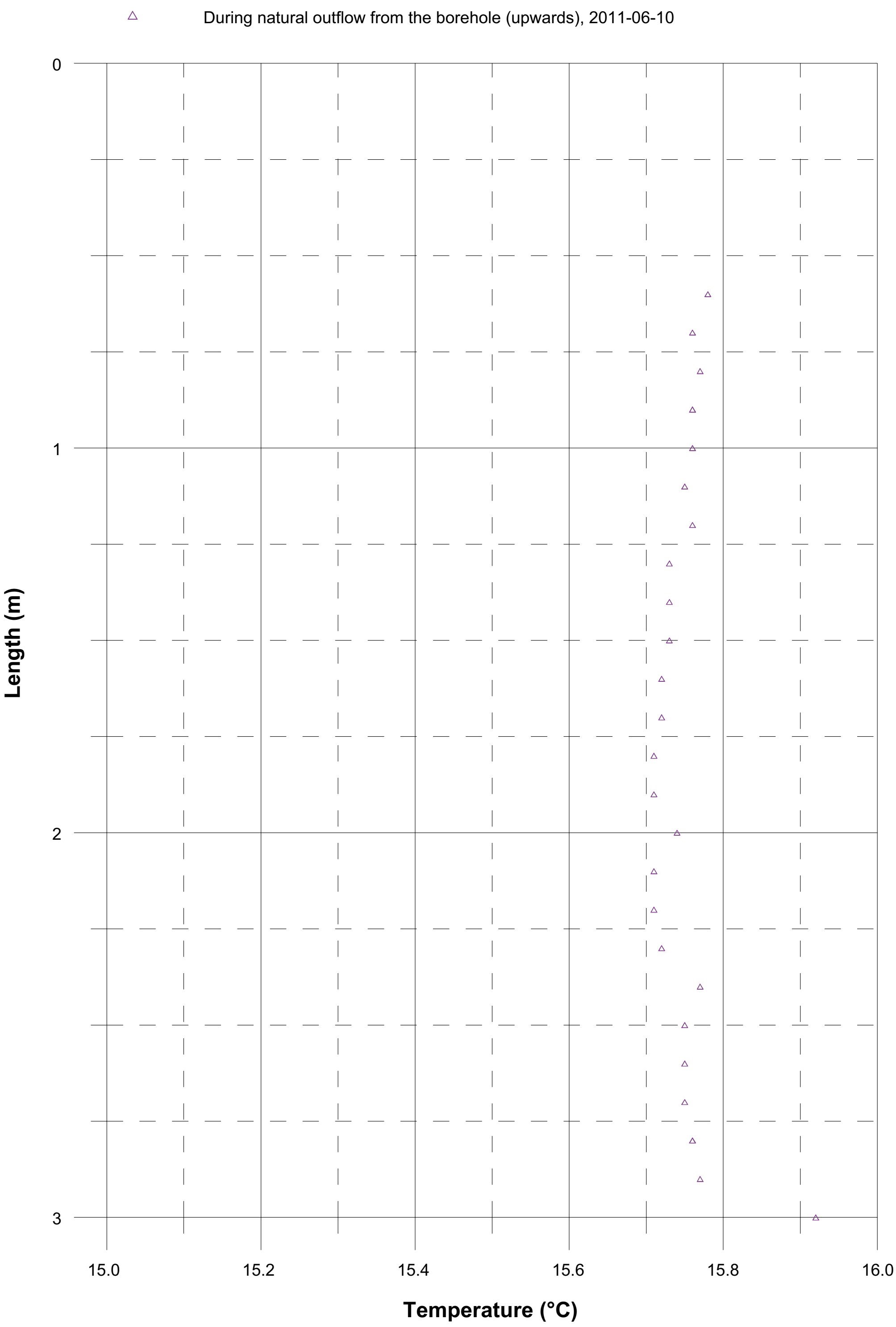
Äspö, borehole KO0017G02

Electrical conductivity of borehole water



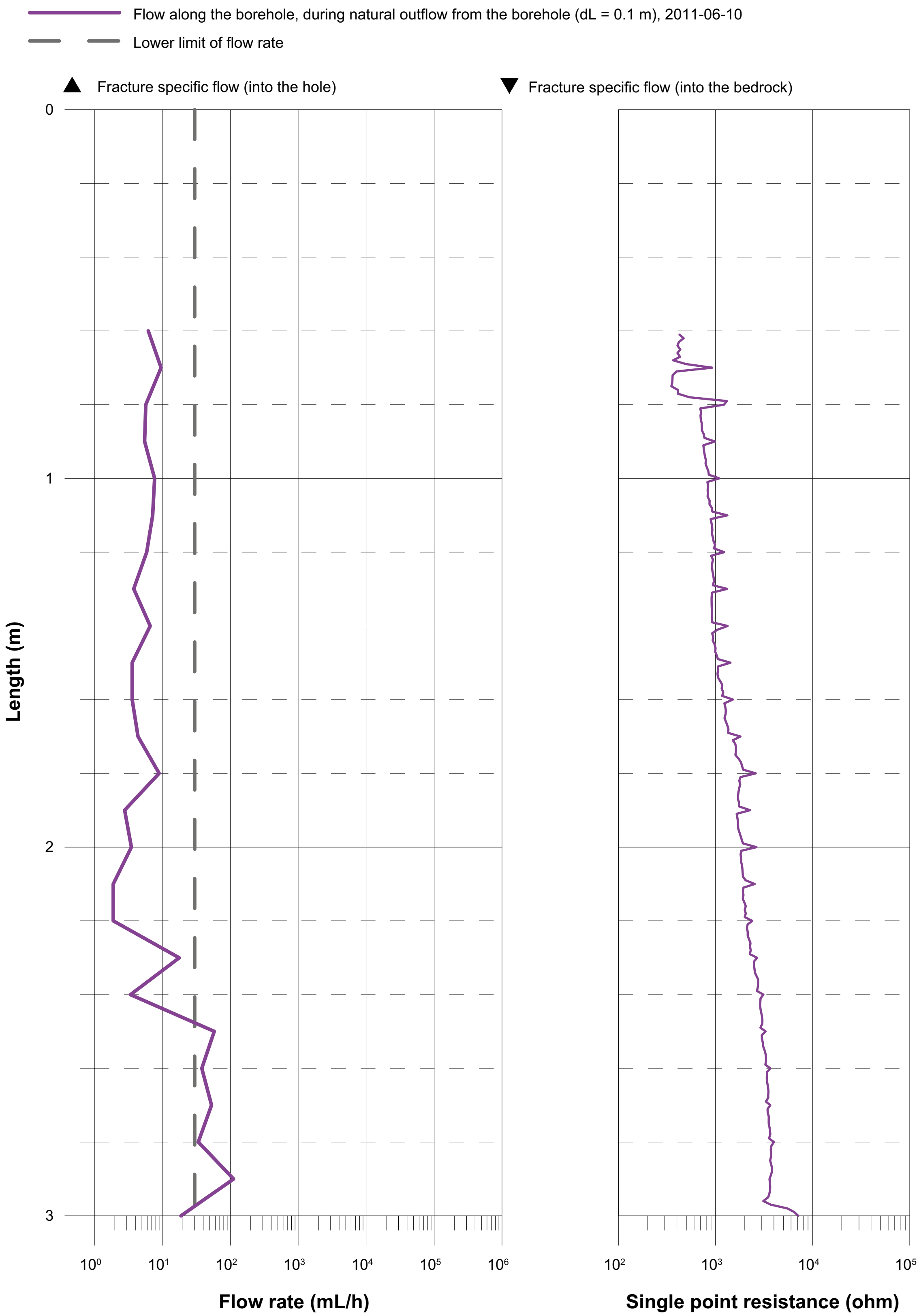
Äspö, borehole KO0017G02

Temperature of borehole water



Äspö, borehole KO0017G02

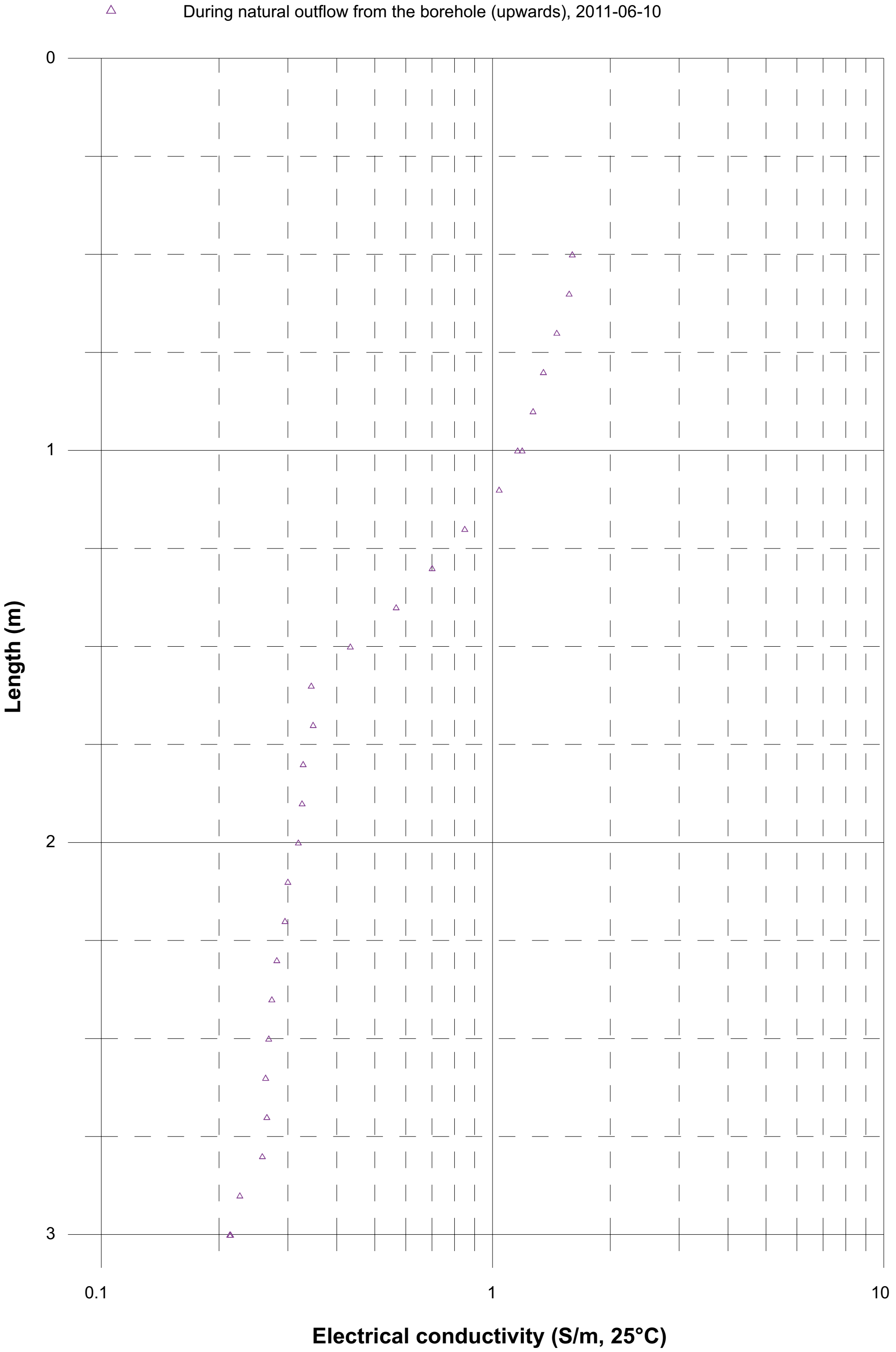
Flow rate and single point resistance



Appendix KO0017G03.1

Äspö, borehole KO0017G03

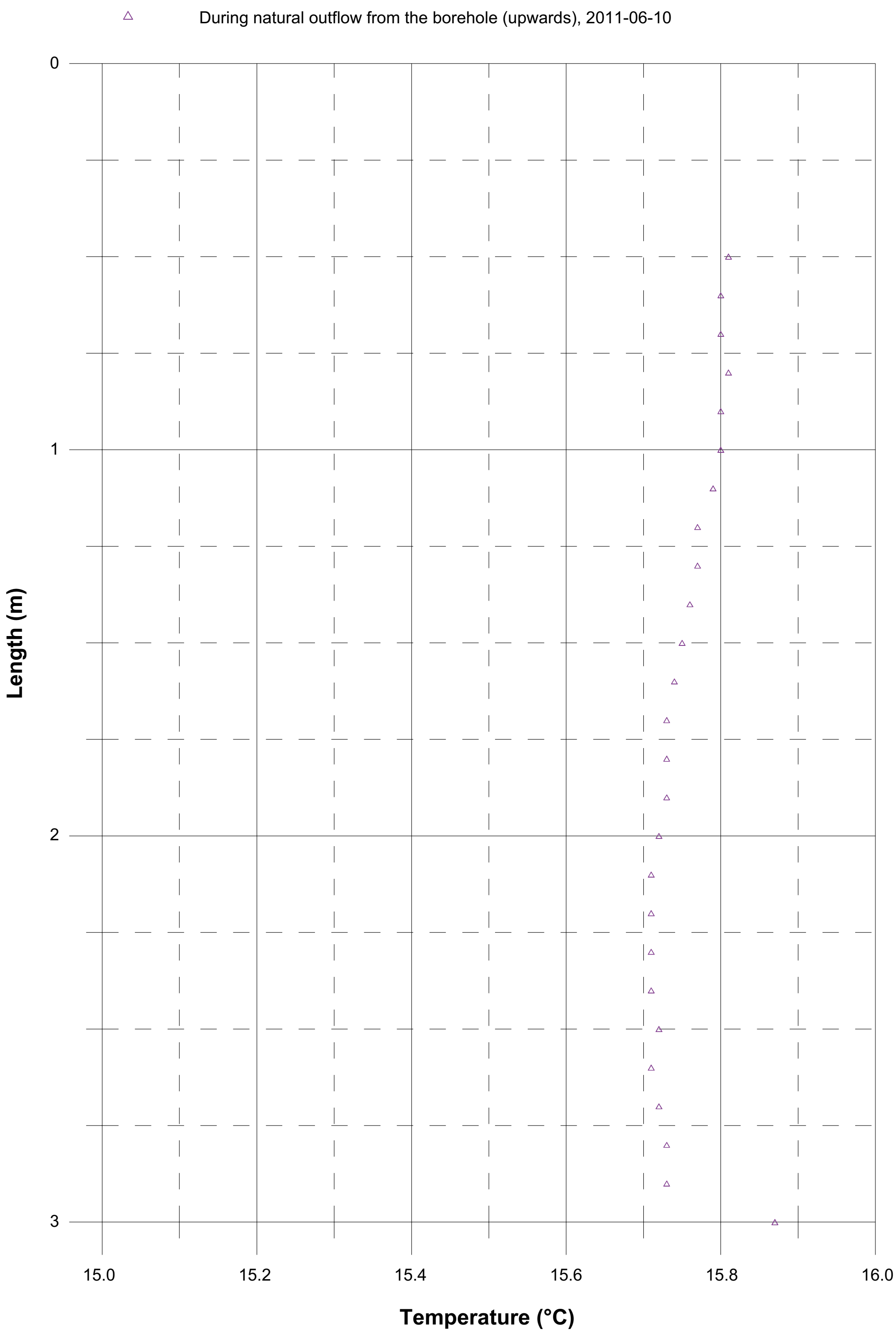
Electrical conductivity of borehole water



Appendix KO0017G03.2

Äspö, borehole KO0017G03

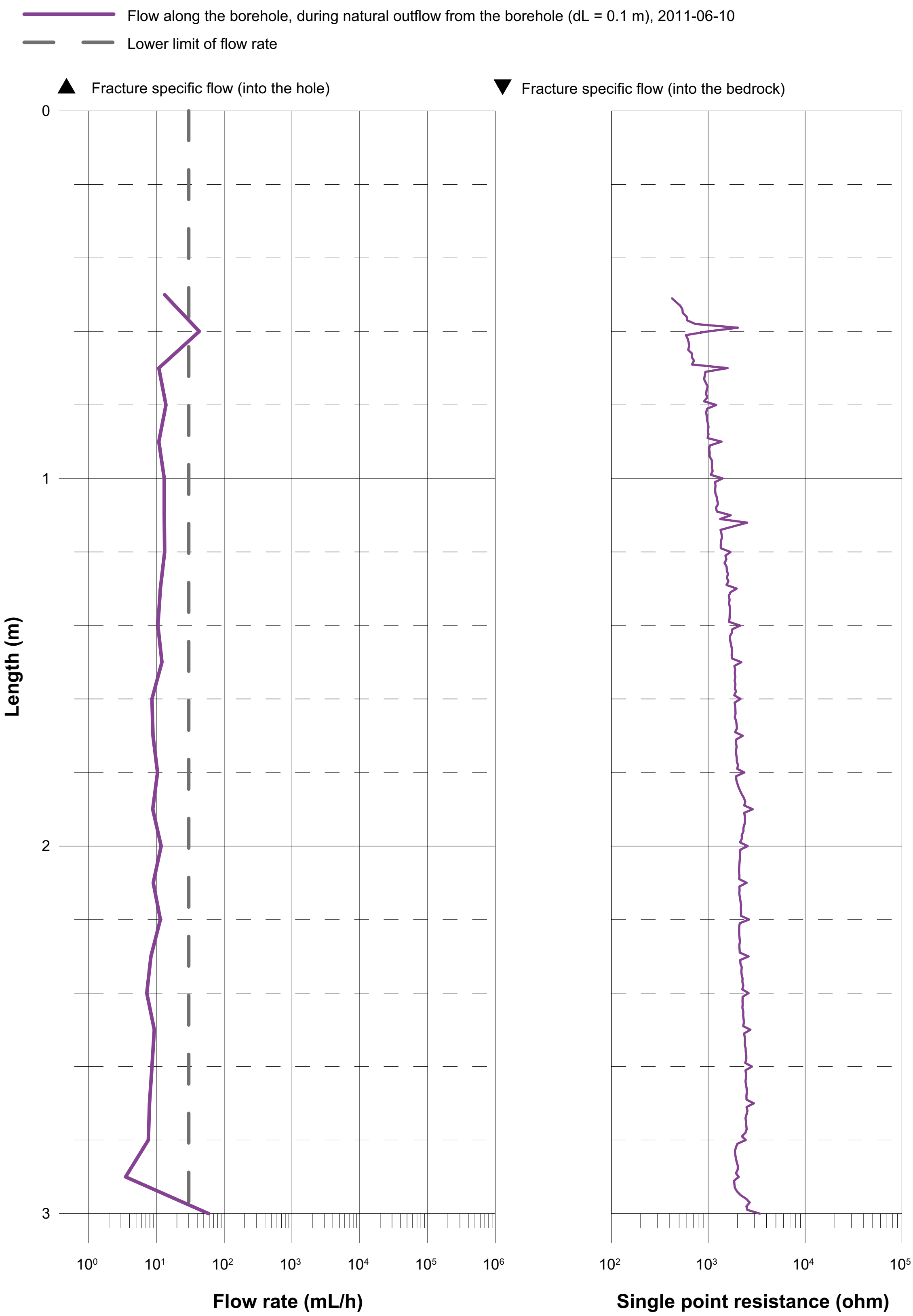
Temperature of borehole water



Appendix KO0017G03.3

Äspö, borehole KO0017G03

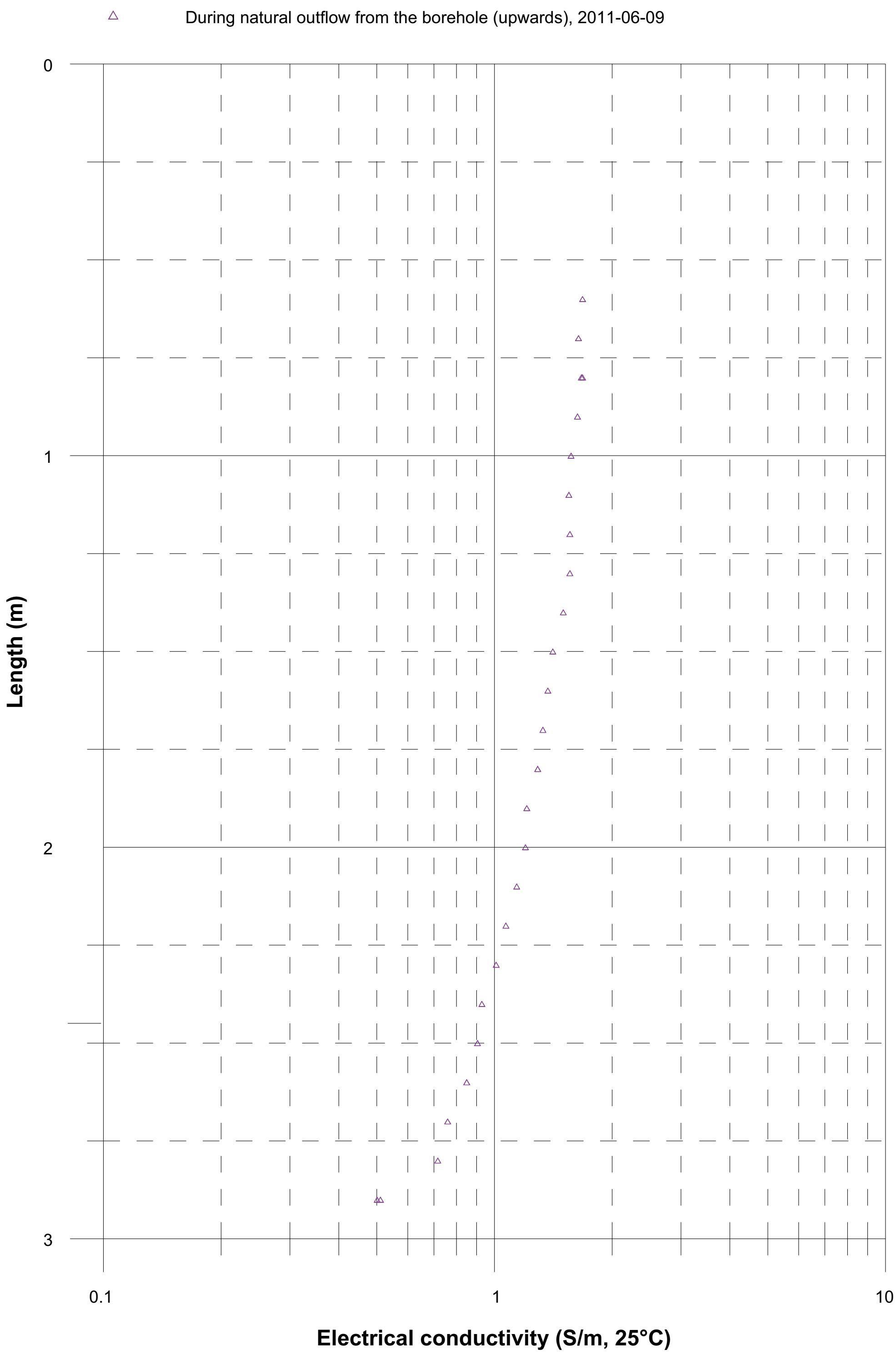
Flow rate and single point resistance



Appendix KO0017G04.1

Äspö, borehole KO0017G04

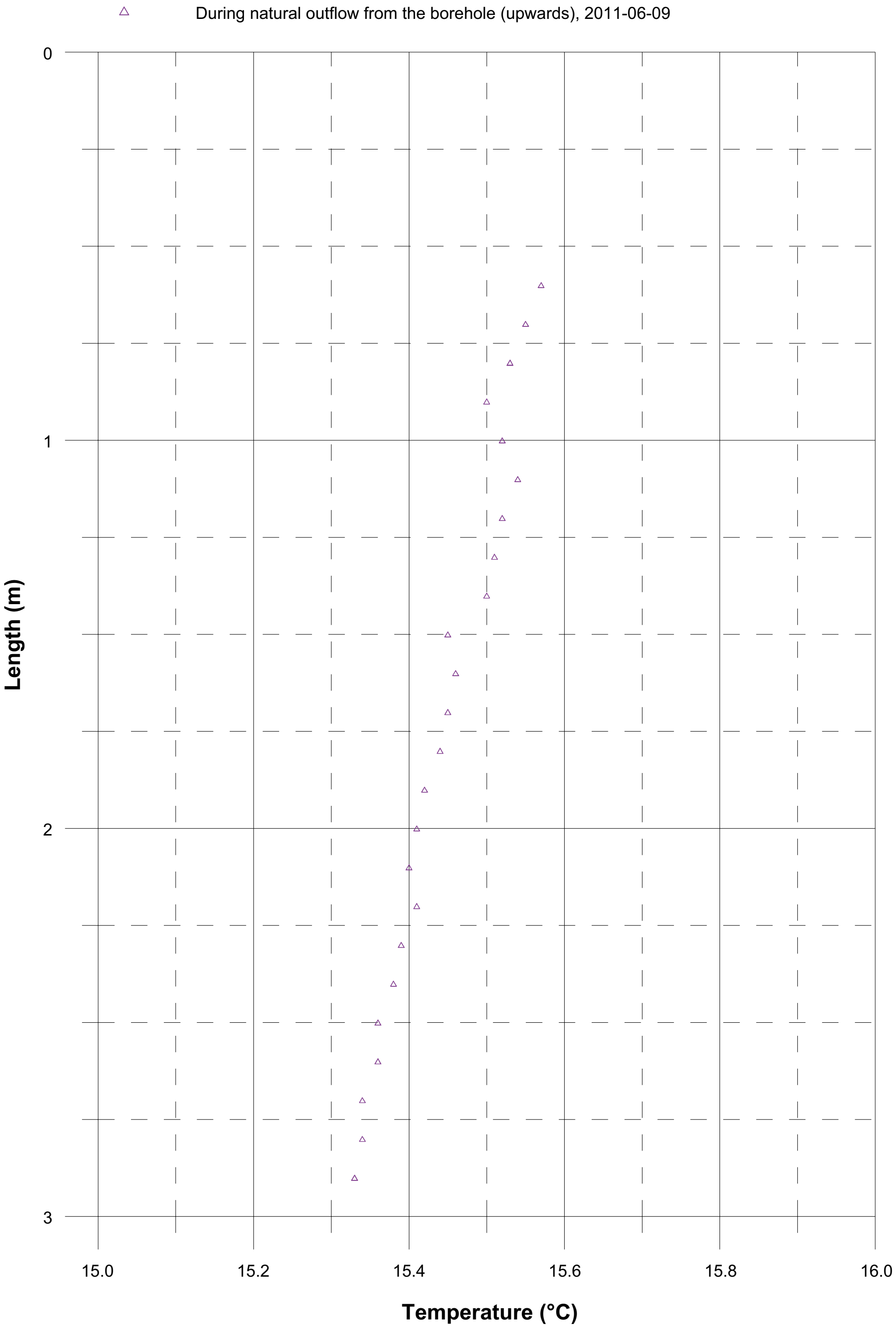
Electrical conductivity of borehole water



Appendix KO0017G04.2

Äspö, borehole KO0017G04

Temperature of borehole water



Appendix KO0017G04.3

Äspö, borehole KO0017G04

Flow rate and single point resistance