International
Progress Report

IPR-01-46

Äspö Hard Rock Laboratory

TRUE Block Scale project

Difference flow measurements in borehole KI0025F02 at the Äspö HRL

Pekka Rouhiainen

Petri Heikkinen

PRG-Tec Oy

October 1998

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel +46 8 459 84 00
Fax +46 8 661 57 19

Äspö Hard Rock
Laboratory

Report no.
IPR-01-46
No.
F56K
Author
Rouhiainen, Heikkinen
Date
Checked by
Date
Approved
Christer Svemar
Date
02-08-23

Äspö Hard Rock Laboratory

TRUE Block Scale project

Difference flow measurements in borehole KI0025F02 at the Äspö HRL

Pekka Rouhiainen
Petri Heikkinen
PRG-Tec Oy

October 1998

Keywords: Groundwater, flow, measurements, bedrock, borehole, Äspö

Abstract

A Difference Flowmeter (DIFF) was used to make measurements of groundwater inflow in borehole KI0025F02 at the Äspö Hard Rock Laboratory. The measurement process started in detailed logging mode. Flow and single point resistance were simultaneously logged using high depth resolution. Measurements continued with a 5 m section length in chosen sections. Inflow to or outflow from these sections was monitored with the borehole open and closed. The calculated hydraulic heads and conductivities are reported.

Sammanfattning

En differensflödesmätare (DIFF) har använts för att göra inflödesmätningar av grundvatten i borrhålet KI0025F02 i Äspö HRL. Mätningen inleddes med högfrekvent loggning av flöde och SP (Single Point resistance). Mätningar gjordes även i utvalda 5 m-sektioner. In- och utflöde från dessa mättes med öppet och stängt borrhål. Den beräknade tryckhöjden och hydrauliska konduktiviteten presenteras.

Contents

List of Figures

1 Introduction

Flow logging is one step in the process of characterising boreholes within the scope of the True Block Scale Projectat at Äspö. It is therefore necessary to evaluate different flowmeters in terms of their accuracy, range, applicability and operational procedures. Redundancy and complementing capabilities using different flowmeters will also be evaluated.

The results of measurements made using the DIFF at the Äspö Hard Rock Laboratory are expected to provide:

- a detailed distribution of groundwater flow in the underground borehole, and

- hydraulic conductivity and head in selected sections of the underground borehole.

This work is one component of the joint project between Posiva Oy (Finland) and SKB (Sweden) signed for the years 1998-2000. The field work has been carried out by PRG-Tec Oy. The instrument used (DIFF) has previously been used for characterisation at Posiva's sites in Finland. An earlier version of the flowmeter was tested at the Äspö Hard Rock Laboratory's Zedex site (Rouhiainen 1995, Rouhiainen 1996).

The DIFF equipment consists of a winch and cable on a trailer, a downhole probe and a PC. SKB provided rods for pushing the probe into the borehole and a rubber cone for packing off the borehole at the collar.

2 Principles of operation

The method described here is a development of the conventional method of measuring flow along a borehole. However, it is not the flow along the hole, but the changes of flow with depth that are useful when carrying out interpretation of the results. Measurement of flow along a hole is problematical, especially when the flow is strong, because small changes in the flow may be difficult to detect under a strong flow. If the changes of flow are measured directly this problem can be avoided.

With the DIFF flow guide, the flow along the borehole is directed so that it does not come into contact with the flow sensor. The flow into or out from the borehole in the test section is the only flow that passes through the flow sensor. Instead of inflatable packers, rubber disks are positioned at each end of the flow guide to isolate the borehole section being measured, see Figure 2.1.

The pressure in the borehole is kept constant using a special pump. This means that the hydraulic head in the hole is constant, since the hydraulic conductivity of the borehole is very high compared to the conductivity of bedrock. The difference in head over the rubber disks used in the flow guide is therefore very small. The rubber disks are designed in such a way that they always press against the wall of the borehole. Difference flow measurements differ from the conventional double-packer tests in that there is no additional hydraulic pressure in the borehole section being measured.

A constant hydraulic head in the borehole implies that the water density in the hole is constant and that there are no losses due to friction. If this is not the case, the hydraulic head at the measuring depth must be determined.

A single difference flow measurement at one depth interval normally takes 12 minutes. This time includes waiting time for temperature stabilisation, a flow measurement by the thermal pulse method, a flow measurement by the thermal dilution method and lifting of the cable to the next depth interval. The thermal dilution method of flow measurement is used to expand the measurement range to include higher flow rates.

The equipment can be used in detailed flow logging mode. The flow measurement is performed using a 1.0 m section length and a 0.1 m depth interval. This technique yields the depth and thickness of conductive zones with a depth resolution of 10 cm. In order to make measurements more rapidly, only the thermal dilution method is used for flow determination. Logging speed in detailed logging mode is about 20 meters in hour.

Time to measure a 200 m long underground borehole in detailed logging is about 13 hours with installation. The difference flow measurement with the depth interval of 5 m takes about 11 hours in an open and 200 m long underground borehole. The measurement is much slower in closed borehole because the borehole must be opened and closed again between each depth interval. At least one hour is needed for pressure stabilisation after closing the borehole.

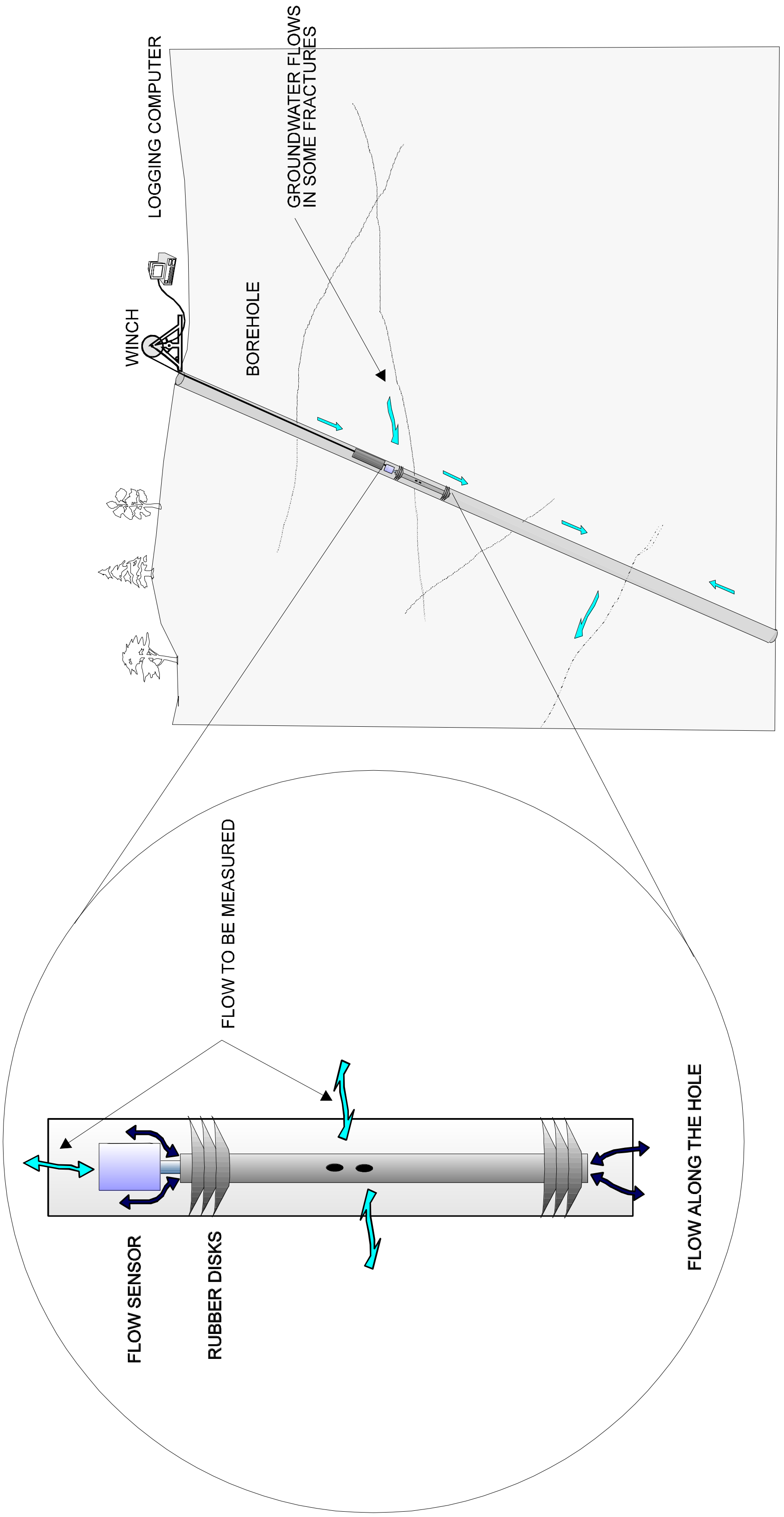


Figure 2-1 *Principles of difference flow measurement.*

3 Interpretation

If measurements are carried out using two levels of potential in the borehole, the hydraulic head of measured zones and their hydraulic conductivity can be calculated. It is assumed that a static flow condition exists.

$$Q_{n1} = K_n \cdot a \cdot (h_0 - h_1) \qquad 3\text{-}1$$
$$Q_{n2} = K_n \cdot a \cdot (h_0 - h_2), \qquad 3\text{-}2$$

where Q_{n1} and Q_{n2} are the measured flows in a zone,
K_n is the hydraulic conductivity of a measured zone,
a is a constant depending on the flow geometry,
h_1 and h_2 are the hydraulic heads in the hole during the two measurements
h_0 is the head of a measured zone far from the hole

Since, in general, very little is known about the flow geometry, cylindrical flow without skin is assumed. The assumption of cylindrical flow geometry is justified because the borehole is at a constant head and there are no strong pressure gradients along the borehole, except at its ends. For cylindrical flow, the constant a is:

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

where L is the length of the measured section,
R is the distance to the distant constant potential h_0 and
r_0 is the radius of the hole.

The distance to the constant potential h_0 is not known and must be chosen. Here R/r_0 is chosen to be 500.

Hydraulic head and conductivity can be deduced from two measurements as follows:

$$h_0 = (h_1 - b \cdot h_2)/(1-b), \qquad 3\text{-}4$$
$$K_n = (1/a) \cdot (Q_{n1} - Q_{n2}) /(h_2 - h_1) \qquad 3\text{-}5$$

where $b = Q_{n1}/Q_{n2}$

Since the actual flow geometry in the borehole is not known, the calculated conductivity values are taken as indicating orders of magnitude. As the calculated hydraulic heads do not depend on the geometrical properties of the borehole, but only on the ratio of the flow rates measured at different heads they should be less sensitive to unknown fracture geometry.

4 Equipment specifications

The DIFF flowmeter monitors the flow of groundwater into or out from a borehole within a defined section. A flow guide is used to isolate the section being measured. Groundwater flowing into and out from the section is guided through the flow sensor. Flow is measured using the thermal pulse and thermal dilution methods. Measured values are transmitted in digital form to the PC. (Rouhiainen and Pöllänen 1998).

Type of instrument:	Difference Flow Meter
Borehole diameters:	56 mm, 66 mm and 76 mm
Geometry of measurement:	Variable length flow guide
Method of flow measurement:	Thermal pulse and thermal dilution
Speed of measurement:	Flow rate dependent
Range of measurement:	0.1 - 5000 ml/min
Additional measurements:	Temperature, single point resistance
Interpreted results:	Hydraulic conductivity and hydraulic head
Winch:	Mount Sopris Wna 10, 0.55 kW, 220V/50Hz.
Logging computer:	PC, Windows 95
Calibrated	August 1998

5 RESULTS

5.1 Field operations

The probe was pushed down into the borehole with aluminium rods. All the measurements were carried out from the bottom upwards. The winch was utilised when lifting the flowmeter in the borehole.

Detailed flow logging and a part of the measurements using a five-metre section length were performed in the open borehole. A change in level of potential in the borehole can be achieved by closing the borehole. The borehole was closed using a rubber cone positioned at the top of the casing tube.

5.2 Detailed flow logging

Detailed flow logging was performed using a 1.0 m section length and a 0.1 m interval. This technique yields the depth and thickness of conductive zones with a depth resolution of 10 cm. In order to make measurements more rapidly, only the thermal dilution method was used for flow determination.

The section length determines the width of a flow anomaly of a single fracture . If the distance between leaky fractures is less than one metre the anomalies will overlap. The electrode of the resistance tool is located within the upper rubber disks. Thus the depth of the resistance anomalies of the leaky fractures fit with the lower side of the flow anomalies.

The depths of the plotted flow results are measured from the tunnel wall to the upper end of the test section. The results of the detailed flow and single point resistance logs are presented in Appendices 1-10. The depths of leaky fractures are also marked in these appendices.

The total flow out of the open borehole was about 56 l/min, about ten times higher than the upper limit of the flow sensor. As there was a risk that this high flow could damage the flow sensor, a flow limiter was installed to protect it. The flow limiter reduces flows that are greater than approximately 2 l/min.

The results obtained during detailed flow logging showed that the flow from fractures into the borehole was distributed among many fractures. Therefore the flow limiter could be removed when making measurements with a 5 m section length.

5.3 Difference flow measurements with 5 m section length

Measurement was begun in the open borehole using a five-metre section length. Since measurements in an open borehole are relatively rapid, the entire length of the borehole between 35 - 200 m was investigated. Several repeated measurements were carried out using a depth change of less than 5 m, typically 0.5 - 1 m. These repeat measurements were performed especially where fractures were situated close to the ends of the test section. In such cases it is not always clear whether a dominating fracture is inside, partially inside or outside the test section. The results of the detailed flow logging showed that there are high flow fractures at the depths of 35, 40, 60 and 200 meters.

The results of difference flow measurements using a 5 m section length in the open borehole are shown in Appendix 11. The flow values are shown in both directions, the left hand side of each diagram represents flow out from the borehole within a test section and the right hand side represents flow into the borehole. The flow scale is logarithmic. The depths at which the results were obtained are given from the tunnel wall to the mid point of the test section. The five meter depth range is also drawn at each point in Appendices 11 - 13.

The most conductive sections at depths between 50 m and 155 m were investigated again after closing the borehole using a rubber cone at the collar. The results obtained are plotted in Appendix 12 together with the corresponding result obtained with the open borehole. The use of an armoured steel cable caused leakage at the position of the cone. This leakage of 0.03 to 0.1 l/min was small compared to the outflow of 56 l/min from the open borehole.

Stabilisation time in the closed borehole varied between 30 minutes and 14 hours (i.e. overnight). The pressure and flow transients are shown in Appendices 14-21. The degree of stabilisation achieved was not equal in all sections. Flow stabilised relatively well in sections 150-155 m, 95-100 m, 70-75 m, 65-70 m and 57.5-62.5 m. In all these cases the stabilisation time was greater than one hour. The last and most stable flow value was taken for the flow plot shown in Appendix 12.

After closing the borehole with the rubber cone, the flow was in most cases negative, water was flowing out from the borehole. Usually, the flow approached zero with time. In some cases it changed sign (i.e. flow into the closed borehole). This happened in sections 90-95 m, 70-75 m, 65-70 m, 57.5-62.5 m and 55-60 m.

In two cases the flow was positive after the borehole was closed. In these cases the flow decreased but was still positive after the time allowed for stabilisation. These sections were 130-135 m and 95-100 m.

The data presented in Appendix 12 were used to calculate hydraulic head and hydraulic conductivity and are plotted in Appendix 13. Hydraulic head and conductivity can be calculated from the flow data using the method described in Section 3 of this report. Hydraulic head is shown in the plots if both of the flows at the same depth are not equal to zero. Hydraulic conductivity is shown if either or both of the flows are not equal to zero.

Because, in most cases, the flow in the closed borehole was not stable, the hydraulic head and conductivity do not always represent stable conditions. In the plot shown in Appendix 13 there are two exceptionally low heads at sections 80-85 m and 85-90 m. The short stabilisation time explains the result in section 80-85 m, see Appendix 18. In all probability, the flow would have approached zero in time. This would mean that the stable value for hydraulic head in this section is about 390 m.

The same explanation does not hold as clearly for section 85-90 m. However, the flow transient in this section was short and still decreasing at its end, see Appendix 17. The stable head value would therefore be higher than that shown in Appendix 13.

Conductivity values are less sensitive to unstable flow conditions in the closed borehole. This is because the flow in an open borehole dominates the conductivity calculations. In the same section, the flow in the open borehole was always more than ten times greater than the flow in the closed borehole.

6 DISCUSSION AND CONCLUSION

Field work using the DIFF proceeded without any specific problems. High flow rates along the borehole did not result in any noticeable increase in the noise level in the flow measurements.

Individual leaky fractures can be mapped using DIFF in the detailed logging mode. It may also be possible to locate these same fractures by using borehole television investigations. A borehole television can provide fracture directions. This could be a basis for a combined analysis of fracture permeability and direction.

The flow in the closed borehole was not always stable. Some of the head values would obviously change with a longer stabilisation time while conductivity values would not essentially change in this case.

The results obtained using DIFF can be compared to the results obtained using other flowmeters, and also with the results obtained from double-packer tests. A precondition of comparisons is that the measurements to be compared are made at the same depths. The precise depth may be a critical factor, especially in cases where fractures are located close to the ends of the test section. It is desirable that the fracture locations shown in Appendices 1-10 are taken into account when carrying out such comparisons.

References

Rouhiainen P. 1995 Difference flow measurements at the Äspö HRL, May 1995. SKB Äspölaboratoriet, international cooperation report 95-04.

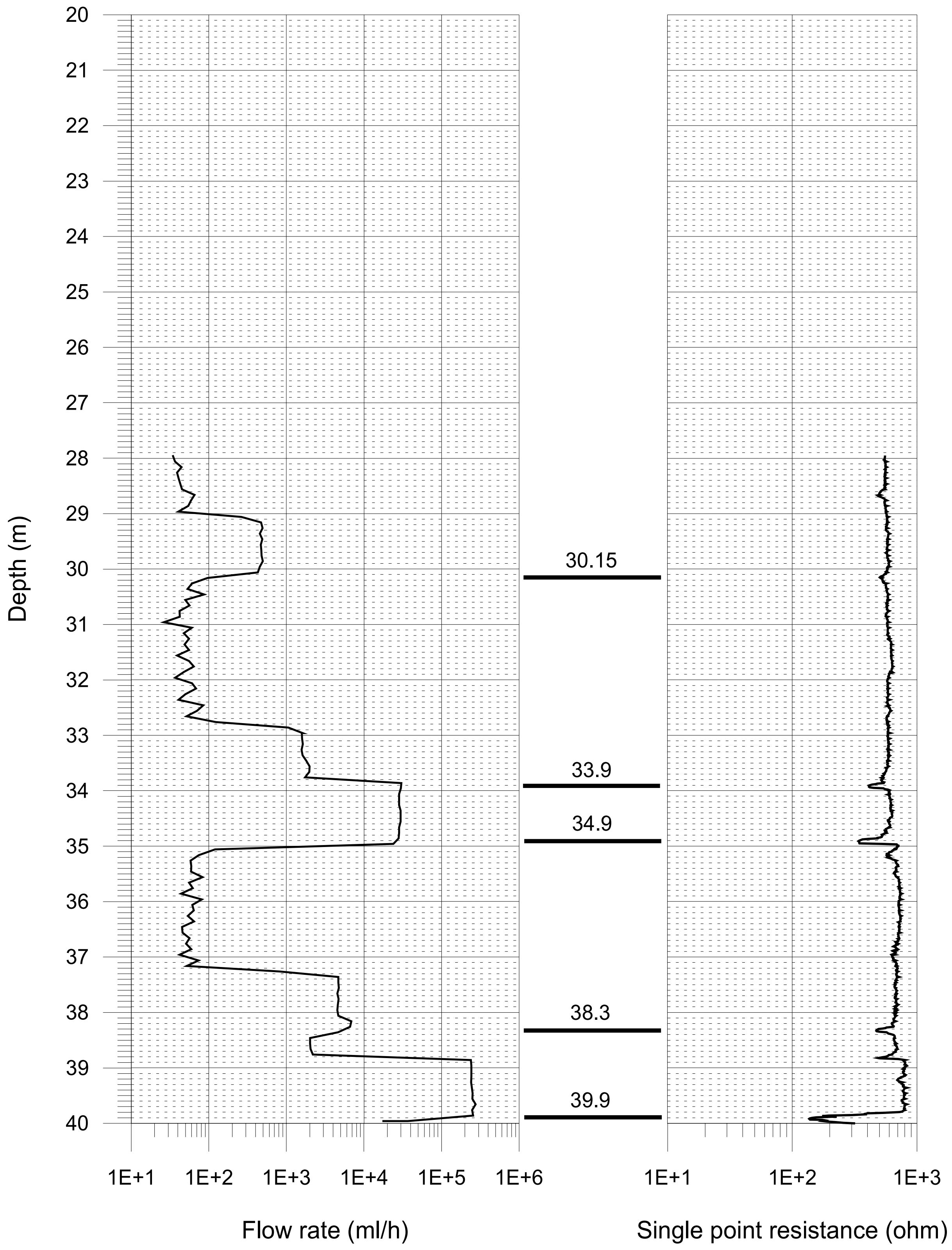
Rouhiainen P. 1996 Complementary evaluation of two types of hydraulic tests performed in boreholes A4, A5 and C5 at the Zedex site, Äspö Hard Rock Laboratory. SKB Äspölaboratoriet, Progress Report HRL -96-26.

Rouhiainen P., Pöllänen J. 1998. Difference flow measurements in Äänekoski, boreholes KR4, KR12 and KR13. Posiva Oy, Working report 98-31e.

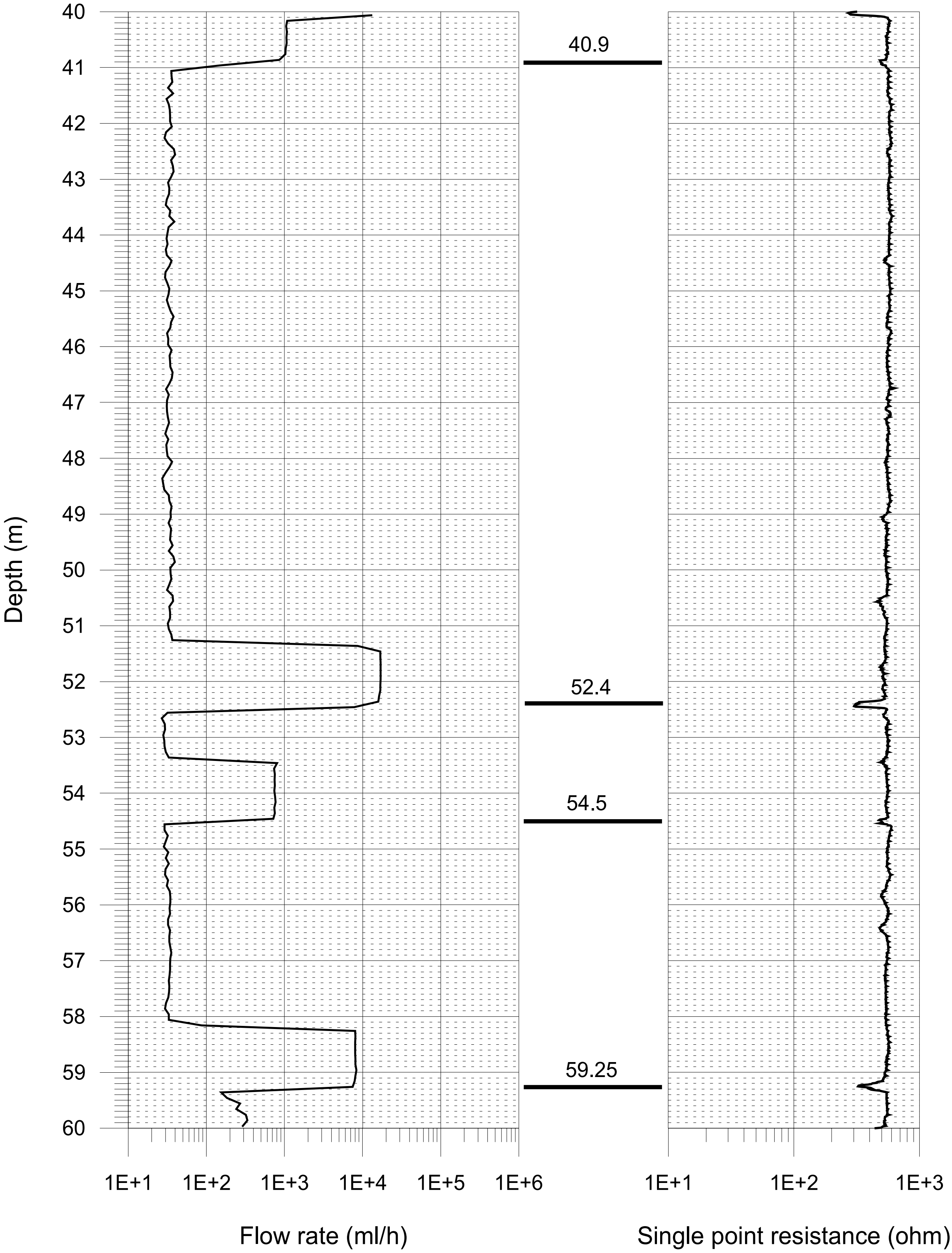
Appendices

Appendix 1 - Appendix 10	DIFF results in detailed logging mode, section length 1 m
Appendix 11	Flow rates in open borehole, section length 5 m
Appendix 12	Flow rates in closed borehole, section length 5 m
Appendix 13	Hydraulic heads and conductivities section length 5 m
Appendix 14 - Appendix 21	Pressure and flow transients during measurements in the closed borehole

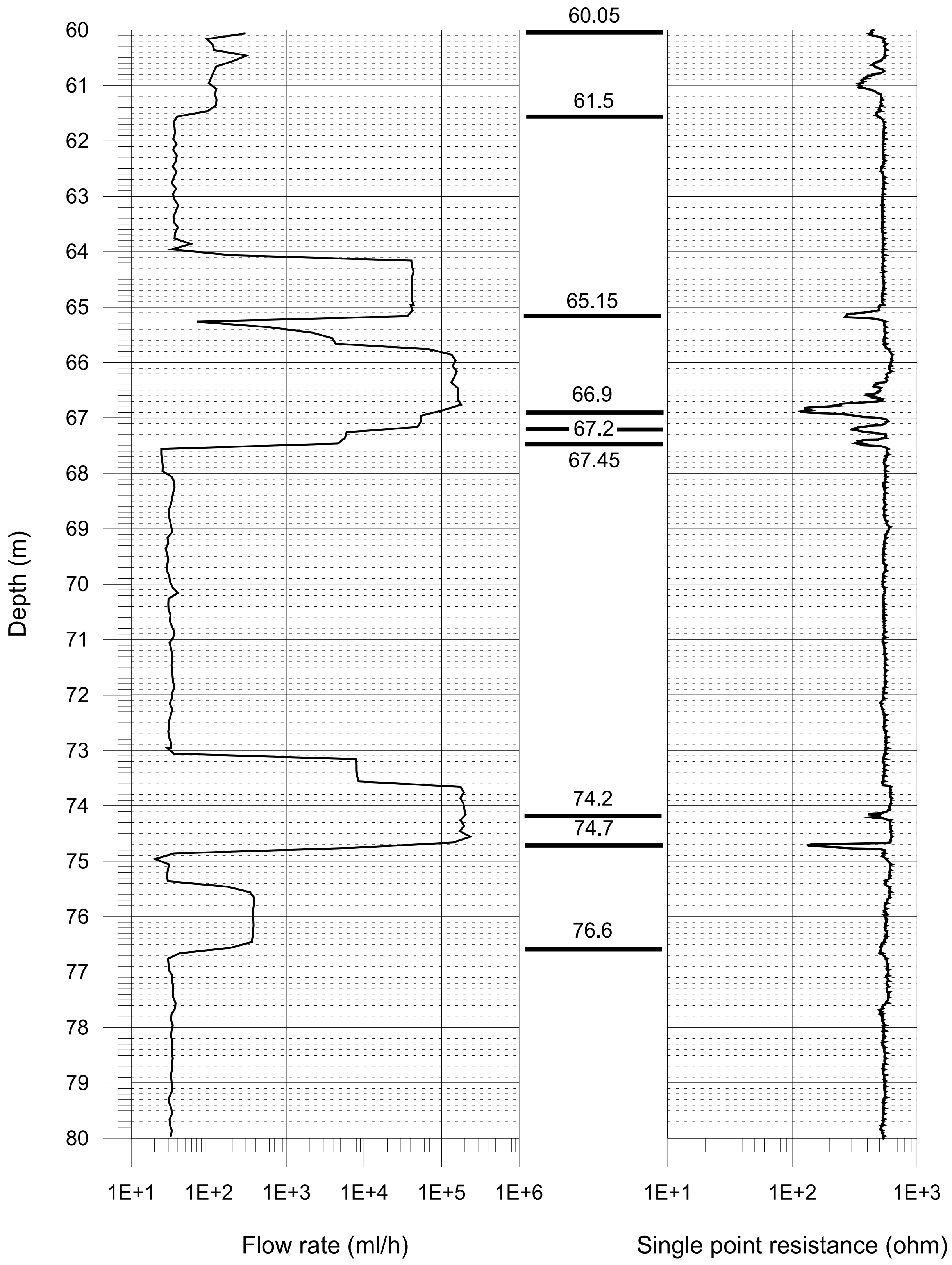
FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KI0025F02



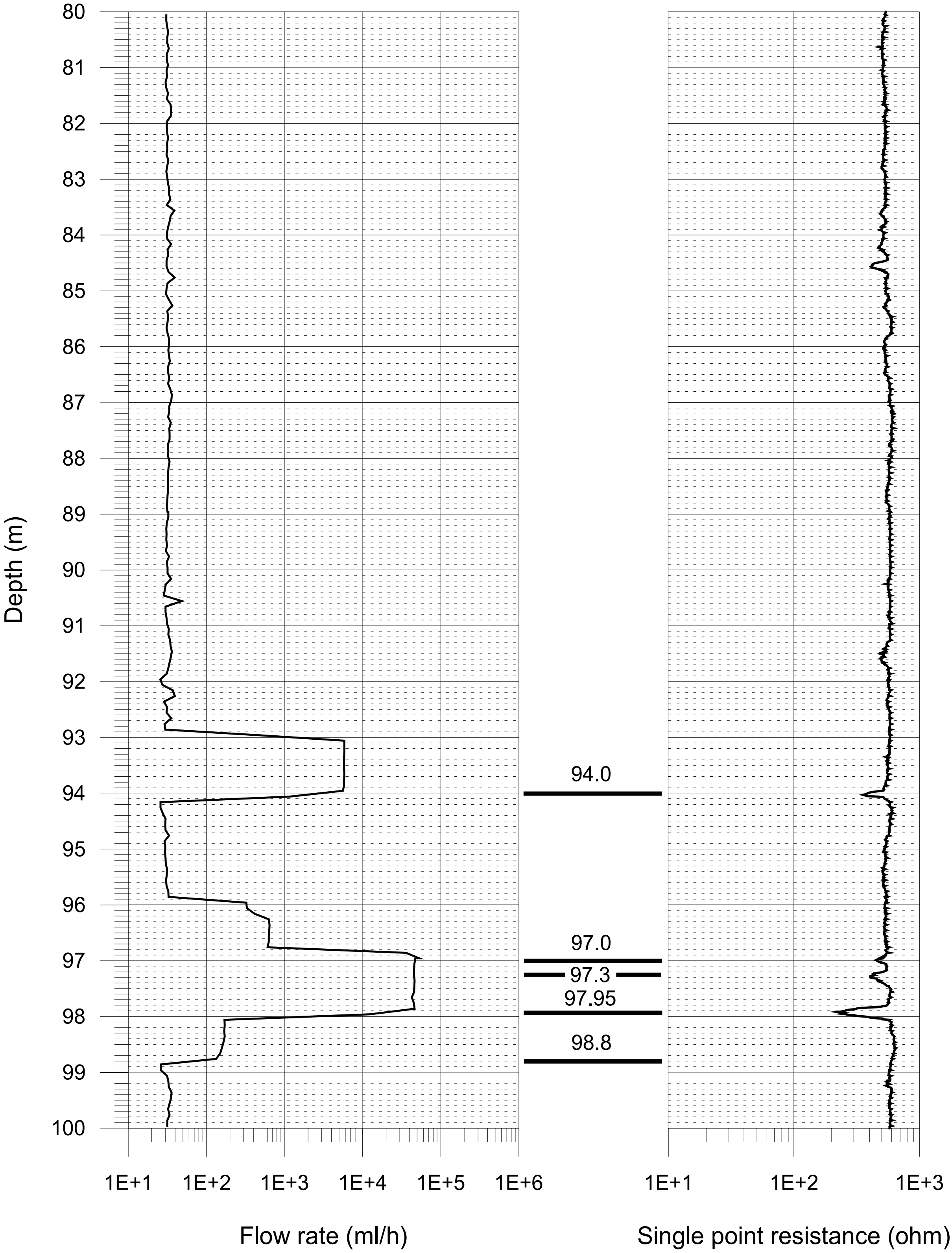
FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KI0025F02



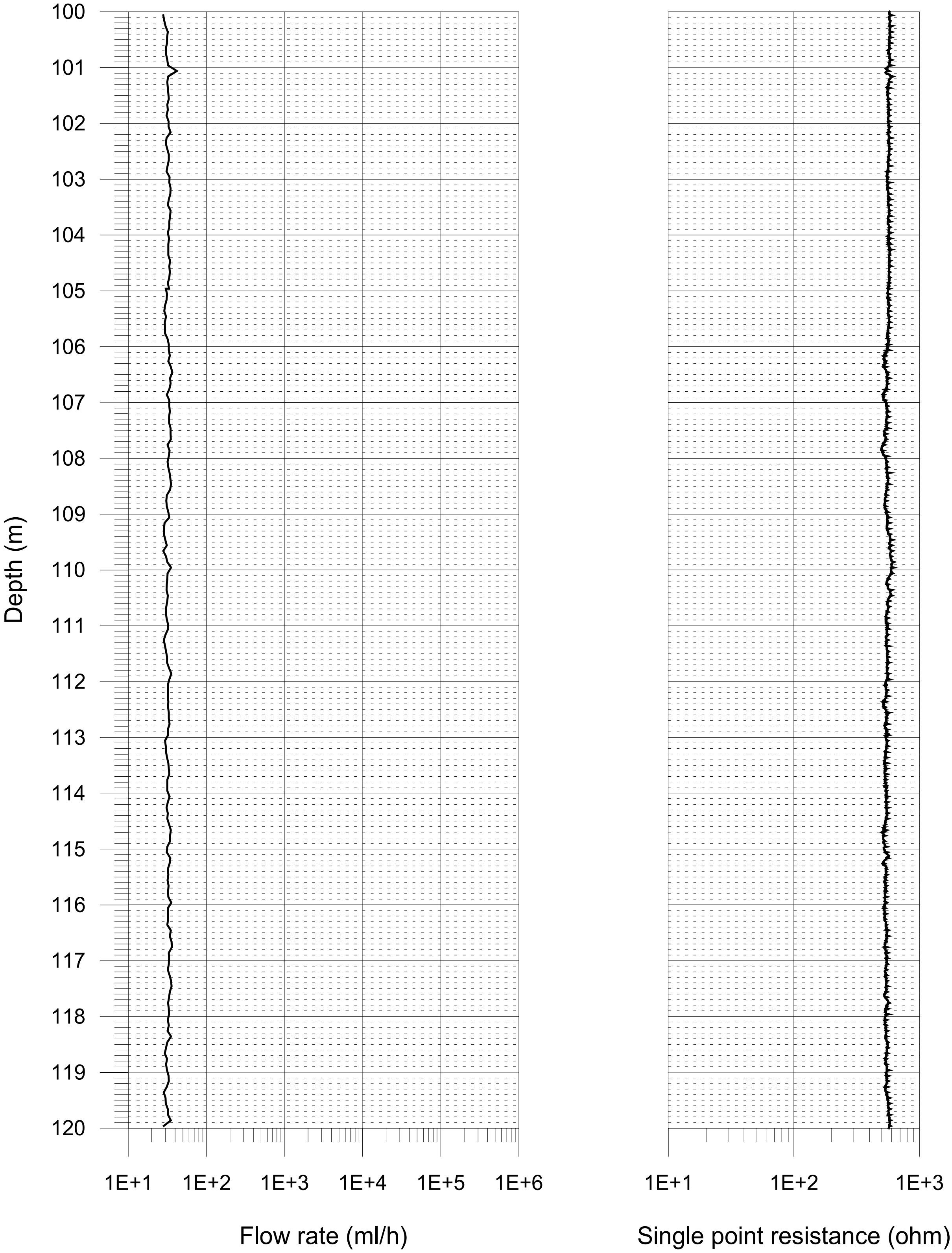
FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KI0025F02



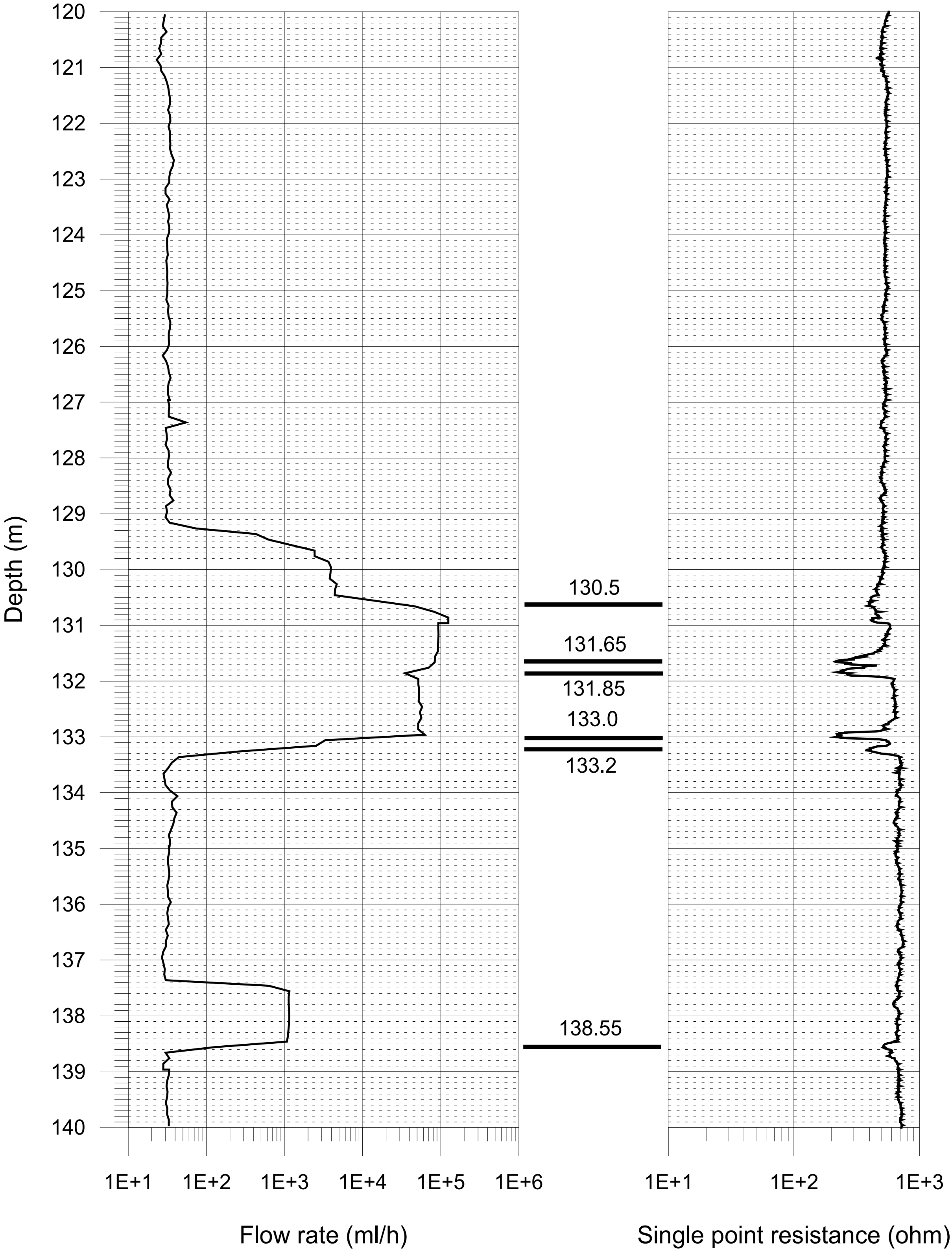
FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KI0025F02



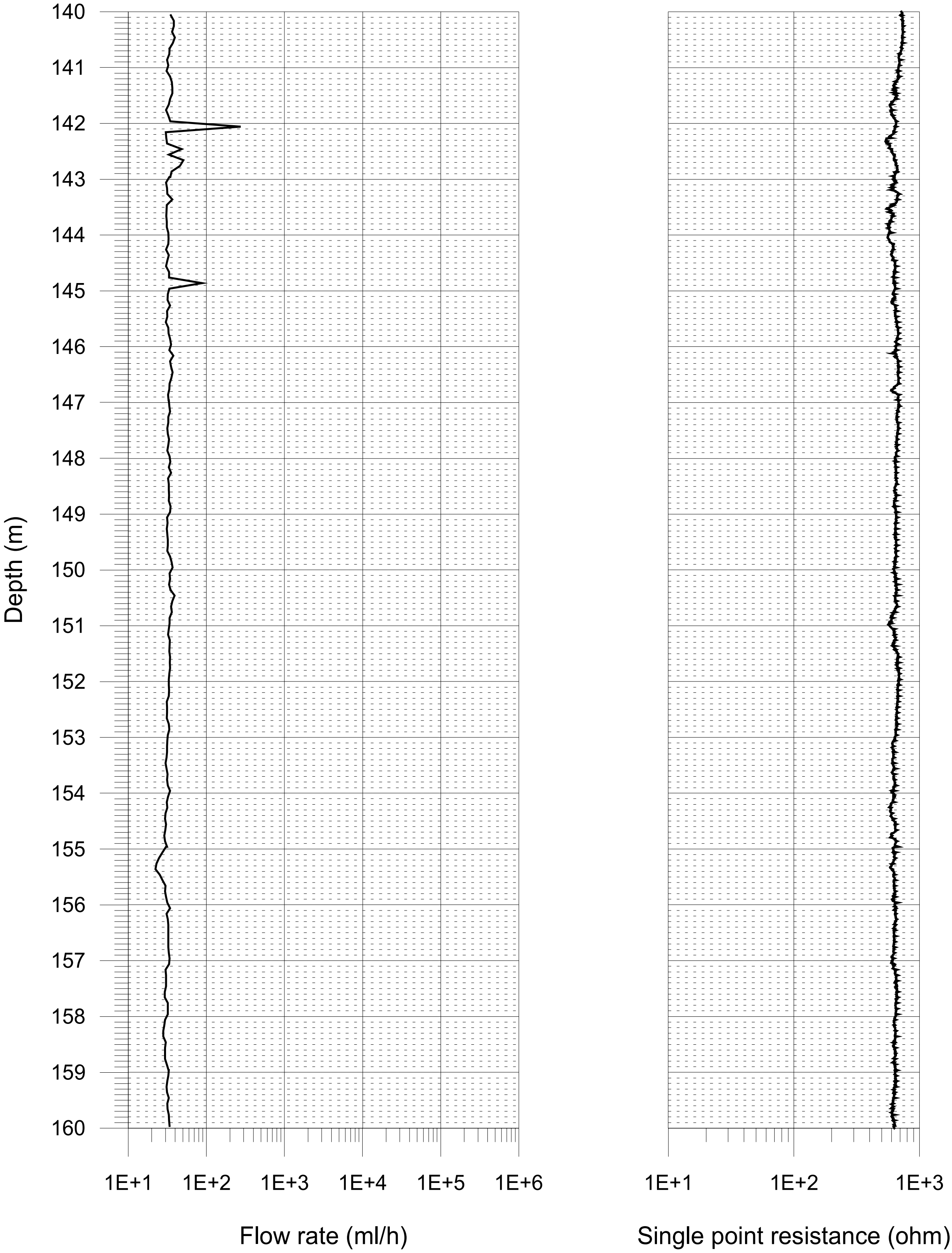
FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KI0025F02



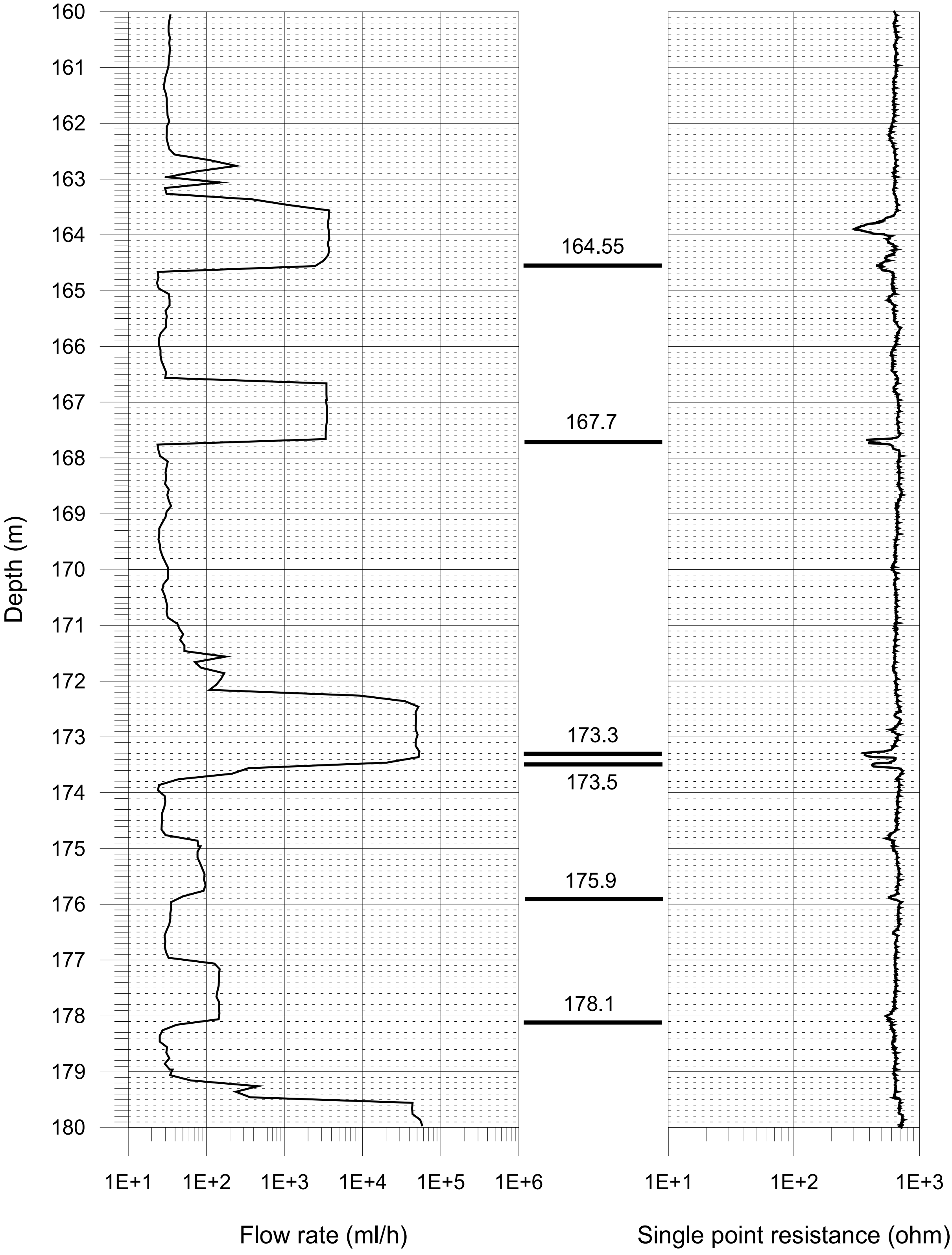
FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KI0025F02



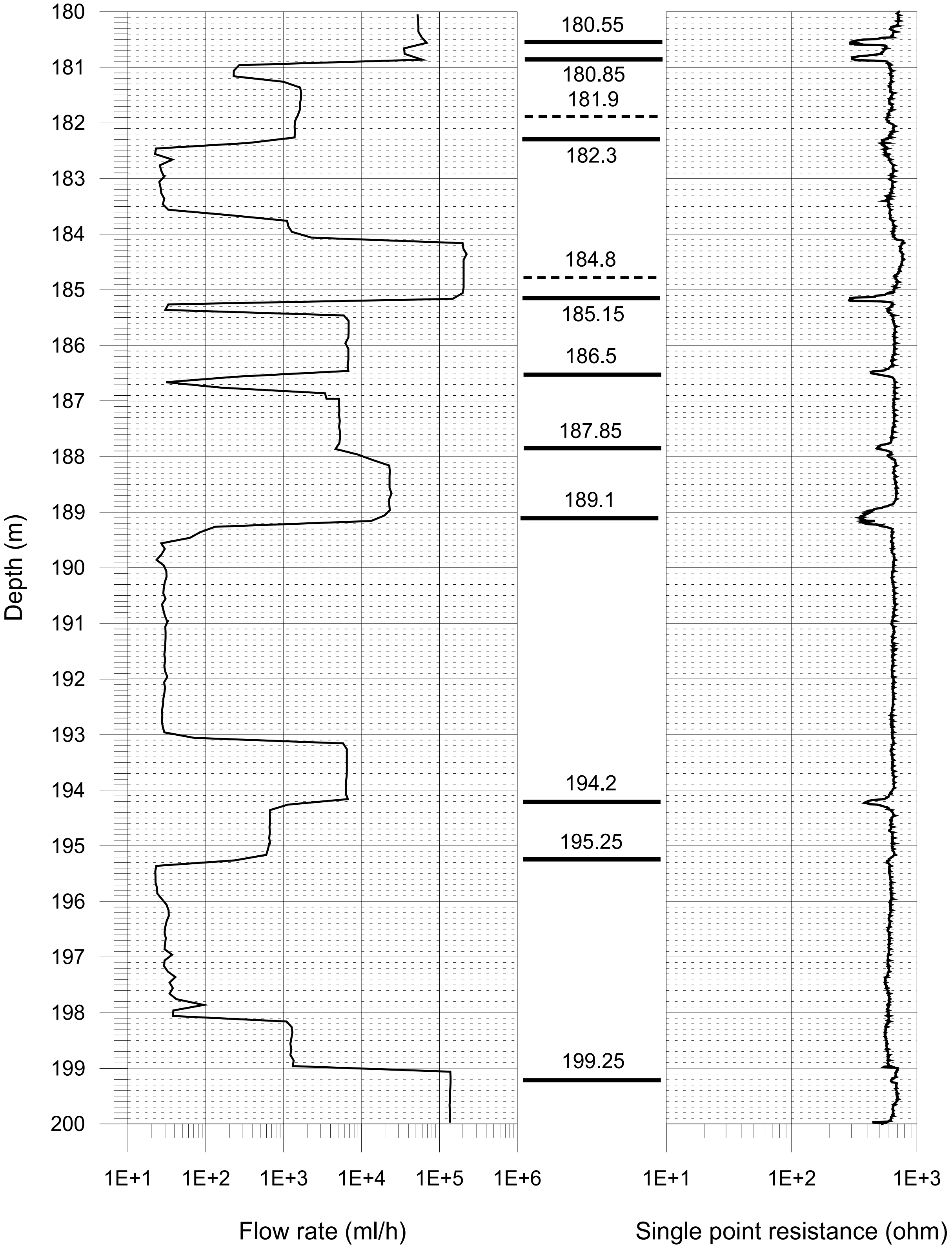
FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KI0025F02



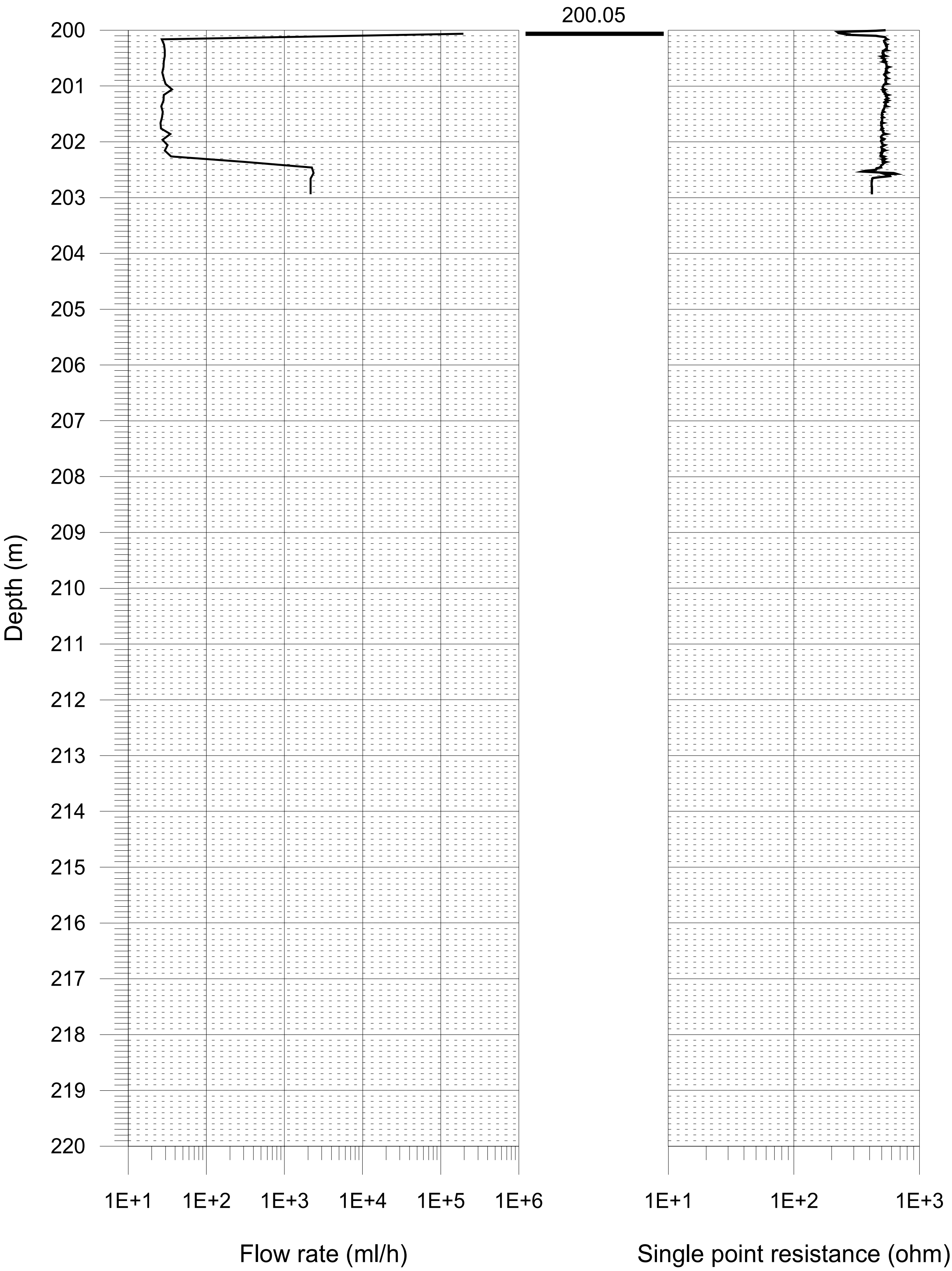
FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KI0025F02



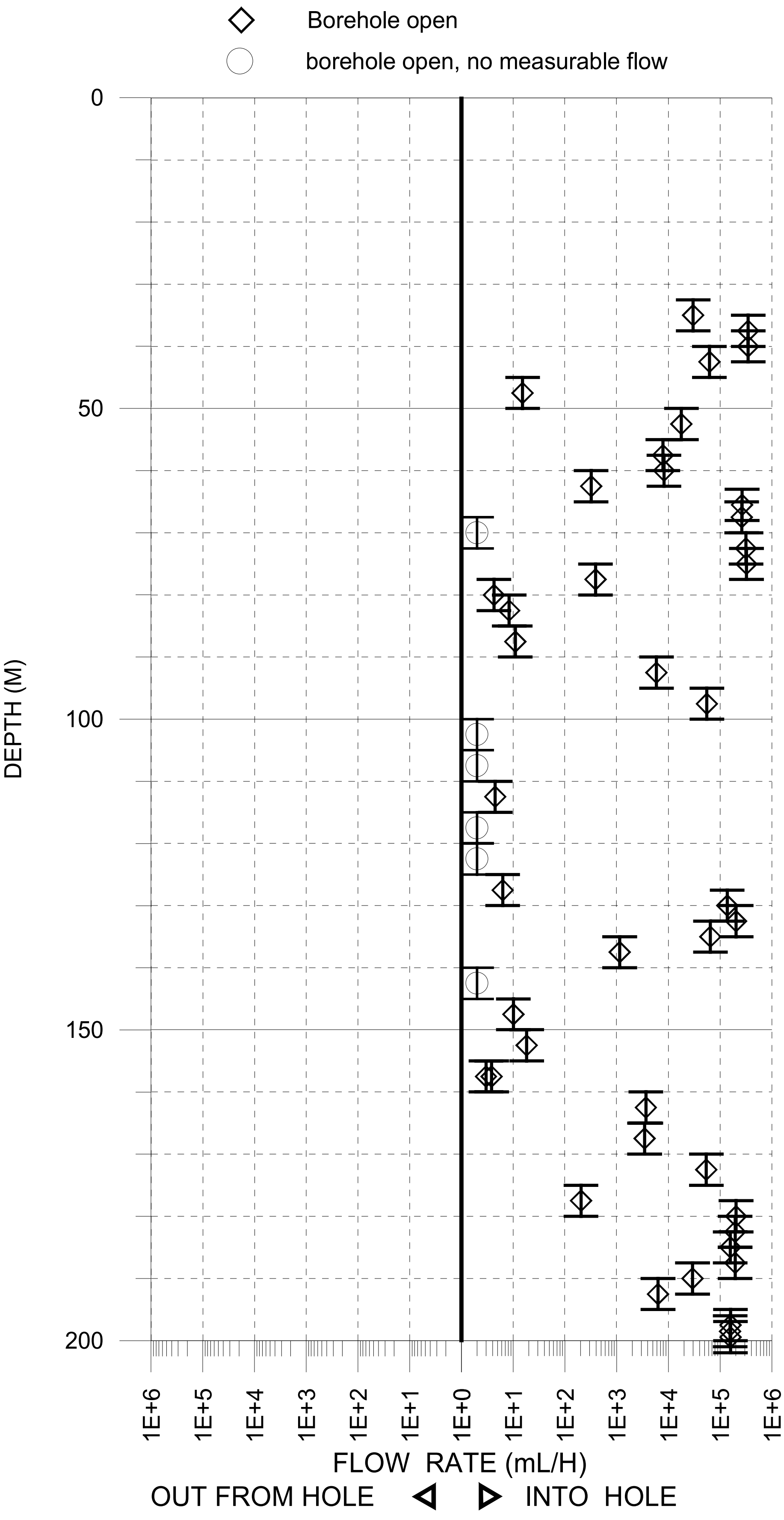
FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KI0025F02



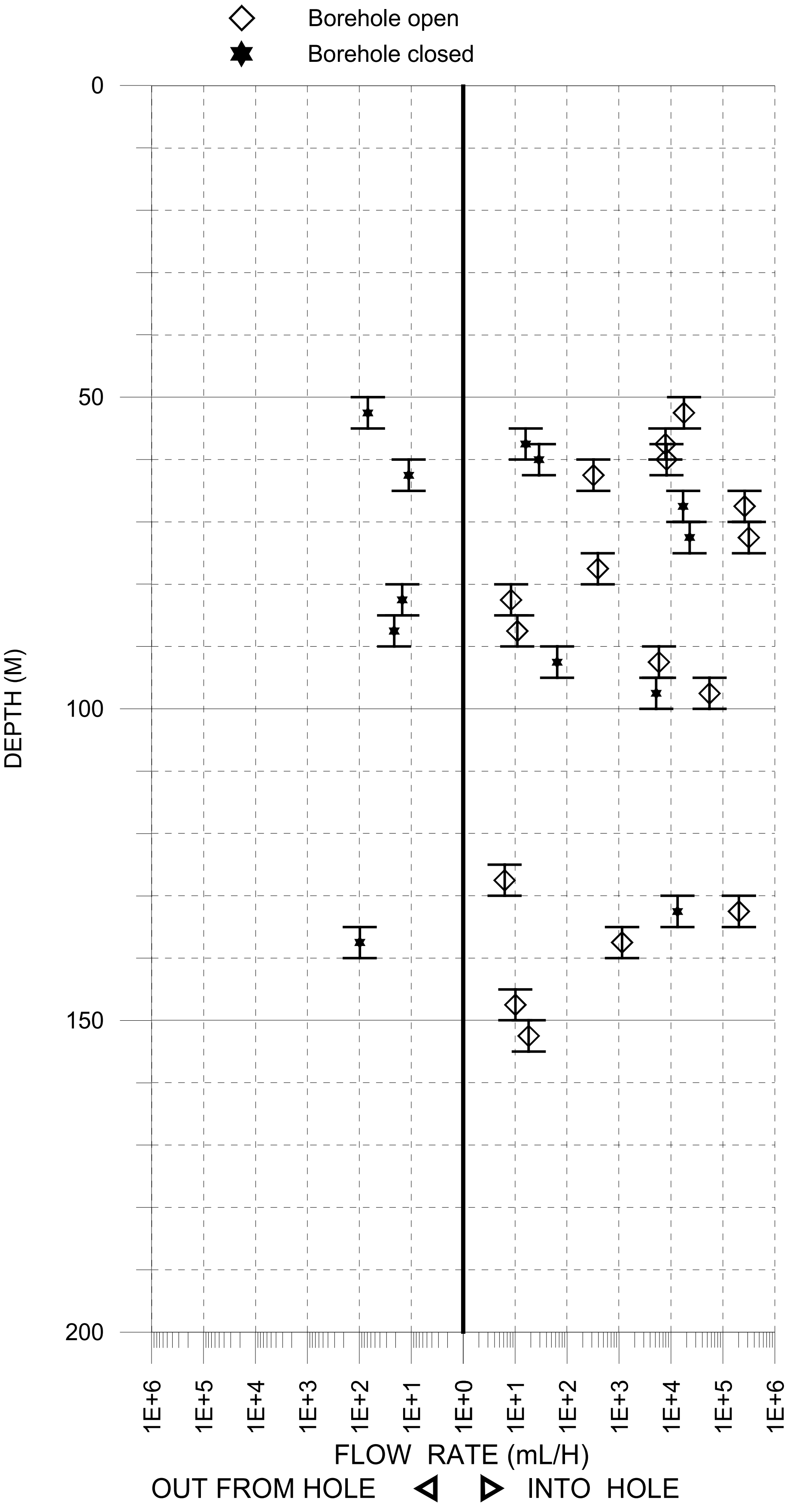
FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KI0025F02



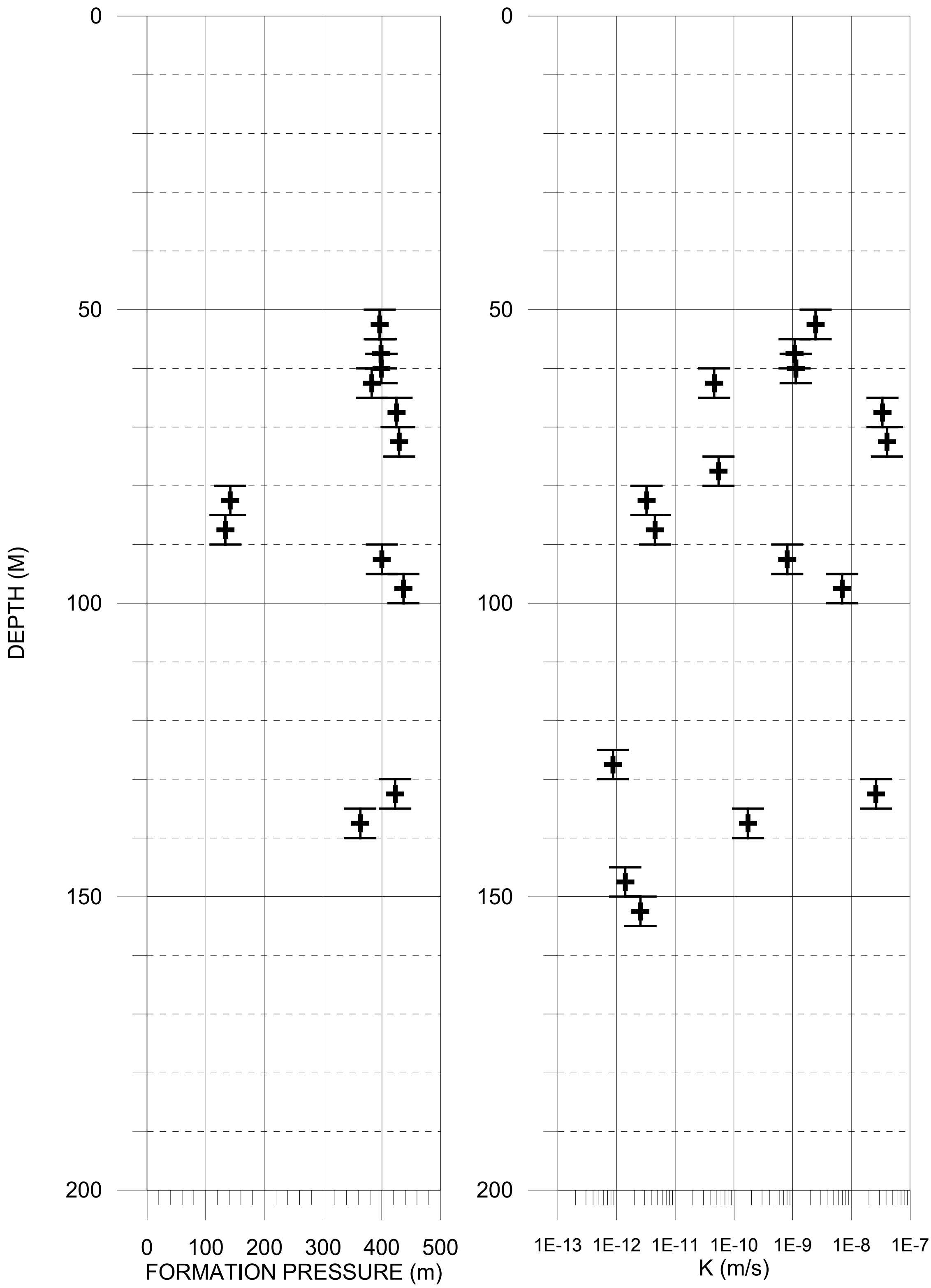
DIFFERENCE FLOW MEASUREMENT, ÄSPÖ, BOREHOLE KI0025F02
FLOW RATES, LENGTH OF SECTION 5 M

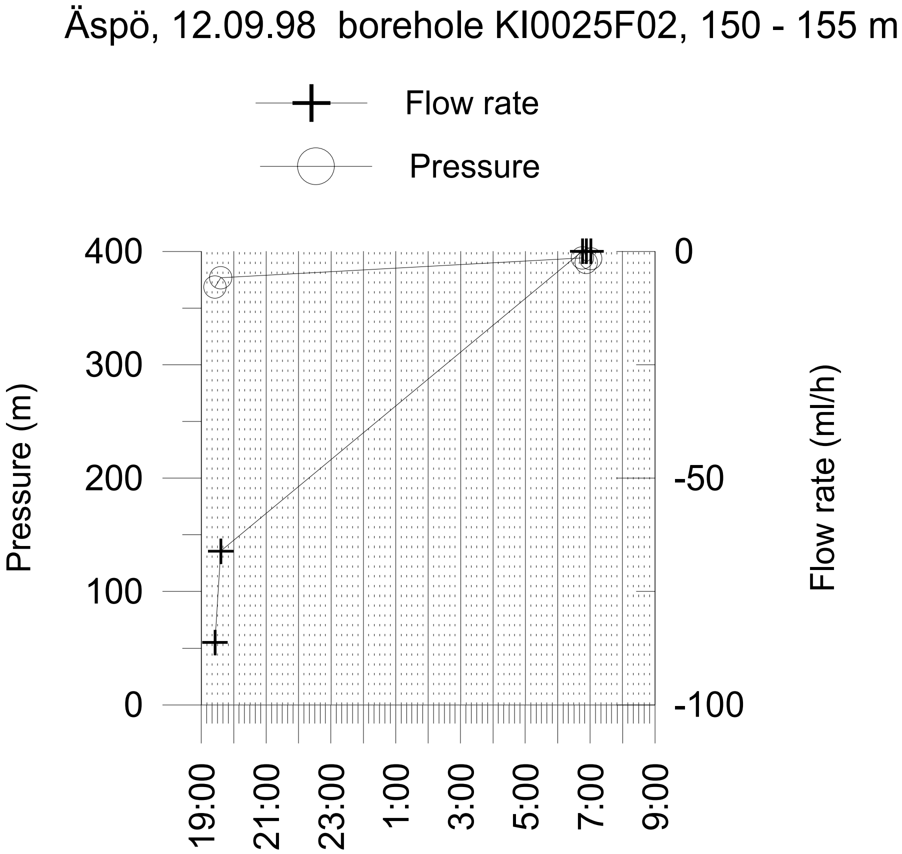


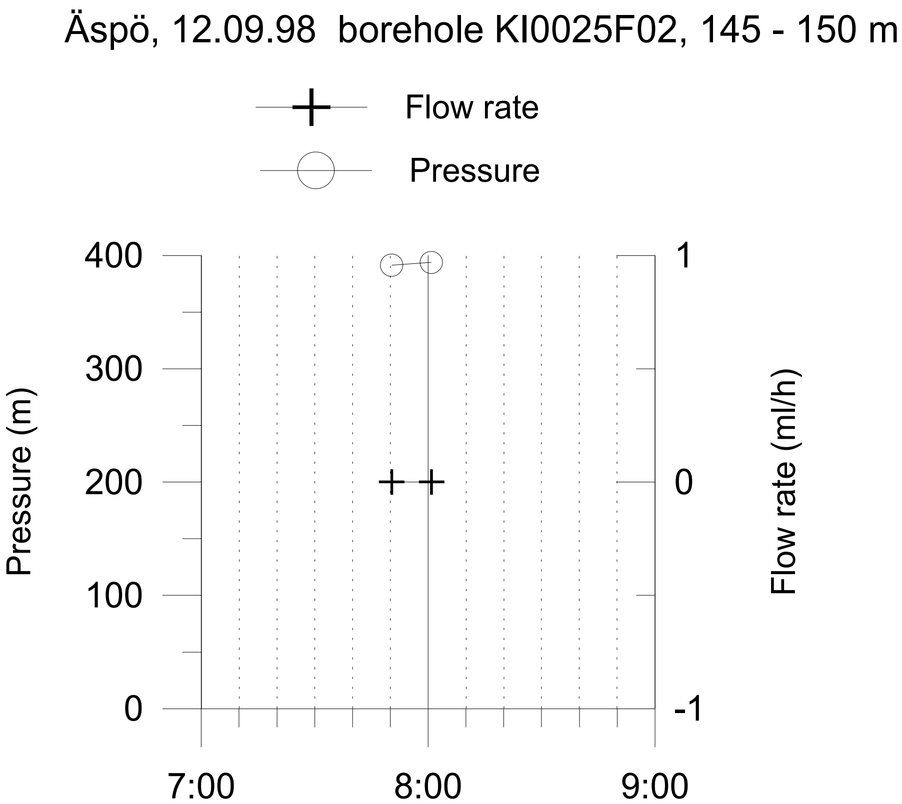
DIFFERENCE FLOW MEASUREMENT, ÄSPÖ, BOREHOLE KI0025F02
FLOW RATES, LENGTH OF SECTION 5 M



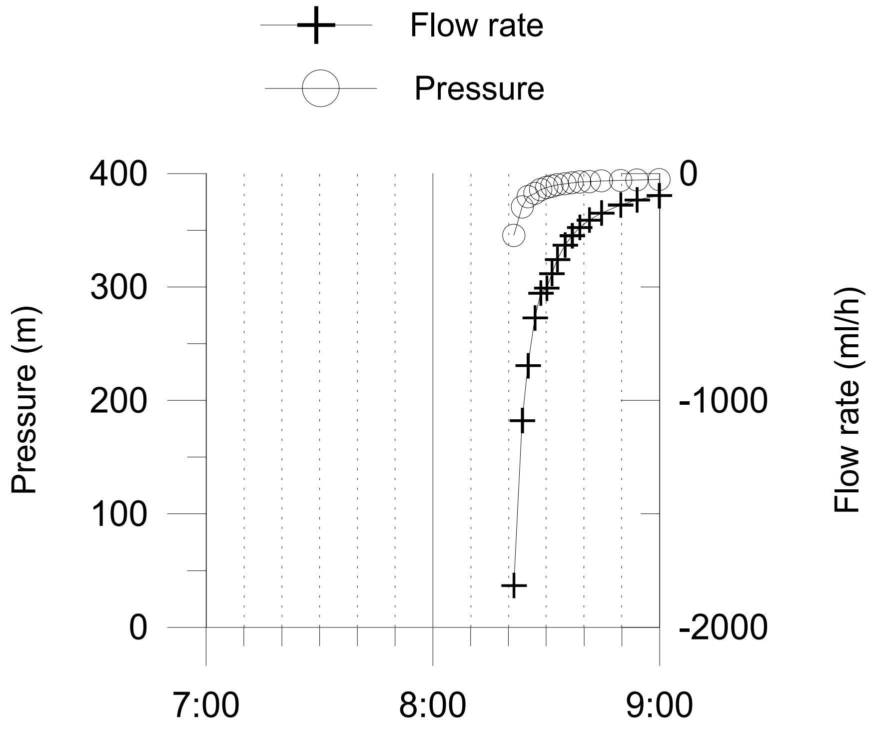
DIFFERENCE FLOW MEASUREMENT, ÄSPÖ, BOREHOLE KI0025F02
FORMATION PRESSURE AND HYDRAULIC CONDUCTIVITY, LENGTH OF SECTION 5 M



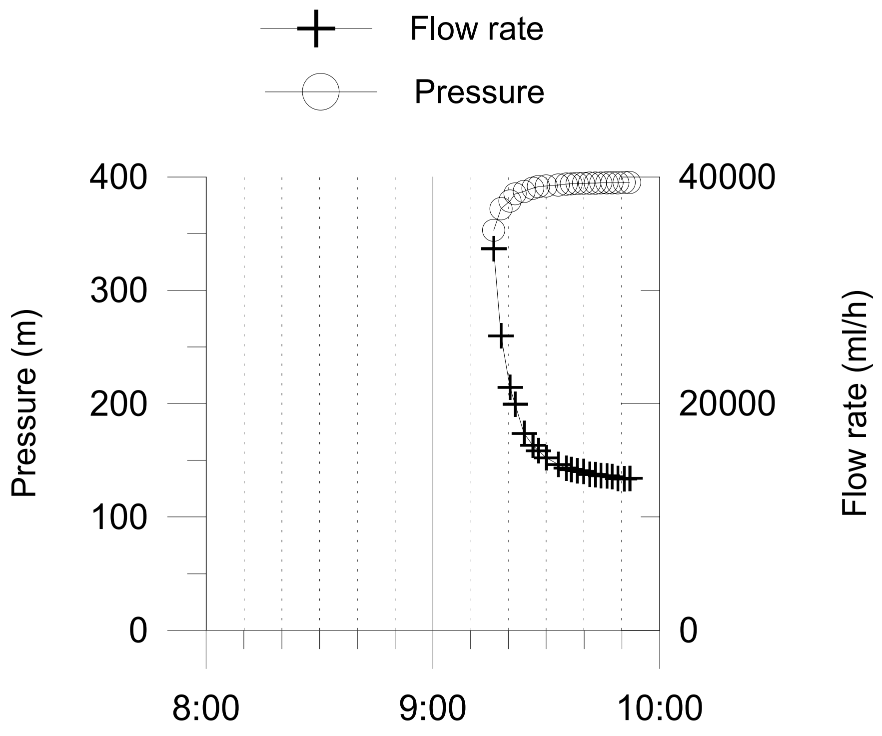

Äspö, 12.09.98 borehole KI0025F02, 150 - 155 m
Flow rate
Pressure
Pressure (m)
Flow rate (ml/h)
400
300
200
100
0
0
-50
-100
19:00
21:00
23:00
1:00
3:00
5:00
7:00
9:00

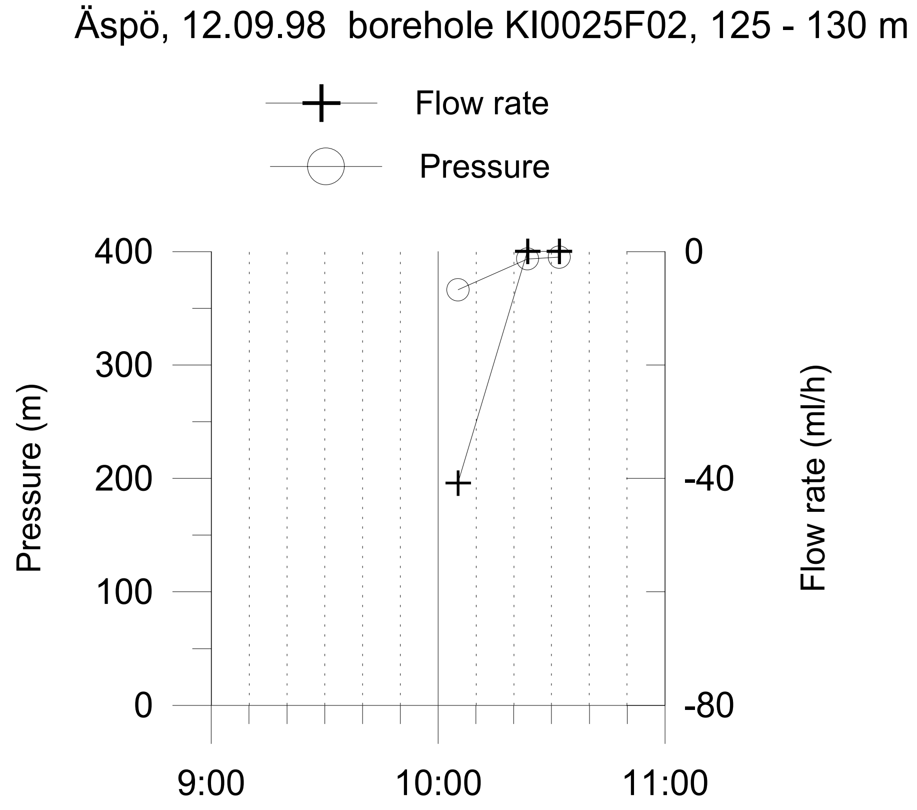

Äspö, 12.09.98 borehole KI0025F02, 145 - 150 m
Flow rate
Pressure
Pressure (m)
Flow rate (ml/h)
400
300
200
100
0
1
0
-1
7:00
8:00
9:00

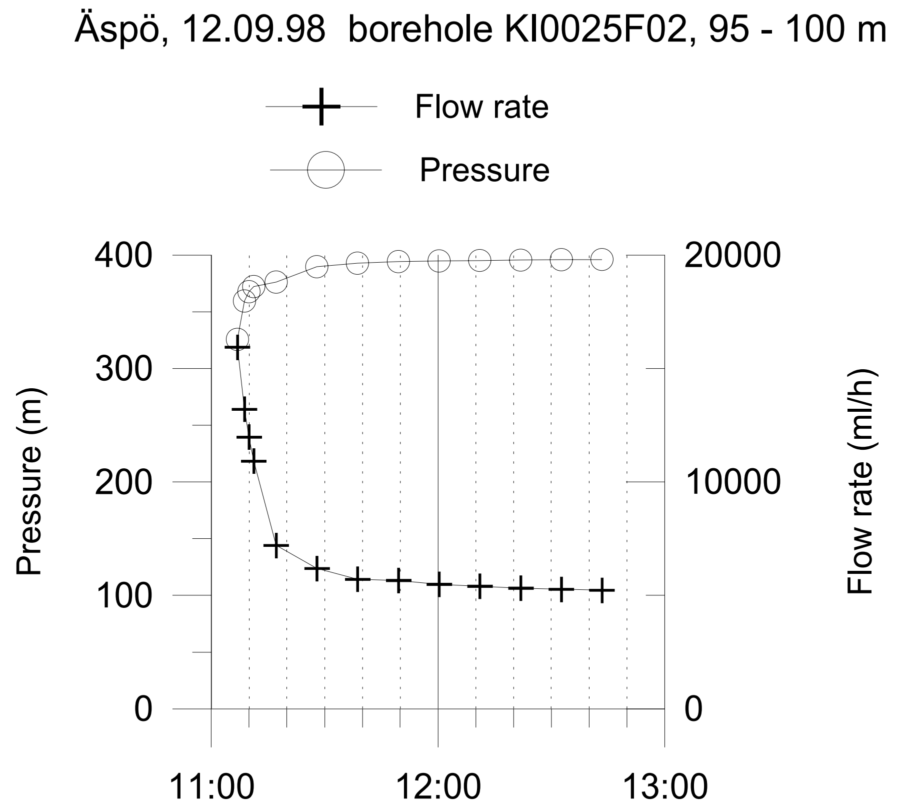
Äspö, 12.09.98 borehole KI0025F02, 135 - 140 m



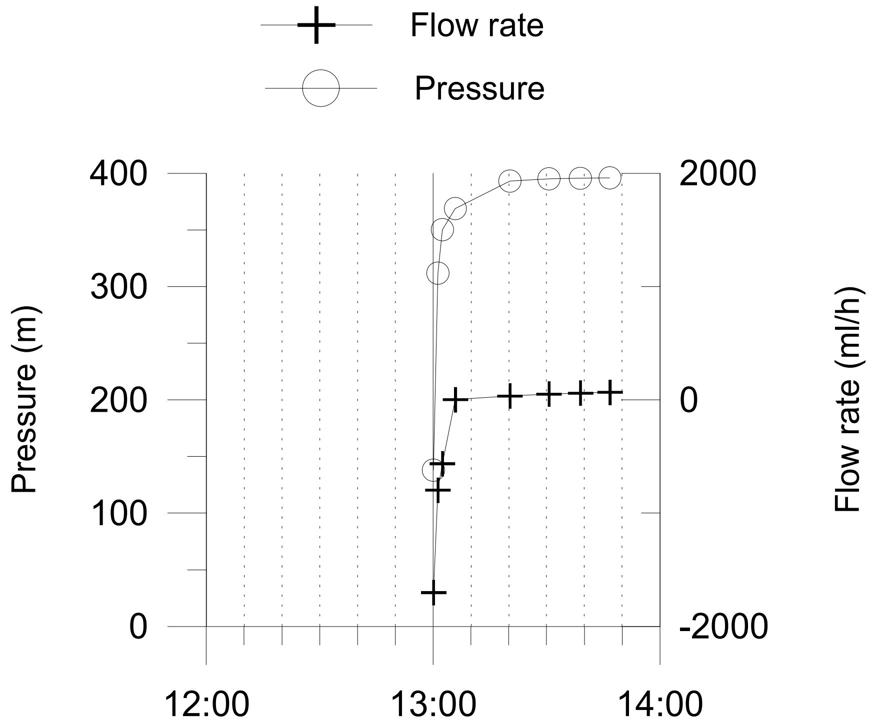
Äspö, 12.09.98 borehole KI0025F02, 130 - 135 m



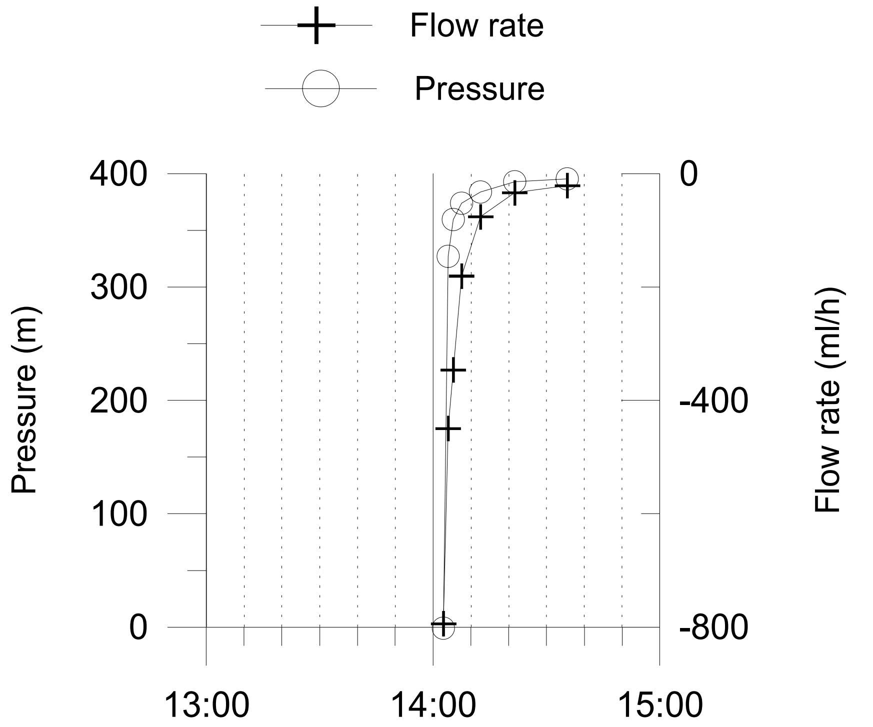

Äspö, 12.09.98 borehole KI0025F02, 125 - 130 m
Flow rate
Pressure
400
300
200
100
0
Pressure (m)
0
-40
-80
Flow rate (ml/h)
9:00
10:00
11:00

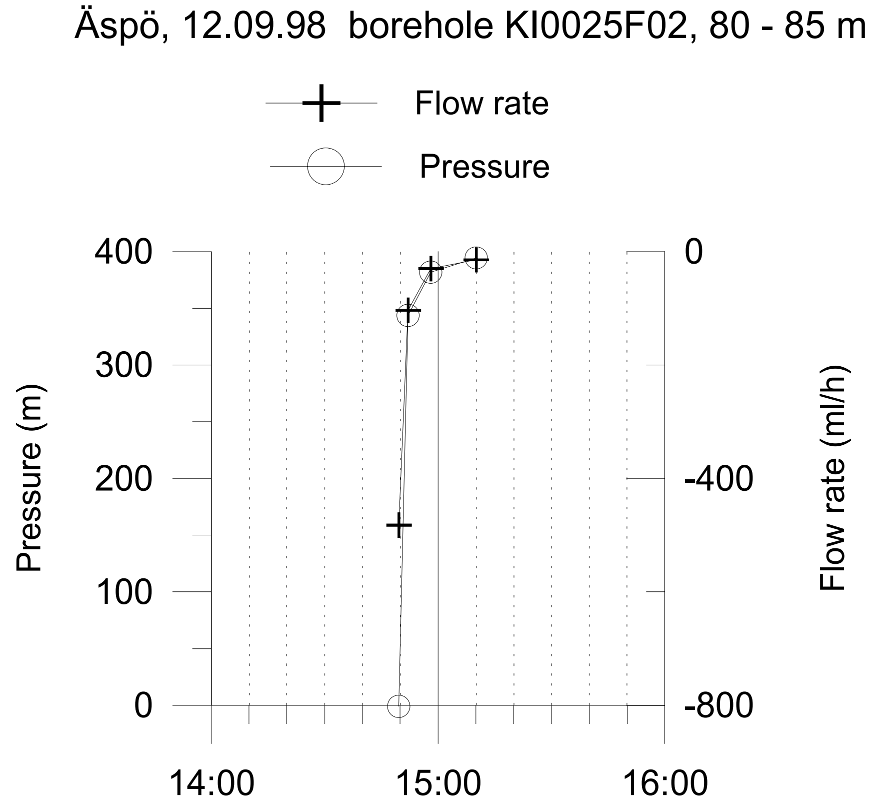

Äspö, 12.09.98 borehole KI0025F02, 95 - 100 m
Flow rate
Pressure
400
300
200
100
0
Pressure (m)
20000
10000
0
Flow rate (ml/h)
11:00
12:00
13:00

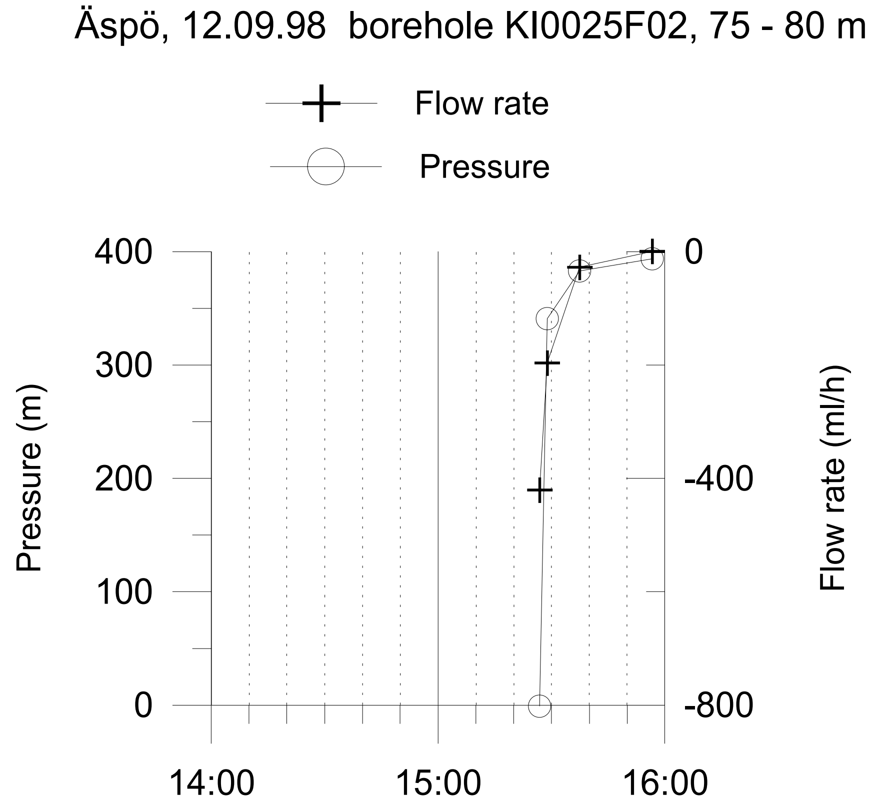
Äspö, 12.09.98 borehole KI0025F02, 90 - 95 m

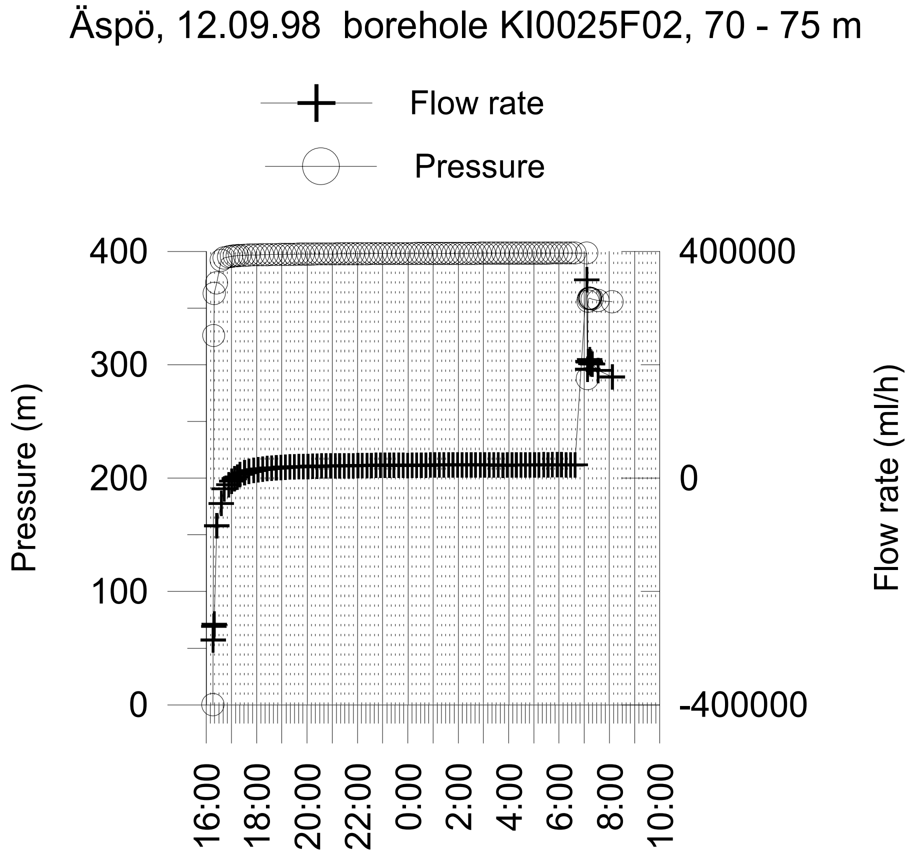


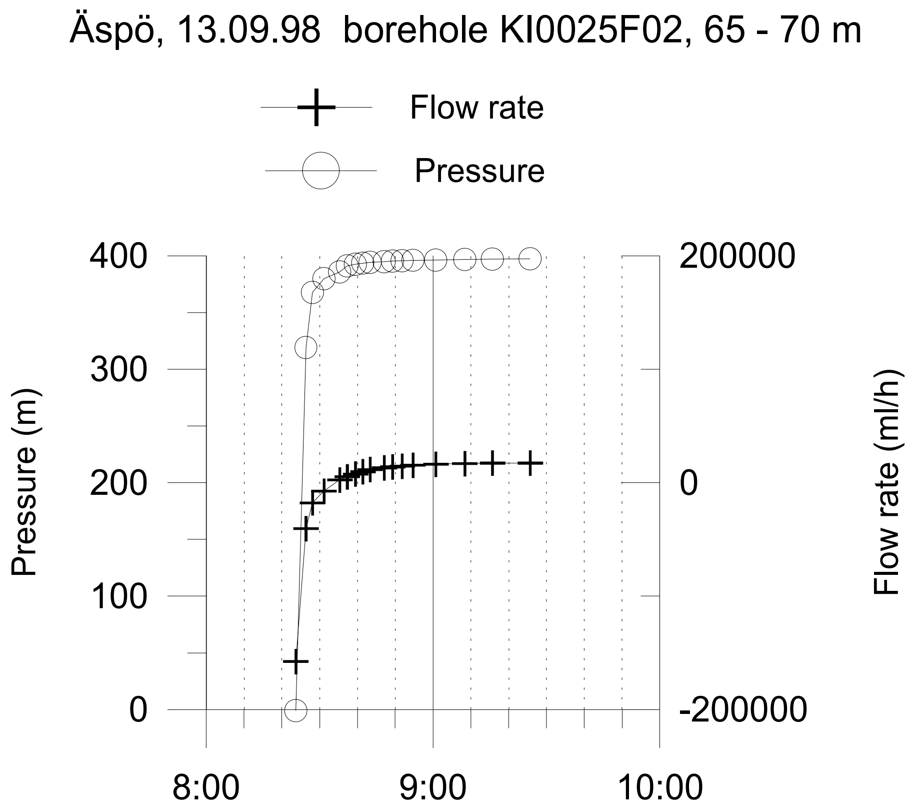
Äspö, 12.09.98 borehole KI0025F02, 85 - 90 m



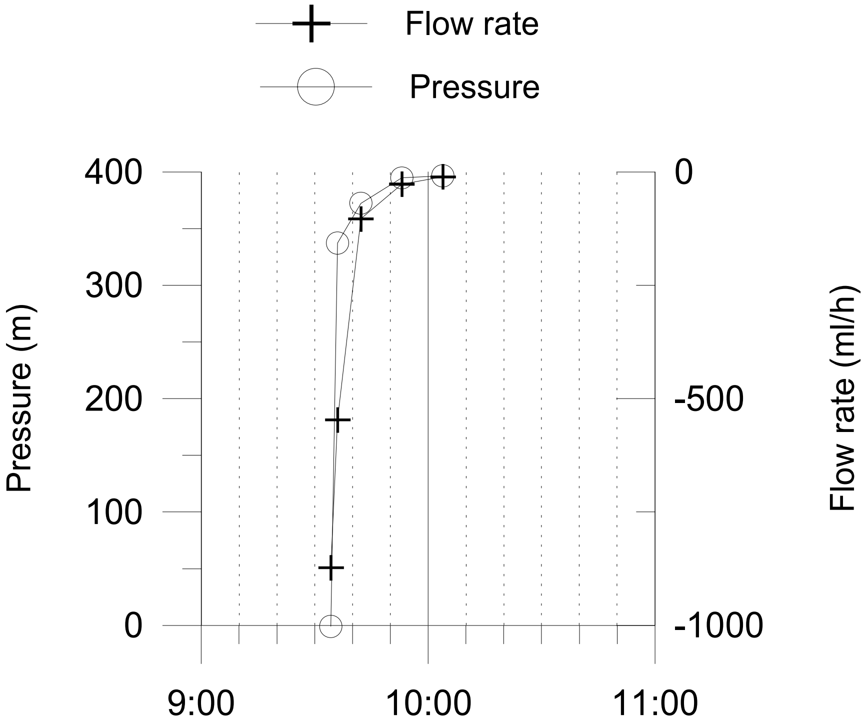

Äspö, 12.09.98 borehole KI0025F02, 80 - 85 m
Flow rate
Pressure
400
300
200
100
0
Pressure (m)
0
-400
-800
Flow rate (ml/h)
14:00
15:00
16:00


Äspö, 12.09.98 borehole KI0025F02, 75 - 80 m
Flow rate
Pressure
400
300
200
100
0
Pressure (m)
0
-400
-800
Flow rate (ml/h)
14:00
15:00
16:00

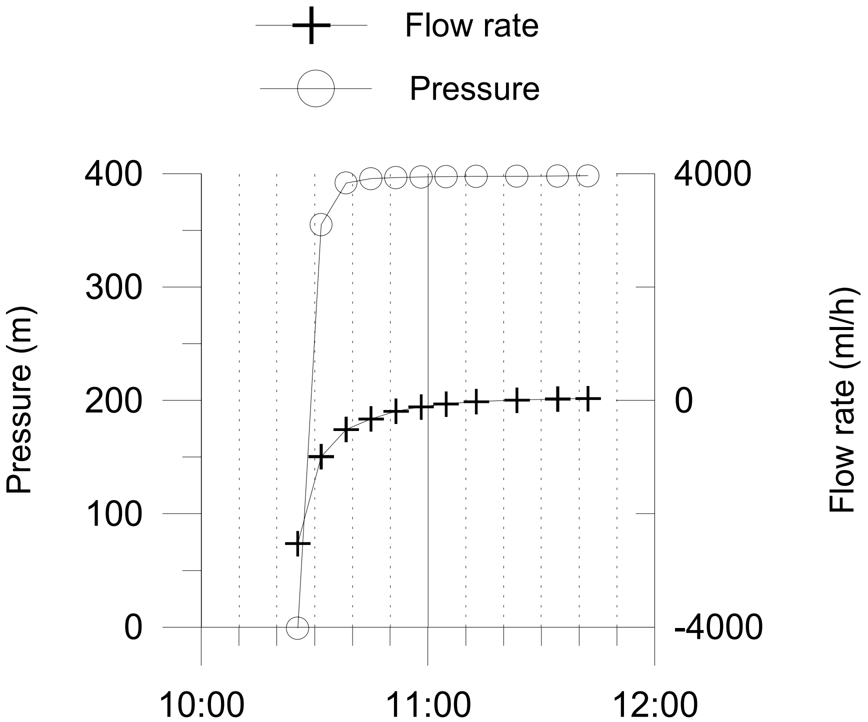

Äspö, 12.09.98 borehole KI0025F02, 70 - 75 m
Flow rate
Pressure
Pressure (m)
Flow rate (ml/h)
400
300
200
100
0
400000
0
-400000
16:00
18:00
20:00
22:00
0:00
2:00
4:00
6:00
8:00
10:00


Äspö, 13.09.98 borehole KI0025F02, 65 - 70 m
Flow rate
Pressure
Pressure (m)
Flow rate (ml/h)
400
300
200
100
0
200000
0
-200000
8:00
9:00
10:00

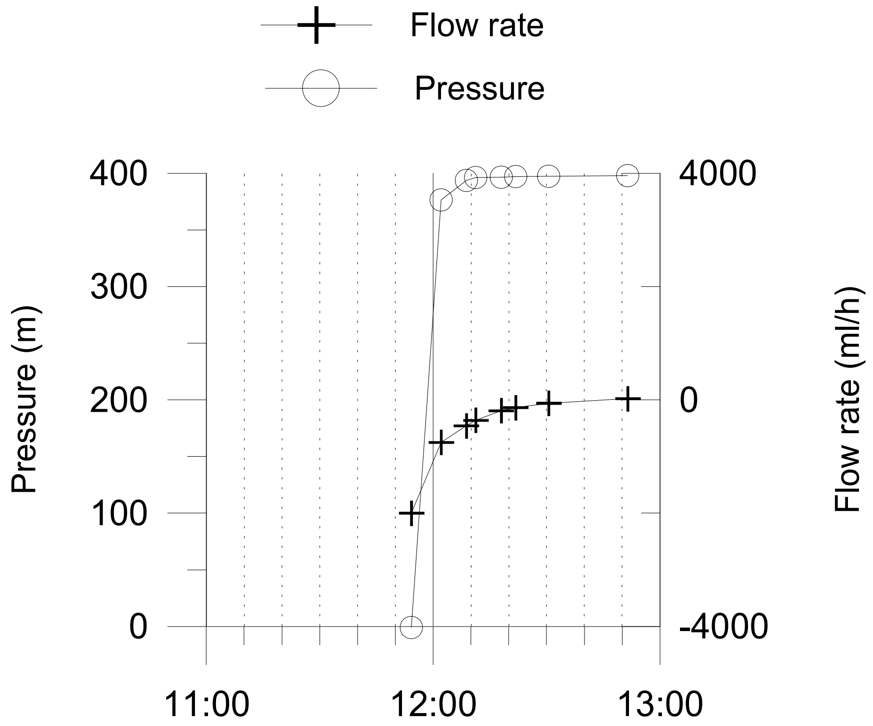
Äspö, 13.09.98 borehole KI0025F02, 60 - 65 m



Äspö, 13.09.98 borehole KI0025F02, 57.5 - 62.5 m



Äspö, 13.09.98 borehole KI0025F02, 55 - 60 m



Äspö, 13.09.98 borehole KI0025F02, 50 - 55 m