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Äspö Hard Rock Laboratory

Flow measurements in boreholes KA3510A and KA2598A at the Äspö HRL

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PRG-Tec OY

December 1998

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Abstract

Two different flowmeters were tested at the Äspö Hard Rock Laboratory.

A Difference Flowmeter (DIFF) was used to make measurements of groundwater inflow in boreholes KA3510A and KA2598A at the Äspö Hard Rock Laboratory. The measurement process started using the detailed logging mode. Flow and single point resistance were simultaneously logged with high depth resolution. In borehole KA3510A measurements continued with a 5 m section length in chosen sections. Inflow to or outflow from these sections was monitored when the borehole was open and when it was closed using a rubber cone at the collar. The calculated hydraulic heads and conductivities are reported.

A Transverse Flowmeter (TRANS) was tested for the first time in underground conditions. The equipment is constructed to measure the flows across a borehole in fractures or fractured zones. The system makes it possible to determine the magnitude of flow and the approximate direction of flow across a borehole. This flowmeter is capable to detect flow rates across the hole that are larger than 1 ml/h (millimetre per hour). This corresponds to a flux value (Darcy velocity) of about $2 \cdot 10^{-9}$ m/s. The results are reported although their representativeness is questionable because of the technical problems encountered.

This report has earlier been published as TD-99-14.

Sammanfattning

Föreliggande rapport redovisar mätprinciper samt fälttester för två olika borrhålsflödesmätare: diffrerensflödesmätaren (DIFF) och transverseflödesnätaren (TRANS). Syftet med testerna var att bedöma metodens applicerbarhet i tunnelförhållanden där höga tryckgradienter råder. Testerna genomfördes i borrhål KA3510A och KA2598A i Äspölaboratoriet. Förutom flödet mättes simultant även bergets elektriska resistivitet.

Resultatet från DIFF visar att metoden även fungerar i tunnelförhållanden där höga tryckgradenter råder. Däremot behöver TRANS –metoden utvecklas vidare innan den kan bli operativ i tunnelförhållanden.

Denna rapport har tidigare publicerats som TD-99-14.

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1 Introduction

Flow logging is one step in the process of characterising bedrock 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 DIFF and TRANS Flowmeters have previously been used for characterisation of bedrock for final disposal of spent nuclear fuel at Posiva's sites in Finland. An earlier version of DIFF 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.

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.

The TRANS equipment can be used in boreholes with a diameter of 56 mm or 76 mm and with borehole length of up to 770 m. The equipment consists of a trailer-mounted winch and cable, a downhole probe and a logging computer situated at ground level (Rouhiainen 1993).

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

- groundwater flow rate across the chosen sections in the underground borehole, and

- groundwater flow direction across the chosen sections in the underground borehole.

The measurements were carried out in borehole KA3510A and in borehole KA2598A. Detailed flow logging using the DIFF was performed in the both boreholes. Measurements for hydraulic conductivity and head in selected section were done in borehole KA2563A as well as all the measurements using the TRANS.

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.

2 Principles of the DIFF Flowmeter

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 with a 0.1 m depth increment. 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 14 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.

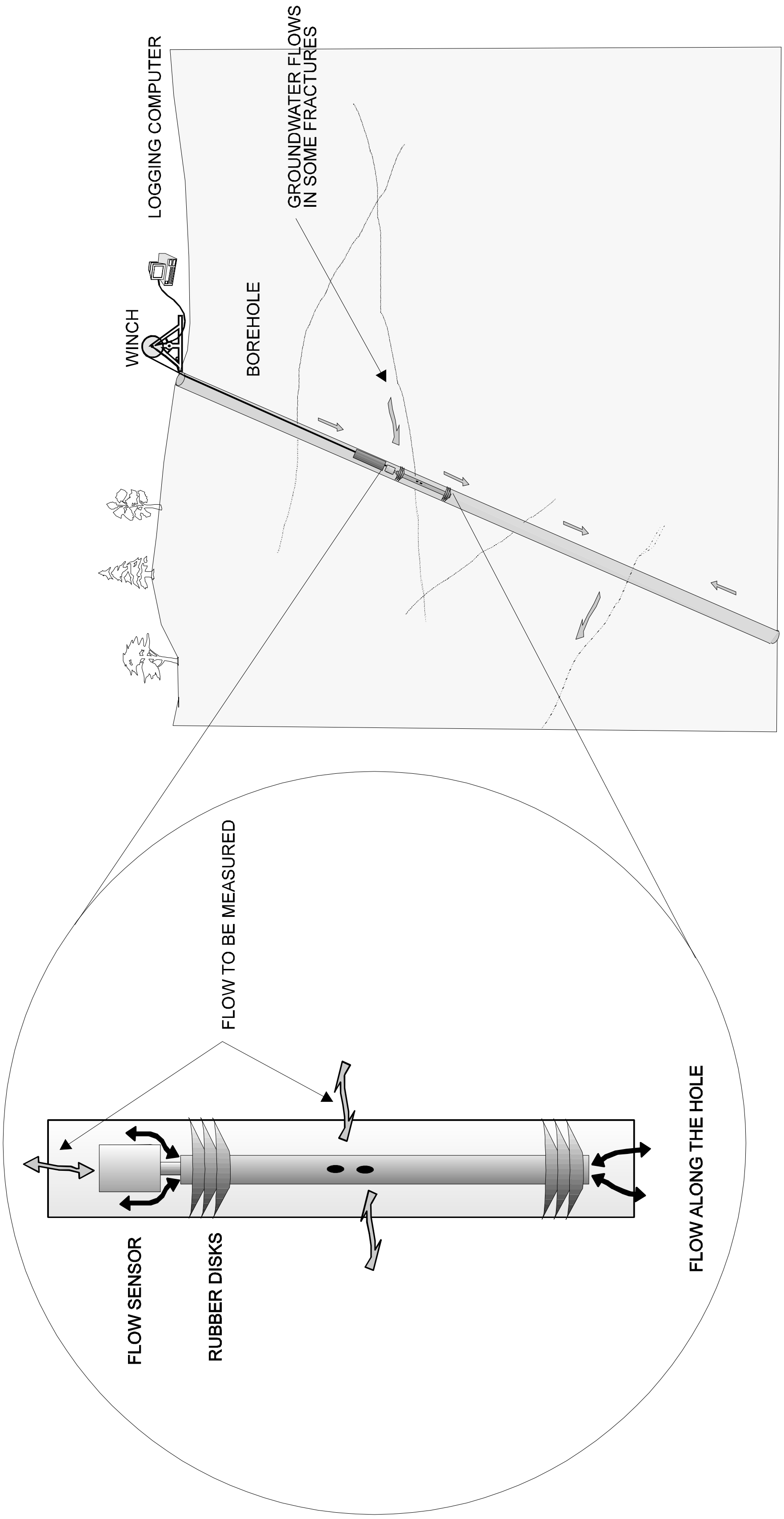

Figure 2-1 *Principles of difference flow measurement.*

3 Interpretation of DIFF results

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 (Bear 1979). It is assumed that a static flow condition exists.

$Q_{n1} = K_n \cdot a \cdot (h_0 - h_1)$ 3-1

$Q_{n2} = K_n \cdot a \cdot (h_0 - h_2)$, 3-2

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:

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

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:

$h_0 = (h_1 - b \cdot h_2)/(1-b)$, 3-4

$K_n = (1/a) \cdot (Q_{n1} - Q_{n2}) / (h_2 - h_1)$ 3-5

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. Equation (3-4) does not contain the geometrical constant which means that the calculated hydraulic head does not depend on the geometrical properties of the zone, but only on the ratio of the flow rates measured at different heads. Therefore the calculated head should be less sensitive to unknown fracture geometry.

4 Specifications of the DIFF Flowmeter

The flowmeter monitors the flow of groundwater into or out from a borehole within a given section. A flow guide is used to separate the section to be measured. The flow guide maintains the section at the same hydraulic head as the rest of the hole. Groundwater flowing through the section is guided past the flow sensor. Flow is measured using the thermal pulse and thermal dilution methods. Measured values are sent in digital form to the PC computer. (Rouhiainen and Pöllänen 1998).

Type of instrument:	Difference Flow Meter.
Borehole diameters:	56 mm, 66 mm and 76 mm.
Geometry of measurement:	A variable length flow guide is used.
Method of flow measurement:	Thermal pulse and thermal dilution methods.
Speed of measurement:	Depends the rate of flows to be measured.
Type of measurement	Inflow and outflow.
Range of measurement:	0.1 - 5000 ml/min in both direction.
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
	Software based on MS Visual Basic
Calibrated	August 1998

5 Results of DIFF measurements

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.

Figure 5-1 *DIFF flow measurement at borehole KA2598A.*

5.2 Detailed flow logging

A detailed flow logging was performed with 1.0 m section length and with 0.1 m point interval. This method provides the depth and thickness of the conductive zones with a depth resolution of 10 cm. To make measurements more quickly, 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 meter the anomalies will be overlapped. 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 - 8 for borehole KA3510A and in Appendices 17 - 25 for borehole KA2598A. The depths of leaky fractures are marked in the appendices of the detailed flow logs.

The total flows out from the open boreholes KA3510A and KA2598A were high, about 30 l/min. There was a risk that this high flow could cause damage to the flow sensor. A flow limiter was installed to the flow sensor to protect it. The flow limiter decreases the measured flows above about 2 l/min.

The flow limiter was also on during the measurements with 5 m section length in borehole KA3510A.

5.3 Difference flow measurements with 5 m section length

The measurements with 5 m section length were carried out only in borehole KA3510A. Measurement was begun in the open borehole. The depth range of 50 - 125 m was measured. Several repeated measurements were carried out with depth change less than 5 m. These repeated measurements were performed especially where fractures were near the ends of the test section. In these cases it is not always clear whether a dominating fracture is inside, partially inside or outside of the test section. On the basis of the detailed flow logging there are fractures at least at the depths of 50 m and 55 m which are located near the ends of the test section.

The results of difference flow measurements with 5 m section length in the open borehole are plotted in Appendix 9. Flow values in the flow rate plots are shown using a logarithmic scale. The flows 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 within a test section. The depths of the plotted results are presented from the tunnel wall to the middle point of the test section.

The sections between 50 and 125 m were measured again in the closed borehole. The borehole was closed using a rubber cone at the collar. The flow values in the closed and in the open borehole are plotted in Appendix 10. A steel armoured cable was used which caused leakage at the cone. The leakage of 0.04 l/min was small compared with the outflow of 32 l/min from the open borehole.

Stabilisation time in the closed borehole varied from 40 minutes to 13 hours (during the night). The pressure and flow transients are drawn in Appendices 12 - 16. The degree of stabilisation of the flow rate was not equal for all sections. It depends on the waiting time after closing the borehole and the fracture system measured. The last and most stabilised flow value was taken for the flow plot in Appendix 12. The degree of stabilisation can be seen in the transient plots in Appendices 12 - 16.

After closing the borehole, the flow was in the most cases negative, water was flowing out from the borehole. The flow usually changed nearer to zero with time. Water flew into the closed borehole in only one section (115 - 120 m, see Appendix 12). This is the section of the highest inflow also in the open borehole.

In two sections the flow measurements were carried out in partially closed borehole. The measured flows and heads were near each other in closed and partially closed borehole in the section 115 - 120 m, see Appendix 10 and 12. According to equation 3 - 5, small errors of head can cause large errors in the calculated hydraulic conductivity in this case.

The section 45.5 - 50.5 m was also measured in partially closed condition. In this section the flow is out from the borehole in closed condition. The pressure in the borehole had to be lowered below 300 m until flow changed to positive, see Appendix 16.

The flow values presented in Appendix 10 were used to calculate hydraulic head and conductivity. They are plotted in Appendix 11. Hydraulic head and conductivity can be calculated from the flows using the method described in Chapter 3. Hydraulic head is presented in the plots if both of the flows at the same depth are not equal to zero. Hydraulic conductivity is presented if both or either of the flows are not equal to zero.

Because the flow in the closed borehole was in most cases not stabile the hydraulic head and conductivity do not always stand for stabile conditions. In spite of this there are clear pressure differences between the fractures as presented in Appendix 11. The lowest calculated pressure was found in the fractures in the section of 49.5 - 54.5 m.

Hydraulic conductivity depends mostly on the flow rate in the open borehole and pressure in the closed borehole. The flow rate in the open borehole was well stabilised and therefore it does not cause errors to the calculated conductivity and head. The pressure in the closed borehole was generally lower than its “final” value. Ten percent error of the pressure in the closed borehole causes an increase of hydraulic conductivity with the same rate, see equation (3-5).

6 Principles of the TRANS Flowmeter

The TRANS Flowmeter is used to measure the groundwater flow across a borehole. A special packer system guides the flow through the flow sensors. Four inflatable seals between conventional packers divide the section selected for measurement into four sectors (Figure 6-1). The length of the measuring section between the packers is two meters. There are flow guides for 56 mm and for 76 mm boreholes (Rouhiainen 1993).

Groundwater may flow from fractures in the rock to some of the four sectors of the flow guide. Tubes from the sectors lead water to the flow sensor above the packer system. The sensor for crosshole flow connects the sectors to one another (Figure 6-1). Water can move freely from each sector to any other sector.

A pipe passing right through the flow guide connects water in the borehole above and below the guide. This pipe short-circuits any possible pressure gradient along the packers.
The flow sensors operate using a modified thermal pulse principle. This provides the minimum resistance to flow and high sensitivity. A weak heat pulse is generated in the water at a point midway between the sensor (Figure 6-1). The monitoring thermistors are positioned symmetrically around the heating point. If there is no water flow, the temperature response at the thermistors will be symmetrical. If water is flowing, there will be a faster and higher response from those thermistors which are in the direction of the water flow.

A hose pump at the surface is used to fill and empty the packer system. There are three magnetic valves in the probe. These are used to take water from the borehole or from the ground surface for the packers and to release the pressure between the packers following inflation of the flow guide. Water for the packers is extracted from the borehole via a filter. A microcontroller is programmed to coordinate both the various measurements and communication with a computer at ground level. A winch with 770 m cable is used to lift and to lower the flowmeter. During the flow measurements pressure in the section and in the borehole are monitored.

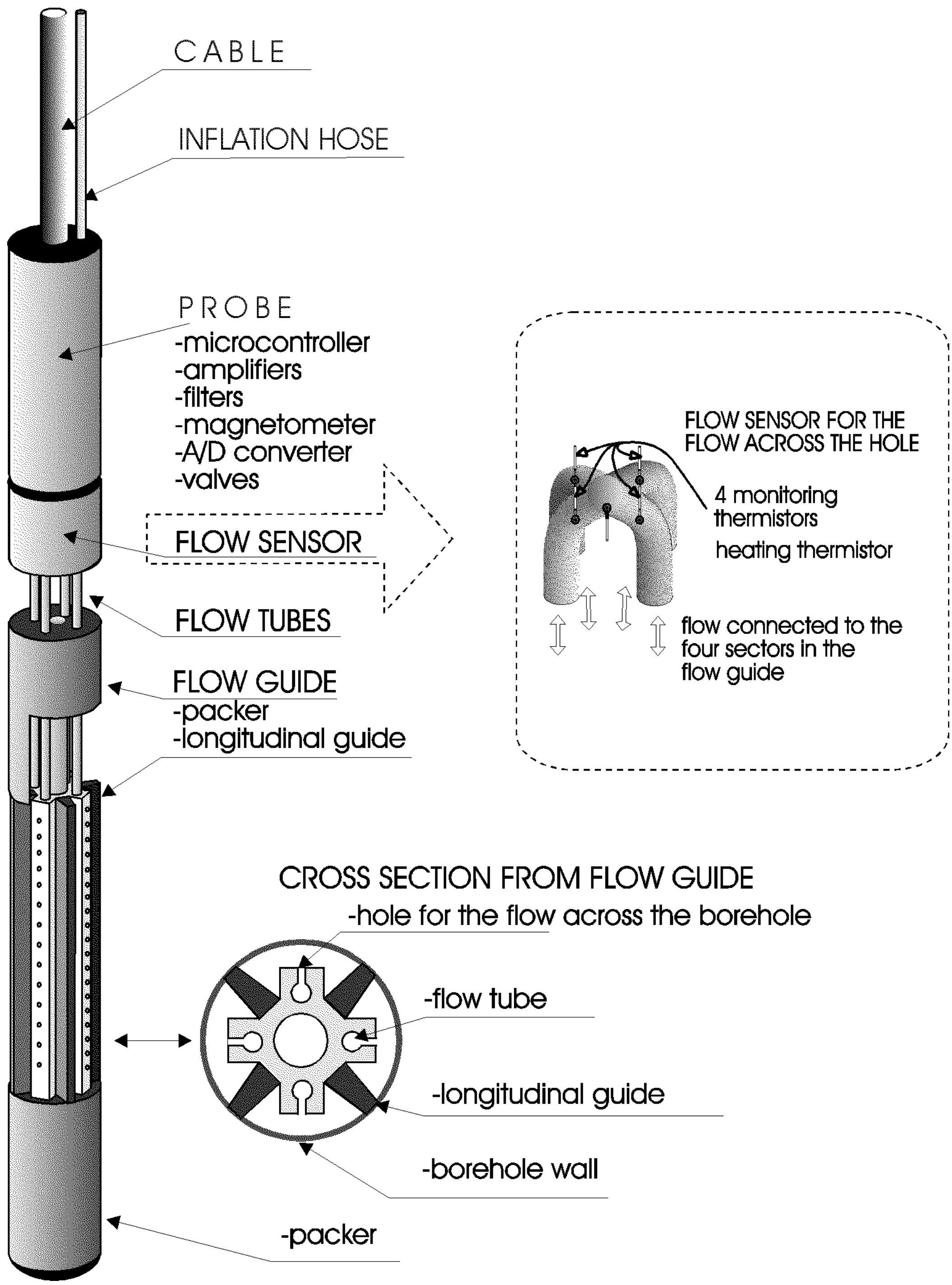

Figure 6-1 *Principles of transverse flow measurement.*

7 Interpretation of TRANS results

The temperature response curves from a measurement of flow across the hole are presented in Appendices 26 and 27. The horizontal time axis starts from the point where a short heat pulse is generated at the middle point of the flow sensor. Temperature increases in the direction of water flow. The interpretation of the flow rate is based on the average velocity of the heat pulse.

The flow sensors must be calibrated for the acquisition of quantitative information. A special calibration pump is used to generate small, steady and known flows.

The sensitivity of the instrument is better than 1 ml/h (millilitre per hour) for the flow across a hole which corresponds to a flux value of about $2 \cdot 10^{-9}$ m/s. The flux value represents the average flow speed of a water molecule in the two metres open hole section.

The system also makes it possible to approximately determine the direction of flow across the hole. The orientation of the instrument itself can be deduced by three flux gate magnetometers. Both 0 and 360 degrees mean that the flow direction is upwards, 180 degrees means that it is downwards. 90 and 270 degrees denote flow direction to the right and left, respectively, spectator towards the borehole.

Flow directions are calculated from the magnetic field components at the probe. The direction refers to the direction of a sector in the flow guide. The real direction of the flow is not exactly the same as this. The distribution of the flow within a sector is not known. Flows do not always come from the sector which is opposite the one to which they are going to. The actual inclination of the flow depends on the orientation of fractures and cannot be determined on the basis of flow measurements alone. The direction of the flow should therefore be taken as the main trend at each depth (Pöllänen, Rouhiainen 1997).

8 Specifications of the TRANS Flowmeter

The flowmeter monitors the groundwater flow into or out from a borehole within a given section. A flow guide is used to separate the section to be measured. The flow guide maintains the section at the same hydraulic head as the rest of the hole. Groundwater flowing through the section is guided past the flow sensor. Flow is measured using the thermal pulse. Measured values are sent in digital form to the PC computer (Pöllänen, Rouhiainen 1997).

Type of instrument	TRANS Flowmeter
Borehole diameters	56 mm, 76 mm
Length of cable	770 m
Calibrated	March 1998
Range of measurement	1 - 2000 ml/hour

9 Results of TRANS measurements

9.1 Description of the field work and the results

The measurements were carried out in a closed borehole. The borehole was closed with a rubber cone at the collar. Additional packers were used 3 m above and below the flow guide. The pressure was measured in the section and in the borehole outside the flowguide but between the additional packers.

The results of the transverse flow measurements are presented in Appendices 28 - 31. The horizontal axis of the plots represents a date in the year 1998. The flow direction is shown as a direction value, 0 and 360 degrees denote upwards and 90 degrees corresponds to the right, spectator to the borehole. Flow across the borehole is normally measured once in an hour. The depth and starting time of the measurements are presented in the lowest section of the combined plots.

The flow magnitude is calculated as the sum of the flows in all the four channels. If the flow is measured in opposite channels, it is summed, not subtracted. The flow direction is calculated as the vector sum of the flows in the four channels. In some cases this method of calculation is problematic. What is the flow direction if water is flowing towards two opposite sectors? The vector sum gives as a result the direction of the sector towards which the flow is fastest. Large variations in flow direction may appear if the two opposite flows are dominant and almost equal.

The combined plots are considered important in providing a general view of the flow conditions in a borehole. In spite of the difficulties with determining flow direction, this information is presented in the combined plot in Appendices 28 - 31.

The detailed results, with the temperature curves, are given in Appendices 26 and 27. These figures are chosen as either the final or the most representative of the measurements made at a particular depth. Normally, the transient caused by inflation of the flow guide had ample time to stabilise.

The range of flow measurement is 1 to 2000 ml/h as mentioned before. However, smaller flow values than 1 ml/h are given in as a result of automatic interpretation in Appendices 26 and 31, though it is not known whether these values have any relevance. They may be caused by some secondary features such as equalising salinity between the sectors or invisible leakage in the packer system.

The pressure in a section was measured after the flow measurements at each depth. The pressure was measured with a pipe filled with water. This pipe can be connected via the magnetic valves to the section to be measured or to the borehole water just above it. The pressure in the section and outside of it between the additional packers was measured with the same tube. Therefore these pressures could not be measured simultaneously.

The pressure results are also given in Appendices 28 - 31. The relative pressure was normally measured several times. The final measurement in each series was always the most stable result.

The first section to be measured was 116-118 m. At this depth there are a group of fractures with the largest inflow in the borehole KA3510A , see Appendix 6. Even when the borehole is closed with the rubber cone at the collar, the flow into the borehole in this section is about 1.5 l/min, see Appendix 10. This flow rate is high compared with the flow range of the TRANS flowmeter (1 - 2000 ml/hour). The additional packers were used to suppress this "internal" flow. The flow guide is inflated to the overpressure of about two bars which is too little in the deep tunnel condition. The calculated hydraulic heads vary between 250 - 400 m, see Appendix 27. The head differences between fractures can be as high as 15 bars in this borehole, see Appendix 11.

Unfortunately there was a small leak in the additional packers. It is normal that the inflation pressure reduces slightly after inflation of packers. In this case the reduction of pressure continued until the pressure in the packers was about the same as the pressure in the borehole between them.

The consequence of the leak can be seen in the pressure behaviour of the borehole between the packers, clearest in Appendix 31. The pressure between the packers usually rises when the packers are inflated. About two hours after the beginning of the measurements, the packers were inflated again. The pressure initially rose. As long as the packers are tight, the pressure is going down towards the pressure of the fracture at the depth of 75.9 m. Two hours later, the pressure is rising towards the pressure of the borehole closed at the collar.

The leak was small and it could not be localised during the measurements. Therefore the flow results do not represent flow across the borehole in controlled conditions. There were a lot of other problems, a part of which could be fixed during the measurements. The packers and rods attached to them, got twisted because of the high pressure. The flow guide leaked because of the break down of a metal support. A valve within the electronics tube leaked causing the flow guide to leak.

9.2 Head, flow rate and direction of flow in KA3510A

9.2.1 Section 116 - 118 m, Appendix 28

During the first period, there was a very small flow in the section of 116 -118 m. The temperature curves of the last flow measurement are presented in Appendix 26. The flow is mainly into two opposite sectors. The a valve into the section under test was opened for pressure monitoring at 6:30 AM September 17, see Appendix 28. At 9:00 AM September 17, borehole KI0025f02 as opened for ten minutes. The pressure response can be seen in Appendix 28, while there is no visible flow response.

9.2.2 Section 116 - 118 m the tool turned, Appendix 29

The flow guide was turned clockwise135 degrees and the measurements continued in the section of 116 -118 m. The temperature curves of the last flow measurement are presented in Appendix 26. The measured flow rate was about 10 ml/hour downwards.

9.2.3 Section 116 - 118 m the tool turned, Appendix 30

The flow guide was turned again clockwise 135 degrees and the measurements continued in the section of 116 -118 m. There is a pressure transient between the additional packers caused by inflation of the packers and the flow guide. The pressure transient apparently causes a high transient in flow. This is an indication of importance of controlled pressure conditions during the measurement. The final flow rate is small, about 2 ml/hour downwards, see Appendix 27.

9.2.4 Section 74 - 76 m, Appendix 31

The flow rate in the section 74 - 76 m was relatively large. It seems to have no correlation to the pressure variation between the additional packers. The flow rate is 250 ml/hour to the left spectator towards the borehole, see Appendix 27.

10 Discussion and conclusion

Field work using the DIFF flowmeter 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 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.

Hydraulic head and conductivity are calculated of the measured flow rates and pressures in the borehole. The reliability of the calculated values depends on the reliability of the measured parameters. Analysis of error in calculated values caused by errors in the measured values can be performed using the equations presented in chapter 3. Reliability of the calculated values depends also on the model used. In this study a simple cylindrical mode was utilised. The reliability does not improve with more complicated models if the model parameters are not known.

The field operation with the TRANS flowmeter was difficult mainly because of the high pressure gradient towards the tunnel. There was a leak in the additional packers during all the measurements causing uncontrolled flow conditions. The packers and the flow guide need to be reinforced for the tunnel work.

One problem in the transverse flow measurements is that the flow conditions are never completely known and it is generally not possible to solve them on the basis of the transverse flow measurements alone. Hydraulic gradient along a borehole may be much larger than across the borehole causing flow that was not aimed to be measured. The use of additional packers is one way to minimise this problem. Features near the borehole such as channelling, skin zone and widening of the borehole may cause results which are difficult to explain.

This study shows that DIFF is fully workable in the tunnel conditions while further development is required for TRANS in order to operate in tunnel conditions at great depth where the pressure gradient towards the tunnel is high.

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Appendices

Appendix 1 - Appendix 8	Borehole KA3510A, DIFF results in detailed logging mode, section length 1 m
Appendix 9	Flow rates in the open borehole KA3510A, section length 5 m
Appendix 10	Flow rates in the closed borehole KA3510A, section length 5 m
Appendix 11	Borehole KA3510A, hydraulic head and conductivity section length 5 m
Appendix 12 - Appendix 16	Borehole KA3510A, Pressure and flow transients during the measurements in the closed borehole
Appendix 17 - Appendix 25	Borehole K2598A, DIFF results in detailed logging mode, section length 1 m
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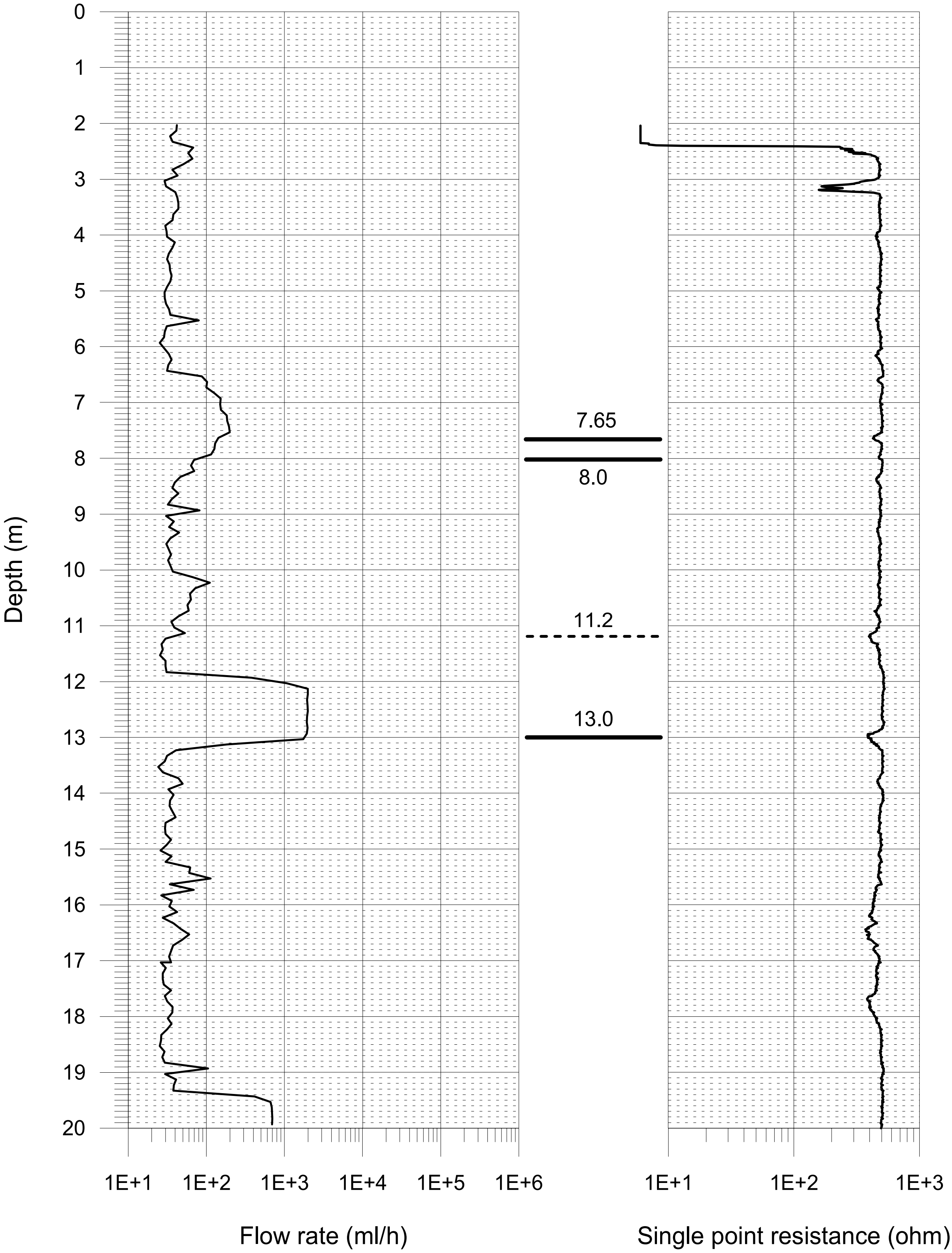
FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KA3510A



Note: A flow limiter was used, it reduces the measured flow rates above 120 l/hour

FLOW RATE AND SINGLE POINT RESISTANCE LOGS
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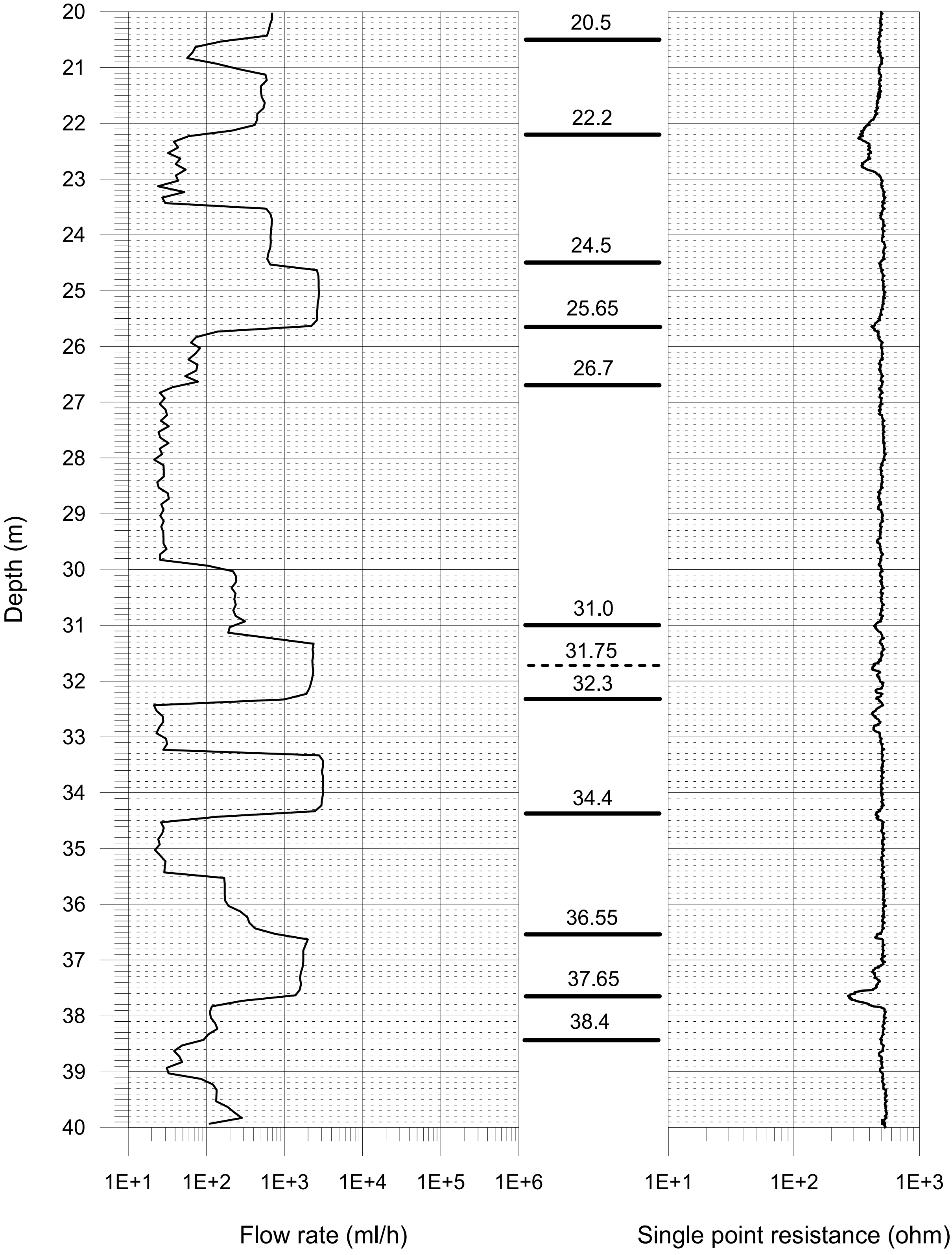

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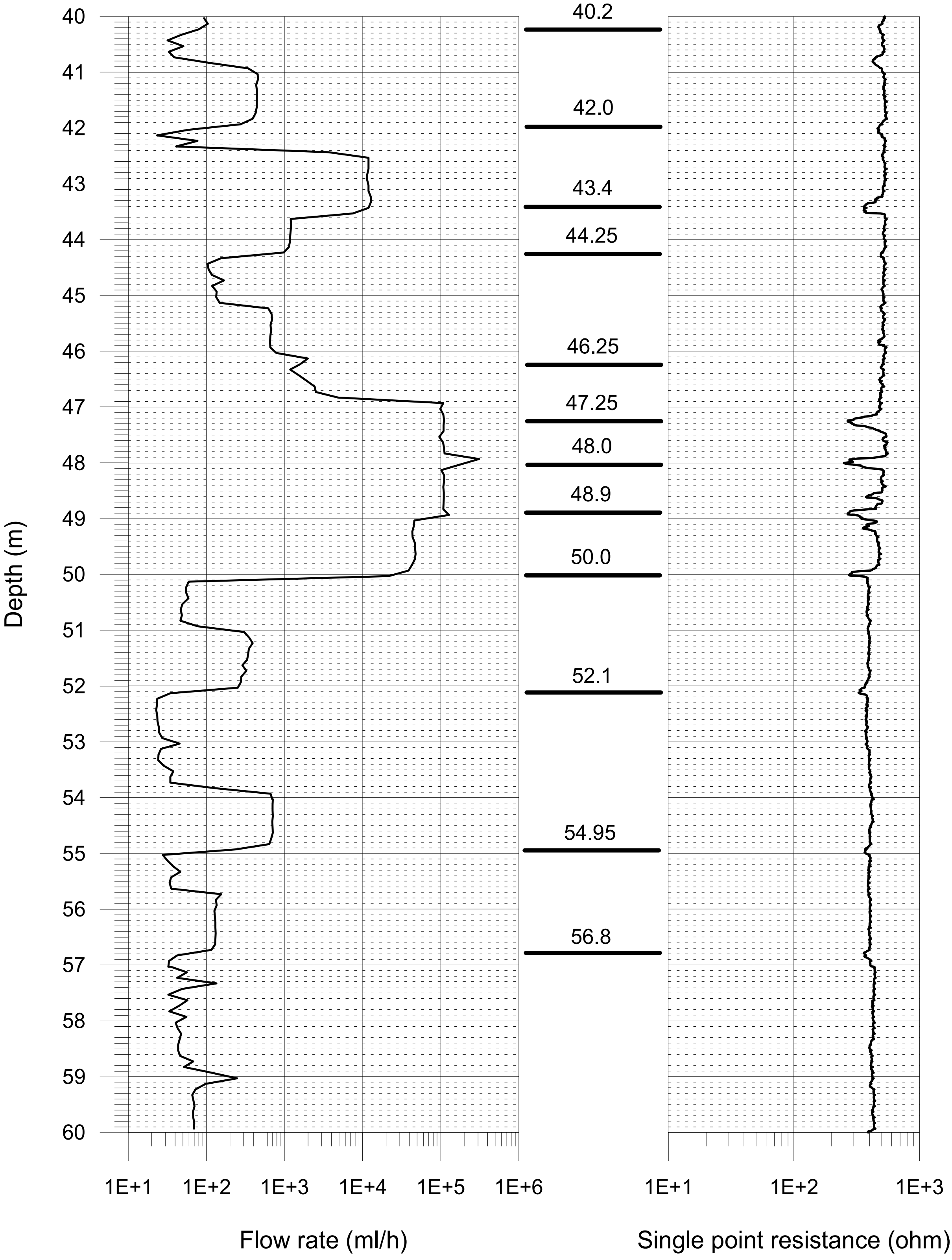
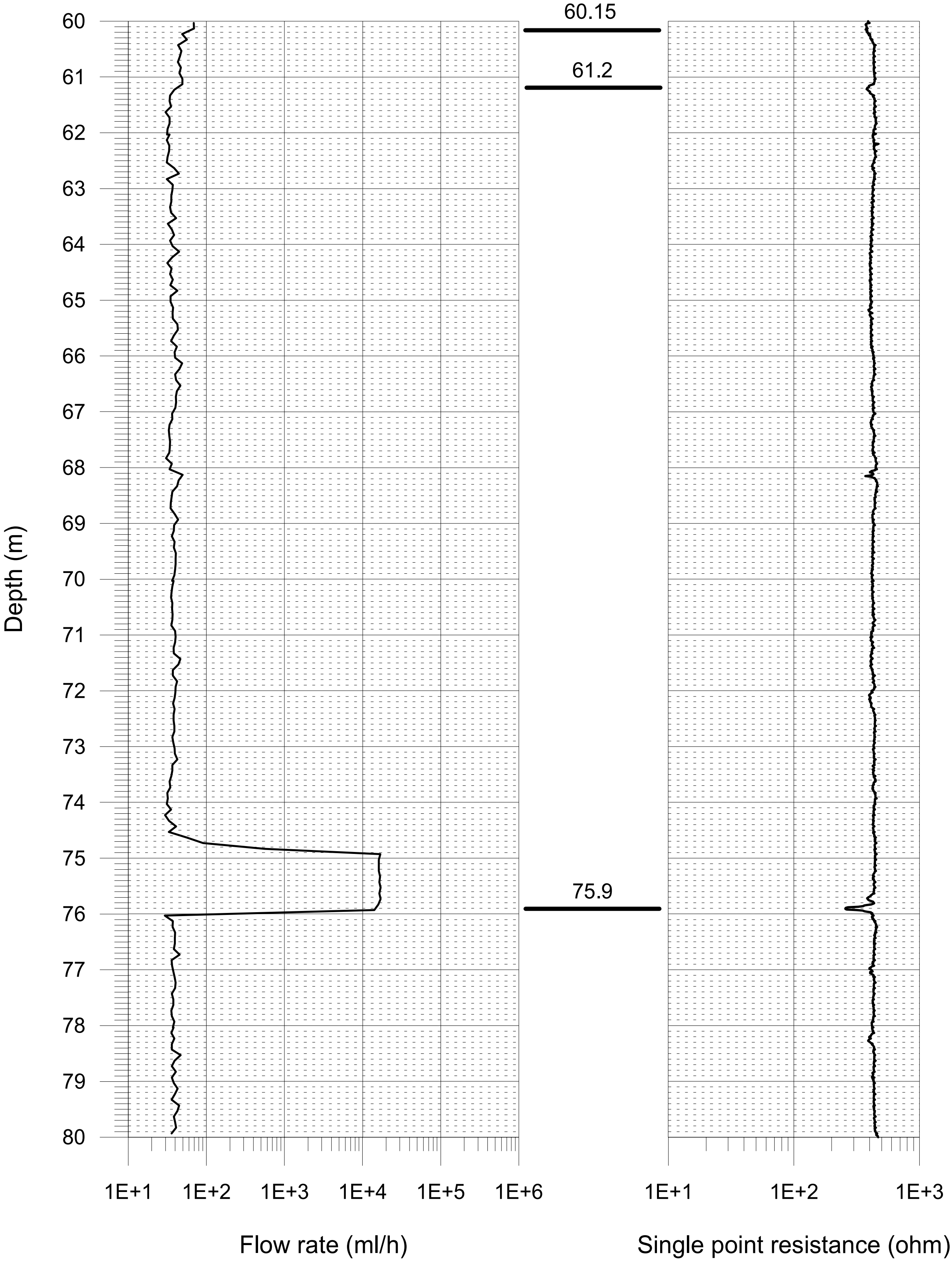
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KA3510A



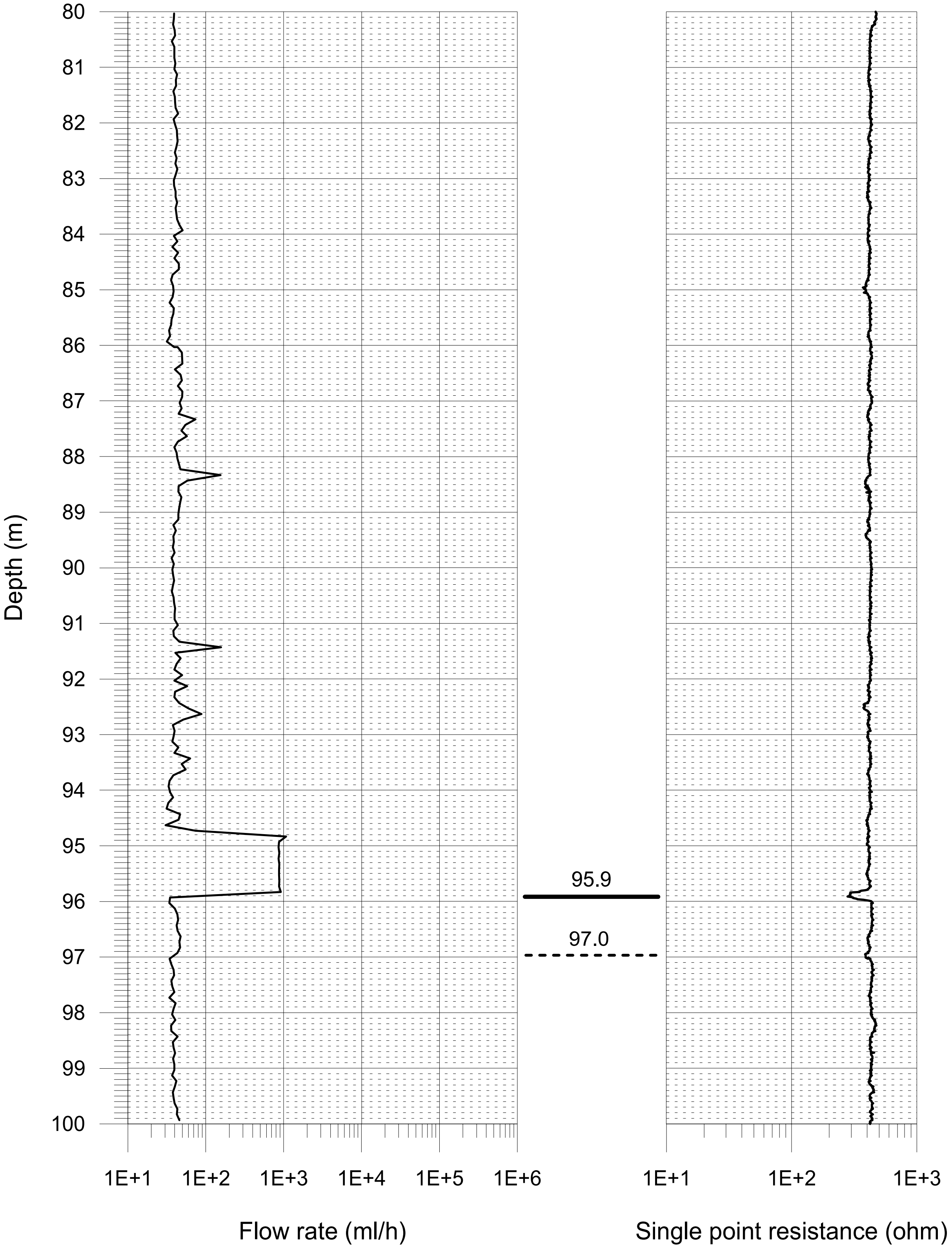
Note: A flow limiter was used, it reduces the measured flow rates above 120 l/hour

FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KA3510A



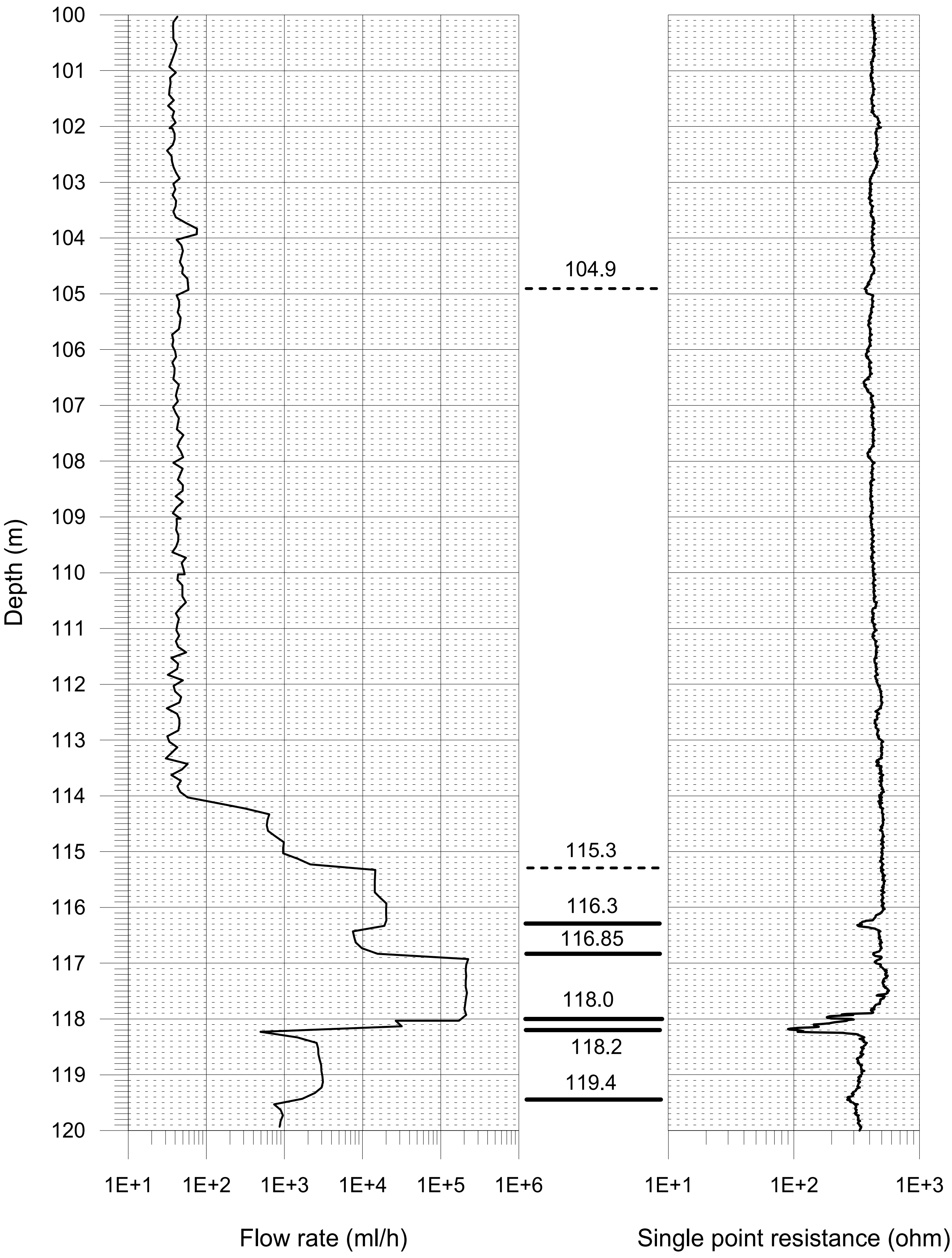
Note: A flow limiter was used, it reduces the measured flow rates above 120 l/hour

FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KA3510A



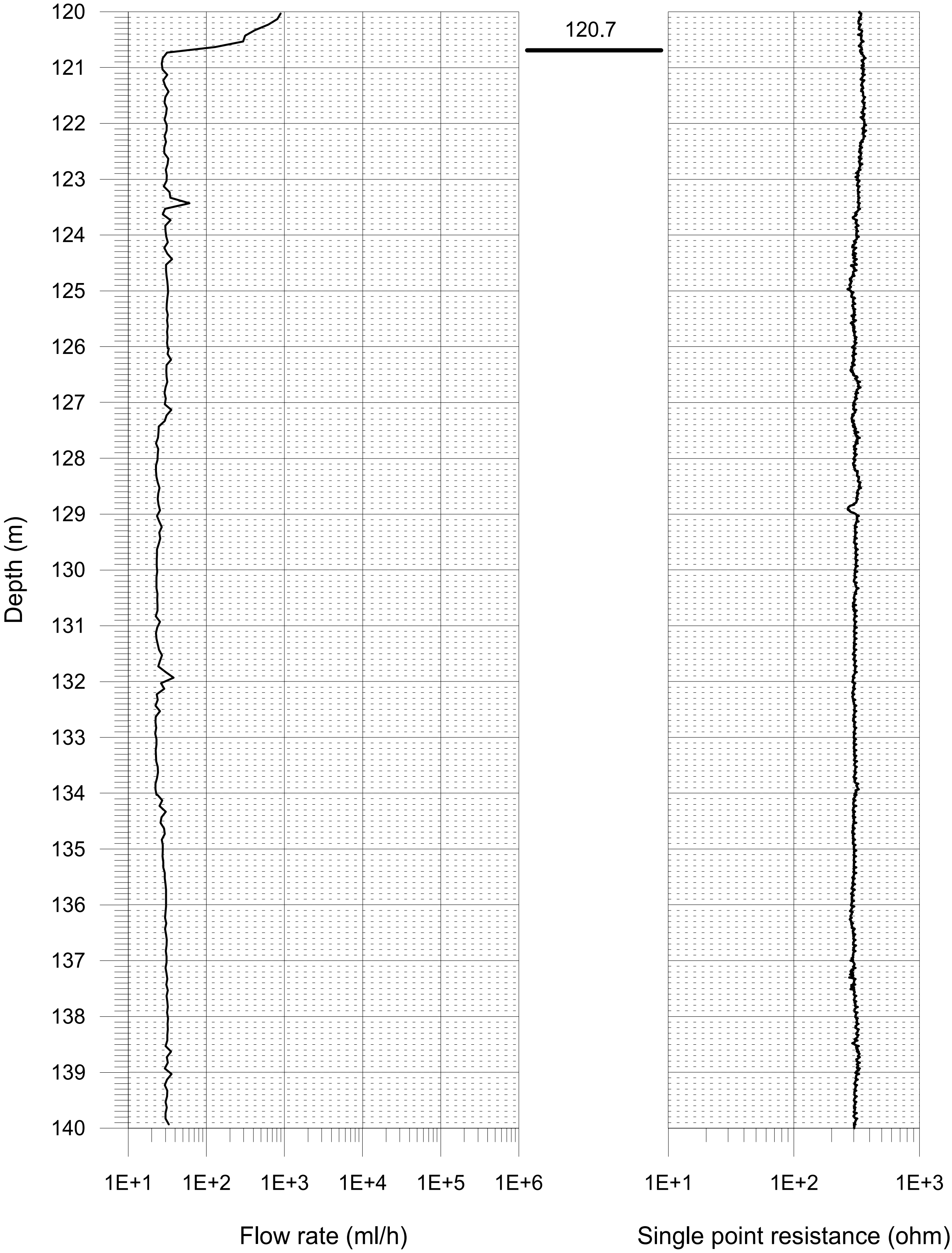
Note: A flow limiter was used, it reduces the measured flow rates above 120 l/hour

FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KA3510A



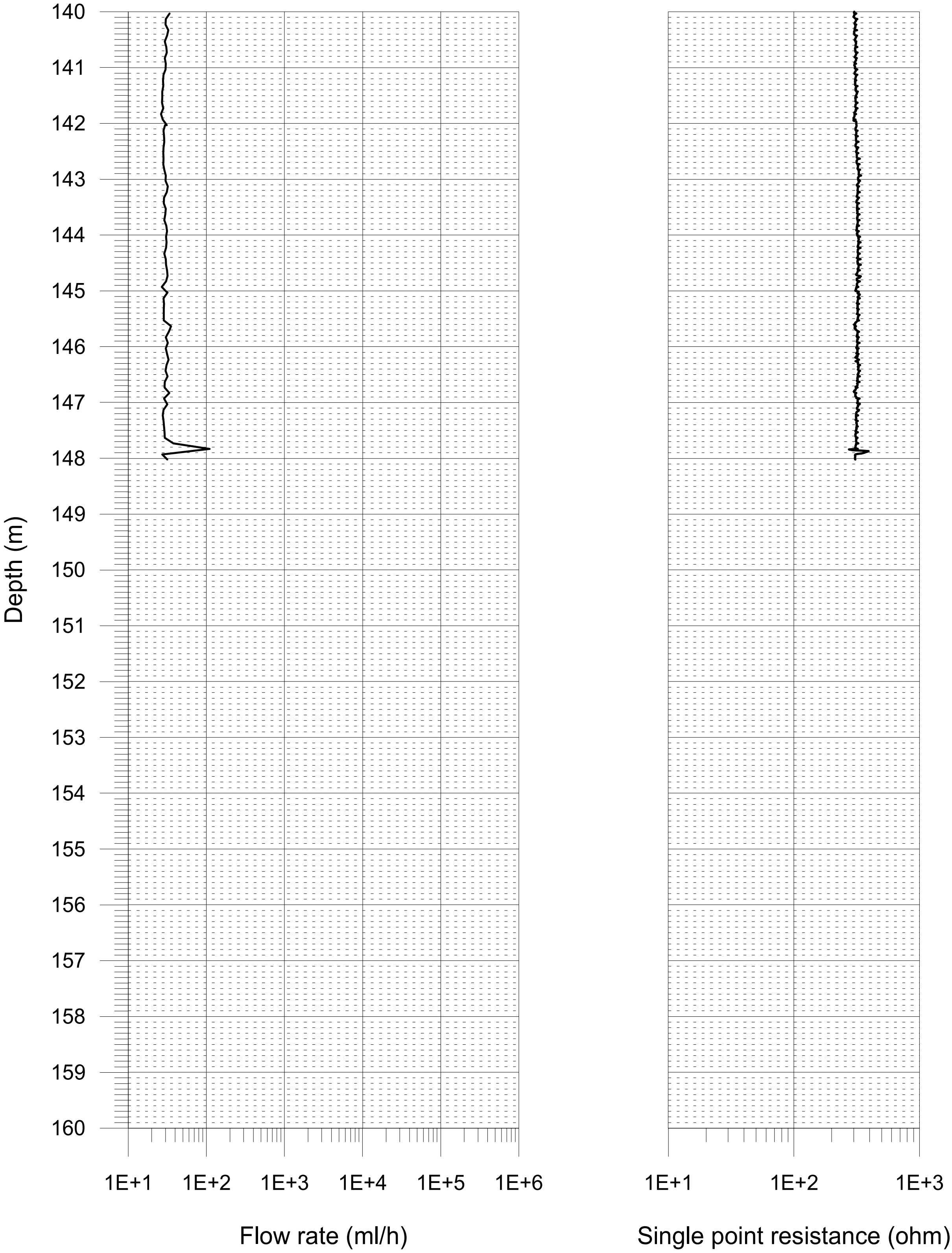
Note: A flow limiter was used, it reduces the measured flow rates above 120 l/hour

FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KA3510A



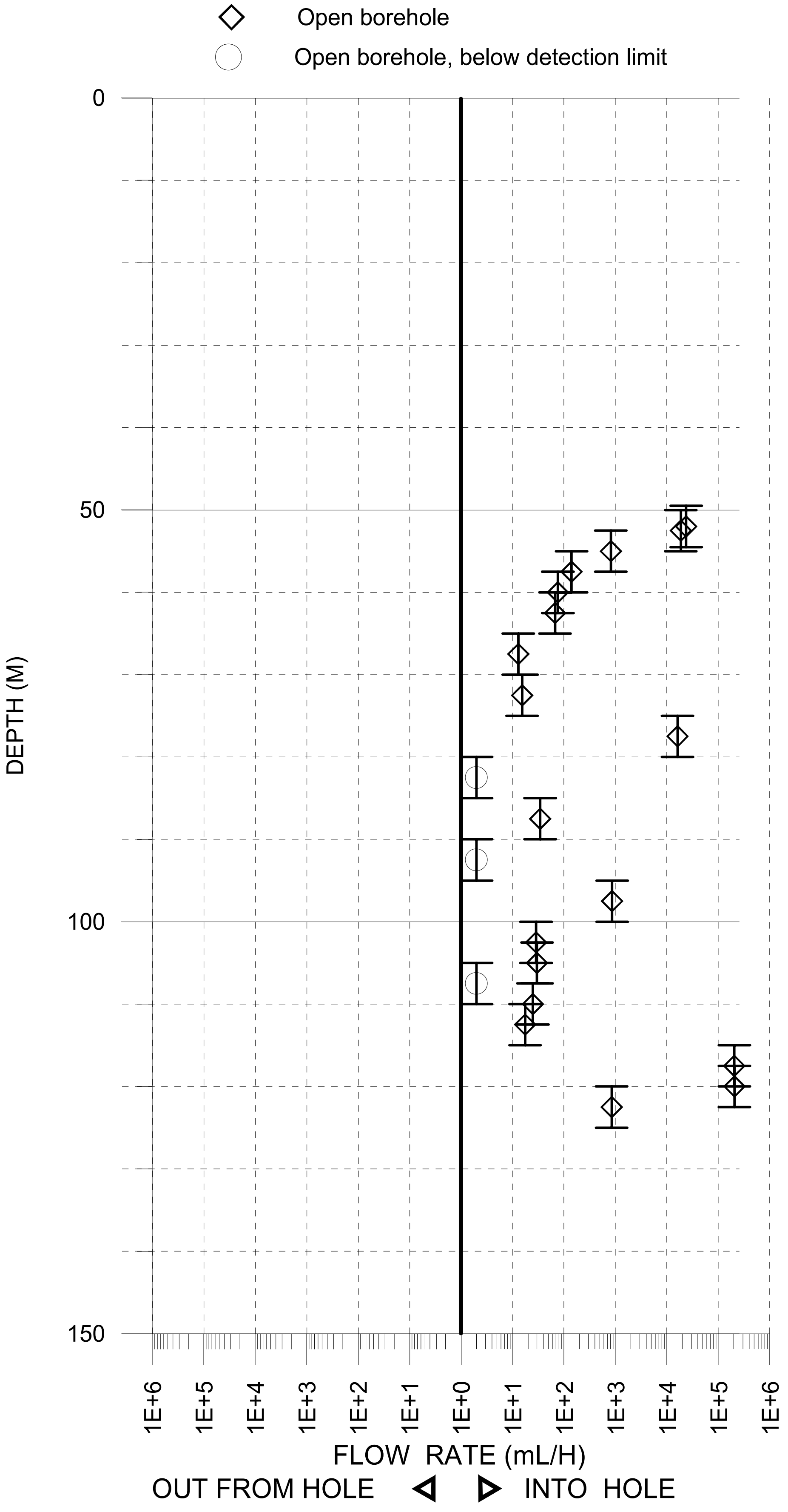
Note: A flow limiter was used, it reduces the measured flow rates above 120 l/hour

FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KA3510A



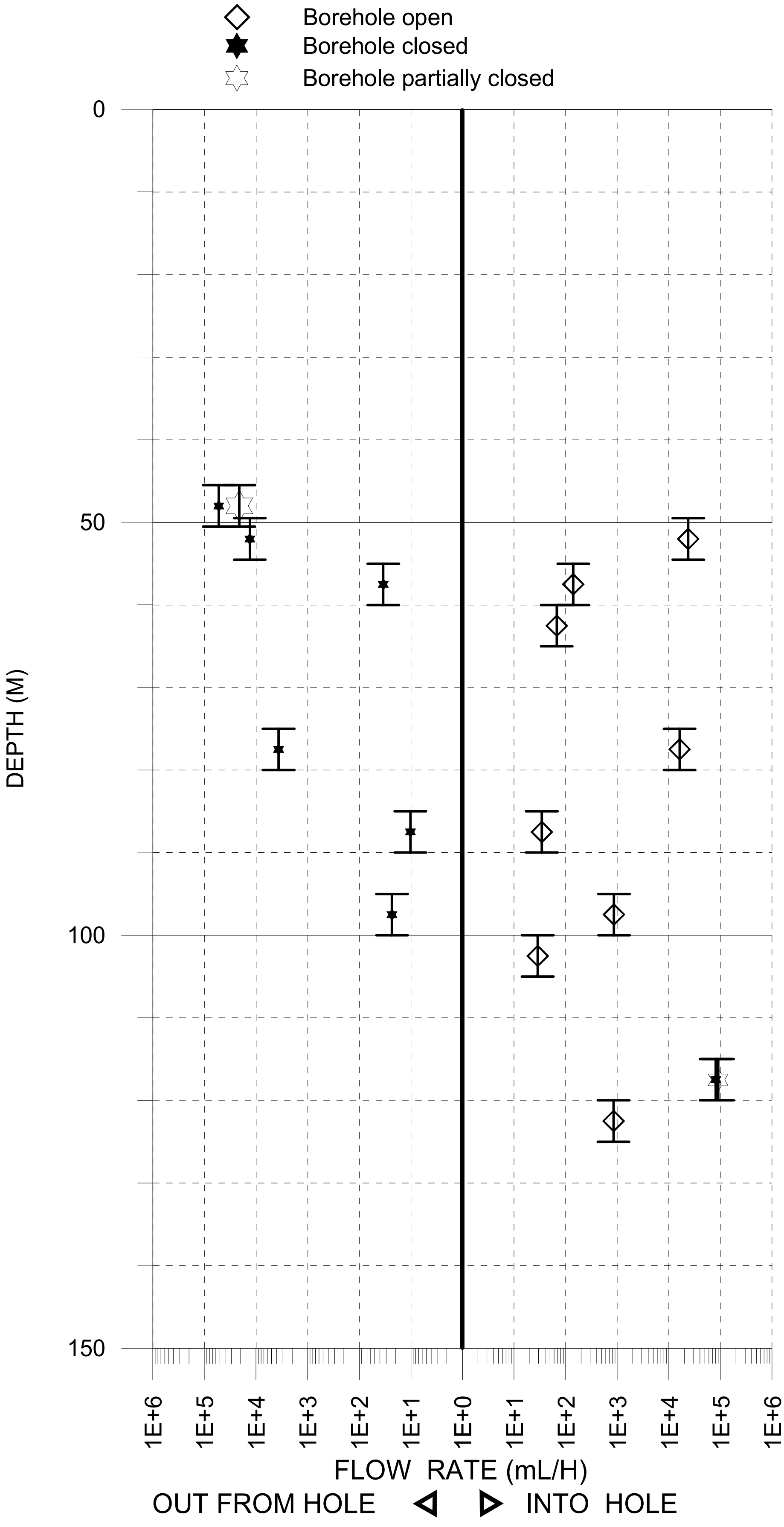
Note: A flow limiter was used, it reduces the measured flow rates above 120 l/hour

DIFFERENCE FLOW MEASUREMENT, ÄSPÖ, BOREHOLE KA3510A
FLOW RATES, LENGTH OF SECTION 5 M

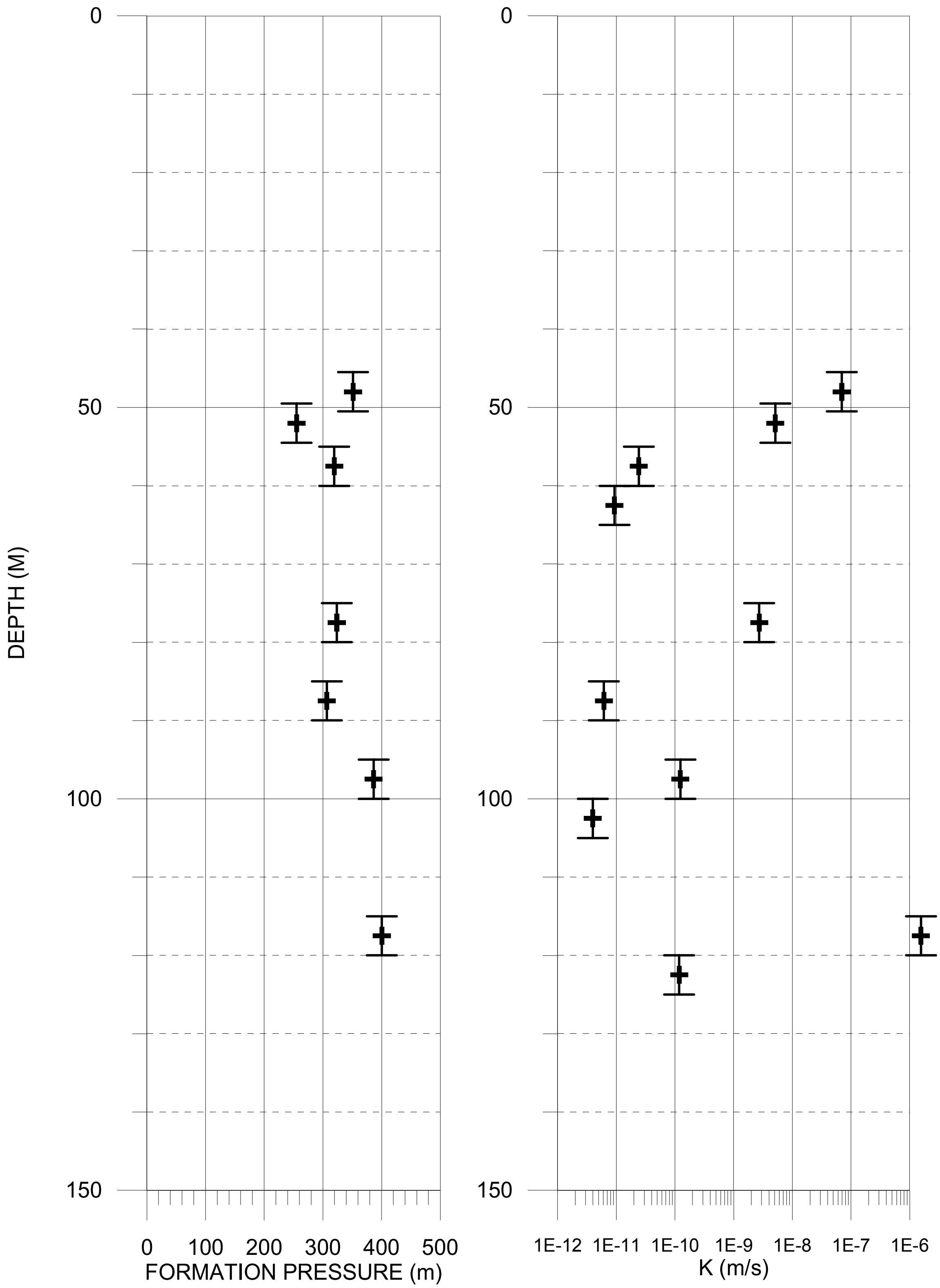


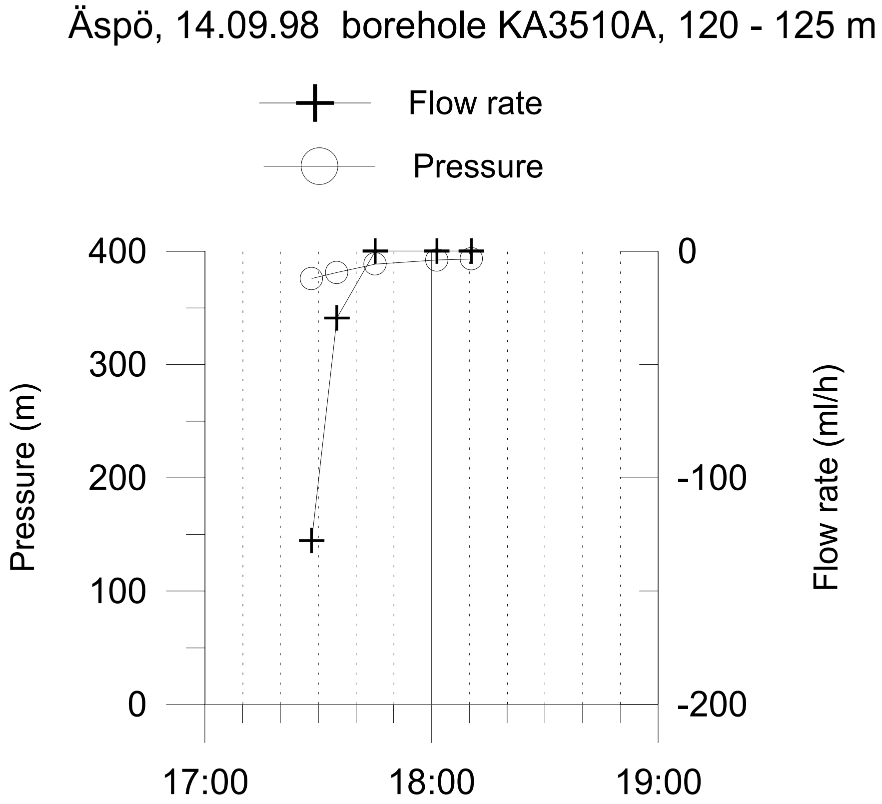
Note: A flow limiter was used, it reduces the measured flow rates above 120 l/hour

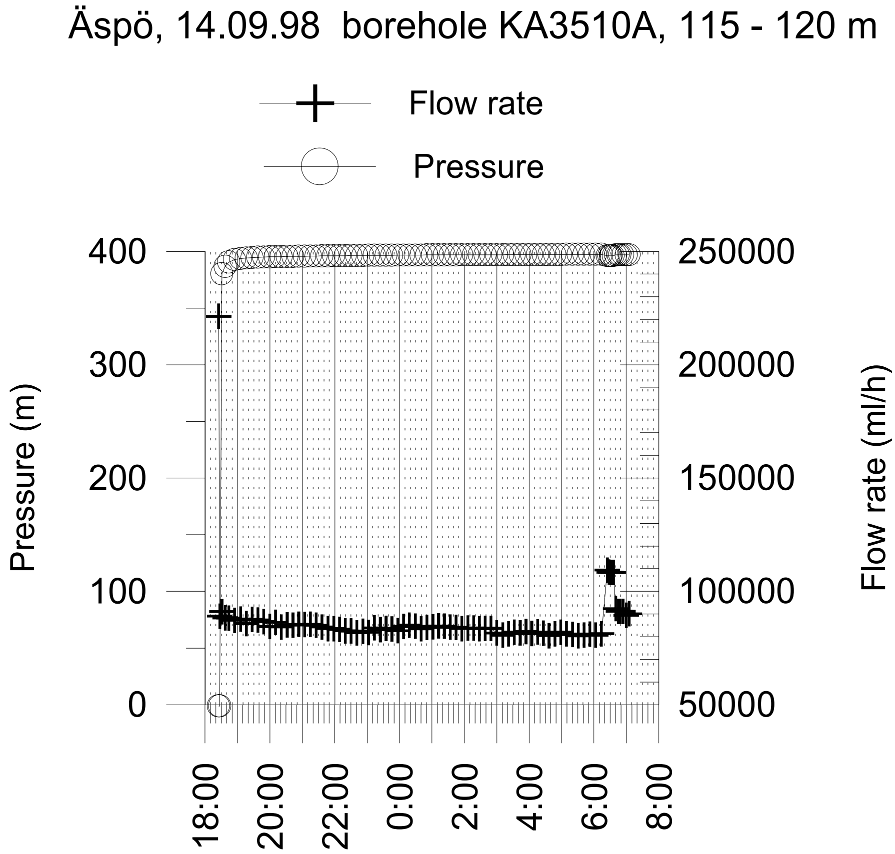
DIFFERENCE FLOW MEASUREMENT, ÄSPÖ, BOREHOLE KA3510A
FLOW RATES, LENGTH OF SECTION 5 M



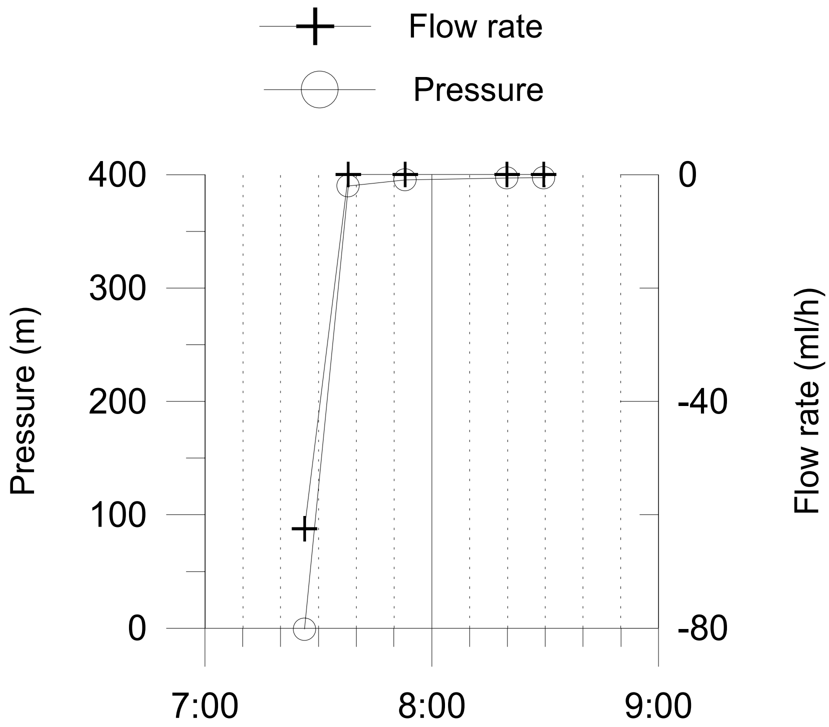
DIFFERENCE FLOW MEASUREMENT, ÄSPÖ, BOREHOLE KA3510A
FORMATION PRESSURE AND HYDRAULIC CONDUCTIVITY, LENGTH OF SECTION 5 M



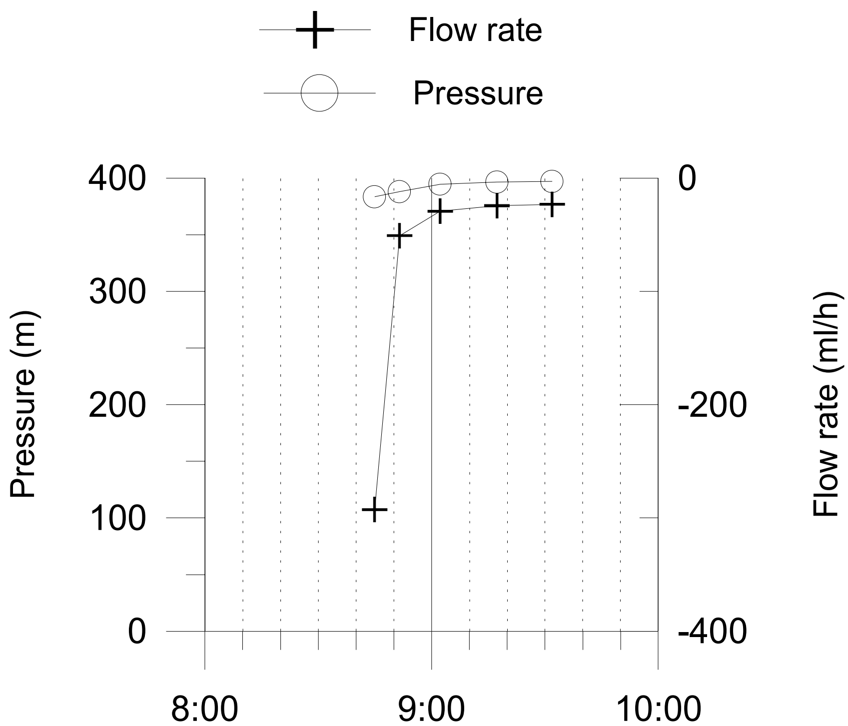

Äspö, 14.09.98 borehole KA3510A, 120 - 125 m
Flow rate
Pressure
Pressure (m)
Flow rate (ml/h)
400
300
200
100
0
0
-100
-200
17:00
18:00
19:00

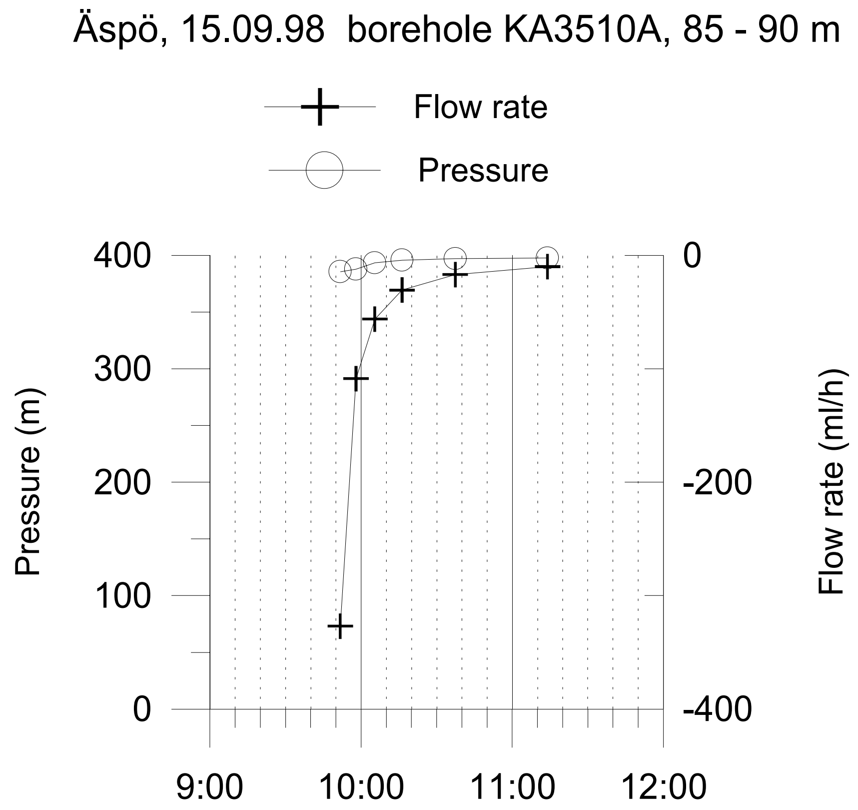

Äspö, 14.09.98 borehole KA3510A, 115 - 120 m
Flow rate
Pressure
Pressure (m)
Flow rate (ml/h)
400
300
200
100
0
250000
200000
150000
100000
50000
18:00
20:00
22:00
0:00
2:00
4:00
6:00
8:00

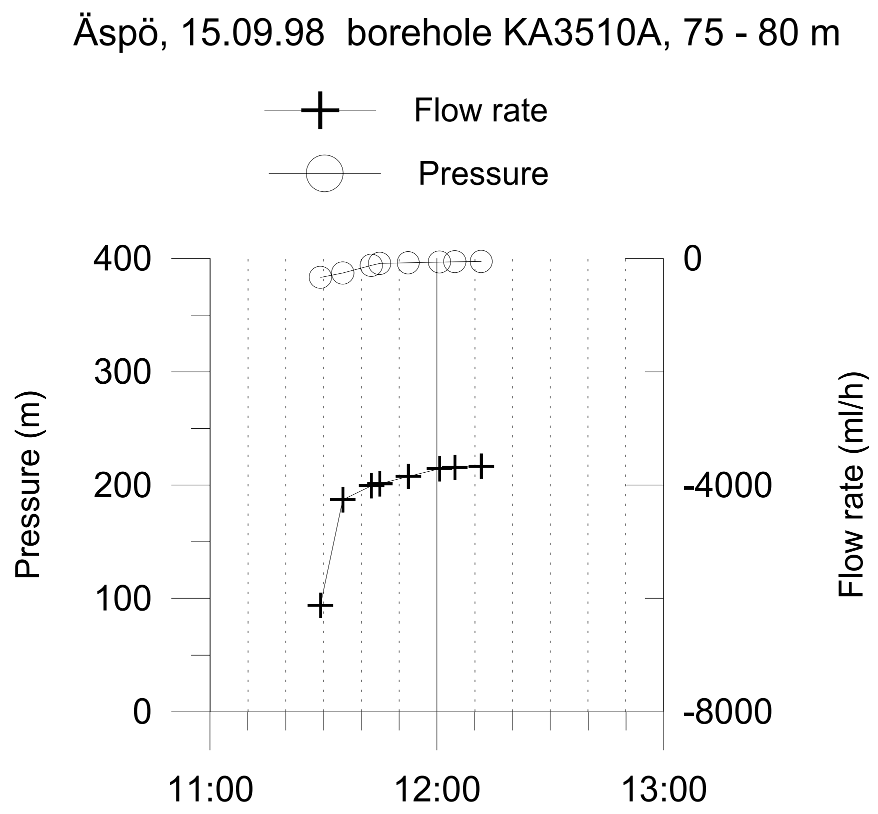
Äspö, 15.09.98 borehole KA3510A, 100 - 105 m

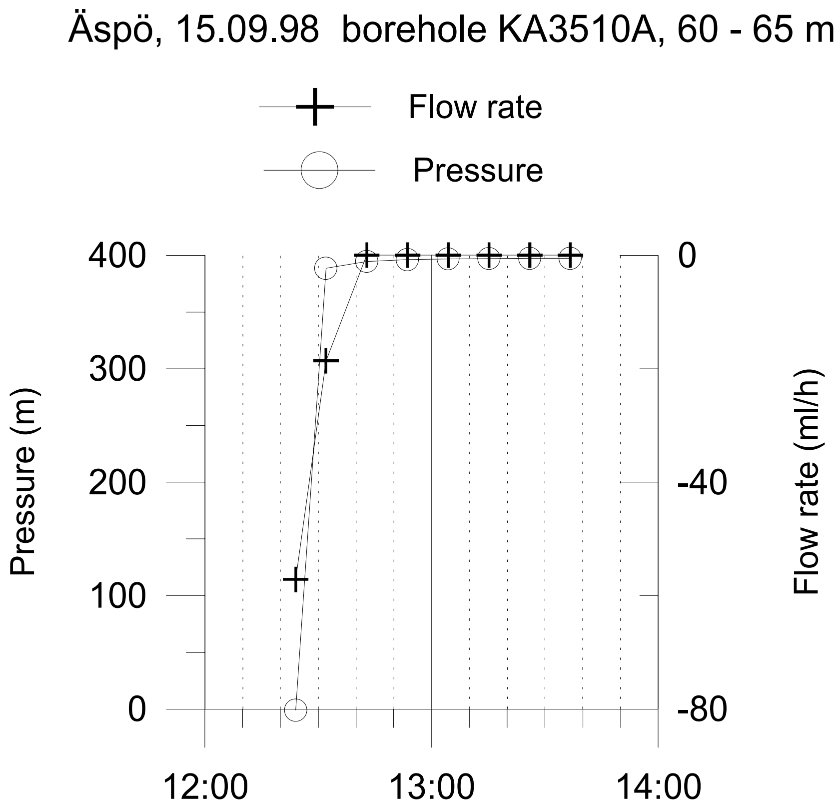


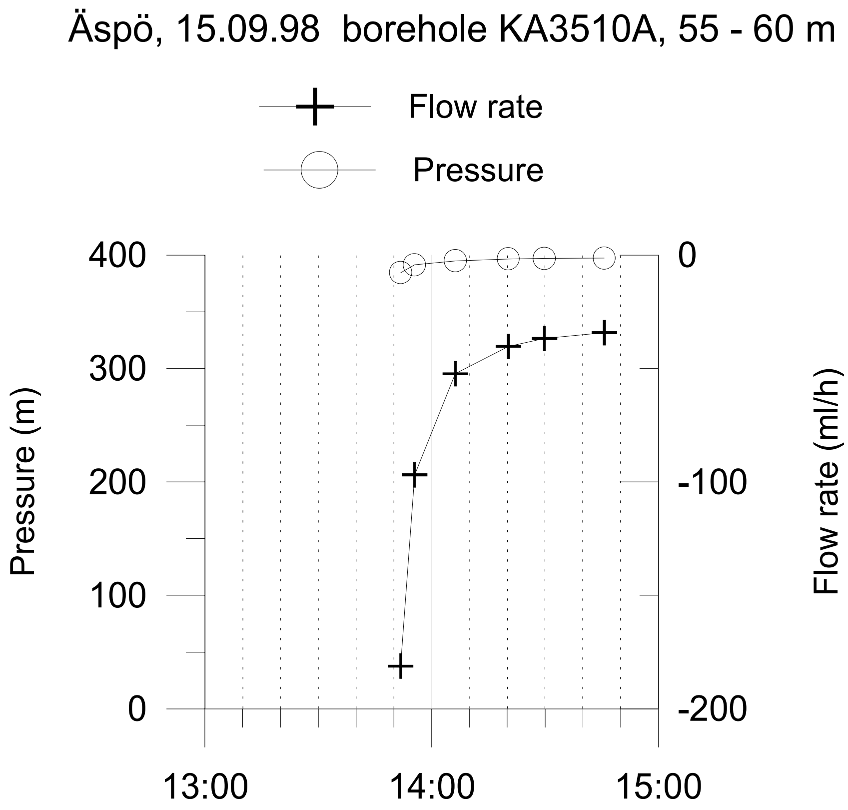
Äspö, 15.09.98 borehole KA3510A, 95 - 100 m



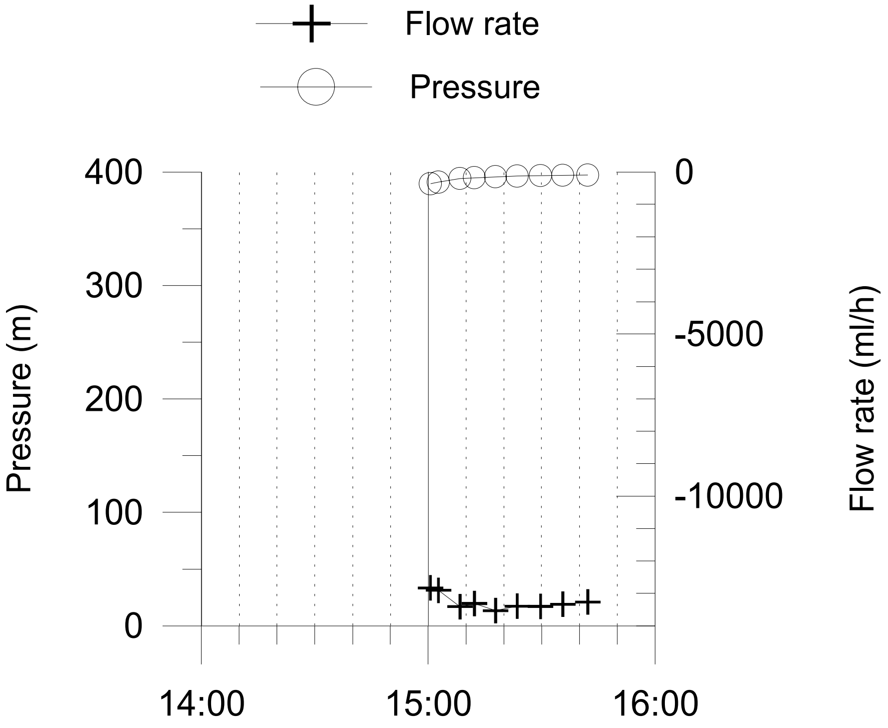

Äspö, 15.09.98 borehole KA3510A, 85 - 90 m
Flow rate
Pressure
400
300
200
100
0
Pressure (m)
0
-200
-400
Flow rate (ml/h)
9:00
10:00
11:00
12:00


Äspö, 15.09.98 borehole KA3510A, 75 - 80 m
Flow rate
Pressure
400
300
200
100
0
Pressure (m)
0
-4000
-8000
Flow rate (ml/h)
11:00
12:00
13:00

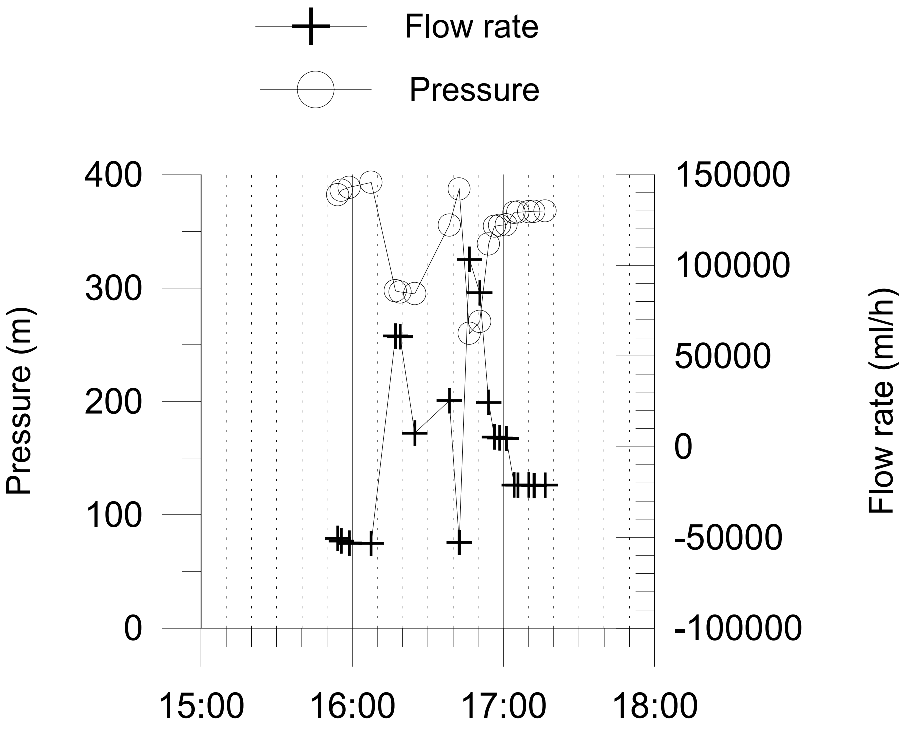

Äspö, 15.09.98 borehole KA3510A, 60 - 65 m
Flow rate
Pressure
Pressure (m)
Flow rate (ml/h)
400
300
200
100
0
-40
-80
12:00
13:00
14:00


Äspö, 15.09.98 borehole KA3510A, 55 - 60 m
Flow rate
Pressure
Pressure (m)
Flow rate (ml/h)
400
300
200
100
0
-100
-200
13:00
14:00
15:00

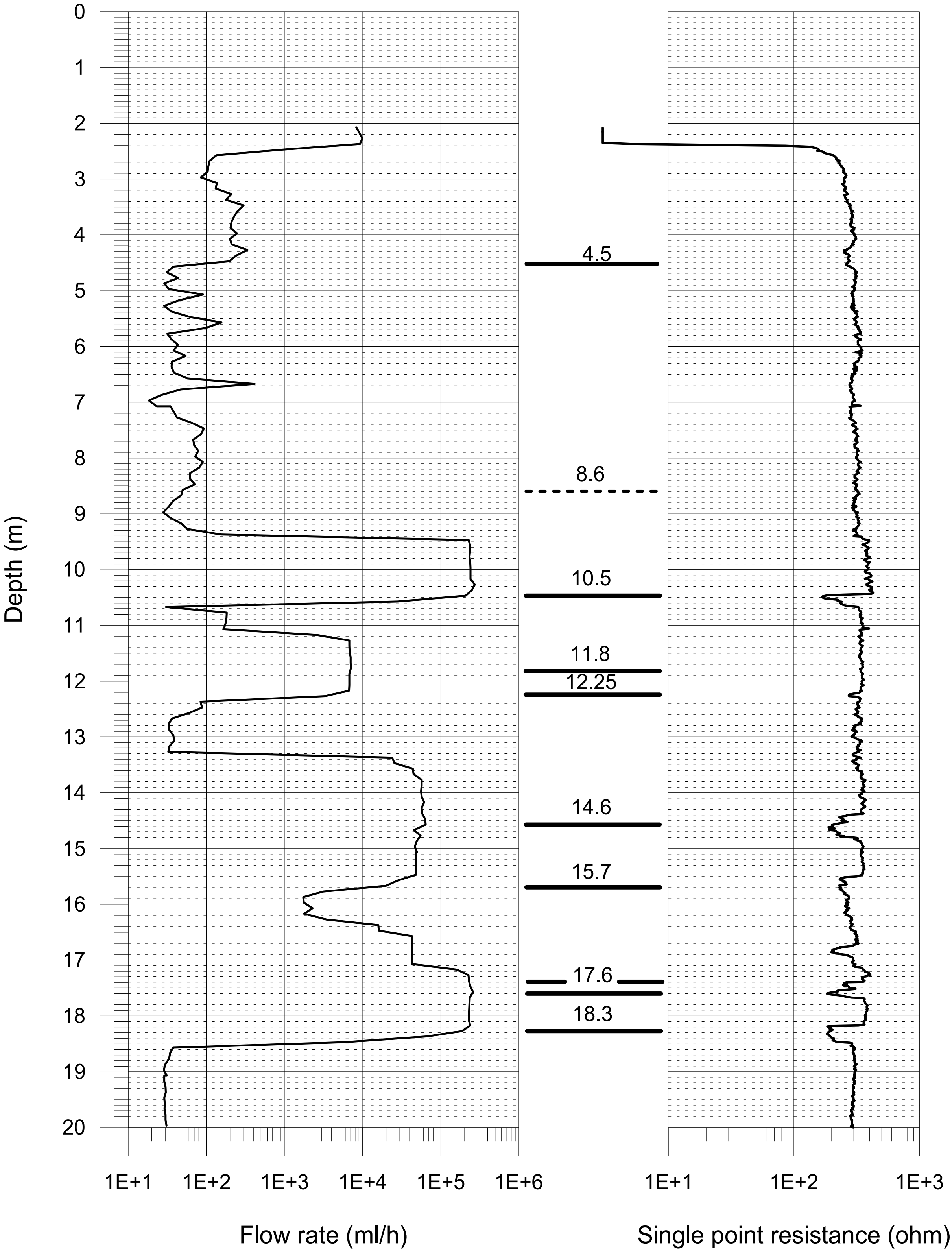
Äspö, 15.09.98 borehole KA3510A, 49.5 - 54.5 m



Äspö, 15.09.98 borehole KA3510A, 45.5 - 50.5 m

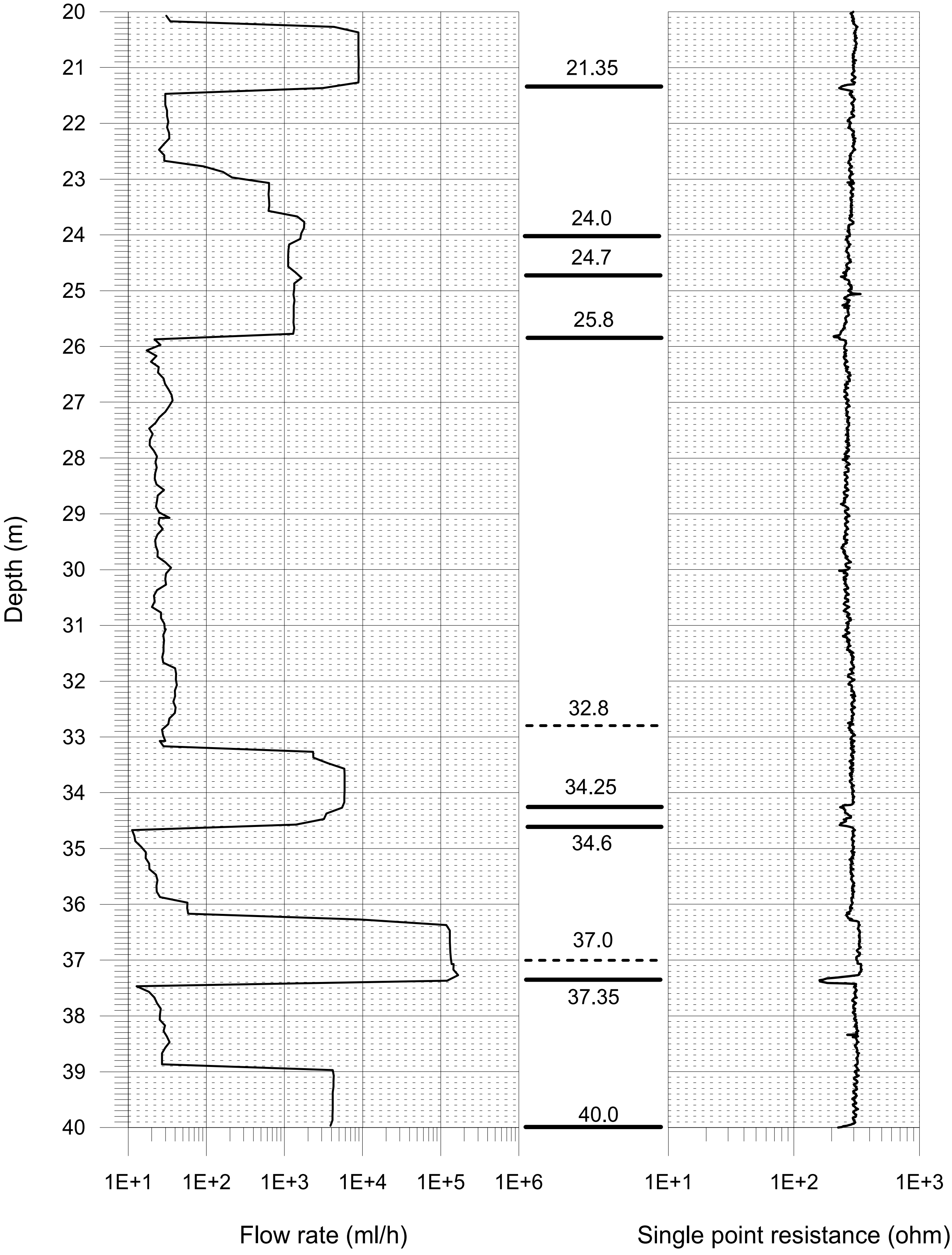


FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KA2598A



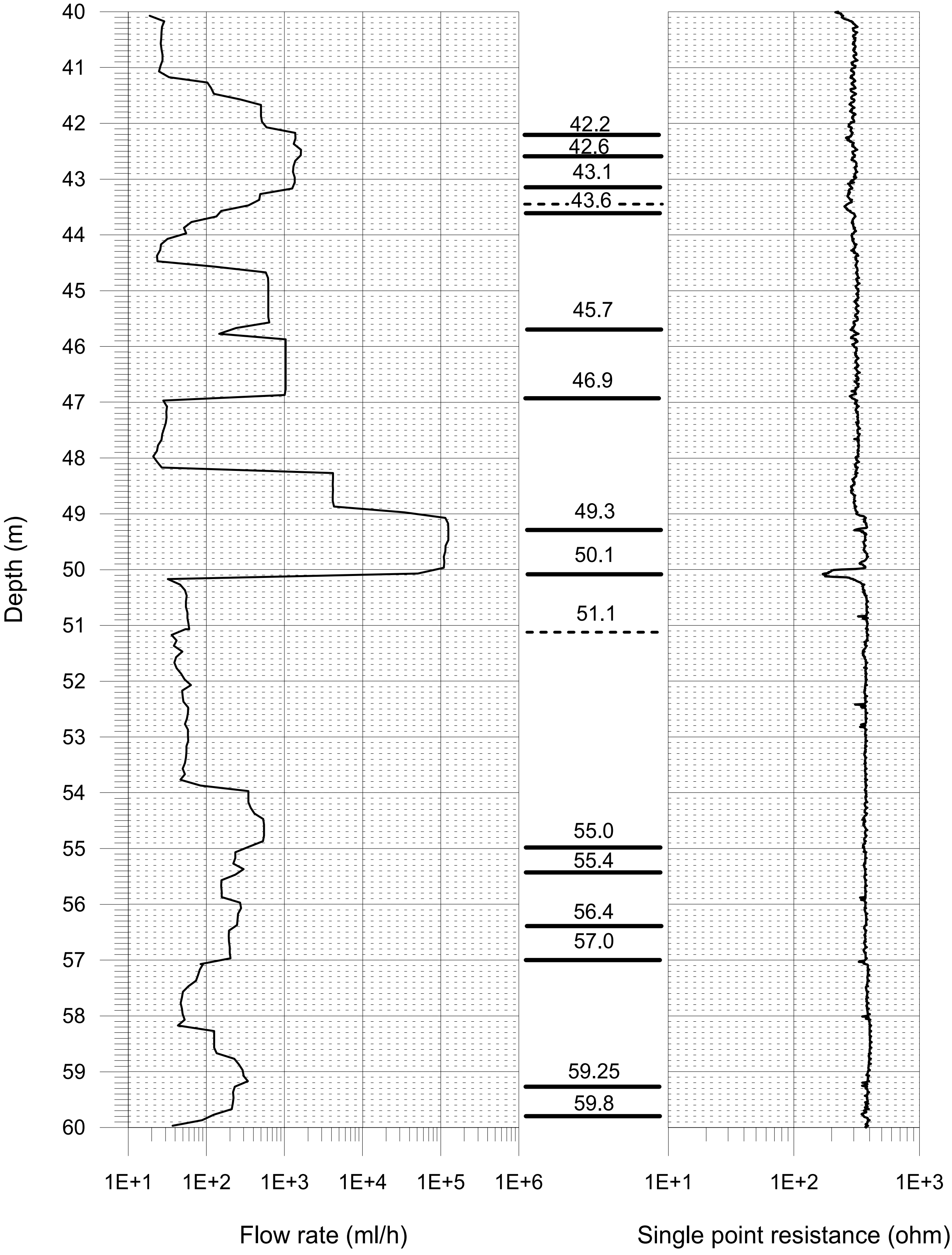
Note: A flow limiter was used, it reduces the measured flow rates above 120 l/hour

FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KA2598A



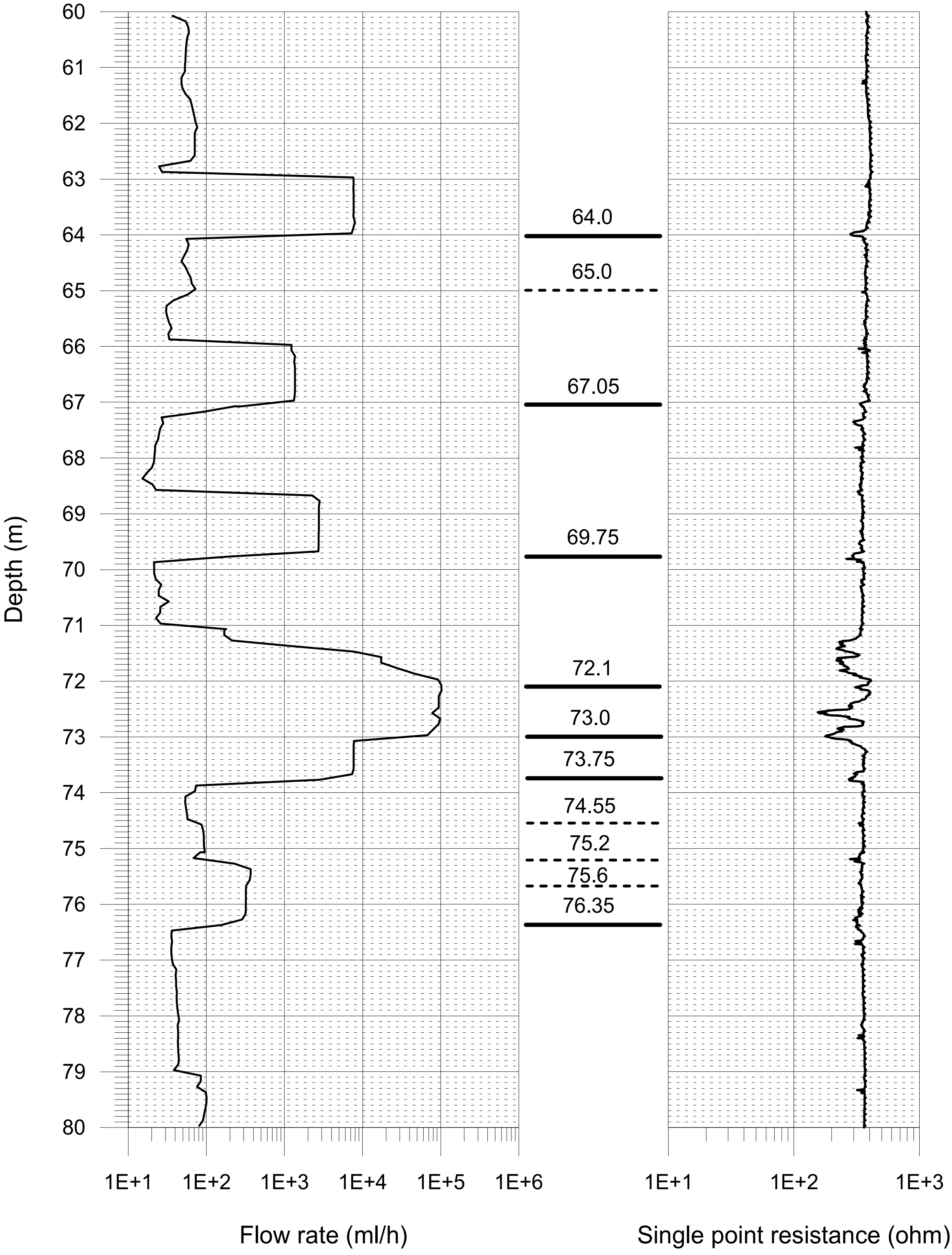
Note: A flow limiter was used, it reduces the measured flow rates above 120 l/hour

FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KA2598A



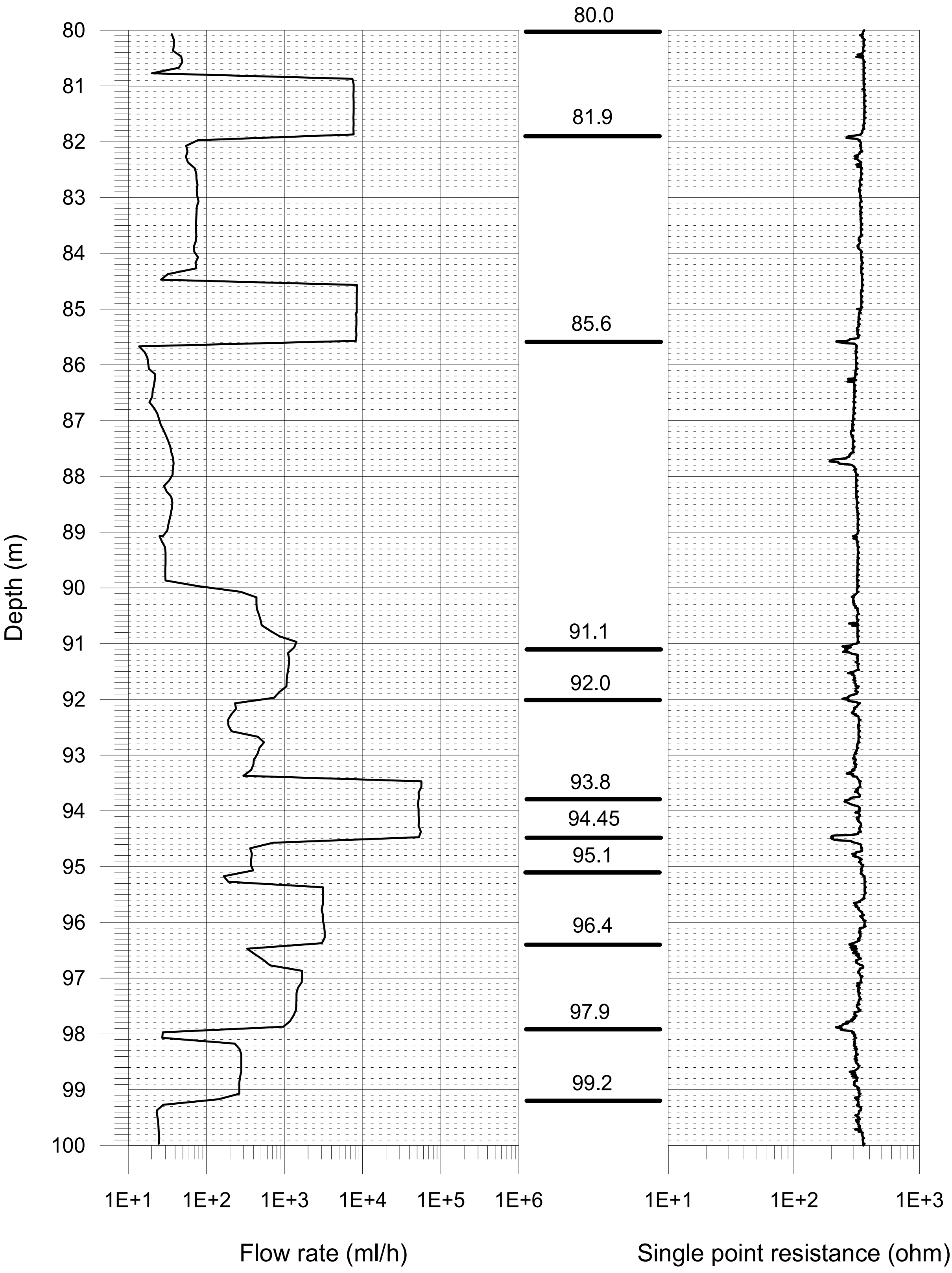
Note: A flow limiter was used, it reduces the measured flow rates above 120 l/hour

FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KA2598A



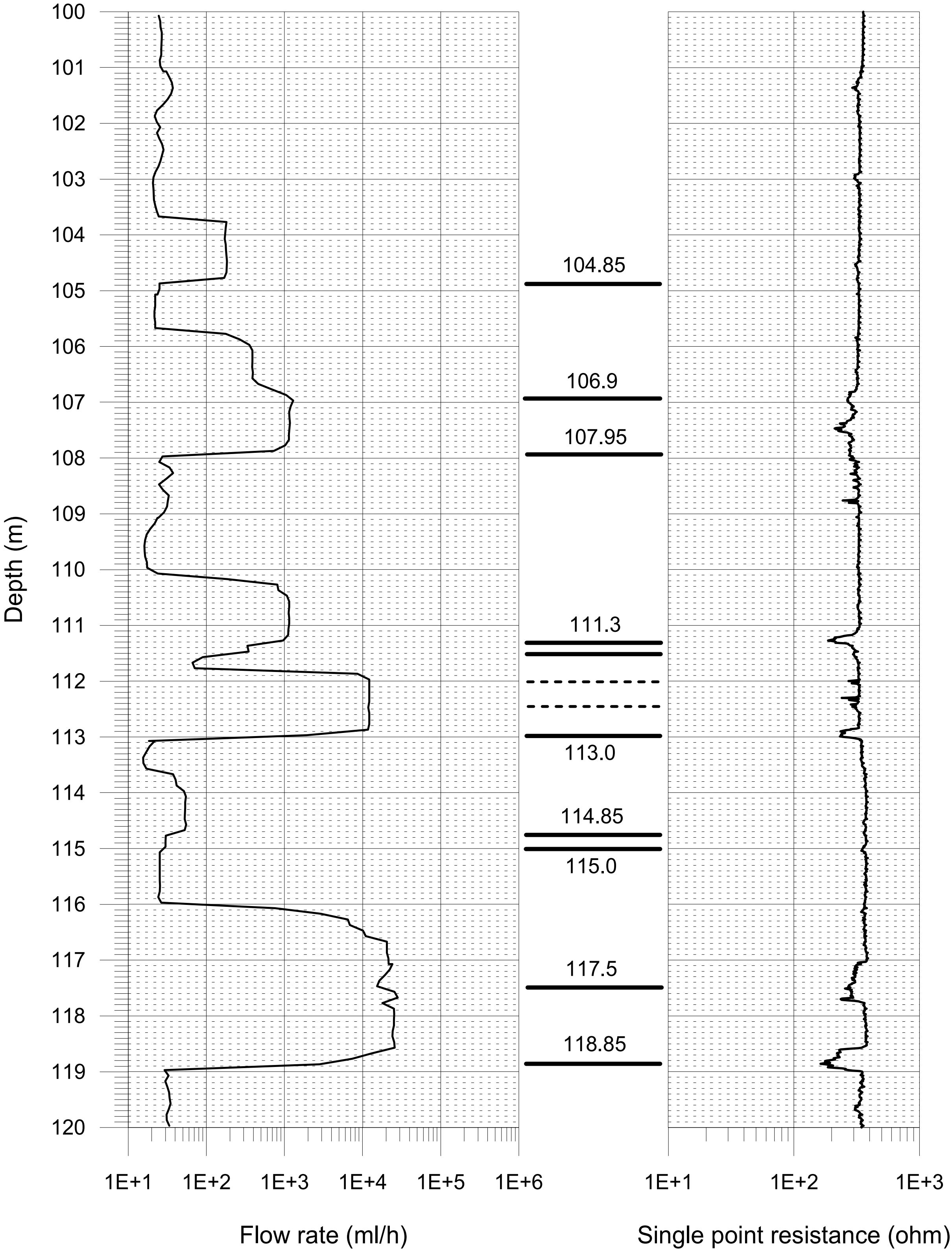
Note: A flow limiter was used, it reduces the measured flow rates above 120 l/hour

FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KA2598A



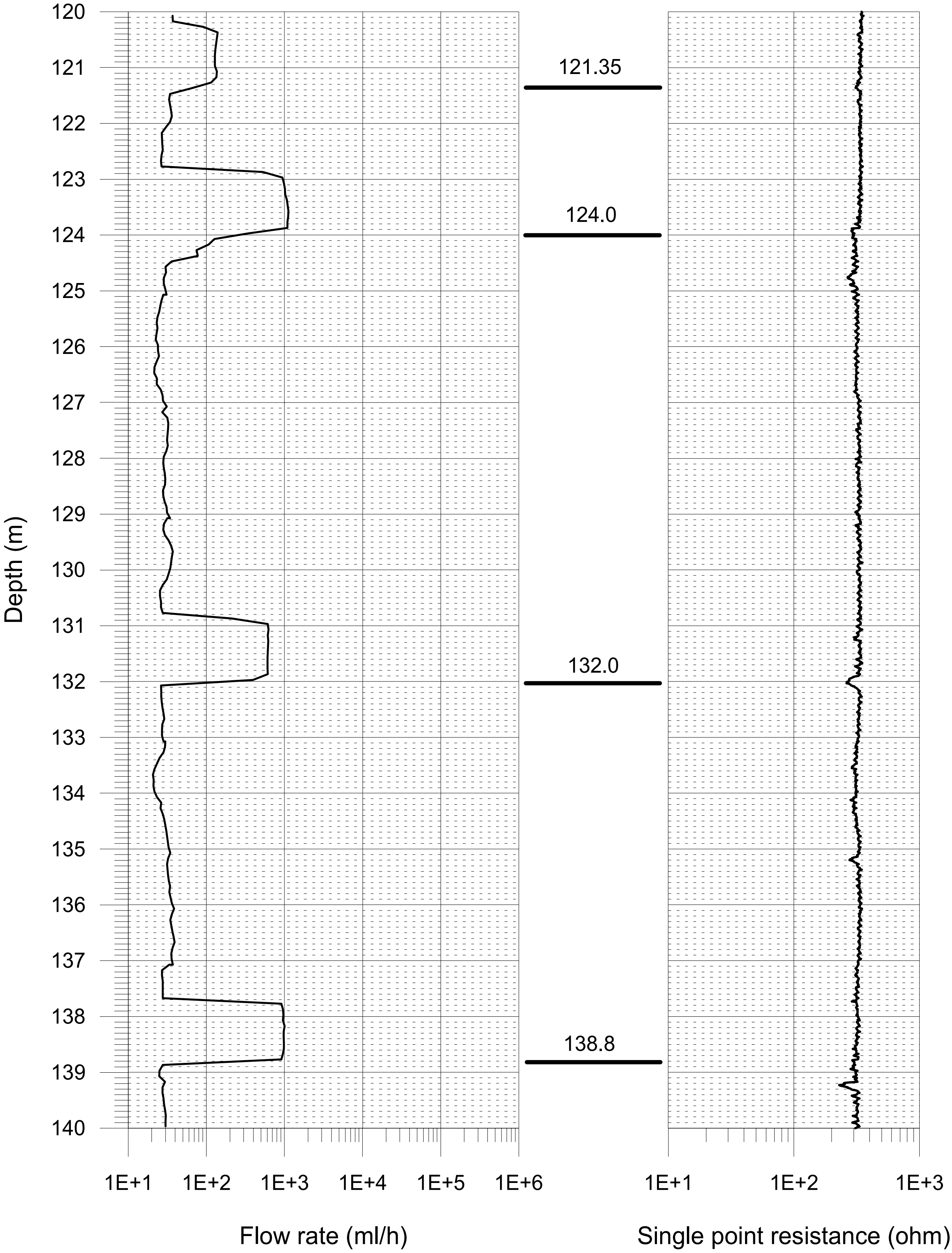
Note: A flow limiter was used, it reduces the measured flow rates above 120 l/hour

FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KA2598A



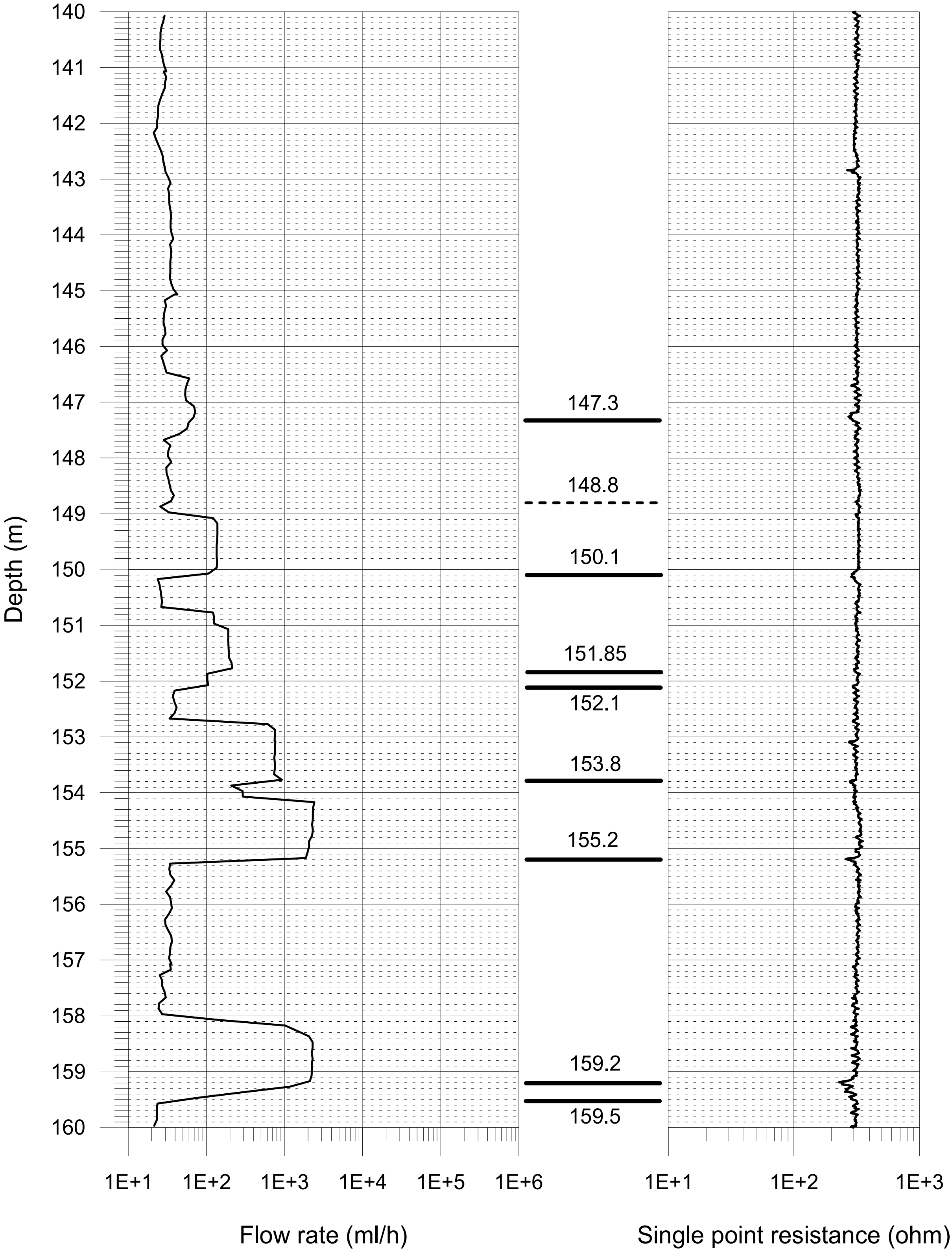
Note: A flow limiter was used, it reduces the measured flow rates above 120 l/hour

FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KA2598A



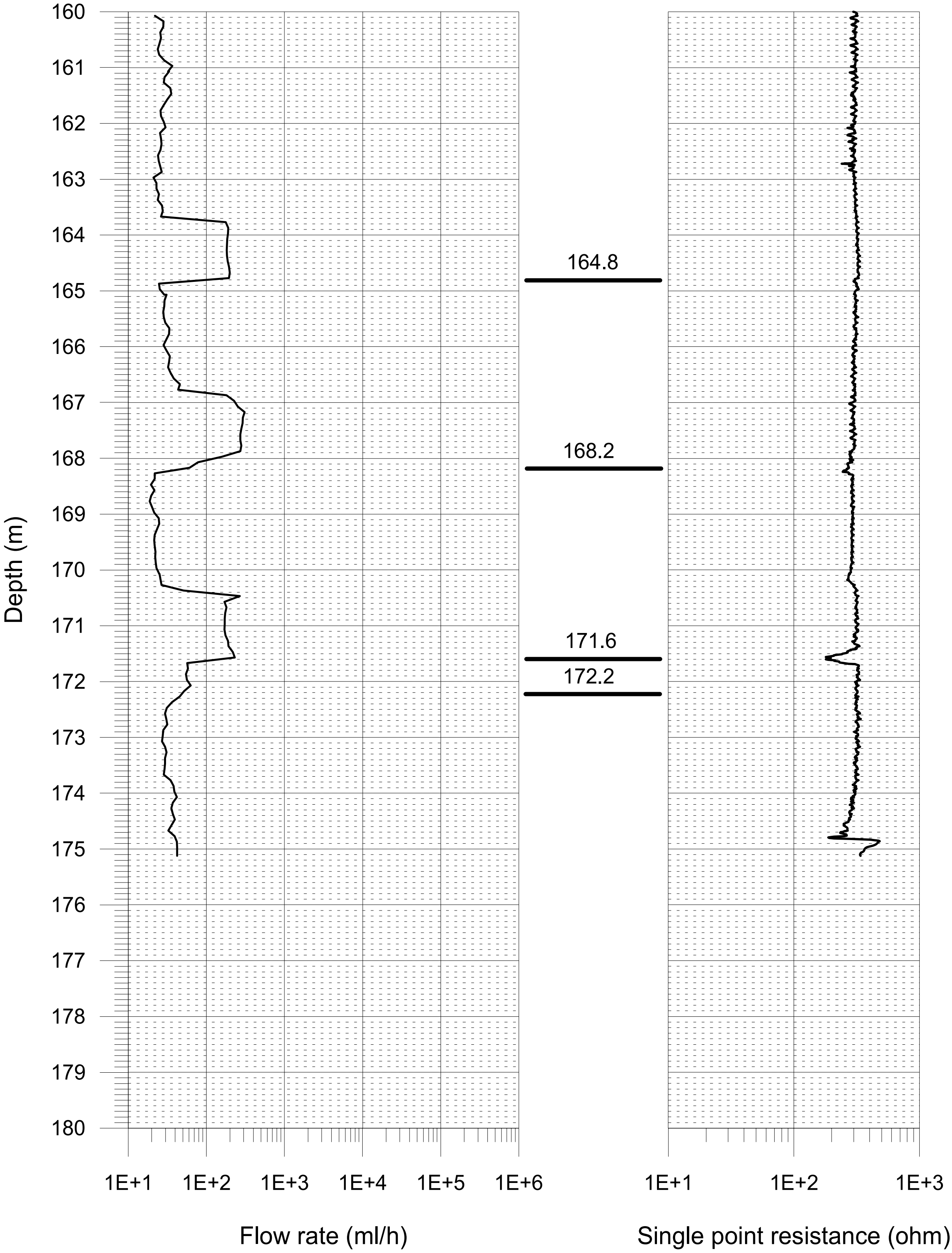
Note: A flow limiter was used, it reduces the measured flow rates above 120 l/hour

FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KA2598A

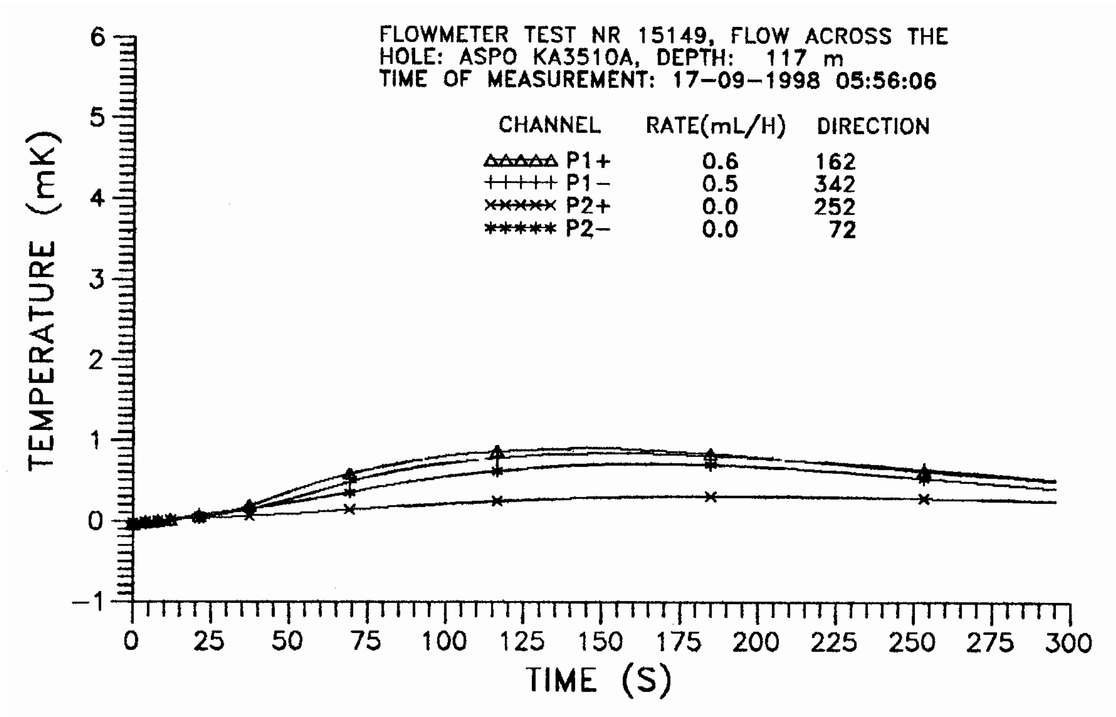


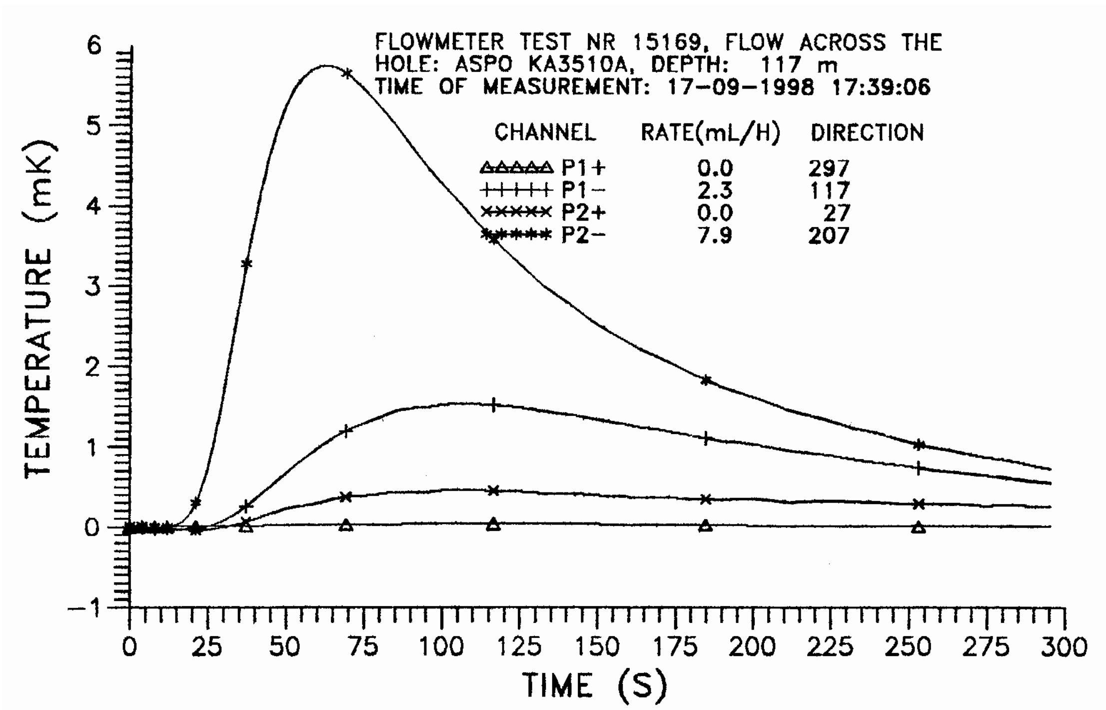
Note: A flow limiter was used, it reduces the measured flow rates above 120 l/hour

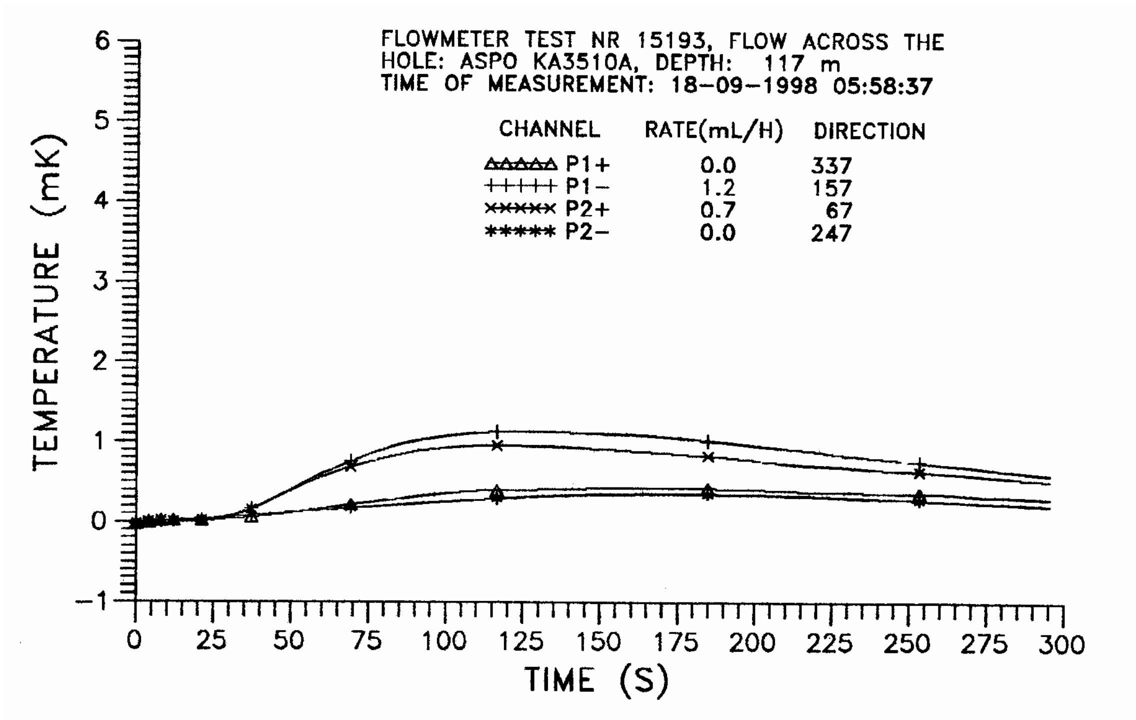
FLOW RATE AND SINGLE POINT RESISTANCE LOGS
DEPTHS OF LEAKY FRACTURES
ÄSPÖ, KA2598A

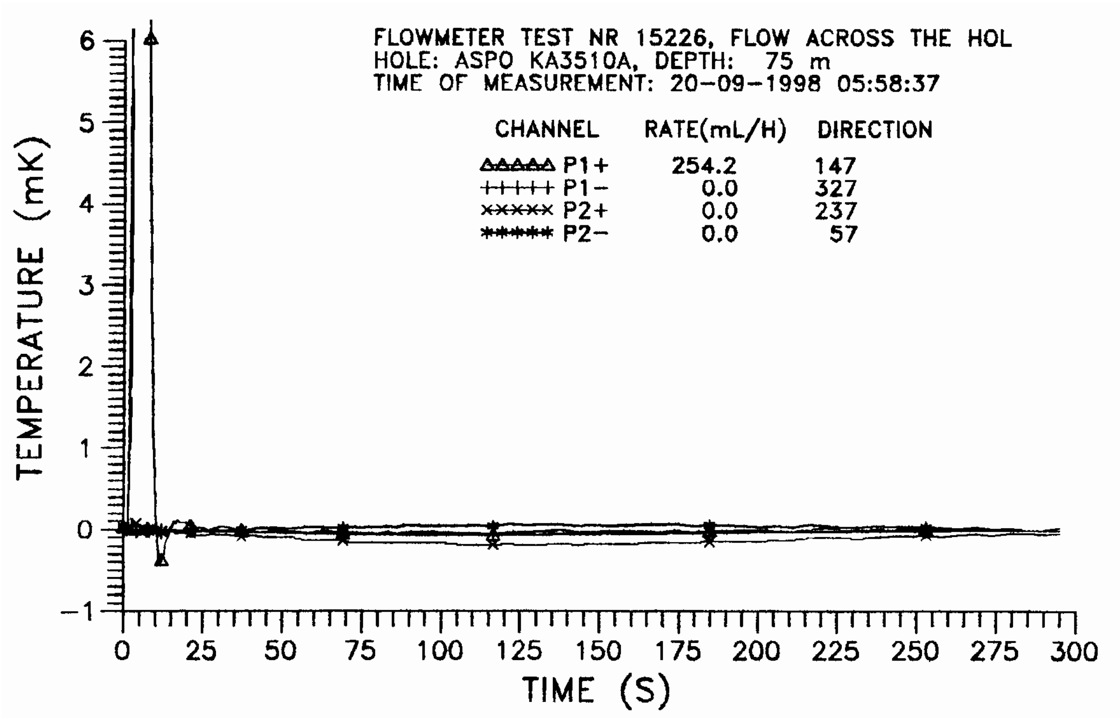


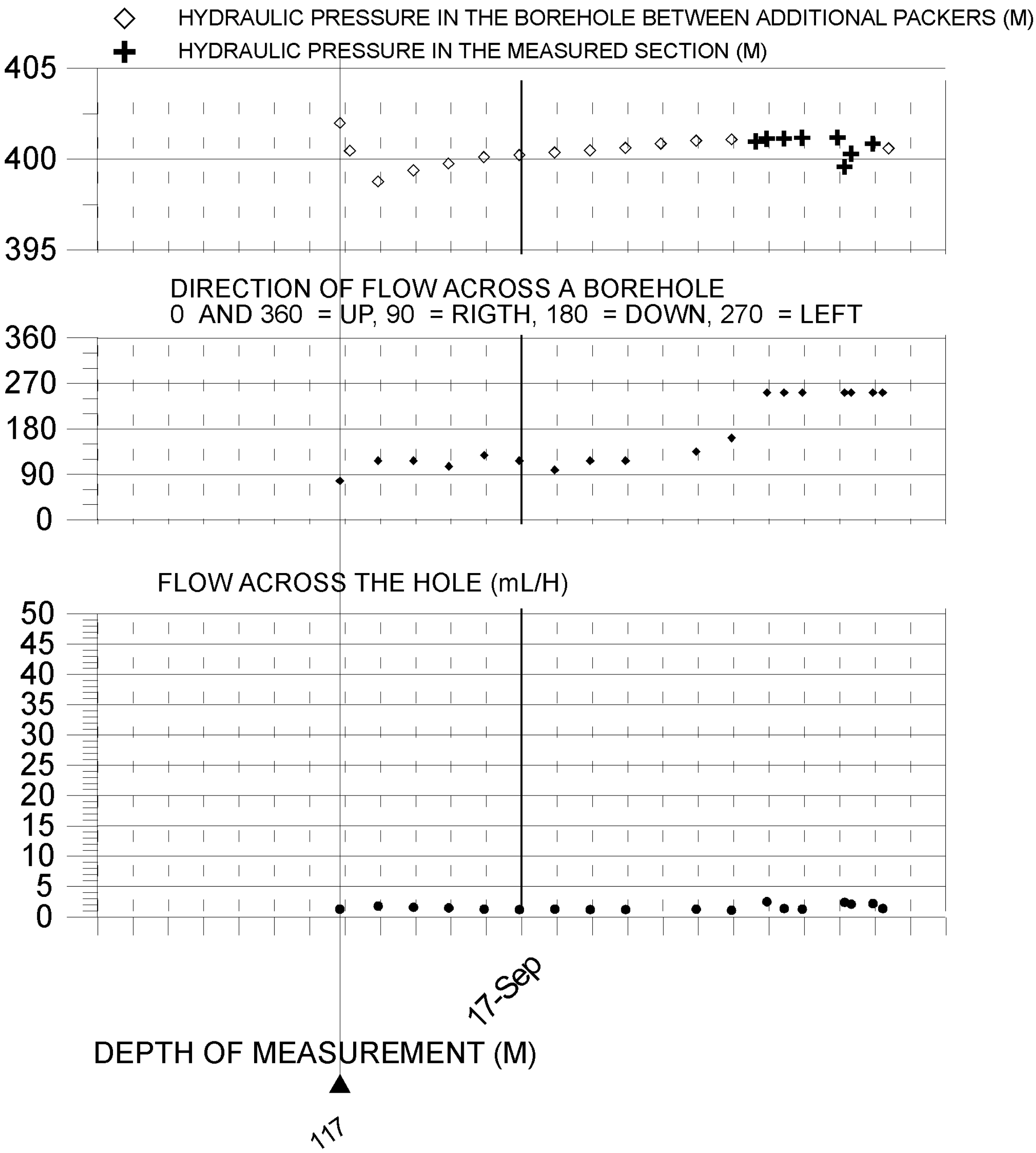
Note: A flow limiter was used, it reduces the measured flow rates above 120 l/hour

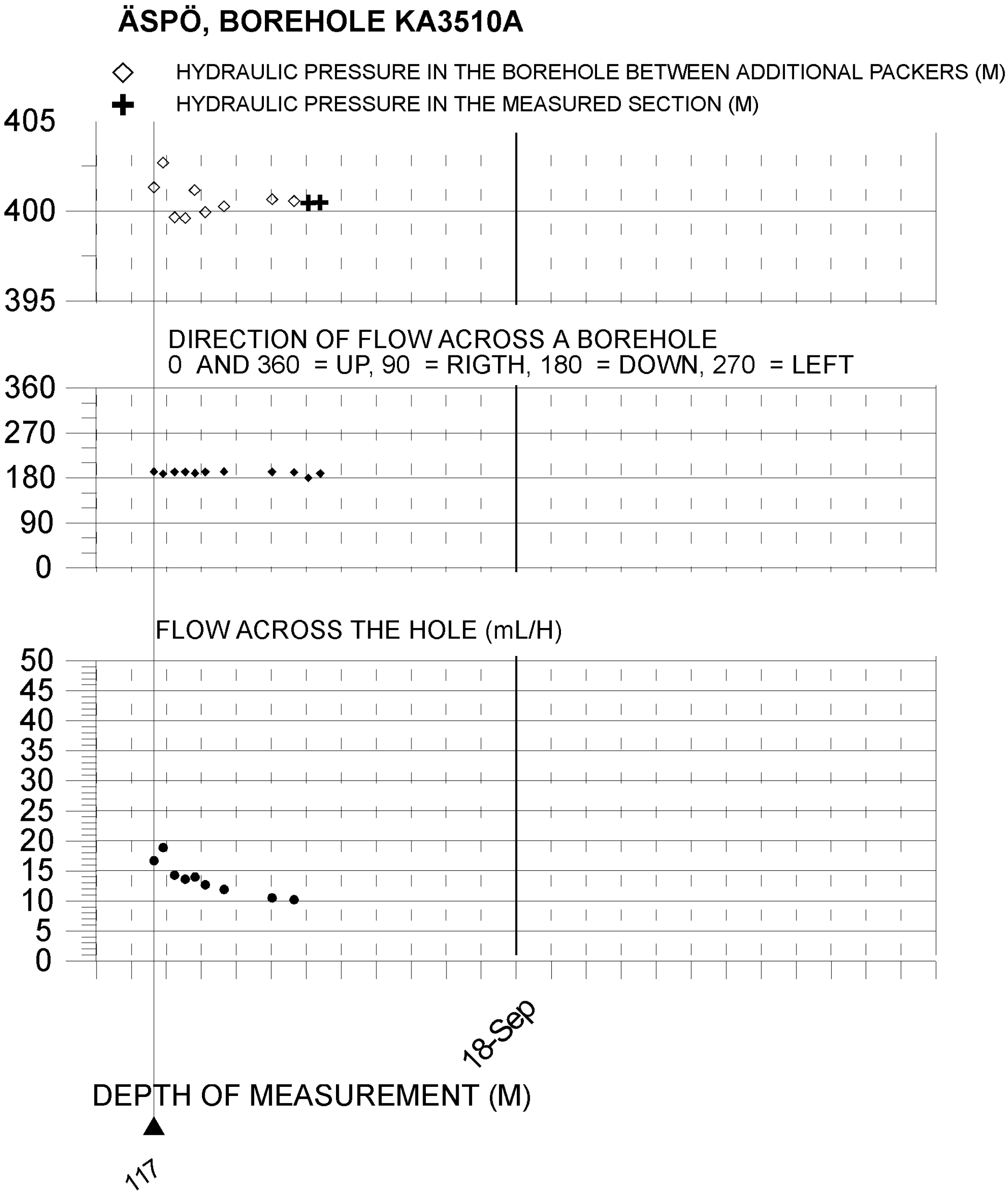

FLOWMETER TEST NR 15149, FLOW ACROSS THE
HOLE: ASPO KA3510A, DEPTH: 117 m
TIME OF MEASUREMENT: 17-09-1998 05:56:06
CHANNEL RATE(mL/H) DIRECTION
P1+ 0.6 162
P1- 0.5 342
P2+ 0.0 252
P2- 0.0 72
TEMPERATURE (mK)
TIME (S)
6
5
4
3
2
1
0
-1
0
25
50
75
100
125
150
175
200
225
250
275
300

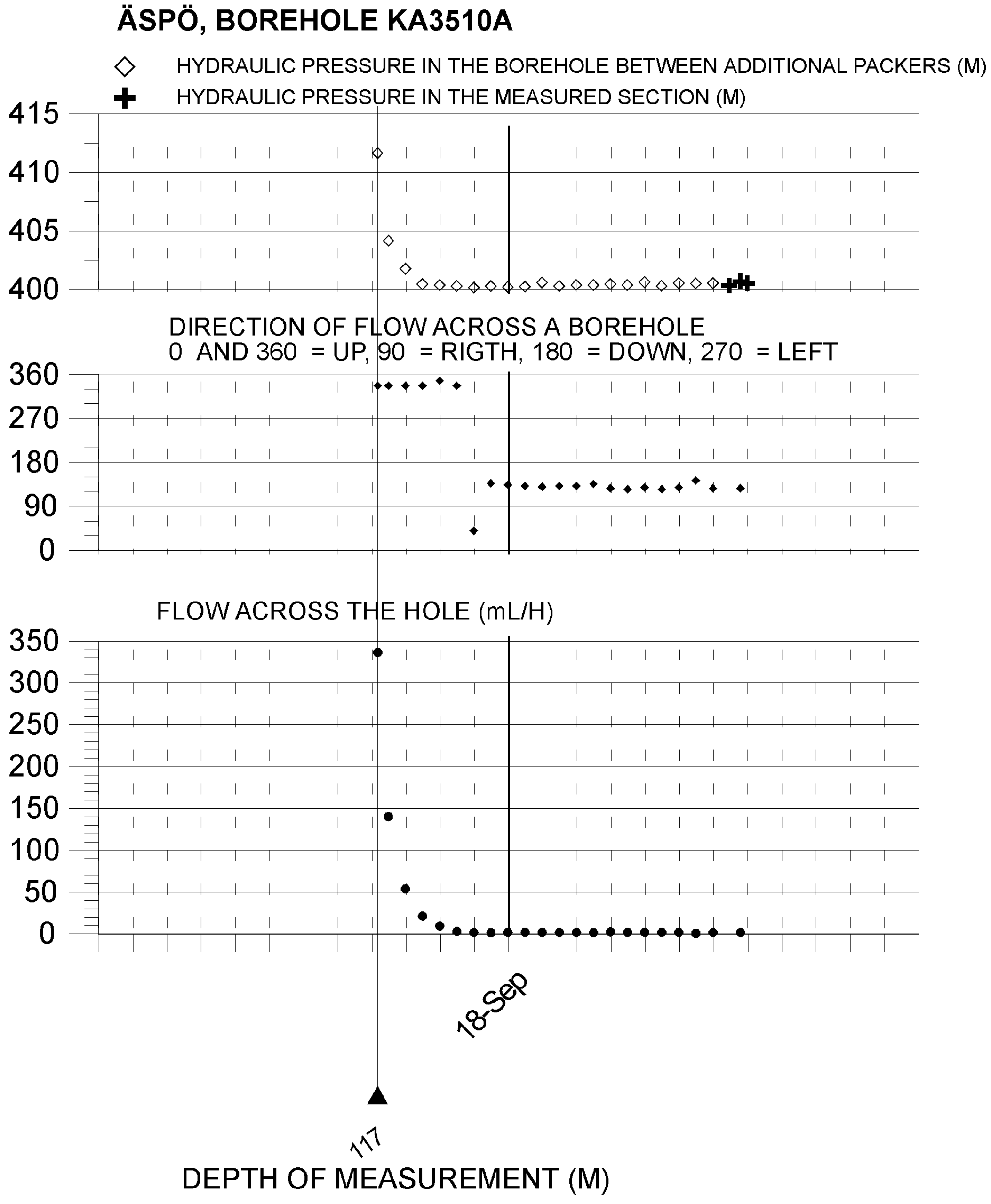

FLOWMETER TEST NR 15169, FLOW ACROSS THE
HOLE: ASPO KA3510A, DEPTH: 117 m
TIME OF MEASUREMENT: 17-09-1998 17:39:06
CHANNEL RATE(mL/H) DIRECTION
P1+ 0.0 297
P1- 2.3 117
P2+ 0.0 27
P2- 7.9 207
TEMPERATURE (mK)
TIME (S)
6
5
4
3
2
1
0
-1
0
25
50
75
100
125
150
175
200
225
250
275
300


FLOWMETER TEST NR 15193, FLOW ACROSS THE
HOLE: ASPO KA3510A, DEPTH: 117 m
TIME OF MEASUREMENT: 18-09-1998 05:58:37
CHANNEL RATE(mL/H) DIRECTION
P1+ 0.0 337
P1- 1.2 157
P2+ 0.7 67
P2- 0.0 247
TEMPERATURE (mK)
TIME (S)

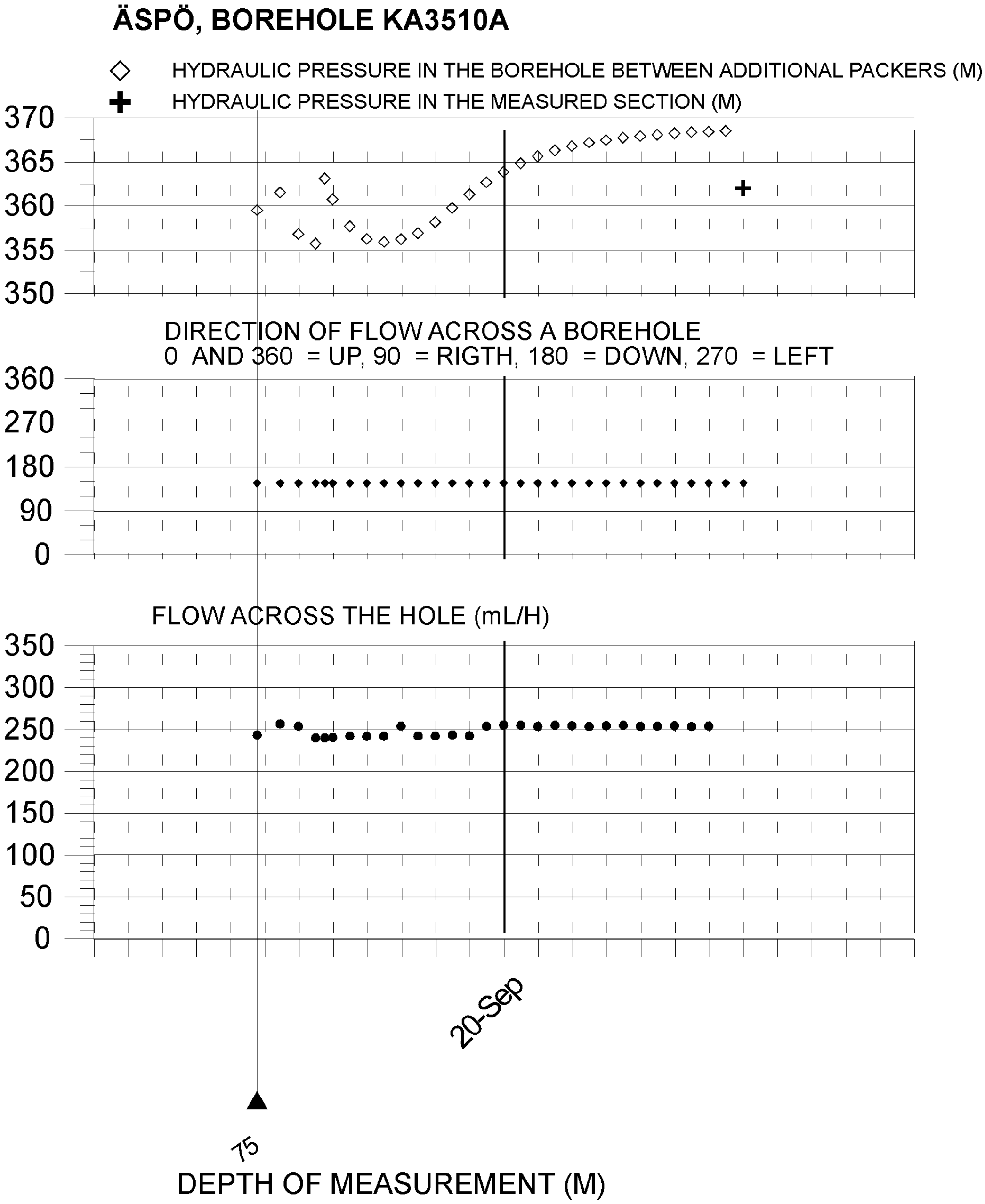

FLOWMETER TEST NR 15226, FLOW ACROSS THE HOL
HOLE: ASPO KA3510A, DEPTH: 75 m
TIME OF MEASUREMENT: 20-09-1998 05:58:37
CHANNEL RATE(mL/H) DIRECTION
P1+ 254.2 147
P1- 0.0 327
P2+ 0.0 237
P2- 0.0 57
TEMPERATURE (mK)
TIME (S)


HYDRAULIC PRESSURE IN THE BOREHOLE BETWEEN ADDITIONAL PACKERS (M)
HYDRAULIC PRESSURE IN THE MEASURED SECTION (M)
405
400
395
DIRECTION OF FLOW ACROSS A BOREHOLE
0 AND 360 = UP, 90 = RIGTH, 180 = DOWN, 270 = LEFT
360
270
180
90
0
FLOW ACROSS THE HOLE (mL/H)
50
45
40
35
30
25
20
15
10
5
0
17-Sep
DEPTH OF MEASUREMENT (M)
117


ÄSPÖ, BOREHOLE KA3510A
HYDRAULIC PRESSURE IN THE BOREHOLE BETWEEN ADDITIONAL PACKERS (M)
HYDRAULIC PRESSURE IN THE MEASURED SECTION (M)
405
400
395
DIRECTION OF FLOW ACROSS A BOREHOLE
0 AND 360 = UP, 90 = RIGTH, 180 = DOWN, 270 = LEFT
360
270
180
90
0
FLOW ACROSS THE HOLE (mL/H)
50
45
40
35
30
25
20
15
10
5
0
18-Sep
DEPTH OF MEASUREMENT (M)
117



ÄSPÖ, BOREHOLE KA3510A
HYDRAULIC PRESSURE IN THE BOREHOLE BETWEEN ADDITIONAL PACKERS (M)
HYDRAULIC PRESSURE IN THE MEASURED SECTION (M)
415
410
405
400
DIRECTION OF FLOW ACROSS A BOREHOLE
0 AND 360 = UP, 90 = RIGTH, 180 = DOWN, 270 = LEFT
360
270
180
90
0
FLOW ACROSS THE HOLE (mL/H)
350
300
250
200
150
100
50
0
18-Sep
117
DEPTH OF MEASUREMENT (M)


ÄSPÖ, BOREHOLE KA3510A
HYDRAULIC PRESSURE IN THE BOREHOLE BETWEEN ADDITIONAL PACKERS (M)
HYDRAULIC PRESSURE IN THE MEASURED SECTION (M)
370
365
360
355
350
DIRECTION OF FLOW ACROSS A BOREHOLE
0 AND 360 = UP, 90 = RIGTH, 180 = DOWN, 270 = LEFT
360
270
180
90
0
FLOW ACROSS THE HOLE (mL/H)
350
300
250
200
150
100
50
0
20-Sep
75
DEPTH OF MEASUREMENT (M)