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Forsmark site investigation

Comparison of measured EC in selected fractures in boreholes KFM02A, KFM03A and KFM04A from difference flow logging and hydro-geochemical characterization – Analysis of observed discrepancies in KFM03A

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April 2005

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Keywords: Forsmark, Hydrogeology, Difference flow logging, Hydro-chemical characterization, Electric conductivity, Conductive fractures, AP PF 400-04-42.

Abstract

The electric conductivity of the water in selected fractures has been measured both in conjunction with difference flow logging and hydro-geochemical characterization in most of the cored boreholes at Forsmark. In this report, a comparison of the results of these two measurements of EC from boreholes KFM02A, KFM03A and KFM04A is made.

In KFM03A, the first difference flow logging campaign was performed in August 2003, with a subsequent hydro-geochemical characterization during October–December. The EC-values were however found to differ significantly between the two measurement periods, with the difference flow logging indicating a much higher electric conductivity. Therefore, a second difference flow logging was carried out in May, 2004, to check the results from the first campaign in KFM03A. The fracture EC-values were consistent between the hydrochemical characterisation and the second difference flow logging.

Possible reasons to the observed discrepancies of the measured EC for the selected fractures in borehole KFM03A between, on one hand, Campaign 1 of the difference flow logging and, on the other side the hydro-geochemical characterization, and the second difference flow logging were investigated. The discrepancies in EC were believed to either depend on instrumental and/or measurement-related problems or on conceptual hydrogeological factors.

It was concluded that the observed differences in the measured EC in the sampled fractures between Campaign 1 and 2 of the difference flow logging in borehole KFM03A were most likely caused by upconing of saline water from deeper parts of the rock along water-bearing, sub-vertical fractures at the bottom of the borehole during pumping of the open borehole. Saline water probably also invaded into conductive fractures intersecting the borehole at higher levels.

Upconing probably occurred during both the rinse pumping campaigns prior to the EC-measurements in Campaign 1 of the difference flow logging and, to a minor extent, from pumping activities in the open borehole during this campaign. The upconing effects of saline water seem to have almost recovered before the subsequent hydro-geochemical characterization respectively Campaign 2 of the difference flow logging.

In boreholes KFM02A and KFM04A, no effects of upconing of saline water were observed, although large water volumes were extracted from the boreholes during the drilling and rinse pumping activities. This fact is probably due to absence of water-bearing sub-vertical fractures at the bottom of these boreholes. Good agreement of fracture-EC was obtained between the hydro-geochemical characterization and the difference flow logging in these boreholes.

Thus, both the hydro-geochemical characterization and difference flow logging campaigns in boreholes with water-yielding fractures in the bottom of the boreholes must, especially if they are sub-vertical or steep, be carefully planned in order to obtain representative EC-values and other hydro-geochemical parameters of the sampled fractures. If upconing occurs during rinse pumping of the boreholes, a sufficiently long time must be allocated to restore the “undisturbed” hydro-geochemical conditions before the measurement campaigns.

Sammanfattning

Den elektriska konduktiviteten av vattnet i utvalda sprickor har mätts både i samband med differensflödesloggning och hydrokemiska karaktärisering i de flesta kärnborrhål i Forsmark. I denna rapport jämförs resultaten från EC-mätningarna vid dessa två typer av mätkampanjer från borrhål KFM02A, KFM03A och KFM04A.

I KFM03A gjordes den första differensflödesloggningen i augusti 2003, och den efterföljande hydrokemiska karaktäriseringen under oktober till december samma år. Resultaten visade på stora skillnader i EC mellan de båda undersökningstillfällena, där differensflödesloggningen ger betydligt högre värden. Därför utfördes en andra differensfl ödesloggningskampanj i maj, 2004 för att kontrollera resultaten från den första kampanjen i KFM03A. God överensstämmelse av sprick-EC erhölls mellan den hydrokemiska karakteriseringen och den andra differensflödesloggningen.

Möjliga orsaker till de observerade skillnaderna för de utvalda sprickorna i borrhål KFM03A mellan å ena sidan kampanj 1 av differensflödesloggningen och, å andra sidan den hydro-kemiska karaktäriseringen och den andra differensflödesloggningen undersöktes. Avvikelserna i EC antogs antingen bero på instrumentella- och/eller mätrelaterade problem eller på konceptuella hydrogeologiska faktorer.

Det fastslogs att de observerade skillnaderna i uppmätt EC i de provtagna sprickorna mellan kampanj 1 och 2 av differensflödesloggningen i borrhål KFM03A sannolikt orsakades av uppträngande saltvatten från djupare delar av berget. Detta antas ske längs vattenförande subvertikala sprickor i botten av borrhålet under pumpning av det öppna borrhålet. Salt vatten trängde sannolikt även in i konduktiva sprickor som skär borrhålet på högre nivåer.

Uppträngning förekom antagligen både under renspumpningskampanjerna före EC-mätningarna i kampanj 1 av differensflödesloggningen och, till en mindre del, från pumpningsaktiviteter i det öppna borrhålet under denna kampanj. Effekterna av det uppträngande saltvattnet tycks nästan ha återhämtats innan den efterföljande hydro-kemiska karaktäriseringen och kampanj 2 av differensflödesloggningen.

I borrhål KFM02A och KFM04A observerades inga effekter av uppträngande salt vatten trots att stora vattenvolymer pumpades upp från borrhålet under borrnings- och renspump ningsaktiviteterna. Detta beror sannolikt på avsaknaden av vattenförande sprickor i botten av dessa borrhål. God överensstämmelse av sprick-EC erhölls från den hydrokemiska karaktäriseringen och differensflödesloggningen i dessa borrhål.

Sålunda måste både den hydrokemiska karaktäriseringen och differensflödes-loggningskampanjer i borrhål med vattenföranade sprickor i botten av hålen, speciellt om dessa är subvertikala eller brantstående, planeras noga för att erhålla representativa EC-värden och andra hydrokemiska parametrar för de provtagna sprickorna. Om uppträngning av saltvatten förekommer under renspumpningen av borrhålen måste tillräckligt lång tid reserveras för att återskapa de ”ostörda” hydrokemiska förhållandena före mätkampanjerna.

Contents

1 Introduction

The electric conductivity of the water in selected fractures is generally measured both in conjunction with difference flow logging and hydro-geochemical characterization in most of the cored boreholes at Forsmark. The results of the difference flow logging campaigns in KFM02A, KFM03A and KFM04A are reported in /1/, /2/ and /3/, respectively, whereas the corresponding results of the hydro-geochemical characterization are presented in /4/, /5/ and /6/. The location of the boreholes is shown in Figure 1-1.

In boreholes KFM02A and KFM04A the EC-results from the two types of measurements were consistent. In KFM03A, a difference flow logging campaign was performed in August 2003, with a subsequent hydro-geochemical characterization during October–December. The EC-values were however in this case found to differ significantly between the two measurement periods. The latter results were c 1.4 times lower than the results obtained from the difference flow logging. Therefore, a second difference flow logging was carried out in May 2004, to check the results from the first campaign in KFM03A. The fracture EC-values turned out to be consistent between the second difference flow logging and the hydrochemical characterization.

This report documents the results of the work described in the activity plan AP PF 400-04-42 (SKB internal controlling document) aiming to explain the reasons to the observed discrepancies in fracture-EC values between different measurements in KFM03A.

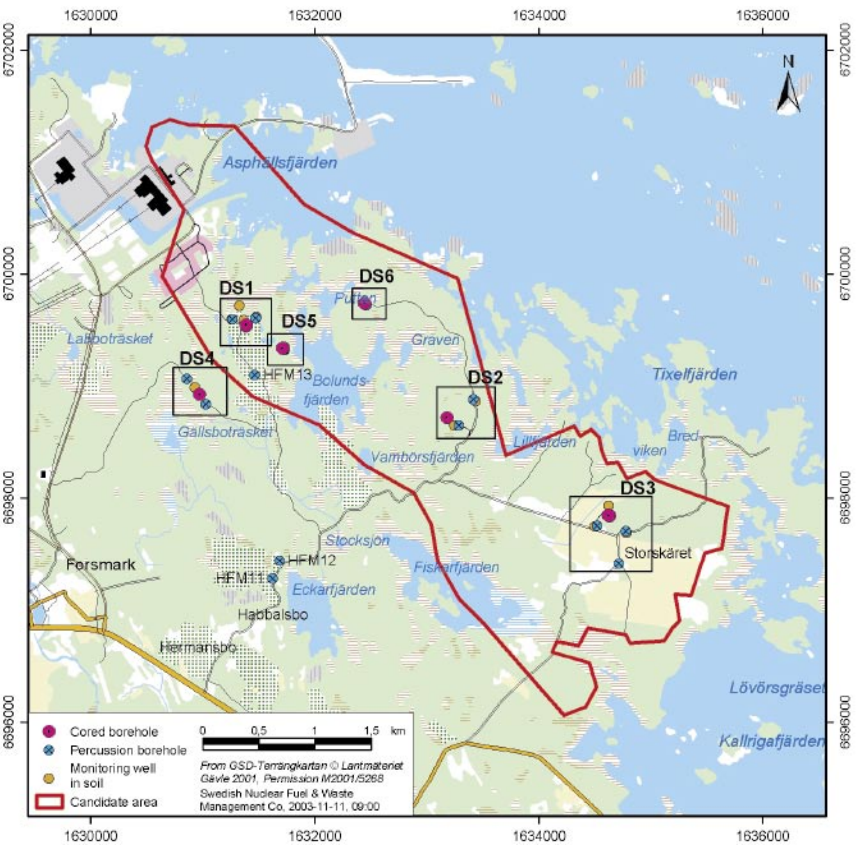

Figure 1-1. *Location of drilling sites DS1-6 at Forsmark. Core borehole KFM02A is situated at DS2, KFM03A at DS3 and KFM04A at DS4.*

2 Objective

The aim of this report is to compare the results of fracture-EC measurements in conjunction with difference flow logging with corresponding measurements performed during the hydro-geochemical characterization in boreholes KFM02A–KFM04A. In particular, the possible reasons to the observed discrepancies of the measured EC for selected fractures in borehole KFM03A between Campaign 1 of the difference flow logging and the hydro-geochemical characterization are addressed. The discrepancies in EC were believed to either depend on instrumental and/or measurement-related problems or on conceptual hydrogeological factors.

Examples of questions to be studied:

- are the results of laboratory measurements of EC on water samples from the measured borehole sections in KFM03A using the DIFF probe and laboratory probe consistent?
- are the water samples extracted from the measured borehole sections during the hydro-geochemical characterization in KFM03A representative for the actual depth in the borehole?
- are the EC-measurements in conjunction with the difference flow logging in KFM03A representative for the actual depth in the borehole?
- did the upconing of saline water from deeper parts of the bedrock occur along borehole KFM03A during previous rinse pumping activities and invasion of saline water into intersecting fractures, thus disturbing the natural hydro-geological conditions in the borehole prior to the first difference flow logging campaign?

By the comparisons of the measured EC in borehole KFM03A, the following potential sources of error were considered:

- leakage around packers and rubber discs by the hydro-geochemical characterization and difference flow logging, respectively, which may cause non-representative conditions,
- open-hole effects, e.g. hydraulic short-circuiting of conductive fractures with different hydro-chemical characteristics,
- too short pumping period before the difference flow logging to achieve representative conditions,
- too short measurement time for a representative EC (particularly for difference flow logging),
- effects of dissolved gases or high flushing water content in the water,
- different drawdown and flow conditions during the measurements,
- upconing effects of saline water along the borehole and into intersecting fractures during rinse pumping,
- remaining disturbances of the hydrogeological borehole conditions from the drilling activity,
- uncertainties in the temperature correction of measured EC.

3 Investigated boreholes – geometry and technical design

3.1 KFM02A

Borehole KFM02A is sub-vertical, c 1,000 m deep, and drilled with telescopic drilling technique. The borehole interval 0–100 m is percussion drilled with a diameter of 254 mm. Due to instabilities and large inflow of water, a stainless steel casing with the inner diameter 200 mm was installed in this interval. The gap between the borehole wall and casing wall was sealed against inflow of groundwater by grouting. The borehole interval c 100–1,000 m was core drilled with the diameter c 77 mm.

Selected main technical data for the telescopic borehole KFM02A are shown in Table 3-1. The reference coordinate system for the X-Y-coordinates is RT90 and RHB70 for the elevation data. The reference point for all length measurements in the borehole is the centre of the top of casing (ToC).

Table 3-1. Selected main technical data of the cored borehole KFM02A. (Data retrieved from SICADA).

Borehole length (m):	1,002.440				
Reference level:	Centre of casing top				
Drilling Period(s):	**From Date**	**To Date**	**Secup (m)**	**Seclow (m)**	**Drilling Type**
	2002-11-20	2002-11-26	0.000	100.400	Percussion drilling
	2003-01-08	2003-03-12	100.420	1,002.440	Core drilling
Starting point coordinate:	**Length (m)**	**Northing (m)**	**Easting (m)**	**Elevation**	**Coord System**
	0.000	6698712.501	1633182.863	7.353	RT90-RHB70
Angles:	**Length (m)**	**Bearing**	**Inclination (– = down)**		
	0.000	275.764	–85.385		
Borehole diameter:	**Secup (m)**	**Seclow (m)**	**Hole Diam (m)**		
	0.000	2.390	0.440		
	2.390	11.800	0.358		
	11.800	100.400	0.251		
	100.420	102.000	0.086		
	102.000	1,002.440	0.077		
Core diameter:	**Secup (m)**	**Seclow (m)**	**Core Diam (m)**		
	100.420	102.000	0.072		
	102.000	1,002.440	0.051		
Casing diameter:	**Secup (m)**	**Seclow (m)**	**Case In (m)**	**Case Out (m)**	
	0.000	100.140	0.200	0.280	
	0.100	11.800	0.265	0.273	

3.2 KFM03A

Selected main technical data for the telescopic borehole KFM03A are shown in Table 3-2. The borehole is cased to c 12 m with a diameter of 0.2 m. The percussion-drilled borehole interval between c 12–100 m is uncased. The borehole length is c 1,000 m and the borehole is almost vertical. The diameter of the core drilled borehole interval (c 102–1,001 m) is c 77 mm. More detailed borehole data are available from SICADA.

Table 3-2. Selected main technical data of the cored borehole KFM03A. (Data retrieved from SICADA).

Borehole length (m):	1,001.190				
Reference level:	Centre of casing top				
Drilling Period(s):	**From Date**	**To Date**	**Secup (m)**	**Seclow (m)**	**Drilling Type**
	2003-03-18	2003-03-28	0.000	100.340	Percussion drilling
	2003-04-16	2003-06-23	100.340	1,001.190	Core drilling
Starting point coordinate:	**Length (m)**	**Northing (m)**	**Easting (m)**	**Elevation**	**Coord System**
	0.000	6697852.096	1634630.737	8.285	RT90-RHB70
Angles:	**Length (m)**	**Bearing**	**Inclination (– = down)**		
	0.000	271.523	–85.747		
Borehole diameter:	**Secup (m)**	**Seclow (m)**	**Hole Diam (m)**		
	0.000	11.960	0.200		
	11.960	100.290	0.196		
	100.290	100.340	0.163		
	100.340	102.050	0.086		
	102.050	1,001.190	0.077		
Core diameter:	**Secup (m)**	**Seclow (m)**	**Core Diam (m)**		
	100.340	102.050	0.072		
	102.050	1,001.190	0.051		
Casing diameter:	**Secup (m)**	**Seclow (m)**	**Case In (m)**	**Case Out (m)**	
	0.000	11.960	0.200	0.208	
	0.000	1.650	0.392	0.406	
	0.000	11.830	0.265	0.273	

3.3 KFM04A

Borehole KFM04A is c 1,000 m deep with an inclination of c 60°, and drilled with telescopic drilling technique. The borehole interval 0–100 m is percussion drilled with a diameter of 247 mm. Due to instabilities and large inflow of water, a stainless steel casing with the inner diameter 200 mm was installed in this interval. The gap between the borehole wall and casing wall was sealed against inflow of groundwater by grouting. The borehole interval c 108–1,000 m was core drilled with the diameter c 77 mm. Selected main technical data for the telescopic borehole KFM04A are shown in Table 3-3.

Table 3-3. Selected main technical data of the cored borehole KFM04A. (Data retrieved from SICADA).

Borehole length (m):	1,001.420				
Reference level:	Centre of casing top				
Drilling Period(s):	**From Date**	**To Date**	**Secup (m)**	**Seclow (m)**	**Drilling Type**
	2003-05-20	2003-06-30	0.000	106.950	Percussion drilling
	2003-08-25	2003-11-19	107.420	1,001.420	Core drilling
Starting point coordinate:	**Length (m)**	**Northing (m)**	**Easting (m)**	**Elevation**	**Coord System**
	0.000	6698921.744	1630978.964	8.771	RT90-RHB70
Angles:	**Length (m)**	**Bearing**	**Inclination (– = down)**		
	0.000	45.244	–60.081		
Borehole diameter:	**Secup (m)**	**Seclow (m)**	**Hole Diam (m)**		
	0.000	12.030	0.350		
	12.030	107.330	0.247		
	107.330	107.420	0.161		
	107.420	108.690	0.086		
	108.690	1,001.420	0.077		
Core diameter:	**Secup (m)**	**Seclow (m)**	**Core Diam (m)**		
	107.420	108.690	0.072		
	108.690	1,000.890	0.051		
	1,000.890	1,001.420	0.062		
Casing diameter*:	**Secup (m)**	**Seclow (m)**	**Case In (m)**	**Case Out (m)**	
	0.000	12.030	0.265	0.273	
	0.000	106.910	0.200	0.208	
	106.910	106.950	0.170	0.208	

* At 103.87 – 106.87 m, a cone is reducing the inner diameter from 193 mm to 80 mm

4 Equipment

Different types of equipment have been used to measure electric conductivity in the boreholes; these equipments are shortly presented in this Chapter.

4.1 Difference flow logging

Unlike traditional types of borehole flow meters, the Posiva Difference flow meter method measures the flow rate into or out of limited sections of the borehole instead of measuring the total cumulative flow rate along the borehole. The advantage of measuring the flow rate in isolated sections is a better detection of the incremental changes of flow along the borehole, which are generally very small and can easily be missed using traditional types of flow meters.

Rubber disks at both ends of the down-hole tool are used to isolate the flow rate in the test section from the flow rate in the rest of the borehole, see Figure 4-1. The flow rate along the borehole outside the isolated test section passes through the test section by means of a bypass pipe and is discharged at the upper end of the down-hole tool.

The Difference flow meter can be used in two modes, in a sequential respectively in an overlapping mode. In the sequential mode, the increment of the measurement section is as long as the section length. It is mainly used for determining the transmissivity and hydraulic head of borehole sections. In the overlapping mode, the increment of the measurement section is shorter than the section length. It is mainly used to determine the location and hydraulic properties of hydraulically conductive fractures along the borehole.

The Difference flow meter measures the flow rate into or out of the test section by means of thermistors, which track both the dilution (cooling) of a thermal pulse and transfer of the thermal pulse with the flowing water. In the sequential mode, both methods are applied, whereas in the overlapping mode, only the thermal dilution method is used because of its faster operation.

Besides incremental changes of flow the down-hole tool of the Difference flow meter can also be used to measure the electric conductivity (EC) of the borehole water and fracture-specific water in-situ. EC profiles of borehole water are generally measured at the start of every measurement campaign. The electrode for the EC measurements is placed on the top of the flow sensor, see Figure 4-1. The fracture-specific EC is normally only measured in high-transmissive sections during pumping in order to speed up the measurements. Prior to the fracture-EC measurements, the water volume in the measurement section is exchanged at least three times. Fracture-specific measurements are normally performed in short sections of 0.5 m or 1 m length. In longer sections, a special spiral structure is used to improve the water circulation in the section.

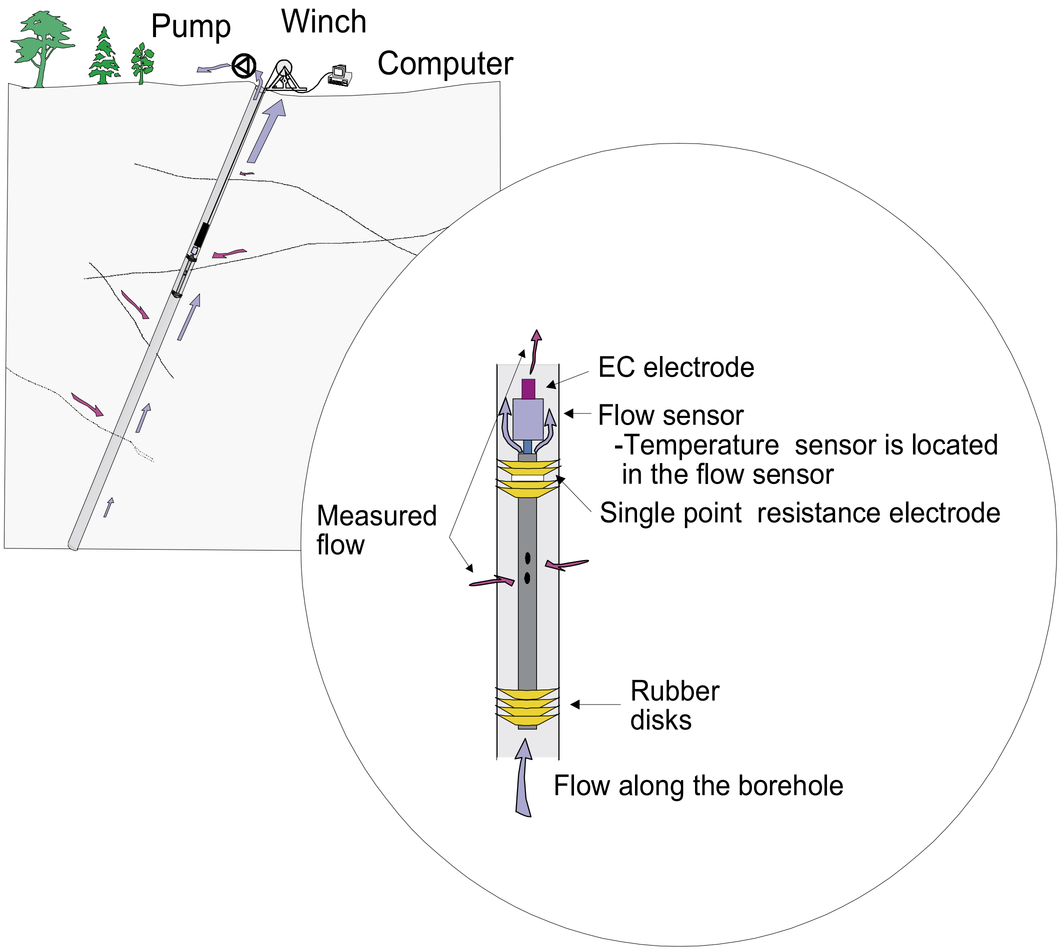

Figure 4-1. *Schematic of the down-hole equipment used in the Posiva Difference flow meter.*

In boreholes KFM02A–KFM04A all the fracture-specific EC-measurements were made in 1 m long sections positioned across the fracture for a certain time during pumping of the borehole. The measured EC is corrected to 25°C from the actual temperature of the water as measured by the temperature sensor, located in the flow sensor, see Figure 4-1. The correction of EC is based on mathematical modelling, described in /7/.

4.2 Hydro-geochemical characterization and logging

4.2.1 The pipe string system (PSS)

The SKB Pipe String System (PSS) consists of a measurement container and down-hole equipment. The system is normally used for hydraulic pumping- and injection tests but can also used for pumping and chemical sampling. The equipment is described in SKB MD 345.100-124 (Pipe String System, SKB internal controlling document).

The PSS unit was combined with a separate chemistry unit for computer work and Chemmac measurements (MYC). This unit is described in SKB MD 434.007 (Mätsystem-beskrivning för mobil ytChemmac, SKB internal controlling document) and SKB MD 433.018 (Mätsystembeskrivning för dataapplikation, SKB internal controlling document).

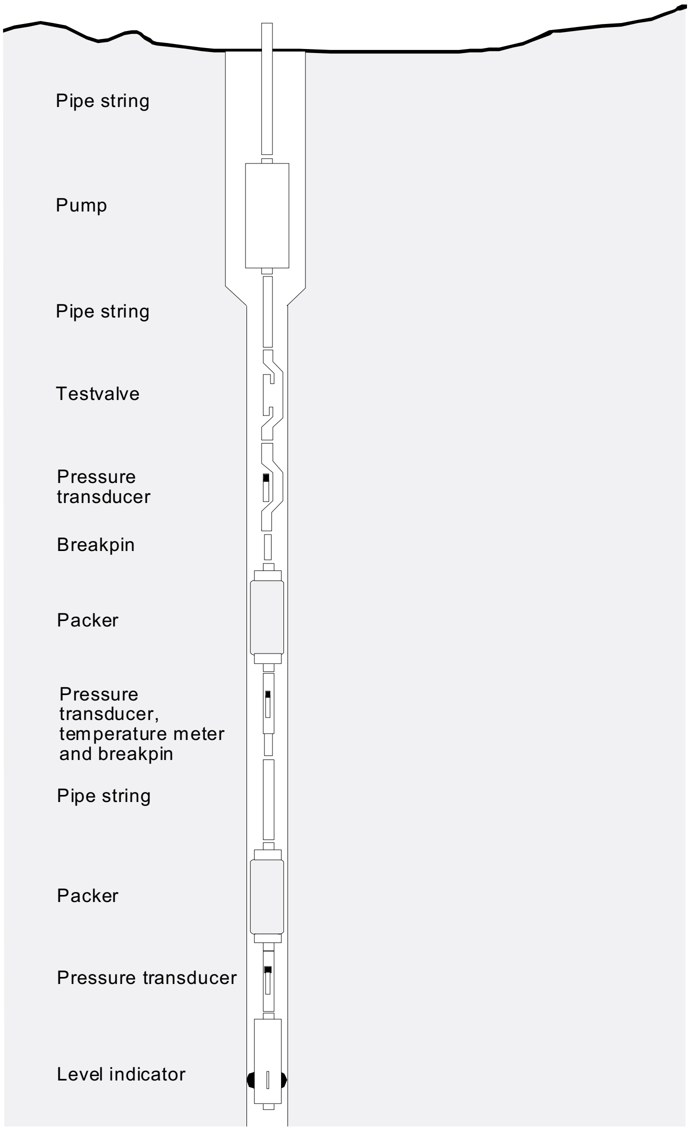

Figure 4-2. *Schematic drawing of the down-hole equipment comprising the PSS3 system. From /11/.*

The Chemmac measurement system in the MYC unit includes communication systems, measurement application and a flow-through cell with electrodes and sensors at the ground surface. The PSS3 equipment is designed for flow rates between 5 and 30–40 L/min. In order to pump at lower flow rates, down to 1 L/min, it is necessary to re-circulate extracted water back to the pump.

4.2.2 The mobile field laboratory (MFL)

The mobile field laboratories used by SKB for water sampling and down-hole measurements consist of a laboratory unit, a hose unit with down-hole equipment and a Chemmac measurement system; the system is presented schematically in Figure 4-3. It is also possible to include a separate unit for computer work (MYC). The different parts of the system are described in the SKB internal controlling documents SKB MD 434.004, 434.005, 434.006, 434.007 and SKB MD 433.018 (Mätsystembeskrivningar för mobil kemienhet allmän del, slangvagn, borrhålsutrustning, mobil ytChemmac och dataapplikation).

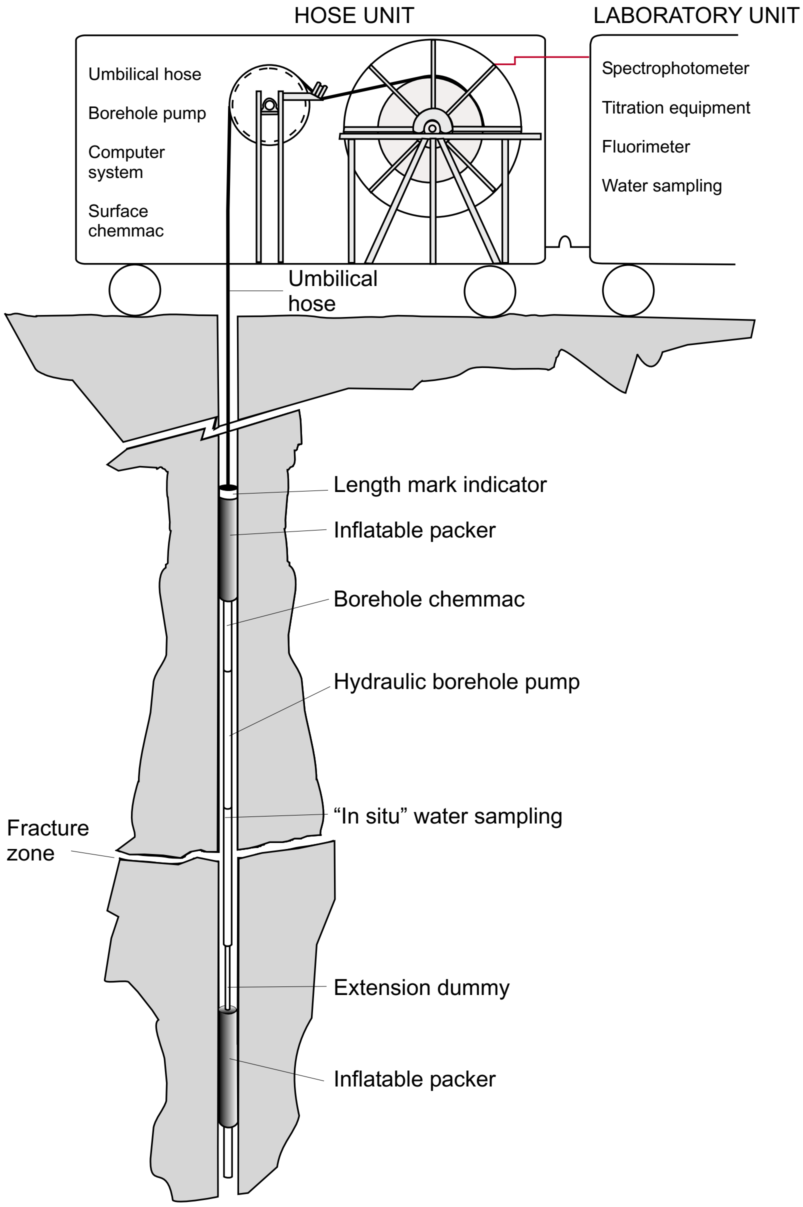

***Figure 4-3.** The mobile chemistry laboratory (MFL) including laboratory unit, hose unit and down-hole equipment. From /5/.*

The Chemmac measurement facilities include communication systems, measurement application and flow-through cells with electrodes and sensors at the ground surface (surface Chemmac) and in the borehole (borehole Chemmac).

The down-hole equipment consists of inflatable packers, pump, borehole Chemmac and the in-situ sampling unit (PVP), allowing measurement (borehole Chemmac) and sampling in-situ in the borehole section (PVP sampling unit). The four sample portions collected with the PVP sampling unit maintain the pressure from the borehole section when lifted to the surface. The portions are used for colloid filtration, gas analyses and microbe investigations.

Some crucial differences between the PSS and the MFL equipment exist:

- The sample water channel/tube of the umbilical hose in the hose unit of the mobile field laboratory has an inner diameter of 4 mm. The pipe string in the PSS3 equipment has 21 mm inner diameter.
- The pipe string is made of aluminium, while the sample water channel/tubing is made of polyamide.
- The maximum flow rate possible with the hose unit pump is in the range of 200–250 mL/min, while the pipe string system has a maximum flow rate of 30–40 L/min (only about 200 mL/min is conducted through the surface Chemmac).
- At low flow rates it is necessary to re-circulate the extracted water to the PSS pump.

The sampling units used in boreholes KFM02A and KFM03A consisted of the hydro-test unit PSS3 and the MYC3 unit for computer work and surface Chemmac measurements. The laboratory unit L3 was used for analysis work. However, for a number of sections the laboratory unit was not placed at the drilling site and thus not directly connected to the outlet of the pumped water during pumping. These sections are: section 413.5–433.5 m in borehole KFM02A /4/ and sections 386.0–391.0 m and 448.0–453.0 m in borehole KFM03A /5/. In KFM04A, only the mobile field laboratory (MFL) was used /6/.

The mobile units used in section 509.0–516.1 m in borehole KFM02A /4/ and section 639.0–646.1 m in KFM03A consisted of the hose unit S3, the laboratory unit L3 and the MYC 3 unit for computer work. However, the laboratory unit was not placed at the drilling site and thus not directly connected to the outlet of the pumped water during the pumping of section 639.0–646.1 m in KFM03A /5/. The mobile units used in borehole KFM04A, sections 230.5–237.6 m and 354.0–361.1 m consisted of the hose unit S2, the laboratory unit L3 and the MYC 2 unit for Chemmac measurements and computer work /6/.

4.2.3 Tube sampler

The sampling equipment used for the hydro-chemical logging consists of a c 1,000 m long polyamide tube divided into units of 50 m. The equipment is described in the method description SKB MD 422.001 (Metodbeskrivning för hydrokemisk loggning, SKB internal controlling document).

A schematic illustration of the equipment used for hydro-chemical logging is shown in Figure 4-4. The tube units, with external and internal diameter of 10 and 8 mm respectively, are connected with couplings. The length of each tube unit is given in Table 4-1. The water content in each unit will constitute one sample and the volume of each sample will be at least two litres. At the lower end of the tube array, a weight is attached to keep it stretched and a check valve mounted to prevent water outflow when lifted. At both ends of each tube unit there is a manual shut off valve.

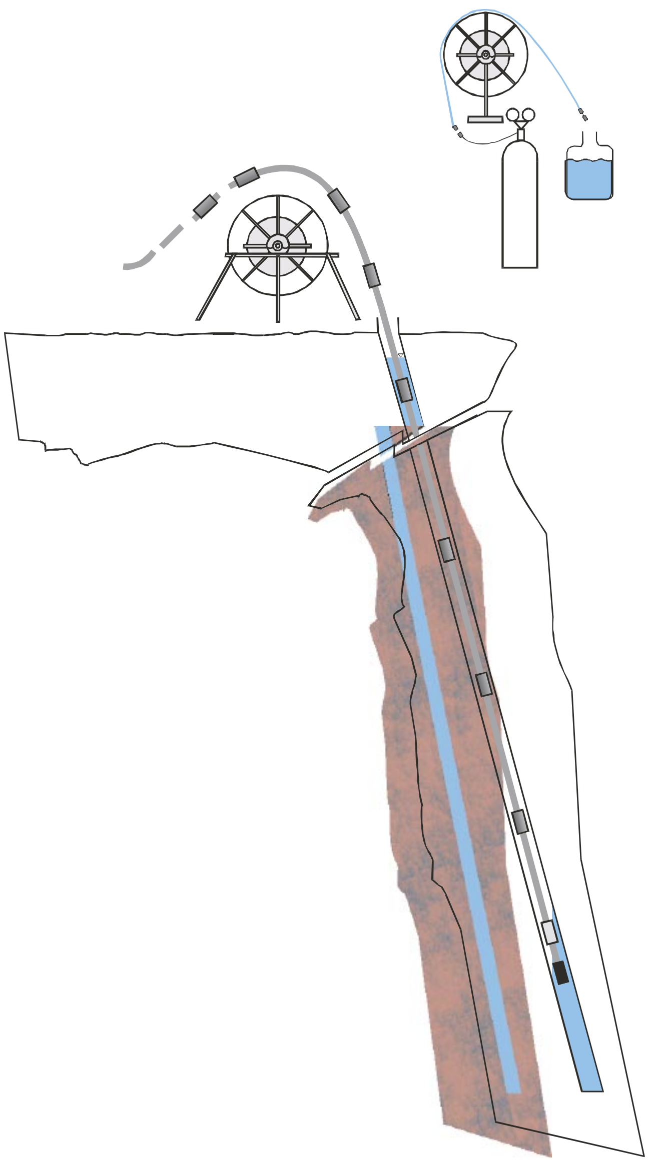

Figure 4-4. *Equipment for hydro-chemical logging in boreholes. At the lower end of the tube array there is a check valve and a weight connected. Each tube unit is approximately 50 m long. From /8/.*

Table 4-1. Length of tube units used in the hydro-chemical logging in boreholes KFM02A, KFM03A and KFM04A. From /8/, /9/ and /10/.

Borehole Unit	KFM02A Length (m)	KFM03A Length (m)	KFM04A Length (m)
1	49.87	49.87	49.71
2	49.62	49.62	50.08
3	49.63	49.63	49.77
4	49.30	49.30	49.28
5	49.20	49.20	49.97
6	49.22	49.22	50.01
7	49.70	49.70	49.85
8	50.62	50.62	49.87
9	50.25	50.25	49.57
10	49.67	49.67	49.72
11	49.72	49.72	49.67
12	49.57	49.57	50.25
13	49.87	49.87	50.62
14	49.85	49.85	49.70
15	50.01	50.01	49.22
16	49.97	49.97	49.20
17	49.28	49.28	49.30
18	49.77	49.77	49.63
19	50.08	50.08	49.62
20	49.71	49.71	49.87
Sum:	994.91	994.91	994.91
Couplings:	2.81	2.81	2.812
Weight:	0.82	0.82	0.817
Total tube length:	**998.539**	**998.539**	**998.539**

5 Methods of analysis

In this chapter an overview of the major conductive fractures and their position in is presented together with hydrogeological starting conditions in the boreholes and in the adjacent rock and fractures.

5.1 Overview of conductive fractures in the boreholes

5.1.1 Borehole KFM02A

In Table 5-1 the position and estimated transmissivity and head of the major hydraulically conductive fractures in borehole KFM02A for which a significant flow under natural (un-pumped) conditions exists are shown /1/. In addition, the direction of flow (inflow or outflow) to/from the borehole under natural conditions is indicated.

Table 5-1 shows that the inflow (recharge) to the borehole mainly occurs in deeper parts (e.g. at c 513.6 m) and the outflow (discharge) in the upper sections (e.g. at c 110.7 m). Both these fractures are interpreted as sub-horizontal /18/. Below 513.6 m no significant conductive fractures are present in borehole KFM02A. Thus, no significant amounts of saline water from deeper parts of the bedrock are likely to enter the borehole and no upconing effects are expected during pumping of the borehole. The borehole interval c 250–300 m consists of porous granite.

Table 5-1. Position and hydraulic properties of the most conductive fractures in borehole KFM02A. From /1/.

Borehole	Position along the borehole (m)	Transmissivity (m^2/s)	Head (m a s l)	Direction of flow under natural conditions
KFM02A	110.7	4.21E–5	1.19	outflow
KFM02A	162.5	7.30E–7	2.61	inflow
KFM02A	171.5	1.31E–6	1.87	inflow
KFM02A	227.8	8.46E–8	2.07	outflow
KFM02A	266.6	9.53E–8	3.00	inflow
KFM02A	301.7	6.46E–8	3.05	inflow
KFM02A	417.3	9.01E–7	3.99	inflow
KFM02A	418.4	1.43E–7	4.06	inflow
KFM02A	437.3	1.07E–7	4.40	inflow
KFM02A	454.0	8.89E–8	4.58	inflow
KFM02A	479.2	5.64E–8	4.69	inflow
KFM02A	480.4	3.79E–7	4.83	inflow
KFM02A	486.1	1.67E–7	4.91	inflow
KFM02A	498.1	2.13E–8	5.01	inflow
KFM02A	506.5	4.21E–8	5.09	inflow
KFM02A	513.6	3.73E–6	4.98	inflow

5.1.2 Borehole KFM03A

In Table 5-2 the position and estimated transmissivity and head of the major hydraulically conductive fractures in borehole KFM03A for which a significant flow under natural (un-pumped) conditions exists are shown /2/. In addition, the direction of flow (inflow or outflow) to/from the borehole under natural conditions is indicated.

No reliable estimations of the fracture head could be made in the borehole interval 100–400 m due to a large inflow along the borehole from the major fracture at c 388.6 m. Table 5-2 indicates that the major inflow to the borehole probably occurs within the fractured interval c 360–390 m, particularly at the high-transmissive fracture at 388.6 m and the main outflow in the borehole interval c 450–650 m. The very high estimated head at the fracture at 986.2 m may indicate inflow of very saline water at the bottom of the borehole, both at natural and pumped conditions.

The difference flow logging in KFM03A /2/ showed that there are several conductive fractures in the borehole interval below c 940 m. The most dominating fractures in this borehole interval are located at c 944.2 m and c 986.2 m (fractures 1 and 2, respectively). Conductive fractures were also identified at lower positions in the borehole, see Table 5-3. The position and orientation (strike and dip) of these fractures have been determined from the corresponding BIPS-images /19/. The BIPS-aperture represents the thickness of the fracture in the BIPS images. The fractures are generally partly filled with fracture minerals. Table 5-3 indicates that the conductive fractures form an interconnected network of sub-horizontal and sub-vertical fractures in this borehole interval.

Table 5-2. Position and hydraulic properties of the most conductive fractures in borehole KFM03A. From /2/.

Borehole	Position along the borehole (m)	Transmissivity (m^2/s)	Head (m a s l)	Direction of flow under natural conditions
KFM03A	120.6	6.52E–8	–	–
KFM03A	130.2	9.55E–8	–	–
KFM03A	358.5	1.56E–6	–	–
KFM03A	362.6	3.66E–8	–	–
KFM03A	364.5	4.04E–7	–	–
KFM03A	364.8	1.31E–6	–	–
KFM03A	365.3	3.00E–7	–	–
KFM03A	368.6	1.44E–6	–	–
KFM03A	369.4	3.35E–7	–	–
KFM03A	371.6	1.35E–6	–	–
KFM03A	372.6	6.48E–7	–	–
KFM03A	373.6	3.67E–7	–	–
KFM03A	380.8	6.06E–7	–	–
KFM03A	388.6*	1.70E–4*	2.75*	inflow*
KFM03A	451.3	6.65E–6	3.48	outflow
KFM03A	454.6	7.16E–8	3.51	outflow
KFM03A	643.9	2.48E–6	5.40	outflow
KFM03A	944.2	3.28E–7	–	–
KFM03A	986.2	1.89E–7	10.74	inflow

* interpreted from flow measurements in the fracture at different borehole head /2/

Table 5-3. Geometrical and hydraulic properties of the most conductive fractures in the borehole interval below 940 m in KFM03A. From /11/.

Fracture no	DIFF- corrected length to fracture (m)	BIPS- corrected length to fracture (m)	Strike (°)	Dip (°)	T_f (m^2/s)	BIPS-Aperture (mm)
1	944.2	944.3	249	32	3.28E–7	6
2	986.2	986.5	30	82	1.89E–7	5
3	992.9	992.9	41	74	4.22E–8	2
4	993.8	993.7	56	78	4.85E–8	2.5
5	994.0	994.1	88	32	1.76E–8	1

Figure 5-1 shows a 3D-image of the interpreted orientation from BIPS of the most conductive fractures below c 940 m in KFM03A listed in Table 5-3. The sub-vertical fractures may possibly contribute to upconing of saline water from deeper parts of the bedrock during open-hole pumping. The extensions of the fractures are unknown and thus only fictive in the images.

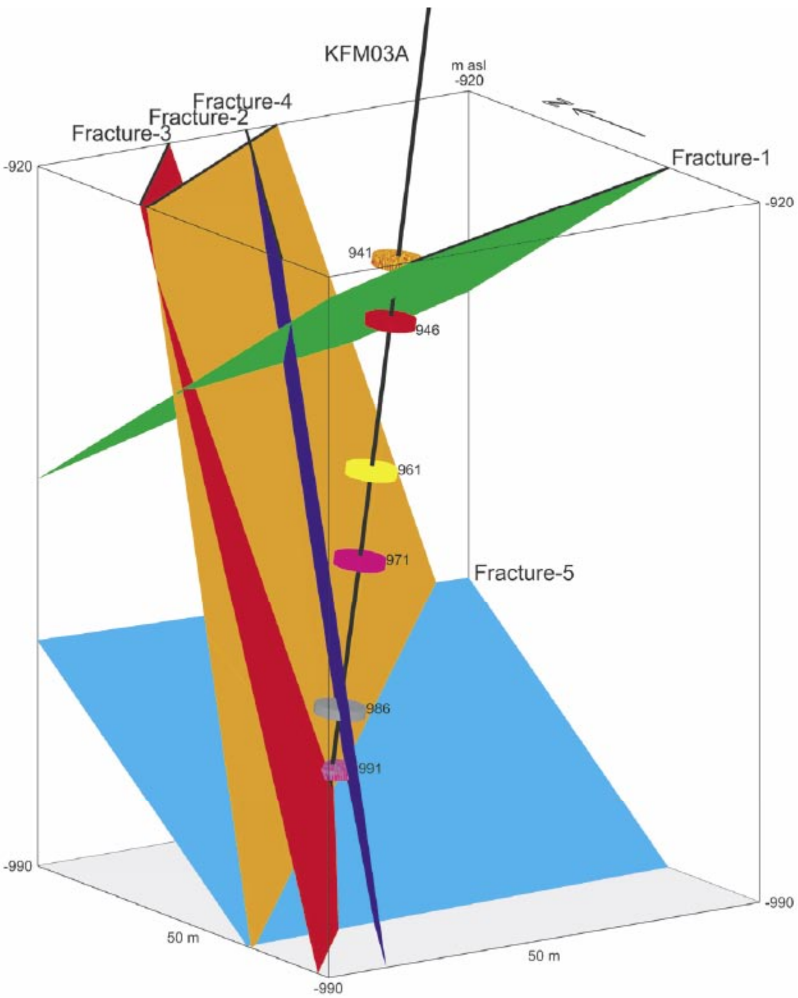

Figure 5-1. Three-dimensional image of interpreted conductive fractures below 940 m from the difference flow logging in borehole KFM03A together with positions of test sections in the injection tests. From /11/.

5.1.3 Borehole KFM04A

In Table 5-4 the position and estimated transmissivity and head of the major hydraulically conductive fractures in borehole KFM04A for which a significant flow under natural (un-pumped) conditions exists are shown /3/. In addition, the direction of flow (inflow or outflow) to/from the borehole under natural conditions is indicated.

Table 5-4. Position and hydraulic properties of the most conductive fractures in borehole KFM04A. From /3/.

Borehole	Position along the borehole (m)	Transmissivity (m^2/s)	Head (m a s l)	Direction of flow under natural conditions
KFM04A	112.4	3.54E–5	3.64	Inflow
	116.1	2.56E–5	3.59	Inflow
	165.1	1.07E–6	4.01	Inflow
	202.8	8.32E–6	4.35	Outflow
	207.1	3.21E–5	4.38	Outflow
	208.2	1.38E–6	4.39	Outflow
	235.6	2.73E–5	4.71	Inflow
	359.8	1.26E–6	5.38	Outflow

Table 5-4 shows that the inflow (recharge) to the borehole mainly occurs in the uppermost part of the borehole (c 112–116 m) and at c 235 m. The major outflow (discharge) occurs in the borehole interval c 202–208 m and at 359.8 m. These fractures are interpreted as sub-horizontal /20/. Below 359.8 m, no significantly conductive fractures are present in borehole KFM04A. Thus, no significant amounts of saline water from deeper parts of the bedrock are likely to enter the borehole and no upconing effects are expected during pumping of the borehole.

5.2 Hydrogeological starting conditions at the field EC measurements

5.2.1 Pumping history prior to the EC-measurements

The actual hydrogeological starting conditions in the borehole and in the adjacent rock and fractures at the measurement times may be very important for the representativity of the fracture-EC-measurements. For example, extensive open-hole pumping for clearing the borehole from drilling debris and flushing water before the measurements may cause saline water to rise along the borehole and into the adjacent rock and fractures (upconing). The degree of upconing depends, among other things, on the actual geology, e.g. fracture pattern in the deeper part of the boreholes. Upconing may occur also during drilling due to the pumping associated with the telescopic drilling technique.

Furthermore, in an open borehole, short-circuiting of naturally existing head differences in fractures intersecting the borehole may affect the hydraulic conditions and the groundwater chemistry in the rock and associated fractures /12/.

EC-measurements are performed along the boreholes before the difference flow logging campaigns, providing EC-profiles which constitute important information on the hydro-geological starting conditions before the corresponding fracture-EC measurements. Such profiles may e.g. indicate if upconing had occurred in the borehole during drilling and rinse pumping before the latter measurements. In addition, the measured EC-profiles from hydro-chemical logging along the boreholes shortly after drilling may provide important information on the starting conditions.

Rough data on the pumped volumes during drilling, during the subsequent rinse pumping and during the difference flow logging campaigns in the actual boreholes compiled below. The pumping records are based on data on estimated total water volumes pumped from the actual boreholes during certain time intervals. From these data, rough average pumping rates during these intervals were calculated. Lists of events, including drilling and pumping history before the EC-measurements during difference flow logging (DIFF) and hydro-geochemical characterization (HCC) in boreholes KFM02A–4A are shown in Tables 5-5 to 5-7. The time periods for the different EC-measurements are also shown in the tables.

Table 5-5. List of selected activities prior to the fracture-EC measurements in borehole KFM02A.

Activity	Time period	Type of pumping	Pumped volume (m^3)	Average flow rate (L/min)*	Comments
Core drilling	2003-01-08–2003-03-12	Intermittent open-hole pumping during the drilling periods	875	c 10	Pumped volume estimated as return water minus flushing water during drilling /13/
Air lift rinse pumping	2003-03-13–2003-03-24	Intermittent open-hole pumping	128	c 10	Several starts and stops of air-lift pumping
Rinse pumping	2003-03-28–2003-03-31	Continuous open-hole pumping	164	c 40	Submersible borehole pump
Hydrochemical logging (HKL)	2003-03-31	No pumping	–	–	Measured profiles of EC and flushing water content along the borehole /8/
Fracture-EC during difference flow logging (DIFF)	2003-05-08–2003-05-11	Continuous open-hole pumping during c 6 days	630	c 75	Average flow rate during pumping, including the fracture-EC measurements /1/
Hydro-geochemical characterization (HCC)	2003-09-01–2004-02-23	Continuous pumping in selected, isolated borehole sections	Pumped volumes ranged from 10 to 930 m^3		Sampled sections: 509–516.1 m, 106.5–126.5 m, 413.5–433.5 m /4/

* Equivalent average continuous flow rate during the entire activity (including any breaks).

Table 5-6. List of selected activities prior to the fracture-EC measurements in borehole KFM03A.

Activity	Time period	Type of pumping	Pumped volume (m^3)	Average flow rate (L/min)*	Comments
Core drilling	2003-04-16–2003-06-23	Intermittent open-hole pumping during the drilling periods	2,081	c 20	Pumped volume estimated as return water minus flushing water during drilling /14/
Air lift pumping	2003-06-23–2003-06-26	Intermittent open-hole pumping	156	c 36	Several starts and stops of air-lift pumping
Rinse pumping	2003-06-28–2003-06-30	Continuous open-hole pumping	251	c 90	Submersible borehole pump
Hydrochemical logging (HKL)	2003-06-30	No pumping	–	–	Measured profiles of EC and flushing water content along the borehole /9/
Rinse pumping	2003-07-28–2003-08-01	Continuous open-hole pumping	660	c 110	Submersible borehole pump
Fracture-EC during difference flow logging (DIFF-1)	2003-08-21–2003-08-25	Continuous open-hole pumping during 8 days	1,000	c 90	Average flow rate during pumping including the fracture-EC measurements /2/
Hydro- geochemical characterization (HCC)	2003-09-16–2003-12-10	Continuous pumping in selected isolated borehole sections	The pumped volume from the sections ranged from 3 to 944 m^3		Sections 386–391 m, 448–453 m, 448.5–455.6 m, 639–646.1 m, 939.5–946.6 m and 980–1,001.2 m /5/
Fracture-EC during difference flow logging (DIFF-2)	2004-05-06–2004-05-08	Continuous open-hole pumping during 5 days	530	c 75	Average flow rate during pumping including the fracture-EC measurements /2/

* Equivalent average continuous flow rate during the entire activity (including any breaks).

Table 5-7. List of selected activities prior to the fracture-EC measurements in borehole KFM04A.

Activity	Time period	Type of pumping	Pumped volume (m^3)	Average flow rate (L/min)*	Comments
Core drilling	2003-05-20–2003-10-30	Intermittent open-hole pumping during the drilling periods	875	c 10	Pumped volume estimated as return water minus flushing water during drilling /15/
Air lift rinse pumping	2003-11-19–2003-11-20	Intermittent open-hole pumping	c 129	c 90	Several starts and stops of air-lift pumping
Rinse pumping	2003-11-20–2003-11-21, 2003-11-25–2003-12-01, 2003-12-10–2003-12-19	Continuous open-hole pumping during the periods	c 1,202	c 30	Submersible borehole pump
Hydrochemical logging (HKL)	2003-12-08	No pumping	–	–	Measured profiles of EC and flushing water content along the borehole /10/
Hydro- geochemical characterization (HCC), first campaign	2004-01-09–2004-02-17	Continuous pumping in selected, isolated borehole sections	8.4		Sampled section: 230.5–237.6 m /6/
Fracture-EC during difference flow logging (DIFF)	2004-03-21–2004-03-22	Continuous open-hole pumping during c 8 days	c 460	c 40	Average flow rate during pumping, including the fracture-EC measurements /3/
Hydro- geochemical characterization (HCC), second campaign	2004-04-14–2004-05-11	Continuous pumping in selected, isolated borehole sections	6		Sampled section: 354.0–361.1 m /6/

* Equivalent average continuous flow rate during the entire activity (including any breaks).

5.2.2 Starting conditions at the fracture-EC measurements

In this section, the hydrogeological starting conditions prior to the fracture-EC-measurements in conjunction with the difference flow logging (DIFF) and hydro-geochemical characterization, respectively, are discussed.

Borehole KFM02A

The EC-measurements during DIFF started c 5 weeks after stop of the rinse pumping campaign and the HCC started c 3.5 months after stop of the DIFF campaign. Table 5-5 shows that a total water volume of c 300 m^3 was extracted from the open borehole during the rinse pumping activities before the EC-measurements during the difference flow logging (DIFF). The most intensive rinse pumping occurred during the continuous pumping with a submersible pump.

Profiles of measured borehole-EC and flushing water content along the borehole during the hydro-chemical logging /8/, just after the rinse pumping campaign, are shown in Figures 5-2 and 5-3, respectively. Figure 5-2 demonstrates that the EC ranges from c 0.2 S/m at the top to c 1 S/m at the bottom of the borehole during the hydro-chemical logging. Figure 5-3 indicates high flushing water content from the drilling in the lower part of the borehole whereas the content was low in the upper part. This fact may be due to the presence of conductive fractures in the upper part and absence of such fractures at the bottom of the borehole, see Section 5.1.

In Appendix 1.1 the measured borehole-EC profiles in KFM02A before and at stop of pumping, respectively, during the difference flow logging campaign are presented. The figure indicates a major inflow of saline water at c 515 m. Below this depth, the borehole-EC is lower. The subsequent pumping during the DIFF campaign only caused a slight general increase of c 10–20% of EC along the borehole. The original shape of the

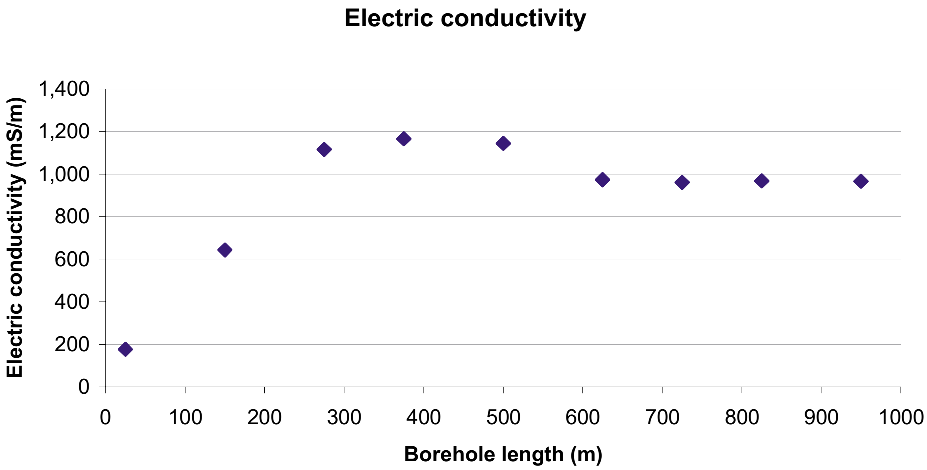

***Figure 5-2.** Measured electric conductivity along borehole KFM02 during the hydro-chemical logging. From /8/.*

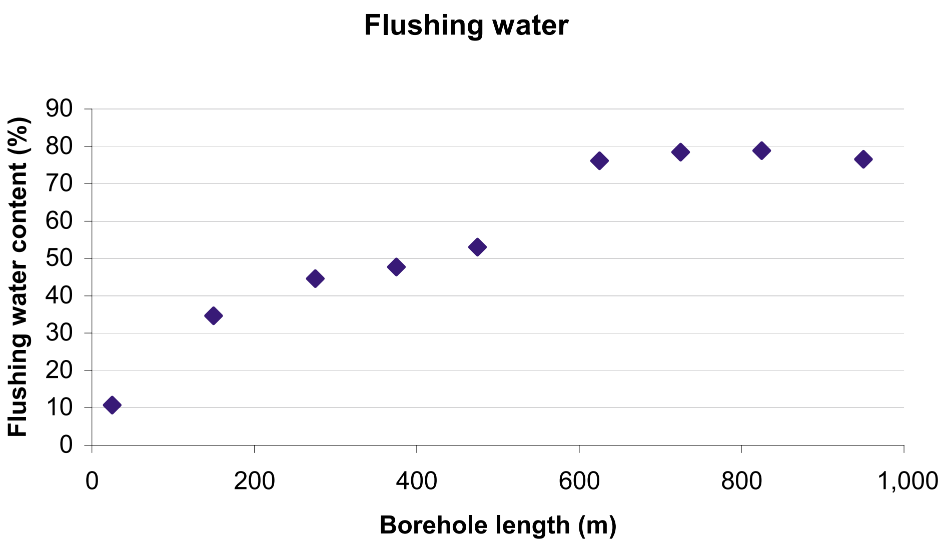

***Figure 5-3.** Measured flushing water content along borehole KFM02A during the hydro-chemical logging. From /8/.*

EC-profiles was maintained during pumping, indicating that no significant upconing of saline water from the bottom of the borehole occurred during pumping. Since c 5 weeks had elapsed since the rinse pumping campaign, relatively undisturbed conditions may be assumed prior to the difference flow logging campaign.

Table 5-5 shows that the only pumping (except the rinse pumping) prior to the hydro-geochemical characterization occurred during the previous DIFF campaign. However, since long time (c 3.5 months) had elapsed since the last pumping in the latter campaign, relatively undisturbed conditions may be assumed prior to the HCC campaign.

Borehole KFM03A

In borehole KFM03A, two separate difference flow logging campaigns including fracture-EC measurements were carried out. The pumping histories in KFM03A after drilling, before and during the first respectively the second campaign, are presented in Table 5-6. The table shows that substantial water volumes were extracted from the open borehole during the rinse pumping before the first DIFF campaign. The fracture-EC measurements during this campaign were carried out c 3 weeks after stop of rinse pumping. The hydro-geochemical characterization started c 3 weeks after stop of the first DIFF campaign. During the subsequent period prior to the second DIFF campaign, no pumping were performed.

Table 5-6 shows that a total water volume of c 1,100 m^3 was extracted from the open borehole during the rinse pumping before the first campaign of difference flow logging (DIFF-1). The most intensive rinse pumping occurred during the continuous pumping with a submersible pump shortly before the first DIFF campaign. In addition, c 1,000 m^3 were extracted from the borehole during the latter campaign before the fracture-EC measurements.

Profiles of borehole-EC and the flushing water content along the borehole during the hydro-chemical logging (HKL) /9/, shortly after drilling, are displayed in Figures 5-4 and 5-5, respectively. Figure 5-4 shows that EC ranges from c 1 S/m at the top to c 2.5 S/m at the bottom of the borehole. Table 5-6 demonstrates that a limited rinse pumping was carried out prior to the HKL activity. Thus, the EC-profile in Figure 5-4 may be assumed to represent relatively undisturbed conditions.

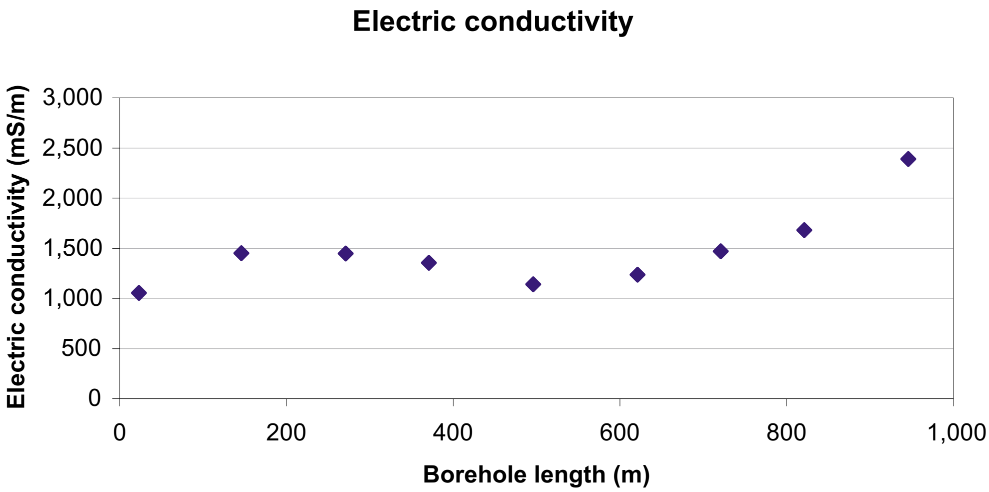

Figure 5-4. *Measured electric conductivity along borehole KFM03A during the hydro-chemical logging. From /9/.*

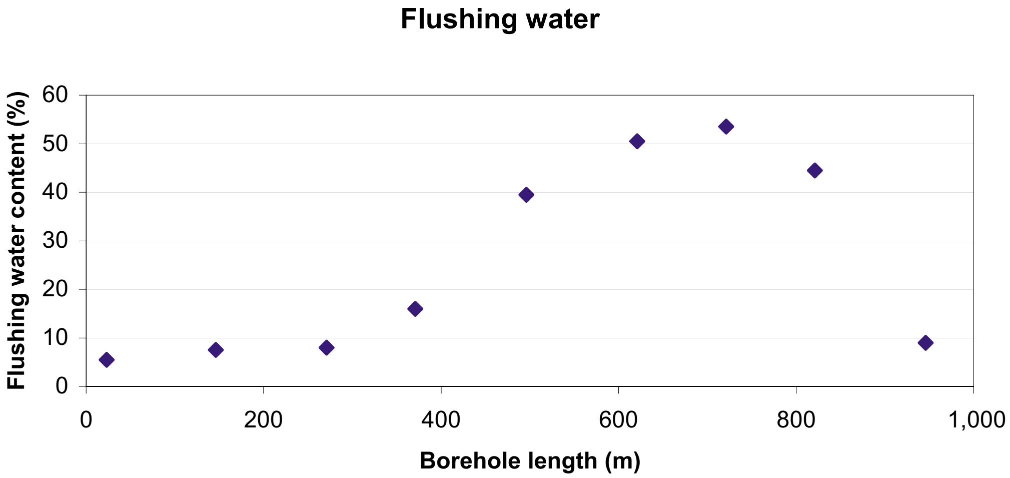

***Figure 5-5.** Measured flushing water content along borehole KFM03A during the hydro-chemical logging. From /9/.*

Figure 5-5 indicates high flushing water content from the drilling in the middle part of the borehole. The conductive fractures at the bottom of the hole caused decreasing flushing water content in this part of the borehole. In Appendix 1.2 the borehole-EC profiles before respectively after the first and the second difference flow logging campaign in KFM03A are illustrated. A major inflow of less saline water occurs at the conductive fracture at c 645 m. Below this depth, the borehole-EC increases which indicates upconing of saline water from the bottom of the borehole, in opposite to the conditions in KFM02A.

Appendix 1.2 shows major differences in the starting conditions for the two flow logging campaigns. At the start of the first campaign, saline water had raised along the entire borehole up to the casing due to the pumping activities before this campaign, cf Figure 5-4. EC remained at a relatively constant level of c 2.6 S/m in the borehole interval c 100–650 m and c 4 S/m at the bottom of the borehole (dark blue and light blue curves in Appendix 1.2). The subsequent pumping during the first difference flow logging campaign (red curve) merely had a minor effect on the borehole-EC profile, indicating that upconing already had occurred at the start of the first campaign.

On the contrary, at the start of the second campaign, the upconing effect had decreased significantly, both regarding the magnitude of EC and the position of the saline water interface (dark brown and light brown curves). EC had decreased to c 0.4 S/m at 100 m depth and to c 2.7 S/m at the bottom of the borehole. The saline water interface had recovered to c 400 m depth in the borehole. During subsequent pumping at the second campaign, the saline water again rose along the borehole up to the pump intake (green and blue curves). Appendix 1.2 clearly demonstrates that the hydrogeological starting conditions at the two DIFF campaigns were significantly different.

Table 5-6 shows that the only pumping (except the rinse pumping) prior to the hydro-geochemical characterization occurred during the DIFF-1 campaign. During the latter campaign c 1,000 m^3 of water was extracted from the open borehole. The HCC campaign started c 2–3 weeks after stop of pumping, but the EC-measurements in the first sample section (386–391 m) were not terminated until 2003-10-07, i.e. c 6 weeks after stop of pumping during the DIFF-1 campaign. It is assumed that most of the upconing effects in the borehole had ceased at that time, see below.

Borehole KFM04A

The pumping history in KFM04A before and during the fracture-EC measurements in conjunction with the difference flow logging and hydro-geochemical characterization is presented in Table 5-7. The first phase of the hydro-geochemical characterization (HCC-1) started c 3 weeks after stop of the rinse pumping campaign. The difference flow logging campaign started c 3 months after stop of rinse pumping. The second phase (HCC-2) started c 3 weeks after the end of the DIFF campaign.

Table 5-7 shows that a total water volume of c 1,300 m^3 was extracted from the open borehole during the rinse pumping before the first phase of HCC (HCC-1). The most intensive rinse pumping occurred during the continuous pumping with a submersible pump shortly before HCC-1. The hydro-chemical logging (HKL) along the borehole was carried out 2003-12-08 by the end of the rinse pumping campaign /10/. Profiles of measured borehole-EC and flushing water content along the borehole during HKL are shown in Figures 5-6 and 5-7, respectively.

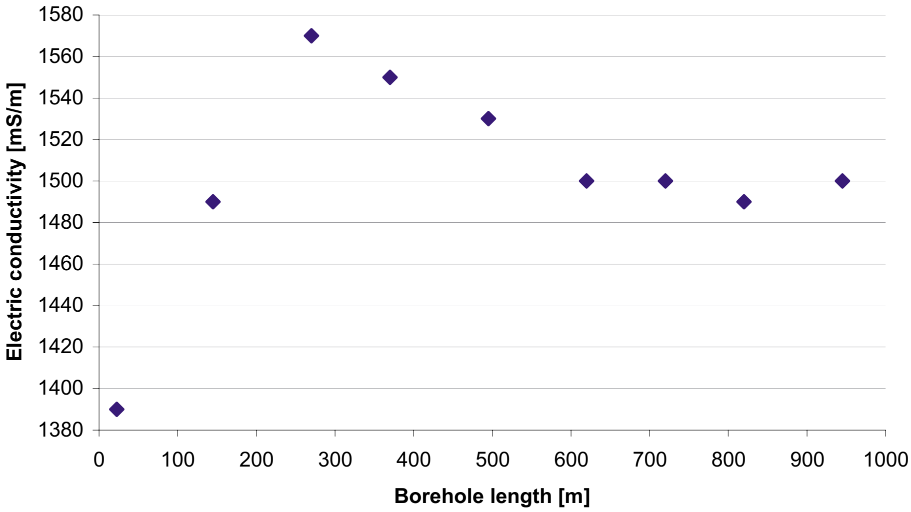

Figure 5-6. *Measured electric conductivity along borehole KFM04A during the hydro-chemical logging. From /10/.*

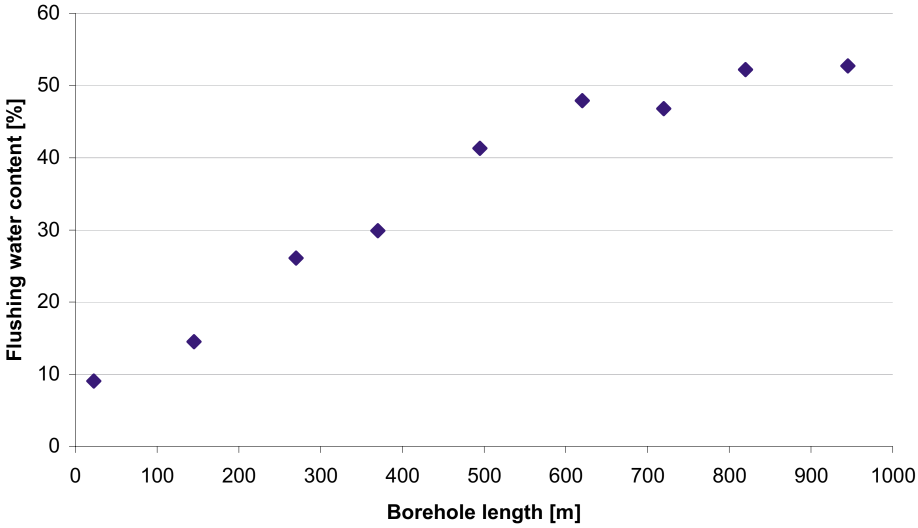

Figure 5-7. *Measured flushing water content along borehole during the hydro-chemical logging. From /10/.*

Figure 5-6 shows that EC increases in the upper part of the borehole to a maximum value of c 1.57 S/m slightly above c 300 m. From this depth, EC decreases to c 1.5 S/m at the bottom of the borehole. Figure 5-7 indicates rather moderate flushing water content from the drilling in the upper c 300 m of the borehole, indicating the presence of conductive fractures in this part of the borehole. Below c 300 m, the flushing water content increased successively towards the bottom of the borehole. This fact indicates absence of conductive fractures in the bottom of the borehole, cf Section 5.3.

In Appendix 1.3, the measured borehole-EC profiles before respectively at the end of the pumping period during the difference flow logging campaign are displayed. The figure indicates a major inflow of low-salinity water at c 115 m. Below this depth, the borehole-EC maintains a relatively constant level at c 1.7 S/m along the borehole at the start of the campaign (dark blue and light blue curves in Appendix 1.3). At c 950 m, a slight increase of EC occurred at a small flow anomaly.

During pumping, EC decreased slightly along the borehole (red and lilac curves). The shape of the EC-profiles is maintained during the pumping, indicating that no significant upconing of saline water from the bottom of the borehole occurred. The reasons to the general, slight decrease of EC during pumping are not known.

According to Table 5-7, no further pumping activities were performed before the second phase of the hydro-geochemical characterization (HCC-2).

5.3 Nonconformities

The analyses in this report were carried out according to the activity plan AP PF 400-04-42 with the following exceptions:

- The data compilation does not include borehole KFM01A as proposed, instead KFM04A is included.
- No compilation of chemical data of water samples was gathered in order to support the EC-measurements.
- None of the options “Complementary EC-measurement in other borehole”, or “Complementary EC-measurement with other method” were performed.

6 Results of the fracture-EC measurements

6.1 Laboratory measurements of EC

Prior to the re-measurements of EC in selected fractures in KFM03A during Campaign 2 of the difference flow logging, EC was measured in the mobile field laboratory (MFL) on extracted water samples from a selection of fractures in conjunction with hydro-geochemical characterization. EC was measured with the same probe as used in difference flow logging (DIFF) as well as using standard laboratory equipment. The primary aim of the laboratory measurements was to compare the measured EC contemporaneously on the same water samples under identical conditions.

In addition, EC of standard fluids with known chemical compositions was measured in the laboratory, as a reference. EC was measured both at c 15°C and c 25°C, respectively, and corrected to 25°C but only the results of the latter measurements are presented here. The results of the laboratory measurements of EC are shown in Table 6-1. For comparison, also the measurements of EC on two water samples from borehole KFM03A from an authorized laboratory are included in the table /5/.

Table 6-1. Results of the laboratory measurements of EC on selected water samples before Campaign 2 of the difference flow logging.

Water sample	EC-corr 25°C (S/m) Lab (DIFF)	EC-corr 25°C (S/m) Lab (MFL)	EC-corr 25°C (S/m) Authorized lab
KFM03A:639.0–646.1 m	1.724	1.559	1.596*
KFM03A:939.5–946.6 m	2.342	2.140	2.012**
Standard fluid 1	1.330	1.291	
Standard fluid 2	11.340	11.170	

* average EC of 5 water samples from the borehole section /5/.
** average EC of 8 water samples from the borehole section /5/.

The laboratory measurements of EC firstly showed that no significant differences of measured EC were obtained using the DIFF-probe and laboratory probe, respectively, for either of the water samples, although slightly higher values were obtained with the DIFF-probe, particularly for the borehole water samples. The results indicated that the observed discrepancies of EC in the field measurements (DIFF and HCC) probably are due to different hydrogeological conditions in the borehole at the actual times of the measurements, rather than to any systematic differences in the two types of field measurements of EC. Thus, some of the potential sources of error discussed in Chapter 2 could be ruled out after the laboratory measurements. However, it was still not possible to draw any firm conclusions of the representativity of two sets of field EC-values for the sampled fractures before the second campaign of the difference flow logging was carried out.

6.2 Fracture-EC measurements in conjunction with difference flow logging

A compilation of the results from selected fractures investigated during the in-situ fracture-EC measurements in conjunction with the difference flow logging campaigns in boreholes KFM02A–KFM04A, together with associated hydraulic data, are presented in Table 6-2 below. Only fractures for which EC subsequently was measured during the hydro-geochemical characterization are included in the table. For some of the fractures, the position of the measurement section was slightly altered in Campaign 2 in KFM03A. However, the same conductive fracture was sampled in Campaign 1 and 2. For the EC-measurements in Campaign 2, neither the head difference (drawdown), nor the flow rate in the measurement sections were reported (except in section 388.0–389.0). EC_f and Te_f denote the final electric conductivity and temperature of the fractures at the end of the measurement periods with the duration t_f.

Table 6-2. Fracture-ECf measurements in conjunction with difference flow logging in boreholes KFM02A–KFM04A together with associated data.

Borehole	Measurement section (m)	Fracture* bh-length (m)	Head diff. s (m)	Flow rate Q (mL/h)	Specific flow Q/s (m²/s)	EC_f-corr 25 °C (S/m)	Te_f °C	t_f (s)
KFM02A	120.1–121.1	120.9	0.45	20,000	1.2×10^{-5}	0.35	7.2	800
KFM02A	426.58–427.58	426.8	5.8	15,000	7.2×10^{-7}	1.58	10.7	2613
KFM02A	513.28–514.28	513.6	5.8	81,100	3.9×10^{-6}	1.56	11.7	939
KFM03A–								
Campaign 1	388.2–389.2		0.25**	150,000**	1.7×10^{-4}	2.336	10.3	800
Campaign 2	388.0–389.0	388.6	0.88	295,000	9.3×10^{-5}	1.645	10.2	3,580
KFM03A–								
Campaign 1	450.9–451.9		6.2	144,300	6.5×10^{-6}	2.280	11.0	806
Campaign 2	450.8–451.8	451.3	n r	n r	n r	1.634	11.0	3,767
KFM03A–								
Campaign 1	643.5–644.5		6.3	53,900	2.4×10^{-6}	2.286	13.4	1,460
Campaign 2	643.4–644.4	643.9	n r	n r	n r	1.617	13.3	75,069
KFM03A–								
Campaign 1	943.9–944.9		6.2	7,370	3.3×10^{-7}	3.291	17.4	11,020
Campaign 2	943.7–944.7	944.2	n r	n r	n r	2.309	17.3	14,420
KFM03A–								
Campaign 1	985.9–986.9	986.2	6.2	4,970	2.2×10^{-7}	3.840	17.9	17,377
Campaign 2	985.9–986.9	986.5	n r	n r	n r	2.890	17.9	14,286
KFM04A	234.99–235.99	235.6	1.3	165,600	3.5×10^{-5}	1.459	8.2	8,000
KFM04A	359.21–360.21	359.8	3.8	14,500	1.1×10^{-6}	1.453	9.4	8,257

* position of conductive fractures along the borehole as identified from the difference flow logging
** from flow measurements at different drawdown in the borehole in conjunction with difference flow logging /2/
n r no recording

The EC-measurements during Campaign 1 of the difference flow logging were performed in August 2003 and Campaign 2 in May 2004, see Table 6-2. Table 6-2 shows that the measured EC was significantly lower in Campaign 2 in comparison to Campaign 1 for all sampled fractures in KFM03A. A possible explanation to this fact is discussed in Section 7.4 below.

6.3 Fracture-EC measurements in the hydro-geochemical characterization

A compilation of the results from the fracture-EC measurements in conjunction with the hydro-geochemical characterization in boreholes KFM02A–KFM04A together with associated administrative and hydraulic data are presented in Table 6-3 below. In borehole KFM02A, the sections 106.5–126.5 m and 413.5–433.5 m were also sampled during the hydro-geochemical characterization but the results of the EC-measurements in these two sections were rejected due to instrumental problems /4/.

The measurement times for the different fractures ranged from 18–51 days during the hydro-geochemical characterization. Table 6-3 shows that the flushing water content was rather high in some of the sections. EC_f and Te_f denote the final electric conductivity and temperature of the fractures at the end of the measurement periods as reported in /1/, /2/ and /3/.

In the sections 386–391 m and 448.5–455.6 m in KFM03A, rinse pumping was performed with the PSS system prior to the hydro-geochemical characterization. The hydraulic evaluation of the rinse pumping in these sections is reported in /16/.

Table 6-3. Fracture-EC measurements during the hydro-geochemical characterization in boreholes KFM02A–KFM04A together with associated data.

Borehole	Section (m)	Fracture* bh-length (m)	Time interval of measurement Start-stop	Measure-ment time (d)	Draw-downs (m)	Flow rate Q (L/min)	Specific flow Q/s (m²/s)	EC_f-corr 25°C (S/m)	Flushing water content (%)
KFM02A	509.0–516.1	513.6	20030901 to 20031021	51	**	0.14	–	1.613 ± 0.020	6.77
KFM03A	386.0–391.0	388.6	20030911 to 20031007	28	1.5	28.5	2.9×10^{-4}	1.637 ± 0.020	0.9
KFM03A	448.5–455.6	451.3	20031009 to 20031027	18	30	2.4	1.3×10^{-6}	1.571 ± 0.020	0.25
KFM03A	639.0–646.1	643.9	20040128 to 20040224	27	n a	0.2		1.529 ± 0.020	4.35
KFM03A	939.5–946.6	943.1	20040225 to 20040329	33	n a	0.2		2.205 ± 0.020	8.75
KFM03A	980.0–1,001.2	986.2	20031114 to 20031209	25	3	0.12	6.7×10^{-7}	2.547 ± 0.020	3.9
KFM04A	230.5–237.6	235.6	20040109 to 20040217	39	n a	0.1–0.26		1.677 ± 0.020	0.4
KFM04A	354.0–361.1	359.8	20040414 to 20040511	27	n a	0.16		1.625 ± 0.020	2.18

* sampled, conductive fractures identified from the difference flow logging
** the drawdown in the section could not be determined
n a not available

6.4 Comparison of measured EC from DIFF and HCC

In this section the results of the fracture-EC measurements in conjunction with the difference flow logging (DIFF) and hydro-geochemical characterization (HCC) in boreholes KFM02A–04A are compared and discussed. Figure 6-1 illustrates a comparison of the EC-measurements in the different boreholes. The figure indicates a good agreement for EC in KFM02A and KFM04A and in Campaign 2 of DIFF in KFM03A, whereas the EC-values in Campaign 1 of DIFF were deviating. Possible explanations to the discrepancies are discussed in Section 6.4.1–3.

A summary of the EC-results for DIFF and HCC for the measured conductive fractures in boreholes KFM02A–KFM04A together with associated data is presented in Table 6-4. The table shows the stop date of the last open-hole pumping activities in the boreholes, totally pumped water volumes from the open boreholes during the rinse pumping and difference flow logging, time intervals and duration of the fracture-EC measurements together with the specific flow and measured EC. More detailed data of the pumped water volumes during the pumping activities in the boreholes are provided in Tables 6-1 to 6-3.

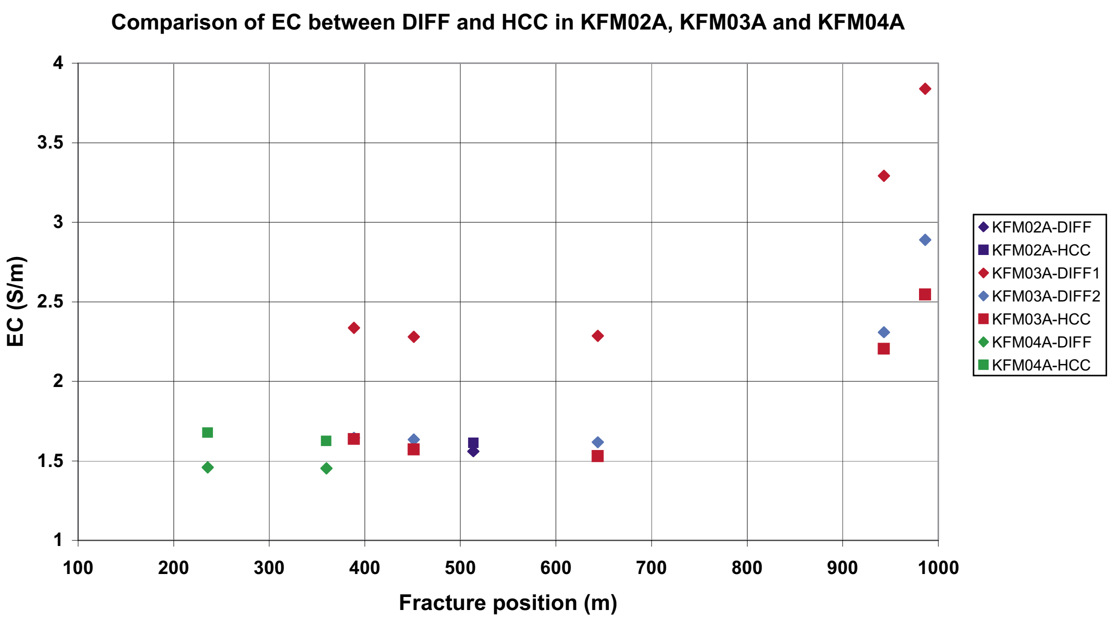

Figure 6-1. *Comparison of measured EC in conjunction with difference flow logging (DIFF) and hydro-geochemical characterization (HCC) in boreholes KFM02A, KFM03A and KFM04A. Fracture position given in borehole length.*

Table 6-4. Comparison of results of EC measurements from difference flow logging and hydro-geochemical characterization in boreholes KFM02A–KFM04A.

Borehole	Type of EC-measurement	Section (m)	Fracture Bh-length (m)	Last pumping finished Date	Pumped water volume (m^3)	Time interval of EC-measurements Start date–stop date	Time since last pumping (d)	Duration of EC-measurement (s, d)	Specific flow Q/s (m^2/s)	EC_f-corr 25°C (S/m)
KFM02A	HCC	509.0–516.1	513.6	20030512	922	20030901–20031021	108	51 d	–	1.613 ± 0.020
KFM02A	DIFF	513.28–514.28	513.6	20030331	292	20030508–20030511	38	939 s	3.9E–6	1.56
KFM03A	HCC/PSS	386.0–391.0	388.6	20030825	2,100	20030911–20031007	16	26 d	2.9E–4	1.637 ± 0.020
KFM03A	DIFF-1	388.2–389.2	388.6	20030801	1,067	20030821–20030825	20	800 s	1.7E–4	2.336
KFM03A	DIFF-2	388.0–389.0	388.6	20030825	2,100	20040506–20040508	252	3,580 s	9.3E–5	1.645
KFM03A	HCC/PSS	448.5–455.6	451.3	20030825	2,100	20031009–20031027	45	18 d	1.3E–6	1.571 ± 0.020
KFM03A	DIFF-1	450.9–451.9	451.3	20030801	1,067	20030821–20030825	20	806 s	6.5E–6	2.280
KFM03A	DIFF-2	450.8–451.8	451.3	20030825	1,067	20040506–20040508	252	3,767 s	–	1.634
KFM03A	HCC	639.0–646.1	643.9	20030825	2,100	20040128–20040224	154	27 d	–	1.529 ± 0.020
KFM03A	DIFF-1	643.5–644.5	643.9	20030801	1,067	20030821–20030825	20	1,460 s	2.4E–6	2.286
KFM03A	DIFF-2	643.4–644.4	643.9	20030825	1,067	20040506–20040508	252	75,069 s	–	1.617
KFM03A	HCC	939.5–946.6	943.1	20030825	2,100	20040225–20040329	181	33 d	–	2.205 ± 0.020
KFM03A	DIFF-1	943.9–944.9	943.1	20030801	1,067	20030821–20030825	20	11,020 s	3.3E–7	3.291
KFM03A	DIFF-2	943.7–944.7	943.1	20030825	1,067	20040506–20040508	252	14,420 s	–	2.309
KFM03A	HCC	980.0–1,001.2	986.2	20030825	2,100	20031114–20031209	80	25 d	6.7 E–7	2.547 ± 0.020
KFM03A	DIFF-1	985.9–986.9	986.2	20030801	1,067	20030821–20030825	20	17,377 s	2.2E–7	3.840
KFM03A	DIFF-2	985.9–986.9	986.2	20030825	1,067	20040506–20040508	252	14,286 s	–	2.890
KFM04A	HCC-1	230.5–237.6	235.6	20031219	1,331	20040109–20040217	20	39 d	–	1.677 ± 0.020
KFM04A	DIFF	234.99–235.99	235.6	20031219	1,331	20040321–20040322	92	8,000 s	3.5E–5	1.459
KFM04A	HCC-2	354.0–361.1	359.8	20040322	1,791	20040414–20040511	22	27 d	–	1.625 ± 0.020
KFM04A	DIFF	359.21–360.21	359.8	20031219	1,791	20040321–20030322	92	8,257 s	1.1E–6	1.453

6.4.1 Borehole KFM02A

In borehole KFM02A, the measured EC from DIFF and HCC could be compared in only one fracture. The elapsed time between the measurements is about 3.5 months, see Table 6-4. Figure 6-1 and Table 6-4 show that the measured EC agrees well for this fracture, despite the fact that rather large water volumes were extracted from the borehole before DIFF and HCC (cf Table 5-5).

The most likely explanation to the good agreement in EC in this borehole is the absence of major conductive fractures in the bottom of the borehole with a potential to transmit saline water along the borehole from deeper parts during open-hole pumping prior to the sampling. In addition, both the DIFF and HCC campaigns started at relatively long times after stop of the rinse pumping campaign when possible effects of these pumping activities can be assumed to have decreased.

6.4.2 Borehole KFM03A

In borehole KFM03A, the measured EC from DIFF and HCC could be compared in five fractures, see Table 6-4.

Figure 6-1 and Table 6-4 show that the measured EC values for all fractures were significantly different in Campaign 1 compared to Campaign 2 of the difference flow logging (DIFF). The EC-values from Campaign 2 were similar to the measured EC in the hydro-geochemical characterization (HCC). The measured EC in Campaign 1 was generally c 1.4 higher than those in Campaign 2 for all fractures measured. Below, potential factors to explain the discrepancies in EC between Campaign 1 and 2 at different stages of the measurements are put forward.

Before Campaign 2 was carried out, the reasons to the discrepancies in the results between DIFF (Campaign 1) and HCC were believed to, possibly, be due to differences in the sampling conditions (e.g. drawdown) or sampling procedures (in-situ and surface measurement points for EC, respectively). It was however concluded that such potential sources were not sufficient to explain the significant discrepancies in the results.

Furthermore, it was suspected that one (or both) type of EC measurenments was possibly not representative for the undisturbed, hydrogeological conditions at the fractures tested. Regarding HCC, non-representative results would possibly occur if one (or both) packers, delimiting the test section, did not seal satisfactorily during the pumping and sampling procedure. However, from analysis of water samples, including isotope analysis, from the sampled sections /5/ together with checks of the actual packer positions from e.g. BIPS images it was confirmed that the extracted water in the HCC indeed was representative for the actual depth in the borehole.

For fracture-EC-measurements with DIFF, there are also a number of potential sources of errors which might lead to non-representative samples, cf Chapter 2. Of these sources, leaks past the rubber discs were assumed to be the most likely potential factor, but such leaks could not be confirmed for the actual measurements. Experiences from comparisons of measurements of fracture-EC from difference flow logging and hydro-chemical characterization in borehole investigations in the Finnish program /17/ were also studied. No obvious explanations to the observed discrepancies in the EC-results between DIFF (Campaign 1) and HCC in borehole KFM03A, related to the performance of the measurements, could though be found prior to the re-measurements of EC in Campaign 2.

Another hypothesis put forward, more related to the actual hydrogeological borehole conditions, was upconing of saline water along the borehole from deeper parts of the rock. Such an upconing would possibly lead to invasion of saline water not only in the borehole but also in part of the fracture system penetrating the borehole and thus cause increased fracture-EC values. The difference flow logging in Campaign 1 identified several, highly conductive fractures at the bottom c 100 m of KFM03A which possibly could act as transmitters of saline water from deeper parts of the rock, cf Section 5.1.2.

The re-measurements of fracture-EC in conjunction with the difference flow logging during Campaign 2, resulted in significantly lower EC-values, similar to those in the hydro-geochemical characterization (HCC) and the laboratory measurements of EC, cf Tables 6-4 and 6-1, respectively. Furthermore, as discussed in Section 5.2.2, the EC-profile along the borehole in Appendix 1.2 before the fracture-EC measurements in Campaign 2 clearly shows that the borehole-EC and thus the upconing effect had recovered significantly since Campaign 1. Borehole-EC had almost returned back to the measured EC-profile during the hydro-chemical logging shortly after drilling, see Figure 6-3. During pumping in Campaign 2, saline water again rose in the borehole and the shape of the borehole-EC profile by the end of the pumping period was similar to the one during pumping in Campaign 1, although at a lower EC-level, cf Appendix 1.2.

It can be assumed that similar hydrogeological starting conditions as in Campaign 2 of the difference flow logging also prevailed at the start of the hydro-geochemical characterization. This fact probably explains the good agreement between these two types of fracture-EC measurements. The measurements in HCC and DIFF (Campaign 2) are considered as the best representative of the “undisturbed” hydro-chemical conditions in the fractures and adjacent rock. However, it may take much longer times until the new state in the rock and fractures, created by the drilling and subsequent open-hole rinse pumping, have fully stabilized.

All the above observations strongly support the hypothesis of upconing as the most important factor in explaining the observed discrepancy between the measured fracture-EC in Campaign 1 and 2, respectively. More saline water had most likely invaded into conductive fractures intersected by the borehole during Campaign 1 and then recovered until Campaign 2. This assumption is further supported by the interpreted sub-vertical dip of some of the most conductive fractures at the bottom of the borehole with the potential to transmit saline water along the borehole from deeper parts of the rock, cf Section 5.1.2. Their potential as transmitters of saline water depends on the (vertical) extension of the fractures. It is assumed that the sub-vertical fractures at the bottom of KFM03A are rather extensive in the vertical direction and connected to a major saline water body below the bottom of the borehole.

Table 5-6 may possibly indicate that the strongest disturbances of the natural hydrogeological conditions in the borehole were caused by the continuous rinse pumping with a submersible pump and a high flow rate from the open borehole shortly before Campaign 1 of the difference flow logging. Thus, it may be assumed that the presence of sub-vertical fractures at the bottom of the borehole in combination with extensive rinse pumping was the main factor in the upconing process. The upconing caused the increased EC along the entire borehole and in intersecting conductive fractures prior to the difference flow logging in Campaign 1 as shown in Appendix 1.2.

6.4.3 Borehole KFM04A

In borehole KFM04A, the measured EC from DIFF and HCC could be compared in two fractures. The rinse pumping campaign in KFM04A ended at December 19, 2003, cf Table 5-6. The EC-measurements in HCC in section 230.5–237.6 m were carried out c 3 weeks after stop of rinse pumping. The fracture-EC measurements in the DIFF campaign were carried out about two months later. Section 354.0–361.1 m was then measured in the second campaign of HCC about one month after the DIFF measurements.

Figure 6-1 and Table 6-4 show that the measured EC agrees well for both fractures, despite the fact that rather large water volumes were extracted from the borehole relatively short time before the first HCC campaign (cf Table 6-3). The most likely explanation to the good agreement in EC in this borehole is the absence of major conductive fractures in the bottom of the borehole with a potential to transmit saline water along the borehole from deeper parts during open-hole pumping prior to the sampling.

Table 6-4 demonstrates that large volumes of water were extracted by open-hole pumping in boreholes KFM03A and KFM04A during the rinse pumping- and difference flow logging campaigns. Although the fracture-EC-measurements during the difference flow logging and in the hydro-geochemical characterization in these boreholes generally started relatively shortly after the last open-hole pumping, discrepancies in measured fracture-EC were only observed in KFM03A. Thus, the most important factor seems to be the geological conditions (i.e. fracture transmissivity and orientations) at the deeper parts of the boreholes in combination with extensive open-hole pumping from the boreholes before the EC-measurements.

7 Conclusions

The observed discrepancies of measured EC in the sampled fractures during Campaign 1 and 2 of the difference flow logging in borehole KFM03A are most likely caused by upconing of saline water from deeper parts of the rock along water-bearing, sub-vertical fractures at the deeper parts of the borehole during pumping of the open borehole. Saline water probably also invaded into conductive fractures intersecting the borehole at higher levels.

Upconing probably occurred during both the rinse pumping campaigns prior to the EC-measurements in Campaign 1 of the difference flow logging and, to a minor extent, from pumping in the open borehole during this campaign. The pumping during the drilling operation of the borehole is also assumed to have limited effect on the fracture-EC measurements. The upconing effects of saline water seem to have almost recovered before the subsequent hydro-geochemical characterization respectively Campaign 2 of the difference flow logging. Good agreement of fracture-EC in KFM03A was obtained between the hydro-geochemical characterization and the difference flow logging in Campaign 2.

In boreholes KFM02A and KFM04A, no effects of upconing of saline water were observed, although large water volumes were extracted from the boreholes during the drilling and rinse pumping activities. This fact is probably due to absence of water-bearing sub-vertical or steep fractures at the bottom of these boreholes. Good agreement of fracture-EC was obtained from the hydro-geochemical characterization and the difference flow logging in these boreholes.

Thus, both the hydro-geochemical characterization and difference flow logging campaigns in boreholes with conductive fractures close to the bottom of the boreholes must be carefully planned, especially if the fractures are steeply dipping, in order to obtain representative EC-values and other hydro-geochemical parameters of the sampled fractures. If upconing occurs during rinse pumping of the boreholes, a sufficiently long time must be allowed to restore the “undisturbed” hydro-geochemical conditions before the measurement campaigns.

If possible, open-hole logging of EC along the boreholes should be carried out before and after each measurement campaign to investigate the starting conditions and the effects of any pumping activities in the borehole during the measurements, particularly in boreholes containing water-conductive fractures at the bottom of the boreholes. Such loggings are generally performed during difference flow logging and may also be performed prior to the hydro-geochemical characterization, e.g. by hydro-chemical logging (HKL).

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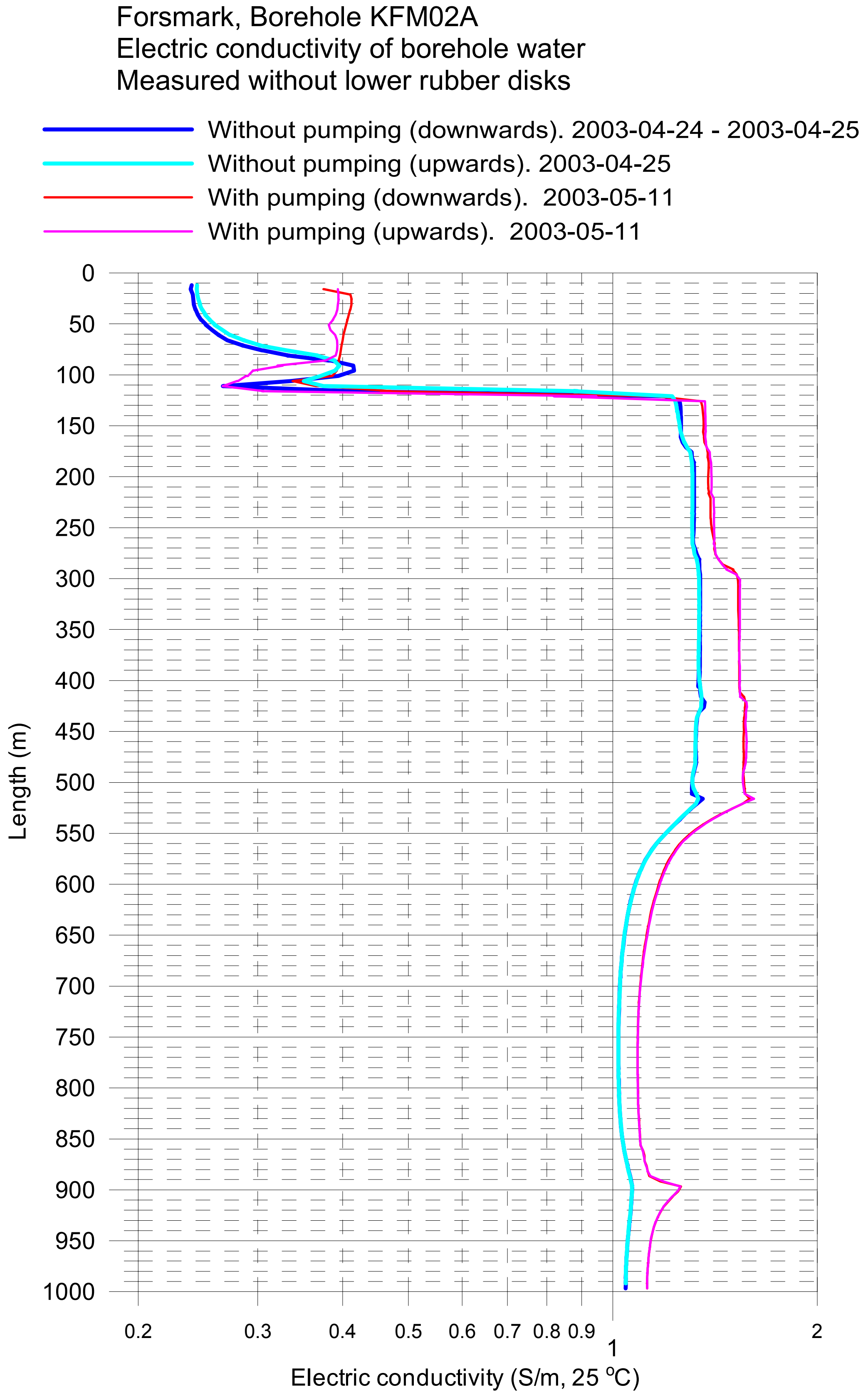
Appendix 1.1 EC vs borehole length in KFM02A



Appendix 1.2 EC vs borehole length in KFM03A

Appendix 1.3 EC vs borehole length in KFM04A