

## **Forsmark site investigation**

### **Drilling of the telescopic borehole KFM02B at drill site DS2**

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September 2007

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*Keywords:* AP PF 400-05-122, AP PF 400-05-126, Core drilling, Overcoring, Drill site DS2.

This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the client.

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## Abstract

At drill site DS2 within the Forsmark investigation area, a 1,000 m deep telescopic borehole, KFM02A, was initially drilled during 2002, indicating low-fractured and hydraulically low-conductive rock at depth, whereas the shallow parts were fractured and to some extent highly water-yielding. In the course of the site investigations a decision was made to drill another telescopic borehole, in order to permit rock stress determinations by overcoring measurements down to repository depth.

This second core drilled borehole at DS2, which is denominated KFM02B, is 573.87 m long and reaches about 565 m in vertical distance from the ground surface (inclined 80.27° from the horizon). The upper part was percussion drilled with 241.6 mm diameter to 87.10 m and was cased with a stainless steel casing after which the gap between the borehole wall and the casing was grouted. These measures entailed that all inflow of ground water to the percussion drilled part of the borehole ceased.

More than 40 rock stress measurement attempts with the overcoring technique were performed between 93–307 m resulting in a better knowledge of the character of the rock stress field inside the Forsmark tectonic lens. However, from the beginning of the rock stress measurement programme difficulties to achieve an efficient cleaning from drill cuttings of the so called pilot borehole, which for each measurement is drilled from the bottom of the ordinary borehole for installation of the measurement probe. This resulted in irregular gluing that often disturbed the measurement. Flushing water and drilling debris was supposed to be discharged into a highly water-yielding fracture at c. 100 m, and when pulling the drill string, the flow of suspended drill cuttings was reversed, i.e. out from the fracture and into the borehole, resulting in settlement of drill cuttings in the pilot hole. In order to seal or at least decrease the hydraulic conductivity of this fracture, a grouting attempt in section 90–129 m was performed.

A sampling- and measurement programme for core drilling provided preliminary information about the geological and hydraulic character of the borehole directly on-site. It also served as a basis for extended post-drilling analyses. E.g. the drill cores together with later produced video images of the borehole wall (so called BIPS-images), were used as working material for the borehole mapping (so called Boremap mapping) performed after drilling. Results of the Boremap mapping of KFM02B are presented in this report. In addition, 106 samples of drill cores for analyses of the hydrogeochemical characteristics of pore space groundwater in low permeable rock were collected, carefully packed according to a special procedure and successfully delivered to a laboratory in Bern.

After completed drilling, grooves were milled into the borehole wall at certain intervals as an aid for length calibration when performing different kinds of borehole measurements after drilling.

Although a better characterization of the rock stress field was achieved than previously, the activity also demonstrated some limitations of the overcoring method with dimension  $\varnothing$  76 at stress levels like those prevailing within the Forsmark candidate area due to micro-fracturing, sometimes resulting in core discing. This problem caused that the overcoring stress measurements were interrupted before repository depth (i.e. at least 400 m vertical depth) was achieved.

## Sammanfattning

På borrhållsplats BP2 i Forsmarks undersökningsområde borrades redan år 2002 ett 1 000 m djupt teleskopborrhål, KFM02A. Borrhålet uppvisade ett sprickfattigt och hydrauliskt sett lågkonduktivt berg mot djupet, medan de övre partierna hade förhöjd sprickfrekvens och i vissa sektioner hög vattenföring. Under platsundersökningens gång beslutades att ytterligare ett teleskopborrhål skulle borraras på denna borrhållsplats för att möjliggöra bergspänningsmätningar med överborrningsmetoden ner till förvarsdjup.

Borrhålet, som benämns KFM02B, blev 573,87 m långt och når cirka 565 m vertikalt (är ansatt med 80,27° lutning från horisontalplanet). Den övre delen av borrhålet hammarborrades med dimension 241,6 mm till 87,10 m och kläddes in med ett rostfritt foderrör. Slutligen cementinjekterades spalten mellan borrhållsvägg och foderrör så att fullgod täthet uppnåddes.

Sammanlagt utfördes ett 40-tal överborrningsmätningar i intervallet 93–307 m. När bergspänningsmätningarna inleddes konstaterades emellertid stora svårigheter att uppnå fullgod limning av mätcellen i det s.k. pilotborrhålet, som borraras från botten av det ordinarie kärnborrhålet vid varje mättillfälle. Problemet misstänktes bero på otillräcklig rengöring av pilotborrhålet från borrhållskax. Eftersom det fanns ett sprickigt parti med hög hydraulisk konduktivitet runt 100 m fanns en misstanke om att spolvatten med suspenderat borrhållskax pressades in i denna spricka för att senare, när rörsträngen drogs upp ur hålet sugas ut i borrhålet. Borrhållskaxet hade därefter möjlighet att sedimentera i pilotborrhålet. För att avtåta inflödena i borrhålet utfördes en injektering i intervallet 90–129 m.

Ett mät- och provtagningsprogram för kärnborrningen gav preliminär information om borrhållsets geologiska och hydrauliska karaktär direkt under pågående borring samt underlag för fördjupade analyser efter borring. Bland de insamlade proverna utgör borrhållskärnorna tillsammans med videofilm av borrhållsväggen (s.k. BIPS-bilder), arbetsmaterialet för den borrhållskartering (s.k. Boremapkartering) som utförs efter borring. Även resultaten från Boremapkarteringen av KFM02B finns redovisad i föreliggande rapport. Dessutom togs 106 kärnprover som förpackades enligt en speciell procedur och skickades till ett laboratorium i Bern för analys av den kemiska sammansättningen av grundvattnet i bergmatrikens porer.

Efter avslutad borring frästes referensspår in i borrhållsväggen med syftet att användas för längdkalibrering i samband med olika typer av borrhållsmätningar som senare utförs i det färdiga borrhålet.

Bergspänningsmätningarna i KFM02B förbättrade kunskaperna om spänningsfälts karaktär inom Forsmarks kandidat område. Mätkampanjen visade emellertid också att överborrningsmetoden i dimension  $\varnothing$  76 mm vid de spänningsnivåer som råder i Forsmarks kandidat område har vissa begränsningar, sannolikt orsakade av mikrouppsprickning i den överborrade borrhållskärnan, som ibland också kan leda till s.k. ore discing. Detta var orsaken till att överborrningskampanjen avbröts innan mätningarna nått förvarsdjup, dvs minst 400 m vertikaldjup.

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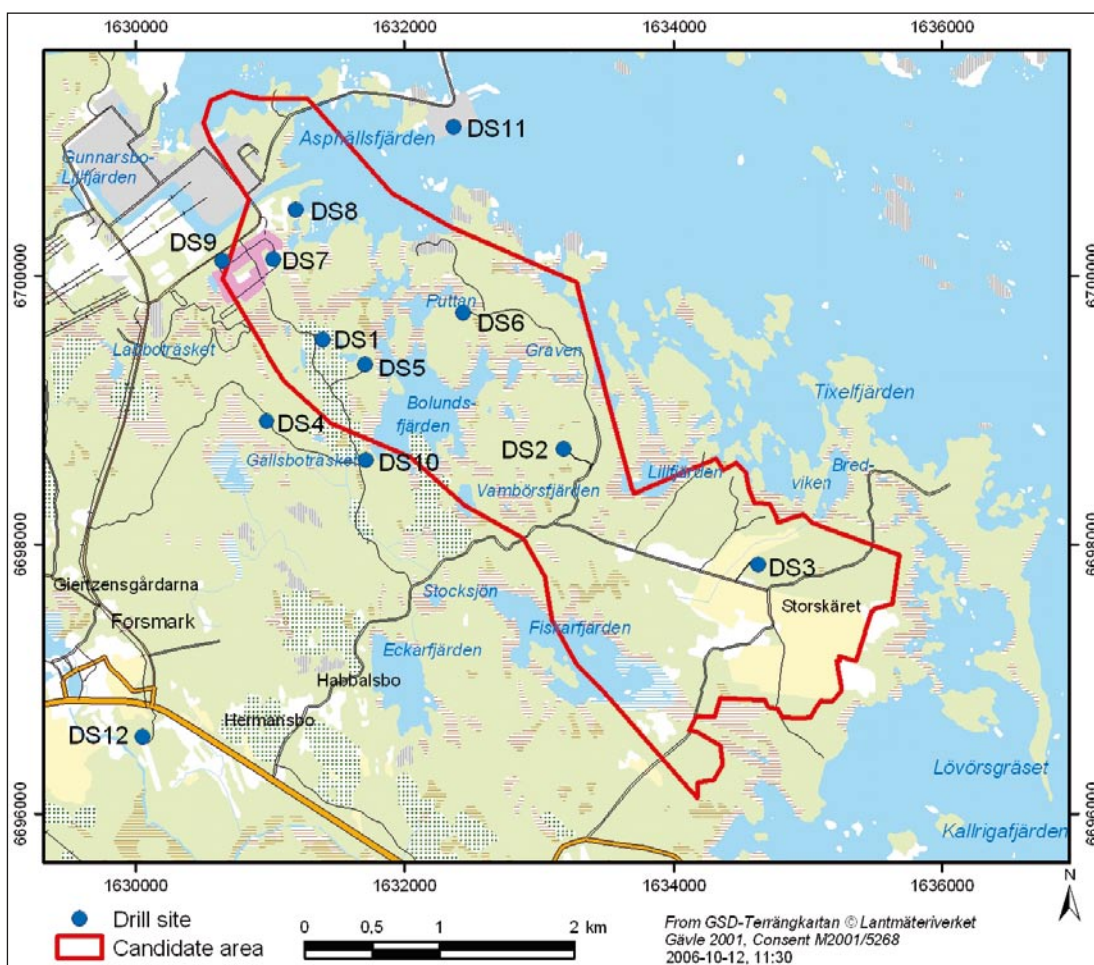
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# 1 Introduction

Site investigations are currently being performed by SKB for location and safety assessment of a deep repository for high level radioactive waste /1/. The investigations are carried out in two Swedish municipalities, Östhammar and Oskarshamn. The site investigation area in Östhammar is situated close to the Forsmark nuclear power facilities /2/ and /3/, see Figure 1-1.

This document reports the results gained by core drilling of borehole KFM02B, which is one of the activities performed within the site investigation at Forsmark. The work was carried out in accordance with Activity Plan AP PF 400-05-122. A sub-activity, sampling of drill cores specimens for analysis of the hydrogeochemical characteristics of pore space groundwater, was conducted in compliance with Activity Plan AP PF 400-05-126. The Activity Plans and other controlling documents for performance of this activity are listed in Table 1-1. These papers are all SKB's internal controlling documents.

Drilling is one important activity within the scope of the site investigations. Three main types of boreholes are produced: core drilled and percussion drilled boreholes in solid rock and short boreholes drilled through the soil layer. The last type may be accomplished by different drilling techniques, e.g. percussion drilling or auger drilling.



**Figure 1-1.** The site investigation area at Forsmark including the candidate area selected for more detailed investigations. Drill sites DS1-12 are marked with blue dots.

**Table 1-1. Controlling documents for performance of the activity.**

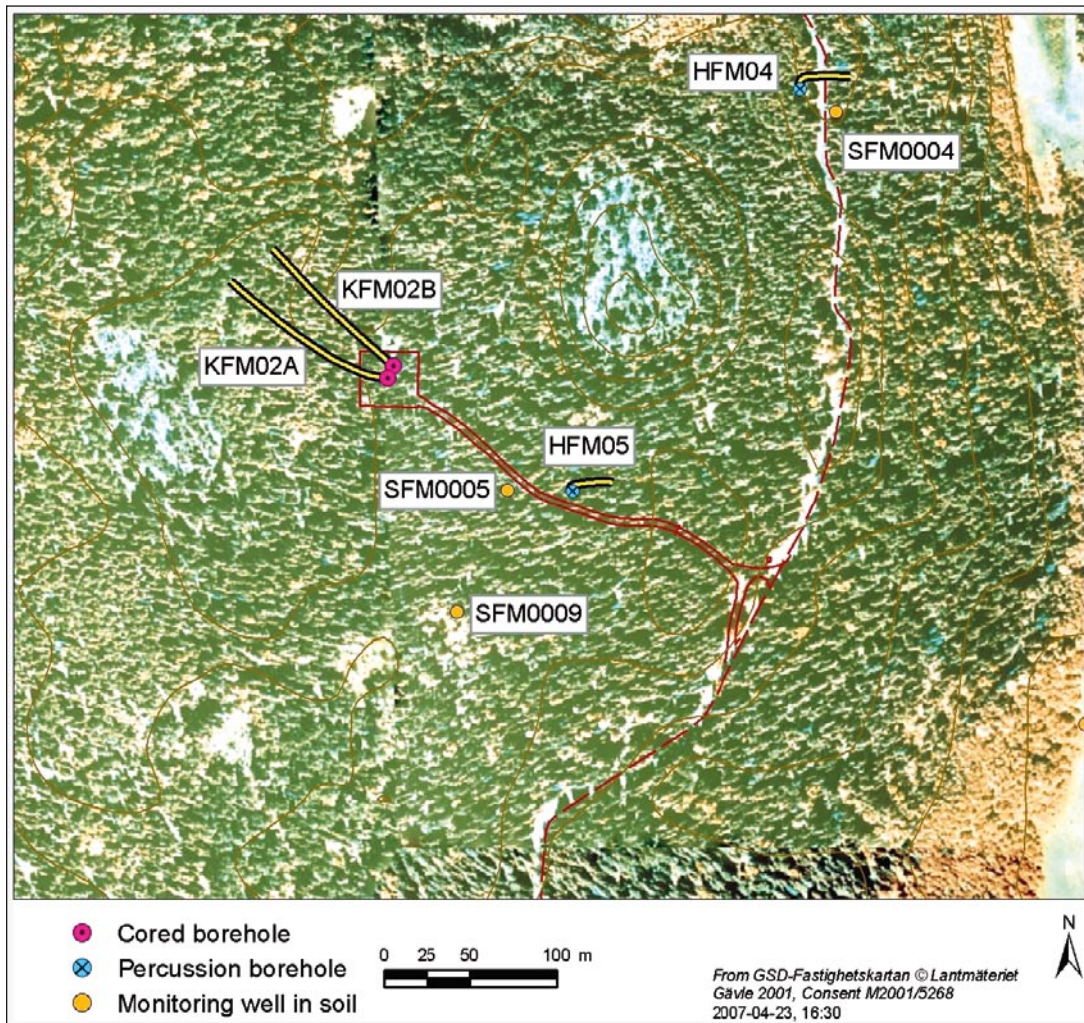
<b>Activity Plan</b>	<b>Number</b>	<b>Version</b>
Teleskopborrning och bergspänningsmätningar i KFM02B.	AP PF 400-05-122	1.0
Pore space groundwater in low permeable crystalline rocks in borehole KFM02B.	AP PF 400-05-126	1.0
<b>Method Descriptions</b>	<b>Number</b>	<b>Version</b>
Metodbeskrivning för kärnborrning.	SKB MD 620.003	2.0
Metodbeskrivning för hammarborrning.	SKB MD 610.003	2.0
Metodbeskrivning för genomförande av hydrauliska enhåls-pumptester.	SKB MD 321.003	1.0
Metodbeskrivning för registrering och provtagning av spolvatten-parametrar samt borrhålsundersökning under kärnborrning.	SKB MD 640.001	1.0
Method Description for in situ stress measurements by means of overcoring using the Borre probe.	SKB MD 181.001	1.0
<b>Method Instructions</b>	<b>Number</b>	<b>Version</b>
Rengöring av borrhålsutrustning och viss markbaserad utrustning.	SKB MD 600.004	1.0
Användning av kemiska produkter och material vid borring och undersökning.	SKB MD 600.006	1.0

The deepest boreholes drilled at the site investigation are drilled with core drilling techniques. In total, three sub-vertical and eleven inclined, approximately 800–1,000 m long, cored boreholes are drilled within the investigation area. Besides the deep holes, six semi-deep (500–800 m) boreholes and five short (100–500 m) boreholes have been core drilled. The boreholes are located at twelve drill sites, see Figure 1-1, where each site may include between one and four cored boreholes as well as percussion drilled holes and soil boreholes. By drilling the deep boreholes, a so called telescopic drilling technique is applied, entailing that the upper c. 60–100 m section of the borehole is percussion drilled with a large diameter ( $\geq 200$  mm), whereas the borehole interval 100–1,000 m is core drilled with a diameter of approximately 76–77 mm.

Prior to drilling of KFM02B, three short or semi-deep boreholes, KFM01B (501 m), KFM07B (299 m) and KFM07C (500 m) were used for overcoring rock stress measurements. In order to carry out supplementary rock stress measurements, focusing especially at the rock volumes close to a major, gently dipping fracture zone, ZFMA2, a new borehole, KFM02B, was drilled at drill site DS2, where the 1,002 m deep telescopic borehole KFM02A had previously been sited. This borehole penetrated deformation zone ZFMA2 within the borehole section 410–520 m. The new borehole at DS2, KFM02B, was drilled to 573.87 m length by applying the telescopic drilling technique. The percussion drilled part to 0–87.15 m was performed between Jan 18<sup>th</sup> and Jan 30<sup>th</sup>, 2006, and the core drilled part between June 6<sup>th</sup>, 2006, and Feb 13<sup>th</sup>, 2007.

Close to the core drilled boreholes at drill site DS2, also percussion drilled boreholes in soil and solid rock have been drilled for different purposes. The lengths of these boreholes vary between a few metres to 221 m. The locations of all boreholes at drill site DS2 are displayed in Figure 1-2.

Results from drilling of the flushing water well HFM05, used for the supply of flushing water when drilling KFM02A and KFM02B, and a monitoring well in hard rock, HFM04, have been reported separately /4/. Results from drilling of KFM02A were reported in /5/ and the geological mapping of borehole KFM02A (so called Boremap mapping) in /6/. The overcoring measurements in borehole KFM02B will be displayed in /7/, whereas the Boremap mapping of KFM02B is presented in /8/.



**Figure 1-2.** Borehole locations at drill site DS2. Besides the telescopic boreholes KFM02A and KFM02B, the drill site includes two monitoring wells in solid rock (HFM04 and HFM05) and two monitoring wells in soil (SFM0004-05). HFM05 was also used as a water well supplying flushing water when drilling KFM02A and KFM02B. The projection of inclined boreholes on the horizontal plane at top of casing is shown in the figure.

Original data from the reported activities are stored in the primary database Sicada. Data are traceable in Sicada by the Activity Plan number (AP PF 400-05-122 for drilling of KFM02B and AP PF 400-05-126 for pore space water sampling and analysis). Only data in databases are accepted for further interpretation and modelling. The data presented in this report are regarded as copies of the original data. Data in the databases may be revised, if needed. Such revisions will not necessarily result in a revision of the P-report, although the normal procedure is that major revisions entail a revision of the P-report. Minor revisions are normally presented as supplements, available at [www.skb.se](http://www.skb.se).



## 2 Objective and scope

The main objectives of drilling deep telescopic boreholes at the site investigation are the following:

- To provide rock samples from the ground surface to the borehole bottom. Percussion drilling through the overburden produces soil samples recovered to the surface by compressed air. These samples are collected with a frequency of one sample per metre. The same sampling frequency is applied for the drill cuttings produced when percussion drilling the upper c. 60–100 m of the solid rock. Below, the core drilling provides (in principle) continuous drill cores down to the borehole bottom. The rock samples collected during drilling are used for lithological, structural and rock mechanical characterization as well as for determination of transport properties of the bedrock from the rock surface to the full drilling depth.
- To render geophysical borehole investigations possible, e.g. TV logging, borehole radar logging and conventional geophysical logging as an aid for the geological/rock mechanical characterization.
- To allow hydraulic borehole tests (single-hole tests as well as interference tests) for characterization of the hydrogeological conditions. As regards KFM02B an interference test combined with a tracer test was performed between the two adjacent boreholes KFM02A and KFM02B.
- To make water sampling possible down to and below repository depth. High-class hydrogeochemical sampling/analysis demands special measures during and after drilling in order to keep the borehole clean. When these measures have been taken, the borehole is categorized as a borehole of chemical type. Only boreholes of this category are approved for advanced hydrogeochemical and microbiological characterization.
- To enable long-term hydraulic and hydrogeochemical monitoring at different levels of the bedrock.

All objectives mentioned above apply to borehole KFM02B, although the hydrogeochemical investigations in this borehole addressed only pore space water in low-conductive rock and not groundwater from water-yielding fractures, which is a more common type of investigations. Another specific objective for borehole KFM2B was to conduct rock stress measurements during drilling by applying the overcoring technique. A key issue was to characterize the stress field and its dependence on the major gently dipping fracture zone ZFMA2.

During drilling, a number of drilling related parameters are monitored by a drilling monitoring system. Part of these data sets, in this report called DMS (Drilling Monitoring System) data, which after drilling are transferred to Sicada, may be used as supplementary data for geological and hydraulic characterization as well as for assessment of technical aspects of the drilling operations. DMS-data are described in this report.

## 3 Equipment

A Puntell MX 1000 percussion drill rig, see Figure 3-1, was engaged for the upper part of drilling borehole KFM02B while the core drilled part was made with an Onram 2000 CCD from Hagby and a B20 core drilling system from Atlas Copco. A short presentation of the drilling equipments is provided below.

### 3.1 Drilling equipment

#### 3.1.1 Drilling equipment on KFM02B

The drilling process was first operated by a percussion drilling machine of Puntell MX 1000 type and continued with an Onram 2000 CCD core drilling system from Hagby. Due to malfunction this equipment was from 113.58 m drilling length exchanged, and the remaining part of the borehole was drilled with a B20 core drilling system from Atlas Copco.

The Puntell percussion drilling system is supplied with separate engines for transportation and power supplies. Water and drill cuttings are retrieved from the boreholes by a 27 bars air-compressor, type Atlas-Copco XRVS 466 Md. Technical specifications of the core drilling machines with fittings are given in Table 3-1.

Core drilling with a wireline system entails recovery of the core barrel via the drilling pipe string, inside which it is hoisted up with the wireline winch. During drilling of boreholes KFM02B, a 3 m triple tube core barrel was used. The nominal core diameter for the  $\varnothing 75.8$  mm part of the borehole is 50.2 mm. Minor deviations from this diameter may however occur.



*Figure 3-1. The Puntell percussion drilling machine in operation on borehole KFM02B.*

**Table 3-1. Technical specifications of the Onram 2000 CCD and the B20 core drilling systems with appurtenances.**

Unit	Manufacturer/type	Specifications	Remarks
<b>Onram 2000</b>	<b>Hagby-Asahi</b>	<b>Capacity for 76–77 mm holes maximum approx. 900–1,500 m depending on choice of drill string</b>	
Flush water pump	Bean	Max flow rate: 170 L/min Max pressure: 103 bars	
Submersible pump	Grundfos SQ	Max flow rate: 200 L/min	
Mobile electrical plant	P250HE with diesel engine Perkins GCD 325	250 KVA, 200 kW, 360 A	Only as reserve as the equipment is served by permanent power
Compressor	Atlas Copco GA75P-13	Max pressure: 12 bars Flow: > 5 L/sec	Electrically supplied
CCD-system	Dunfoss		Standard system modified for core drilling by the manufacturer
<b>B20</b>	<b>Atlas Copco Craelius</b>	<b>Capacity for 76–77 mm holes maximum approx. 1,500 m</b>	
Flush water pump	Trido 140	Max flow rate: 140 L/min Max pressure: 70 bars	
Submersible pump	Grundfos SQ	Max flow rate: 200 L/min	
Mobile electrical plant	Atlas Copco QAS 300 GD engine with Volvo TAF 1032 TAD	300 KVA	Only as reserve as the equipment is served by permanent power
Compressor	Atlas Copco GA75P-13	Max pressure: 13 bars Flow rate 169 L/sec at 12.5 bars	Electrically supplied
CCD-system	Atlas Copco		Standard system modified for core drilling by the manufacturer

### 3.1.2 Rock stress measurement device

Three-dimensional *Borre* probe (Figure 3-2) equipment where used for the rock stress measurements in KFM02B.

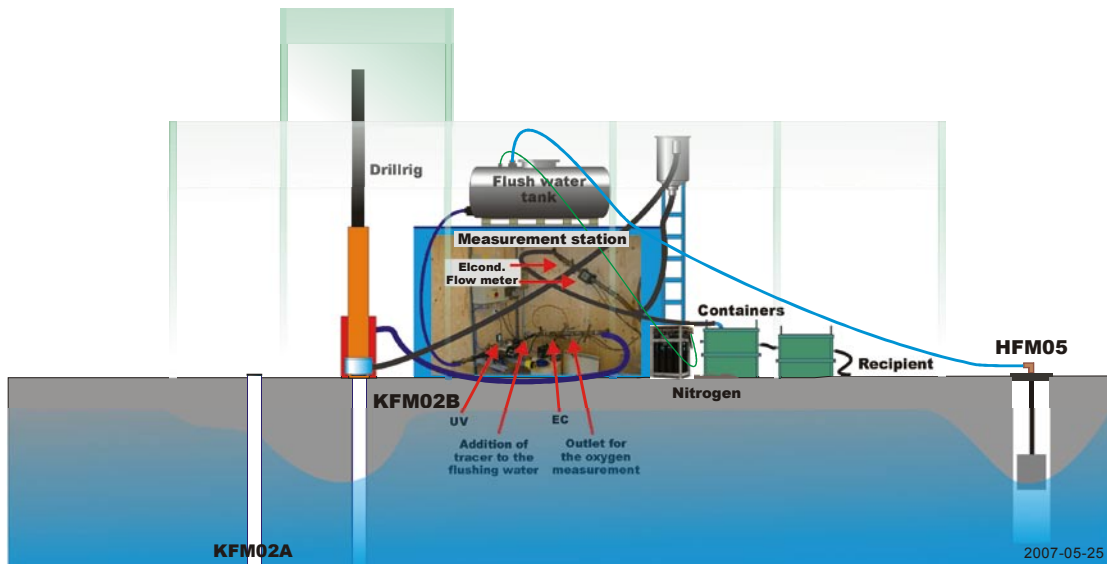
### 3.1.3 Flushing/return water system – function and equipment

Core drilling involves pumping of flushing water down the drill string, through the drill bit and out into the borehole in order 1) to conduct frictional heat away from the drill bit, and 2) to enhance the recovery of drill cuttings to the ground surface. The cuttings, suspended in the flushing water (in general mixed with groundwater), are forced from the borehole bottom to the ground surface via the gap between the borehole wall and the drilling pipes. A schematic illustration of the flushing/return water system when drilling KFM02B at DS2 is shown in Figure 3-3. Below, the following equipment systems and their functions are briefly described:

- equipment for preparing the flushing water,
- equipment for measuring flushing water parameters (flow rate, pressure, electrical conductivity and dissolved oxygen),
- equipment for air-lift pumping while drilling,
- equipment for storage and discharge of return water.



**Figure 3-2.** The logger unit, part of the Borre probe, is released from data to the portable computer.



**Figure 3-3.** Schematic illustration of the flushing/return water system when drilling KFM02B at DS2. For measurements of the accumulated return water volume, a mechanical water gauge was used.

### **Preparing the flushing water**

The water well used for the supply of flushing water for core drilling of KFM02B was a percussion drilled well in hard rock, HFM05 (see Figure 1-2), situated approximately 125 m from the drill site.

The water quality from the HFM05 well had been analysed in advance and considered as sufficiently good to serve as flushing water for KFM11A.

Besides these basic demands on the flushing water quality, which were fulfilled when drilling KFM02B, the flushing water was also prepared in three steps before use, in accordance with SKB MD 620.003 (Method Description for core drilling).

- 1) Incoming water from the water well was pumped into the flush water tank (see Figure 3-3).
- 2) Nitrogen was bubbled through the water in the tank in order to expel oxygen which might be dissolved in the water (see Figure 3-3). Expelled oxygen was discharged through a pressure reducing valve. Oxygen must be avoided in the flushing water because it is a critical parameter in the programme for hydrogeochemical characterization of the groundwater. The water was then kept continuously under a positive nitrogen pressure (about 1 bar) until pumped down into the borehole.
- 3) The incoming water from the tank was exposed to UV-radiation (inside the measurement station) before entering the trace dosing equipment, illustrated in Figure 3-3. The microbe content in the water was thereby radically reduced.
- 4) An organic tracer dye, Uranine, was added by the tracer dosing feeder at a concentration of 0.2 mg/L, before the water was pumped into the borehole, see Figure 3-3. Labelling the flushing water with the tracer aims at enabling detection of the flushing water content in groundwater samples collected in the borehole during or after drilling.

### ***Measurement of flushing water parameters***

The total quantity of water supplied to the borehole was acquired by counting the number of filled water tanks used, multiplied by the tank volume.

The following flushing water parameters were measured on-line when pumping the flushing water into the borehole:

- flow rate,
- pressure,
- electrical conductivity,
- dissolved oxygen.

Data were stored in a drilling monitoring system, see Section 3.3.3. Technical specifications of the measurement instruments are presented in Table 3-2.

The total quantity of water supplied to the borehole, used as a double-check of the flow measurements, was acquired by manual reading of flow meters and a conductivity meter. The readings were stored and then afterwards compared to the automatic readings, which served as data quality check.

**Table 3-2. Technical specifications of instruments used for measurement of flushing water parameters.**

<b>Instrument</b>	<b>Manufacturer/type</b>	<b>Range of measurement</b>	<b>Remarks</b>
Flow meter	Krohne IFC 010-D	1–350 L/min	Inductive
Electrical conductivity	Kemotron 2911	1 mS/cm–200 mS/cm 0.1 mS/m–20 S/m	
Oxygen	Orbisphere model 3600		

### ***Air-lift pumping while drilling***

Air-lift pumping during drilling of telescopic boreholes involves pumping of compressed air into the percussion drilled portion of the borehole, forcing it to emerge at a depth of about 40–100 m, depending on the depth of the percussion drilled borehole section. As the air expands in rising out of the borehole, it lifts the water up, thereby producing the air-lift pumping effect. The resulting pressure drop entails transport of much of the mixture of water and drill cuttings from the bottom of the hole up to the surface, see Figure 3-4. The resulting return water is a mixture of flushing water, groundwater from fracture zones in the rock and drill cuttings. Some of the flushing water and drill cuttings will, however, be forced into the local fracture systems, and a minor part will be left in the borehole. The air-lift pumping is continued throughout the drilling period.

The air-lift pumping equipment in KFM02B consisted of several main components, see Table 3-3 and Figure 3-4.

Core drilling beneath the large-diameter percussion drilled part of the borehole demands installation of a support casing, in order to avoid vibrations of the drill pipe string. This is accomplished by an inner support casing, which is further stabilized by an outer support casing supplied with steel “wings” resting against the borehole wall, see Figure 3-4. When installing the outer support casing, it was lowered into the borehole together with the hoses for air-lift pumping with a mobile crane. The ejector tube was fit to the outer support casing, about 200 mm above the bottom of the telescopic borehole. A 22 mm supply hose and a 40 mm return hose were connected to the ejector tube as shown in Figure 3-5. With this construction, the air leaving the ejector hose, reducing the pressure in the lower part of the ejector tube, thereby helping to lift drill cuttings from the bottom of the hole.

### ***Storage and discharge of return water***

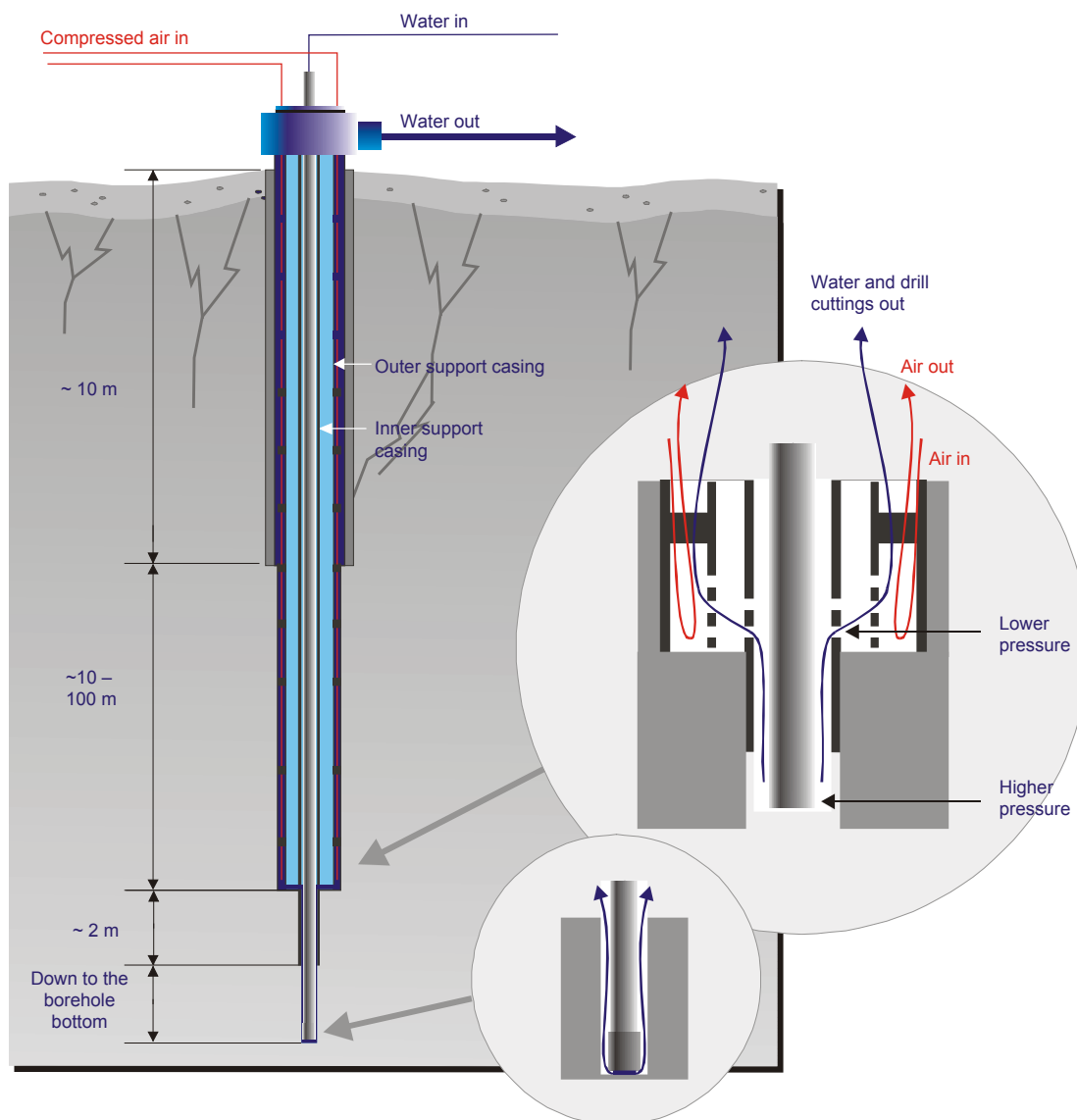
At the surface level, the return hose was connected to a return pipe between the discharge head and the first return water container. The return water was discharged from the borehole via an expansion vessel and a flow meter to two containers, in which the drill cuttings separated out in the sedimentation container. Since the return water had an increased salt content, it could not, for environmental reasons, be discharged into any fresh water recipient, but had to be pumped from the container via a 1 km long pipe string to the Baltic Sea.

**Table 3-3. Air-lift pumping equipment used in KFM02B.**

<b>Components</b>	<b>KFM02B</b>
Air compressor, 12 bars/10 m <sup>3</sup> /min	X
Electrical supply cubicle, at least 16 A	X
Outer support casing, 98/89 mm diameter	88 m
Inner support casing, 84/77 mm diameter	89 m
2 Ejector pumps, each contained;*	
PEX hose, 1 × 22 mm	2 × 90 + 30** m
PEM hose, 1 × 40 mm	2 × 90 + 20** m
Air nozzle	
PEX hose, 1 × 22 mm	88 + 30** m
Expansion vessel (= discharge head)	X
PEM hose: 20 bars, 32 mm diameter (pressure transducer)	90 m
Pressure sensor, 10 bars, instrumentation and data-logging unit	X

\* Two mammoth pumps are always installed in each telescopic bore hole.

\*\* Extended hose; PEX connected to air compressor and PEM connected to Cyclone.

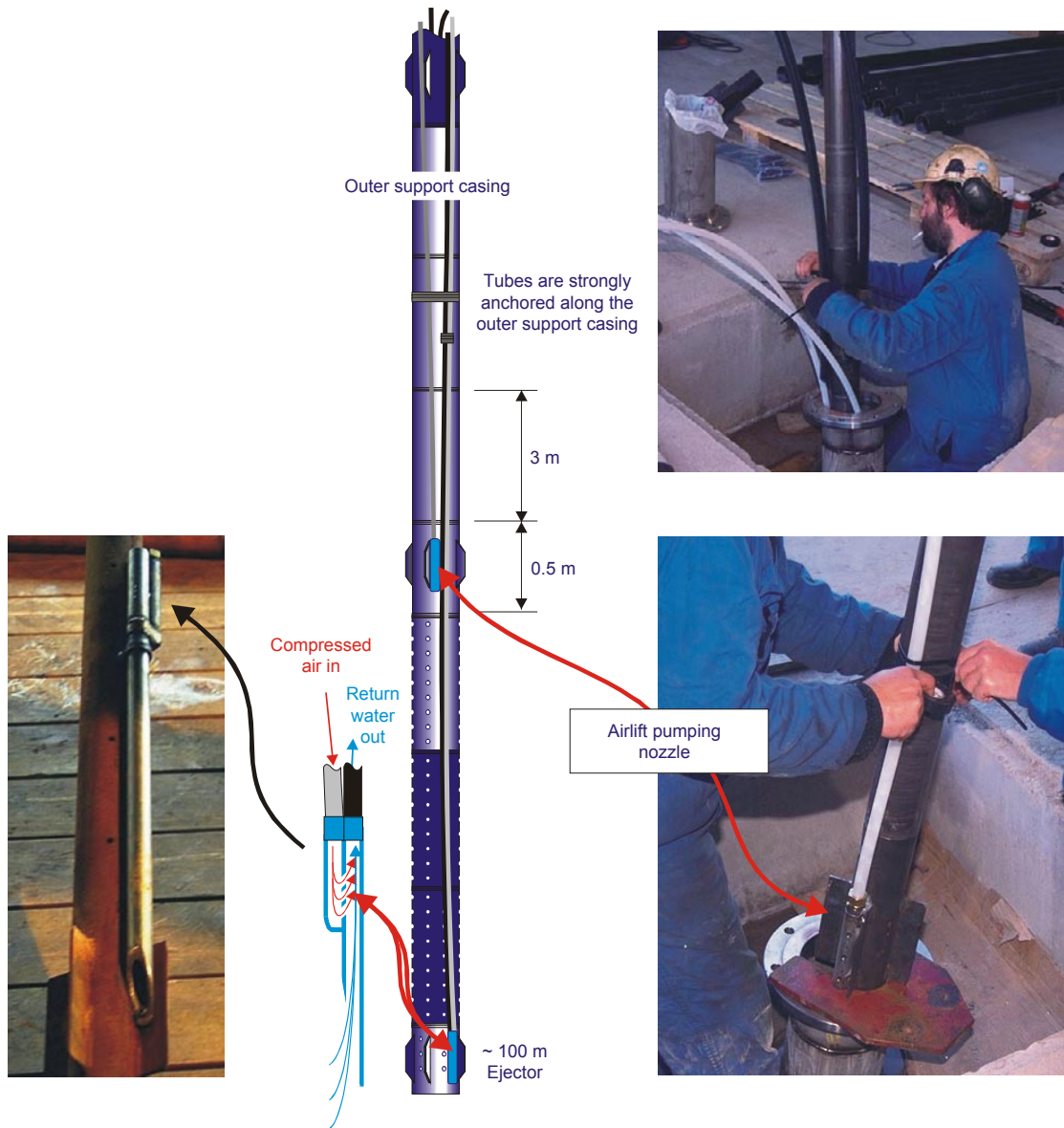


**Figure 3-4.** Air-lift pumping during core drilling of a telescopic borehole. Schematic representation, where the drilling depths are only approximate. The air and instrumentation hoses are secured to the outer support casing. The compressed air raises the flushing water and drill cuttings from the hole. Return water flows between the borehole wall and the drill pipe string and then through holes in the support casing before being transported up to the surface.

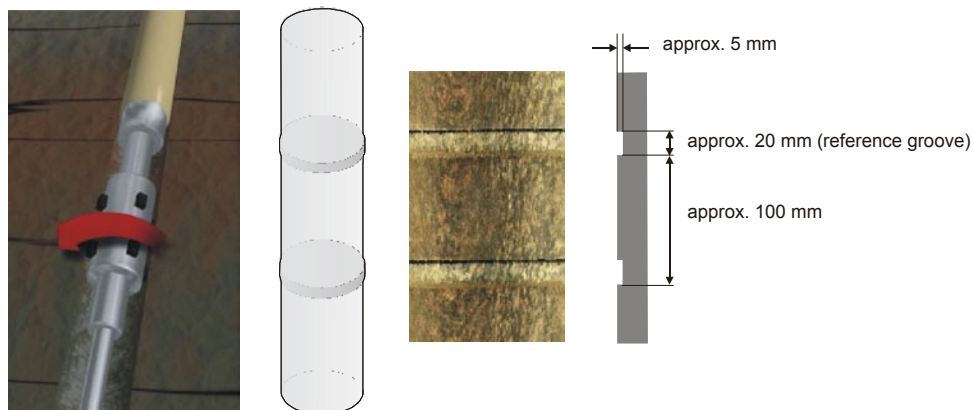
### 3.1.4 Groove milling equipment

After completion of drilling, borehole KFM02B have been used and will further be used for a variety of borehole measurements, employing many types of borehole instruments with different stretching characteristics (pipe strings, wires, cables etc). In order to provide a system for length calibration in the borehole, reference grooves have been milled into the borehole wall with a specially designed tool at regular levels, see Figure 3-6. This was carried out after drilling, but with use of the drilling machine and drill pipe string.

At each level where milling was performed, two 20 mm wide grooves were milled with a distance of 10 cm between them. After milling, the reference grooves were detected with the SKB level indicator (a calliper). A BIPS-survey provided the final confirmation that the grooves exist.



**Figure 3-5.** Schematic representation of connection and installation of air-lift pumping nozzle and ejector on the outer protective casing.



**Figure 3-6.** Layout and design of reference grooves.



### **3.1.5 Equipment for deviation measurements**

After completion of drilling, a deviation measurement was carried out with a Reflex Maxibor™-system, which is an optical, i.e. non-magnetic measurement system. Azimuth and dip are measured at every third metre. The collaring point coordinates and the measured values are used for calculating the coordinates of the position of the borehole at every measurement point.

Also another method, based on magnetic accelerometer technique, was applied for deviation measurements in order to check the validity of the Maxibor™-measurements. The surveying instrument used was the Flexit Smart Tool System.

At the time of drilling KFM02B, the Maxibor™-method was assessed as the most reliable of different deviation methods tested by SKB, and Maxibor-data stored in the database Sicada were normally assigned as the only deviation data set permitted to be used (so called “in use displayed data”) even if another or several deviation methods had been applied in a borehole as well. However, in connection with a major quality revision regarding orientation of all identified geological objects (fractures, fracture zones rock contacts etc) conducted by SKB during late autumn 2006 to winter/early spring 2007, a reassessment of the reliability of deviation measurement methods was made, whereby the Flexit-method was judged as providing the most reliable results. Therefore a revision was made also for borehole KFM02B, and today Flexit-data provide the in use displayed deviation data set. However, all available deviation measurements, i.e. for borehole KFM02B Flexit- as well as Maxibor-data have been used for estimation of the uncertainty of deviation data.

Results from the deviation measurements stored in Sicada are presented in Section 5.5.5.

## **4 Execution**

### **4.1 General**

The activity drilling of and performance of overcoring rock stress measurements in KFM02B was conducted in compliance with Activity Plan AP PF 400-05-122, referring to SKB MD 620.003 (Method Description for core drilling). The drilling operations included the following parts:

- preparations,
- mobilisation, including lining up the machine and measuring the position,
- drilling, measurements, over-coring and sampling during drilling,
- finishing off field work,
- data handling.

The items are presented more in detail in Sections 4.2–4.6.

### **4.2 Preparations**

The preparations included the contractor's service and function control of his equipment. The machinery was supplied with fuel, oil and grease entirely of the types stated in SKB MD 600.006, see Table 1-1. Finally, the equipment was cleaned in accordance with SKB MD 600.004. Table 1-1.

### **4.3 Execution of drilling at KFM02B**

#### **4.3.1 Mobilization**

Mobilization onto and at the site included preparation of the drill site, transport of drilling equipment, flushing water equipment, sampling boxes for drill cores, as well as hand tools etc. Furthermore, the mobilization consisted of cleaning of all in-the-hole equipment at level one in accordance with SKB MD 600.004, lining up the machine and final function control of all equipment.

#### **4.3.2 Drilling of section 0–87.15 m**

Drilling started with the Puntell machine with NO-X 280 down to 3.23 m followed by drilling to 87.15 m with diameter 156.2 mm and reaming to 87.10 m with 241.6 mm and cement grouting of the gap between the casing and the borehole wall. The soil depth was approximately 0.84 m.

#### **4.3.3 Core drilling, measurements and sampling during drilling**

By core drilling of borehole KFM02B, two borehole dimensions were applied. section 87.15–88.61 m was drilled with a borehole diameter of 75.8 mm after which the section was reamed to 86 mm. Drilling continued with 75.8 mm in section 88.61–113.58 m with the Onram 2000 rig and after exchange to the Atlas Copco B20 machine the borehole was completed to 573.87 m with a diameter of 75.8 mm.

Core drilling is associated with a programme for sampling, measurements and other activities during and immediately after drilling, cf. SKB MD 620.003. However, for different reasons, during drilling of KFM02B some deviations from this programme could not be avoided. The major discrepancy compared to SKB MD 620.003 was the overcoring rock stress measurements during drilling. In order to elucidate the nonconformities, the programme according to the Method Description is presented in Section 4.6, Table 4-1, together with the actual performance when drilling KFM02B.

A special programme for sampling drill cores to determine pore space groundwater in low permeable crystalline rocks in the borehole was included in the activities during the drilling. It was however conducted in compliance with Activity Plan AP PF 400-05-126. Results will be reported separately in /12/.

Results from the measurements and registrations during core drilling are presented in Chapter 5.

#### **4.4 Finishing off work**

The concluding work included the following items:

- 1) The borehole was flushed for about 10 hours in order to clean it from drilling debris adhered to the borehole walls, settled at the bottom of the hole or suspended in the water.
- 2) The drill string was pulled.
- 3) The borehole was secured with a lockable stainless steel flange.
- 4) The core drilling equipment was removed, the site cleaned and a joint inspection made by SKB and the contractor.

#### **4.5 Data handling/post processing**

Minutes for several items with the following headlines: Activities, Cleaning of the equipment, Drilling, Borehole, Core drilling penetration rate, Deliverance of field material and Discrepancy report were filled in by the field crew, and collected by the Activity Leader, who made a control of the information and had it stored in the SKB database Sicada and are traceable by the Activity Plan number.

## 4.6 Nonconformities

Nitrogen air flushing was performed in order to improve cleaning of the borehole from drilling debris.

The core drilling operation resulted in a number of nonconformities with the Method Description. These are presented in Table 4-1 below.

**Table 4-1. Programme for sampling, measurements, registrations and other activities during and immediately after core drilling according to SKB MD 620.003 AP PF 400-05-122, and the actual performance during drilling of borehole KFM02B.**

Activity	Performance and frequency according to SKB MD 620.004 and, for the last item, AP PF 400-05-122	Performance and frequency during drilling of KFM02B
Registration of drilling- and flushing water parameters.	Registration during the entire drilling.	According to programme.
Core sampling.	Continuous sampling of the entire drilled section.	According to programme.
Deviation measurements.	Normally performed every 100 m and after completion of drilling.	One Maxibor measurement after 243 m and two measurements after completion of drilling and two measurements with Flexit.
Hydraulic tests.	Normally performed every 100 m, and also when penetrating larger conductive fractures/zones. The tightness of the drilling pipe string should be controlled before each test.	No measurements performed.
Water sampling.	Normally performed every 100 m, and also when penetrating larger conductive fractures/zones. The tightness of the drilling pipe string should be controlled before each test.	No measurements performed.
Absolute pressure measurements.	Normally during natural pauses in drilling.	No measurements performed.
Groove milling in the borehole wall, normally at each 50 m.	Normally performed after completion of drilling.	Nine (double) grooves performed.
Over-coring rock stress measurements.	Measurements at 4 different levels.	Performed at 93–151 m, 156–181 m, 217–256 m and 300–307 m.

## 5 Results

All data were stored in the Sicada database. An overview of the drilling progress of borehole KFM02B is given in Section 5.1, whereas geometrical data and technical design are presented in Section 5.2.

Results from drilling and measurements during drilling are accounted for in:

- Section 5.3 (drilling 0–87.15 m).
- Section 5.4 (drilling 87.15–573.87 m).
- Section 5.5 (measurements while drilling and sampling of pore space groundwater in low permeable rock).

Well Cad-presentations of borehole KFM02B are shown in:

- Appendix A (percussion drilled part of KFM02B).
- Appendix B (entire borehole KFM02B).

The Well Cad plots are composite diagrams presenting the most important technical and geo-scientific results from drilling and investigations made during and immediately after drilling.

### 5.1 Drilling progress KFM02B

Borehole KFM02B was drilled during a period of slightly more than 7.5 months including summer holidays, see Figure 5-1. The prolonged drilling period was mainly due to the much time consuming overcoring rock stress measurements, but partly also to the drilling performance with only one shift/day, seven days a week. At the end of the pore space water sampling period, the drilling machine could only work 4 days a week, due to that the remote analysis laboratory kept closed during week ends. It should also be mentioned that numerous problems occurred with the rock stress measurements, among others gluing problems (the measurement probe is glued towards the wall of the pilot borehole), technical problems with the *Borre* probe (see Section 3.1.2), discing of the pilot drill core etc. Due to this kind of difficulties, many measurement attempts at each level were unsuccessful.

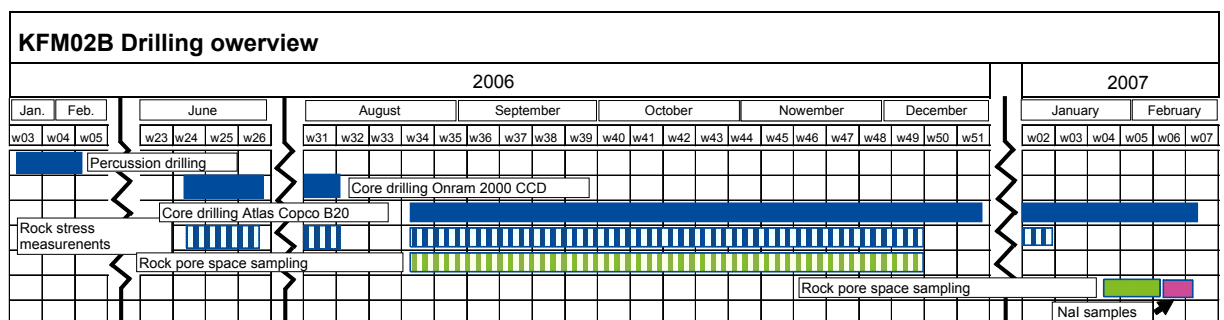


Figure 5-1. Overview of the drilling performance of borehole KFM02B.

## 5.2 Geometrical and technical design of borehole KFM02B

Administrative, geometric and technical data for the core drilled borehole KFM02B are presented in Table 5-1. The technical design of the borehole is illustrated in Figures 5-2.

**Table 5-1. Administrative, geometric and technical data for borehole KFM02B.**

Parameter	
Borehole name	KFM02B
Location	Forsmark, Östhammar municipality, Sweden
Drill start date	Jan 18 <sup>th</sup> , 2006
Completion date	Feb 13 <sup>th</sup> , 2007
Drilling period	2006-01-18 to 2006-01-30 (0–87.15 m) 2006-06-08 to 2007-02-13 (87.15–573.87 m)
Contractor core drilling	Drillcon Core AB
Percussion drill rig	Puntell MX 1000
Core drill rig	Onram 2000 CCD (87.15–113.58 m) Atlas Copco B20 (113.58–573.87 m)
Position KFM02B at top of casing (RT90 2.5 gon V 0:–15 / RHB 70)	N 6698719.19 E 1633186.29 Z 7.62 (m.a.s.l.) Bearing (0–360°): 313.06° Inclination (0–90°): –80.27°
Position KFM02B at bottom of hole (RT90 2.5 gon V 0:–15 / RHB 70)	N 6698787.17 E 1633116.46 Z –557.89 (m.a.s.l.) Bearing (0–360°): 314.60° Inclination (0–90°): –79.17°
Borehole length	573.87 m
Borehole diameter and length	From 0.15 m to 3.23 m: 339 mm From 3.23 m to 87.10 m: 241.6 mm From 87.10 to 87.15 m: 156.2 mm From 87.15 m to 88.61 m: 86.0 mm From 88.61 m to 573.87 m: 75.8 mm
Casing diameter and length	$\varnothing_o/\varnothing_i = 323.9 \text{ mm}/319.7 \text{ mm}$ 0.15 m to 3.15 m $\varnothing_o/\varnothing_i = 339 \text{ mm}/281 \text{ mm}$ 3.15 m to 3.23 m $\varnothing_o/\varnothing_i = 208 \text{ mm}/200 \text{ mm}$ 0 m to 80.55 m $\varnothing_o/\varnothing_i = 210 \text{ mm}/200 \text{ mm}$ 80.55 m to 86.55 m $\varnothing_o/\varnothing_i = 208 \text{ mm}/170 \text{ mm}$ 86.55 to 86.60 m
Transition cone inner diameter	At 83.51 m: 0.197 m At 88.55 m: 0.080 m
Drill core dimension	87.15–573.87 m/ $\varnothing$ 50.2 mm
Core interval	87.15–573.87 m

# Technical data

## Borehole KFM02B

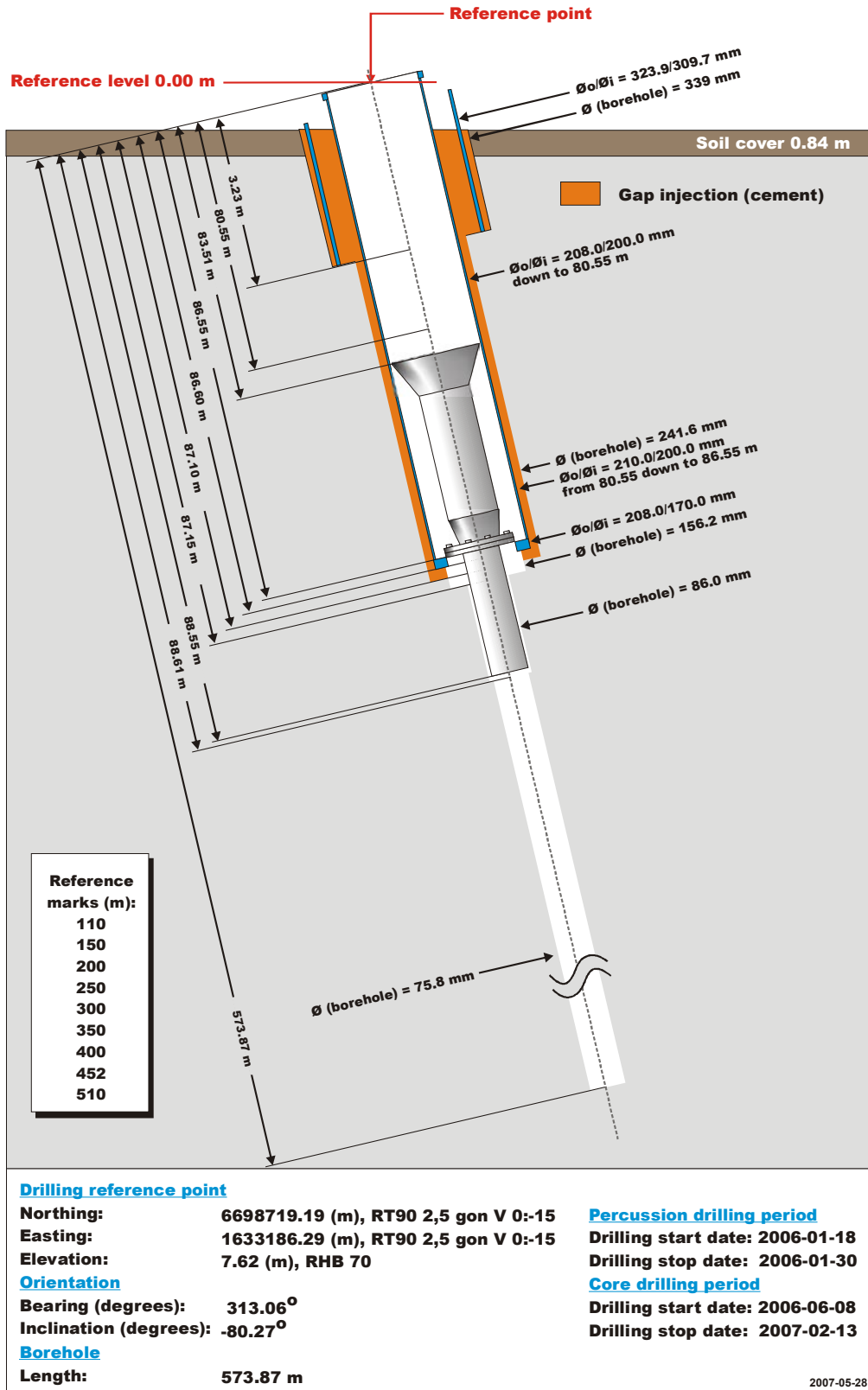


Figure 5-2. Technical data of borehole KFM02B.

## 5.3 Percussion drilling KFM02B 0–87.15 m

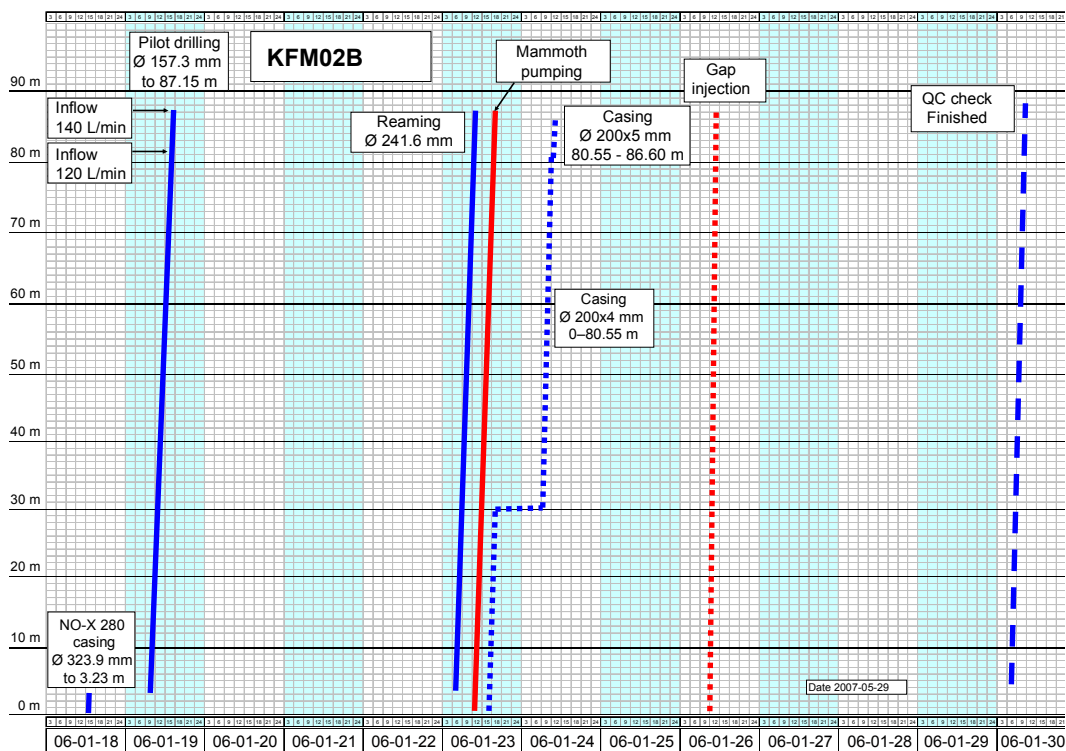
### 5.3.1 Drilling

Drilling of the section 0–87.15 m was progressing between Jan 18<sup>th</sup>, 2006, and Jan 30<sup>th</sup>, 2006, and the logistics for the drilling operations is presented in Figure 5-3. As mentioned in Section 4.3.2, the upper part to 3.23 m of the borehole was drilled and cased according to NO-X 280. During pilot drilling to 87.15 m, an unstable section with increased fracturing and a water inflow of 140 L/min was encountered at 81 m length. The fracturing in the percussion drilled part of KFM02B, is also in line with the results from the nearby borehole KFM02A.

The borehole was therefore, after reaming to 241.6 mm, cased with an Ø 200/208 mm stainless steel casing to 80.55 m and a reinforced casing between 80.55–86.60 m. Finally, the gap between the casing and the borehole wall was cement grouted, so that the water inflow ceased completely.

### 5.3.2 Measurements while drilling

During, and immediately after drilling, a program for sampling and measurements was applied, cf. Section 4.3.3. Some of the results are displayed in the Well Cad-presentation in Appendix A (deviation measurements, penetration rate and rock type distribution), whereas other results (flow data and electrical conductivity) are used only as supporting data for on-site decisions.



**Figure 5-3.** Percussion drilling progress (depth and activity versus calendar time). “Inflow” in the figure refers to accumulated groundwater inflow.



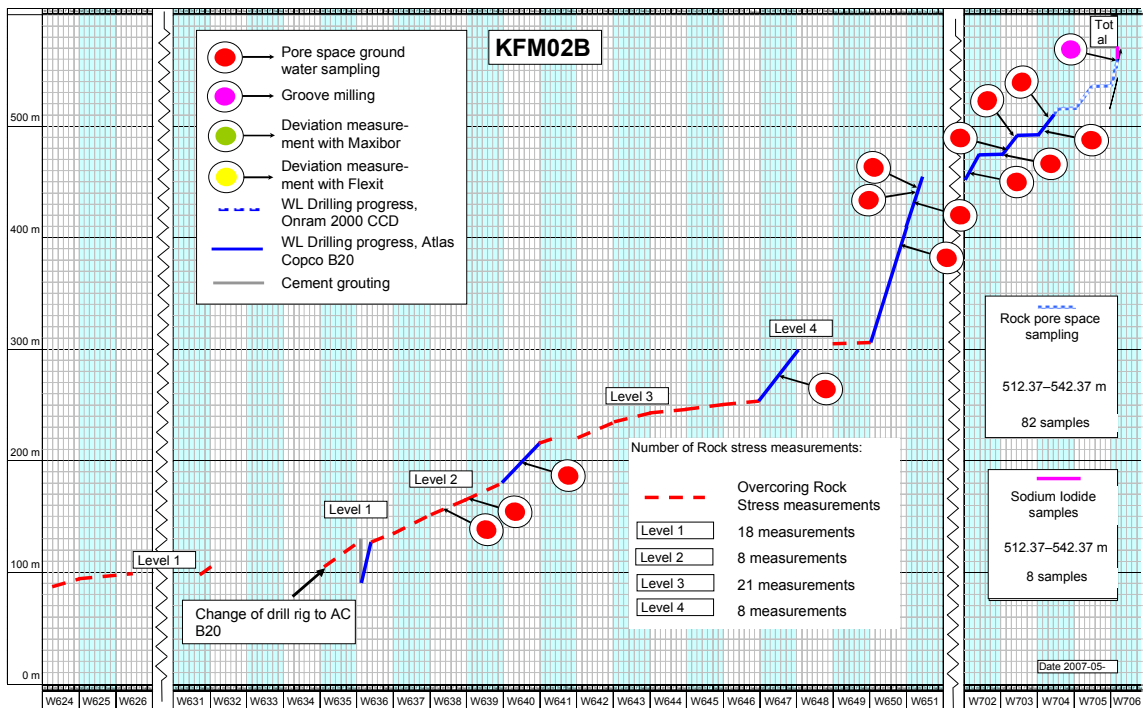
## 5.4 Core drilling KFM02B 87.15–573.87 m

### 5.4.1 Drilling

After the percussion drilling, a break followed until the drilling of section 87.15–573.87 m was performed in between June 6<sup>th</sup> and February 13<sup>th</sup>, 2007, (Figure 5-4).

The results from drilling of KFM02B concerning lithological distribution as well as fracture frequency and characteristics were almost exactly in accordance with the results from the nearby KFM02A (the two boreholes are at the surface situated only c. 8 m from each other). Several water-yielding gently dipping fracture zones were encountered in both boreholes down to c. 510 m drilling length. The overcoring stress measurements commenced at level one (93–151 m), but were soon interrupted when the drilling rig had to be exchanged for technical reasons, cf. Section 5.4.3.

A major water inflow at c. 100 m drilling length was encountered. At this level, due to fractured rock, also several breaks of the pilot drill cores occurred, indicating unfavourable conditions for overcoring measurements. Arguments were brought up for cement grouting of the fractured section, which was a trap for drilling debris. When pulling the drill string drill cuttings were flowing back into the borehole and settled in the pilot hole. discharged into to decrease the inflow and after permission from the Security Assessments, 500 kg Lafarge cement, was pumped into the section between 90–127.20 m. After the cement had settled, the borehole was drilled again where after the stress measurements continued at additional three more levels, down to 307 m drilling length.



**Figure 5-4.** Core drilling progress KFM02B (length versus calendar time). The diagram is also showing the logistics for the overcoring rock stress measurements and the rock pore space groundwater sampling, sodium iodide test sampling (see text below), groove milling and deviation measurements.

As for borehole KFM07C a newly developed equipment for nitrogen flushing was used, where the end of the hose was outfitted with a nozzle, designed to fit into the pilot borehole. The relatively large water inflow into the gently dipping fracture zones made it possible to flush the borehole frequently, and a clean pilot borehole was a prerequisite for effective gluing of the *Borre* probe used for overcoring rock stress measurements.

When the rock stress measurement had been finished, the frequency of pore space groundwater sampling was increased. Towards the end of drilling, the flushing water was labelled with a new tracer, sodium iodide (NaI). Normally the flushing water is labelled with the tracer Uranine to a concentration of 0.2 mg/L, but this concentration is too low to permit analyses of the amount of flushing water in the pore space groundwater. Therefore a much higher concentration of sodium iodine, 1.0 g/L, was introduced. However, the first attempt of adding the highly concentrated NaI into the flushing water failed, but when the equipment was modified it finally succeeded. Drilling was completed at 573.87 m drilling length in early February, 2007.

#### **5.4.2 Core sampling KFM02B**

A preliminary on-site core logging was performed continuously.

#### **5.4.3 Rock stress measurement KFM02B**

During the period June 15<sup>th</sup>, 2006, to December 13<sup>th</sup>, 2006, overcoring rock stress measurements were conducted in the near vertical borehole KFM02B, with the three-dimensional *Borre* probe. Measurements were attempted at four levels in the borehole, 93–151 m, 156–181 m, 217–256 m and 300–307 m.

From the beginning of the core drilling continuous problems with the technical performance of the Onram 2000 drilling machine caused much time delay. The problems culminated when the steering system, completely unexpectedly, dropped the drill string in the borehole. Unfortunately, the *Borre* probe was mounted at the bottom of the string, and when it smashed into the borehole bottom, the probe was completely destroyed, including loss of collected data. Even after service and maintenance, the Contractor could not guarantee the reliability of the steering system of the Onram 2000 machine. Therefore the Contractor decided, fully supported by SKB, to exchange the Onram machine to the Atlas Copco B20, which just had finished drilling of borehole KFM07C. During two weeks in August 2006 the drilling equipments were exchanged and the rock stress measurements could continue.

Other problems during the stress measurement campaign were the character of the stress field with increased deviatoric stresses, entailing several measurement failures due to micro-fracturing in the over cored rock samples. Also difficulties with gluing the strain rosettes of the *Borre* probe towards the pilot hole wall also caused also a prolonged measurement period compared to initial plans. Performance and results of the overcoring rock stress measurements in borehole KFM02B are presented in /7/.

### **5.5 Measurements while drilling KFM02B**

During, and immediately after drilling, a program for sampling and measurements was applied, cf. Section 4.3.3. Some of the results are displayed in the Well Cad-presentation in Appendix B (deviation measurements, penetration rate and rock type distribution), whereas other results (flow data and electrical conductivity) are used only as supporting data for on-site decisions. Below, in Sections 5.4.1–5.4.8, the results of the water balance, Uranine content, groove milling and deviation measurements made after completed drilling of KFM02B are commented on.

### 5.5.1 Flushing water and return water flow parameters

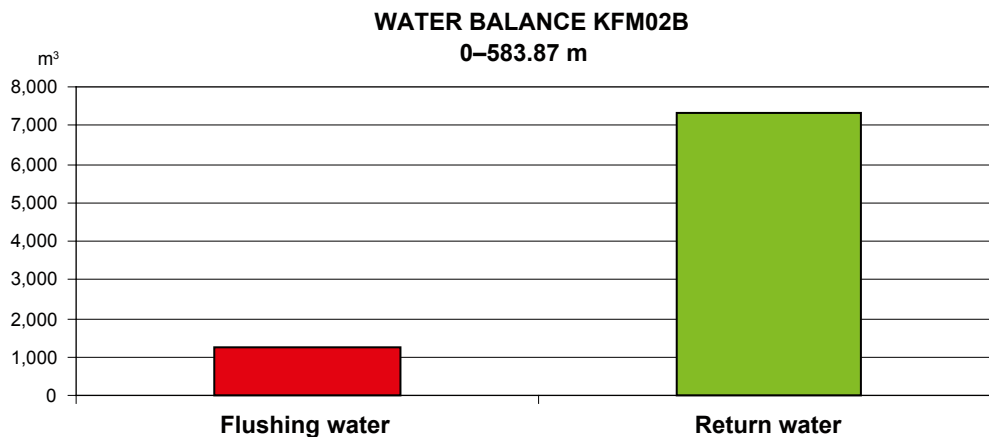
#### **Flushing water and return water flow rate measurements – water balance**

As borehole KFM02B is a telescopic borehole, in which pumping is performed continuously during drilling, it is important to estimate the amount of flushing water that is pumped into the borehole during drilling in relation to the amount of return water recovered in order to, by this water balance calculation, render an assessment of the impact on the aquifer of the drilling possible. A flow gauge in the measurement station, registered the flushing water flow rate, see Figure 3-6. The return water was measured by another flow meter, mounted online with the discharge pipeline, see Figure 3-6.

Figure 5-5 displays the accumulated volumes of flushing water respectively return water from the entire drilling period (results from Uranine measurements are presented in the next section), whereas Figure 5-6 illustrates the accumulated volume of flushing water and return water versus time during core drilling. From the accumulated volumes of flushing water and return water at the end of the drilling period, the return water/flushing water quotient may be calculated, in this case resulting in a quotient as high as 6.32. This is an effect of the major efforts that were made for cleaning the borehole from drilling debris by flushing with nitrogen during simultaneous air-lift pumping. Also the high groundwater inflow in the upper section (at about 100 m) as well as the prolonged drilling and measurement period between April 2006 and February 2007 had a great impact on the result of the water balance measurements. A large volume of flushing water was used although there were two long breaks, for summer holiday in July 2006 and a Christmas break by the end of December 2006 to the second week of January 2007.

#### **Uranine contents of flushing water KFM02B**

During the drilling period, sampling of flushing water and analyses of the tracer contents were performed systematically with a frequency of approximately one sample per 20–30 m drilling length, except in section 200–350 m where only a few samples were collected, see Figure 5-7. Like in all boreholes, except for KFM01A, a dosing feeder controlled by a flow meter was used for labelling the flushing water with Uranine at a concentration of 0.2 mg/L. The concentration of Uranine has been stable except at a few occasions, see Figure 5-7. According to notations in the log book, the amount of Uranine added to the borehole was 250 g. If the average of Uranine concentration values in the flushing water and in return water are used to calculate the amount of Uranine added to and recovered from the borehole, the calculations give 233 g, and 368 g respectively. The excess amount of Uranine recovered from the borehole may be due to remaining Uranine in the aquifer from previous drilling in the area (possibly of KFM10A). Since the last samples of return water show low or relatively low concentrations of Uranine, it seems plausible that most of the tracer has been recovered.



**Figure 5-5.** The total volume of flushing water used during core drilling of KFM02B was 1,224 m<sup>3</sup>. During the same period, the total volume of return water was amounted to 7,737 m<sup>3</sup>. The return water/flushing water balance is then 6.32, i.e. much exceeding 1.0.

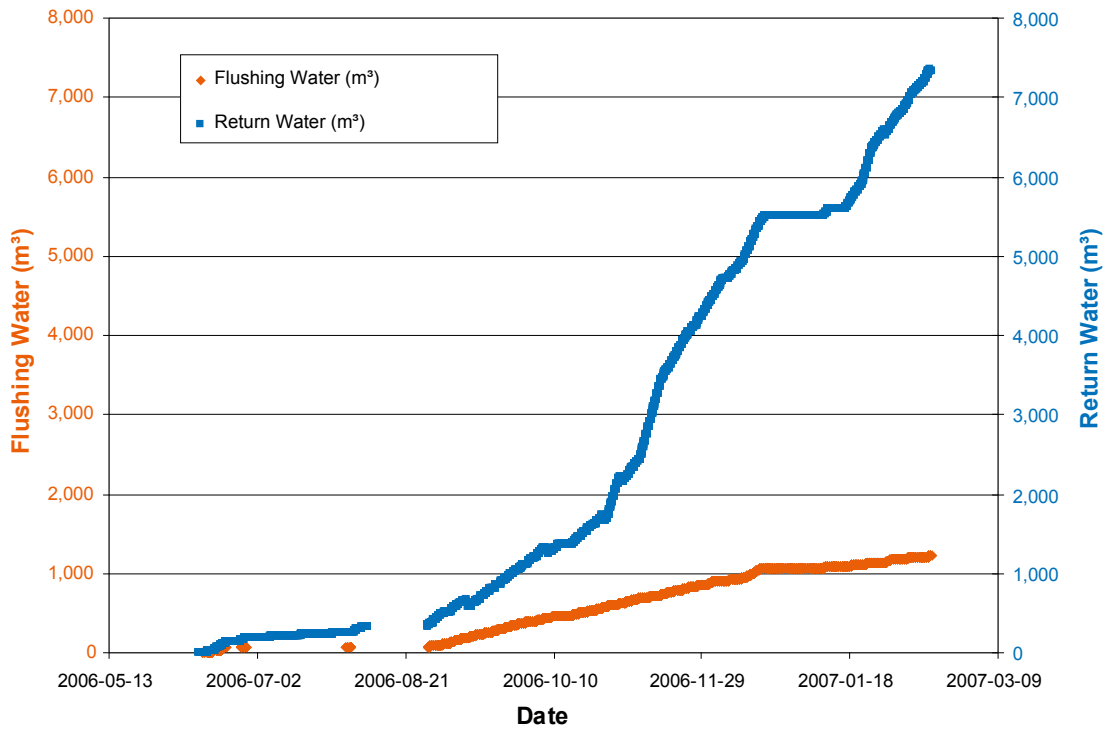


Figure 5-6. The total volume of flushing water and return water versus time during drilling of borehole KFM02B.

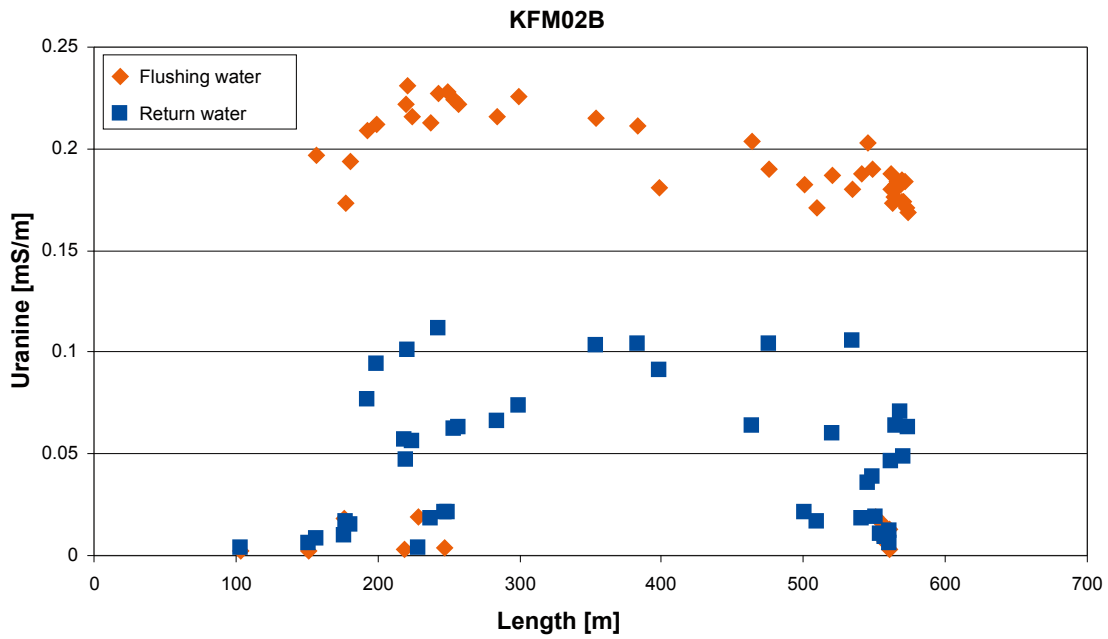


Figure 5-7. Uranine content versus drilling length in flushing water during drilling of borehole KFM02B.

### 5.5.2 Electric conductivity of flushing water

Flushing water was supplied from percussion borehole HFM05 (cf. Section 3.1.3). A sensor in the measurement station registered the electric conductivity (EC) of the flushing water on-line before it entered the borehole, see Figure 3-3. Another sensor for registration of the electric conductivity (Figure 5-8) of the return water was positioned between the surge diverter (discharge head) and the sedimentation containers, see Figure 3-3.

The electrical conductivity (salinity) of the flushing water from the 200.10 m deep supply well HFM05 with its major inflow at c. 156 m has from start an EC-value of c. 950 mS/m but increases to around 1,200 mS/m when drilling ran more frequently after the exchange of drilling rig. From c. 250 m the EC-value drops to c. 1,050 mS/m and has thereafter a decreasing trend to the borehole end. This indicates that by increasing draw-down in HFM05A, the proportion of shallow, less saline water increases.

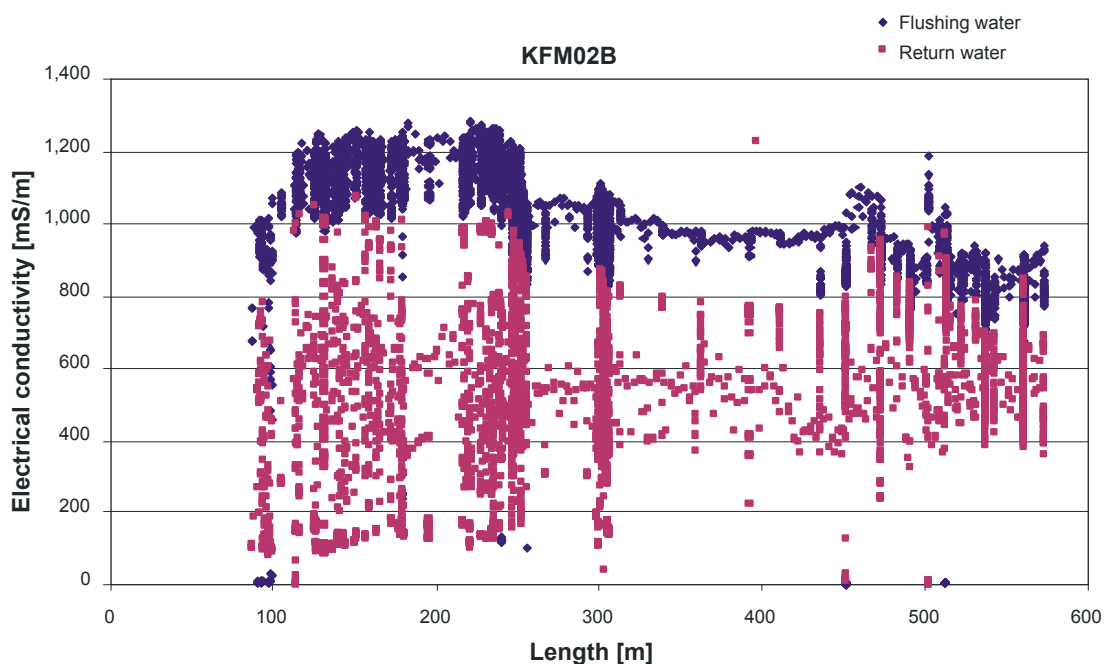
The average electrical conductivity of the return water is always lower than the EC-values of the flushing water. The most probable explanation is that the shallow groundwater inflow dominates completely in KFM02B.

### 5.5.3 Chemical composition of flushing water

The results from chemical analyses of flushing water from the supply well HFM05 are compiled in Appendix C. The flushing water was sampled during drilling, for the following reasons:

- Initially, to check if the quality was satisfactory. The main concern is the content of organic constituents, which should be low, preferably below 5 mg/L. The reason is that introduction of hydrocarbons may affect the microbiological flora in the borehole, which would obstruct a reliable characterization of the in situ microbiological conditions.

To monitor the groundwater chemical composition during drilling. The chemical composition of the flushing water is important when estimating the effect, or correcting for the effect, of remaining flushing water in water samples collected from borehole KFM02B for chemical analyses.



**Figure 5-8.** Electrical conductivity of flushing water from HFM05 and return water from KFM02B. The amount of values in the dataset has been reduced as well as cleaned from outliers.

The microbe content in the flushing water was not determined during drilling of KFM02B. The microbe results from drilling of the preceding boreholes KFM05A /9/ and KFM06A /10/ showed convincingly that the cleaning procedure works well. It was therefore concluded that check of microbes at all drilling occasions was no longer necessary.

The flushing water was sampled at two occasions during drilling. As shown in Appendix C, the chemical composition of the groundwater from HFM05 changed somewhat during the drilling period. For example, the chloride concentration decreased from 3,910 to 3,400 mg/L from the first to the second and last sample. The percussion borehole HFM05 has been used before as flushing water supply well and the concentration of Total Organic Carbon (TOC) was known to be sufficiently low. The two samples collected during the drilling period showed the TOC concentrations 3.8 and 4.5 mg/L, respectively, i.e. well below 5.0 mg/L. Hence, the flushing water well was used without further measures (e.g. using an active carbon filter system for reduction of organic substances as was applied when drilling KFM01A /11/).

#### **5.5.4 Sampling pore space groundwater in low permeable rocks**

An additional sampling of drill cores was introduced when drilling KFM02B. The methodology to determine the chemistry of pore space ground water was initially developed at the Äspö HRL and was also successfully applied to borehole KFM06A at Forsmark /10/, although including a major logistic effort. This resulted in a continued sampling programme regarding the remaining boreholes to be drilled in the target area, KFM01D, KFM08C and KFM02B.

The sampling is basically quite simple but speed and care are necessary to prevent any potential evaporation of the pore space groundwater when the drill core has been retrieved and is first exposed to the atmosphere. The different measures during the sampling are described further down, see Table 5-2 and Figure 5-9.

Immediately after the core was recovered from the borehole, a representative and homogeneous c. 40 cm long core specimen was selected. After photo-documentation, the sample was placed in a heavy duty plastic bag and flushed with nitrogen to remove the air. Thereafter the nitrogen was completely evacuated, and the plastic bag was carefully sealed. The packed sample was placed in an additional plastic bag and the evacuation and sealing procedure was repeated. Finally, the double packed sample was placed in a plastic bag lined with aluminium foil, flushed with nitrogen, evacuated and sealed and in similar fashion as carried out for the previous plastic bags. The well preserved sample was packed in a shock proofed portable aluminium box that within 24 hours was delivered to the laboratory, in this case at the University of Bern.

In borehole KFM02B, sampling was carried out and this procedure was successfully repeated for all 106 occasions, see Table 5-2.

Sampling of cores for determining pore space groundwater was made for every 50 m length between 158.82–509.96 m, continuously between 512.37–542.37 m and for every three metres between 549.48–573.87 m (see Table 5-2 below). During the sampling in the last section (549.48–573.87 m) a different tracer than usual, sodium iodide (NaI), was introduced for labelling the flushing water at a concentration of 1.0 g/L. Generally, the flushing water is labelled with the organic dye Uranine at the concentration 0.2 mg/L. However, this concentration is too low to permit analyses of the amount of flushing water in the pore space groundwater. However, the first attempt of adding the high concentrated NaI into the flushing water failed, but when the equipment was modified it finally succeeded.

Sampling of pore space groundwater is reported in /12/.

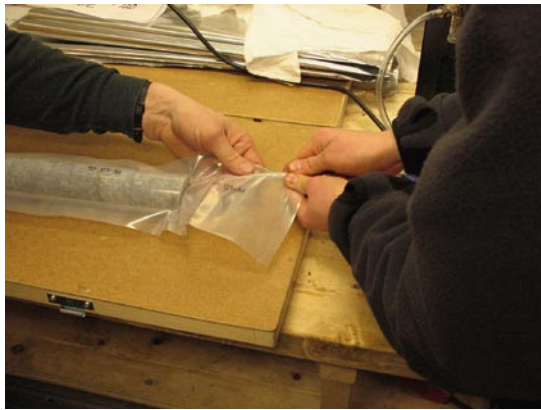
**Table 5-2. Sampling of drill cores for determination of pore space groundwater.**

Activity	Start date	Idcode	Secup (m)	Seclow (m)
Rock pore water – sampling	2006-09-20 12:26	KFM02B	158.82	159.00
Rock pore water – sampling	2006-09-25 14:08	KFM02B	171.63	172.02
Rock pore water – sampling	2006-10-05 13:16	KFM02B	210.45	210.83
Rock pore water – sampling	2006-11-23 15:59	KFM02B	286.97	287.34
Rock pore water – sampling	2006-12-17 12:12	KFM02B	393.08	393.49
Rock pore water – sampling	2006-12-18 16:30	KFM02B	430.62	430.86
Rock pore water – sampling	2006-12-19 13:08	KFM02B	441.29	441.60
Rock pore water – sampling	2006-12-19 16:35	KFM02B	447.87	448.25
Rock pore water – sampling	2007-01-09 15:34	KFM02B	459.64	460.03
Rock pore water – sampling	2007-01-17 16:19	KFM02B	473.88	474.25
Rock pore water – sampling	2007-01-17 17:31	KFM02B	478.71	479.07
Rock pore water – sampling	2007-01-18 11:08	KFM02B	490.29	490.63
Rock pore water – sampling	2007-01-22 15:50	KFM02B	498.64	499.03
Rock pore water – sampling	2007-01-25 09:14	KFM02B	509.66	509.96
Rock pore water – sampling	2007-01-25 10:30	KFM02B	512.37	512.76
Rock pore water – sampling	2007-01-25 10:30	KFM02B	512.76	513.15
Rock pore water – sampling	2007-01-25 10:30	KFM02B	513.15	513.52
Rock pore water – sampling	2007-01-25 11:39	KFM02B	513.52	513.84
Rock pore water – sampling	2007-01-29 12:10	KFM02B	513.84	514.24
Rock pore water – sampling	2007-01-29 12:10	KFM02B	514.24	514.65
Rock pore water – sampling	2007-01-29 12:10	KFM02B	514.65	515.02
Rock pore water – sampling	2007-01-29 12:10	KFM02B	515.02	515.35
Rock pore water – sampling	2007-01-29 14:04	KFM02B	515.35	515.73
Rock pore water – sampling	2007-01-29 14:04	KFM02B	515.73	515.97
Rock pore water – sampling	2007-01-29 14:04	KFM02B	515.97	516.26
Rock pore water – sampling	2007-01-29 14:04	KFM02B	516.26	516.57
Rock pore water – sampling	2007-01-29 14:04	KFM02B	516.57	516.87
Rock pore water – sampling	2007-01-29 15:49	KFM02B	516.87	517.18
Rock pore water – sampling	2007-01-29 15:49	KFM02B	517.18	517.49
Rock pore water – sampling	2007-01-29 15:49	KFM02B	517.49	517.71
Rock pore water – sampling	2007-01-29 15:49	KFM02B	517.71	517.98
Rock pore water – sampling	2007-01-29 15:49	KFM02B	517.98	518.37
Rock pore water – sampling	2007-01-30 10:57	KFM02B	518.37	518.74
Rock pore water – sampling	2007-01-30 10:57	KFM02B	518.74	519.03
Rock pore water – sampling	2007-01-30 10:57	KFM02B	519.03	519.35
Rock pore water – sampling	2007-01-30 10:57	KFM02B	519.35	519.73
Rock pore water – sampling	2007-01-30 10:57	KFM02B	519.73	519.87
Rock pore water – sampling	2007-01-30 13:56	KFM02B	519.87	520.27
Rock pore water – sampling	2007-01-30 13:56	KFM02B	520.27	520.65
Rock pore water – sampling	2007-01-30 13:56	KFM02B	520.65	520.99
Rock pore water – sampling	2007-01-30 13:56	KFM02B	520.99	521.37
Rock pore water – sampling	2007-01-30 15:30	KFM02B	521.37	521.72
Rock pore water – sampling	2007-01-30 15:30	KFM02B	521.72	521.99
Rock pore water – sampling	2007-01-30 15:30	KFM02B	521.99	522.23
Rock pore water – sampling	2007-01-30 15:30	KFM02B	522.23	522.55
Rock pore water – sampling	2007-01-30 15:30	KFM02B	522.55	522.87
Rock pore water – sampling	2007-01-31 08:22	KFM02B	522.87	523.25
Rock pore water – sampling	2007-01-31 08:22	KFM02B	523.25	523.65

Activity	Start date	Idcode	Secup (m)	Seclow (m)
Rock pore water – sampling	2007-01-31 08:22	KFM02B	523.65	524.02
Rock pore water – sampling	2007-01-31 08:22	KFM02B	524.02	524.37
Rock pore water – sampling	2007-01-31 09:41	KFM02B	524.37	524.75
Rock pore water – sampling	2007-01-31 09:41	KFM02B	524.75	525.16
Rock pore water – sampling	2007-01-31 09:41	KFM02B	525.16	525.55
Rock pore water – sampling	2007-01-31 09:41	KFM02B	525.55	525.87
Rock pore water – sampling	2007-01-31 11:01	KFM02B	525.87	526.27
Rock pore water – sampling	2007-01-31 11:01	KFM02B	526.27	526.56
Rock pore water – sampling	2007-01-31 11:01	KFM02B	526.56	527.02
Rock pore water – sampling	2007-01-31 11:01	KFM02B	527.02	527.35
Rock pore water – sampling	2007-01-31 13:44	KFM02B	527.35	527.74
Rock pore water – sampling	2007-01-31 13:44	KFM02B	527.74	528.13
Rock pore water – sampling	2007-01-31 13:44	KFM02B	528.13	528.51
Rock pore water – sampling	2007-01-31 13:44	KFM02B	528.51	528.86
Rock pore water – sampling	2007-01-31 15:01	KFM02B	528.86	529.26
Rock pore water – sampling	2007-01-31 15:01	KFM02B	529.26	529.67
Rock pore water – sampling	2007-01-31 15:01	KFM02B	529.67	530.02
Rock pore water – sampling	2007-01-31 15:01	KFM02B	530.02	530.37
Rock pore water – sampling	2007-01-31 16:24	KFM02B	530.37	530.76
Rock pore water – sampling	2007-01-31 16:24	KFM02B	530.76	531.14
Rock pore water – sampling	2007-01-31 16:24	KFM02B	531.14	531.48
Rock pore water – sampling	2007-01-31 16:24	KFM02B	531.48	531.87
Rock pore water – sampling	2007-02-01 08:15	KFM02B	531.87	532.25
Rock pore water – sampling	2007-02-01 08:15	KFM02B	532.25	532.63
Rock pore water – sampling	2007-02-01 08:15	KFM02B	532.63	532.96
Rock pore water – sampling	2007-02-01 08:15	KFM02B	532.96	533.37
Rock pore water – sampling	2007-02-01 09:35	KFM02B	533.37	533.76
Rock pore water – sampling	2007-02-01 09:35	KFM02B	533.76	534.17
Rock pore water – sampling	2007-02-01 09:35	KFM02B	534.17	534.38
Rock pore water – sampling	2007-02-01 09:35	KFM02B	534.38	534.87
Rock pore water – sampling	2007-02-01 10:41	KFM02B	534.87	535.26
Rock pore water – sampling	2007-02-01 10:41	KFM02B	535.26	535.53
Rock pore water – sampling	2007-02-01 10:41	KFM02B	535.53	535.89
Rock pore water – sampling	2007-02-01 10:41	KFM02B	535.89	536.37
Rock pore water – sampling	2007-02-05 09:24	KFM02B	536.37	536.75
Rock pore water – sampling	2007-02-05 09:24	KFM02B	536.75	537.14
Rock pore water – sampling	2007-02-05 09:24	KFM02B	537.14	537.46
Rock pore water – sampling	2007-02-05 09:24	KFM02B	537.46	537.87
Rock pore water – sampling	2007-02-05 11:35	KFM02B	537.87	538.29
Rock pore water – sampling	2007-02-05 11:35	KFM02B	538.29	538.72
Rock pore water – sampling	2007-02-05 11:35	KFM02B	538.72	539.03
Rock pore water – sampling	2007-02-05 11:35	KFM02B	539.03	539.37
Rock pore water – sampling	2007-02-05 14:10	KFM02B	539.37	539.80
Rock pore water – sampling	2007-02-05 14:10	KFM02B	539.80	540.21
Rock pore water – sampling	2007-02-05 14:10	KFM02B	540.21	540.59
Rock pore water – sampling	2007-02-05 14:10	KFM02B	540.59	540.87
Rock pore water – sampling	2007-02-05 14:10	KFM02B	540.87	541.24
Rock pore water – sampling	2007-02-05 14:10	KFM02B	541.24	541.52
Rock pore water – sampling	2007-02-05 14:10	KFM02B	541.52	541.97



Activity	Start date	Idcode	Secup (m)	Seclow (m)
Rock pore water – sampling	2007-02-05 14:10	KFM02B	541.97	542.37
Rock pore water – sampling	2007-02-06 12:09	KFM02B	549.48	549.84
Rock pore water – sampling	2007-02-06 14:39	KFM02B	553.98	554.36
Rock pore water – sampling	2007-02-06 16:10	KFM02B	556.26	556.59
Rock pore water – sampling	2007-02-06 17:35	KFM02B	559.65	560.00
Rock pore water – sampling	2007-02-13 09:47	KFM02B	562.26	562.68
Rock pore water – sampling	2007-02-13 11:12	KFM02B	565.06	565.51
Rock pore water – sampling	2007-02-13 13:25	KFM02B	569.14	569.56
Rock pore water – sampling	2007-02-13 14:39	KFM02B	573.43	573.87



**Figure 5-9.** The photos show the careful handling of the samples for pore space groundwater in low permeable rock performed in KFM01D. The same procedure was applied in KFM02B. To the upper left the core has been recovered from the borehole and is placed in a nitrogen filled plastic bag from which the nitrogen is evacuated. To the upper right the plastic bag is permanently heat sealed. To the lower left the sample is well preserved in two plastic bags and a third plastic bag lined with aluminium foil is also permanently heat sealed. Finally, to the lower right, the sample is placed in a shock proofed aluminium box that within 24 hours is delivered to the University of Bern.

### 5.5.5 Groove milling KFM02B

A compilation of length to the reference grooves and if they were detected are given in Table 5-3. The positions of the grooves are determined from the length of the drilling pipes used at the milling process. The length is measured from the upper part of the upper two grooves.

### 5.5.6 Recovery of drill cuttings

The theoretical volume of the percussion drilled and reamed part of the borehole (0–88.15 m) is c. 2.8 m<sup>3</sup>. Weighing of drill cuttings and comparison with the weight of the theoretical volume was not carried out due to the relatively high water flow. This caused an uncontrolled overflow of return water with suspended drill cuttings, making it difficult to obtain reliable results of drill cuttings estimations. However, it seems probable that the percussion drilled part was well cleaned from debris, since casing driving and gap grouting to full borehole length worked well, without obstruction from settled drill cuttings.

The theoretical difference in borehole volume of the core drilled part of KFM02B and the drill core is calculated to be 1.241 m<sup>3</sup>. This volume should correspond to the amount of drill cuttings produced during drilling. If a density of 2,650 kg/m<sup>3</sup> (approximate figure for granitites in the Forsmark area) is applied, the total weight of the theoretical amount of debris is estimated at 3,288 kg. The calculated dry weight of the debris from the core drilling recovered and weighed in the containers is 2,581 kg. The difference between the theoretically produced and recovered dry weight of debris is 708 kg, which gives a recovery of 78.5%.

The recovery figure could be commented on. The dwell time in the container system is too short for sedimentation of the suspended finest fractions. No estimation was made of the amount of suspended material, but the true recovery is probably somewhat higher than 78.5%. It should also be observed, that weighing of the container including water and debris is associated with some uncertainty.

However, it seems plausible that some drilling debris has been injected into the fracture system of the formation, especially in the permeable sections with increased fracture frequency above c. 500 m in the borehole.

### 5.5.7 Deviation measurements in KFM02B

The principles of the equipment for deviation measurements were explained in Section 3.1.5. Also the changed strategy for deviation measurements during the site investigations was commented on, including the fact that the Flexit method is now the principal method applied for deviation measurements, also in borehole KFM02B. When Maxibor<sup>TM</sup> measurements or deviation measurements with some other method have been performed as well, these may be used for uncertainty determinations of the deviation measurements.

**Table 5-3. Reference grooves in KFM02B.**

Reference groove at (m)	Detection with the SKB level indicator	Confirmed from BIPS	Reference groove at (m)	Detection with the SKB level indicator	Confirmed from BIPS
110	Yes	Yes	350	Yes	Yes
150	Yes	Yes	400	Yes	Yes
200	Yes	Yes	452	Yes	Yes
250	Yes	Yes	510	Yes	Yes
300	Yes	Yes			

The quality control program of deviation measurements is mostly concentrated to the handling of the instrument as well as to routines applied for the performance. It is not possible to execute an absolute control measurement, as no long borehole is available permitting exact determination of the position of both the borehole collar and the borehole end (e.g. in a tunnel) with an independent method. The strategy for quality control is instead based on comparison of results from repeated deviation measurements.

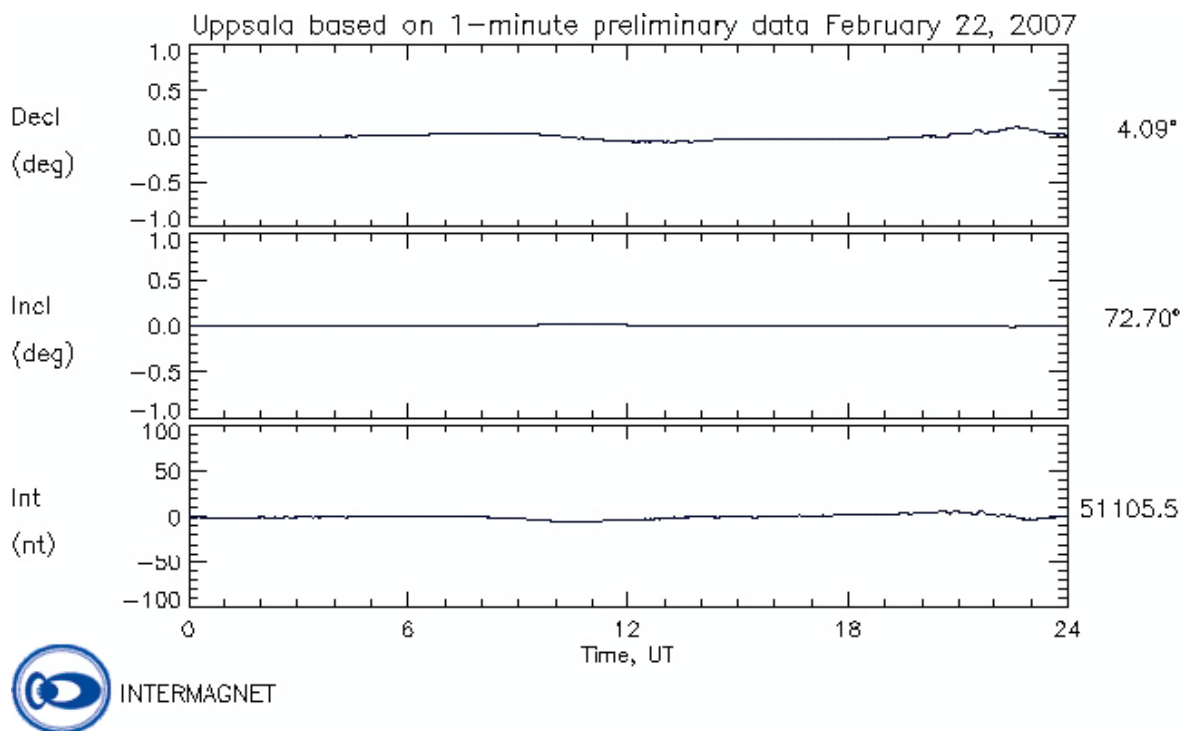
To ensure high quality measurements with the Flexit tool, the disturbances of the magnetic field must be small. In Uppsala, a measuring station provides one-minute magnetic field values that are available on the Internet at [www.intermagnet.org](http://www.intermagnet.org) and gives sufficient information. The magnetic field variation during February 22<sup>nd</sup> and March 8<sup>th</sup>, 2007, is seen in Figure 5-10 and Figure 5-11 shows minor disturbances when the Flexit survey in KFM02B was performed.

In the following a systematic description of the construction of the revised deviation data for borehole KFM02B is given.

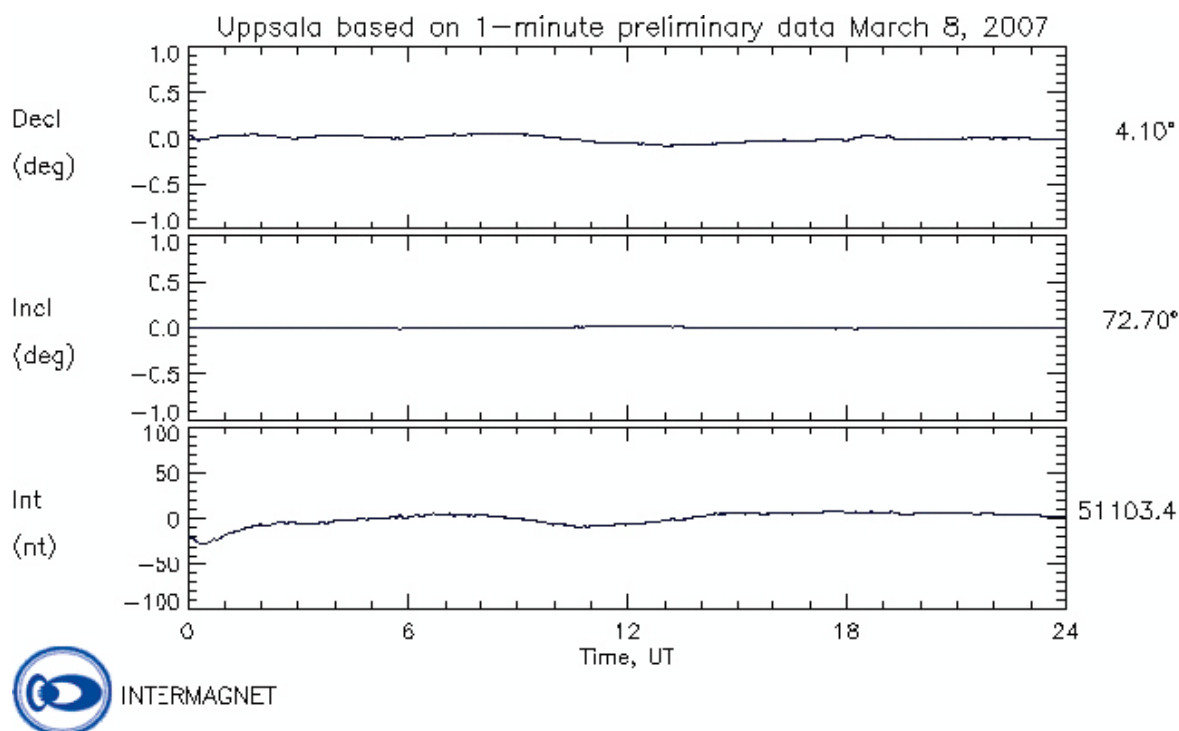
The data used are two Reflex Maxibor™ loggings to 567 m and one logging to 243 m and two Flexit loggings to 570 m, see Table 5-4. The two complete Maxibor surveys were carried out every 3 m upwards and downwards. With the Flexit Smart Tool System, deviation measurements in borehole KFM02B were two measurements carried out every 3 m downwards at two different occasions. The two Flexit surveys downwards, with activity numbers 13151886 and 13151874 and the two complete Maxibor surveys, with activity numbers 13148092 and 13148093, provided almost repeatable results, and were therefore chosen for the construction of the EG154 deviation file to be “in use displayed” in Sicada (see explanation in Section 3.1.6). This file is designated as EG154.

The EG154-activity specifies the deviation measurements used in the resulting calculation is presented in Table 5-5. The upper sections start at 99 m, so that bearing (magnetic method) should not be effected by the 85 m steel casing.

A subset of the resulting deviation file together with the estimated radius uncertainty is presented in Table 5-6.



**Figure 5-10.** Magnetic field variation during the Flexit survey performed on February 22<sup>nd</sup>, 2007.



**Figure 5-11.** Magnetic field variation during the Flexit survey performed on March 8<sup>th</sup>, 2007.

**Table 5-4. Activity data for the five deviation measurements approved for KFM02B. The two magnetic measurements with activity numbers 13151886 and 13151874 as well as the two complete Maxibor measurements with activity number 13148092 and 13140893 were used for calculation of a final borehole deviation. All five measurements were used for calculation of the uncertainty.**

Activity id	Activity type code	Activity	Start date	Idcode	Secup (m)	Seclow (m)	Flags
13148092	EG156	Maxibor measurement	2007-02-14 07:00	KFM02B	3	567	CF
13148093	EG156	Maxibor measurement	2007-02-14 11:00	KFM02B	3	567	CF
13135859	EG156	Maxibor measurement	2007-11-07 00:00	KFM02B	3	243	F
13151886	EG157	Magnetic – accelerometer measurement	2007-03-08 07:55	KFM02B	3	570	CF
13151874	EG157	Magnetic – accelerometer measurement	2007-02-22 08:15	KFM02B	3	570	CF
13151926	EG154	Borehole deviation multiple measurements	2007-05-28 11:00	KFM02B			I C

**Table 5-5. Contents of the EG154 file (multiple borehole deviation intervals).**

Deviation activity id	Deviation angle type	Approved secup (m)	Approved seclow (m)
13148092	Bearing	3.00	567.00
13148092	Inclination	3.00	567.00
13148093	Bearing	3.00	567.00
13148093	Inclination	3.00	567.00
13151874	Bearing	99.00	570.00
13151874	Inclination	3.00	570.00
13151886	Bearing	99.00	570.00
13151886	Inclination	3.00	570.00

**Table 5-6. Deviation data from KFM02B from every approx. 100 m elevation calculated from EG154. Inclination, bearing and radius uncertainty are also included.**

Borehole	Length (m)	Northing (m)	Easting (m)	Elevation (m)	Inclination (degrees)	Bearing (degrees)	Inclination uncertainty	Bearing uncertainty	Radius uncertainty
KFM02B	0	6698719.19	1633186.29	7.62	-80.27	313.06	0.185	1.661	0.000
KFM02B	108	6698730.76	1633173.28	-98.97	-80.74	310.78	0.185	1.661	0.504
KFM02B	210	6698741.96	1633160.77	-199.58	-80.32	312.82	0.185	1.661	0.992
KFM02B	312	6698753.72	1633148.34	-300.13	-80.32	313.92	0.185	1.661	1.488
KFM02B	414	6698766.10	1633136.19	-400.65	-80.10	316.85	0.185	1.661	1.991
KFM02B	516	6698779.37	1633123.92	-501.03	-79.44	317.36	0.185	1.661	2.515
KFM02B	573.87	6698787.17	1633116.46	-557.89	-79.17	314.60	0.185	1.661	2.829

The calculated deviation (EG154-file) in borehole KFM02B shows that the borehole is almost straight and has only an absolute deviation of 2.1 m compared to an imagined straight line following the dip and strike of the borehole start point (Figure 5-12).

The “absolute deviation” is here defined as the shortest distance in space between a point in the borehole at a certain borehole length and the imaginary position of that point if the borehole had followed a straight line with the same inclination and bearing as of the borehole collaring.

### 5.5.8 Consumables

The special type of thread grease (silicon based) used in this particular borehole was certified according to SKB MD 600.006, Version 1.0, Instruction for the use of chemical products and material during drilling and surveys. Oil and grease consumptions are given in Table 5-7 and 5-8 below.

The amounts of grout for sealing the casing and some fractures in the borehole are reported in Table 5-9 below.

**Table 5-7. Oil and grease consumption during percussion drilling of KFM02B.**

Borehole ID	Hammer oil (percussion drilling) Preem Hydra 46	Compressor oil (percussion drilling) Schuman 46
KFM02B	10L	Below detection limit

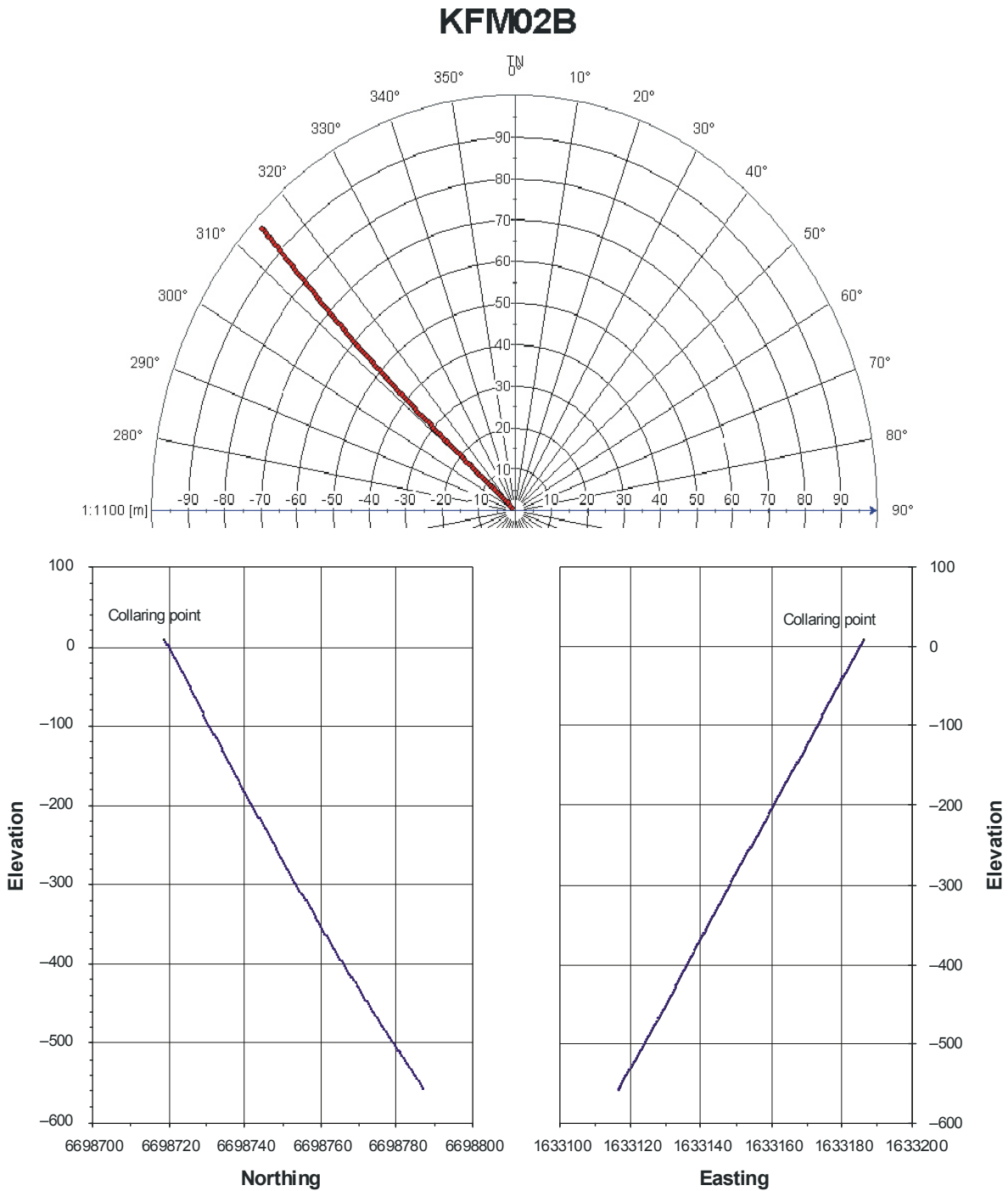
**Table 5-8. Grease, oil and diesel consumption during core drilling of KFM02B.**

Borehole ID	Thread grease	Grease for the drilling machine	Engine oil	Hydraulic oil	Engine diesel
	Üni Silikon L50/2	Statoil AB	Castrol Tecton 15W-40	Premium ECO HT-E 46	OKQ8 Diesel miljöklass 1
KFM02B	11 kg	6.4 kg	Estimated 3 L	90 L	0 L

**Table 5-9. Cement consumption KFM02B.**

Borehole ID	Casing length (m)	Cement weight (Aalborg Portland cement/microsilica)	Cement volume [L]	Grouting method	Remarks (final pressure)	Date
KFM02B	0.15–86.54	1,548 kg	1,505	Packer	Not registrated	2006-01-26
KFM02B	0.00–2.00	72 kg	70	Gap	Not registrated	2006-01-30
KFM02B	90.00–127.20	500 kg*		Packer/Hose	0 bar	2006-09-04

\*Lafarge cement.



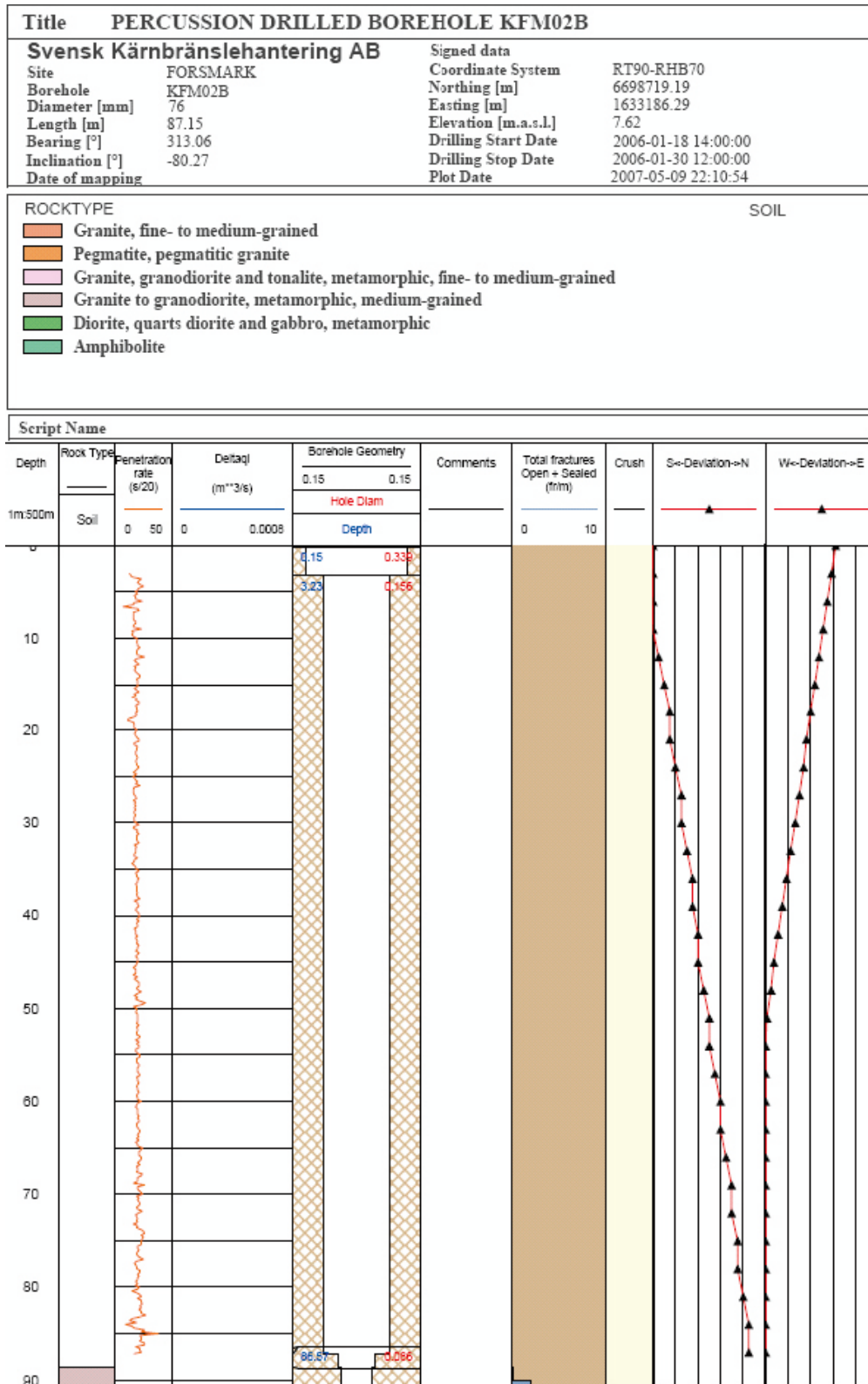
**Figure 5-12.** Upper figure is a horizontal projection and lower figures are two vertical projections of the in use-flagged deviation data from KFM02B.

## References

- /1/ **SKB, 2001.** Site investigations. Investigation methods and general execution programme. SKB TR-01-29, Svensk Kärnbränslehantering AB.
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- /12/ **Waber H N, Smellie J A T, 2007.** Forsmark site investigation. Borehole KFM02B: Characterisation of pore water. Part I: Diffusion experiments, SKB P-report in progress, Svensk Kärnbränslehantering AB.

## Appendix A

### Well cad presentation of the percussion drilled part of borehole KFM02B





## Appendix B

### Well cad presentation of the entire borehole KFM02B

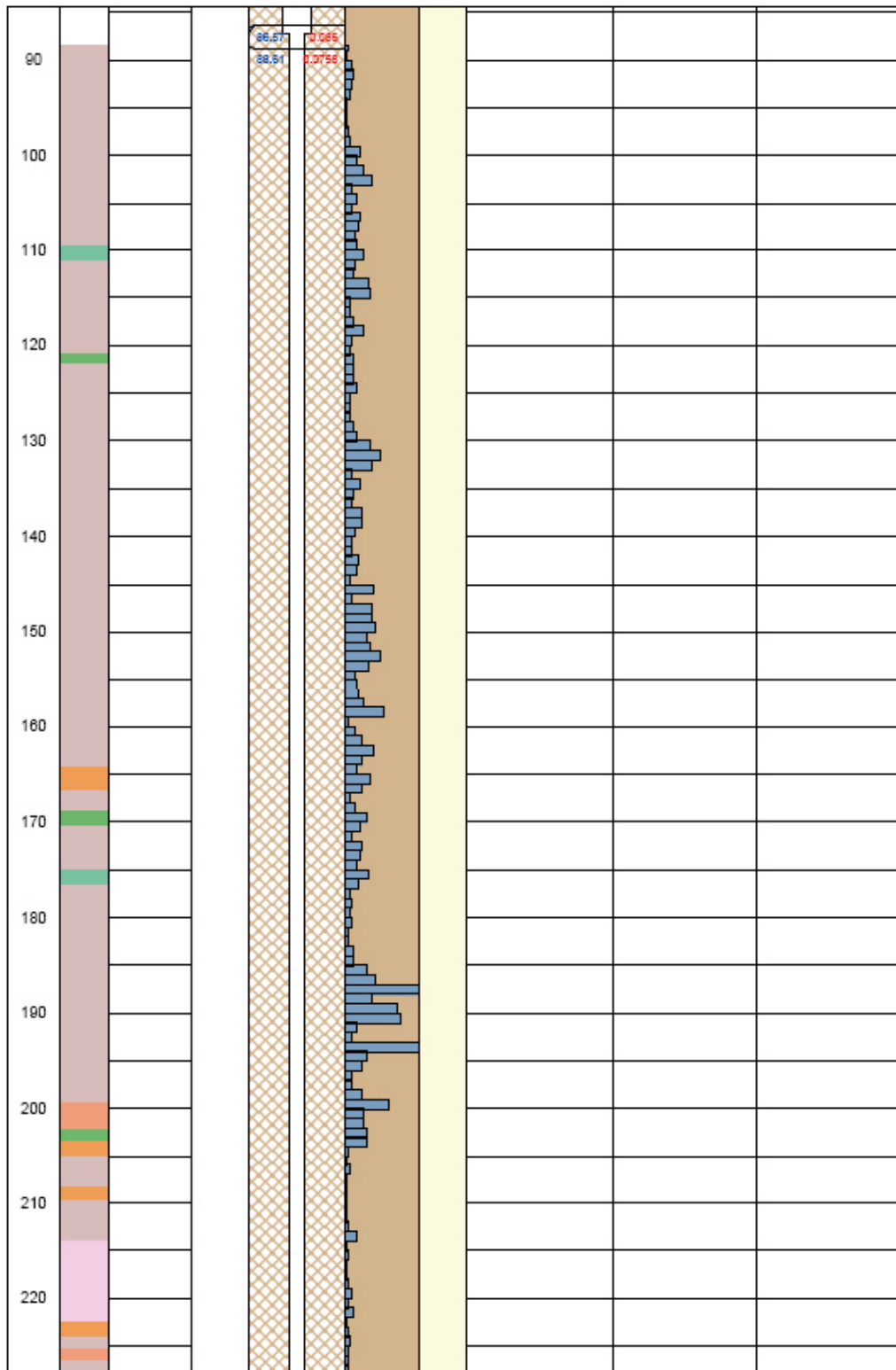
Title		KFM02B	
<b>Svensk Kärnbränslehantering AB</b>			
Site	FORSMARK	Signed data	
Borehole	KFM02B	Coordinate System	RT90-RHE70
Diameter [mm]	76	Northing [m]	6698719.19
Length [m]	573.87	Easting [m]	1633186.29
Bearing [°]	313.06	Elevation [m.a.s.l.]	7.62
Inclination [°]	-80.27	Drilling Start Date	2006-01-18 14:00:00
Date of mapping		Drilling Stop Date	2007-02-13 12:00:00
		Plot Date	2007-05-09 22:10:54

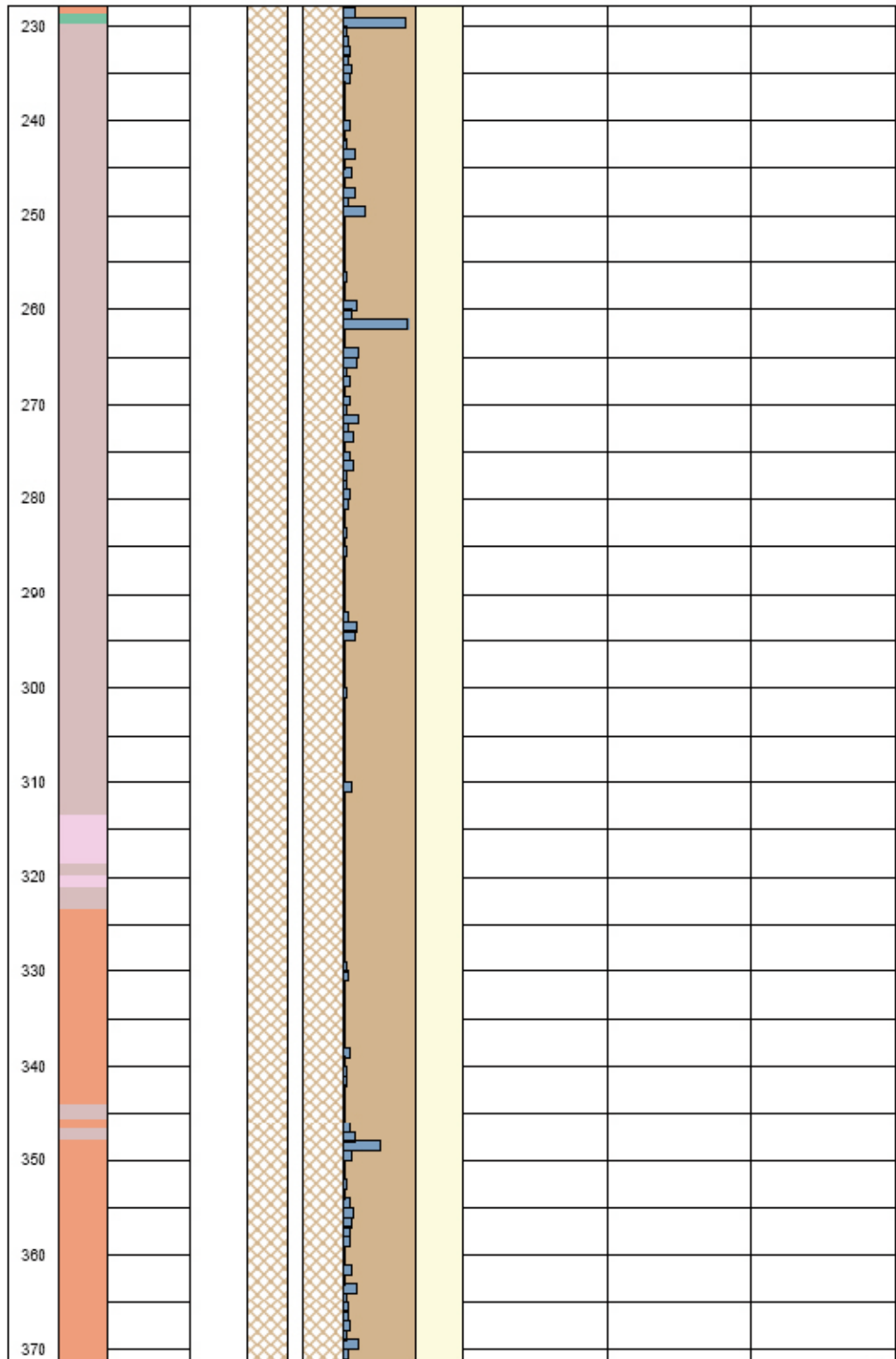
  

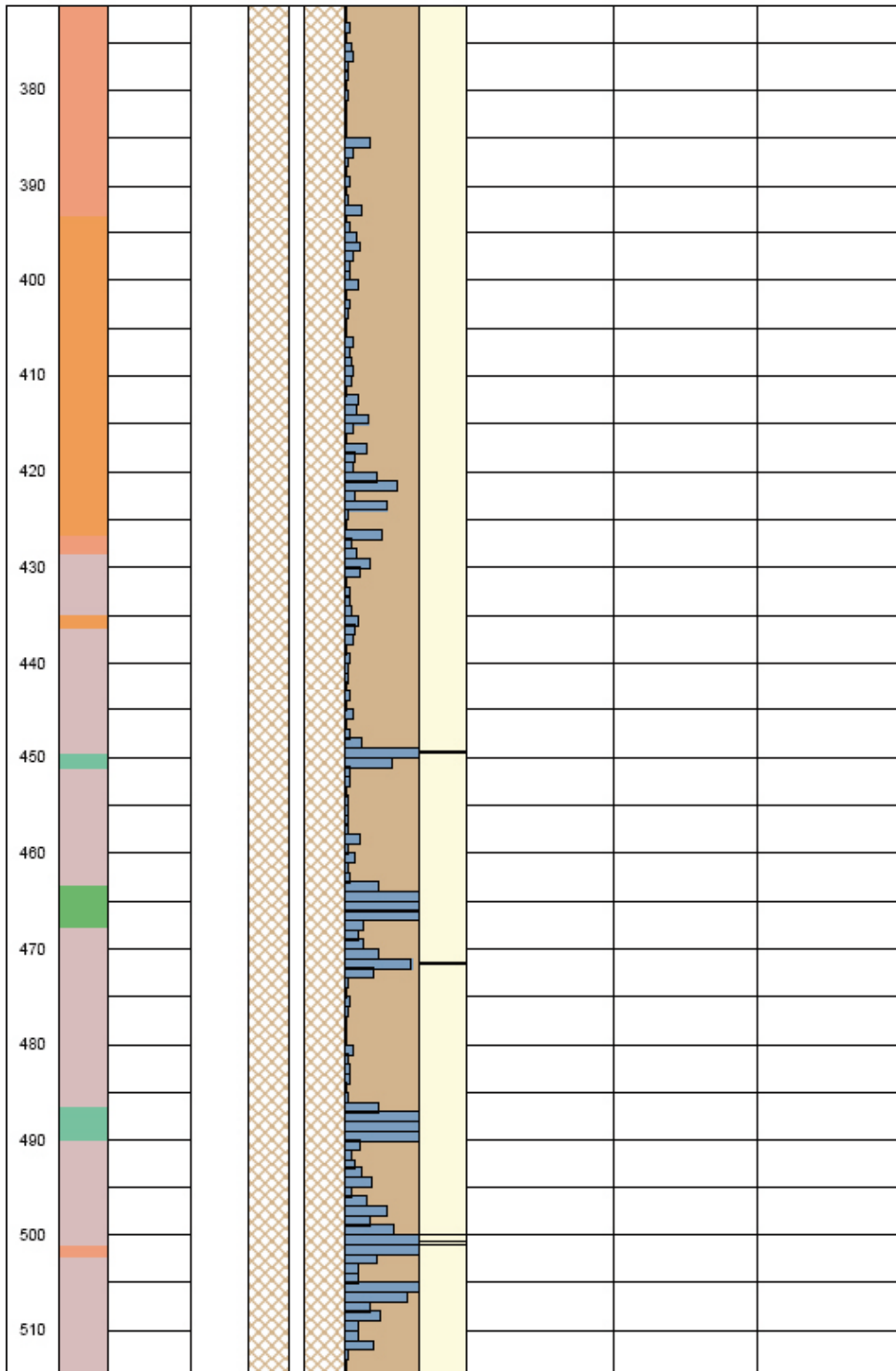
ROCKTYPE FORSMARK		SOIL
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<span style="display: inline-block; width: 15px; height: 10px; background-color: #f4a460; border: 1px solid black;"></span>	Pegmatite, pegmatitic granite	
<span style="display: inline-block; width: 15px; height: 10px; background-color: #f4a460; border: 1px solid black;"></span>	Granite, granodiorite and tonalite, metamorphic, fine- to medium-grained	
<span style="display: inline-block; width: 15px; height: 10px; background-color: #f4a460; border: 1px solid black;"></span>	Granite to granodiorite, metamorphic, medium-grained	
<span style="display: inline-block; width: 15px; height: 10px; background-color: #f4a460; border: 1px solid black;"></span>	Diorite, quartz diorite and gabbro, metamorphic	
<span style="display: inline-block; width: 15px; height: 10px; background-color: #f4a460; border: 1px solid black;"></span>	Amphibolite	

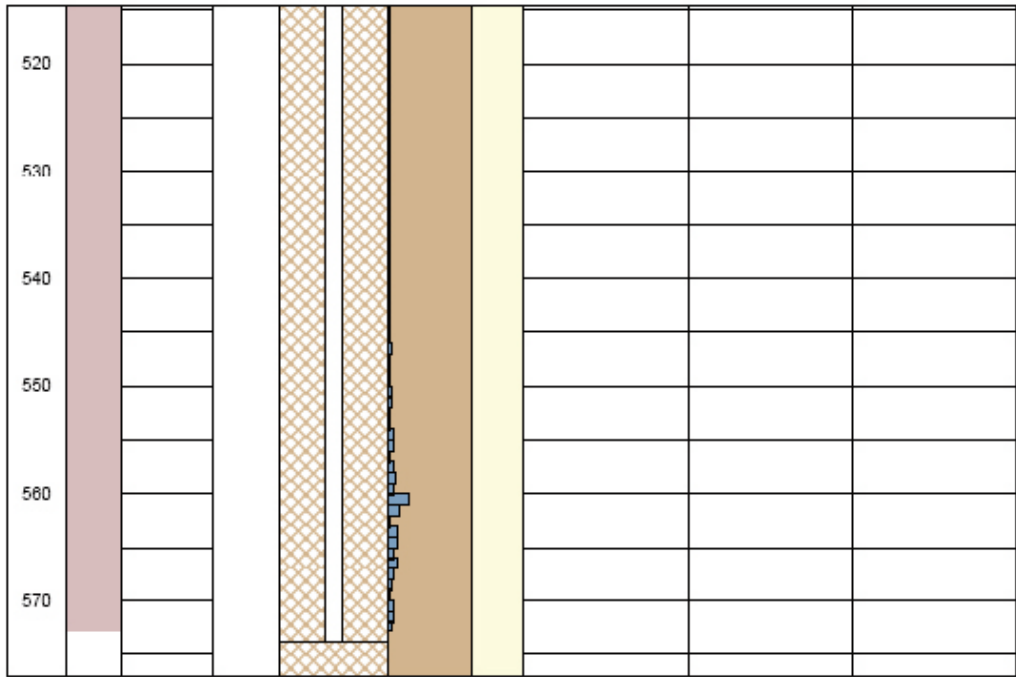
  

Script Name										
Depth [m:50cm]	Rock Type	Penetration rate (m/20min)	Delta <i>q</i> (m <sup>2</sup> /s)	Borehole Geometry		Fracture Frequency (1/m)	Crush	Feed Force Cyl	Rot Speed	Water Flow
		0 60		0.25 0.25	Hole Diam			Feed Press Cyl	Drill Water	Water Press
	Soil	Feed Speed (cm/min)		Casing depth	0 40					
0				0.15 0.339						
10				3.23 8.156						
20										
30										
40										
50										
60										
70										
80										









## Appendix C

### Chemical analyses from flushing water well HFM05

Date	IDCODE	Sample No.	Charge Bal %	Na mg/L	K mg/L	Ca mg/L	Mg mg/L	HCO <sub>3</sub> <sup>-</sup> mg/L	Cl <sup>-</sup> mg/L	SO <sub>4</sub> <sup>2-</sup> mg/L	SO <sub>4</sub> _S mg/L	Br mg/l	F <sup>-</sup> mg/L	Si mg/L	Li mg/L	Sr mg/L	I <sup>-</sup> mg/l	TOC mg/L	pH	EiCond mS/m
2006-09-11	HFM05	12374	-1.3	1,560	38.8	672	180	159	3,910	312	115	17.8	1.61	7.17	0.052	5.05	0.055	3.8	7.3	1,200
2007-01-10	HFM05	12561	-3.9	1,230	36.6	605	157	187	3,400	277	102	14.2	1.51	7.59	0.048	4.54	0.038	4.5	7.26	1,040

Date	IDCODE	Sample No.	δ <sup>2</sup> H ‰ SMOW	<sup>3</sup> H TU	δ <sup>18</sup> O ‰ SMOW	<sup>14</sup> C pmC	δ <sup>13</sup> C ‰ PDB	<sup>10</sup> B/ <sup>11</sup> B no unit	δ <sup>34</sup> S ‰ CDT	<sup>87</sup> Sr/ <sup>86</sup> Sr no unit	δ <sup>37</sup> Cl ‰ SMOC
2006-09-11	HFM05	12374	-83.2	1.3	-9.9	34.31	-6.66	0.238	25.2	0.719364	0.07
2007-01-10	HFM05	12561	-76.4	A	-10.1	A	-6.94	0.2464	25.3	0.719343	A

A = results will be reported later.