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Drilling of borehole KFM01C and the telescopic borehole KFM01D at drill site DS1

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Keywords: AP PF 400-05-089, AP PF 400-05-108, Core drilling, Telescopic drill holes, Drill site DS1.

Abstract

The major part of the deep boreholes drilled within the scope of the Forsmark site investigations are performed as telescopic boreholes, entailing that no drill core is produced between the bedrock surface and c. 60–100 metres below. However, also traditional cored boreholes are drilled at some locations in order to retrieve drill core also from shallow depths.

At drill site DS1 within the Forsmark investigation area, a 1,000 m deep telescopic borehole, KFM01A, and a 500 m deep traditional cored borehole, KFM01B, were drilled in 2002–2003, indicating low-fractured and low-conductive rock at depth, below c. 300 m, whereas the shallow parts were fractured and to some extent highly water yielding. During the course of site investigation, decisions were made to extend the drilling programme at DS1 with two more inclined boreholes, one traditional cored borehole and one telescopic hole.

The first borehole, which is denominated KFM01C, is a 450.02 m long traditional hole, inclined 49.61° from the horizon, and with bearing 165.35° from N. It reaches about 332 m in vertical distance from the ground surface. A percussion drilling machine performed the soil drilling and installed a stainless steel casing to 6.15 m before core drilling commenced. By drilling KFM01C, the existence of a flat lying fracture zone encountered at c. 50–70 m in the previously drilled boreholes KFM01A and 1B was verified. Further, KFM01C has enhanced the knowledge of the steeply dipping fracture zone ZFMENE0060A.

The second borehole, KFM01D, is an 800.24 m long telescopic borehole, inclined 54.90° and with bearing 35.03°. This borehole reaches about 612 m vertical depth from the ground surface. During pilot drilling of section 0–89.77 m with the diameter 160 mm, an unstable, fractured section at 68 m borehole length, interpreted as the same gently dipping fracture zone as was encountered in KFM01A, 1B and 1C was penetrated. This zone was heavily water-yielding, and measured an inflow of 420 L/min. Due to the high water capacity and unstable borehole wall, the borehole was reamed to Ø 245 mm, whereupon a stainless steel casing was installed, and the gap between the borehole wall and the casing was grouted. These activities entailed that all inflow of groundwater to the percussion drilled part of the borehole ceased.

A sampling- and measurement programme for percussion drilling and another programme for core drilling provided preliminary but current information about the geological and hydraulic character of the boreholes 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 for the borehole mapping (so called Boremap mapping) performed after drilling. Results of the Boremap mapping of KFM01C and KFM01D are included in this report.

After completed drilling of KFM01C and KFM01D, grooves were milled into the borehole wall at certain intervals as an help for length calibration when performing different kinds of borehole measurements after drilling.

One experience from drilling of KFM01C and 1D is that the quartz rich bedrock in Forsmark is hard to drill, resulting in rapid wearing of drill bits. Other lasting impressions from the drilling are the water yielding gently dipping fracture zones encountered in the shallow part of the bedrock and the, on the other hand, very low fracture frequency and low water yielding capacity of the major part of the core drilled section of KFM01C and 1D.

Sammanfattning

De flesta djupa borrhål inom Forsmarks platsundersökning utförs som s k teleskopborrhål, varför borrkärna saknas i avsnittet från bergytan ner till ca 60–100 m. På vissa platser i undersökningsområdet borras dock även traditionella kärnborrhål i syfte att erhålla borrkärna även från berggrundens ytligare delar.

På borrplats BP1 i Forsmarks undersökningsområde borrades mellan 2002–2003 ett 1000 m djupt teleskopborrhål, KFM01A, samt ett 500 m djupt traditionellt kärnborrhål, KFM01B. Borrhålen uppvisade ett sprickfattigt och lågkonduktivt berg mot djupet, under ca 300 m, medan de övre partierna hade förhöjd sprickfrekvens och i vissa sektioner hög vattenföring. Under platsundersökningens gång beslutades att utöka borrprogrammet på borrplats BP1 med ytterligare två lutande borrhål, ett teleskopborrhål och ett traditionellt borrhål.

Det första borrhålet, som benämns KFM01C, är ett 450,02 m långt traditionellt kärnborrhål, som är ansatt med 49,61° lutning från horisontalplanet i riktning 165,35° samt når ca 332 m vertikaldjup. En hammarborrmaskin utförde jordborrningen och drev ett rostfritt foderrör ner till 6,15 m innan kärnborrningen kunde påbörjas. Vid kärnborrningen i den övre delen påträffades permeabelt, sprucket och instabilt berg som verifierade den subhorisontella sprickzon som vid ca 50–70 m påträffats i de tidigare borrade hålen på BP1. Dessutom utökades kunskapen om den brantstående sprickzon som benämns ZFMENE0060A.

Det andra borrhålet, KFM01D, är ett 800,24 m långt teleskopborrhål ansatt med 54,90° lutning och med bäringen 35,04°. Detta borrhål når ca 612 m vertikaldjup. Under pilotborrningen av avsnittet 0–89,77 m med diametern 160 mm påträffades ett instabilt, sprucket avsnitt vid 68 m och med hög vattenföring, där 420 L/min uppmättes. Detta borrhålsavsnitt tolkades som varande samma flacka sprickzon som påträffats tidigare mellan ca 50 och 70 m i KFM01A, 1B och 1C. Eftersom borrhålet var instabilt och kraftigt vattenförande rymdes det upp till 245 mm diameter, och kläddes in med ett rostfritt foderrör, varefter spalten mellan borrhålsvägg och foderrör cementinjekterades, så att allt vatteninflöde i denna del av borrhålet upphörde.

Ett mät- och provtagningsprogram för kärnborrningen av KFM01C och KFM01D gav preliminär information om borrhålens geologiska och hydrauliska karaktär direkt under pågående borrning samt underlag för fördjupade analyser efter borrning. Bland de insamlade proverna utgör borrkärnorna tillsammans med videofilm av borrhålsväggen (s k BIPS-bilder), underlagsmaterialet för den borrhålskartering (s k Boremapkartering) som utförs efter borrning. Även resultaten från Boremapkarteringen av KFM01C och KFM01D finns redovisad i föreliggande rapport.

Efter avslutad borrning av KFM01C och KFM01D frästes referensspår in i borrhålsväggen med syftet att användas för längdkalibrering i samband med olika typer av borrhålsmätningar som senare utförs i de färdiga borrhålen.

En erfarenhet från borrningen av KFM01C och 1D är att den kvartsrika berggrunden i Forsmark är svårborrad och att borrkronslitaget är högt. Andra bestående intryck är dels de subhorisontella, delvis kraftiga vattenförande zoner som på träffats i den övre delen av borrhålet, dels att, omvänt, sprickfrekvensen och vattenföringen i större delen av de kärnborrade partierna av borrhålen visade sig vara mycket låga.

Contents

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/, see Figure 1-1.

Drilling is one important activity within the scope of the site investigations. Three main types of boreholes are produced, 1) core drilled and 2) percussion drilled boreholes in solid rock and 3) boreholes drilled through regolith. The last type may be accomplished by different drilling techniques, e.g. percussion drilling and auger drilling.

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.

This document reports the results gained by drilling the relatively short borehole KFM01C and the semi-deep telescopic borehole KFM01D at drill site DS1, which is one of the activities performed within the site investigation at Forsmark. The work was carried out in accordance with activity plans AP PF 400-05-089 and AP PF 400-05-108, respectively.

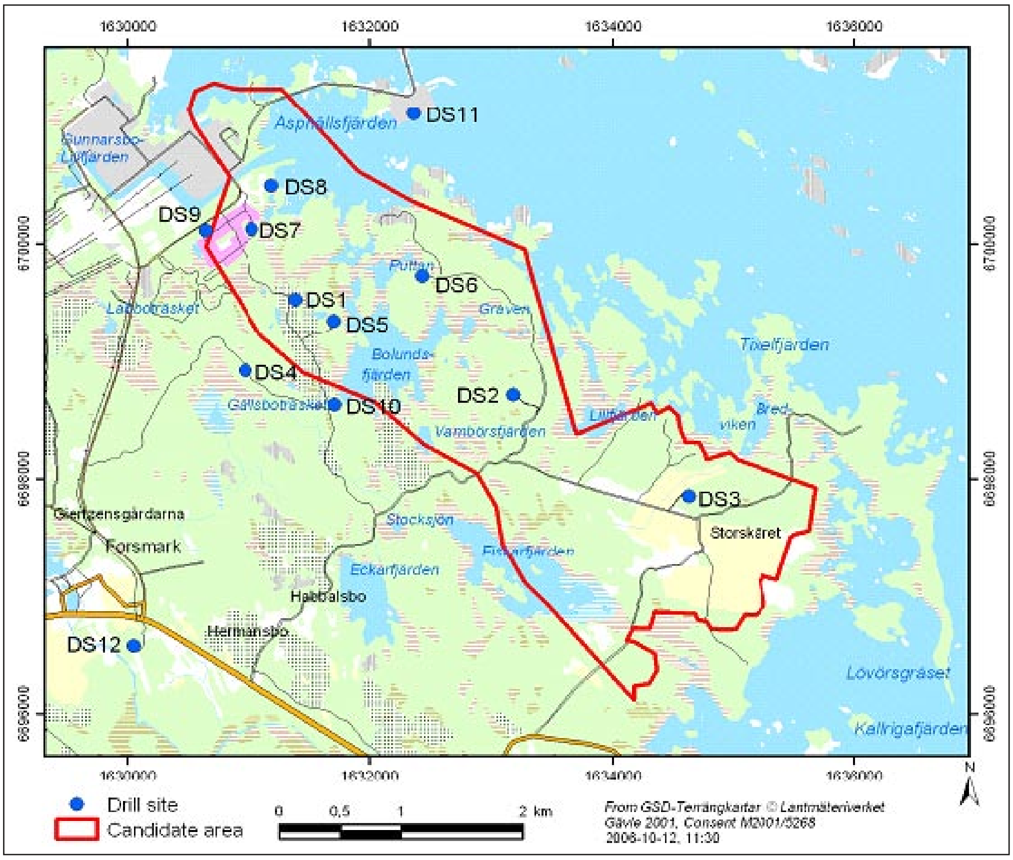


Figure 1-1. *The site investigation area at Forsmark including the candidate area selected for more detailed investigations. Drill sites DS1–12 are marked with blue dots.*

Table 1-1 presents controlling documents for performing these activities are listed. Both activity plans and method descriptions are SKB's internal controlling documents.

By drilling many (although not all) of the deepest boreholes, so called telescopic drilling technique is applied, meaning that the upper c. 60–100 metres of the borehole are percussion drilled with a large diameter (c. 193 mm), whereas the borehole section below is core drilled with a diameter of approximately 76–77 mm. This technical approach was applied also when drilling KFM01D, which has a total drilling length of 800.24 m. The borehole is inclined c. 55 degrees from the horizontal plane, entailing that the vertical depth of the borehole is c. 612 m, whereas the horizontal extension of the borehole is approximately 509 m.

Borehole KFM01C, which has a total drilling length of 450.02 m, was drilled with traditional core drilling technique. This hole is inclined c. 50 degrees from the horizontal plane, and the vertical depth is about 332 m. The horizontal extension of the borehole is c. 300 m.

Borehole KFM01C is not of the so called SKB chemical-type whereas KFM01D is. This implies that KFM01D, besides aimed for geological and hydrogeological studies, is prioritized for hydrogeochemical and microbiological investigations, prompting that all DTH (Down The Hole) equipment used during and/or after drilling must undergo special cleaning procedures, see Chapter 4.

Drill site DS1 is located in the north-western part of the candidate area, c. 1 km from the Forsmark power facilities. The area is covered by forest and is characterized by small lakes tied off from the nearby Baltic Sea in, from a geological point of view, recent times. The present coastline is situated about 2 km north-east of the drill site (Figure 1-1). Close to the deep boreholes at drill site DS1, 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 approximately 200 m. The locations of all boreholes at drill site DS1 are shown in Figure 1-2.

Drilling of KFM01C was performed during two periods, Oct 26th, 2005, (percussion drilling) and Nov 5th to Nov 29th, 2005, (core drilling). Drillcon Core AB from Sweden, was engaged for the drilling commission. Two different drilling equipments were employed for drilling KFM01C, a percussion drilling machine for drilling the upper c. 6 metres, whereas core drilling of the remaining part (section 6.15–450.02 m) was carried out with a wireline core drilling system.

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

Activity plan	Number	Version
Borrning av teleskopborrhål KFM01C	AP PF 400-05-089	1.0
Borrning av teleskopborrhål KFM01D	AP PF 400-05-108	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för hammarborrning	SKB MD 610.003	2.0
Metodbeskrivning för kärnborrning	SKB MD 620.003	1.0 Sant
Metodbeskrivning för registrering och provtagning av spolvattenparametrar samt borrkax under kärnborrning	SKB MD 640.001	1.0
Metodbeskrivning för pumptest, tryckmätning och vattenprovtagning i samband med wireline-borrning	SKB MD 321.002	1.0
Method instructions	**Number**	**Version**
Rengöring av borrhålsutrustning och viss markbaserad utrustning	SKB MD 600.004	1.0
Användning av kemiska produkter och material vid borrning och undersökning	SKB MD 600.006	1.0
Analys av injektions- och enhålspumptester	SKB MD 320.004	1.0

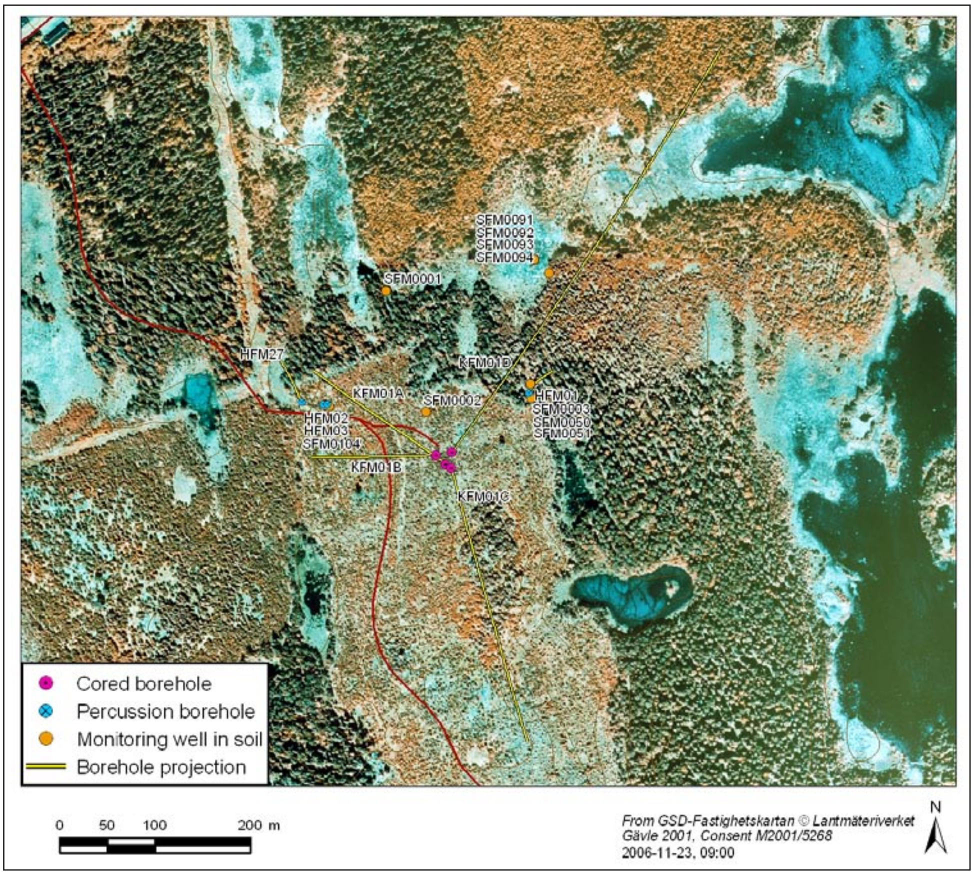


Figure 1-2. *Borehole locations at and near drill site DS1. Besides the core drilled boreholes KFM01A, KFM01B, KFM01C and KFM01D, the area incorporates three monitoring wells in bedrock (HFM01, HFM02 and HFM03), and ten monitoring wells in the unconsolidated overburden. The projection of inclined boreholes on the horizontal plane at the ground surface (top of casing) is shown in the figure.*

Also drilling of KFM01D was performed during two periods, between Nov 22nd to Dec 5^{th,}, 2005, (percussion drilling) and Dec 17th, 2005 to Feb 18th, 2006, (core drilling). Drillcon Core AB was engaged for the drilling commission. Two different drilling equipments were employed for drilling KFM01D, a percussion drilling machine for drilling the upper c. 90 metres, whereas core drilling of the remaining part (section 89.77–800.24 m) was carried out with a wireline core drilling system.

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 400-05-089 and 400-05-108, respectively). 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.

2 Objective and scope

The main objectives of drilling deep telescopic boreholes and semi-deep cored boreholes at the site investigation are the following:

- To provide rock samples from the ground surface to the borehole bottom. When using telescopic technique, 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 60–100 m, the core drilling provides (in principle) continuous drill cores down to the borehole bottom, which also is the case when core drilling technique is used from the surface. 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, in some cases performed as tracer tests) for characterization of the hydrogeological conditions.
- 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 KFM01D, while KFM01C is not performed for hydrogeochemical and microbiological characterization. A specific objective for borehole KFM01C was to investigate a presumed deformation zone named ZFMENE0060A regarding lithological and structural conditions.

One specific objective for borehole KFM01D was to intersect zone ZFMENE0061 in order to document the character of this zone close to repository depth. Earlier modelling work also suggests that the gently dipping zone ZFMA2 would be intersected in the upper part of borehole KFM01D.

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

Different types of drilling machines were employed for drilling boreholes KFM01C and KFM01D. While using a Nemek 710 percussion machine for drilling through the soil and into the solid rock, 0–6.15 m at KFM01C, the upper c. 90 metres in KFM01D were drilled with a percussion drilling machine of type Puntel MX 1000.

For the core drilling of section 6.15 to 450.02 m in KFM01C and section 89.77 to 800.24 m in KFM01D, a Wireline-76 core drilling system, type Atlas Copco Craelius B20, was engaged. After the ordinary drilling period of KFM01C an Onram 1000 core drilling machine was hired for some additional work.

3.1 Percussion drilling equipment

Both the Nemek and the Puntel percussion machines were equipped with separate engines for transportation and power supplies. Water and drill cuttings were retrieved from the borehole by a 27 bars air-compressor, type Atlas-Copco XRVS 455 Md.

At drilling site DS1, the bedrock is covered by approximately 3–12 m of sandy-silty till with some boulder contents. This part had to be cased off. To achieve a borehole as straight as possible in this type of soil, the choice of technique is important. In this case the NO-X technique was applied, following the principles and dimensions presented in Figure 3-1. The NO-X technique is described more in detail in SKB MD 610.003 (Method Description for percussion drilling). Figure 3-1 is a schematic diagram where the drilling depths presented are approximate. The true depths in the respective drilling sequences performed in KFM01C and in KFM01D are presented in Section 5.2 respectively 5.6.

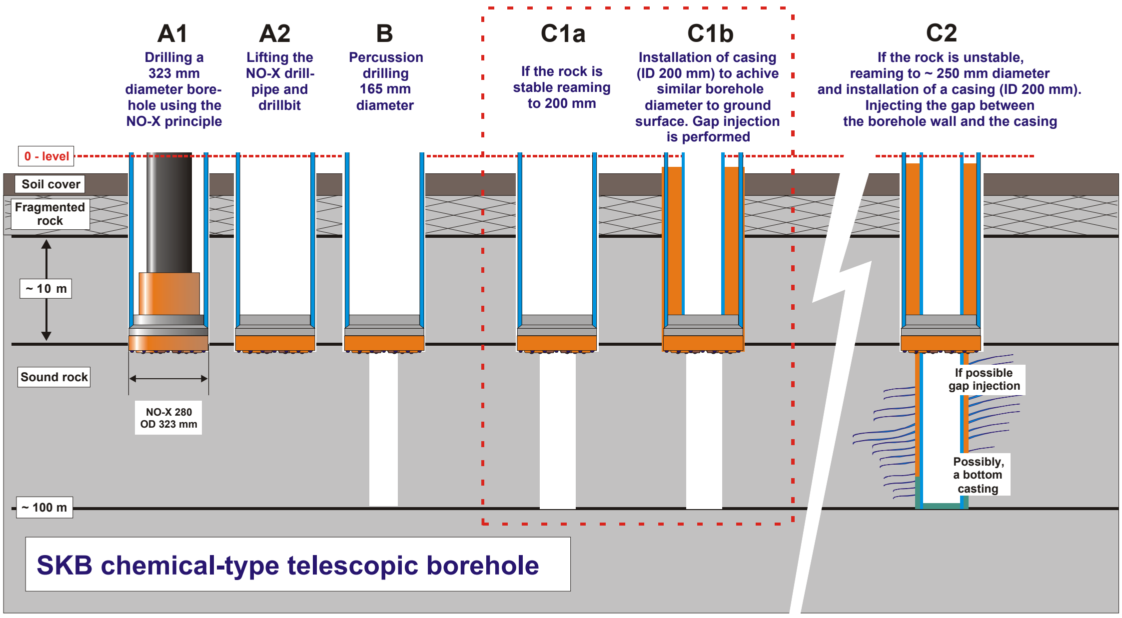


Figure 3-1. *Schematic diagram showing the various stages of drilling the 0–100 m section of an SKB chemical-type telescopic borehole. The letters and numerals above each stage refer to some of the operations described in Sections 3.4.1 and 3.4.2 in SKB MD 620.003.*

3.2 Grouting technique

For investigation of the groundwater conditions, especially the hydrogeochemical characteristics, in the cored part of a telescopic borehole, it is essential that the deeper groundwater is not mixed with surface water or groundwater from shallow parts of the bedrock. Therefore, if large inflows of groundwater are met with during percussion drilling of a telescopic borehole, it is essential to prevent it from permeating into deeper parts of the bedrock. This is achieved by cement grouting of water yielding fractures or fracture zones, as they come across. The simplest method is to fill part of the borehole with cement and to continue drilling after setting of the cement. This is also an effective method to stabilize the borehole wall e.g. if a highly fractured and unstable section is penetrated.

If the percussion drilled part of a telescopic borehole is fractured and water yielding, it is in SKB site investigation boreholes normally cased to the full drilling length. The gap between the borehole wall and the casing is then cement grouted, which further decreases or, often, completely prevents, inflow of shallow groundwater to the borehole. Application of cement in the gap between the borehole wall and the casing pipe can be performed according to different techniques. Two variants are illustrated in Figure 3-2.

Borehole KFM01D was grouted after installation of the $Ø_i$ 200 mm, 89 m long casing (C2 in Figure 3-1). After installation of the casing, gap injection through a packer was applied.

3.3 Core drilling equipment

3.3.1 The wireline-76 system

For drilling the cored part of boreholes KFM01C and KFM01D, a wireline-76 system, type Atlas Copco JKS Boyles B20 APC, was employed. The drilling process is operated by an electrically-driven hydraulic system supplied with a computer control. The drilling capacity for 76–77 mm holes is maximum c. 1,500 metres. The drill pipes and core barrel used belong to the AC Corac N3/50 NT triple-tube system. The original Corac tubes are modified in this version to fulfil the demands from SKB with minimum 50 mm drill core diameter. Technical specifications of the drilling machine with fittings are given in Table 3-1.

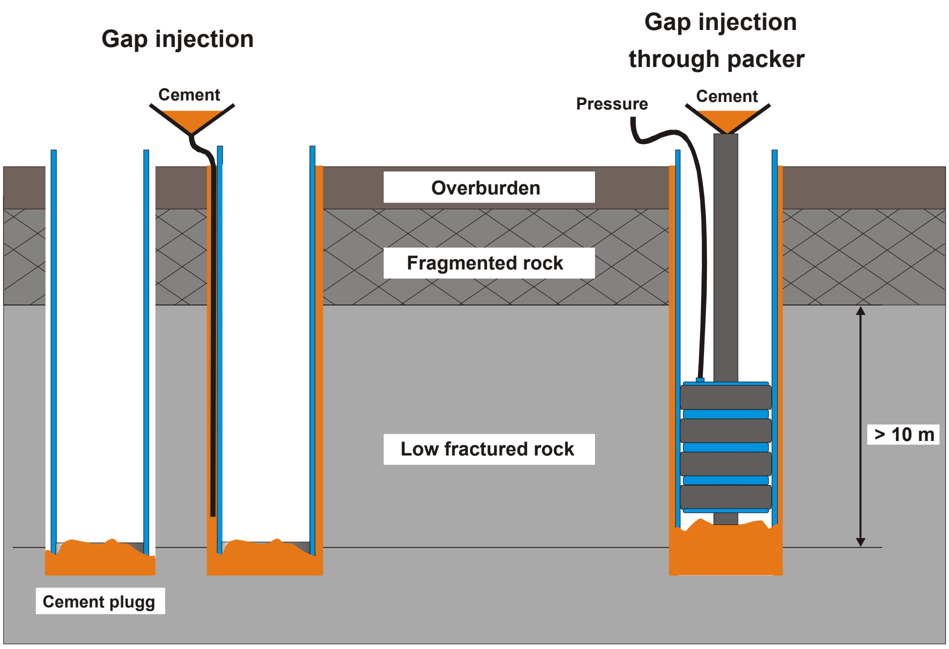


Figure 3-2. *Gap injection techniques. In order to fill the gap between the borehole wall and the casing, different techniques may be applied. To the left, a flexible hose is lowered between the casing and the borehole wall, and to the right the grouting is performed through a borehole packer.*

Table 3-1. Technical specifications of the B20 APC-system from Atlas Copco Boyle with appurtenances.

Unit	Manufacturer/type	Specifications	Remarks
B20	Atlas Copco Craelius	Capacity for 76–77 mm holes maximum approx. 900–1,500 m depending on choise of drill string	
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 engined 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	Danfoss		Standard system modified for core drilling by the manufacturer

3.3.2 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 drill pipes. However, if the borehole has penetrated water conductive rock fractures, part of, and sometimes all of the return water from the borehole, including drill cuttings, may be forced into these fractures. This renders a correct characterization of the in situ hydraulic and hydrogeochemical conditions more difficult, due to partial or complete clogging by drill cuttings and due to the contribution of 'foreign' flushing water in the fracture system.

In order to reduce these negative effects, SKB has developed a specially designed flushing water and return water system. The equipment consists of the components shown in Figure 3-3. The system includes equipment for pumping, transport and storage of water. The flushing/return water system may be divided into:

- 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.

Preparing the flushing water

The quality of the flushing water must fulfil specific demands, which are especially important when drilling telescopic boreholes of SKB chemical type. The water needs to be almost biologically clean, i.e. the contents of microbes and other organic constituents needs to be low. The chemical composition should be similar to that which is to be expected in the aquifer penetrated by the telescopic borehole itself. Foreign substances, like oil and chemicals, must be avoided.

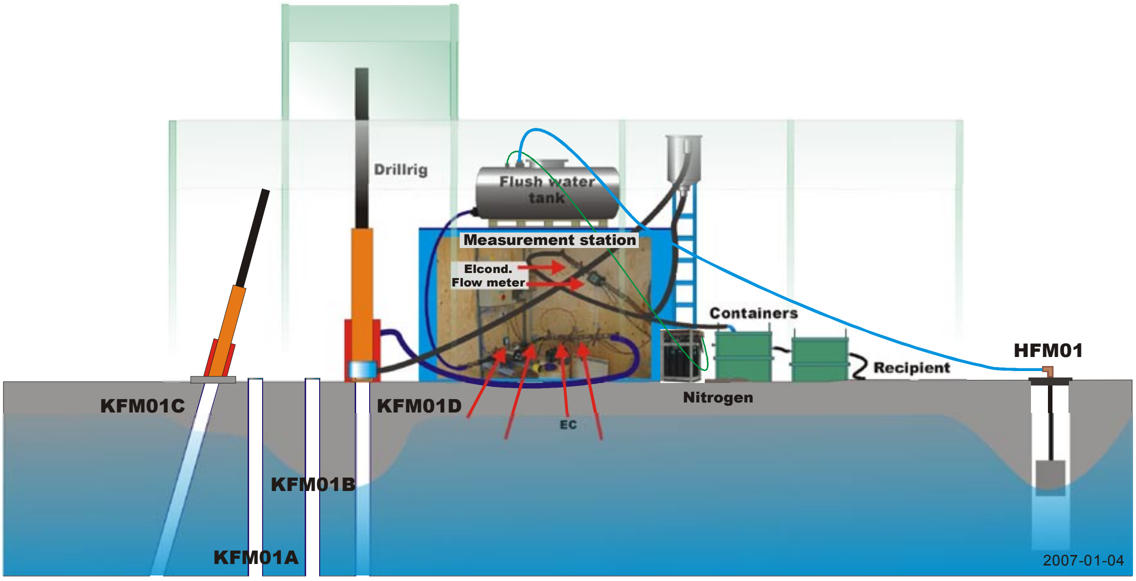


Figure 3-3. *Schematic illustration of the flushing/return water system when drilling KFM01C and KFM01D at DS1. The measurement station included logger units and an UV-radiation unit. For flushing water flow rate and pressure measurements, the drilling machine gauges were applied.*

The water well used for the supply of flushing water for core drilling of KFM01C and KFM01D was a percussion drilled well in hard rock, HFM01, situated at DS1 approximately 30 m from KFM01C and KFM01D. The HFM01 well had earlier been used for flushing water supply for drilling of KFM01A and KFM01B, and the water quality was analysed and considered as sufficiently good to serve as flushing water for KFM01C and KFM01D.

Besides these basic demands on the flushing water quality, which were fulfilled when drilling KFM01C and KFM01D, the flushing water was also prepared in three steps before use, in accordance with SKB MD 620.003.

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 tracer dosing equipment, illustrated in Figure 3-3. The microbe contents 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 contents in groundwater samples collected in the borehole during or after drilling.

Measurement of flushing water parameters

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 using automatic flow meters both on the drilling rig and inside the container.

Air-lift pumping while drilling

Air-lift pumping during core drilling of telescopic boreholes (in this activity performed during drilling of KFM01D) involves pumping of compressed air into the percussion drilled portion of the telescopic borehole, forcing it to emerge at a depth of about 80–100 m. 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 KFM01D consisted of several main components, see Table 3-3 and Figure 3-4.

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

Instrument	Manufacturer/type	Range of measurement	Remarks
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		

Table 3-3. Air-lift pumping equipment used in KFM01D.

Item	KFM01D
Air Compressor, 12 bars/10 m³/min	X
Electrical supply cubicle, at least 16 A	X
Outer support casing, 98/89 mm diameter	89 m
Inner support casing, 84/77 mm diameter	89 m
2 Ejector pumps, each contains;*	
PEX hose, 1 x 22 mm	2 x 90+30**m
PEM hose, 1 x 40 mm	2 x 90+30**m
Air nozzle	
PEX hose, 1 x 22 mm	88+30**m
Expansion vessel (= discharge head)	X
PEM hose: 20 bars, 32 mm diameter (pressure gauge)	90 m
Pressure sensor, 10 bars, instrumentation and data-logging unit	X

* Always two mammoth pumps are installed in each telescopic bore hole.
** Extended hose; PEX connected to air compressor and PEM connected to Cyclone.

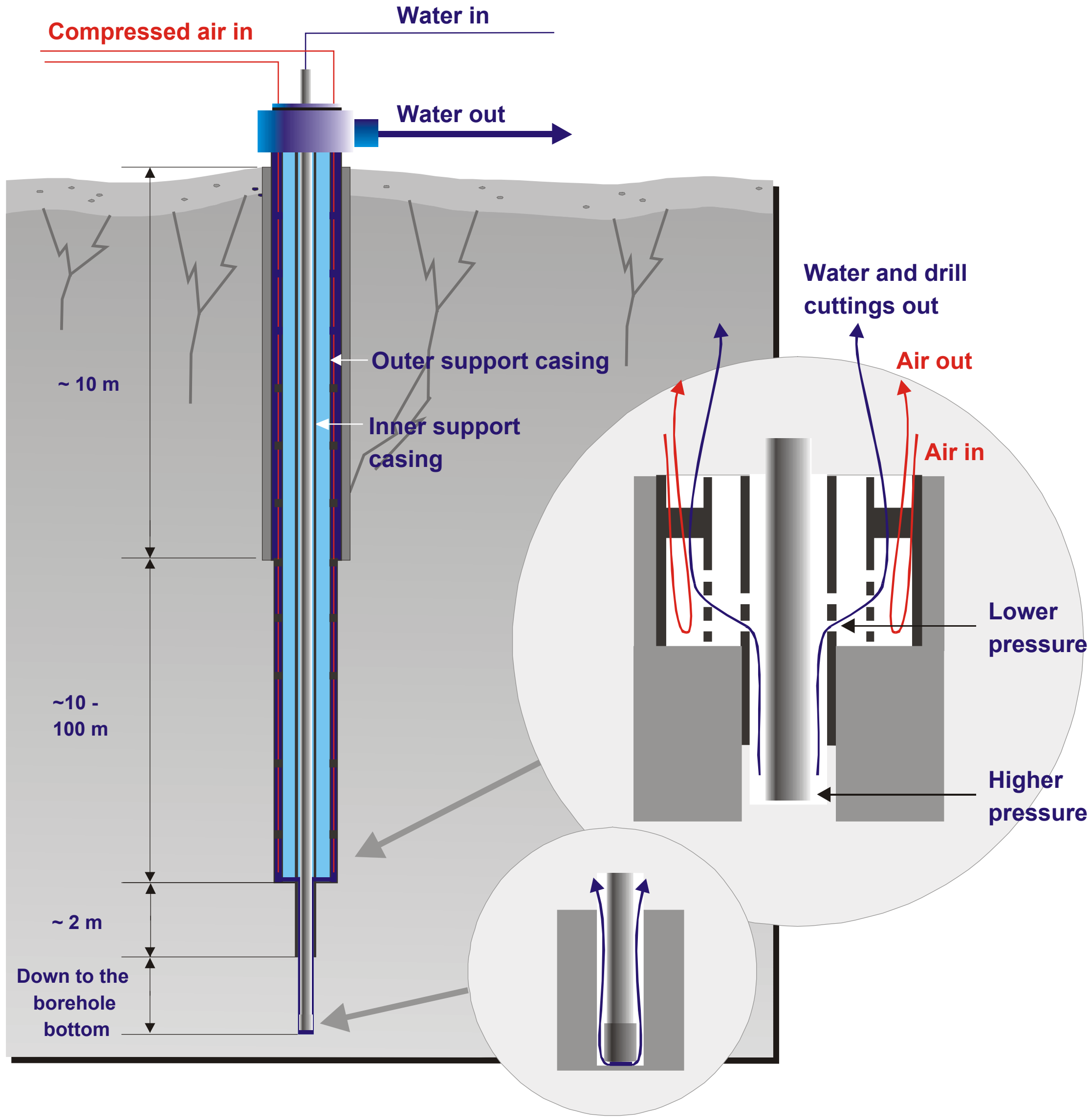


Figure 3-4. Air-lift pumping during core drilling of a telescopic borehole. Schematic representation, where the drilling depths are only approximate. The air and instrumentation hoses are secured to the outer support casing. The compressed air raises the flushing water and drill cuttings from the hole. 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.

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 in KFM01D, 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 28 mm return hose were connected to the ejector tube as shown in Figure 3-5. With this construction, the air leaving the ejector rose, reducing the pressure in the lower part of the ejector tube, helping to lift drill cuttings from the bottom of the hole.

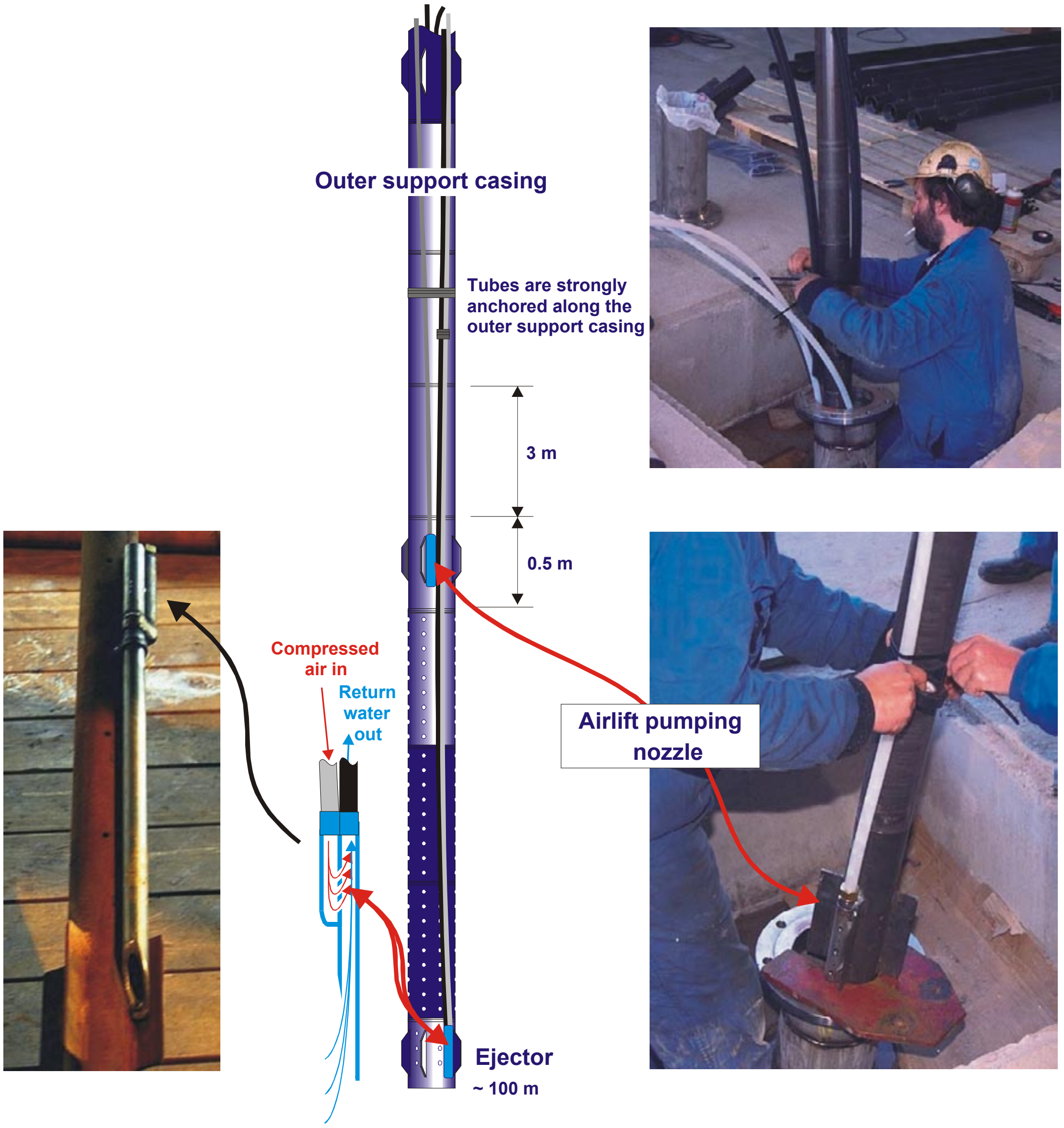


Figure 3-5. *Schematic representation of connection and installation of air-lift pumping nozzle and ejector on the outer protective casing.*

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, see Figures 3-3 and 3-6. The return water was discharged from the borehole via the expansion vessel and a flow meter to three containers, in which the drill cuttings separated out in three sedimentation steps. The cuttings were preserved in the containers for later weighing. Due to environmental restrictions, the return water was pumped through an exit pipe string directly to the Baltic Sea.

The flow rate and electrical conductivity of the return water were measured and data stored in the data-logging system. Technical specifications of the measurement instruments are given in Table 3-4.

Flow rate- and other flushing water data were continuously stored in an automatic data-logging system, see Section 3.3.3. As a back-up and double-check, 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.

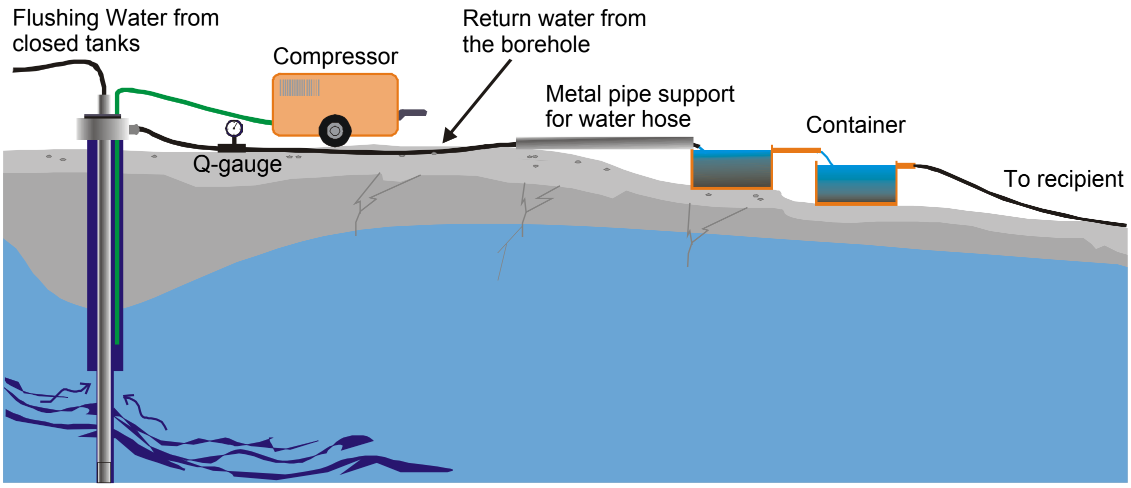


Figure 3-6. *Return water system. Air-lift pumping raises the return water, consisting of flushing water, groundwater and drill cuttings, from the borehole. The cuttings separate out in three stages in the containers (where they are preserved for later weighing), after which the water is pumped to an approved recipient.*

Table 3-4. Technical specifications for instruments used for measurement of return water parameters.

Instrument	Manufacturer/type	Range of measurement	Remarks
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	

3.3.3 Drilling monitoring system

The Boyles B20 drilling machine is supplied with a computer based logging kit integrated in the steering system (cf. Section 3.3.1). The parameters logged are those used for automatic operation of the drilling machine.

A log-file name, a time- or depth-interval and parameters to be logged are selected from a menu. The system produces files in ASCII format, which can be transferred into several Windows programs for further analyses.

The following parameters are automatically registered: date, time, mode, status, rotation pressure (bar), feed force on drill bit (kp), feed force on cylinder (kp), feed pressure (bar), flushing water flow rate (L/min), flushing water pressure (bar), rotation speed (rpm), penetration rate (cm/min), drill length (cm), bit position (cm), feed position (1/10 mm), rod weight (kg) and rod pressure (bar). The parameter "mode" represents the current activity in the drilling cycle, whereas "status" gives an explanation to drill stops and also indicates when a drilling sequence is finished.

For the geoscientific data acquisition, the following technical parameters are of primary interest:

- time
- drill bit position
- penetration rate
- feed force
- rotation speed.

However, during drilling of the telescopic boreholes at Forsmark, the registration is extended to include also the following flushing water parameters:

- electric conductivity
- dissolved oxygen

as well as the return water parameters:

- flow rate
- electric conductivity.

The system is also provided with devises for convenient sampling of flushing water and return water for analysis of the Uranine contents.

Finally, the level of the groundwater table in the borehole was registered during drilling.

3.3.4 Groove milling equipment

After completion of drilling, boreholes KFM01C and KFM01D are to 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 were milled into the borehole wall with a specially designed tool at regular levels. This was carried out after drilling, but with use of the drilling machine and pipe string.

At each level, two 20 mm wide grooves were milled with a distance of 10 cm between them, see Figure 3-7. 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.

3.3.5 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 Maxobor™-measurements. The surveying instrument used was the Flexit Smart Tool System.

At the time of drilling KFM01C and KFM01D, 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 the 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 summer 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 boreholes KFM01C and KFM01D, and to-day Flexit-data are in use displayed. However, all available deviation measurements (i.e. for boreholes KFM01C and KFM01D, 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 Sections 5.4.4 and 5.8.6.

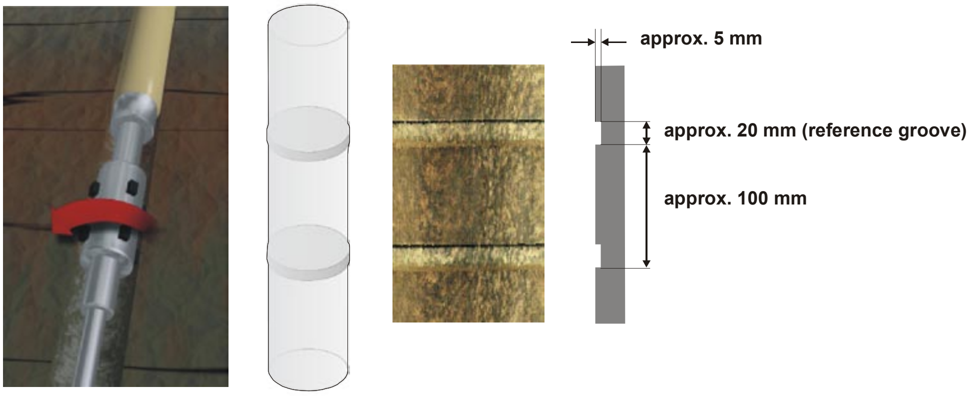


Figure 3-7. *Layout and design of reference grooves. The milling tool shown to the left.*

3.3.6 Equipment for borehole stabilization in KFM01C

A new technique for stabilization of borehole walls, designated the Plex technique, has been developed and tested by SKB, see Figure 3-8. The Plex system can be applied for mechanical stabilization of unstable parts of the borehole wall after part of or the entire borehole has been drilled. This was applied in borehole KFM01C, see Section 5.4.8. The system components, comprising a reamer, a packer with a steel plate (perforated or non-perforated) and a top valve, are assembled on top of each other in one single unit. The tool is designed for the N-dimension. By using the same pilot drill bit and ring gauge as used for drilling the borehole in question, the tool is well adjusted to the true borehole diameter. Only one rod trip is required for reaming, expanding the steel tube and verifying the inner diameter of the borehole. Using a perforated or non-perforated steel plate is optional. A perforated plate is applied if hydraulic characterization of the unstable section remains to be done.

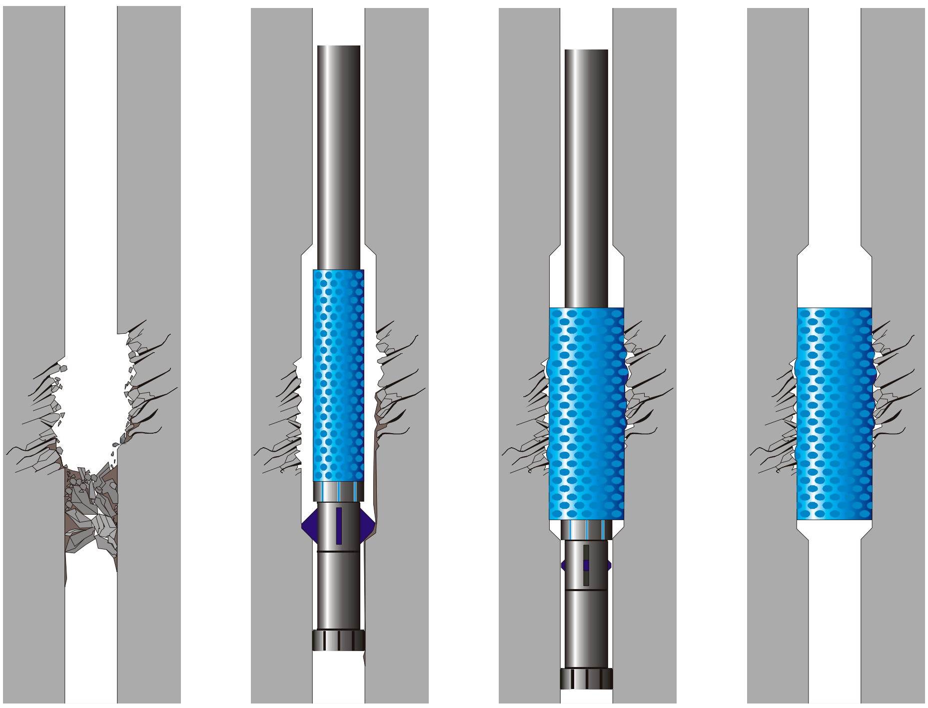


Figure 3-8. *Schematic figure illustrating the sequence of measures when stabilizing a fractured and unstable section in a core drilled borehole of N-dimension with a perforated steel plate by applying the Plex system. The tool is descended, the 80 cm long unstable section is reamed, the packer is inflated as to expand the steel plate against the reamed part of the borehole wall, the packer is deflated and the tool is retrieved. As the steel tube is perforated, the stabilization does not prevent hydraulic testing of the stabilized section.*

4 Execution

4.1 General

The activity of KFM01C was conducted in compliance with Activity Plan AP PF 400-05-089, whereas KFM01D was performed according to Activity Plan AP PF 400-05-108, both referring to SKB MD 620.003 (Method description for core drilling), see Table 1-1. The drilling operations included the following parts:

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

Each item is presented more in detail below.

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. Finally, the equipment was cleaned in accordance with SKB MD 600.004.

4.3 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.

4.4 Drilling of KFM01C

4.4.1 Percussion drilling 0–6.15 m

Drilling started with the Nemek machine with NO-X (borehole diameter 151 mm) through the soil and down into solid rock at 6.15 m. The soil depth is 2.44 m at KFM01C.

4.4.2 Core drilling 6.15–450.02 m, measurements and sampling during drilling and finishing off work

Drilling continued with NQ-core drilling and then reaming to 113 mm diameter to 11.96 m length and installation of an inner support casing with OD/ID 90/77 mm which was cement grouted. Then core drilling continued from 11.96 m to the final borehole length 450.02 m with borehole diameter Ø 75.8 mm.

Core drilling serves many purposes, cf. Chapter 2. One of the most essential objectives is to provide (in principle) continuous rock samples, i.e. drill cores, down to the borehole bottom, which allows a lithological, structural and rock mechanical characterization of the bedrock. The drill cores are also used for determination of transport properties of the rock and, sometimes, for the study of chemical characteristics of the pore water in the rock matrix.

Core drilling with a wireline system involves recovery of the core barrel via the drilling pipe string, inside which it is hoisted up with the wireline winch. During drilling of borehole KFM01C, a 3 m triple tube core barrel was used. The nominal core diameter for the Ø 75.8 mm part of the borehole is 50.5 mm. Minor deviations from this diameter may, however, occur.

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 KFM01C some deviations from this programme could not be avoided. In order to elucidate the nonconformities, the programme according to the Method Description is presented in Section 4.4.3, Table 4-1, together with the actual performance when drilling KFM01C.

Results of mapping of the drill core samples are presented in /3/, whereas the remaining measurements and registrations during core drilling are presented in Chapter 5.

Finishing off work included measurements of the final diameter of the drill bit after reaming to Ø 245 mm. The borehole was secured with a lockable stainless steel flange. The drilling equipment was removed, the site cleaned and a joint inspection made by SKB and the Contractor.

4.4.3 Nonconformities

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

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

4.4.4 Additional work

After completion of the ordinary drilling, a new drill rig, an Onram 1000, was established on the drill site to clear the borehole from gravels that fell out from the borehole wall in the unstable zone at approximately 205 m depth.

4.5 Drilling of KFM01D

4.5.1 Percussion drilling 0–89.77 m, measurements and sampling during drilling and finishing off work

The percussion drilling started with drilling through the overburden during simultaneous casing driving and subsequent gap injection. These activities followed the principles described in Sections 3.1 and 3.2. The borehole was drilled and cased with $Ø_i$ 310 mm casing to 11.61 m. After the gap injection, drilling continued and the borehole was extended to 89.77 m with the pilot bit. Finally the hole was reamed with 245 mm to 89.72 m.

The borehole was cleaned from drill cuttings by a “blow out” with the compressor working at maximum capacity during 30 minutes. This also served as a hydraulic capacity test of the borehole, as the recovery of the groundwater table was registered after the compressor had been turned off. The results were used as a rough capacity test of the percussion drilled part of the borehole, used on-site i.e. for preparation of the gap injection of the casing, see below.

Table 4-1. Programme for sampling, measurements, registrations and other activities during and immediately after core drilling according to SKB MD 620.003 compared to the actual performance during drilling of borehole KFM01C.

Activity	Performance and frequency according to SKB MD 620.004	Performance and frequency during drilling of KFM01C
Registration of drilling- and flushing water parameters.	Described in Section 3.3.2. Registration during the entire drilling.	According to programme.
Registration of the groundwater level in the borehole during drilling.	Every 10th second.	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 complete measurement with the Maxibor system and two complete measurements with the Flexit system.
Measurements of the difference in length between the compressed drilling pipe string and as extended by its own weight.	Normally performed every 100 m.	Values presented in Figure 5-9 are from material properties of the drill pipe string.
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 test made.
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 test made.
Absolute pressure measurements.	Normally during natural pauses in drilling.	No test made.
Groove milling in the borehole wall, normally at each 100 m.	Normally performed after completion of drilling.	Eight grooves performed.

In order to seal water-yielding fractures in the percussion drilled section, the gap between the casing and borehole wall was grouted using the packer and hose techniques illustrated in Figure 3-2. After grouting, the recharge of water into the borehole ceased completely.

Measurements and sampling while percussion drilling (and immediately after drilling) were performed according to a specific measurement-/sampling programme, which was applied in association with the Ø 161 mm drilling sequence. The measurement-/sampling programme performed was in accordance with SKB MD 610.003, see Table 1-1, and included:

1) Sampling of drill cuttings at every third metre. Each sample consists of three individual samples collected one per metre. The samples were stored in a plastic bottle marked with a sample number. Ocular inspection and a preliminary description of the mineral contents were made on-site as a basis for classification of the rock type.
2) Manual measurements of the penetration rate at every 20 cm.
3) Observation of the flow rate (if any) at every 20 cm. When a significant increase of the flow rate was noticed, it was measured using a graduated vessel and a stop-watch.
4) Observation of the water colour at every 20 cm.
5) Measurement of the electric conductivity of the groundwater at every three metres.

Finishing off work included measurements of the final diameter of the drill bit after reaming to Ø 245 mm. The borehole was secured with a lockable stainless steel flange. The drilling equipment was removed, the site cleaned and a joint inspection made by SKB and the Contracter.

4.5.2 Core drilling 89.77–800.24, measurements and sampling during drilling and finishing off work

Core drilling of borehole KFM01D was performed with two borehole dimensions. Section 89.77–91.48 m was drilled with a borehole diameter of 86.0 mm, whereas the main part of the borehole, section 91.48–800.24 m, was drilled with Ø 75.8 mm. The inner Ø 84/77 mm support casing was fitted into the short Ø 86 mm borehole. In this way the casing was centralized in the borehole and fixed laterally. The outer Ø 98/89 mm support casing is resting on the bottom of the percussion drilled borehole, see Figure 3-4.

Like the percussion drilling, the core drilling is associated with a programme for sampling, measurements and other activities during and immediately after drilling, cf. SKB MD 620.003 (Table 1-1). However, like when drilling KFM01C, some deviations from this programme occurred during drilling of KFM01D. The programme according to the Method Description is presented in Section 4.5.3, Table 4-2, together with the actual performance when drilling KFM01D.

Results of mapping of the drill core samples are presented in /4/, whereas the remaining measurements and registrations during core drilling are presented in Chapter 5.

Besides the activities mentioned in Table 4-2, cleaning of the flushing water system using 2% (by volume) Sodium-hypochlorite solution was performed prior to drill start.

The concluding work included the following items:

1) The borehole was flushed for about 19 hours during simultaneous air-lift pumping 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. After finished flushing/air-lift pumping, the recovery of the groundwater table was registered as an estimate of the hydraulic conditions of the entire borehole. The results are presented in Chapter 5.
2) The drill string was pulled.
3) The inner support casing was removed with aid of a crane lorry.
4) The outer support casing was removed with the same crane lorry.
5) The discharge head was removed.
6) Using the drill rig, a stainless steel transition cone was installed between the reamed and percussion drilled respectively the cored part of the borehole, as shown in Figure 5-12. The cone is located at 86.42–91.43 m.

Finishing off work included groove milling, flushing and cleaning by nitrogen. The borehole was secured with a lockable stainless steel flange. The drilling equipment was removed, the site cleaned and a joint inspection was made by SKB and the Contracter.

4.5.3 Nonconformities

The drilling operation resulted in a number of nonconformities with the Method Description. These deviations are presented in Table 4-2 below.

The last item in Table 4-2 may be commented on. All drilling debris produced during drilling (percussion drilling as well as core drilling) was collected in the sedimentation containers of the return water system, see Figures 3-3 and 3-6 (except the finest fractions which stayed suspended in the discharge water from the third container). The collected drill cuttings from the core drilled part were weighed after completed drilling in order to obtain a measure of the drill cuttings recovery.

Table 4-2. Programme for sampling, measurements, registrations and other activities during and immediately after core drilling according to SKB MD 620.003 compared to the actual performance during drilling of borehole KFM01D.

Activity	Performance and frequency according to SKB MD 620.004	Performance and frequency during drilling of KFM01D
Registration of drilling- and flushing water parameters.	Described in Section 3.3.2. Registration during the entire drilling.	According to programme.
Registration of the groundwater level in the borehole during drilling.	Every 10th second.	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 measurement after completion of drilling with the Maxibor system and two measurement with the Flexit system.
Measurements of the difference in length between the compressed drilling pipe string and as extended by its own weight.	Normally performed every 100 m.	Values presented in Figure 5-30 are from material properties of the drill pipe string.
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 test made.
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 test made.
Absolute pressure measurements.	Normally during natural pauses in drilling.	No test made.
Groove milling in the borehole wall, normally at each 100 m.	Normally performed after completion of drilling.	Thirteen grooves performed.
Collecting and weighing of drilling debris.	Drilling debris settled in containers weighed after completed drilling.	Not carried out for the percussion drilled part of the borehole. According to programme for the core drilled part.
Flushing of the entire borehole.	After finishing the borehole.	Ordinary flushing combined with nitrogen flushing.

4.6 Data handling

4.6.1 Performance

Minutes for several items with the 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 caused it to be stored in the SKB database Sicada.

4.6.2 Nonconformities

None.

4.7 Environmental programme

4.7.1 Performance

A program according to SKB´s routine for environmental control was followed throughout the activity. A checklist was filled in and signed by the Activity Leader, who also filed it in the SKB archive.

4.7.2 Nonconformities

None.

5 Results

All data were stored in the Sicada database. An overview of the drilling progress of boreholes KFM01C and KFM01D is given in Section 5.1, whereas geometrical data and technical design are presented in Sections 5.2 and 5.6 for KFM01C and KFM01D, respectively.

Results from drilling and measurements during drilling KFM01C are accounted for in:
Section 5.3 (drilling KFM01C),
Section 5.4 (measurements while drilling),
Section 5.5 (additional work).

Well Cad-presentations of borehole KFM01C are shown in Appendix A. The Well Cad plots are composite diagrams presenting the most important technical and geoscientific results from drilling and investigations made during and immediately after drilling.

Results from drilling and measurements during and after drilling of KFM01D are accounted for in:
Section 5.7 (drilling KFM01D),
Section 5.8 (measurement while drilling),
Section 5.9 (recovery measurements after nitrogen pumping.

Well Cad-presentations of borehole KFM01D are shown in Appendix B.

5.1 Drilling progress

When the Forsmark site investigation programme started early 2002, drill site DS1 was prepared for drilling of the first core drilled borehole, KFM01A (a telescopic hole), which was followed by drilling of KFM01B (a traditional cored borehole) during 2003. In late 2005 drilling machines were back, now for drilling a traditional cored borehole, KFM01C before Christmas 2005, as well as a telescopic borehole KFM01D, percussion drilled before Christmas 2005 and core drilled, inside a tent, during January–February 2006. Furthermore, another drilling machine had to come back to KFM01C for cleaning the borehole in January 2006, see Figure 5-1.

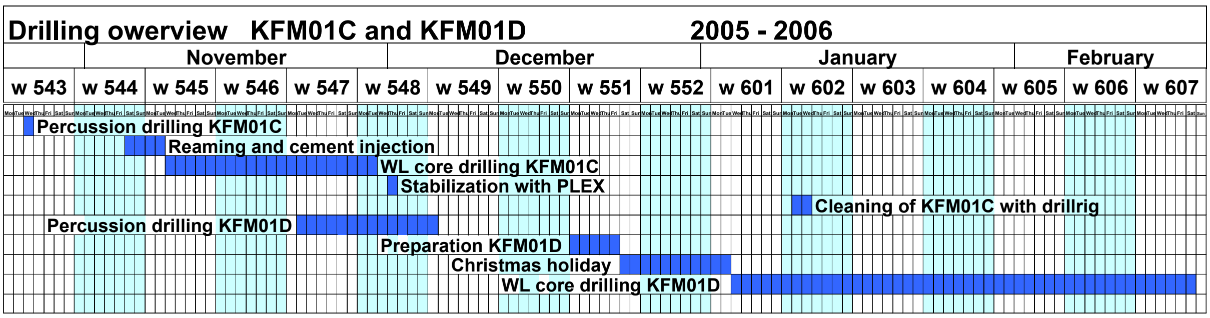


Figure 5-1. *Overview of the performance of boreholes KFM01C and KFM01D at DS1.*

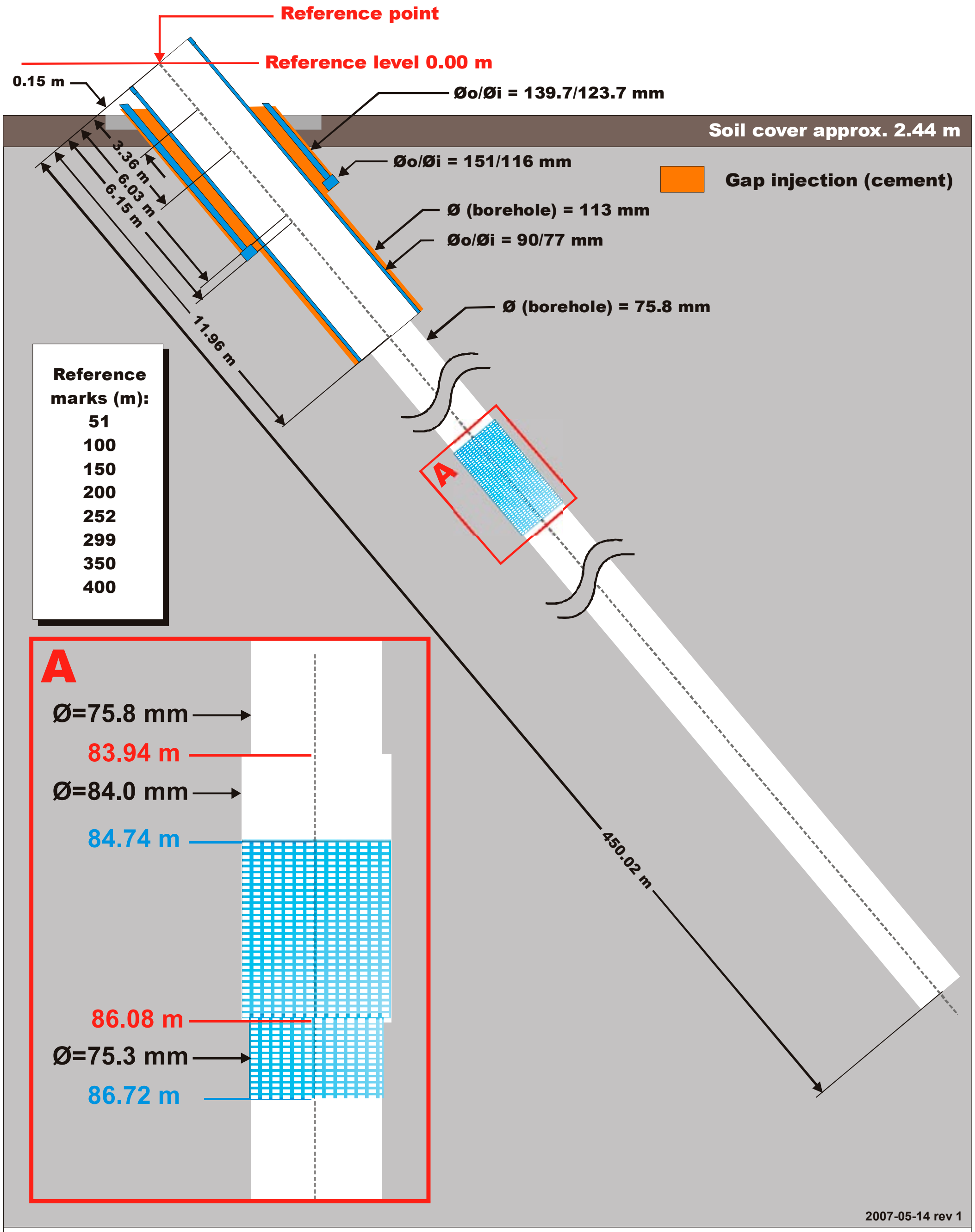
5.2 Geometrical data and technical design of borehole KFM01C

Administrative, geometric and technical data for the core drilled borehole KFM01C are presented in Table 5-1. The technical design of the borehole is illustrated in Figure 5-2.

Table 5-1. Administrative, geometric and technical data for borehole KFM01C.

Parameter	
Borehole name	KFM01C
Location	Forsmark, Östhammar municipality, Sweden
Drill start date	October 26, 2005
Drill stop date	November 29, 2005
Percussion drilling period	2005-10-26 (0–6.15 m)
Core drilling period	2005-11-05 to 2005-11-29 (6.15–450.02 m)
Stabilization	2005-12-01 (Plex)
Contractor core drilling	Drillcon Core AB
Core drill rig	Atlas Copco Craelius B20
Additional work	2006-01-16 to 2006-01-17 (Cleaning section 0–448.3 m with an Onram 1000 machine)
Sub contractor percussion drilling	Sven Andersson i Uppsala AB
Percussion drill rig	Nemek 710
Position KFM01C at top of casing (RT90 2.5 gon V 0:–15 / RHB 70)	N 6699526.14 E 1631403.75 Z 2.91 (m.a.s.l.)
	Azimuth (0–360°): 165.35° Dip (0–90°): –49.61°
Position KFM01C at bottom of hole (RT90 2.5 gon V 0:–15 / RHB 70)	N 6699237.16 E 1631483.03 Z –332.70 (m.a.s.l.)
	Azimuth (0–360°): 164.53° Dip (0–90°): –45.87°
Soil depth	2.44 m
Borehole length	450.02 m
Borehole diameter and length	From 0 m to 6.15 m: 151 mm
	From 6.15 m to 11.96 m: 113 mm
	From 11.96 to 83.94 m: 75.8 mm
	From 83.94 to 86.08 m: 84 mm
	From 86.08 to 86.72 m: 75.3 mm
	From 86.72 m to 450.02 m: 75.8 mm
Casing diameter and length	Øo/Øi = 139.7/123.7 mm from 0 m to 6.15 m
	Øo/Øi = 90/77 mm from 0 to 11.96 m
	Plex from 84.74 to 86.72 m
Drill core dimension	Ø 50 mm from 6.15 to 450.02 m
Core interval	6.15–450.02 m
Average length of core recovery	2.73 m
Number of runs	165
Diamond bits used	6
Average bit life	72.7 m/bit

Technical data
Borehole KFM01C



Drilling reference point

Northing: 6699526.14 (m), RT90 2,5 gon V 0:-15
Easting: 1631403.75 (m), RT90 2,5 gon V 0:-15
Elevation: 2.91 (m), RHB 70

Orientation

Bearing (degrees): 165.35°
Inclination (degrees): -49.61°

Borehole

Length: 450.02 m

Percussion drilling period

Drilling start date: 2005-10-26
Drilling stop date: 2005-10-26

Core drilling period

Drilling start date: 2005-11-05
Drilling stop date: 2005-11-29

Additional work (Plex)

Start date: 2005-12-01
Stop date: 2005-12-01

Additional work (reaming of borehole)

Start date: 2006-01-16
Stop date: 2006-01-17

Figure 5-2. *Technical data of borehole KFM01C.*

5.3 Drilling KFM01C

5.3.1 Overburden drilling 0–6.15 m KFM01C

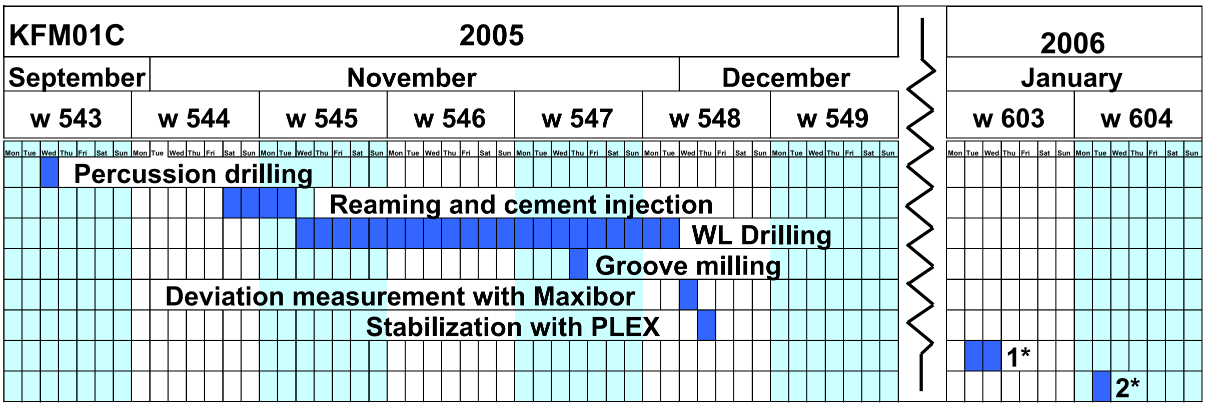
Drilling with the percussion drilling machine was performed to 6.15 m borehole length on Oct 26th, 2005 (Figures 5-1and 5-3). A casing with diameter 139.7/123.7 mm and a casing shoe was mounted to 6.15 m. With the Boyles B20, NQ core drilling and reaming to 113 mm to 11.96 m was performed, after which grouting of the 90/77 mm stainless steel casing was made. The soil cover has 2.44 metres vertical depth from ground surface.

5.3.2 Core drilling 6.15–450.02 m KFM01C

The core drilling progress during the period from November 5th to November 29th, 2005, is presented in Figures 5-3 and 5-4.

Drilling of traditional cored boreholes in highly fractured rock often causes water loss, meaning that the flushing water and drilling debris are pressed into the permeable part of the rock. During core recovery, when the inner tube is winched up, a decreased water pressure is induced, causing the drilling debris and flushing water to recharge into the borehole. It is often difficult to resume drilling, as drilling debris can clog the drill bit channels and prevent efficient cooling of the bit. However, it seems that the rock conditions at DS1 is an exception. Perhaps the upper part of the bedrock is so fractured that the major part of drilling debris remained in the rock formation as no drilling problems occurred. As the borehole was aimed to penetrate fracture zone ZFMENE0060A, the core displays a higher average fracture frequency than usual. Presumably permeable, fractured rock does not wear out drill bits as quickly as more homogeneous rock, which resulted in an average lifetime of drill bits of 72.7 drilled metres per drill bit, which is the longest lifetime achieved so far at Forsmark, e.g. it is c. 44 m longer compared to drilling of the nearby borehole KFM01A.

Generally, in an inclined borehole there is a higher risk of outfall from the borehole wall. In KFM01C, an obstacle was often noticed when the drill rods passed a section at c. 85 metres drilling length. After completion of drilling at 450.02 m, a decision was made to stabilize the borehole wall with a perforated steel plate, see Section 5.4.8.



1* In January 2006 an Onram 1000 drilling rig cleaned the borehole. 2* Flexit measurement.

Figure 5-3. Overview of the performance of borehole KFM01C.

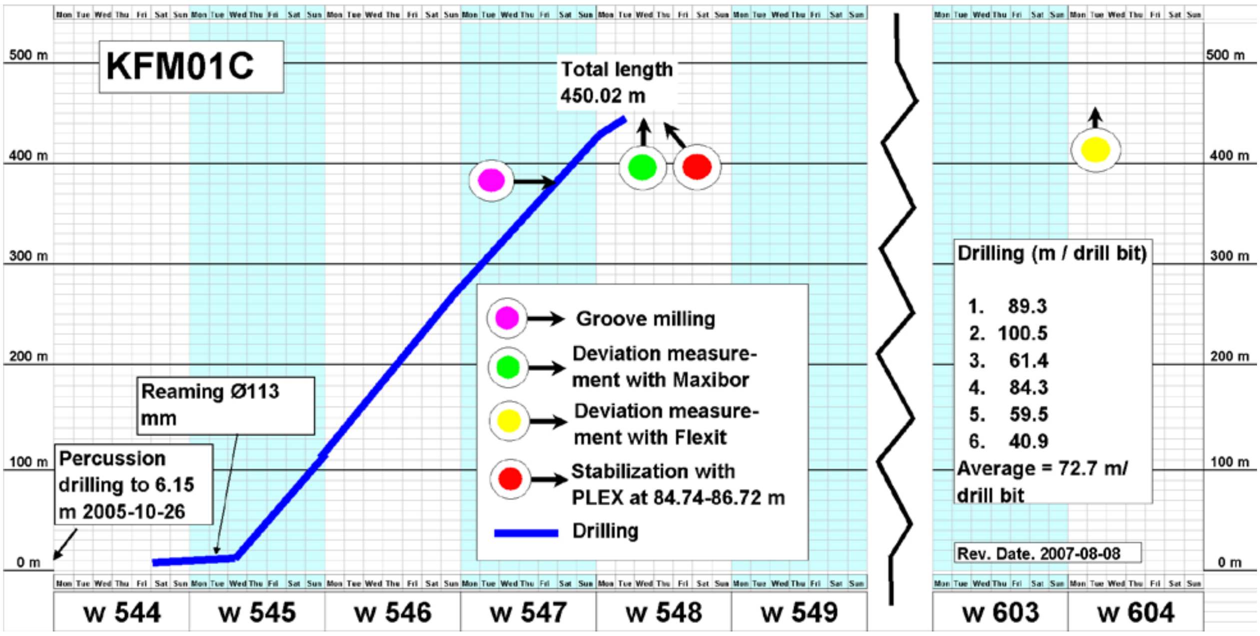


Figure 5-4. *Core drilling progress versus calendar time KFM01C. The diagram also includes logistics for deviation measurement with two methods, groove milling and stabilization of the borehole, as well as number of drill bits used.*

5.4 Measurements while drilling

During and immediately after drilling, a program for sampling and measurements was applied cf. Section 4.4.2. The results are presented in Sections 5.4.1–5.4.7 below.

5.4.1 Core sampling

A preliminary on-site core logging was performed continuously in connection with the drilling.

5.4.2 Flushing water and return water flow parameters – water balance

Flushing water and return water flow rate measurements – water balance

The accumulated volumes of flushing water and return water is illustrated in the histogram in Figure 5-5, from which the return water/flushing water quotient for the drilling period may be calculated, in this resulting in very low quotient 0.27 for KFM01C.

Uranine contents of flushing water and return water

An organic tracer, Uranine, was automatically added to the flush water tank, see Section 3.3.2. During the second half of the drilling period, sampling of flushing water and return water for analysis of the tracer contents was performed systematically with a frequency of approximately one sample per 20 m drilling length, see Figure 5-6. According to the logging book, 60 g Uranine was added to the borehole. The diagram in Figure 5-6 indicates that a large share of the Uranine is remaining in the formation after completed drilling.

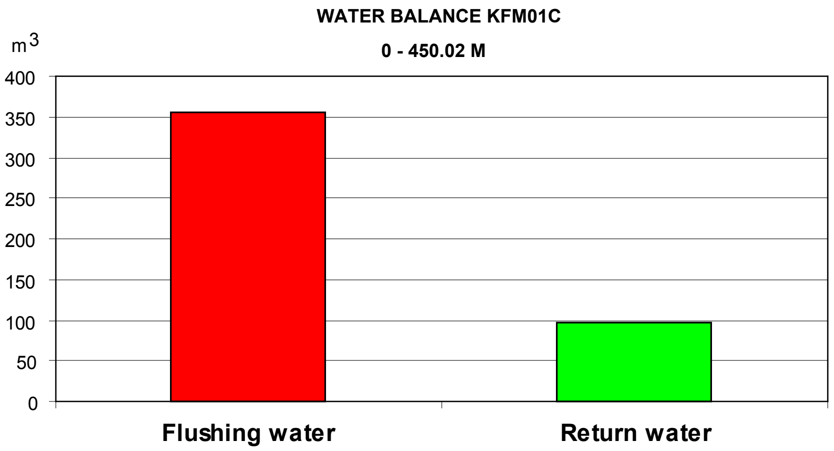


Figure 5-5. Total amounts of flushing water and return water during drilling of borehole KFM01C. The total volume of flushing water used during core drilling amounted to 355 m³. During the same period, the total volume of return water was 97 m³. The return water/flushing water balance is then 0.27, i.e. far below 1.0 due to major flushing water loss in the shallow sections of increased fracturing.

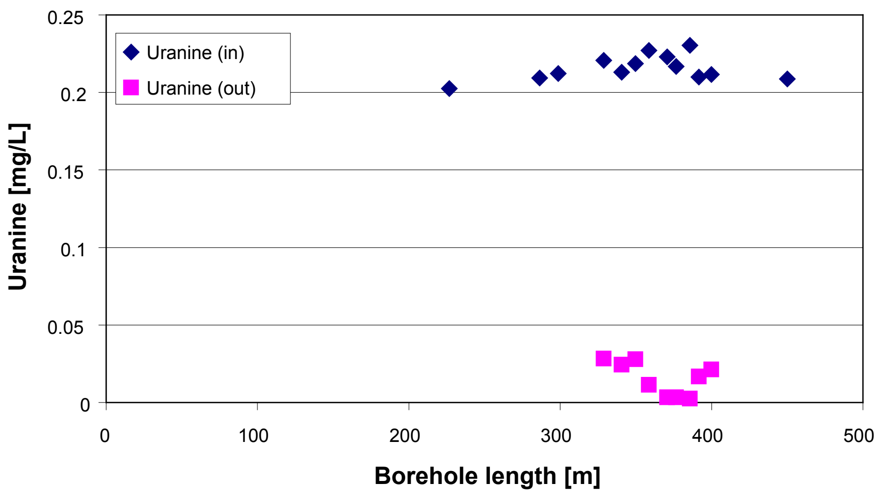


Figure 5-6. Uranine contents in the flushing water consumed and the return water recovered versus drilling length during drilling of borehole KFM01C. An automatic dosing equipment, controlled by a flow meter, accomplished the labelling with Uranine.

5.4.3 Deviation measurements in KFM01C

The principles of the equipment for deviation measurements were explained in Section 3.3.5. 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 KFM01C. When Maxibor™ measurements or deviation measurements with some other method have been performed as well, these may be used for uncertainty determinations of the deviation measurements.

The quality control program of deviation measurements is mostly concentrated to the handling of the instrument as well as 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. To ensure high quality measurements with the Flexit tool, the disturbances of the magnetic field must be low. In Uppsala, a measuring station provides one-minute magnetic field values that are available on the Internet at www.intermagnet.org and gives sufficient information. The magnetic field variation during January 24th, 2006, is seen in Figure 5-7 and shows only minor disturbances when the Flexit survey in KFM01C was performed.

In the following a systematic description of the construction of the revised deviation data for borehole KFM01C is given.

The data used are one complete Reflex Maxibor™-logging and two Flexit-loggings to 448 m borehole length, see Table 5-2. With the Flexit Smart Tool System, deviation measurements in borehole KFM01C were carried out every 3 m downwards and every 30 m upwards. These two surveys, with activity identities 13132007 and 131320006, respectively, provided almost repeatable results, and were therefore chosen for the construction of the deviation file to be "in use displayed" in Sicada (see explanation in Section 3.3.5). This file is designated EG154.

Table 5-2. Activity data for the three deviation measurements approved for KFM01C. The two magnetic measurements were used for calculation of a final borehole deviation, whereas all three measurements were used for calculation of the deviation uncertainty.

Activity Id	Activity type code	Activity	Start Date	Idcode	Secup (m)	Seclow (m)	Flags*
13132007	EG157	Magnetic – accelerometer measurement	2006-01-24 12:15:00	KFM01C	15.00	448.00	CF
13132006	EG157	Magnetic – accelerometer measurement	2006-01-24 13:55:00	KFM01C	18.00	448.00	CF
13110835	EG156	Maxibor measurement	2005-11-30 00:00:00	KFM01C	0.00	447.00	
13140599	EG154	Borehole deviation multiple measurements	2006-12-14 08:00:00	KFM01C			IC

* C = Comment, F = File, I = In-use flag.

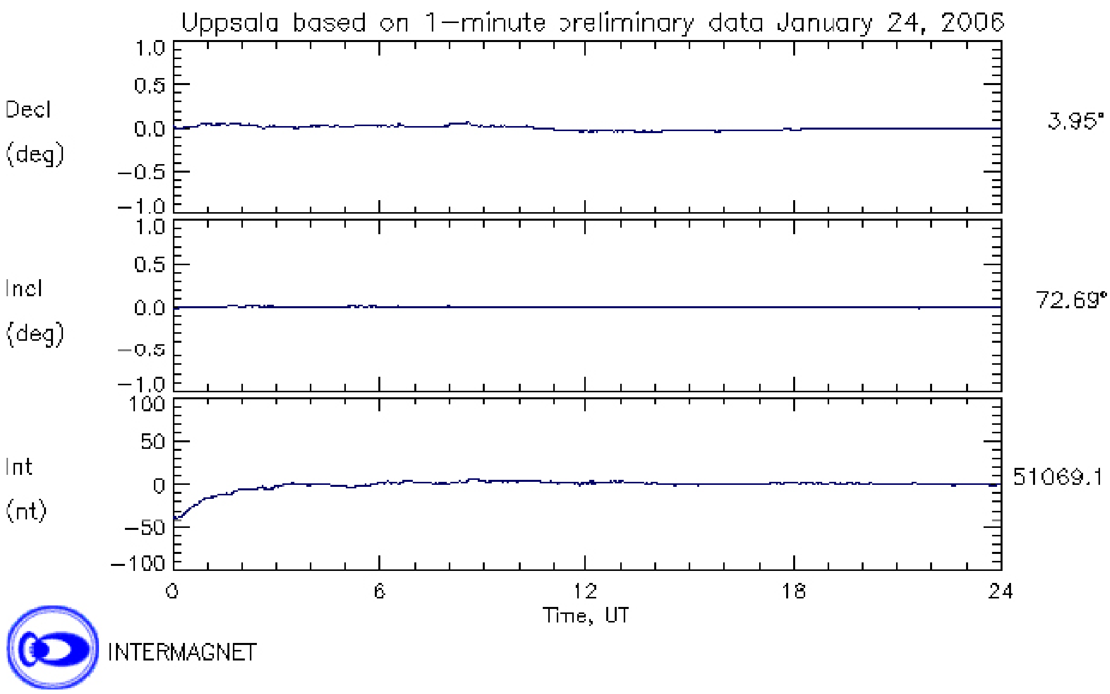


Figure 5-7. *Magnetic field variation during the Flexit survey performed on January 24th, 2006.*

The EG154-activity specifying the deviation measurements used in the resulting calculation is presented in Table 5-3. The upper sections for bearing start at 15 m and 18 m so that the values (measured with magnetic method) should not be influenced by the 9 m steel casing.

The calculated deviation (EG154-file) in borehole KFM01C shows that the borehole deviates slightly upwards but is laterally almost straight with an absolute deviation of only 11.4 m compared to an imagined straight line following the dip and strike of the borehole start point (Figure 5-8). 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.

A subset of data from the resulting deviation file together with estimated inclination-, bearing- and radius uncertainties are presented in Table 5-4. The radius uncertainty is at every point in the borehole represented by a circle surrounding the hole. The radius of this circle = radius uncertainty in that point.

5.4.4 Measurements of the length difference between the compressed drilling pipe string and as extended by its own weight

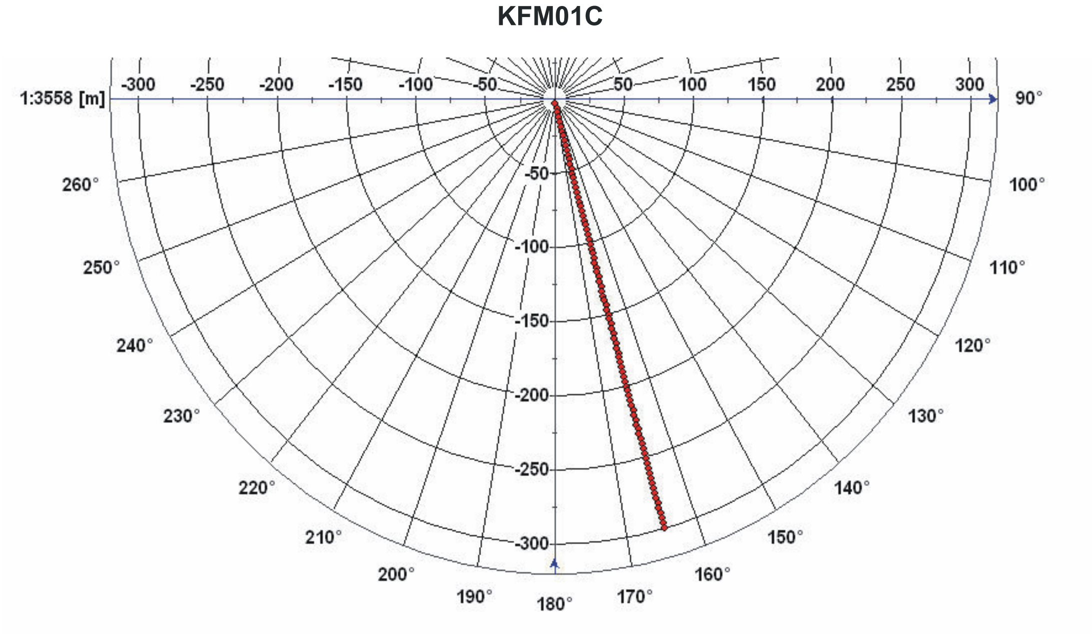
All length values used for measurements in the borehole and of the drill core originate from registrations of the length of the drill pipe string. However, such registrations involve a small error depending on the gravitational stretching of the pipe string when hanging freely and thus exposed to its own weight. When the pipe string is lowered to the borehole bottom, and the lifting force from the drill rig is set to zero, the pipe string will be resting on the borehole bottom and thus relieved from the previous load, and the stretching will cease. Instead, the load from the pipe string will now cause compression, and to some extent bending of it.

Table 5-3. Contents of the EG154 file (multiple borehole deviation intervals) from KFM01C.

Idcode	Deviation activity Id	Deviation angle type	Approved secup (m)	Approved seclow (m)
KFM01C	13132006	BEARING	18.00	448.00
KFM01C	13132006	INCLINATION	18.00	448.00
KFM01C	13132007	BEARING	15.00	448.00
KFM01C	13132007	INCLINATION	15.00	448.00

Table 5-4. Deviation data from KFM01C at every approximately 100 m vertical length calculated from EG154. Inclination-, bearing- and radius uncertainty values are also included.

Borehole	Northing (m)	Easting (m)	Length (m)	Elev. (m)	Elev. Uncert.	Incl.	Bearing	Incl. Uncert.	Bearing Uncert.	Radius Uncert.
KFM01C	6699526.14	1631403.75	2.91	0	0	–49.61	165.35	0.136	0.414	0
KFM01C	6699441.02	1631426.18	–99.44	135	0.21	–49.06	164.18	0.136	0.414	0.635
KFM01C	6699355.17	1631449.82	–200.91	270	0.42	–48.09	164.73	0.136	0.414	1.278
KFM01C	6699267.24	1631474.48	–300.33	405	0.64	–46.13	164.54	0.136	0.414	1.937
KFM01C	6699237.16	1631483.03	–332.70	450.02	0.71	–45.87	164.53	0.136	0.414	2.163



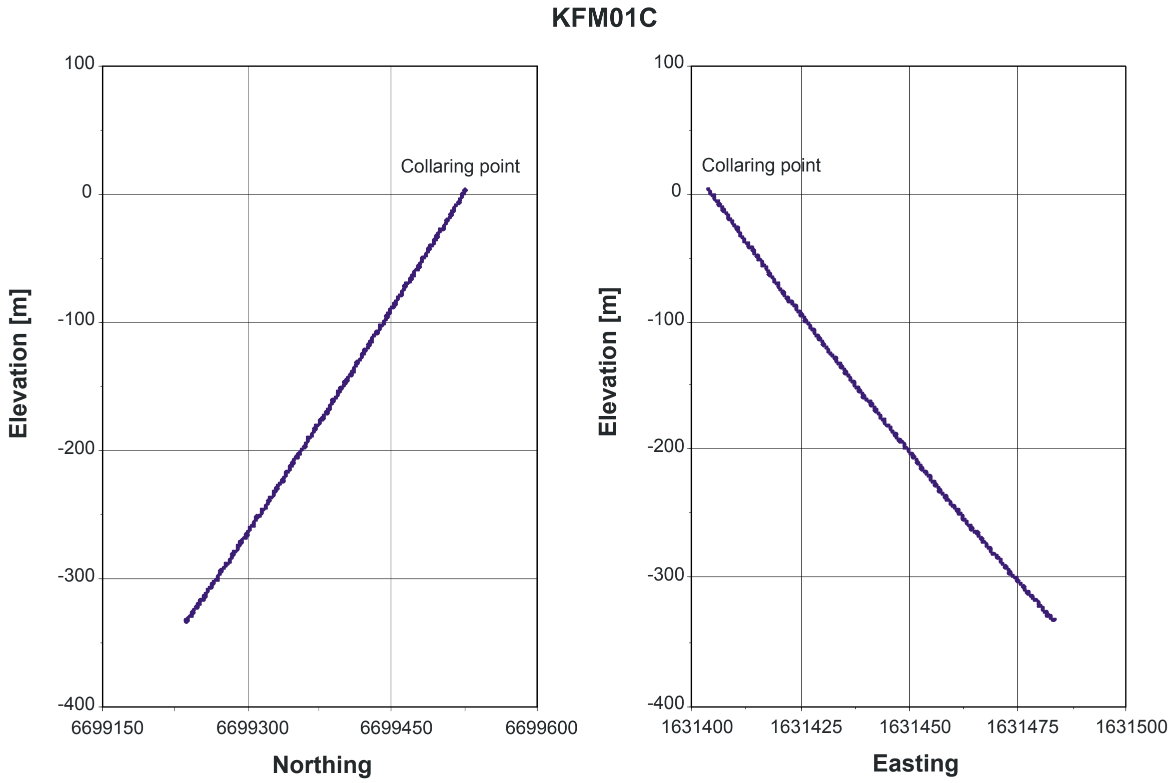


Figure 5-8. *Upper figure is a horizontal projection and lower figures are vertical projections of the in use-flagged deviation data from KFM01C.*

By measuring the length difference between these two conditions, it was hoped that the length error could be determined for different lengths of the pipe string and for different inclinations of the borehole. The practical difficulties and uncertainties in the results however turned out to be considerable. Therefore it is recommended that the length error is determined from the diagram in Figure 5-9, which is based on load tests performed in the laboratory by the manufacturer of the drill pipes.

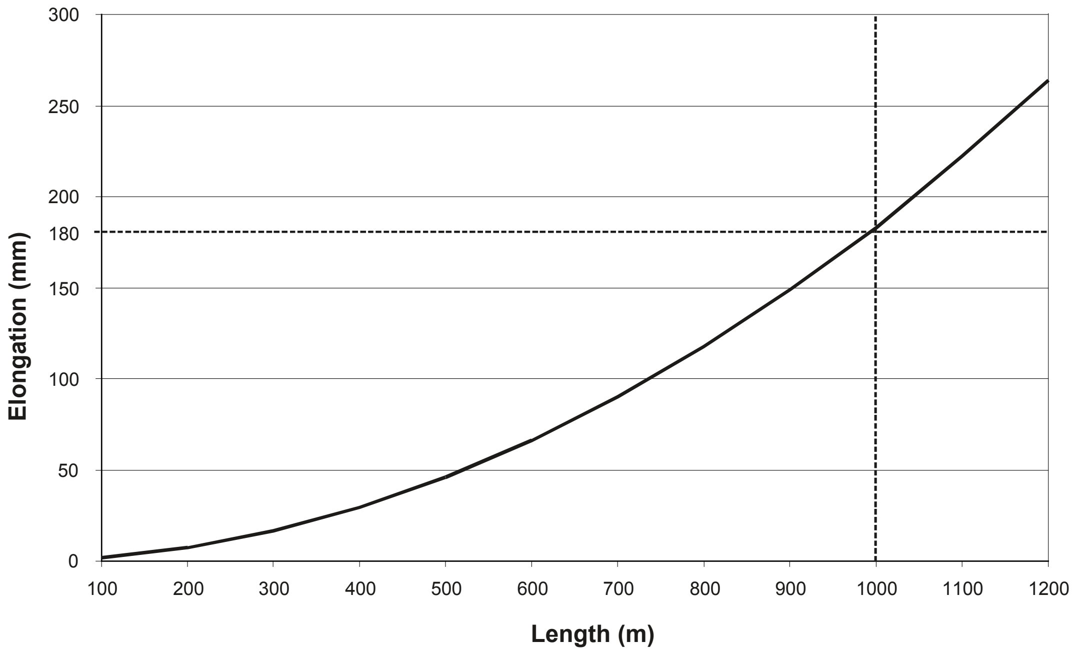


Figure 5-9. *The diagram illustrates the elongation of the WL-76 drill pipe string when hanging in a vertical water filled borehole. Values from laboratory load tests of the drill pipes.*

As seen in the diagram, the maximum elongation at 1,000 m length in a vertically drilled borehole is 180 mm. In inclined boreholes the elongation of the pipe string should theoretically be less.

5.4.5 Groove milling

A compilation of length to the reference grooves and a comment on the success of detecting the grooves are given in Table 5-5. The positions of the grooves are determined from the length of the drill pipes used at the milling process. The length is measured from the upper part of the upper two grooves.

5.4.6 Consumables

The amounts of oil products consumed and thread grease used during core drilling of KFM01C are reported in Table 5-6.

Table 5-5. Compilation of length to the reference grooves. 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.

Reference groove at (m)	Detection with the SKB level indicator	Confirmed from BIPS
51.00	Yes	Yes
100.00	Yes	Yes
150.00	Yes	Yes
200.00	Yes	Yes
252.00	Yes	Yes
299.00	Yes	Yes
350.00	Yes	Yes
400.00	Yes	Yes

Table 5-6. Oil and grease consumption during core drilling of KFM01C.

Borehole ID	Thread grease Unisilikon L50/2	Grease for the drilling machine Castrol AB	Engine oil Castrol Tection 15W-40	Hydraulic oil Premium ECO HT-E 46	Engine diesel OKQ8 Diesel miljöklass 1
KFM01C	1.2 kg	0.8 kg	No consumption measured	No consumption measured	No consumption measured

The special type of thread grease (silicon based) used during core drilling in this particular borehole was certified according to SKB MD 600.006 (Table 1-1). The experience from a technical point of view of the grease is not fully satisfactory. Although expensive, the grease has a low adhesion capacity to the threads, and the lubrication characteristics are not as favorable as for conventional lubricants.

Cement consumption for sealing the gap between the casing and the borehole wall is reported in Table 5-7.

5.4.7 Stabilization of KFM01C

Ensuing completion of drilling of a borehole at the site investigation, an extensive borehole measurement programme is conducted. During drilling of KFM01C, when the drill string was moved up- and downwards, indications of instability were observed as the rods often hooked at c. 85 m. The drill core from this interval with surroundings is shown in Figure 5-10. It was decided to stabilize this part of the borehole to ensure that the planned borehole measurement programme could be performed in KFM01C.

The stabilization system selected was the so called Plex-system described in Section 3.3.6. The following sequence of actions were taken (cf. Figures 3-8 and 5-11):

- The instable section between 83.94–86.08 m was reamed to 84 mm.
- The Plex tool supplied with one perforated stainless steel plate was attached to the drill pipe string and lowered into the borehole.
- The packer was inflated with an excess pressure of between 60–70 bars whereby the perforated stainless steel plate was forced into the reamed part of the borehole wall.
- The packer was deflated whereupon the tool was retrieved from the borehole.

After the Plex operation, the entire borehole was logged with the BIPS-camera, see Figure 5-11. The video images show that the perforated plate is mounted with an overlap of the lower part of the reamed section and 0.64 m of the traditional borehole. Unfortunately, the plate must have got caught and followed the Plex-tool during the movement downwards and in this way been mounted in the section between 84.74– 86.72 m.

After the Plex stabilization, the borehole measurement programme has been possible to perform, although the lower part of the stabilized section (between 86.08 m and 86.72 m) is narrow (Ø 75.3 mm), making it difficult for some borehole instruments to pass through. Because the steel plate is perforated, it was also possible to perform hydraulic tests in the entire borehole.

Table 5-7. Cement consumption for grouting the percussion drilled part of KFM01C and for sealing the gap between the casing and the reamed borehole wall.

Borehole ID	Length (m)	Cement volume Aalborg Portland Cement/microsilica	Grouting method	Remarks
KFM01C	0–11.96 m	150 kg/66 kg	Hose	Gap injection

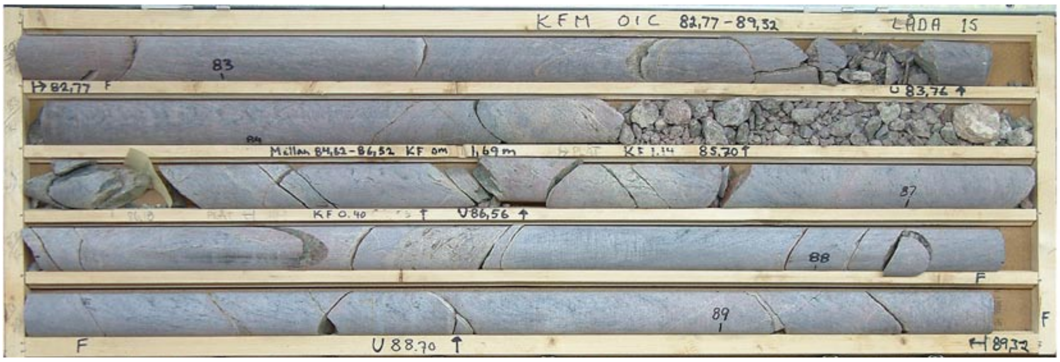


Figure 5-10. Drill core from instable section in borehole KFM01C.

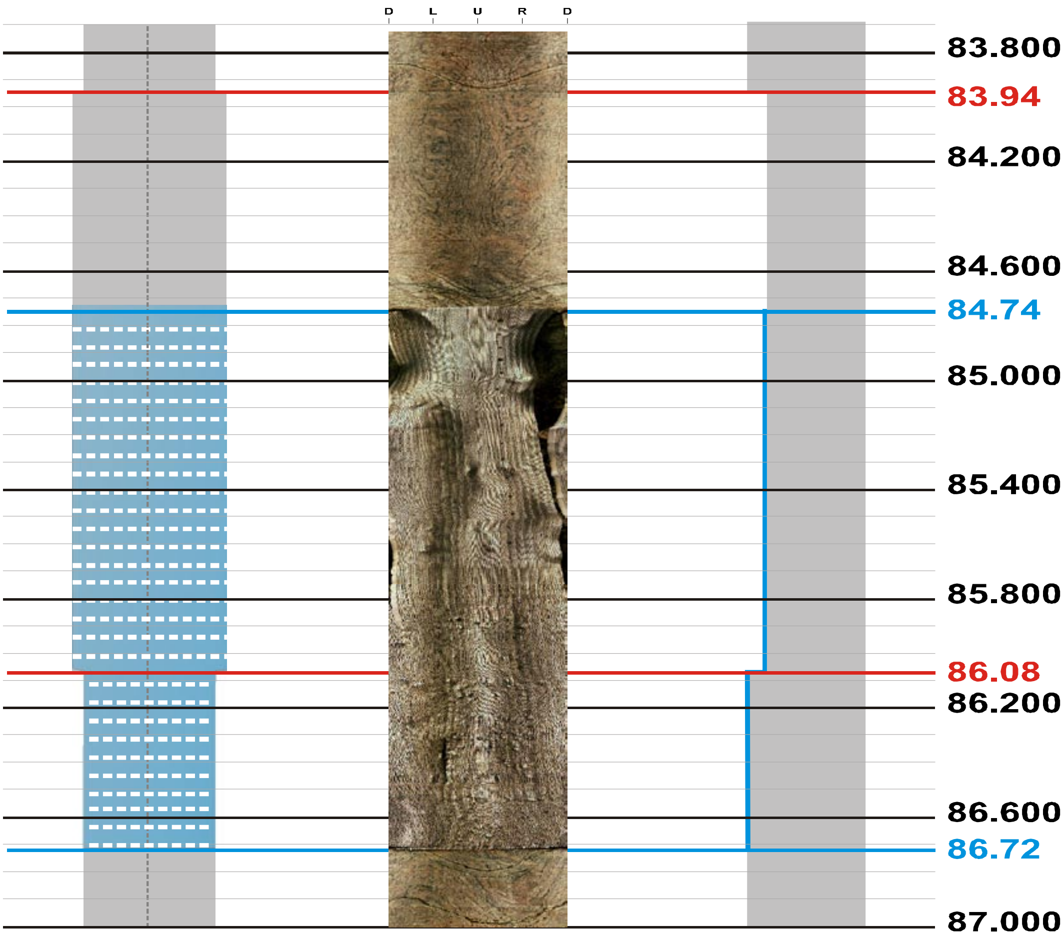


Figure 5-11. Schematic figure of the stabilized section in borehole KFM01C with BIPS images of the borehole section after stabilization with the Plex system.

5.5 Additional work in KFM01C

After the activities during drilling were completed, the detector used for indication of the grooves milled into the borehole wall was obstructed around c. 208 m, and the instrument could not be lowered further. An Onram1000 drilling machine was established in the middle of January, 2006, on the drill site for cleaning the borehole. The stop was probably caused by a minor outfall of rock fragments from the stabilized zone at c. 85 m. The problematic interval could be penetrated just by slowly descending the drill rods during simultaneous flushing and rotation. However, the last two metres of the borehole were probably saturated with fine drilling debris, as the channels of the drill bit were clogged, which prevented efficient cooling and flushing. At 448.30 m drilling length it was no longer possible to continue. After finishing the cleaning operation, the borehole was logged with a “dummy” to ensure that no problems still remained. The dummy logging was successful resulting in that the activities could proceed according to the programme.

5.6 Geometrical data and technical design of borehole KFM01D

Administrative, geometric and technical data for the telescopic borehole KFM01D are presented in Table 5-8. The technical design of the borehole is displayed in Figure 5-12.

Table 5-8. Administrative, geometric and technical data for borehole KFM01D.

Parameter	
Borehole name	KFM01D
Location	Forsmark, Östhammar municipality, Sweden
Drill start date	November 22, 2005
Completion date	February 18, 2006
Percussion drilling period	2005-11-22 to 2005-12-05 (0–89.77 m)
Core drilling period	2005-12-17 to 2006-02-18 (89.77–800.24 m)
Contractor core drilling	Drillcon Core AB
Core drill rig	Atlas Copco Craelius B20
Sub contractor percussion drilling	Sven Andersson i Uppsala AB
Percussion drill rig	Puntel MX 1000
Position KFM01D at top of casing (RT90 2.5 gon V 0:–15 / RHB 70)	N 6699542.07 E 1631404.52 Z 2.95 (m.a.s.l.)
	Azimuth (0–360°): 35.03° Dip (0–90°): –54.90°
Position KFM01D at bottom of hole (RT90 2.5 gon V 0:–15 / RHB 70)	N 6699967.75 E 1631684.15 Z –612.48 (m.a.s.l.)
	Azimuth (0–360°): 31.17° Dip (0–90°): –45.09°
Soil depth	5.99 m
Borehole length	800.24 m
Borehole diameter and length	From 0 m to 11.61 m: 339 mm
	From 11.61 m to 89.72 m: 245 mm
	From 89.72 to 89.77 m: 160 mm
	From 89.77 m to 91.48 m: 86 mm
	From 91.48 m to 800.24 m: 75.8 mm
Casing diameter and length	Øo/Øi = 323.9/309.7 mm 0 to 11.61 m
	Øo/Øi = 208.0/200.0 mm 0 m to 89.72 m
Transitional cone	86.42–91.43 m
Drill core dimension	89.77–91.48 m/Ø 72 mm
	91.48–800.24 m/Ø 51 mm
Core interval	89.77–800.24 m
Average length of core recovery	2.69 m
Number of runs	264
Diamond bits used	19
Average bit life	37.2 m

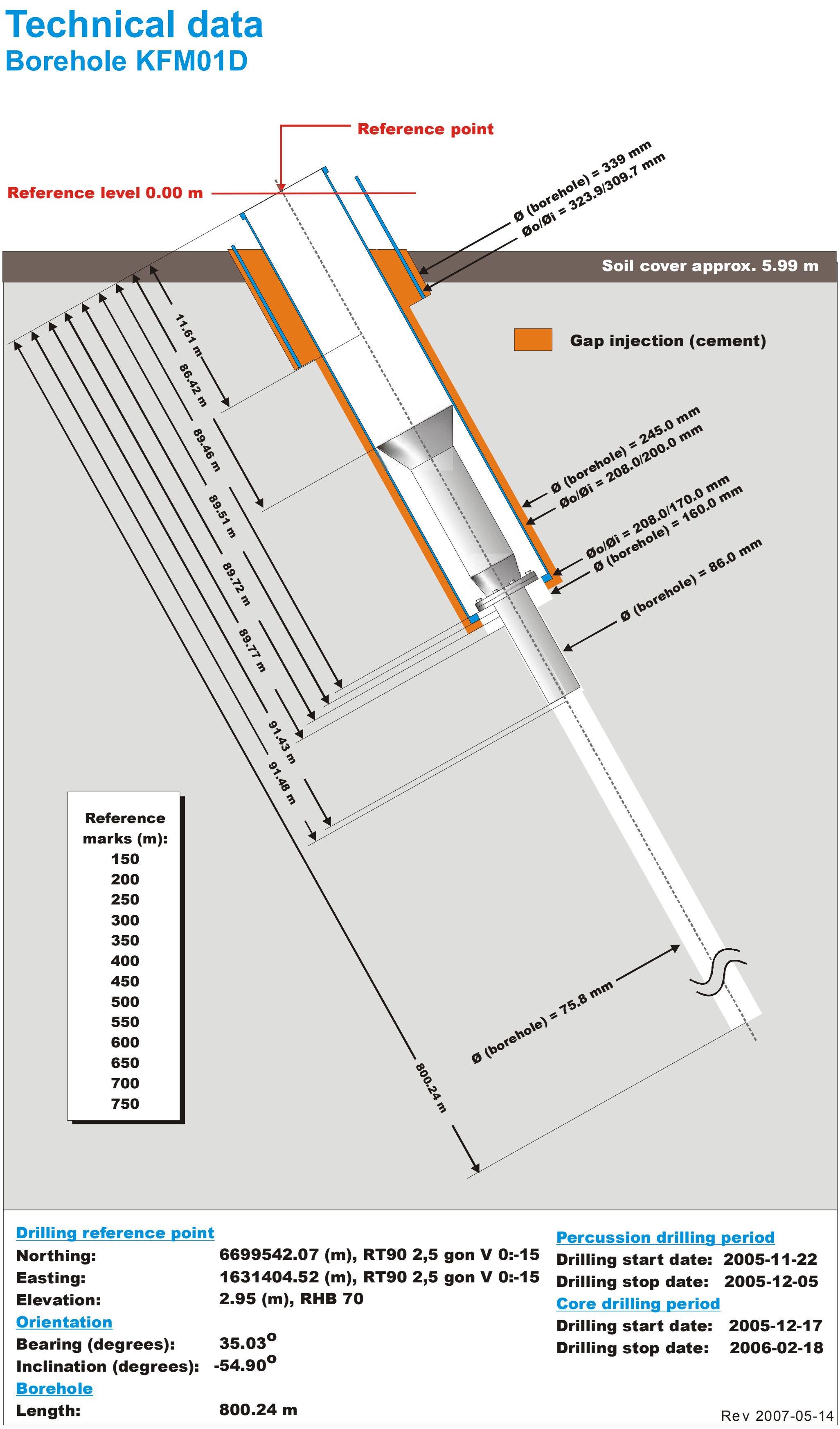


Figure 5-12. *Technical data of borehole KFM01D.*

5.7 Drilling KFM01D

Borehole KFM01D was drilled during a period of one month and a half (Figure 5-13).

5.7.1 Percussion drilling 0–89.77 m KFM01D

Drilling period

The percussion drilling was conducted during Nov 22nd to Dec 5th, 2005, see Figure 5-14, with a Puntel MX 1000 percussion drill rig. The soil and the uppermost part of the bedrock was drilled with NO-X 115 down to 11.61 m. After gap injection, drilling continued to 89.77 m, and finally the hole was reamed to Ø 245 mm to 89.72 m.

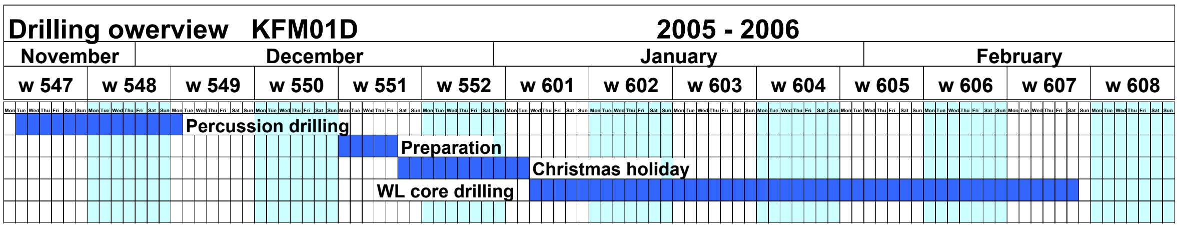


Figure 5-13. Overview of the drilling performance of borehole KFM01D.

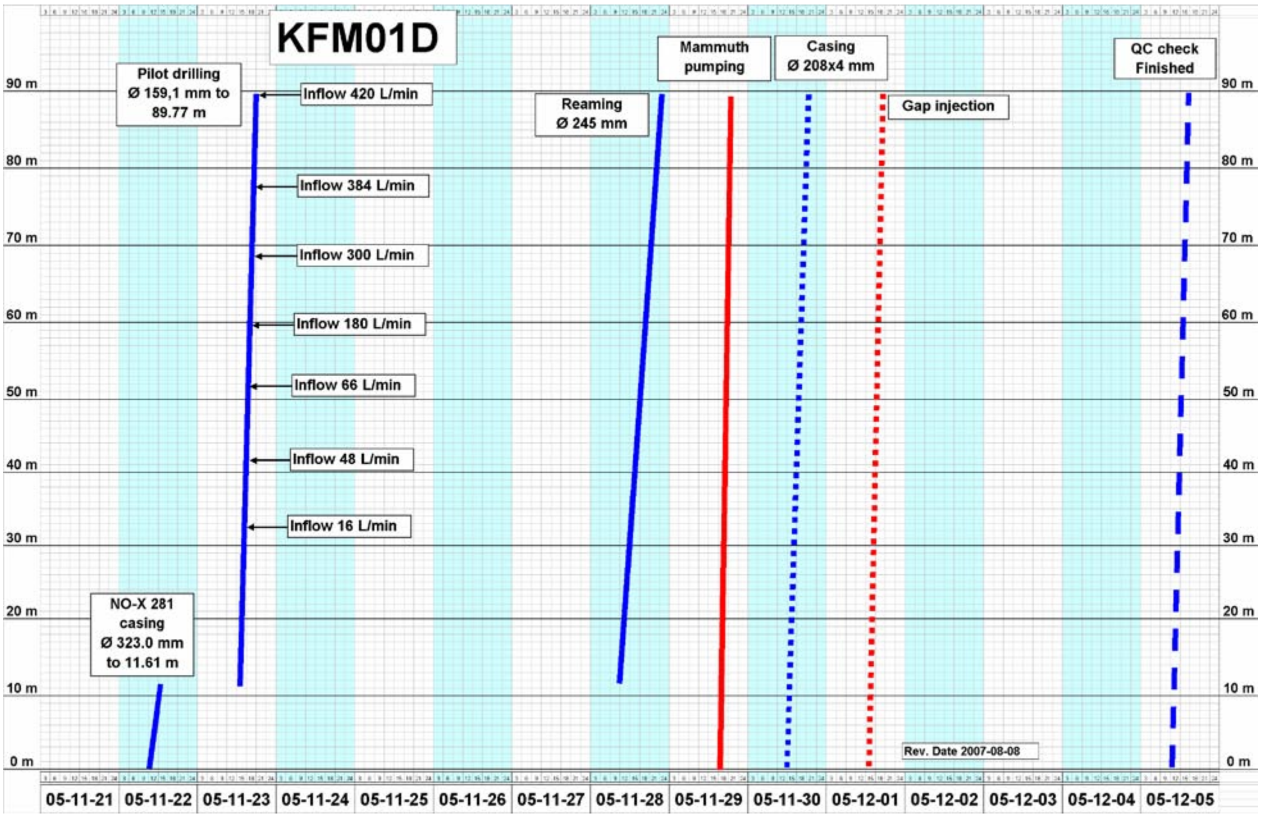


Figure 5-14. Percussion drilling progress versus calendar time for borehole KFM01D.

Drilling performance

As mentioned in Section 4.5.1, the upper part of of the borehole, to 11.16 m, was drilled and cased applying NO-X 280. During pilot drilling an unstable section with increased fracturing and large water inflow measuring 420 L/min was encountered at 68 m length. The fracturing is also in line with the results from the percussion drilled part of KFM01A as well as the results from the traditional core drilled boreholes KFM01B and KFM01C. Borehole KFM01D was extended to 89.77 m and, after reaming to 245.0 mm, cased with a 200/208 mm stainless steel casing to 89.72 m. Finally the gap between the casing and the borehole wall was cement grouted, so that the water inflow ceased completely.

5.7.2 Core drilling 89.77–800.24 KFM01D

Drilling period

After the percussion period drilling, establishing of an Atlas Copco B20 drill rig started, see Figure 5-15. At first NQ was drilled for the support casing used during core drilling of telescopic boreholes (see Section 3.3.2).

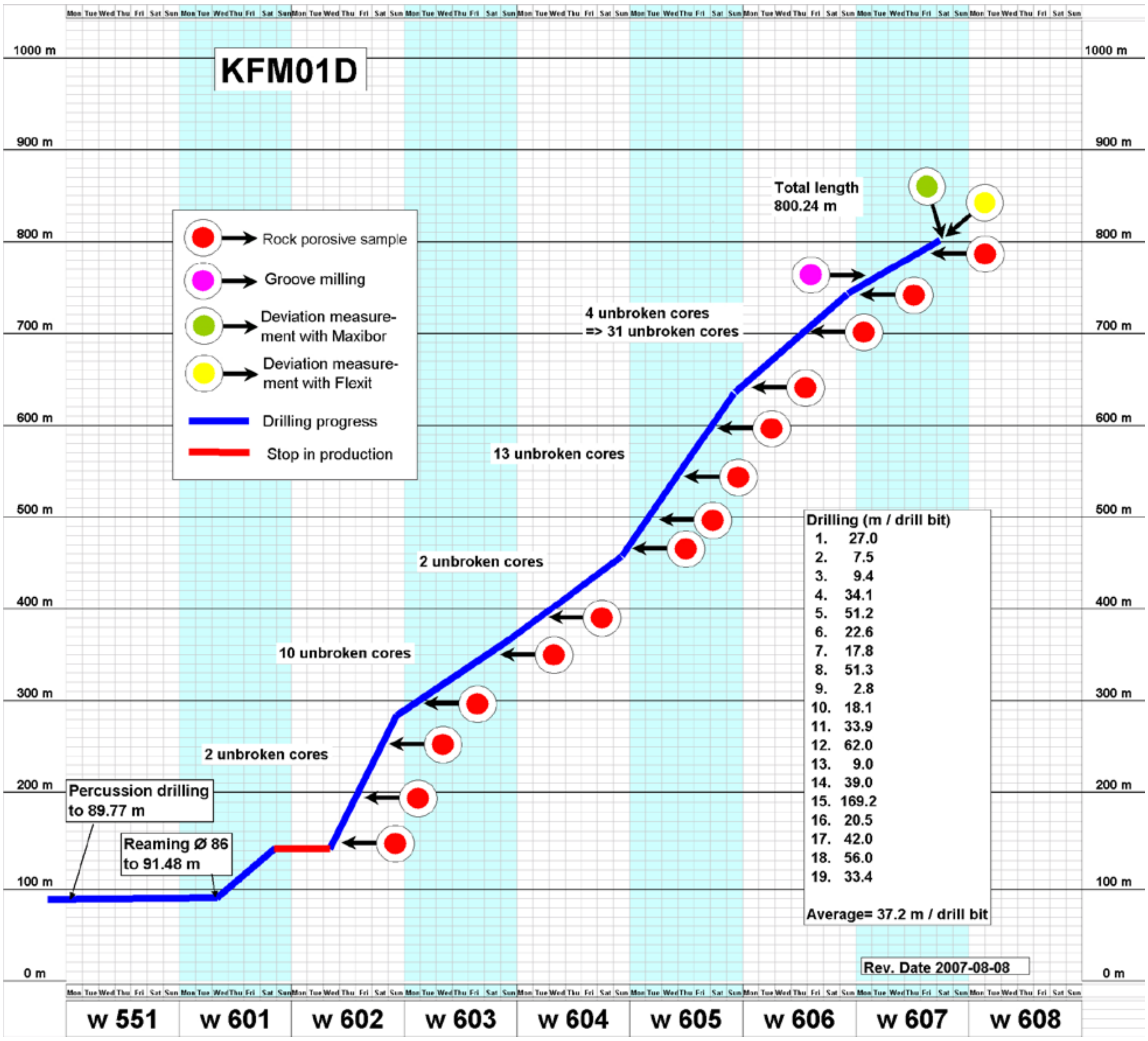


Figure 5-15. Core drilling progress versus calendar time for borehole KFM01D. The figure includes logistics for WL-drilling, groove milling, Maxibor- and Flexit deviation measurements and rock pore sampling, as well as number of unbroken cores and drill bits used.

Drilling performance

The bedrock within the so called Forsmark tectonic lens has appeared to be hard to drill, probably to a large extent depending on a high quartz contents. The bedrock at DS1, being located in the centre of the tectonic lens, is typical for this kind of resistant-to drilling type of rock, and the average life-time of drill bits when drilling KFM01D was only 37.2 m per bit, which however is slightly better than 27 m obtained when drilling KFM01A. This improvement may be due to a positive quality trend for developing drill bits since drilling of KFM01A early in 2002. It may also be interesting to compare with the drill bit lifetime 72.7 m obtained during drilling of KFM01C, which is twice as good as the result from KFM01D. This might be explained by the higher degree of fracturing of the bedrock penetrated by KFM01C, cf. Section 5.3.2.

5.8 Measurements while drilling

Core drilling of KFM01D was associated with a programme for sampling, measurements and other activities during and immediately after drilling as mentioned in Section 4.5.2. The results are presented below.

5.8.1 Registration of drilling parameters

A selection of results from drilling parameter registration is presented in diagrams below. As regards the complete dataset of drilling parameters, it is referred to Sicada, were data are traceable by the activity plan number.

Drill bit position versus time

Figure 5-16 illustrates how drilling proceeded versus time. Usually, the drilling in Forsmark has been carried out with seven shifts per week. During drilling of KFM01D the drilling pace was increased, and drilling was performed 24 hours a day from Monday to Thursday, extended with extra day-shifts from Friday morning to Sunday night.

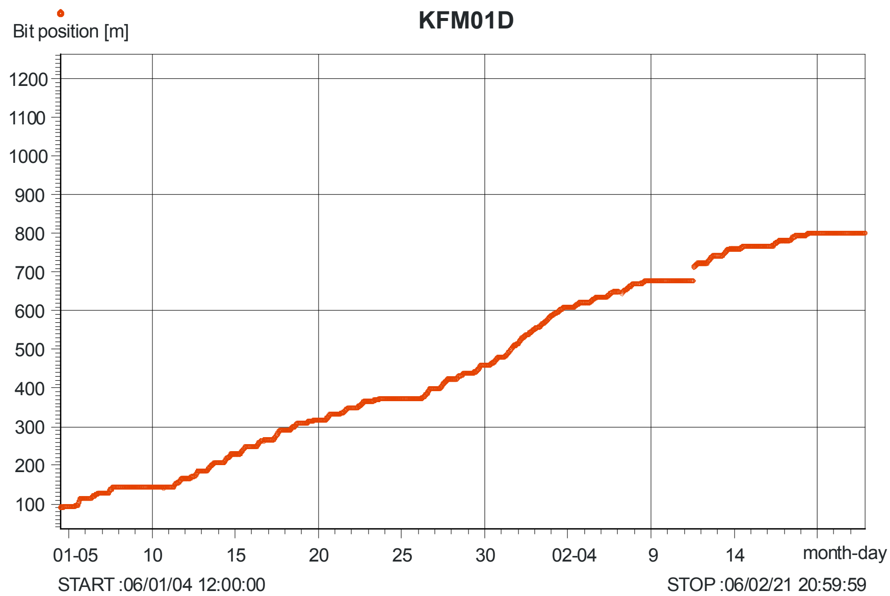


Figure 5-16. *Drill bit position in KFM01D versus time.*

Penetration rate

The penetration rate, see Figure 5-17, was in average almost the same as during drilling of KFM01A. Initially, the penetration rate started with 15 cm/min, but fell successively back to c. 11–12 cm/min, corresponding to increasing frictional resistance of return water flow, which is discharged via the narrow gap between the borehole wall and the pipe string.

5.8.2 Flushing water ande return water parameters

Flushing water and return water flow rate measurements – water balance

As borehole KFM01D is of SKB chemical type, it is important to estimate the amount of flushing water pumped into the borehole during drilling as well as the amount of return water recovered, to permit a water balance calculation. A flow gauge in the measurement station registered the flushing water flow rate, see Figure 3-3. The return water was measured by another flow meter, mounted on-line with the discharge pipe line, see Figures 3-3 and 3-6.

However, the return water is normally a mixture of flushing water and groundwater from the formation penetrated by the borehole. In order to estimate the amount of remaining flushing water in the formation and in the borehole after drilling, one must also study the contents of the Uranine tracer dye in the flushing water and return water. This enables a mass balance calculation from which the flushing water contents in the borehole can be determined.

Figure 5-18 illustrates the accumulated volume of flushing water and return water versus time during core drilling, whereas Figure 5-19 displays the accumulated volumes of flushing water and return water from the entire drilling period, giving a return/flushing water quotient of 1.40 [1,080/772] (results from the Uranine measurements are presented in the next section).

However, in Figure 5-19 a loss of flushing water at shallow depths in the borehole is observed as well as significant excess of return water at depths exceeding c. 200 m. This reflects the fact that when the drill bit position is close to water conductive fractures in the borehole, flushing water is forced into these fractures, because the flushing water pressure much exceeds that of the groundwater in the formation. When the drill bit has passed this section, the pressure gradient will eventually be reversed due to the air-lift pumping in the upper part of the borehole. If no other highly water conductive fractures are penetrated, where flushing water losses may occur, larger amounts of return water (groundwater and flushing water) are then extracted from the borehole than flushing water is supplied to it.

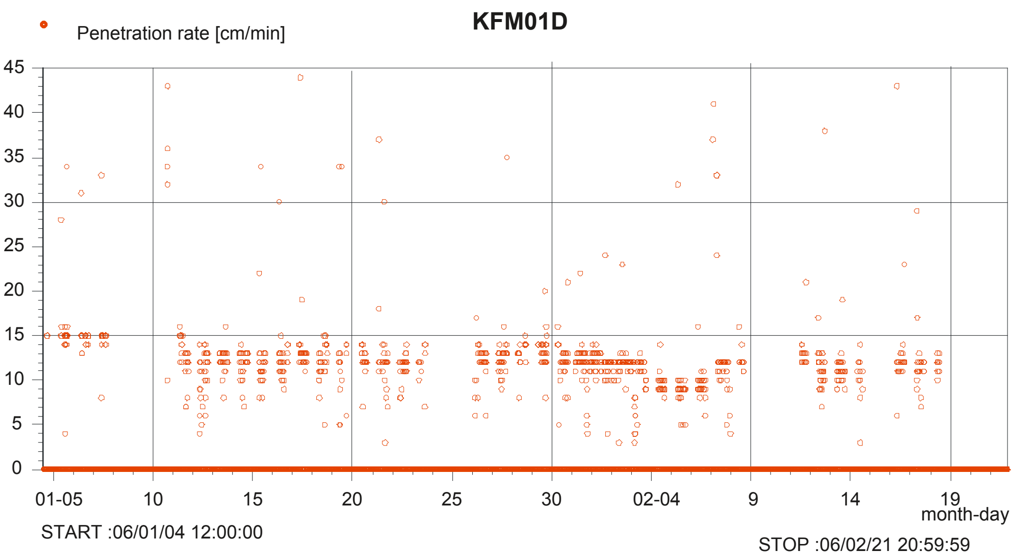


Figure 5-17. *Penetration rate during core drilling of KFM01D.*

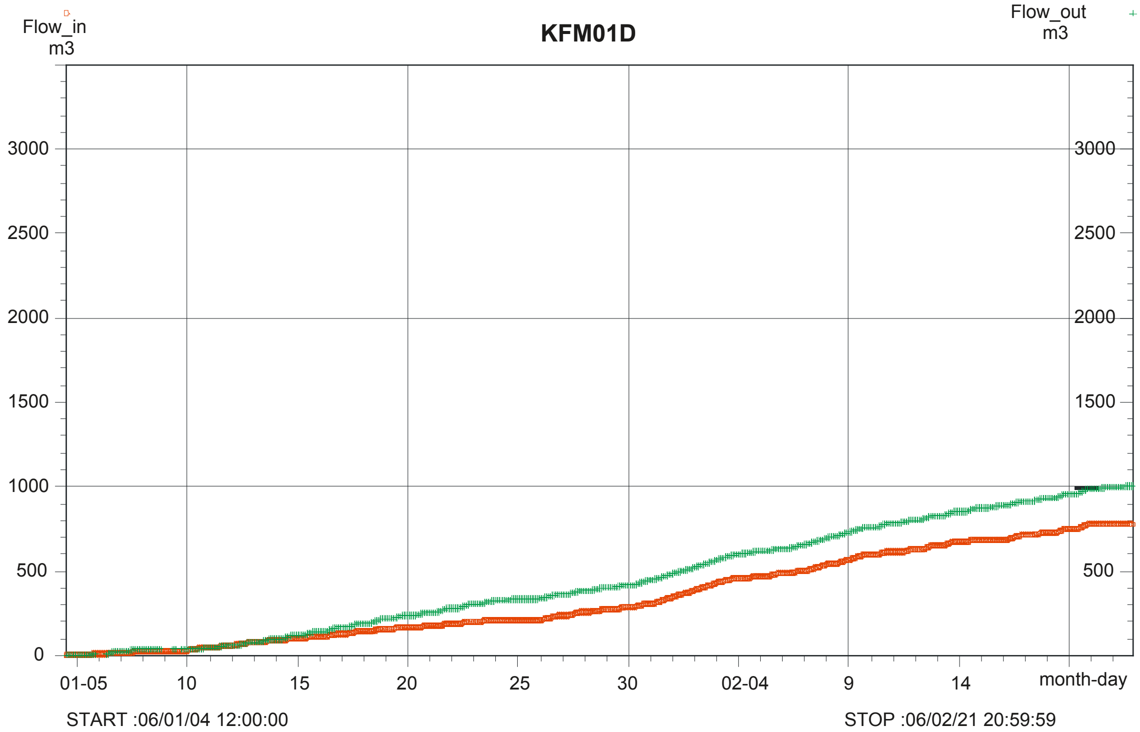


Figure 5-18. *Accumulated volumes of flushing water (red) and return water (green) versus time during core drilling of borehole KFM01D.*

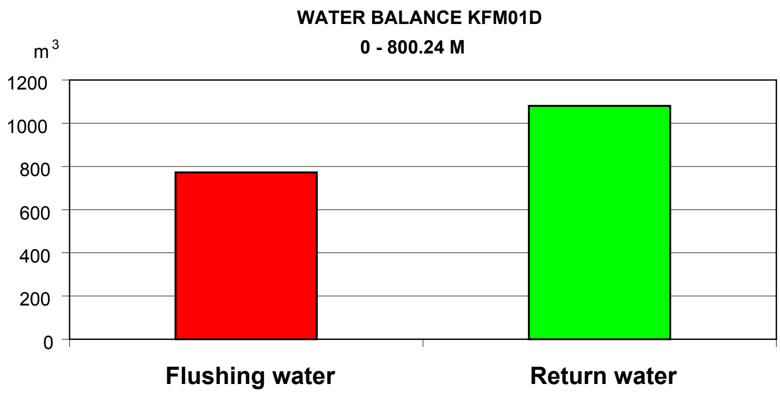


Figure 5-19. *Total amounts of flushing water and return water during drilling of borehole KFM01D. The total volume of flushing water used during core drilling amounted to 772 m³. During the same period, the total volume of return water was 1,080 m³, which results in a return water/flushing water balance of 1.40.*

Uranine contents of flushing water and return water – mass balance

During the drilling period, sampling and analysis of flushing water and return water for analysis of the contents of Uranine was performed systematically with a frequency of approximately one sample every fourth hour during the drilling period, see Figure 5-20. Like in all telescopic drilled boreholes, with the exception of KFM01A and KFM01B, a dosing feeder controlled by a flow meter was used for labelling the flushing water with Uranine to a concentration of 0.2 mg/L. The low values of Uranine contents at sections at c. 570–620 m and c. 700–800 m are more depending of that they were sampled before the Uranine had been properly mixed with the flushing water, than of an erroneous dosage. Because of that, these values have also been excluded in the average calculations below.

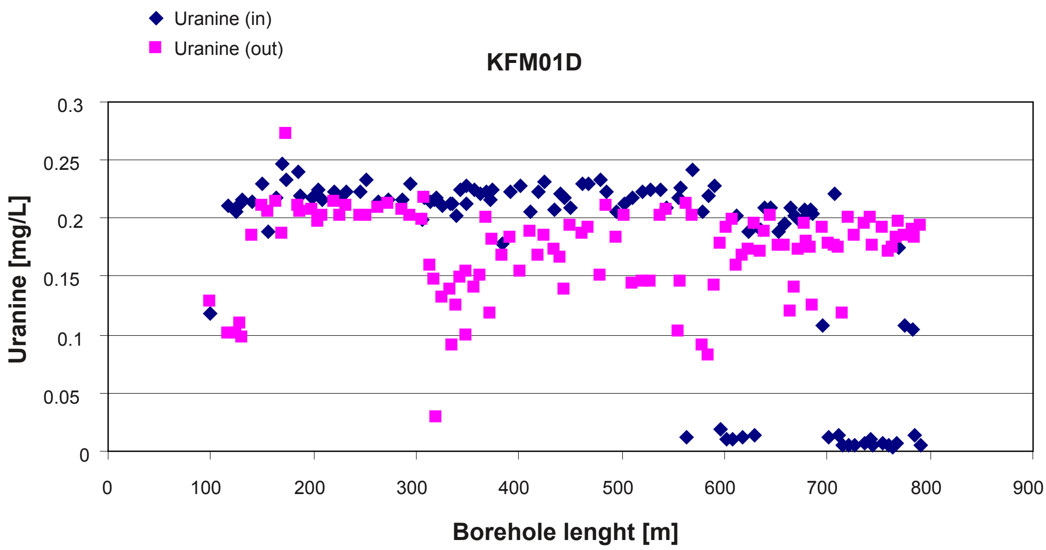


Figure 5-20. *Uranine contents in the flushing water consumed and in the return water recovered versus drilling length during drilling of borehole KFM01D. Automatic dosing equipment, controlled by a flow meter, accomplished the labelling with Uranine.*

A mass balance calculation of the accumulated volumes of flushing water and recovered flushing water in the return water indicates that the major part of the flushing water added to the borehole was recovered. According to the notations in the logbook, the amount of Uranine added to the borehole was 160 g. From the average Uranine concentration and the total volume of flushing water used, the amount of Uranine added is calculated to 163 g. The amount of Uranine recovered in the return water is calculated to 186 g. The excess amount of recovered Uranine is probably due to Uranine remaining in the groundwater formation after the previous drilling of KFM01C.

Figure 5-21 illustrates the variations of flushing water and return water flow rate together with variations of the groundwater table during core drilling of borehole KFM01D. The return water flow rate depends on the hydraulic transmissivity of the borehole, as well as on the draw-down accomplished by the air-lift pumping. To cool the drill bit and keep the borehole bottom clean, drilling usually requires a flushing water flow rate of c. 25 L/min. However, immediately after a core recovery, a temporarily higher flushing water flow rate is often applied.

As the upper 90 m of the borehole are cased and cement grouted, there was no return water inflow above the core drilled part of the borehole. To avoid vibrations in the drill rods, no mammoth pumping was carried out in the beginning of the drilling period. The measurements of the groundwater table indicate moderate water inflow into the borehole as the draw-dawn has a linear drop, while the recovery seldom reaches the normal groundwater head. The results indicate absence of major ground water inflows to the borehole at larger depths, which also is in line with the earlier results achieved from drilling of KFM01A.

Flushing water pressure

The flushing water pressure measured during drilling of borehole KFM01D is exposed in Figure 5-22. The borehole diameter was 75.8 mm, and the borehole was drilled with a different in-the-hole equipment, the so called Corac system, that gives a lower flushing water pressure compared to the Hagby WL76-system, which has been used in most telescopic boreholes drilled at Forsmark, e.g. KFM01A.

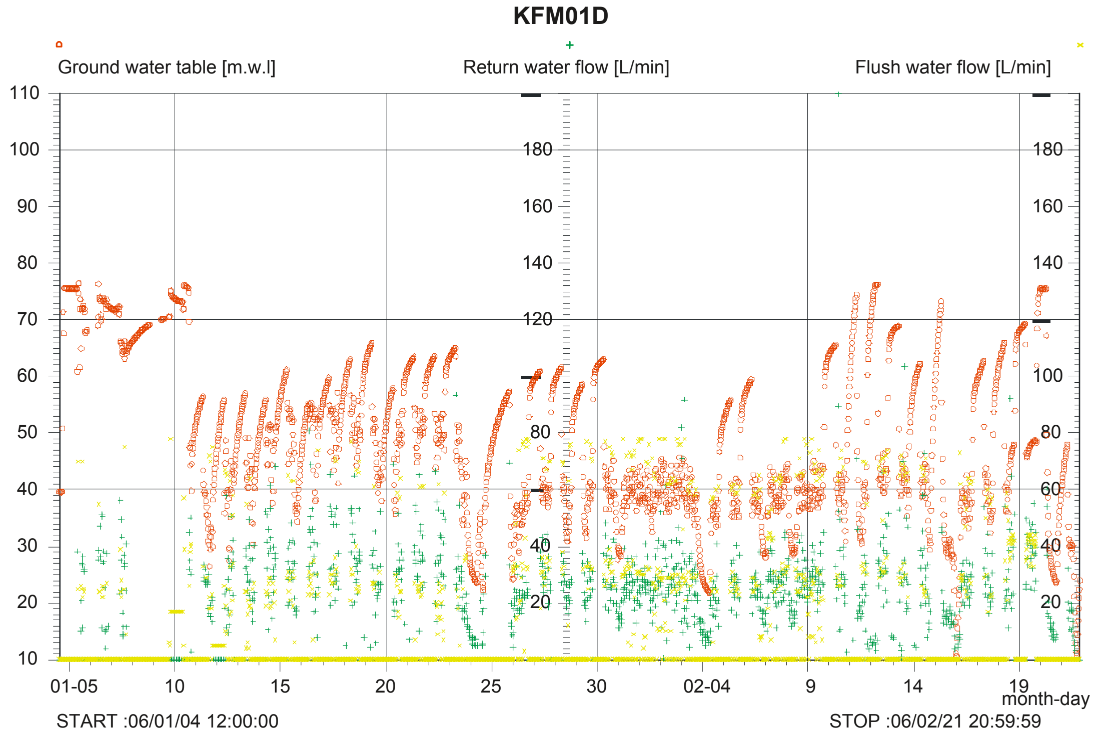


Figure 5-21. Ground water table (red), flushing water flow rate (yellow) and return water flow rate (green) versus time during core drilling of borehole KFM01D.

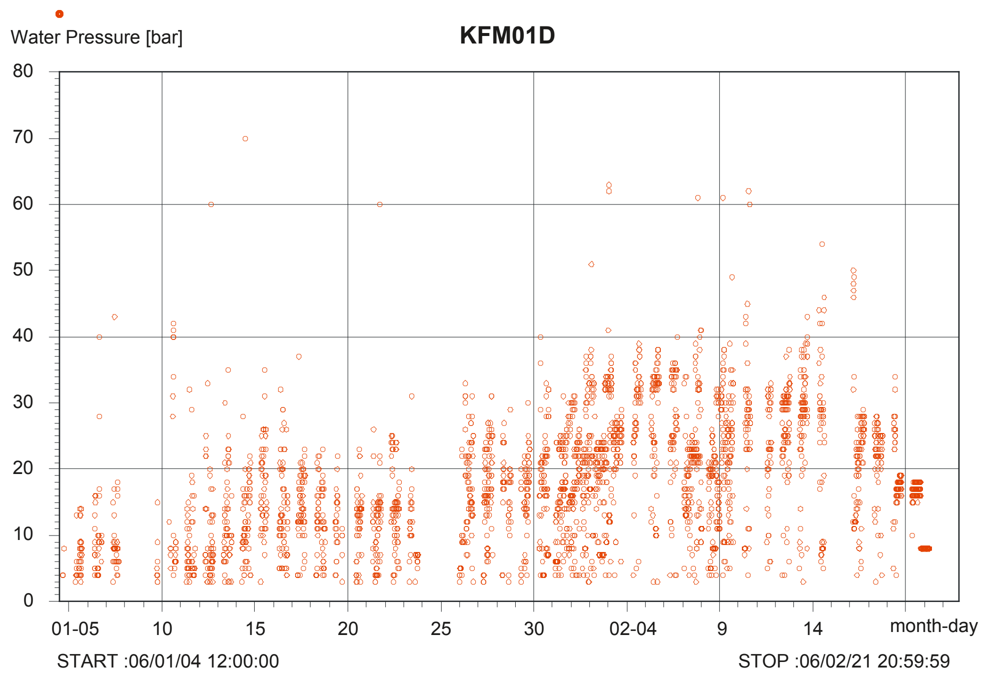


Figure 5-22. Flushing water pressure versus drilling length when drilling KFM01D.

5.8.3 Electric conductivity of flushing water

Flushing water was supplied from percussion borehole HFM01 (cf. Section 3.3.2). A sensor in the measurement station registered the electric conductivity (EC) of the flushing water on-line before it was pumped into the borehole, see Figure 3-3.

Another sensor for registration of the electric conductivity of the return water (see Figure 5-23) 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 200.20 m deep supply well HFM01 with its major inflow at c. 40–55 m is quite constant, c. 450 mS/m, during the drilling period. This also corresponds with the results achieved when HFM01 supplied the drilling of KFM01A with flushing water during the summer 2002.

The peaks observed in the return water diagram are due to daily drilling stops. At the end of every day shift, flushing was interrupted, whereupon formation water recharged into the borehole because the mammoth pumping was shut off. When air flushing restarted, the EC-value of the mixed return water was higher for a short period, due to temporarily higher contents of formation water than the day before.

5.8.4 Contents of dissolved oxygen in flushing water

In Figure 5-24, the level of dissolved oxygen is plotted versus time. The contents of dissolved oxygen has generally been kept between 0.5–1.5 mg/L. Only between January15th and 18th, 2006, the dissolved oxygen contents raised to c. 4 mg/L, probably because of a temporary lack of nitrogen used for expelling the oxygen.

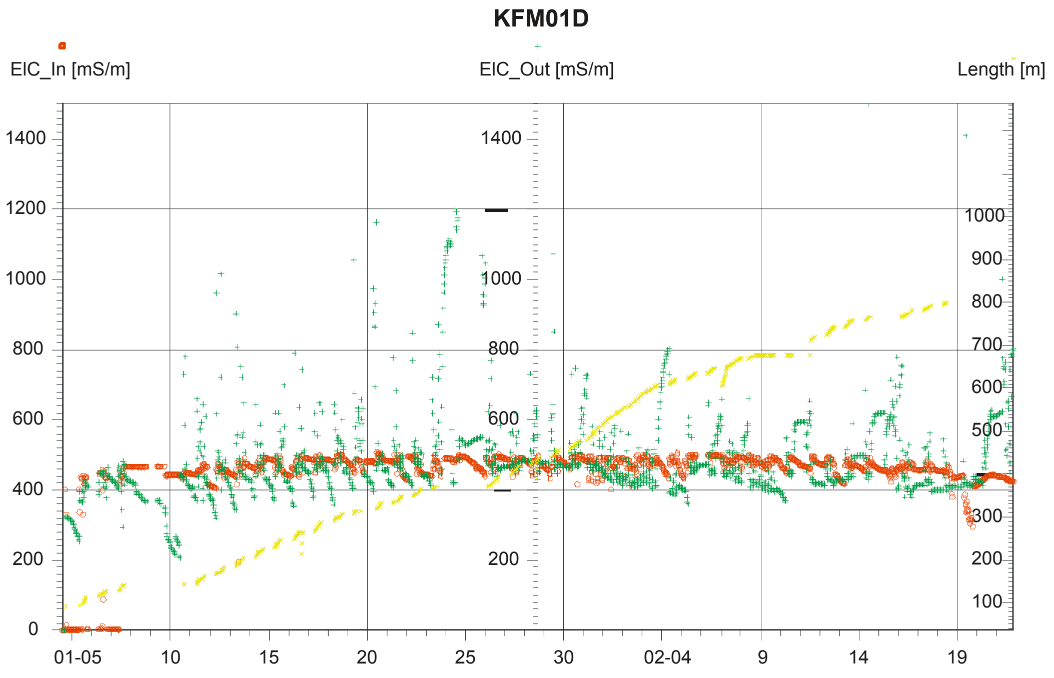


Figure 5-23. Electrical conductivity of flushing water from HFM01 and return water from KFM01D. The amount of values in the dataset has been reduced as well as cleaned from outliers.

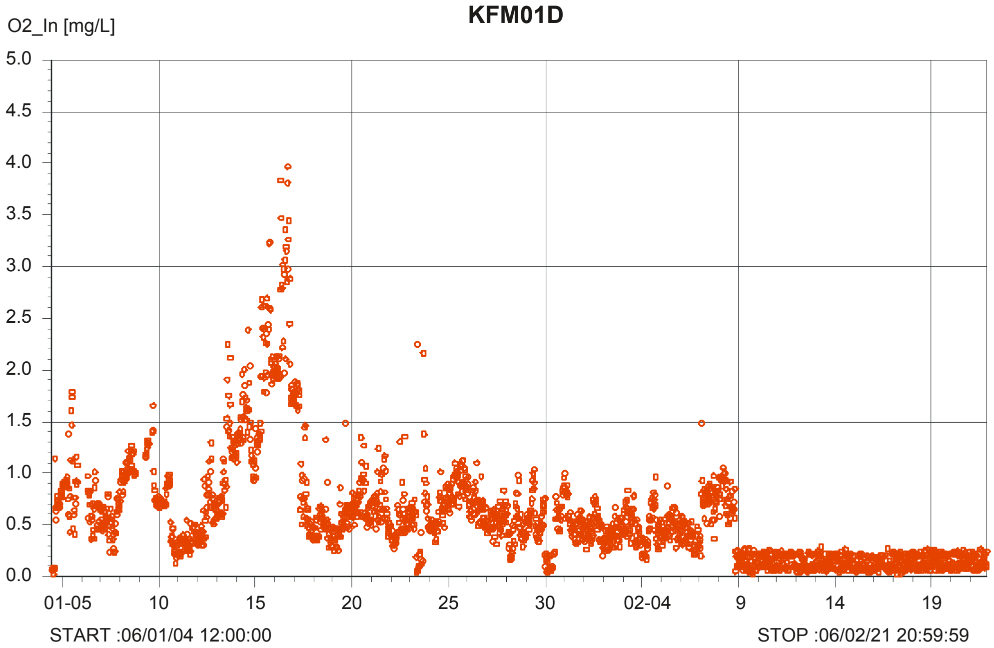


Figure 5-24. *Dissolved oxygen contents in the flushing water versus time when drilling KFM01D.*

5.8.5 Chemical composition of flushing water

The flushing water from the supply well HFM01 was sampled at two occasions during drilling, see Appendix C. Results from previous sampling and analysis of groundwater from HFM01 are compiled in /5/. The sampling during drilling was made for the following reasons:

- Initially, to check if the quality was satisfactory. The main concern is the contents 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 the borehole for chemical analyses.

As shown in Appendix C, the chemical composition of the groundwater from HFM01 is stable during the drilling period.

The percussion borehole HFM01 has been used before as flushing water supply well and the concentration of Total Organic Carbon (TOC) was known to be a somewhat elevated /8/ (should preferably fall below 5.0 mg/L). Two samples were collected during the drilling period of KFM01D and the TOC concentration was in the range 7.4–7.9 mg/L. However, the elevation of the TOC-contents was judged as limited, and 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 /8/).

The microbe contents of the flushing water was not determined during drilling of KFM01D. The microbe results from drilling of the preceding boreholes KFM05A and KFM06A /6, 7/, showed convincingly that the cleaning procedure applied when drilling all cored boreholes works well. It was therefore concluded that check of microbes at all drilling occasions was no longer necessary.

5.8.6 Registration of the groundwater level in KFM01D

To enhance the recovery of drill cuttings from the borehole, air-flush (mammoth) pumping was applied during the entire drilling period. The pumping capacity was checked by registration of the groundwater level in the borehole, below plotted versus time of the drilling period (Figure 5-25).

From the beginning, the mammoth pumping was not used, because vibrations in the drilling string at large drawdowns. Combined with low-conductive hydraulic conditions in the borehole, the deficiency of flushing entailed an accumulation of drilling debris in the lower part of the telescopic borehole. This caused the mammoth pumps to be clogged. By applying reversed flushing, one of the two mammoth pumps was rinsed, and from c. 144 m drilling length the mammoth pumping functioned satisfactorily. When pumping was restarted, a rapid draw-down occurred, which was adjusted to approximately 35–45 m below top of casing.

Drilling was performed 24 hours a day from Monday to Thursday, extended with extra day-shifts from Friday morning to Sunday night. At the nightly stop of drilling and pumping during the weekends the groundwater table recovered very slowly. Obviously the inflow of groundwater to borehole is very low, which corresponds to the results achieved when drilling KFM01A.

5.8.7 Core sampling

The average drill core length per run obtained from the drilling was 2.69 m. Due to the low fracture frequency at depth, thirty three 3 m long unbroken drill cores were recovered. Fracture minerals were relatively well preserved. Rotation marks on the drill core occurred, but with a low frequency. A preliminary on-site core logging was performed continuously.

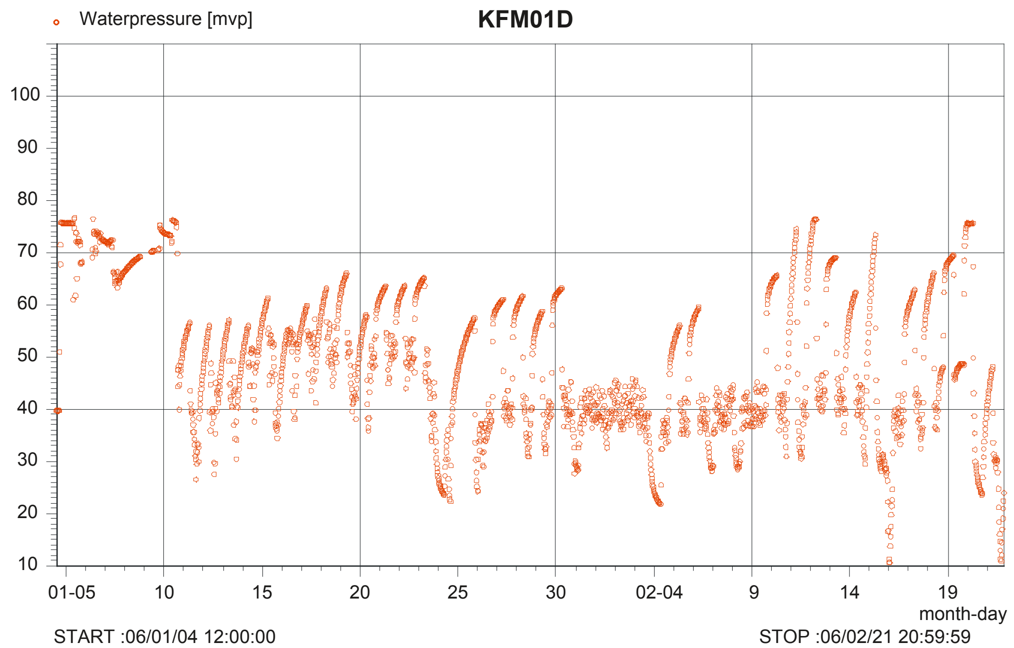


Figure 5-25. *Variation of the level of the groundwater table in KFM01D during drilling.*

5.8.8 Sampling pore space groundwater in low permeable rock

An additional sampling of drill cores was carried out when drilling KFM01D. The methodology for sampling and chemical analysis of pore space groundwater was initially developed at the Äspö HRL and was successfully applied to the previously drilled borehole KFM06A /9/, although including a major logistic effort. This resulted in a continued sampling programme from the remaining boreholes to be drilled in the target area, besides in KFM01D also in KFM08C and KFM02B.

The sampling is basically quite simple but speed and care are crucial to prevent any potential evaporation of the groundwater when the drill core is first exposed to the atmosphere. The different measures during the sampling are described in the text below and in Figure 5-26. The sampling dates and levels are given in Table 5-9.

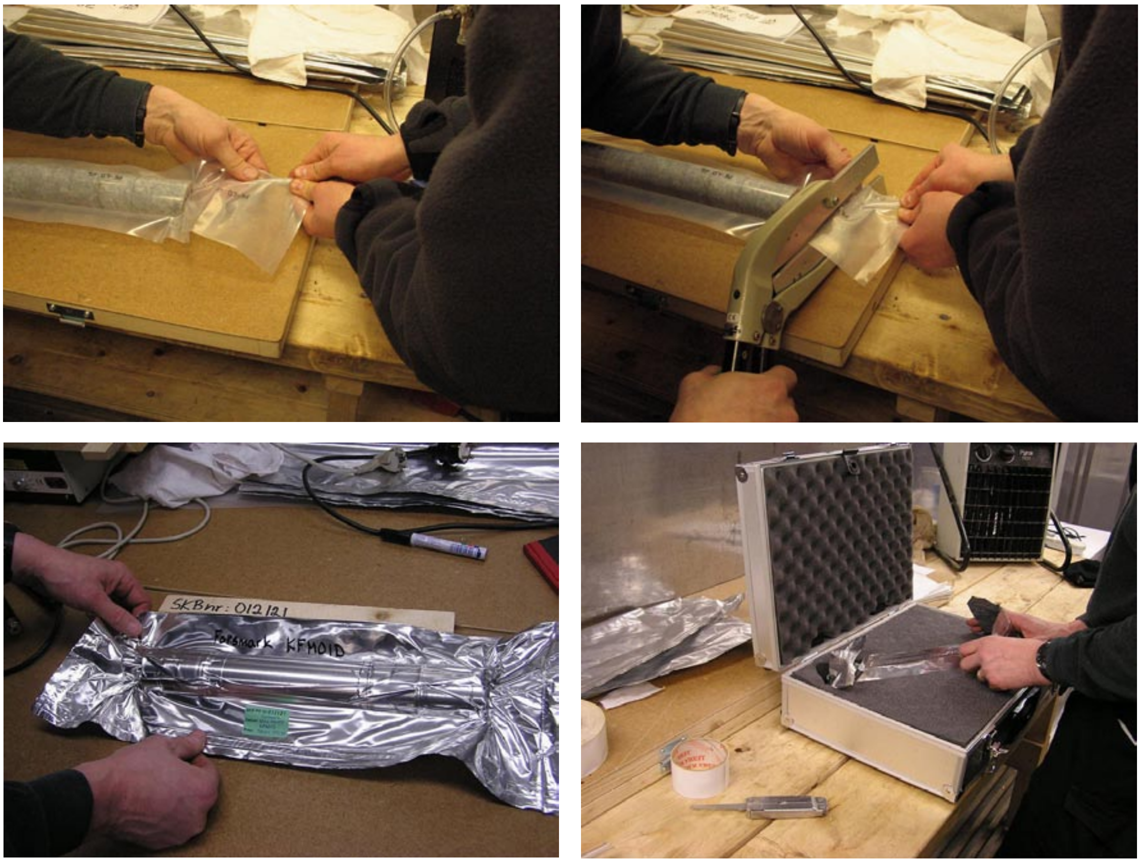


Figure 5-26. *The photos show the careful handling of the samples for pore space groundwater in low permeable rocks performed in KFM01D. To the upper left the core has been recovered from the borehole and is placed in a nitrogen filled plastic bag from which the nitrogen is evacuated. To the upper right 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.*

Table 5-9. Sampling of drill cores from KFM01D for determination of pore space groundwater.

Activity	Start date	Idcode	Secup (m)	Seclow (m)
Rock pore water – sampling	2006-01-07 15:04	KFM01D	140.47	140.91
Rock pore water – sampling	2006-01-13 12:12	KFM01D	193.57	193.89
Rock pore water – sampling	2006-01-16 10:10	KFM01D	254.93	255.32
Rock pore water – sampling	2006-01-18 10:32	KFM01D	298.94	299.24
Rock pore water – sampling	2006-01-22 10:29	KFM01D	351.94	352.20
Rock pore water – sampling	2006-01-26 16:20	KFM01D	393.50	393.88
Rock pore water – sampling	2006-01-30 10:39	KFM01D	462.59	462.98
Rock pore water – sampling	2006-01-31 14:02	KFM01D	499.90	500.20
Rock pore water – sampling	2006-02-01 19:37	KFM01D	544.11	544.35
Rock pore water – sampling	2006-02-03 12:33	KFM01D	600.10	600.39
Rock pore water – sampling	2006-02-06 13:08	KFM01D	642.92	643.31
Rock pore water – sampling	2006-02-09 15:22	KFM01D	700.08	700.43
Rock pore water – sampling	2006-02-13 09:50	KFM01D	747.09	747.49
Rock pore water – sampling	2006-02-17 13:36	KFM01D	790.38	790.73

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 KFM01D sampling was carried out at every 50 m drilling length, and the above described procedure was repeated at all fourteen occasions.

5.8.9 Recovery of drill cuttings

The theoretical volume of the percussion drilled and reamed part of the borehole (0–89.77 m) is c. 4.23 m^3. 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 volume of the core drilled part of KFM01D and the drill core is calculated to be 1.783 m^3. This volume should correspond to the amount of drill cuttings produced during drilling. If a density of 2,650 kg/m^3 (approximate figure for granitoids in the Forsmark area) is applied, the total weight of the theoretical amount of debris is estimated at 4,725 kg. The calculated dry weight of the debris from the core drilling recovered and weighed in the containers is 3,250 kg. The difference between the theoretically produced and recovered dry weight of debris is 1,475 kg, which gives a recovery of 69%.

The recovery figure could be commented on. The dwell time in the system is too short for settling of the suspended finest fractions. No estimation was made of the amount of suspended material, but the true recovery is probably higher than 69%. It should also be observed, that weighing of the container including water and debris is associated with some uncertainty.

The low fracture frequency and the absence of major fracture zones below the cased part, indicates that only minor amounts of drilling debris might have been injected into the fracture system of the bedrock.

5.8.10 Deviation measurements KFM01D

The principles of the equipment for deviation measurements were explained in Section 3.3.5. 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 KFM01D. As pointed out in Section 5.4.4, when Maxibor™ measurements or deviation measurements with some other method have been performed as well, these may be used for uncertainty determinations of the deviation measurements.

As mentioned in Section 5.4.4, to ensure high quality measurements with the Flexit tool, the disturbances of the magnetic field must be low. The magnetic field variation during March 28th and November 29th, 2006, obtained from www.intermagnet.org and displayed in Figure 5-27 and Figure 5-28, shows only minor disturbances when the Flexit survey in KFM01D was performed.

In the following a systematic description of the construction of the revised deviation data for borehole KFM01D is given.

The data used are one complete Reflex Maxibor™ logging and three Flexit-loggings to 795 m borehole length, see Table 5-10. With the Flexit Smart Tool System, two deviation measurements in borehole KFM01D were carried out every 3 m downwards and one every 30 m upwards. These three surveys, with activity numbers 13132053, 13132052 and 13138475, provided almost repeatable results, and were therefore chosen for the construction of the deviation file to be "in use displayed" in Sicada (see explanation in Section 3.3.5). This file is designated EG154.

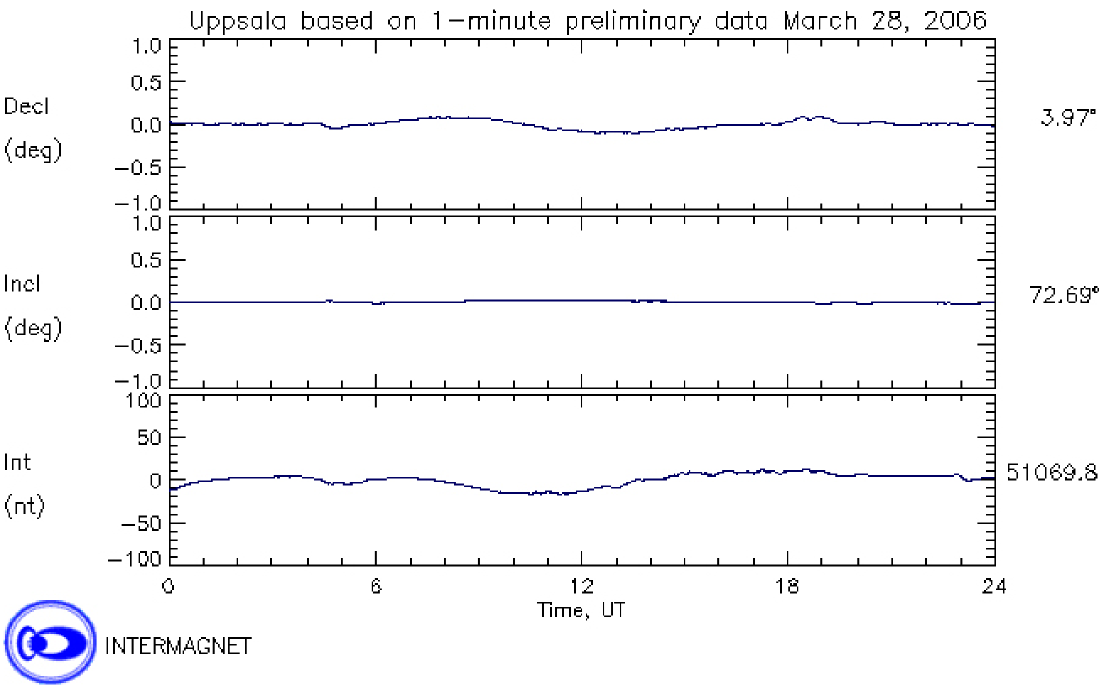


Figure 5-27. Magnetic field variation during the Flexit survey performed on March 28th, 2006.

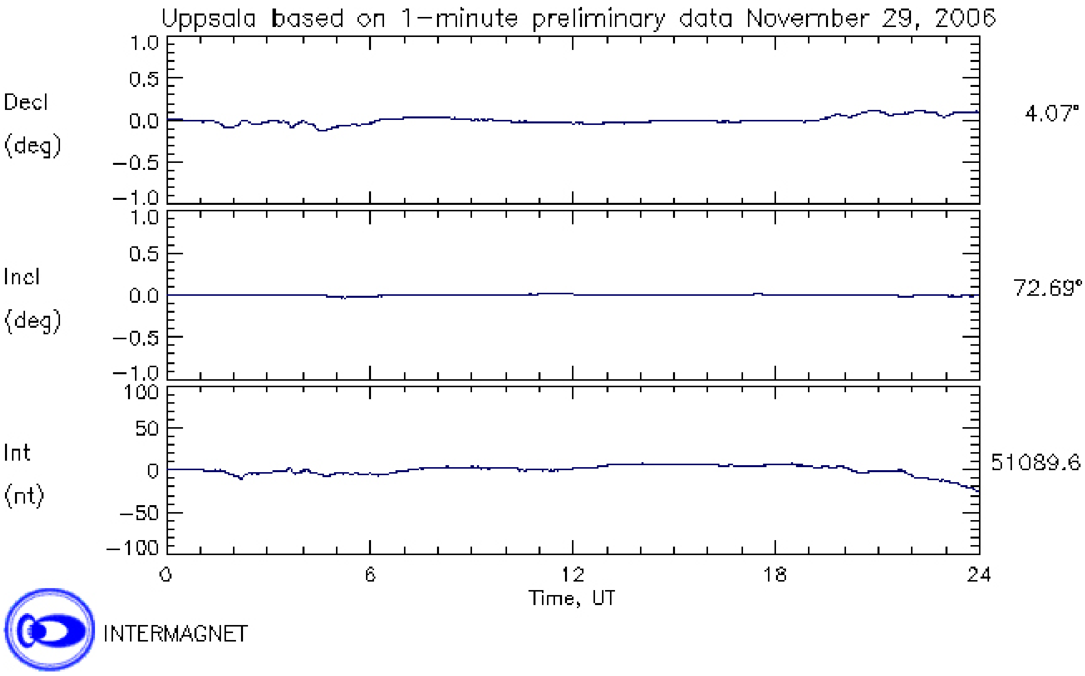


Figure 5-28. *Magnetic field variation during the Flexit survey performed on November 29th, 2006.*

Table 5-10. Activity data for the three deviation measurements approved for KFM01D. The two magnetic measurements were used for calculation of a final borehole deviation, whereas all three measurements were used for calculation of the deviation uncertainty.

Activity ID	Activity type code	Activity	Start date	Idcode	Secup (m)	Seclow (m)	Flags
13102425	EG156	Maxibor measurement	2006-02-21 00:00:00	KFM01D	3.00	798.00	
13132053	EG157	Magnetic – accelerometer m.	2006-03-28 12:40:00	KFM01D	3.00	795.00	CF
13132052	EG157	Magnetic – accelerometer m.	2006-03-28 16:10:00	KFM01D	45.00	795.00	CF
13138475	EG157	Magnetic – accelerometer m.	2006-11-29 08:00:00	KFM01D	3.00	795.00	CF
13140595	EG154	Borehole deviation multiple m.	2006-12-14 10:00:00	KFM01D			I C

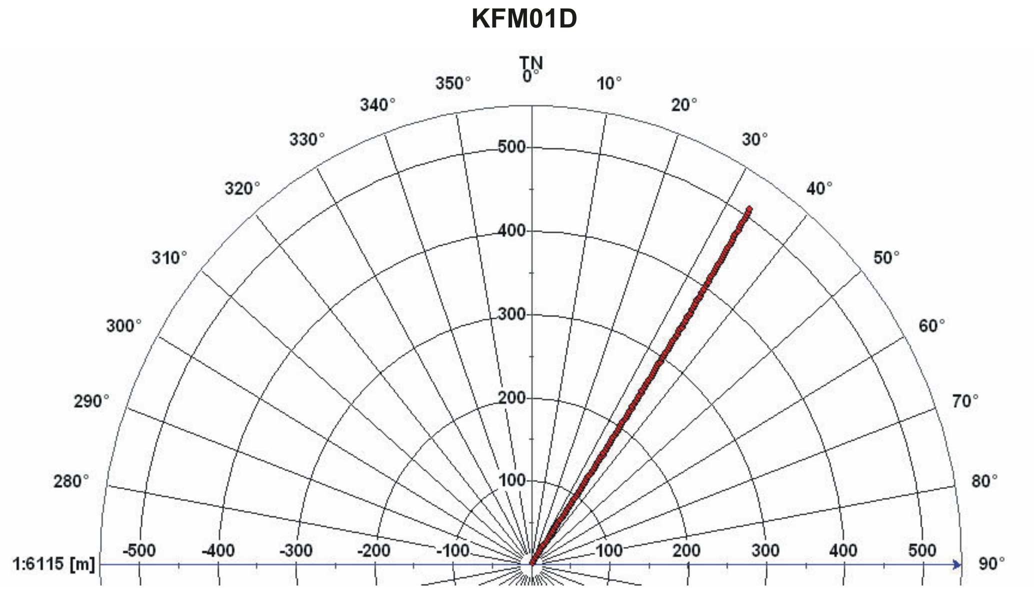
* C = Comment, F = File, I = In-use flag.

The EG154-activity specifying the deviation measurements used in the resulting calculation is presented in Table 5-11. The upper values for bearing start at 93 m and 95 m so that they should not be influenced by the 90 m steel casing (measurements by magnetic method). Since the inclination measurements are performed with accelerometer technique, the inclination values are not disturbed by the casing.

Table 5-11. Contents of the EG154 file (multiple borehole deviation intervals) from KFM01D.

Idcode	Deviation activity Id	Deviation angle type	Approved secup (m)	Approved seclow (m)
KFM01D	13132052	BEARING	95.00	795.00
KFM01D	13132052	INCLINATION	45.00	795.00
KFM01D	13132053	BEARING	93.00	795.00
KFM01D	13132053	INCLINATION	3.00	297.00
KFM01D	13138475	BEARING	93.00	795.00
KFM01D	13138475	INCLINATION	3.00	795.00

The calculated deviation (EG154-file) in borehole KFM01D show that the borehole deviates upwards and slightly to the left with an absolute deviation of 64.6 m compared to an imagined straight line following the dip and strike of the borehole start point (Figure 5-29). A subset of data from the resulting deviation file together with the estimated inclination-, bearing and radius uncertainties are presented in Table 5-12. For explanation of "absolute deviation" and radius uncertainty, see Section 5.4.4.



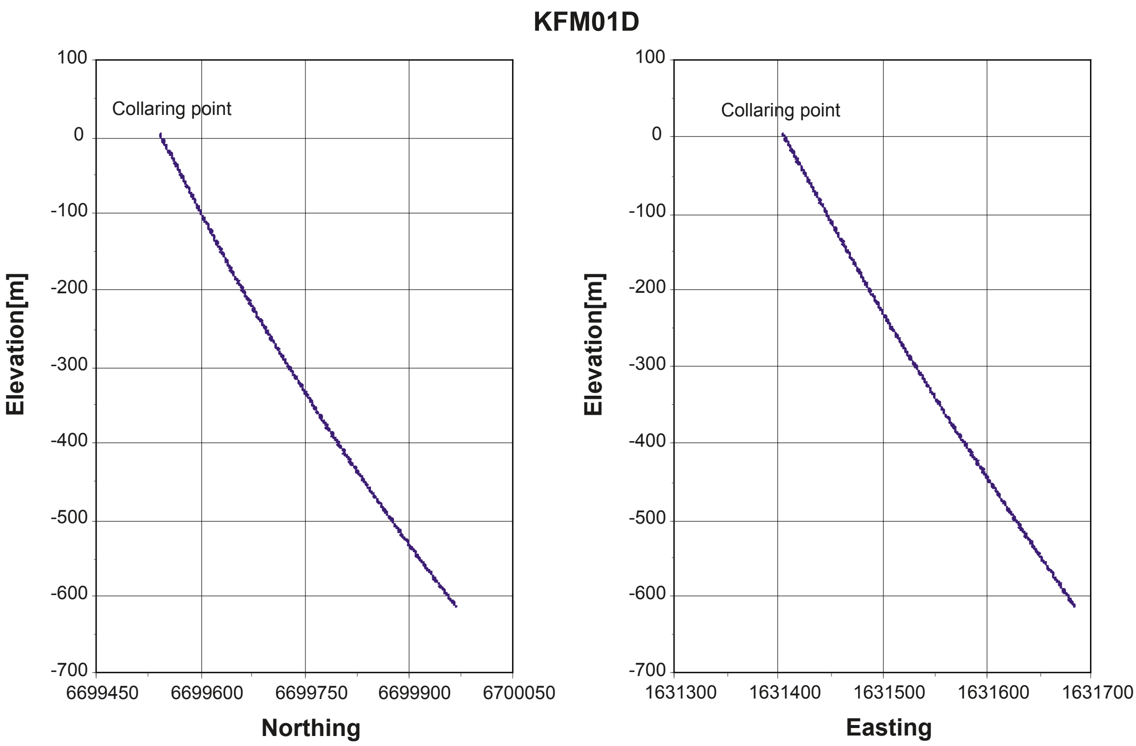


Figure 5-29. *Upper figure is a horizontal projection and lower figures are two vertical projections of the in use-flagged deviation data from KFM01D.*

Table 5-12. Deviation data from KFM01D from every approximately 100 m vertical length calculated from EG154. Inclination-, bearing- and radius uncertainties are also included.

Borehole	Length	Northing (m)	Easting (m)	Elev.	Elev. Uncert.	Incl.	Bearing	Incl. Uncert.	Bearing Uncert.	Radius Uncert.
KFM01D	0	6699542.07	1631404.52	2.95	0	–54.90	35.04	0.43	0.755	0
KFM01D	126	6699601.32	1631446.22	–100.14	0.54	–54.83	35.24	0.43	0.755	0.955
KFM01D	249	6699660.81	1631487.19	–199.68	1.09	–53.04	33.93	0.43	0.755	1.907
KFM01D	378	6699727.74	1631531.92	–300.46	1.69	–49.99	33.02	0.43	0.755	2.969
KFM01D	510	6699799.26	1631578.89	–400.96	2.33	–48.55	32.47	0.43	0.755	4.097
KFM01D	645	6699875.79	1631627.72	–500.87	3.01	–46.93	31.90	0.43	0.755	5.293
KFM01D	783	6699957.32	1631677.87	–600.26	3.73	–45.16	30.75	0.43	0.755	6.555
KFM01D	800.24	6699967.75	1631684.15	–612.48	3.82	–45.09	31.17	0.43	0.755	6.715

5.8.11 Measurements of the length difference between the compressed drilling pipe string and as extended by its own weight

All length values used for measurements in the borehole and of the drill core originate from registrations of the length of the drill pipe string. However, such registrations involve a small error depending on the gravitational stretching of the pipe string when hanging freely and thus exposed to its own weight. When the pipe string is lowered to the borehole bottom, and the lifting force from the drill rig is set to zero, the pipe string will be resting on the borehole bottom and thus relieved from the previous load, and the stretching will cease. Instead, the load from the pipe string will now cause compression, and to some extent bending of it.

By measuring the length difference between these two conditions, it was hoped that the length error could be determined for different lengths of the pipe string and for different inclinations of the borehole. The practical difficulties and uncertainties in the results however turned out to be considerable. Therefore it is recommended that the length error is determined from the diagram in Figure 5-30, which is based on load tests performed in the laboratory by the manufacturer of the drill pipes.

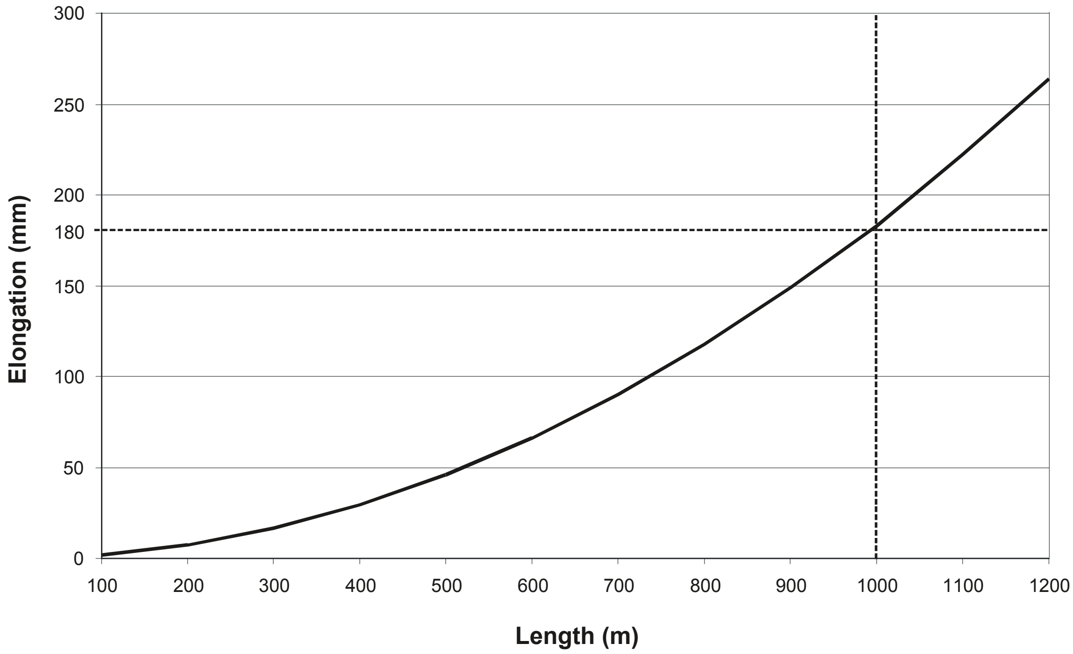


***Figure 5-30.** The diagram illustrates the elongation of the WL-76 drill pipe string when hanging in vertical water filled borehole. Values from laboratory load tests of the drill pipes.*

As seen in the diagram, the maximum elongation at 1,000 m length in a vertically drilled borehole is 180 mm. In inclined boreholes the elongation of the pipe string should theoretically be less.

5.8.12 Groove milling

A compilation of length to the reference grooves and a comment on the success of detecting the grooves are given in Table 5-13. The positions of the grooves are determined from the length of the drill pipes used at the milling process. The length is measured from the upper part of the upper two grooves.

5.8.13 Consumables

The amount of oil products consumed during drilling of KFM01D as well as grout used for gap injections of the respective casings are reported in Tables 5-14 and 5-15. Unfortunately, oil products consumed during percussion drilling were not measured but regarding hammer oil and compressor oil, these products are indeed entering the borehole but are, on the other hand, continuously retrieved from the borehole due to the permanent air flushing during drilling. After completion of drilling, only minor remainders of the products are left in the borehole.

The special type of thread grease (silicon based) used during core drilling in this particular borehole was certified according to SKB MD 600.006 (Table 1-1). The experience from a technical point of view of the grease, is not fully satisfactory. Although expensive, the grease has a low adhesion capacity to the threads, and the lubrication characteristics are not as favourable as for conventional lubricants.

Table 5-13. Compilation of length to the reference grooves. 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.

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
150	Yes	Yes	500	Yes	Yes
200	Yes	Yes	550	Yes	Yes
250	Yes	Yes	600	Yes	Yes
300	Yes	Yes	650	Yes	Yes
350	Yes	Yes	700	Yes	Yes
400	Yes	Yes	750	Yes	Yes
450	Yes	Yes			

Table 5-14. Oil and grease consumption during core drilling of KFM01D.

Borehole ID	Thread grease (core drilling) Unisilikon L50/2	Grease for the drilling machine Statoil AB	Engine oil Castrol Tection 15W-40	Hydraulic oil Premium ECO HT-E 46	Engine diesel OKQ8 Diesel miljöklass 1
KFM01D	8.5 kg	1.6 kg	No consumption measured	50 L	50 L

Table 5-15. Cement consumption for grouting the percussion drilled part of KFM01D and for sealing the gap between the casing and the reamed borehole wall.

Borehole ID	Length (m)	Cement volume Aalborg Portland Cement/microsilica	Grouting method	Remarks
KFM01D	0.0–89.312	3,204 kg/3,115 L	Gap injection	
KFM01D	0.0–1.23	72 kg/70 L	Gap injection	

5.8.14 Recovery measurements after cleaning by air-lift pumping

As there is only a low groundwater inflow to borehole KFM01D, the recovery is slow. According to a tough drilling schedule, the final activities in the borehole did not permit an undisturbed groundwater recovery ensuing stop of pumping. However, at c. 766 m drilling length, the rig was repaired during the nigh shift, whereby a non-disturbed recovery of the groundwater table was monitored. The results are displayed in Figure 5-31. Pressure registration was performed during 12 hours and the water yielding capacity could be determined from the diagram. An inflow of <5 L/min at a drawdown of 40 m was estimated.

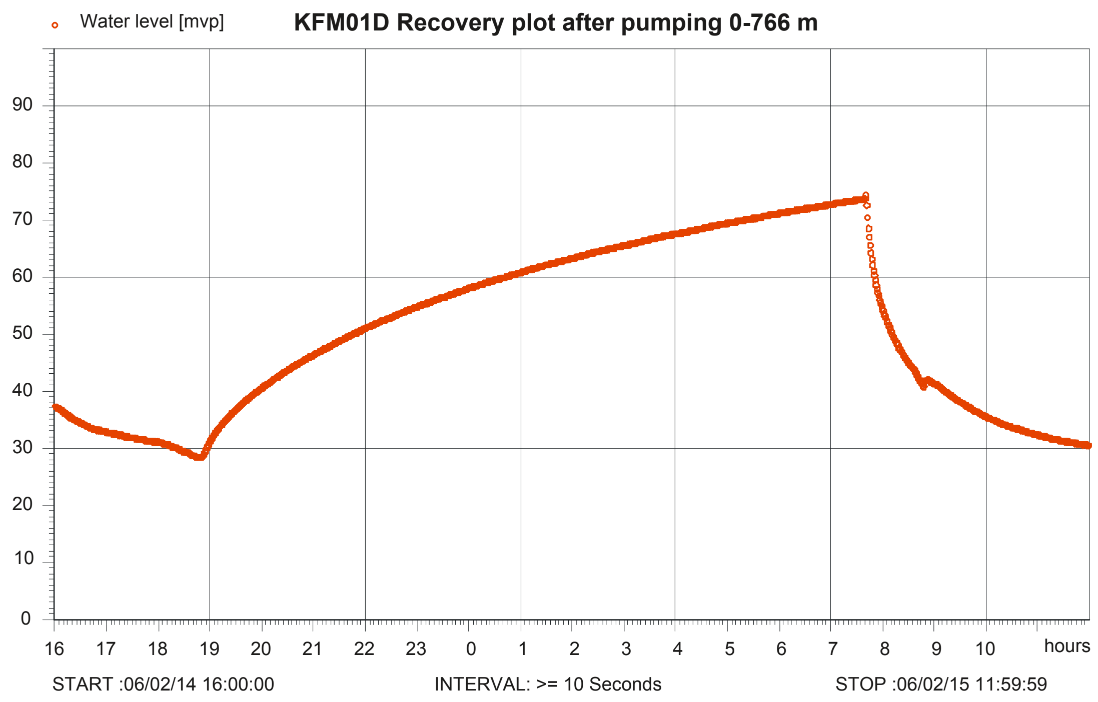


Figure 5-31. *Recovery of groundwater table in section 0–766 m of KFM01D aftera temporary stop of air-lift pumping.*

References

/1/ **SKB, 2001.** Site investigations. Investigation methods and general execution programme. SKB TR-01-29, Svensk Kärnbränslehantering AB.

/2/ **SKB, 2002.** Execution programme for the initial site investigations at Forsmark. SKB P-02-03, Svensk Kärnbränslehantering AB.

/3/ **SKB, 2006.** Döse, C & Samuelsson, E. Forsmark site investigation. Boremap mapping of core drilled borehole KFM01C. SKB P-06-133, Svensk Kärnbränslehantering AB.

/4/ **SKB, 2006.** Pettersson, J, Skogsmo, G, von Dalwigk, I, Wängnerud, A, Berglund, J. Forsmark site investigation. Boremap mapping of telescopic drilled borehole KFM01D. SKB P-06-132, Svensk Kärnbränslehantering AB.

/5/ **SKB, 2003.** Nilsson, A-C. Forsmark site investigation. Sampling and analyses of groundwater in percussion drilled boreholes and shallow monitoring wells at drillsite DS2. SKB P-03-48, Svensk Kärnbränslehantering AB.

/6/ **SKB, 2004.** Hallbeck, L, Pedersen, K, Kalmus, A. Forsmark site investigation. Control of microorganism content in flushing water used for drilling of KFM05A. SKB P-04-285, Svensk Kärnbränslehantering AB.

/7/ **SKB, 2003.** Pedersen, K. Forsmark site investigation. Control of microorganism content in flushing water used for drilling of KFM06A. SKB P-05-81, Svensk Kärnbränslehantering AB.

/8/ **SKB, 2003.** Claesson, L-Å & Nilsson, G. Forsmark site investigation. Drilling of the telescopic borehole KFM01A at drilling site DS1. SKB P-03-32, Svensk Kärnbränslehantering AB.

/9/ **SKB, 2005.** Waber, H. N. & Smellie, J.A.T. Forsmark site investigation. Borehole KFM06A: Characterisation of pore water. Part 1. Diffusion experiments. SKB P-05-196, Svensk Kärnbränslehantering AB.

Appendix A

Well Cad presentation of KFM01C

Title KFM01C

Svensk Kärnbränslehantering AB

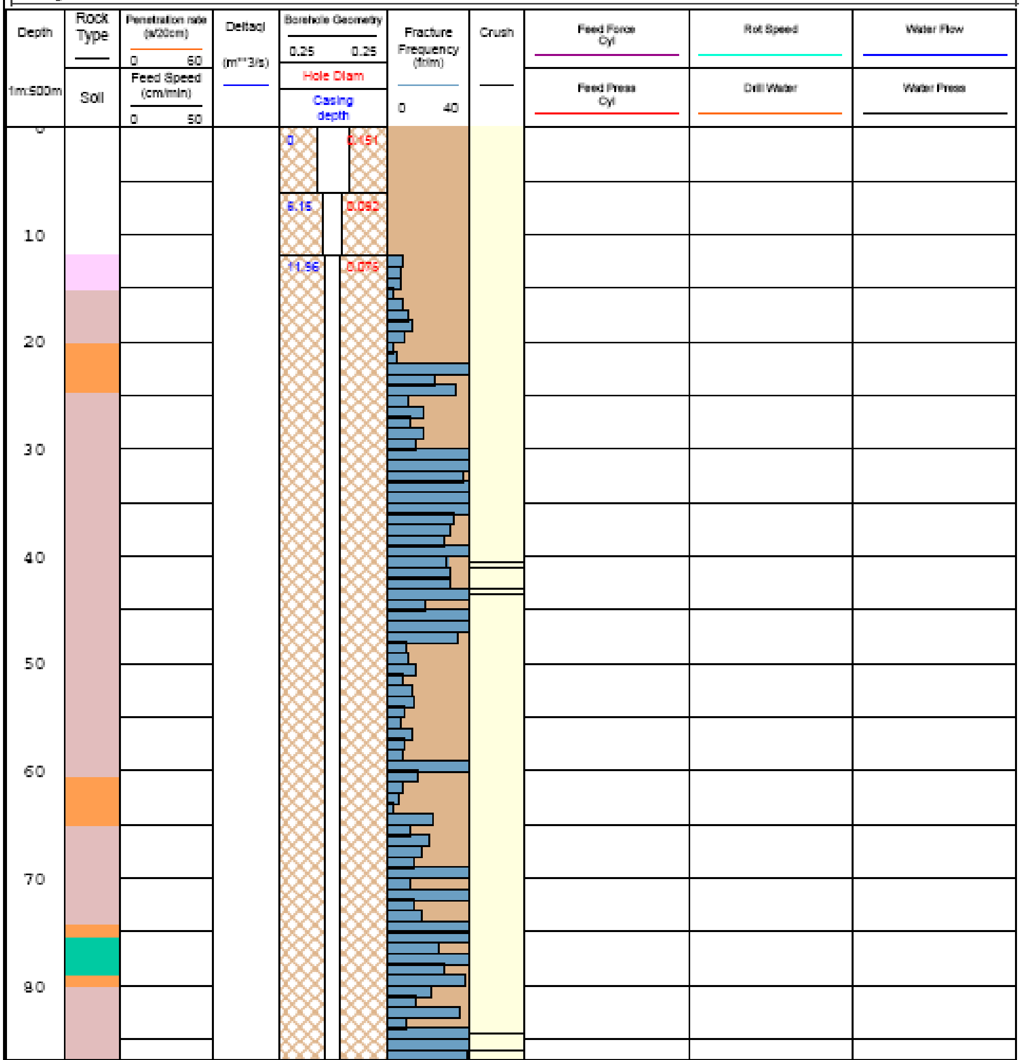
Site	FORSMARK	Signed data	
Borehole	KFM01C	Coordinate System	RT90-RHB70
Diameter [mm]	76	Northing [m]	6699526.14
Length [m]	450.02	Easting [m]	1631403.75
Bearing [°]	165.35	Elevation [m.a.s.l.]	2.91
Inclination [°]	-49.61	Drilling Start Date	2005-10-26 13:56:00
Date of mapping		Drilling Stop Date	2005-11-29 13:52:00
		Plot Date	2006-08-27 21:13:11

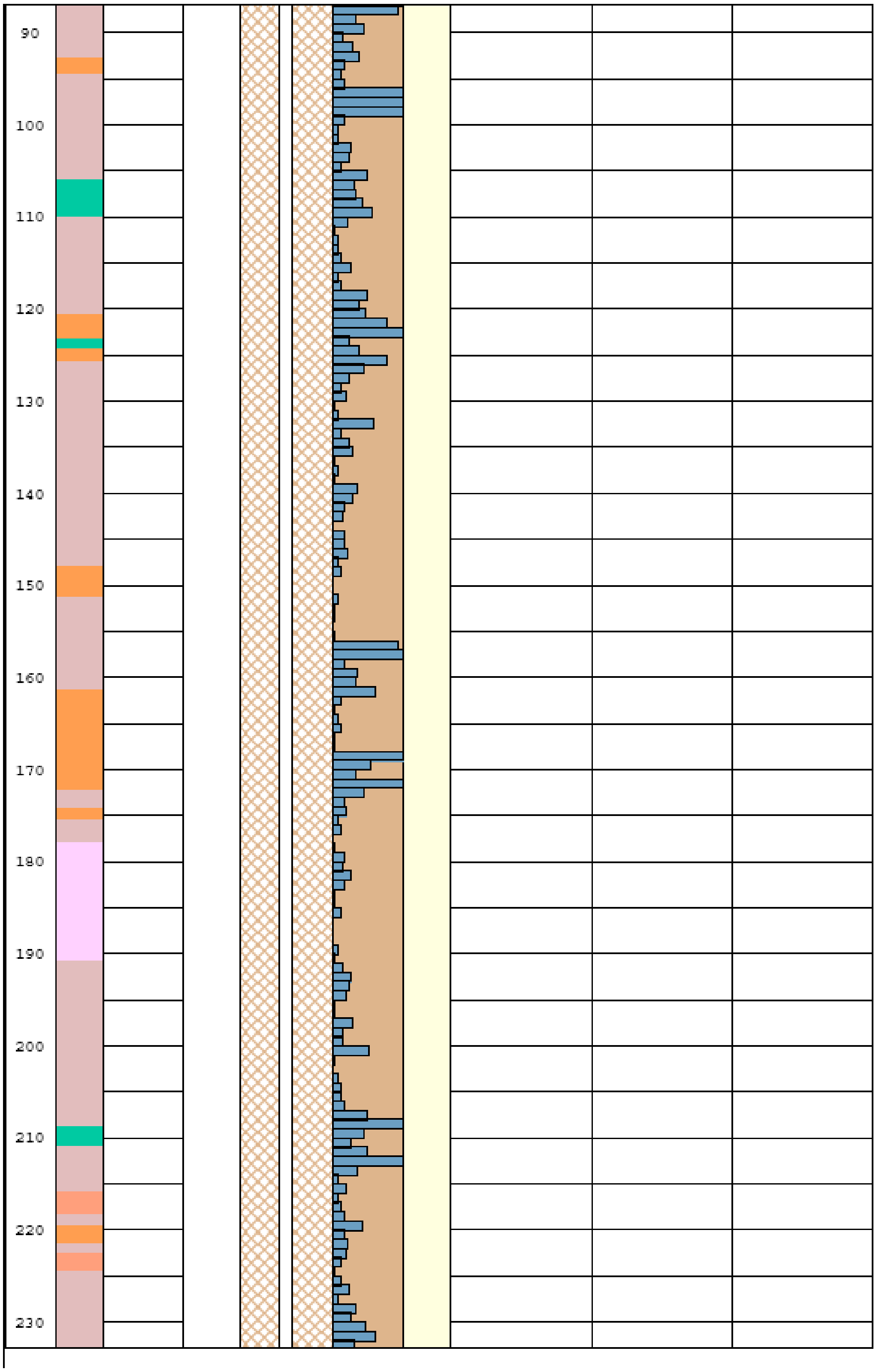
ROCKTYPE FORSMARK

- Granite, fine- to medium-grained
- Pegmatite, pegmatitic granite
- Granite, granodiorite and tonalite, metamorphic, fine- to medium-grained
- Granite, metamorphic, aplitic
- Granite to granodiorite, metamorphic, medium-grained
- Amphibolite
- Felsic to intermediate volcanic rock, metamorphic

SOIL

Script Name

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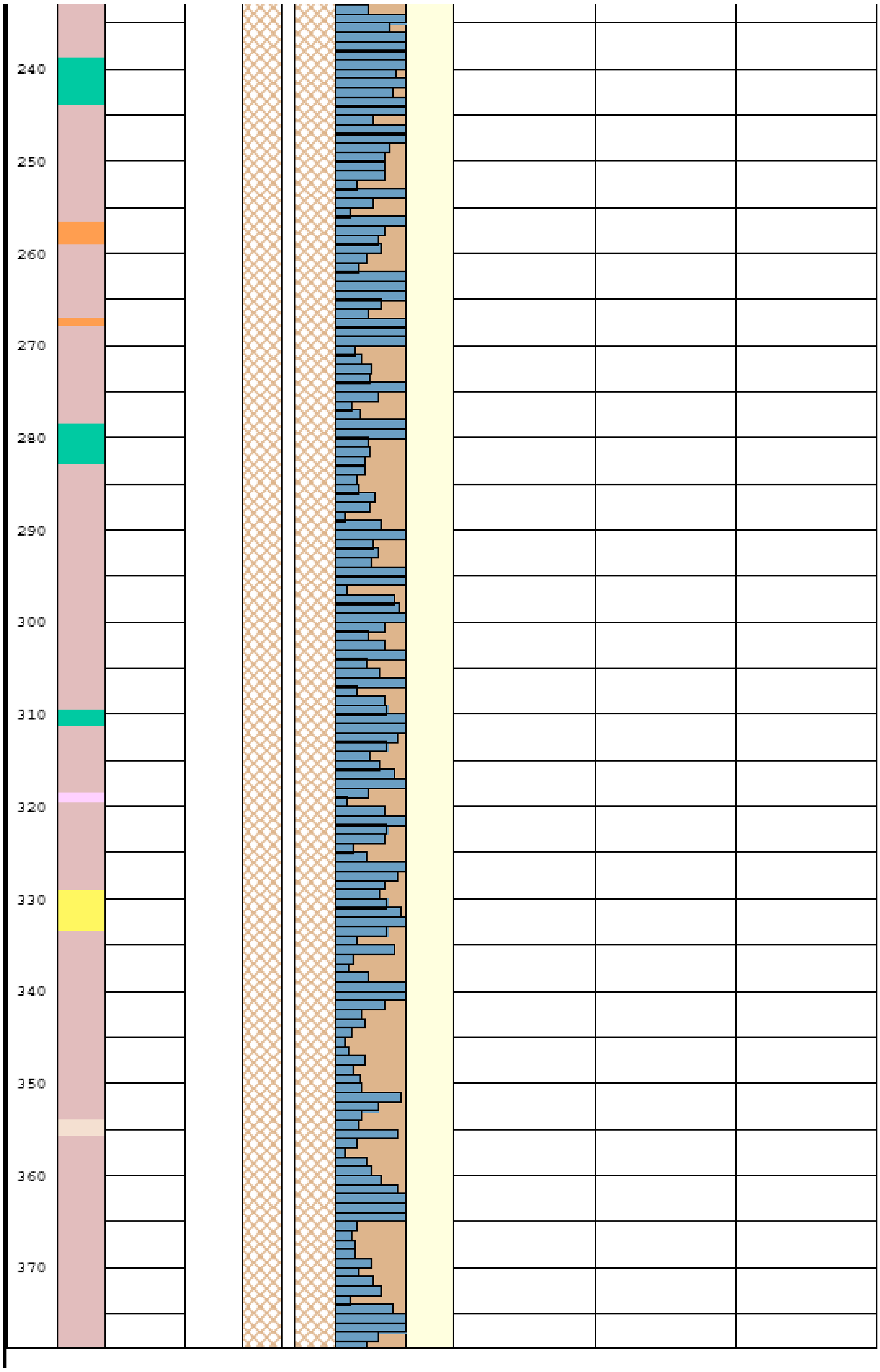
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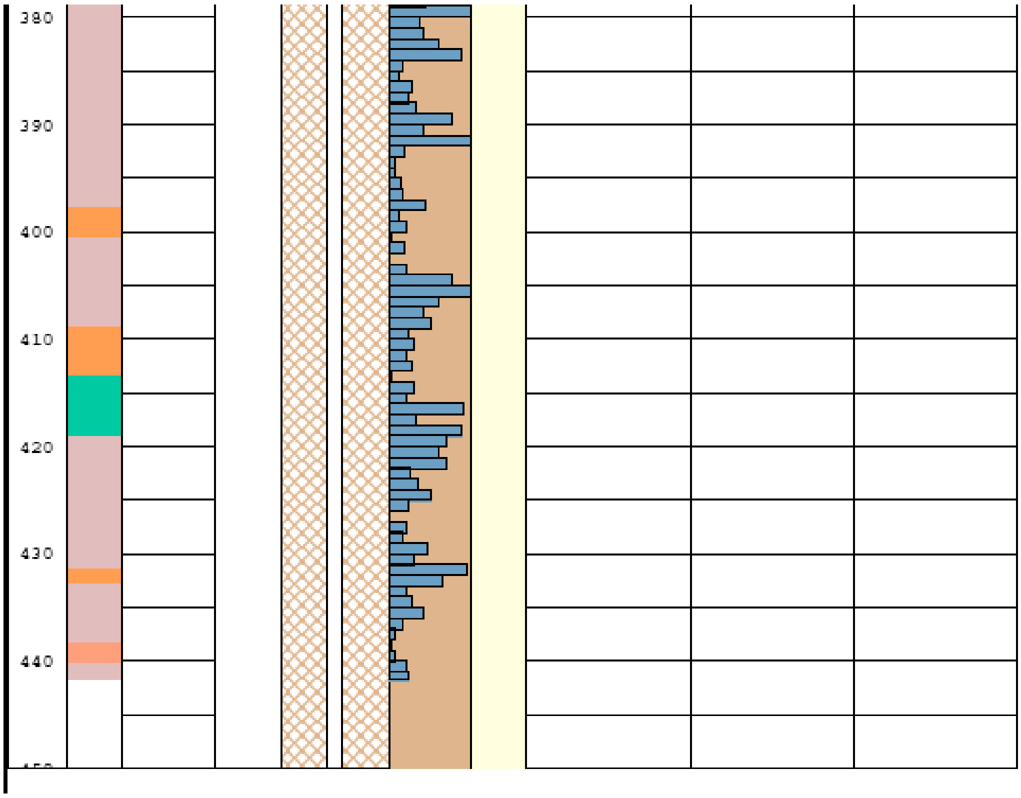

380
390
400
410
420
430
440

Well Cad presentation of KFM01D

Title KFM01D

Svensk Kärnbränslehantering AB

Site	FORSMARK	Signed data	
Borehole	KFM01D	Coordinate System	RT90-RHB70
Diameter [mm]	76	Northing [m]	6699542.07
Length [m]	800.24	Easting [m]	1631404.52
Bearing [°]	35.03	Elevation [m.a.s.l.]	2.95
Inclination [°]	-54.90	Drilling Start Date	2005-11-22 07:00:00
Date of mapping		Drilling Stop Date	2006-02-18 14:30:00
		Plot Date	2006-08-27 21:13:11

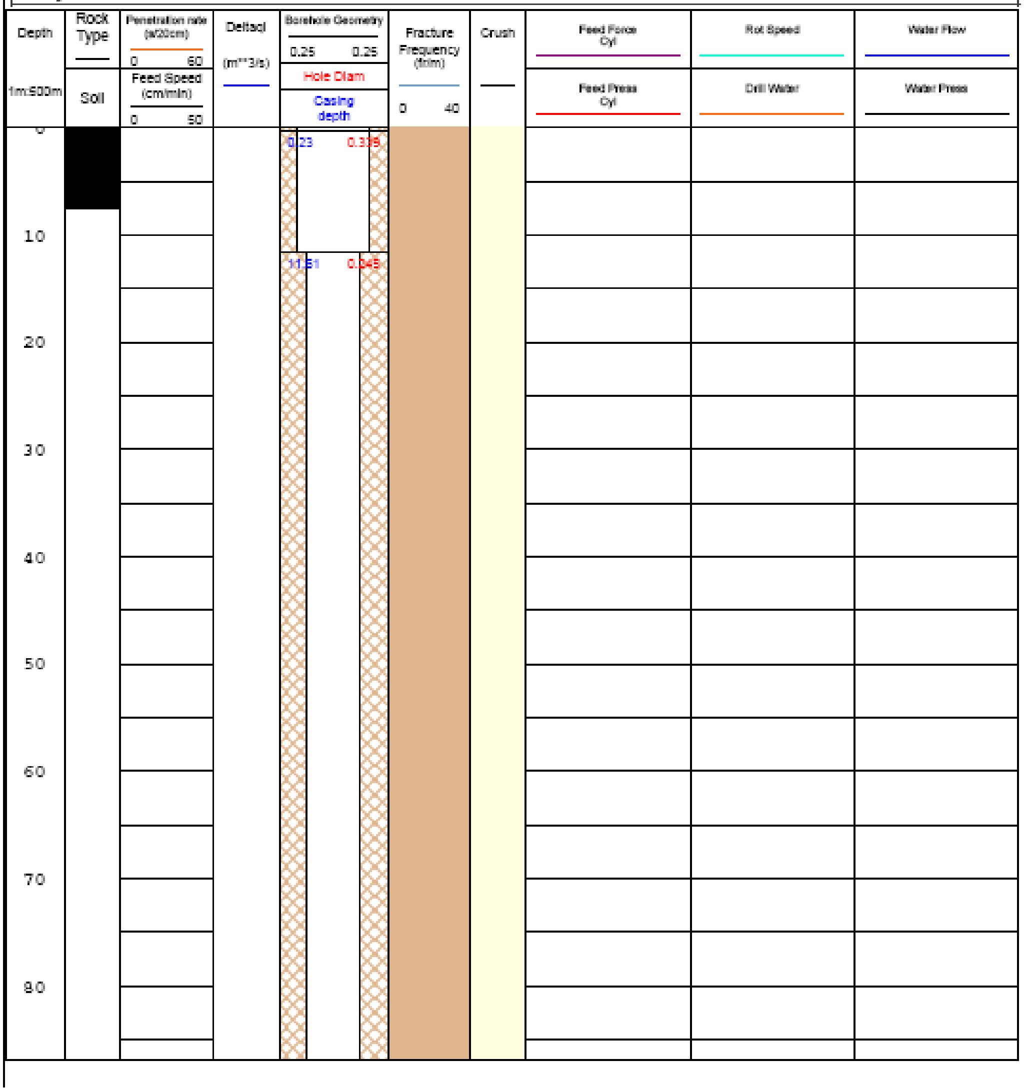
ROCKTYPE FORSMARK

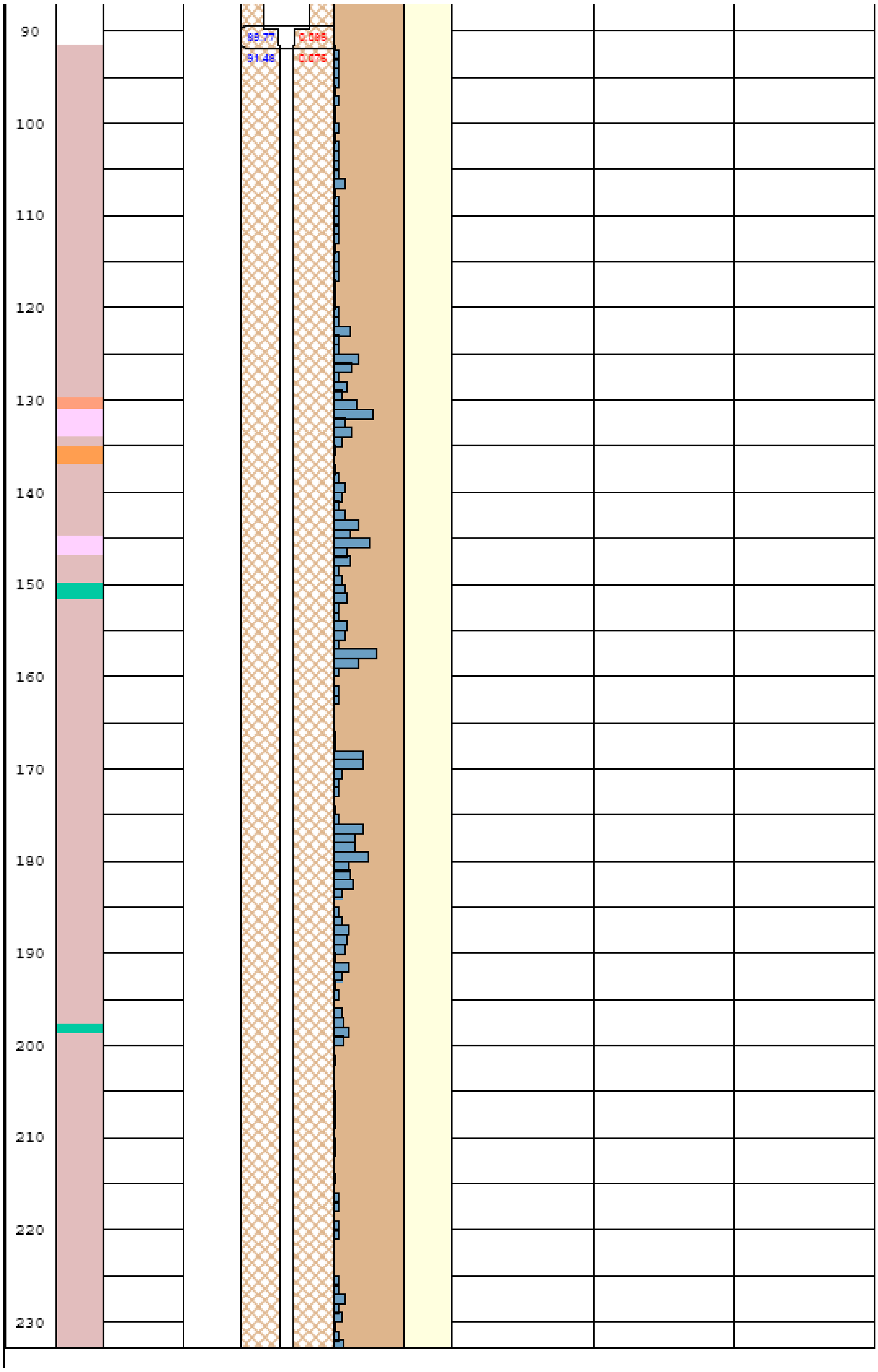
- Granite, fine- to medium-grained
- Pegmatite, pegmatitic granite
- Granite, granodiorite and tonalite, metamorphic, fine- to medium-grained
- Granite, metamorphic, aplitic
- Granite to granodiorite, metamorphic, medium-grained
- Amphibolite
- Felsic to intermediate volcanic rock, metamorphic

SOIL

- Soil

Script Name





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230
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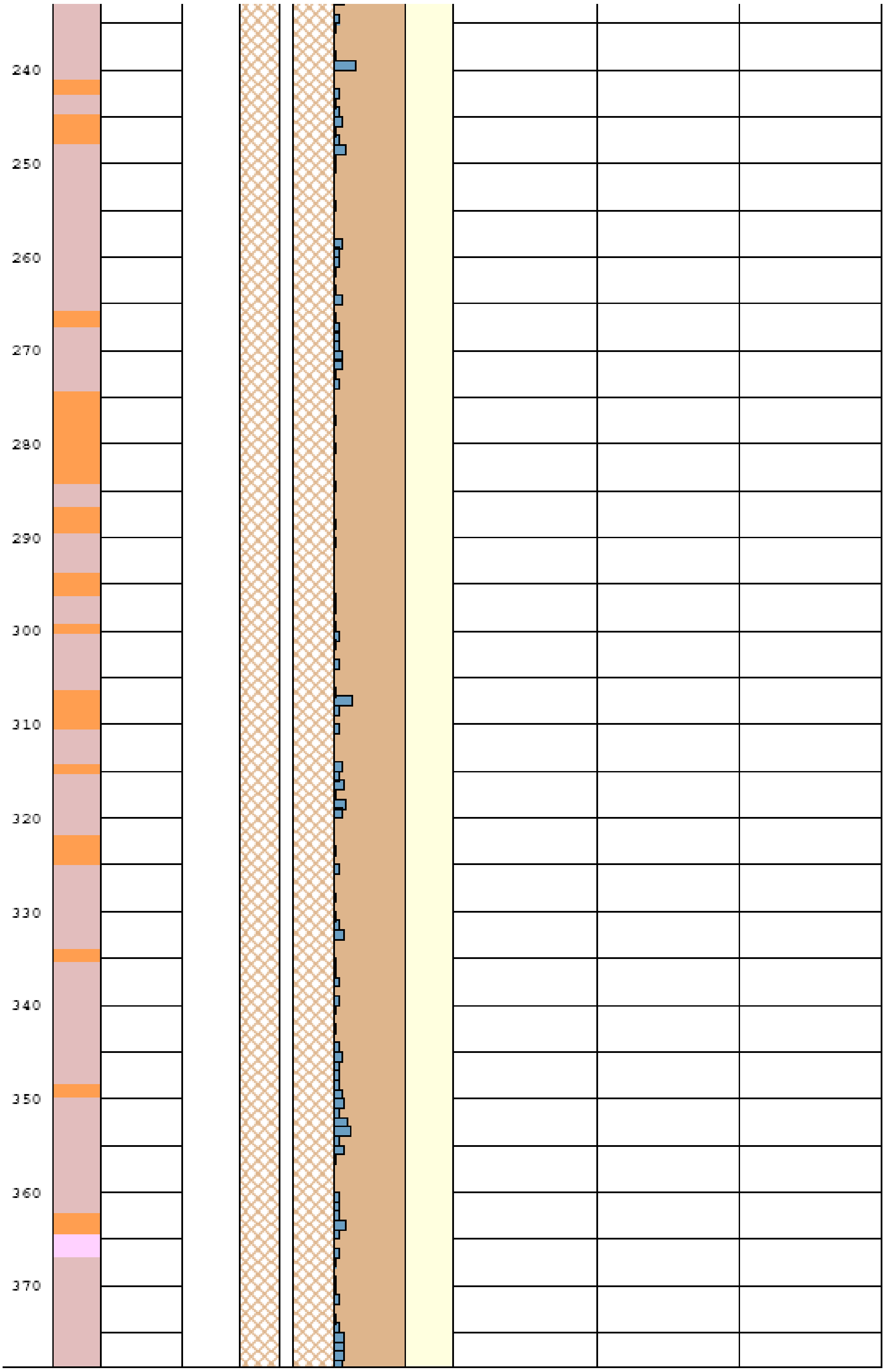
91.48
0.085
0.076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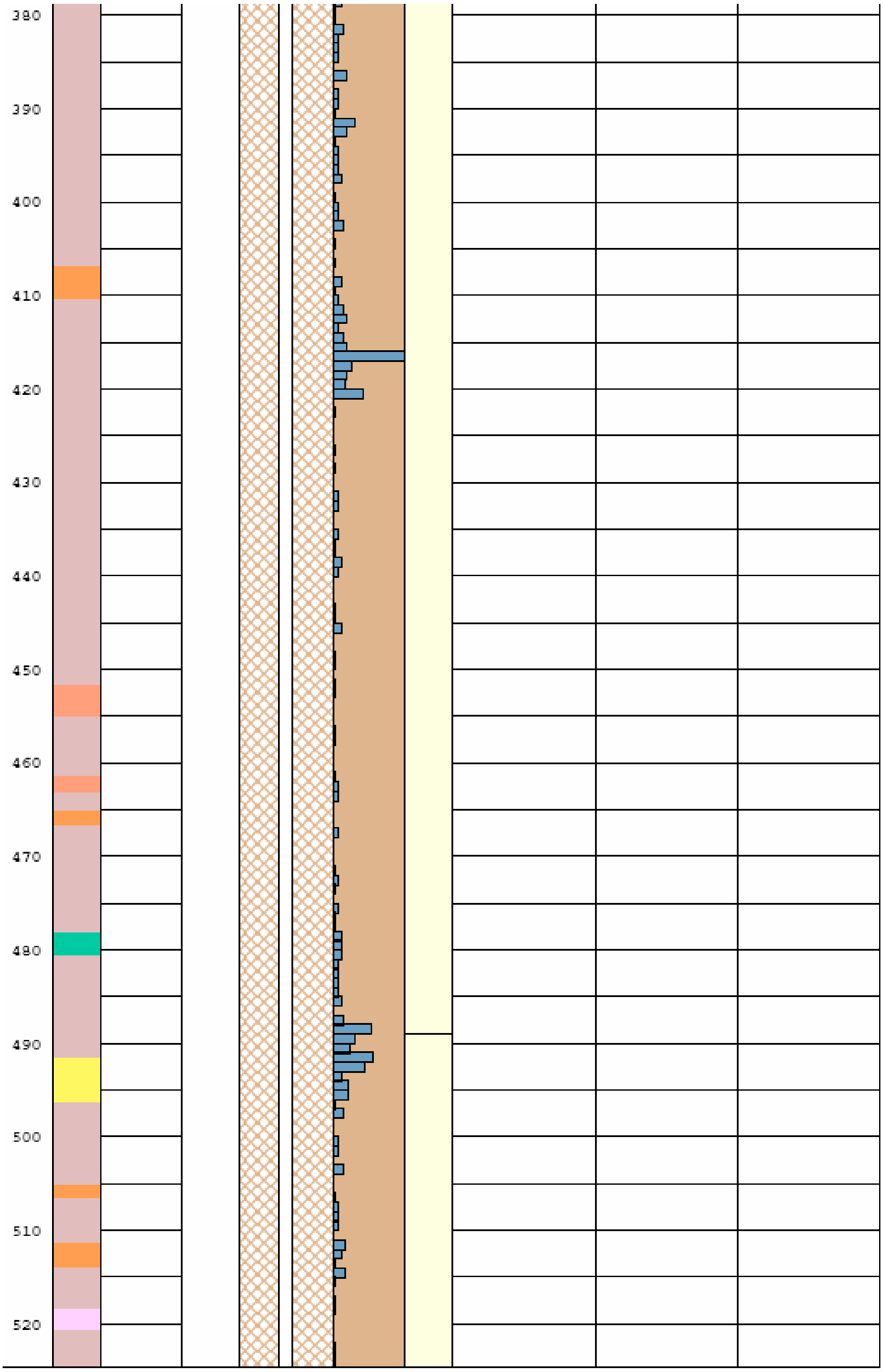

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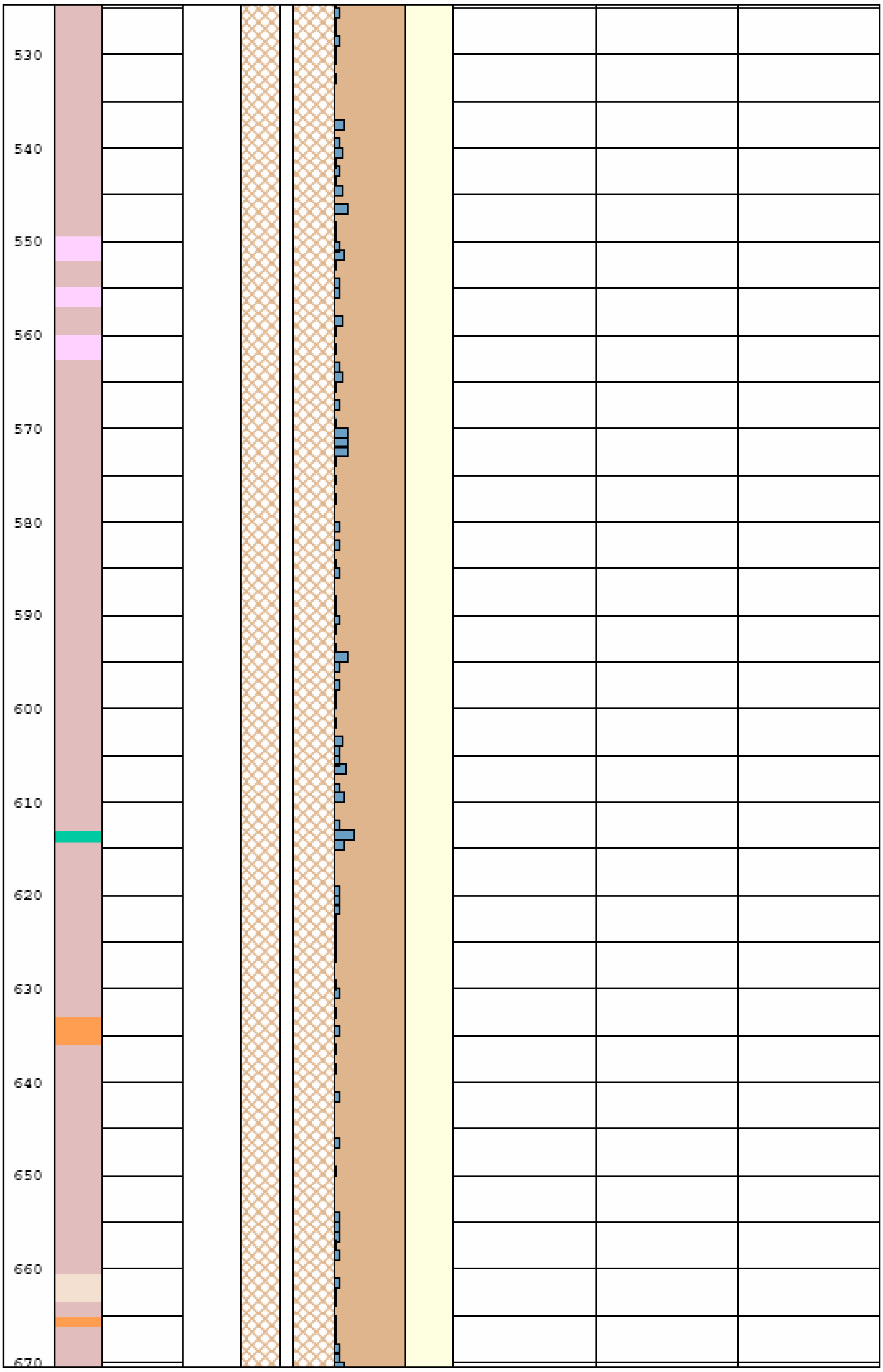
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660
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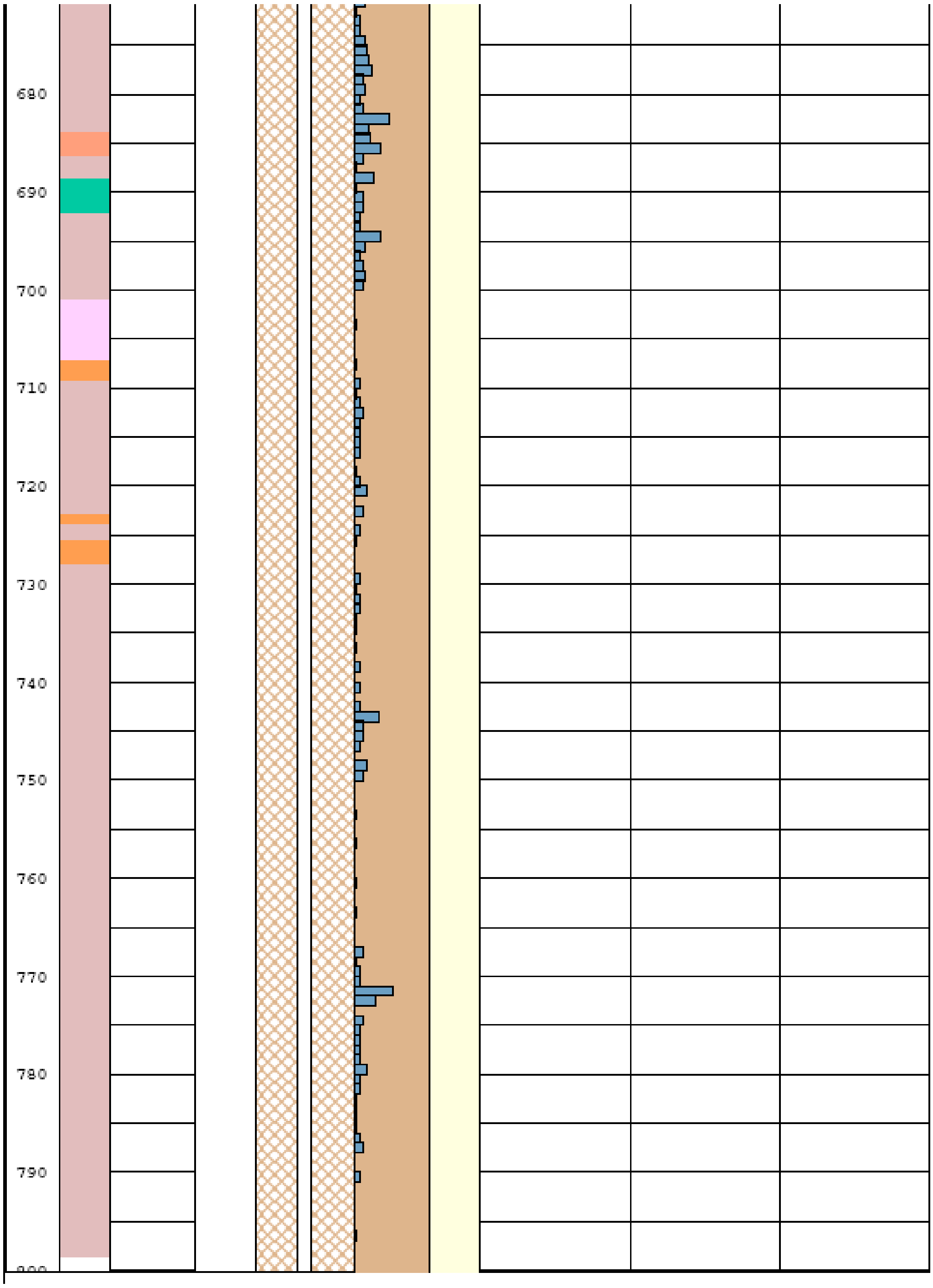
680
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700
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760
770
780
790

Appendix C

Chemical analyses of flushing water from HFM01

Date	IDCODE	Sample No.	Charge Bal%	Na mg/L	K mg/L	Ca mg/L	Mg mg/L	HCO_3^- mg/L	Cl^- mg/L	SO_4^{2-} mg/L	SO4_S mg/L	Br mg/l	F^- mg/L	Si mg/L	Li mg/L	Sr mg/L	TOC mg/L	pH	ElCond mS/m
2006-01-23	HFM01	12067	–1.64	748	21.8	189	55.1	357	1,340	217	77.9	4.63	1.71	7.25	0.023	1.03	7.9	7.68	488
2006-02-13	HFM01	12075	–1.83	736	22.3	176	52.2	360	1,300	205	74.5	7.22	2	6.69	0.217	0.969	7.4	7.68	484

Date	IDCODE	Sample No.	δ^2H ‰ SMOW	^3H TU	$\delta^{18}O$ ‰ SMOW	^{14}C pmC	$\delta^{13}C$ ‰ PDB	$^{10}B/^{11}B$ no unit	$\delta^{34}S$ ‰ CDT	$^{87}Sr/^{86}Sr$ no unit	$\delta^{37}Cl$ ‰ SMOC
2006-01-23	HFM01	12067	–74.9	4.4	–10.4	48.98	–9.28	0.2391	18.6	0.726212	0.00
2006-02-13	HFM01	12075	–76.3	3.9	–10.5	48.5	–9.62	0.2372	25.1	0.72615	–0.04