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Forsmark site investigation

Drilling of the telescopic borehole KFM10A at drill site DS10

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March 2007

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Keywords: AP PF 400-05-109, Percussion drilling, Core drilling, Telescopic borehole, Drill site DS10.

Abstract

The major part of the deep boreholes drilled within the scope of the Forsmark site investigations are performed with so called telescopic technique. The upper c 60–100 metres are percussion drilled in two drilling sequences, pilot drilling with a diameter of about 160 mm, respectively reaming to a diameter of c 200–250 mm. Below the percussion drilled part, the borehole is core drilled with a diameter of approximately 76–77 mm to full length.

Performance of and results from drilling and measurements during drilling of borehole KFM10A, drilled at Forsmark by applying telescopic technique, are presented in this report. This borehole is 500.16 m long, at its starting point inclined 50.05° from the horizon, and reaches about 360 m in horizontal distance. The borehole is primarily intended for geological and hydrogeological studies, but since it is of so called SKB chemical type, it is also specially prepared for detailed hydrogeochemical and microbiological investigations.

During pilot drilling of section 0–60.73 m with the diameter 158.1 mm, an unstable, fractured section, interpreted as a gently dipping fracture zone, was encountered in between 37–56 m. This zone was rather weekly water-yielding, and an inflow of 72 L/min was measured. After reaming to Ø 244 mm, the percussion drilled part was cased with a stainless steel casing, and the gap between the borehole wall and the casing was grouted. These measures entailed that all inflow of groundwater to the percussion drilled part of the borehole ceased.

A relatively complicated flushing water/return water system is applied for core drilling of the telescopic boreholes. The flushing water is prepared in several steps before use, and the return water is taken care of, as to permit drill cuttings to settle before the water is conducted to an approved recipient. During drilling, a number of technical and flushing water/return water parameters are registered in order to obtain a good control of the drilling process and to permit an estimation of the impact on the rock aquifer penetrated by the borehole of flushing water and drilling debris. The conclusion after drilling of KFM10A was that only relatively small amounts of flushing water and drill cuttings penetrated the fracture system.

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 borehole directly on-site. It also served as a basis for extended post-drilling analyses. For example, the drill cores and the samples of drill cuttings, together with later produced video images of the borehole wall (so called BIPS-images), were used for mapping of the borehole (so called Boremap mapping) performed after drilling. A diagram of the Boremap mapping results is included in this report.

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

One experience from drilling of KFM10A is that the quartz-rich bedrock in Forsmark is hard to drill, entailing 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, low fracture frequency and low water-yielding capacity of the major part of the core drilled section of KFM10A.

Sammanfattning

De flesta djupa borrhål inom Forsmarks platsundersökning utförs som s k teleskopborrhål. Det innebär att de övre ca 60–100 metrarna hammarborras i två steg, pilotborrning med dimensionen ca 160 mm följd av upprymning till ca 200–250 mm diameter. Avsnittet därunder kärnborras med 76–77 mm diameter. Resultaten från borrhål KFM10A i Forsmark, som har utförts med teleskopborrningsteknik, redovisas i denna rapport. Borrhålet är ansatt med en lutning av 50,05° från horisontalplanet, är 500,16 m långt och når cirka 360 m i horisontell riktning. KFM10A är primärt avsett för geologiska och hydrogeologiska undersökningar, men eftersom det är utfört som ett så kallat kemiprioriterat borrhål, är det även förberett att utnyttjas för detaljerade hydrogeokemiska och bakteriologiska undersökningar. Därför måste all utrustning som används i borrhålet, både vid borrning och mätning, rengöras och desinficeras enligt speciella instruktioner.

Vid hammarborrning av avsnittet 0–60,73 m med diametern 158,1 mm påträffades ett instabilt, sprucket avsnitt vid ca 37–56 m, vilket tolkades som en flackt stupande sprickzon med ett inflöde av ca 72 L/min. För att stabilisera borrhålet upprymdes det till Ø 244 mm. Därefter kläddes det in med rostfritt foderrör, och slutligen cementinjekterades spalten mellan borrhålsvägg och foderrör, så att allt vatteninflöde i den hammarborrade delen av teleskopborrhålet upphörde.

Under kärnborrningsfasen vid utförandet av teleskopborrhål används ett relativt komplicerat spol- och returvattensystem, där spolvattnet prepareras i olika moment före användning. Returvattnet leds till ett system av containrar, där borrkaxet sedimenterar i två steg innan returvattnet leds vidare till godkänd recipient. Under borrningen registreras ett antal borr- och spolvattenparametrar, så att god kontroll uppnås dels avseende borrningens tekniska genomförande, dels beträffande den påverkan av spolvatten och borrkax som grundvattenakviféren i anslutning till borrhålet utsätts för. Slutsatsen efter borrningen av KFM10A var att endast relativt små mängder spolvatten och borrkax har trängt ut i spricksystemet.

Ett mät- och provtagningsprogram för hammarborrningen och ett annat program för kärnborrningen gav preliminär information om borrhålets geologiska och hydrauliska karaktär direkt under pågående borrning samt underlag för fördjupade analyser efter borrning. Bland de insamlade proverna utgör borrkärnorna från den kärnborrade delen av borrhålet och borrkax-proverna från den hammarborrade delen, tillsammans med videofilm av borrhålsväggen (s k BIPS-bilder), underlaget för den borrhålskartering (s k Boremap-kartering) som utförs efter borrning. Ett resultatdiagram från Boremapkarteringen av KFM10A finns redovisad i denna rapport.

Efter avslutad borrning frästes referensspår in i borrhålsväggen med syftet att användas för längdkalibrering i samband med olika typer av borrhålsmätningar som senare utförs i det färdiga borrhålet.

En erfarenhet från borrningen av KFM10A är att den kvartsrika berggrunden i Forsmark är svårborrad och att borrkroneslitaget är högt. Andra bestående intryck är dels de flacka, vattenförande zoner som påträffades i den övre delen av KFM10A, dels att, omvänt, sprickfrekvensen och vattenföringen i större delen av det kärnborrade partiet av borrhålet visade sig vara 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 respectively 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 technique. So far (March 2007), three sub-vertical and eight inclined, approximately 800–1,000 m long, cored boreholes have been drilled within the investigation area. Besides the deep holes, twelve semi-deep (c 100–900 m borehole length) boreholes have been core drilled. The locations of the drill sites in question, DS1 to DS12, are illustrated in Figure 1-1.

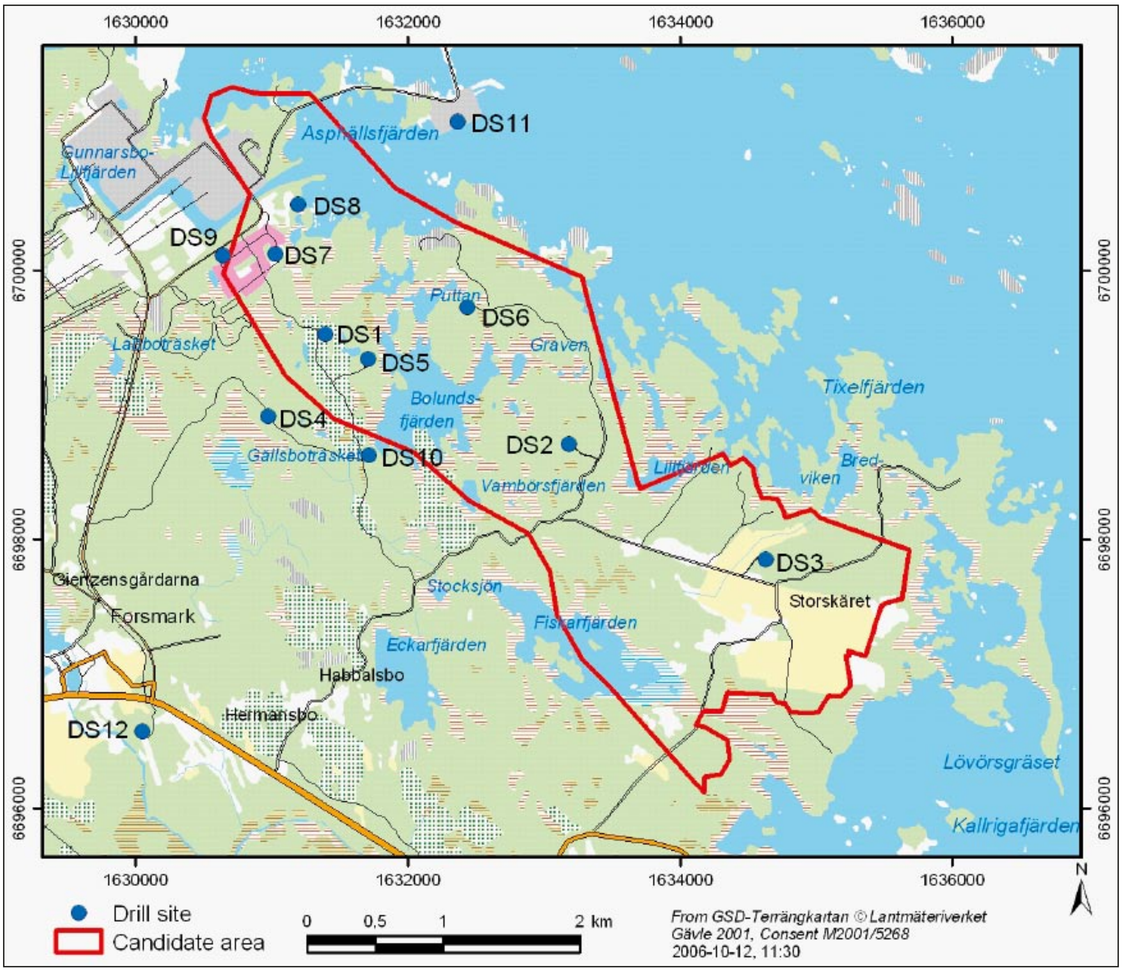

Figure 1-1. *The site investigation area at Forsmark including the candidate area selected for more detailed investigations. Drill sites DS1-12 are marked with blue dots.*

This document reports the data and results gained by drilling the semi-deep telescopic borehole KFM10A at drill site DS10, which is one of the activities included in the site investigations at Forsmark. The work was carried out in compliance with Activity plan AP PF 400-05-109.

In Table 1-1 controlling documents for performing this activity are listed. Both activity plans, method descriptions and method instructions are SKB's internal controlling documents.

By drilling many (although not all) of the deep 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 (≥ 200 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 KFM10A, which has a total drilling length of 500.16 m. The borehole is inclined c 50 degrees from the horizontal plane, entailing that the horizontal extension of the borehole is approximately 360 m. Borehole KFM10A is of the so called SKB chemical-type. This implies that the borehole, besides 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 DS10 is located just south of the candidate area, c 2.5 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 KFM10A, also percussion drilled boreholes in soil and solid rock have been drilled for different purposes at DS10.

The lengths of these boreholes vary between a few metres to approximately 151 m. The locations of all boreholes at drill site DS10 are shown in Figure 1-2.

Drilling of KFM10 was performed during two periods, between Dec 6th to Dec 19th, 2005, (percussion drilling) and March 14th to June 1st, 2006, (core drilling). Drillcon Core AB, Nora, Sweden, was engaged for the drilling commission. Two different drilling equipments were employed for drilling KFM10A, a percussion drilling machine for drilling the upper c 60 metres, whereas core drilling of the remaining part (section 60.73–500.16 m) was carried out with a wireline core drilling system.

In the present report, performance of and results from drilling of KFM10A are presented. The report also treats investigations made during and immediately after drilling. All data are stored in the SICADA database, and are traceable by the activity plan number.

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

Activity plan	Number	Version
Borrning av teleskopborrhål KFM10A	AP PF 400-05-109	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för hammarborrning	SKB MD 610.003	2.0
Metodbeskrivning för kärnborrning	SKB MD 620.003	1.0
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

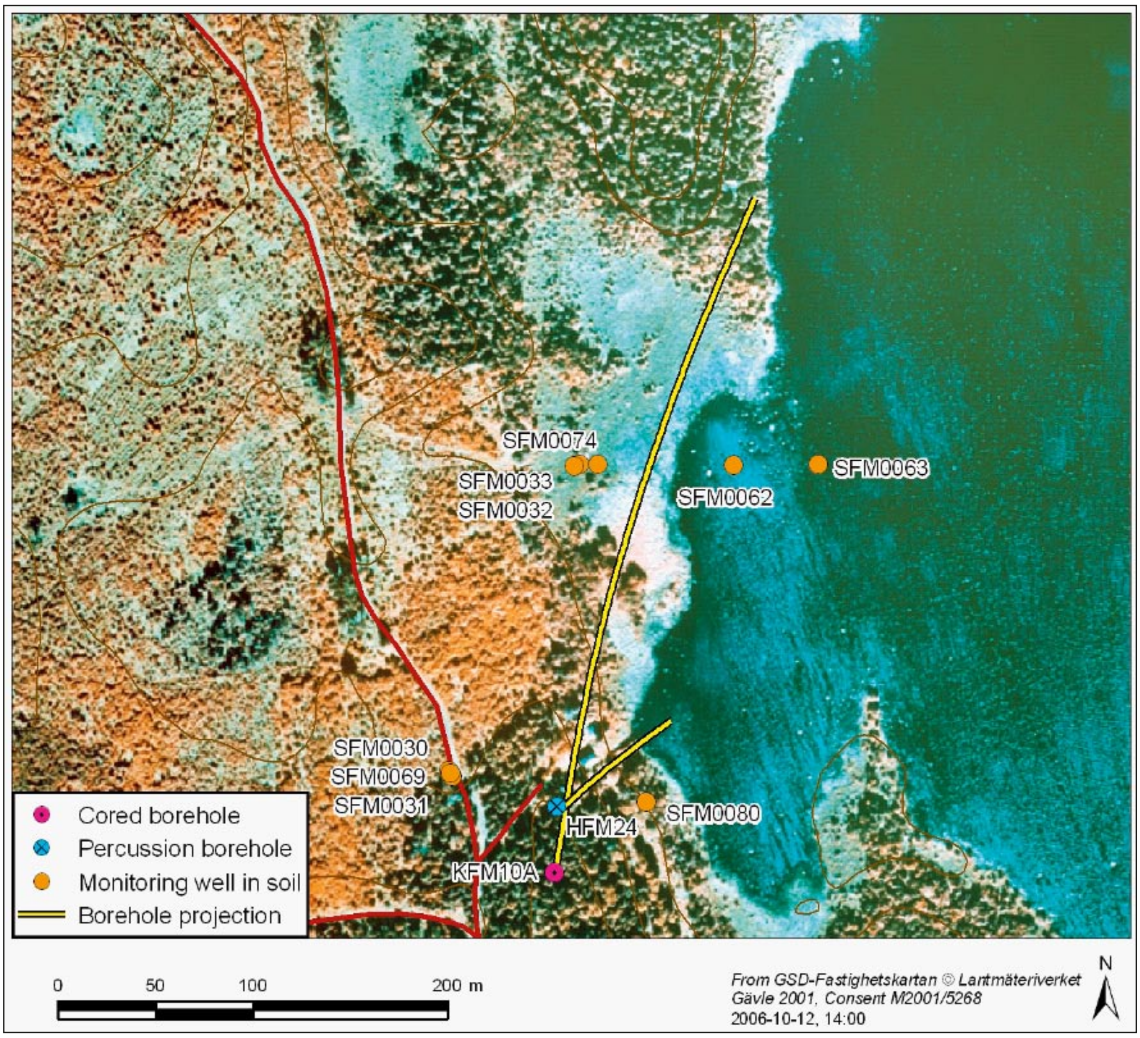

Figure 1-2. *Borehole locations at and near drill site DS10. Besides the core drilled borehole KFM10A, the area incorporates a monitoring well in bedrock (HFM24) and one monitoring well in the unconsolidated overburden (SFM0080). The projection of inclined boreholes on the horizontal plane at the ground surface (top of casing) is shown in the figure.*

2 Objective and scope

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

- To provide rock samples from the ground surface to the borehole bottom. Percussion drilling through the overburden produces soil samples recovered to the surface by compressed air. These samples are collected with a frequency of one sample per metre. The same sampling frequency is applied for the drill cuttings produced when percussion drilling the upper c. 60–100 m of the solid rock. Below, the core drilling provides (in principle) continuous drill cores down to the borehole bottom. The rock samples collected during drilling are used for lithological, structural and rock mechanical characterization as well as for determination of transport properties of the bedrock from the rock surface to the full drilling depth.
- To render geophysical borehole investigations possible, e.g. TV logging, borehole radar logging and conventional geophysical logging as an aid for the geological/rock mechanical characterization.
- To allow hydraulic borehole tests (single hole tests as well as interference tests, 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 KFM10A. A specific objective for borehole KFM10A was to investigate the major fracture zone ZFMNE00A2 as well as the minor zones ZFMNE0123 and ZFMNE103.

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.

Furthermore, a number of hydraulic tests and water samplings are normally performed during the drilling process, whereby a specifically designed test system, a so called wireline probe, is utilized.

3 Equipment

Two types of drilling machines were employed for drilling borehole KFM10A. The upper c 60 metres were drilled with a percussion drilling machine of type Puntel MX 1000. For core drilling of section 60.73–500.16 m, a Corac N wireline core drilling system, type Diamec 282E, was engaged.

3.1 Percussion drilling equipment

The Puntel percussion machine is equipped with separate engines for transportation and power supplies. Water and drill cuttings were retrieved from the borehole by a 12.5 bars air-compressor, type Atlas-Copco GA75P-13.

At drill site DS10, the bedrock is covered by approximately one metre of gravel. This part had to be cased off with a solid pipe (NO-X 280). To obtain 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 KFM10A are presented in Section 5.2.

3.2 Injection 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 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 KFM10A was grouted after installation of the $Ø_i$ 200 mm, 60 m long casing. Gap injection through a packer was applied and a few days later the grouting was completed by filling the gap between the casing and the borehole wall up to surface with use of a hose.

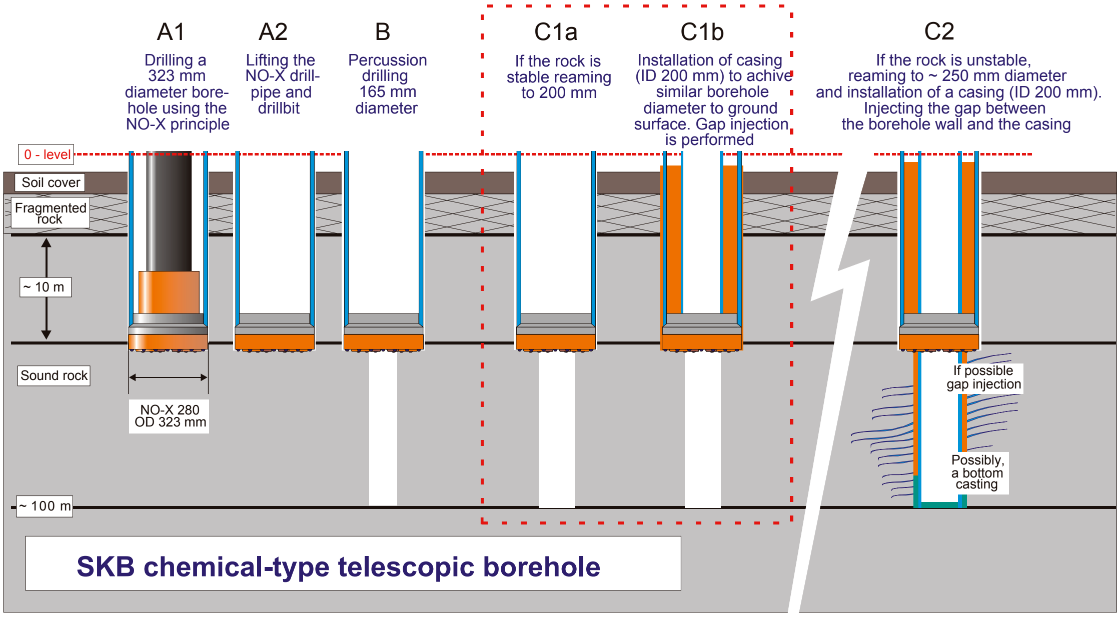

Figure 3-1. Schematic diagram showing the various stages of drilling the 0–100 m section of an SKB chemical-type telescopic borehole. The letters and numerals above each stage refer to some of the operations described in Sections 3.4.1 and 3.4.2 in SKB MD 620.003, Version 1.0.

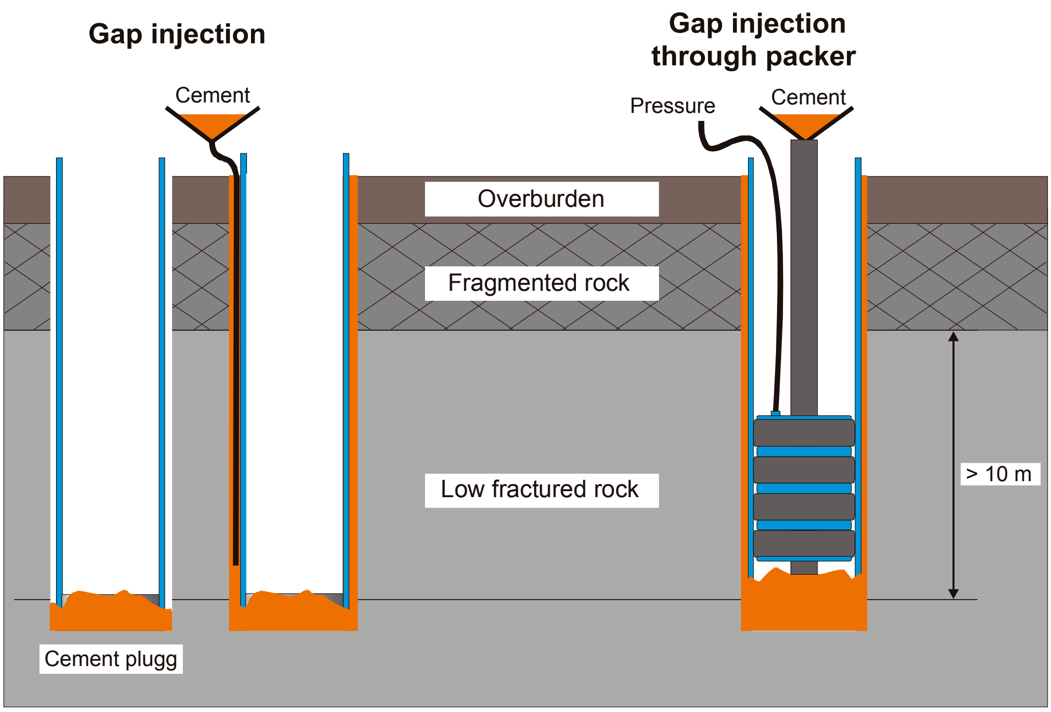

Figure 3-2. Gap injection techniques. In order to fill the gap between the borehole wall and the casing, different techniques may be applied. To the left, a flexible hose is lowered between the casing and the borehole wall, and to the right the grouting is performed through a borehole packer.

3.3 Core drilling equipment

3.3.1 The wireline-76 system

For drilling the cored part of borehole KFM10A, a Corac wireline system, type Diamec 282E, was employed. The drilling process is operated by an electrically-driven hydraulic system supplied with a pilot steering. The drilling capacity with AC Corac N3/50 NT drill pipes is maximum c 900 metres. The drill pipes and core barrel used fulfil SKB´s demand for a triple-tube system. Technical specifications of the drilling machine with fittings are given in Table 3-1.

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.

Table 3-1. Technical specifications of the Diamec 282E-system from Atlas Copco with appurtenances.

Unit	Manufacturer/Type	Specifications	Remarks
Diamec 282E	Atlas Copco	Capacity for Corac N3/50NT pipes is maximum approx. 900 m	
Flush water pump	Trido 140 H	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	300 KVA, Diesel engine Volvo TAD1032GE	
Compressor	Atlas Copco GA75P-13	Max pressure: 12.5 bars Flow: Max 169 L/sec	Electrically supplied

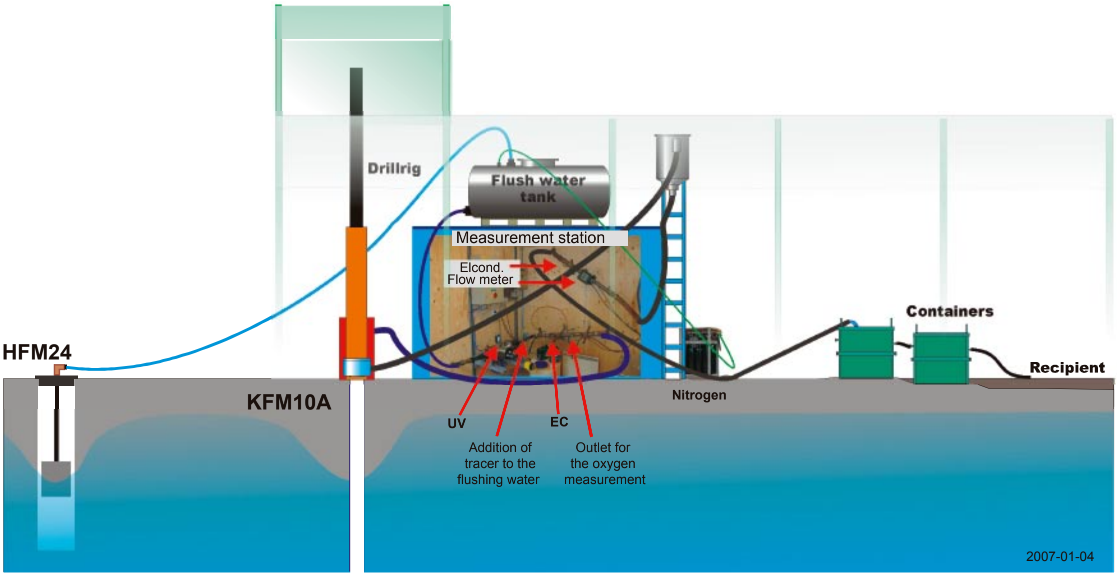

Figure 3-3. *Schematic illustration of the flushing/return water system when drilling KFM10A at DS10. The measurement station included logger units and an UV-radiation unit. For flushing water flow rate and pressure measurements, the drilling machine gauges were applied.*

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 content 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.

The water well used for the supply of flushing water for core drilling of KFM10A was a percussion drilled well in hard rock, HFM24, situated at DS10 approximately 20 m from KFM10A. The water quality from the HFM24 well had been analysed and considered as sufficiently good to serve as flushing water for KFM10A.

Besides these basic demands on the flushing water quality, which were fulfilled when drilling KFM10A, the flushing water was also prepared in three steps before use, in accordance with SKB MD 620.003 (Method description for core drilling).

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

Measurement of flushing water parameters

The 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 counting the number of filled water tanks used, multiplied by the tank volume.

Air-lift pumping while drilling

Air-lift pumping during core drilling involves pumping of compressed air into the percussion drilled portion of the telescopic borehole, forcing it to emerge at a depth of about 40–60 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 KFM10A consisted of the following main components, see Figure 3-4:

- Compressor, 12 bars/10 m^3/min.
- 60.5 m outer support casing, 98/89 mm diameter.
- 62.5 m inner support casing, 84/77 mm diameter.
- PEM hose: 20 bars, 22 mm diameter, 240 m.
- PEM hose: 20 bars, 40 mm diameter, 120 m.
- Expansion vessel (= discharge head).
- Pressure sensor, 10 bars, instrumentation and data-logging unit.
- Electrical supply cubicle, at least 16 A.
- Ejector tube.

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

Instrument	Manufactorer/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		

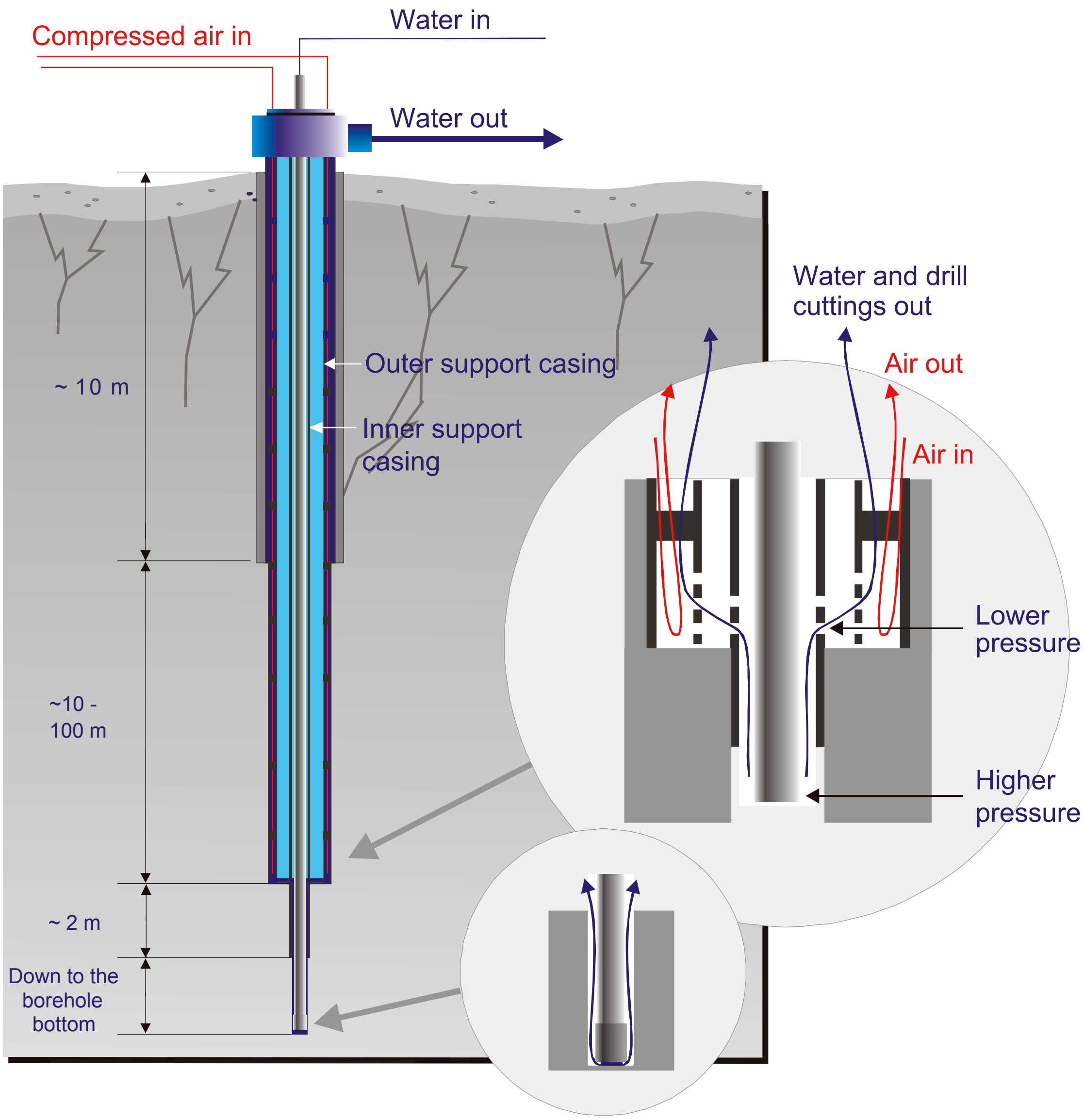

Figure 3-4. *Air-lift pumping during core drilling of a telescopic borehole. Schematic representation, where the drilling depths are only approximate. The air and instrumentation hoses are secured to the outer support casing. The compressed air raises the flushing water and drill cuttings from the hole. 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, it was lowered into the borehole together with the hoses for air-lift pumping with a mobile crane. The ejector tube was fit to the outer support casing, about 200 mm above the bottom of the telescopic borehole. A 22 mm supply hose and a 40 mm return hose were connected to the ejector tube as shown in Figure 3-5. With this construction, the air leaving the ejector rose, reducing the pressure in the lower part of the ejector tube, helping to lift drill cuttings from the bottom of the hole.

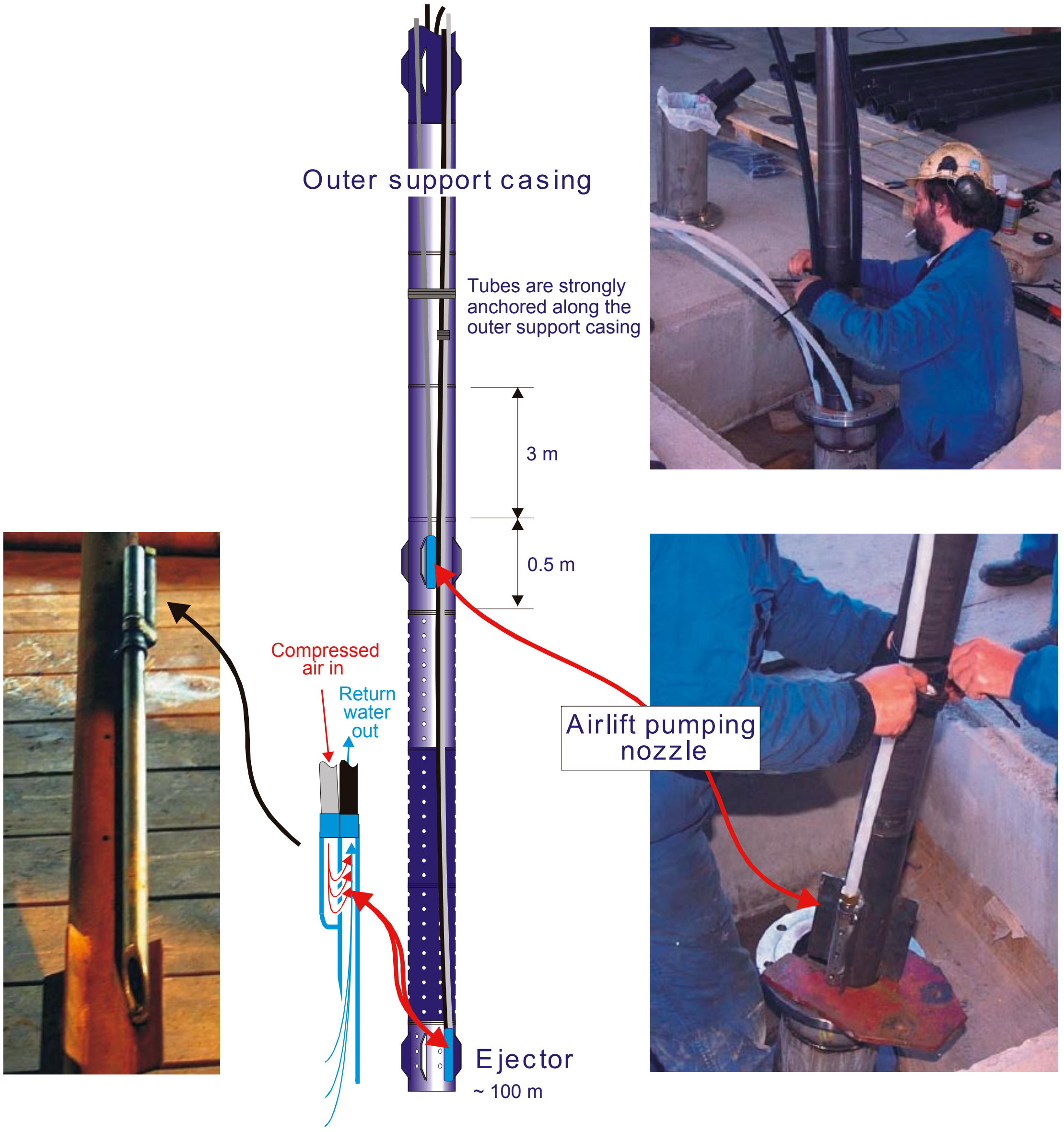

Figure 3-5. *Schematic representation of connection and installation of air-lift pumping nozzle and ejector on the outer protective casing.*

Storage and discharge of return water for KFM10A

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 recipient, Bolundsfjärden.

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

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.

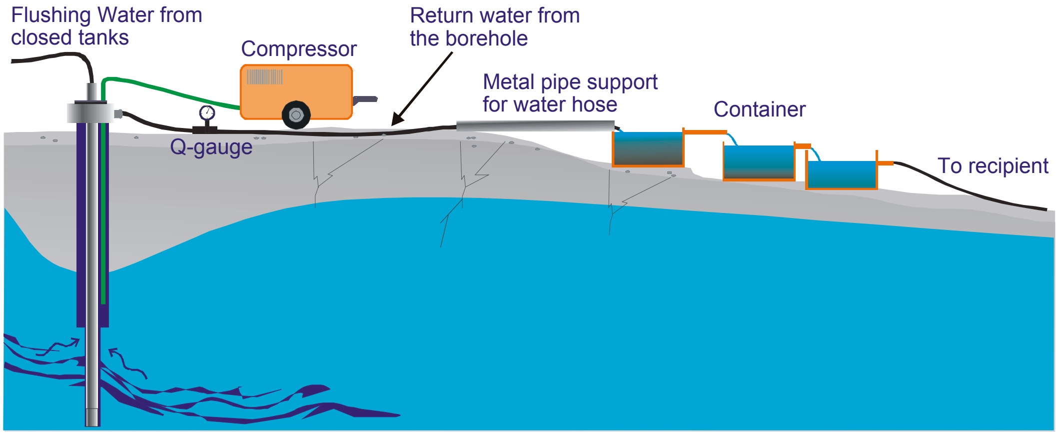

Figure 3-6. *Return water system. Air-lift pumping raises the return water, consisting of flushing water, groundwater and drill cuttings, from the borehole. The cuttings separate out in three stages in the containers (where it is preserved for later weighing), after which the water is pumped to an approved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

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

Instrument	Manufactorer/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 Diamec drilling machine had no computer system for logging the drill parameters. Therefore a couple of manually notes were made in the driller´s logg.

The following notes were registered: sudden change in penetration rate and sudden drop in feed force. Both types were noted by length but without quantification. The lengths were marked with a decimetre accuracy.

However, during drilling of KFM10A, registration also include 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 content.

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

3.3.4 Groove milling equipment

After completion of drilling, the borehole is 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

During drilling of borehole KFM10A, deviation measurements were made after completed drilling, in order to check the straightness of the borehole. The measurements were initially performed 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 KFM10A in order to check the validity of the MAXIBOR™ measurements. The surveying instrument used was the FLEXIT Smart Tool System.

At the time of drilling KFM10A, the MAXIBOR™-method was assessed as the most reliable of different deviation methods tested by SKB, and MAXIBOR-data stored in the database SICADA were normally assigned as the only deviation data set permitted to be used (so called "in use displayed data") even if another or several deviation methods had been applied in a borehole as well. However, in connection with a major quality revision regarding orientation of all identified geological objects (fractures, fracture zones rock contacts etc) conducted by SKB during late autumn 2006 to winter/early spring 2007, a reassessment of the reliability of deviation measurement methods was made, whereby the FLEXIT-method was judged as providing the most reliable results. Therefore a revision was made also for borehole KFM10A, and to-day FLEXIT-data are the in use displayed deviation data set. However, all available deviation measurements, i.e. for borehole KFM10A FLEXIT- as well as MAXIBOR-data have been used for estimation of the uncertainty of deviation data.

Results from the deviation measurements and data handling are presented in Section 5.4.9.

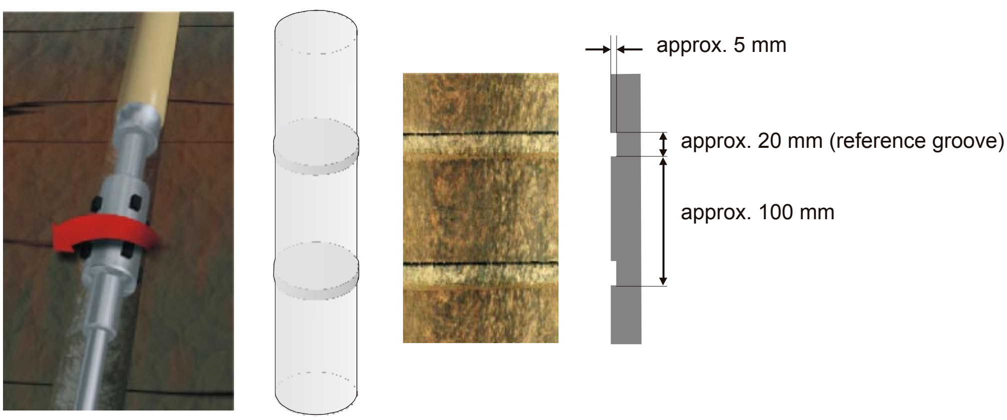

***Figure 3-7.** Layout and design of reference grooves.*

4 Execution

4.1 Percussion drilling of borehole section 0–60 m in KFM10A

The percussion drilling operations included:

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

The first four items are treated in the present section (Section 4.1), whereas the last two activities, together with the corresponding items for core drilling, are presented in Sections 4.3 and 4.4.

4.1.1 Preparations

The preparation stage included the Contractor's service and function control of his equipment. The machinery was obliged to be supplied with fuel, oil and grease exclusively of the types stated in SKB MD 600.006, see Table 1-1. Finally, the equipment was cleaned in accordance with the cleaning instruction in SKB MD 600.004, see Table 1-1, for boreholes of SKB chemical type.

4.1.2 Mobilization

Mobilization onto and at the site included preparation of the drill site, transport of drilling equipment as well as of sampling pots for soil and drill cuttings, hand tools and other necessary outfit. Furthermore, the mobilization included cleaning of all in-the-hole equipment at level two in accordance with SKB MD 600.004, lining up the machine and final function control.

4.1.3 Drilling, measurements and sampling during drilling

The percussion drilling started with drilling through the overburden during simultaneous casing driving (NO-X 280) 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 12.31 m. The continued percussion drilling through solid rock was performed with a 158.1 mm drill bit to 60.73 m drilling length. For stabilization of the entire percussion drilled part, the borehole was reamed to 244.0 mm to 60.68 m length and a stainless steel $Ø_i$ 200 mm casing was then installed to 60.39 m length.

Before installing the casing, 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.

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 technique 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 158.1 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 content was 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.

Results from the remaining measurements and observations are presented in Chapter 5.

4.1.4 Finishing off work

Finishing off work included measurements of the final diameter of the drill bit after reaming to Ø 244.0 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.

4.1.5 Nonconformities

The length of the percussion drilled part of KFM10A became 60.73 m instead of 40–50 m as suggested in the activity plan.

4.2 Core drilling of KFM10A

The core drilling operations included:

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

The first four items are presented in Section 4.2, while the last two activities are referred to in Sections 4.3 and 4.4.

4.2.1 Preparations

As for percussion drilling, 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.

4.2.2 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, hand tools etc. Furthermore, the mobilization included cleaning of all in-the-hole equipment at level two in compliance with SKB MD 600.004, lining up the machine and final function control of all equipment.

4.2.3 Drilling, measurements and sampling during drilling

Core drilling of borehole KFM10A was performed with two borehole dimensions. Section 60.73–62.68 m was drilled with a borehole diameter of 86.0 mm, whereas the main part of the borehole, section 62.68–500.16 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 during drilling resting on the bottom of the percussion drilled borehole, see Figure 3-4.

Core drilling with Ø 75.8 mm of the main part of the borehole 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 drill pipe string, inside which it is hoisted up with the wireline winch. During drilling of borehole KFM10A, 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.

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, for different reasons, during drilling of KFM10A 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 4.2.4, Table 4-1, together with the actual performance when drilling KFM10A.

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.

Besides the activities mentioned in Table 4-1, 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 10 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, injected into the fracture system 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 percussion drill rig, a stainless steel transition cone was installed between the reamed and cased percussion drilled respectively the cored part of the borehole, as shown in Figure 5-4. The cone is located at 57.25–62.35 m.
7) The borehole was again secured with the lockable stainless steel flange.
8) The core drilling equipment was removed, the site cleaned and a joint inspection made by SKB and the Contractor.

4.2.4 Nonconformities

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

Comments: 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 get a measure of the drill cuttings recovery.

When the support casing was to be recovered it was stacked in the borehole and during an attempt with an air-operated hammer the pipe seam in the casing was broken. The work was temporarily interrupted.

An new attempt to release the support casing, now with a percussion drilling machine on Aug 2nd to Aug 3rd, 2006, failed. A decision was made to mill the borehole with an Onram 1000 core drilling rig. It started Aug 7th and was done Aug 21st, 2006. The transition cone was installed Aug 22nd, 2006.

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 KFM10A.

Activity	Performance and frequency according to SKB MD 620.004	Performance and frequency during drilling of KFM10A
Registration of drilling- and flushing water parameters.	Described in Section 3.3.2. Registration during the entire drilling.	No registration of drilling parameters. Flushing water parameters: 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.	Two measurement after completion of drilling with the MAXIBOR-system and two with the FLEXIT-system.
Measurements of the difference in length between the compressed drill pipe string and as extended by its own weight.	Normally performed every 100 m.	Values presented in Figure 5-15 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 drill pipe string should be controlled before each test.	No test.
Water sampling.	Normally performed every 100 m, and also when penetrating larger conductive fractures/zones. The tightness of the drill pipe string should be controlled before each test.	No test.
Absolute pressure measurements.	Normally during natural pauses in drilling.	No test.
Groove milling in the borehole wall, normally at each 100 m.	Normally performed after completion of drilling.	Eight grooves performed. All grooves were detectable.
Collecting and weighing of drilling debris.	Drilling debris settled in containers weighed after finished 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 and including nitrogen.	According to programme.

4.3 Data handling

4.3.1 Performance

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

4.3.2 Nonconformities

None.

4.4 Environmental programme

4.4.1 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.

4.4.2 Nonconformities

None.

5 Results

Original data from the reported activity are stored in the primary database SICADA. Data are traceable in SICADA by the Activity plan number (AP PF 400-05-109). 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.

This chapter is structured as follows:

- Section 5.1 – an overview of the drilling progress
- Section 5.2 – geometrical data and technical design
- Section 5.3 – results from percussion drilling
- Section 5.4 – results from core drilling

Well Cad plots are composite diagrams presenting the most important technical and geo-scientific results from drilling and investigations made during and immediately after drilling. Well Cad presentations of boreholes KFM10A are shown in:

- Appendix A (percussion drilled part)
- Appendix B (the complete borehole)
- Appendix C (analyses from flushing water)

5.1 Drilling progress KFM10A

The drilling operations were performed during two periods between Dec 6th to Dec 19th, 2005, (percussion drilling) and March 14th to June 1st, 2006, (core drilling), see Figure 5-1.

5.1.1 Percussion drilling 0–60.73 m

Percussion drilling is normally a rapid drilling method compared to core drilling. However, the relatively complex approach applied for the drilling and especially the grouting sequences when drilling KFM10A, resulted in a working period from 2005-12-06 to 2005-12-19 (Figure 5-2).

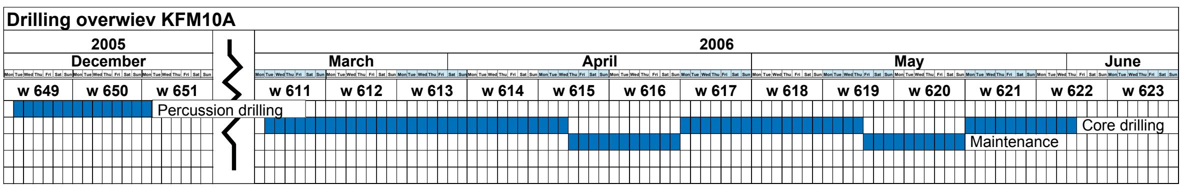

Figure 5-1. Overview of the drilling performance of borehole KFM10A.

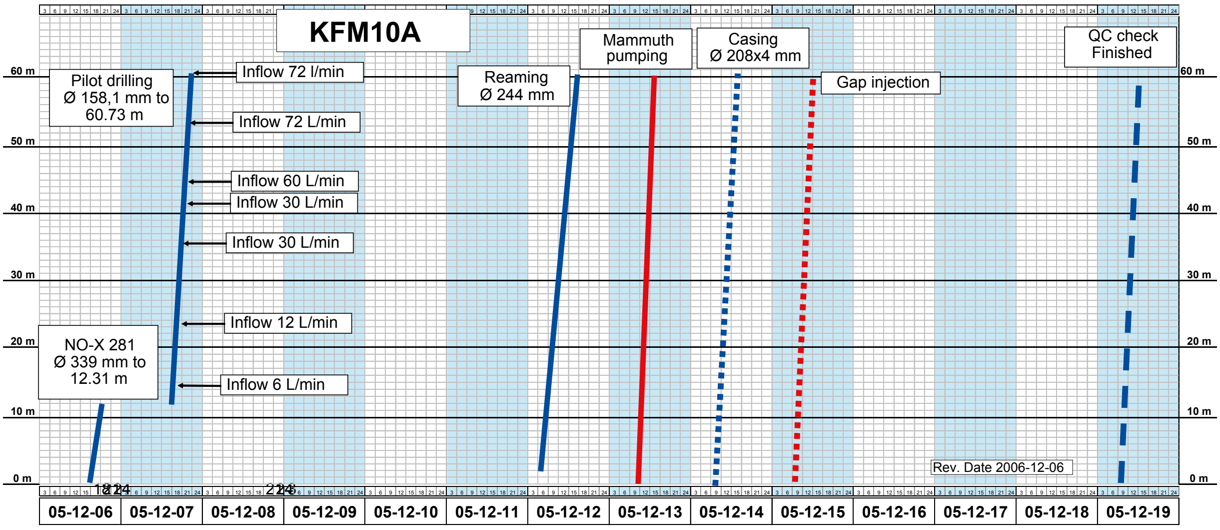

Figure 5-2. Percussion drilling progress (depth and activity versus calendar time). "Inflow" in the figure refers to accumulated groundwater inflow.

5.1.2 Core drilling period

After percussion drilling of section 0–60.73 m, after which followed a break of three months, core drilling commenced. The progress of the core drilling from 2006-03-14 to 2006-06-01, is presented in Figure 5-1. The pace of drilling decreases versus time, due to with increasing borehole length, retrieval of the core barrel, e.g. for change of drill bit, becomes more and more time consuming.

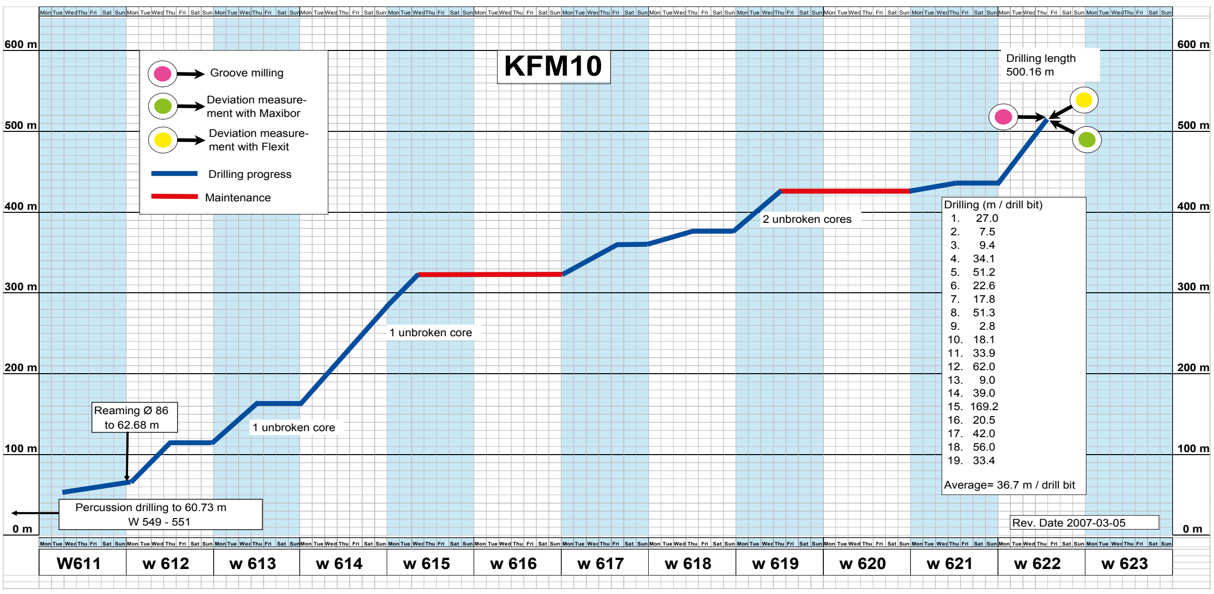

Figure 5-3. Drilling progress (depth and activity versus calendar time).

5.2 Geometrical and technical design of borehole KFM10A

Administrative, geometric and technical data for the telescopic borehole KFM10A are presented in Table 5-1. The technical design is illustrated in Figure 5-4.

Table 5-1. Administrative, geometric and technical data for borehole KFM10A.

Parameter	
Borehole name	KFM10A
Location	Forsmark, Östhammar municipality, Sweden
Drill start date	Dec 06, 2005
Completion date	June 01, 2006
Percussion drilling period	2005-12-06 to 2005-12-19
Core drilling period	2006-03-14 to 2006-06-01
Contractor core drilling	Drillcon Core AB
Subcontractor percussion drilling	Sven Andersson i Uppsala AB
Percussion drill rig	Puntel MX 1000
Core drill rig	Diamec 282E
Position at top of casing (RT90 2.5 gon V 0:-15 / RHB 70)	N 6698629.17 E 1631715.90 Z 4.51 (m.a.s.l.) Azimuth (0–360°):10.42° Dip (0–90°): –50.05°
Position at bottom of hole (RT90 2.5 gon V 0:–15 / RHB 70)	N 6698974.66 E 1631819.10 Z –338.08 (m.a.s.l.) Azimuth (0–360°): 24.77° Dip (0–90°): –34.87°
Borehole length	500.16 m
Borehole diameter and length	From 0.00 m to 12.31 m: 0.339 m From 12.31 m to 60.68 m: 0.244 m From 60.68 m to 60.73 m: 0.158 m From 60.73 m to *62.68 m: 0.086 m From 62.68 m to 500.16 m: 0.076 m * The Ø 86 mm borehole was extended to ensure a clean borehole when the casing was removed and before the transition cone was installed.
Casing diameter and drilling length	$Ø_o/Ø_i$ = 323 mm/310 mm to 12.23 m Casing shoe $Ø_i$ = 281 mm between 12.23 and 12.31 m $Ø_o/Ø_i$ = 208 mm/200 mm to 60.34 m Casing shoe $Ø_i$ = 170 mm between 60.34 and 60.39 m
Transition cone outer and inner diameter	At 57.25 m: 0.195 m At 62.35 m : 0.080 m
Drill core dimension	60.73–62.51m/ Ø 60 mm 62.51–500.16 m/ Ø 51 mm
Core interval	60.73–500.16 m
Average length of core recovery	2.54 m
Number of runs	173
Diamond bits used	19
Average bit life	36.70 m

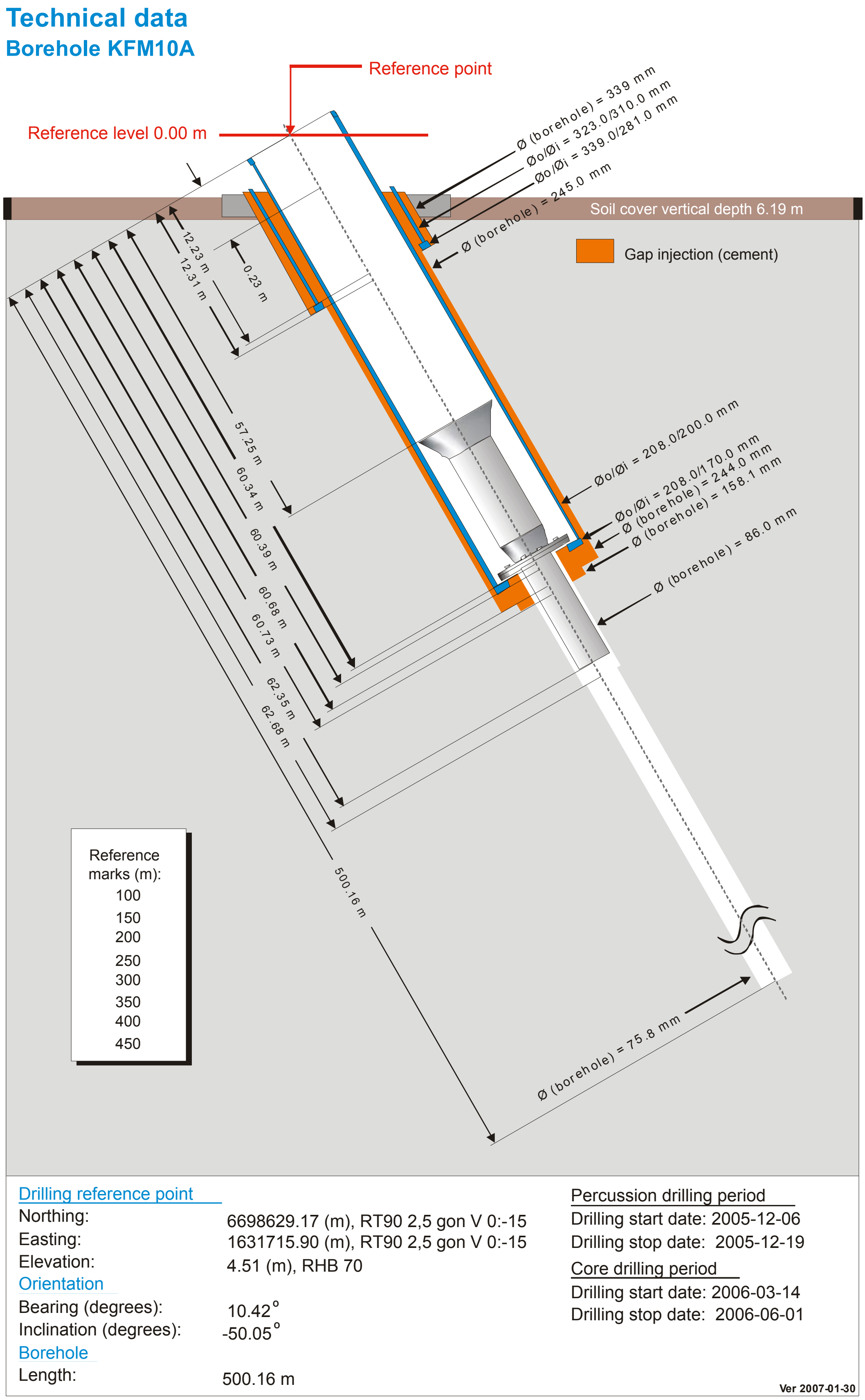

Figure 5-4. *Technical data of borehole KFM10A.*

5.3 Percussion drilling KFM10A 0–60.73 m

5.3.1 Drilling

As mentioned in Section 4.1.3, the upper 12.31 m of the borehole was drilled and cased with NO-X 280. During pilot drilling to 60.73 m moderately fractured rock and an inflow of 72 L/min was observed. The fact that the borehole is inclined more than usual (50.05º) implies a higher risk of outfall from the borehole wall, and therefore the borehole section to 60.68 m was reamed to 244 mm and a stainless steel casing was installed, Finally, the gap between the casing and the borehole wall was cement grouted, so that the water inflow ceased completely.

5.3.2 Measurements while drilling

During, and immediately after drilling, a program for sampling and measurements was applied, cf Section 4.1.3. Some of the results are displayed in the Well Cad presentation in Appendix A (penetration rate and rock type distribution), whereas other results (flow data and electrical conductivity) are only used as supporting data for on-site decisions.

5.4 Core drilling KFM10A 60.73–500.16 m

5.4.1 Drilling

The bedrock within the so called Forsmark tectonic lens has appeared to be relatively hard to drill, probably to a large extent depending on the high quartz content. As drill site DS10 is located in the centre of the tectonic lens, the bedrock composition was prior to drilling assumed to be of similar character. The upper 150 metres of the bedrock at DS10 are though more fractured, which resulted in longer life-time of the drill bits. However, in average, the life-time was 36.7 m drilled metres per drill bit in KFM10A, which is much lower than more recently drilled boreholes. On the other hand there is a broad variation of the life-time, and actually the longest life-time observed for a drill bit during the site investigations (169 m) was also recorded when drilling KFM10A. The life-time of a drill bit is probably depending on the skill of the drillers and on the condition of the drilling machine as much as on anything else.

On the whole, even if there is a positive trend for developing drill bits with longer life-time, core drilling in the Forsmark granite is still more time consuming and costly than in average granites.

5.4.2 Measurements while drilling

During, and immediately after drilling, a program for sampling, measurements, registration of technical and geoscientific parameters and some other activities was applied, as described in Section 4.2.3. The results are presented in Sections 5.4.3–5.4.13 below.

Mapping of the drill core samples from KFM10A is presented in /3/.

5.4.3 Registration of drilling parameters

Only two manually observed parameters are noted in the driller´s log, i.e. sudden change in penetration rate and sudden drop in feed force. Both types were noted by length but without quantification. The lengths were marked with a decimetre accuracy.

5.4.4 Registration and sampling of flushing water and return water

Flushing water and return water flow rate – water balance

As borehole KFM10A 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 pipeline, 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 content of the Uranine tracer dye in the flushing water and return water. This enables a mass balance calculation from which the flushing water content in the borehole can be determined.

Figure 5-5 illustrates the accumulated volume of flushing water and return water versus time during core drilling, while Figure 5-6 displays the accumulated volumes of flushing water and return water from the entire drilling period, giving a return water/flushing water quotient of 1.93 (results from Uranine measurements are presented in the next section).

However, in Figure 5-5 a loss of flushing water at shallow depths in the borehole is observed, as well as a significant excess of return water at depths exceeding c 480 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 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.

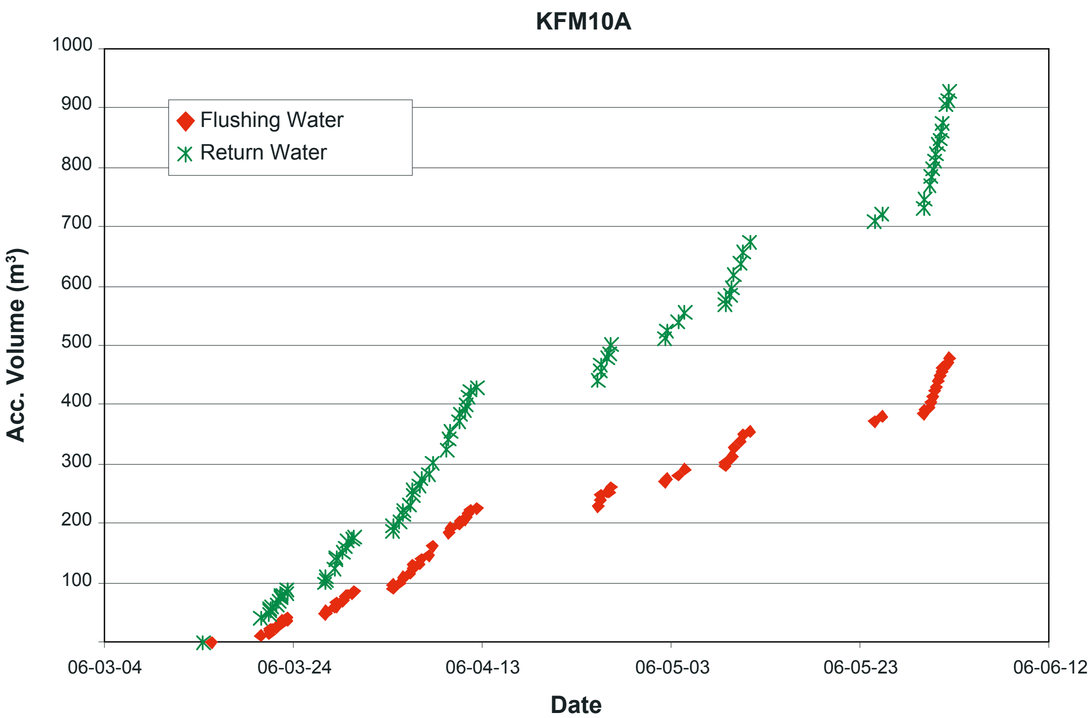

Figure 5-5. *Accumulated volumes of flushing water (red) and return water (green) versus time during core drilling of borehole KFM10A.*

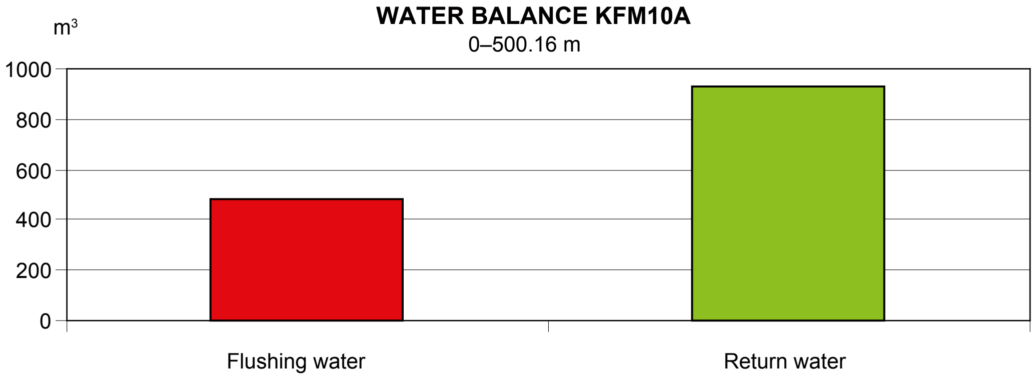

Figure 5-6. Total amounts of flushing water and return water during drilling of borehole KFM10A. The total volume of flushing water used during core drilling was amounted to 479 m³. During the same period, the total volume of return water was 926 m³. The return water/flushing water balance is then as high as 1.93, due to the large inflow of groundwater into the upper part of the cored borehole.

Uranine content 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 content of Uranine was performed systematically with a frequency of approximately one sample per every fourth hour during the drilling period, see Figure 5-7. Like in all boreholes drilled during the site investigation except 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.

Usually, a mass balance calculation of the accumulated volumes of flushing water and recovered flushing water in the return water suggests that flushing water is lost in the borehole. According to notations in the logbook, the amount of Uranine added to the borehole was 95 g. If the averages of the Uranine concentration values in the flushing water and in the return water are used to calculate the amount of Uranine added to and recovered from the borehole, the calculations give 84 g and 116 g respectively. Because a higher amount of Uranine cannot be recovered from the borehole than added to it, the calculation using average values has in this borehole resulted in an unacceptably high unreliability. After finished drilling, the water chemistry sampling in KFM10A also showed that flushing water still remain in the borehole.

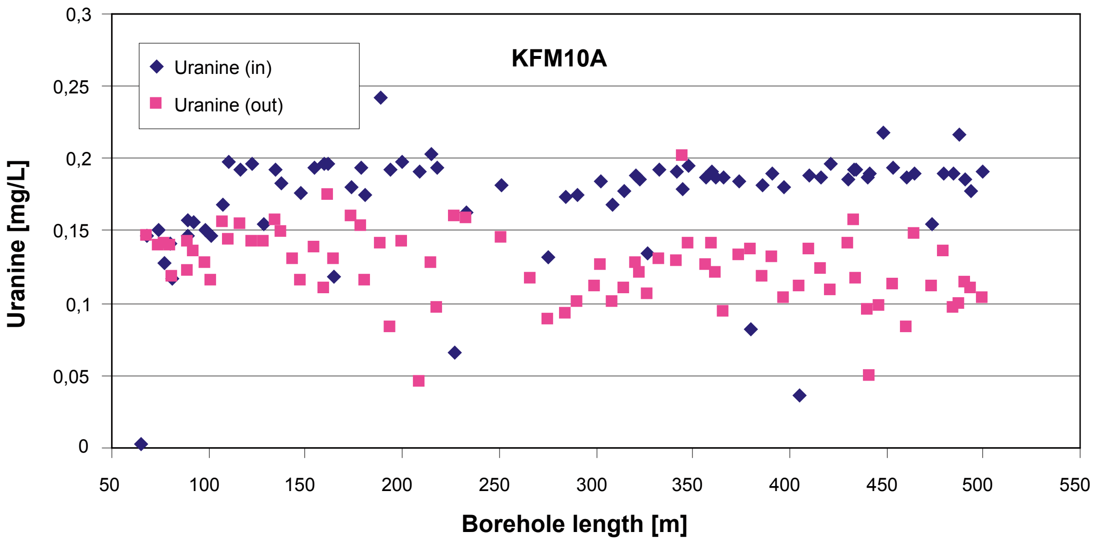

Figure 5-7. Uranine content in the flushing water consumed and the return water recovered versus drilling length during drilling of borehole KFM10A. An automatic dosing equipment, controlled by a flow meter, accomplished the labelling with Uranine.

Electric conductivity of flushing water and return water

Flushing water was supplied from percussion borehole HFM024. A sensor in the measurement station registered the electric conductivity (EC) of the flushing water on-line before the water entered the borehole, see Figure 3-3.

Another sensor for registration of the electric conductivity (Figure 5-8) of the return water was positioned between the surge diverter (discharge head) and the sedimentation containers (Figure 3-3).

The electrical conductivity (salinity) of the flushing water from the 151.35 m deep supply well HFM24 with its major inflow at c 46–52 m is extraordinarily low compared to the other supply wells used in the Forsmark drilling program.

At the beginning of every week the EC-value was c 250 mS/m but decreased to around 150 mS/m by the end of the week, see Figure 5-8. This indicates that by increasing draw-down in HFM24, the proportion of shallow, less saline water increased. During the week-end stops, the salinity recovered to the normal, undisturbed EC-level.

The average electrical conductivity of the return water from KFM10A (Figure 5-8) increased to c 800 mS/m almost immediately after start of drilling but was then almost constant during the drilling period. The results indicate a larger inflow of relatively saline water already in the upper part of the borehole and that the shallow groundwater inflow dominates completely in KFM10A. Even if the distance between the supply well and KFM10A is only c 30 m, the boreholes obviously penetrate different, or partly different, water reservoirs in the shallow part of the bedrock.

Content of dissolved oxygen in flushing water

In Figure 5-9, the level of dissolved oxygen is plotted versus time. The content of dissolved oxygen has generally been kept between 2–4 mg/L. Only during one week in late April the dissolved oxygen content raised above the upper limit approved, 5 mg/L, probably because of lack of nitrogen.

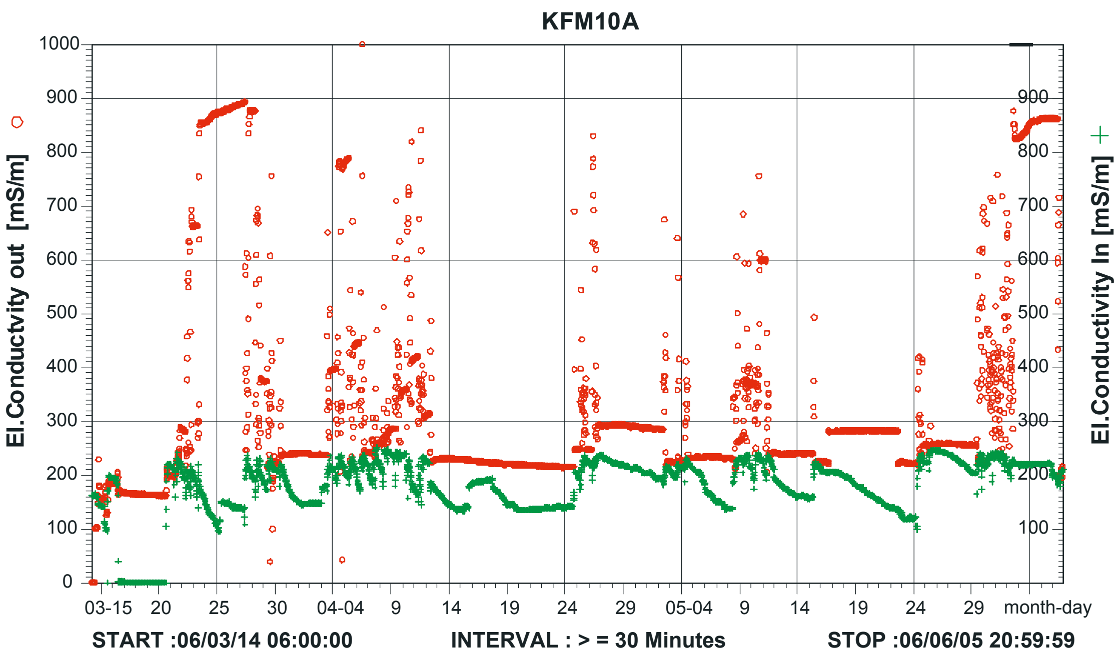

Figure 5-8. *Electrical conductivity of flushing water from HFM24 and return water from KFM10A. The amount of values in the dataset has been reduced as well as cleaned from outliers.*

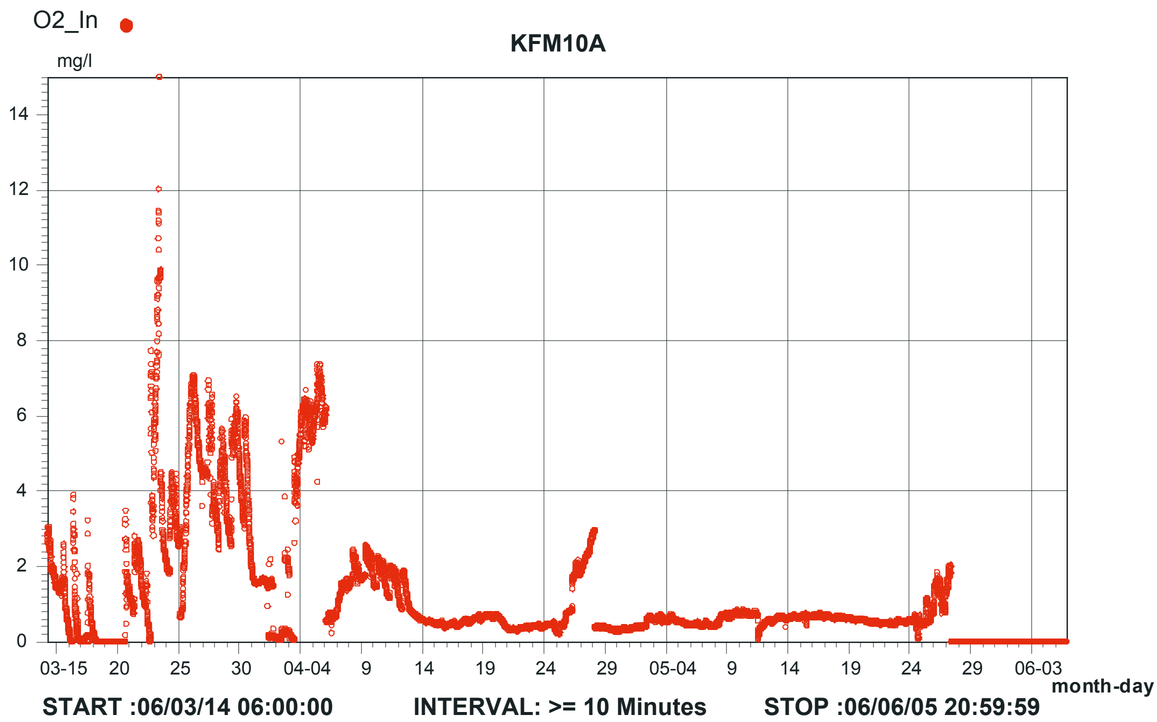

Figure 5-9. *Dissolved oxygen content in the flushing water versus time when drilling KFM10A.*

Flushing water quality

The results from chemical analyses of flushing water from the supply well HFM24 are compiled in /4/. The flushing water was sampled during drilling, for the following reasons:

- Initially, to check if the quality was satisfactory. One main concern is the content of organic constituents, which should be low, preferably below 5 mg/L. The reason is that introduction of hydrocarbons may affect the microbiological flora in the borehole, which would obstruct a reliable characterization of the in situ microbiological conditions.
- To monitor the groundwater chemical composition during drilling. The chemical composition of the flushing water is important when estimating the effect, or correcting for the effect, of remaining flushing water in water samples collected from borehole KFM10A for chemical analyses.

The microbe content in the flushing water was not determined during drilling of KFM10A. The microbe results from drilling of the preceding boreholes KFM05A /5/ and KFM06A /6/ showed convincingly that the cleaning procedure works well. It was therefore concluded that check of microbes at all drilling occasions was no longer necessary.

The results concerning organic constituents and water composition are presented and commented on below.

Organic constituents

Three flushing water samples were collected from HFM24 during the drilling period and the TOC concentration appeared to be somewhat too high, i.e. in the range 9.8–11.0 mg/L. However, 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 /7/).

Chemical composition of flushing water

The results from analysis of two flushing water samples are presented in Appendix C.

5.4.5 Groundwater sampling and analyses during drilling

No sample was collected.

5.4.6 Registration of the groundwater level in KFM10A

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 5-10).

From the beginning, the mammoth pumping was set at the maximum draw-down, but after the major inflow in the upper part had been encountered, the draw-down was adjusted to approximately 15–17 m below top of casing. Shortly before the end of drilling, the draw-down was again decreased, to approximately 13 m.

Drilling was performed continuously during Monday–Thursday. During the weekend stop of drilling and pumping, the groundwater table recovered rapidly due to recharge of groundwater into the borehole, resulting in the (positive) peaks in the diagram. This confirms that the total inflow of formation water in the upper part of the borehole (but below the upper cased and grouted parts) was high. When pumping was restarted, a rapid draw-down occurred.

5.4.7 Core sampling

The average drill core length per run obtained from the drilling was 2.54 m. Only four unbroken cores were recovered. Fracture minerals were relatively well preserved. Rotation marks on the drill core occurred with a pretty high frequency. A preliminary on-site core logging was performed continuously.

5.4.8 Recovery of drill cuttings

The theoretical volume of the percussion drilled and reamed part of the borehole (0–60 m) is c 2.5 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

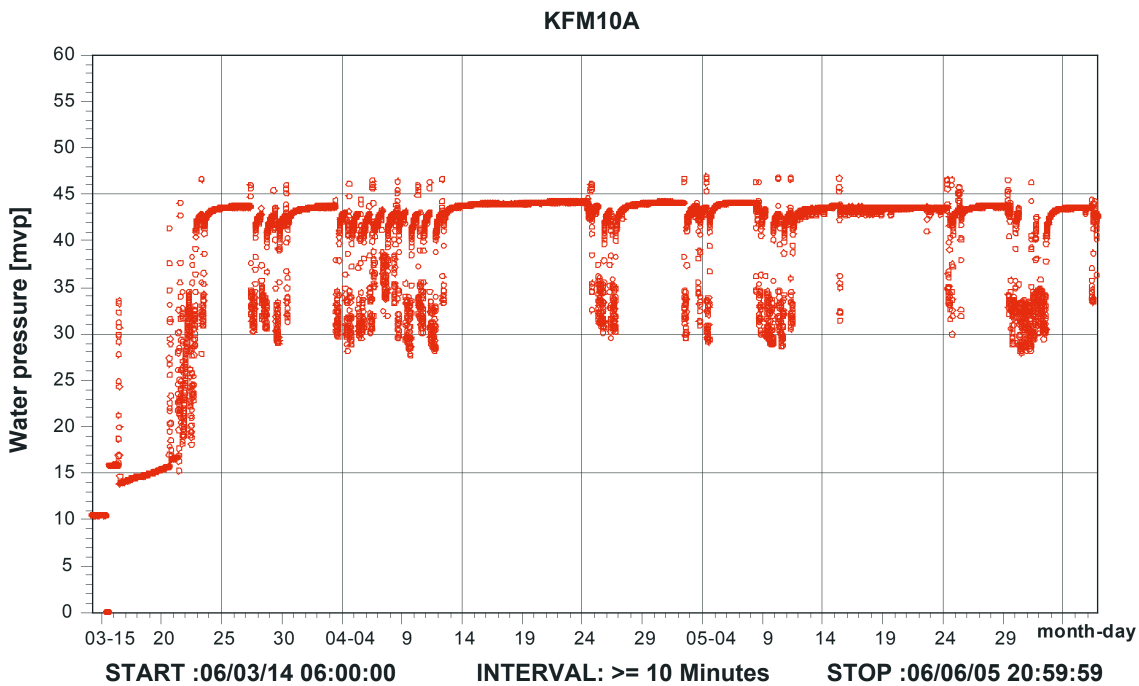

Figure 5-10. Variation of the level of the groundwater table in KFM10A during drilling.

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 KFM10A and the drill core is calculated to be 1.103 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 granitites in the Forsmark area) is applied, the total weight of the theoretical amount of debris is estimated at 2,935 kg. The calculated dry weight of the debris from the core drilling recovered and weighed in the containers is 2,628 kg. The difference between the theoretically produced and recovered dry weight of debris is 307 kg, which gives a recovery of 89.6%.

The recovery figure could be commented on. The dwell time in the system is too short for sedimentation of the suspended finest fractions. No estimation was made of the amount of suspended material, but the true recovery must be somewhat higher than 89.6%. It should also be observed, that weighing of the container including water and debris is associated with some uncertainty.

However, it seems plausible that drilling debris has been injected into the fracture system of the formation, especially in the permeable sections with increased fracture frequency above c 150 m in the borehole.

5.4.9 Deviation measurements

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 KFM10A. 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 small. A measuring station in Uppsala provides one-minute magnetic field values that are available on the Internet at www.intermagnet.org and give sufficient information. The magnetic field variation during June 15th and Dec 6th, 2005, is seen in Figures 5-11 and 5-12, respectively and shows only minor disturbances when the FLEXIT-surveys in KFM10A were performed.

In the following a systematic description of the construction of the revised deviation data for borehole KFM10A is given.

The deviation data used are two FLEXIT-loggings to 495 m and 498 m borehole length, respectively, and one complete MAXIBOR™-logging, i.e. to 498 m, see Table 5-2. With the FLEXIT Smart Tool System, the deviation measurements in borehole KFM10A were carried out every 3 m downwards at two different occasions. These two surveys, with activity numbers 13134859 and 113138898, 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 as EG154.

The EG154-activity specifies the deviation measurements used in the resulting calculation presented in Table 5-3. The different length of the upper sections between the bearing and the inclination are chosen due to that the magnetic accelerometer measurement (bearing) is influenced by the 60 m steel casing which is not the case for the inclinometer measurements (inclination).

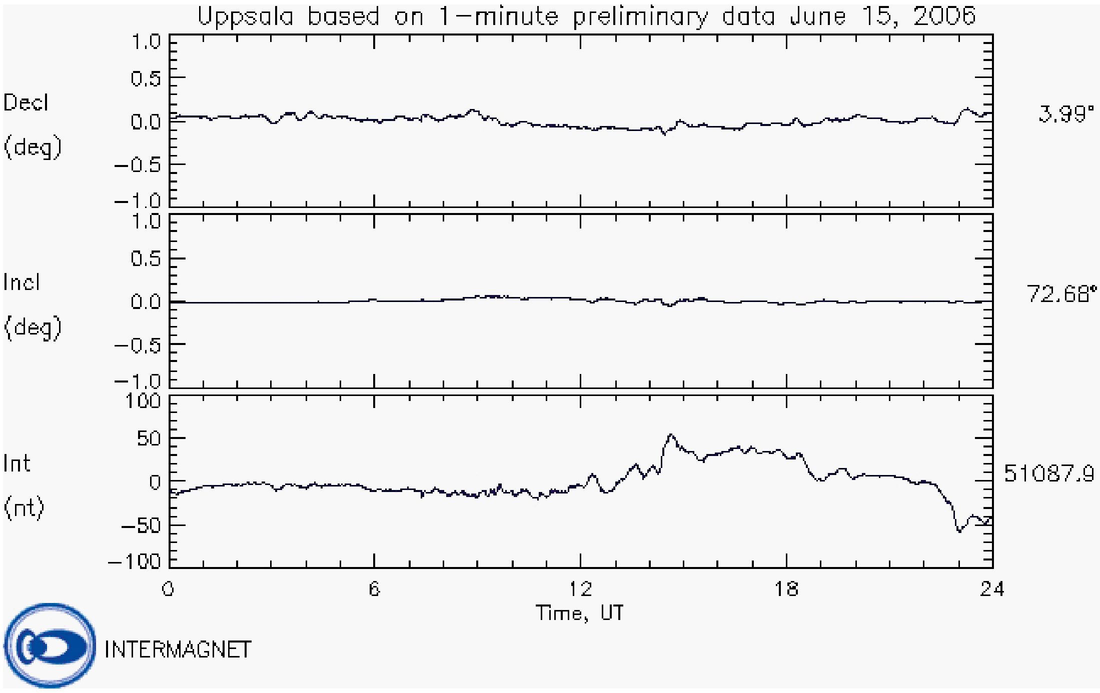

***Figure 5-11.** Magnetic field variation during the FLEXIT-survey performed June 15th, 2005.*

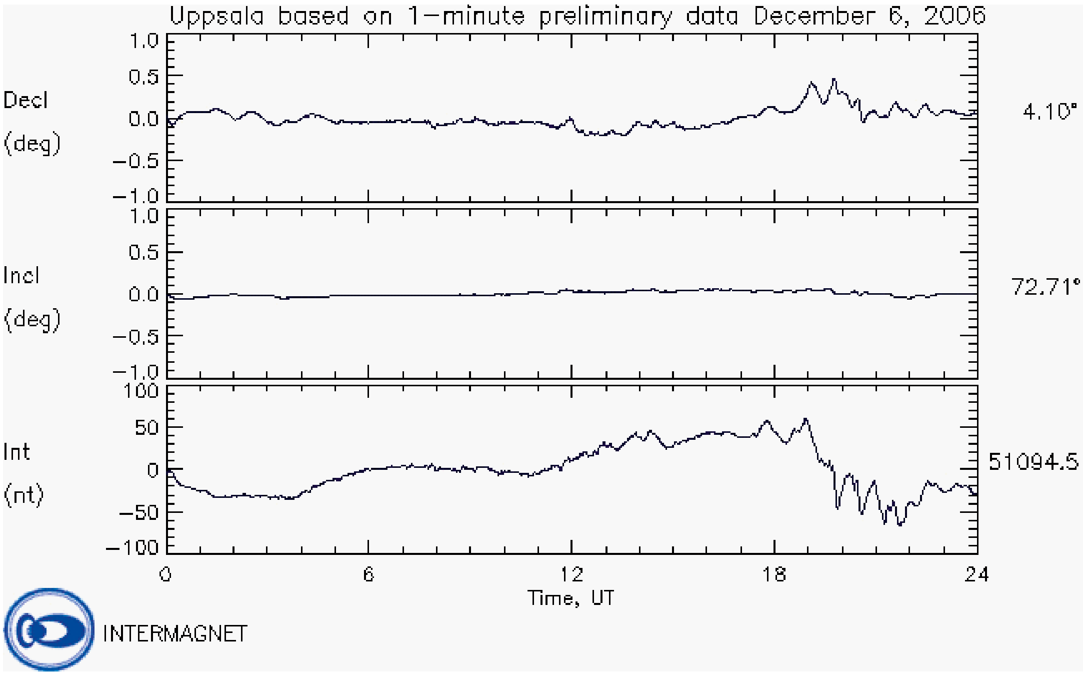

***Figure 5-12.** Magnetic field variation during the FLEXIT-survey performed Dec 6th, 2006.*

Table 5-2. Activity data for the three deviation measurements approved for KFM10A (from SICADA). The two magnetic measurements were used for calculation of the final borehole deviation file, whereas all three measurements were used for calculation of the uncertainty.

Activity Id	Activity Type Code	Activity	Start Date	Idcode	Secup (m)	Seclow (m)	Flags
13114904	EG156	MAXIBOR - measurement	2006-06-06 08:00	KFM10A	0.00	498.00	
13134859	EG157	Magnetic - accelerometer meas.	2006-06-15 15:20	KFM10A	3.00	498.00	CF
13138898	EG157	Magnetic - accelerometer meas.	2006-12-06 07:25	KFM10A	3.00	495.00	F
13140514	EG154	Borehole deviation multiple meas.	2006-12-13 09:00	KFM10A			I C

Table 5-3. Content of the EG154 file (multiple borehole deviation intervals).

Deviation Activity Id	Deviation Angle Type	Approved Secup (m)	Approved Seclow (m)
13134859	Bearing	66.00	498.00
13134859	Inclination	3.00	498.00
13138898	Bearing	66.00	498.00
13138898	Inclination	3.00	498.00

The calculated deviation (EG154-file) in borehole KFM10A shows that the borehole deviates upwards and to the right with an absolute deviation of 68 m compared to an imagined straight line following the dip and strike of the borehole start point (Figures 5-13 and 5-14). 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 the resulting deviation file is presented in Table 5-4 and the estimated radius uncertainty is presented in Table 5-5.

Table 5-4. Deviation data from KFM10A for approximately every 100 m vertical length calculated from EG154.

Borehole	Length (m)	Northing (m)	Easting (m)	Elevation (m)	Inclination (degrees)	Bearing (degrees)
KFM10A	0	6698 629.17	1631 715.90	4.51	–50.13*	10.42*
KFM10A	138	6698 718.71	1631 731.15	–99.37	–47.26	11.16
KFM10A	279	6698 814.78	1631 755.76	–199.50	–43.09	17.25
KFM10A	435	6698 926.52	1631 797.55	–299.83	–37.28	23.85
KFM10A	500.16	6698 974.66	1631 819.10	–338.08	–34.87	24.77

* The starting values of inclination and bearing in EG154 are calculated, and may therefore show a discrepancy against the values seen in Borehole direction surveying (EG151).

Table 5-5. Uncertainty data for the deviation measurements in KFM10A for approximately every 100 m vertical length calculated from EG154.

Borehole	Length (m)	Northing (m)	Easting (m)	Elevation (m)	Inclination Uncertainty	Bearing Uncertainty	Radius Uncertainty
KFM10A	0	6698629.17	1631715.90	4.51	0.43	0.68	0
KFM10A	138	6698718.71	1631731.15	–99.37	0.43	0.68	1.07
KFM10A	279	6698814.78	1631755.76	–199.50	0.43	0.68	2.25
KFM10A	435	6698926.52	1631797.55	–299.83	0.43	0.68	3.66
KFM10A	500.16	6698974.66	1631819.10	–338.08	0.43	0.68	4.28

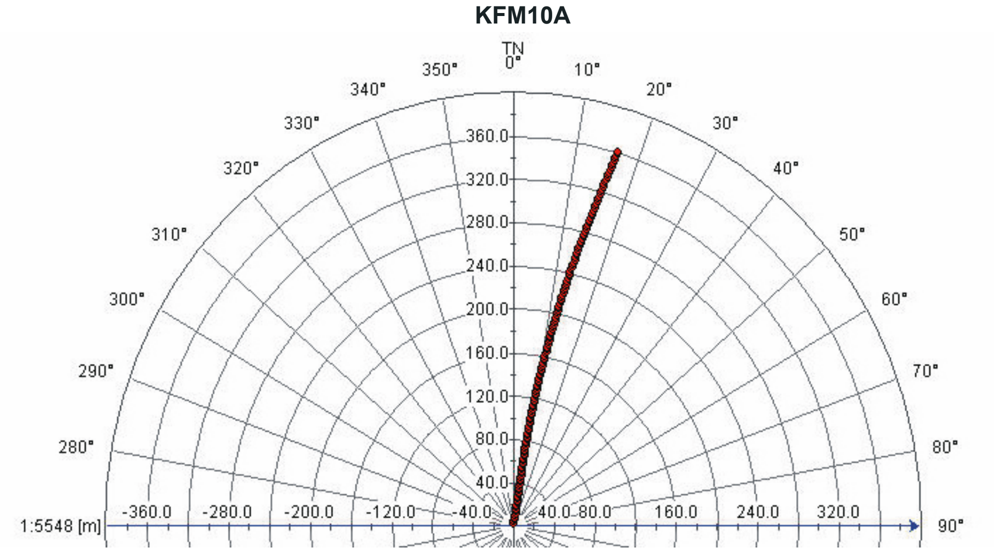

Figure 5-13. Horizontal projection of measured deviation of KFM10A.

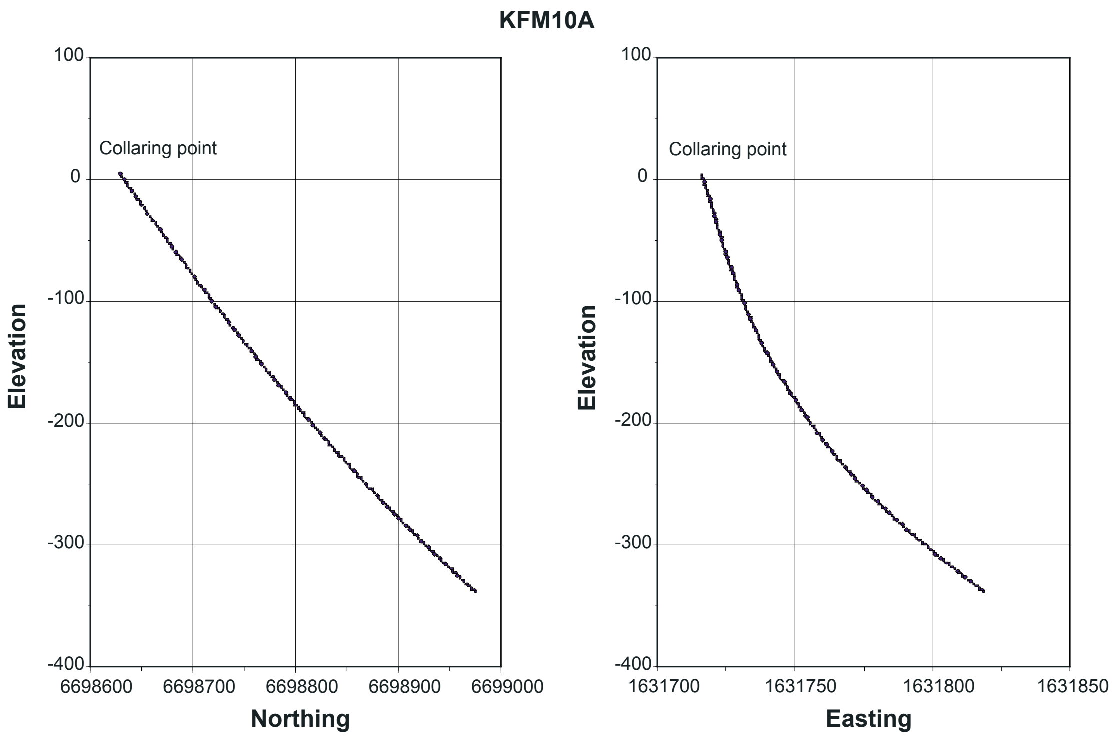

Figure 5-14. Two vertical projections of measured deviation in KFM10A.

5.4.10 Groove milling

A compilation of length to the reference grooves and a comment on the success of detecting the grooves are given in Table 5-6. 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.

5.4.11 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 5-15, which is based on load tests performed in the laboratory by the manufacturer 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.

5.4.12 Consumables

The amount of oil products consumed during drilling of KFM10A, thread grease used during core drilling, and grout used for gap injections of the respective casings are reported in Tables 5-7 and 5-8. Regarding hammer oil and compressor oil, these products are indeed entering the borehole but are, on the other hand, continuously retrieved from it 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 favorable as for conventional lubricants.

Table 5-6. Reference grooves in KFM10A.

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

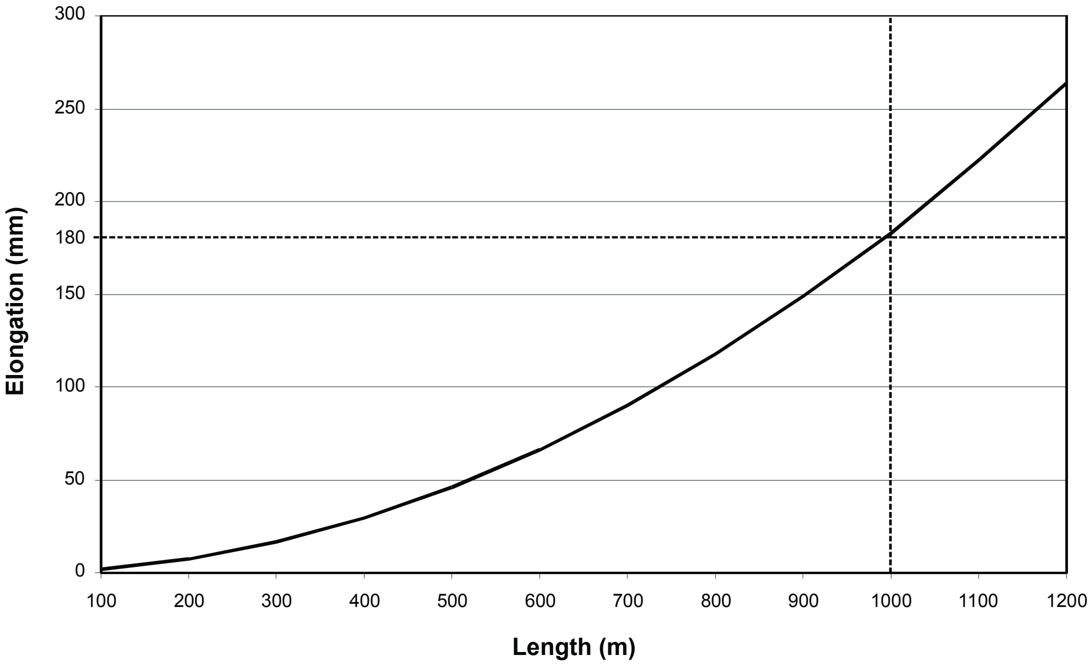

Figure 5-15. The diagram illustrates the elongation of the WL-76 drilling pipe string when hanging in a vertical water filled borehole. Values from laboratory load tests of the drill pipe string.

Table 5-7. Oil and grease consumption during drilling of KFM10A.

Borehole ID	Hammer oil (percussion drilling) Preem Hydra 46	Compressor oil (percussion drilling) Schuman 46	Thread grease (core drilling) Unisilikon L50/2
KFM10A	10L	No consumption measured	5 kg

Table 5-8. Cement consumption for grouting the percussion drilled part of KFM10A 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
KFM10A	0.0–60.39	2,880 kg/2,800 L	Hose	Entire borehole
KFM10A	0.23–2.50	144 kg/140 L	Hose	Continued grouting from the top of the borehole

5.4.13 Recovery measurements after cleaning by air-lift pumping

The final cleaning of KFM10A by air-lift pumping caused a draw-down of 12 m. After completed pumping, the recovery of the groundwater table was monitored. The results are displayed in the diagram of Figure 5-16. Groundwater level registration was conducted during five hours, and the water-yielding capacity could be determined from the resulting groundwater level versus time diagram. An inflow of > 90 L/min at a drawdown of 12 m was estimated.

Borehole HFM24 is located c 40 m north of drill site DS10. The pumping activities in KFM10A revealed a clear hydraulic connection between HFM24 at shallow levels (< 100 m).

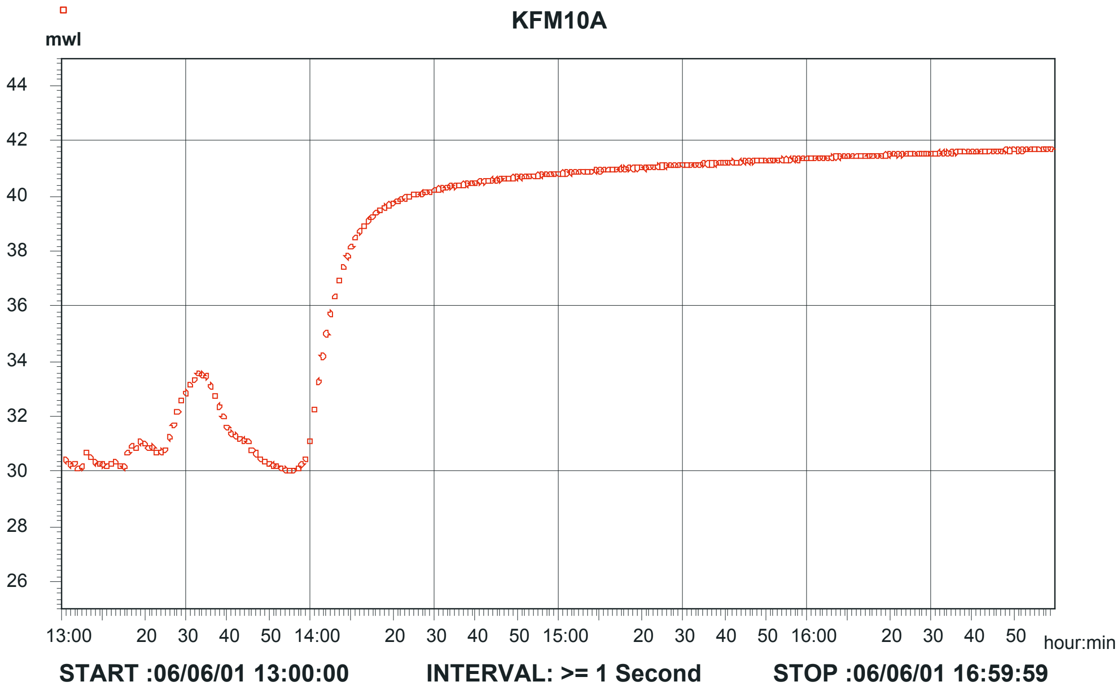

Figure 5-16. *Recovery of groundwater table in section 0–500.16 m of KFM10A after stop of air-lift pumping.*

6 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. Site investigations at Forsmark. Boremap mapping of telescopic drilled borehole KFM10A. SKB P-06-204, Svensk Kärnbränslehantering AB.

/4/ **SKB, 2006.** Berg, C. Forsmark site investigation. Sampling and analyses of groundwater from percussion drilled boreholes. Results from the boreholes HFM14, HFM23, HFM24, HFM25, HFM26, HFM27, HFM28, HFM29, HFM30, HFM32, HFM33, HFM34 and HFM35. SKB P-06-231, Svensk Kärnbränslehantering AB.

/5/ **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.

/6/ **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.

/7/ **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.

Appendix A

Well Cad-plot of the percussion drilled part of borehole KFM10A

Title	PERCUSSION DRILLED BOREHOLE KFM10A		
Svensk Kärnbränslehantering AB		Signed data	
Site	FORSMARK	Coordinate System	RT90-RHB70
Borehole	KFM10A	Northing [m]	6698629.17
Diameter [mm]	158	Easting [m]	1631715.90
Length [m]	60.73	Elevation [m.a.s.l.]	4.51
Bearing [°]	10.42	Drilling Start Date	2005-12-06 09:00:00
Inclination [°]	-50.05	Drilling Stop Date	2005-12-19 15:00:00
Date of mapping		Plot Date	2007-01-31 22:09:16

ROCKTYPE
- Granite, fine- to medium-grained
- Pegmatite, pegmatitic granite
- Granite, granodiorite and tonalite, metamorphic, fine- to medium-grained
- Granite to granodiorite, metamorphic, medium-grained
- Amphibolite

SOIL
- Soil

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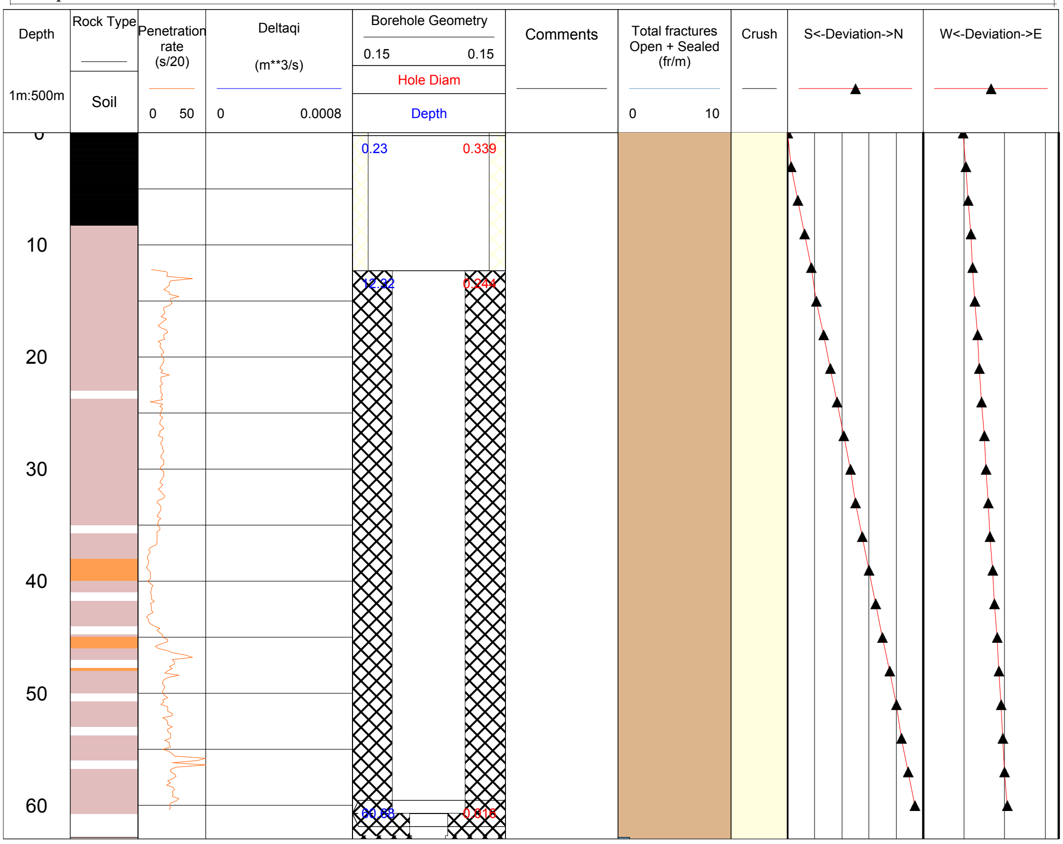

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Well Cad-plot of the complete (percussion drilled and core drilled) borehole of KFM10A

Title	**KFM10A**		
Svensk Kärnbränslehantering AB		**Signed data**	
Site	FORSMARK	**Coordinate System**	RT90-RHB70
Borehole	KFM10A	**Northing [m]**	6698629.17
Diameter [mm]	76	**Easting [m]**	1631715.90
Length [m]	500.16	**Elevation [m.a.s.l.]**	4.51
Bearing [°]	10.42	**Drilling Start Date**	2005-12-06 09:00:00
Inclination [°]	-50.05	**Drilling Stop Date**	2006-06-01 15:00:00
Date of mapping		**Plot Date**	2007-01-31 22:09:16

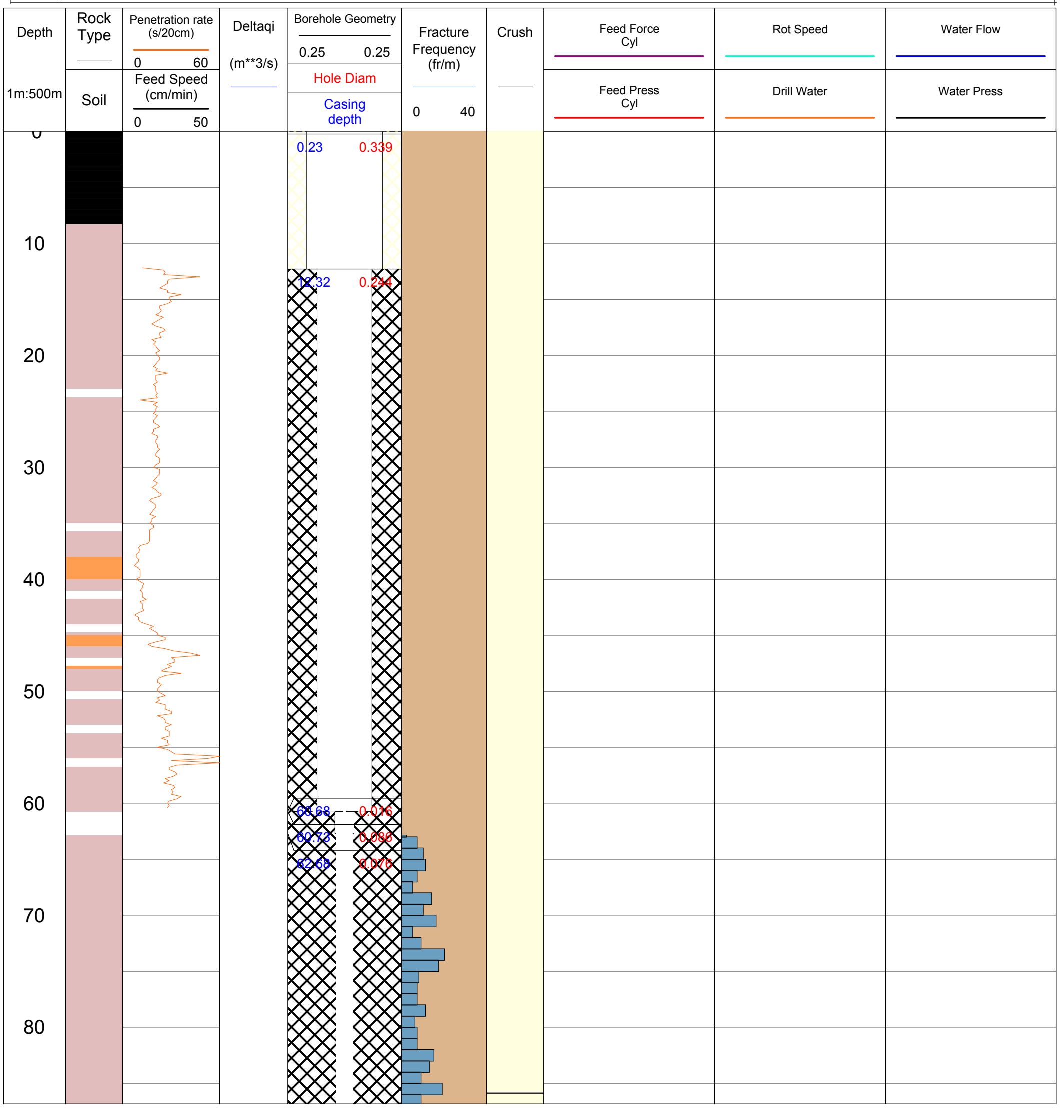
ROCKTYPE FORSMARK

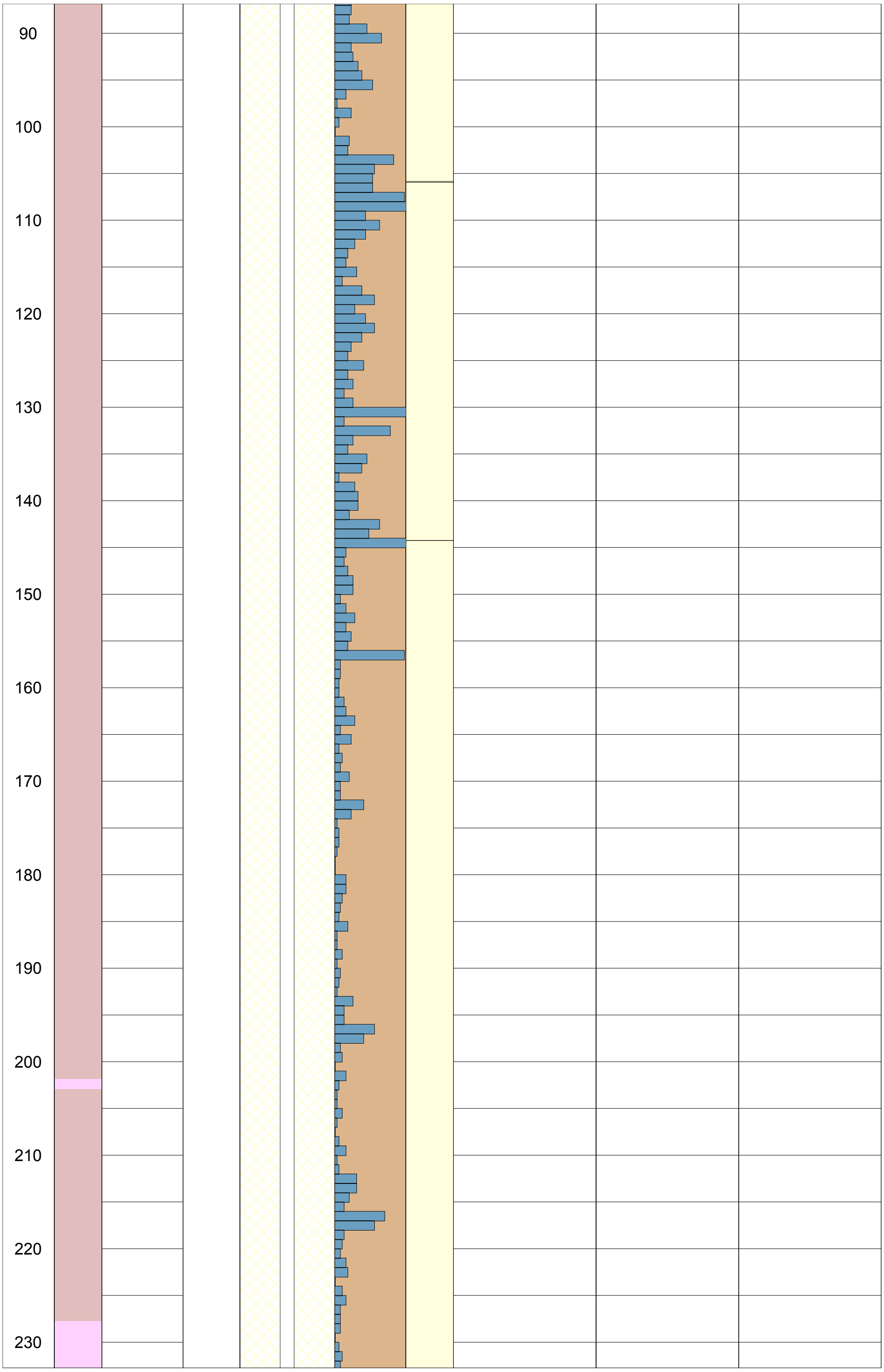
- **Granite, fine- to medium-grained**
- **Pegmatite, pegmatitic granite**
- **Granite, granodiorite and tonalite, metamorphic, fine- to medium-grained**
- **Granite to granodiorite, metamorphic, medium-grained**
- **Amphibolite**

SOIL

- **Soil**

Script Name

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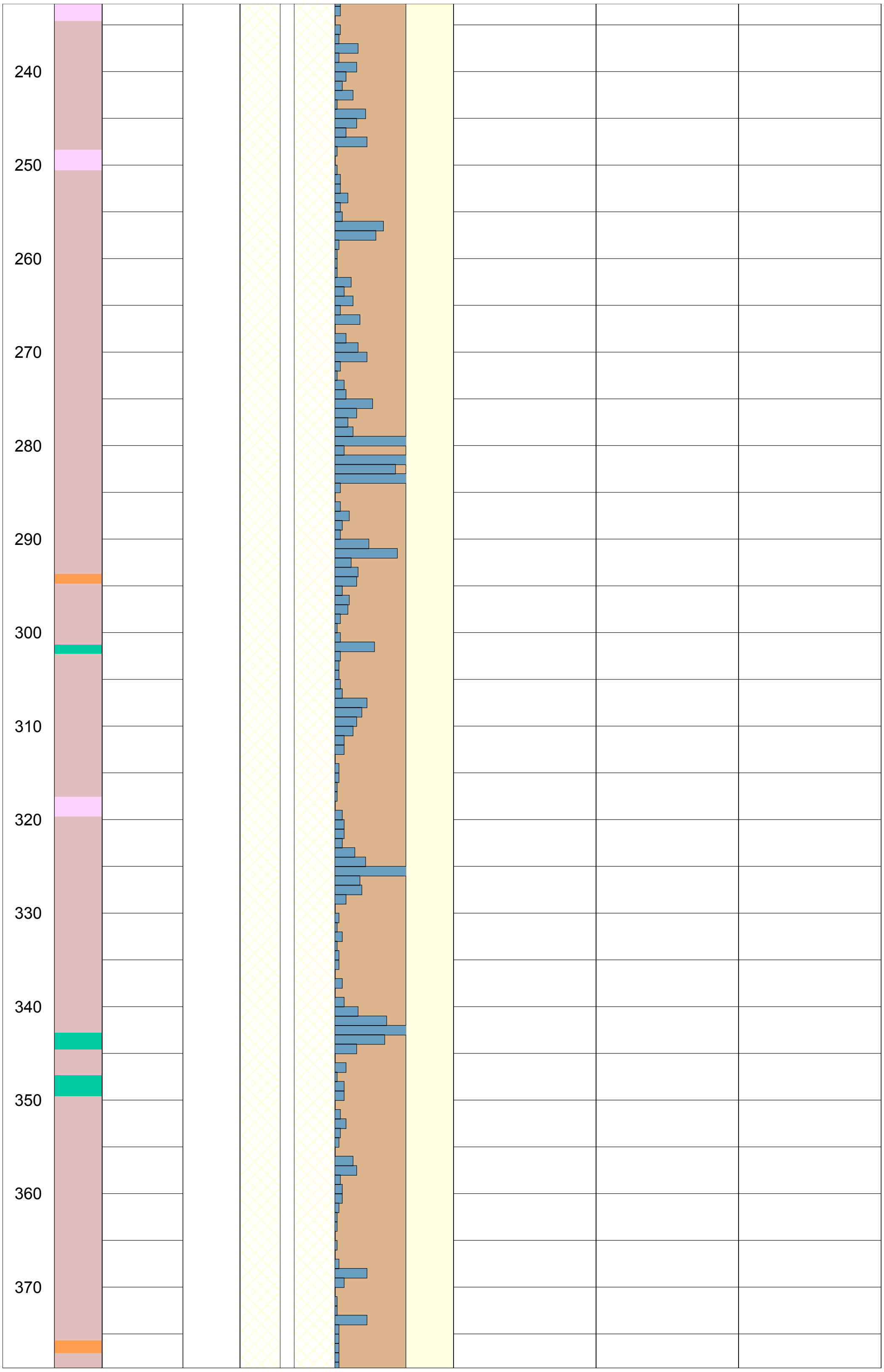
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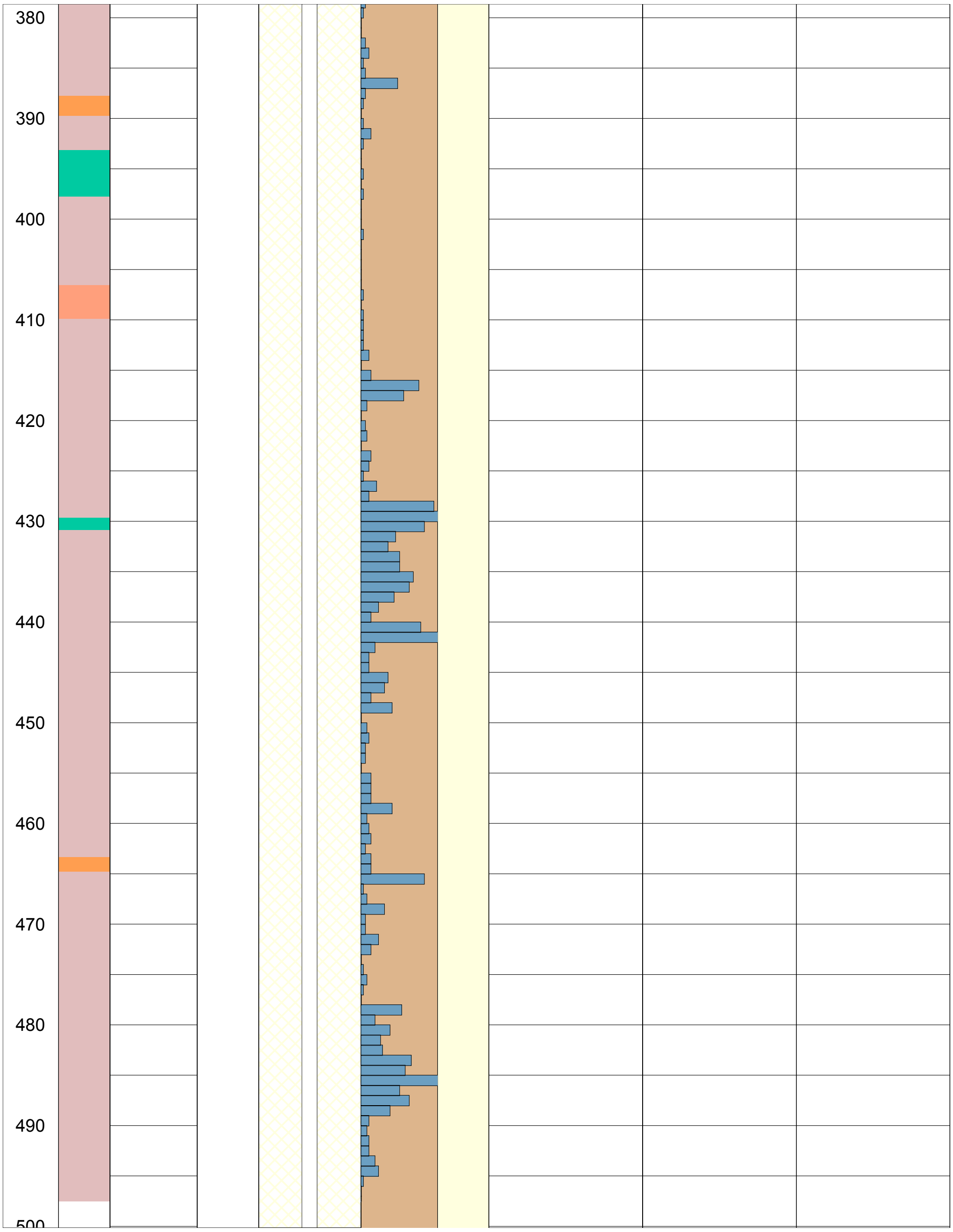
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Appendix C

Results from the flushing water samples

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
2005-12-21	HFM24	12029*	-2.11	354	14.9	108	25.2	369	558	113	37.9	1.85	1.74	7.02	0.020	0.775	9.8	7.53	255
2006-04-06	HFM24	12222	-1.62	340	14.3	102	23.4	391	501	103	36.5	1.63	1.45	7.32	0.017	0.675	11	7.66	237

* Sample collected before drilling to check TOC concentration.

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
2006-04-06	HFM24	12222	-80.1	7.5	-10.9	61.07	-11.6	0.2378	18.9	0.723908	0.02