P-07-45

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Drilling of the telescopic borehole KFM11A at drill site DS 11

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September 2007

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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 77 mm to full length.

Performance of and results from drilling and measurements during drilling of borehole KFM11A, drilled at Forsmark by applying telescopic technique, are presented in this report. This borehole is 851.21 m long, at its starting point inclined 60.86° from the horizon, and reaches about 456 m in horizontal distance and approximately 716 m in vertical depth. The borehole is primarily intended for geological 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 0–71.06 m with the diameter 160.2 mm, a few fracture zones was encountered and an inflow of 50 L/min was measured for the total length. After reaming to ∅ 242 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 KFM11A 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 KFM11A, partly in the highly fractured Singö deformation zone north-east of the Forsmark tectonic lens with the candidate area, is that the average length of recovered drill cores was relatively short, although the wearing of drill bits was similar to that within the candidate area, indicating roughly the same drilling resistance. Other impressions from the drilling are that part of the borehole wall was instable, especially the upper contact of the Singö deformation zone. However, in spite of the high degree of fracturing, the water yielding capacity of KFM11A was not conspicuously high.

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 ca 77 mm diameter. Resultaten från borrhål KFM11A i Forsmark, som har utförts med teleskopborrningsteknik, redovisas i denna rapport. Borrhålet är ansatt med en lutning av 60,86° från horisontalplanet, är 851,21 m långt och når ca 456 m i horisontell riktning och ca 716 m vertikaldjup. KFM11A är ett så kallat kemiprioriterat borrhål vilket innebär att det planeras för att utnyttjas för detaljerade hydrogeokemiska och bakteriologiska undersökningar, varför all utrustning som används i borrhålet, både vid borrning och mätning, måste rengöras och desinficeras enligt speciella instruktioner.

Vid hammarborrning av avsnittet 0–71,06 m med diametern 160,2 mm påträffades ett mindre antal sprickor och ett inflöde av ca 50 L/min uppmättes då hammarborrhålet nått sin fulla längd. För att stabilisera borrhålet upprymdes det först till ∅ 242 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 helt 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 KFM11A 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 borrkaxproverna 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 KFM11A 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 borrhål KFM11A, vilket riktades för att penetrera Singözonen, dvs den regionala deformationszon som mot nordost avgränsar den tektoniska linsen i Forsmark med kandidatområdet, är att upptagslängderna genomsnittligt blev kortare än vid borrningen inom kandidatområdet. Borrkroneslitaget var dock jämförbart med i tidigare borrhål, vilket indikerar likartat borrmotstånd. Andra intryck är att bornhålsväggen delvis var instabil, speciellt i den övre delen av att Singözonen. Däremot medförde inte den generellt höga sprickfrekvensen någon uppseendeväckande hög vattenkapacitet.

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/ and /3/, 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 as well as 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.

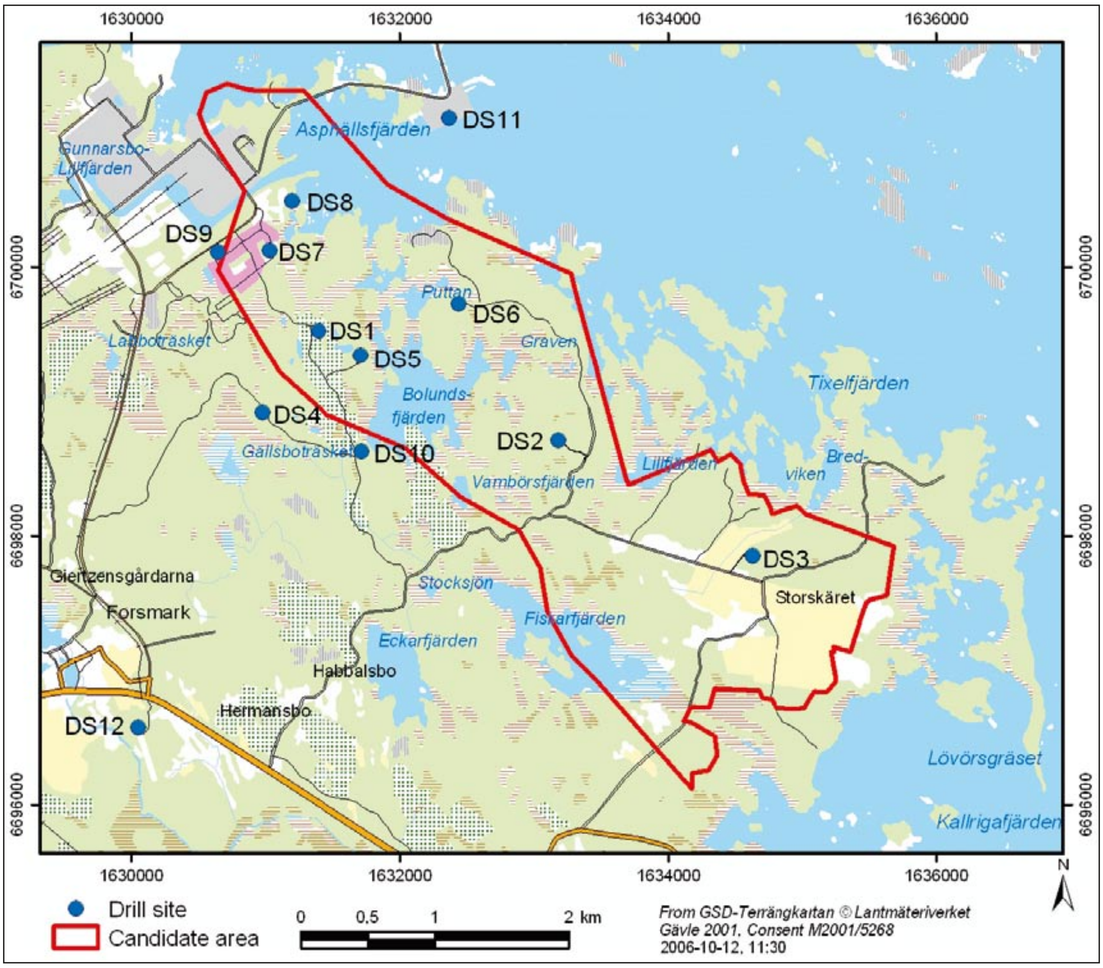


__Figure 1-1.__ The site investigation area at Forsmark including the candidate area selected for more detailed investigations. Drill sites DS1-12 are marked with blue dots.

This document reports the data and results gained by drilling the deep telescopic borehole KFM11A at drill site DS11, 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 400-06-025. Additional work as cleaning and stabilization of the borehole is also reported. These extra efforts were made according to Activity Plan AP PF 400-07-006.

In Table 1-1 controlling documents for performing these activities 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 KFM11A, which has a total drilling length of 851.21 m. The borehole is inclined 60.86 degrees from the horizontal plane, entailing that the horizontal extension of the borehole is approximately 456 m and the vertical depth c. 716 m. Borehole KFM11A 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 DS11 is located c. 0.7 km north-east of the candidate area and c. 2 km from the Forsmark power facilities and very close to the SFR office and tunnel entrance. The site is settled on gravel fill consisting of excavated rock material from the SFR tunnel system, which has been used extensively to eliminate elevation differences at and between the small islands in this area.

Close to KFM11A, also three percussion drilled boreholes in solid rock, HFM33, HFM34 and HFM35, have been drilled for groundwater level and hydrochemical monitoring. HFM33 was also used as a flushing water supply well when drilling KFM11A. The lengths of these boreholes vary between approximately 140 m and 201 m. The locations of all boreholes at drill site DS11 are shown in Figure 1-2.

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

Activity Plan	**Number**	**Version**
Borrning av teleskopborrhål KFM11A	AP PF 400-06-025	1.0
Rensning, upprymning samt stabilisering i teleskopborrhål KFM11A	AP PF 400-07-006	1.0
Method Descriptions	**Number**	**Version**
Metodbeskrivning för hammarborrning	SKB MD 610.003	2.0
Metodbeskrivning för kärnborrning	SKB MD 620.003	2.0
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 DS11. Besides the core drilled borehole KFM11A, the area incorporates a flushing water well (HFM33), and two monitoring wells in bedrock (HFM34-35). Also HFM33 will later be used as a monitoring well. The projection of inclined boreholes on the horizontal plane at the ground surface (top of casing) is shown in the figure.*

Drilling of KFM11A was performed during three periods, between April 12th to May 2nd, 2006 (percussion drilling), and August 29th to November 16th, 2006 (core drilling). Finally additional work was conducted between March 14th and April 2nd, 2007. Drillcon Core AB, Nora, Sweden, was engaged for the drilling commission. Two different drilling equipments were employed for drilling KFM11A, a percussion drilling machine for drilling the upper c. 71 metres, whereas core drilling of the remaining part (section 71.06–851.21 m) was carried out with a wireline core drilling system. The additional work was made with the same core drilling machine.

In the present report, performance of and results from drilling, cleaning and stabilization of KFM11A are presented. The report also treats investigations made during and immediately after drilling. Original data from the reported activity are stored in the primary database Sicada, where they are traceable by the Activity Plan numbers (AP PF 400-06-025 and AP PF 400-07-006). Only data in SKB's 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 data revisions entail a revision of the P-report. Minor data revisions are normally presented as supplements, available at www.skb.se.

2 Objective and scope

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

- To provide rock samples from the ground surface to the borehole bottom. Percussion drilling through the overburden produces soil samples recovered to the surface by compressed air. These samples are collected with a frequency of one sample per metre. The same sampling frequency is applied for the drill cuttings produced when percussion drilling the upper c. 60–100 m of the solid rock. Below, the core drilling provides (in principle) continuous drill cores down to the borehole bottom. The rock samples collected during drilling are used for lithological, structural and rock mechanical characterization as well as for determination of transport properties of the bedrock from the rock surface to the full drilling depth.
- To render geophysical borehole investigations possible, e.g. TV logging, borehole radar logging and conventional geophysical logging as an aid for the geological/rock mechanical characterization.
- To allow hydraulic borehole tests (single-hole tests as well as interference tests, 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 KFM11A. A specific objective for borehole KFM11A was to investigate the regional Singö deformation zone, in the site modelling work designated ZFMNW0001. Key properties that needed to be determined along the zone were the orientation, thickness, fracture orientation and fracture mineralogy. The relative importance of ductile and brittle deformation along the zone also needed to be addressed. Geological data at shallower levels along the Singö deformation zone are available from earlier construction work. However, data from deeper crustal levels along the zone were lacking. selection of sites for complementary percussion drilling took into consideration the occurrence of other, lower confidence deformation zones, as well as lineaments in the vicinity of the sites, in order to improve the understanding of the geological significance of these structures.

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

Two types of drilling machines were employed for drilling borehole KFM11A. The upper c. 71 metres were drilled with a percussion drilling machine of type Commacchio MC 1500. For core drilling of section 71.06–851.21 m, an Onram 2000 CCD wireline core drilling system, was engaged. Also for the additional work the Onram 2000 CCD was used.

3.1 Percussion drilling equipment

The Commacchio MC 1500 percussion machine was 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 XRUS 455.

At drill site DS11, the bedrock is covered by approximately six metres 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 KFM11A are presented in Section 5.2.

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

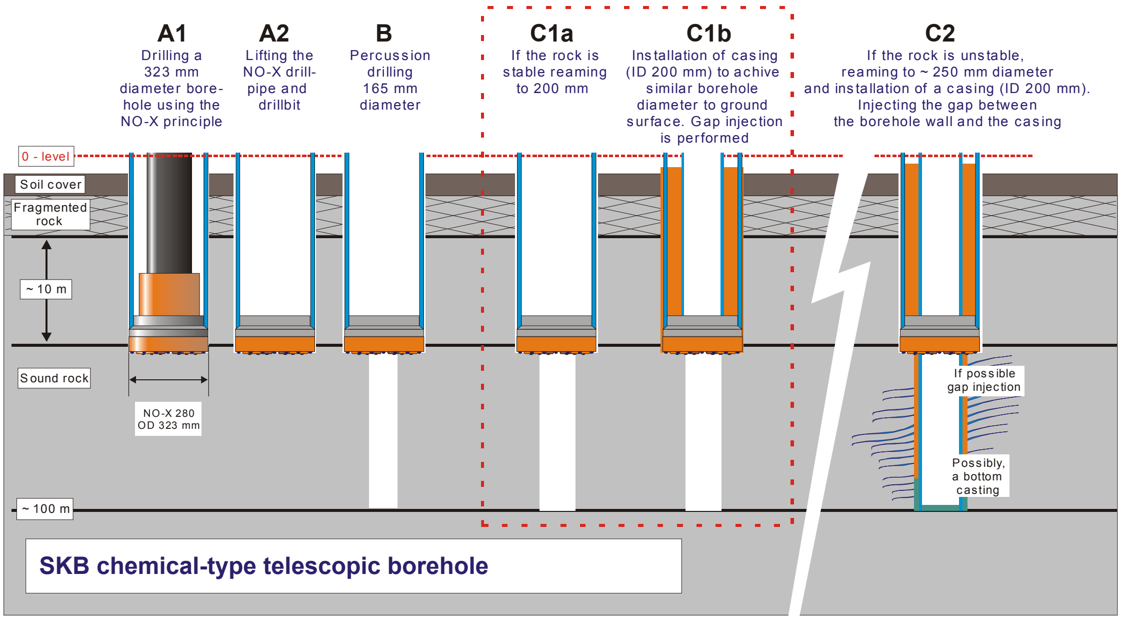


Figure 3-1. *Schematic diagram showing the various stages of drilling the 0–100 m section of an SKB chemical-type telescopic borehole. The letters and numerals above each stage refer to some of the operations described in Sections 3.4.1 and 3.4.2 in SKB MD 620.003.*

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 the 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 KFM11A was grouted after installation of the $\varnothing_i$ 200 mm, 70.80 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 the use of a hose.

3.3 Core drilling equipment

3.3.1 The wireline-76 system

For drilling the cored part of borehole KFM11A, a Wireline-76 core drilling system, type Onram 2000 CCD, 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 demands for a triple-tube system. Technical specifications of the drilling machine with fittings are given in Table 3-1.

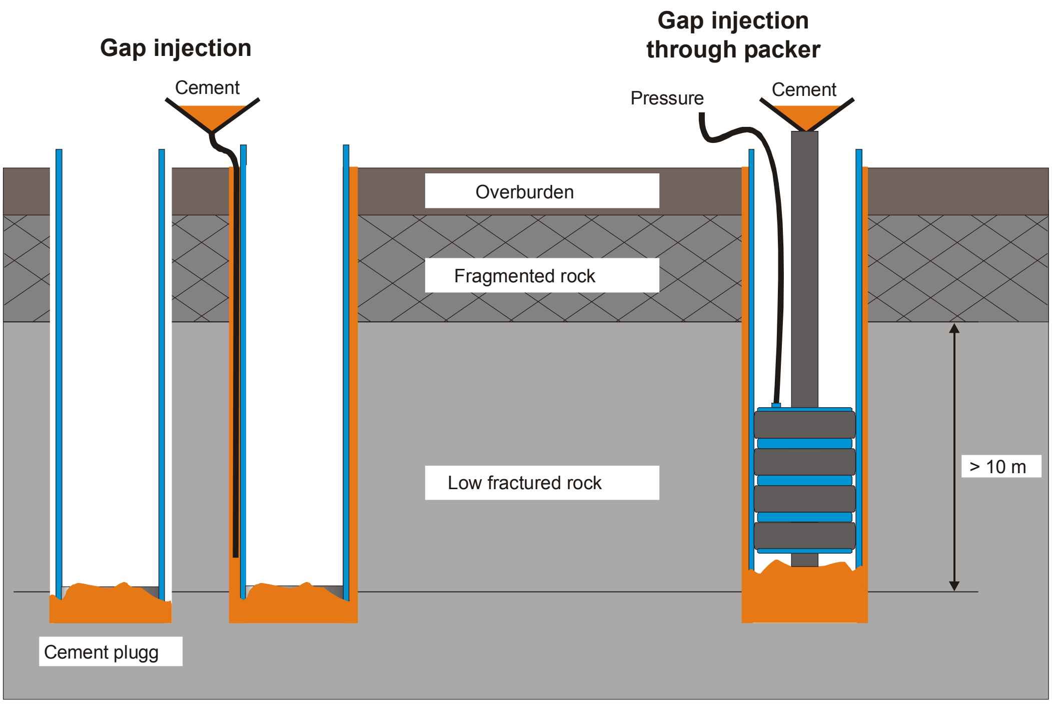


Figure 3-2. *Gap injection techniques. In order to fill the gap between the borehole wall and the casing, different techniques may be applied. To the left, a flexible hose is lowered between the casing and the borehole wall, and to the right the grouting is performed through a borehole packer.*

Table 3-1. Technical specifications of the Onram 2000 CCD-system from Hagby-Asahi with appurtenances.

Unit	Manufacturer/type	Specifications	Remarks
Onram 2000	Hagby-Asahi	Capacity for 76–77 mm holes maximum approx. 900–1,500 m depending on choice of drill string	
Flush water pump	Bean	Max flow rate: 170 L/min Max pressure: 103 bars	
Submersible pump	Grundfos SQ	Max flow rate: 200 L/min	
Mobile electrical plant	P250HE with diesel engine Perkins GCD 325	250 KVA, 200 kW, 360 A.	
Compressor	Atlas Copco GA75P-13	Max pressure: 12 bars Flow: > 5 L/sec	Electrically supplied
CCD-system	Dunfoss		Standard system modified for core drilling by the manufacturer

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 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 must 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, have to be avoided.

The water well used for the supply of flushing water for core drilling of KFM11A was a percussion drilled borehole in hard rock, HFM33, situated at DS11 approximately 170 m from KFM11A. The water quality from the HFM33 well was analysed in advance and considered as sufficiently good to serve as flushing water for KFM11A.

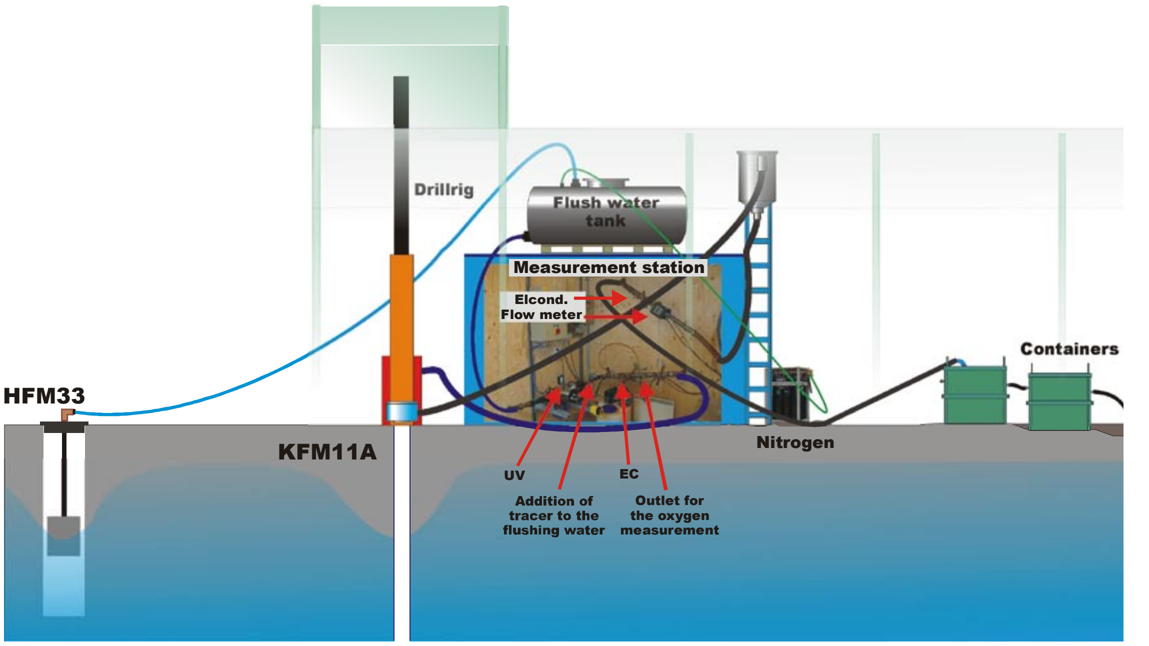


Figure 3-3. Schematic illustration of the flushing/return water system when drilling KFM11A at DS11. The measurement station included logger units and an UV-radiation unit. For flushing water flow rate and pressure measurements, the drilling machine gauges were applied.

Besides these basic demands on the flushing water quality, which were fulfilled when drilling KFM11A, the flushing water was also prepared in three steps before use, in accordance with SKB MD 620.003 (Method Description for core drilling).

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

Measurement of flushing water parameters

The 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.

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	
Electrical Conductivity	YOKOGAWA SC72	0.1 μ/cm–20 S/m	Hand held instrument
Oxygen	Orbisphere model 3600		

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

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 KFM11A consisted of several main components, see Table 3-3 and Figure 3-4.

Table 3-3. The main components of the air-lift pumping equipment in KFM11A.

Components	Remarks
Compressor, 12 bars/10 m³/min	Yes
Electrical supply cubicle, at least 16 A	Yes
Outer support casing, 98/89 mm diameter	60.0 m
Inner support casing, 84/77 mm diameter	61.5 m
2 Ejector pumps, each contains;*	
PEX hose, 1 x 22 mm	2 x 70 + 30** m
PEM hose, 1 x 40 mm	2 x 70 + 20** m
Air nozzle	
PEX hose, 1 x 22 mm	60 + 30 m
Expansion vessel (= discharge head)	Yes
PEM hose: 20 bars, 32 mm diameter (pressure transducer)	70 m
Pressure sensor, 10 bars, instrumentation and data-logging unit	Yes

* Two separate mammoth pumps are always installed in a telescopic bore hole.

** Extend hose: PEX connected to air compressor and PEM connected to Cyclone.

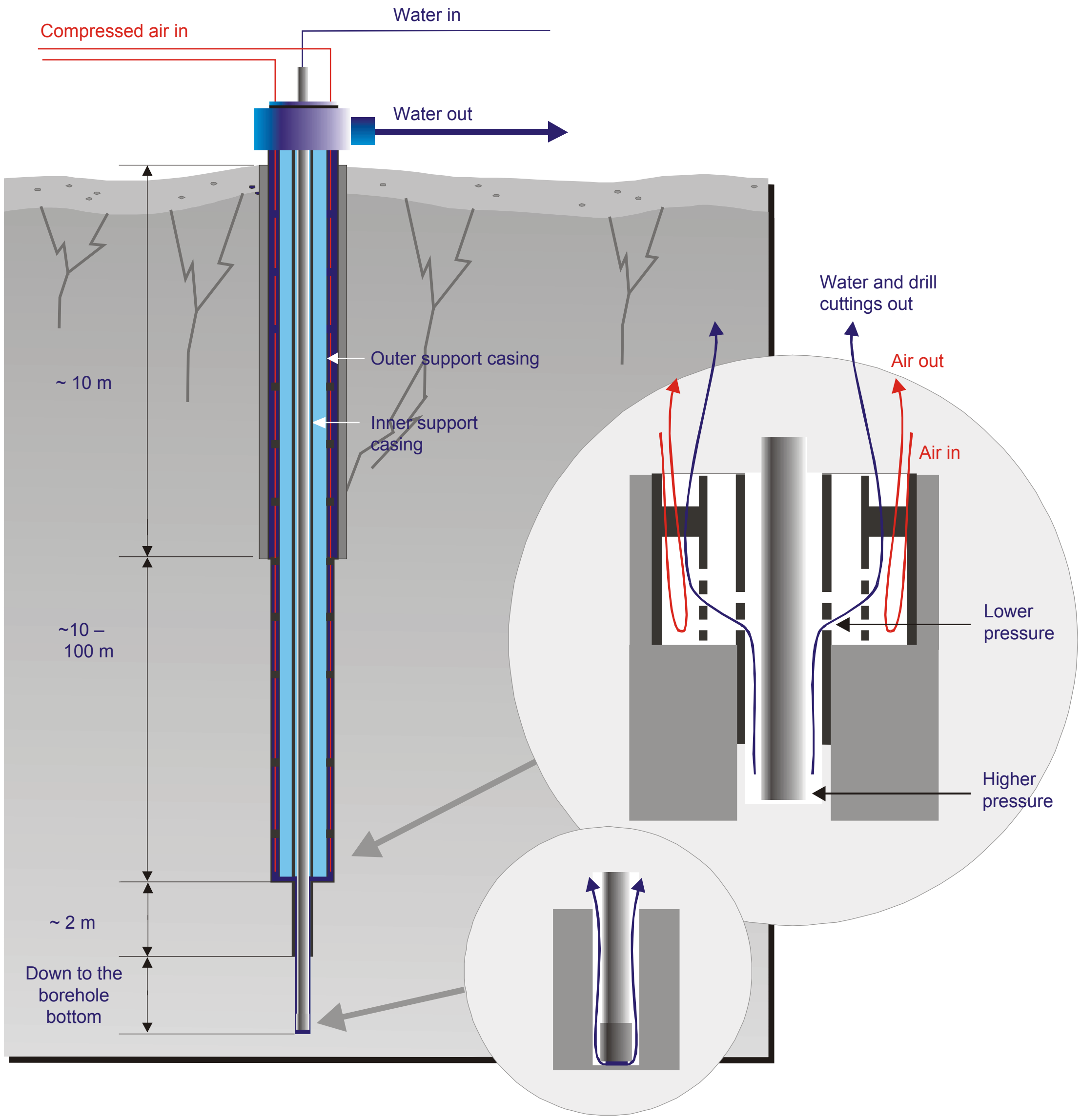


Figure 3-4. *Air-lift pumping during core drilling of a telescopic borehole. Schematic representation, where the drilling depths are only approximate. The air and instrumentation hoses are secured to the outer support casing. The compressed air raises the flushing water and drill cuttings from the hole.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

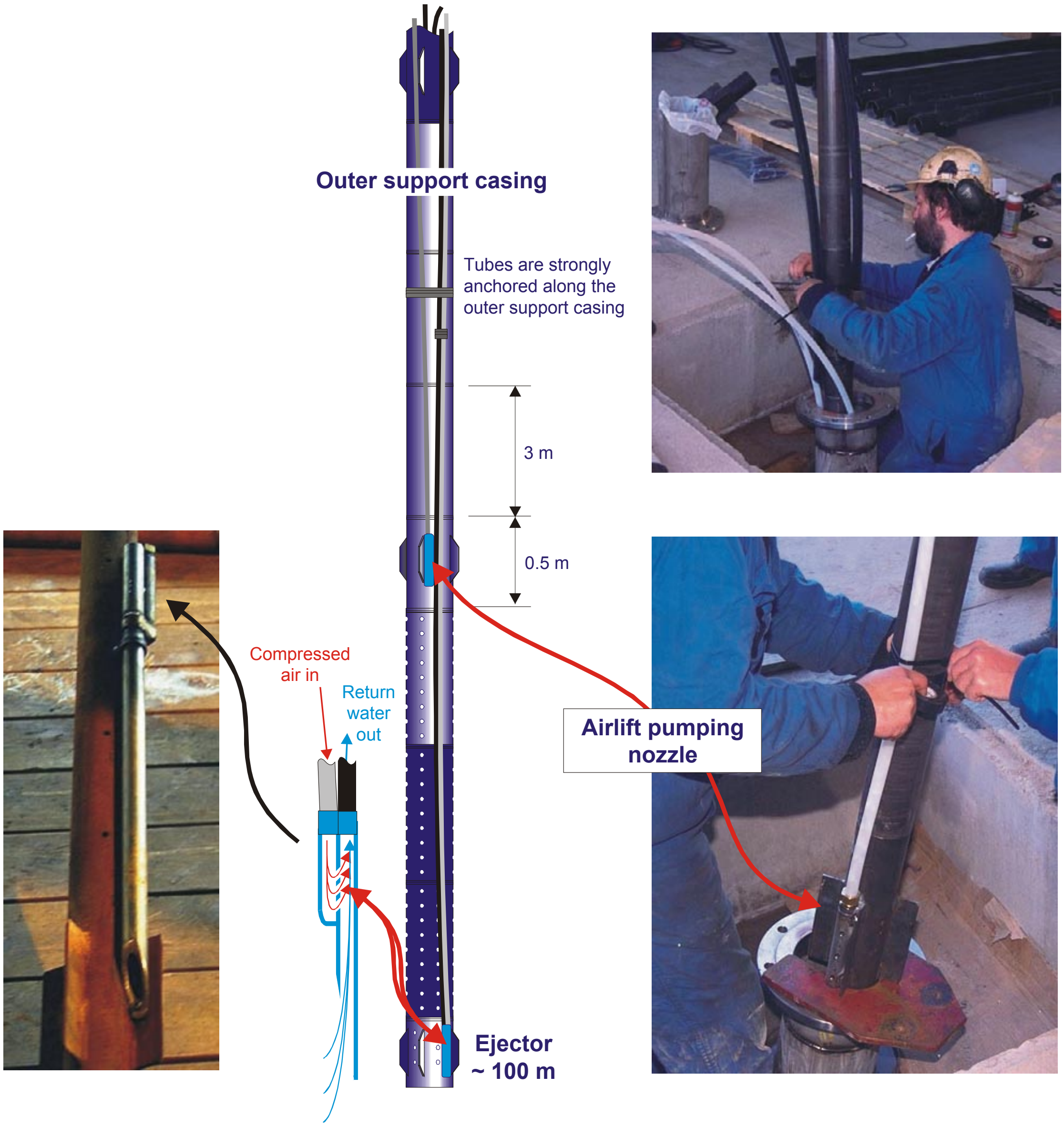


Figure 3-5. *Schematic representation of connection and installation of air-lift pumping nozzle and ejector on the outer protective casing.*

Storage and discharge of return water for KFM11A

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 two containers, in which the drill cuttings separated out in two 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, 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.

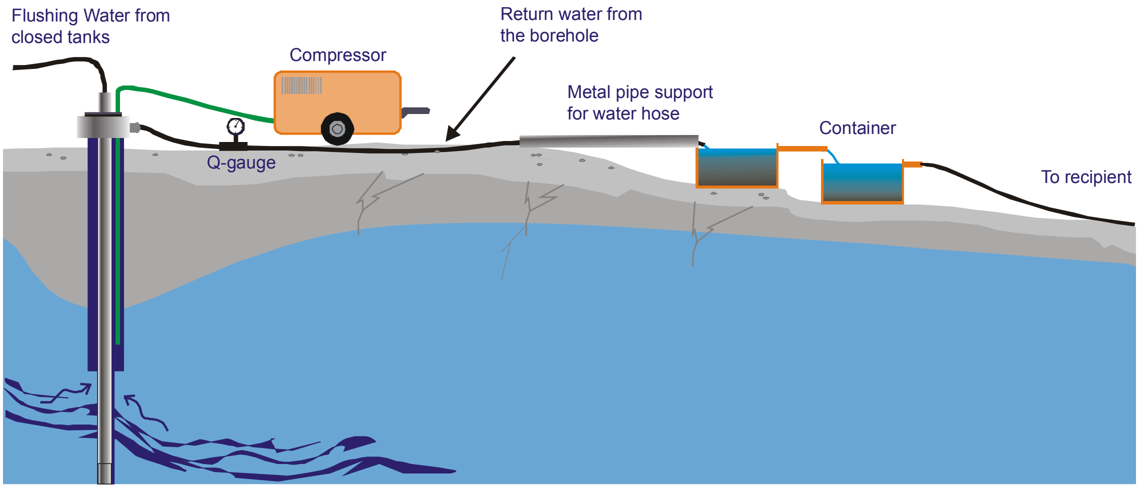


__Figure 3-6.__ Return water system. Air-lift pumping raises the return water, consisting of flushing water, groundwater and drill cuttings, from the borehole. The cuttings separate out in two stages in the containers (where they are preserved for later weighing), after which the water is pumped to an 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	
Electrical Conductivity	YOKOGAWA SC72	0.1 μ/cm–20 S/m	Hand held instrument

3.3.3 Drilling monitoring system

The ONRAM 2000-CCD 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.

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, 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

After completed drilling of borehole KFM11A, deviation measurements were made 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 KFM11A in order to check the validity of the Maxibor™ measurements. The surveying instrument used was the FLEXIT Smart Tool System.

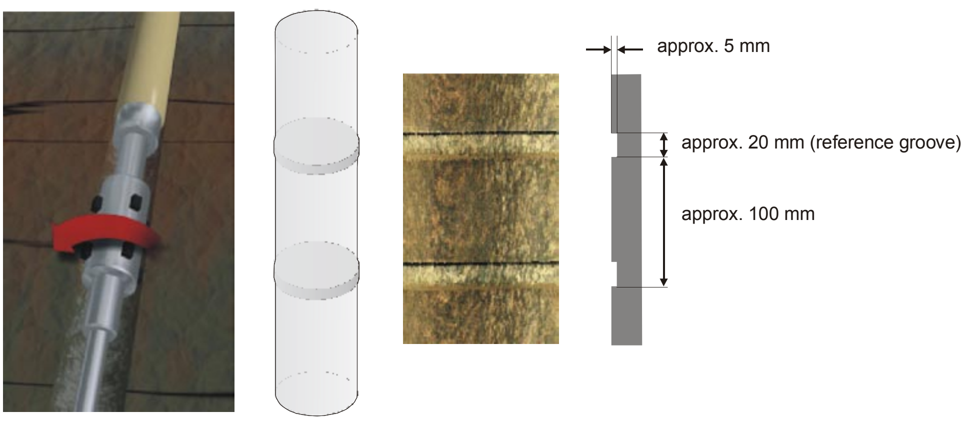


Figure 3-7. *Layout and design of reference grooves.*

At the time of drilling KFM11A, 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 KFM11A, and to-day Flexit-data are the in use displayed deviation data set. However, all available deviation measurements, i.e. for borehole KFM11A 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.

3.3.6 Equipment for borehole stabilization

A new technique for stabilization of borehole walls, designated the Plex technique, has just recently been developed and tested by SKB, see Figure 3-8. The Plex system can be applied for mechanical stabilization of unstable sections of the borehole wall after part of or the entire borehole has been drilled. 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.

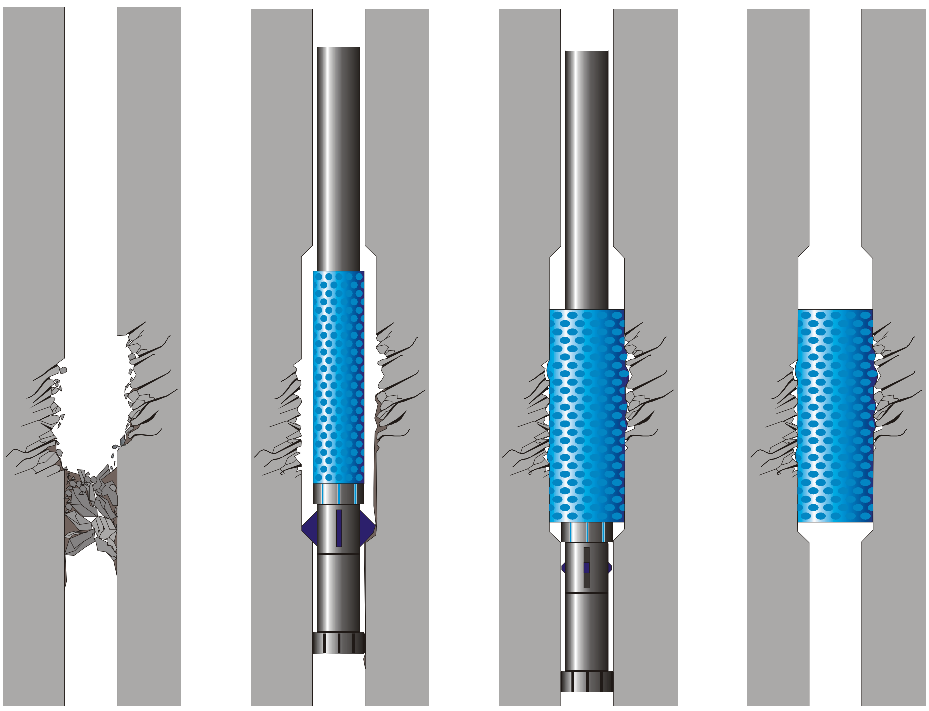


***Figure 3-8.** Schematic figure illustrating the sequence of measures when stabilizing a fractured and unstable section in a core drilled borehole of N-dimension with a perforated steel plate by applying the Plex system. The tool is descended, the 198 cm long unstable section is reamed, the packer 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 Percussion drilling of borehole section 0–71.06 m in KFM11A

The percussion drilling operations included:

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

The first four items are treated in Sections 4.1.1–4.1.4, whereas the last two activities, together with the corresponding items for core drilling, are presented in Sections 4.3 and 4.4, respectively.

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 facilities. 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 $\varnothing_i$ 310 mm casing to 12.30 m. The continued percussion drilling through solid rock was performed with a 160.2 mm drill bit to 71.06 m drilling length. For stabilization of the entire percussion drilled part, the borehole was reamed to 242.0 mm to 71.00 m length and a stainless steel $\varnothing_i$ 200 mm casing was then installed to 70.80 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 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 ∅ 160.2 mm drilling sequence. This programme was performed 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 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 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 ∅ 242.0 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 KFM11A became 71.06 m compared to 70 m that was suggested in the Activity Plan.

4.2 Core drilling of KFM11A

The core drilling operations included:

- 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.

The first four items are presented in Sections 4.2.1–4.2.4, 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 KFM11A was performed with two borehole dimensions. Section 71.06–851.21 m was drilled with ∅ 77.3 mm, whereafter the section 71.06–72.81 m was reamed to 86 mm borehole diameter. The inner ∅ 84/77 mm support casing was fitted into the short ∅ 86 mm borehole. In this way the casing was centralized in the borehole and fixed laterally in its lower part. The outer ∅ 98/89 mm support casing, which is supplied with steel wings towards the borehole wall, is during drilling resting on the bottom of the percussion drilled borehole, see Figure 3-4.

Core drilling with ∅ 77.3 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 space 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 KFM11A, a 3 m triple tube core barrel was used. The nominal core diameter for the ∅ 77.3 mm part of the borehole is 50.8 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 KFM11A 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 KFM11A.

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 4-1, 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 a wheel loader, 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 67.66–72.71 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.

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 KFM11A.

Activity	Performance and frequency according to SKB MD 620.004	Performance and frequency during drilling of KFM11A
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.	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 5-19 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.	Fifteen (double) grooves performed. The milling at 801 m was not 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.

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 inner support casing was to be recovered it got stuck in the borehole and one of the pipe threads in the casing broke. By milling the broken casing it finally got loose and was successfully recovered.

Also the last milling for grooves at 801 m partly failed as the packer was damaged. These grooves are not detectable.

During the final QC control of the borehole a dummy was lost had to be left resting on the bottom of the borehole.

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

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 geoscientific results from drilling and investigations made during and immediately after drilling. Well Cad presentations of boreholes KFM11A are shown in:

- Appendix A (percussion drilled part).
- Appendix B (the complete borehole).

5.1 Drilling progress KFM11A

The drilling operations of KFM11A were performed during two periods, between April 12th to May 2nd, 2006 (percussion drilling), and August 29th to November 16th, 2006 (core drilling). Additional work to clean, ream and stabilize the borehole with the Plex-system and to finally clean the hole from metal junk was made from March 14th to April 2nd, 2007, see Figure 5-1.

5.1.1 Percussion drilling 0–71.06 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 KFM11A, resulted in a relatively long working period, from 2006-04-12 to 2006-05-02 (Figure 5-2).

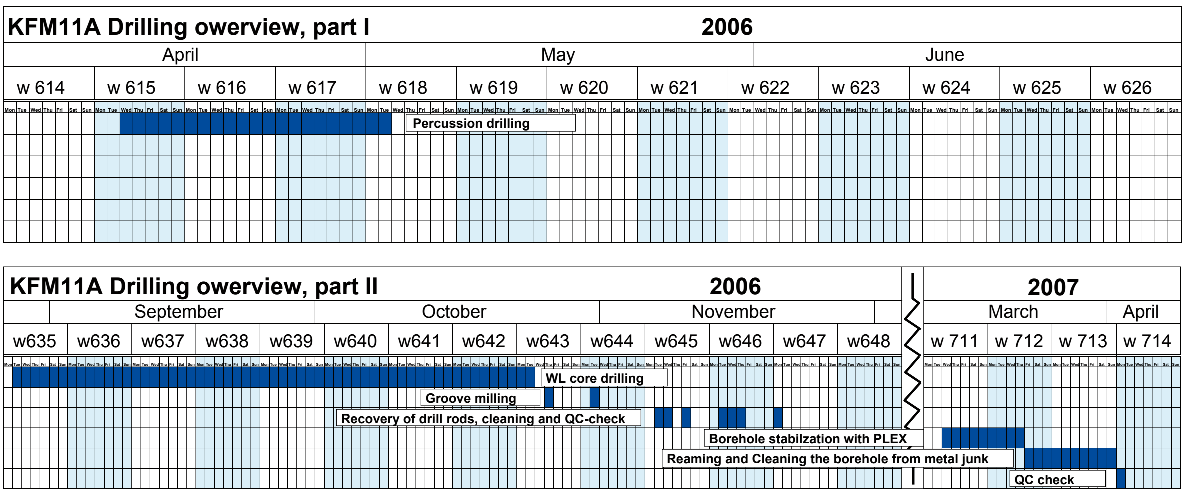


Figure 5-1. Overview of the drilling performance of borehole KFM11A.

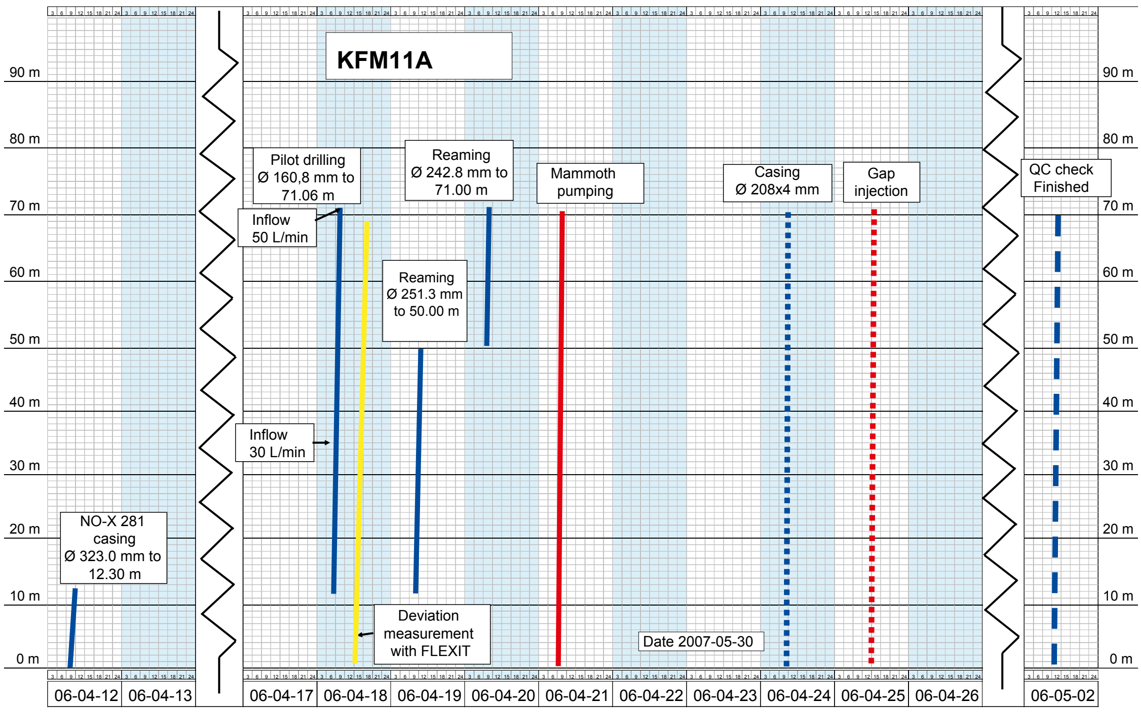


Figure 5-2. *Percussion drilling progress (depth and activity versus calendar time). "Inflow" in the figure refers to accumulated groundwater inflow.*

5.1.2 Core drilling period

After percussion drilling of section 0–71.06 m, a break of four months followed, whereafter core drilling commenced. The progress of the core drilling from 2006-08-29 to 2006-11-16, 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. At the very end of the drilling period a number of problems occurred. When closing down and screwing apart the six metres long drill rods to 3 m length, the rods were dropped in the borehole, causing two extra working shifts to recover the rods all the way from borehole bottom. In addition, for the final quality control, a dummy was lowered with a wire into the borehole, downwards and upwards, but just when it reached TOC (Top Of Casing), the wire lock opened and the dummy fell down in the borehole. The problems continued, when the ∅ 84 mm inner support casing got stuck in the reamed part and another working shift had to be used to clean the hole from the casing and thereafter, just below the telescopic borehole bottom, extend the reaming of the ∅ 86 mm section. Finally, the rig was removed and the transition cone was mounted on November 20th, 2006.

The investigation programme commenced, and geophysical logging as well as BIPS/radar were successfully measured. But the difference flow logging could be performed only to c. 480 m because the borehole wall had previously turned out to be instable at c. 500 m, causing another dummy to be jammed at c. 500 m borehole length, thereby blocking up the hole. It was therefore decided to clean and thereafter stabilize the borehole, resulting in that a new drilling machine was engaged, performing this additional work between 2007-03-14 and 2007-04-02, see also Section 5.5.

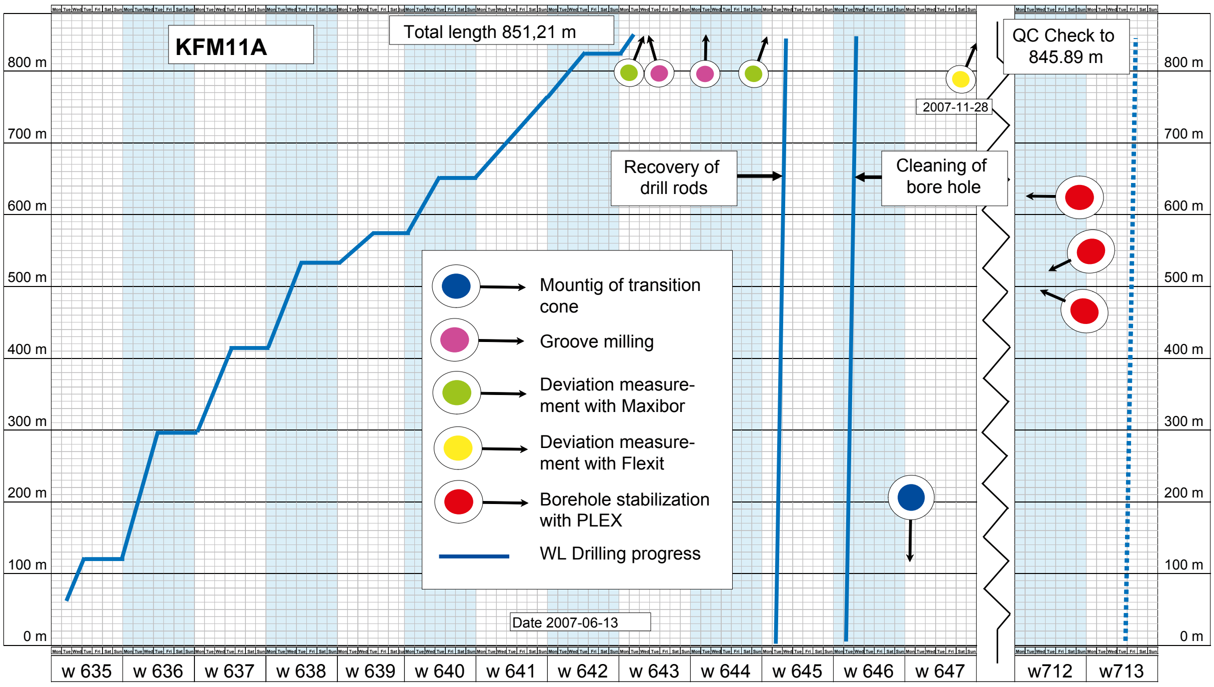


Figure 5-3. *Drilling progress (length and activity versus calendar time).*

5.2 Geometrical and technical design of borehole KFM11A

Administrative, geometric and technical data for the telescopic borehole KFM11A are presented in Table 5-1. The technical design is illustrated in Figure 5-4.

5.3 Percussion drilling KFM11A 0–71.06 m

5.3.1 Drilling

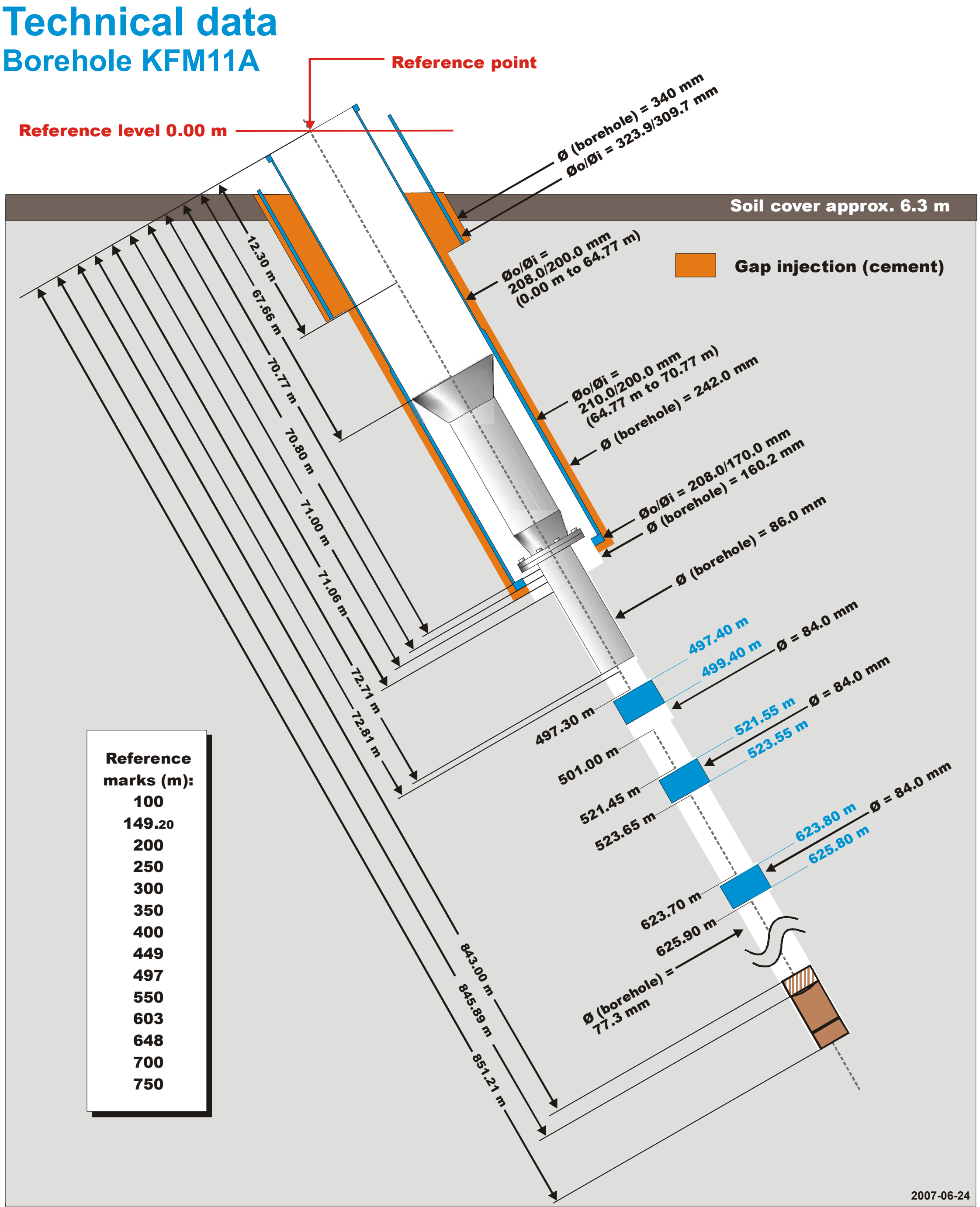
As mentioned in Section 4.1.3, the upper 12.30 m of the borehole was drilled and cased with NO-X 280. During pilot drilling to 71.06 m a medium fractured rock with an inflow of 50 L/min was observed. Generally, drilling in KFM11A was expected to be hazardous and as an inclined borehole has a higher risk of instability than a vertical borehole, the borehole section to 71.00 m was reamed to 242 mm and a stainless steel casing was installed to 70.80 m. Finally, the gap between the casing and the borehole wall was cement grouted, so that the water inflow ceased completely.

5.3.2 Measurements while drilling

During, and immediately after drilling, a program for sampling and measurements was applied, cf. Section 4.1.3. 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.

Table 5-1. Administrative, geometric and technical data for borehole KFM11A.

Parameter	
Borehole name	KFM11A
Location	Forsmark, Östhammar municipality, Sweden
Drill start date	April 12th, 2006
Completion date	Nov 16th, 2006
Percussion drilling period	2006-04-12 to 2006-05-02
Core drilling period	2006-08-29 to 2006-11-16
Additional work period	2007-03-14 to 2007-04-02
Contractor core drilling	Drillcon Core AB
Subcontractor percussion drilling	Sven Andersson i Uppsala AB
Percussion drill rig	Commacchio MC 1500
Core drill rig	Onram 2000 CCD
Position at top of casing (RT90 2.5 gon V 0:-15 / RHB 70)	N 6701103.82 E 1632366.75 Z 2.95 (m.a.s.l.) Azimuth (0–360°): 40.25° Dip (0–90°): –60.86°
Position at bottom of hole (RT90 2.5 gon V 0:-15 / RHB 70)	N 6701425.50 E 1632690.49 Z –713.24 (m.a.s.l.) Azimuth (0–360°): 43.64° Dip (0–90°): –51.43°
Borehole length	851.21 m
Borehole diameter and length	From 0.00 m to 12.30 m: 0.340 m From 12.30 m to 71.00 m: 0.242 m From 71.00 m to 71.06 m: 0.1602 m From 71.06 m to 72.81 m: 0.086 m From 72.81 m to 851.21 m: 0.0773 m
Casing diameter and drilling length	$\varnothing_o/\varnothing_i$ = 324 mm/310 mm to 12.30 m Casing shoe $\varnothing_i$ = 281 mm between 12.22 and 12.30 m $\varnothing_o/\varnothing_i$ = 208 mm/200 mm to 64.77 m $\varnothing_o/\varnothing_i$ = 210 mm/200 mm to 70.77 m Casing shoe $\varnothing_i$ = 170 mm between 70.77 and 70.80 m
Transition cone outer and inner diameter	At 67.66 m: 0.195 m At 72.71 m : 0.080 m
Drill core dimension	71.06–851.15 m/∅ 51 mm
Core interval	71.06–851.15 m (0.06 m core cut remaining in borehole)
Average length of core recovery	2.17 m
Number of runs	358
Diamond bits used	12
Average bit life	64.3 m/drill bit



Drilling reference point

Northing: 6701103.82 (m), RT90 2,5 gon V 0:-15
Easting: 1632366.75 (m), RT90 2,5 gon V 0:-15
Elevation: 2.95 (m), RHB 70

Orientation

Bearing (degrees): 40.25°
Inclination (degrees): -60.86°

Borehole

Length: 851.21 m

Percussion drilling period

Drilling start date: 2006-04-12
Drilling stop date: 2006-05-02

Core drilling period

Drilling start date: 2006-08-29
Drilling stop date: 2006-11-16

Additional work

Reaming and PLEX setting
Start date: 2007-03-14
Stop date: 2007-04-02

Figure 5-4. *Technical data of borehole KFM11A.*

5.4 Core drilling KFM11A 71.06–851.21 m and measurements while drilling

The final drilling efforts within the Forsmark site investigation programme aimed at characterizing the two regional deformation zones demarcating the Forsmark candidate area to the north-east and south-west respectively. To the north-east, drilling in the Singö deformation zone (ZFMNW0001) was experienced during the investigations for the SFR facility, a tunnel system for final disposal of low- and medium level radioactive waste, during the period 1978–1980. Part of the Singö deformation zone appeared to be highly fractured but moderately water-yielding, and with a varying lithological composition. Much of these characteristics of the rock were also found when drilling KFM11A.

Generally, the fracture frequency in KFM11A is two to three times higher than in boreholes drilled inside the candidate area, i.e. within the Forsmark tectonic lens. A significantly increased fracture frequency was observed from c. 495 m, which corresponds with the upper border of Singö deformation zone, which later in the drilling period caused major instability problems, see also Sections 5.1.2 and 5.5.

The varying rock composition as well as the high fracture frequency, probably caused an unusually short average length of core recovery, 2.17 m, whereas the average lifetime of the drill bit was 64.3 drilled metres. The life-time of a drill bit is depending on a combination of the quality of the drill bit, the skilfulness of the drilling crew, the condition of the drilling machine, as well as of the bedrock properties.

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 5.4.1–5.4.13 below.

5.4.1 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 AP PF 400-06-025.

Penetration rate

The conspicuous variation of rock types and fracture frequency in KFM11A, see Appendix B, also had a great influence on the penetration rate, see Figure 5-5. The penetration rate was probably pre-set to 12 cm/min, which is the dominating value down to c. 450 m drilling length, although with considerable variations to about 275 m, where minor shallow fracture zones were encountered alternating with competent rock. When drilling approaches the upper contact of the Singö deformation zone just before 500 m drilling length, the appearance of the penetration rate curve changes rather abruptly, and displays continuous minor and major variations reflecting increased fracture frequency and rapid changes of rock types.

Rotation pressure

Figure 5-6 illustrates the rotation pressure versus drilling length and Table 5-2 presents the drilling lengths where drill bits were exchanged.

There is a significant correlation between the variation of the rotation pressure and exchange of drill bits. From start the rotation pressure displays an increasing trend to c. 150 bars at 500 m drilling length, but when a drill bit is exchanged, the rotation pressure immediately falls back to less than 100 bars. Between 500 and 700 m, the increasing trend is discontinued, possibly reflecting less competent rock within the Singö zone. After 700 m, the rotation pressure again increases, which probably is caused by larger friction as the borehole deviation increases

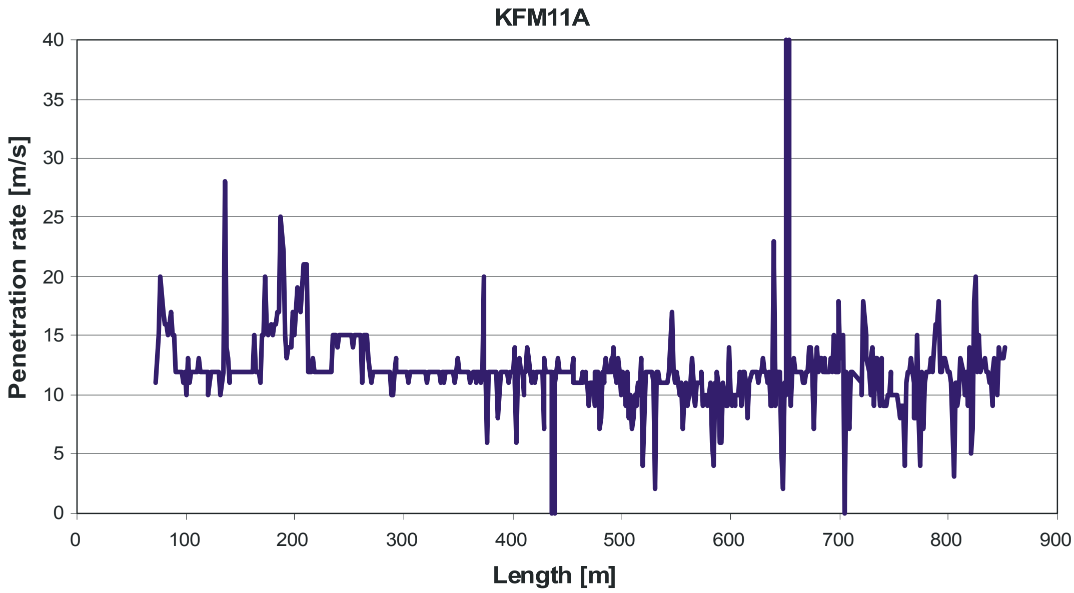


Figure 5-5. *Penetration rate during core drilling of KFM11A.*

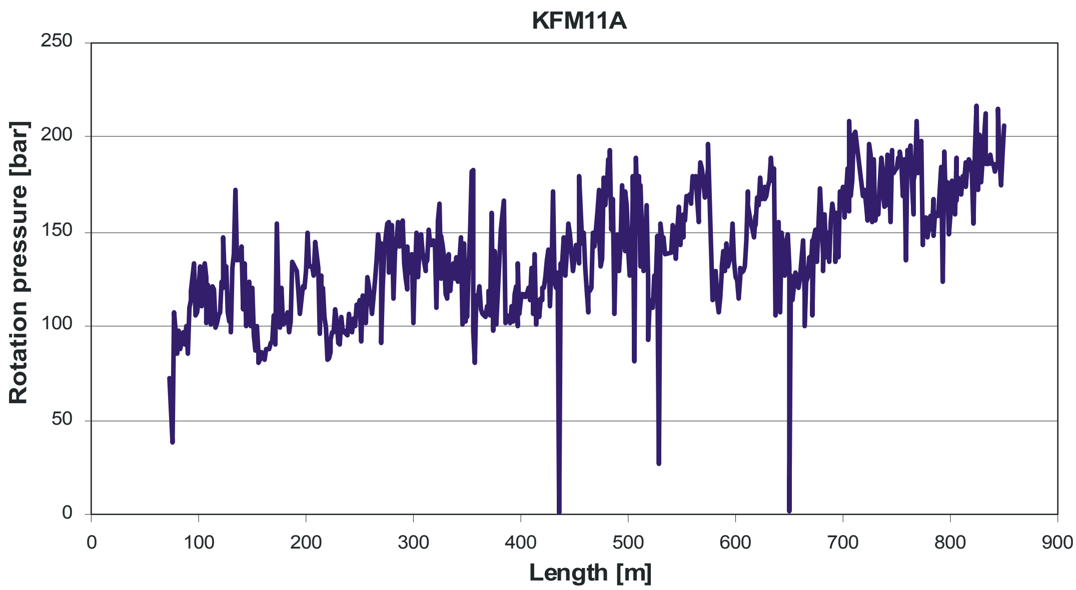


Figure 5-6. *Rotation pressure during core drilling of KFM11A.*

with length. However, the rotation pressure decrease in connection with drill bit exchanges is repeated throughout the entire borehole. When restarting the drilling, low rotation pressure with a new drill bit is probably due to a combination of the borehole bottom being properly flushed and cleaned, and that the drill crew is extra careful form start using the new drill bit. When the diamond segments are worn out and/or if drilling debris remains in the borehole, the rotation pressure increases.

Table 5-2. Change of drill bit during drilling of KFM11A.

Change of drillbits [m]
73.08
151.32
219.85
384.87
577.44
637.80
651.13
657.74
712.30
773.71
825.94
851.21

Feed force

In Figure 5-7 the feed force is plotted versus borehole length.

The software for the steering system had earlier been upgraded, but during drilling of the previous borehole KFM08C large disturbances occurred again. After maintenance and exchanging of spare parts and transducers to the hydraulic units, the system has functioned well and has been able to maintain a better control of the drilling parameters. Generally, the level of the feed force when drilling KFM11A was lower compared to the feed force registered when drilling boreholes in Forsmark inside the candidate area with the Onram 2000 CCD machine.

The feed force has an overlaying undulating display, but to some extent the feed force drops almost immediately just after a drill bit has been exchanged and the drilling is restarted. When drilling is continued, the diamond segments get worn out, higher friction is induced, which results in increased feed force, until a new drill bit is applied again.

A generally decreased level of feed force is observed in the lower part of the borehole, corresponding to drilling in the Singö deformation zone with its relatively low-competent rock.

Rotation speed

The rotation speed diagram, Figure 5-8, shows from start an almost constant rotation speed of 850 rpm with only minor variations to approximately 575 m, where it drops to c. 800 rpm and later oscillates between c. 800 and 850 rpm. Sudden drops in the curve represent drilling shut off. It is also worth to mention that the rotation speed is set by the drill crew and can therefore be changed to adapt to different conditions as variations in rock type, fracture frequency etc.

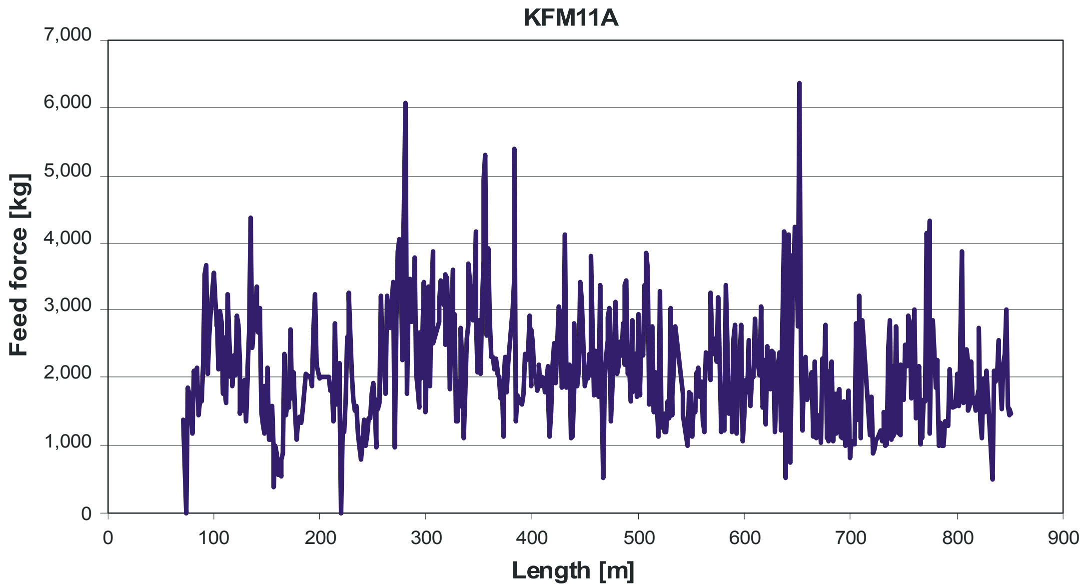


Figure 5-7. Feed force versus borehole length during drilling of borehole KFM11A.

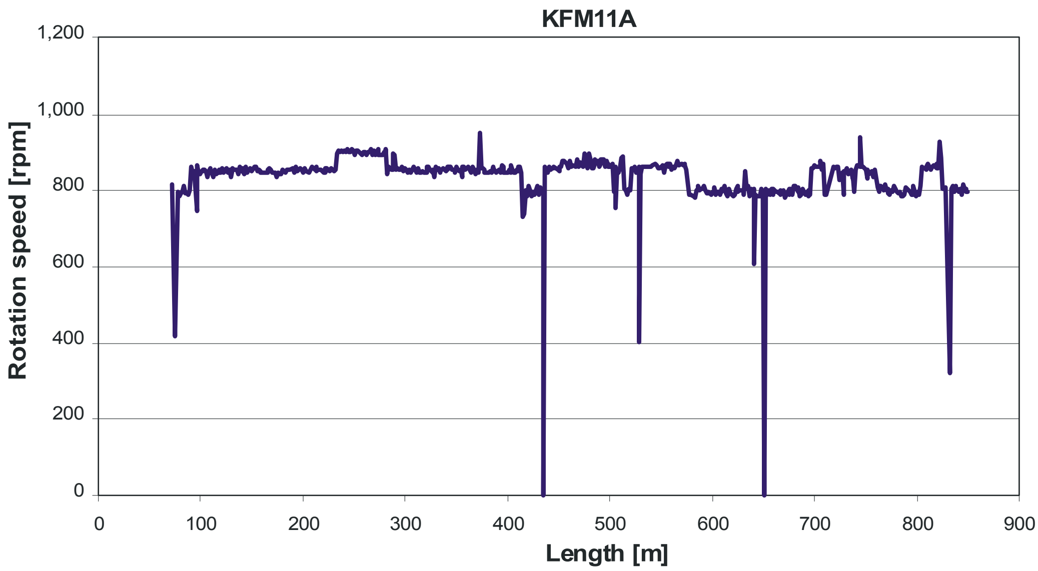


Figure 5-8. Rotation speed versus borehole length during drilling of KFM11A.

5.4.2 Flushing water and return water flow parameters

Flushing water and return water flow rate measurements – water balance

As borehole KFM11A 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, in order 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 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 5-9 illustrates the accumulated volume of flushing water and return water versus time during core drilling, whereas Figure 5-10 displays the accumulated volumes of flushing water and return water from the entire drilling period, giving a return water/flushing water quotient of 2.83 [2,712/959] (results from Uranine measurements are presented in the next section). This relatively high quotient is due to a relatively high water-yielding capacity of the borehole in combination with repeated long periods of return water flushing.

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 per every fourth hour during the drilling period, see Figure 5-11. 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 195 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 160 g and 244 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. No explanation to this has so far been found. After finished drilling, the water chemistry sampling in KFM11A also showed that flushing water still remains in the borehole.

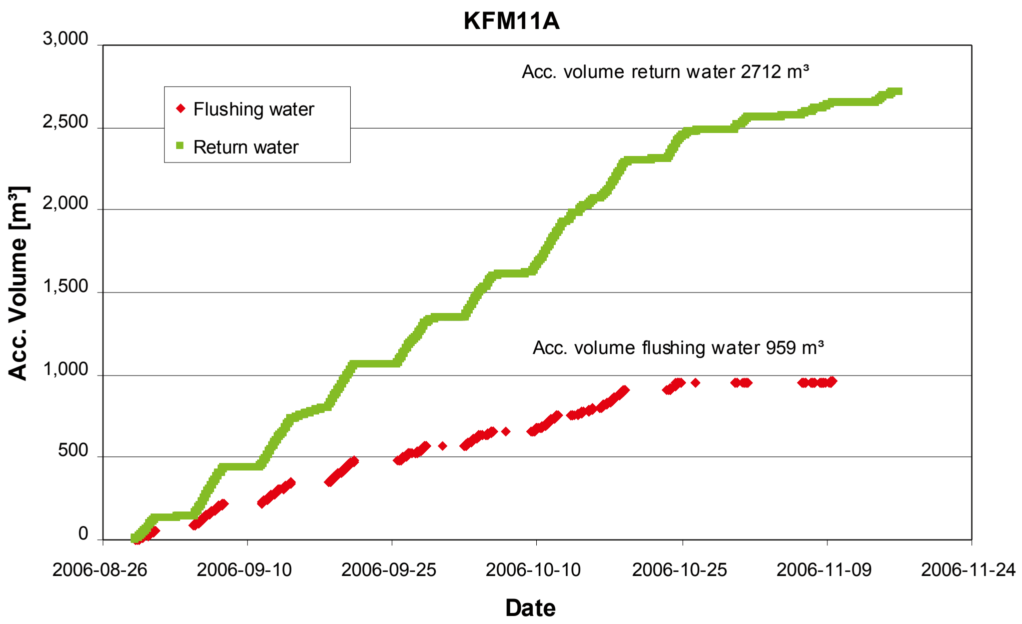


Figure 5-9. *Accumulated volumes of flushing water (red) and return water (green) versus time during core drilling of borehole KFM11A.*

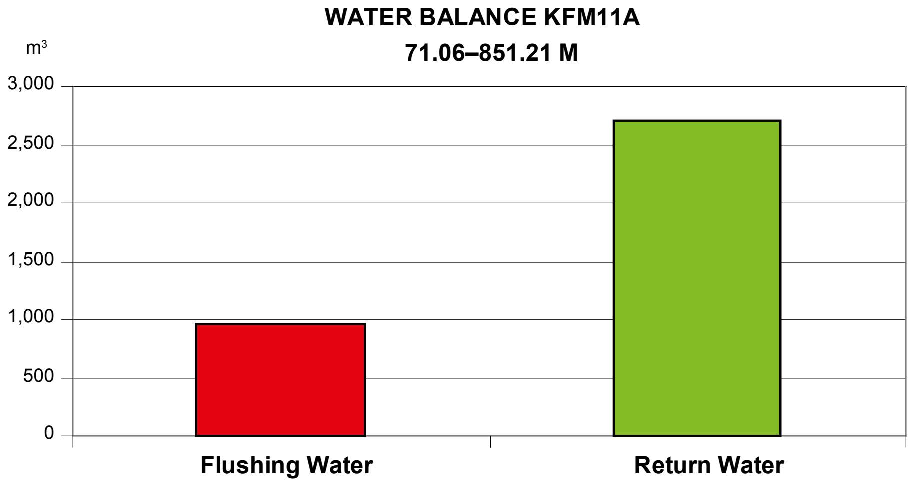


Figure 5-10. Total amounts of flushing water and return water during drilling of borehole KFM11A. The total volume of flushing water used during core drilling was amounted to 959 m³. During the same period, the total volume of return water was 2,712 m³ resulting in a return water/flushing water balance of 2.83.

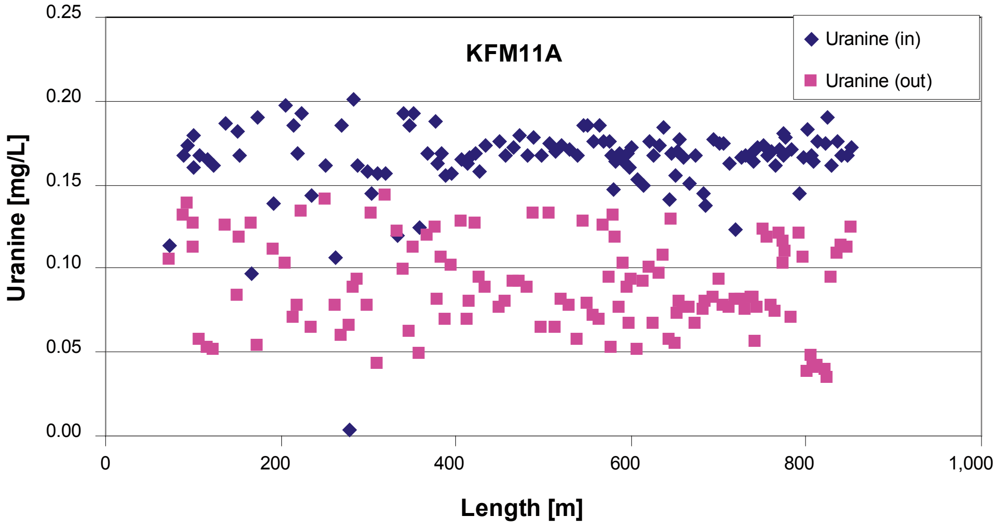


Figure 5-11. Uranine content in the flushing water consumed and the return water recovered versus drilling length during drilling of borehole KFM11A. An automatic dosing equipment, controlled by a flow meter, accomplished the labelling with Uranine.

Flushing water pressure

The flushing water pressure measured during drilling of borehole KFM11A is exposed in Figure 5-12.

Like in several other core drilled boreholes in Forsmark the borehole diameter was 77.3 mm, i.e. increased c. 1 mm compared to in the first deep cored borehole KFM01A. This resulted in generally lower flushing water pressure than in KFM01A.

After an almost continuous increase of flushing water pressure versus borehole length, the trend is interrupted at c. 385 m, which coincides with change to a new drill bit. The water pressure is then almost constant to 450 m, where a continuously increasing trend to c. 577 m is prevailing, when a new drill bit is mounted. Finally, from c. 650 m the water pressure decreases down to below 40 bars at 700 m drilling length, and is then relatively constant at 45–50 bars to the borehole end.

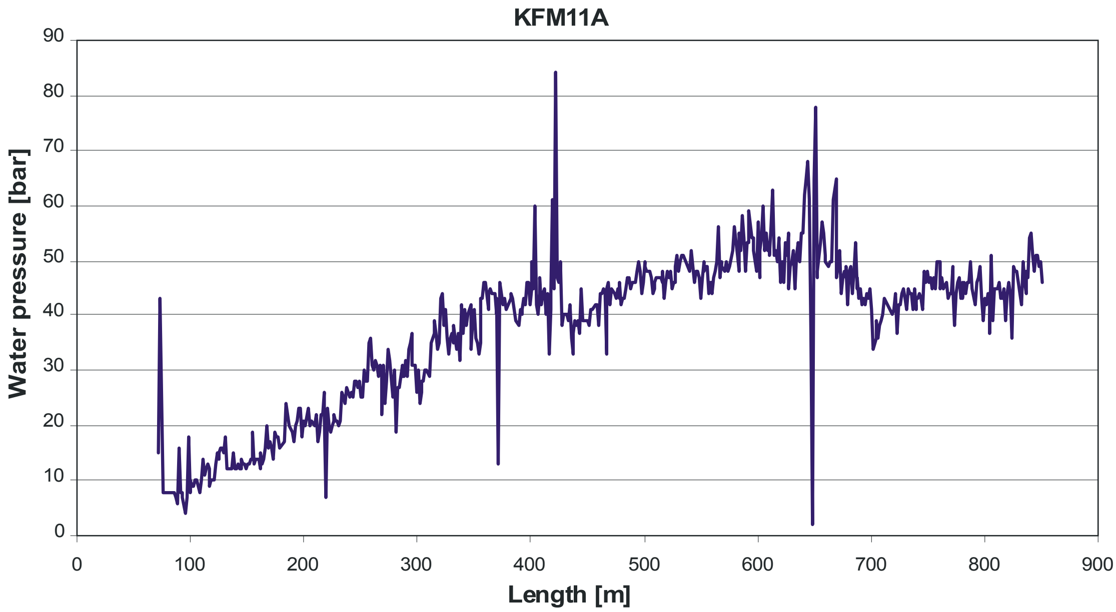


Figure 5-12. Flushing water pressure versus borehole length.

5.4.3 Electric conductivity of flushing water and return water

Flushing water was supplied from percussion borehole HFM33, see Figure 1-2. 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 of the return water was positioned between the surge diverter (discharge head) and the sedimentation containers (Figure 3-3). The results of the EC-measurements are displayed in Figure 5-13.

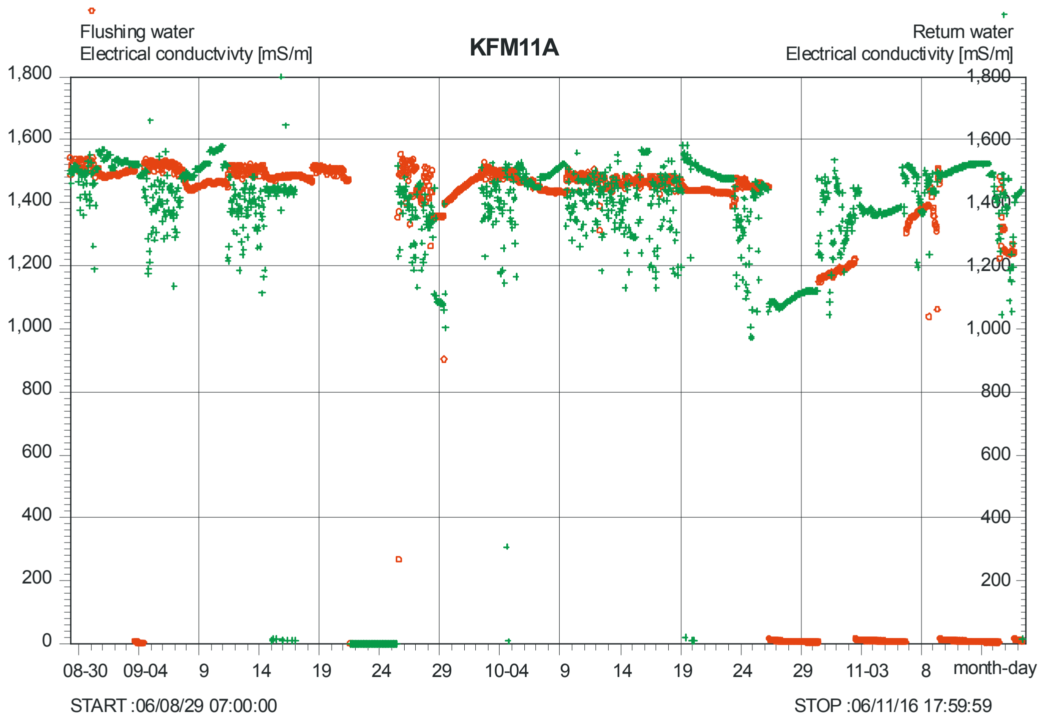


Figure 5-13. Electrical conductivity of flushing water from HFM33 and return water from KFM11A. The amount of values in the dataset has been reduced as well as cleaned from outliers.

The electrical conductivity (salinity) of the flushing water from the 140.20 m deep supply well HFM33 with its major inflow at c. 136 m is extraordinarily high compared to other supply wells used in the Forsmark drilling program.

From start of drilling the EC-value was amounted to c. 1,500 mS/m and was then almost constant during the drilling period.

The average electrical conductivity of the return water from KFM11A is from the beginning lower or almost equal to the EC-value of the flushing water. Only towards the borehole end some occasions occurred where the EC-value of the return water was higher than that of the flushing water.

The results indicate a moderate inflow of relatively saline water already in the upper part of the borehole and that the shallow groundwater inflow dominates in KFM11A throughout the drilling period.

5.4.4 Contents of dissolved oxygen in flushing water

In Figure 5-14, the level of dissolved oxygen in the flushing water is plotted versus time. The concentration of dissolved oxygen has generally been kept between 2–8 mg/L but the sensor has probably not been in function after October 9th, 2006. The probe for measuring dissolved oxygen is very sensitive and is more of a laboratory instrument. Due to the rough field conditions during the drilling period, it was difficult to obtain an optimal function of the instrument. To ensure sufficiently low concentration of oxygen in the flushing water, the flushing water tank was continuously bubbled with nitrogen during the drilling period.

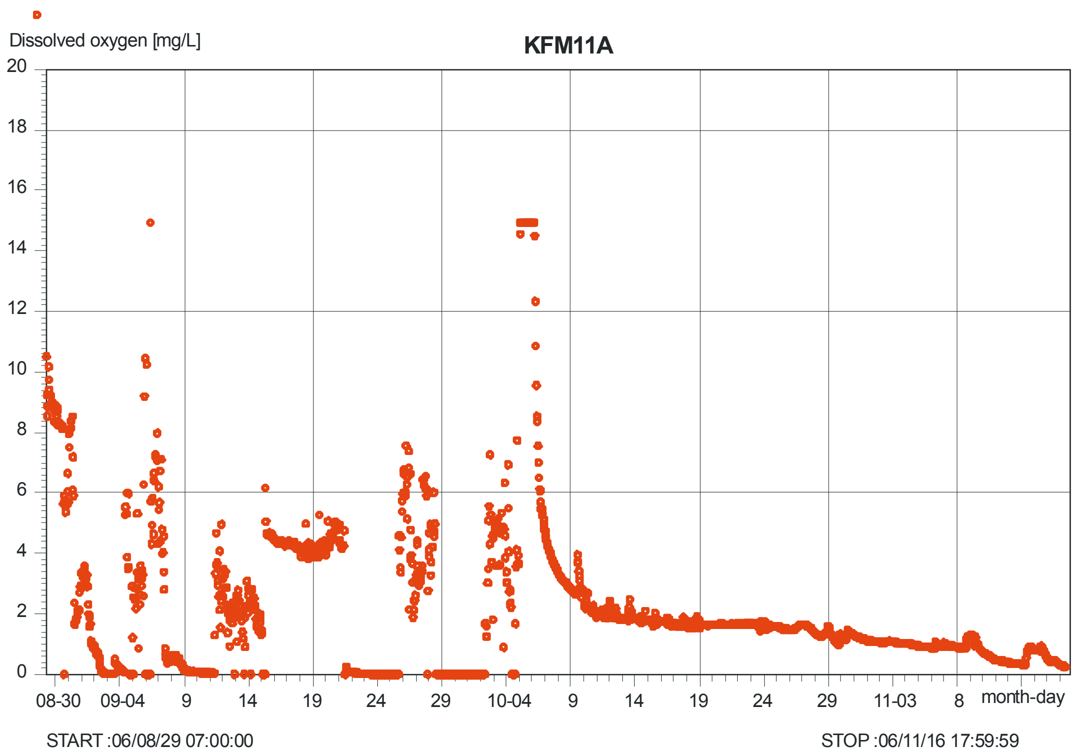


Figure 5-14. *Dissolved oxygen contents in the flushing water versus time when drilling KFM11A.*

5.4.5 Chemical composition of flushing water

Results from previous sampling and chemical analyses of groundwater from the supply well HFM33 are compiled in /5/. The flushing water was also sampled twice during drilling, for the following reasons:

- Initially, to check if the quality was satisfactory. One 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 borehole KFM11A for chemical analyses.

The results from analysis of samples are presented in Appendix C. Only the contents of organic substances (TOC) are here commented on. The TOC concentration appeared to be low, i.e. in the range 1.7–2.0 mg/L, i.e. well below 5.0 mg/L. The flushing water well was therefore 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 content in the flushing water was not determined during drilling of KFM11A. The microbe results from drilling of the preceding boreholes KFM05A /6/ and KFM06A /7/ showed convincingly that the cleaning procedure works well. It was therefore concluded that check of microbes at all drilling occasions was no longer necessary.

5.4.6 Registration of the groundwater level in KFM11A

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 5-15).

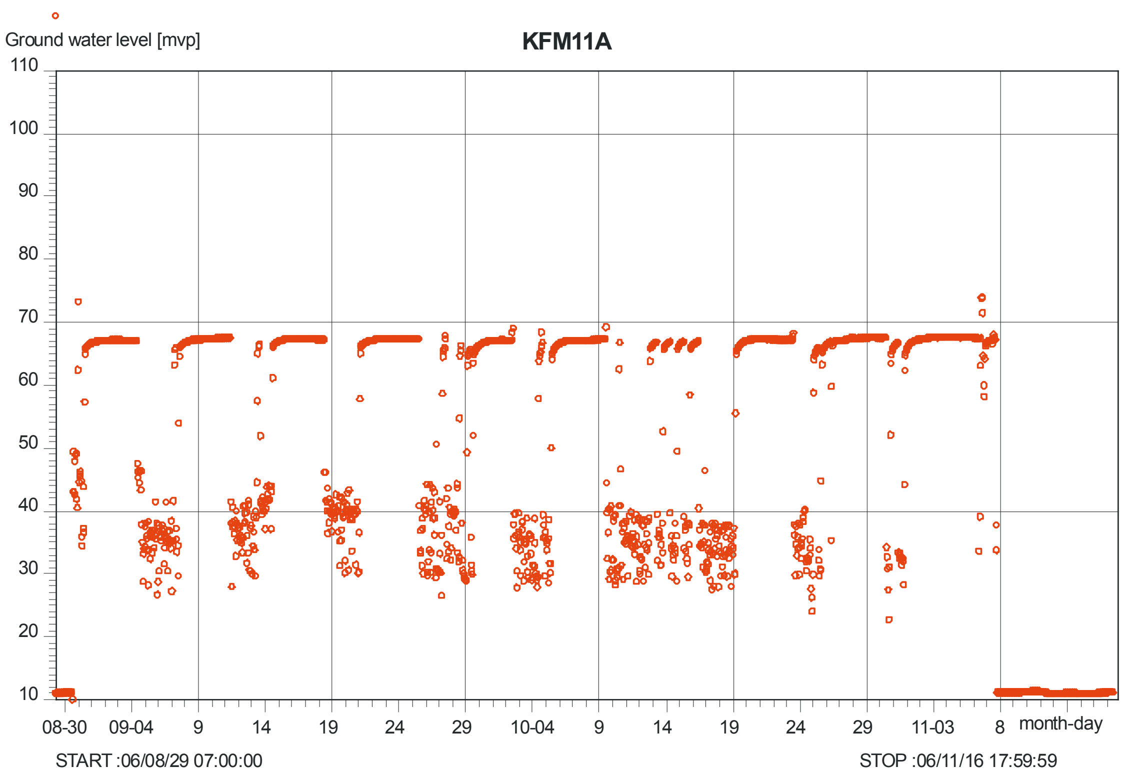


Figure 5-15. *Groundwater level versus time in KFM11A during drilling.*

From the beginning, the mammoth pumping was set at a draw-down of approximately 20 m, as the drill crew noted vibrations in the drill string with increased draw-down. However, from about 120 m borehole length the draw-down was adjusted to approximately 30–35 m and was kept at that level for almost the entire drilling period.

Drilling was performed continuously during Monday to Thursday, 24 hours a day. 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 2.17 m. Only four unbroken cores were recovered. Fracture minerals were relatively well preserved. Rotation marks on the drill core occurred, however with a pretty low frequency. A preliminary on-site core logging was performed continuously. The borehole is drilled to 851.21 m but the recovered core length is 851.15 m, implying that a core cut of 0.06 m is still remaining in the borehole.

5.4.8 Recovery of drill cuttings

The theoretical borehole volume of the percussion drilled and reamed part of KFM11A (0–71.06 m) is c. 3.7 m^3. Weighing of drill cuttings and comparison with the weight of the theoretical volume was however not carried out due to the relatively low water inflow during drilling, which caused claying. Therefore water had to be added and the air-flushing with the compressor to lift the cuttings and clean the hole had to be enhanced. This caused an uncontrolled overflow of return water with suspended drill cuttings, making it difficult to obtain reliable results of drill cuttings estimations. However, it seems probable that the percussion drilled part was well cleaned from debris, since casing driving and gap grouting to full borehole length worked well, without obstruction from settled drill cuttings.

The theoretical difference in borehole volume of the core drilled part of KFM11A and the drill core is calculated to be 2.07 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 5,486 kg. The calculated dry weight of the debris from the core drilling recovered and weighed in the containers is 4,047 kg. The difference between the theoretically produced and recovered dry weight of debris is 1,452 kg, which gives a recovery of 73.8%.

The recovery figure could be commented on. It was estimated that the amount of drill cuttings in the second container was very small and therefore this container was not weighed. Furthermore, the dwell time in the return water discharge 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 must be somewhat higher than 73.8% if these two minor amounts of drilling debris would be taken into consideration. On the other hand, the increased contents of felsic to intermediate volcanic rocks in KFM11A /4/ compared to inside the candidate area (which is dominated by granitoid variants), would imply a somewhat higher average density than 2,650 kg/m^3. This would result in a lower recovery quotient. It should also be observed that weighing of the containers including return water and debris is associated with some uncertainty. However, it seems plausible that some amounts of drilling debris have been injected into the fracture system of the formation, especially in the permeable sections with increased fracture frequency.

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 KFM11A. 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 to routines applied for the performance. It is not possible to execute an absolute control measurement, as no long borehole is available permitting exact determination of the position of both the borehole collar and the borehole end (e.g. in a tunnel) with an independent method. The strategy for quality control is instead based on comparison of results from repeated deviation measurements.

To ensure high quality measurements with the Flexit-tool, the disturbances of the magnetic field must be small. 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 November 28th, 2006, is seen in Figure 5-16 and displays only minor disturbances when the Flexit-surveys in KFM11A were performed.

In the following a systematic description of the construction of the revised deviation data for borehole KFM11A is given.

The deviation data used are two Flexit-loggings to 840 m borehole length and two complete Maxibor™-loggings to 843 m, see Table 5-3. With the Flexit Smart Tool System, the deviation measurements in borehole KFM11A were carried out every 3 m downwards an upwards at one occasion. These two surveys, with activity numbers 13138423 and 13138432, 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.

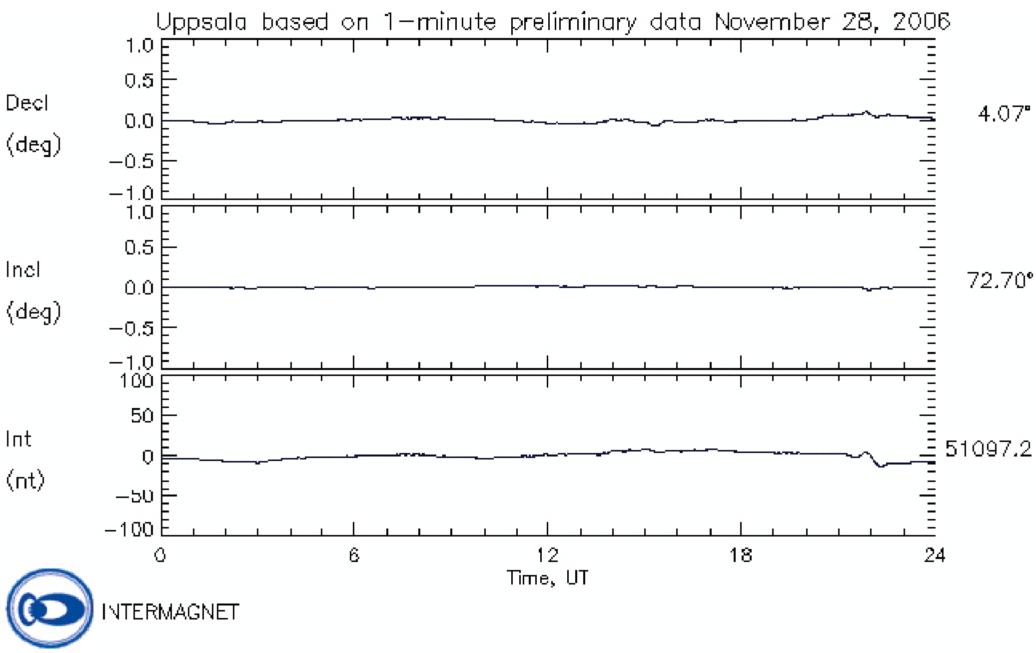


Figure 5-16. Magnetic field variation during the Flexit-survey performed Nov 28th, 2006.

Table 5-3. Activity data for the three deviation measurements approved for KFM11A (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 deviation uncertainty.

Activity id	Activity type code	Activity	Start date	Idcode	Secup (m)	Seclow (m)	Flags
13135951	EG156	MAXIBOR-measurement	2006-11-06 11:00	KFM11A	3.00	843.00	CF
13135952	EG156	MAXIBOR-measurement	2006-11-06 15:00	KFM11A	3.00	843.00	CF
13138423	EG157	Magnetic – accelerometer meas.	2006-11-28 12:55	KFM11A	3.00	840.00	CF
13138432	EG157	Magnetic – accelerometer meas.	2006-11-28 16:25	KFM11A	3.00	840.00	CF
13140521	EG154	Borehole deviation multiple meas.	2006-12-13 18:00	KFM11A			I C

The EG154-activity specifies the deviation measurements used in the resulting calculation presented in Table 5-4. The different lengths of the upper sections between the bearing and the inclination are chosen due to that the magnetic accelerometer measurement (bearing) is influenced by the 70 m steel casing if the measurements are performed too close, which is not the case for the inclinometer measurements (inclination).

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

The calculated deviation (EG154-file) in borehole KFM11A shows that the borehole deviates upwards and slightly to the right with an absolute deviation of 62 m compared to an imagined straight line following the dip and strike of the borehole start point (Figures 5-17 and 5-18). The “absolute deviation” is here defined as the shortest distance in space between a point in the borehole at a certain borehole length and the imaginary position of that point if the borehole had followed a straight line with the same inclination and bearing as of the borehole collaring.

5.4.10 Groove milling

A compilation of length to the reference grooves and a comment on the success of detecting the grooves are given in Table 5-7. 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. When milling the last grooves at 801 m the packer was damaged and therefore no detectable grooves were found.

Table 5-4. Contents of the EG154 file (multiple borehole deviation intervals).

Deviation activity id	Deviation angle type	Approved secup (m)	Approved seclow (m)
13138423	Bearing	78.00	840.00
13138423	Inclination	3.00	840.00
13138432	Bearing	78.00	840.00
13138432	Inclination	3.00	840.00

Table 5-5. Deviation data from KFM11A for approximately every 100 m elevation calculated from EG154.

Borehole	Length (m)	Northing (m)	Easting (m)	Elevation (m)	Inclination (degrees)	Bearing (degrees)
KFM11A	0	6701103.82	1632366.75	2.95	–60.94*	40.25
KFM11A	117	6701144.67	1632402.74	–100.59	–62.26	42.77
KFM11A	231	6701183.26	1632440.92	–200.82	–60.47	45.34
KFM11A	345	6701222.78	1632482.45	–299.35	–59.09	48.66
KFM11A	462	6701263.21	1632528.73	–398.90	–57.47	47.32
KFM11A	585	6701310.08	1632578.69	–501.05	–54.55	45.83
KFM11A	708	6701361.86	1632629.90	–600.16	–53.05	43.94
KFM11A	834	6701417.74	1632683.09	–699.78	–51.53	43.65
KFM11A	851.21	6701425.50	1632690.49	–713.24	–51.43	43.64

* 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 5-6. Uncertainty data for the deviation measurements in KFM11A for approximately every 100 m elevation calculated from EG154.

Borehole	Length (m)	Northing (m)	Easting (m)	Elevation (m)	Inclination uncertainty	Bearing uncertainty	Radius uncertainty
KFM11A	0	6701103.82	1632366.75	2.95	1.045	0.695	0.00
KFM11A	117	6701144.67	1632402.74	–100.59	1.045	0.695	2.13
KFM11A	231	6701183.26	1632440.92	–200.82	1.045	0.695	4.21
KFM11A	345	6701222.78	1632482.45	–299.35	1.045	0.695	6.29
KFM11A	462	6701263.21	1632528.73	–398.90	1.045	0.695	8.43
KFM11A	585	6701310.08	1632578.69	–501.05	1.045	0.695	10.67
KFM11A	708	6701361.86	1632629.90	–600.16	1.045	0.695	12.92
KFM11A	834	6701417.74	1632683.09	–699.78	1.045	0.695	15.21
KFM11A	851.21	6701425.50	1632690.49	–713.24	1.045	0.695	15.53

Table 5-7. Reference grooves in KFM11A.

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
100	Yes	Yes	497	Yes	Yes
149	Yes	Yes	550	Yes	Yes
200	Yes	Yes	603	Yes	Yes
250	Yes	Yes	648	Yes	Yes
300	Yes	Yes	700	Yes	Yes
350	Yes	Yes	750	Yes	Yes
400	Yes	Yes	801*	No	No
449	Yes	Yes			

* Not detectable as the packer was damaged when milling was conducted.

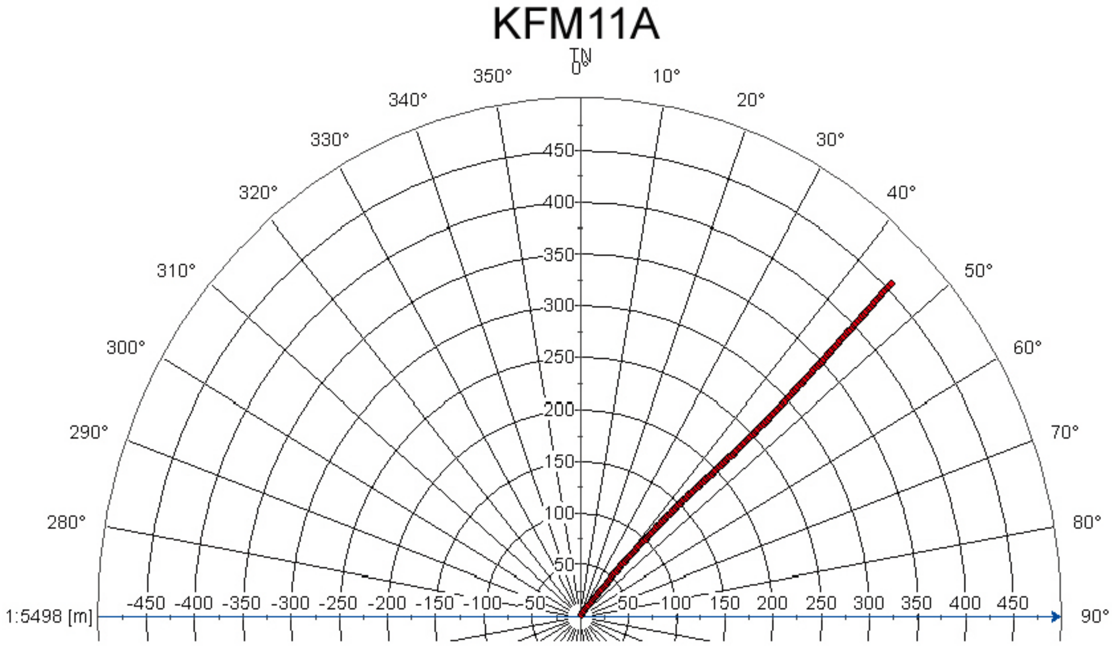


***Figure 5-17.** Horizontal projection of in use-flagged deviation of KFM11A.*

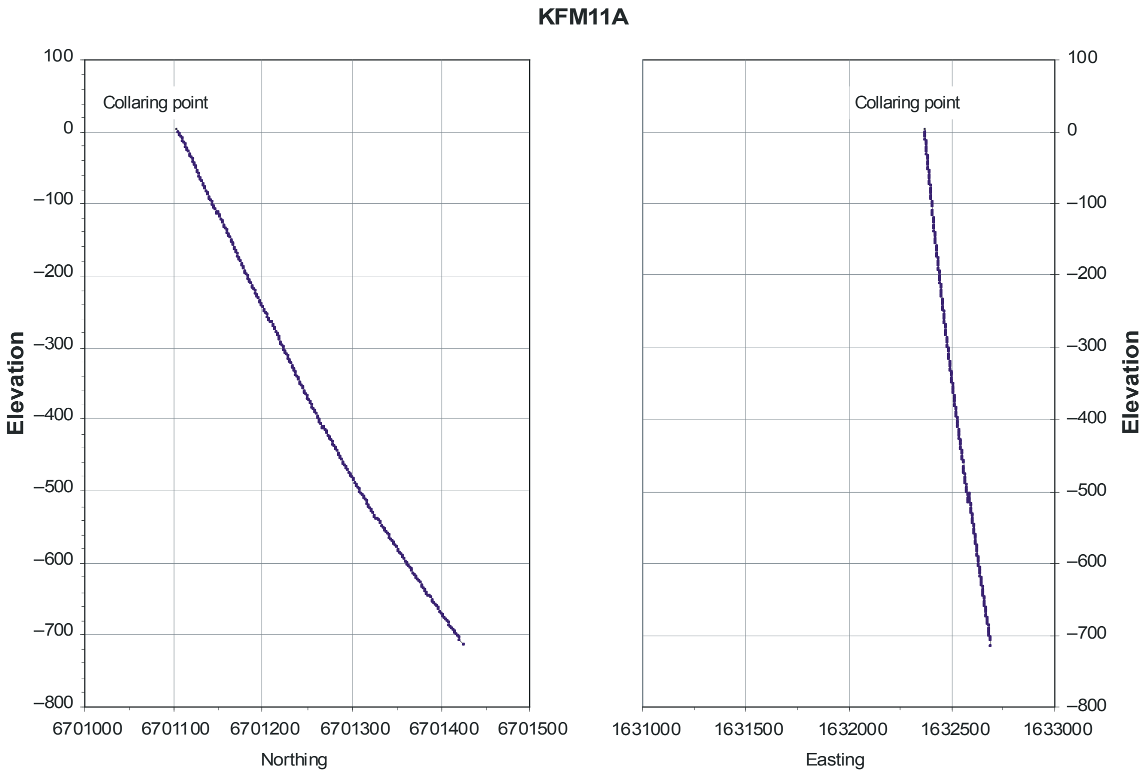


***Figure 5-18.** Two vertical projections of in use-flagged deviation of KFM11A.*

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 5-19, 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 the percussion drilled part of KFM11A (0–70 m), thread grease used during core drilling, and grout used for gap injections of the respective casings are reported in Tables 5-8, 5-9 and 5-10. 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.

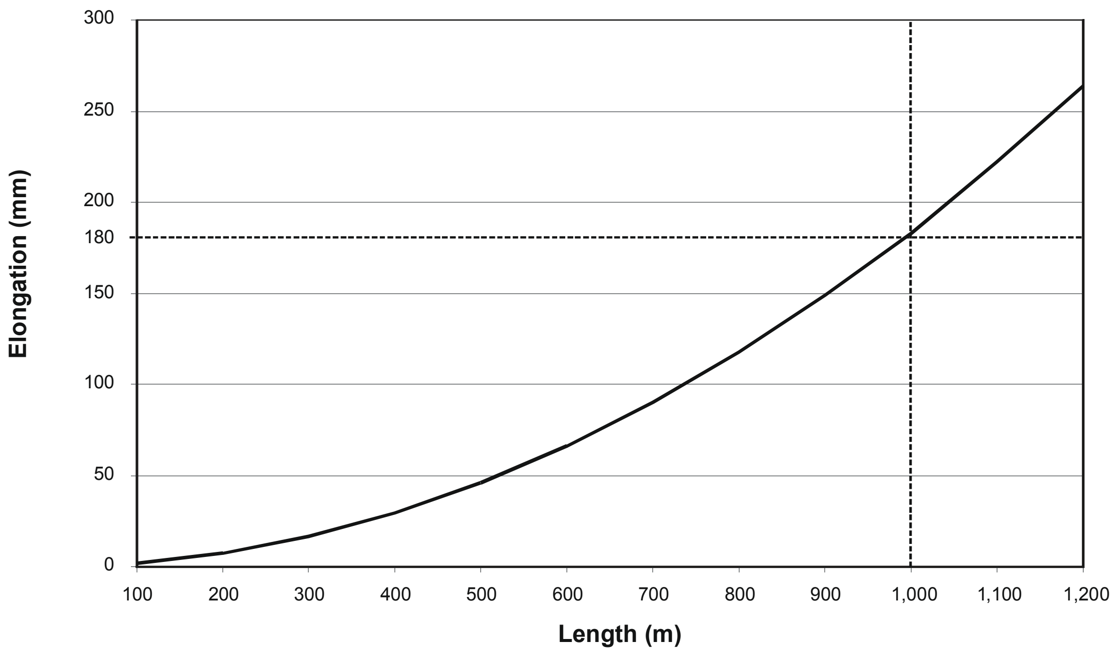


Figure 5-19. *The diagram illustrates the elongation of the WL-76 drilling pipe string when hanging in a vertical water filled borehole. Values from laboratory load tests of the drill pipe string.*

Table 5-8. Oil and grease consumption during percussion drilling of KFM11A.

Borehole ID	Hammer oil (percussion drilling) Preem Hydra 46	Compressor oil (percussion drilling) Schuman 46
KFM11A	12 L	Below detection limit

Table 5-9. Grease, oil and diesel consumption during core drilling of KFM11A.

Borehole ID	Thread grease	Grease for the drilling machine	Engine oil	Gear box oil	Hydraulic oil	Engine diesel
	Üni Silikon L50/2	Statoil AB	Castrol Tection 15W-40		Premium ECO HT-E 46	OKQ8 Diesel miljöklass 1
KFM11A	7.6 kg	4.7 kg	15 L	5 L	40 L	15,500 L

Table 5-10. Cement consumption for grouting the percussion drilled part of KFM11A and for sealing the gap between the casing and the reamed borehole wall.

Borehole ID	Length (m)	Cement weight / volume (Aalborg Portland Cement/microsilica)	Grouting method	Remarks
KFM11A	10.50–71.10	1,152 kg/1,280 L	Gap injection	

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 motive for using these products is their leniency from the environmental point of view. An important geoscientific argument supporting the use of the selected grease brand instead of some hydrocarbon based grease is that the latter may contaminate the borehole walls and the groundwater with hydrocarbons. For a reliable characterization of in situ hydrogeochemical conditions such contamination must be avoided.

However, 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.

5.4.13 Recovery measurements after cleaning by air-lift pumping

The final cleaning of KFM11A by air-lift pumping caused a draw-down of 40 m. After completed pumping, the recovery of the groundwater table was monitored. The results are displayed in the diagram of Figure 5-20. 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 26 L/min at a drawdown of 30 m was estimated.

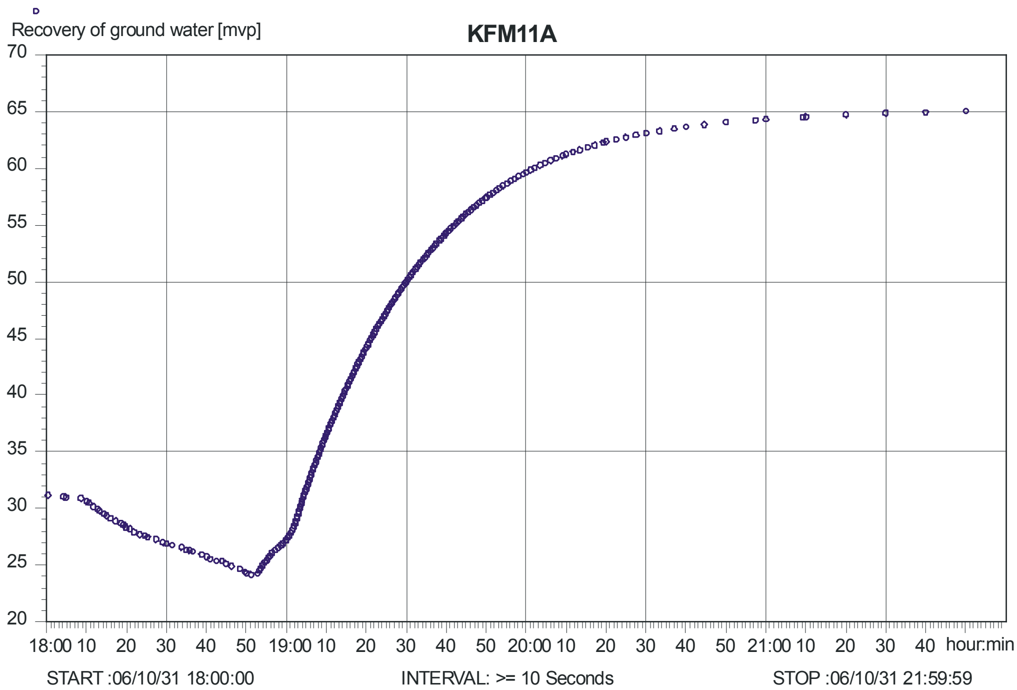


Figure 5-20. *Recovery of groundwater table in section 0–851.21 m of KFM11A after stop of air-lift pumping.*

5.5 Additionell work

5.5.1 Stabilization KFM11A

The final drilling operations within the Forsmark site investigation programme aimed at characterizing the regional fracture zones demarcating the Forsmark tectonic lens to the north-east and south-west, respectively. The Singö deformation zone (ZFMNW0001) to the north-east had previously been investigated during the pre-investigation of the SFR facility in 1977–1980, but further information was needed.

Drilling of inclined boreholes in highly fractured rock involves an increased risk of instable sections of the borehole wall, implying a higher risk for borehole instruments to get stuck. Initially, measurements along the complete borehole length with geophysical logging and BIPS/radar were successful, even though the BIPS measurement confirmed the occurrence of unstable sections with higher risk of rock outfall, especially in the lower part of the borehole, i.e. within the Singö zone.

For characterizing the hydrogeological conditions of KFM11A, the Posiva Flow Log was applied. This instrument seals off the test sections with rubber wings, and when lowered in a borehole, the wings continuously scrape against the borehole wall, which involves an increased risk of jamming. Initially, a dummy (a copy of the PFL-tool, including the rubber wings) was lowered into the borehole several times before it suddenly got wedged at c. 500 m drilling length, i.e. in the very upper part of the Singö zone. During attempts to rescue this dummy, also another dummy got caught at the same section. Due to these obstacles the PFL-logging could be conducted only to c. 480 m.

The Forsmark modelling group gave high priority to achieve hydrogeological and hydrogeo-chemical data from the Singö deformation zone and therefore a decision was made to use a drill rig for:

- rinsing the borehole by pushing the dummies to the bottom,
- stabilizing three borehole sections (identified from the PFL dummy logging and BIPS) with the Plex technique and,
- cleaning the borehole bottom, either by catching the dummies or by destroying them by drilling.

The Plex-system for stabilization of the borehole wall is described in Section 3.3.6. The following sections were stabilized, in chronological order; see Table 5-11.

The sections where the Plex-plates were installed (after eliminating the obstacles) are commented below.

Section 623.70–625.90

The following sequence of actions was carried out (cf. Figures 3-8 and 5-21):

- The Plex tool, supplied with one perforated stainless steel plate and the reamer, was attached to the drill pipe string and lowered into the borehole.
- The instable section between 623.70–625.90 m was reamed to ∅ 84 mm.
- 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 between 623.80–625.80 m.
- The packer was deflated after which the tool was retrieved from the borehole.

Section 497.30–501.00

The following sequence of actions was applied (cf. Figures 3-8 and 5-22):

- The Plex tool, supplied with one perforated stainless steel plate and the reamer, was attached to the drill pipe string and lowered into the borehole.
- The instable section between 497.30–501.00 m was reamed to ∅ 84 mm.
- 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 between 497.40–499.40 m.
- The packer was deflated after which the tool was retrieved from the borehole.

After installation of the first Plex-plate at this level, the intention was to install another plate just below. However, the packer broke, and also the diamond segments of the drill bit were worn out, entailing that probably part of the section below the plate had not been reamed to the full size, and the work had to be interrupted.

Table 5-11. Sections reamed and stabilized with PLEX in KFM11A.

Borehole	Section reamed to ∅ 84	PLEX	Comments
KFM11A	623.70–625.90	623.80–625.80	
KFM11A	497.30–501.00	497.40–499.40	Plate was damaged
KFM11A	521.45–523.65	521.55–523.55	

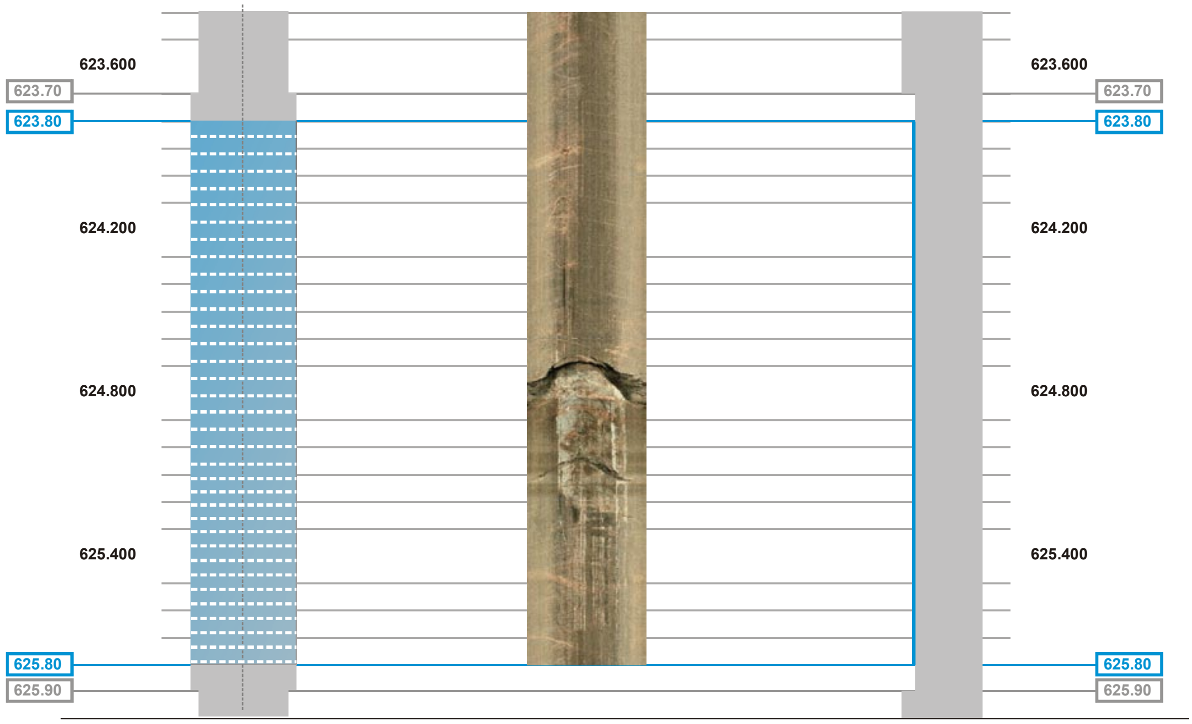


Figure 5-21. *Schematic figure of the first stabilized section in borehole KFM11A with BIPS-images of the borehole section after stabilization with the Plex system.*

After restoring the Plex-tool (new packer and new segments) it was lowered into the borehole again. and reaming now continued just below the first plate. Unfortunately, in order to stabilize the drill string, a centralizer was mounted on the core barrel above the Plex-tool. When reaming continued below the plate, the centralizer (impregnated with diamonds) damaged the first mounted plate, and probably a loose part of the plate was wedged between the drill string and the borehole wall, as it was not possible to continue the reaming.

The Plex-tool was again retrieved from the borehole and the section was re-drilled using the ordinary in-hole equipment. As it now was possible to pass through at c. 500 m, it was decided to interrupt further installation of plates in this section, because there was some uncertainty about where the first plate was located after it had been partly damaged. If a new plate was installed over an existing part, the borehole dimension could be too tight. Also the extended reaming below the plate had cleaned the borehole wall loose fragments making it more stable as it was.

After the Plex operation, part of the borehole was logged with the BIPS-camera, see Figure 5-22. The video images show that the perforated plate is damaged, and as the camera was close to be wedged between the plate and the borehole wall, the measurement was interrupted. Later on a decision was made to use the PSS3-equipement and expand a packer over the plate, which hopefully would mould the plate back on place. In early June, after two attempts, the plate was successfully moulded and injection tests and water sampling could be performed.

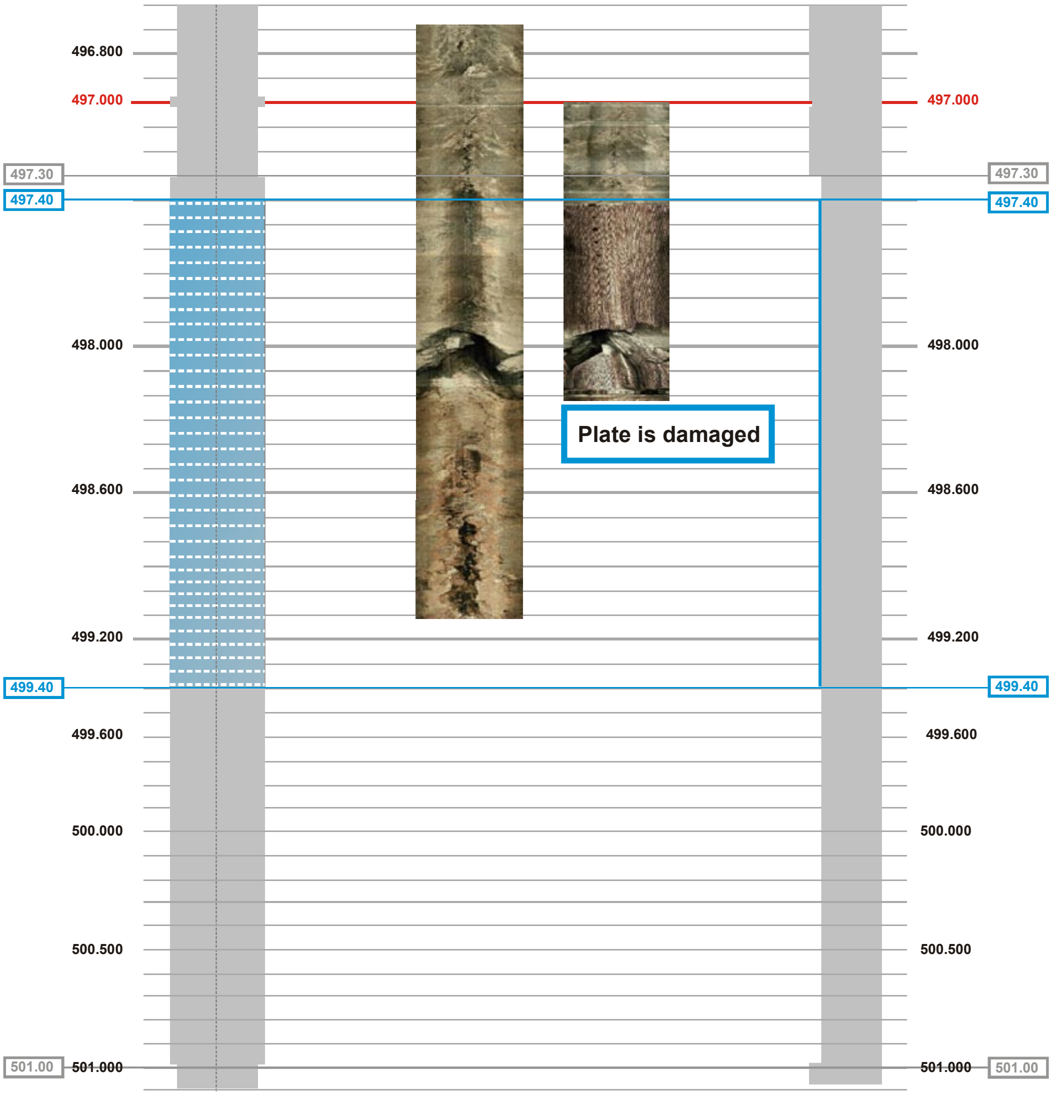


Figure 5-22. *Schematic figure of the second stabilized section in borehole KFM11A with BIPS-images of the borehole section after stabilization with the Plex system.*

Section 521.45–523.65

The following sequence of actions was carried out (cf. Figures 3-8 and 5-23):

- The Plex tool, supplied with one perforated stainless steel plate and the reamer, was attached to the drill pipe string and lowered into the borehole.
- The instable section between 521.45–523.65 m was reamed to ∅ 84 mm.
- 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 between 521.55–523.55 m.
- The packer was deflated after which the tool was retrieved from the borehole.

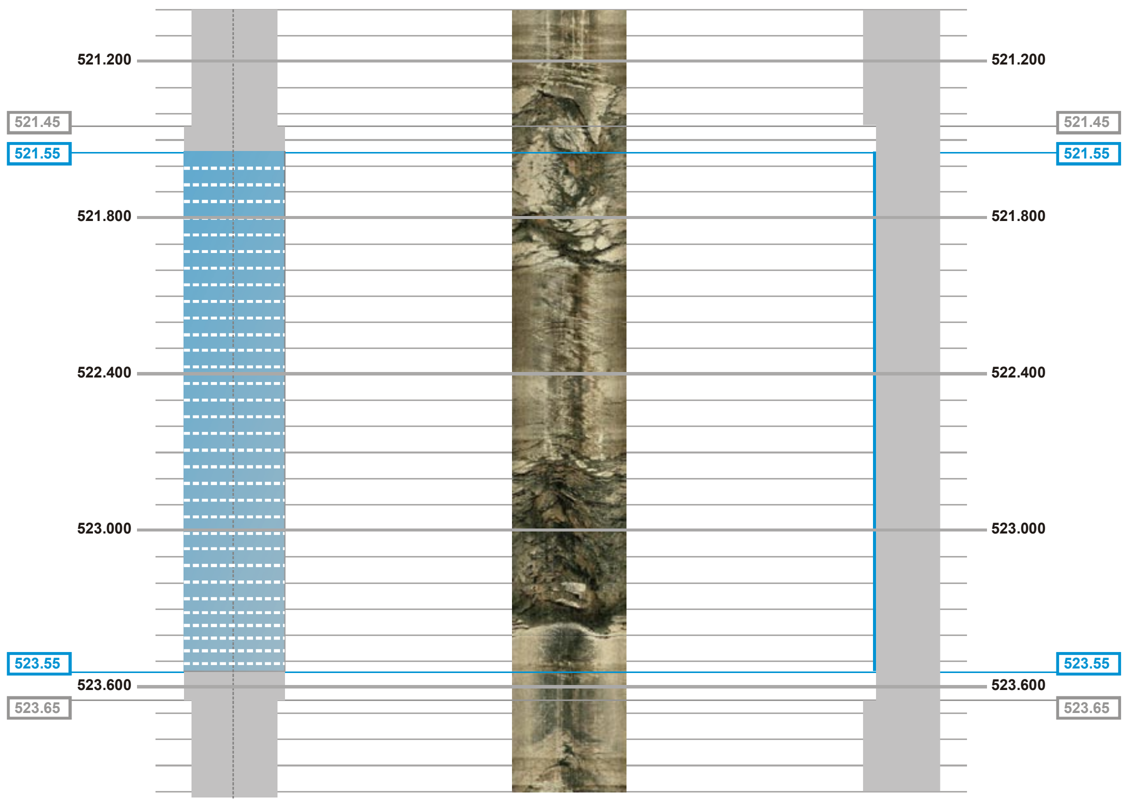


Figure 5-23. Schematic figure of the third stabilized section in borehole KFM11A with BIPS-images of the borehole section after stabilization with the Plex system.

5.5.2 Borehole rinsing

After having established the drilling rig at the borehole, the first measure of the rinsing work was to push the two dummies from c. 500 m to the bottom of the borehole. When this had been successfully carried out, the reaming and stabilization with the Plex-method of the three instable borehole sections were performed, see Section 5.5.1.

When also these activities were completed, the borehole rinsing could resume. At the bottom of the borehole, two dummies, i.e two modified drill rods were located. It was decided to mill the top of the upper dummy in order to get it clean. Thereafter a rod recovery tap was joined to the lower end of the drill string and lowered into the upper section of the dummy. When rotating the rods, the recovery tap grabs harder and harder until it gets stuck at the top of object to be retrieved. When the driller has judged that the tap has grabbed the dummy, the drill rods are pulled out of the borehole. Unfortunately, when the last rod was seen at the surface, no dummy was attached to the recovery tap.

After failing to recover the dummies, a decision was made to clear the hole by drilling the dummies to pieces. For that purpose a special drill bit (Z-bit) is used. After milling c. 1 m, rotation became increasingly difficult, involving a higher risk of the in-hole equipment getting stuck in the borehole, and therefore the cleaning work was terminated. The borehole was now cleared to 845.89 m. However, the injection tests performed later stopped, for safety reasons, already at 843.00 m borehole length.

6 References

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

/3/ **SKB, 2005.** Programme for further investigations of geosphere and biosphere. SKB R-05-14, Svensk Kärnbränslehantering AB.

/4/ **SKB, 2007.** Samuelsson, E. Site investigations at Forsmark. Boremap mapping of telescopic drilled borehole KFM11A. SKB P-07-104, Svensk Kärnbränslehantering AB.

/5/ **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.

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/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.

Well Cad-plot of the percussion drilled part of borehole KFM11A

Title PERCUSSION DRILLED BOREHOLE KFM11A

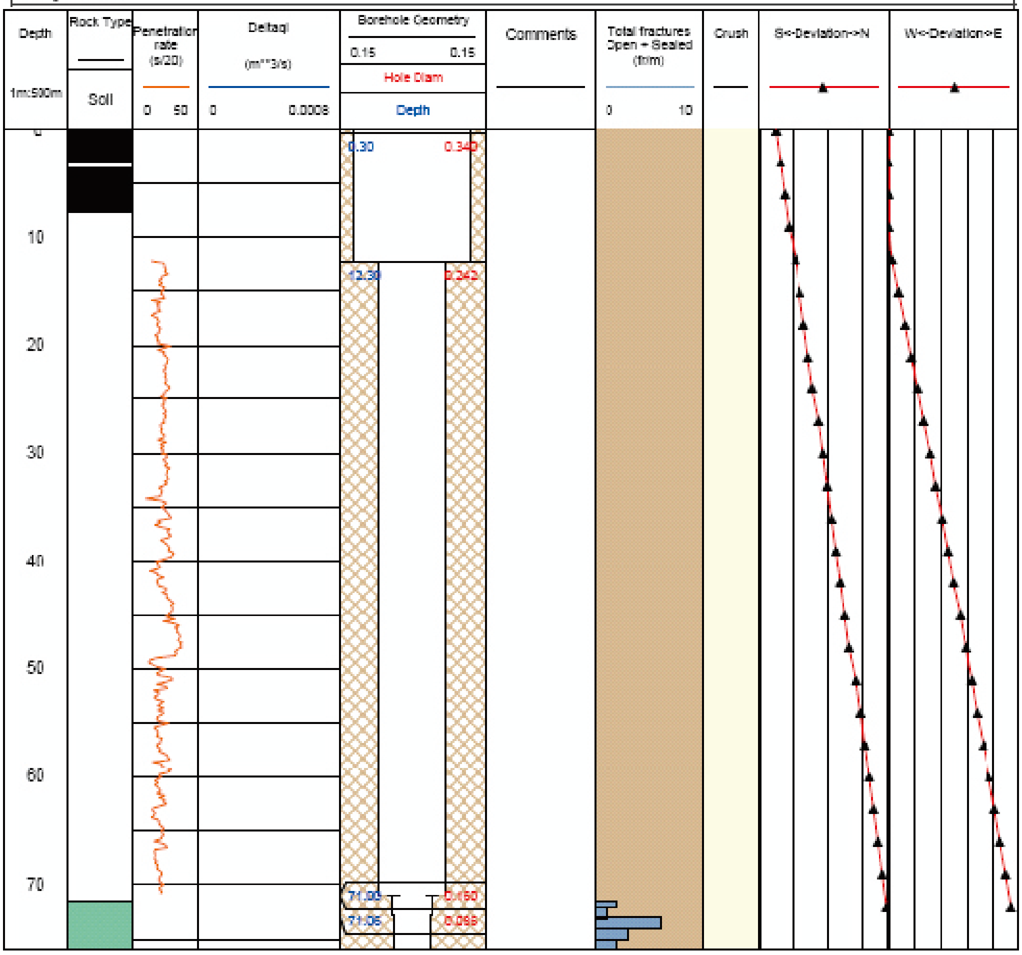
Svensk Kärnbränslehantering AB

Site	FORSMARK	Signed data	
Borehole	KFM11A	Coordinate System	RT90-RHB70
Diameter [mm]	242.00	Northing [m]	6701103.82
Length [m]	71.06	Easting [m]	1632366.75
Bearing [°]	40.25	Elevation [m.a.s.l.]	2.95
Inclination [°]	-60.86	Drilling Start Date	2006-04-12 08:00:00
Date of mapping		Drilling Stop Date	2006-05-02 16:30:00
		Plot Date	2007-06-17 23:13:46

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

SOIL
- Soil

Script Name



Appendix B

Well Cad-plot of the complete borehole KFM11A

Title KFM11A

Svensk Kärnbränslehantering AB

Site	FORSMARK	Signed data	
Borehole	KFM11A	Coordinate System	RT90-RHB70
Diameter [mm]	77	Northing [m]	6701103.82
Length [m]	851.21	Easting [m]	1632366.75
Bearing [°]	40.25	Elevation [m.a.s.l.]	2.95
Inclination [°]	-60.89	Drilling Start Date	2006-04-12 08:00:00
Date of mapping		Drilling Stop Date	2006-11-16 16:30:00
		Plot Date	2007-06-11 23:45:06

ROCKTYPE FORSMARK
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- Pegmatite, pegmatitic granite
- Granitoid, metamorphic
- Granite, granodiorite and tonalite, metamorphic, fine- to medium-grained
- Granite, metamorphic, aplitic
- Granite to granodiorite, metamorphic, medium-grained
- Granodiorite, metamorphic
- Amphibolite
- Calc-silicate rock (skarn)
- Felsic to intermediate volcanic rock, metamorphic

SOIL
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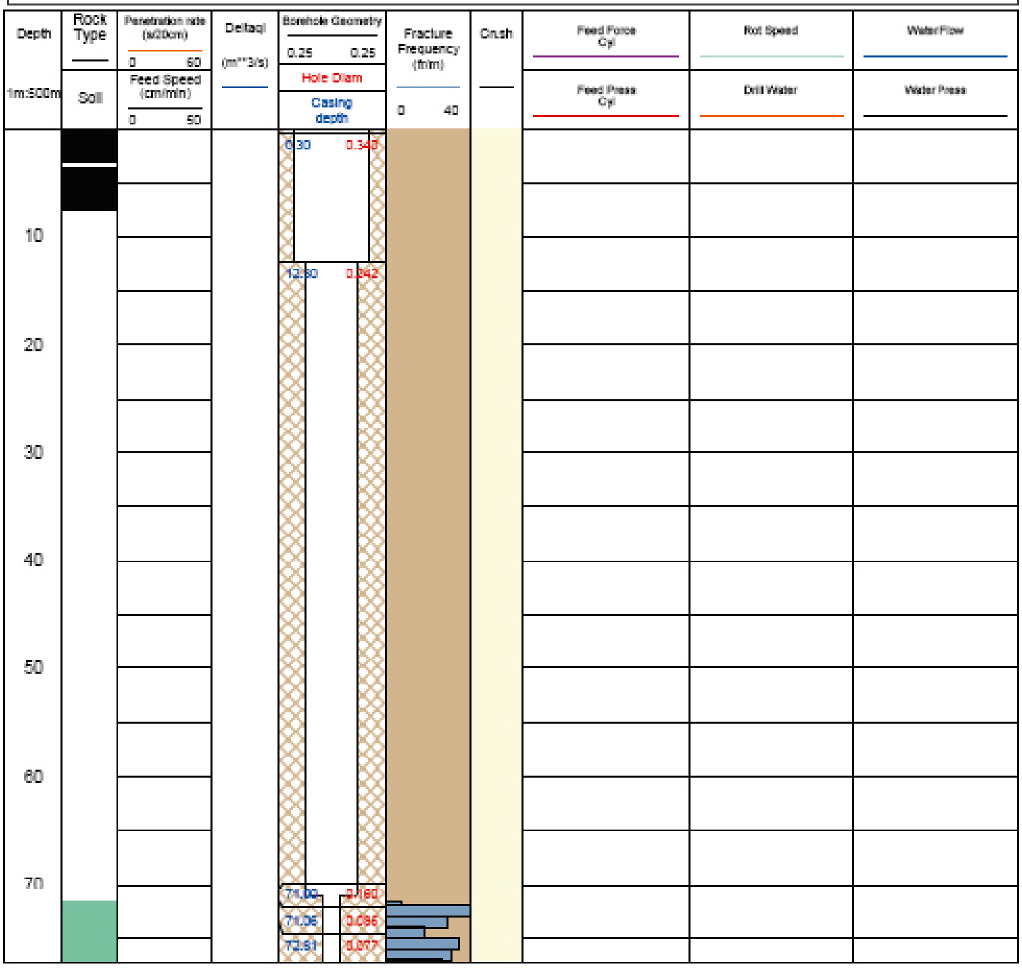

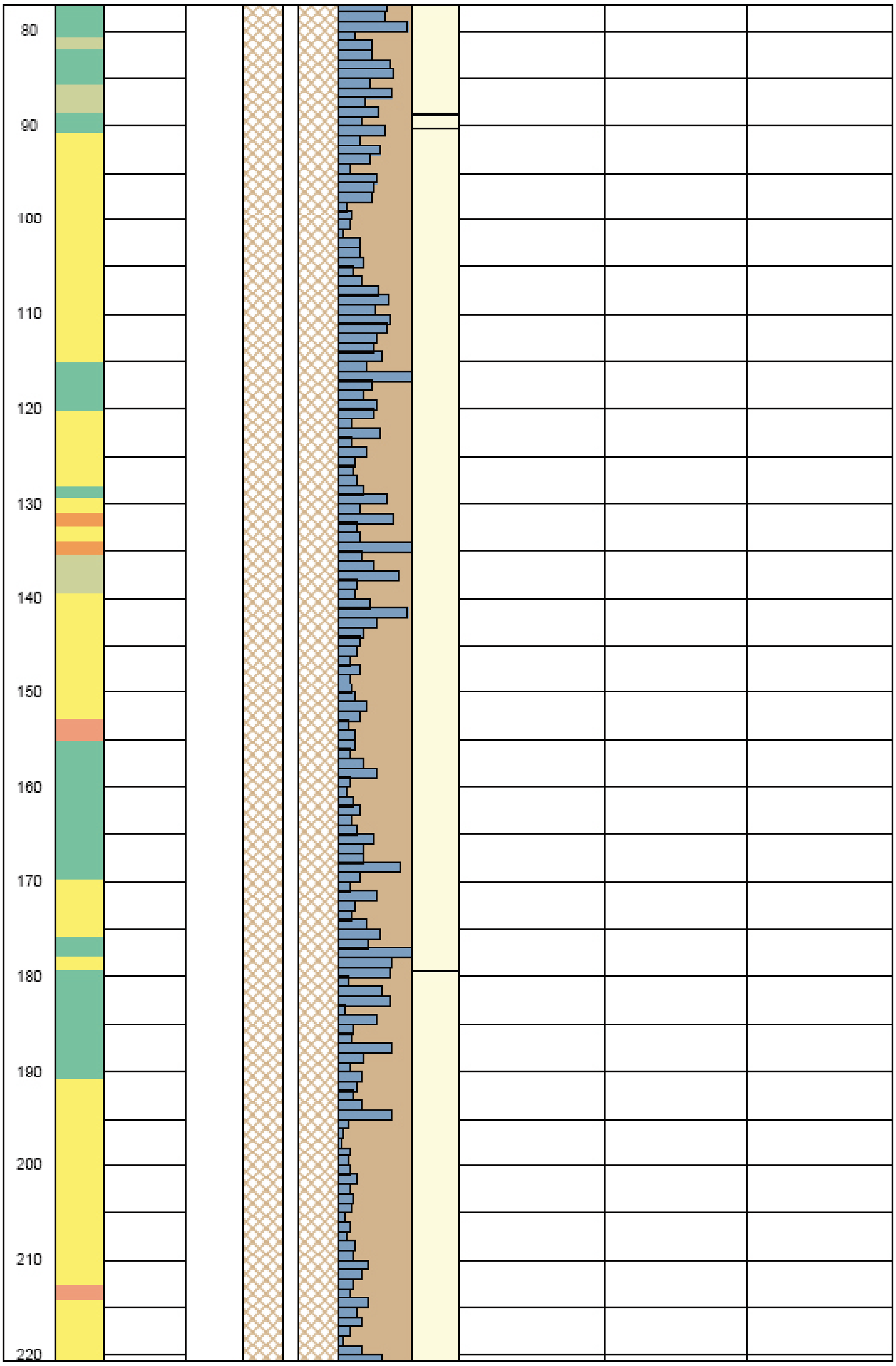
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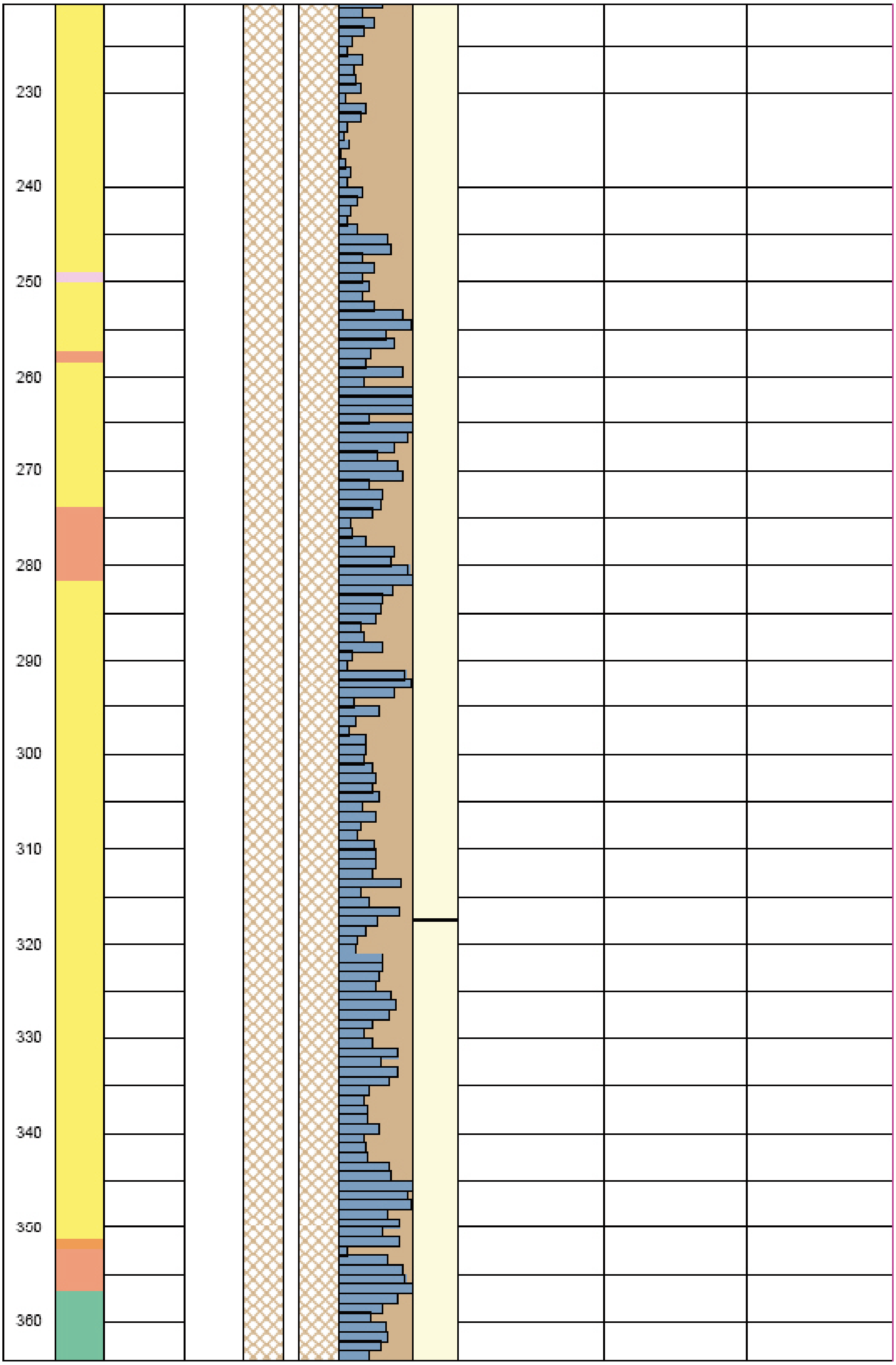
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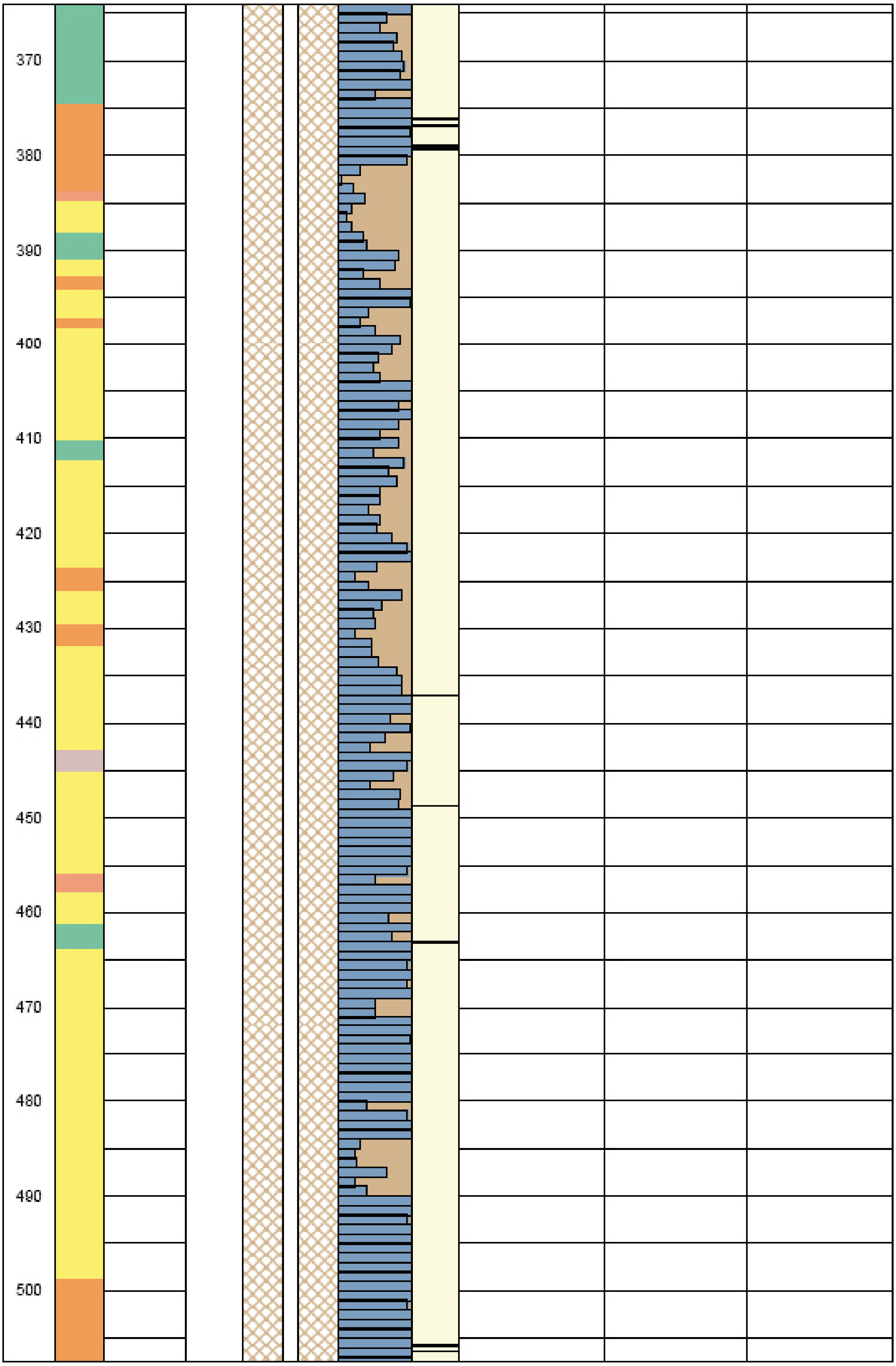
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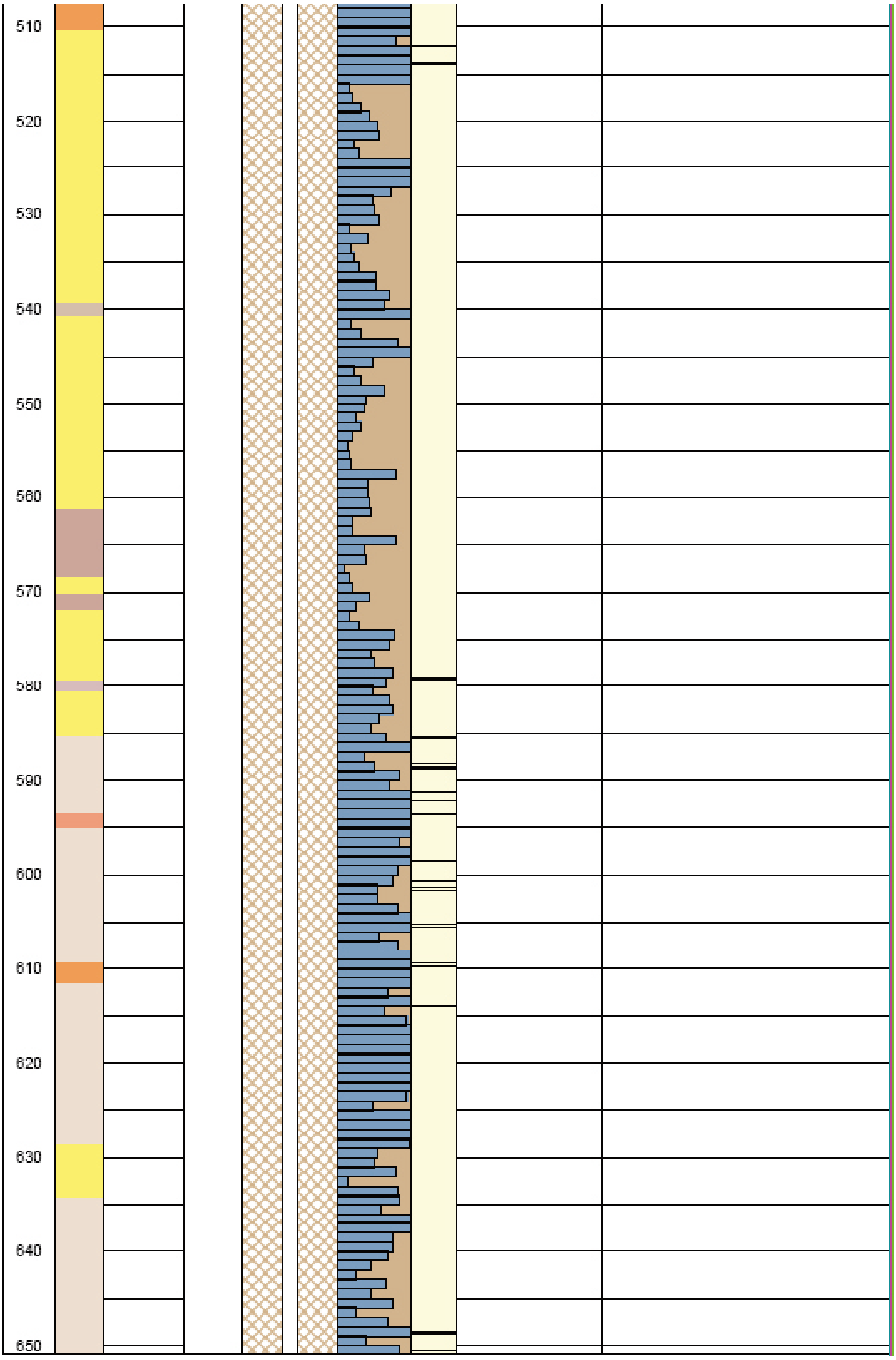
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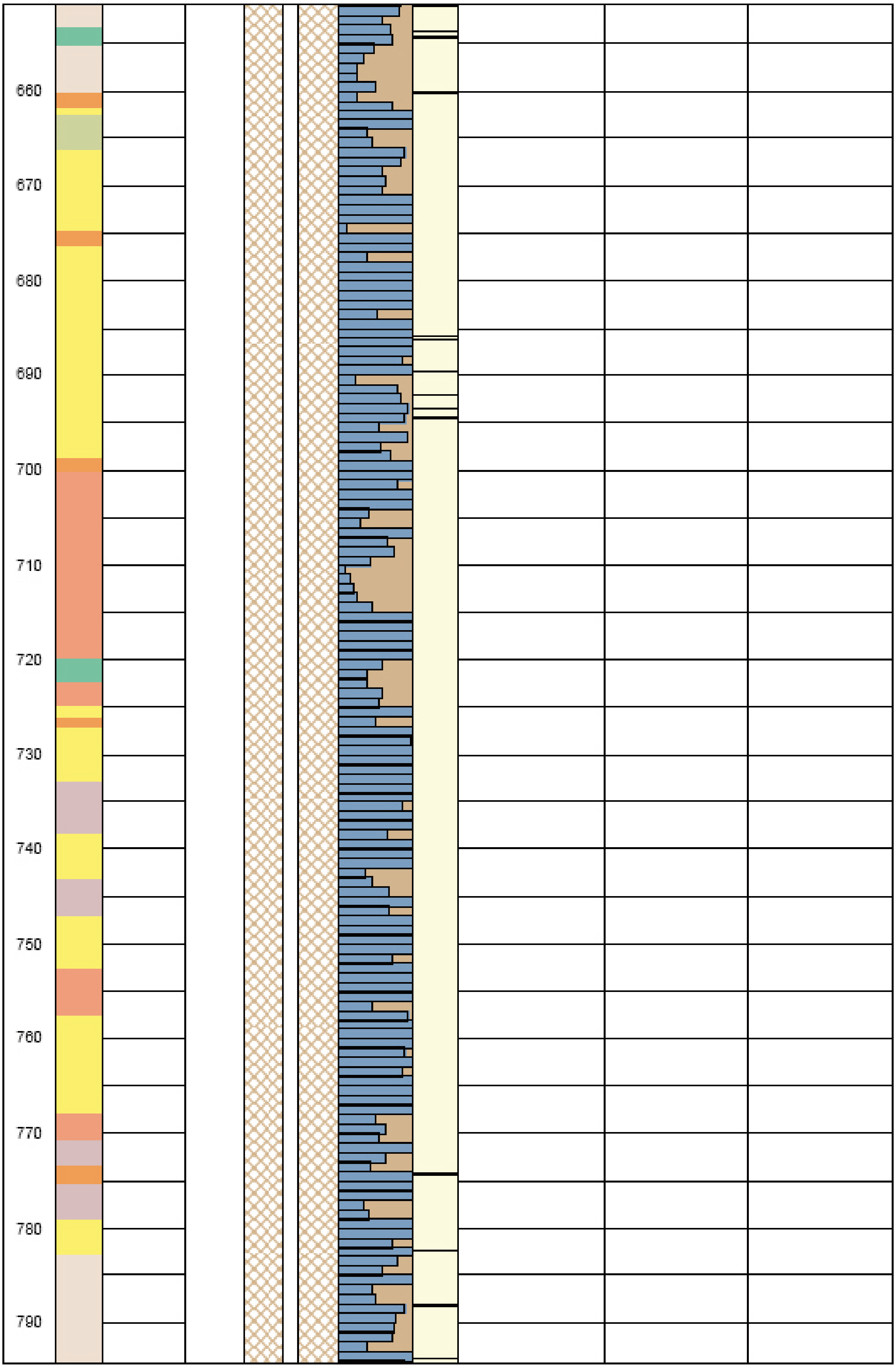
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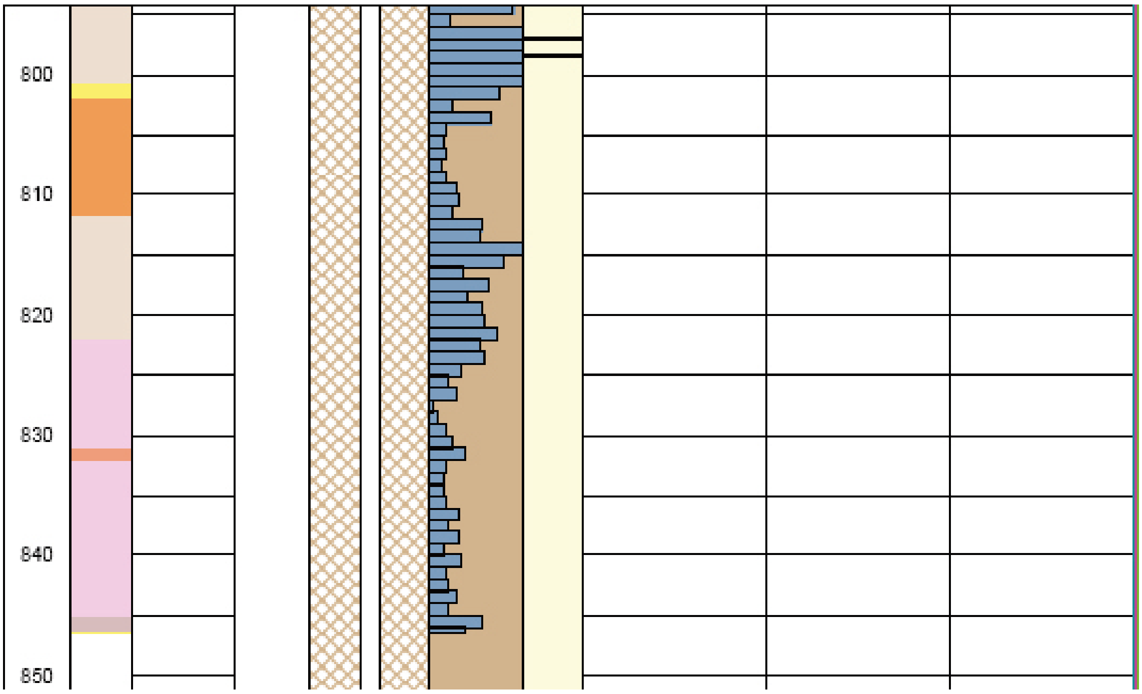
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Appendix C

Chemical analyses from the flushing water

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
2006-09-11	HFM33	12373	–1.23	2,100	41	881	248	124	5,240	451	171	21.6	1.22	7.0	0.067	7.58	2.0	7.30	1,550
2006-09-27	HFM33	12377	–0.79	2,070	42.7	897	250	121	5,180	452	171	21.9	1.18	6.88	0.066	7.00	1.7	7.13	1,530

Date	IDCODE	Sample No.	$\delta^{2}H$ ‰ SMOW	^{3}H 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
2006-09-11	HFM33	12373	–72.1	1.5	–8.5	19.72	–4.76	0.2396	26.3	0.719257	0.07
2006-09-27	HFM33	12377	–74.3	1.6	–8.5	A	–4.43	0.2396	26.4	0.719634	0.6

A = results will be reported later.