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Steered core drilling of borehole KFM24

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Abstract

Performance of and results from drilling and measurements during drilling of borehole KFM24 at the Forsmark geological investigation site for a future repository for high-level nuclear waste are presented in this report. KFM24, which is designed as a so-called telescopic borehole of SKB chemistry type, is 550.17 m long and is at its starting point inclined 83.11° from the horizon, and reaches a vertical depth of about 546 m. The main purpose of drilling this borehole was to gain detailed information of the geological characteristics at the site where a future skip-shaft for the underground repository will be built, and also to investigate the hydrogeochemical conditions.

The purpose of the 14 performed steered drillings was that the position of the borehole end would diverge as little as possible from a theoretical borehole, completely straight, but inclined by 83.11°. The steered drilling resulted in difference for the borehole end in the vertical direction of 0.32 m upwards and in horizontal direction 2.8 m to the left (west) from the target point at 550 m borehole length. At 340 m length, the borehole passes the future vertical shaft for the nuclear waste repository by a distance of 3.75 m to the north-east.

During pilot drilling of the percussion drilled section 0–35.68 m with the diameter 164.0 mm, an accumulated groundwater inflow of 15 L/min was recorded for the total borehole length. After reaming this section to Ø 248.0 mm, the percussion drilled, "telescopic" 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 SKB 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 discharged to an approved recipient.

In order to obtain a good control of the drilling process and to permit an estimation of the impact on the groundwater present in the rock volume penetrated by the borehole a number of technical and flushing water/return water parameters are registered during drilling.

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. This information also served as a basis for extended post-drilling analyses, e.g. the drill cores, together with later produced OPTV-images of the borehole wall, were used for Boremap mapping of the borehole performed after drilling.

Sammanfattning

Ett styrt borrhål, KFM24, borrades inom Forsmarks geologiska undersökningsområde inför byggandet av ett framtida förvar för använt kärnbränsle i syfte att inhämta mer detaljerad geologisk, hydrologisk och hydrogeokemisk kunskap om förhållandena på den plats där ett skipschakt för underjordsförvaret planeras att drivas. Borrhålet utfördes med teleskopborrningsteknik och är ett borrhål av så kallad SKB kemityp, vilket innebär att det också ska nyttjas för detaljerade hydrogeokemiska undersökningar. Utförandet och resultaten från borrningen liksom av mätningar under borrningen av borrhål KFM24 presenteras i denna rapport.

Det 550,17 m långa borrhålet, som är utfört med teleskopborrningsteknik, är ansatt med en lutning av 83,11° från horisontalplanet och har ett vertikaldjup på cirka 546 m. För att hålla det styrda borrhålet inom kravbilden, det vill säga att dess slutpunkt ska hamna så nära slutpunkten på ett teoretiskt helt rakt hål med 83,11° lutning som möjligt, utfördes 14 styrningar. Resultatet blev att slutpunkten för borrhålet hamnade 0,32 m ovanför och 2,8 m till väster om det teoretiska raka borrhålets slutpunkt. Borrhålet passerar det planerade schaktet på ett avstånd av 3,75 m vid cirka 340 meters längd.

Vid hammarborrning av avsnittet 0–35,68 m med diametern 164,0 mm uppmättes ett totalt inflöde av cirka 15 L/min för hela hålets längd. För att stabilisera borrhålet rymdes det till Ø 248,0 mm och därefter kläddes det in med rostfritt foderrör. Slutligen cementinjekterades spalten mellan borrhålsvägg och foderrör, så att allt vatteninflöde i den hammarborrade delen av teleskopborrhålet upphörde.

Under kärnborrningsfasen vid teleskopborrningen används ett relativt komplicerat spol- och returvattensystem, där spolvattnet prepareras i följande steg: returvattnet leds till ett system av containrar, där borrkaxet sedimenterar i två steg innan returvattnet leds vidare till godkänd recipient, i detta fall havet. 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.

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, tillsammans med OPTV-bild av borrhålsväggen underlag för borrhålskartering som utförs efter borrning.

Contents

1 Introduction

The spent nuclear fuel from the Swedish nuclear power plants is planned to be deposited in a geological repository at about 500 m depth in the Forsmark area, close to the Forsmark power plants. To protect humans and environment in the long perspective, SKB recommends an underground repository built in crystalline bedrock.

During the period 2002–2009, SKB performed geoscientific and ecological site investigations at two sites in Sweden, Oskarshamn and Forsmark. After having assessed the Forsmark site as being the most favourable in 2009, a long term monitoring programme of a number of earth science parameters and biological objects was initiated.

In March 2011, an application for building a repository for spent nuclear waste at the Forsmark site was handed in. At the same time the Spent Fuel Project was initiated with the assignment to plan, built and test the facility.

The facility consists of one part that is situated above ground and connected to an underground part that is dimensioned to hold 6 000 copper canisters containing spent nuclear fuel, see Figure 1-1. Ramp and different vertical shafts connect the above ground facility with the sub-surface part. The sub-surface area is in turn divided into a central and deposition area. The design of the facility is described in SKB (2016).

This document reports the data and results gained by drilling the steered telescopic borehole KFM24 as a part of the preparatory investigation programme of Project Spent Fuel Repository at SKB. The percussion- and core drilling operations were carried out at the site shown in Figure 1-2 in accordance with the activity plan AP SFK-16-002. Controlling documents for performing this activity are listed in Table 1-1. Both activity plans and method descriptions are SKB's internal controlling documents.

Drillcon Core AB, Nora, Sweden was engaged for the core drilling commission and Zublin Scandinavia AB for percussion drilling. Two different drilling equipments were used, a percussion rig for drilling the telescopic part, whereas a large core drilling rig was employed for drilling the cored borehole. Support was provided from SKB-personnel regarding measurements and tests during drilling.

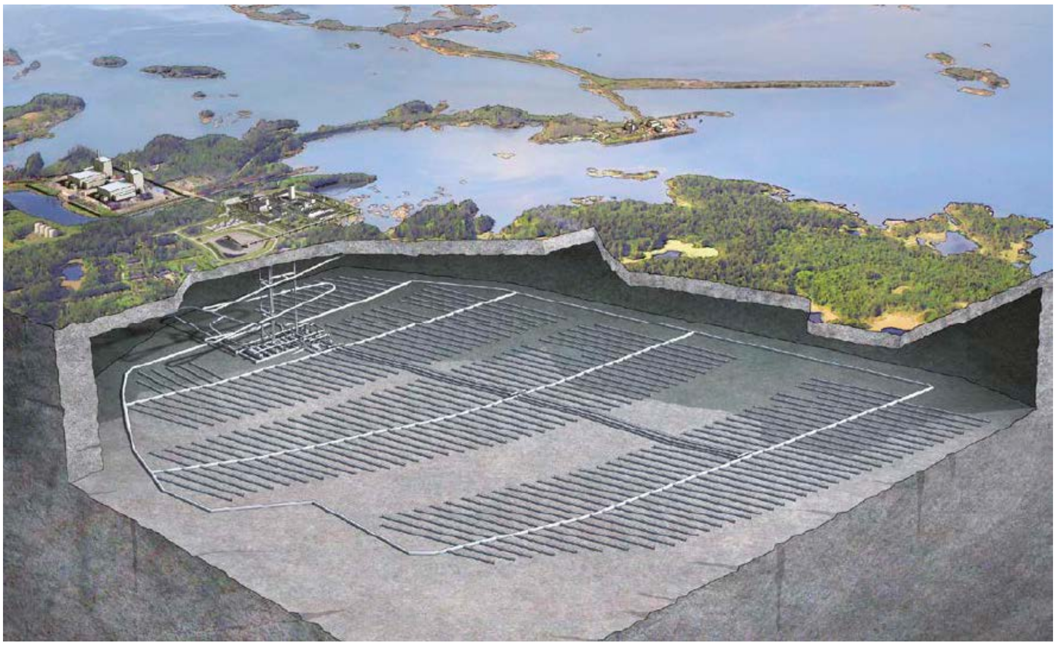

Figure 1-1. *Illustration of a possible design of Spent Fuel Repository at Forsmark.*

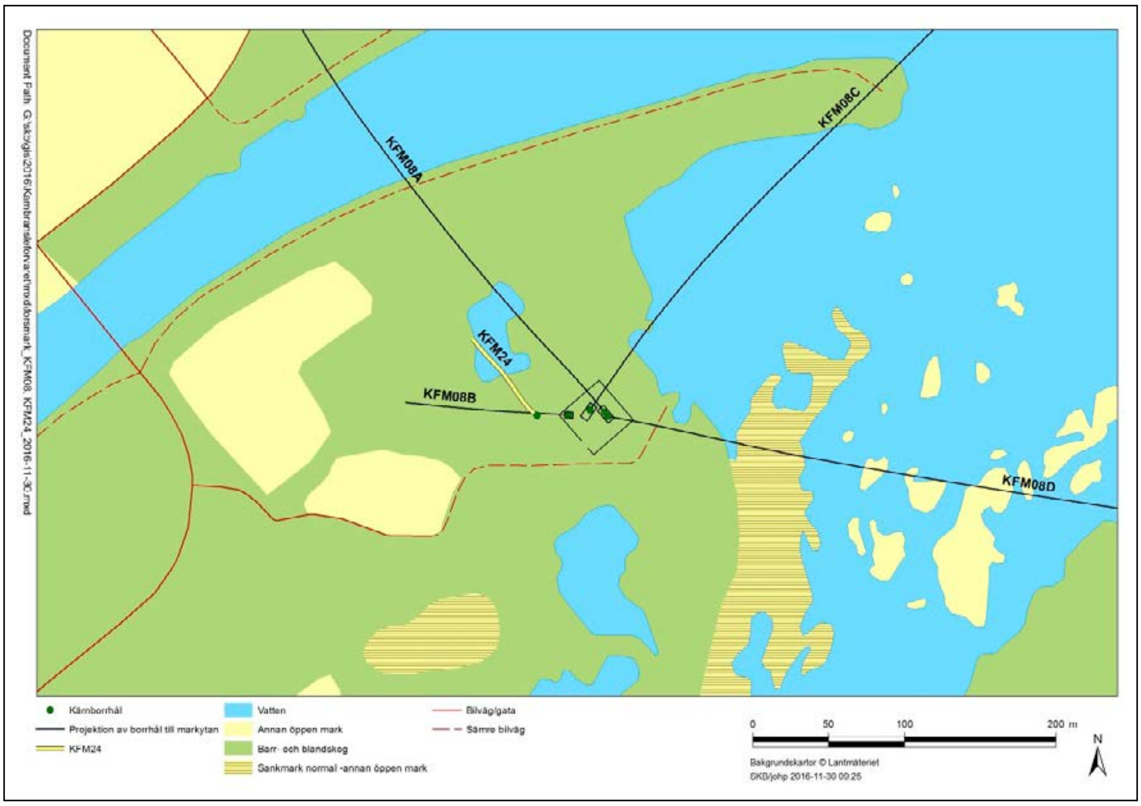

***Figure 1-2.** Location of the drill site for KFM24 close to drill site 8.*

The telescopic part of KFM24 was percussion drilled during the period March 30th to April 4th, 2016, and core drilling and measurements were carried out during the period April 10th to June 13th, 2016. Original data from the reported activity are stored in the primary database Sicada. Data are traceable in Sicada by the Activity Plan number (AP SFK-16-002). Only data from Sicada are accepted for further interpretation and modelling. The data presented in this report are regarded as copies of the original data. Data in Sicada may be revised, if needed. Such revisions will not necessarily result in a revision of the P-report, although the normal procedure is that major revisions also entail a revision of the P-report. Minor revisions are normally presented as supplements, available at www.skb.se.

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

Activity plan	**Number**	**Version**
Styrd kärnborrning av teleskopborrhål KFM24	AP SFK-16-002	1.0
Method documents	**Number**	**Version**
Metodbeskrivning för kärnborrning	SKB MD 620.003	3.0
Metodbeskrivning för hammarborrning	SKB MD 610.003	4.0
Metodinstruktion för rengöring av borrhålsutrustning och viss markbaserad utrustning	SKB MD 600.004	1.0
Metodinstruktion för användning av kemiska produkter och material vid borrning och undersökningar	SKB MD 600.006	1.0
Metodbeskrivning för genomförande av hydrauliska enhålspumptester.	SKB MD 321.003	1.0
Metodbeskrivning för registrering och provtagning av spolvattenparametrar samt vägning av borrkax under kärnborrning.	SKB MD 640.001	2.0
Metodbeskrivning för krökningsmätning av hammar- och kärnborrhål	SKB MD 224.001	2.0

2 Aim

From a geoscientific perspective, the primary aim of borehole KFM24 was to provide fundamental geological, hydrogeological and hydrochemical information with bearing on the proposed shaft location.

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

- To provide rock samples from the ground surface down 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. 10–100 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 make geophysical borehole investigations possible, e.g. OPTV logging, PFL-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 sample water 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 KFM24 with the exception that no sampling of soil- and rock samples from the percussion drilled section from the ground surface to c. 35 meter was performed.

During drilling, a number of drilling related parameters were 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. The DMS-data from KFM24 are described in this report.

3 Equipment

Two types of drilling machines were used for drilling the telescopic borehole KFM24. The upper c. 35 meters were drilled with a percussion drilling machine of type Commacchio 1500 S. Core drilling c. 35–550 m was performed with a Wireline-76 core drilling system, type Boyles B20 APC.

3.1 Percussion drilling equipment

The Commacchio percussion machines are equipped with separate engines for transportation and power supplies. Water and drill cuttings were retrieved from the borehole by a 30 bars and 35.4 m^3/min air-compressor, type Atlas-Copco XRXS 566, see Figure 3-1.

At drill site, the bedrock is covered by approximately 3 m of gravel fill. 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 3-2. The NO-X technique is described more in detail in SKB MD 610.003 (Method Description for percussion drilling). Figure 3-2 is a schematic diagram where the drilling depths presented are approximate. The true depths in the respective drilling sequences performed in KFM24 are presented in Section 5.2.

3.2 Grouting technique

For investigation of the groundwater conditions, especially the hydrogeochemical characteristics, of 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 occur during percussion drilling of a telescopic borehole, it is essential to prevent it from permeating into deeper parts of the borehole. 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 an effective method to stabilize the borehole wall as well, e.g. if a highly fractured and unstable section is encountered.

Figure 3-1. *To the left the Commacchio percussion rig seen on the drill site. To the right the NO-X 280 casing is prepared for drilling through the overburden.*

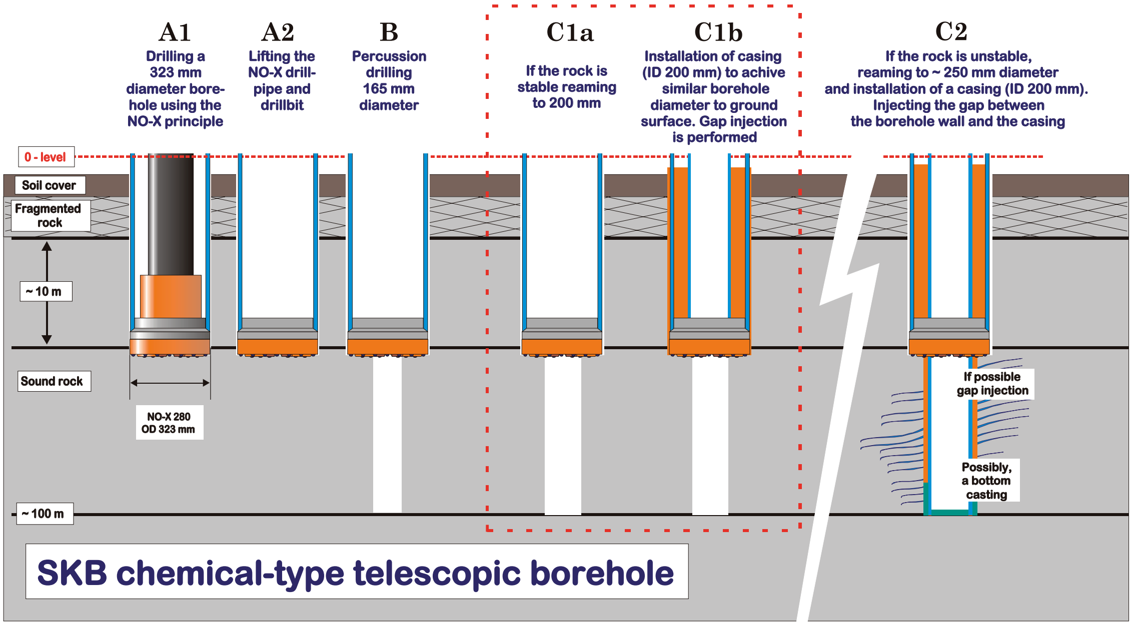

Figure 3-2. *Schematic diagram showing the various stages of drilling the 0-100 m section of an SKB chemical-type telescopic borehole. The letters and numerals above each stage refer to some of the operations described in Sections 3.4.1 and 3.4.2 in SKB MD 620.003.*

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

Borehole KFM24 was grouted at two occasions: 1) after installation of the $\text{Ø}_o/\text{Ø}_i$ 208/200 mm, 5.88 meter long casing (C2 in Figure 3-2) a bottom plug was grouted just below the casing, 2) gap injection was performed through a packer whereby satisfactory grouting results were obtained.

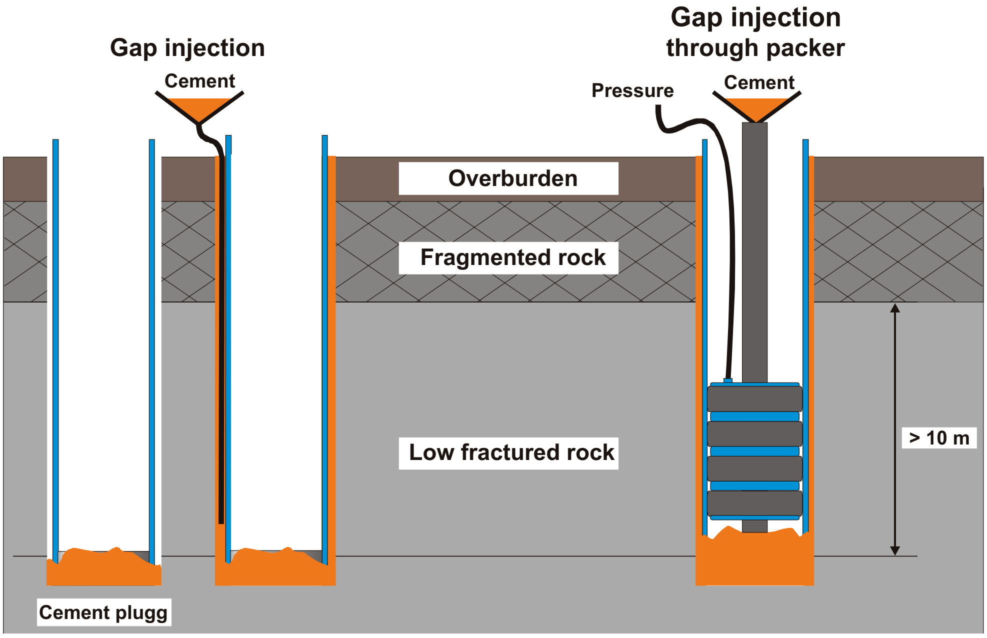

Figure 3-3. *Gap injection techniques. In order to fill the gap between the borehole wall and the casing, different techniques may be applied. To the left, a flexible hose is lowered between the casing and the borehole wall, and to the right the grouting is performed through a borehole packer.*

3.3 Core drilling equipment

3.3.1 The wireline-76 system

For drilling the cored parts of boreholes KFM24, a wireline-76 system, type Boyles B20 APC, was employed (Figure 3-4). The drilling process is operated by an electrically-driven hydraulic system supplied with a computer control. The drill pipes and core barrel used belong to the Sandvik WL76 triple-tube system. Technical specifications of the drilling machine with fittings are given in Table 3-1.

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

Unit	Manufacturer/Type	Specifications	Remarks
Boyels B20 ABC	Atlas-Copco	Capacity for 76–77 mm holes maximum approx. 900–1 500 m depending on drill string dimension	Supplied with an integrated CAT diesel engine that supports two hydraulic pumps
Flush water pump	Bean	Max flow rate: 142 L/min Max pressure: 100 bars	
Compressor	Cramo	Max pressure: 8 bars Flow: > 1.5 L/sec	Electrically supplied

3.3.2 Flushing/return water system – function and equipment

Core drilling involves pumping of flushing water down the drill string, through the drill bit and out into the borehole in order to

1) conduct frictional heat away from the drill bit,

2) 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 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.

Figure 3-4. *Drilling rig Boyles B20 APC.*

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 3-5. The system includes equipment for pumping, transport and storage of water. The flushing water-/return water system may be divided into equipment for:

- Preparing the flushing water.
- Measuring flushing water parameters (flow rate, pressure and electrical conductivity).
- Air-lift pumping while drilling.
- Storage and discharge of return water.

Preparing the flushing water

The quality of the flushing water must fulfil specific criteria, 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 used for supply of flushing water for core drilling of KFM24 was tap water from Forsmark´s Kraftgrupp AB.

The flushing water was prepared before used in accordance with SKB MD 620.003 (Method description for core drilling), with an organic dye tracer, Uranine, which was added to the flushing water at a concentration of 0.2 mg/L before the water was pumped into the borehole (Figure 3-5). The tracer was thoroughly mixed with the flushing water in the tank. Labelling the flushing water with the tracer aims at enabling detection of flushing water contents in groundwater samples collected in the borehole during or after drilling. In order to reduce the contents of dissolved oxygen in the flushing water, nitrogen gas was continuously flushed through the flushing water tank (Figure 3-5).

Measurement of flushing water parameters

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

- Flow rate.
- Water pressure.
- Electrical conductivity.

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.

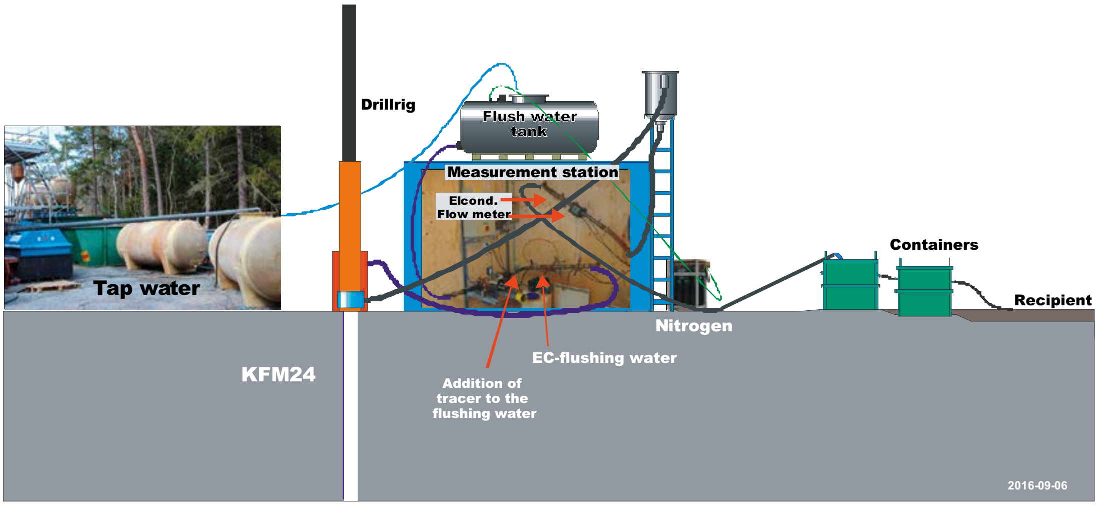

Figure 3-5. *Schematic illustration of the flushing-/return water system when drilling KFM24. The measurement station included logger units and a flush water tank. Flushing water was supplied from a water tap at Forsmark's Kraftgrupp AB.*

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 c onductivity	Kemotron 2911	1 mS/cm–200 mS/cm 0.1 mS/m–20 S/m	

Air-lift pumping while drilling

Air-lift pumping during core drilling telescopic boreholes involves pumping of compressed air into the percussion drilled portion of the borehole, forcing it to emerge at a depth of about 35–100 m depending on the depth of the percussion drilled borehole section, the groundwater yield and the capacity of the air-lift pump. 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 (Figure 3-6). 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 KFM24 consisted of several main components, see Table 3-3 and Figure 3-6.

Table 3-3. Air-lift pumping equipment used in KFM24.

Item	KFM24
Air compressor, 8 bars/0.8 m³/min	X
Electrical supply cubicle, at least 16 A	X
Outer support casing, Ø 98/89 mm diameter	36 m
Inner support casing, Ø 84/77 mm diameter	35.5 m
2 Ejector pumps, each contains;*	
PEX hose, 1 x Ø 22 mm	2 x 35 + 10** m
PEM hose, 1 x Ø 40 mm	2 x 35 + 15** m
Expansion vessel (= discharge head)	X
PEM hose: 20 bars, Ø 32 mm (pressure transducer)	35 m
Pressure transducer, 10 bars, instrumentation and data-logging unit	X

* Two separate mammoth pumps system are always installed in a telescopic borehole.
** Extended hose; PEX connected to air compressor and PEM connected the cyclone.

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 (Figure 3-6). When installing the outer support casing in KFM24, it was lowered into the borehole together with the hoses for air-lift pumping with a tractor. 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 3-7. With this construction, the air leaving the ejector hose, reduces the pressure in the lower part of the ejector tube, helping to lift drill cuttings from the bottom of the hole.

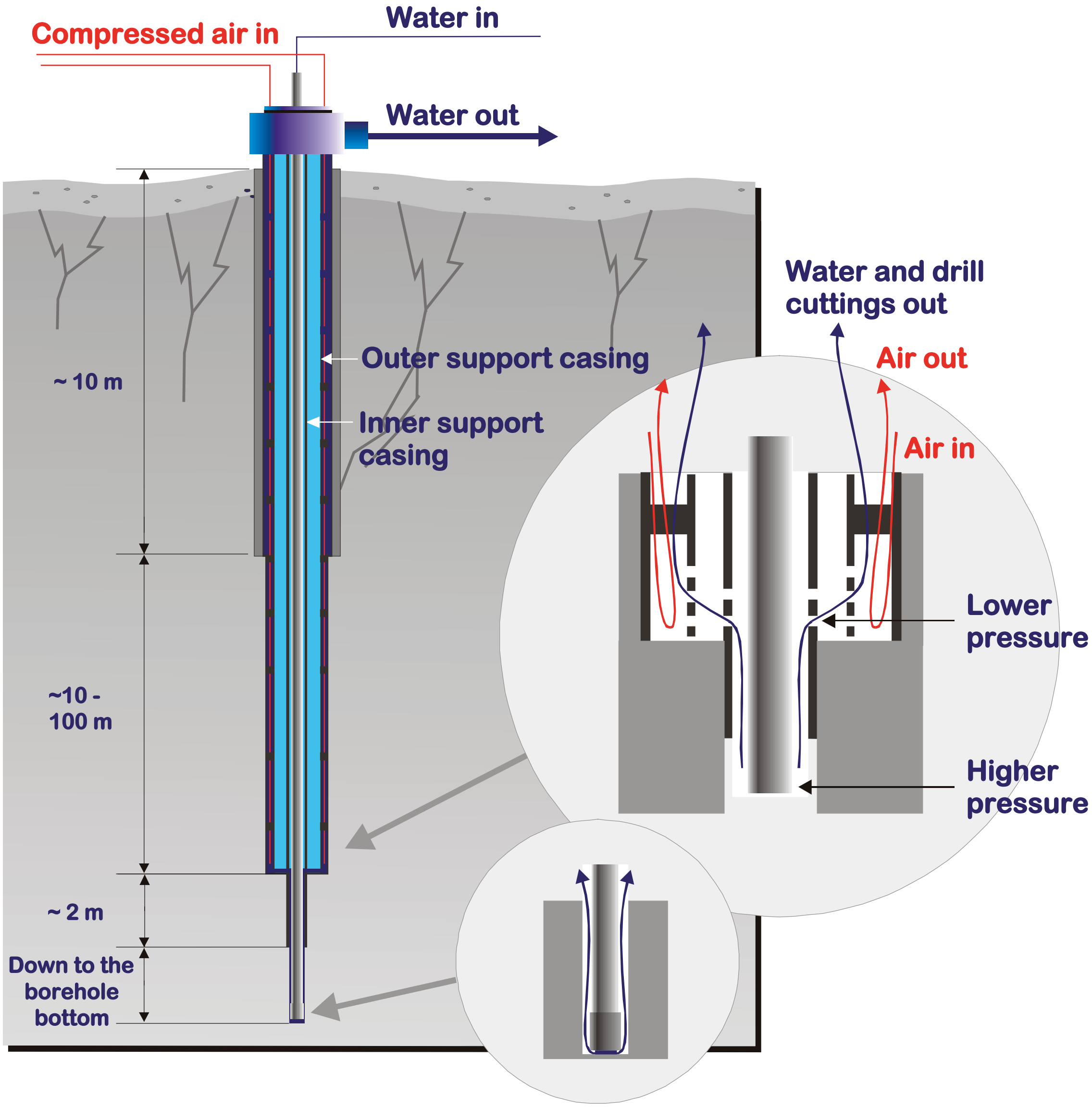

Figure 3-6. *Air-lift pumping during core drilling of a telescopic borehole. Schematic representation, where the drilling depths are only approximate. The air and instrumentation hoses are secured to the outer support casing. The compressed air raises the flushing water and drill cuttings from the hole. Return water flows between the borehole wall and the drilling pipe string and then through holes in the support casing before being transported up to the surface.*

Storage and discharge of return water

At the surface level, the return hose was connected to a return pipe between the discharge head and the first return water container, see Figure 3-5 and Figure 3-8. 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 three sedimentation steps. The cuttings were preserved in the containers for later weighing. Due to environmental restrictions, the return water was pumped through an exit pipe string directly to the Baltic Sea.

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

Flow rate and other flushing water data were continuously stored in an automatic data-logging system, see Section 3.3.3. As a back-up and double-check, the total quantity of water supplied to the borehole was acquired by counting the number of filled water tanks used, multiplied by the tank volume.

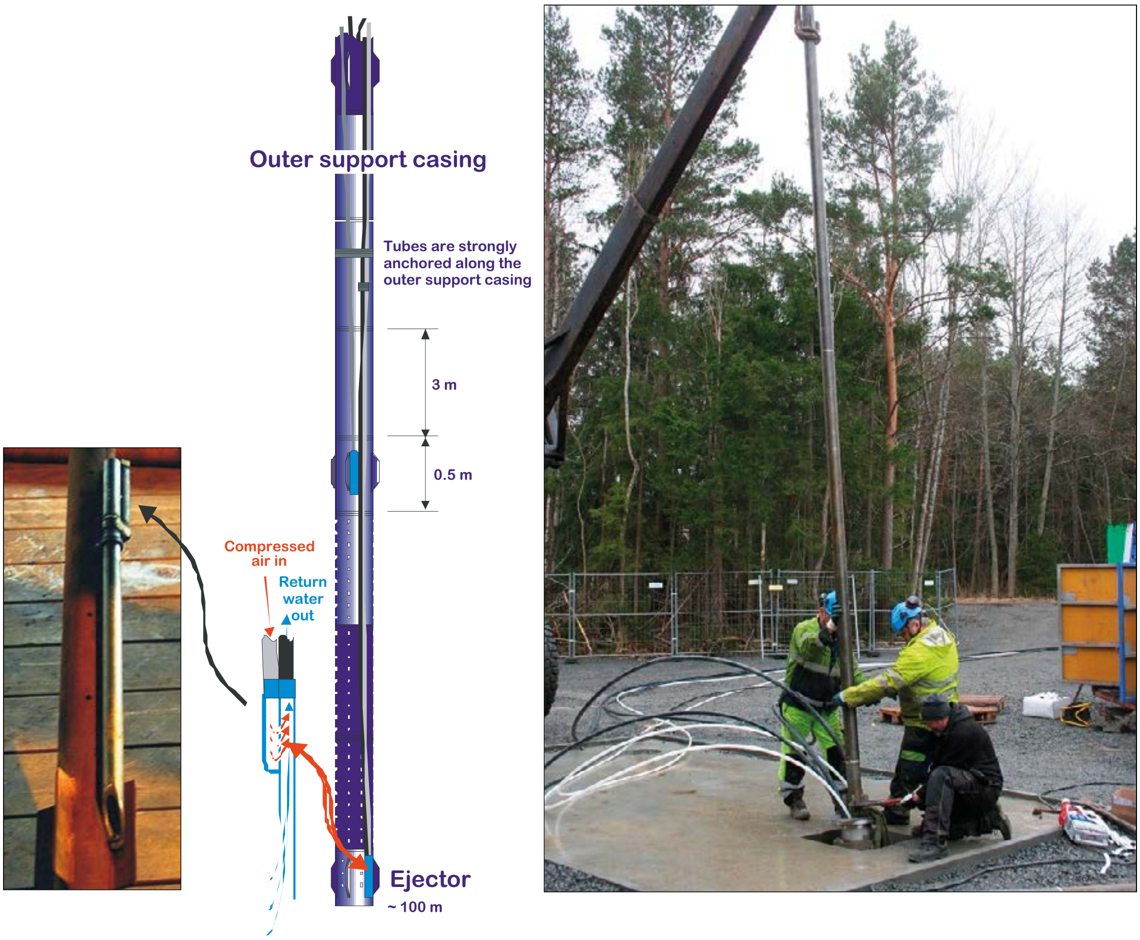

Figure 3-7. *Schematic representation of connection and installation of air-lift ejectors on the outer protective casing.*

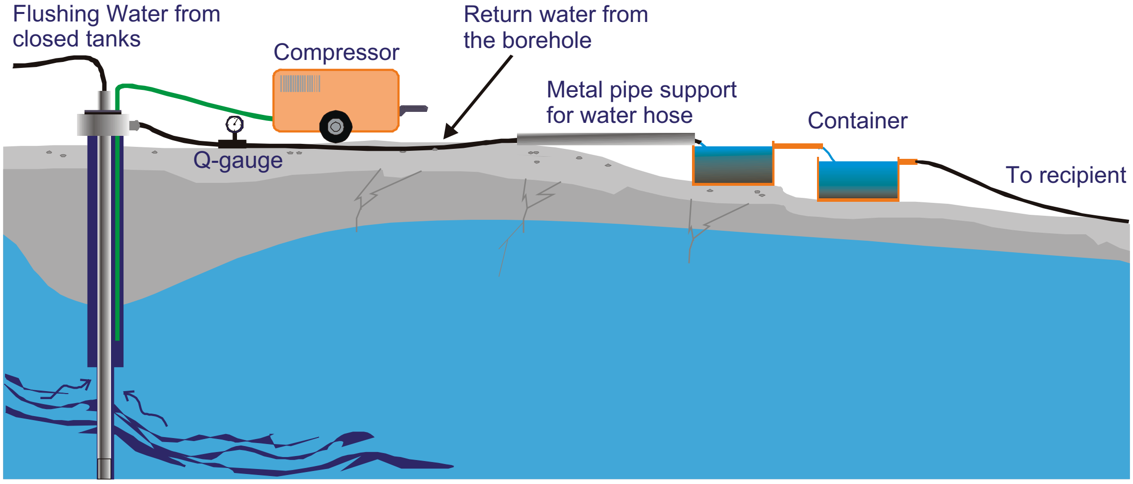

Figure 3-8. *Return water system. Air-lift pumping raises the return water, consisting of flushing water, groundwater and drill cuttings, from the borehole. The cuttings separate out in three stages in the containers (where they are preserved for later weighing), after which the water is pumped to an approved recipient.*

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

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

3.3.3 Drilling monitoring system

The Boyles B20 drilling machine employed was supplied with a computer control system but was not equipped with a data logger for storing data. The registration in the SKB logger system included the parameters electric conductivity of the flushing water, and electric conductivity and flow rate of the return water. The system is also provided with a device 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.

3.4 Steering tool

The DeviDrill™ WL design is a directional wireline core barrel with an adjustable eccentric housing that allows for various dogleg[1] settings[2]. The eccentric housing is kept at a fixed orientation by expandable pads that can be pressed out against the borehole wall and are operated by circulating fluid pressure (Figure 3-9). With the DeviDrill™ system the borehole is steered to the selected target, and by surveying with the DeviTool™ (Pee Wee) and Reflex Gyro the borehole trajectory is controlled. The DeviDrill system for steered drilling is applicable only to boreholes with a diameter of 76 mm (N-size).

By using wire-line technique the DeviDrill is quickly activated to correct the steering direction (Figure 3-9). The Pee-Wee tool is mounted within an inner tube placed inside the DeviDrill at the borehole bottom. A protractor (360°) is attached to the drill pipe, and after winching up the inner tube with the Pee-Wee instrument, a toolface[3] reading is used for calculating how much the drill string needs to be rotated (with a pipe wrench) to obtain the correct steering direction.

Finally, to safeguard that the accurate orientation is achieved, the Pee-Wee tool is pumped back into the drill string to the DeviDrill, a reading is taken, and the instrument is winched back out of the drill string for data check. A tolerance of ±3° is regarded as acceptable by Devico.

***Figure 3-9.** DeviDrill core barrel. Left: When water pressure increases (to about 20 bars), the sliding packer expands and locks the barrel in its position. Right: The end of the DeviDrill. The drill bit gives a 31.5 mm core in sections where steering is applied.*

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[1] Dogleg: The measure of the curvature of the borehole trajectory (given as angular degrees/30 m). The maximum curvature stipulated for KFM24 was 0.1°/m which can be expressed as 3/30 m, i.e. dogleg = 3.

[2] Setting of the DeviDrill regulates the strength of the imposed steering on a scale from 0 to 8 (where 0 is "no steering" and 8 implies a strong imposed curvature (dog leg)). The scale is not linear and the setting is therefore not directly correlated to the dogleg curve. The setting and the effect of the steering is dependent on a number of variables. In KFM24 a setting between 1.8–1.9 was used.

[3] The parameter TF (toolface) provides (over 360 degrees) the orientation towards which the DeviDrill steers. "Zero" is oriented up along the drill stem; TF 270 implies active steering "to the left" etc.

Generally, there are always some differences between new tools, especially for a DeviDrill™ system that is subjected to high pressure and strong mechanical stress. Moreover the tool consists of more than 200 different parts, some standard parts, but also many special components made in only small series. For the steered KBS-3H borehole drilled at Äspö, 2014 (Nilsson 2015), and for drilling in Onkalo, Finland, in 2015 Devico used a new core barrel. In knowledge of the coming steered drilling commission at Forsmark, this core barrel has been kept in storage, and was in due time served and prepared to be used for steering of borehole KFM24. A DeviDrill™ tool is usually served on site after 30 meters steered drilling. After 14 steerings over a total drilling length of 30.83 meter in KFM24, it was necessary to grease the bearings and change bushings in order to preserve a high quality tool.

4 Geometrical premises

4.1 Percussion drilling

The percussion drilling operations includes:

1) Preparations.
2) Mobilization, including lining up the machine and measuring the position.
3) Drilling, measurements, and sampling during drilling.
4) Finishing off work.
5) Data handling.
6) Environmental control.

The four first items are treated in the next section (Section 4.2), whereas the last two activities, together with the corresponding items for core drilling, are presented in Section 4.3.

4.2 Initial activities

4.2.1 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 and Figure 4-1, for boreholes of SKB chemical type.

Figure 4-1. *By using hot water the drilling rig and drill rods are washed before the equipment is moved into position on a concrete platform at the drill site.*

4.2.2 Mobilization

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

4.2.3 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 a $Ø_i$ 310 mm casing to 5.88 meter. The continued percussion drilling through solid rock was performed with a 164 mm drill bit to 36.68 meters drilling length. For stabilization of the entire percussion drilled part, the borehole was reamed to 248 mm to 35.64 meters length, and a stainless steel $Ø_i$ 200 mm casing was then installed to 35.41 meters length.

Before installing the casing, the borehole was cleaned from drill cuttings by using ejector pumping (Figure 4-2). This also served as a rough hydraulic interference test. All surrounding boreholes are connected to the Forsmark HMS (Hydraulic Monitoring System), and the groundwater level variations are continuously registered. The pumping also served as a rough capacity test of the percussion drilled part of the borehole, from which the results could be used on-site i.e. for preparation of the gap injection of the casing, see below.

Figure 4-2. *Cleaning of the telescopic section to 35.68 m of borehole KFM24 before the casing is installed. The air compressor supplies an ejector so that the mixture of water and drilling debris from the borehole bottom is flushed through the pipe up to the surface.*

In order to prevent leakage from a nearby wetland, as well as to seal water-yielding fractures in the percussion drilled section, the gap between the casing and borehole wall was grouted using the packer technique illustrated in Figure 3-2. After grouting, the recharge of water into the borehole ceased completely.

Measurements and sampling while percussion drilling and immediately after drilling were performed according to a specific measurement/sampling programme, which was applied in association with the Ø 164 mm drilling sequence. Sampling of drilling debris, that is included in the normal sampling programme for percussion drilling described in SKB MD 610.003 (see Table 1-1), was exluded because of its benefits and usability compared to the effort of collecting was estimated to be low.

1) Observation of the flow rate (if any) at every three meters rod. When a significant increase of the flow rate was noticed, it was measured using a graduated vessel and a stop-watch.
2) Measurement of the electric conductivity of the groundwater at every three metres.

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

4.2.4 Finishing off work

Finishing off work included measurements of the final diameter of the drill bit after reaming to between approximately 248 mm (lower reamed part) in KFM24. The borehole was then secured with lockable stainless steel flange. The drilling equipment was removed, the site cleaned and a joint inspection made by SKB and the Contractor.

4.2.5 Nonconformities

As mentioned in Section 4.2.3 it was decided before start of drilling to exclude sampling of drilling debris while drilling.

4.3 Core drilling

The core drilling operations included:

1) Preparations.
2) Mobilisation, including lining up the machine and measuring the position.
3) Drilling, steerings, measurements and sampling during drilling.
4) Finishing off work.
5) Data handling.
6) Environmental control.

4.3.1 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.

4.3.2 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 the entire equipment system.

4.3.3 Drilling, measurements and sampling during steered core drilling

Core drilling of borehole KFM24 was performed with two borehole dimensions. section 35.68–37.25 meter was drilled with a borehole diameter of 86.0 mm, whereas the main part of the borehole, section 37.25–500.17 meter, was drilled with Ø 76.5 mm. The inner Ø 84/77 mm support casing was fitted into the short Ø 86 mm borehole. In this way the casing was centralized in the borehole and fixed laterally. The outer Ø 98/89 mm support casing is during drilling resting on the bottom of the percussion drilled borehole, see Figure 3-6.

Core drilling with Ø 76.5 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 the borehole KFM24, a 3 m triple tube core barrel was used. The nominal core diameter for the Ø 76.5 mm part of the borehole is 45.0 mm. Minor deviations from this diameter may, however, occur. In addition, directional drilling was performed in 14 sections. The nominal core diameter for the steered sections is 31.5 mm.

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 KFM24 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 4.3.4, Table 4-1, together with the actual performance when drilling KFM24.

Results of mapping of the drill core samples from KFM24 are presented in Dahlin and Maskenskaya (2017)., 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 in the measurement container using a 2 % (by volume) sodium-hypochlorite solution was performed prior to drill start.

The concluding work included the following items:

1) The boreholes was flushed for about ½ hour 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.
2) The drill string was pulled.
3) The inner support casing was removed with aid of a wheel loader.
4) The outer support casing was removed with the same wheel loader.
5) The discharge head was removed.
6) Using the wheel loader, a stainless steel transition cone was installed between the reamed percussion drilled and the cored part of the borehole, as shown in Figure 4-3 and Figure 5-3. The cone in KFM24 is located at 32.59–37.17 meter.
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.

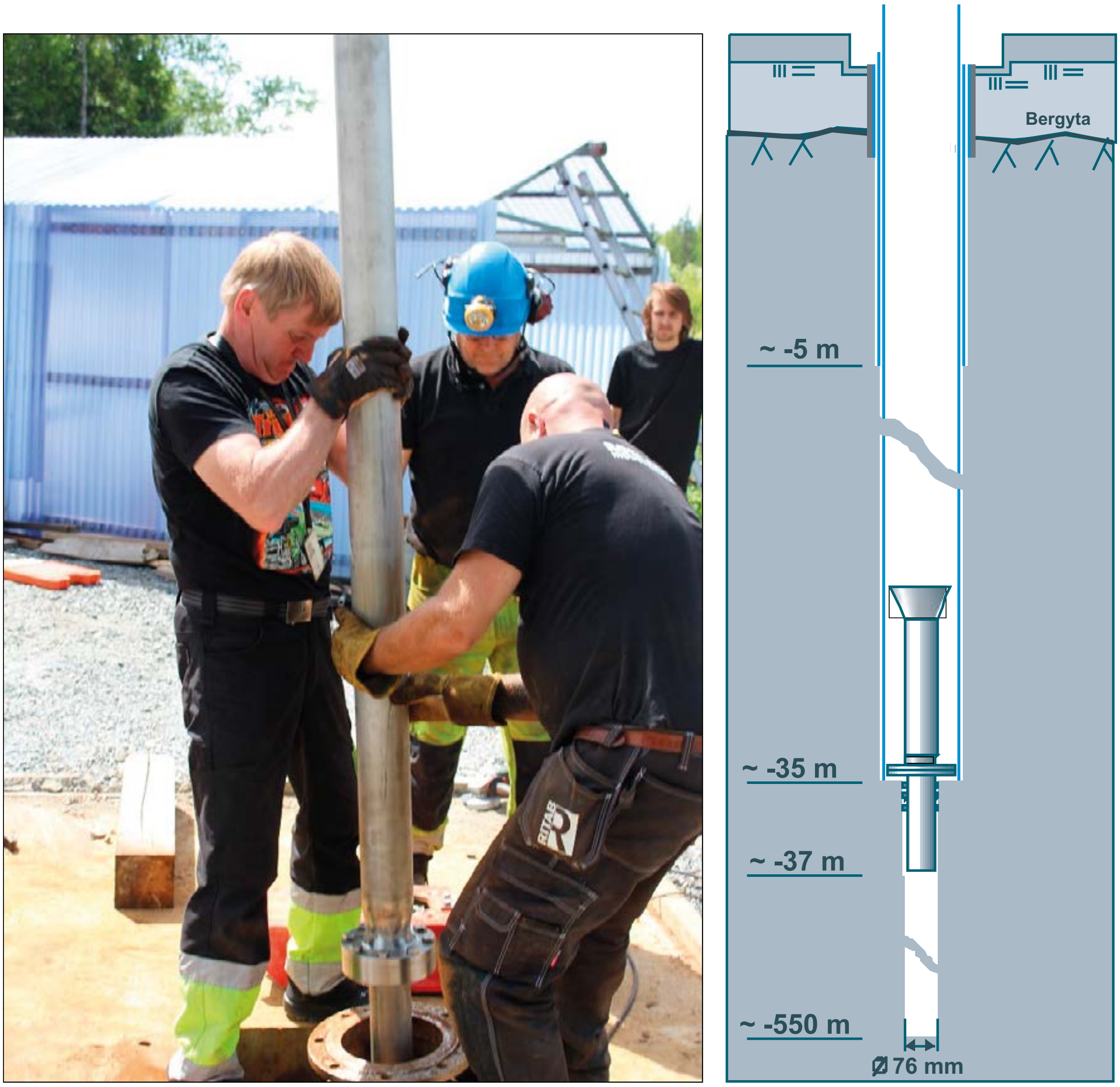


Figure 4-3. *Schematic illustration of the transition cone between the upper, wide section and the lower, slim part of a telescopic borehole. In KFM24, the entire upper, percussion drilled part was cased.*

4.3.4 Nonconformities in KFM24

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

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 KFM24.

Activity	Performance and frequency according to SKB MD 620.004	Performance and frequency during drilling of KFM24
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 Reflex Gyro-system and two with the Pee-Wee-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 5-13 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.	Not performed.
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.

Two major nonconformities in conjunction with drilling of KFM24 should be especially noted:

- Excluded sampling of drilling debris during percussion drilling.
- Excluded groove milling.

The groove milling is not needed when using an insertion rig for of drilling subsequent borehole loggings and the sampling of drilling debris during percussion drilling was determined as unnesseracy, as described in Section 4.2.3, why it was decided that these two activities should not be performed.

The last item but one in Table 4-1 may be commented on. All drilling debris produced during drilling (percussion drilling as well as core drilling) was collected in the sedimentation containers of the return water system (except the finest fractions which stayed suspended in the discharge water from the second container). The collected drill cuttings from the core drilled part were weighed after completed drilling in order to obtain a measure of the drill cuttings recovery.

5 Results

This chapter is structured as follows:

- Section 5.1 – General
- Section 5.2 – Drilling progress of KFM24
- Section 5.3 – Geometrical data and technical design of KFM24
- Section 5.4 – Percussion drilling 0–35,68 m.
- Section 5.5 – Core drilling 35,68–550,17 m.
- Section 5.6 – Steering

5.1 General

Since Forsmark was selected for location of the Swedish final storage of high level nuclear waste in 2009, a major work for projecting and design of the underground facility has been carried out. Unfortunately, when the design was finished and presented, it was found that a future major shaft (skip shaft) empties into a wetland that houses a large number of rare and protected frogs (swedish: "gölgrodor", latin: Pelophylax lessonae). To overcome this conflict, new habitats have been created in safe environments in the neighborhood to which the frogs are supposed to migrate.

However, this skip shaft is planned to be excavated from the ground surface and downwards, simultaneously as the excavation of an access ramp (see Figure 1-1). Due to that technique and machinery for downwards excavation are seldom used, the project engineers need detailed specifications of various geoscientific conditions in order to be able to formulate trustable tender documents for procuration of the machine. This aim was to be fulfilled by drilling a cored borehole placed as close as possible to the position of the future skip shaft.

The telescopic borehole KFM24 at drill site 24 (DS24) is located between DS8 and the above mentioned wetland (see Figure 1-2 and Figure 5-1). This was the presently most suitable and available place in order to drill the borehole KFM24 as close as possible to the planned shaft.

Figure 5-1. *Drill site DS24 located between DS8 (in the background) and the wetland in front.*

To avoid the borehole to penetrate planned tunnels into the repository, it was also necessary to make the drilling very straight in a predefined direction. Furthermore, the tectonic lens in which the repository will be built is generally characterized by a very low permeability at depth. Therefore there is a shortage of water samples for hydrogeochemical analyses from the tectonic lens. Consequently, borehole KFM24 offers an opportunity to increase the number of available groundwater sampling points, if water-bearing fractures are encountered during drilling. KFM24 therefore had to be drilled as a borehole of SKB chemical type.

All these demands resulted in a borehole design with an upper percussion drilled section, followed by a steered core drilled section to 550 m borehole length.

5.2 Drilling progress KFM24

Drilling of borehole KFM24 was carried out during two periods, between March 30th, 2016, and April 04th, 2016, (percussion drilling) and April 10th, 2016, to June 13th, 2016, (steered core drilling), see Figure 5-2.

5.2.1 Percussion drilling period

Percussion drilling is a rapid drilling method compared to core drilling. Although a relatively complex approach is applied when drilling telescopic boreholes with two drilling sequences, casing driving and gap injection, percussion drilling of KFM24 could be completed after a rather short total working period of about four days, see Figure 5-2.

5.2.2 Core drilling period

Ensuing percussion drilling of section 0–35.68 m, immediate establishment of cored drilling equipment followed, whereupon the core drilling operations commenced. The progress of the core drilling from 2016-04-10 to 2016-06-13, is presented in Figure 5-2. The pace of drilling decreases versus time, due to that with increasing borehole length, retrieval of the core barrel, e.g. for change of drill bit, becomes more and more time consuming.

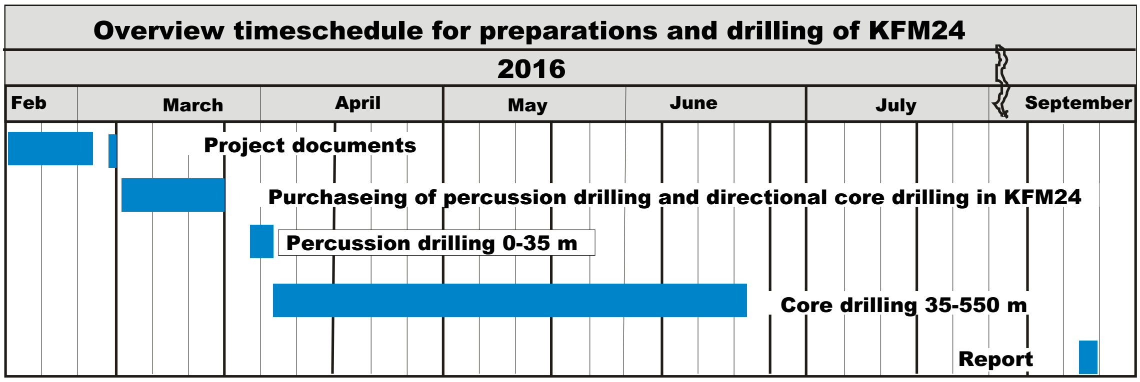


Figure 5-2. Overview of the drilling performance of borehole KFM24.

5.3 Geometrical data and technical design of borehole KFM24

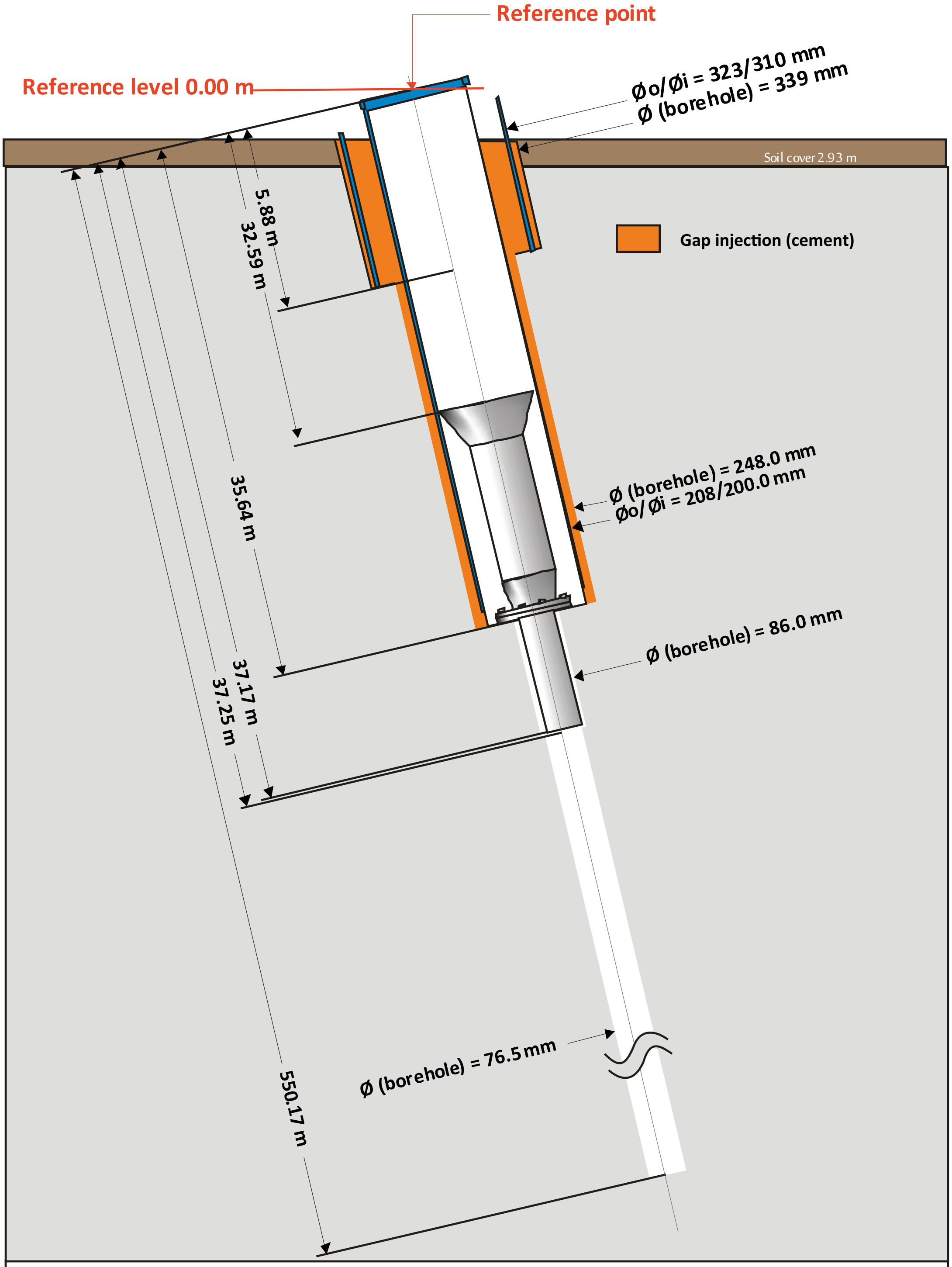
Administrative, geometric and technical data for the telescopic borehole KFM24 are presented in Table 5-1. The technical design is illustrated in Figure 5-3.

Table 5-1. Administrative, geometric and technical data for borehole KFM08C.

Parameter	
Borehole name	KFM24
Location	Forsmark, Östhammar municipality, Sweden
Drill start date	April 30th, 2016
Completion date	June 13th, 2016
Percussion drilling period	2016-03-30 to 2016-04-04
Core drilling period	2016-04-10 to 2016-06-13
Contractor core drilling	Drillcon Core AB
Subcontractor percussion drilling	Zublin Skandinavia AB
Percussion drill rig	Commacchio 1500 S
Core drill rig	Boyles B20 APC
Position KFM24 at top of casing (RT90 2.5 gon V 0:-15 / RHB 70)	N 6700492.20 E 1631152.50 Z 1.03 (m.a.s.l.) Azimuth (0–360°): 311.07° Dip (0–90°): –83.85°
Position KFM24 at bottom of hole (RT90 2.5 gon V 0:-15 / RHB 70)	N 6700542.87 E 1631109.78 Z –545.09 (m.a.s.l.) Azimuth (0–360°): 318.27° Dip (0–90°): –82.27°
Borehole length	550.17 m
Borehole diameter and length	From 0.00 m to 5,88 m: 0.3390 m From 5.88 m to 35.41 m: 0.248 m From 35.41 m to 35.64 m: 0.198 m From 35.64 m to 35.68 m: 0.164 m From 35.68 m to 37.25 m: 0.0860 m From 37.25 m to 550.17 m: 0.0765 m
Casing diameter and drilling length	$Ø_o/Ø_i$ = 323 mm/310 mm to 5.80 m $Ø_o/Ø_i$ = 339 mm/281 mm to 5.88 m $Ø_o/Ø_i$ = 208 mm/200 mm to 35.41 m
Transition cone inner diameter	At 32.59 m: 0.197 m At 37.18 m : 0.080 m
Drill core dimension	35.68–550.17 m/ Ø45 mm
Drillcon core dimension for steered sections	14 steerd sections between 39.84–467.34 m have a core diameter of 31.5 mm.
Core interval	35.68–550.17 m
Average length of core recovery	2.58 m
Number of runs	188 Conventional drilling 14 Steered drilling
Diamond bits used	12
Average bit life	40 m

Technical data

Borehole KFM24



Drilling reference point

Northing: 6700492.20(m), RT90 2,5 gon V 0:-15
Easting: 1631152.50(m), RT90 2,5 gon V 0:-15
Elevation: 1.03(m), RHB 70

Orientation

Bearing (degrees): 311.07°
Inclination (degrees): -83.85°

Borehole

Length: 550.17 m

Percussion drilling period

Drilling start date: 2016-03-30
Drilling stop date: 2016-04-01

Core drilling period

Drilling start date: 2016-04-10
Drilling stop date: 2016-06-15

2016-06-23

Figure 5-3. *Technical data borehole KFM24.*

5.4 Percussion drilling 0–35.68 m

5.4.1 Drilling

As mentioned in Section 4.2.3, the upper section, down to 5.88 m of the borehole, was drilled and cased with NO-X 280. During pilot drilling to 35.68 m a water inflow of 15 L/min was encountered at 24.5 m (drilling length). Even if no other highly fractured rock section was observed, but to be absolutely certain that the nearby wetland would not be drained into KFM24, the borehole section 5.88–35.64 m was reamed to 248 mm, and a 200 mm stainless steel casing was installed. The gap between the casing and borehole wall was cement grouted, thereby sealing the gap completely, so that the water inflow ceased.

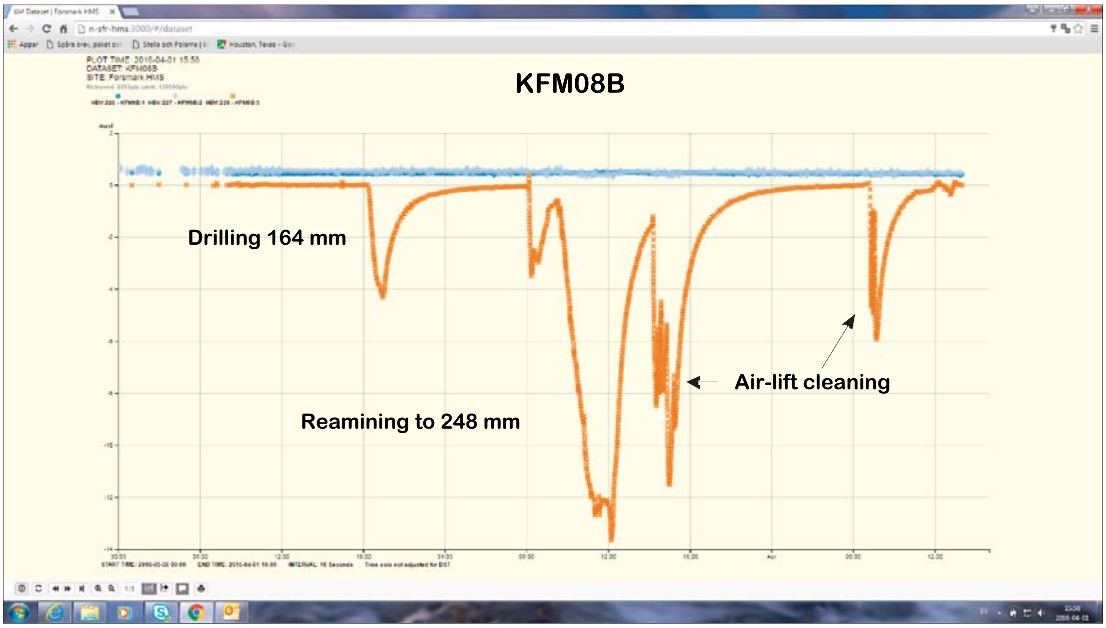
5.4.2 Measurements while drilling

During, and immediately after drilling, a program for sampling and measurements was applied, cf. Section 4.2.3. Below, the results of the deviation measurements made after completed percussion drilling of KFM24 are commented on.

Percussion drilling uses compressed air as the energy source for driving the drill hammer. The compressed air is also lifting the drilling debris and inflowing water from the borehole to the ground surface. This air-lift pumping effect may be regarded as a hydraulic interference test. When a water inflow of 15 L/min at 24.5 m length occurred, significant disturbances in the nearby located borehole KFM08B were registered by the monitoring system (HMS), see Figure 5-4. During reaming to 248 mm, when an increased air-flow rate was needed for drilling, a draw-down of almost 14 m was observed.

Borehole deviation

Much effort was devoted to obtain a correct starting direction of the borehole (Figure 5-5) but when the NO-X casing had been drilled to 5.88 m, the azimuth was observed to have changed to 311° instead of the pre-decided and measured in value of 321°. This large deviation was probably caused by the drill bit sliding anti-clokwise before it took hold of the inclined rock surface at c. 3 m. Fortunately, the inclination remained stable, but when the percussion borehole was completed at 35.68 m, the azimuth deviation continued to rotate anti-clockwise. This had a great impact on the steered drilling that from the beginning had to be focused on forcing the hole in the correct direction as soon as possible, se Section 5.6.2.



PLOT TIME: 2016-04-01 15:58
DATASET: KFM08B
SITE: Forsmark HMS

Figure 5-4. HMS monitoring. A significant draw-down is observed in the nearby borehole KFM08B during drilling, reaming and cleaning of the percussion borehole KFM24 to 35.68 m length.

Figure 5-5. *Reflectors are taped on the NO-X 280 casing, and with a total station measurement are performed so that the start direction can be calculated.*

5.5 Core drilling 35.68–550.17 m

5.5.1 Drilling

The drill site DS24 is located as close to the wetland (puddle) as possible without risking drainage or contamination of the borehole or vice versa.

Drill site DS24 is located within the tectonic lens, and the borehole KFM24 is drilled through the so-called rock domain RFM29 (Olofsson et al. 2007), the rock types of which (mainly medium-grained metamorphic granite to granodiorite) completely dominate the tectonic lens. The major part of the borehole is very low-fractured, and several unbroken 3 m long drill cores were recovered. The rock is also characterized by a very low hydraulic conductivity, as could be observed during drilling.

The drillability of the Forsmark bedrock, especially within the tectonic lens, has appeared to be relatively low, probably depending to a large extent on the high quartz content. This has been a challenge for the drill bit manufactures, and when drilling the steered borehole KFM24 a series of modified drill bits were applied.

Steered drilling costs increase by drilling length, mainly due to several in-and out transportation of drill rods before a steering and measuring cycle is completed. Theoretically, the use of a stiff core barrel equipped with soft drill bits would minimize the natural deviation during the conventional drilling in hard rock. For that purpose a hexagon core barrel, that is twice as heavy as other barrels, was used (Figure 5-6). Unfortunately, the drilling contractor was only equipped with a few diamond rich bits with soft matrix. Combined with a life time of around only 20–25 m these drill bits were soon consumed. As only standard drill bits were then available, this affected the natural deviation while performing conventional drilling, especially in inclination, se Section 5.6. In Figure 5-7 different types of worn-out drill bits are shown. Drill bit no 1 melted and swelled, causing a broken drill rod that took 11 shifts for rescue before the drilling could continue.

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 4.3.3. The results are presented in Sections 5.5.2–5.5.6 below.

Figure 5-6. *The Hexgon core barrel used for conventional drilling in N-size.*

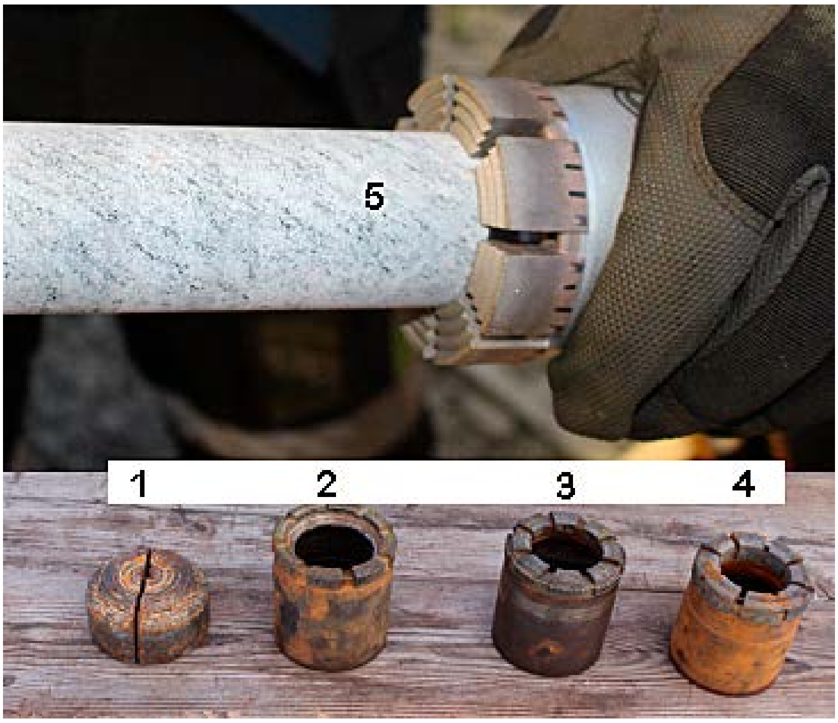


Figure 5-7. *The picture shows four different types of worn-out drill bits, no 1–4. No 5 is a new drill bit. No1 is completely melted due to lack of flush water cooling. No 2 has a worn out interior dimension. The diamonds on the drill bit face have vanished and the drill bit steel is visible. No 3 has a worn out outer dimension, the diamonds having vanished on the drill bit faces causing zero penetration rate and a possible drill bit breakdown. Finally, no 4 has clogged water channels, probably due to unsuitable matrix hardness for the existing rock conditions.*

Core sampling

The average summed up drill core length retrieved per drilling run was 2.36 m (section 35.68–550.17 m but excluding the fourteen steering sections). Fracture minerals were relatively well preserved. A preliminary core logging was carried out continuously in conjunction with the drilling.

5.5.2 Registration and sampling of flushing water and return water

Flushing water and return water flow rate – water balance

As borehole KFM24 is of SKB chemical type, it is important to estimate the amount of flushing water pumped into the borehole during drilling as well as the amount of return water recovered to permit a water balance calculation. A flow gauge in the measurement station, registered the flushing water flow rate, see Figure 3-5. The return water was measured by another flow meter, mounted on-line with the discharge pipeline, see Figure 3-5 and Figure 3-8.

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

Figure 5-8 illustrates the accumulated volume of flushing water and return water versus time during core drilling, while Figure 5-9 displays the accumulated volumes of flushing water and return water from the entire drilling period, giving a return water/flushing water quotient of 1.10 (results from Uranine measurements are presented in the next section).

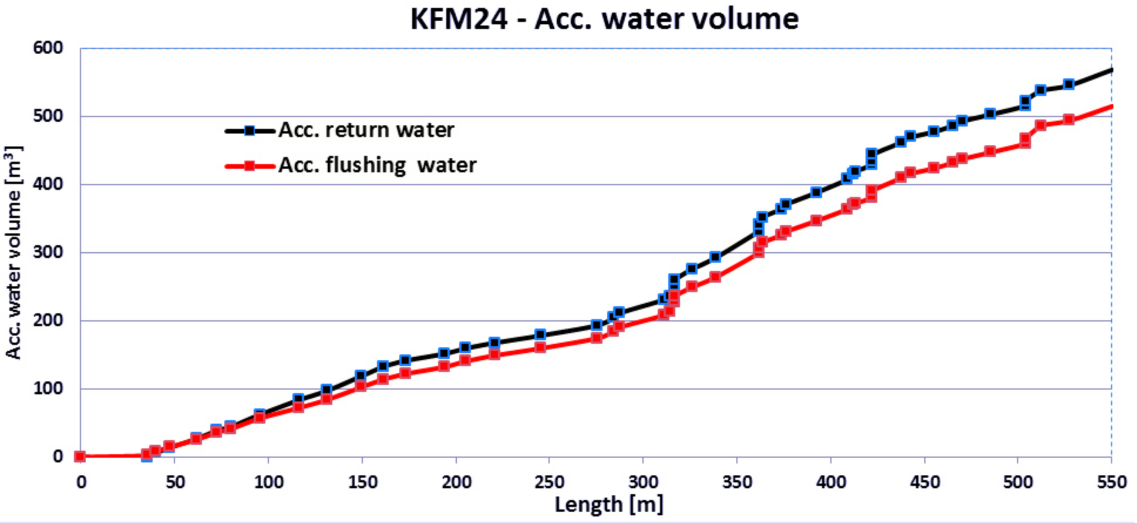


Figure 5-8. *Accumulated volumes of flushing water (red) and return water (green) versus time during core drilling of borehole KFM24.*

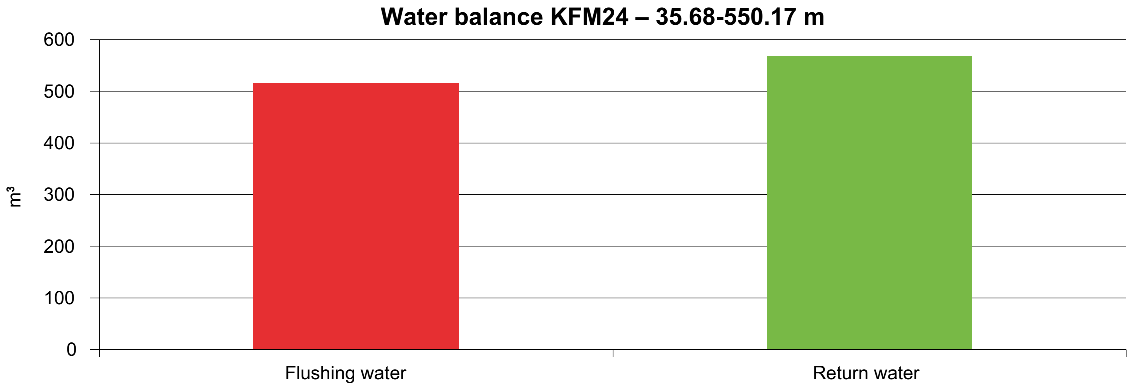


Figure 5-9. *Total amounts of flushing water and return water during drilling of borehole KFM04. The total volume of flushing water used during core drilling was amounted to 514 m^3. During the same period, the total volume of return water was 568 m^3. The return water/flushing water balance is then as low as 1.10, due to the small inflow of groundwater into the cored borehole.*

Uranine content of flushing water and return water – mass balance

During the drilling period, sampling and analysis of flushing water and return water for analysis of the content of Uranine was performed systematically with a frequency of approximately one sample per every 15–20 m drilling length, see Figure 5-10. 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 injected in the borehole versus recovered flushing water in the return water suggests that part of the flushing water is lost in the borehole. According to notations in the logbook, the amount of Uranine added to the borehole was 105 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 103 g and 100 g respectively. Since the different calculated values are in the same range it is most likely that most of the tracer has been recovered.

This result, which is very favourable from a hydrogeochemical aspect, has previously not always been observed when drilling cored boreholes at Forsmark, especially not in the 1 000 m long boreholes. This difference may be a combined effect of variations in the occurrence of hydraulically active fractures and fracture zones in different boreholes, and that the mammoth pumping is more effective in shorter boreholes than in longer holes. After finished drilling, the water chemistry sampling in KFM24 confirmed a low content of flushing water in a sampled section at 399 m length.

Electric conductivity of flushing water and return water

Flushing water was supplied from a water tap at Forsmarks's Kraftgrupp AB. 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 3-5. 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 3-8). The results of the EC-measurements are displayed in Figure 5-11. The electrical conductivity of the flushing water (tap water) is constant at c. 30 mS/m through the complete drilling period.

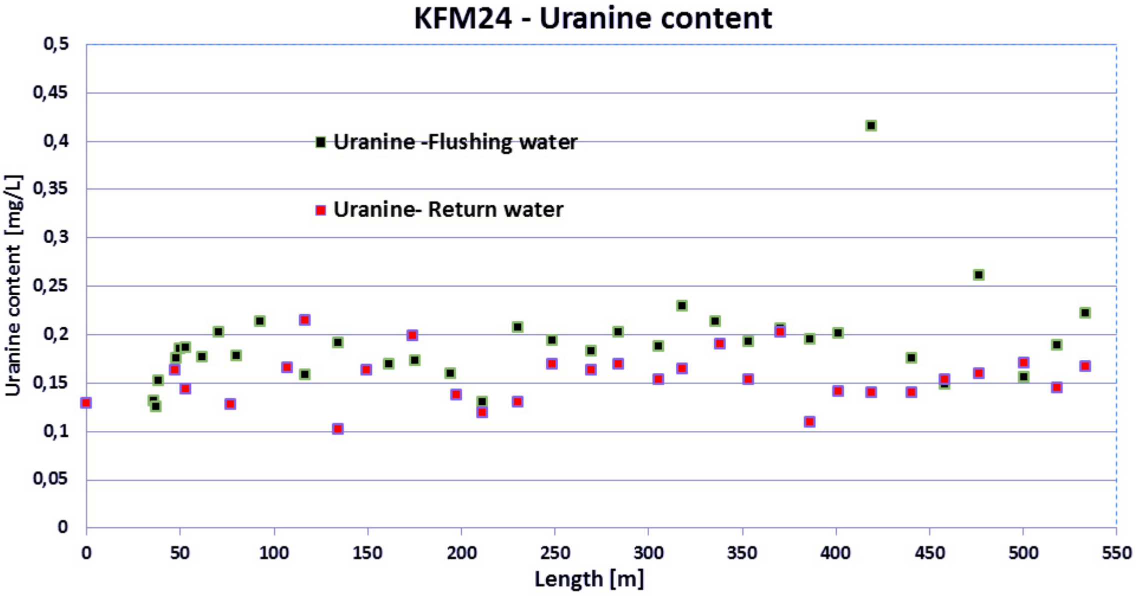


__Figure 5-10.__ Uranine content in the flushing water consumed and the return water recovered versus drilling length during drilling of borehole KFM24. An automatic dosing equipment, controlled by a flow meter, accomplished the labelling with Uranine.

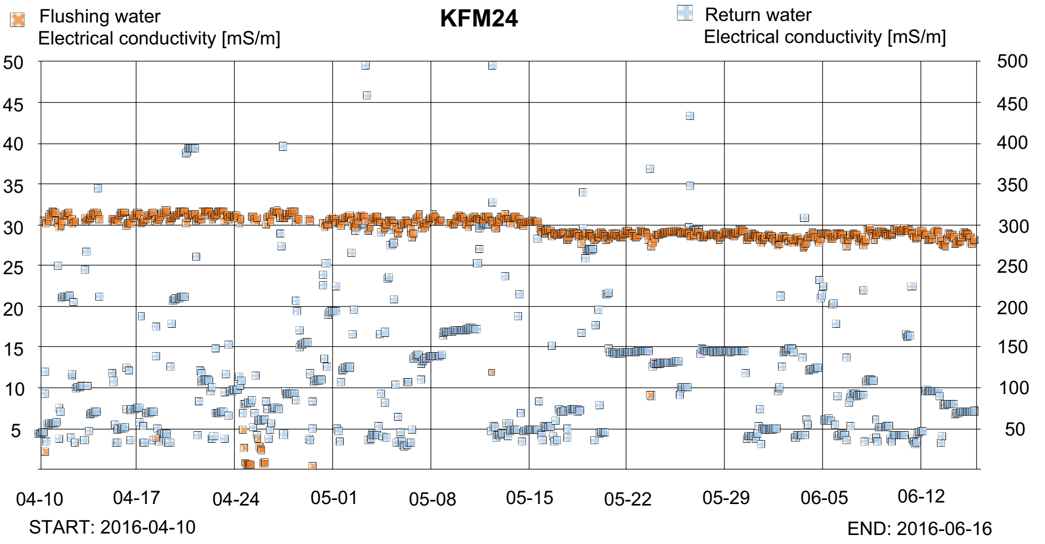


Figure 5-11. Electrical conductivity of flushing water (tap water) and return water from KFM24. The amount of values in the dataset has been reduced and presents data every 2 hours.

The return water is a mixture of flushing water (tap water) and groundwater discharged from water-yielding fractures penetrated by the borehole, The average electrical conductivity of the return water from KFM24 (Figure 5-11) is from start at the same level as the tap water but is soon rising to 300 mS/m, although there is a scatter of EC-values between 30 and 300 mS/m indicating imperfect mixing of tap water and groundwater in the water recovered from the borehole. After further drilling for another day, the EC-value has a peak reaching 500 mS/m, before it is stabilized at c. 200 mS/m. and as tap water only has an EC-value of 30 mS/m. The results indicate a minor groundwater inflow at the upper part of the borehole and only minor, or possibly no inflow at all, at larger depths.

Registration of the groundwater level in KFM24

As explained previously, 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 ground water level in the borehole, below plotted versus time of the drilling period (Figure 5-12).

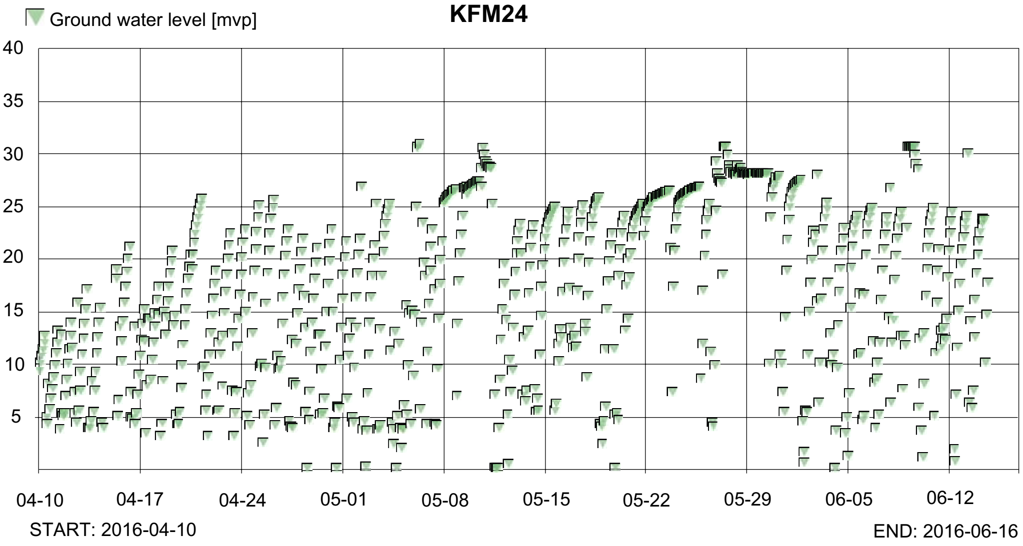


Figure 5-12. Groundwater level versus time in KFM24 during drilling.

The drilling was performed continuously 7-days a week with 11 working hours per day and completed with an extra night shift between May 4th and May 13th. However, mechanical disturbances on the drilling rig caused long periods when no drilling was conducted. The mammoth pump was set at a pumping capacity aimed to cause a draw-down of c. 25 m. From the beginning, during the 13-hours rest per night, the groundwater table could not recover completely to the original level. It was only during longer stops of drilling and pumping that the groundwater table could recover due to recharge of groundwater into the borehole, resulting in the (positive) peaks shown in the diagram. When pumping was re-started, a simultaneous draw-down occurred.

These results presented in Figure 5-11 and Figure 5-12, confirm that the total inflow of formation water below the upper cased and grouted parts of the borehole was very low.

5.5.3 Recovery of drill cuttings

The theoretical borehole volume of the percussion drilled and reamed part of KFM24 (0-35.68 m) is c. 1.6 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 plausible 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 KFM24 and the drill core is calculated to be 1.529 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 4 050 kg. The calculated dry weight of the debris from the core drilling recovered and weighed in the containers was 3 864 kg. The difference between the theoretically produced and recovered dry weight of debris is 186 kg, which gives a recovery of 95.0 %.

The recovery figure could be commented on. 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 if the weight of that had been included in the calculation, the recovery figure would have been somewhat increased.

It should also be observed that weighing of the containers including return water and debris is associated with some uncertainty. However, it seems reasonable to conclude that very little drilling debris has been forced into the fracture system of the formation, due to the fact that the complete borehole was characterized by a very low hydraulic conductivity.

5.5.4 Nitrogen flushing and pumping in in KFM24

The final effort, before the drilling activity was concluded, was to rinse the borehole in order to minimize the contents of drilling debris or other unwanted material left in the borehole. For this purpose, nitrogen flushing was used. A hydraulic hose was lowered to the borehole bottom and connected to high pressurized nitrogen gas bottles.

Usually, a borehole is nitrogen flushed, until the recovered return-water is judged (by optical observation) to be clean or with a minimum content of drilling debris. KFM24 was flushed between June 16th 10:00 and June17th 12:06, 2016, before this was achieved. The estimated recovered water volumes of these activities were 11.6 m^3 (Table 5-2).

Table 5-2. Nitrogen flushing period and estimated uplift of groundwater from KFM24 (from EG036).

ID	Pressure (bar)	From	To	Volume (L)	Blow out
KFM24	70	2016-06-16 10:00	2016-06-16 10:02	1 000	
KFM24	110	2016-06-16 12:37	2016-06-16 12:55	1 500	12:05
KFM24	105	2016-06-16 14:16	2016-06-16 14:46	1 800	14:46
KFM24	100	2016-06-16 16:32	2016-06-16 16:51	1 500	16:51
KFM24	100	2016-06-16 18:54	2016-06-16 19:17	1 800	19:17
KFM24	100	2016-06-17 07:24	2016-06-17 07:54	1 500	07:54
KFM24	100	2016-06-17 08:55	2016-06-17 09:22	1 000	08:55
KFM24	88	2016-06-17 12:06	2016-06-17 12:33	1 500	12:06

5.5.5 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. 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 load of its own weight, and the stretching will stop. 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 5-13, which is based on load tests performed in the laboratory by the manufacturer of the drill pipes.

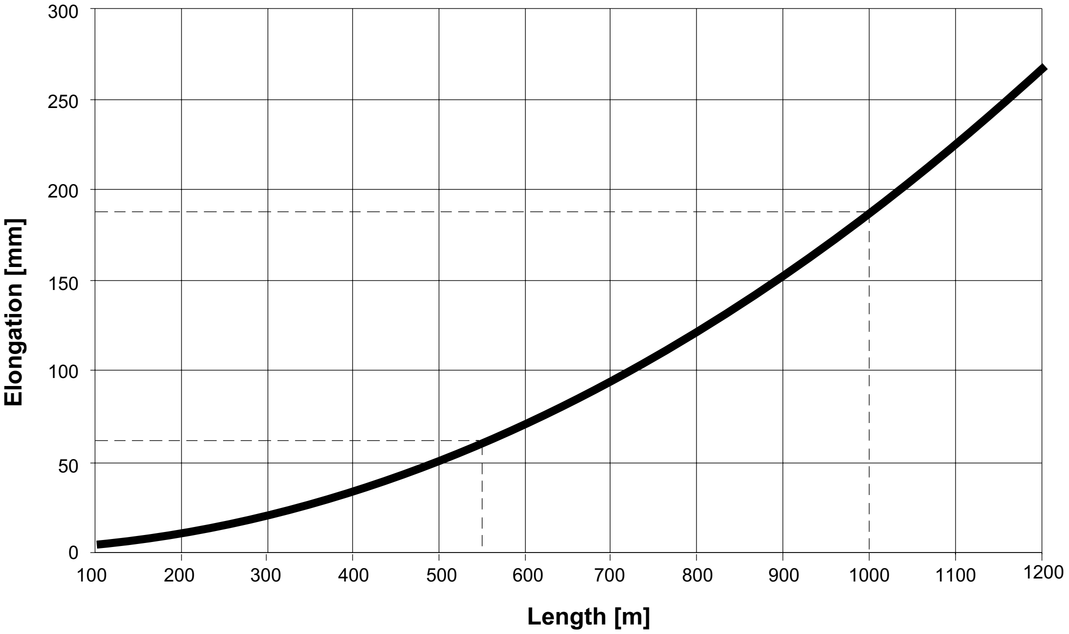


Figure 5-13. The diagram illustrates the elongation of the WL-76 drilling pipe string when hanging in a vertical water filled borehole. Values from laboratory load tests of the drill pipe string.

As seen in the diagram, the maximum elongation at 550 m length in a vertically drilled borehole is 65 mm. In inclined boreholes the elongation of the pipe string should theoretically be less.

5.5.6 Consumables

The amount of oil products consumed during core drilling, thread grease, and grout used for gap injections of the respective casings are reported in Table 5-3 and Table 5-4. Regarding hammer oil and compressor oil, consumption was below detection limit. The two latter products are indeed entering the borehole but are, on the other hand, continuously retrieved from the borehole due to the permanent air flushing during drilling. After completion of drilling, only minor remainders of the products are left in the borehole.

The special type of thread grease (silicon based) used during core drilling in this particular borehole was certified according to SKB MD 600.006 (Table 1-1). The motive for using this product is its 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.

Table 5-3. Grease, oil and diesel consumption during core drilling of KFM24A.

Borehole ID	Thread grease Üni Silikon L50/2	Grease for the drilling machine Statoil AB	Engine oil Castrol Tection 15W-40	Gear box oil	Hydraulic oil Premium ECO HT-E 46	Engine diesel OKQ8 Diesel environmental class 1
KFM24	4.6 kg	3.2 kg	15 L	5 L	60 L	8500 L

Table 5-4. Cement consumption for grouting the percussion drilled part of KFM24 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
KFM24	0.0–35.65	800 kg/600 L	Gap injection	

5.6 Steering

5.6.1 Steering strategy

After the location of the start point for KFM24 had been established, the strategy for borehole KFM24 was to drill it as straight as possible and to make it pass at the northern side of the planned vertical shaft at 5 m distance at c. 340 m drilling length. Furthermore, the end point at 550 m length should ideally be within a circle of 3 m radius from the endpoint at 550 m of a theoretical, completely straight borehole (Figure 5-14).

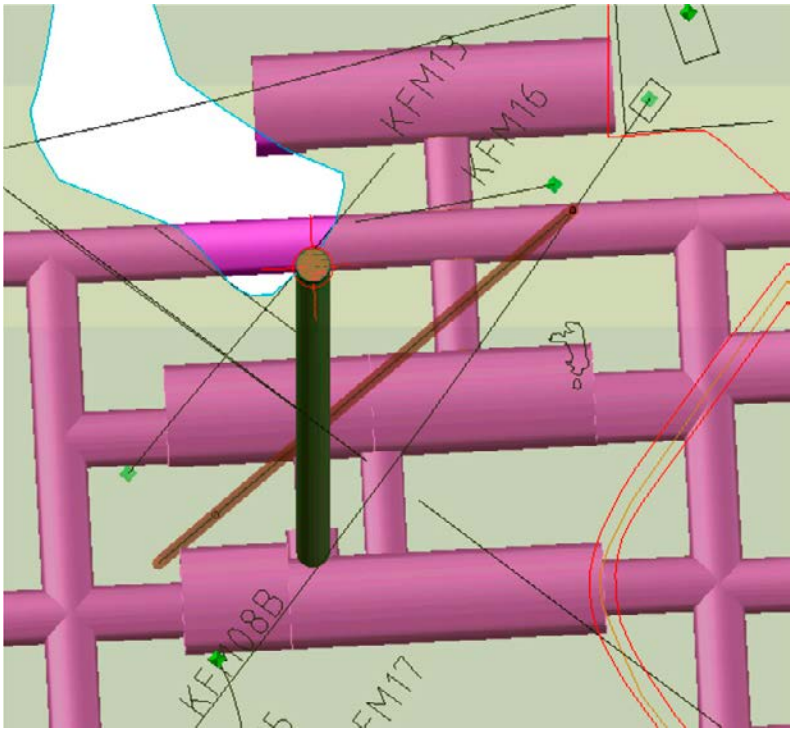


***Figure 5-14.** Part of the central area of the planned repository with accessory tunnels (pink) seen from above and to the north. The brown-green cylinder indicates the future skip shaft, and the brown line illustrates KFM24. The target area for the bottom of KFM24 was aimed to end up between the two halls of the central area of the repository.*

5.6.2 Steering with the DeviDrill

Figure 5-15 and Figure 5-16 illustrate the results of the steering operations in borehole KFM24. The figures should be read in such a manner that the area between the plot and the theoretical line represents the accumulated deviation, i.e. staying below the line for a long time means that the inclination (or azimuth) is decreased, whereas staying above means an increase. So, when the plot and the theoretical line coincide, the hole is exactly on track with respect to inclination (or azimuth).

Steerings no 1 to no 7

Data from the steerings no 1–7 are presented in Figure 5-15 and commented on below. As mentioned in Section 5.4.2 the percussion drilling of the upper telescopic borehole caused a significant anti-clockwise deviation in azimuth. After installation of a casing in the percussion drilled part of the telescopic hole, core drilling was made to 39.68 m before the first deviation measurement was performed. Already at this length the azimuth had decreased to 308° whereas inclination was still stable at c. 83°, meaning that a steering to the right had the highest priority. However, since experience from performance of careful steering in Forsmark rock types did not exist, it was decided to use a medium level of settings that functioned well when drilling the KBS-3H borehole K08028F01 at Äspö (Nilsson 2015).

Therefore steering no 1 used setting 1.6, drilling length 2.11 m and toolface 110°. The ensuing deviation measurement indicated a significant effect on the azimuth to the right and also a steeper inclination.

Accordingly, steering no 2 used the same setting, an extended drilling length to 2.42 m and directed 115°, which continued the trend to the right and downwards.

Steering no 3 used a higher setting, but the direction was 95°, continuing the trend to the right. Now a moderate decrease in inclination occurred. Steering no 4 was directed to 65°, that gave a moderate trend to the right, while the inclination planned out. After further 45 m conventional drilling to

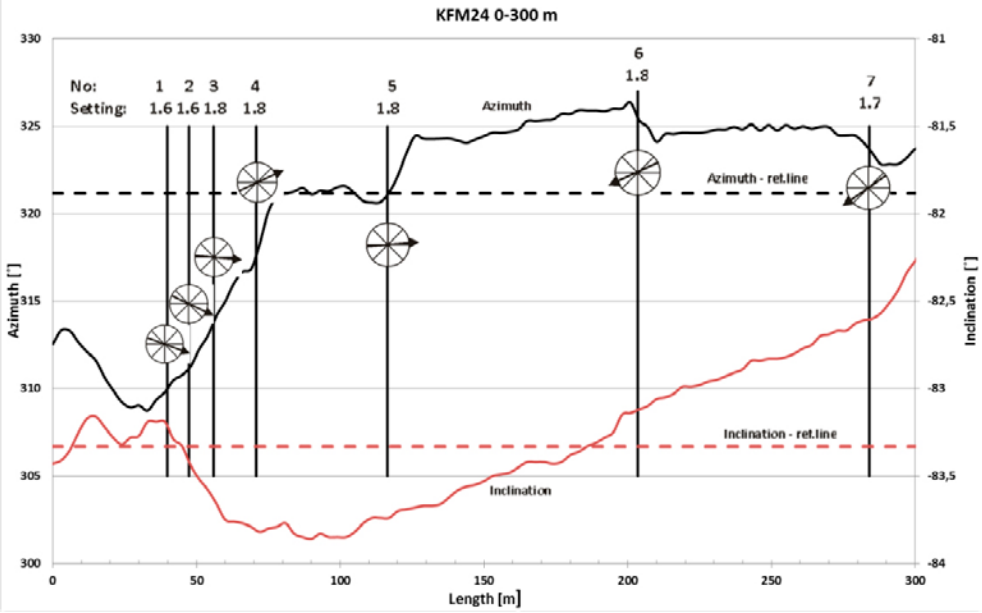


Figure 5-15. *The results represent an average calculation of all gyro and Pee-Wee deviation measurements in borehole KFM24 in section 0–300 m. Seven steered drillings were carried out in this section. The black arrows show the position as well as the direction of the DeviDrill barrel.*

116.42 m, steering no 5 was directed to 85° which continued the moderate rise of azimuth, whereas inclination now had a more natural steady rise upwards. Regular deviation measurements confirmed a slow increased azimuth as well as inclination. Conventional drilling continued, resulting in that the borehole position at 200 m in vertical was 10 cm below and in horizontal 1.1 m to the west of the theoretical straight borehole.

At 203.52 m the azimuth value was above the reference line, and if the trend should continue, the borehole position would start going to the west. However, at 340 m length, borehole KFM24 passes the planned vertical shaft, and to avoid the risk that the borehole at this depth would end up too close to the shaft, it was necessary to break the trend to the right in time. Therefore steering no 6 was directed 245° and drilled 1.88 m, which resulted in decreased azimuth but had only a minor effect on the inclination. Conventional drilling continue, and regular deviation measurements showed a more constant azimuth and a steady raise of inclination. At 284.04 m steering no 7 was directed 235° m, aiming to lower both azimuth and inclination. After 2.32 m of steered drilling, the entrepreneur unfortunately had to continue drilling with conventional drill bits, as all softer, more suitable bits were worn-out.

Steerings no 8 to no 14

Data from steering no 8–14 are presented in Figure 5-16 and are commented on below. When using harder drill bits during the conventional drilling than during steerings no 1–7, probably a harder pressure was applied, that effected the inclination to rise with a steeper gradient. Even if the borehole position at 300 m with margin fulfilled the requirements, it was now necessary to reduce the inclination. Otherwise the deviation upwards would increase rapidly and very soon fall outside the requirements. Therefore steering no 8 and 9 were directed downwards and with an increased setting to counteract the natural upward deviation and resulted in a significant lower inclination but also gave the azimuth a smoothly trend to the right. Steering no 10 lowered both the inclination and azimuth. This was followed by no 11 that was drilled 2.62 m and directed 170°, which lowered the inclination and stabilized the azimuth values. The strong natural deviation in inclination continued. Steering no 12 lowered the inclination to the reference line. By changing direction to 145° for steering no 13 also the azimuth raised smoothly. Finally, it was necessary at 465 m length to conduct steering no 14, now directed 160°. This steering lowered the inclination.

Conventional drilling continued and control deviation measurements indicated that the end position would come to stay inside the requirements, entailing that the borehole was finished at 550 m length without further steerings. Final deviation measurements with the gyro could be performed to 548 m. The position at the borehole end is assessed to be vertically 32 cm above and horizontally 2.8 m to the right of the target at 550.17 m length.

Table 5-5 presents a summary of the results of the 14 steering performed in borehole KFM24.

Table 5-5. Fourteen steered drillings were carried out and the results are commented on in the right column.

Steering nr	Section (m)	Aim	Toolface	Setting	Comments on the results
1	39.84–41.95	Depending on the natural conditions during the percussion drilling to 35.68 m, the start direction is more than 10º off, measured to 311.07° while the straight borehole from start should be directed in 321.147°. Therefore, a number of steering's must be directed to the north-east in order to get the borehole position closer to the reference line. Initially, a medium setting value is used for the first steered drilling of 2.11 m length.	110º	1.6	The first steering shows a clear direction to the right and downwards. The natural tendency should be upwards. The same intense of setting can continuously be used.
2	47.39–49.81	By extending the drilling length and continue using the same values of setting and toolface, probably an even more significant change in direction to the north-east is achieved.	115º	1.6	Similar outcome as from the first steering, and the extended drilling length shows clear direction to the north-east and downwards.
3	55.94–57.88	Still necessary to steer the borehole direction to the north-east, but by changing the toolface a bit upwards it is possible to level out the inclination. Also shortening the drilling length to 1.94 m as the setting is increased to 1.8.	95º	1.8	The third steering results in a borehole direction clearly to the north-east, whereas the direction downwards starts to level out.
4	70.77–72.66	Continued steering to the right so that the borehole position may reach the straight reference line in azimuth, but also turn the toolface more upwards to level out inclination. Keep a drilling length to 1.89 m.	65º	1.8	The fourth steering results in a moderate direction to the north-east while the vertical changes level out. Now conventional drilling can be extended, combined with regular control measurements.
5	116.42–118.47	As the borehole position still is to the left, and as the effect of the trend to right ceased out and the natural tendency upwards has started, steering no 5 is directed to the north-east with a toolface of 85° and drilled 2.05 m.	85°	1.8	Finally, the borehole direction in azimuth reaches the reference line for 321°. Continue with conventional drilling combined with regular control measurements.
6	203.52–205.40	After further conventional drilling and measurement for 85, the borehole position is coming closer to the straight borehole. However, if drilling continues, the borehole position will cross the straight line and at c. 300 m length, when the borehole passes the vertical shaft, it could be to the left of the straight line. For safety reasons steering no 6 is aimed to slow the movement to the north-east and is therefore directed to the south-west. Drilling length 1.88 m.	245º	1.8	The azimuth decreased and continued quit stable meaning that conventional drilling could be continued for further 80 m.
7	284.04–286.36	Continue to decrease the deviation to the north-east and also begin to lower the inclination downwards as the natural deviation strives the borehole upwards.	235º	1.7	The outcome was an increased gradient of the inclination directed upwards, probably because of changing fabricate of the drill bit. The earlier (softer) drill bits used had a moderate upward trend. However, the contractor had no more bits of this type available.

Steering nr	Section (m)	Aim	Toolface	Setting	Comments on the results
8	311.46–314.09	Firstly, the inclination must be lowered significantly as the standard drill bits are not favourable. Secondly, also continue to decrease the tendency sideways in order to minimize the risk when passing the shaft at 340 m length.	205°	2	A significantly lower inclination that also decreased the azimuth.
9	326.34–328.29	Primarily, the inclination must be lowered. Drilling length 1.95 m.	190°	2	Again a moderate change of the inclination downwards and the azimuth to the left that soon ceased. When extending the conventional drilling, the rise upwards continues.
10	361.83–363.83	Repeating steering no 9.	190°	2	Moderate change of the inclination downwards and the azimuth to the left.
11	373.70–376.32	Continue steering downwards but changing toolface to 170° and extending the steering length to 2.62 m.	170°	2	The steering continues to lower the inclination, but the strong natural deviation upwards quite soon forces the inclination to rise.
12	413.50–415.90	Must continue steering downwards with drilling length 2.40 m.	160°	2	Significant change of inclination downwards, that is on the limit of the allowed borehole curvature.
13	440.84–443.06	In order to avoid the borehole trajectory to exceed the curvature limit, the setting is decreased to 1.8. Directed downwards and smoothly to the north-east.	145°	1.8	Moderate change of inclination downwards.
14	465.00–467.34	The last steering, no 14, in the borehole is continuously aimed at bending the borehole downwards.	160°	1.9	Moderate change of inclination downwards. Even if the natural deviation upwards continues, Devico’s software prognosticates that the borehole ends at 2.7 m to the left at 550 m length. As this is inside the requirements (± 3 m), the borehole can be finalized without further steering’s.

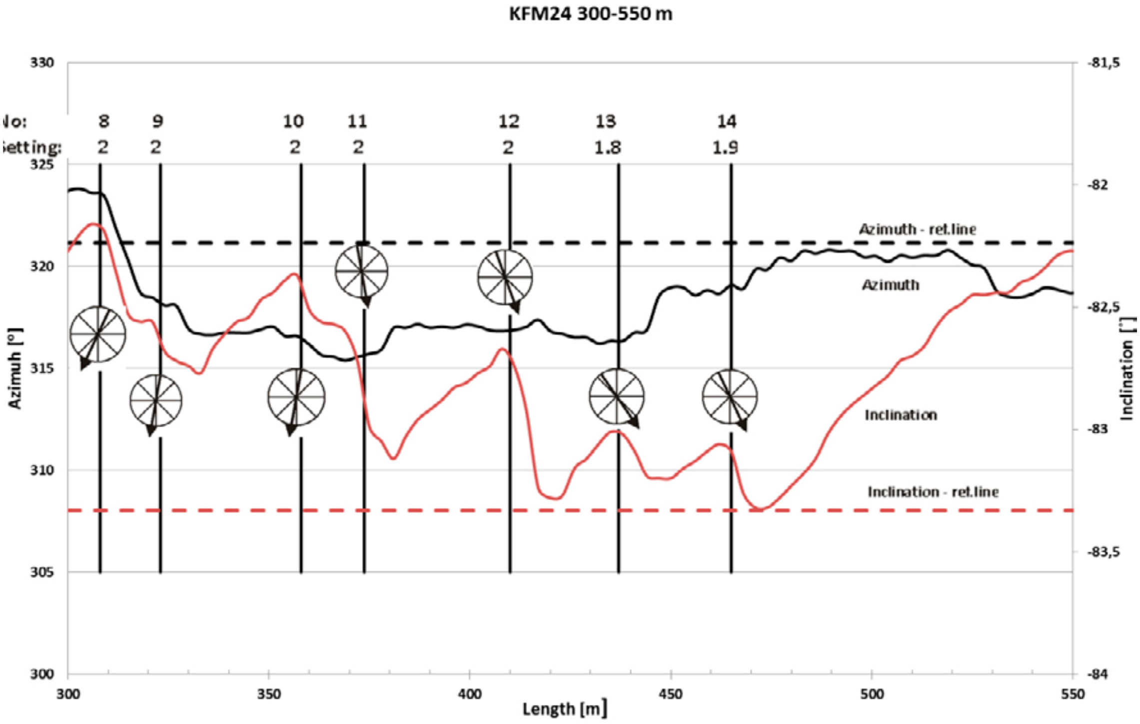


Figure 5-16. *The results represent an average calculation of all gyro and Pee-Wee deviation measurements in borehole KFM24 in section 300–550 m. Seven steered drillings were carried out in this section. The black arrows show the position as well as the direction of the DeviDrill barrel.*

5.7 Outcome of steerings in relations to stipulated requirements

Measurements with the ReflexGyro must be carried out in an open (non-cased) borehole, entailing time-consuming operation, especially at great depths, since the drill pipes have to be hoisted down and up. The instrument must be handled carefully to acquire data of high accuracy. With a steep borehole direction and the drill rig mounted inside a container, it was necessary to build a scaffold and a platform around the top of the drilling rig. The insertion rig engine was mounted in a firm foothold, and was centralized and bolted on the beam 3 m up (Figure 5-17). However, despite these preparations, already from the beginning disturbances on measuring data occurred frequently, probably caused by movements of the platform both due to wind and working activities on the platform. When the insertion rig was adapted to use new square pipes, data quality was approved as these pipes prevent rotation of the tool.

However, it was decided necessary to modify the measurement technique by using an analogue length meter for determination of the instrument position. Furthermore, in order to stabilize the tool, centralizers were mounted on the instrument. Finally, lowering the tool with the wire-line winch rendered a significant improvement in data quality.

The magnetic DeviShot instrument (Pee Wee) is by design adapted for use together with wire-line technology, and is pumped through the Sandvik N3 core tube. This means that the measurements (including data management and input for decision making) can be carried out rapidly, including data management up to the final result. The instrument was used to orient the directional core barrel (tool face) and to make quick measurements, especially of the inclination.

All approved deviation data produced during drilling of KFM24, both with the ReflexGyro and DeviShot tool, have continuously been merged, and by an average calculation procedure an upgraded working file has been created. This file was used for decision making during the drilling operation. After completion of drilling KFM24, two gyro measurements of the entire borehole length were performed. Strictly statistically, in order to determine the final position of a borehole, all measurements should be used in the average calculation. When magnetic data and gyro data are separated and compared, obvious differences are observed, see Figure 5-18 and Figure 5-19.

However, regarding inclination data, the differences are limited (Figure 5-19), probably due to the fact that the accelerometers used for measuring inclination are equal in most types of deviation tools, also in the ReflexGyro and DeviShot tools. On the other hand, a magnetic instrument based on magnetometer technology measures azimuth in relation to magnetic north. Changes in the magnetic field intensity and magnetic interference may introduce a false deviation for azimuth. However, in combination with that the DeviShot tool generates unique data for each station, and that the rock types penetrated by KFM24 contain very low contents of magnetite, the magnetic azimuth should be trustable.

Figure 5-17. *Left: The insertion rig engine was mounted in a firm foothold, and was centered and bolted on the beam 3 m up. Right: Measurement with the gyro. The instrument is attached to 20 mm steel rods, and the engine is set to move the probe one metre at a time when a measure is taken.*

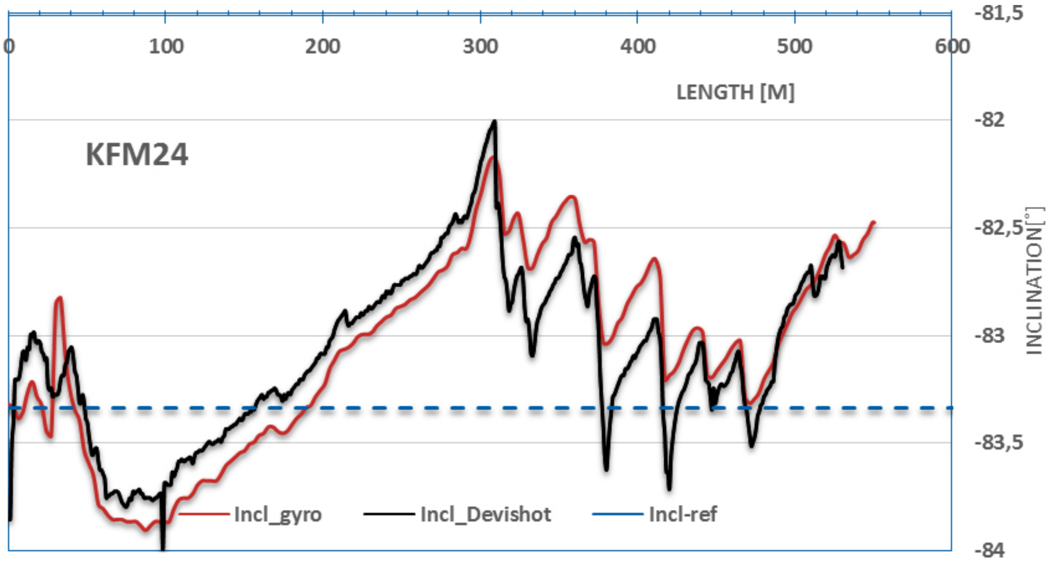


***Figure 5-18.** Comparison between averagely calculated data for inclination delivered from DeviShot (magnetic tool) and the ReflexGyro, respectively. Devishot data presented with 1 m accuracy, while ReflexGyro data has 3 m point distance.*

The magnetic declination at Forsmark is 3.44°, and this value is corrected for in the azimuth data, but still the difference compared to gyro data is remarkably large, that can be seen in Figure 5-19. The different data sets show comparable profiles, and the differences in azimuth and inclination are 2.5° and 0.2°, respectively. Based on this argument, all approved measurements were used, both for calculating the decision file during drilling, and for Sicada to calculate the final position of KFM24.

The discussions made before drilling pointed out that with percussion drilling of the upper part of the borehole it is difficult to achieve an exact borehole start orientation. Consequentially, it was found that the borehole from start had significant orientation sideways to the left (Figure 5-19), that probably accentuated further by that the starting direction is pointing to the left, before the initial seven steering's managed to turn the borehole to the right. At 300 m length the borehole position was very close on the target line.

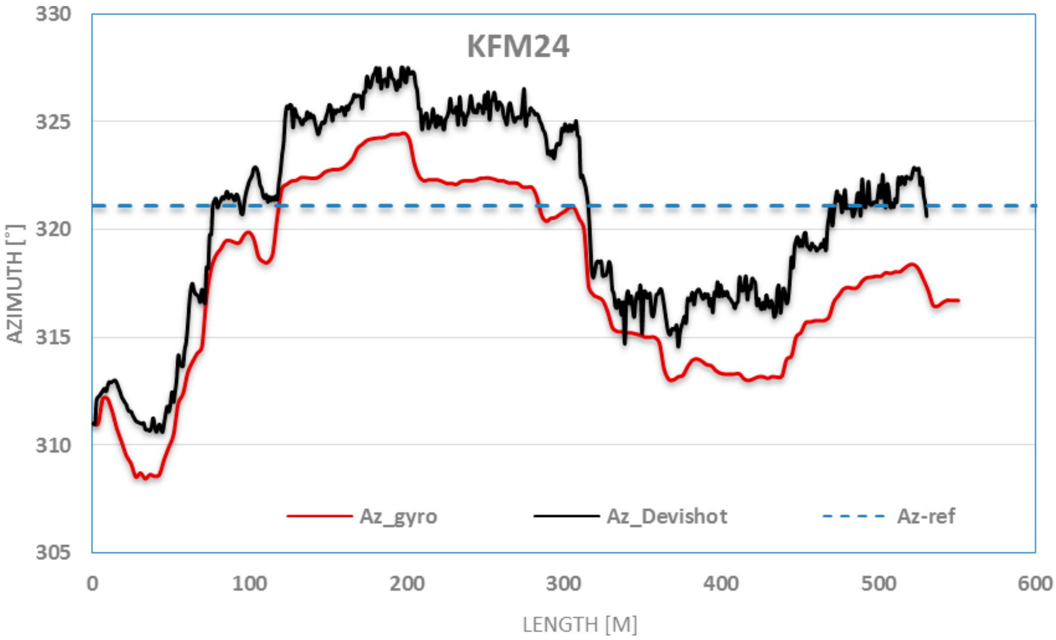


***Figure 5-19.** Comparison between averagely calculated data for azimuth delivered from DeviShot (magnetic tool) and the ReflexGyro, respectively. The difference between magnetic north and the coordinate system used is 3.44°, which has been added to the DeviShot values.*

After 300 m the remaining harder drill bits increased the natural deviation upwards, entailing seven additional steerings, aimed to lower the tendency upwards, were needed, while the orientation to the left was allowed to continue, before it was decided to finalize the borehole with conventional drilling from 467 m. When the x,y,z-coordinates later were calculated, the deviation of the hole at the borehole end (550 m) appeared to be c. 32 cm upwards and 2.8 m to the west (Figure 5-20).

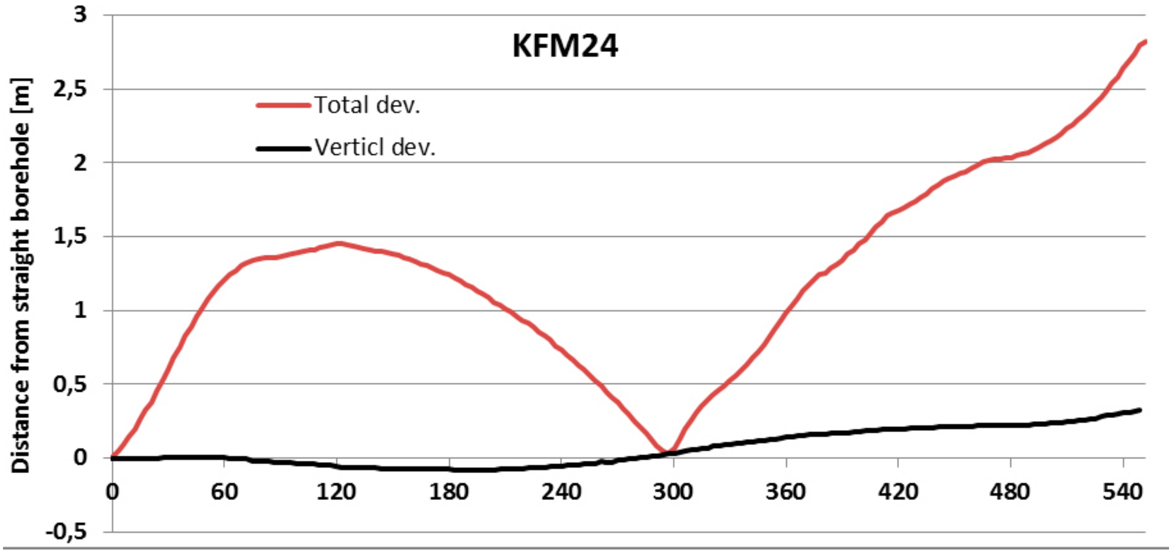


***Figure 5-20.** The final distance of borehole KFM24 from an imagined straight borehole trajectory is presented, where the vertical distance is black and the total distance is red.*

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Arkitektkopia AB, Bromma, 2017

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