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Forsmark site investigation

Drilling of five percussion boreholes, HFM11–12 and HFM 17–19, on different lineaments

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May 2004

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Summary

Investigations of lineaments indicated by geological and geophysical surveys constitute an important part of the site investigations in Forsmark. Among available investigation methods, drilling through the lineament and succeeding borehole logging are the most important. In this report, results from percussion drilling of five investigation boreholes in connection with lineaments located at different parts inside and just outside the Forsmark candidate area are presented.

Two of boreholes, HFM11 and HFM12, were drilled through the so called Eckarfjärden fracture zone, a regional fracture zone striking WNW-ESE just south-west of the candidate area. Borehole HFM11 was inclined c 49° from the horizontal plane and drilled to 182.35 m borehole length. The corresponding values for HFM12, which was drilled in the opposite direction to that of HFM11, are 209.55 m and c 49° (i.e. the same inclination). The drilling confirmed a pre-drilling hypothesis that the Eckarfjärden zone is steeply dipping and water-bearing. Significant hydraulic connections were observed between the two boreholes, which are situated about 120 m from each other.

Borehole HFM17, sited along the road between drilling sites DS2 and DS6, is 210.65 m long and sub-vertical (inclined c 84° from the horizon). The aim of the borehole was to investigate if different lineaments north-west, east and west of the borehole are inclined in a way that they may be penetrated by the borehole. At present, the most plausible interpretation is that a lineament north-west of the borehole, striking SW-NE, represents the intersection with the ground surface of a flat-dipping, water-bearing structure, intersected by the borehole at about 30 m borehole length.

HFM18 was sited just east of lake Lillfjärden and was inclined towards this. The borehole is 180.65 m long and inclined c 59° from the horizontal plane. It seems believable, that HFM18 intersects the reflection seismic reflector A4 at about 40 m borehole length, as well as another reflector, I1, at c 145 m and that these reflectors represent fracture zones.

Finally, borehole HFM19 was drilled between drilling site DS5 and an already existing percussion borehole, HFM13. Significant hydraulic connections between HFM13 and drilling site DS5 had earlier been demonstrated. HFM19 was drilled to 185.20 m drilling length and was inclined about 58° from the horizon. The pre-drilling expectations were, that hydraulic connections between HFM19 and drilling site DS5 as well as between HFM19 and HFM13 could be proved. Significant hydraulic responses were indeed observed at drilling site DS5 during drilling of HFM19. However, it cannot be definitely concluded that HFM19 is hydraulically linked to HFM13. This indicates a degree of complexity regarding the hydraulic and structural conditions at this part of the candidate area, which remains to be sorted out during the continued investigations.

Sammanfattning

Undersökningar av lineament som indikerats genom geologiska och geofysiska mätkampanjer är en väsentlig del av platsundersökningen vid Forsmark. Bland tillgängliga undersökningsmetoder hör borrning genom det aktuella lineamentet och efterföljande borrhålsloggning till de viktigaste. I denna rapport redovisas resultaten av borrning av fem hammarborrhål i anslutning till lineament inom och strax utanför olika delar av Forsmarks kandidatområde.

Av de fem hammarborrhålen borrades två, HFM11 och HFM12, genom den s k Eckarfjärdszonen, en regional sprickzon som stryker i västnordvästlig riktning strax sydväst om kandidatområdet. Borrhål HFM11 är 182,35 m långt och gradat ca 49° från horisontalplanet. HFM12, som borrades i motsatt riktning mot HFM11 och är 209,55 m långt, har ungefär samma flacka lutning mot horisontalplanet. Borrningarna konfirmerade att Eckarfjärdszonen är brant stående och vattenförande. Hydrauliskt samband kunde konstateras mellan de två borrhålen som är belägna ca 120 m från varandra.

Borrhål HFM17, beläget invid vägen mellan borrplatserna BP2 och BP6, är 210,65 m långt och sub-vertikalt (stupar ca 84° från horisontalplanet). Syftet med borrhålet var att undersöka om olika lineament nordväst, väster respektive öster om borrhålet har en sådan lutning att de kunde genomborras av detta. Den för närvarande mest troliga tolkningen är att lineamentet nordväst om HFM17 representerar skärningen med markytan av en flack, vattenförande struktur som genomskärs av borrhålet vid ca 30 m borrhålslängd.

HFM18 ansattes strax öster om Lillfjärden och riktades mot denna. Hålet är 180,65 m långt och gradat ca 59° mot horisontalplanet. Borrhålet skär med relativt stor sannolikhet dels den reflektionsseismiska reflektorn A4 vid ca 40 m borrhålslängd, dels en annan reflektor, I1, vid ca 145 m. Uppenbarligen representerar reflektorerna sprickzoner.

Hammarborrhål HFM19, slutligen, borrades mellan borrplats BP5 och ett befintligt hammarborrhål, HFM13, som under borrningen visade sig stå i hydrauliskt samband med BP5. HFM19 borrades till en längd av 185,20 m och ansattes med en lutning av ca 58° från horisontalplanet. Förväntningen var att tydliga hydrauliska samband skulle påvisas under borrningen mellan såväl HFM19 och borrplats BP5 som mellan HFM19 och HFM13. Signifikanta hydrauliska responser mellan HFM19 och BP5 konstaterades visserligen. Däremot kan det inte med säkerhet sägas att HFM19 och HFM13 står i hydrauliskt samband med varandra, vilket en viss komplexitet i de hydrauliska och strukturgeologiska förhållandena i denna del av kandidatområdet, något som återstår att reda ut under de fortsatta undersökningarna.

Contents

1 Introduction

SKB performs site investigations for location and safety assessment of a deep repository for high level radioactive waste /1/. The investigations are performed in two Swedish municipalities: Östhammar and Oskarshamn. The investigation area in Östhammar is situated close to the nuclear power plant at Forsmark /2/, see Figure 1-1.

Drilling is one important activity performed within the scope of the site investigations rendering geoscientific characterization of the bedrock down to and beyond repository depth possible. Three main types of boreholes are produced: core drilled boreholes, percussion drilled boreholes in bedrock and boreholes drilled through unconsolidated soil.

The initial phase of the investigations includes drilling of three, c 1000 m deep boreholes within the candidate area, at drilling sites DS1, DS2 and DS3, see Figure 1-1. These three boreholes were succeeded by a fourth 1000 m borehole, starting at drilling site DS4 outside the candidate area, and inclined towards this. A fifth 1000 m-borehole has recently been drilled at drilling site DS5, and preparations for a sixth deep borehole are currently being made at drilling site DS6. Drilling sites DS4, DS5 and DS6 are shown in Figure 1-1.

All mentioned drilling sites also incorporate percussion drilled boreholes in bedrock and in soil. During the continued investigations, several additional drilling sites for deep core drilled boreholes will be established.

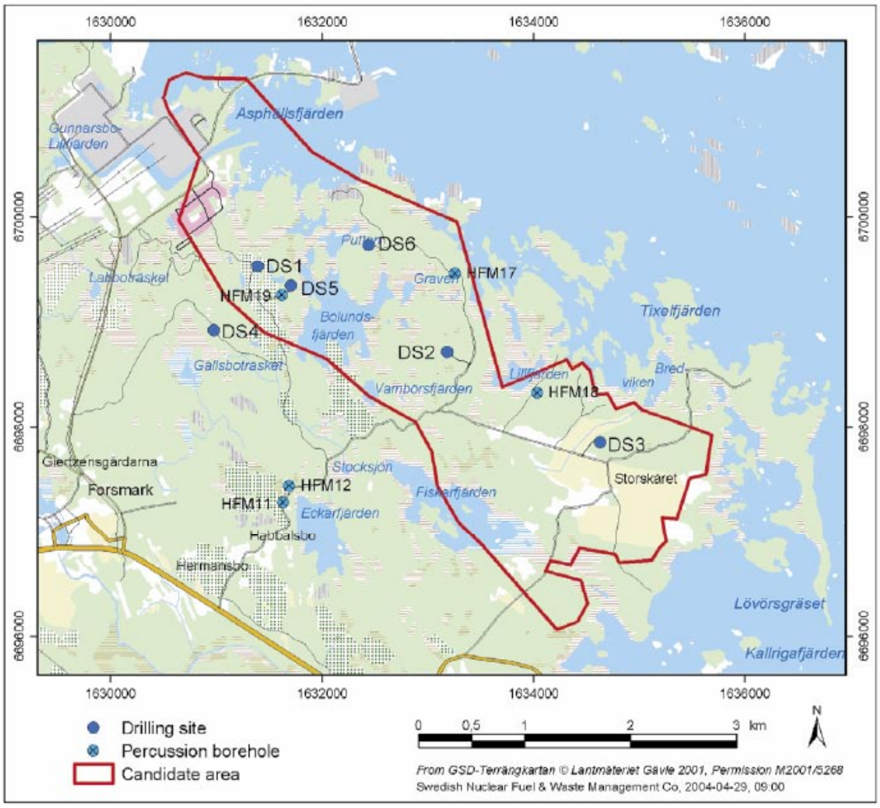


__Figure 1-1.__ The investigation area at Forsmark including the candidate area selected for more detailed investigations. Drilling sites DS1-6 are marked with blue dots, the percussion drilled boreholes HFM11-12 and HFM17-19 with blue and crossed dots.

Besides drilling deep and shallow boreholes at specific drilling sites for deep boreholes, a programme for investigation of lineaments by percussion drilling is proceeding. In order to gain as much geoscientific information as possible, many aspects have to be considered when siting each of the borehole.

In the present report, performance of and results from drilling of five percussion boreholes in bedrock, HFM11–12 and HFM17–19, see Figure 1-1, are presented. The report also treats investigations made during and immediately after drilling, including the results obtained.

Boreholes HFM11 and HFM12 were produced for extended investigations of the Eckarfjärden fracture zone, Figure 1-2, for which the drilling sites were selected by an informal group of expert geologists called GeoNet.

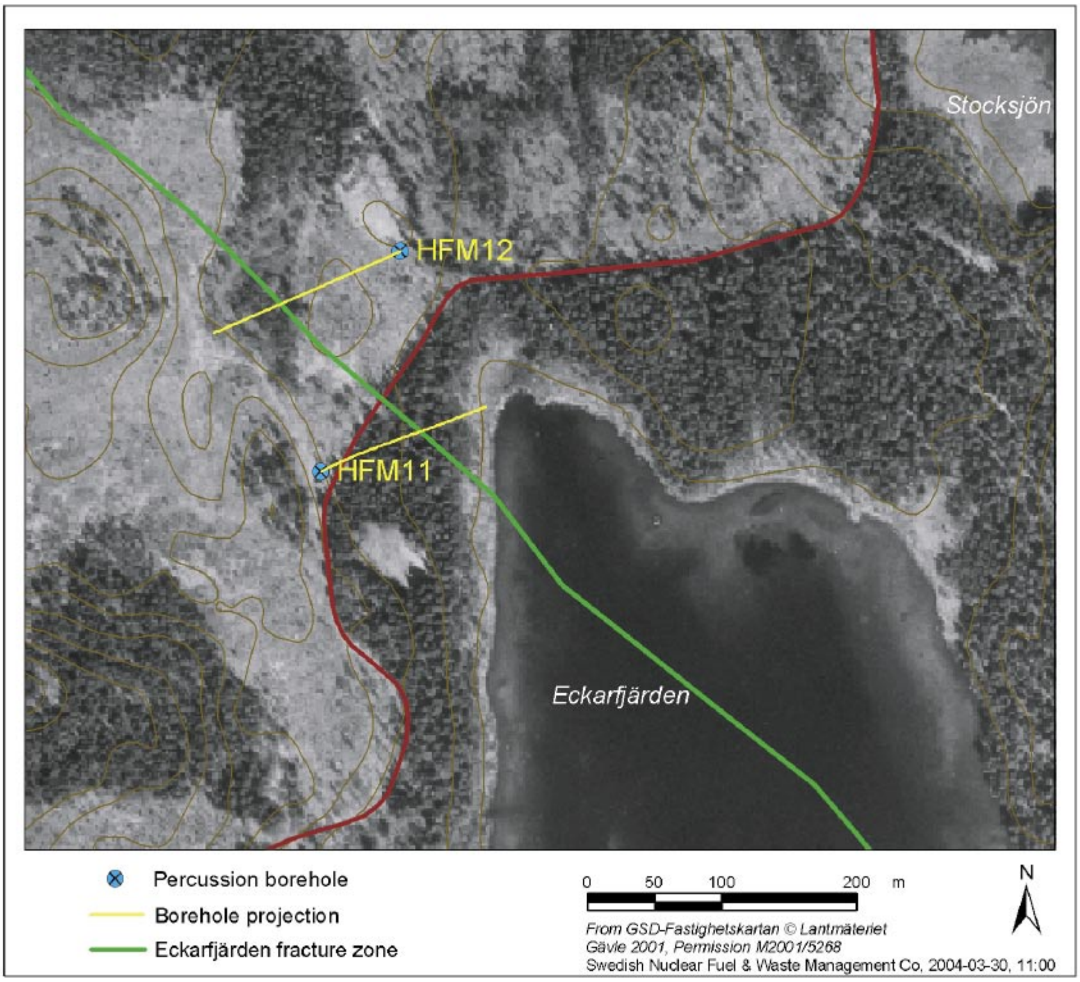


Figure 1-2. *Borehole locations close to Eckarfjärden. The projections of the boreholes on the horizontal plane at ground level (top of casing) are shown. The Eckarfjärden fracture zone is illustrated as a green line on the map.*

Boreholes HFM17, HFM18 and HFM19 (Figures 1-3, 1-4 and 1-5) were drilled for investigation of different lineaments and seismic reflectors indicated by several studies. Motives for siting of these boreholes was reported in SKB Decision, document 1020305, Version 1.0 (SKB internal controlling document).

All mentioned percussion drilled boreholes will also serve as a monitoring wells, enabling long-term study of groundwater levels and groundwater-chemical composition.

The drilling operations were performed by Sven Andersson in Uppsala AB, with support from SKB-personnel regarding measurements and tests during drilling. A Nemek 407 RE percussion drilling machine was employed for drilling four of the five boreholes (HFM11–12 and HFM17–18). The fifth borehole, HFM19, was drilled with a percussion drilling machine of type Puntel MX 1000, also from Sven Andersson in Uppsala AB (cf Chapter 3).

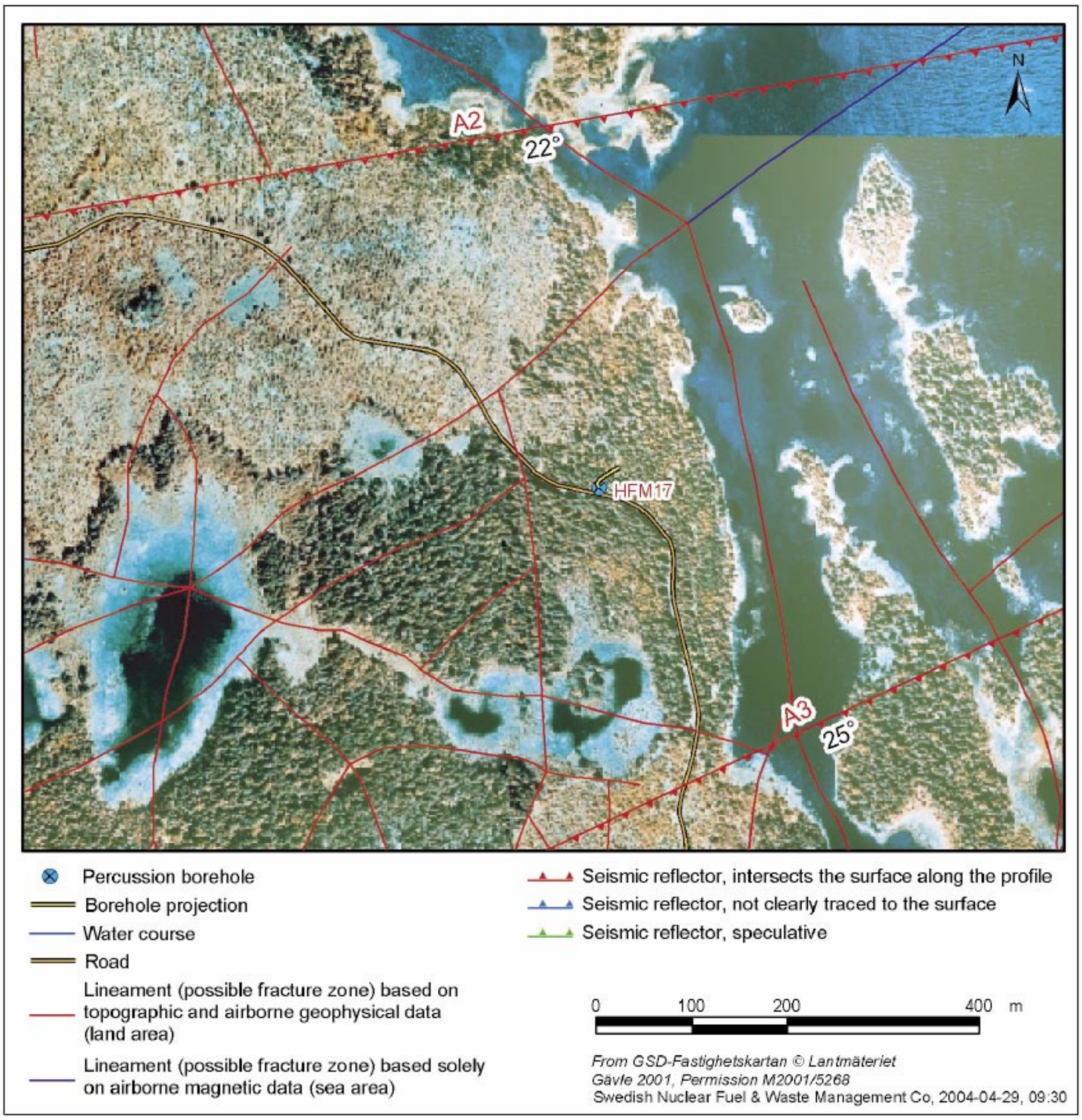


Figure 1-3. *Location of HFM17 just north of Kalvskärsdalen along the road to drilling site DS6. The projection of the borehole on the horizontal plane at ground level (top of casing) is shown.*

Drilling and measurements were performed in compliance with Activity Plans AP PF 400-03-59, Version 1.0 (HFM11–12), and AP PF 400-03-97, Version 1.0 (HFM17–19). The Activity Plans refer to SKB MD 610.003, Version 1.0 (Method Description for Percussion Drilling). The Activity Plans and Method Description are SKB internal controlling documents.

Figure 1-4. *Location of HFM18 approximately 100 m east of Lillfjärden. The projection of the borehole on the horizontal plane at ground level (top of casing) is shown.*

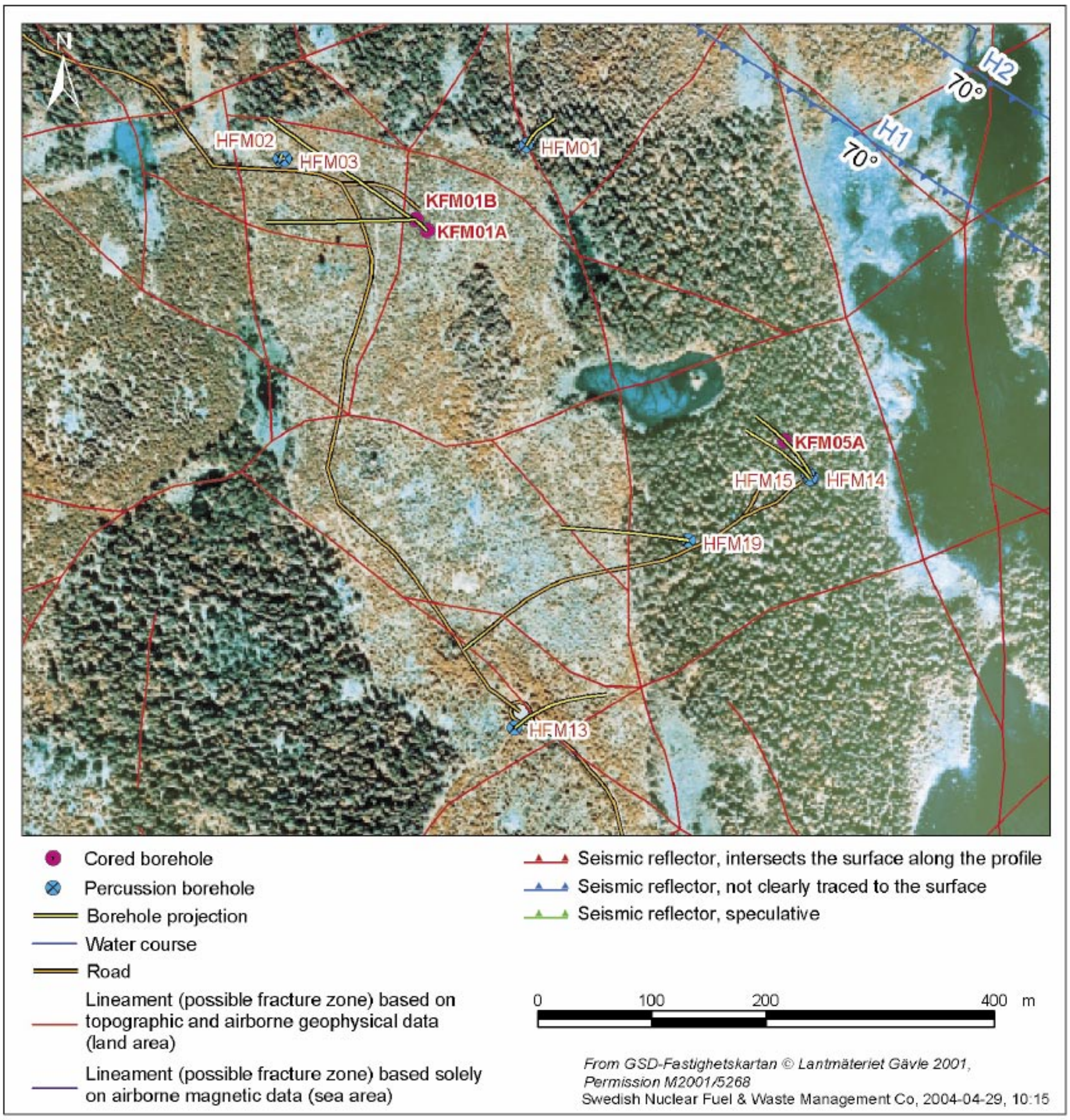


Figure 1-5. *Location of HFM19 west of Bolundsfjärden along the road to drilling site DS5. The projection of the borehole on the horizontal plane at ground level (top of casing) is shown.*

2 Objective, borehole siting strategy and scope

Lineament investigations are fundamental for all work on structural geology. For the site investigations, it is of outmost importance to reveal whether a lineament reflects a structure in the bedrock, or merely a topographic anomaly, e.g. a glacier-induced depression in the soil layer or any other, similar surface-related phenomenon. For lineaments representing a zone of brittle deformation, it is essential to determine properties like lithological characteristics (including alteration), fracture frequency, rock mechanical parameters, hydraulic transmissivity and hydrogeochemical composition.

Boreholes penetrating the lineament make the necessary investigations for the above purposes possible. Whether core drilling or percussion drilling shall be applied, must be decided for each individual borehole. Percussion drilling is a rapid and hence cost-effective drilling method, which, in combination with advanced methods for borehole investigations in many cases offers an attractive solution for lineament investigations.

During the autumn 2003 discussions regarding regional fracture zones and some less prominent but still important lineaments within the Forsmark investigation area accelerated. A decision was made to investigate whether or not the Eckarfjärden fracture zone (a regional lineament situated outside the candidate area and already known to represent a fracture zone) had a steep dip, the degree of alteration and deformation, and if any water-bearing sections could be traced. Later on, the discussion continued and highlighted the question whether flat lying water-conductive zones cut through the Eckarfjärden fracture zone or not, and to what extent such zones exist within the entire candidate area.

Siting of borehole HFM17 was guided by the relatively complex issue whether the north-easterly striking lineament north of the borehole (Figure 1-3) represents a flat-dipping fracture zone, and if the two lineaments striking north-south on both sides of the borehole are inclined or steep.

Borehole HFM18 was inclined towards structures A4 and I1 in Figure 1-4, which represent the intersection with the ground surface of reflectors interpreted from a reflector seismic survey /9/. A lineament, also striking north-east, just north of the borehole was a target for borehole HFM18 as well.

Finally, borehole HFM19 (see Figure 1-5) was inclined towards the north-south trending lineament west of the borehole with the primary aim to verify or reject if this lineament represents a fracture zone and, it so, to characterize it regarding dip, transmissivity etc. Hydraulic connections between drilling site DS5 and percussion borehole HFM13 were previously observed during drilling of HFM13. A secondary aim with HFM19 was to investigate if this connection could be explained by one or several flat-dipping structures.

All five percussion drilled boreholes will also be used in the long-term groundwater level monitoring and groundwater sampling programme. Data gained during monitoring of undisturbed conditions will be part of the characterization of the groundwater conditions of the shallow part of the bedrock.

Boreholes HFM11–12 and HFM17–19 are of so called SKB chemical type, implying that they are prioritized for hydrogeochemical and bacteriological investigations. The practical consequence of this is that all DTH (Down The Hole)-equipment used during and/or after drilling must undergo severe cleaning procedures, see Section 4.1.

3 Equipment

In this chapter short descriptions are given of the drilling system, the technique and equipment for gap injection of the borehole casing and of the instrumentation used for deviation measurements performed after completion of drilling. Also the equipment used for measurements and sampling during drilling is briefly commented on.

3.1 Drilling equipment

Drilling of four (HFM11–12 and HFM17–18) of the five percussion boreholes described in this report was performed with a Nemek 407 RE DTH percussion drilling machine (Figure 3-1), supplied with various accessory equipment. The fifth borehole (HFM19) was accomplished with a drilling machine of type Puntel MX 1000 (Figure 3-2).

The Nemek machine, which was operated by a one-man drill crew, is equipped with separate engines for transportation and power supplies. Water and drill cuttings were discharged from the borehole with an Atlas-Copco XRVS 455 Md 27 bars diesel compressor. The drilling DTH-hammer (Down The Hole) was of type Secoroc 5", operated in the borehole by a Driconeq 76 mm pipe string.

Figure 3-1. *The Nemek 407 percussion drilling machine employed for drilling boreholes HFM11–12 and HFM17–18.*

Figure 3-2. *The Puntel drilling machine engaged for drilling borehole HFM19.*

Also the Puntel machine, which was operated by a two-men drill crew, is equipped with separate engines for transportation and power supplies, and the same type of compressor as for the Nemek machine was used for discharging water and drill cuttings from the borehole.

Cleaning of all DTH-equipment was performed with a high-capacity steam cleaner of type Kärcher HDS 1195.

3.2 Gap injection technique and equipment

In order to prevent surface water and shallow groundwater to infiltrate into deeper parts of the borehole, the normal procedure is to grout the gap between the borehole wall and the casing pipe with cement. The cement application may be performed by different technical approaches and equipment. Two variants of gap injection with cement are illustrated in Figure 3-3. In HFM11–12 and HFM17–19, only the borehole packer technique was applied.

3.3 Technique and equipment for deviation measurements

Deviation measurements in HFM11–12 and HFM17–19 were performed with a Reflex EZ-shot (magnetic) camera. Azimuth and dip were measured every third metre. The coordinates for the collaring point and the measured values from the EZ-shot were used for calculating the coordinates for every measured point along the borehole.

3.4 Equipment for measurements and sampling during drilling

Flow measurements during drilling were conducted using measuring vessels of different sizes and a stop watch. Measurements of drilling penetration rate were accomplished with a carpenter's rule and a stop watch.

Samples of soil and drill cuttings were collected in sampling pots and groundwater in small bottles. The electrical conductivity of the groundwater was measured by a Kemotron 802 field measuring devise.

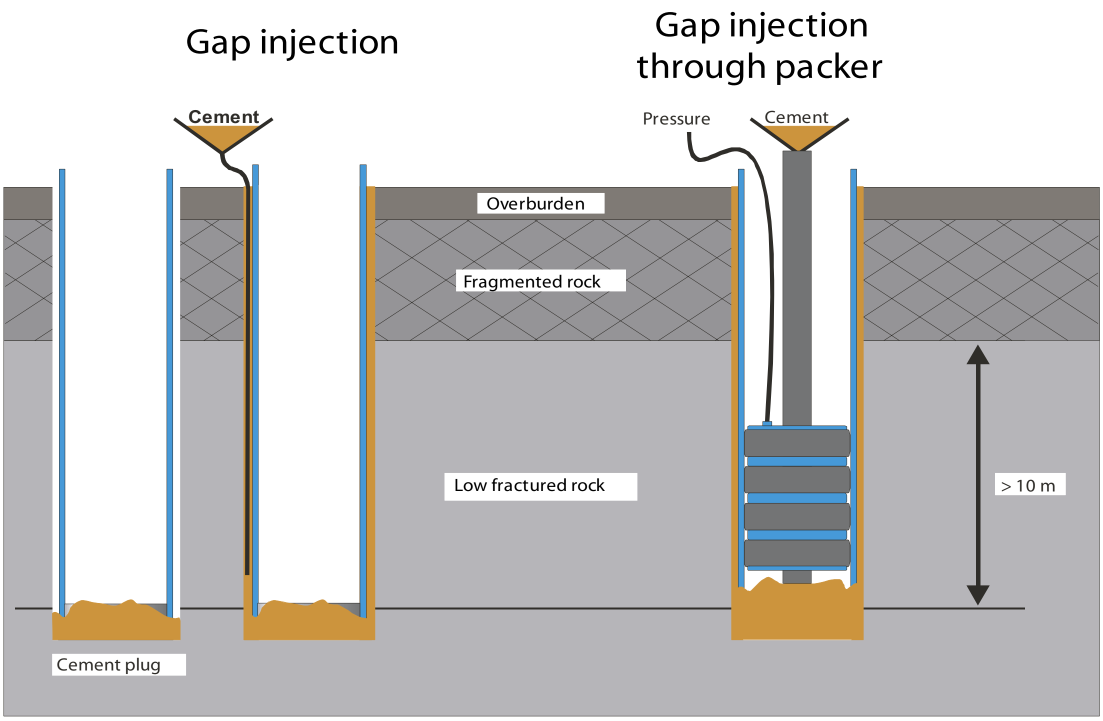


Figure 3-3. *Gap injection technique. In order to grout the gap between the borehole wall and the casing, two different systems may be used. To the left, filling up a cement-water mixture with a flexible hose is shown. To the right, injection is performed through a borehole packer.*

4 Execution

Drilling of boreholes HFM11–12 and HFM17–19 was carried out in compliance with SKB MD 610.003 (Method Description for Percussion Drilling), including the following items:

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

4.1 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, Version 1.0 (Method Instruction for Chemical Products and Materials). Finally, part of the equipment was cleaned in accordance with SKB MD 600.004, Version 1.0 (Method Instruction for Cleaning Borehole Equipment and certain Ground-based Equipment) at level two, used for SKB boreholes of chemical type (the remaining part of the equipment was cleaned on-site). SKB MD 600.004 and SKB MD 600.006 are both SKB internal controlling documents.

4.2 Mobilization

Mobilization onto and at the site started with preparation of the drilling site and transport of drilling and accessory equipment to the drilling site. The mobilization also comprised on-site cleaning of all DTH-equipment at level two according to SKB MD 600.004, lining up the machine and final function control.

4.3 Drilling, measurements and sampling during drilling

4.3.1 Drilling through the overburden – boreholes HFM11 and HFM12

In normal Swedish terrain, the rock surface is often covered with a more or less thick stratum of unconsolidated rock material, e.g. till. The procedure of drilling a percussion borehole is in this case divided into three drilling sequences: 1) drilling and casing driving through the overburden and fragmented rock, 2) drilling and continued casing driving a distance into fresh, low-fractured rock, and 3) continued drilling in solid rock. The bedrock where boreholes HFM11 and HFM12 are situated is till covered, and hence drilling was performed according to these three sequences. Figure 4-1 schematically illustrates the different steps carried out.

Drilling through the overburden may be accomplished by using different technical approaches. In the present commission, so called Ejector NO-X was applied in HFM11 and HFM12. The prefix "ejector" indicates that the discharge channels for the flushing medium, in this case compressed air, are constructed in such a way that the exposure of the penetrated soil layers to compressed air is reduced, compared to conventional systems.

The NO-X system represents a method for concentric drilling and casing driving through the overburden. A circular pilot bit, attached to a DTH-hammer shank, and with large internal flushing holes and external flushing grooves, is connected to a symmetrical ring bit (reamer) with an internal bayonet coupling (cf Figure 4-1). The pilot bit and the ring bit are both rotating clockwise, thereby drilling a borehole with a diameter large enough to let the casing easily slip down into the reamed borehole. The ring bit is rotating freely against the casing shoe, which is welded to the lower end of the casing. The casing is non-rotating during drilling.

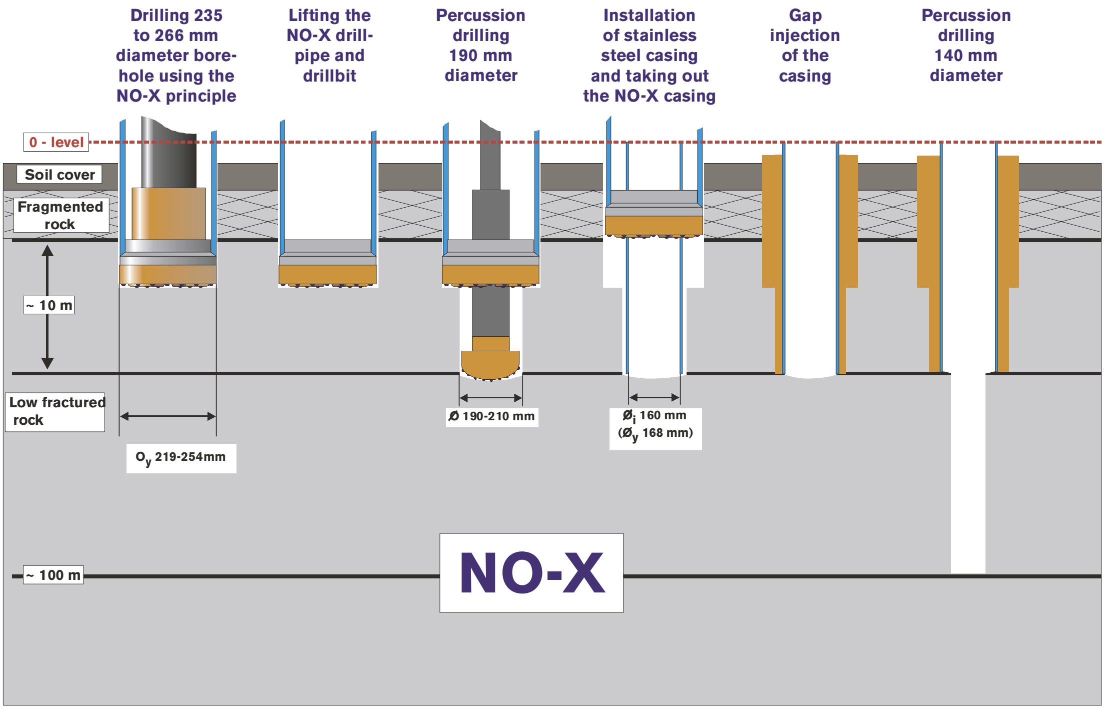


Figure 4-1. The different steps included in the performance of the percussion drilled boreholes HFM11–12.

Drilling through the overburden of boreholes HFM11–12 basically followed the principles for the Ejector-NO-X system. However, the method was to some extent applied in a non-conventional manner. During drilling of a borehole with the diameter 235 mm, a temporary steel casing with an external diameter of 219 mm was driven through the till overburden and through fragmented rock a short distance into fresh, low-fractured rock, see Figure 4-1. The drill pipes with the drillhammer and pilot bit were then retrieved from the borehole. A percussion drill bit was lowered into the borehole inside the temporary casing, and a borehole with a diameter of 190 mm was drilled 12.00 m in HFM11 respectively 14.90 m in HFM12 into high-quality, low-fractured rock.

Again the drill pipe, drillhammer and drill bit were retrieved, whereupon a stainless steel casing with the external/internal diameter 168/160 mm was descended in the borehole in 3 m-lengths, which were successively welded together.

4.3.2 Drilling through the overburden – boreholes HFM17–19

In boreholes HFM17–19, a TUBEX-system was applied for drilling through the overburden and some metres into solid rock (Figure 4-2). TUBEX is an alternative system for simultaneous drilling and casing driving based on a pilot bit and an eccentric reamer (cf Figure 4-2). The borehole drilled is slightly larger than the external diameter of the casing tube, which permits the casing tube to follow the drill bit down the hole.

4.3.3 Gap injection – all boreholes

When the casing string had been firmly installed in the boreholes, the narrow gap between the borehole wall and the outer wall of the casing was grouted with a cement/water-mixture according to the borehole packer technique illustrated in Figure 3-3.

4.3.4 Percussion drilling in solid rock – all boreholes

After the casing was set in boreholes HFM11–12 respectively HFM17–19, drilling could continue and was now performed to the full borehole length applying conventional percussion drilling technique. Before start of drilling, the diameter of the drill bit was measured. In this last drilling step, the initial borehole diameter (approximately the same as the drill bit diameter) is normally 140 mm, see Figures 4-1 and 4-2. However, a diameter decrease of about 1 mm/100 m drilling length is to be expected when drilling in the rock types prevailing in the Forsmark area. For boreholes deeper then 100 m, the drill bit normally has to be grinded.

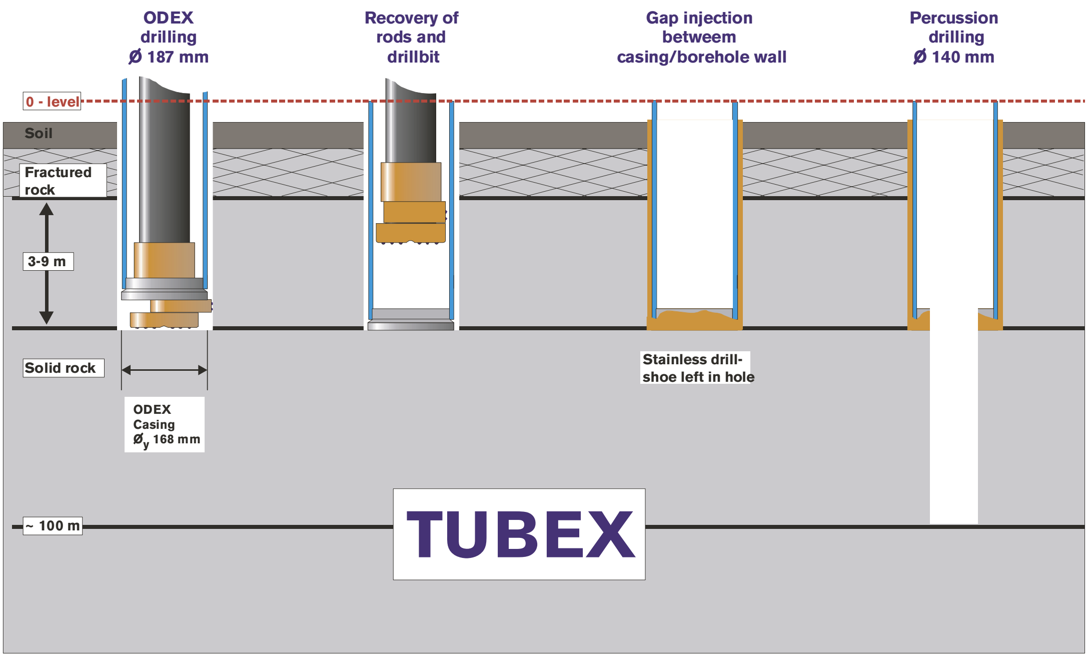


Figure 4-2. *The different steps included in the performance of the percussion drilled boreholes HFM17–19.*

4.3.5 Sampling and measurements during drilling – all boreholes

During drilling, a sampling and measurement program was performed, which included:

- Collecting one soil sample per metre drilling length. Analysis and results are reported in /3/.
- Collecting one sample per 3 m drilling length of drill cuttings from the bedrock (Figure 4-3). Each sample consists of three individual samples collected at every metre borehole length, and stored in one plastic box marked with a sample number. As far as possible, mixing of the three individual samples was avoided. A first description of the material was made on-site, including the mineral content and rock structure, which gave a preliminary classification of the rock type. These samples were later examined more thoroughly and interpreted together with a BIPS-log (so called Boremap mapping) /4/, /5/ and /6/.
- Measurements of the penetration rate (one measurement per 20 cm drilling length). The time needed for the drill bit to sink 20 cm was recorded manually in a paper record.
- Performing one observation of groundwater flow (if any) and water colour per 20 cm drilling length and a measurement of the flow rate at each major flow change observed. The measured values were noted in a paper record.
- Measurements of the electrical conductivity of the groundwater (if any) at every 3 m drilling length (noted in a paper record).

The results from the third and fourth items were used as supporting data for the Boremap mapping mentioned above. The last item gave information used on-site about hydraulic and hydrogeochemical characteristics of the penetrated aquifers at the respective drilling sites.

Figure 4-3. *Sampling of one sample per 3 m drilling length of drill cuttings from the bedrock.*

4.4 Finishing off work

Finishing off work included rinsing of the borehole from drill cuttings by a "blow out" with the compressor at maximum capacity during 30 minutes. The recovery of the groundwater table after rinsing was recorded, enabling a rough on-site evaluation of hydraulic parameters. The drill pipes were then retrieved from the hole, and the diameter of the drill bit was measured. A deviation survey of the borehole completed the measurement programme during and immediately after drilling.

Recovered drill cuttings and groundwater when drilling in solid bedrock were, for environmental reasons, not allowed to spread out on the ground surface, but was conducted to and collected in a steel container. After completion of drilling, the container was removed from the site and emptied at an approved deposit.

Finally, the borehole was secured by a stainless steel lockable cap, mounted on the casing, and the equipment was removed. The site was cleaned and a joint inspection made by representatives from SKB and the Contractor, to ensure that the site had been satisfactorily restored.

4.5 Data handling

Minutes with the following headlines: Activities, Cleaning of equipment, Drilling, Borehole, Percussion drilling penetration rate, Deliverance of field material and Discrepancy report were collected by the Activity Leader, who made a control of the information, and had it stored in the SKB database SICADA /7/.

4.6 Environmental control

A programme according to SKB's routine for environmental control was complied with throughout the activity. A checklist was filled in and signed by the Activity Leader, and finally filed in the SKB archive.

4.7 Nonconformities

Grouting of the gap between the casing and the borehole wall by applying the packer technique described in Section 3.2 could not be completed in HFM17. An instability in the borehole wall probably caused the gap to became too narrow to allow the cement to reach the ground surface.

5 Results

All data were stored in the SICADA database under field note nos 178 (HFM11), 179 (HFM12), 256 (HFM17), 257 (HFM18), respectively 258 (HFM19) /7/.

Below, a summary of the data acquired is presented.

5.1 Design of the percussion drilled boreholes HFM11, HFM12, HFM17, HFM18 and HFM19

Administrative, geometric, and technical data for the percussion drilled boreholes HFM11–12 and HFM17–19 are presented in Table 5-1. The technical design of each borehole is illustrated in Appendix A, Figures A-1, A-2, A-3, A-4 and A-5.

Table 5-1. Administrative, geometric and technical data for boreholes HFM11–12 and HFM17–19.

Parameter	HFM11	HFM12	HFM17	HFM18	HFM19
Drilling period	From 2003-08-21 to 2003-09-02	From 2003-09-03 to 2003-09-16	From 2003-12-01 to 2003-12-08	From 2003-12-10 to 2003-12-16	From 2003-12-02 to 2003-12-18
Borehole inclination (collaring point)	–49.32° (– = downwards)	–49.05° (– = downwards)	–84.19° (– = downwards)	–59.36° (– = downwards)	–58.10° (– = downwards)
Borehole bearing	63.51°	245.16°	318.58°	313.30°	280.91°
Borehole length	182.35 m	209.55 m	210.65 m	180.65 m	185.20 m
Borehole diameter	From 0.00 m to 3.10 m: 0.235 m	From 0.00 m to 4.30 m: 0.235 m	From 0.00 m to 8.00 m: 0.176 m	From 0.00 m to 9.00 m: 0.178 m	From 0.00 m to 12.04 m: 0.180 m
	From 3.10 m to 11.90 m: 0.190 m	From 4.30 m to 14.90 m: 0.189 m	From 8.00 m to 210.65 m: decreasing from 0.138 m to 0.136 m	From 9.00 m to 180.65 m: decreasing from 0.140 m to 0.138 m	From 12.04 m to185.20 m: decreasing from 0.140 m to 0.137 m
	From 11.90 m to 182.35m: decreasing from 0.140 m to 0.139 m	From 14.90 m to 209.55 m: decreasing from 0.138 m to 0.135 m			
Casing length	11.90 m	14.90 m	8.00 m	9.00 m	12.04 m
Casing diameter	$Ø_o/Ø_i$ = 168 mm/160 mm to 11.90 m	$Ø_o/Ø_i$ = 168 mm/160 mm to 14.90 m	$Ø_o/Ø_i$ = 168 mm/160 mm to 8.00 m	$Ø_o/Ø_i$ = 168 mm/160 mm to 9.00 m	$Ø_o/Ø_i$ = 168 mm/160 mm to 12.04 m
	$Ø_o/Ø_i$ = 168 mm/146 mm between 11.88 and 11.90 m	$Ø_o/Ø_i$ = 168 mm/146 mm between 14.88 and 14.90 m	$Ø_o/Ø_i$ = 168 mm/146 mm between 7.98 and 8.00 m	$Ø_o/Ø_i$ = 168 mm/146 mm between 8.98 and 9.00 m	$Ø_o/Ø_i$ = 168 mm/146 mm between 12.02 and 12.04 m
Drill bit diameter	Start of drilling: 0.140 m End of drilling: 0.139 m	Start of drilling: 0.138 m End of drilling: 0.135 m	Start of drilling: 0.138 m End of drilling: 0.136 m	Start of drilling: 0.140 m End of drilling: 0.138 m	Start of drilling: 0.140 m End of drilling: 0.137 m
Collaring point coordinates (system RT90 2.5 gon V/ RHB70)	Northing: 6697283.40 m Easting: 1631636.33 m Elevation: 7.56 m.a.s.l.	Northing: 6697446.46 m Easting: 1631695.67 m Elevation: 7.03 m.a.s.l.	Northing: 6699461.95 m Easting: 1633261.31 m Elevation: 3.75 m.a.s.l.	Northing: 6698326.86 m Easting: 1634037.37 m Elevation: 5.04 m.a.s.l.	Northing: 6699257.59 m Easting: 1631626.93 m Elevation: 3.66 m.a.s.l.

5.2 Consumables

The amount of oil products consumed in each borehole during drilling, and grout used for gap injection of the respective casings is reported in Tables 5-2 and 5-3. The cement was of low alkalic type, consisting of microsilica (920–D) and white cement (Aalborg Portland CEM I, 52.5N).

Regarding contamination risks, albeit some amounts of hammer oil and compressor oil reach the borehole, they are, on the other hand, continuously retrieved due to the permanent air flushing during drilling. After completion of drilling, only minor remainders of the products are left in the borehole.

Table 5-2. Oil consumption.

Borehole ID	Hammer oil Preem Hydra 46	Compressor oil Schuman 46
HFM11	7 L	Not detected
HFM12	7 L	Not detected
HFM17	6 L	Not detected
HFM18	5.5 L	Not detected
HFM19	8 L	Not detected

Table 5-3. Consumption of cement grout.

Borehole ID	Casing length	Cement volume (Aalborg Portland Cement/microsilica)	Grouting method
HFM11	11.90 m	125/55 kg	Packer technique
HFM12	14.90 m	100/40 kg	Packer technique
HFM17	8.00 m	50/20 kg	Packer technique
HFM18	9.00 m	50/22 kg	Packer technique
HFM19	12.04 m	50/20 kg	Packer technique

5.3 Borehole deviation

The deviation measurements made in boreholes HFM11, 12, 17, 18 and 19 are presented in Table 5-4 as approximate deviation at the end (bottom point) of the borehole compared to an imagined straight line following the dip and strike of the borehole collaring point.

Table 5-4. Deviation of boreholes HFM11, 12, 17, 18 and 19.

Borehole	Inclination	Bearing	Metres up/down	Metres right/left
HFM11	–49.32°	63.51°	13 m up	16 m right
HFM12	–49.05°	245.16°	15 m up	15 m right
HFM17	–84.19°	318.58°	2 m up	34 m right
HFM18	–59.36°	313.30°	8 m up	24 m left
HFM19	–58.10°	280.91°	11 m down	16 m left

5.4 Well Cad presentation

Technical as well as geoscientific results obtained during drilling are presented in the so called Well Cad plots in Appendix B, Figures B-1, B-2, B-3, B-4 and B-5.

5.5 Hydrogeological observations

5.5.1 Observations during drilling

At 12 m drilling length in borehole HFM11, an inflow of 4 L/min was encountered. The electrical conductivity of the groundwater (EC-value) amounted to 60 mS/min (see Figure 5-1), indicating fresh water conditions. The groundwater inflow suddenly increased to 36 L/min at 110 m. Obviously, the contributing groundwater at this level had a higher salinity, since the EC-value instantly increased to 700 mS/m. Two additional inflows were observed, at 149 m and 158 m, resulting in a stabilised EC-value of 900 mS/m.

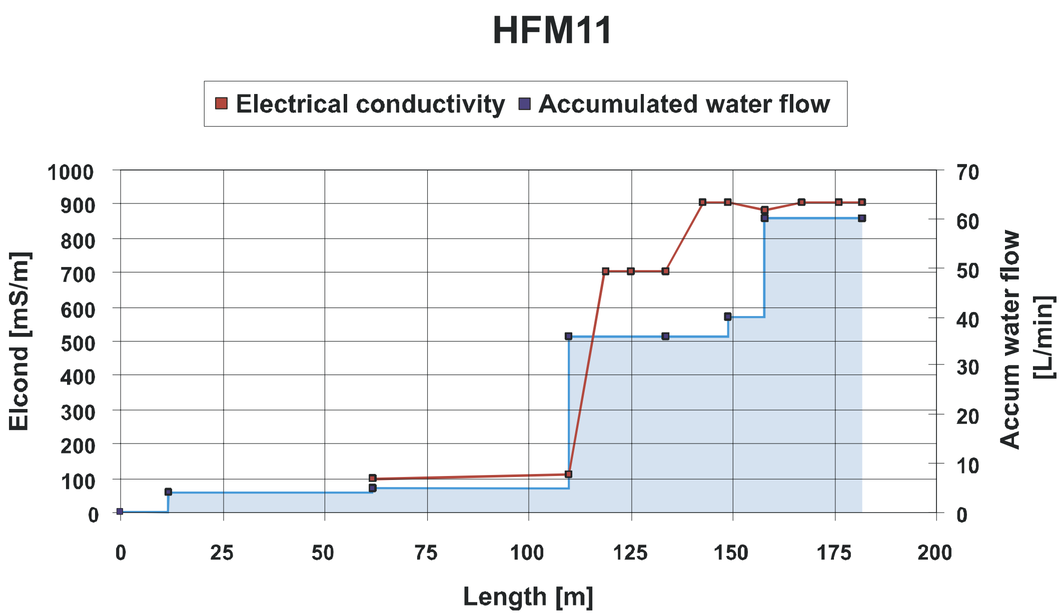


Figure 5-1. Electrical conductivity and accumulated groundwater flow rate versus drilling length in HFM11.

No measurable inflow of groundwater was observed in the upper part of borehole HFM12, although the drilling debris was clammy with damp. The first groundwater inflow was struck at 107–110 m, yielding 10 L/min with an EC-value of 1330 mS/m, see Figure 5-2. The accumulated groundwater flow rate increased step-wisely and reached 30 L/min at c 170 m, while the EC-value decreased to a stabilized level of about 1100 mS/m, which persisted to the end of drilling.

When drilling HFM17 between 30–32 m, an inflow of 50 L/min with an EC-value of 300 mS/m was observed, se Figure 5-3. The accumulated water flow seems to increase temporarily to c 95 L/min between 122–172 m, which may be interpreted as a minor aquifer being emptied or, possibly, as slightly erroneous flow rate measurements. However, the flow rate falls back to 70 L/min at the end of drilling. The EC-values fluctuate between 200–300 mS/m. The relatively low values and falling trend indicate shallow groundwater conditions. It seems probable, that practically the entire groundwater flow emerges from the water-bearing structure at 30–32 m.

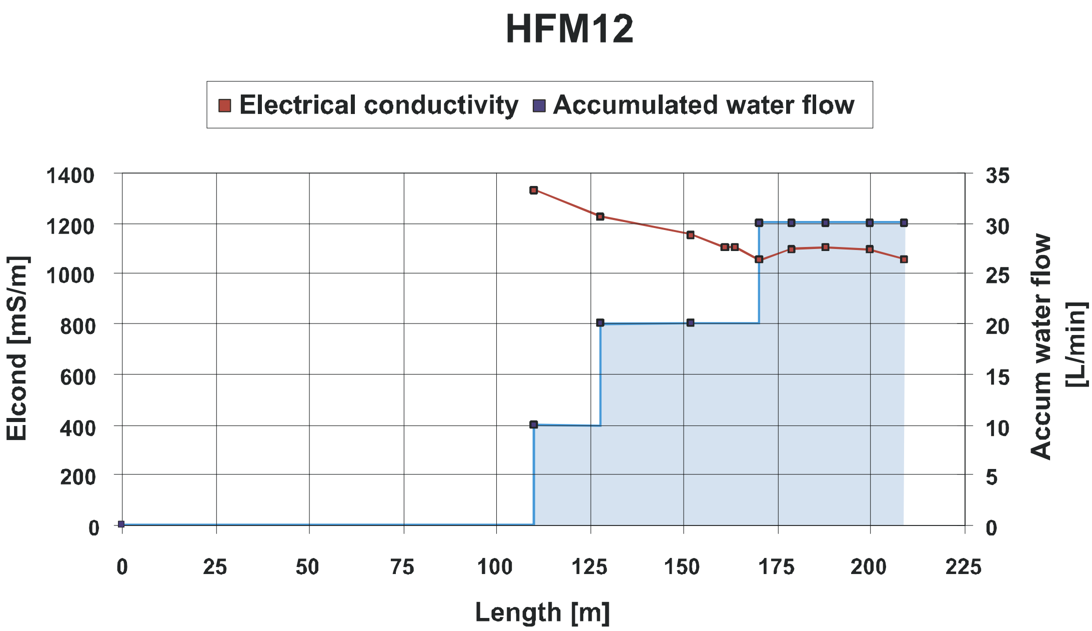


Figure 5-2. *Electrical conductivity and accumulated groundwater flow rate versus drilling length in HFM12.*

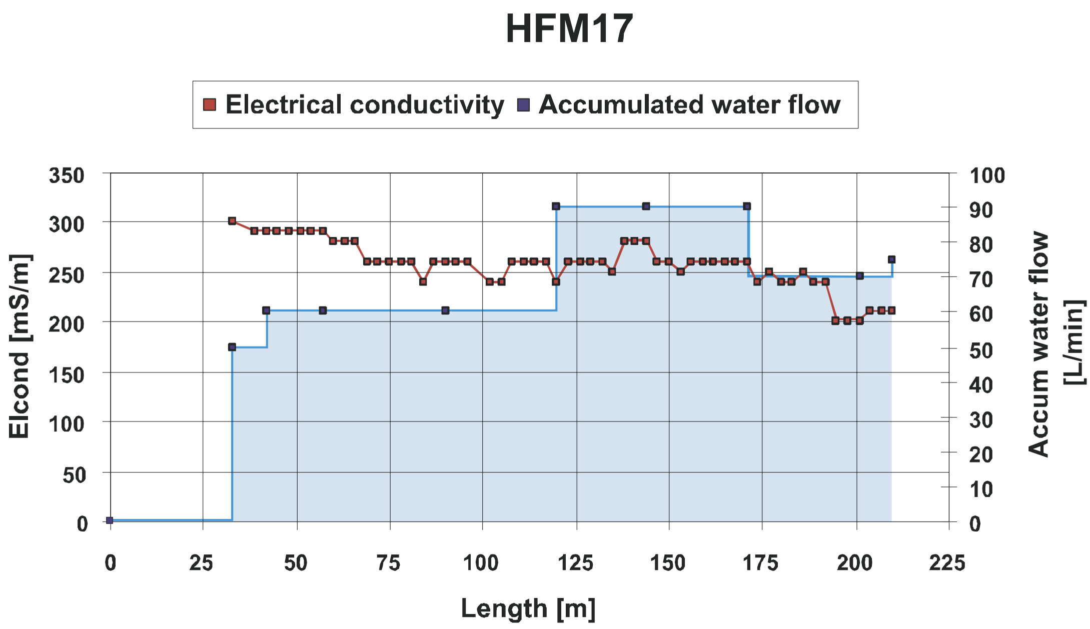


Figure 5-3. *Electrical conductivity and accumulated groundwater flow rate versus drilling length in HFM17.*

The first measurable groundwater inflow, 25 L/min with an EC-value of 100 mS/m, in HFM18 was observed at 32–35 m, see Figure 5-4. The accumulated water flow increased stepwise to 110 L/min, whereas the EC-value was quite constant. However, at about 150 m drilling length, the EC-value increased to 150 mS/m, probably indicating up-coning of slightly more saline water, since the EC-increase did not correspond to any extra groundwater contribution.

No measurable inflow of groundwater was observed until about 120–125 m drilling length in borehole HFM19, although the drilling debris was damp. When drilling between 122–125 m, the first water inflow of 20 L/min with an EC-value of 800 mS/m was observed, see Figure 5-5. The flow rate kept constant, whereas the EC-value varied between 600–700 mS/m until 172 m drilling length, indicating semi deep water conditions. At 172 m, the borehole intersected a flat-dipping fracture zone, whereby the accumulated water flow increased to 160 L/min and the EC-value to about 1500 mS/m.

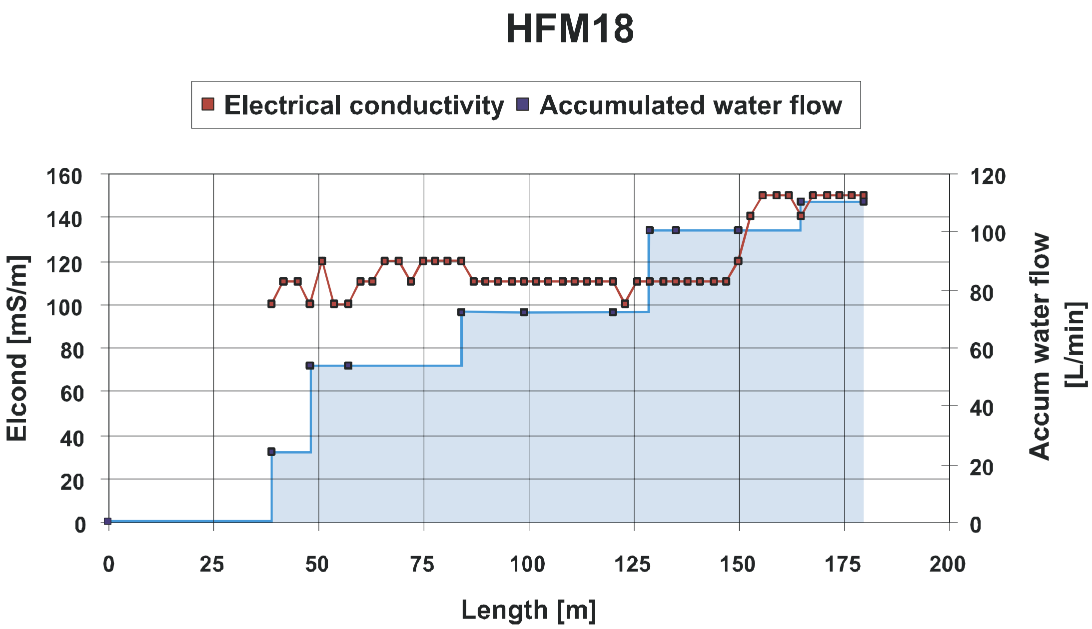


Figure 5-4. Electrical conductivity and accumulated groundwater flow rate versus drilling length in HFM18.

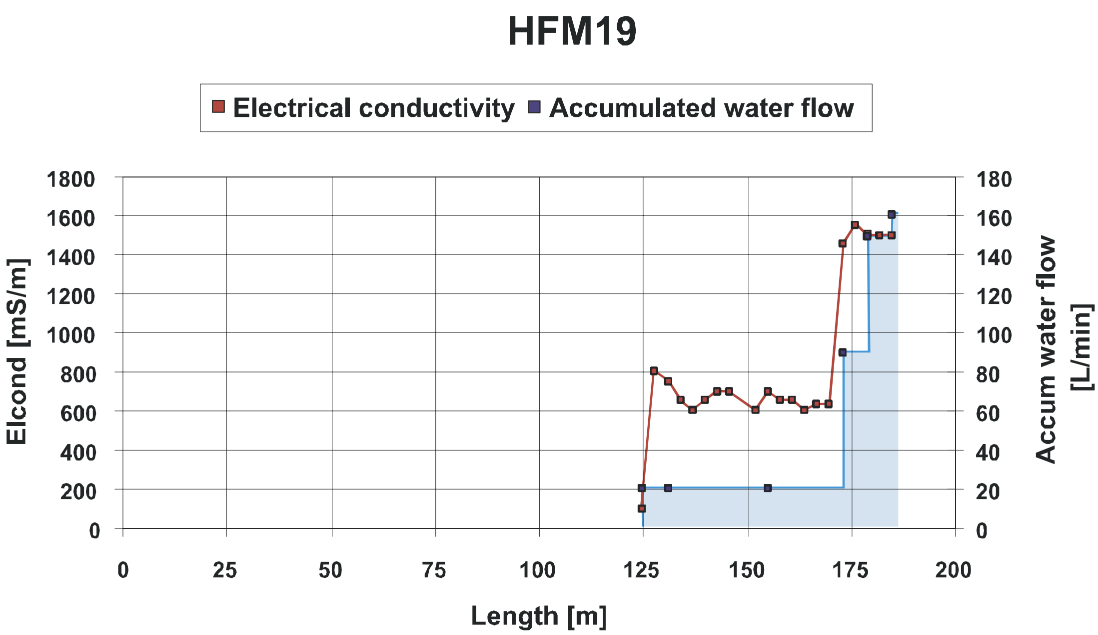


Figure 5-5. Electrical conductivity and accumulated groundwater flow rate versus drilling length in HFM19.

5.5.2 Hydraulic responses – interpreted structural setting

Interpretation of results from boreholes HFM11–12

During drilling of HFM12, distinct hydraulic responses were observed in HFM11 (Figure 5-6). Small changes in the groundwater level were monitored during drilling down to 110 m drilling length. However, when drilling section 110–152 m, a very significant drawdown was observed, but during the weekend stop, the groundwater table in HFM11 recovered almost to pre-drilling level. Continued drilling in sections 152–170 m and 170–209 m and the final air flushing resulted in similar hydraulic responses, but since the drilling periods were longer, and the borehole deeper, the drawdown was larger.

The increased fracture frequencies in the two boreholes, indicated during drilling by increased penetration rate, and the inflow of groundwater occur at such levels (see Figures B-1 and B-2 in Appendix B), that the Eckarfjärden fracture zone must be interpreted as steep. Interpretation of the observed hydraulic responses does not necessarily indicate a direct hydraulic connection between the boreholes. The water flow may instead follow a more complex fracture pattern (Figure 5-7). This interpretation is based on the signature of the responses in Figure 5-6.

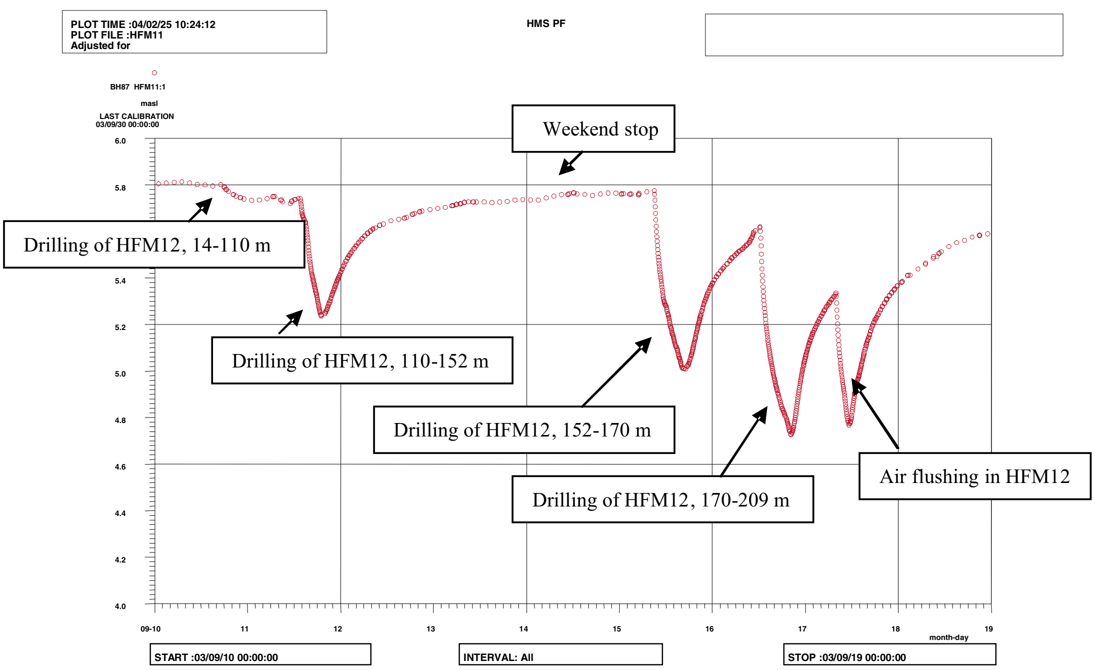


***Figure 5-6.** Hydraulic responses in HFM11 during drilling of HFM12.*

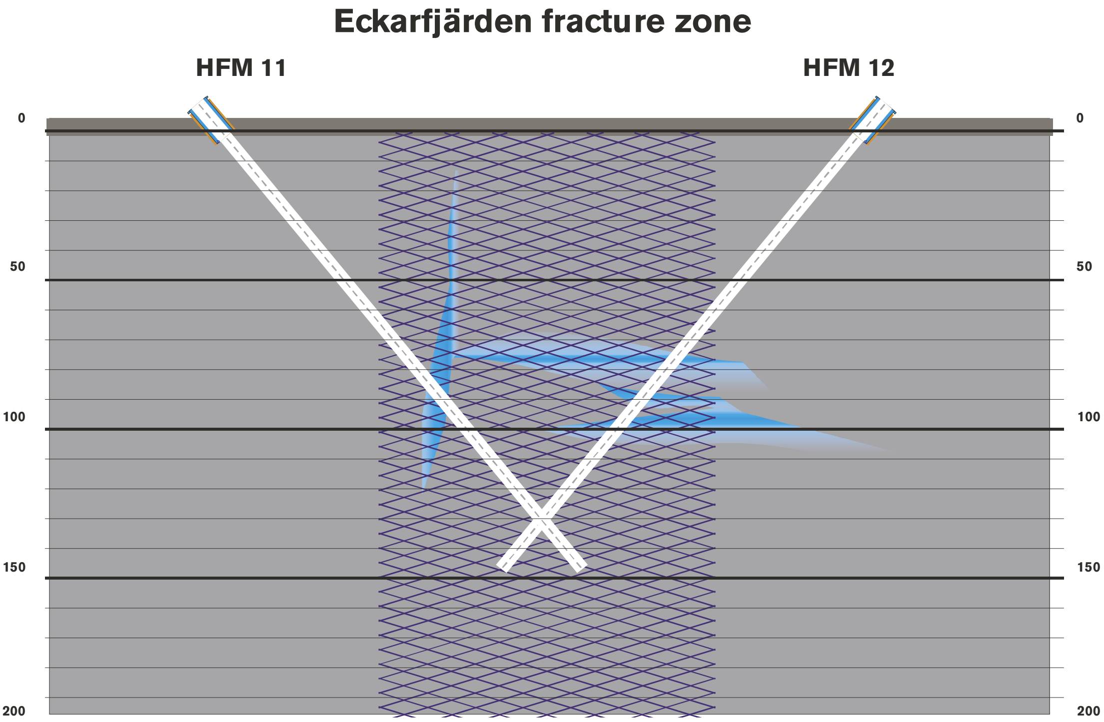


Figure 5-7. *Tentative, simplified interpretation of the structural conditions in the steeply dipping Eckarfjärden fracture zone. The blue schlieren symbolize the observed, possibly complex network of water-bearing fractures.*

Interpretation from borehole HFM17

A conceivable interpretation of the results from borehole HFM17 is, that the water-bearing structure penetrated by HFM17 at 30 m borehole length (Figure 5-8) is associated with the lineament striking SW-NE approximately 160 m north-west of borehole HFM17 (See Figure 1-3). If so, the lineament represents the intersection with the ground surface of a flat-dipping structure (dipping 10–12° from the horizontal plane). Alternative interpretations are that either one (or both) north-south trending lineaments east and west of the borehole is inclined towards the borehole and intersected by it. On the other hand, it seems unlikely that the zone indicated by reflector A2, supposed to outcrop approximately 400 m north-west of HFM17 and having a flat dip of 22° /9/, was hit by borehole HFM17.

Interpretation of the results from borehole HFM18

On the south-eastern side of Lillfjärden, a number of structures have been indicated from the geological and geophysical surveys performed during the site investigation (see Figure 1-4). Borehole HFM18 has penetrated a water-yielding zone at about 40 m borehole length. It seems relatively plausible that this structure represents the seismic reflector A4 (Figure 5-9). A possible, but uncertain interpretation is that the water-yielding zone at 145 m is associated with the reflection seimic reflector I1 (Figure 1-4). Whether this reflector is identical with the NNE-SSW striking lineament shown in Figure 1-4 or not remains to be investigated.

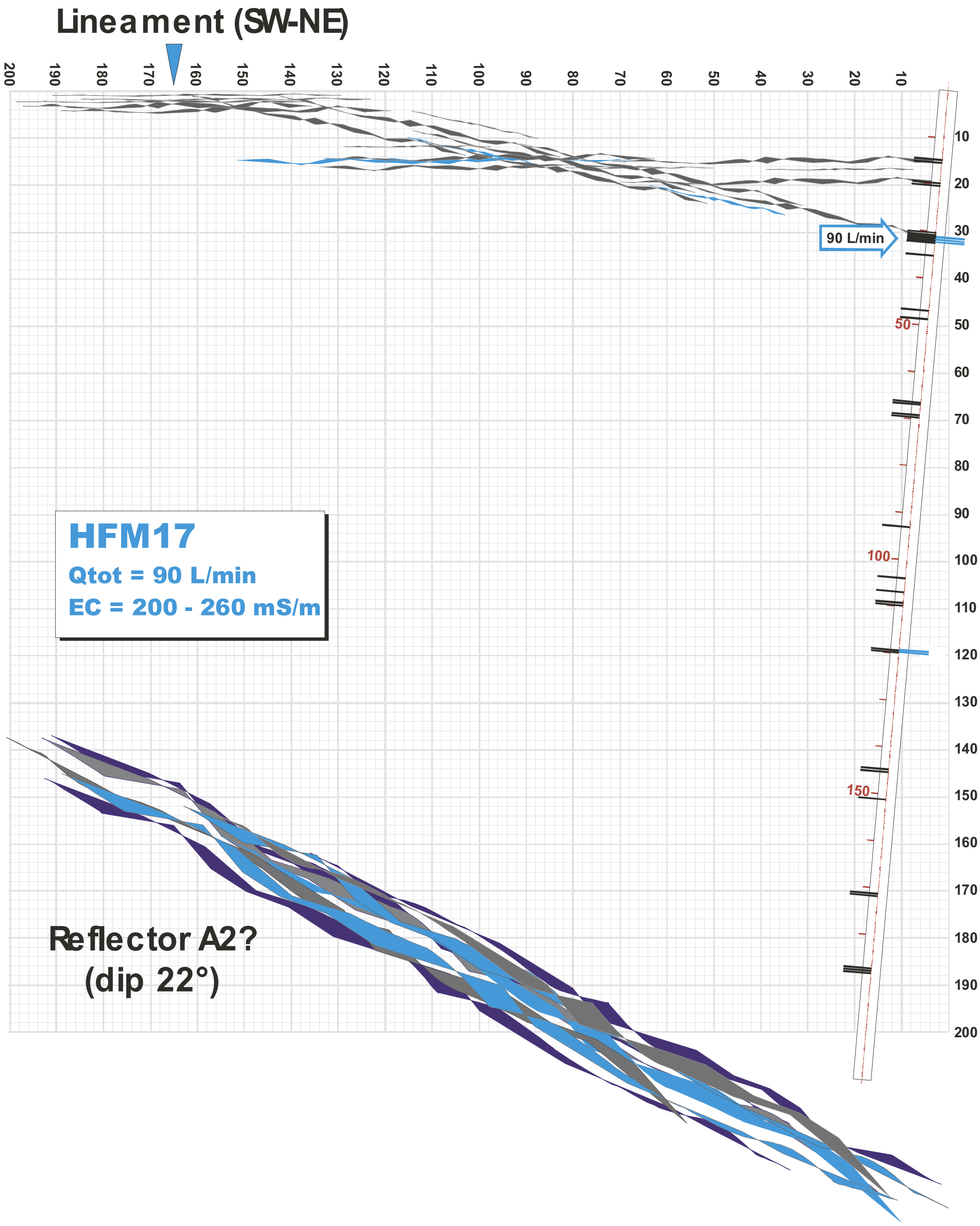


Figure 5-8. Tentative, simplified interpretation of the structural conditions just north of Kalvskärsdalen along the road to drilling site DS6. The blue schlieren symbolize the observed water-bearing fractures intersected by the borehole.

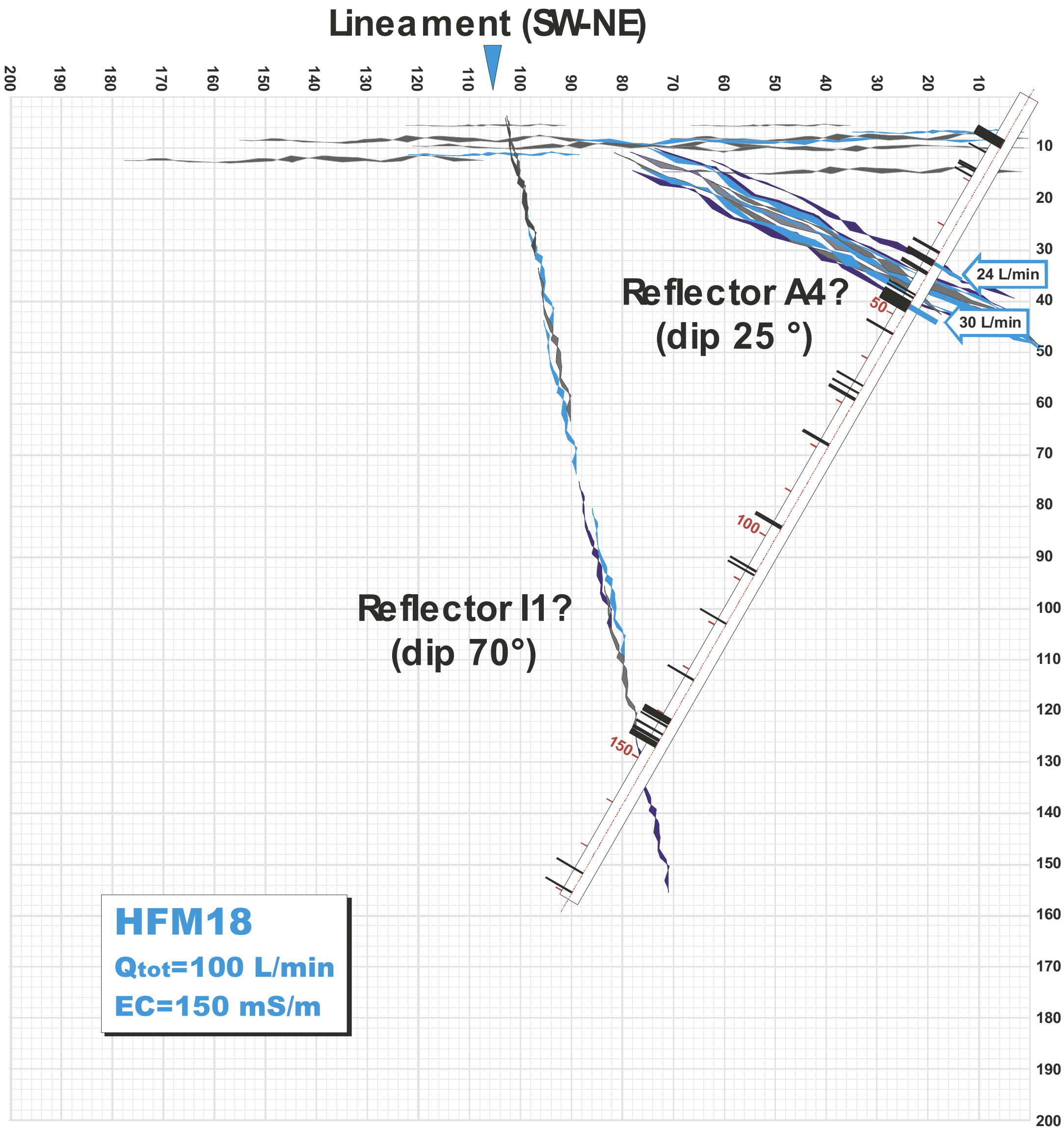


Figure 5-9. *Tentative, simplified interpretation of the structural conditions in the area east of Lillfjärden. The blue schlieren symbolize the observed water-bearing fractures encountered during drilling.*

Interpretation of the results from borehole HFM19

The groundwater level was monitored in HFM13, HFM14 and HFM15 during drilling of HFM19. Figure 5-10 shows that the variation of the groundwater table in HFM13 is so limited, that no certain conclusion can be drawn whether a hydraulic connection between HFM13 and HFM19 exists or not.

Quite differently, when drilling through a water-yielding zone at 170 m borehole length in borehole HFM19, significant responses were observed in boreholes HFM14 and HFM15, both situated at drilling site DS5 (Figure 5-11 and Figure 5-12). Very distinct and significant responses had also earlier been observed between the boreholes at DS5 and HFM13 /8/.

The results from drilling of borehole HFM19 and simultaneous observation of groundwater level fluctuations in surrounding boreholes have demonstrated that the hydraulic connections between drilling site DS5 and boreholes HFM13 and HFM19 are complex and at the present state not fully understood.

A speculative hypothesis is illustrated in Figure 5-13, where the water-yielding zone at 165–175 m borehole length in HFM19 has been associated with a structure indicated by the seismic reflector B4 (Figure 1-5). The north-south trending lineament west of the borehole is interpreted to be steep and may be represented by a water-yielding zone at 122 m borehole length.

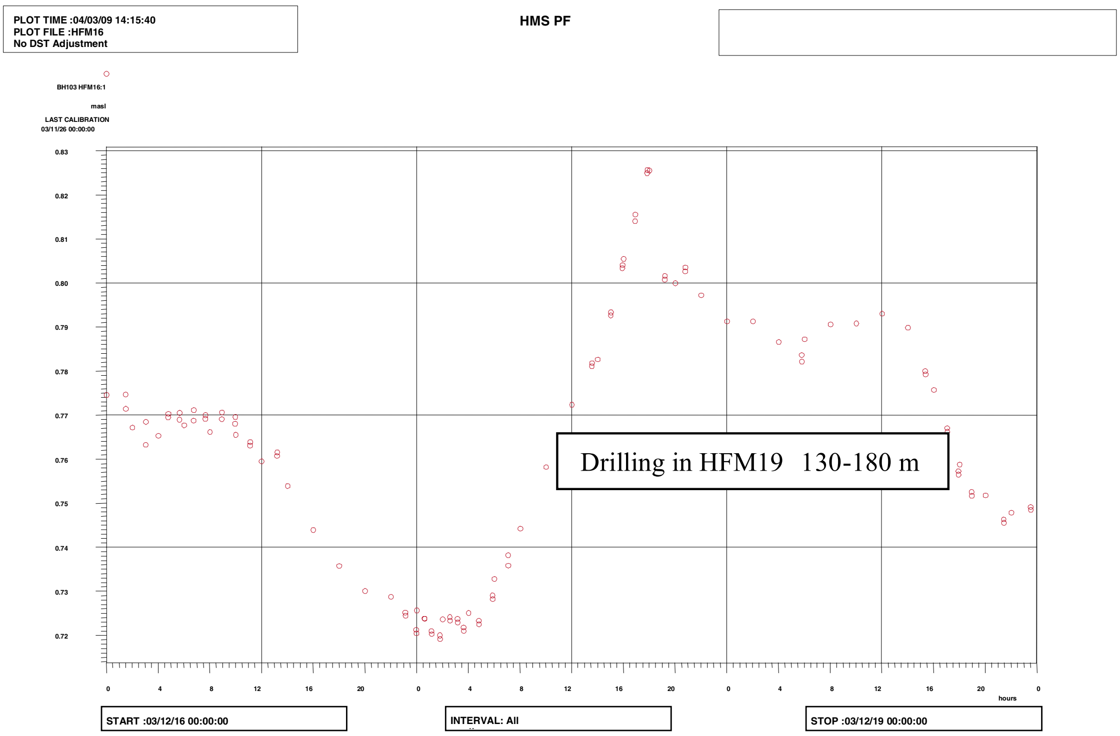


Figure 5-10. *Groundwater level observations in HFM13 when drilling HFM19.*

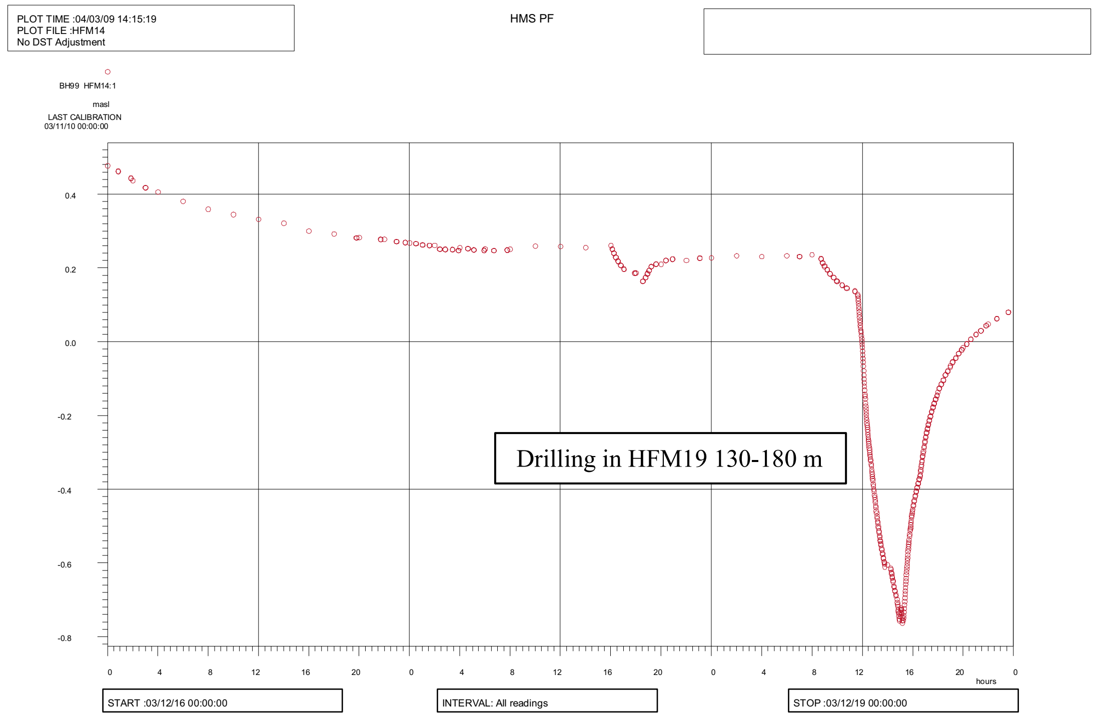


Figure 5-11. *Groundwater level observations in HFM14 when drilling HFM19.*

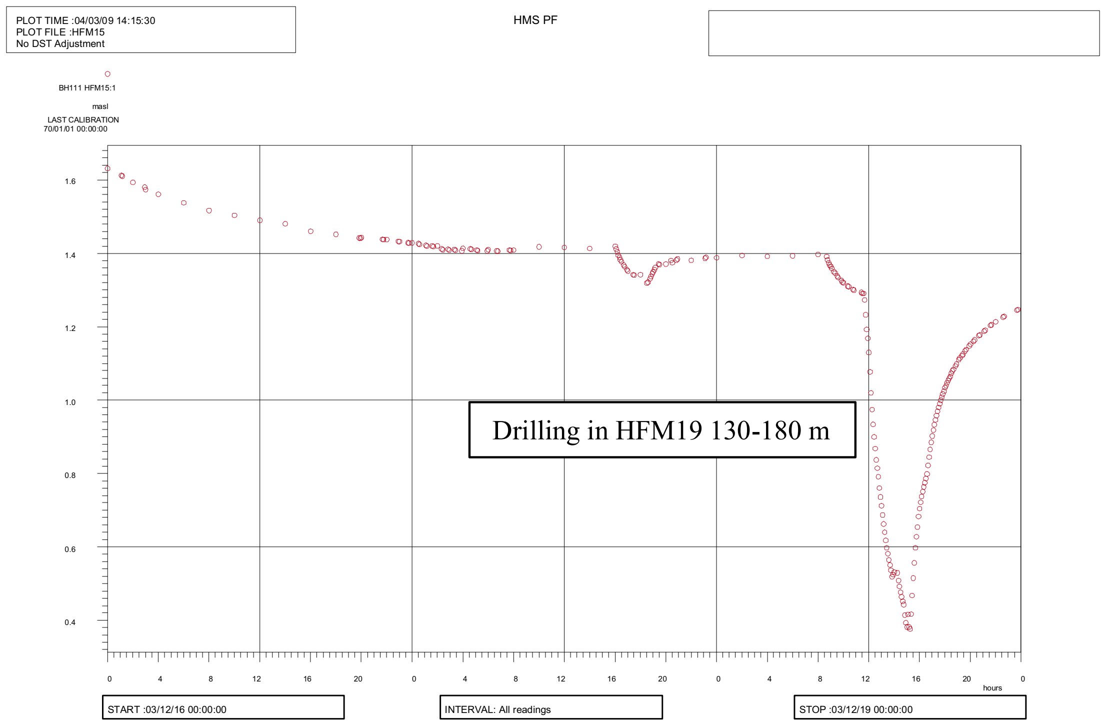


Figure 5-12. *Groundwater level observations in HFM15 when drilling HFM19.*

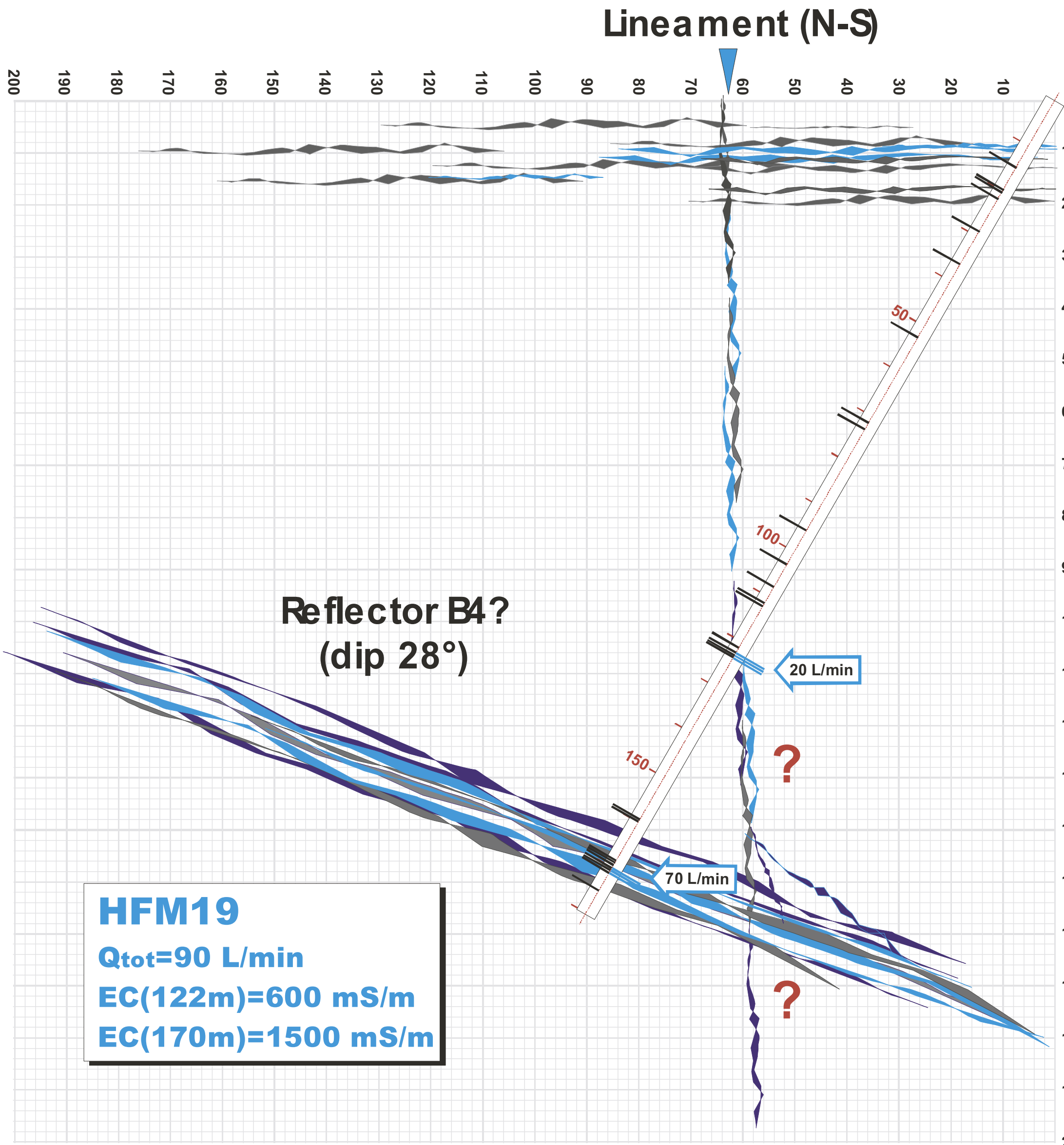


Figure 5-13*. Tentative, simplified interpretation of the structural and hydraulic conditions in the area west of Bolundsfjärden along the road to drilling site DS5. The blue schlieren symbolize the observed water-bearing fractures penetrated by the borehole.*

References

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

/2/ **SKB, 2001**. Execution programme for the initial site investigations at Forsmark. SKB P-02-03, Svensk Kärnbränslehantering AB.

/3/ **SKB, 2003.** Sohlenius, G. & Rudmark, L. Forsmark. Forsmark site investigation. Mapping of unconsolidated Quaternary deposits 2002–2003. Stratigraphical and analytical data. SKB P-03-14, Svensk Kärnbränslehantering AB.

/4/ **SKB, 2004.** Nordman, C. Forsmark. Boremap mapping of percussion boreholes HFM09–12. SKB P-04-101. Svensk Kärnbränslehantering AB.

/5/ **SKB, 2004.** Nordman, C. Forsmark. Boremap mapping of percussion boreholes HFM16–18. SKB P-04-113. Svensk Kärnbränslehantering AB.

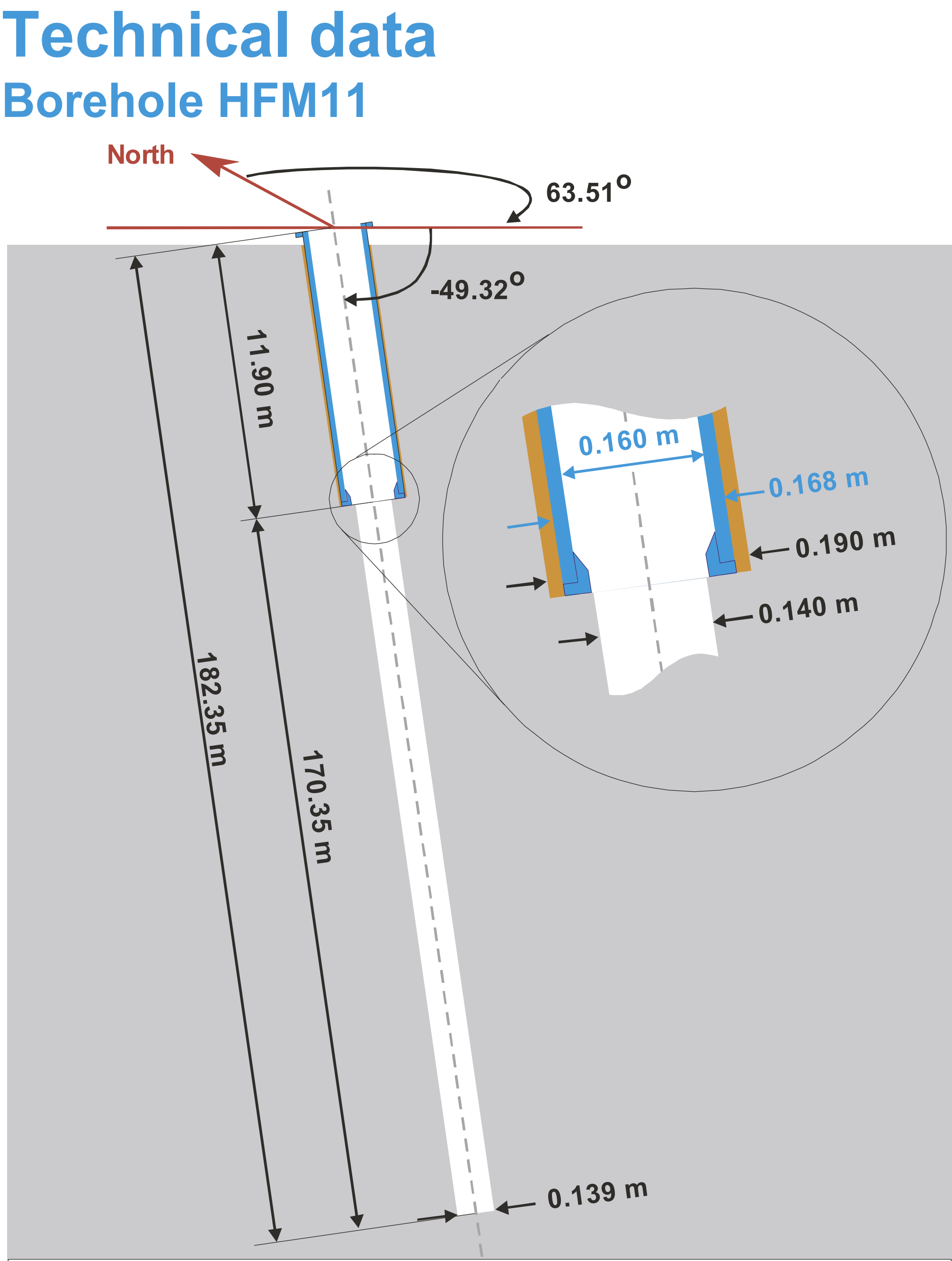
/6/ **SKB, 2004.** Nordman, C. Forsmark. Boremap mapping of percussion boreholes HFM13–15 and HFM19. SKB P-04-112. Svensk Kärnbränslehantering AB.

/7/ **SICADA.** Field Note Nos Forsmark 178, 179, 256, 257 and 258.

/8/ **SKB, 2004.** Drilling of three groundwater monitoring wells, HFM13–15 and one groundwater monitoring well in soil, SFM0058, at drilling site DS5. SKB P-04-85. Svensk Kärnbränslehantering AB.

/9/ **SKB, 2002.** Juhlin, C Bergman, B Palm, H. Reflection seismic studies in the Forsmark area-stage 1. SKB R-02-43, Svensk Kärnbränslehantering AB.

Technical design of boreholes HFM11–12 and HFM17–19



Drilling reference point

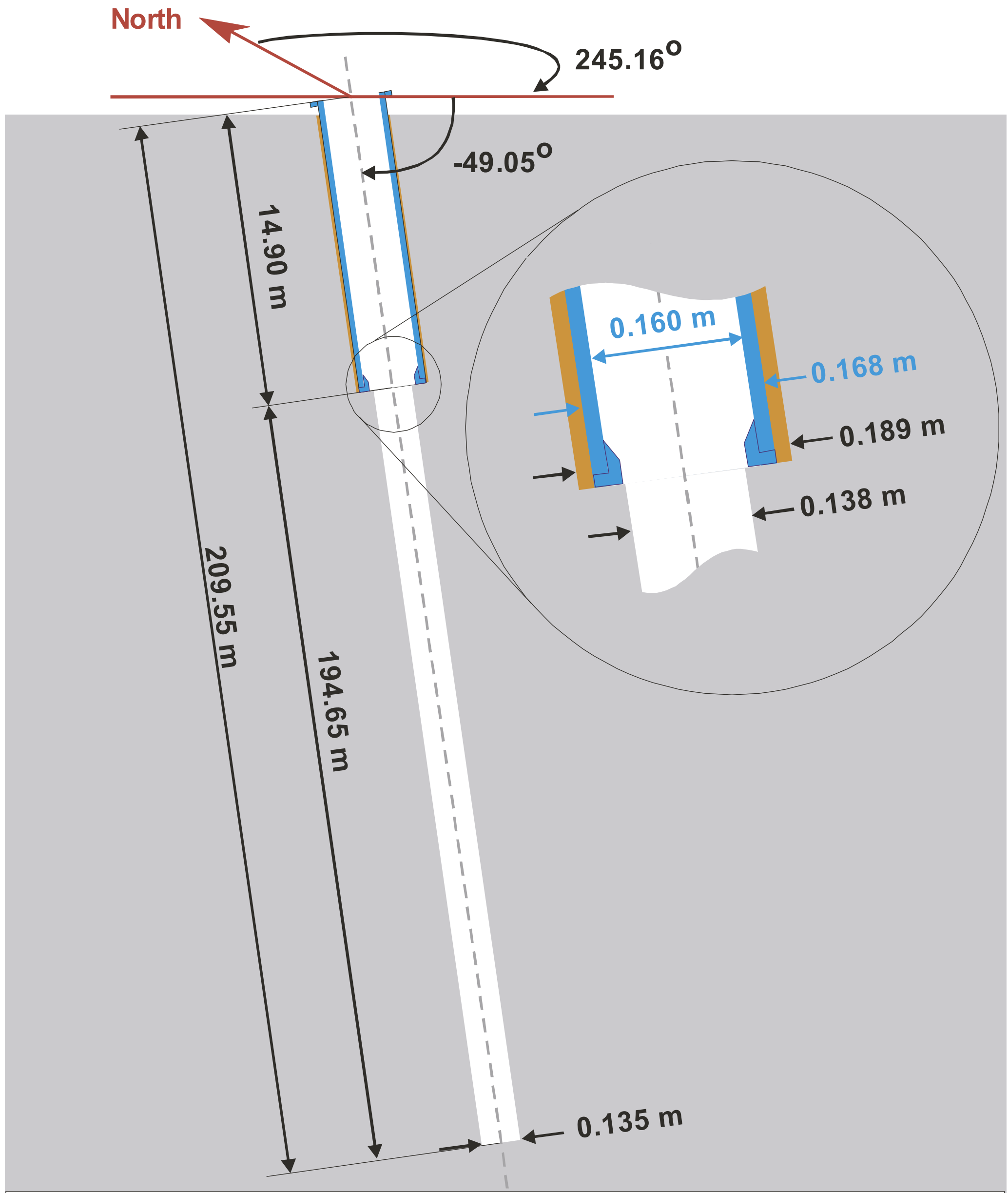
Northing:	6697283.40	(m), RT90 2,5 gon V 0:-15
Easting:	1631636.33	(m), RT90 2,5 gon V 0:-15
Elevation:	7.56	(m), RHB 70

Drilling period

Drilling start date:	2003-08-21
Drilling stop date:	2003-09-02

Figure A-1. *Technical data for borehole HFM11.*

Technical data
Borehole HFM12

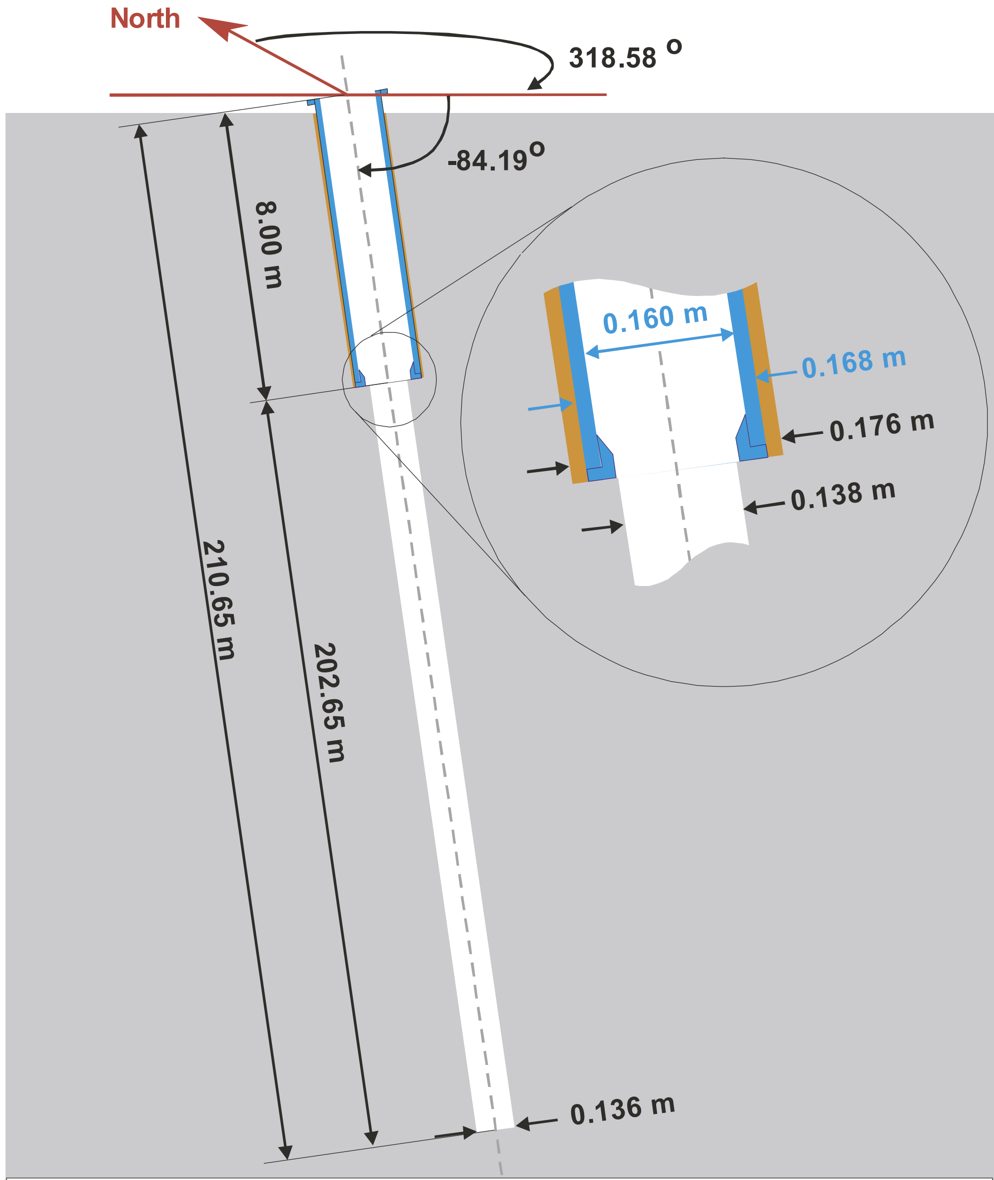


Drilling reference point		
Northing:	6697446.46	(m), RT90 2,5 gon V 0:-15
Easting:	1631695.67	(m), RT90 2,5 gon V 0:-15
Elevation:	7.03	(m.a.s.l.), RHB 70
Drilling period		
Drilling start date:	2003-09-03	
Drilling stop date:	2003-09-16	

Figure A-2. *Technical data for borehole HMF12.*

Technical data

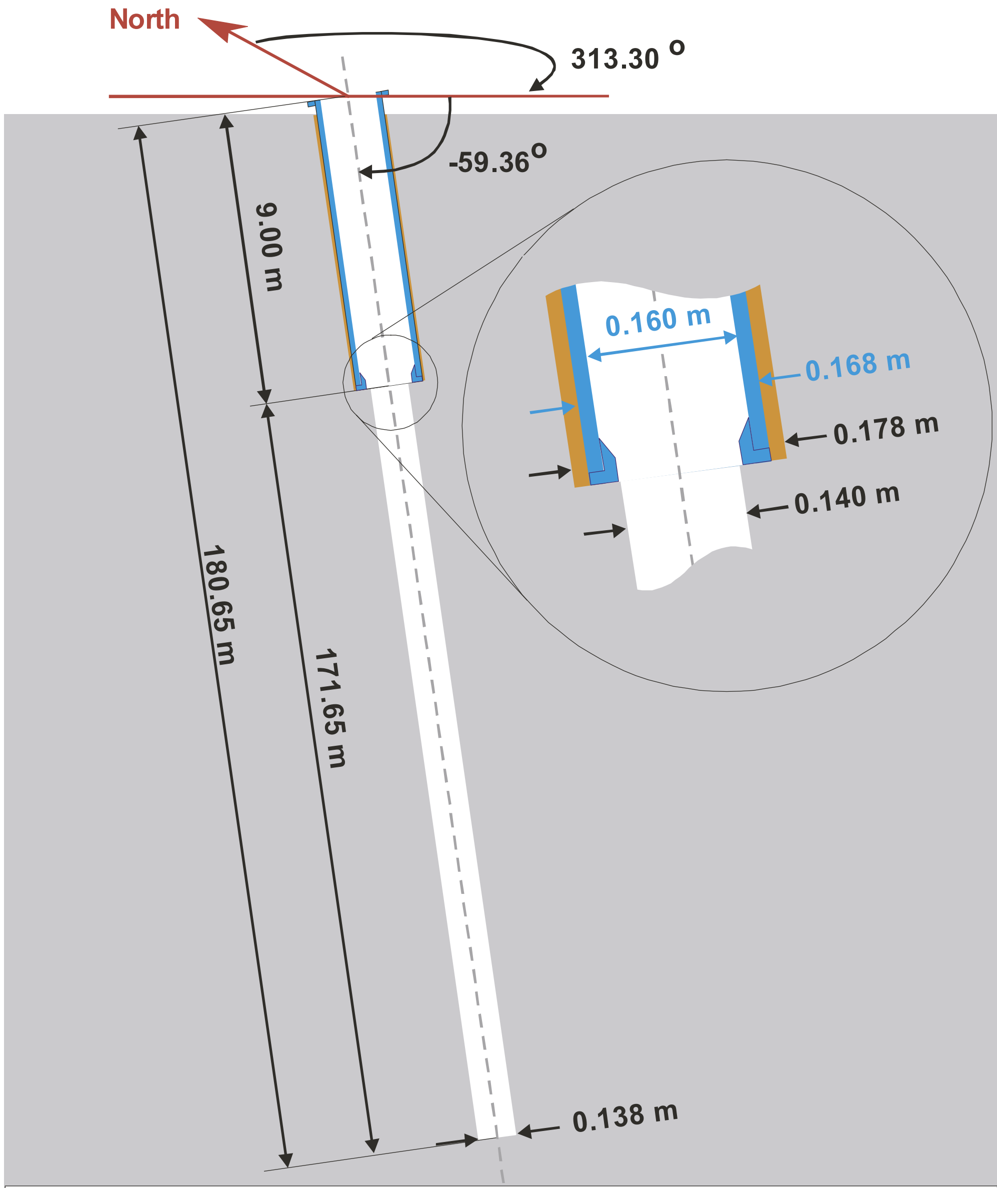
Borehole HFM17



Drilling reference point		
Northing:	6699461.95	(m), RT90 2,5 gon V 0:-15
Easting:	1633261.31	(m), RT90 2,5 gon V 0:-15
Elevation:	3.75	(m.a.s.l.), RHB 70
Drilling period		
Drilling start date:	2003-12-01	
Drilling stop date:	2003-12-08	

Figure A-3. *Technical data for borehole HMF17.*

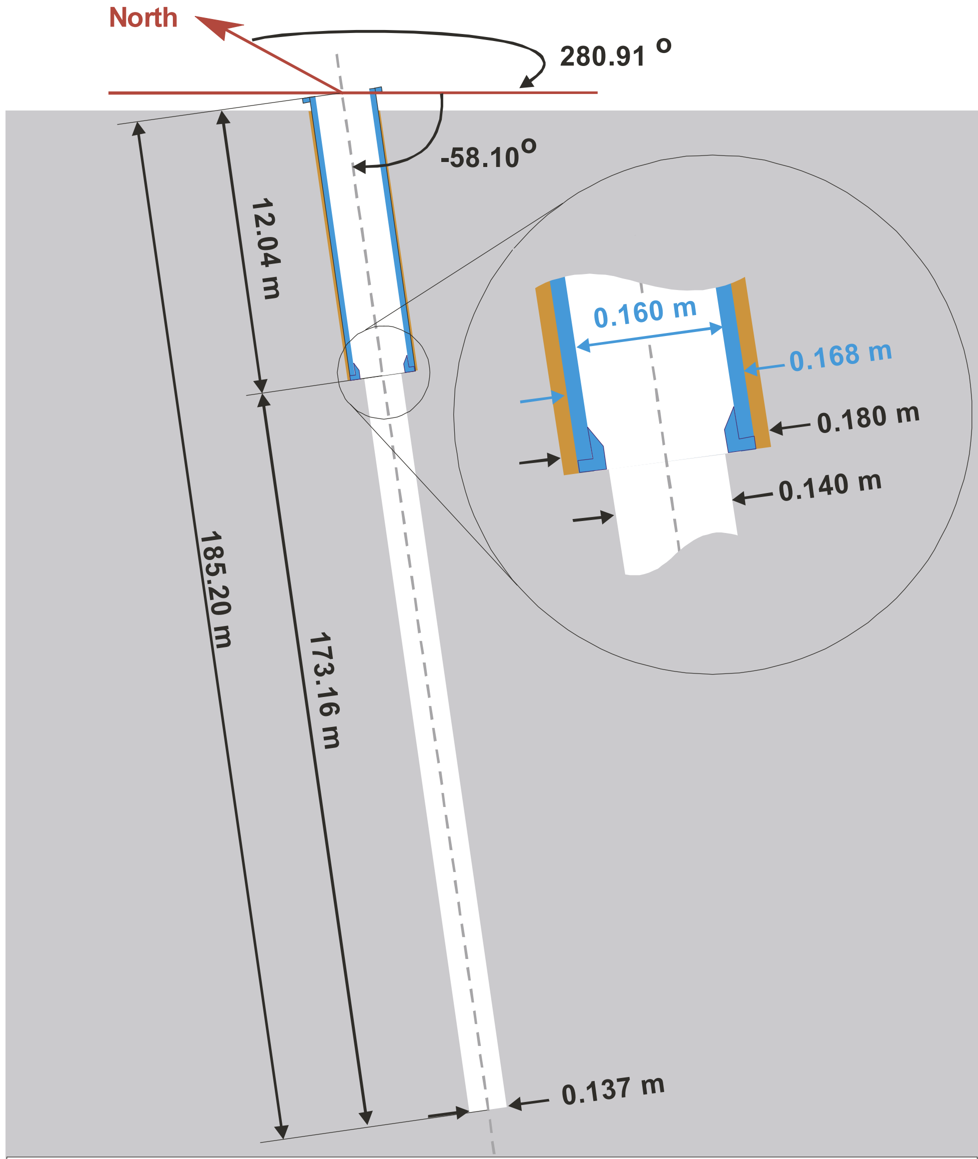
Technical data
Borehole HFM18



Drilling reference point		
Northing:	6698326.86	(m), RT90 2,5 gon V 0:-15
Easting:	1634037.37	(m), RT90 2,5 gon V 0:-15
Elevation:	5.04	(m.a.s.l.), RHB 70
Drilling period		
Drilling start date:	2003-12-10	
Drilling stop date:	2003-12-16	

Figure A-4. *Technical data for borehole HMF18.*

Technical data
Borehole HFM19



Drilling reference point

Northing:	6699257.59	(m), RT90 2,5 gon V 0:-15
Easting:	1631626.93	(m), RT90 2,5 gon V 0:-15
Elevation:	3.66	(m.a.s.l.), RHB 70

Drilling period

Drilling start date:	2003-12-02
Drilling stop date:	2003-12-18

Figure A-5. *Technical data for borehole HMF19.*

Appendix B

Well Cad presentations of boreholes HFM11–12 and HFM17–19

Title PERCUSSION DRILLED BOREHOLE HFM11

Svensk Kärnbränslehantering AB

Site	FORSMARK	**Coordinate System**	RT90-RHB70
Borehole	HFM11	**Northing [m]**	6697283.40
Diameter [mm]	139	**Easting [m]**	1631636.33
Length [m]	182.35	**Elevation [m.a.s.l.]**	7.56
Bearing [°]	63.51	**Drilling Start Date**	2003-08-21 12:16:00
Inclination [°]	-49.32	**Drilling Stop Date**	2003-09-02 16:04:00
Date of mapping	2004-04-06 11:30:00	**Plot Date**	2004-04-05 21:03:30

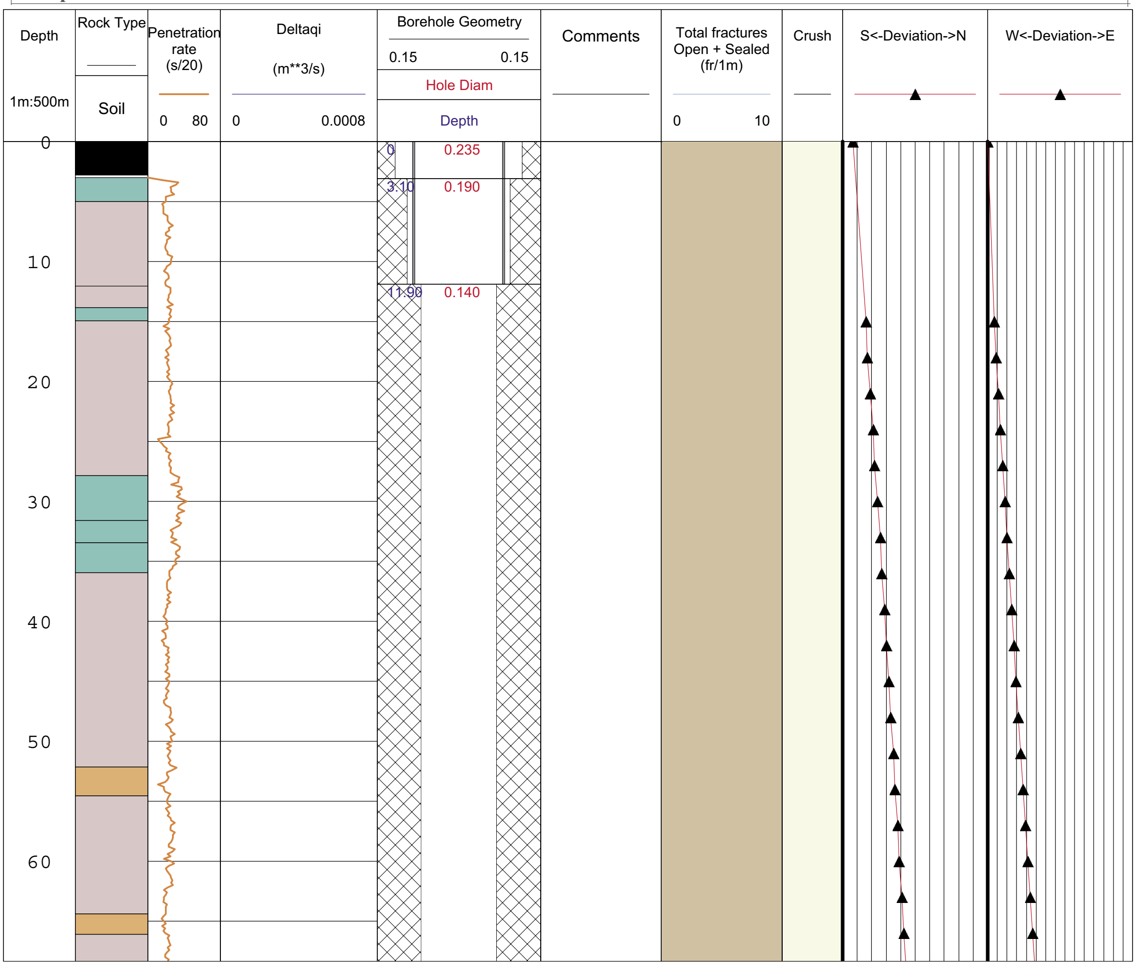
ROCKTYPE FORSMARK

- **Pegmatite, pegmatitic granite**
- **Granite, metamorphic, aplitic**
- **Granite to granodiorite, metamorphic, medium-grained**
- **Amphibolite**

SOIL

- **Soil**

Script Name



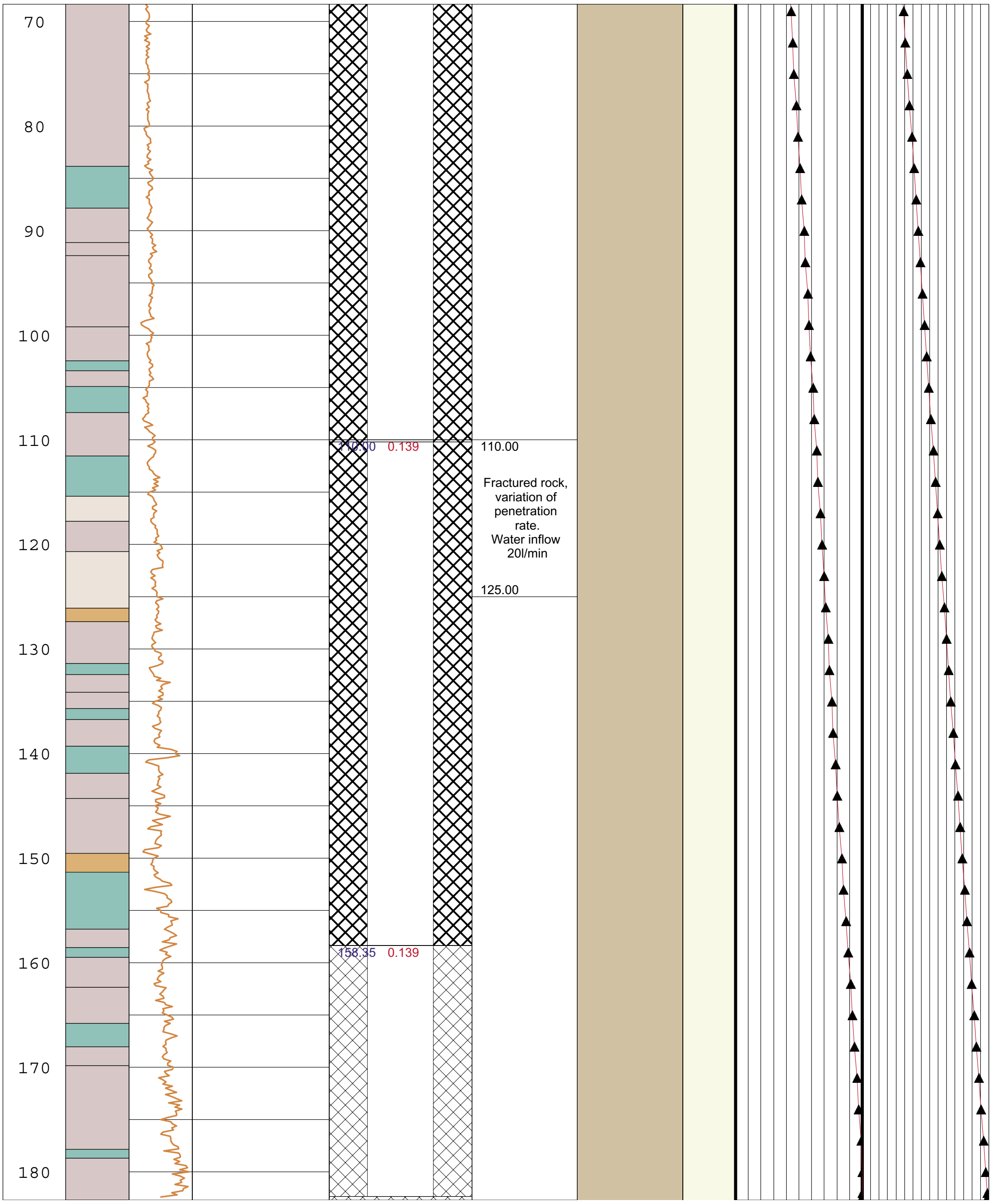


Figure B-1. *Technical and geoscientific data acquired during drilling of borehole HFM11.*

Title	PERCUSSION DRILLED BOREHOLE HFM12		
Svensk Kärnbränslehantering AB			
Site	FORSMARK	**Coordinate System**	RT90-RHB70
Borehole	HFM12	**Northing [m]**	6697446.46
Diameter [mm]	135	**Easting [m]**	1631695.67
Length [m]	209.55	**Elevation [m.a.s.l.]**	7.03
Bearing [°]	245.16	**Drilling Start Date**	2003-09-03 13:30:00
Inclination [°]	-49.05	**Drilling Stop Date**	2003-09-16 15:00:00
Date of mapping	2004-04-06 16:28:00	**Plot Date**	2004-05-05 21:00:37

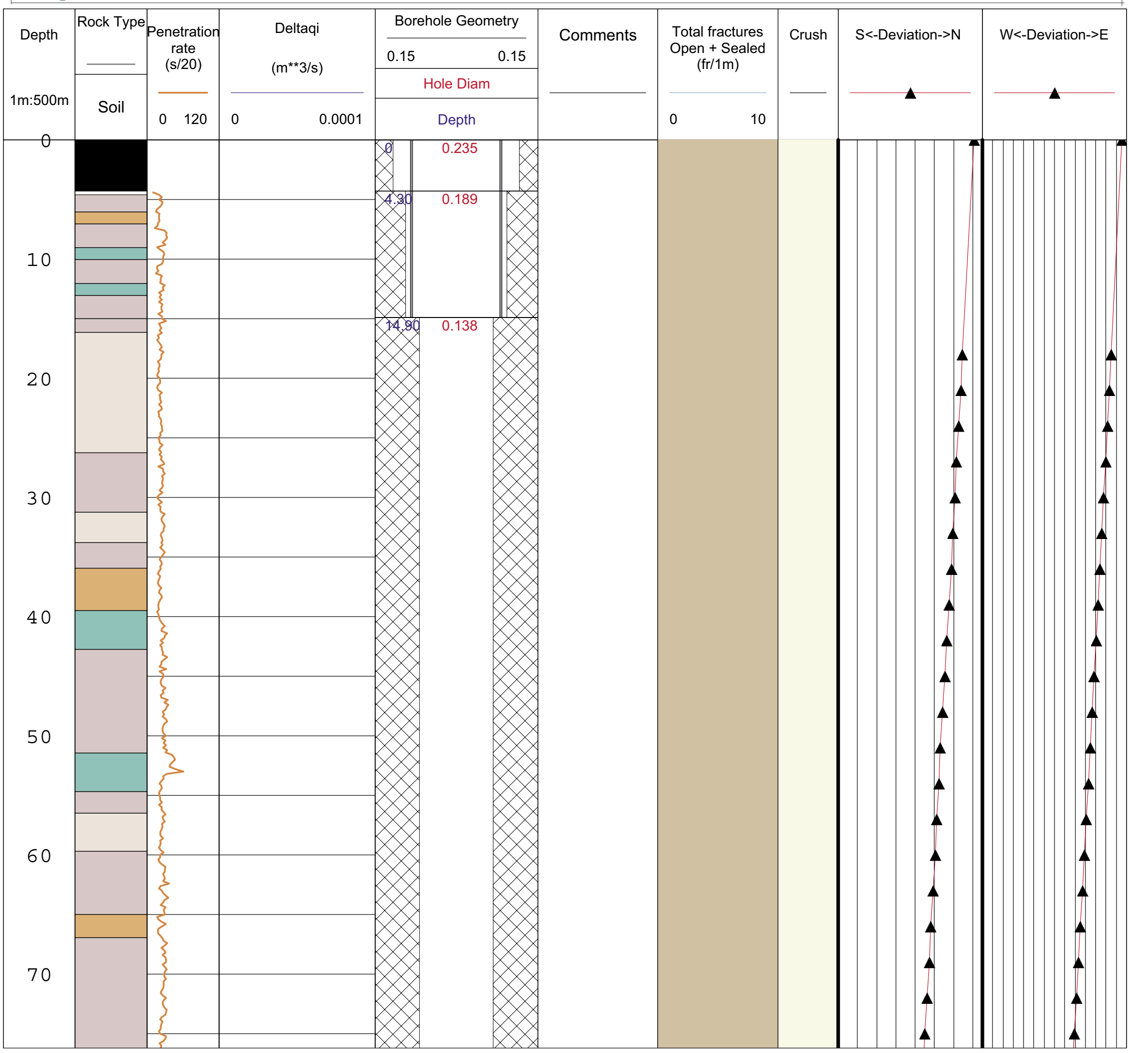
ROCKTYPE FORSMARK

- **Pegmatite, pegmatitic granite**
- **Granite, metamorphic, aplitic**
- **Granite to granodiorite, metamorphic, medium-grained**
- **Ultramafic rock, metamorphic**
- **Amphibolite**

SOIL

- **Soil**

Script Name



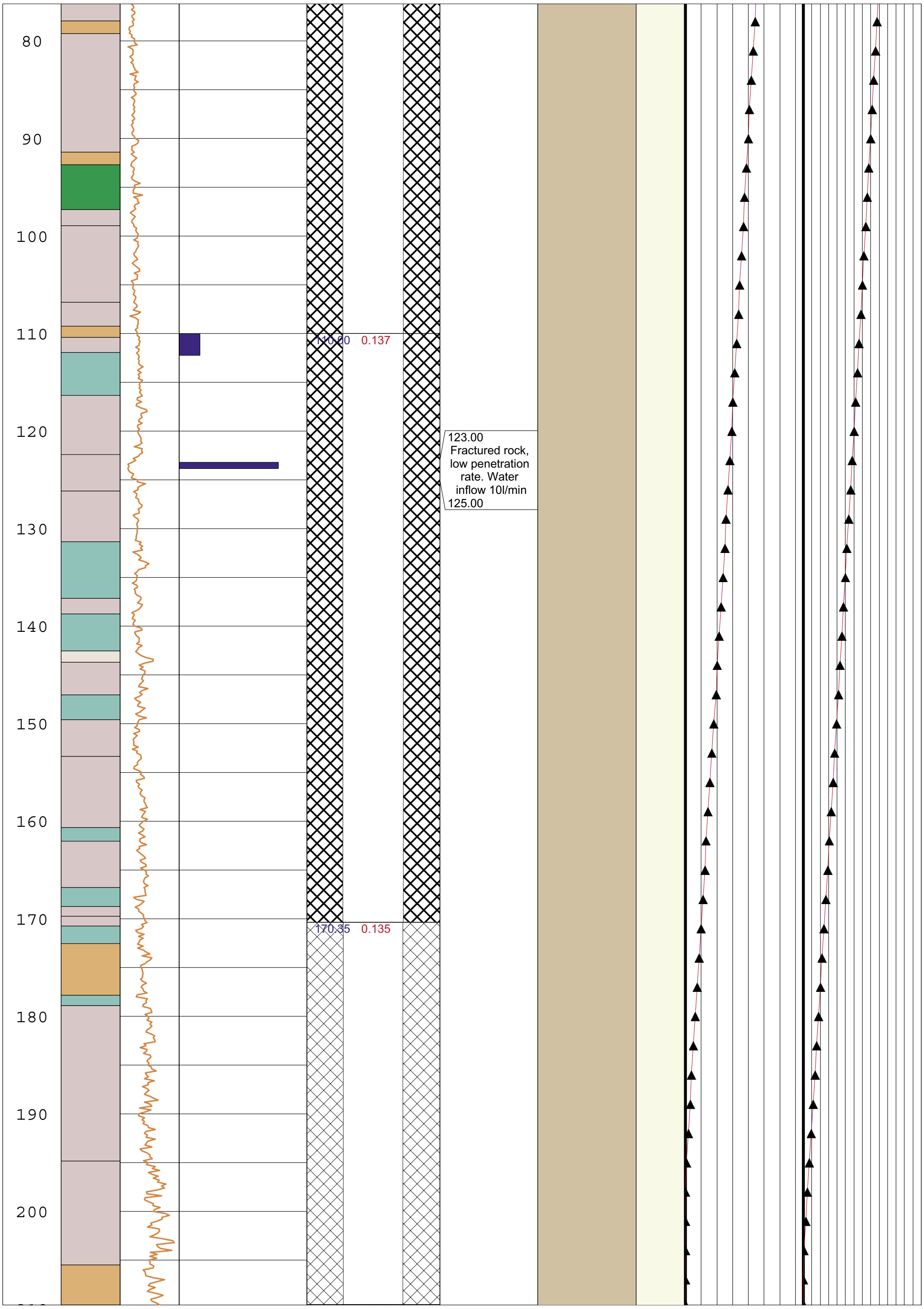


Figure B-2. *Technical and geoscientific data acquired during drilling of borehole HFM12.*

Title	PERCUSSION DRILLED BOREHOLE HFM17		

Svensk Kärnbränslehantering AB

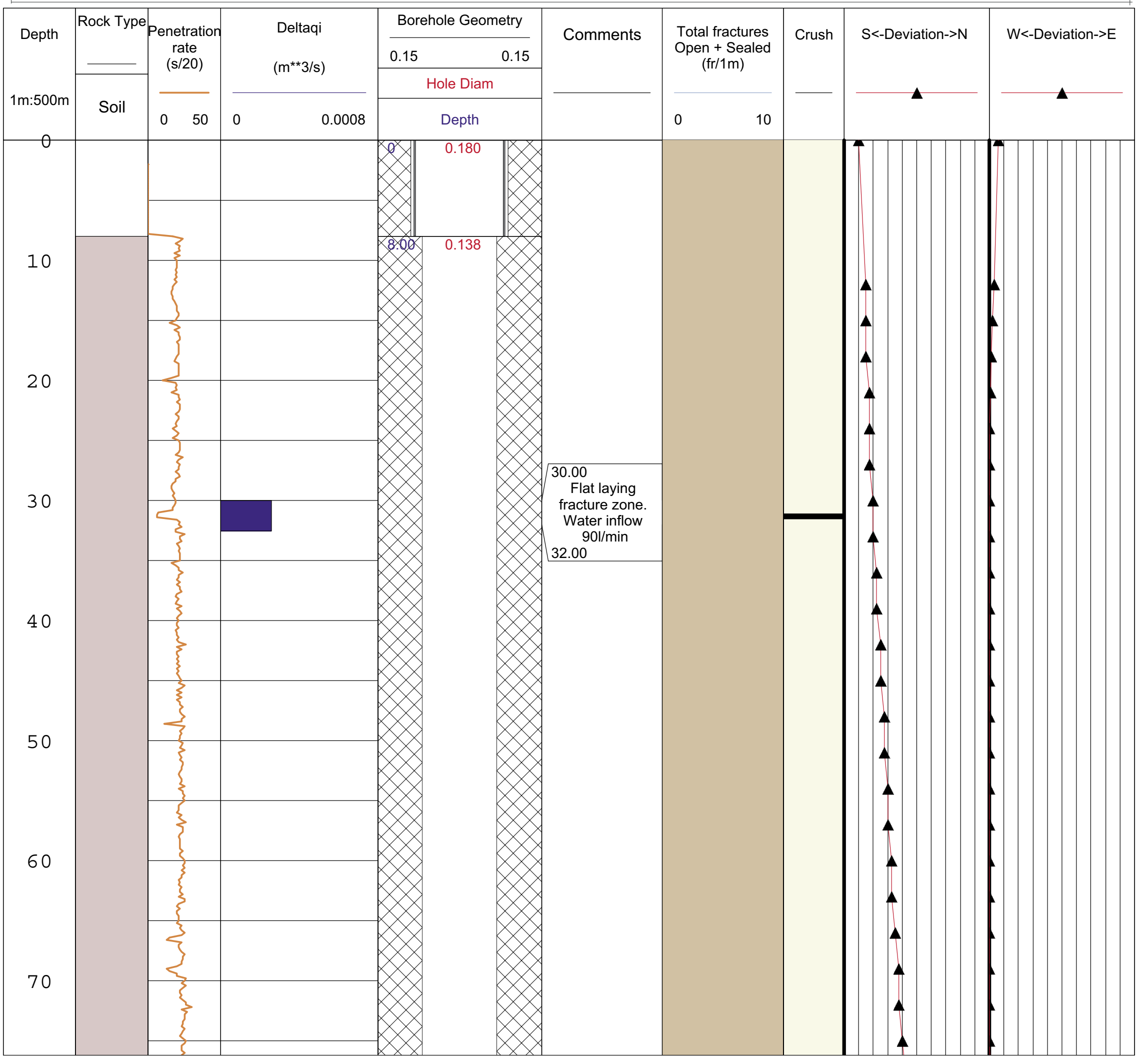
Site	FORSMARK	**Coordinate System**	RT90-RHB70
Borehole	HFM17	**Northing [m]**	6699461.95
Diameter [mm]	136	**Easting [m]**	1633261.31
Length [m]	210.65	**Elevation [m.a.s.l.]**	3.75
Bearing [°]	318.58	**Drilling Start Date**	2003-12-01 14:30:00
Inclination [°]	-84.19	**Drilling Stop Date**	2003-12-08 19:00:00
Date of mapping	2004-05-11 14:24:00	**Plot Date**	2004-05-12 08:11:56

ROCKTYPE FORSMARK

- **Pegmatite, pegmatitic granite**
- **Granite to granodiorite, metamorphic, medium-grained**

SOIL

Script Name



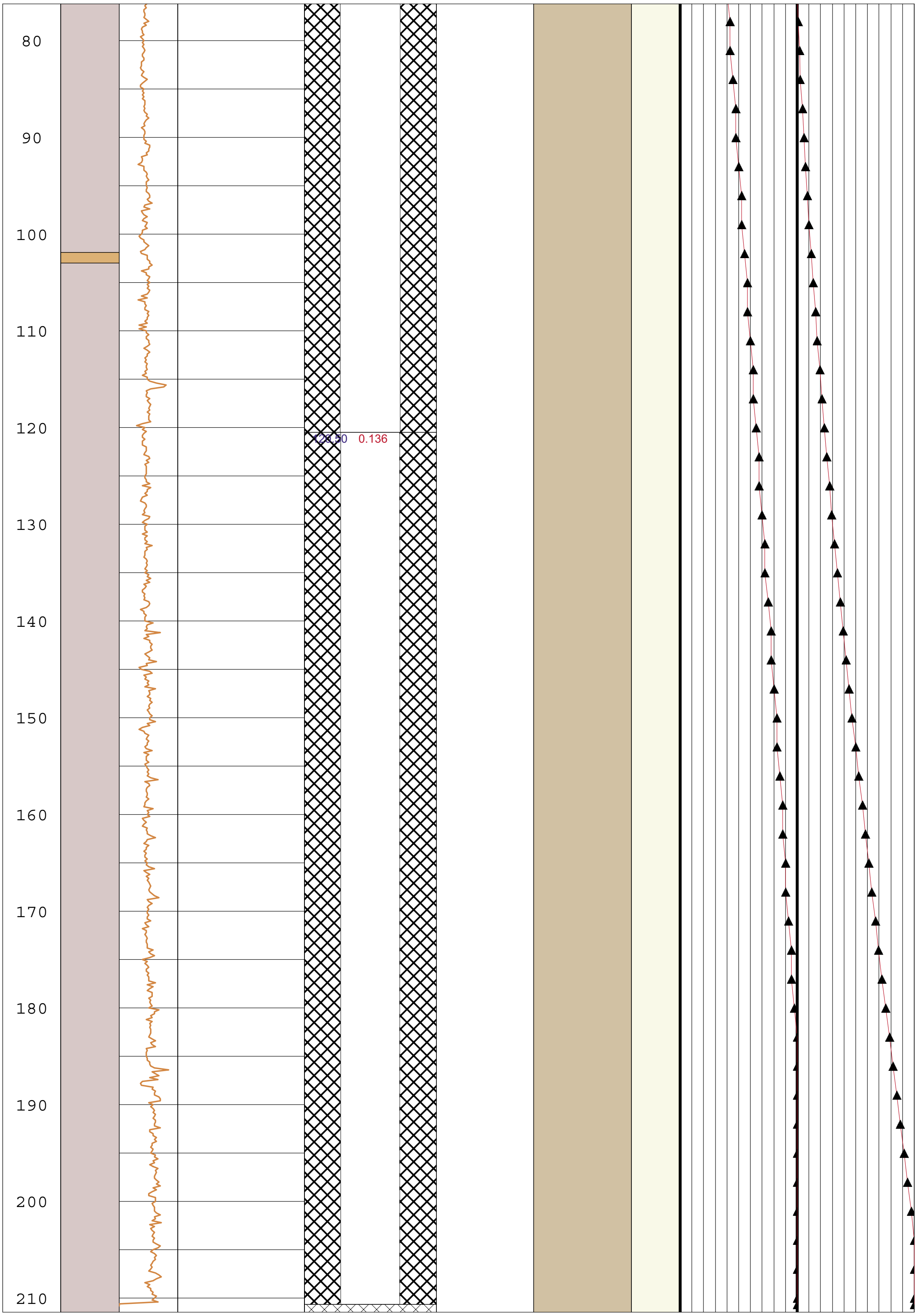


Figure B-3. *Technical and geoscientific data acquired during drilling of borehole HFM17.*

Title	PERCUSSION DRILLED BOREHOLE HFM18		
Svensk Kärnbränslehantering AB			
Site	FORSMARK	**Coordinate System**	RT90-RHB70
Borehole	HFM18	**Northing [m]**	6698326.86
Diameter [mm]	138	**Easting [m]**	1634037.37
Length [m]	180.65	**Elevation [m.a.s.l.]**	5.04
Bearing [°]	313.30	**Drilling Start Date**	2003-12-10 12:30:00
Inclination [°]	-59.36	**Drilling Stop Date**	2003-12-16 20:00:00
Date of mapping	2004-05-14 10:44:00	**Plot Date**	2004-06-07 21:05:05

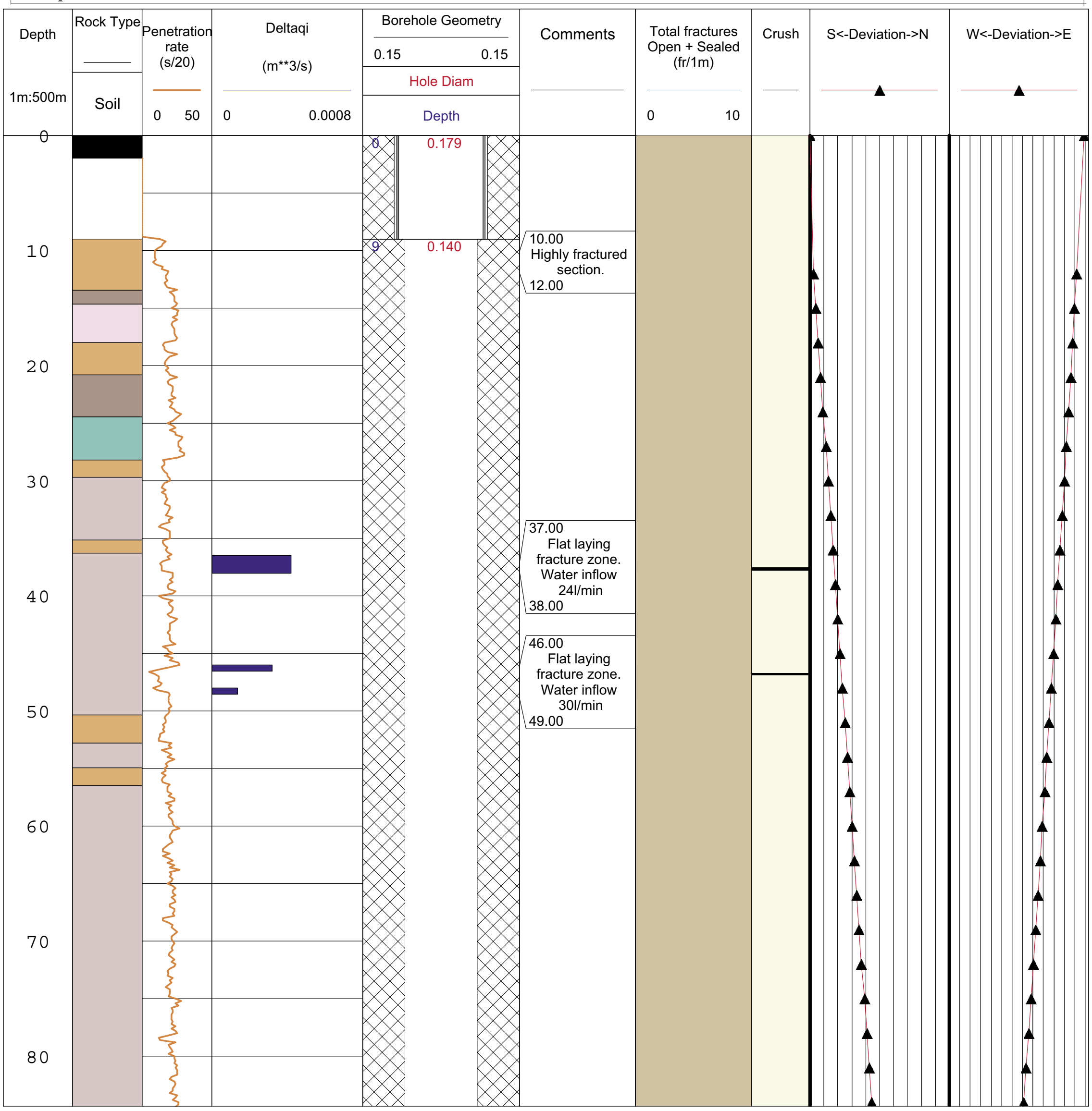
ROCKTYPE FORSMARK

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

SOIL

- **Soil**

Script Name



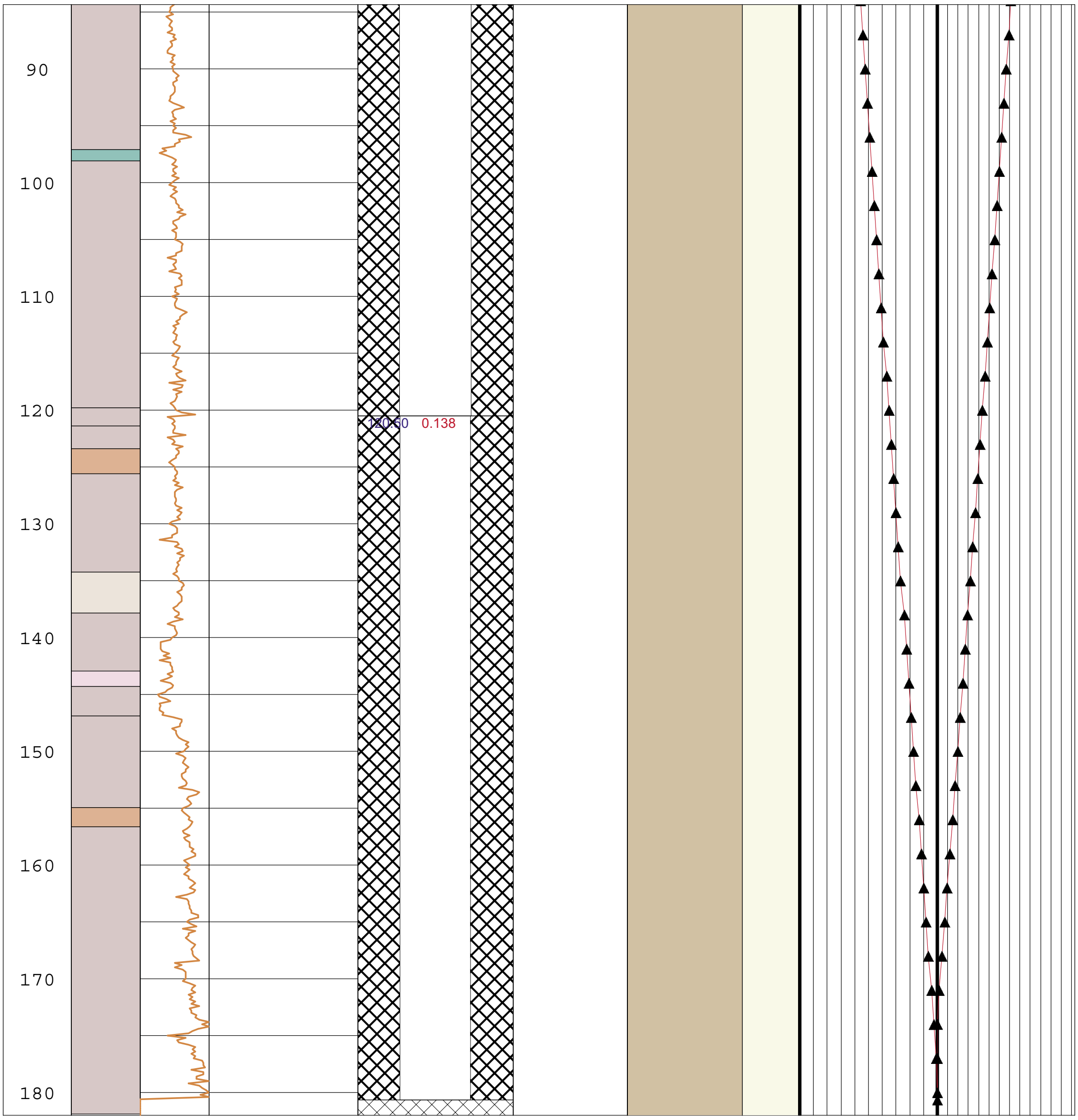


***Figure B-4.** Technical and geoscientific data acquired during drilling of borehole HFM18.*

Title **PERCUSSION DRILLED BOREHOLE HFM19**

Svensk Kärnbränslehantering AB

Site	FORSMARK	**Coordinate System**	RT90-RHB70
Borehole	HFM19	**Northing [m]**	6699257.59
Diameter [mm]	137	**Easting [m]**	1631626.93
Length [m]	185.20	**Elevation [m.a.s.l.]**	3.66
Bearing [°]	280.91	**Drilling Start Date**	2003-12-02 11:10:00
Inclination [°]	-58.10	**Drilling Stop Date**	2003-12-18 16:55:00
Date of mapping	2004-05-18 16:26:00	**Plot Date**	2004-05-25 21:04:56

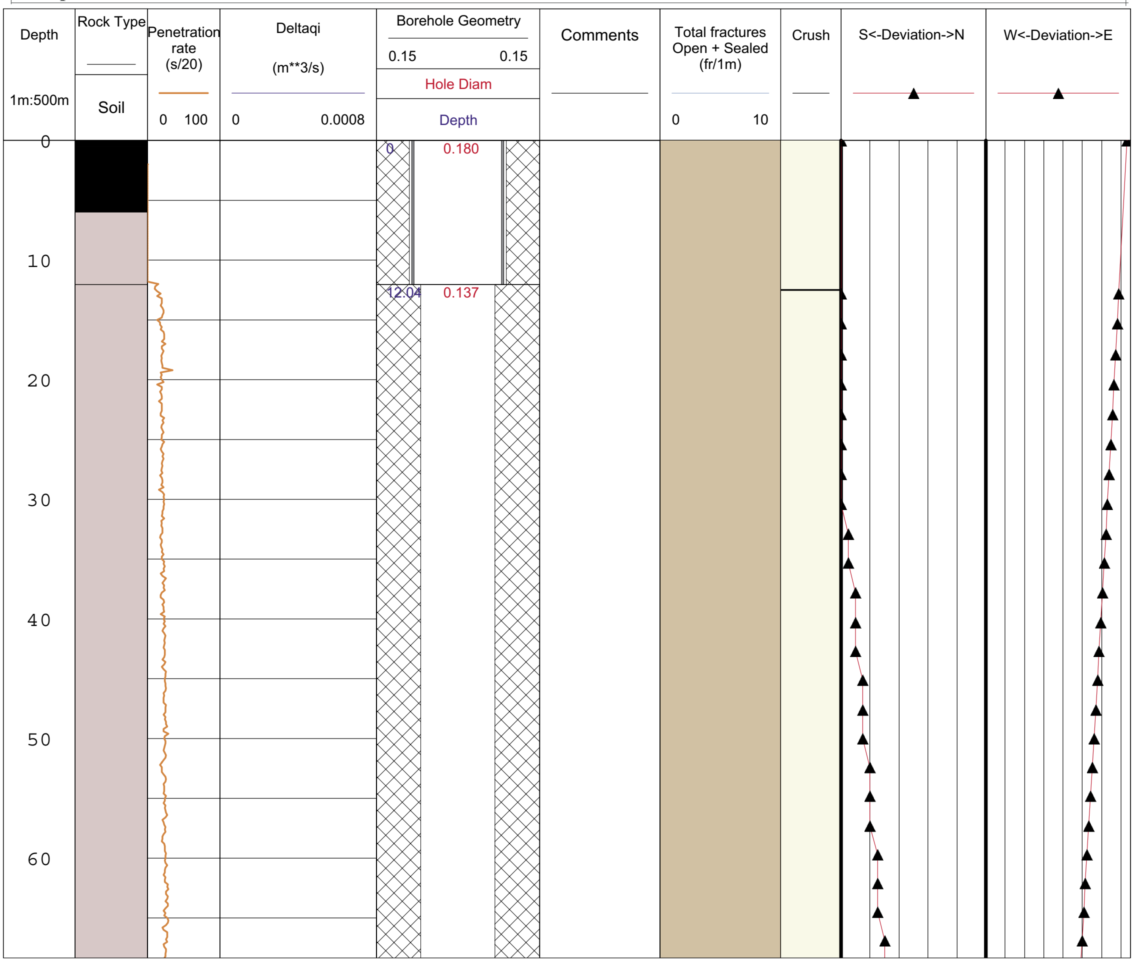
ROCKTYPE FORSMARK

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

SOIL

- **Soil**

Script Name



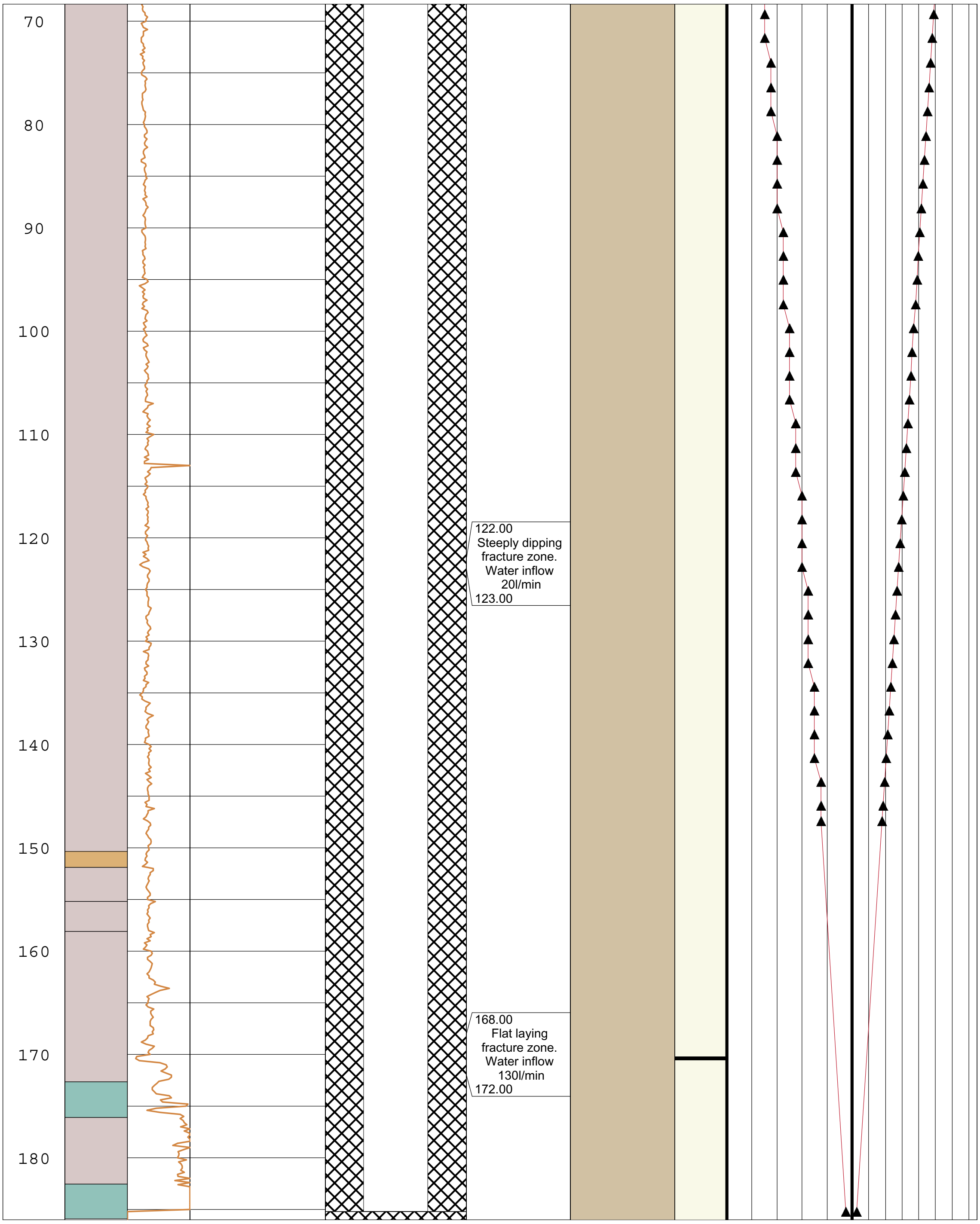


Figure B-5. *Technical and geoscientific data acquired during drilling of borehole HFM19.*