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Site investigation SFR

Hydraulic tests, flow logging and chemical sampling

Borehole HFR106

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September 2009

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Abstract

SKB conducts bedrock investigations for a future extension of the final repository for short-lived radioactive waste (SFR) at Forsmark in the Östhammar municipality. As a part of this investigation borehole HFR106 was drilled on a small island adjacent to the wave breaker outside SFR.

The main objectives of the hydraulic tests in this percussion borehole were to investigate the hydraulic characteristics of the rock (e.g. occurrence and hydraulic transmissivity of different hydraulic conductors) and to obtain water samples for determinations of the water chemistry characteristics for larger hydraulic anomalies in the borehole.

The borehole HFR106 was drilled in June and July 2009 and preliminary observations during drilling indicated rather high inflow of water. Geosigmas spinner equipment was used for the hydraulic tests as well as for the chemical sampling in the borehole. For the hydraulic test, the borehole was pumped until a steady state pressure was achieved. Then the borehole was logged using a spinner that is lowered at a constant rate in the opposite direction to the flow. During this procedure, also temperature and electric conductivity down the borehole were measured. The logged data were adjusted for decreasing borehole diameter and the transmissivity of the detected anomalies were then calculated.

Two large anomalies were detected at 38–40 m and 177.3–178.5 m borehole length and selected for water sampling and chemical analyses. The water samples from these fractures were collected by sealing off borehole sections at 36–41 m and at 175–190 m borehole length (down to the bottom of the borehole) with packers. Water was pumped from the borehole sections and three water samples were collected from each section after discharge of 1, 3 and 5 section volumes, respectively.

The transient evaluation of the single hole hydraulic test in HFR106 resulted in the total borehole transmissivity of $5.2 \cdot 10^{-5}$ m^2/s and it was concluded that a linear flow regime dominates the borehole. Two significant flow anomalies were detected from the flow logging.

Sammanfattning

SKB bedriver bergundersökningar inför en framtida utbyggnad av slutförvaret för kortlivat radioaktivt avfall (SFR) vid Forsmark i Östhammars kommun. Som en del av denna undersökning borrades undersökningsborrhålet HFR106 på en kobbe utanför piren vid SFR.

Huvudsyftet med de hydrauliska testerna i borrhålet var att undersöka de hydrauliska egenskaperna i berget (t.ex. förekomst av och hydraulisk transmissivitet hos olika hydrauliska ledare) och att ta vattenprover för analys av grundvattnets kemiska egenskaper i de påträffade flödesanomalierna.

HFR106 borrades i juni och juli 2009 och borrningen indikerade en ganska hög transmissivitet för hålet. Geosigmas egen spinnerutrustning användes för de hydrauliska och kemiska mätningarna. De hydrauliska testerna utfördes så att borrhålet pumpades tills en konstant grundvattennivå/avsänkning uppnåddes i hålet. Därefter sänktes spinnern i hålet mot den pumpade flödesriktningen och spinnerns varvtal loggades. Även temperatur och elektrisk konduktivitet loggades under sänkningen. De loggade värdena korrigerades för avtagande borrhålsdiameter och transmissiviteten för de detekterade anomalierna beräknades.

Två stora anomalier observerades vid 38–40 och 177–178,5 meter borrhålslängd och valdes för vattenprovtagning och kemisk analys. Vattenproverna från dessa sprickor togs ut genom att avgränsa sektioner vid 36–41 m och vid 175–190 m (botten av borrhålet) med manschetter. Vatten pumpades från dessa sektioner och tre prov togs ut från varje sektion efter omsättning av 1, 3 respektive 5 sektionsvolymer.

Den transienta utvärderingen av enhålstestet i HFR106 resulterade i en total borrhålstransmissivitet på $5{,}2 \cdot 10^{-5}$ m^2/s och det konstaterades att en linjär flödes regim dominerar borrhålet. Två egentliga flödesanomalier identifierades från flödesloggningen

Contents

1 Introduction

SKB conducts bedrock investigations for a future extension of the final repository for radioactive operational waste (SFR) in Forsmark in the Östhammar municipality. The extension project named "Projekt SFR-utbyggnad" consists of a number of sub projects. One of those is the sub project "Investigations" to which this activity belongs.

This document reports the results of the hydraulic testing of the percussion-drilled borehole HFR106. The test was carried out as a pumping test combined with flow logging. No other hydraulic tests had been carried out in the borehole before this campaign. Three water samples were collected from each one of the two detected anomalies by additional pumping between packers the day after the pumping test.

The borehole HFR106 is situated on the small islet adjacent to the pier outside the SFR and SKB site office, see Figure 1-1.

All time notations in this report are made according to Swedish Summer Time (SSUT), UTC +2 h.

The work was carried out in accordance to SKB internal controlling documents; see Table 1-1. Data and results were delivered to the SKB site characterization database Sicada, where they are traceable by the Activity Plan number.

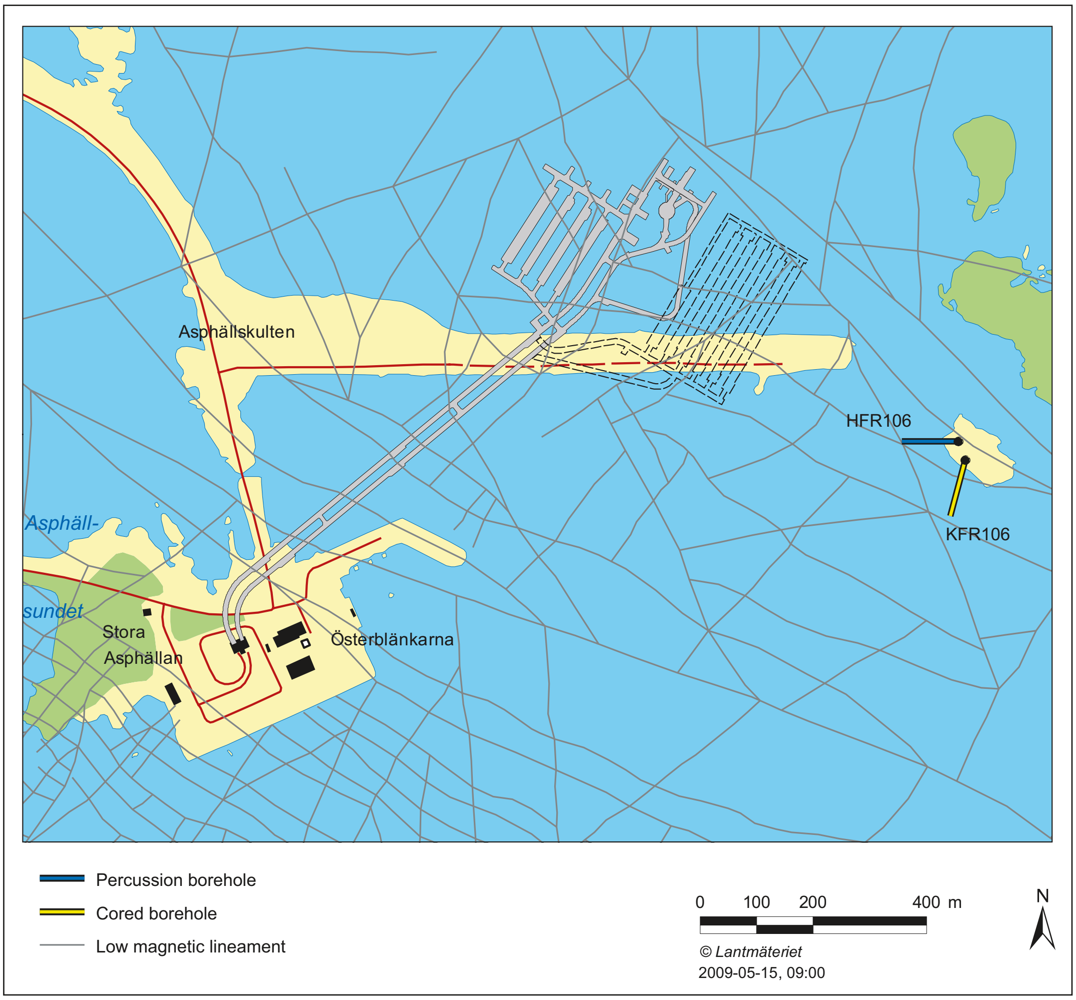


Figure 1-1. Map showing the location of the borehole HFR106.

Table 1-1. SKB Internal controlling documents for performance of the activity.

Activity Plan	Number	Version
Hydrotest och vattenprovtagning i hammarborrhål HFR106	AP SFR-09-013	1.0
Method Documents	**Number**	**Version**
Metodbeskrivning för hydrauliska enhålspumptester	SKB MD 321.003	1.0
Metodbeskrivning för flödesloggning	SKB MD 322.009	1.0
Instruktion för analys av injektions- och enhålspumptester	SKB MD 320.004	1.0
Mätsystembeskrivning för HydroTestutrustning för HammarBorrhål, HTHB	SKB MD 326.001	3.0
Enkel vattenprovtagning i hammarborrhål och kärnborrhål	SKB MD 423.002	2.0

2 Objectives

The objective of the flow logging in borehole HFR106 was to investigate the hydraulic properties of the penetrated rock volumes, and to identify the position and hydraulic character of major inflows (which may represent e.g. sub-horizontal fracture zones). Another aim was to collect water samples for chemical analyses in order to investigate the groundwater composition in two larger hydraulic anomalies in the borehole.

3 Scope

3.1 Borehole data

Technical borehole data are displayed in Figure 3-1. The reference point in the borehole is always top of casing (ToC). The Swedish National coordinate system (RT90 2.5 gon W) is used in the x-y-plane together with RHB70 in the z-direction. Northing and Easting refer to the top of the borehole at top of casing. The borehole diameter in Figure 3-1, measured as the diameter of the drill bit, decreases more or less along the borehole due to wearing of the drill bit.

3.2 Test performed

The different test types conducted in the borehole, as well as the test periods, are presented in Table 3-1.

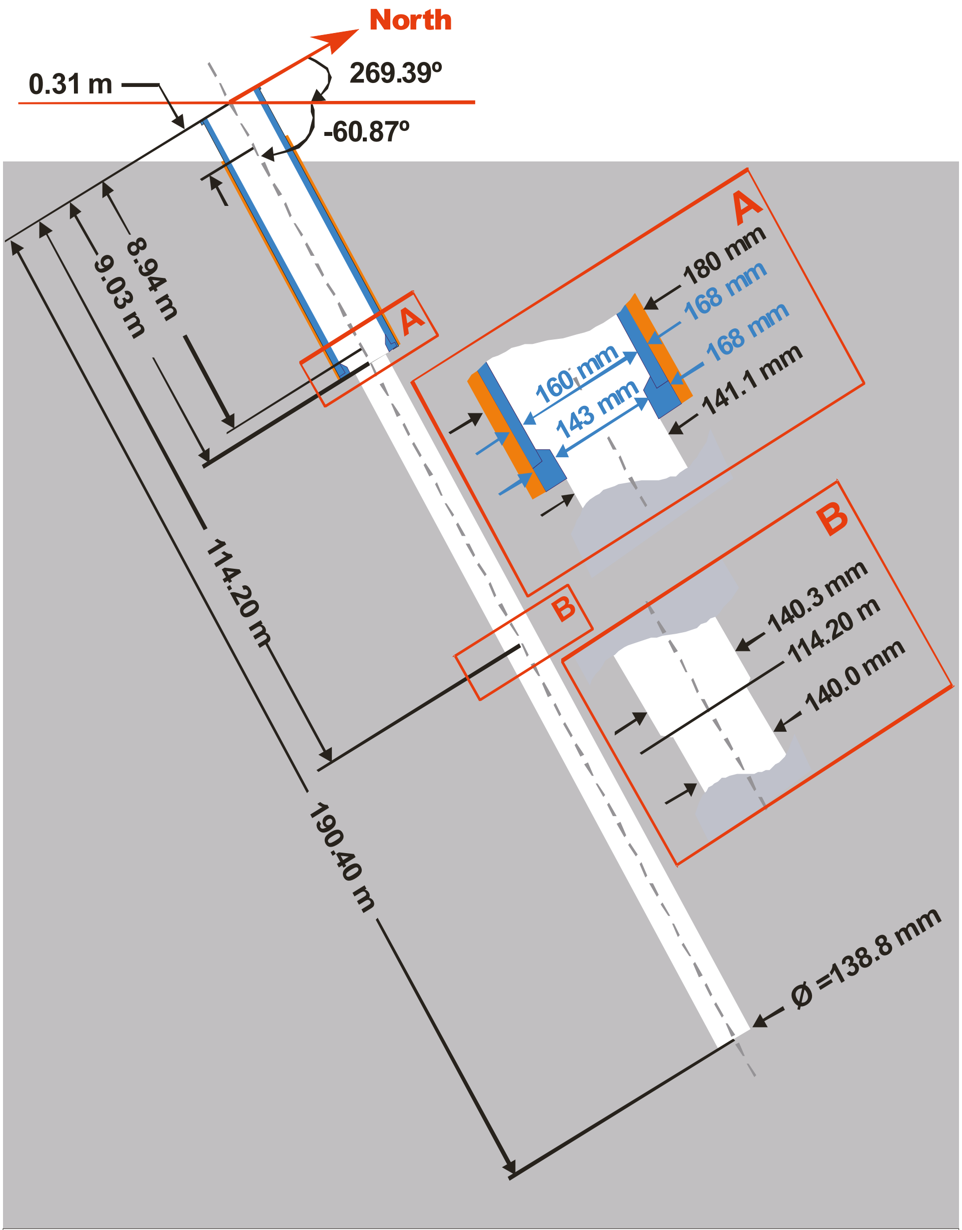
After the pumping test, continued pumping was conducted in order to collect water samples for chemical analyses, see Section 6.2. During the test, soundings of the groundwater level in the pumped borehole were also made (when possible).

Table 3-1. Borehole tests performed.

Bh ID	Test section (m)	Test type [1]	Test config.	Test start date and time (YYYY-MM-DD tt:mm)	Test stop date and time (YYYY-MM-DD tt:mm)
HFR106	9.03–190.4	1B	Open hole	2009-07-07 09:53	2009-07-08 10:20
HFR106	12.5–185.0	6, L-EC, L-Te	Open hole	2009-07-07 16:41	2009-07-07 19:51

[1] 1B: Pumping test-submersible pump, 6: Flow logging–Impeller, L-EC: EC-logging, L-Te: temperature logging.

Technical data
Borehole HFR106



Drilling reference point

Northing:	6701574.11	(m), RT90 2,5 gon V 0:-15
Easting:	1633579.85	(m), RT90 2,5 gon V 0:-15
Elevation:	1.27	(m), RHB 70

Drilling period

Drilling start date:	2009-06-23
Drilling stop date:	2009-07-02

rev 2008-07-03

Figure 3-1. *Technical drawing of borehole HFR106.*

4 Description of equipment

4.1 Overview

4.1.1 Flow logging

The spinner equipment developed by Geosigma AB is used in the flow logging tests, see Figure 4-1.

Geosigmas equipment for flow logging uses a submersible pump and a spinner to measure the water flow in a borehole. The borehole is normally pumped until a steady-state is reached. Then the spinner probe is lowered against the flow, down the borehole registering the spin pulses.

The pulses are generated by a rotating impeller, see Figure 4-2 and transmitted to a data logger at the surface. The spinner probe also contains transducers for electrical conductivity and temperature. To direct the major part of the borehole flow through the spinner probe, the probe is adapted to different borehole diameters. For borehole diameters above 100 mm this is obtained by using adjustable plastic guides and rubber discs mounted at the down-hole end of the spinner probe (see Figure 4-2). In smaller diameter boreholes an outer tube, slightly smaller than the borehole, is mounted outside the original spinner probe. The original spinner probe is 43 mm in diameter, which makes it possible to perform logging in boreholes down to 46 mm in diameter.

When logging a borehole the probe and its cable are lowered at a constant speed using an electric motor. The speed of this motor is adjustable enabling the logging speed to be altered due to different conditions and demands of the test.

To keep track of the position of the probe the signal cable is passing a measuring wheel mounted on the borehole casing. When the probe has been lowered to the starting position a submersible pump and a pressure transducer is lowered in the borehole as well. The equipment is designed for the spinner to be lowered down to a maximum borehole length of 370 m.

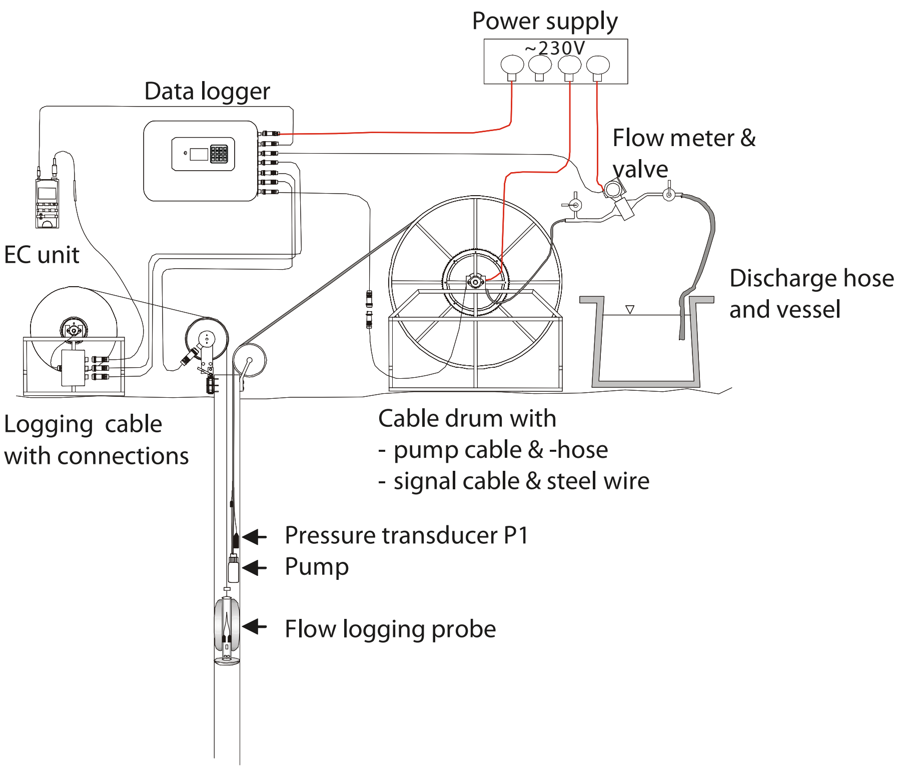


Figure 4-1. *Schematic test set-up for a pumping test in an open borehole in combination with flow logging with HTHB. (From SKB MD 326.001, SKB internal document).*

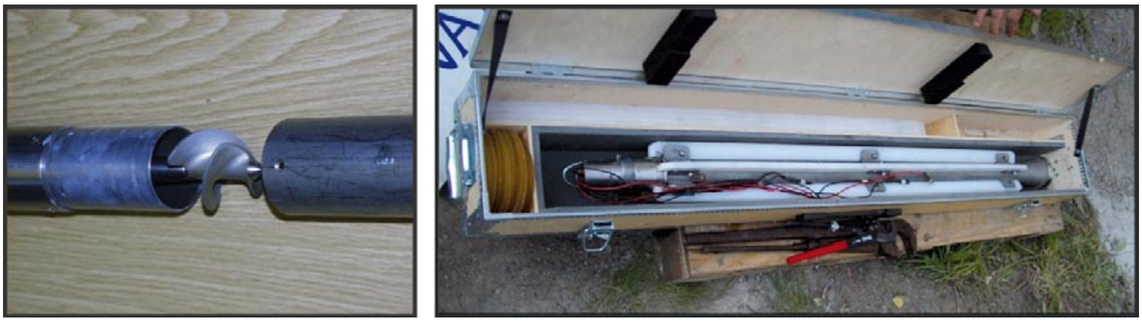


Figure 4-2. Spinner mounted in the probe tube and spinner probe with plastic guides. Discs for different borehole diameters are kept in the left compartment.

4.1.2 Pumping and injection between packers

The spinner system is designed to perform pumping- and injection tests in open percussion drilled boreholes, see Figure 4-1, as well as in isolated sections of the boreholes, see Figure 4-3. In this activity the packer system was used for water sampling in two isolated sections of the borehole.

The borehole equipment includes a submersible borehole pump with housing, expandable packers, pressure sensors and a pipe string and/or hose. During flow logging, the sensors measuring temperature and electric conductivity as well as down-hole flow rate are also employed. At the top of the borehole, the total flow/injection rate is manually adjusted by a control valve and monitored by an electromagnetic flow meter. A data logger samples data at a frequency determined by the operator.

The packers are normally expanded by water (nitrogen gas is used for pressurization) unless the groundwater level is too low, or the risk of freezing makes the use of water unsuitable. In such cases, the packers are expanded by nitrogen gas. A folding pool is used to collect and store the discharged water from the borehole for subsequent use in injection tests (if required).

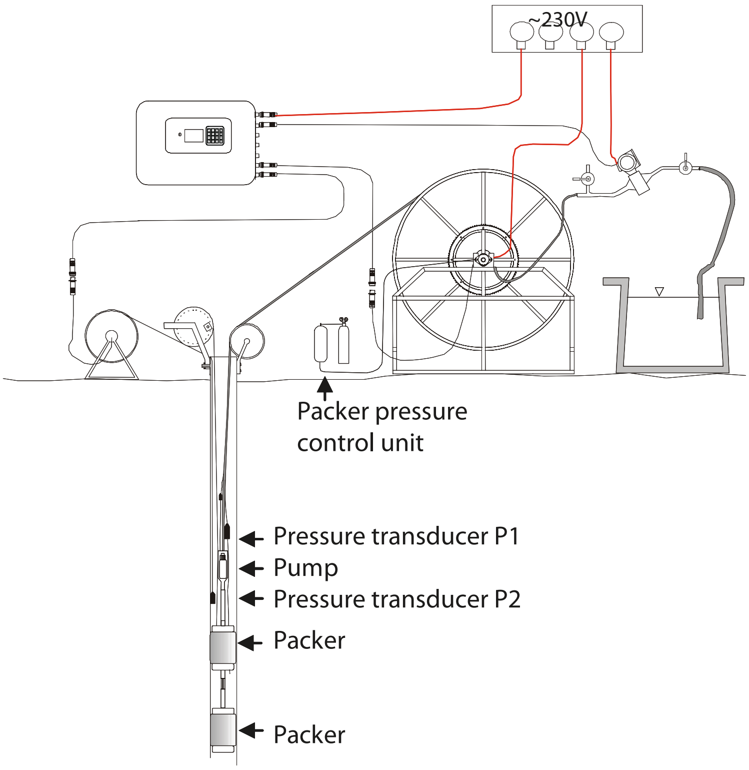


Figure 4-3. Schematic test set-up for a pumping test in an isolated borehole section with HTHB. (From SKB MD 326.001, SKB internal document).

4.2 Measurement sensors

Technical data of the sensors used together with estimated data specifications of the test system for pumping tests and flow logging are given in Table 4-1.

Table 4-2 presents the position of sensors for each test together with the level of the pump-intake of the submersible pump. The following types of sensors are used: pressure (P), temperature (Te), electric conductivity (EC). Positions are given in metres from the reference point, i.e. top of casing (ToC), to the lower part. The sensors measuring temperature and electric conductivity are located in the impeller flow-logging probe and the position is thus varying during a test. For specific information about the position at a certain time, the actual data files have to be consulted.

Equipment affecting the wellbore storage coefficient is given in terms of diameter of submerged item. Position is given as “in section” or “above section”. The volume of the submerged pump (~ 4 dm^3) is not involved in the wellbore storage since the groundwater level always is kept above the top of the pump in open boreholes.

In addition, the theoretical wellbore storage coefficient C for the actual test configurations and geometrical data of the boreholes were calculated, see Section 5.3.1. Since the drawdown occurred above the end of casing, the value of C in Table 4-2 was calculated using the casing diameter.

Table 4-1. Technical data of measurement sensors used.

	Type	Measuring range	Resolution	Accuracy
Pressure transducer	Druck PTX 161/D sg	1,000 kPa	0.04 kPa	±0.25% full scale (BSL)
Flow meter (flow at surface)	Krohne Aquaflux 010D, DN20	0–80 l/min	0.003 l/min	± 0.8% o. r. Q>5 l/min*
Spinner (flow in borehole)	SEBA M1	–	1 l/min	± 0.5 l/min**
Temperature	INOR	0–50°C	0.002°C	± 0.5°C
Electrical conductivity	Cole Parmer	0–11,000 mS/m	0.0038% of adjusted range	± 10% o.r.
Length measuring wheel	Leine&Linde (pulse signal)	–	3 mm	± 0.3 m, L< 100 m ± 0.5 m, L> 100 m

* increasing to c 3% o.r. at 1.5 l/min.

** relates to the flow through the spinner probe (not borehole flow).

Table 4-2. Position of sensors (from ToC) and of equipment that may affect wellbore storage for the different hydraulic tests performed.

Borehole information				Sensors		Equipment affecting wellbore storage (WBS)			
ID	Test interval (m)	Test config	Test type [1]	Type	Position (m b ToC)	Function	Position [2] relative test section	Outer diameter (mm)	C (m^3/Pa)
HFR106	9.03–190.4	Open hole	1B	P (P1)	7.5 [3]	Signal cable	Above section	8	$2.3 \cdot 10^{-6}$
					9.0 [3]	Pumping hose	Above section	25	$2.3 \cdot 10^{-6}$
	9.03–185.0	Open hole	6	EC, Te, Q	12.5–185.0	Signal cable	In section	10	$2.3 \cdot 10^{-6}$

[1] 1B: Pumping test-submersible pump, 6: Flow logging–Impeller incl. EC-logging (EC) and temperature logging (Te).

[2] Position of equipment that can affect wellbore storage. Position given as “In Section” or “Above Section”.

[3] The pressure transducer and the pump was lowered 1.5 meter before the start of spinner logging.

4.3 System limitations

The lower measurement limit for the pumping tests with the spinner system may be expressed in terms of specific flow (Q/s). For pumping tests, the practical lower limit is based on the minimum flow rate for which the system is designed (5 L/min) and an estimated maximum allowed drawdown for practical purposes (c 50 m) in a percussion borehole. These values correspond to a practical lower measurement limit (Q/s-L) of $2 \cdot 10^{-6}$ m^2/s for the pumping tests.

Similarly, the practical, upper measurement limit of the spinner system is estimated from the maximal flow rate (c 80 L/min) and a minimal drawdown of c 0.5 m, which is considered significant in relation to e.g. background fluctuations of the pressure before and during the test. These values correspond to an estimated, practical upper measurement limit (Q/s-U) of $3 \cdot 10^{-3}$ m^2/s for pumping tests with spinner.

5 Execution

5.1 Preparations and equipment checks

All sensors included in the measuring system are calibrated at the Geosigma engineering service station in Uppsala. Calibration is generally performed on a yearly basis, but more often if needed. The latest calibrations of temperature and electrical conductivity were performed in April 2008 and of spinner flow in February 2009. If a sensor is replaced at the test site, calibration of the new sensor can be carried out in the field (except the flow probe) or alternatively, in the laboratory after the measurements.

Prior to the tests, an equipment check was performed to establish the operating status of sensors and other equipment. In addition, calibration constants were implemented and checked. To check the function of the pressure sensor P1 (cf. Figure 4-1), the pressure in air was recorded and found to be as expected. While lowering the pressure sensor into the borehole, measured pressure coincided well with the total head of water ($p/\rho \cdot g$). The temperature sensor displayed expected values in both air and water.

The sensor for electric conductivity displayed a zero value in air and a reasonable value in borehole water.

The measuring wheel (used to measure the position of the flow logging probe) and the sensor attached to it indicated a length that corresponded well to the pre-measured length marks on the signal cable.

Before the tests, cleaning of equipment as well as time synchronisation of clocks and data loggers were performed according to the Activity Plan.

5.2 Procedure

5.2.1 Overview

Before the actual flow logging and pumping was performed the access to the borehole was tested by lowering of a dummy probe

The main pumping test was preceded by a shorter capacity test (the day before) to determine a proper pumping flow rate. During the capacity test the flow rate was changed, depending on the obtained response. After the hydraulic test in HFR106, pumping was performed in two sealed off sections including the two detected anomalies in order to collect water samples for chemical analyses.

The main pumping was performed as a constant flow rate test followed by a pressure recovery period. Flow logging was conducted at the end of the flow period.

The measuring probe was lowered down to the starting point in the upper part of the borehole. The submersible pump and a pressure transducer were then lowered in the borehole to a position about 2.5 m above the spinner probe. The pumping was then started and the flow rate was kept at a constant level to achieve approximately steady-state conditions before the spinner probe was lowered in the borehole at a constant speed. For the present test a speed of c 3 m/min was chosen.

When the probe reached a position a few metres above the bottom of the borehole, the pump was shut off and the test was finished. This was done in order to avoid the drill cuttings that accumulate at the bottom of boreholes. Naturally, the test would have been stopped at a higher level if the dummy probe test had indicated access difficulties.

5.2.2 Details

Single-hole pumping and injection tests

The pumping in borehole HFR106 lasted for c 10 h followed by a recovery period of c 14 h.

The recording frequency of pressure and flow during the test started at 1 sample per second and was then altered to a sequence where the sampling interval increased over time, from 1 up to 600 seconds.

Flow logging

During flow logging the locations of inflows along the borehole are identified while pumping.

The flow logging is carried out as a relative measurement where pulses are induced by a spinner (rotating impeller) placed inside a probe tube. The probe is lowered in the borehole, in the opposite direction to the borehole flow, at an even speed controlled by an electrical motor. The rotation of the spinner and hence number of pulses generated is dependent on the water flow in the borehole passing through the probe. The linearity in the relation between pulses per second and flow through the probe is considered as very good. This is confirmed by calibrations of the equipment.

While moving the probe along the borehole, temperature, flow and electric conductivity data are recorded together with time and borehole length at each measuring point.

Flow logging is performed during the later part of the pumping test. The logging starts when the pressure in the borehole is approximately stable. The time needed to complete the flow logging survey depends on the length of the borehole and the logging velocity. Generally, between 1–3 hours is needed for a percussion borehole of 100–200 m length.

5.3 Analyses and interpretation

This section provides a comprehensive general description of the procedure used when analysing data from the hydraulic test.

5.3.1 Single-hole hydraulic tests

Firstly, a qualitative evaluation of the actual flow regimes (wellbore storage, pseudo-linear, pseudo-radial or pseudo-spherical flow) and possible outer boundary conditions during the hydraulic test is performed. The qualitative evaluation is made from analyses of log-log diagrams of drawdown and/or recovery data together with the corresponding derivatives versus time. In particular, pseudo-radial flow (2D) is reflected by a constant (horizontal) derivative in the diagrams. Pseudo-linear and pseudo-spherical flow is reflected by a slope of the derivative of 0.5 and –0.5, respectively, in a log-log diagram. Apparent no-flow- and constant head boundaries are reflected by a rapid increase and decrease of the derivative, respectively.

From the results of the qualitative evaluation, appropriate interpretation models for the quantitative evaluation of the test are selected. In general, a certain period with pseudo-radial flow can be identified during the pumping tests. Consequently, methods for single-hole, constant-flow rate or constant drawdown tests for radial flow in a porous medium described in Almén et al. 1986 /1/ and Morosini et al. 2001 /2/ are generally used by the evaluation of the test. For tests indicating a fractured- or borehole storage dominated response, corresponding type curve solutions are used by the routine analyses.

If possible, transient analysis is applied on both the drawdown- and recovery phase of the test. The recovery data are plotted versus Agarwal equivalent time. Transient analysis of drawdown- and recovery data are made in both log-log and lin-log diagrams as described in the Instruction (SKB MD 320.004). In addition, a preliminary steady-state analysis (e.g. Moye's formula, denoted T_M) is made for comparison according to the following equations:

$$T_M = \frac{Q_p \cdot \rho_w \cdot g}{dp_p} \cdot C_M \qquad \text{Equation 5-1}$$

$$C_M = \frac{1 + \ln\left(\frac{L_w}{2r_w}\right)}{2\pi} \qquad \text{Equation 5-2}$$

where

Q_p = flow rate by the end of the flow period (m^3/s)

ρ_w = density of water (kg/m^3)

g = acceleration of gravity (m/s^2)

C_M = geometrical shape factor (–)

dp_p = pressure change (Pa)

r_w = borehole radius (m)

L_w = section length (m)

The transient analysis was performed using the aquifer test analysis software Aqtesolv which enables both visual and automatic type curve matching with different analytical solutions for a variety of aquifer types and flow conditions. The evaluation is performed as an iterative process of type curve matching and non-linear regression on the test data. For the flow period as well as the recovery period of the constant flow rate tests, a model presented by Dougherty and Babu 1984 /3/ for constant flow rate tests with radial flow, accounting for wellbore storage and skin effects, is generally used for estimating transmissivity, storativity and skin factor for actual values on the borehole- and casing radius.

Aqtesolv also includes other models, for example models for discrete fractures (horizontal and vertical, respectively) intersecting the borehole, causing pseudo-linear flow. For tests characterized by pseudo-spherical (leaky) flow relevant models are also available, e.g. Moench 1985 /4/ for single-hole pumping tests together with Hantush 1959 /5/ and Hantush 1955 /6/ for the flow and recovery period, respectively, of constant head tests. Where single fracture flow is dominant, pseudo-linear flow, e.g. Gringarten and Ramey 1974 /7/ is adaptable. If appropriate, these models may be used in specific cases.

The effective casing radius may be estimated from the analysis of tests affected by wellbore storage. The wellbore storage coefficient can be calculated from the simulated effective casing radius, see below. The effective wellbore radius concept is used to account for negative skin factors.

An empirical regression relationship between storativity and transmissivity, Equation 5-3 is used according to the instruction SKB MD 320.004. Firstly, the transmissivity and skin factor are obtained by type curve matching on the data curve using a fixed storativity value of 10^{-6}. From the transmissivity value obtained, the storativity is then estimated according to Equation 5-3 and the type curve matching is repeated.

$$S=0.0007 \cdot T^{0.5} \qquad \text{Equation 5-3}$$

where

S=storativity (–)

T=transmissivity (m^2/s)

In most cases the change of storativity does not significantly alter the calculated transmissivity by the new type curve matching. Instead, the estimated skin factor, which is directly correlated to the storativity, is altered correspondingly.

The nomenclature used for the simulations with the Aqtesolv code is presented in the beginning of Appendix 2.

Estimations of the borehole storage coefficient, C, based on actual borehole geometrical data (net values) and the water compressibility (for isolated sections) were presented in Table 4-2. The borehole storage coefficient may also be estimated from the early test response with 1:1 slope in a log-log diagram /2/ or alternatively, from the simulated effective casing radius according to Equation 5-4. These values on C may be compared with the net values of the wellbore storage coefficient based on actual borehole geometrical data. The estimated values on C from the test data may differ from the net values due to deviations of the actual geometrical borehole data from the anticipated, e.g. regarding the borehole diameter, or presence of fractures or cavities with significant volumes and/or higher effective compressibility of the test equipment (e.g. packers).

For pumping tests in an open borehole (and in the interval above a single packer) the wellbore storage coefficient may be calculated as:

$C=\pi\ r_{we}^2/\rho g$ Equation 5-4

where

r_{we} = borehole radius where the changes of the groundwater level occur (either r_w or r_c) or alternatively, the simulated effective casing radius r(c)

r_w = nominal borehole radius (m)

r_c = inner radius of the borehole casing (m)

r(c) = simulated effective casing radius (m)

ρ = density of water (kg/m^3)

g = acceleration of gravity (m/s^2)

5.3.2 Flow logging

The actual borehole diameter in a percussion drilled borehole, measured as the diameter of the drill bit, is most often deviating from the nominal diameter. Furthermore, the borehole diameter is normally somewhat larger than the diameter of the drill bit, depending, among other things, on the rock type. The diameter is also decreasing towards depth due to successive wearing of the drill bit. Since the number of counts registered by the spinner in the flow logging probe to a high degree is depending on the borehole diameter, it is generally not possible to use a calibration of the spinner for one single diameter.

For the above reasons the spinner counts, corrected for logging in the undisturbed borehole, are used as relative flow measurements and the flow at a certain borehole length (Q(L)) is determined according to:

$Q(L) = C(L)/\ C_T \cdot Q_{FT}$ Equation 5-5

where

C(L) = spinner counts per sec at length L

C_T = spinner counts per sec at top of logged interval

Q_{FT} = flow at top of logged interval

If the flow logging can be carried out all the way from the lower end of the casing to the bottom of the borehole or if no flow exists above the top of the flow logged interval, Q_{FT} will be equal to the total pumped flow measured at the surface (Q_p).

During pumping, flow logging can only be carried out from the borehole bottom up to a certain distance below the submersible pump (c 2.5 m). If it is not possible to place the pump high enough in the casing there will be a remaining part of the borehole that cannot be flow-logged, although high inflow zones may sometimes be located here. In such cases it is necessary to supplement the flow logging with injection or pumping tests above the highest logged level to be able to determine the flow at top of the flow logged interval (Q_{FT}). Alternatively, if other information (e.g. BIPS logging or drilling information) clearly shows that no inflow occurs in this part of the borehole, no supplementary tests are necessary.

Flow along the borehole, calculated according to Equation 5-5, is plotted, together with temperature and electric conductivity of the borehole fluid, versus borehole length. From these plots, flow anomalies are identified, i.e. borehole intervals over which changes of flow exceeding c 1 L/min occurs. The size of the inflow from an anomaly is determined by the actual change in flow rate across the anomaly. In most cases, the flow changes are accompanied by changes in temperature and/or electric conductivity of the fluid.

Depending on if supplementary tests are carried out, two different methods are employed for estimating the transmissivity of individual flow anomalies in the flow logged interval of the borehole. In both cases the transmissivity of the entire borehole (T) is estimated from the transient analysis of the pumping test.

Method 1

If no significant inflow exists above the flow logged interval, the transmissivity of an individual flow anomaly (T_i) is calculated from the measured inflow (dQ_i) at the anomaly, the discharge Q_p and the calculated transmissivity of the entire borehole (T) according to:

$$T_i = dQ_i / Q_p \cdot T \qquad \text{Equation 5-6}$$

The cumulative transmissivity $T_F(L)$ versus the borehole length (L) as determined from the flow logging may be calculated according to:

$$T_F(L) = Q(L) / Q_p \cdot T \qquad \text{Equation 5-7}$$

Method 2

If additional hydraulic tests show that there exist significant flow anomalies above the flow logged interval, the transmissivity T_A for the non flow logged interval is estimated from these tests. In this case the resulting transmissivity of the flow-logged interval (T_{FT}) is calculated according to:

$$T_{FT} = \Sigma T_i = (T - T_A) \qquad \text{Equation 5-8}$$

where T_A is the transmissivity of the non flow-logged interval.

The resulting flow at the top of the flow logged interval Q_{FT} may be calculated from:

$$Q_{FT} = Q_p \cdot T_{FT}/T \qquad \text{Equation 5-9}$$

The transmissivity of an individual flow anomaly (T_i) is calculated from the relative contribution of the anomaly to the total flow at the top of the flow logged interval (dQ_i/ Q_{FT}) and the calculated transmissivity of the entire flow-logged interval (T_{FT}) according to:

$$T_i = dQ_i / Q_{FT} \cdot T_{FT} \qquad \text{Equation 5-10}$$

The cumulative transmissivity $T_F(L)$ at the borehole length (L) as determined from the flow logging may be calculated according to:

$$T_F(L) = Q(L) / Q_{FT} \cdot T_{FT} \qquad \text{Equation 5-11}$$

6 Results

6.1 Nomenclature and symbols

The nomenclature and symbols used for the results of the pumping tests and flow logging are according to the instruction for analysis of single-hole pumping tests, SKB MD 320.004, and the methodology description for impeller flow logging, SKB MD 322.009.

Nomenclature:

Q/s = specific flow for the borehole and flow anomalies respectively (m^2/s)
dQ_i = measured inflow (m^3/s)
K_r = hydraulic conductivity, radial direction (m/s)
T = transmissivity (m^2/s)
T_M = steady-state transmissivity calculated from Moye's formula (m^2/s)
T_T = judged best estimate of transmissivity (from transient evaluation) (m^2/s)
T_i = estimated transmissivity of flow anomaly (m^2/s)
S_s = specific storage (m^{-1})
S = storativity (–)
C = wellbore storage coefficient
K_Z/K_r = ratio of hydraulic conductivities in the vertical and radial direction (set to 1)
S_w = skin factor (–)
r(w) = borehole radius (m)
r(c) = effective casing radius (m)
R_f = fracture radius (m)
p_0 = air pressure (kPa)
p_i = absolute pressure in test section before start of flow period (kPa)
p_p = absolute pressure in test section at stop of flow period (kPa)
p_F = absolute pressure in test section at stop of recovery period (kPa)
Q_p = pumped flow rate during flow period (m_3/s)
V_p = volume pumped (m^3)
t_P = total flow time (s)
t_F = total recovery time (s)

6.2 Water sampling and analyses

Water samples for chemical analyses were collected in two delimited sections of borehole HFR106, see Table 6-1. The analytical results are presented in Appendix 2.

Table 6-1. Water samples collected in borehole HFR106 and submitted for analysis.

Idcode	Date and time	Section (m)	Pumped volume (m^3)	SKB class	Sample no	Remarks
HFR106	2009-07-08 18:09	175.0–190.4	237	WC100	16327	Closed-hole test
HFR106	2009-07-08 18:54	175.0–190.4	711	WC100	16328	Closed-hole test
HFR106	2009-07-08 19:42	175.0–190.4	1,185	WC100	16329	Closed-hole test
HFR106	2009-07-10 13:39	36.0–41.0	77	WC100	16330	Closed-hole test
HFR106	2009-07-10 14:14	36.0–41.0	231	WC100	16331	Closed-hole test
HFR106	2009-07-10 14:42	36.0–41.0	385	WC100	16332	Closed-hole test

All the six samples show acceptable charge balance and also consistency between electrical conductivity and chloride concentration, indicating consistent data sets for the major constituents. Furthermore, the groundwater composition is reasonably stable for the three samples from the shallow section. The three samples from the deep section, on the other hand, show a trend towards more saline water with pumping time and the composition of the first collected sample resembles the samples from the shallow section. This trend is probably due to a decreasing contribution from the water column present in the borehole as the pumping proceeds. For this reason, it is uncertain whether the last deep sample represents the formation water at this position in the borehole or whether the salinity would have increased even more if the sampling had continued.

Some observations from the compilation of chemical data are listed below:

- As expected, Uranine is not present in the samples since Uranine marked flushing water is not used for drilling of percussion boreholes. A measurable Uranine concentration might have indicated hydraulic connection with one of the previously drilled core boreholes but this was not the case.
- The salinity of the groundwaters from both borehole sections is close to the salinity of modern Baltic Sea water outside Forsmark. As expected the chloride concentration is somewhat higher in the deep section compared to the shallow section. Taken together, the magnesium concentrations (129–140 mg/L), the oxygen-18 signatures ($\delta^{18}O$ between –8.6 and –10‰V SMOW) and the tritium contents of the groundwaters (5.5–9.8 TU) indicate a considerable contribution of water from the present Baltic Sea. The tritium contents in the deep section show a decreasing trend which may imply that the last water sample does not fully represent formation water of the hydraulic anomaly. Continued pumping and more samples whould have been needed in order to minimise the contribution of mixed section water and to verify the representativity.
- High concentrations of some trace metals are observed in a few samples. This is probably due to contamination from borehole equipment during drilling and subsequent investigations. Especially the first sample from the deep section (Sample no. 16327) shows enhanced concentrations of iron, aluminium, chromium, cupper, lead, zinc, vanadium, among others. Also the uranium concentration deviates from the two other samples, see next point.
- High uranium concentrations were encountered also in the two sections of this borehole like in the previously investigated SFR-boreholes. The samples from the shallow section show a high and relatively stable uranium concentration between 115 and 137 μg/L, while the samples from the deep section show a decreasing trend from 115 to 67 μg/L. This may be due to decreasing contribution from the water column present in the borehole section and a higher uranium concentration in this water compared to the water of the water yielding fracture.

6.3 Single-hole hydraulic tests

The results of the single-hole hydraulic test are presented in this section. Atmospheric pressure and precipitation were monitored at the site during the testing period. However, the measured data have not been corrected, e.g. for changes of the atmospheric pressure or tidal fluctuations. For the actual type of single-hole tests such corrections are generally not needed considering the relatively short test time and large drawdown applied in the boreholes. For longer tests with a small drawdown applied, corrections may be necessary.

Drilling records and other activities were checked in the SKB database Sicada to identify possible interference on the hydraulic test data from activities in nearby boreholes during the test periods. However, according to Sicada no such activities took place during the test period.

6.3.1 Borehole HFR106: 9.0–190.4 m

General test data for the open-hole pumping test in HFR106 are presented in Table 6-2.

The atmospheric pressure during the entire test period in HFR106 is presented in Figure 6-1. During the hydraulic test period 090707 09:35–090708 10:20 the atmospheric pressure varied c 0.4 kPa, i.e. only c 0.7% of the total displacement of 5.73 m, and thus the effect of atmospheric pressure variations on the test result is considered negligible. Between 8 and 10 am 090707, 10 mm precipitation were measured in the area but this does not seem to affect the ground water level during the test.

Table 6-2. General test data, pressure, groundwater level and flow data for the open-hole pumping test in borehole HFR106.

General test data				
Borehole	HFR106 (9.0–190.4 m)			
Test type	Constant rate withdrawal and recovery test			
Test section (open borehole/packed-off section):	Open borehole			
Test No	1			
Field crew	J. Harrström, T. Svensson, GEOSIGMA AB			
Test equipment system	Geosigma spinner			
General comment	Single pumping borehole			
	Nomenclature	**Unit**	**Value**	
Borehole length	L	m	190.4	
Casing length	L_c	m	9.03	
Test section-secup	Secup	m	9.0	
Test section-seclow	Seclow	m	190.4	
Test section length	L_w	m	181.4	
Test section diameter	$2 \cdot r_w$	mm	top 141.1 bottom 138.8	
Test start (start of pressure registration)		yymmdd hh:mm:ss	090707 09:53	
Packer expanded		yymmdd hh:mm:ss		
Start of flow period		yymmdd hh:mm:ss	090707 09:53	
Stop of flow period		yymmdd hh:mm:ss	090707 20:06	
Test stop (stop of pressure registration)		yymmdd hh:mm:ss	090708 10:21	
Total flow time	t_p	Min	612	
Total recovery time	t_F	Min	843	

Pressure data	**Nomenclature**	**Unit**	**Value**	**GW Level (masl)** [1]
Absolute pressure in test section before start of flow period	p_i	kPa	151.3	–0.28
Absolute pressure in test section at stop of flow period	p_p	kPa	99.5	
Absolute pressure in test section at stop of recovery period	p_F	kPa	149.8	–0.66
Maximal pressure change in test section during the flow period	dp_p	kPa	56.2	

Manual groundwater level measurements			**GW level**	
Date YYYY-MM-DD	**Time tt:mm:ss**	**Time (min)**	**(m b ToC)**	**(m a s l)**
2009-07-06	10:30	–1403	2.08	–0.55
2009-07-08	10:20	1467	2.59	–0.99

Flow data	**Nomenclature**	**Unit**	**Value**
Flow rate from test section just before stop of flow period	Q_p	m^3/s	$8.3 \cdot 10^{-4}$
Mean (arithmetic) flow rate during flow period [2]	Q_m	m^3/s	$8.3 \cdot 10^{-4}$
Total volume discharged during flow period [2]	V_p	m^3	30.5

[1] From the manual measurements of groundwater level.

[2] Calculated from integration of the transient flow rate curve during the injection period.

Comments on test

The day before test start, a short capacity test was performed in HFR106 during observation of the drawdown response. The flow rate was first set to 52 L/min for about 15 minutes and then lowered to 45 L/min for another 5 minutes. By the end of the capacity test, the drawdown was c 1.5 m. The actual pumping test was conducted as a constant flow rate test (c 50 L/min) with the intention to achieve (approximately) steady-state conditions during the flow logging. The drawdown at the end of the 10-hour pumping period was c 5.73 m.

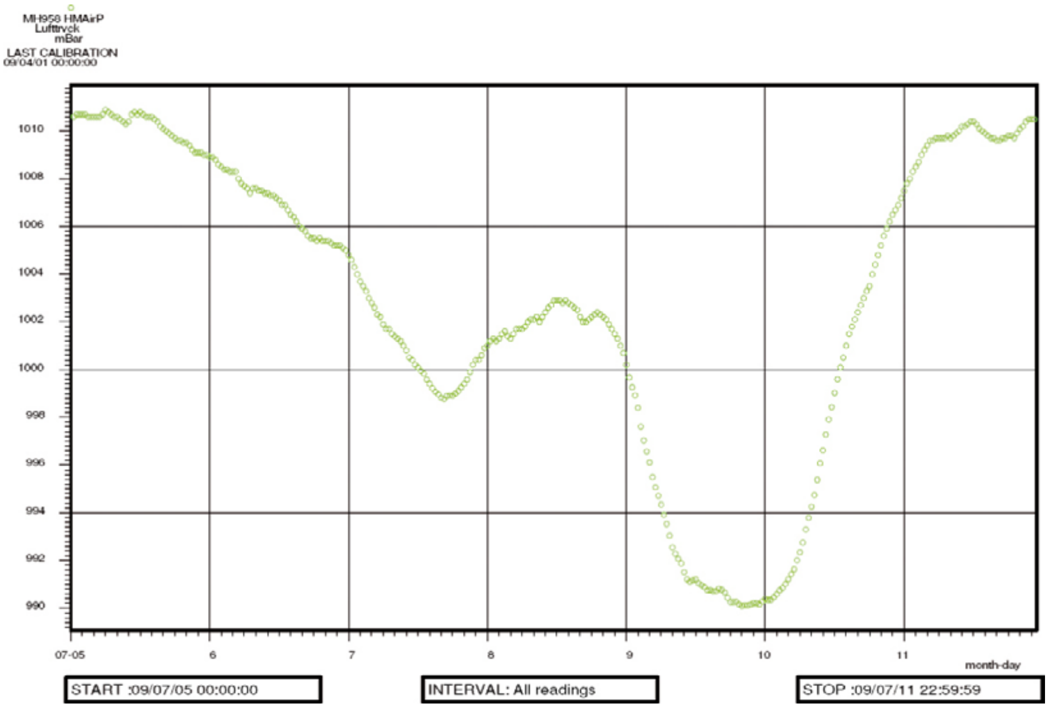


Figure 6-1. *Atmospheric pressure during the test period in HFR106.*

During the flow logging, the pump stopped after about 7.5 hours of pumping due to overheating in a distribution box. This stop is seen as a drawdown peak in the plot in Figure 6-2. To ensure that no anomalies were missed due to the power failure, the spinner was raised about 20 m before the pressure had stabilized and the logging started again.

Some problems with the loggers memory function caused overwriting of some data and the first hours of pumping data is missing. This is however not assumed to affect the evaluation of the pumping test.

Interpreted parameters and flow regimes

Selected test diagrams according to the Instruction for analysis of injection- and single-hole pumping tests are presented in Appendix 1.

Transient evaluation of transmissivity was performed for both the flow- and recovery period, estimated both by transient evaluation (T_T) using the Dougherty-Babu model for radial flow and Gringarten-Ramey model for linear flow (Appendix 1; Figure A-1–Figure A-8,) and with a stationary evaluation according to Moye (T_M), se Equation 5-1.

Since data is missing in the beginning of the draw down period and a pump stop occurred in the middle of the pumping, the derivate is scattered and difficult to interpret. Both pseudo-linear and pseudo-radial flow is possible interpretations of the flow regime. The diagnostics of the Aqtesolv fit shows that pseudo-linear flow regime is dominated. This is also, to some degree, supported by the results from the flow logging (Figure 6-11) showing only two dominant fractures in the borehole.

The representative transmissivity (T_T) is chosen from the transient evaluation of the draw down period with the Gringarten-Ramey model for linear flow and a plot of the evaluation in Aqtesolve is seen in Figure 6-3. Evaluation with a two-dimensional model also indicates a linear flow. The agreement between the evaluations of the flow and recovery period regarding transmissivity and skin factor is good. But the plot of the drawdown evaluation shows a better fit to the data and is therefore chosen as representative.

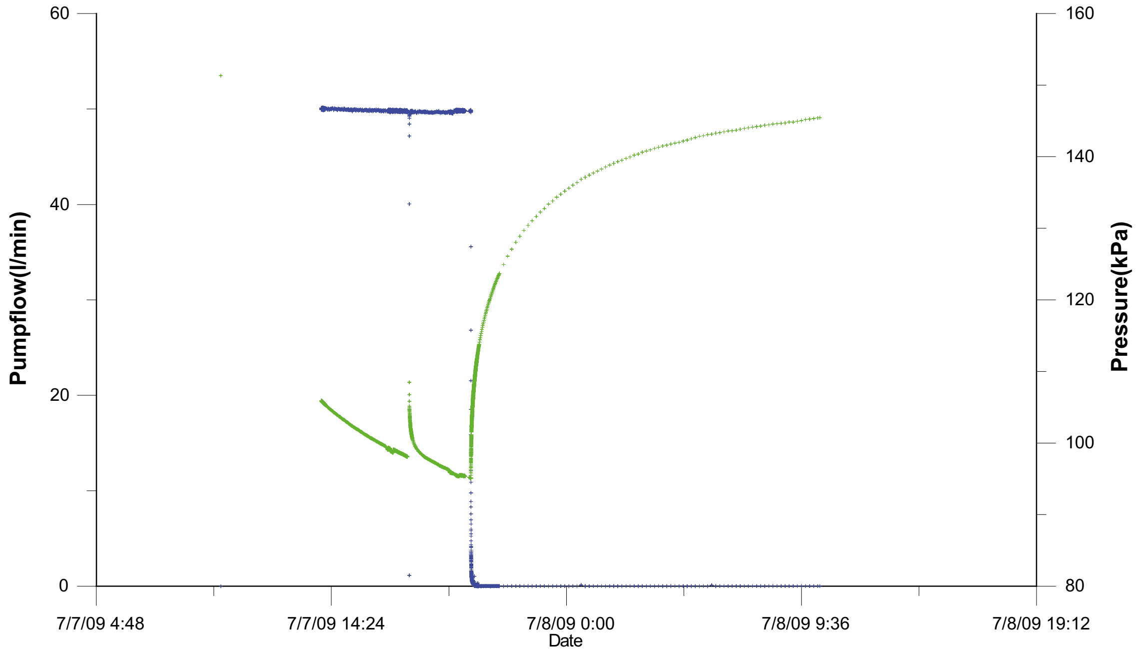


Figure 6-2. *Linear plot of flow rate (Q) and pressure (P) versus time during the open-hole pumping test in HFR106 in conjunction with flow logging.*

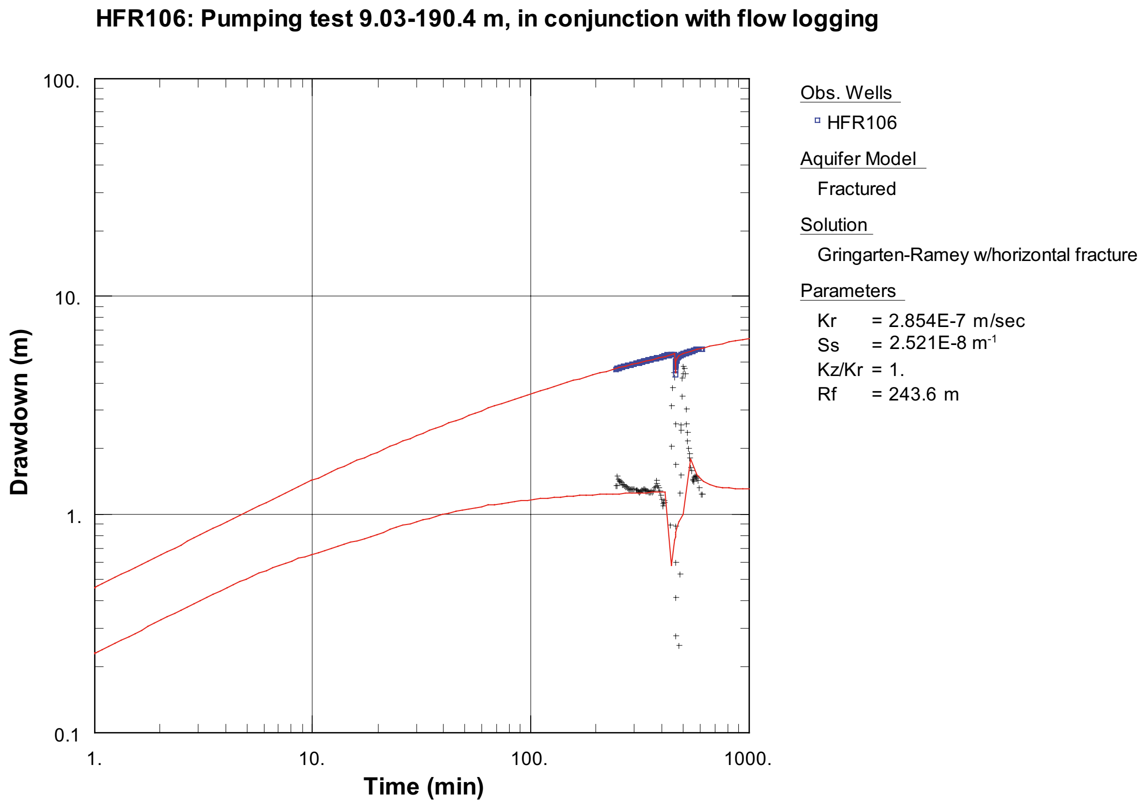


Figure 6-3. *Log-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole pumping test in HFR106. Single-fracture, one-dimension model.*

6.4 Flow logging

General test data for the flow logging in borehole HFR106 are presented in Table 6-3.

Logging results

The nomenclature used in this report is according to the method description for flow logging. The measured flow distribution along the borehole during the flow logging together with the electric conductivity (EC) and temperature of the borehole fluid are presented in Figure 6-4.

The figure presents calculated borehole flow rates according to Equation 5-5. The logging of the borehole started at about 13.7 m below top of casing which is where the borehole casing ends. Since no water inflow above about 40 m was detected during drilling of the borehole Method 1 in section 5.3.2 was used to evaluate the flow logging.

The flow logging shows two anomalies, at 38–40 m and at 177.3–178.5 m borehole length, respectively. A small change in temperature during the logging in undisturbed conditions indicates slightly warmer water from the anomaly at 38–40 m.

The logged flow data plotted in Figure 6-4 is very scattered and this is probably due to the rough walls of the borehole, causing the spinner to move down at an irregular speed. This is verified by a part of the borehole which is logged twice (c 120–140 m). Exactly the same scattering pattern was observed from both logging sequences which indicate that the effect is caused by the boreholes appearance.

The results of the flow logging in borehole HFR106 are presented in Table 6-4 below. The inflow from the individual flow anomalies (dQ_i) are calculated as the difference between the borehole flow above and below the anomaly, calculated from Equation 5-5. Then the corresponding transmissivity values (T_i) are calculated from Equation 5-6. The borehole transmissivity for the entire borehole (T) is taken from the transient evaluation of the pumping test, performed in conjunction with the flow logging (cf. 6.3.1).

In Table 6-4 the interpreted anomalies and their extension along the borehole as well as calculated inflow values and estimated transmissivity values are presented.

Table 6-3. General test data, groundwater level and flow data for the flow logging in borehole HFR106.

General test data				
Borehole	HFR106			
Test type(s) [1]	6, L-EC, L-Te			
Test section:	Open borehole			
Test No	1			
Field crew	J. Harrström, T. Svensson, GEOSIGMA AB			
Test equipment system	Geosigma spinner			
General comments	Single borehole pumping			
	Nomenclature	**Unit**	**Value**	
Borehole length		m	190.4	
Pump position (lower level)		m	At surface	
Flow logged section–Secup		m	9.03	
Flow logged section–Seclow		m	185	
Test section diameter	2·rw	mm	top 141.1 bottom 138.8	
Start of flow period		yymmdd hh:mm	090707 09:53	
Start of flow logging		yymmdd hh:mm	090707 16:41	
Stop of flow logging		yymmdd hh:mm	090707 19:51	
Stop of flow period		yymmdd hh:mm	090707 20:06	
Groundwater level	**Nomenclature**	**Unit**	**G.w-level (m b ToC)**	**G.w-level (m a s l) [2]**
Groundwater level in borehole, at undisturbed conditions , open hole	h_i	m	2.08	–0.55
Groundwater level (steady state) in borehole, at pumping rate Q_p	h_p	m		
Displacement during flow logging at pumping rate Q_p	s_{FL}	m		5.73
Flow data	**Nomenclature**	**Unit**	**Flow rate**	
Flow rate at the end of pumping period	Q_p	m^3/s	$8.3 \cdot 10^{-4}$	
Minimal change of borehole flow rate to detect flow anomaly	dQ_{Anom}	m^3/s	$1.7 \cdot 10^{-5}$	

[1)] 6: Flow logging-Impeller, L-EC: EC-logging, L-TE: temperature logging.

[2)] Calculated from the manual measurements of groundwater level.

Table 6-4. Interpreted anomalies, calculated flows and estimated transmissivities along borehole HLR106.

Anomaly (#)	Bh-length (m)	dQi (l/min)	TI (m^2/s)	Supporting information
1	177.3–178.5	20.00	2.1E–05	Temp, (EC)
2	38–40	30.00	3.1E–05	Temp, (EC)
∑Bh	9.03–178.5	50.00	5.2E–05	

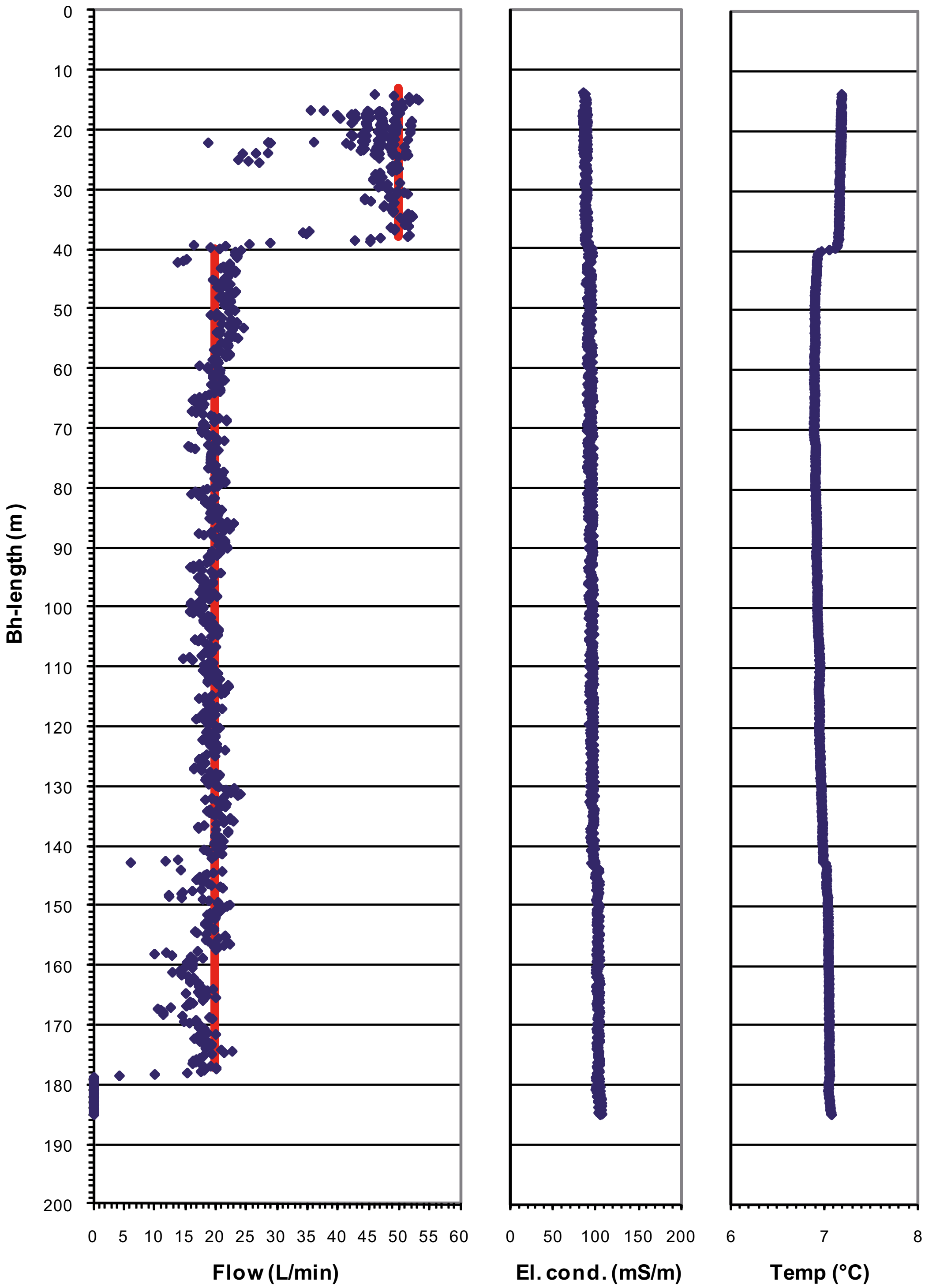


Figure 6-4. *Inflow distribution together with electrical conductivity and temperature of the borehole fluid along borehole HFR106 during flow logging.*

6.5 Summary of hydraulic tests

Data and parameters calculated from the hydraulic test in HFR106 are presented in Table 6-5 and in the test summary sheet in Table 6-6.

Both the evaluation with the 2 D model according to Dougherty-Babu, with negative skin, and the 1 D model according to Gringarten-Ramey, with best fit, indicate that the linear flow regime is dominating the borehole. This is valid both for pumping and recovery periods, (cf. section 6.3.1). The flow logging also show two evident anomalies, one at 38–40 m and one at 177.3–178.5 m.

Table 6-5. Summary of calculated hydraulic parameters from the hydraulic test performed in borehole HFR106 in the SFR area.

Borehole ID	Section (m)	Flow anomaly interval (m)	Test type [1]	Q/s (m^2/s)	T_M (m^2/s)	T_T (m^2/s)	S_s (m^{-1})	C [2] (m^3/Pa)	V_p (m^3)
HFR106	9.03–190.4		1B	$1.4\cdot10^{-4}$	$1.9\cdot10^{-4}$	$5.2\cdot10^{-5}$	$2.5\cdot10^{-8}$	$2.3\cdot 10^{-6}$	30.5
	12.5–185.0 (f)	38.0–41.0	6	$8.7\cdot10^{-5}$	$7.6\cdot10^{-5}$	$2.1\cdot10^{-5}$			
	12.5–185.0 (f)	177.3–178.5	6	$5.8\cdot10^{-5}$	$1.1\cdot10^{-4}$	$3.1\cdot10^{-5}$			

[1] 1B: Pumping test-submersible pump, 6: Flow logging–Impeller.

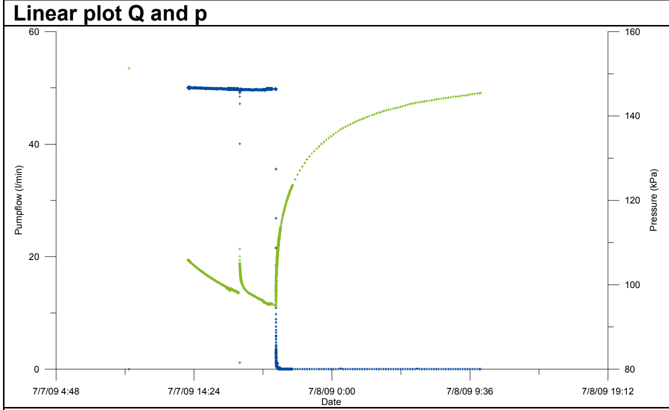
[2] When the fictive casing radius r(c) can be obtained from the parameter estimation in the transient analyses, C is calculated according to Equation 5-4.

(f) Flowlogged interval.

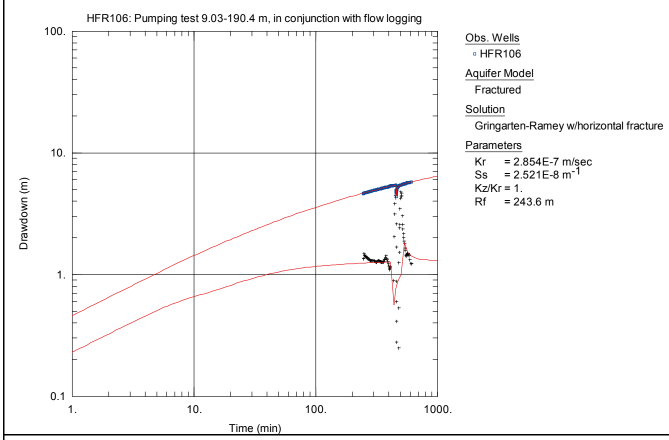
Table 6-6. Test Summary Sheet for the injection test in HFR106, section 9.03–190.4 m.

Test Summary Sheet			
Project:	SFR - utbyggnad	Test type:	3
Area:	Forsmark	Test no:	1
Borehole ID:	HFR106	Test start:	2009-07-07 09:53
Test section (m):	9.03-190.4	Responsible for test performance:	Geosigma AB J. Harrström, T. Svensson
Section diameter, $2 \cdot r_w$ (m):	top 0.160 bottom 0.140	Responsible for test evaluation:	Geosigma AB S. Jönsson, P.Thur

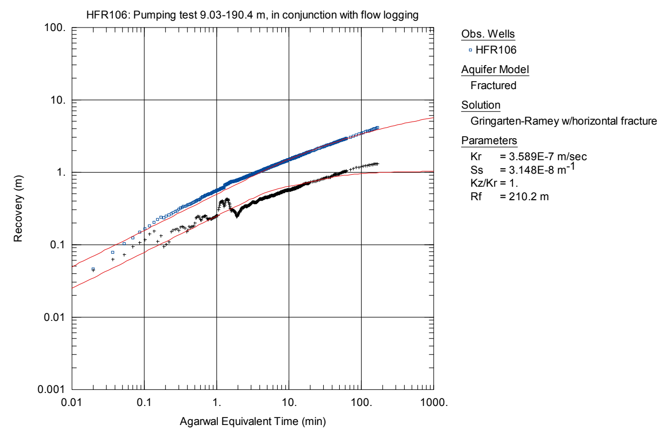
Linear plot Q and p



Log-Log plot incl. derivate- flow period



Log-Log plot incl. derivative- recovery period



Flow period*		**Recovery period***	
Indata		**Indata**	
p_0 (kPa)			
p_i (kPa)	151.3		
p_p(kPa)	99.8	p_F (kPa)	149.8
Q_p (m^3/s)	$8.3 \cdot 10^{-4}$		
tp (min)	612	t_F (min)	843
S		S	
EC_w (mS/m)			
Te_w(gr C)			
Derivative fact.	0.1	Derivative fact.	0.2
Results		**Results**	
Q/s (m^2/s)	$1.4 \cdot 10^{-4}$		
T_{Moye}(m^2/s)	$1.9 \cdot 10^{-4}$		
Flow regime:	PLF	Flow regime:	PLF
t_1 (min)	246	dt_{e1} (min)	612
t_2 (min)	612	dt_{e2} (min)	843
T_w (m^2/s)	$5.2 \cdot 10^{-5}$	T_w (m^2/s)	$6.5 \cdot 10^{-5}$
S_w (-)		S_w (-)	
K_{Sw}(m/s)		K_{sw} (m/s)	
S_{sw} (1/m)	$2.5 \cdot 10^{-8}$	S_{sw} (1/m)	$3.1 \cdot 10^{-8}$
C (m^3/Pa)	$2.3 \cdot 10^{-6}$	C (m^3/Pa)	$2.3 \cdot 10^{-6}$
C_D (-)		C_D (-)	
S_w (-)		S_w (-)	
T_{GRF}(m^2/s)		T_{GRF}(m^2/s)	
S_{GRF}(-)		S_{GRF}(-)	
D_{GRF} (-)		D_{GRF} (-)	

Interpreted formation and well parameters.

Flow regime:	PLF	C (m^3/Pa)	$2.3 \cdot 10^{-6}$
t_1 (min)	246	C_D (-)	
t_2 (min)	612	S_w (-)	
T_T (m^2/s)	$5.2 \cdot 10^{-5}$		
S (-)			
K_s (m/s)			
S_s (1/m)	$2.5 \cdot 10^{-8}$		

Comments:

A pseudo-linear flow may be seen both during the flow period and during the recovery. The early phase of the flow period is missing due to logging failure and wellbore storage is therefore neither confirmed or excluded.

The results from the pumping period are chosen as the most representative.

An alternative evaluation can be made using a model for radial flow regime.

7 References

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/3/ **Dougherty, D E, D K Babu, 1984.** Flow to a partially penetrating well in a double-porosity reservoir, Water Resour. Res., 20 (8), 1116–1122.

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/7/ **Gringarten A C, Ramey H J, 1974.** Unsteady state pressure distributions created by a well with a single horizontal fracture, partial penetration or restricted entry. Soc. Petro. Engrs. J, pp. 413–429.

Plots of pumping test evaluations in Aqtesolve

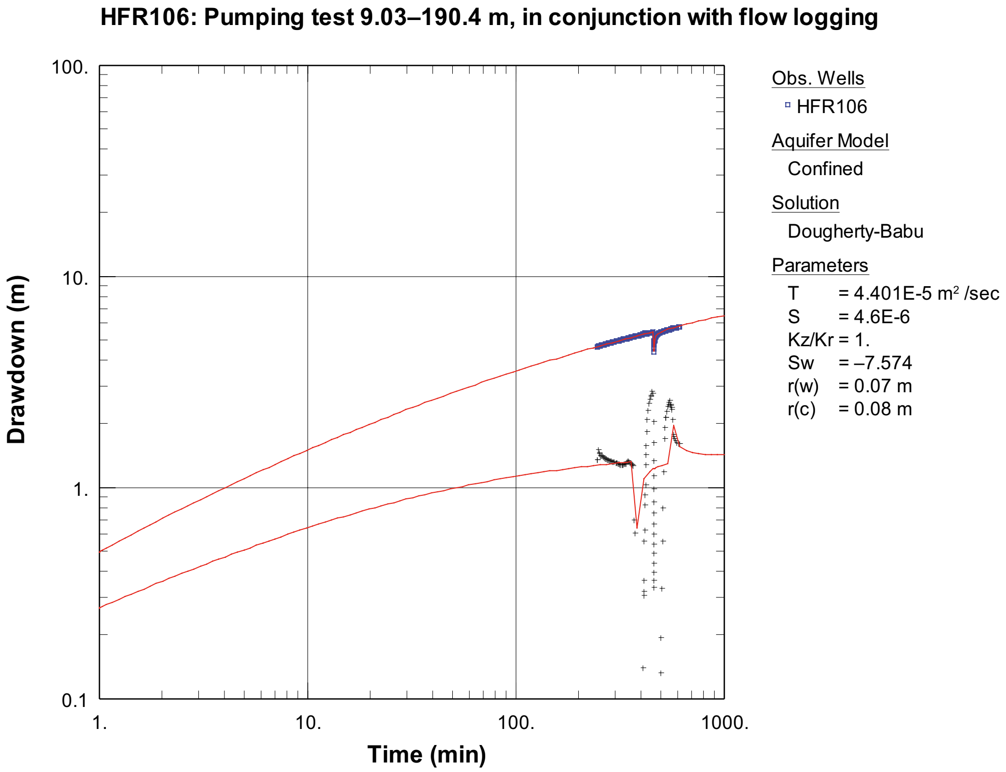

Figure A-1. *Log-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole pumping test in HFR106. Radial, two-dimension model.*

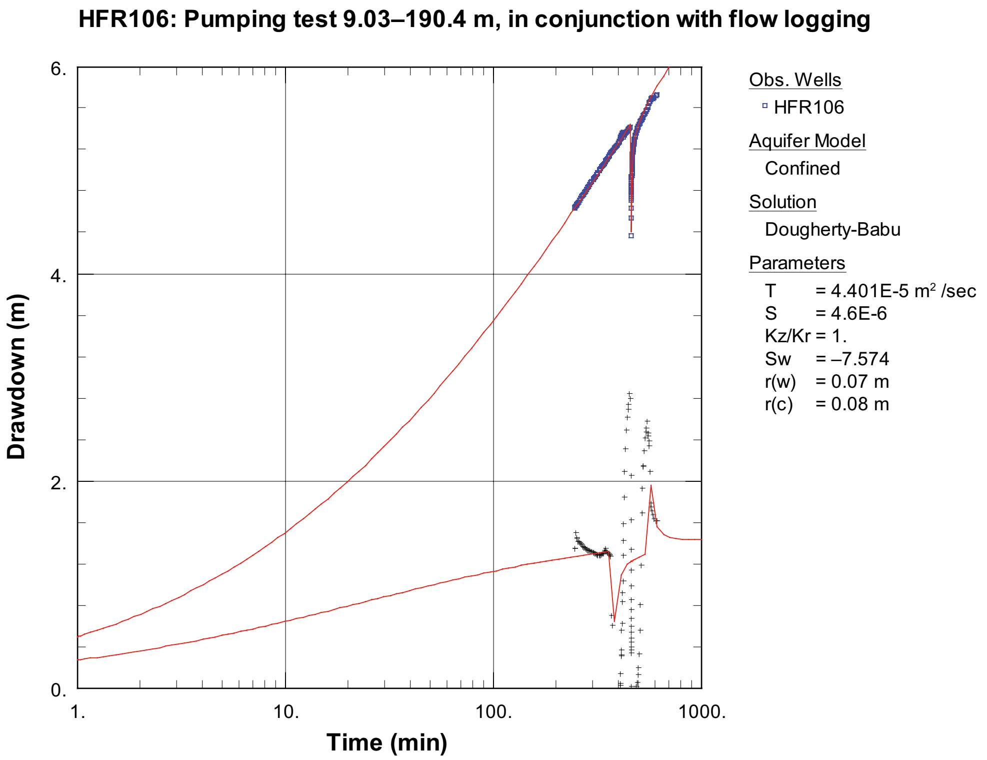

Figure A-2. *Lin-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole pumping test in HFR106. Radial, two-dimension model.*

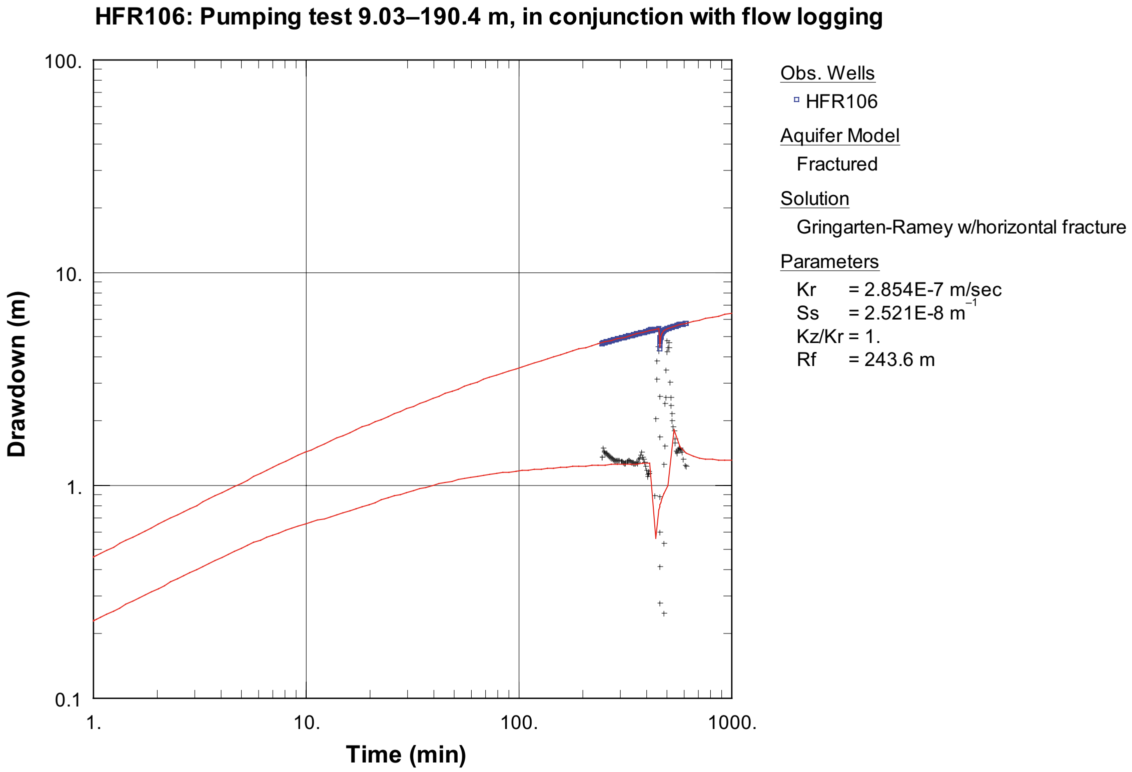

Figure A-3. *Log-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole pumping test in HFR106. Single-fracture, one-dimension model.*

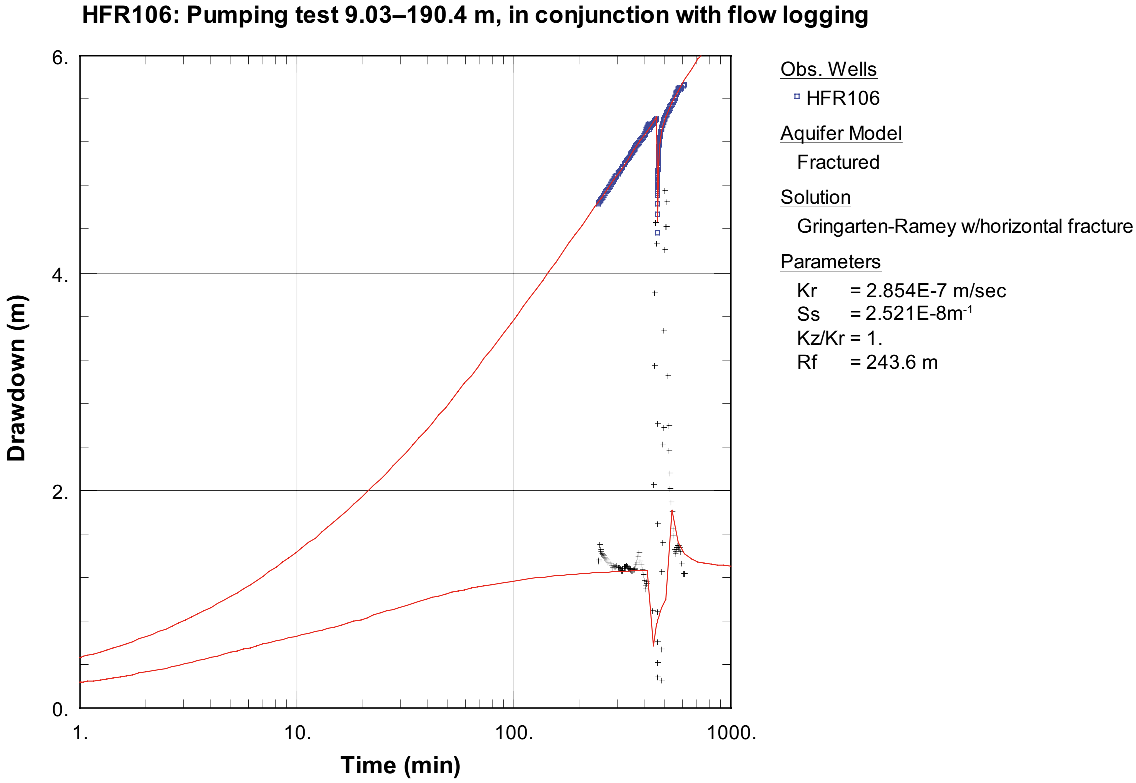

Figure A-4. *Lin-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole pumping test in HFR106. Single-fracture, one-dimension model.*

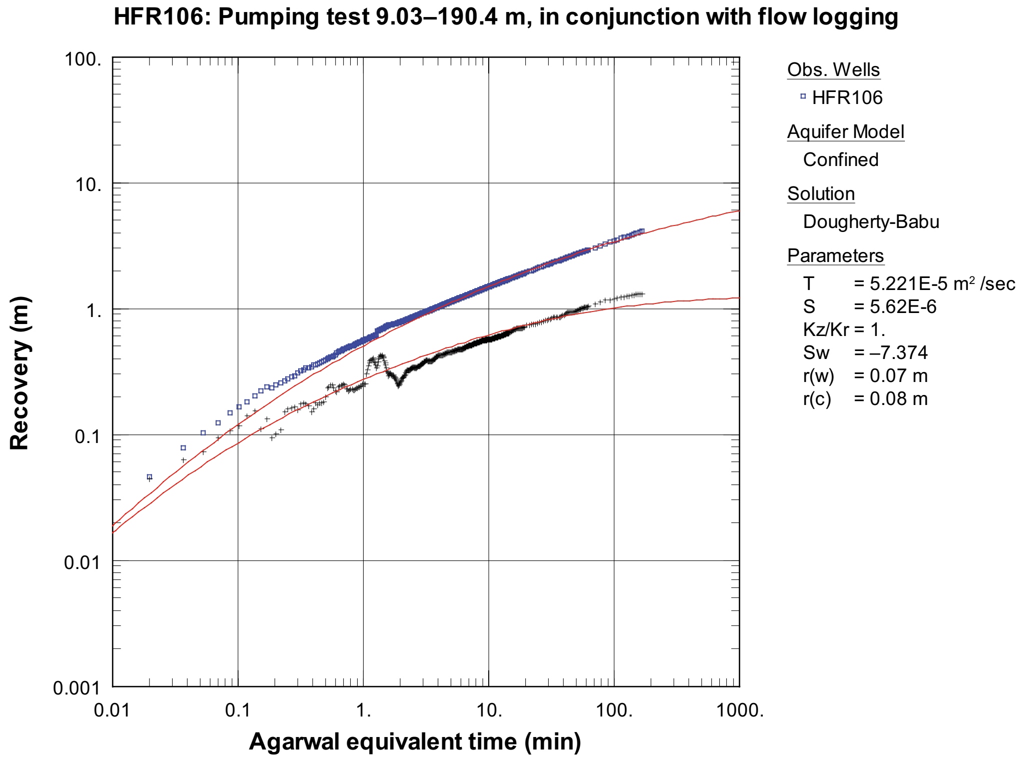

Figure A-5. *Log-log plot of recovery (blue □) and recovery derivative (black +) versus time during the open-hole pumping test in HFR106. Radial, two-dimension model.*

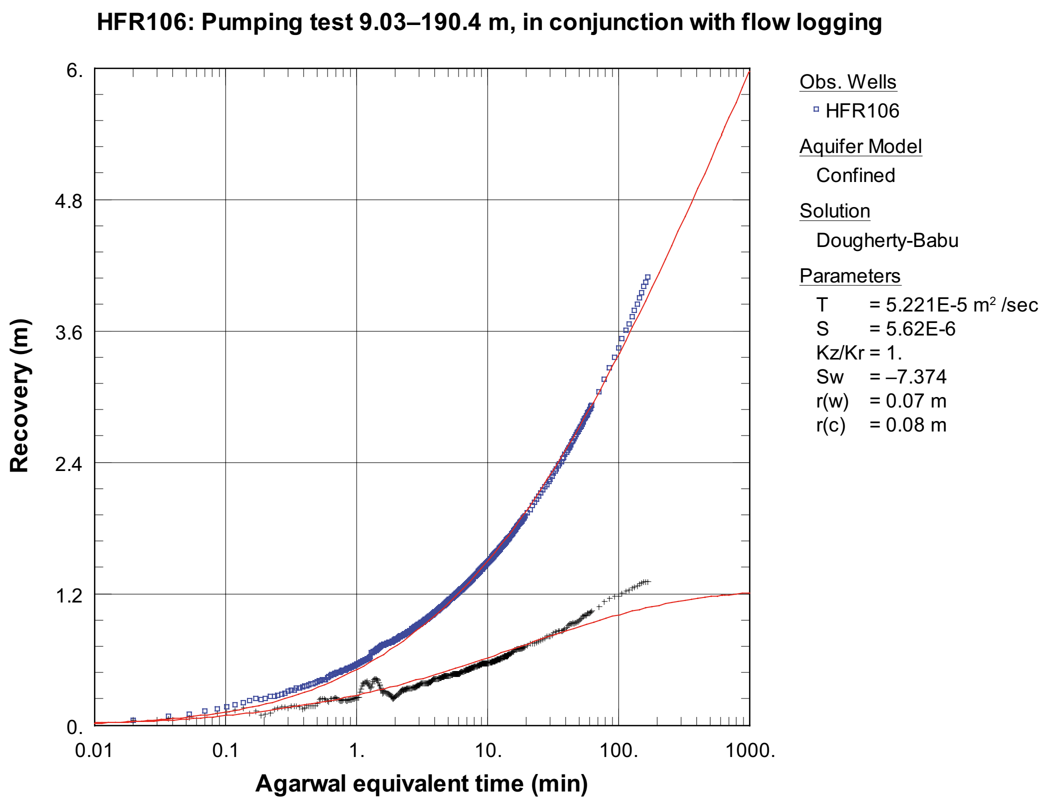

Figure A-6. *Lin-log plot of recovery (blue □) and recovery derivative (black +) versus time during the open-hole pumping test in HFR106. Radial, two-dimension model.*

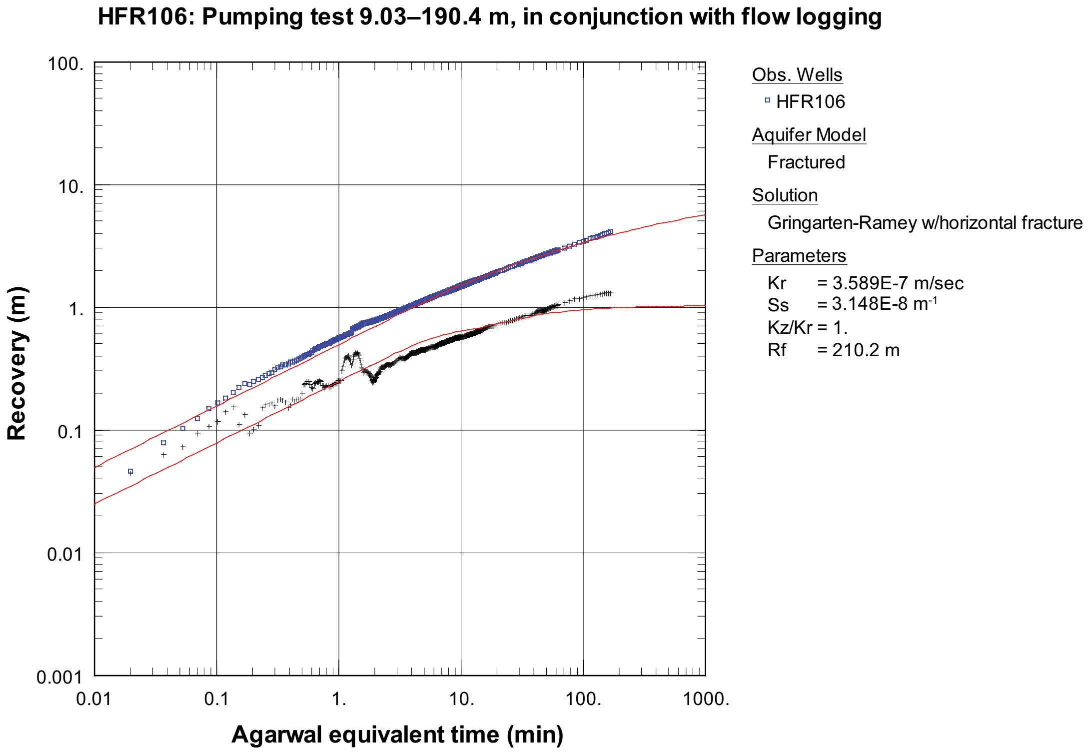

Figure A-7. *Log-log plot of recovery (blue □) and recovery derivative (black +) versus time during the open-hole pumping test in HFR106. Single-fracture, one-dimension model.*

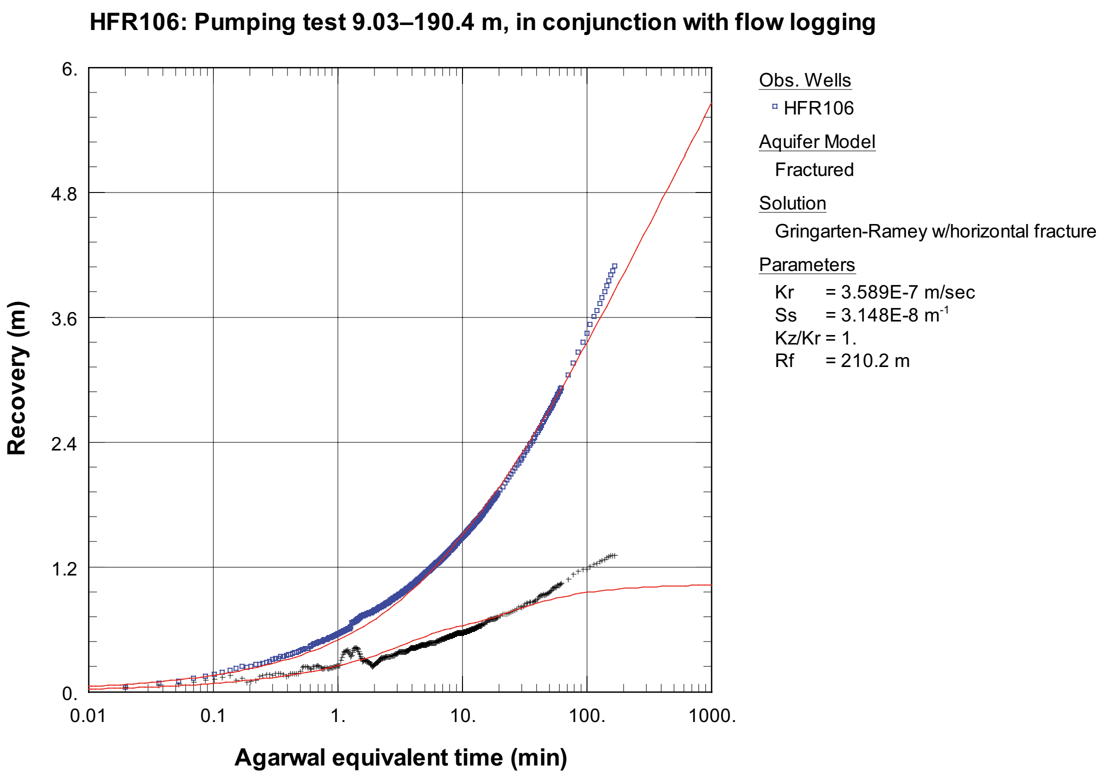

Figure A-8. *Lin-log plot of recovery (blue □) and recovery derivative (black +) versus time during the open-hole pumping test in HFR106. Single-fracture, one-dimension model.*

Appendix 2

Chemistry data from water sampling

Water composition

Sample No.	Date	Secup (mbl)	Seclow (mbl)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	HCO_3 (mg/l)	Cl (mg/l)	SO_4 (mg/l)	SO_4-S (mg/l)	Br (mg/l)	F (mg/l)	Si (mg/l)	Fe (mg/l)	Fe-tot (mg/l)	Fe(II) (mg/l)	Mn (mg/l)
16327	2009-07-08	175.0	190.4	1,470	31.7	267	129	151	2,860	348	124	9.53	1.18	8.02	4.70	2.66	1.03	0.638
16328	2009-07-08	175.0	190.4	1,440	24.7	416	131	130	3,150	322	122	10.9	1.23	6.22	0.970	0.937	0.746	0.739
16329	2009-07-08	175.0	190.4	1,490	22.0	467	130	122	3,290	304	115	11.3	1.26	5.81	0.689	0.628	0.627	0.797
16330	2009-07-10	36.0	41.0	1,420	35.5	199	132	155	2,630	345	127	8.82	1.12	5.27	0.309	0.272	0.252	0.534
16331	2009-07-10	36.0	41.0	1,480	36.0	209	134	156	2,750	357	130	9.05	1.13	5.53	0.342	0.341	0.341	0.557
16332	2009-07-10	36.0	41.0	1,420	35.6	222	140	155	2,750	355	129	9.02	1.13	5.57	0.373	0.366	0.366	0.570

Sample No.	Li (mg/l)	Sr (mg/l)	pH (pH unit)	EC (mS/m)	Uranine (ug/l)	TOC (mg/l)	DOC (mg/l)	I (mg/l)	NO_2-N (mg/l)	NO_3-N (mg/l)	NO_2+NO_3-N (mg/l)	NH_4-N (mg/l)	PO_4-P (mg/l)	PO_4-P HLYSIS (mg/l)	P (mg/l)	RCB (%)
16327	0.0392	3.210	7.53	896.0	0.00	2.5	2.3	0.0239	0.0005	0.0553	0.0558	0.3030	–0.0005	0.0096	0.02420	–1.25
16328	0.0405	5.440	7.48	960.0	0.05	2.4	1.9	0.0301	0.0003	0.0172	0.0175	0.2620	–0.0005	0.0022	–0.00500	–1.97
16329	0.0438	6.520	7.50	1,000.0	0.05	1.6	1.6	0.0449	0.0003	0.0206	0.0209	0.2710	–0.0005	0.0005	–0.00500	–1.30
16330	0.0313	2.010	7.55	840.0	0.00	2.5	2.4	0.0179	0.0003	0.0215	0.0217	0.3070	–0.0005	0.0005	–0.00500	–0.77
16331	0.0328	2.160	7.51	861.0	0.05	2.4	2.2	0.0167	0.0002	0.1920	0.1920	0.3240	–0.0005	0.0019	–0.00500	–0.91
16332	0.0296	2.120	7.47	873.0	0.10	2.3	2.3	0.0118	0.0002	0.0871	0.0872	0.3520	–0.0005	0.0015	–0.00500	–1.72

Isotopes

Sample No.	Date	Secup (mbl)	Seclow (mbl)	$\delta^{34}S$ SO_4 (‰ CDT)	$^{10}B/^{11}B$ (no unit)	$^{87}Sr/^{86}Sr$ (no unit)	δ^2H (‰ V SMOW)	^3H (TU)	$\delta^{18}O$ (‰ V SMOW)
16327	2009-07-08	175.0	190.4	20.8	0.2365	0.716678	–70.0	8.5	–8.90
16328	2009-07-08	175.0	190.4	22.2	0.2355	0.716668	–77.7	6.7	–10.10
16329	2009-07-08	175.0	190.4	22.5	0.2360	0.716653	–78.9	5.5	–10.00
16330	2009-07-10	36.0	41.0	21.4	0.2370	0.716352	–66.0	9.8	–8.60
16331	2009-07-10	36.0	41.0	21.4	0.2374	0.716591	–66.0	8.9	–8.70
16332	2009-07-10	36.0	41.0	21.4	0.2373	0.716613	–67.6	9.2	–8.80

Abreviations and explanations:
mbl = metre borehole length
EC = Electrical Conductivity
PO_4-P HYLYSIS = method including acidic hydrolysis
RCB = Relative Charge Balance

Trace elements

Sample No.	Date	Secup *(mbl)*	Seclow *(mbl)*	Al *(ug/l)*	As *(ug/l)*	B *(ug/l)*	Ba *(ug/l)*	Cd *(ug/l)*	Cr *(ug/l)*	Cu *(ug/l)*	Co *(ug/l)*	Hg *(ug/l)*	Ni *(ug/l)*	Mo *(ug/l)*	Pb *(ug/l)*	V *(ug/l)*
16327	2009-07-08	175.0	190.4	1,070	1.60	685	52.8	0.0981	2.00	9.06	0.846	-0.002	2.60	10.6	31.2	2.88
16328	2009-07-08	175.0	190.4	146	0.800	756	57.9	0.0545	0.447	2.94	0.251	-0.002	1.50	9.86	3.86	0.401
16329	2009-07-08	175.0	190.4	26.1	0.700	765	59.7	-0.02	-0.04	0.880	0.103	-0.002	0.744	10.1	0.521	0.0947
16330	2009-07-10	36.0	41.0	124	0.800	679	36.6	0.0379	0.880	2.21	0.267	-0.002	1.48	8.75	0.605	0.324
16331	2009-07-10	36.0	41.0	11.6	0.900	683	36.3	0.0250	0.104	0.788	0.219	-0.002	1.09	7.97	0.262	0.270
16332	2009-07-10	36.0	41.0	65.4	0.800	737	39.9	0.0300	0.156	0.974	0.201	-0.002	0.778	9.45	0.308	0.319

Sample No.	Date	Secup *(mbl)*	Seclow *(mbl)*	Zn *(ug/l)*	U *(ug/l)*	Th *(ug/l)*	Sc *(ug/l)*	Rb *(ug/l)*	Y *(ug/l)*	Zr *(ug/l)*	In *(ug/l)*	Sb *(ug/l)*	Cs *(ug/l)*	La *(ug/l)*	Hf *(ug/l)*	Tl *(ug/l)*	Ce *(ug/l)*
16327	2009-07-08	175.0	190.4	32.5	115	0.576	0.437	21.0	11.0	3.13	-0.2	0.562	0.878	2.24	0.0859	-0.05	4.84
16328	2009-07-08	175.0	190.4	14.5	77.4	-0.2	-0.4	22.3	3.32	0.764	-0.2	0.462	0.752	0.337	0.0207	-0.05	0.685
16329	2009-07-08	175.0	190.4	7.19	66.8	-0.2	-0.4	21.8	2.50	0.229	-0.2	0.530	0.735	0.0926	-0.02	-0.05	0.156
16330	2009-07-10	36.0	41.0	24.7	122	-0.2	-0.4	12.0	1.67	0.187	-0.2	0.412	0.101	0.0854	-0.02	-0.05	0.160
16331	2009-07-10	36.0	41.0	6.86	115	-0.2	-0.4	12.3	1.88	-0.1	-0.2	0.343	-0.1	0.0405	-0.02	-0.05	0.0796
16332	2009-07-10	36.0	41.0	6.60	137	-0.2	-0.4	12.5	1.93	0.102	-0.2	0.431	-0.1	0.0469	-0.02	-0.05	0.0712

Sample No.	Date	Secup *(mbl)*	Seclow *(mbl)*	Pr *(ug/l)*	Nd *(ug/l)*	Sm *(ug/l)*	Eu *(ug/l)*	Gd *(ug/l)*	Tb *(ug/l)*	Dy *(ug/l)*	Ho *(ug/l)*	Er *(ug/l)*	Tm *(ug/l)*	Yb *(ug/l)*	Lu *(ug/l)*
16327	2009-07-08	175.0	190.4	0.567	2.52	0.655	0.116	1.05	0.152	1.10	0.272	0.872	0.116	0.844	0.133
16328	2009-07-08	175.0	190.4	0.0853	0.372	0.108	0.0206	0.1790	0.0298	0.224	0.0609	0.219	0.0276	0.219	0.0362
16329	2009-07-08	175.0	190.4	-0.02	0.0991	0.0258	-0.02	0.0746	-0.02	0.106	0.0373	0.147	-0.02	0.137	0.0252
16330	2009-07-10	36.0	41.0	0.0225	0.0912	0.0276	-0.02	0.0501	-0.02	0.0835	0.0272	0.105	-0.02	0.102	-0.02
16331	2009-07-10	36.0	41.0	-0.02	0.0423	-0.02	-0.02	0.0437	-0.02	0.0850	0.0278	0.0979	-0.02	0.107	0.0213
16332	2009-07-10	36.0	41.0	-0.02	0.0432	-0.02	-0.02	0.0492	-0.02	0.0914	0.0301	0.114	-0.02	0.123	0.0224