R-06-21

Hydrogeological single-hole interpretation of KLX02, KLX03, KLX04, KAV04A and B, HAV09–10 and 9 HLXxx boreholes

Laxemar subarea – version 1.2

Ingvar Rhén, Torbjörn Forsmark,
Ingela Forssman, Miriam Zetterlund
SWECO VIAK

April 2006

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

SKB

ISSN 1402-3091
SKB Rapport R-06-21

Hydrogeological single-hole interpretation of KLX02, KLX03, KLX04, KAV04A and B, HAV09–10 and 9 HLXxx boreholes

Laxemar subarea – version 1.2

Ingvar Rhén, Torbjörn Forsmark,
Ingela Forssman, Miriam Zetterlund
SWECO VIAK

April 2006

Keywords: Hydrogeology, Hydraulic tests, Difference flow measurements, Injection tests, Pumping tests, Fractures, Crush.

Abstract

In most boreholes drilled during the Site Investigations performed by SKB several types of hydraulic tests are performed as; hydraulic tests during drilling with Wireline probe, difference flow logging with Posiva Flow Log, and the injection tests with SKB's PSS equipment. In this report the hydraulic data (here called primary data) are compiled borehole wise to get an overview of data available and borehole specific results. These results, and the report SKB R-06-20, are basis for the Site Descriptive Model (SDM) Laxemar version 1.2 but also future SDMs.

This report covers hydraulic tests performed in the core drilled boreholes KLX02, KLX03, KLX04, KAV04A and B as well as percussion drilled boreholes HAV09–10 and 9 HLXxx boreholes. Preliminary tests in test scale 100 m from KLX05 and KLX06 were also used.

Sammanfattning

I de flesta borrhål som borras under platsundersökningarna utförda av SKB utförs flera typer av hydrauliska tester såsom; hydrotester under borrning med wireline utrustning, differensflödesloggning med Posiva flödeslogg och injektionstester med SKB PSS utrustning. I denna rapport sammanfattas hydrotestdata (här kallade primära data) borrhål för borrhål för att ge en översikt på tillgängliga data samt borrhålsspecifika resultat. Resultaten i denna rapport och SKB R-06-20 utgör underlag för platsmodell Simpevarp version 1.2 men också framtida platsmodeller.

Denna rapport omfattar hydrotester utförda i borrhålen KLX02, KLX03, KLX04, KAV04A och B samt hammarborrhålen HAV09–10 och 9 HLXxx borrhål. Preliminära tester i 100 m skalan från KLX05 och KLX06 har också använts.

Contents

1 Introduction

In most boreholes drilled during the Site Investigations several types of hydraulic tests are performed as; hydraulic tests during drilling, difference flow logging, and injection tests. Hydraulic tests performed in the core drilled boreholes KLX02, KLX03, KLX04, KAV04A and B, as well as percussion drilled boreholes HAV09–10 and 9 HLXxx boreholes at Oskarshamn were conducted during 2003 and 2004. A few preliminary tests made during drilling in test scale 100 m from KLX05 and KLX06 were also used. The locations of these boreholes within the Oskarshamn area are shown in Figure 1-1.

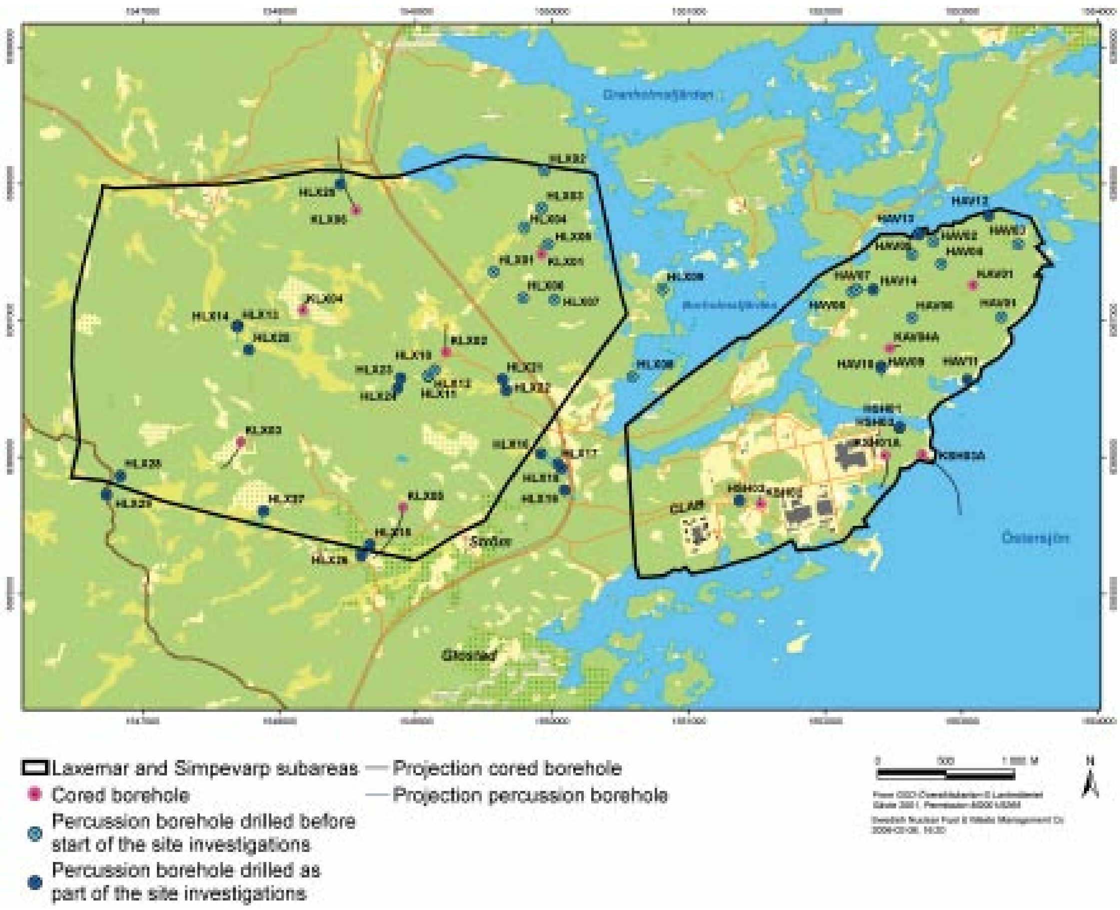


Figure 1-1. Overview map of core-drilled and percussion-drilled boreholes in the Laxemar and Simpevarp subareas at stage model version Laxemar 1.2. Location of the core-drilled boreholes with new data for model version Laxemar 1.2: KLX02, KLX03, KLX04, KAV04A and B.

2 Objective and scope

The objective of this report is to compile the hydraulic data (here called primary data) borehole wise to get an overview of data available and borehole specific results for the present Site Descriptive Model (SDM) but also future SDMs. The analysis of these data and subsequent hydrogeological modelling for the Hydrogeological SDM are presented in /SKB 2006/ and /Rhén et al. 2006b/.

This report covers hydraulic tests performed in the core drilled boreholes KLX02, KLX03, KLX04, KAV04A and B as well as percussion drilled boreholes HAV09–10 and 9 HLXxx boreholes. A few preliminary tests made during drilling in test scale 100 m from KLX05 and KLX06 were also used. References to primary documentation are given in Chapter 3.

3 Methodology

A number of hydraulic tests are used as essentially standardised methods in Table 3-1 boreholes drilled during the site investigations. These are summarised in and briefly described below.

Table 3-1. Principal methods used during initial site investigations for measurement and evaluation of hydraulic parameters.

Measurement equipment	Acronym for method	Acronym for method variant	Type of test performed	Comments
Pipe String System	PSS		Pumping injection tests performed as constant rate tests. Injection tests performed as constant head test. Impulse test is an option..	Transient data collected. Evaluation based on transient or stationary conditions. Test in cored boreholes. Injection tests before the Site investigations were made with other equipment than PSS but are indicated in tables as "PSS".
Hydraulic test system percussion boreholes	HTHB		Pumping or injection tests performed as constant rate tests. Flow logging with impeller is an option.	Transient data collected. Evaluation based on transient or stationary conditions.
Wire Line Probe	WLP	WLP-pt	Pumping tests with WLP in cored boreholes.	Transient data collected. Evaluation based on transient or stationary conditions.
		WLP-ap	Absolute pressure measurement with WLP in cored boreholes.	Transient data collected.
Posiva Flow Log	PFL	PFL-s	Difference flow logging (section). Electrical conductivity (EC) and temperature of the borehole fluid as well as Single Point resistance (SP) is measured during different logging sequences.	Purpose is to estimate test section transmissivity and undisturbed pressure. Two logging sequences. Evaluation is based on stationary conditions.
		PFL-f	Difference flow logging (flow-anomaly).	Purpose is to estimate flow distribution and use PFL-s to estimate transmissivity for fractures/features. One single logging sequence.
Slug test			Slug or bail test.	Normally just performed in boreholes completed in the overburden.

Most core holes are drilled with the so called telescope drilling method, see Figure 3-1. In brief, the telescope drilling method is based on the construction of a larger diameter hole (200 mm diameter) to a length of normally 100 m followed by a cored section to full length. The larger diameter section can either be percussion drilled or reamed with a percussion bit after core drilling of a pilot hole.

The telescope drilling method helps to minimise contamination of the rock with drilling fluid, enhancing the possibility of obtaining more representative water samples. This drilling scheme also makes it possible to pump at larger flow rates with a submersible pump (if needed) and allows monitoring of a fairly large amount of borehole sections using a multi-packer system. The draw back is that the upper 100 m, the wider part, can not be hydraulically tested in the same way as the rest of the borehole. However, an auxiliary 100 m long core borehole is sometimes drilled nearby from surface in order to sample geological and hydraulic data from the uppermost 100 m of the rock that is lost in the telescope borehole.

More details about the drilling can be found in /e.g. Ask and Samuelsson 2004b/.

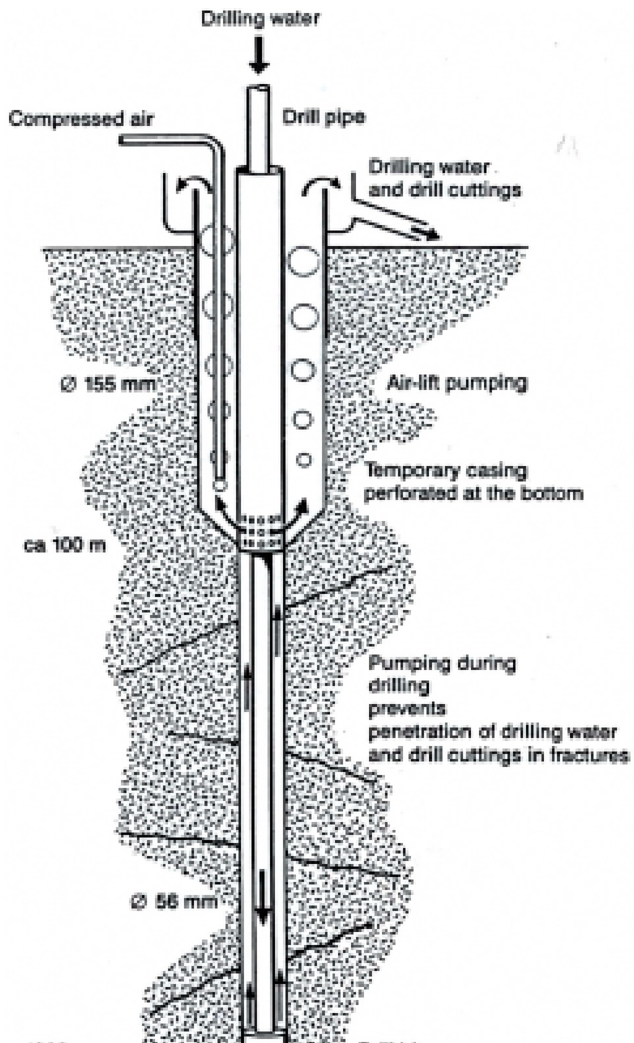


Figure 3-1. A sketch of the telescopic drilling method with air-lift pumping for retrieval of drilling water and cuttings.

3.1 Hydraulic tests during drilling

Hydraulic tests can be performed during the drilling with wire-line based equipment, see Figures 3-2 and 3-3. The hydraulic tests include pumping tests and measurements of the absolute pressure and are generally performed for every 100 m of the drilled borehole.

The wireline probe equipment has been developed by SKB. With this equipment, water sampling, pump tests and measurements of absolute pressure in a borehole section can be made without having to lift the drill stem. Hydraulic tests performed during drilling are generally affected to some degree by disturbances caused by the drilling operations. Transients from changes in pressure, temperature and salinity can affect the hydraulic response curves. However, these data are useful for a first, preliminary, assessment of hydraulic properties and serves also as back-up data if the PSS measurements fail.

The principal components are:

- an inflatable packer,
- a probe fitted with pressure gauges for the test section and for the packer,
- a water sampler,
- a submersible pump (placed in the upper part of the drill stem),
- a flow meter (placed at the ground surface).

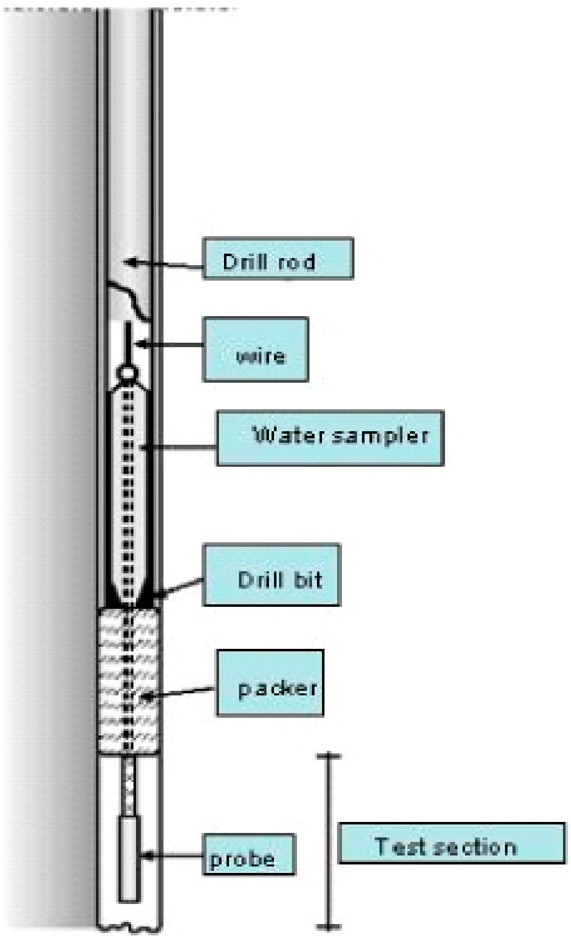


Figure 3-2. The wireline probe and its emplacement in the hole.

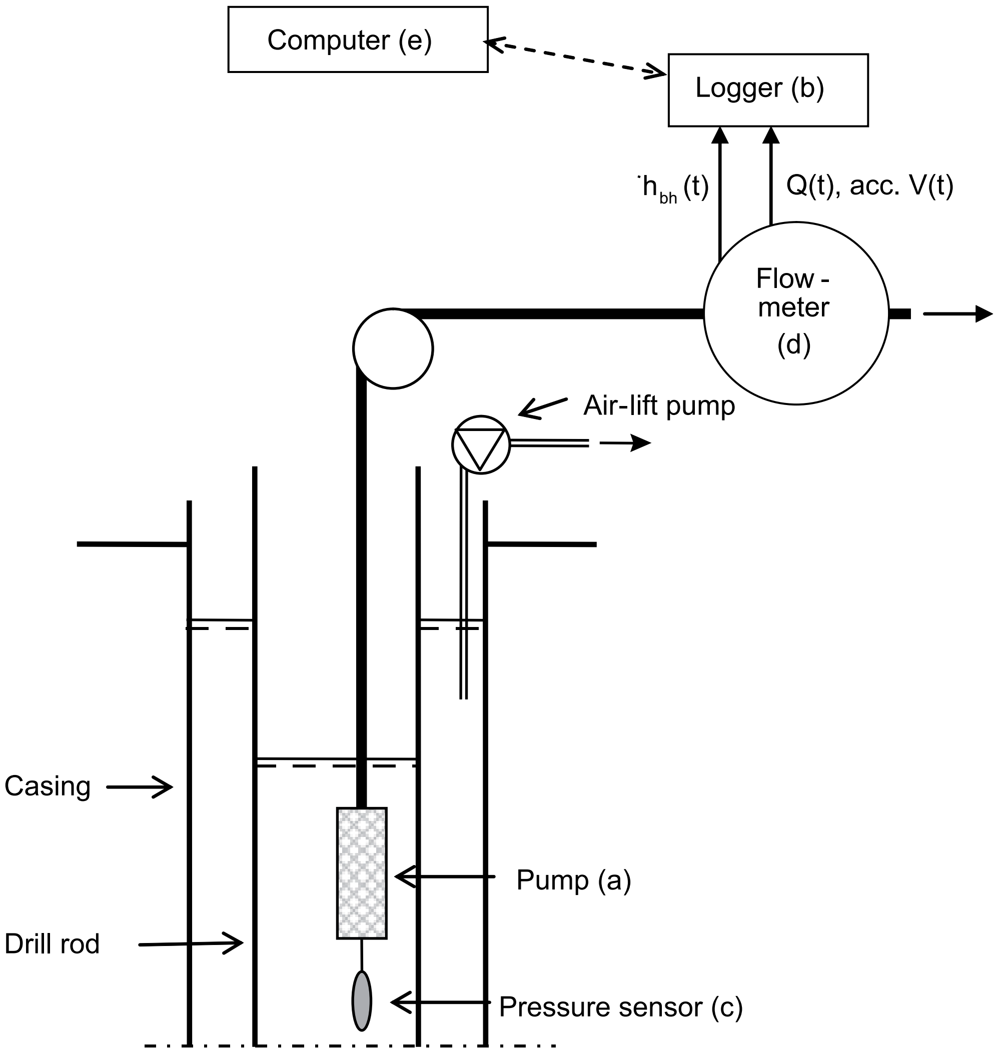


***Figure 3-3.** The equipment used in the upper part of the borehole and on surface for pump tests and water sampling during drilling.*

The probe and packer are lowered through the drill stem into position at the drill bit. The test section is between the lower end of the packer and the bottom of the borehole, see Figure 3-2. Before the pumping tests are made, measurements for absolute pressure and a leakage test of the drill string are done.

Pumping tests

The wireline probe is emplaced at the bottom of the drill stem. A submersible pump is lowered into the upper part of the drill stem at a length of about 40 m. The test section is hydraulically connected to the drill stem by opening a valve in the probe at a pre-determined pressure. This creates a passage between the test section and the water column in the drill stem. The packer remains expanded during the entire test. Water is pumped from the drill stem and the pressure in the test section and packer are recorded in a data logger in the probe. The pumped surface flow rate is recorded to a data logger on the ground surface. The pressure transducer is situated 1.10 m below the lower end of the packer. The test consists of a pressure drawdown phase and a recovery phase. Typically the pumping time is three hours with a recovery phase of the same duration. However, the duration is sometimes adapted to the hydraulic situation of the tested section. The tests are normally carried out in sections of about 100 m length.

The lowest measurable flow rate is generally ca 2L/min but occasionally flow rates down to 0.5 L/min have been possible to measure. Applied drawdown is generally ca 35 m, which then with 2L/min gives the measurement limit: $Q/s = 1E–6\ m^2/s$ and $T_M = 1.15E–6\ m^2/s$.

Water sampling

The equipment for water sampling is the same as for the pumping tests. The water volume in the section is removed at least three times by pumping water out of the test section. The water in the test section is then replaced by formation water and a sample is collected. The wireline probe, with a maximum sample volume of 5 litres, is subsequently brought to the surface.

Pumping tests and water sampling are normally performed as an integrated activity. The aim is to characterize the hydrochemistry as well as the hydrology in the bedrock when the conditions are least affected by hydraulic short circuiting in the borehole.

Absolute pressure measurement

The wireline probe is placed in position at the drill bit. The packer is inflated and the pressure build-up in the test section is recorded for a period of at least eight hours, typically this is done overnight. The measuring range for the pressure gauge is 0–20 MPa (± 0.05% FSD).

More details about the routines and tests during drilling can be found in /e.g. Ask and Samuelsson 2004b/.

3.1 Posiva flow logg (PFL)

A schematic description of the Posiva Flow Log is shown on Figures 3-4 and 3-5.

After completion of the drilling, the Posiva Flow Log (PFL) is generally applied in the cored borehole. The section logging (PFL-s) is made with a test section length (length between rubber discs) of 5 m and a step length (distance between successive tests sections) of 0.5 m (5/0.5), with the purpose of measuring transmissivity in 5 m sections and indicating flowing sections with a resolution of 0.5 m, useful for planning of the hydrogeochemistry sampling and the flow-anomaly logging. The flow-anomaly logging (PFL-f) is made with a test section length of 1 m and a step length of 0.1 m (1/0.1) when moving the test tool along the borehole, with the purpose of identifying individual flowing fractures. PFL-s logging is performed in two sequences; with and without pumping. PFL-f logging is performed just with pumping.

The flow logging (1/0.1) logging is performed where (5/0.5) logging identified flow anomalies. Estimates of transmissivity based on PFL-s are based on two established heads (or drawdowns) (h_1, h_2). The head h_1 is established without pumping (h_1 = undisturbed water level in borehole) and h_2 with pumping (h_2 generally = h_1–10 m) in the borehole associated with two corresponding flow rates (Q_{s1}, Q_{s2}) from the test section. If the upper measurement limit of the flow rate is reached in a test, the test in that test section is later repeated with a smaller drawdown.

The flow-anomaly logging, PFL-f, is only performed with one head (h_2) and the fracture flow (Q_{f2}) is measured, therefore the h_1 and flow Q_{f1} must be approximated as follows. The same h_1 as for the corresponding section with (5/0.5) measurement, that straddles the flow anomaly, is used as well as setting $Q_{f1} = Q_{s1}$, if Q_{s1} was possible to estimate for the section. If no value was possible to estimate it is assumed that $Q_{f1} = 0$.

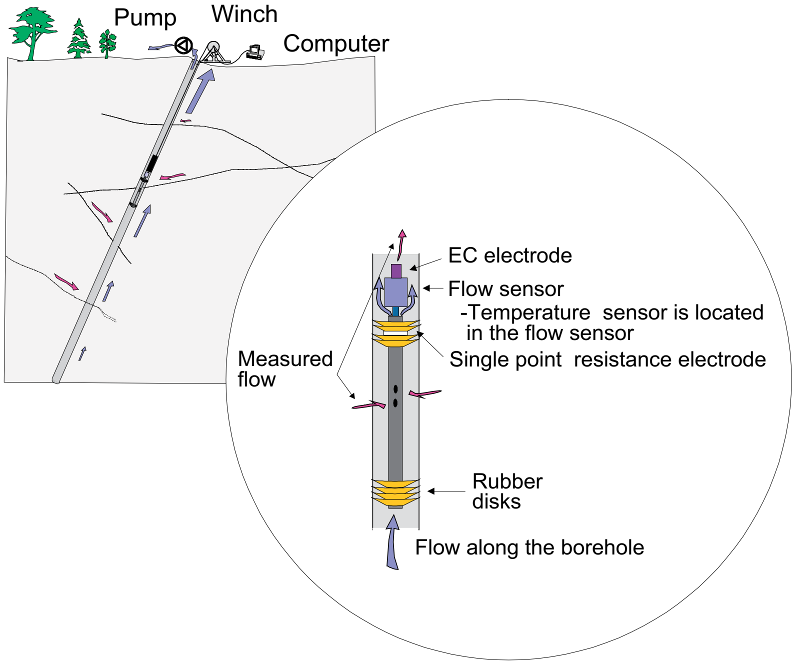


Figure 3-4. *Schematic of the downhole equipment used in the Difference flow meter. /Rouhiainen et al. 2005/.*

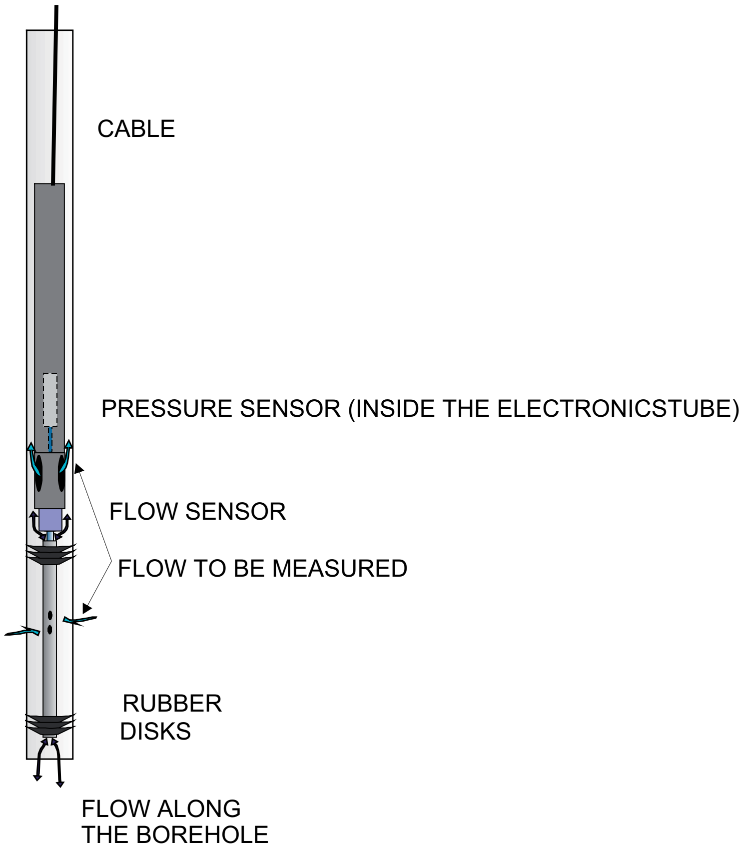


Figure 3-5*. The absolute pressure sensor is located inside the electronics tube and connected through a tube to the borehole water. /Rouhiainen et al. 2005/.*

Thiem's equation /Thiem 1906/ or /e.g. in Kruseman and de Ridder 1991/ is used to calculate the transmissivity T_s for PFL-s representing a 5 m section and T_f for PFL-f representing a fracture, or hydraulic feature. The latter is often rather distinct, within a dm or so, in the borehole. Furthermore, the undisturbed hydraulic head (h) in the formation outside the test section (h_s for PFL-s and h_f for PFL-f) is measured. If no flow rate is possible to measure during PFL-s (without pumping), only the fracture (or hydraulic feature) transmissivity (T_f) is estimated. It is assumed that the influence radius divided by the borehole radius is can be approximated to a ratio of 500, corresponding to an influence radius of 19 m if the borehole diameter is 0.076 m. It is thus assumed that undisturbed formation pressure exists at a radial distance of c. 19 m. As a steady state solution is employed the evaluated transmissivity may be affected by a skin factor.

The "*Theoretical* (lower) *measurement limit*" for PFL (under optimal conditions) is estimated at ca T = 1.7 E–10 m^2/s, based a minimum flow rate of 6 mL/h, 10 m drawdown and 19 m influence radius applied in Thiem's equation. (Theoretical measurement limit, as outlined in /Rouhiainen and Sokolnicki 2005/). /Rouhiainen and Sokolnicki 2005/ describe the finding that due to a rough borehole wall, effects of fine particles in the borehole, high flow rates along the borehole, or gas in the water-filled borehole, the actual measurement limit adopted in the evaluation is in general higher than the Theoretical measurement limit, and may also vary along the borehole. Most likely gas is not a big problem as the pressure decrease in the borehole is very limited during the test. The actual, "*Practical measurement limit*" is evaluated from what is considered to be the noise level in the measurements. In some boreholes, one can see some PFL-f measurements below the measurement limit. The reason is that the Practical measurement limit estimated from the measurement is approximate, and in a few cases it was judged that a flow anomaly was present and could be identified, even though the flow was lower than the PFL-s based Practical measurement limit.

More details about the tests and field data can be found in /e.g. Rouhiainen and Sokolnicki 2005/.

(In some earlier reports presenting PFL logging, a test employing the same test section length and step length as well as two different draw downs, was denoted "Sequential flow logging with PFL"and corresponds to PFL-s. Tests with a step length smaller than the test section length were denoted "overlapping flow logging with PFL", (PFL-o) and corresponds to PFL-f.)

3.2 Pipe string system (PSS)

A schematic description of the Pipe String System is shown on Figures 3-6 to 3-8.

Subsequently to PFL measurements, injection tests with the Pipe String System (PSS) are made starting with 100 m test sections, then 20 m sections within all 100 m sections with flow rates above the measurement limit and then 5 m sections in the borehole section 300–700 m in all 20 m sections with flow rates above measurement limit. The 20 and 5 m sections not measured for the above reason are assigned the value of the measurement limit of the specific capacity (Q/s) for the 100 m and 20 m sections, respectively. These Q/s values are then applied in the steady state solution by /Moye 1967/ to estimate a measurement limit in terms of a transmissivity value.

The standard lower measurement limit of flow rate for injection tests is 1 mL/min (1.7×10^{-8} m^3/s). In Table 3-2 the lower (robust) measurement limits based on the standard lower measurement limit for flow are shown. Occasionally lower flow rates than 1 mL/min can be measured and considered reliable, have been used for the estimation of the transmissivity.

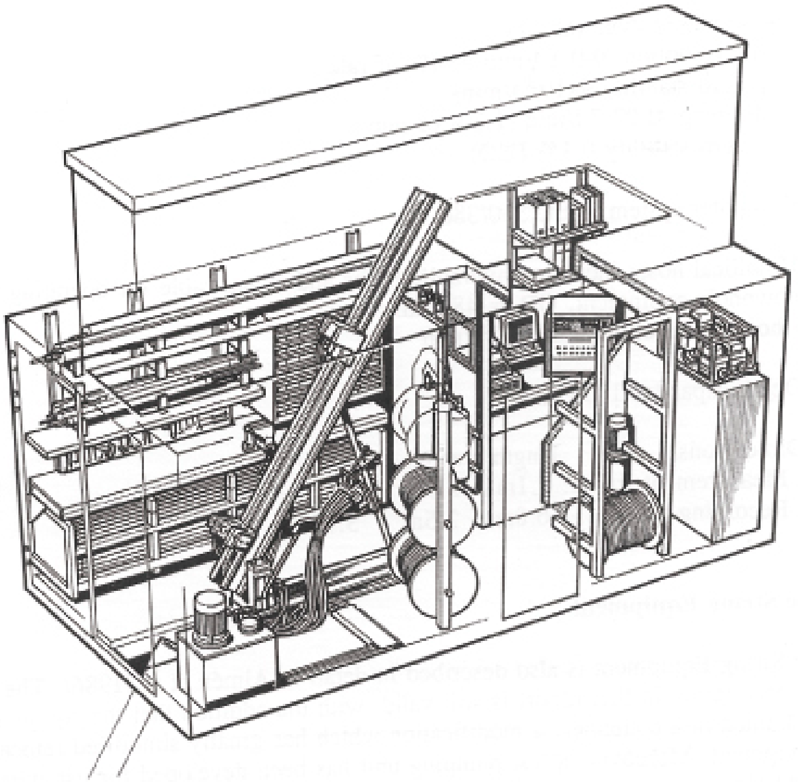


Figure 3-6. *A view of the layout and equipment of PSS2.*

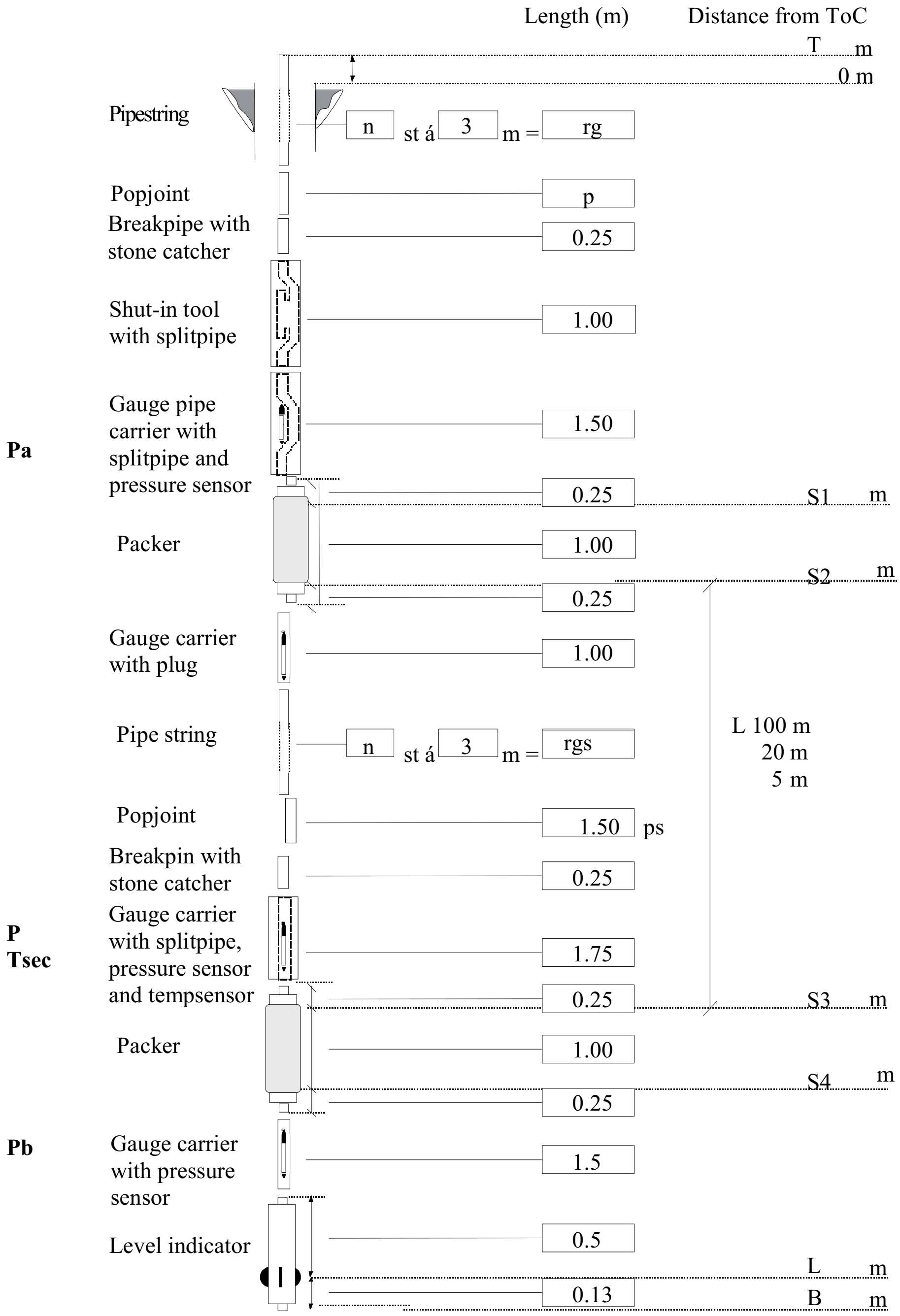


Figure 3-7. *Schematic drawing of the down-hole equipment in the PSS2 system.*

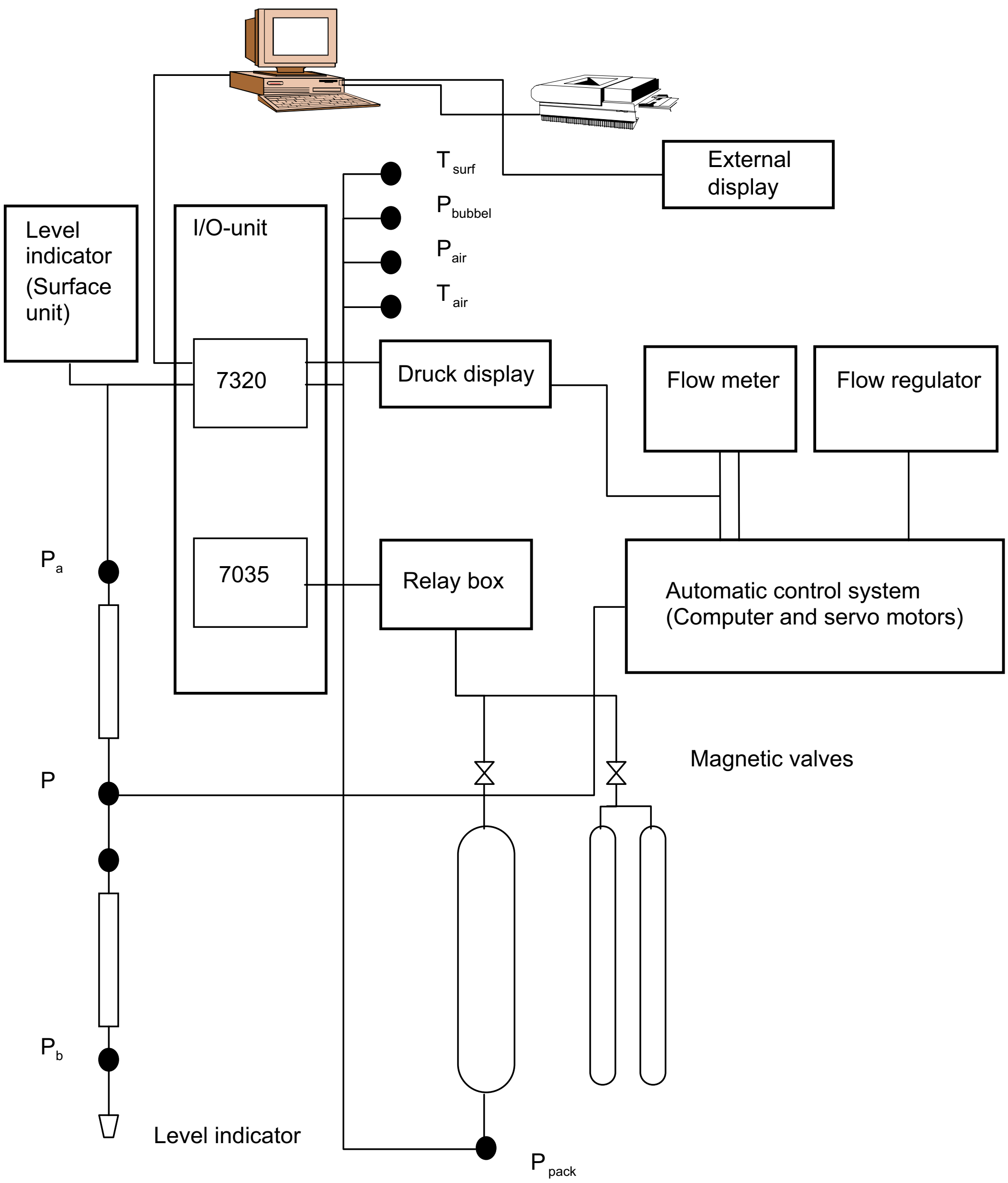


Figure 3-8. *Schematic drawing of the data acquisition system and the flow regulation control system in PSS2.*

Applied injection pressure is generally 20 kPa above static formation pressure with injection time 20–45 min. In some sections with small flow rates the test was performed manually with short injection followed by recovery, treating the test as a pulse test. The transmissivities evaluated from pulse tests may be significantly lower than the measurements limits shown in Table 3-2. These T-values from pulse tests should be considered as uncertain values, more indicating very tight rock.

Table 3-2. Estimated standard lower measurement limits for specific flow and steady-state transmissivity for injection tests on different measurement scales /Ludvigson et al. 2004/.

Borehole	r_w (m)	L_w (m)	Q-measl-L (m³/s)	Injection pressure (kPa)	Q/s-measl-L (m²/s)	Factor C in Moye's formula	T_M-min (m²/s)
KSH02	0.038	100	1.7×10^{-8}	200	8.5×10^{-10}	1.30	1.1×10^{-9}
KSH02	0.038	20	1.7×10^{-8}	200	8.5×10^{-10}	1.05	8.6×10^{-10}
KSH02	0.038	5	1.7×10^{-8}	200	8.5×10^{-10}	0.825	6.8×10^{-10}

The tests are evaluated as transient tests giving Transmissivity (T_T) and skin factor (assuming a storage coefficient S = 1E–6). T_T is evaluated for the first seen radial flow period in a test. Steady state evaluation of transmissivity (T_M) based on /Moye 1967/ is also made. If it was not possible to evaluate T_T, the T_M values are used as "best choice" (BC) for the test section in question.

More details about the PSS equipment can be found in /Rahm and Enachescu 2005a/.

3.3 Boremap data

The geological mapping of the cores and the interpreted rock domains (related to model version Laxemar 1.2) by the geologists are in some figure presented. The interpreted correlation between hydraulic parameters and geological features are not presented in this report but in the /Rhén et al. 2006b/ (for model version Laxemar 1.2).

3.4 Correlation of boremap data and PFL flow anomalies

The measured flow anomalies with PFL have such good accuracy in position in the boreholes that they can generally be related to one or a few mapped open fractures using the Boremap data base and the BIPS images of the borehole wall, An example of the results from the PFL-f is shown together with Boremap data (open fractures, partly open fractures and crush zones) and the interpreted rock domains and deformations zones in Figures 3-9 and 3-10.

In the core mapping each fracture is classified as "Sealed", "Open" or "Partly open" and with a judgement as to how certain the geologist is of this classification – expressed as "Certain", "Probable" and "Possible". "Partly open" refers to BIPS observations of the borehole wall indicating an aperture (channel) in an unbroken core – these observations are few. Measured PFL-f flow anomalies are classified as "Certain" or "Uncertain". Both the core-mapped data and the flow anomalies are rigorously length corrected and it is expected that the positions of PFL-f objects along the boreholes normally can be correlated to mapped geological features within 0.2–0.3 m

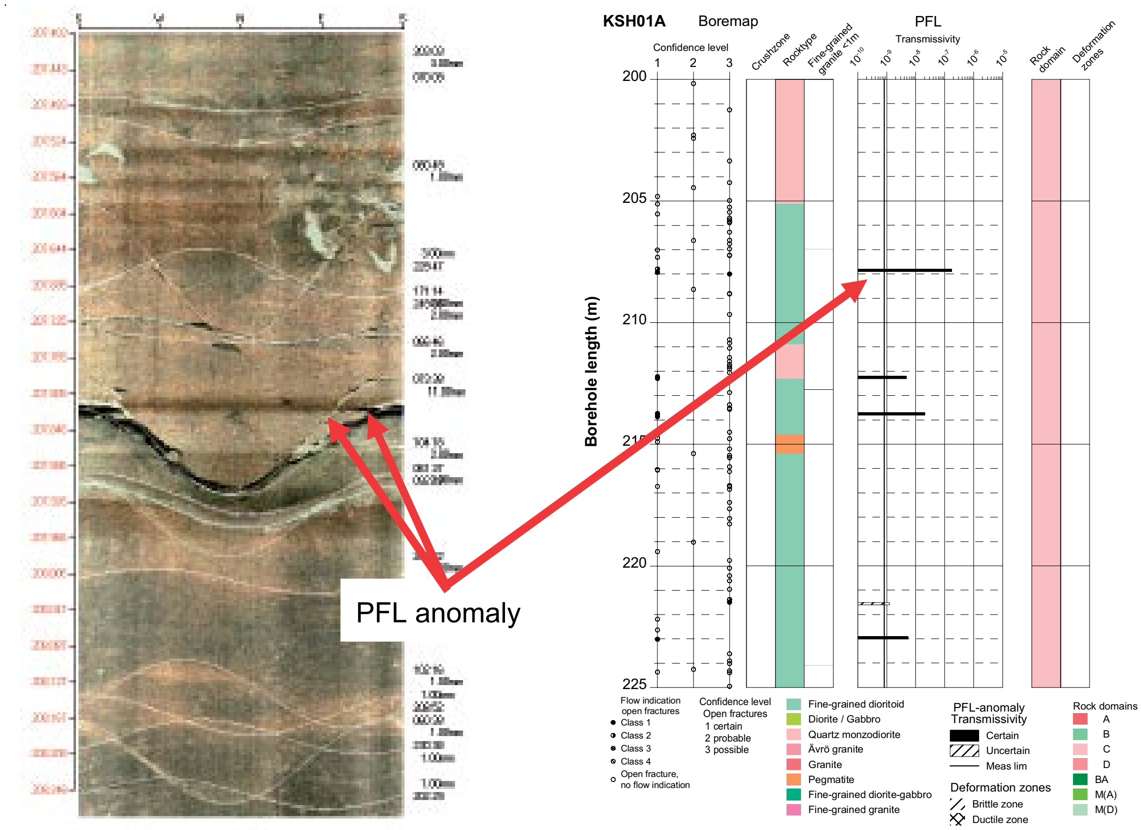


Figure 3-9. *Close-up of BIPS image of a borehole section in borehole KSH01A. Shown object: T (m²/s) = 1.72E–7. Generally open fractures cannot be seen in BIPS as in the example above. White lines represents different mapped objects as open and sealed fractures, rock contacts etc. /Forssman et al. 2005a/.*

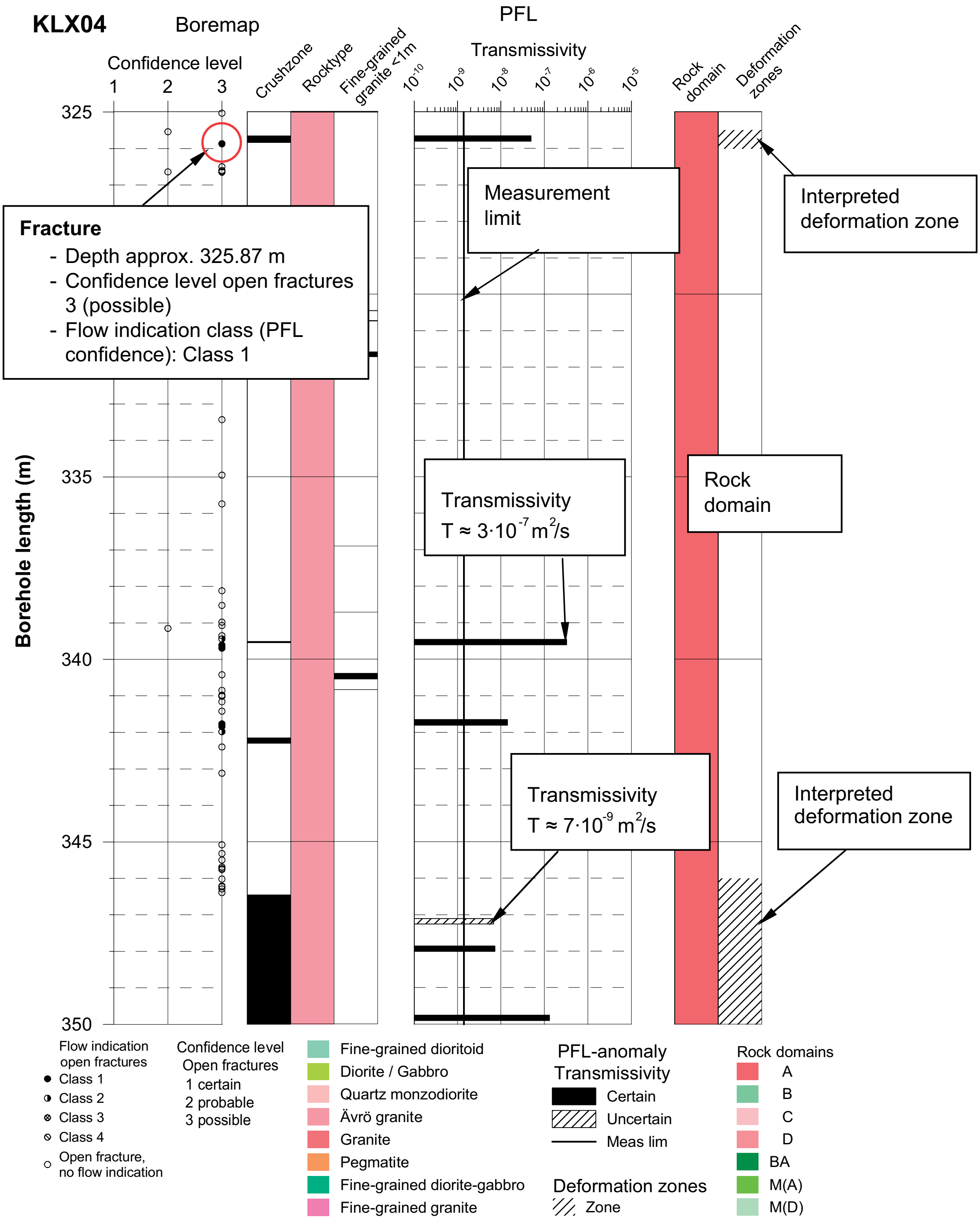


Figure 3-10. *Example of a diagram including an overview of the interpretation of the flow anomalies and mapped open fractures./Forssman et al. 2005b/.*

As a first assumption when correlating core-mapped data and flow anomalies, all open and partly open fractures, as well as crush zones, are assumed to be possible flowing features. In most cases, one or several open fractures were identified within 0.2 m from a given flow anomaly. Only in a few cases were there no "open fractures", "partly open fractures" or "crush zones" that could be linked to within 0.5 m of a flow anomaly, probably indicating that a fracture mapped as "sealed" should have been classified as "open". In such cases one could generally find "sealed fractures" classified as "Probable" or "Possible" near the flow anomaly.

As the flow-anomalies in most cases could be correlated to individual open fractures, fracture properties, e.g. orientation can be coupled to the flow anomaly. The uncertainty classification of fractures and flow anomalies also provides a basis for sensitivity analysis. This is to be focus of future work. Details of this evaluation are presented in /Forssman et al. 2005b/.(Similar work for Simpevarp version 1.2 was presented in /Forssman et al. 2005a/.

It is emphasised that the PFL-anomaly data have been the main input to the development of hydraulic DFN models. They have been used to obtain transmissivity information and as a calibration target for conductive fracture frequency. The DFN models were developed using assumptions of how fractures connect, are orientated, and whether they are open or closed etc.

In Figure 3-10 an example is shown on how parts of the results are presented. Below some comments are made on how to interpret the figure.

Flow indication confidence levels for open fractures (PFL confidence)

The classification of "flow indication level of confidence", or the PFL confidence, is defined as the distance between the anomaly and the interpreted fracture. That is, if the anomaly has a flow indication in class 1, the interpreted fracture is within 1 dm from the anomaly. In the same way, the anomaly has the flow indication class 2, if the interpreted fracture is within 2 dm from the anomaly. Four classes have been defined;

Class 1 0–1 dm.

Class 2 1–2 dm.

Class 3 2–3 dm.

Class 4 3–4 dm.

This classification is used in the figures in this report. In the database for this evaluation, only the numbers (1–4) are used to describe the PFL confidence.

Features with PFL confidence > 4 are rare and considered to be non-significant. Therefore, they are not plotted in the diagrams.

Confidence level open fractures

The confidence level for open fractures describes the certainty with which the fracture is interpreted. In this report, three levels of confidence in the SICADA database are used;

Level 1 Certain.

Level 2 Probable.

Level 3 Possible.

4 Data used for the single-hole interpretation

4.1 Overview of tests performed

Cored boreholes KLX02, KLX03, KLX04, KAV04A,B, and percussion boreholes HAV09–10 and 6 HLXxx boreholes have been tested during the early stages of the initial site investigations and were available for the Laxemar 1.2 modelling. In the cored boreholes hydraulic tests with the wire-line probe (WLP), the Posiva flow logging tool (PFL) and the Pipe String System (PSS) were performed in most boreholes. In percussion holes HAV09–10 and 6 HLXxx boreholes airlift tests or pumping tests were performed.

Single-hole hydraulic tests and interference tests conducted prior to the onset of the ongoing initial site investigations (historical data) were carried out at Äspö, Ävrö, Hålö, Mjälen, Laxemar and the Simpevarp peninsula /e.g. Rhén et al. 1997abc/. Some of these existing data are commented on in this section (KLX02), but have not been re-evaluated.

The single-hole hydraulic tests conducted in the cored boreholes and percussion boreholes are listed in Table 4-1 through Table 4-6 and Figures 4-1 to 4-4 show an overview of the hydraulic tests in core holes related to the elevation of the upper most and lower most test section. In Appendix 1 the overview of the hydraulic tests is related to the borehole length, the same as in the Tables in Chapter 4. Old tests in core holes on Ävrö and Laxemar are also shown in the figures. The tests performed in KLX02 shown in Table 4-1 were also shown in /Rhén et al. 2006a/. In this report the only new data for KLX02 is the approximate estimation of PFL-f based on the available reports and the data base in SICADA.

The hydraulic tests conducted in the percussion boreholes and some of the tests in the core holes were performed as open-hole pumping tests using submersible pump (“ pump test” in tables) or airlift pumping (“airlift test” in tables). The hydraulic tests performed in the cored boreholes were made during drilling, as pumping tests and included measurements of absolute pressure made using the SKB-developed Wire-Line Probe (WLP).

PSS tests have been performed in KLX03 but were not available for model version L1.2.

The drilling process and the tests during drilling in cored boreholes are described by /Ask et al. 2005cd/. The drilling and some simple hydraulic tests in percussion boreholes were reported by /Ask and Samuelsson 2004abc, Ask et al. 2004, 2005ab, Ask and Zetterlund 2005/, and the PFL measurements by /Ludvigson and Hansson 2002, Rouhiainen 2000, Pöllänen and Sokolnicki 2004, Rouhiainen et al. 2005, Rouhiainen and Sokolnicki 2005/. PSS tests were reported by /Rahm and Enachescu 2004abc/. Pumping test in KLX04 was reported in /Rahm and Enachescu 2005/ and a combined interference test and tracer test in KLX02 and HLX10 was reported in /Gustafsson and Ludvigson 2005/. Evaluation methods and data are presented in the above reports.

No drill report is available for HLX10 (as for HLX11 and HLX12) but some data is found in /Ekman 2001, Andersson 1994/. Earlier collected data from KLX02 is complied in /Ekman 2001, Andersson 1994/.

Table 4-1. Hydraulic tests performed in cored borehole KLX02 (Tests performed before and during the Site Investigations, UCM: flow logging measuring the water velocity using acoustic waves (Doppler Effect)).

Bore-hole ID	Borehole length (m)	Upper limit Secup (m)	Lower limit Seclow (m)	No. of tests	Type of test performed	Test scale (m)	Step length (for moving test section) (m)
KLX02	1,700.50	798.00	1,101.50	1	Airlift test	~300	–
		1,427.00	1,700.50	1	Airlift test	~300	–
		3.0	76	1	Pumping test	~100	–
		3.0	142	1	Pumping test	~100	–
		3.0	200	1	Pumping test	~200	–
		3.0	205.00	1	Pumping test	~200	–
		207.00	505.00	1	Pumping test	~300	–
		505.00	803.00	1	Pumping test	~300	–
		805.00	1,103.00	1	Pumping test	~300	–
		1,103.50	1,401.50	1	Pumping test	~300	–
		201.00	1,700.50	1	Pumping test	1,500	–
		205.92	1,399.92	398	Flow logging –PFL-s	3	3
		200.50	1,440.50	–	Flow logging – UCM	–	0.1
		300	545	49	PSS – transient injection	5	–
		204	1,004	48	PSS – transient injection	20	–
		204	1,004	8	PSS – transient injection	100	–

Table 4-2. Hydraulic tests performed in cored borehole KLX03 (WLP: WireLine probe (tests during drilling), PFL: Posiva Flow Logging).

Borehole ID	Borehole length (m)	Upper limit Secup (m)	Lower limit Seclow (m)	No. of tests	Type of test performed	Test scale (m)	Step length (for moving test section) (m)
KLX03	1,000.42	101.3	992.42	179	PFL-s, difference flow logging-section	5	5
		110.2	970.5	–	PFL-f, difference flow logging-flow-anomaly[1]	1	0.1
		11.65	1,000.42	1	Pumping test	≈1,000	–
		103	1,000.42	9	Pumping tests with WLP	≈100	–

[1] Borehole section for PFL-f is based on PFL-s measurements.

Table 4-3. Hydraulic tests performed in cored borehole KLX04 (WLP: WireLine probe (tests during drilling), PFL: Posiva Flow Logging).

Borehole ID	Borehole length (m)	Upper limit Secup (m)	Lower limit Seclow (m)	No. of tests	Type of test performed	Test scale (m)	Step length (for moving test section) (m)
KLX04	993.49	100.2	986.22	177	PFL-s, difference flow logging-section	5	5
		101.4	973.1	–	PFL-f, difference flow logging-flow-anomaly[1]	1	0.1
		12.24	993.49	1	Pumping test	≈1,000	–
		103	993.49	9	Pumping tests with WLP	≈100	–
		300.41	685.78	77	PSS – transient injection	5	–
		105.21	983.05	44	PSS – transient injection	20	–
		105.11	986.11	9	PSS – transient injection	100	–

[1] Borehole section for PFL-f is based on PFL-s measurements.

Table 4-4. Hydraulic tests performed in cored borehole KLX03 (WLP: WireLine probe (tests during drilling), PFL: Posiva Flow Logging).

Borehole ID	Borehole length (m)	Upper limit Secup (m)	Lower limit Seclow (m)	No. of tests	Type of test performed	Test scale (m)	Step length (for moving test section) (m)
KLX05	1,000.2	0	1,000.2	10	Pumping tests with WLP	≈100	–
KLX06	994.94	103	994.94	9	Pumping tests with WLP	≈100	–

Table 4-5. Hydraulic tests performed in cored borehole KAV04A, B (WLP: WireLine probe (tests during drilling), PFL: Posiva Flow Logging).

Borehole ID	Borehole length (m)	Upper limit Secup (m)	Lower limit Seclow (m)	No. of tests	Type of test performed	Test scale (m)	Step length (for moving test section) (m)
KAV04A	1,001.2	100.16	996.17	179	PFL-s, difference flow logging-section	5	5
KAV04B	101.03	20.3	95.5	–	PFL-f, difference flow logging-flow-anomaly[1]	1	0.1
KAV04A		102.1	894.4	–	PFL-f, difference flow logging-flow-anomaly[1]	1	0.1
KAV04A		100	1,001.2	1	Pumping test	≈1,000	–
KAV04A		100	1,001.2	9	Pumping tests with WLP	≈100	–
KAV04A		105.17	903.35	42	PSS – transient injection	20	–
KAV04A		105.17	998.2	9	PSS – transient injection	100	–

[1] Borehole section for PFL-f is based on PFL-s measurements.

Table 4-6. Hydraulic tests performed in percussion boreholes HAV09–10 and 6 HLXxx boreholes.

Borehole ID	Borehole length (m)	Upper limit Secup (m)	Lower limit Seclow (m)	No. of tests	Type of test performed	Test scale (m)	Step length (for moving test section) (m)
HAV09	200	14.9	200	1	Airlift test	≈100	–
HAV10	100	11.9	100	1	Airlift test	≈100	–
HLX10	85	0	85	1	Pumping test	≈100	–
HLX13	200	11.87	200	1	Airlift test	≈100	–
HLX14	115.9	11.9	115.9	1	Airlift test	≈100	–
HLX18	181.2	15.12	181.2	1	Pumping test	≈100	–
HLX20	202.2	9.12	202.2	1	Pumping test	≈100	–
HLX22	163.2	9.1	163.2	1	Pumping test	≈100	–
HLX24	175.2	9.1	175.2	1	Pumping test	≈100	–
HLX25	202.5	6.12	202.5	1	Pumping test	≈100	–
HLX32	162.6	12.3	162.6	1	Pumping test	≈100	–

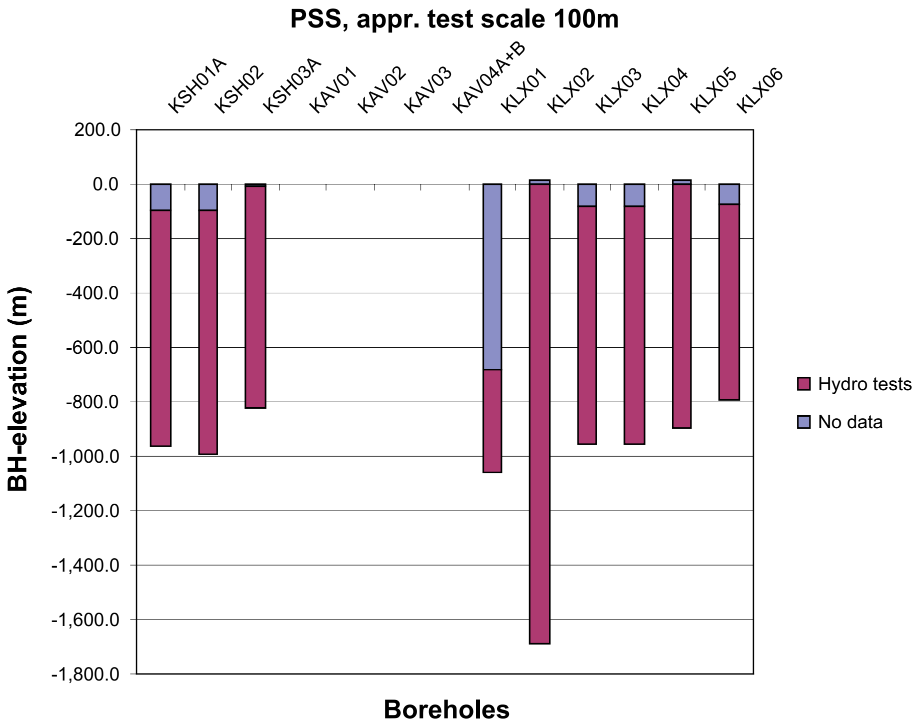


Figure 4-1. *Overview of hydraulic tests with PSS in approximate test scale 100 m, used for Laxemar model 1.2.*

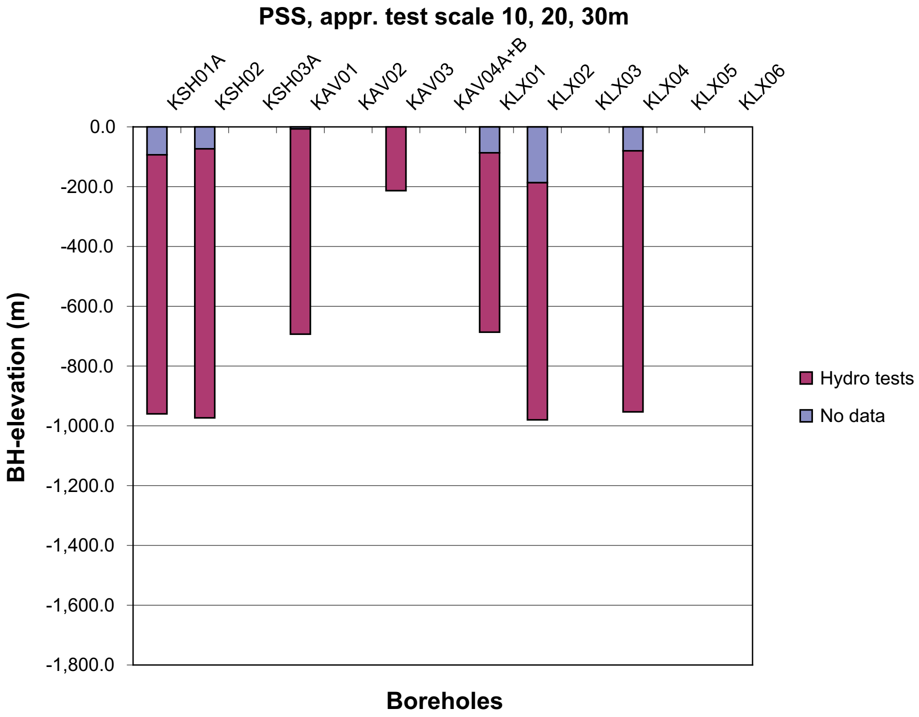


Figure 4-2. *Overview of hydraulic tests with PSS in approximate test scale 10, 20 or 30 m, used for Laxemar model 1.2.*

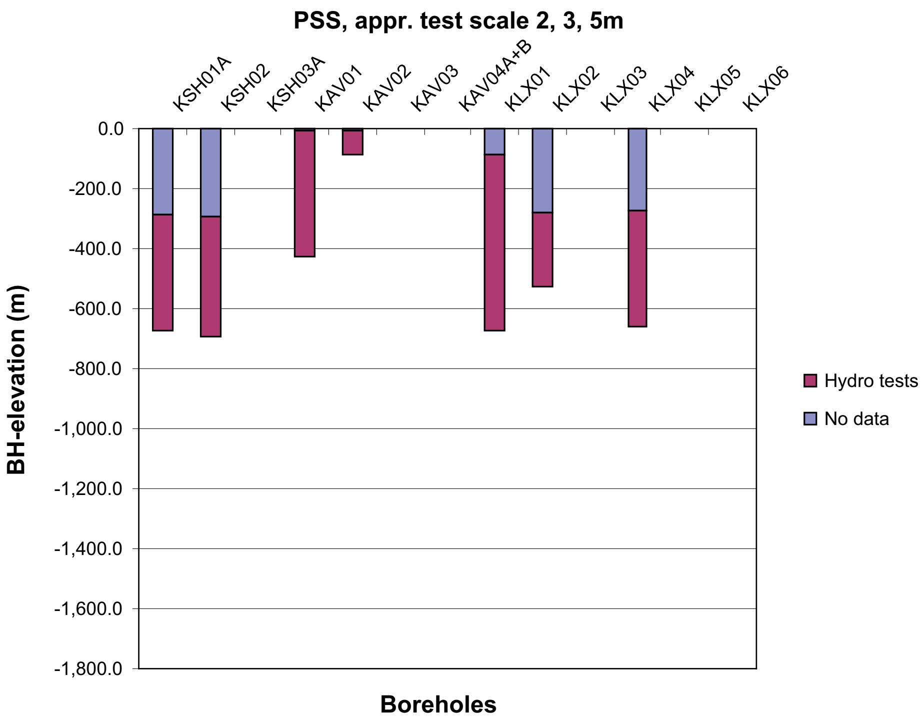


Figure 4-3. *Overview of hydraulic tests with PSS in approximate test scale 2, 3 or 5 m, used for Laxemar model 1.2*

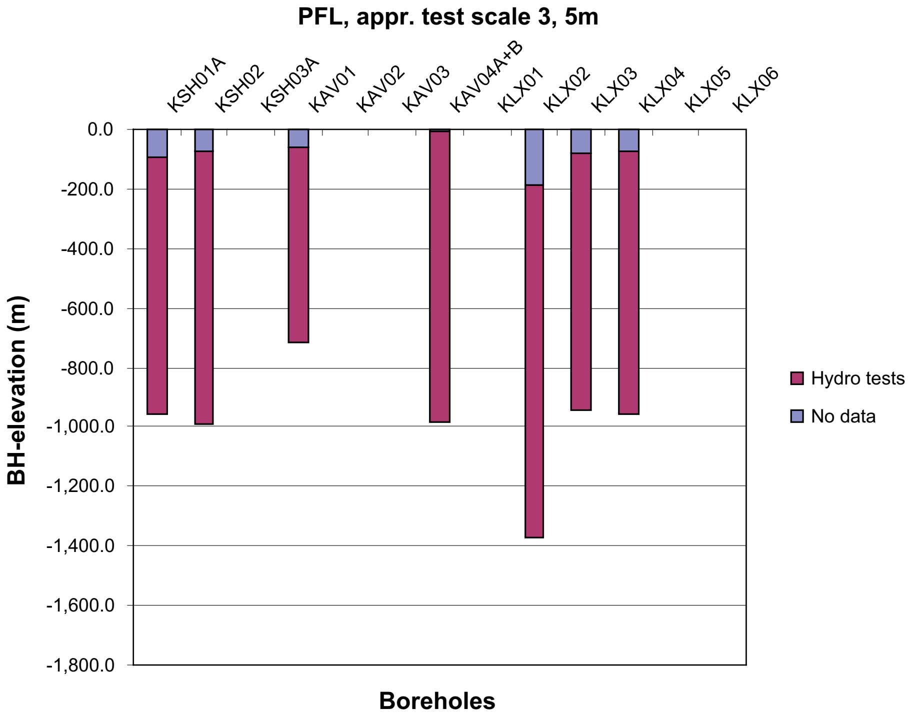


Figure 4-4. *Overview of hydraulic tests with PFL in approximate test scale 5 m, used for Laxemar model 1.2*

5 Results

In this chapter the results from the hydraulic tests in boreholes are summarized. In Sections 5.1 to 5.6 the main results from the PSS injection- and pumping tests are shown together with some geological data in a number of figures. Figure 5-1 for KLX02 was also shown in /Rhén et al. 2006a/, and is only here shown to get are more complete view of the KLX02 borehole. The only measurements available for L1.2 modelling in KLX03 were PFL and WLP and in KLX05 and KLX06 were WLP measurements, which can be seen in Figures 5-4, 5-6 and 5-7.

In Section 5.7 and 5.8 the comparison between methods as well as statistics for individual boreholes are presented.

PFL-Boremap figures

In Section 3.5 the structure and data presented in the figure is explained.

PFL-PSS-Boremap figures

PFL measurements: Left most is the PFL-s (5 m sections) shown together with the estimated lower measurement limit for PFL-s.

PSS measurements: The PSS measurements are shown in three diagrams, with tests scales: 2, 3 or 5 m; 10, 20 or 30 m; 100 m. The lower (robust) measurement limit is shown as a black line, and is based on the smallest flow rate that generally is possible to measures with PSS, the standard applied injection pressure and using /Moye 1967/ to estimate the transmissivity (For old tests performed before the Site Investigations, the measurement limits given in the data base have been used). However, in each test it is judged if the test conditions are so good that a reliable flow rate below "the flow rate generally possible to measure" is measured. If this happens, the measured flow rate is used for the calculations of the transmissivity, and the evaluated T may be a bit lower than the robust lower measurement limit. In tight sections sometimes pulse tests have been used and they may indicate more than magnitudes lower values than the robust lower measurement limit. These values must me considered very uncertain. For values that have been classified as measurement limit values (value type (VT) = –1 in the figures) one should expect that the real value is as high as or lower than the reported value.

"T-BC" or "K-BC"stands for "Transmissivity – best choice" or Hydraulic conductivity – best choice"; If a transient evaluation is available for a test section this value is used as representative (best choice) value for the section, otherwise the steady state value (based on /Moye 1967/) is used.

If no PSS tests were available, the WLP- measurements are shown.

For comparison the PFL-f transmissivity values have been summed up for the corresponding PSS test sections and plotted in the PSS diagrams.

Geology: The mapped fracture frequency, crush zone, rock type as well as interpreted rock domains and deformation zones from the geological model is shown. The fracture frequency shown is the estimated numbers of all open fractures: fractures mapped as open+fractures mapped as partly open+estimated of open fractures in crush zone (assumed that there are 40 open fractures per metre crush zone).

"Borehole depth" in figures corresponds to borehole length.

In Appendix 2 all PSS measurements are shown as transmissivity instead of hydraulic conductivity. In these figures the PFL-f (transmissivity of individual fractures) are also plotted.

Data presented

PFL-f for KLX02 was not available for model version S1.2 but was made available for L1.2. In KLX02 the core mapping was updated to the standards of the Site Investigations down to 1,000 m borehole depth. Below 1,000 m in KLX02, the old core mapping in the SICADA data base has been translated to the Site Investigation nomenclature.

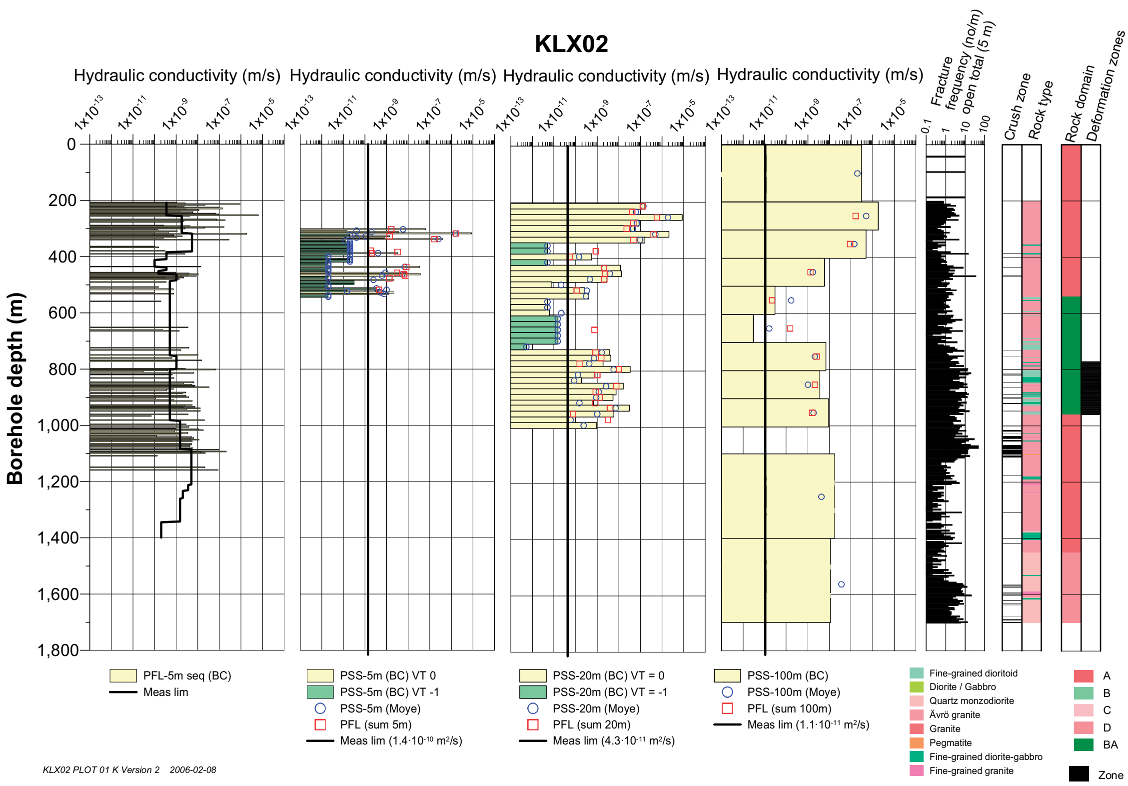


__Figure 5-1.__ Hydraulic conductivity of borehole KLX02 based on PSS and PFL-s data and Boremap data (fracture frequency (mean per 5 m) crush zones and rock type) and evaluated rock domains and deformation zones. (Borehole depth: length along the borehole.)

5.1 KLX02

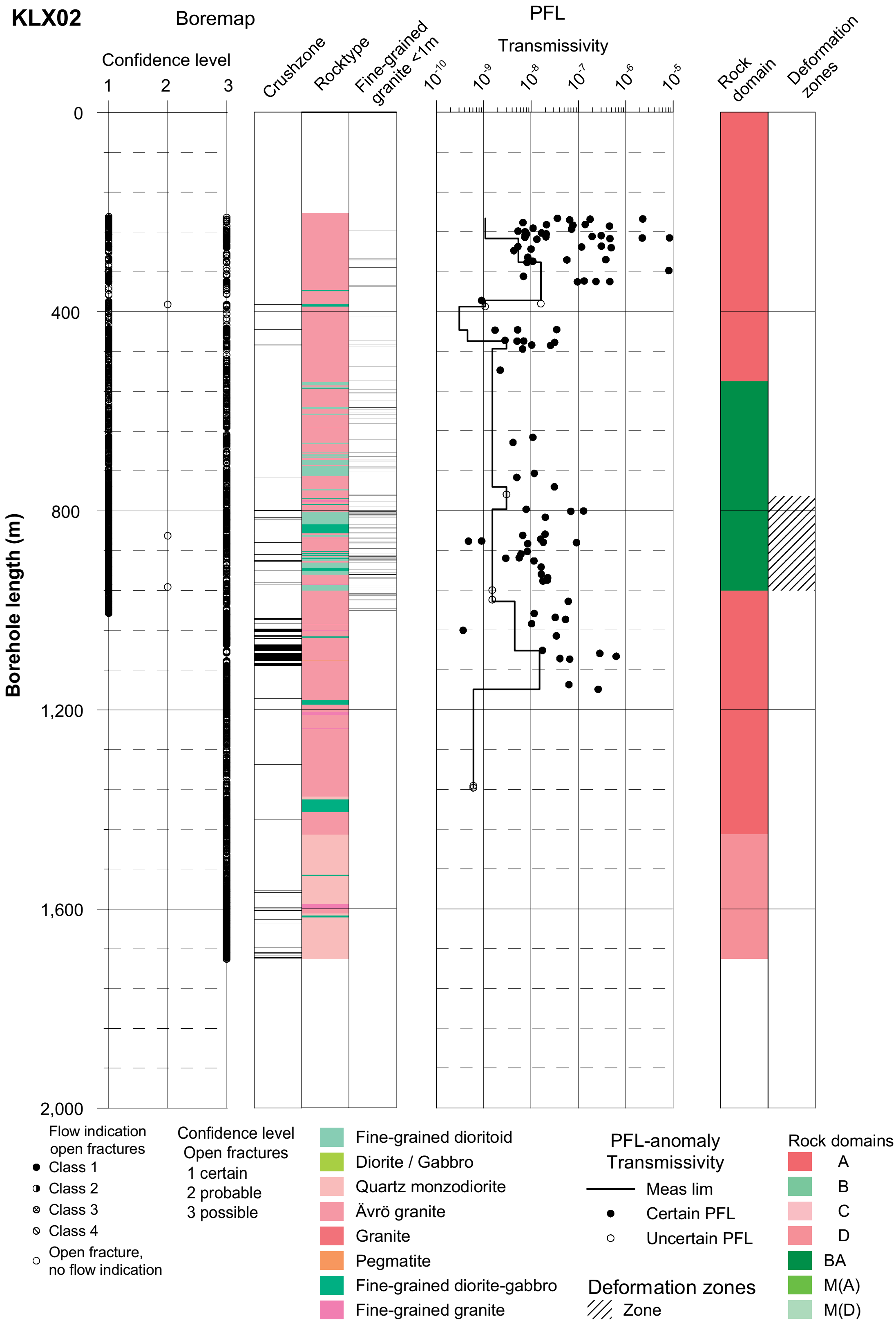


Figure 5-2. *Transmissivity of hydraulic features of borehole KLX02 based on interpretation of reported data to get approximate estimate of PFL-f data, Boremap data (open fractures, partly open fractures and crush zones, rock type and veins of fine-grained granite) and the interpreted rock domains and deformations zones /Forssman et al. 2005b/.*

5.2 KLX03

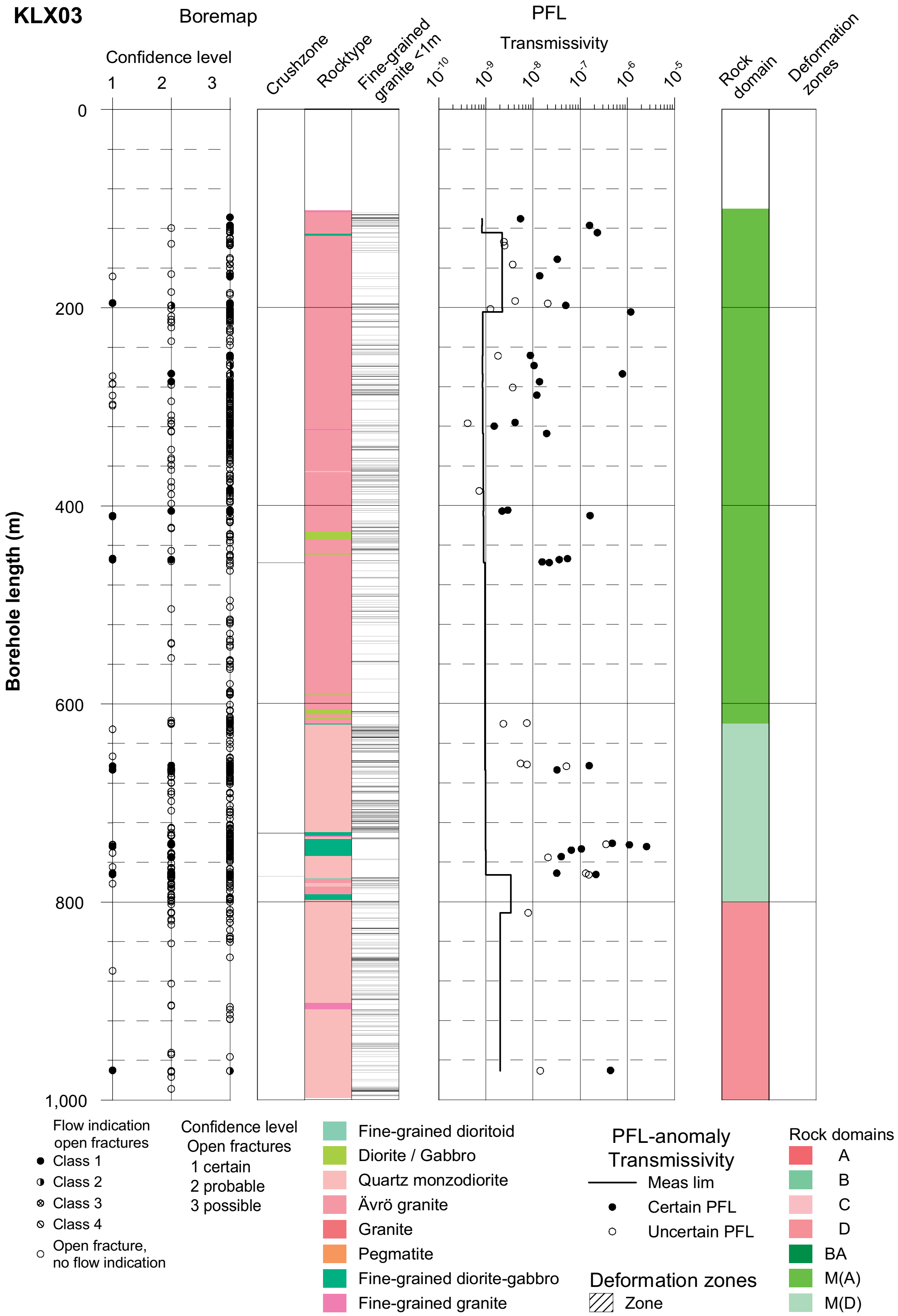


Figure 5-3. Transmissivity of hydraulic features of borehole KLX03 based on PFL-f data, Boremap data (open fractures, partly open fractures and crush zones, rock type and veins of fine-grained granite) and the interpreted rock domains and deformations zones /Forssman et al. 2005b/.

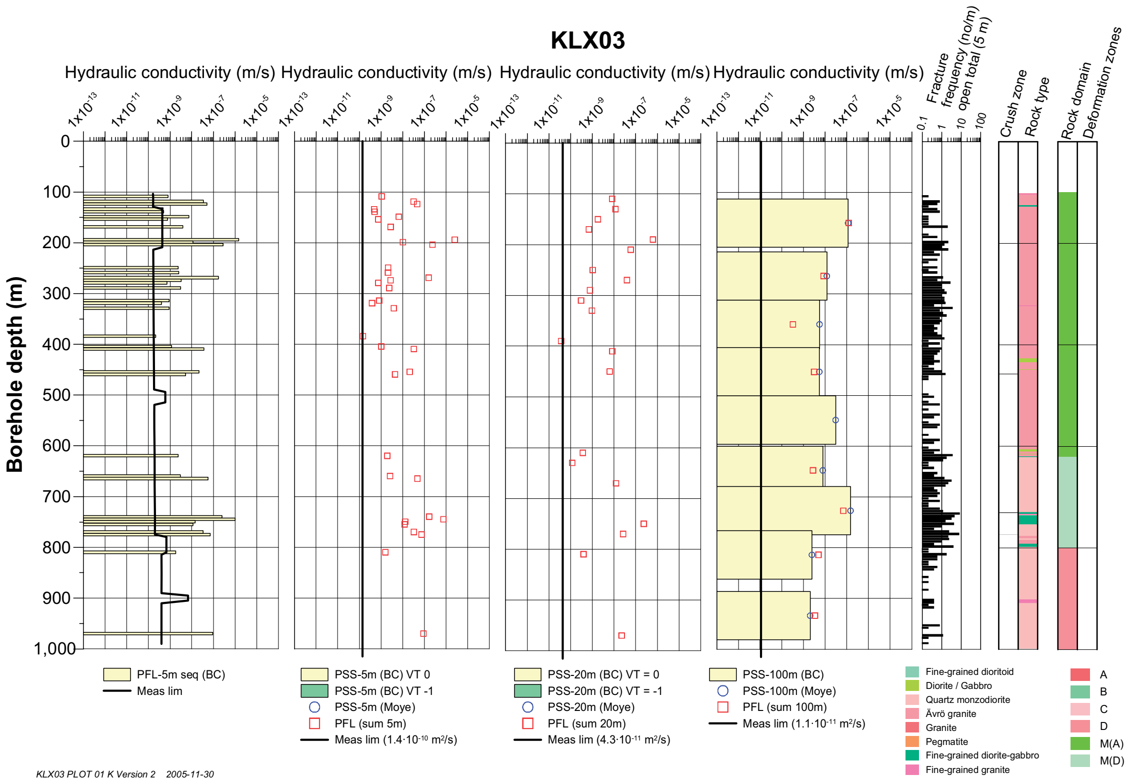


***Figure 5-4.** Hydraulic conductivity of borehole KLX03 based on WLP and PFL-s data and Boremap data (fracture frequency (mean per 5 m) crush zones and rock type) and evaluated rock domains and deformation zones. Observe that the WLP tests scale varies but is approximately 100 m, and the test sections overlap a bit in some cases and in some cases they are side by side. It is only in plot (due to the choice of the minimum test section length as width of the bar) that there seem to be gaps in the measurements. (Borehole depth: length along the borehole.)*

5.3 KLX04

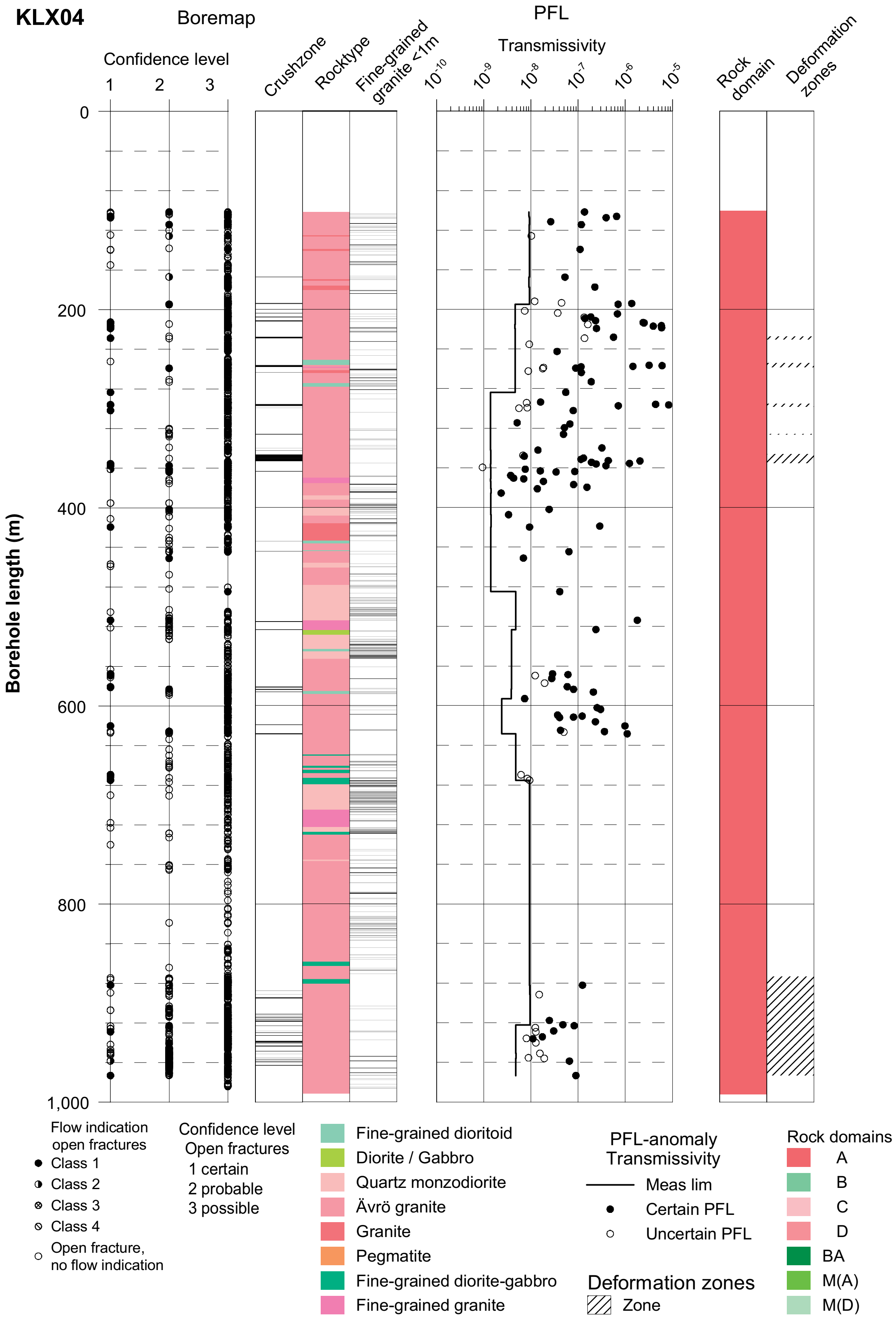


Figure 5-5. Transmissivity of hydraulic features of borehole KLX04 based on PFL-f data, Boremap data (open fractures, partly open fractures and crush zones, rock type and veins of fine-grained granite) and the interpreted rock domains and deformations zones /Forssman et al. 2005b/.

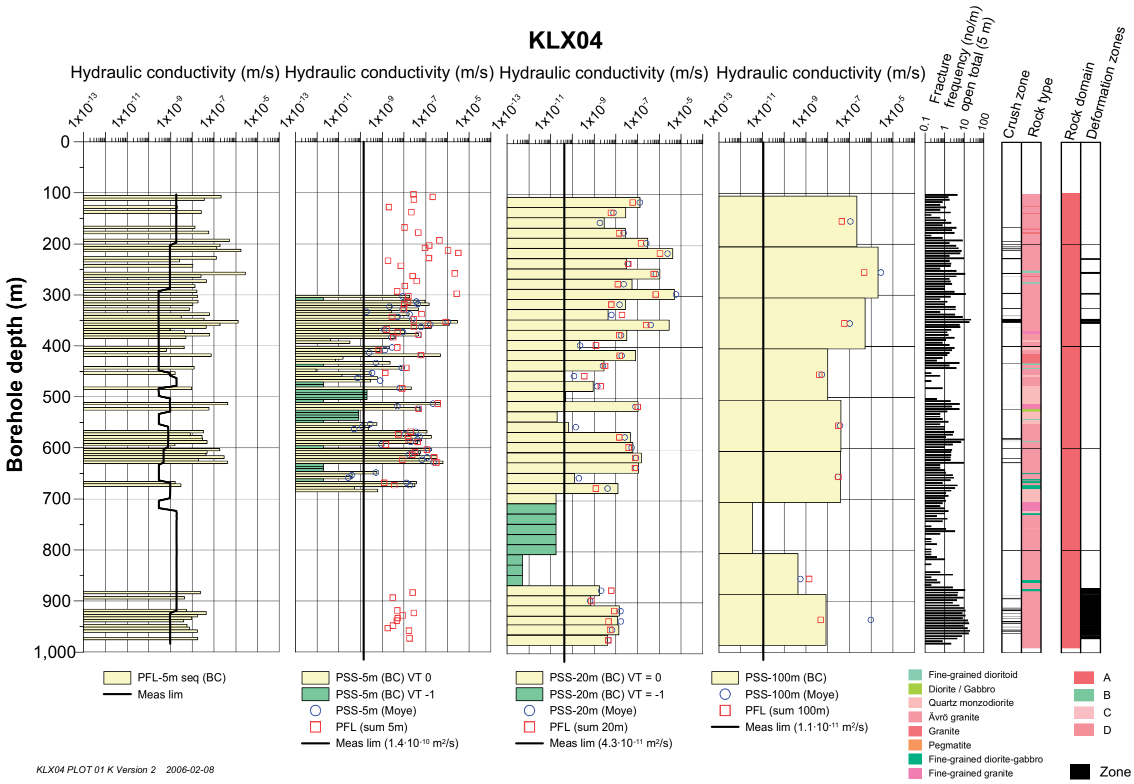


***Figure 5-6.** Hydraulic conductivity of borehole KLX04 based on PSS data and Boremap data (fracture frequency (mean per 5 m) crush zones and rock type) and evaluated rock domains and deformation zones. (Borehole depth: length along the borehole.)*

5.4 KLX05

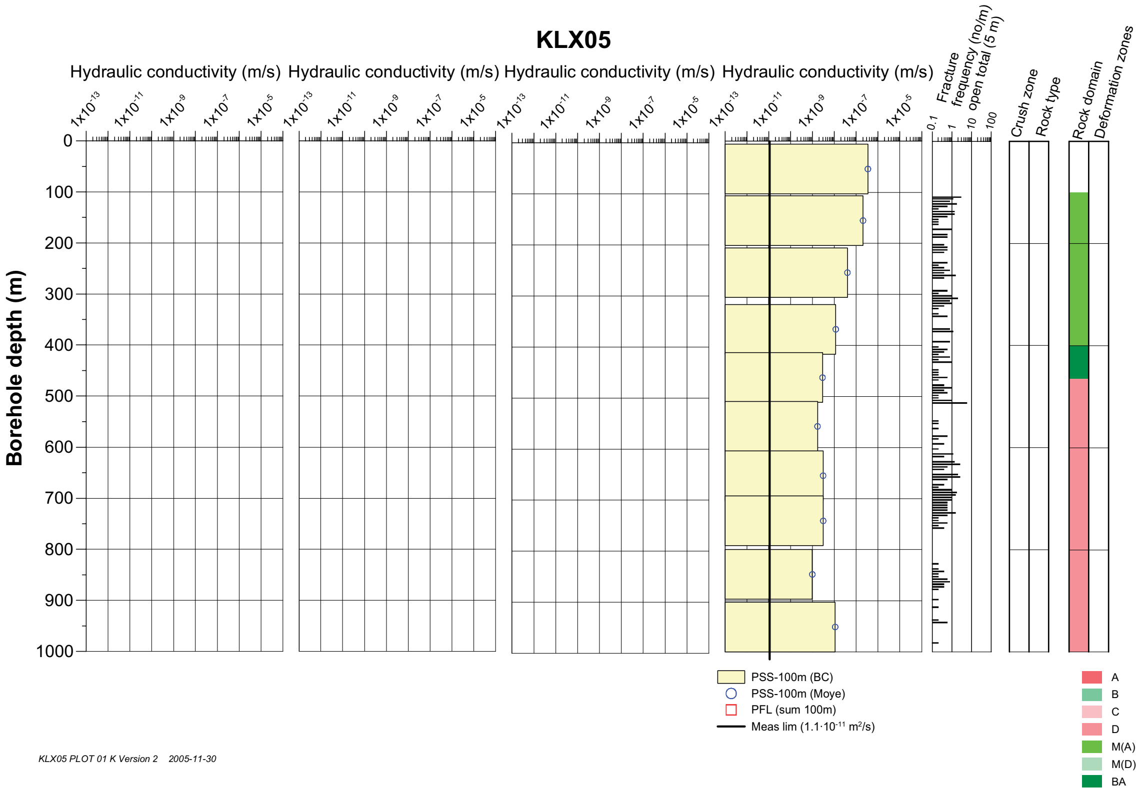


Figure 5-7. *Hydraulic conductivity of borehole KLX05 based on WLP data and Boremap data (fracture frequency (mean per 5 m) crush zones and rock type) and evaluated rock domains and deformation zones. (Borehole depth: length along the borehole.)*

5.5 KLX06

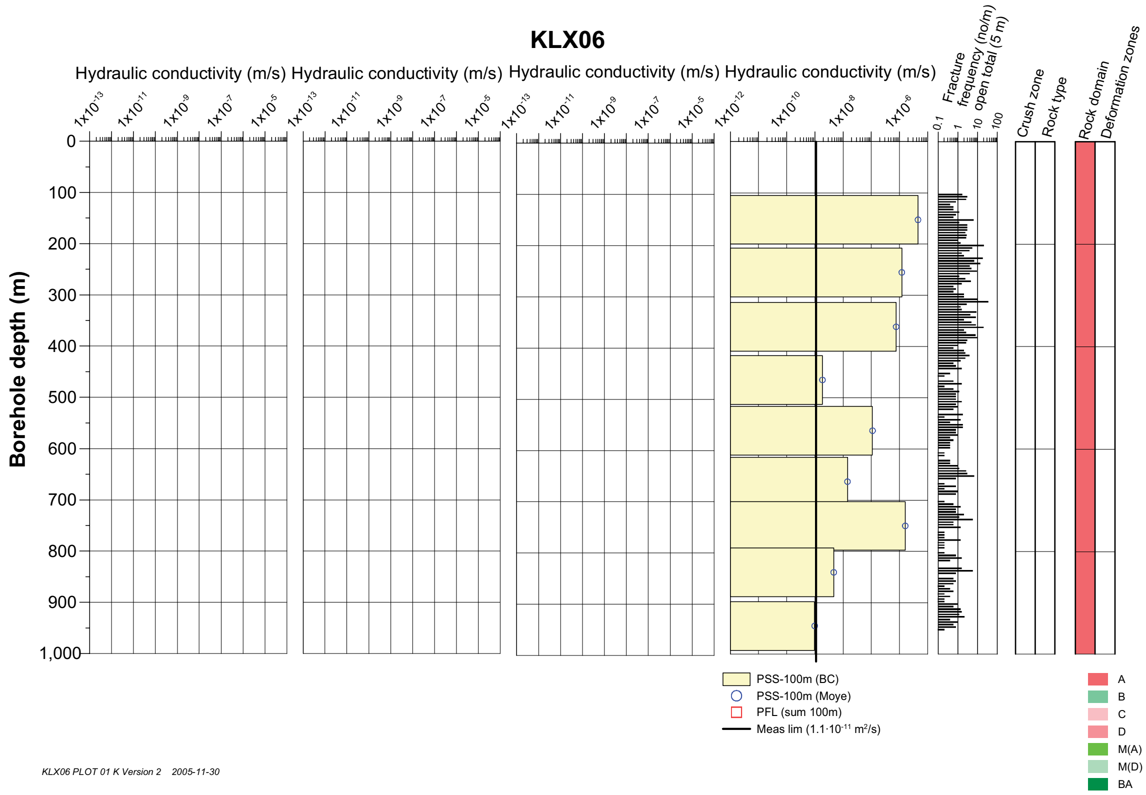


Figure 5-8. Hydraulic conductivity of borehole KLX06 based on WLP data and Boremap data (fracture frequency (mean per 5 m) crush zones and rock type) and evaluated rock domains and deformation zones. (Borehole depth: length along the borehole.)

5.6 KAV04

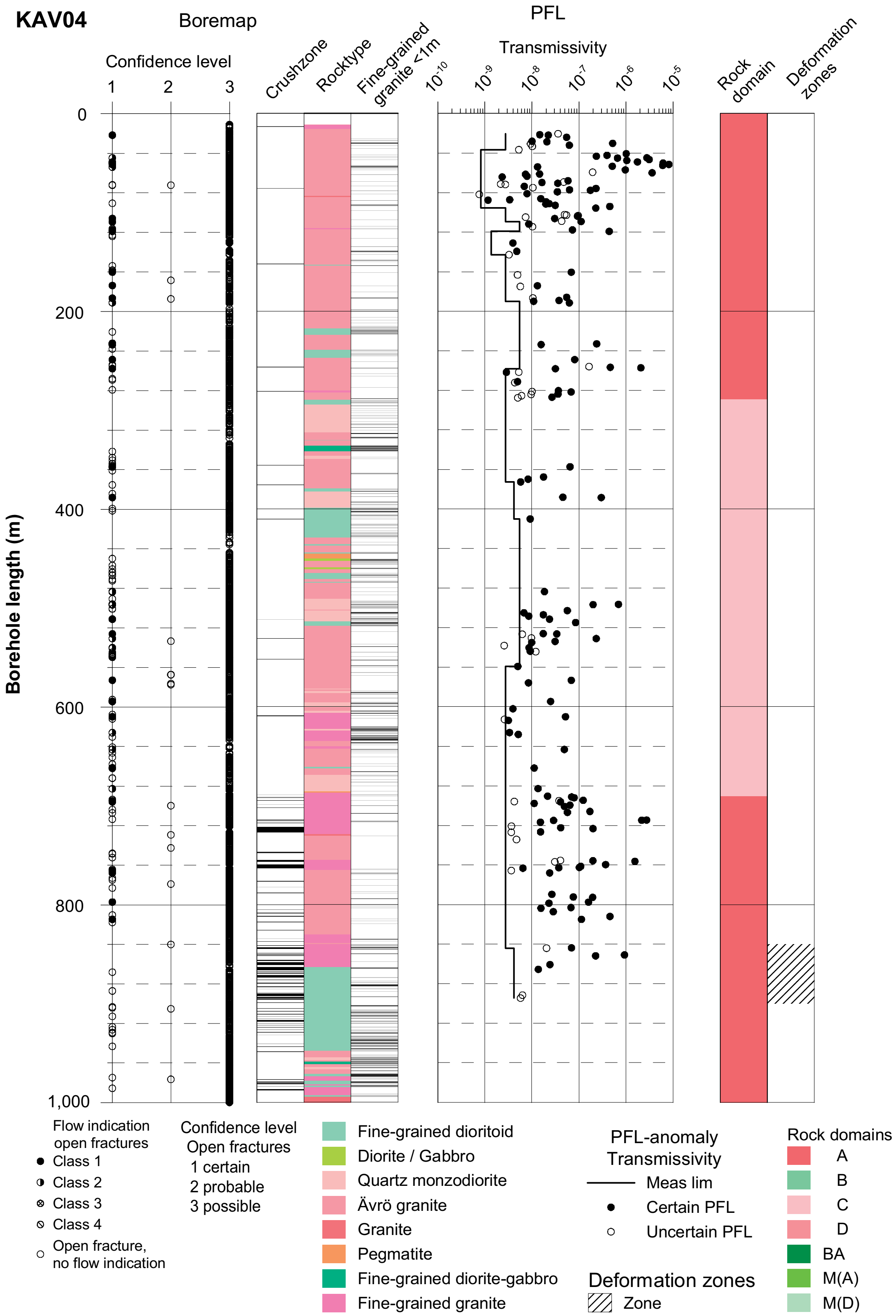


Figure 5-9. Transmissivity of hydraulic features of borehole KAV04(A+B) based on PFL-f data, Boremap data (open fractures, partly open fractures and crush zones, rock type and veins of fine-grained granite) and the interpreted rock domains and deformations zones /Forssman et al. 2005b/.

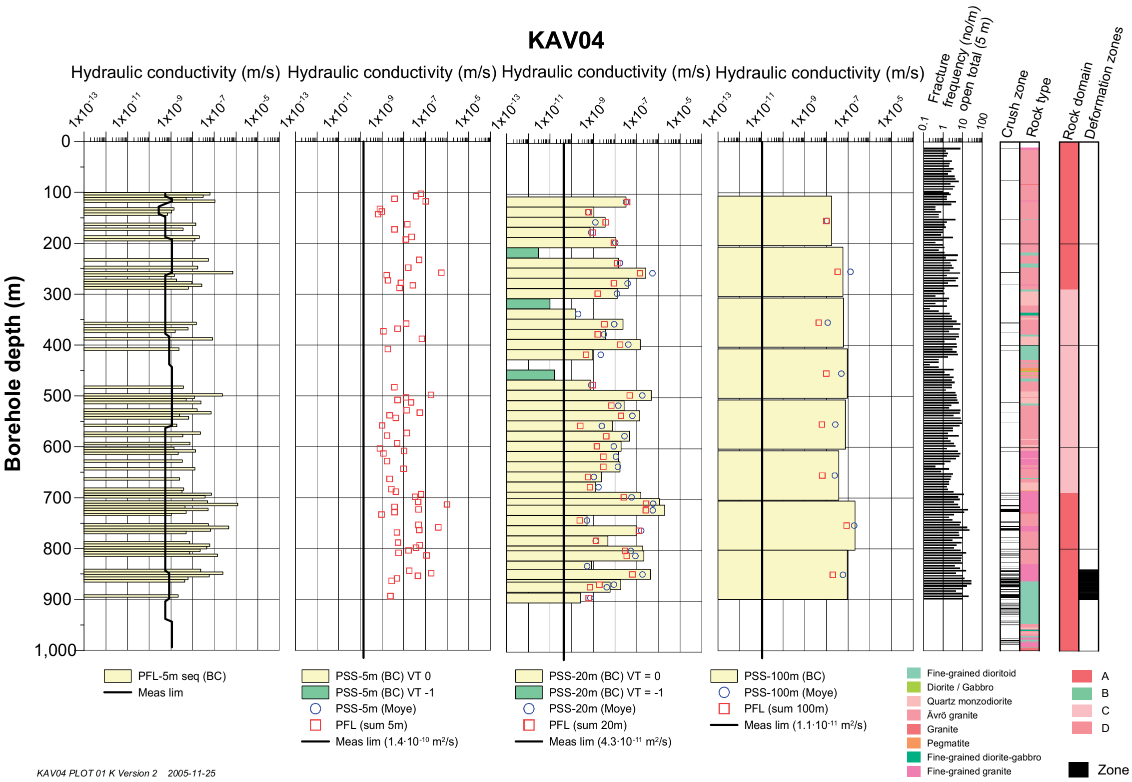


Figure 5-10. *Hydraulic conductivity of borehole KAV04(A+B) based on old injection tests similar to PSS and PFL-s data and Boremap data (fracture frequency (mean per 5 m) crush zones and rock type) and evaluated rock domains and deformation zones. (Borehole depth: length along the borehole.)*

5.7 Comparing test methods and evaluation methodologies

5.7.1 PFL-s compared to PFL-f

The flow logging with PFL is performed in two modes as described above. The evaluated transmissivities for the individual hydraulic features (PFL-f) were summed up to the corresponding 5 m sections measured by PFL-s and are shown in Figure 5-11. As can be seen, the PFL-s mostly compare well with the PFL-f summed transmissivities for the individual hydraulic features. The simplified approach for PFL-f appears to be accurate. The deviations shown in KLX02 are not surprising due to the approximate evaluation of the flow anomalies from reports and data base (PFL-f was not made in KLX02 as performed during the Site Investigations.).

In KLX04 there is one point with a larger deviation. The reason is that one flow anomaly near the casing is very close to the outer limits for the PFL-s test section and probably the length correction is not perfect there.

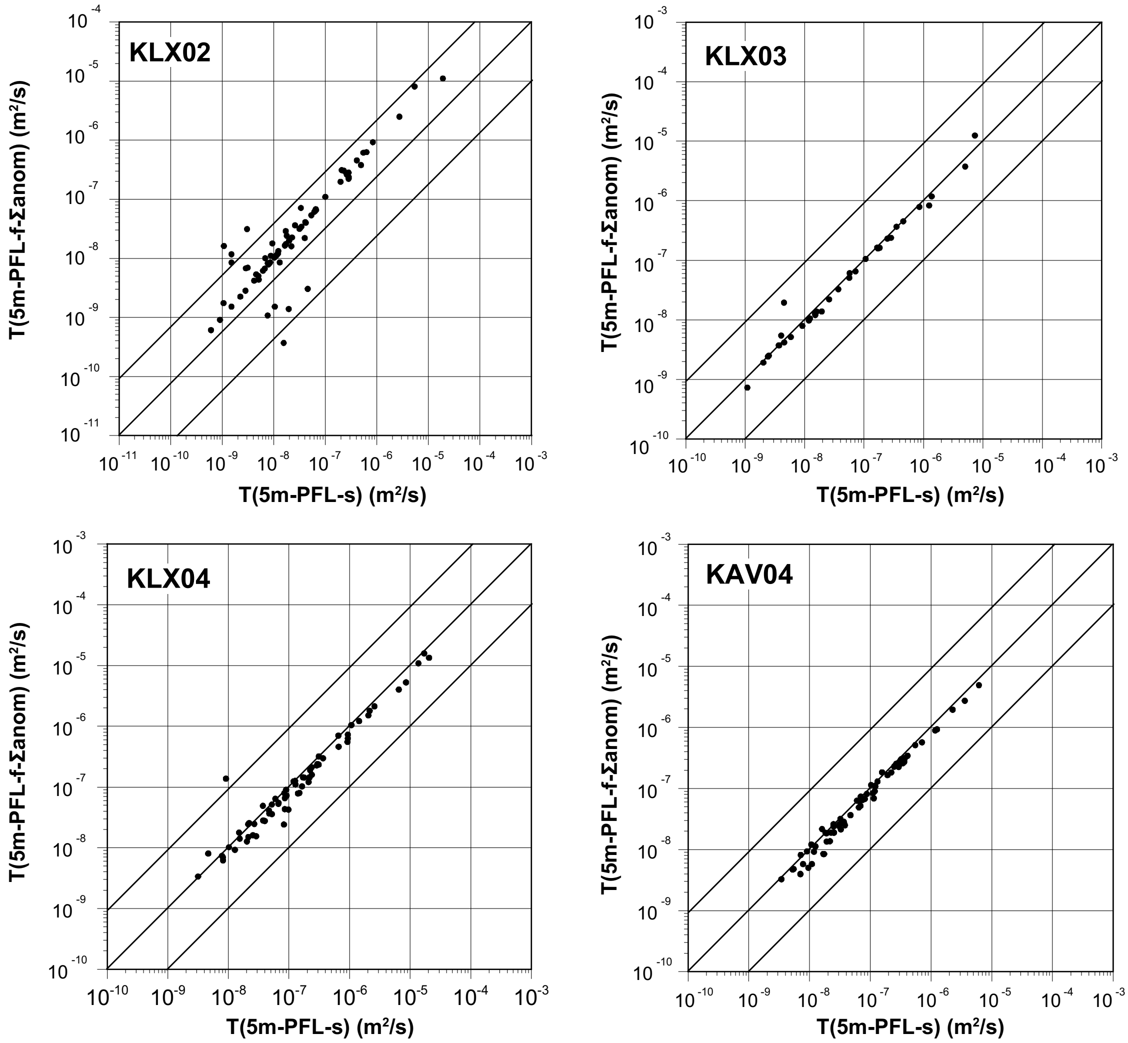


Figure 5-11. *Cross plot of transmissivity from PFL: Transmissivities evaluated for 5 m sections (T(5 m-PFL-s) versus transmissivities for the individual hydraulic features (PFL-f) summed up to 5 m sections (T(5 m-PFL-f-Σ anom) in the plot). (The bounding lines to the 1:1 line: 0.1 and 10 times 1:1 value.)*

5.7.2 PSS steady state compared to PSS transient and sum PFL-f

Transmissivity evaluated using /Moye, 1967/ (T_Moye) from PSS has been jointly compared with the evaluated transient transmissivities (T_T) from PSS and the summed-up transmissivities from the hydraulic features based on PFL-f, see example comparative plot for 20 m test scale in Figures 5-12 to 5-14. Despite the use of different test and evaluation methods, most of the transmissivities plot close to the 1:1 line within a range of 0.1 to 10 of the value on the x-axis. The transmissivity estimates therefore seem robust. However, one can notice that the transient evaluation of T seems to be systematically (although not always) a bit larger at all measured tests scales (5, 20 and 100 m). This means that there is generally a positive skin factor and that the transient evaluation of T (T_T) should be more representative for the formation than T_Moye. T_T is always used as the best choice value, as mentioned earlier.

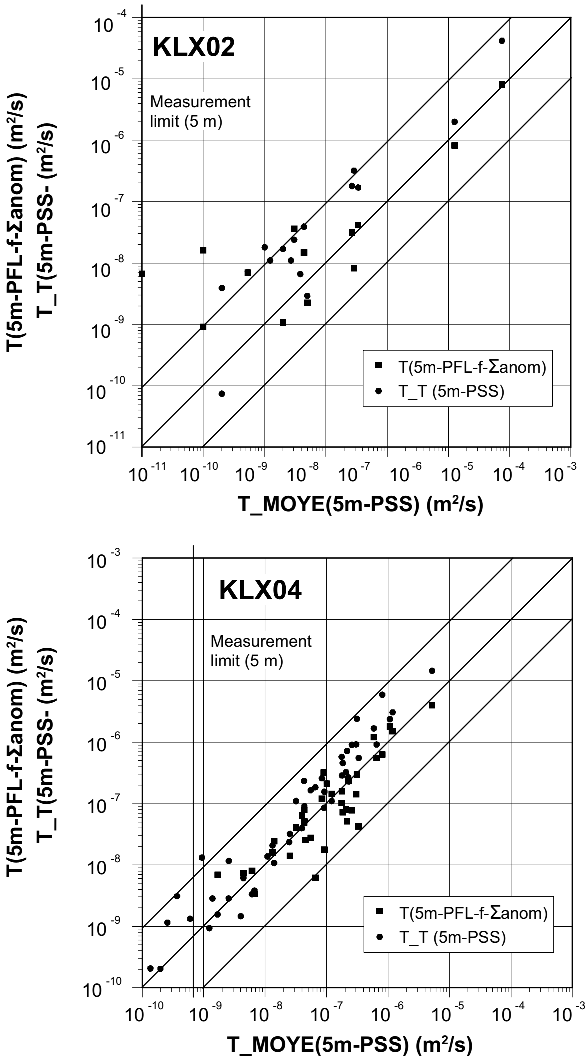


Figure 5-12. *Cross plot of transmissivity PSS steady state vs. PSS transient and sum PFL-f: Transmissivities based on PSS data and steady state evaluation (T_Moye) versus transmissivities for the individual hydraulic features summed up to 2, 5 or 10 m sections (T(Xm-PFL-f-Σanom)) in the plot) and transmissivities based on PSS and transient evaluation ((T_T(5 m-PSS)) in the plot). (The bounding lines to the 1:1 line: 0.1 and 10 times 1:1 value.)*

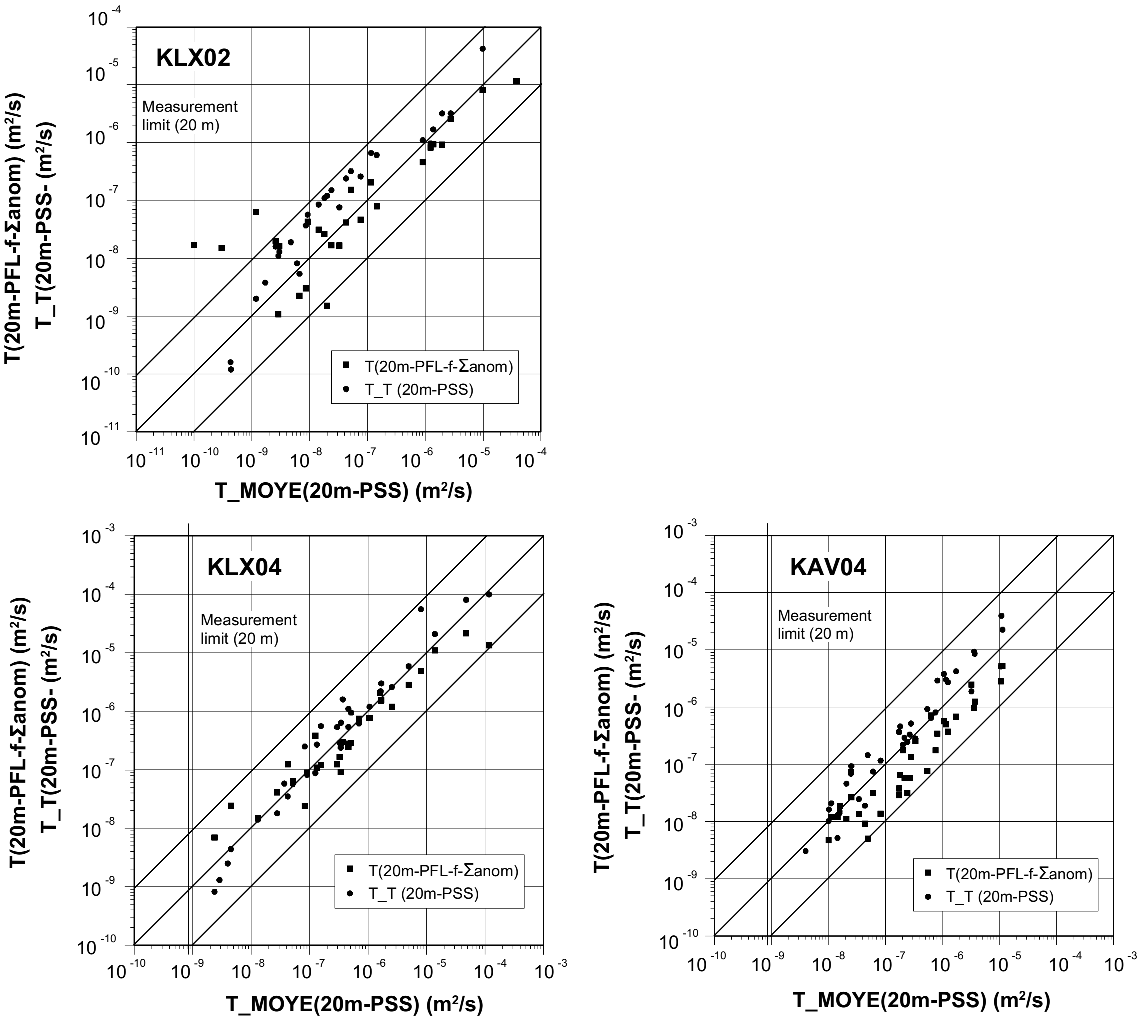


Figure 5-13. *Cross plot of transmissivity PSS steady state vs. PSS transient and sum PFL-f: Transmissivities based on PSS data and steady state evaluation (T_Moye) versus transmissivities for the individual hydraulic features summed up to 20 m sections (T(20 m-PFL-Σanom)) in the plot) and transmissivities based on PSS and transient evaluation ((T_T(20 m-PSS)) in the plot). (The bounding lines to the 1:1 line: 0.1 and 10 times 1:1 value.)*

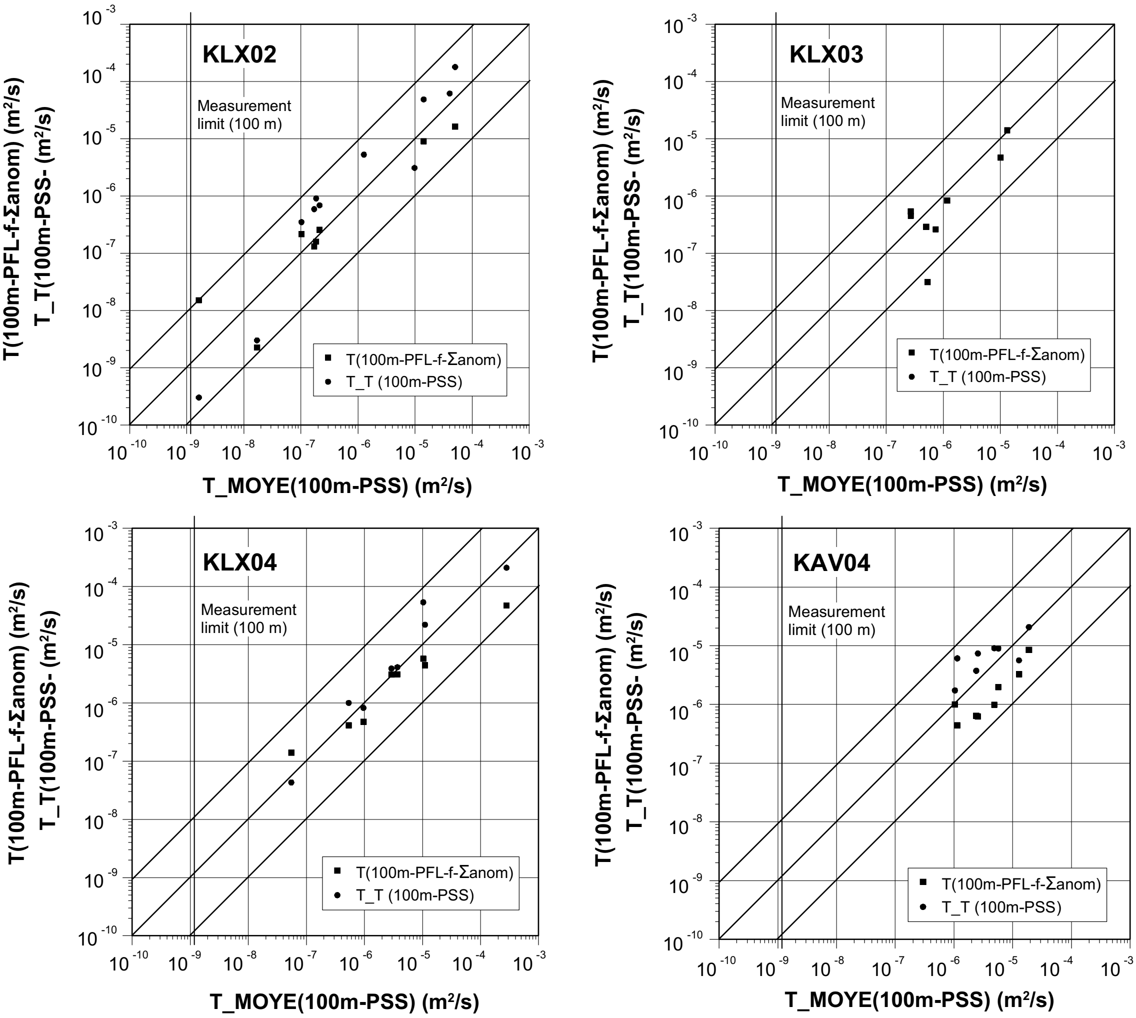


Figure 5-14. *Cross plot of transmissivity PSS steady state vs. PSS transient and sum PFL-f: Transmissivities based on PSS data and steady state evaluation (T_Moye) versus transmissivities for the individual hydraulic features summed up to 100 m sections (T(100 m-PFL-Σanom)) in the plot) and transmissivities based on PSS and transient evaluation ((T_T(100 m-PSS)) in the plot). (The bounding lines to the 1:1 line: 0.1 and 10 times 1:1 value.)*

5.7.3 PSS compared to summed up smaller section PSS

The PSS tests were also compared by summing up the 20 m tests sections to 100 m section see Figure 5-15. Only the “Best Choice values” (see beginning of Chapter 5) are compared. Only 100 m sections with measured 20 m sections are plotted (If 100 m test section tests indicated very low transmissivities, no tests in the 20 m test scale were performed and thus not compared in the figures. However, for statistics of 20 m test section, these sections have been assigned measurement limits values equal to the transmissivity of the 100 m test section. See next chapter)

The sum of 20 m sections generally is found to compare well with the corresponding 100 m sections for all all boreholes. However, there is a slight tendency for the sum of the values for the 20 m sections to be a bit higher than the corresponding 100 m section. This is in accord with experiences from the investigations for the Äspö Hard Rock Laboratory /Rhén et al. 1997c/.

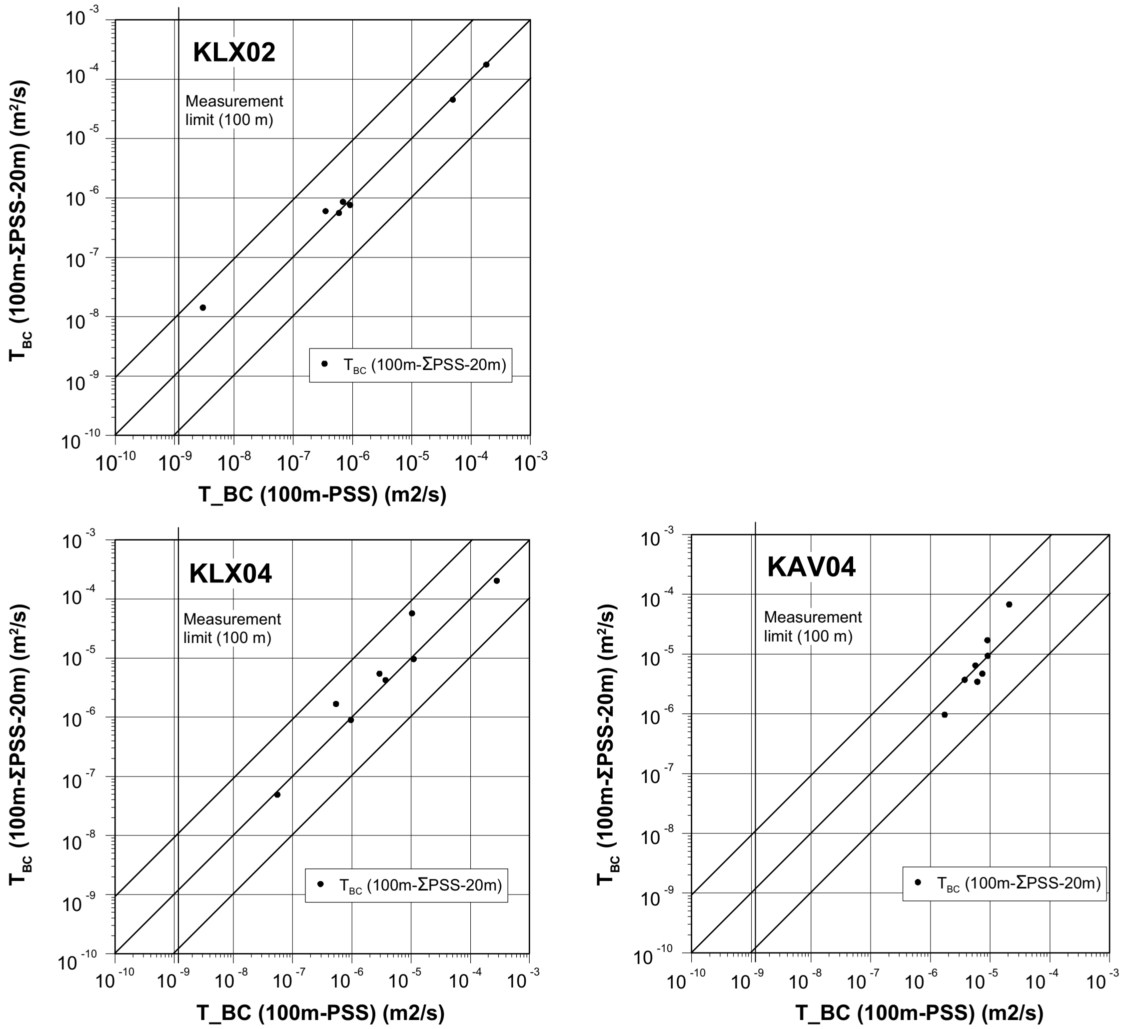


Figure 5-15. Cross plot of transmissivity PSS 100 m test section vs. sum PSS 20 m test section. (The bounding lines to the 1:1 line: 0.1 and 10 times 1:1 value.)

5.8 Statistics of single hole test results

Data from the hydraulic tests performed in the boreholes have been compiled and univariate statistics have been calculated and compared with data from other cored boreholes in the Simpevarp area, where similar tests have been conducted.

Hydraulic conductivity (or transmissivity) evaluated from hydraulic tests with the same test section length often fit rather well to a lognormal distribution. When the test section length decreases, the number of tests below the lower measurement limit of the equipment increases. The data set is hence "censored", which has to be taken into account when choosing a statistical distribution that should describe the measured values above the measurement limit as well as possible. A data set is said to be truncated if the number of unmeasured values is unknown and it is censored if this number is known /Jensen et al. 2000/. For censored data below the measurement limit, the fitted distribution can be used to estimate the properties below the measurement limit, but these estimates are of course associated with uncertainty. When performing modelling based on the fitted distribution it has to be decided if extrapolation below the measurement limit is reasonable and whether there is a definite lower limit (below the lower measurement limit) for the property in question due to e.g. conceptual considerations. In crystalline rock, the matrix permeability sets the physical lower limit, cf /e.g. Brace 1980/. The matrix hydraulic conductivity of crystalline rock is generally found to be ca 1E–14 to 1E–13 m/s.

The standard procedure for describing the hydraulic material properties from single-hole test data is to fit the logarithm of the data to a normal distribution, also taking the censored data into account. The associated statistics normally include the mean and standard deviation (std) of Y, $Y = \log_{10}(X)$, X = hydraulic conductivity (K) or transmissivity (T), where the mean of $\log_{10}(X)$ corresponds to the geometric mean of X. Occasionally, the number of measurements below the lower measurement limit is greater than the number above the measurement limit, see Figure 5-16 . However, it is here argued that the above methodology (the fitting of the statistical distribution to values above the lower measurement limit – the "known values") is the appropriate way to describe a dataset with censored values. This while measured values above the measurement limit are fairly well reproduced by the distribution which also indirectly accounts for the values below the measurement limit. A power law distribution may work equally well, but this has not been tested here.

5.8.1 Statistics of single hole tests – sequential measurements

In Tables 5-1 through Table 5-3 the univariate statistics are shown for the PFL-s and PSS tests for each borehole. In Table 5-4 data previously evaluated for Äspö is shown for comparison. In Appendix 3 and 4 details of the statistical distributions are shown.

The "theoretical" lower measurement limit for PFL (under optimal conditions) is estimated at c. T = 1.7 E–10 m^2/s, based a minimum flow rate of 6 mL/h, 10 m drawdown and 19 m influence radius applied in Thiems equation. (Theoretical measurement limit outlined in /Rouhiainen and Sokolnicki 2005/). Due to effects of fine particles or gas in the water-filled borehole, the measurement limit that is considered in the evaluation is in general higher and may vary along the borehole, see Figures 5-16 through Figure 5-22. In some boreholes one can see some PFL-f measurements below the measurement limit. The reason is that the measurement limit estimated from the measurement is approximate, and in a few cases it was judged that a flow anomaly was possible to estimate that turned out to be a bit lower than the PFL-s based measurement limit.

The measurement limit for PSS is more stable and generally lower than that for PFL-s. The tests using PSS are therefore essential, especially for confirming the conductivity of the rock in the lower transmissivity range.

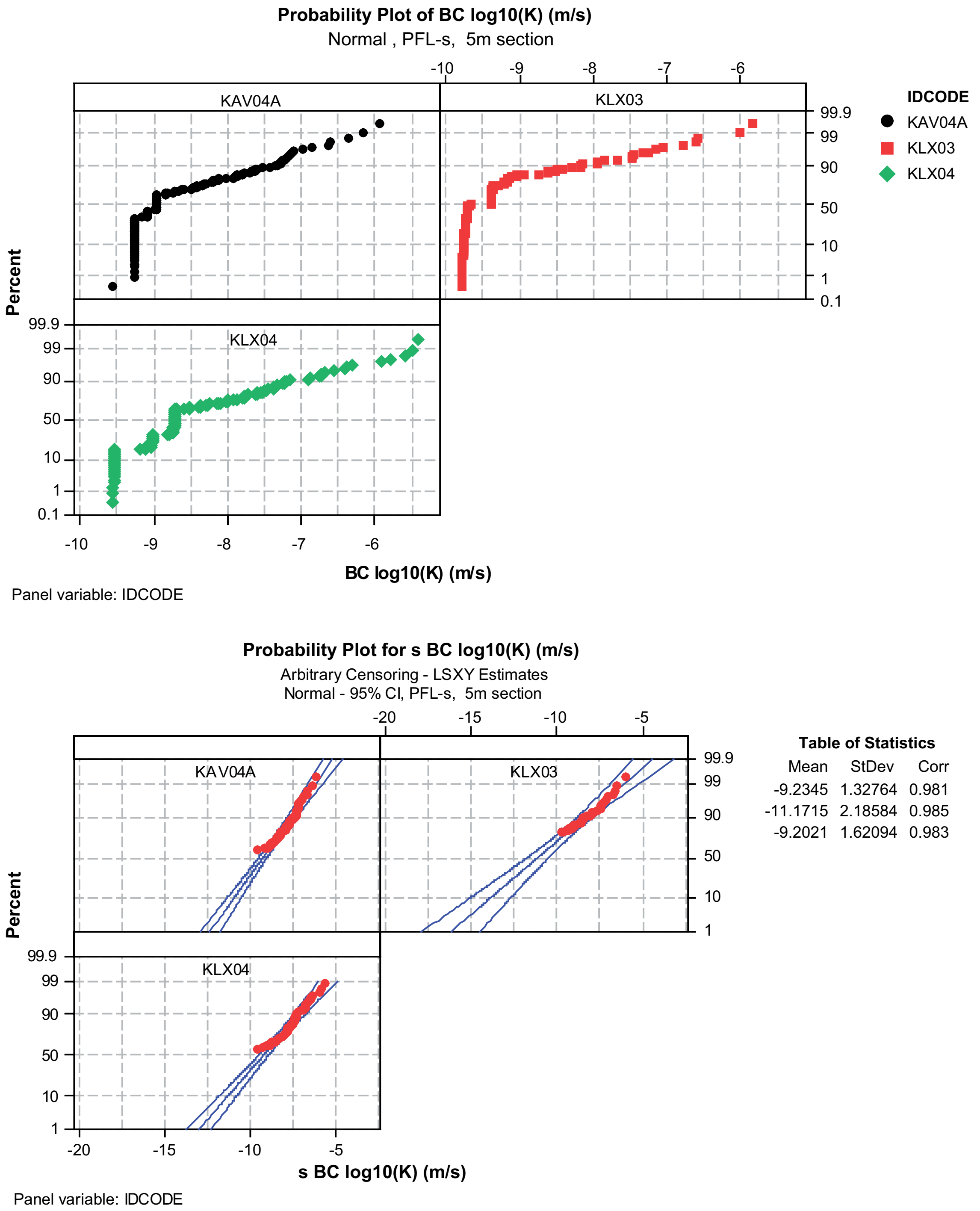


Figure 5-16. *Example of statistical distributions plotted as Normal distributions. Top: All data including measurement limit values are plotted. Bottom: Statistical analysis of the values shown in the top figure, setting all measurement limit values as Censord values result in the matched mean and standard deviations shown in the caption.*

Table 5-1. Univariate statistics for hydraulic tests performed in cored boreholes. Method employed: PFL-s, Section Posiva Flow Logging. "Lower meas. Limit" in the table is the Practical measurement limit for PFL-s. K: m/s.

Borehole	Test type	Section upper (m)	Section lower (m)	Test scale (m)	Sample size, all	Sample size below the lower meas. lim values	Lower meas. Limit [1], Log10 K [2] Log10(m/s)	Mean Log10 K Log10(m/s)	Std Log10 K (–)
KLX02	PFL-s	205.92	1,399.92	3	398	276	(–10)–(–8.3)	–9.8	1.27
KLX03	PFL-s	101.3	992.42	5	178	142	(–9.8)–(–8.2)[3]	–11.2	2.19
KLX04	PFL-s	100.2	986.22	5	177	110	(–9.6)–(–8.7)	–9.2	1.62
KAV04A	PFL-s	100.16	996.17	5	179	110	(–9.6)–(–9.0)	–9.2	1.33

[1] Measurement limit estimated from in situ test results, "Practical measurement limit". The measurement limit may vary along the borehole. Max and min values are shown in the table.

[2] PFL-s: Theoretical lower measurement limit (under optimal conditions) is K = 3.3E–11 m/s (Log_{10}(K(m/s)) = –10.5) for test section length 5 m (or equvalently T = 1.7E–10 m^2/s).

[3] Only a few values near the upper range

Table 5-2. Univariate statistics for hydraulic tests performed in cored boreholes. Method employed: PSS. (If only one test is available for a certain test scale, only a value is given in column "K".) K: m/s.

Borehole	Test type	Section upper (m)	Section lower (m)	Test scale (m)	Sample size	Sample size below the lower meas.lim values	Lower meas. limit[1] Log10 K Log10(m/s)	K Log10(K) Log10(m/s)	Mean Log10 K Log10(m/s)	Std Log10 K (–)
KLX02	PSS	300	545	5	49	33	(–11.7)–(–9.5)		–11.2	2.50
	PSS	204	1,004	20	48	15	(–11.3)–(–10.8)		–9.7	2.08
	PSS	204	1,004	100	8	0	(≈ –11.7)		–8.34	1.78
	PSS[2]	3	1,700.5	100–300	11	0	(≈ –11)		– 8.11	1.71
	Pump t[3]	202.95	1,700.5	≈1,000	1	–	–	–7.1		
KLX03	WLP	103	1,000.42	≈100	9	0	(–6)		–8.0	0.69
	Pump t	11.65	1,000.42	1,000	1	–	–	–7.4		
KLX04	PSS	300.41	685.78	5	77	19	(–11.7)–(–9.7)		–9.2	2.0
	PSS	105.21	983.05	20	44	8	(–12.3)–(–10.7)		–8.7	1.99
	PSS	105.11	986.11	100	9	0	(≈–12.6)		–8.1	1.92
	Pump t	12.24	993.49	1,000	1	–	–	–6.8		
KLX05	WLP	0	1,000.2	≈100	10	0	(–6)		–8.1	0.85
KLX06	WLP	103	994.94	≈100	9	0	(–6)		–7.3	1.57
KAV04B	Pump t	19.53	95.93	≈100	1	–	–	–6.4		
KAV04A	PSS	105.17	903.35	20	42	4	(–13.3)–(–10.8)		–8.2	1.44
	PSS	105.17	998.2	100	9	1	(≈–12.6)		–7.9	1.64
	Pump t	100	1,001.2	≈1,000	1	–	–	–7.6		

[1] Measurement limit estimated from in situ test data.

[2] Old test data made with similar equipment as PSS+new test data made with PSS.

[3] Old test data.

Table 5-3. Univariate statistics for hydraulic tests performed in percussion-drilled boreholes. Methods used: Airlift tests, Pumping test (with submersible pump), HTHB-p: Pumping test or injections test, HTHB-f: flow logging. (If only one test is available for a certain test scale, only a value is given in column “K”.) K: m/s.

Borehole	Test type	Section upper (m)	Section lower (m)	Test scale (m)	Sample size	Sample size below the lower meas.lim values	Lower meas. limit[1] Log10 K Log10(m/s)	K Log10(K) Log10(m/s)	Mean Log10 K Log10(m/s)	Std Log10 K (–)
BH in Table 5-3	Air lift/pump test	–	–	≈100	11	0	≈–7.7[2]	–	–6.9	1.19
HAV09	Air lift	14.9	200	≈100	1		≈–7.7[2]	–8.7		
HAV10	Air lift	11.9	100	≈100	1		≈–7.7[2]	–8.1		
HLX10	Pump test	0	85	≈100	1		≈–7.7[2]	–5.7		
HLX13	Air lift	11.87	200	≈100	1		≈–7.7[2]	–8.7		
HLX14	Air lift	11.9	115.9	≈100	1		≈–7.7[2]	–7.0		
HLX18	Pump test	15.12	181.2	≈100	1		≈–7.7[2]	–6.6		
HLX20	Pump test	9.12	202.2	≈100	1		≈–7.7[2]	–6.7		
HLX22	Pump test	9.1	163.2	≈100	1		≈–7.7[2]	–5.8		
HLX24	Pump test	9.1	175.2	≈100	1		≈–7.7[2]	–5.4		
HLX25	Pump test	6.12	202.5	≈100	1		≈–7.7[2]	–6.0		
HLX32	Pump test	12.3	162.6	≈100	1		≈–7.7[2]	–6.9		

[1] Mixed tests: airlift tests and pumping tests. Parameters evaluated from airlift tests are regarded as being uncertain as measured flow rates and drawdown/recovery curves generally are more uncertain than using submersible pump that gives more stable measurements.

[2] For a 100 m section with 50 m drawdown with HTHB. Airlift pumping may give lower values.

Table 5-4. Compilation of data from boreholes at Äspö from /Rhén et al. 1997c/. K: m/s.

Borehole	Test type	Section upper (m)	Section lower (m)	Test scale (m)	Sample size	Lower meas. limit[1] Log10 K Log10(m/s)	Mean Log10 K Log10(m/s)	Std Log10 K (–)
KAS02–KAS08	Inj.test	c 100	500–800	3	1,105		–7.8 to –9.7	1.12 to 2.08

[1] Measurement limit estimated from field results.

/Rhén et al. 1997c/ estimated a geometric mean K = 1.6E–8 m/s with a standard deviation (Log10K) of 0.96 for well data obtained from the well archive of the Swedish Geological Survey (area approximately corresponding to the NE part of the municipality of Oskarshamn) and percussion holes located at Äspö, Ävrö, Mjälen. Hålö and Laxemar. The test scale was approximately 100 m. Subsequently, /Follin et al. 1998/ estimated a geometric mean K = 6.3E–8 m/s for wells sunk in the bedrock within the municipality of Oskarshamn as found in the SGU well archive. The test scale in this case varied between 10 and 100 m. Both analyses included wells intercepting fracture zones, if present.

5.8.2 Statistics of single hole tests – flow anomaly measurements

The difference flow logging and the core mapping with the Boremap system in the core drilled boreholes KLX02, KLX03, KLX04, KAV04A and KAV04B at Oskarshamn, were conducted during year 2000, 2003 and 2004. These data have been used to identify individual geological mapped features as fractures or crush zones that correspond to flow anomalies identified with the Posiva Flow Log/Difference Flow (PFL) method /Forssman et al. 2005b/.

A few general results are shown in Tables 5-5 and 5-6 and Figures 5-16 to 5-19. Table 5-5 shows some mean geological characteristics for the borehole interval measured with PFL. Table 5-6 shows an overview of some main characteristic of how the flow anomalies couples to different geological features.

In several cases a flow anomaly can be connected to several fractures if they are close to the anomaly. In most of these cases it can be assumed that it may be one of the interpreted fractures, some of them, or even all of them that causes the flow anomaly.

In Figures 5-17 and 5-18 one can note that KAV04B behaves different from the others, much higher frequency of flow anomalies but similar frequencies of fractures. This borehole covers depths 0–100 m but the others 100 m and deeper. Possibly one can here see an effect of the effective rock stress, smaller rock stress near the surface that opens up more fractures compared to deeper situated fractures.

In Figure 5-18 indicates a positive correlation between open fractures and PFL anomalies, except for KAV04B, which differs possibly because of the rock stress situation.

Figure 5-19 indicates that the relative frequency: PFL-f frequency/open fracture-frequency is 0.03–0.08 for depth greater than 100 m and around 0.25 near surface (0–100 m depth), though the last is very uncertain as it is based on only one borehole.

It can be noted that the mapped partly open fractures are very few. It should also be observed that KLX02 was not drilled with trippel-tube technique, which possibly caused more artificially open fractures. To some extent this may affect the mapped No of open fractures, as it sometimes is difficult to judge if a core break is artificial or should be mapped as open.

Table 5-5. Boremap data for the PFL-f measured interval in KLX02, KLX03, KLX04, KAV04A and KAV04B.

Object	KLX02	KLX03	KLX04	KAV04A	KAV04B
Measured interval in the borehole with PFL-f (interval based on PFL-s as it guides PFL-f measurements)	205.92–1,399.92	101.3–992.42	100.2–986.22	100.16–996.17	19.53–95.93
No of open fractures mapped as Total /(Certain/ Probable/Possible) in the PFL-f measured interval	2103/(1590/2/511)	679/(25/188/466)	2009/(77/402/1530)	3200/(134/15/305)	205/(12/1/192)
Mean fracture frequency of open fractures (Total)	1.76	0.76	2.24	3.57	2.68
No of partly open fractures mapped as Total /(Certain/ Probable/Possible) in the PFL-f measured interval	105/(18/1/86)	4/(1/0/0)	13/(8/1/4)	7/(4/0/3)	0
Mean fracture frequency of partly open fractures (Total)	0.03	0.003	0.06	0.09	0.01
No of crush zones in the PFL-f measured interval	38	3	53	78	1
Appr. No of fractures in crush zones (assuming 40 fr./m)	2,064.8	16.4	828	1,666.4	9.6
Mean No of fractures in a crush zone	54.3	5.5	15.6	21.4	9.6
Mean fracture frequency of Total open fractures (All open+partly open+crush zone fractures)	3.52	0.78	3.22	5.52	2.82
No of sealed fractures mapped as Total/(Certain/ Probable/Possible) in the PFL-f measured interval	856/(849/2/4) 1 unclassified	3696/(3693/0/3)	3476/(3461/5/9) 1 unclassified	4727/(4678/1/44) 4 unclassified	379/(374/0/5)
Mean fracture frequency of sealed fractures (Total)	0.72	4.15	3.87	5.28	4.96

Table 5-6. Flow anomalies in KLX02, KLX03, KLX04, KAV04A and KAV04B.

Object	KLX02	KLX03	KLX04	KAV04A	KAV04B
Measured interval in the borehole with PFL-f (interval based on PFL-s as it guides PFL-f measurements)	205.92–1,399.92	101.3–992.42	100.2–986.22	100.16–996.17	19.53–95.93
Total No of PFL anomalies (“Certain””+”Uncertain”)	102	55	129	134	54
No of PFL anomalies mapped as “Certain”	95	34	98	101	44
No of PFL anomalies mapped in crush zones	12	1	34	30	1
Mean feature frequency of PFL anomalies (Total)	0.085	0.062	0.144	0.150	0.707
No of crush zones in the PFL-f interval, Total/No.with one or more PFL-f anomalies	38/11	3/1	53/23	78/18	1/1
Mean feature frequency of crush zones with PFL anomalies	0.29	0.33	0.43	0.23	1
No of Geological features (fractures+crush zones/crush zones) identified with distance <0.2 m from PFL anomaly	212	89	338	374	88
No of Geological features (fractures or crush zones) identified with distance 0.2–0.4 m from PFL anomaly	12	4	1	0	7
No of Geological features (fractures or crush zones) identified with distance 0.4–0.5 m from PFL anomaly	7	1	0	0	0
No of Geological features (fractures or crush zones) identified with distance > 0.5 m from PFL anomaly	0	2	1	1	0
No of PFL anomalies not correlated to open fractures	6	2	3	0	2
Number of sealed fractures (broken/unbroken) within a distance of 1 dm from PFL anomalies not correlated to open fractures or crush zones	0/3	1/0	3/0	0/0	1/0
Number of sealed fractures (broken/unbroken) within a distance > 1 dm from PFL anomalies not correlated to open fractures or crush zones	3/3	2/0	1/0	0/0	1/0

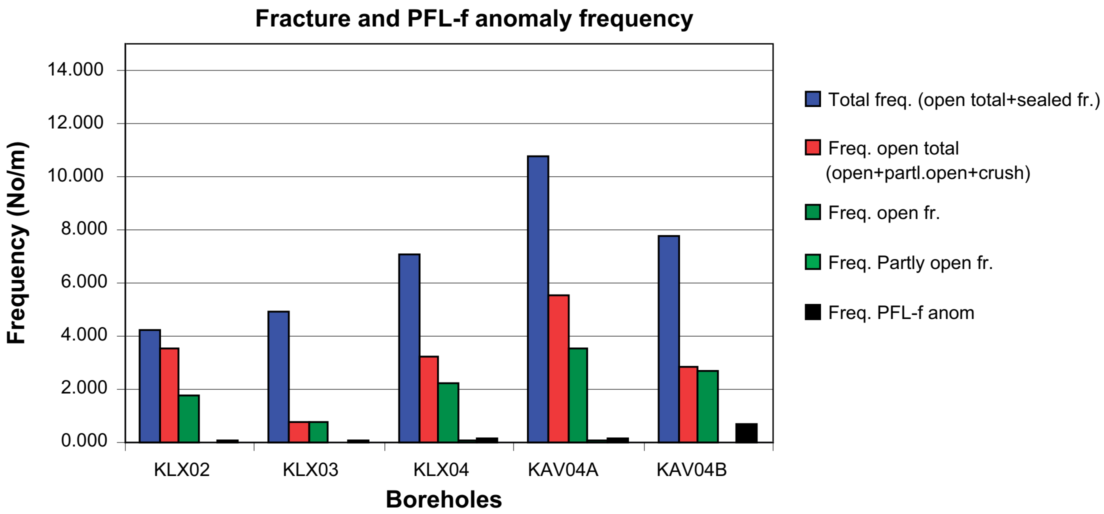


Figure 5-17. Frequency of fractures (open fractures, Partly open fractures, open total fractures (open+partly open+estimated No of open fractures in crush) and Total No of fracture (open total+sealed) and PFL-f anomalies. All fractures mapped as "Certain", "Probable" and "Possible" are included in each fracture category.

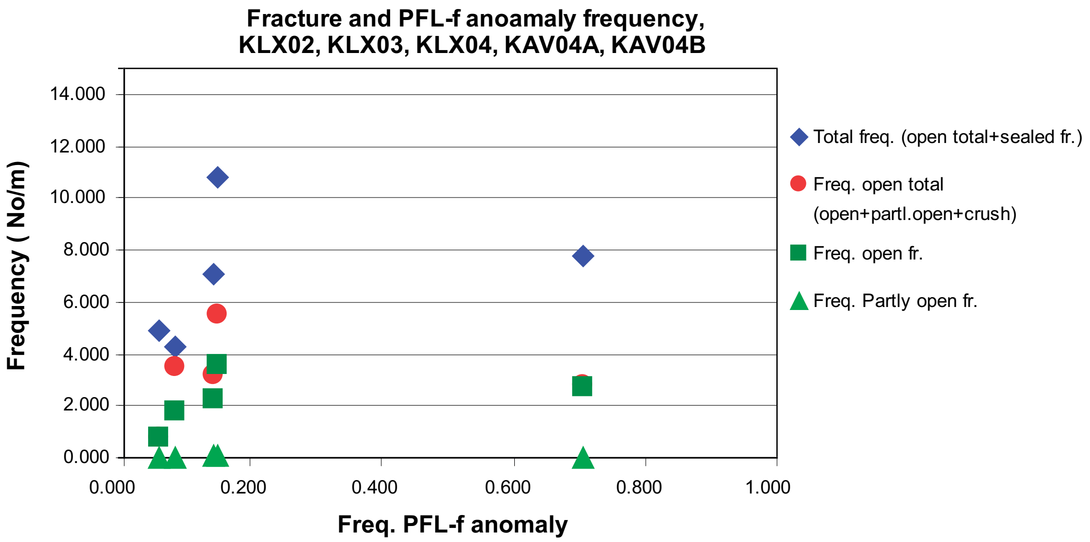


Figure 5-18. Cross plot of Frequency of fractures (open fractures, Partly open fractures, open total fractures (open+partly open+estimated No of open fractures in crush) and Total No of fracture (open total+sealed) versus frequency for PFL-f anomalies. All fractures mapped as "Certain", "Probable" and "Possible" are included in each fracture category.

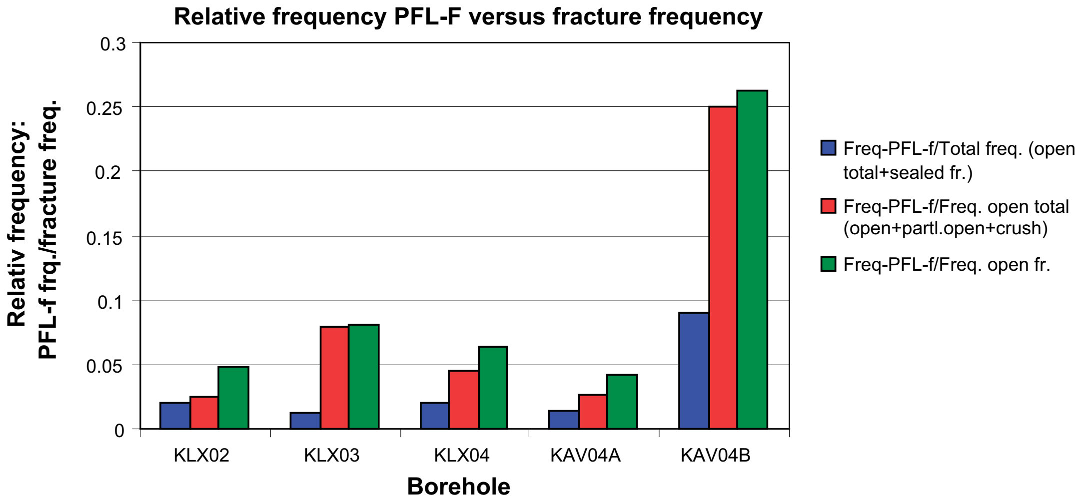


Figure 5-19. *Relative frequency of PFL-f flow anomalies in relation to fractures (open fractures, open total fractures (open+partly open+estimated No of open fractures in crush) and Total No of fracture (open total+sealed) and PFL-f anomalies. All fractures mapped as "Certain", "Probable" and "Possible" are included in each fracture category.*

One flow anomaly may represent several fractures, due to the resolution of the PFL-f measurements (ca 0.1–0.2 m) and the number of open fracture in the PFL-f measurement interval. In the correlations studies of Posiva Flow Logg anomalies to core mapped features /Forssman et al. 2005ab/ some PFL-f anomalies are connected to several possible open fractures, and it is said that one or all of them may be contributing to the PFL-f anomaly. Mapped crush in the core also represents part of the rock that is likely to be several fractures. Below an attempt is made to see what the transmissivity distribution of fractures can be, if we assume that the all possible open fractures connected to a PFL-f anomaly actually are flowing and that the rough estimate of number of fractures in a crush zone are all flowing. These assumptions are if of course uncertain, but gives some idea of a lower limits for the transmissivity distributions. Below it is explained in more detail.

In Tables 5-7 and 5-8 and Figure 5-20 the statistics for all flow anomalies, only flow anomalies coupled to single fractures mapped fractures and flow anomalies coupled to mapped crush zones. The transmissivity distributions for single fractures have also been estimated, based on the following assumptions: If a flow anomaly have been connected to X fractures (as possible object that are flowing, one or all of X) the transmissivity was estimated as T-PFL-anomaly/X. If the flow anomaly was connected to a crush zone, the number of fractures was estimated as the borehole length of the crush zone in m multiplied with 40 fr./m. (This is the general way of estimating the fracture frequency in crush zones in SICADA.). However, the maximum No. of fractures coupled to a flow anomaly was set to 10, based on that generally flow anomaly is detected with some 2 dm. It is thus unrealistic to assign 40 fractures for a 1 m crush zone with just one flow anomaly. These estimates of the fracture transmissivity are of course uncertain, but can be seen as some lower limit for the transmissivity distribution. The following should be recognized:

Transmissivities associated with fractures ("Per fracture…" in Table 5-7 and 5-8 and Figure 5-20):

- Mean: As the maximum number of possible fractures from the PFL-f interpretation is used, the estimated mean should probably be smaller than the true mean for the fractures. The true mean for the fractures can be as for the flow anomalies or smaller, but not smaller than "per fracture.." value.

- Standard deviation: As the flow transmissivity in just divided with the number of possible fractures, the standard deviation is probably underestimated to some extent.

Transmissivities associated with crush ("Per fracture…" in Table 5-7 and 5-8 and Figure 5-20):

- Mean: As the maximum number of possible fractures is based on a rough generalization the estimated mean may possibly be larger or smaller than the true mean for the fractures, but still give a tendency in the right direction. The true mean for the fractures should probably be lower than for the flow anomalies as we can expect that the crush consists of several fractures.
- Standard deviation: As the flow transmissivity in just divided with the number of possible fractures, the standard deviation is probably underestimated to some extent.

In Table 5-9 the statistics of the flow anomalies, with deformations zones identified in the geological single-hole interpretation included, between elevation intervals; 0 to –300 m, –300 to –700 m and below –700 m. Figure 5-21 shows the statistics for elevation interval; –300 to –700 m. The purpose is to indicate the properties that are of most interest for the deep repository. From the table both the statistics of the flow anomaly transmissivity and a rough measure of the frequency of flow anomalies, above the measurement limit for the flow anomalies, can be read. Table 5-10 shows the statistics of the flow anomalies , with deformations zones identified in the geological single-hole interpretation excluded, between elevation intervals; 0 to –300 m, –300 to –700 m and below –700 m.

One or several flow anomalies have been observed in some, but not all, mapped crush zones. If several flow anomalies were observed in a borehole section mapped as crush, these transmissivities were summed up to represent the transmissivity of the crush zone. In Table 5-11 and Figure 5-22 the statistics for the transmissivity for crush zones, based on data were transmissivities were possible to estimate, are shown. The geometric mean transmissivity is ca 10 times greater for crush zones (as individual features) than for individual fractures outside the mapped crush zone, comparing hole by hole data in Tables 5-7 and 5-8 with 5-11. However, the uncertainty is great considering confidence limits.

For crush zones with several flow anomalies, the statistics of the transmissivities of the flow anomalies for each crush zone were estimated, see Table 5-12.

From the PFL data one can estimate the specific capacity (Q/s) for each flow anomaly, and in principle Q/s = T. Calculated T/(Q/s) = 1 to 0.98 for all boreholes but KLX02, which have rather large variation. The old data for KLX02 is however much more uncertain than the new measurements.

It should be stressed that the statistics in Tables 5-7 to 5-12 is based on transmissivity values above a measurement limit. There are geological features (fractures and crush zones) that most likely have transmissivities below this limit.

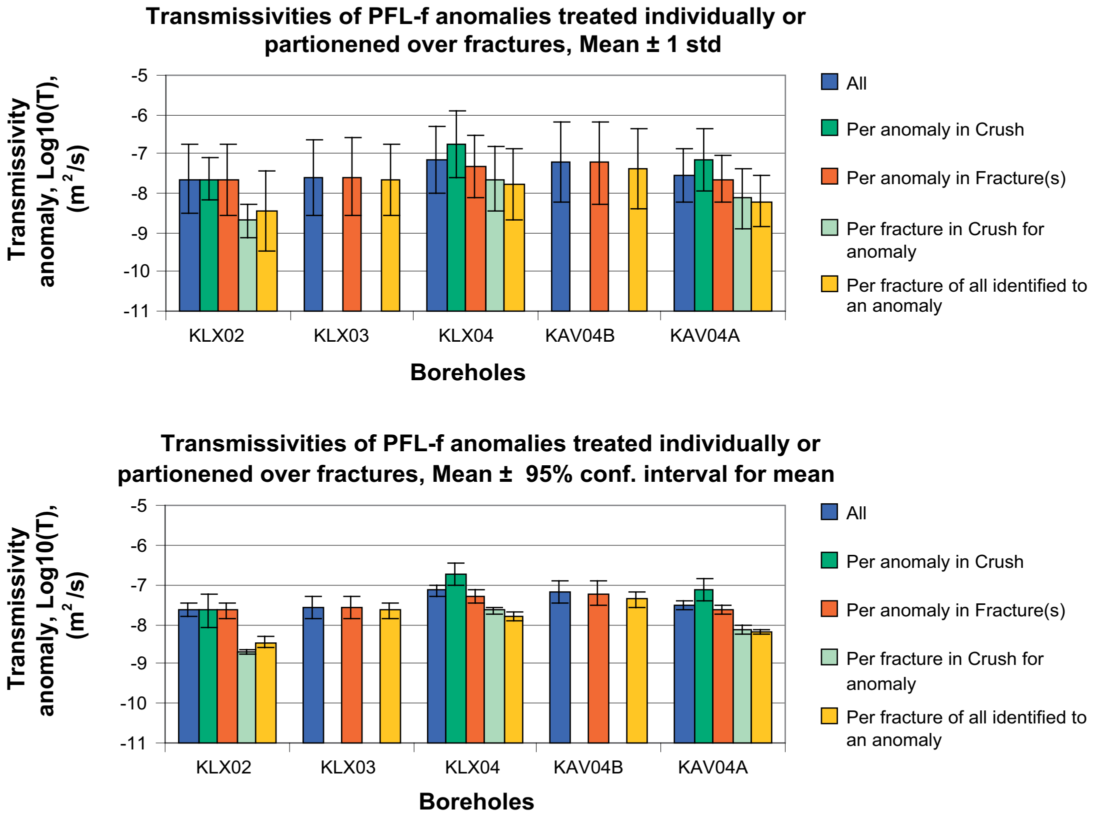


Figure 5-20. *Transmissivity distribution of PFL-f flow anomalies and fractures. Plotted categories: All flow anomalies, All flow anomalies found in crush zones, All flow anomalies related to fractures not in crush zone, Fracture transmissivity for flow anomalies found in crush zones, Fracture transmissivity for flow anomalies related to fractures not in crush zone. (Tables 5-7 and 5-8.)*

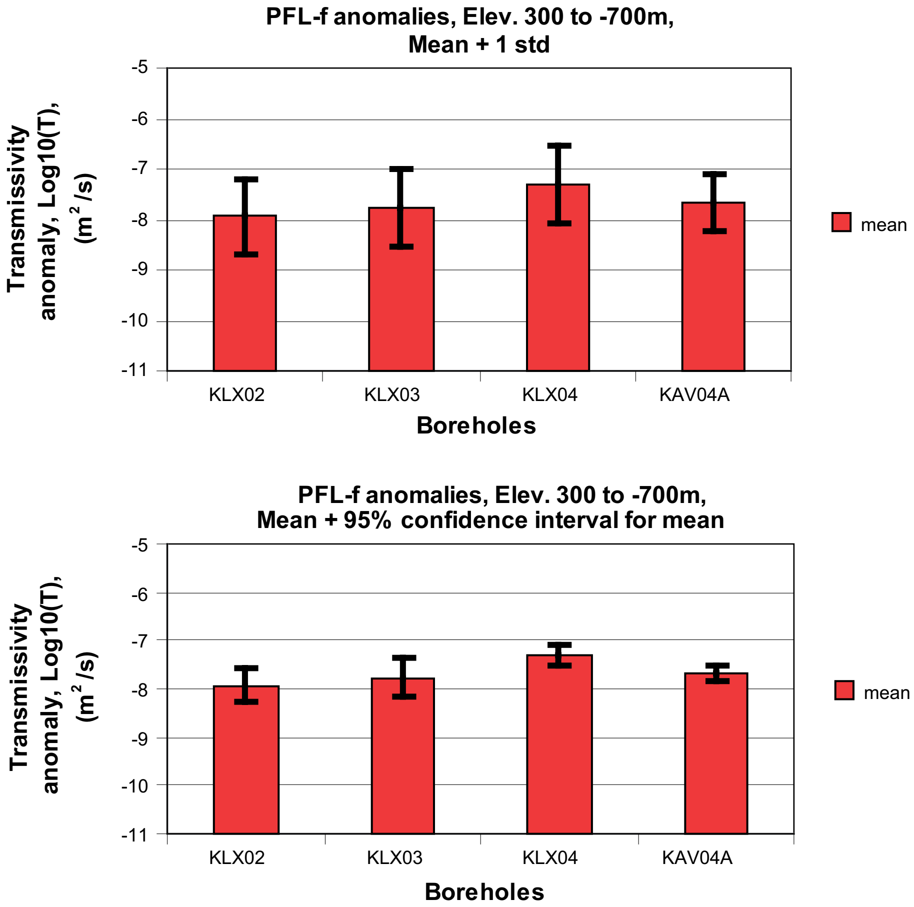


Figure 5-21. *Transmissivity distribution of PFL-f flow anomalies. Plotted categories: All flow anomalies, data from elevation –300 to –700 m. (Table 5-9.)*

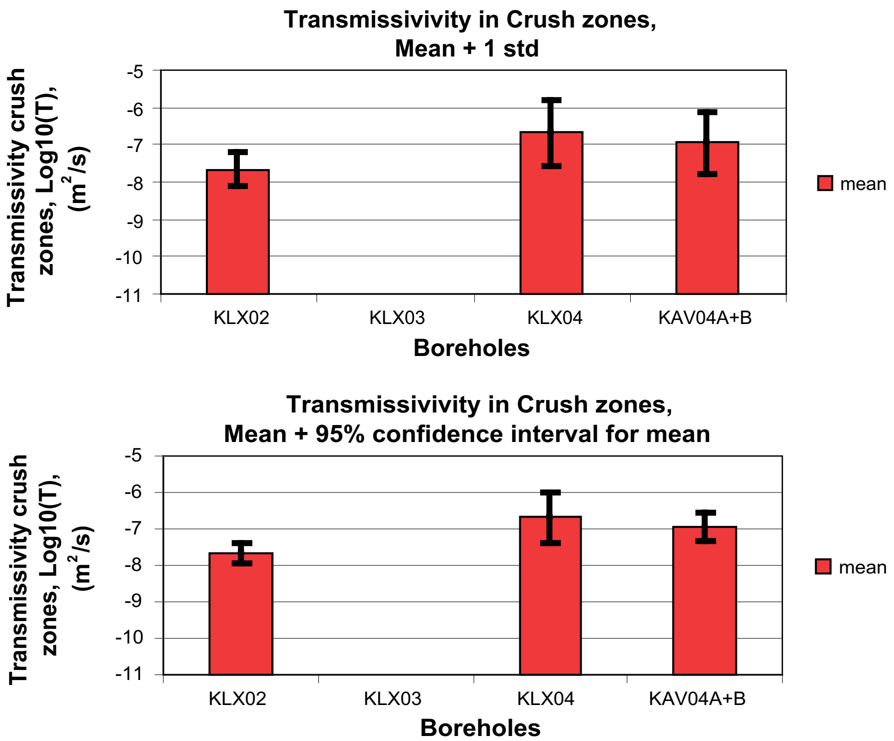


Figure 5-22. *Transmissivity distribution for crush zones based on the sum of PFL-f flow anomalies for each crush zone. (Table 5-11.)*

Table 5-7. Univariate statistics for hydraulic tests performed in cored boreholes based on lognormal distribution see Appendix 5. Method employed: PFL-f. The flow anomalies were divided into two classes, those within a crush zone: "Per anomaly in Crush" and those out side a crush zone: "Per anomaly in Fracture(s)". Statistics "Per fracture xxxx" is based on dividing the PFL-anomaly transmissivity with all fractures mapped as possible for causing the flow anomaly. In crush it is assumed to be 40 fractures/m. The maximum No. of fracture is assumed to be 10 both for anomalies associated with crush or individual fractures Sample size always refer to No. of anomalies or estimated (see text) No of fractures. Secup and seclow refers to borehole interval measured with PFL.

Borehole	Test type	Secup (m)	Seclow (m)	Sample type (m)	Sample size	Lower meas. limit[1] Log10 T (m^2/s)	Mean Log10(T) (m^2/s)	Std Log10(T) (m^2/s)	Conf.lim Log10(T) Mean±D, conf.level 0.95: D (m^2/s)
KLX02	PFL-f	205.92	1,399.92	All	102	(–10)–(–8.3)	–7.65	0.87	0.17
	PFL-f	205.92	1,399.92	Per anomaly in Crush	9		–7.65	0.53	0.41
	PFL-f	205.92	1,399.92	Per anomaly in Fracture(s)	93		–7.65	0.89	0.18
	PFL-f	205.92	1,399.92	Per fracture in Crush for anomaly	115		–8.70	0.44	0.08
	PFL-f	205.92	1,399.92	Per fracture of all identified to an anomaly	205		–8.47	1.02	0.14
KLX03	PFL-f	101.3	992.42	All	55	(–9.8)–(–8.2)[1]	–7.58	0.96	0.26
	PFL-f	101.3	992.42	Per anomaly in Crush	1		–		
	PFL-f	101.3	992.42	Per anomaly in Fracture(s)	54		–7.58	0.97	0.26
	PFL-f	101.3	992.42	Per fracture in Crush for anomaly	1		–	–	–
	PFL-f	101.3	992.42	Per fracture of all identified to an anomaly	105		–7.66	0.93	0.26
KLX04	PFL-f	100.2	998.22	All	129	(–9.6)–(–8.7)	–7.15	0.85	0.15
	PFL-f	100.2	998.22	Per anomaly in Crush	34		–6.73	0.85	030
	PFL-f	100.2	998.22	Per anomaly in Fracture(s)	95		–7.30	0.80	0.16
	PFL-f	100.2	998.22	Per fracture in Crush for anomaly	305		–7.65	0.82	0.09
	PFL-f	100.2	998.22	Per fracture of all identified to an anomaly	270		–7.79	0.90	0.11

[1] Only a few values near the upper range.

Table 5-8. Univariate statistics for hydraulic tests performed in cored boreholes based on lognormal distribution see Appendix 5. Method employed: PFL-f. The flow anomalies were divided into two classes, those within a crush zone: "Per anomaly in Crush" and those out side a crush zone: "Per anomaly in Fracture(s)". Statistics "Per fracture xxxx" is based on dividing the PFL-anomaly transmissivity with all fractures mapped as possible for causing the flow anomaly. In crush it is assumed to be 40 fractures/m. The maximum No. of fracture is assumed to be 10 both for anomalies associated with crush or individual fractures. Sample size always refer to No. of anomalies or estimated (see text) No of fractures. Secup and seclow refers to borehole interval measured with PFL.

Borehole	Test type	Secup (m)	Seclow (m)	Sample type (m)	Sample size	Lower meas. limit[1] Log10 T (m^2/s)	Mean Log10(T) (m^2/s)	Std Log10(T) (m^2/s)	Conf.lim Log10(T) Mean±D, conf.level 0.95: D (m^2/s)
KAV04B	PFL-f	19.53	996.17	All	54	(–9.6)–(–9.0)	–7.21	1.04	0.28
	PFL-f	19.53	996.17	Per anomaly in Crush	1		(–6.64)	–	–
	PFL-f	19.53	996.17	Per anomaly in Fracture(s)	53		–7.22	1.05	0.29
	PFL-f	19.53	996.17	Per fracture in Crush for anomaly	10		–(7.64)	–	–
	PFL-f	19.53	996.17	Per fracture of all identified to an anomaly	100		–7.38	1.02	0.20
KAV04A	PFL-f	19.53	996.17	All	134	(–9.6)–(–9.0)	–7.53	0.68	0.12
	PFL-f	19.53	996.17	Per anomaly in Crush	30		–7.14	0.78	0.29
	PFL-f	19.53	996.17	Per anomaly in Fracture(s)	104		–7.64	0.60	0.12
	PFL-f	19.53	996.17	Per fracture in Crush for anomaly	269		–8.14	0.78	0.09
	PFL-f	19.53	996.17	Per fracture of all identified to an anomaly	345		–8.20	0.66	0.07

[3] Only a few values near the upper range

Table 5-9. Univariate statistics for hydraulic tests performed in cored boreholes based on lognormal distribution see Appendix 5. Method employed: PFL-f. Sample size always refer to No. of anomalies. Data based on elevation reasonable for repository depth. (Confidence limits for mean Log10(T) is expressed as the deviation D from mean in the table; for confidence level of 0.95 the mean will be within value "Mean Log10(T)" ±D.

Borehole	Test type	Upper elevation limit (m)	Lower elevation limit (m)	Bh length (m)	Sample type (m)	Sample size	P10 PFL-f anom. No./m	Lower meas. limit[1] Log10 T (m^2/s)	Mean Log10(T) (m^2/s)	Std Log10(T) (m^2/s)	D Conf.lim Log10(T): Mean±D, conf. level 0.95: (m^2/s)
KLX02	PFL-f	–186	–300	114	All	37	0.32	(–10)–(–8.3)	–7.23	0.93	0.31
	PFL-f	–300	–700	402	All	21	0.052	(–10)–(–8.3)	–7.93	0.75	0.34
	PFL-f	–700	–1,372	678	All	44	0.065	(–10)–(–8.3)	–7.87	0.74	0.22
KLX03	PFL-f	–79	–300	229	All	25	0.11	(–9.8)–(–8.2)[1]	–7.81	1.05	0.43
	PFL-f	–300	–700	411	All	16	0.039	(–9.8)–(–8.2)[1]	–7.77	0.78	0.42
	PFL-f	–700	–944	251	All	14	0.056	(–9.8)–(–8.2)[1]	–6.96	0.72	0.42
KLX04		–75	–300	225	All	53	0.24	(–9.6)–(–8.7)	–6.82	0.92	0.25
		–300	–700	403	All	59	0.15	(–9.6)–(–8.7)	–7.30	0.78	0.20
		–700	–957	258	All	17	0.066	(–9.6)–(–8.7)	–7.62	0.38	0.20
KAV04A	PFL-f	–89	–300	211	All	43	0.20	(–9.6)–(–9.0)	–7.59	0.66	0.20
	PFL-f	–300	–700	401	All	52	0.13	(–9.6)–(–9.0)	–7.66	0.57	0.16
	PFL-f	–700	–982	284	All	39	0.14	(–9.6)–(–9.0)	–7.29	0.77	0.25
KAV04B	PFL-f	–10	–85	76	All	54	0.71	(–9.6)–(–9.0)	–7.21	1.04	0.28

Table 5-10. Univariate statistics for hydraulic tests performed in cored boreholes based on lognormal distribution see Appendix 5. Method employed: PFL-f. Sample size always refer to No. of anomalies. Data based on elevation reasonable for repository depth. (Confidence limits for mean Log10(T) is expressed as the deviation D from mean in the table; for confidence level of 0.95 the mean will be within value "Mean Log10(T)" ±D. Sample type "No DZ" means that PFL-f anomalies in deformation zones from geological single hole interpretation and deterministically defined deformation zones for Laxemar model 1.2 in RVS are excluded.

Borehole	Test type	Upper elevation limit (m)	Lower elevation limit (m)	Bh length (m)	Sample type (m)	Sample size	P10 PFL-f anom. No./m	Lower meas. limit1 Log10 T (m^2/s)	Mean Log10(T) (m^2/s)	Std Log10(T) (m^2/s)	D Conf.lim Log10(T): Mean±D, conf. level 0.95: (m^2/s)
KLX02	PFL-f	–186	–300	104	No DZ	32	0.31	(–10)–(–8.3)	–7.23	0.95	0.34
	PFL-f	–300	–700	402	No DZ	21	0.052	(–10)–(–8.3)	–7.93	0.75	0.34
	PFL-f	–700	–1,372	488	No DZ	21	0.043	(–10)–(–8.3)	–7.77	0.89	0.41
KLX03	PFL-f	–79	–300	229	No DZ	25	0.11	(–9.8)–(–8.2)[1]	–7.81	1.05	0.43
	PFL-f	–300	–700	392	No DZ	15	0.038	(–9.8)–(–8.2)[1]	–7.87	0.70	0.39
	PFL-f	–700	–944	178	No DZ	3	0.017	(–9.8)–(–8.2)[1]	–7.44	0.94	2.3
KLX04		–75	–300	215	No DZ	44	0.20	(–9.6)–(–8.7)	–7.01	0.85	0.26
		–300	–700	393	No DZ	51	0.13	(–9.6)–(–8.7)	–7.34	0.77	0.22
		–700	–957	158	No DZ	1	0.0063	(–9.6)–(–8.7)	–	–	–
KAV04A	PFL-f	–89	–300	211	No DZ	43	0.20	(–9.6)–(–9.0)	–7.59	0.66	0.20
	PFL-f	–300	–700	391	No DZ	52	0.13	(–9.6)–(–9.0)	–7.66	0.57	0.16
	PFL-f	–700	–982	160	No DZ	31	0.19	(–9.6)–(–9.0)	–7.25	0.78	0.29
KAV04B	PFL-f	–10	–85	76	No DZ	54	0.71	(–9.6)–(–9.0)	–7.21	1.04	0.28

Table 5-11. Univariate statistics for hydraulic tests performed in cored boreholes based on lognormal distribution see Appendix 5. Method employed: PFL-f. Sample size always refer to No. of crush zones. "Crush Total" refers to the all the crush zones observed in the borehole section and "Crush, sum T-anom" the number of crush zones with one or several PFL-anomalies. Secup and seclow refers to borehole interval measured with PFL.

Borehole	Test type	Secup (m)	Seclow (m)	Sample type (m)	Sample size	Lower meas. limit[1] Log10 T (m^2/s)	Mean Log10(T) (m^2/s)	Std Log10(T) (m^2/s)	Conf.lim Log10(T) Mean±D, conf.level 0.95: D (m^2/s)
KLX02	PFL-f	205.92	1,399.92	Crush, Total	38				
KLX02	PFL-f	205.92	1,399.92	Crush, sum T-anom	11	(–10)–(–8.3)	–7.66	0.44	0.30
KLX03	PFL-f	101.3	992.42	Crush, Total	3				
KLX03	PFL-f	101.3	992.42	Crush, sum T-anom	1	(–9.8)–(–8.2)[1]	(–7–66)	–	–
KLX04	PFL-f	100.2	998.22	Crush, Total	53				
KLX04	PFL-f	100.2	998.22	Crush, sum T-anom	9	(–9.6)–(–8.7)	–6.68	0.90	0.69
KAV04A+B	PFL-f	19.53	996.17	Crush, Total	79				
KAV04A+B[2]	PFL-f	19.53	996.17	Crush, sum T-anom	19	(–9.6)–(–9.0)	–6.94	0.84	0.40

[1] Only a few values near the upper range.

[2] Only one crush with one anomaly in KAV04B.

Table 5-12. Univariate statistics for hydraulic tests performed in cored boreholes based on lognormal distribution. Method employed: PFL-f. Sample size always refer to No. of anomalies in a crush zone. Secup and seclow refers to borehole interval measured with PFL.

Borehole	Test type	Secup (m)	Seclow (m)	Sample type (m)	Sample size	Lower meas. limit[1] Log10 T (m^2/s)	Mean Log10(T) (m^2/s)	Std Log10(T) (m^2/s)
KLX02	PFL-f	205.92	1,399.92	Several anomalies in Crush	2	(–10)–(–8.3)	–7.87	(0.58)
KLX04	PFL-f	100.2	998.22	Several anomalies in Crush	2	(–9.6)–(–8.7)	–6.80	(0.1)
KLX04	PFL-f	100.2	998.22	Several anomalies in Crush	2	(–9.6)–(–8.7)	–6.56	(0.44)
KLX04	PFL-f	100.2	998.22	Several anomalies in Crush	4	(–9.6)–(–8.7)	–5.87	(0.75)
KLX04	PFL-f	100.2	998.22	Several anomalies in Crush	2	(–9.6)–(–8.7)	–5.61	(0.76)
KLX04	PFL-f	100.2	998.22	Several anomalies in Crush	6	(–9.6)–(–8.7)	–7.03	(0.98)
KAV04A	PFL-f	19.53	996.17	Several anomalies in Crush	3	(–9.6)–(–9.0)	–6.26	(1.11)
KAV04A	PFL-f	19.53	996.17	Several anomalies in Crush	4	(–9.6)–(–9.0)	–7.59	(0.73)
KAV04A	PFL-f	19.53	996.17	Several anomalies in Crush	3	(–9.6)–(–9.0)	–6.64	(0.79)
KAV04A	PFL-f	19.53	996.17	Several anomalies in Crush	5	(–9.6)–(–9.0)	–7.20	(0.66)
KAV04A	PFL-f	19.53	996.17	Several anomalies in Crush	2	(–9.6)–(–9.0)	–7.42	(0.37)

6 References

Andersson O, 1994. Deep drilling and documentation of a 1,700 m deep borehole at Laxemar, Sweden, SKB TR-94-02. Svensk Kärnbränslehantering AB.

Ask H, Samuelsson L-E, Zetterlund M, 2004. Oskarshamn site investigation. Percussion drilling of boreholes HLX15, HLX26, HLX27, HLX28, HLX29 and HLX32 for investigation of lineament NW042. SKB P-04-235. Svensk Kärnbränslehantering AB.

Ask H, Samuelsson L-E, 2004a. Oskarshamn site investigation. Drilling of two flushing water wells, HAV09 and HAV10. SKB P-04-150. Svensk Kärnbränslehantering AB.

Ask H, Samuelsson L-E, 2004b. Oskarshamn site investigation. Drilling of two percussion boreholes, HLX 13 and HLX14. SKB P-04-234. Svensk Kärnbränslehantering AB.

Ask H, Samuelsson L-E, 2004c. Oskarshamn site investigation. Percussion drilling of borehole HLX20 for investigation of lineament EW002. SKB P-04-236. Svensk Kärnbränslehantering AB.

Ask H, Zetterlund M, 2005. Oskarshamn site investigation. Percussion drilling of boreholes HLX16, HLX17, HLX18 and HLX19. SKB P-05-190. Svensk Kärnbränslehantering AB.

Ask H, Samuelsson L-E, Zetterlund M, 2005a. Oskarshamn site investigation. Percussion drilling of boreholes HLX21, HLX22, HLX23, HLX24, HLX25, HLX30, HLX31 and HLX33 for investigation of lineament EW007. SKB P-05-55. Svensk Kärnbränslehantering AB.

Ask H, Morosini M, Samuelsson L-E, Ekström L, Håkansson N, 2005b. Oskarshamn site investigation. Drilling of cored borehole KLX03. SKB P-05-111. Svensk Kärnbränslehantering AB.

Ask H, Morosini M, Samuelsson L-E, Ekström L, Håkansson N, 2005c. Oskarshamn site investigation. Drilling of cored borehole KLX04. SKB P-05-111. Svensk Kärnbränslehantering AB.

Ask H, Morosini M, Samuelsson L-E, Ekström L, Håkansson N, 2005d. Drilling of cored borehole KAV04. Oskarshamn site investigation. SKB P-05-25. Svensk Kärnbränslehantering AB.

Brace W F, 1980. Permeability of Crystalline and Argillaceous Rocks. Int. J. Rock. Mech. & Geomech. Abstr. Vol. 17, pp. 241–251.

Ekman L, 2001. Project deep drilling KLX02 – Phase 2, Methods, scope of activities and results. Summary report SKB TR-01-11. Svensk Kärnbränslehantering AB

Follin S, Årebäck M, Axelsson C-L, Stigsson M, Jacks G, 1998. Förstudie Oskarshamn. Grundvattnets rörelse, kemi och långsiktiga förändringar (in Swedish). SKB R-98-55. Svensk Kärnbränslehantering AB.

Forssman I, Zetterlund M, Forsmark T, Rhén I, 2005a. Oskarshamn site investigation. Correlation of Posiva Flow Log anomalies to core mapped features in KSH01A, KSH02A and KAV01. SKB P-05-65, Svensk Kärnbränslehantering AB.

Forssman I, Zetterlund M, Forsmark T, Rhén I, 2005b. Oskarshamn site investigation. Correlation of Posiva Flow Log anomalies to core mapped features in KLX02, KLX03, KLX04, KAV04A and KAV04b. SKB P-05-241, Svensk Kärnbränslehantering AB.

Jensen J L, Lake L W, Corbett P W M, Goggin D J, 2000. Statistics for petroleum engineers and geoscientists, Handbook of Petroleum Exploration and Production, 2, Second ed, Elsevier, Amsterdam.

Gustafsson E, Ludvigson J-E, 2005. Oskarshamn site investigation. Combined interference test and tracer test between KLX02 och HLX10. SKB P-05-20. Svensk Kärnbränslehantering AB.

Kruseman G P, de Ridder N A, 1991. Analysis and evaluation of pumping test data, ILRI publication 47, Wageningen.

Ludvigson J-E, Hansson K, 2002. Methodology study of Posiva difference flow meter in borehole KLX02 at Laxemar. SKB R-01-52. Svensk Kärnbränslehantering AB.

Ludvigson J-E, Levén J, Källgården J, Jönsson S, 2004. Oskarshamn site investigation. Single-hole injection tests in borehole KSH02. SKB P-04-247. Svensk Kärnbränslehantering AB.

Moye D G, 1967. Diamond drilling for foundation exploration. Civil Eng. Trans., Inst. Eng. Australia, p 95–100.

Pöllänen J, Sokolnicki M, 2004. Oskarshamn site investigation – Difference flow measurements in borehole KAV04A and KAV04B. P-04-216. Svensk Kärnbränslehantering AB.

Rahm N, Enachescu C, 2004a. Hydraulic injection tests in borehole KLX02, 2003, Laxemar. SKB P-04-288. Svensk Kärnbränslehantering AB.

Rahm N, Enachescu C, 2004b. Oskarshamn site investigation. Hydraulic injection tests in borehole KAV04A, 2004. Sub-area Simpevarp. SKB P-04-291. Svensk Kärnbränslehantering AB.

Rahm N, Enachescu C, 2004c. Oskarshamn site investigation. Hydraulic injection tests in borehole KLX04, 2004. Sub-area Laxemar. SKB P-04-292. Svensk Kärnbränslehantering AB.

Rahm N, Enachescu C, 2005. Oskarshamn site investigation. Pumping tests and water sampling in borehole KLX04, 2004. Sub-area Laxemar. SKB P-05-16. Svensk Kärnbränslehantering AB.

Rhén I, Bäckblom G, Gustafson G, Stanfors R, Wikberg P, 1997a. Äspö HRL – Geoscientific evaluation 1997/2. Results from pre-investigations and detailed characterization. Summary Report. SKB TR-97-03. Svensk Kärnbränslehantering AB.

Rhén I, Gustafson G, Wikberg P, 1997b. Äspö HRL – Geoscientific evaluation 1997/4. Results from pre-investigations and detailed site characterization. Comparisons of predictions and observations. Hydrogeology, groundwater chemistry and transport of solutes. SKB TR-97-05. Svensk Kärnbränslehantering AB.

Rhén I, Gustafson G, Wikberg P, 1997c. Äspö HRL – Geoscientific evaluation 1997/5. Models based on site characterization 1986–1995. SKB TR-97-06. Svensk Kärnbränslehantering AB.

Rhén I, Forsmark T, Forssman I, Zetterlund M, 2006a. Hydrogeological single-hole interpretation of KSH01, KSH02, KSH03, KAV01 and HSH01–03, Preliminary site description, Simpevarp subarea – version 1.2, SKB R-06-20, Svensk Kärnbränslehantering AB.

Rhén I, Forsmark T, Forssman I, Zetterlund M, 2006b. Evaluation of hydrogeological properties for Hydraulic Conductor Domains (HCD) and Hydraulic Rock Domains (HRD), Preliminary site description, Laxemar subarea – version 1.2, SKB R-06-22, Svensk Kärnbränslehantering AB.

Rouhiainen P, 2000. Äspö Hard Rock Laboratory – Difference flow measurements in borehole KLX02 at Laxemar. SKB IPR-01-06. Svensk Kärnbränslehantering AB.

Rouhiainen P, Sokolnicki M, 2005. Oskarshamn site investigation. Difference flow logging of borehole KLX04. Subarea Laxemar. SKB P-05-68. Svensk Kärnbränslehantering AB.

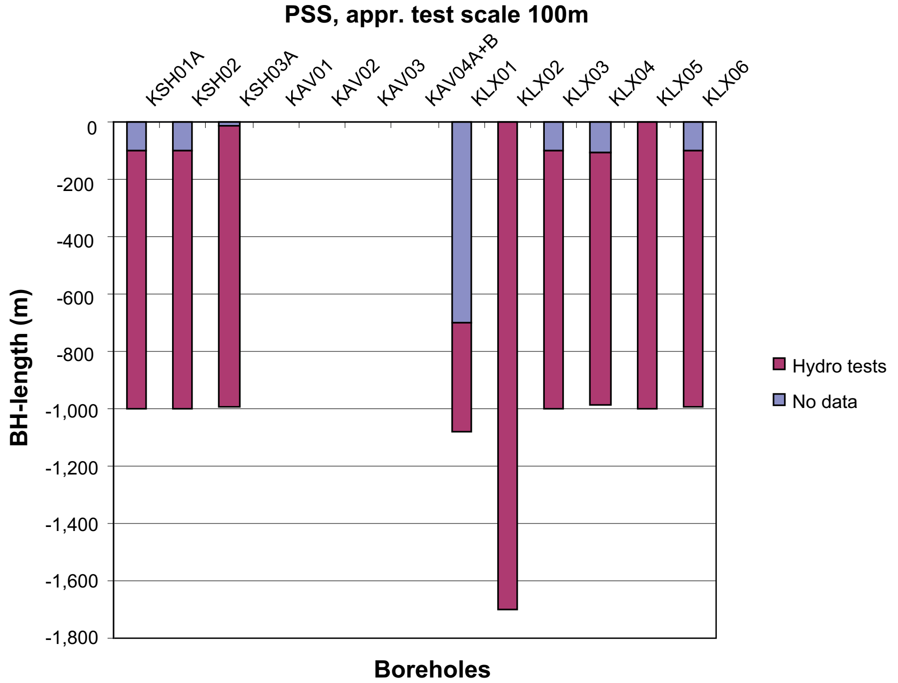
Rouhiainen P, Pöllänen J, Sokolnicki M, 2005. Oskarshamn site investigation. Difference flow logging of borehole KLX03. Subarea Laxemar. SKB P-05-67. Svensk Kärnbränslehantering AB.

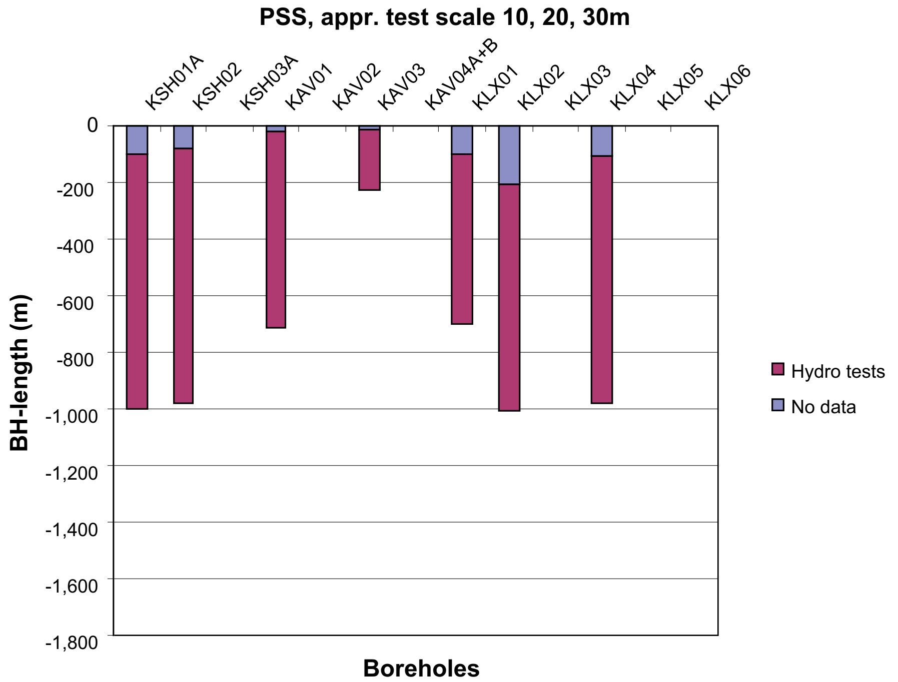
SKB, 2006. Preliminary site description. Laxemar subarea – version 1.2. SKB R-06-10. Svensk Kärnbränslehantering AB.

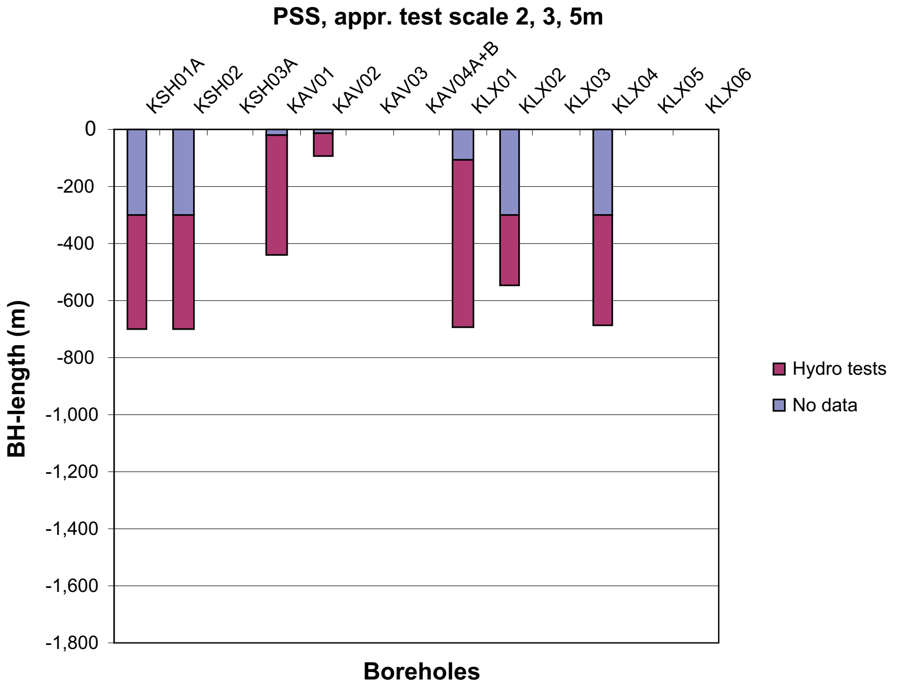
Thiem G, 1906. Hydrologische Methoden. Gebhardt, Leibzig, 56pp.

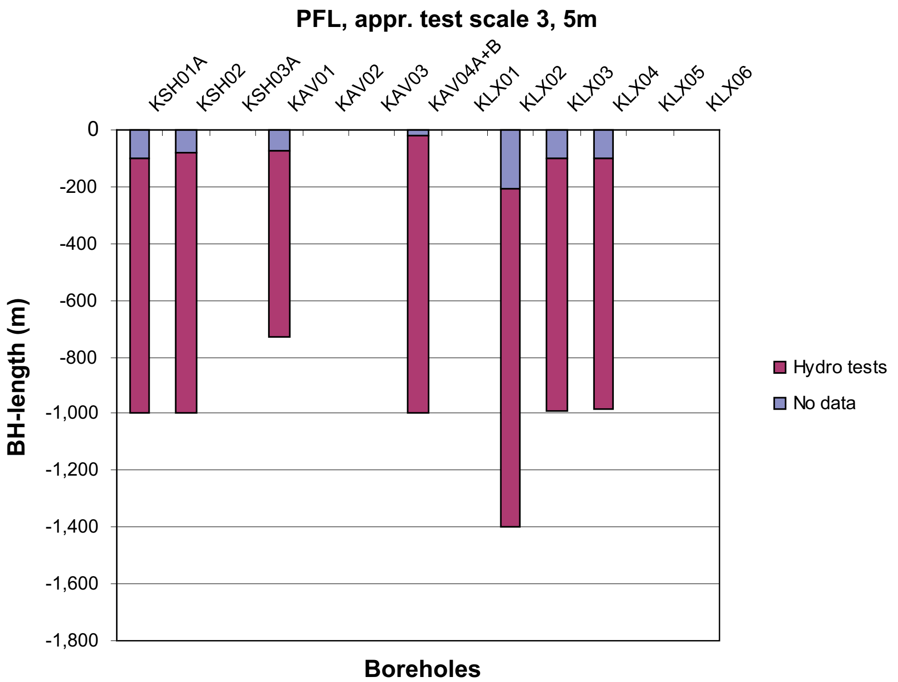
Appendix 1

Overview of hydraulic tests in core boreholes available for L1.2



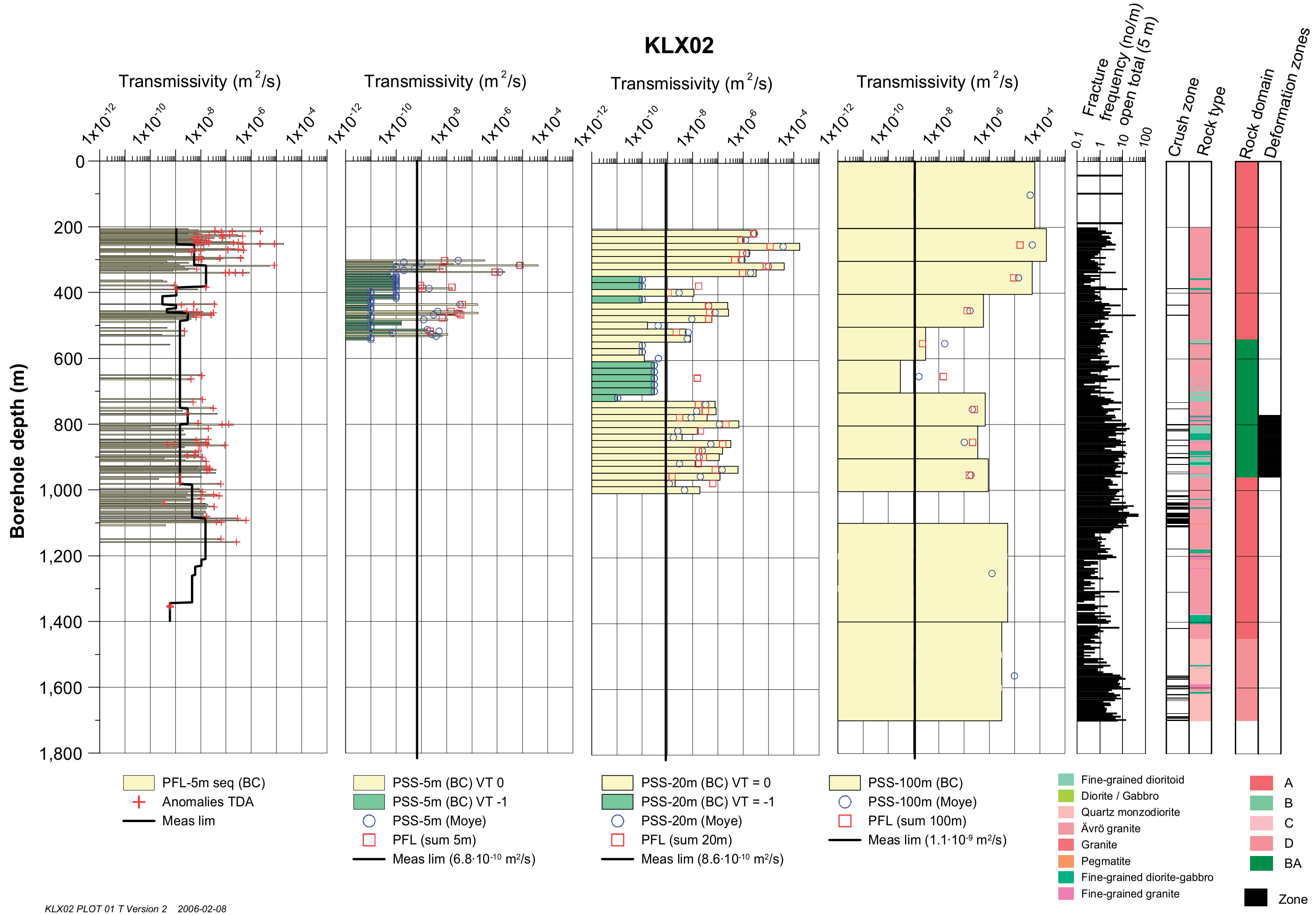


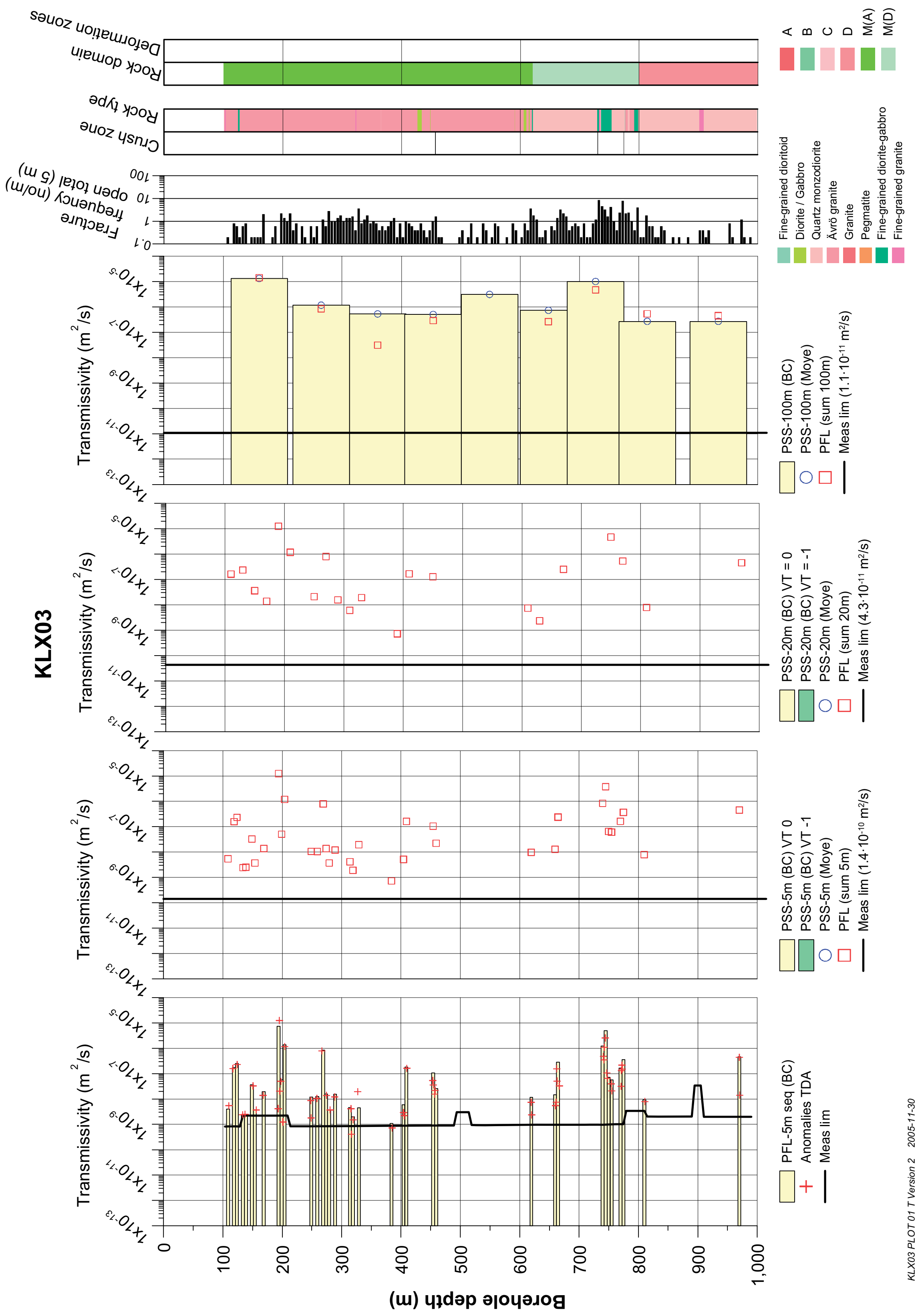

PSS, appr. test scale 2, 3, 5m
KSH01A
KSH02
KSH03A
KAV01
KAV02
KAV03
KAV04A+B
KLX01
KLX02
KLX03
KLX04
KLX05
KLX06
0
-200
-400
-600
-800
-1,000
-1,200
-1,400
-1,600
-1,800
BH-length (m)
Boreholes
Hydro tests
No data

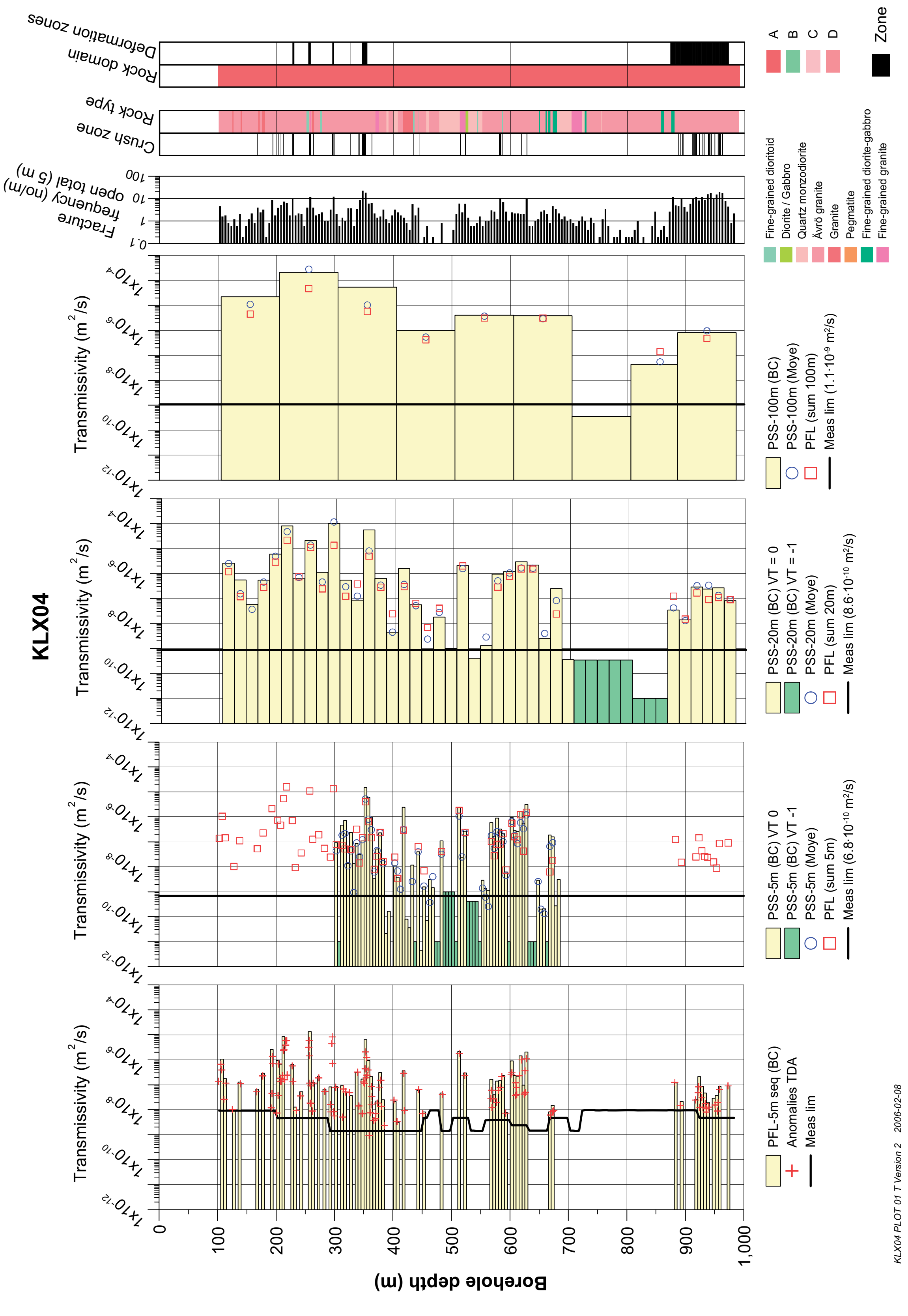

PFL, appr. test scale 3, 5m
KSH01A
KSH02
KSH03A
KAV01
KAV02
KAV03
KAV04A+B
KLX01
KLX02
KLX03
KLX04
KLX05
KLX06
0
-200
-400
-600
-800
-1,000
-1,200
-1,400
-1,600
-1,800
BH-length (m)
Boreholes
Hydro tests
No data

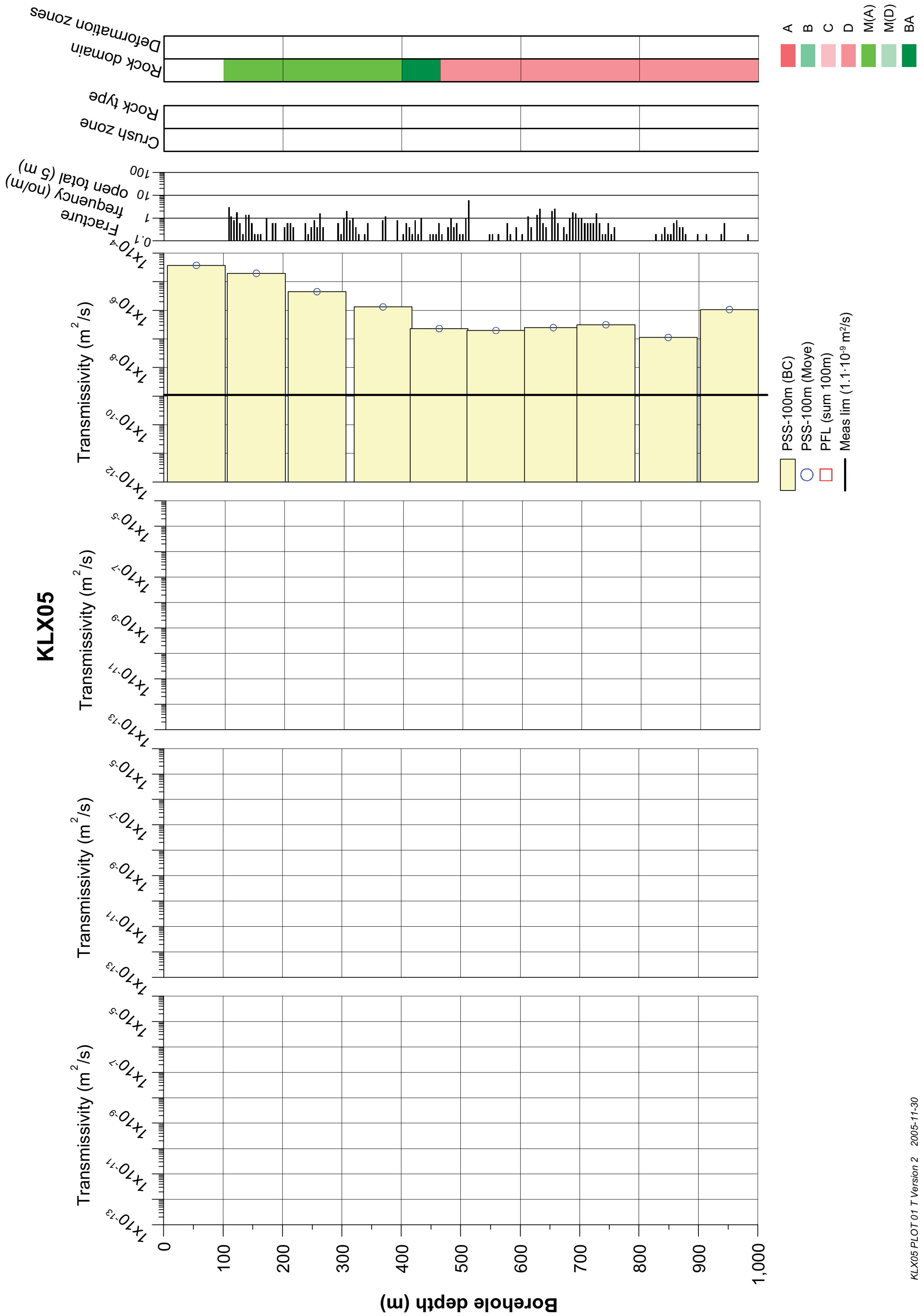
Appendix 2

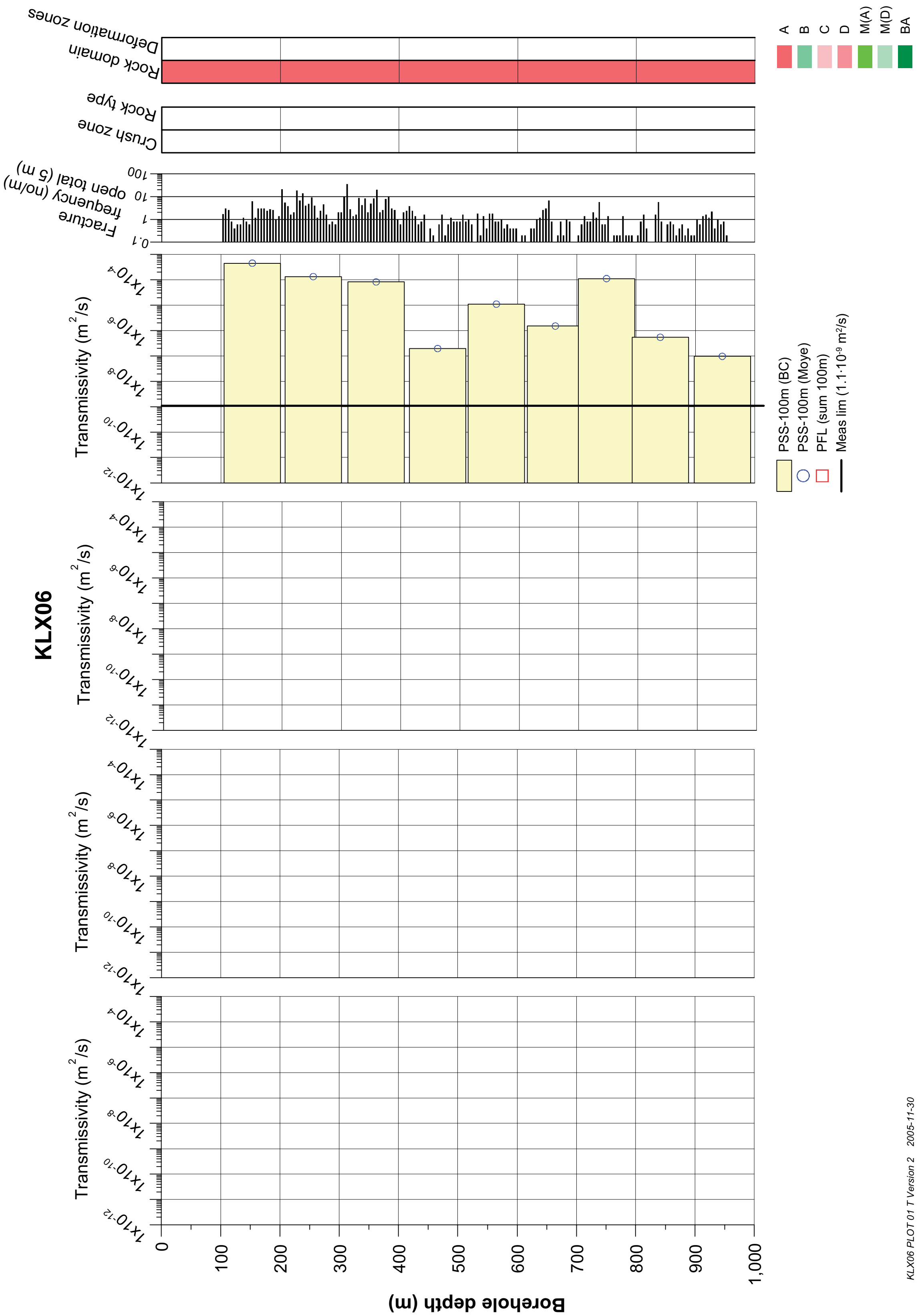
Hydraulic tests results for core holes, expressed as transmissivities



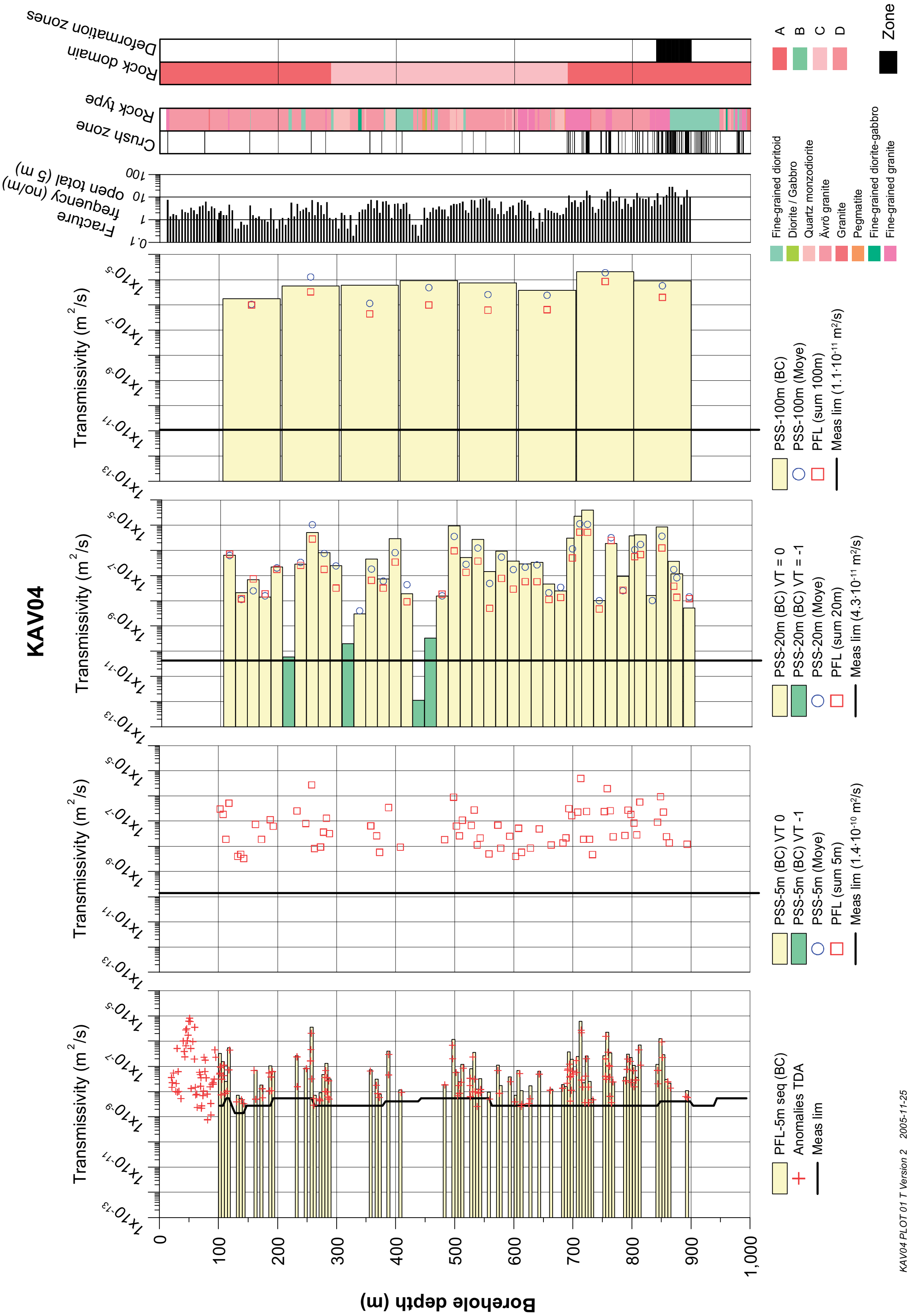

KLX03
Deformation zones
Rock domain
Crush zone
Rock type
Fracture frequency (no/m) open total (5 m)
Transmissivity (m²/s)
Borehole depth (m)
PSS-100m (BC)
PSS-100m (Moye)
PFL (sum 100m)
Meas lim (1.1·10⁻¹¹ m²/s)
PSS-20m (BC) VT = 0
PSS-20m (BC) VT = -1
PSS-20m (Moye)
PFL (sum 20m)
Meas lim (4.3·10⁻¹¹ m²/s)
PSS-5m (BC) VT 0
PSS-5m (BC) VT -1
PSS-5m (Moye)
PFL (sum 5m)
Meas lim (1.4·10⁻¹⁰ m²/s)
PFL-5m seq (BC)
Anomalies TDA
Meas lim
Fine-grained dioritoid
Diorite / Gabbro
Quartz monzodiorite
Ävrö granite
Granite
Pegmatite
Fine-grained diorite-gabbro
Fine-grained granite
A
B
C
D
M(A)
M(D)
KLX03 PLOT 01 T Version 2 2005-11-30


KLX04
Deformation zones
Rock domain
Rock type
Crush zone
Fracture frequency open total (no/m) (5 m)
Transmissivity (m²/s)
Borehole depth (m)
PSS-100m (BC)
PSS-100m (Moye)
PFL (sum 100m)
Meas lim (1.1·10⁻⁹ m²/s)
PSS-20m (BC) VT = 0
PSS-20m (BC) VT = -1
PSS-20m (Moye)
PFL (sum 20m)
Meas lim (8.6·10⁻¹⁰ m²/s)
PSS-5m (BC) VT 0
PSS-5m (BC) VT -1
PSS-5m (Moye)
PFL (sum 5m)
Meas lim (6.8·10⁻¹⁰ m²/s)
PFL-5m seq (BC)
Anomalies TDA
Meas lim
Fine-grained dioritoid
Diorite / Gabbro
Quartz monzodiorite
Ävrö granite
Granite
Pegmatite
Fine-grained diorite-gabbro
Fine-grained granite
A
B
C
D
Zone
KLX04 PLOT 01 T Version 2 2006-02-08


KLX05
Deformation zones
Rock domain
Rock type
Crush zone
Fracture frequency (no/m) open total (5 m)
0.1
1
10
100
Transmissivity (m²/s)
1x10⁻⁴
1x10⁻⁶
1x10⁻⁸
1x10⁻¹⁰
1x10⁻¹²
1x10⁻⁵
1x10⁻⁷
1x10⁻⁹
1x10⁻¹¹
1x10⁻¹³
Borehole depth (m)
0
100
200
300
400
500
600
700
800
900
1,000
PSS-100m (BC)
PSS-100m (Moye)
PFL (sum 100m)
Meas lim (1.1·10⁻⁹ m²/s)
A
B
C
D
M(A)
M(D)
BA
KLX05 PLOT 01 T Version 2 2005-11-30



KLX06
Deformation zones
Rock domain
Rock type
Crush zone
Fracture frequency (no/m) open total (5 m)
0.1
1
10
100
Transmissivity (m²/s)
1x10⁻¹²
1x10⁻¹⁰
1x10⁻⁸
1x10⁻⁶
1x10⁻⁴
Borehole depth (m)
0
100
200
300
400
500
600
700
800
900
1,000
PSS-100m (BC)
PSS-100m (Moye)
PFL (sum 100m)
Meas lim (1.1·10⁻⁹ m²/s)
A
B
C
D
M(A)
M(D)
BA
KLX06 PLOT 01 T Version 2 2005-11-30


KAV04
Borehole depth (m)
0
100
200
300
400
500
600
700
800
900
1,000
Transmissivity (m²/s)
1x10⁻¹³
1x10⁻¹¹
1x10⁻⁹
1x10⁻⁷
1x10⁻⁵
Fracture frequency (no/m) open total (5 m)
0.1
1
10
100
Crush zone
Rock type
Rock domain
Deformation zones
PFL-5m seq (BC)
Anomalies TDA
Meas lim
PSS-5m (BC) VT 0
PSS-5m (BC) VT -1
PSS-5m (Moye)
PFL (sum 5m)
Meas lim (1.4·10⁻¹⁰ m²/s)
PSS-20m (BC) VT = 0
PSS-20m (BC) VT = -1
PSS-20m (Moye)
PFL (sum 20m)
Meas lim (4.3·10⁻¹¹ m²/s)
PSS-100m (BC)
PSS-100m (Moye)
PFL (sum 100m)
Meas lim (1.1·10⁻¹¹ m²/s)
Fine-grained dioritoid
Diorite / Gabbro
Quartz monzodiorite
Ävrö granite
Granite
Pegmatite
Fine-grained diorite-gabbro
Fine-grained granite
A
B
C
D
Zone
KAV04 PLOT 01 T Version 2 2005-11-25

Appendix 3

Probability distributions of hydraulic tests in boreholes PSS measurements

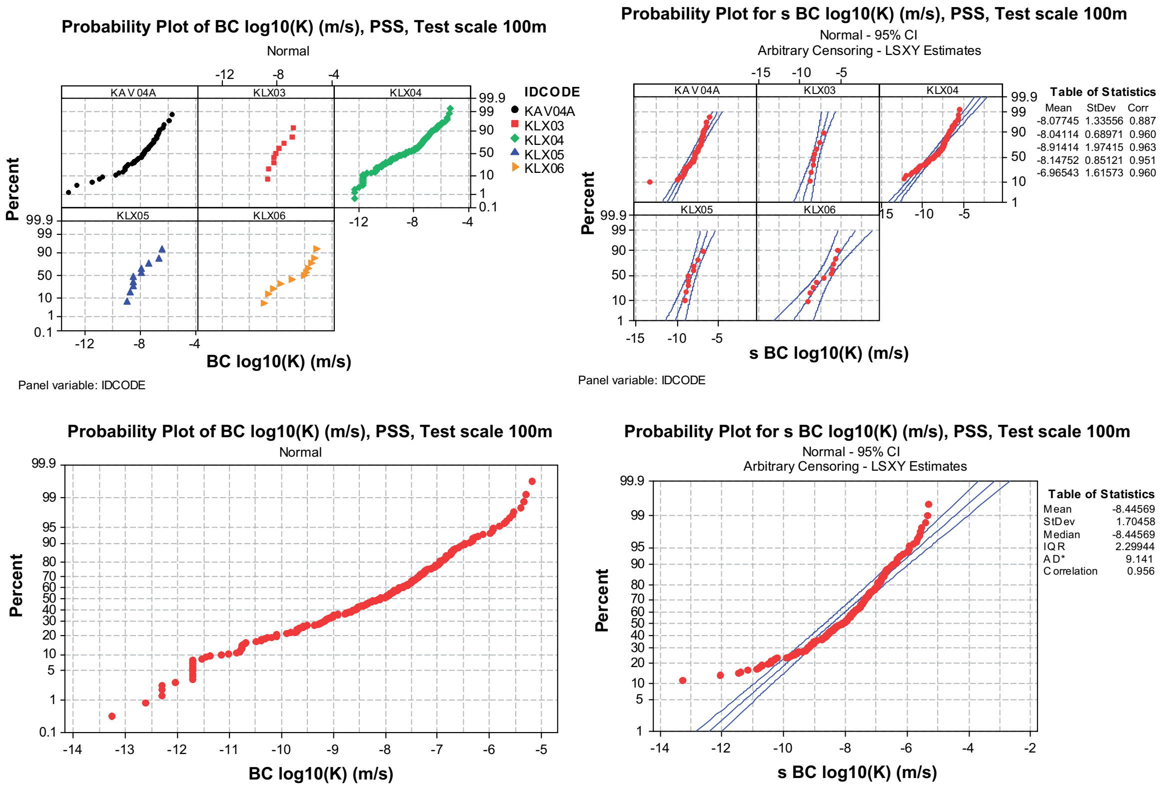


Figure A3-1. *Probability distribution plots of PSS measurements, test scale 100 m. Boreholes KAV04A, KLX03, KLX04, KLX05, KLX06.*

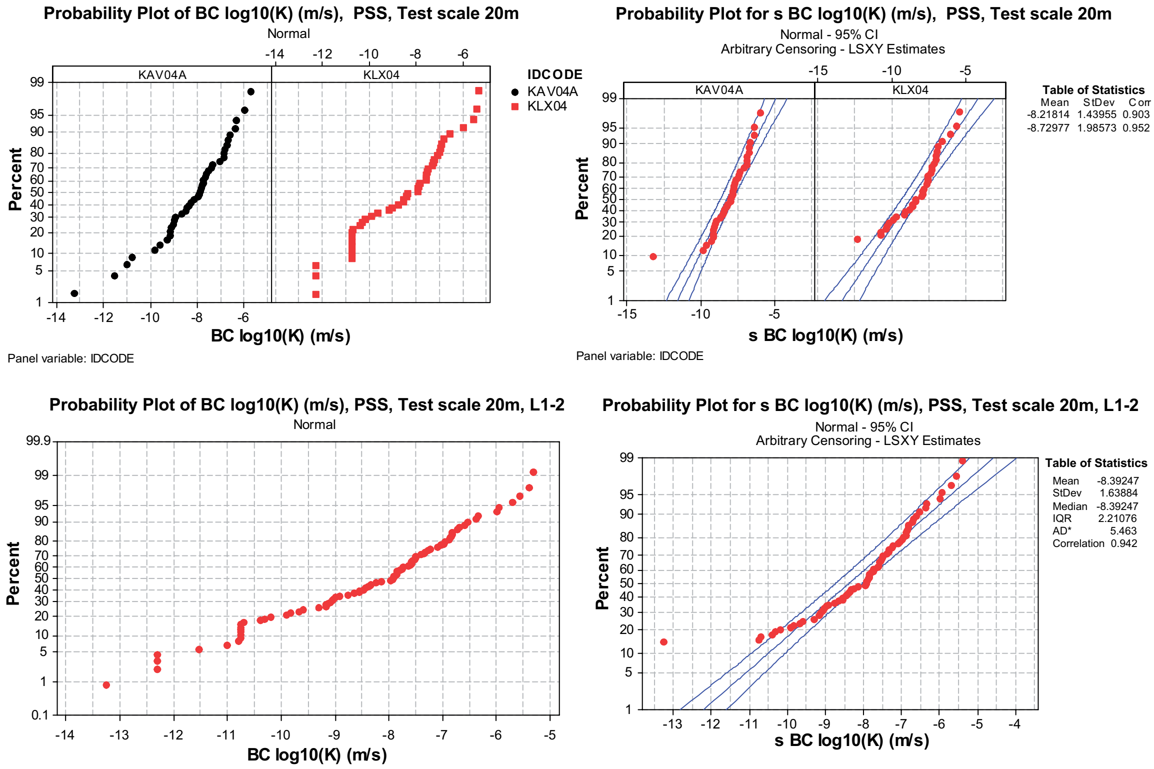


***Figure A3-2.** Probability distribution plots of PSS measurements, test scale 20 m. Boreholes KAV04A, KLX04.*

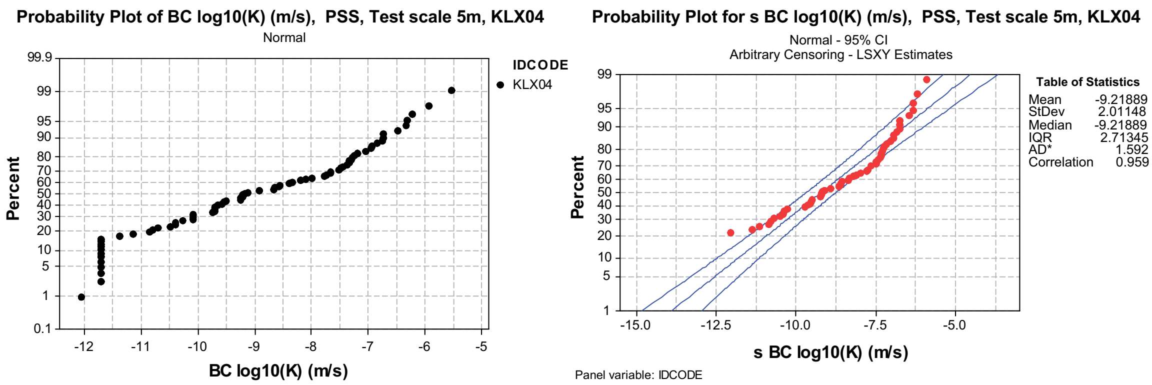


***Figure A3-3.** Probability distribution plots of PSS measurements, test scale 5 m. Borehole KLX04.*

Probability distributions of hydraulic tests in boreholes Sequential PFL measurements (PFL-s)

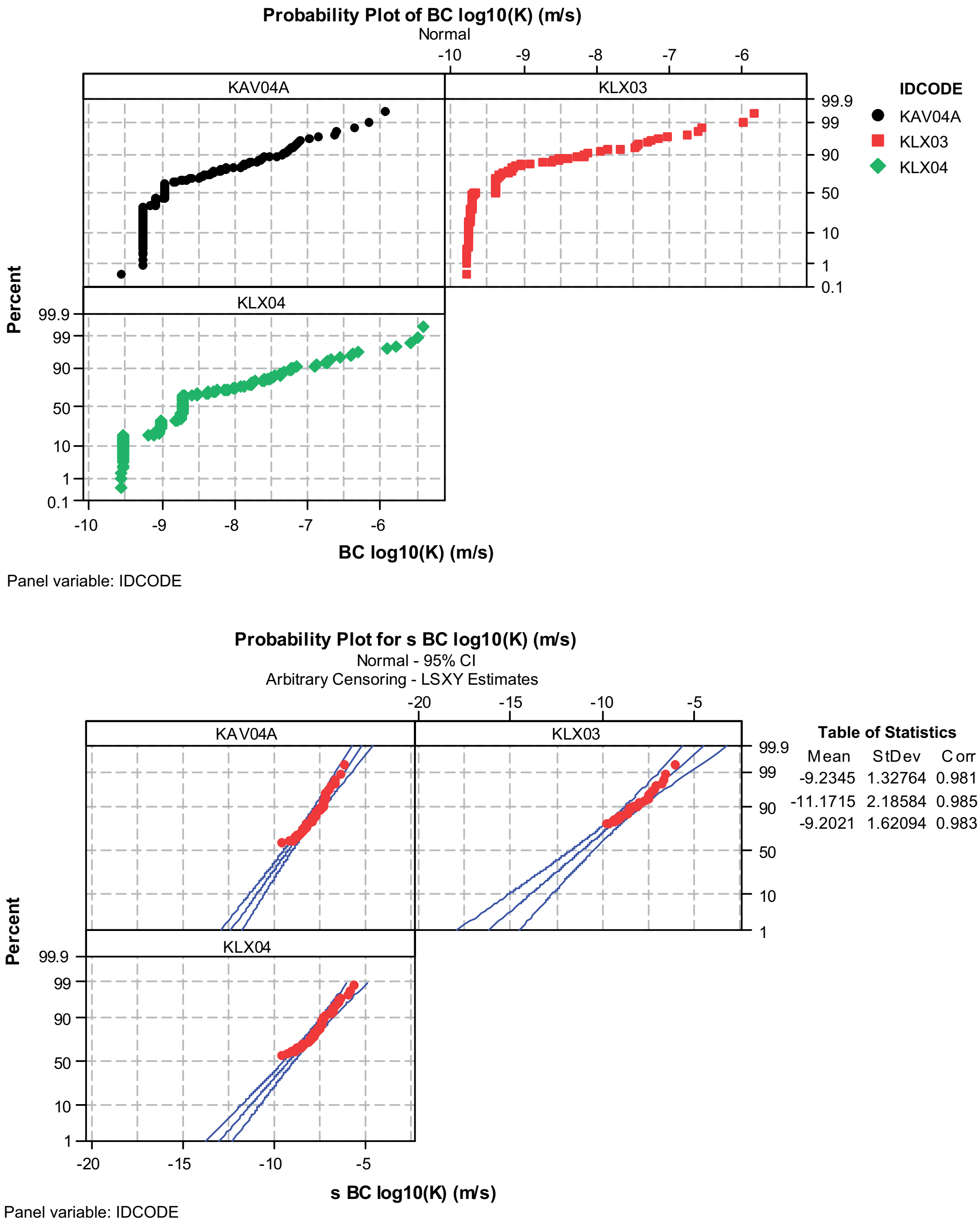


Figure A4-1. Probability distribution plots of PFL sequential measurements in KLX03, KLX04 and KAV04A. Tests scale 5 m.

Appendix 5

Probability distributions of hydraulic tests in boreholes PFL flow anomaly measurements (PFL-f)

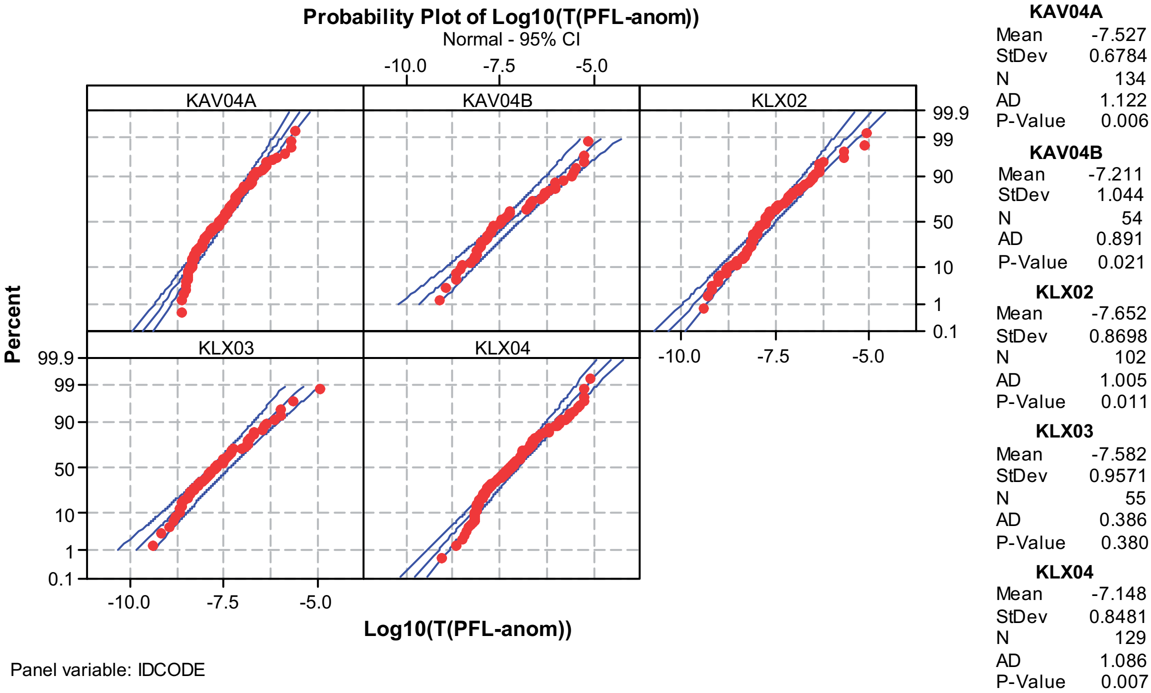
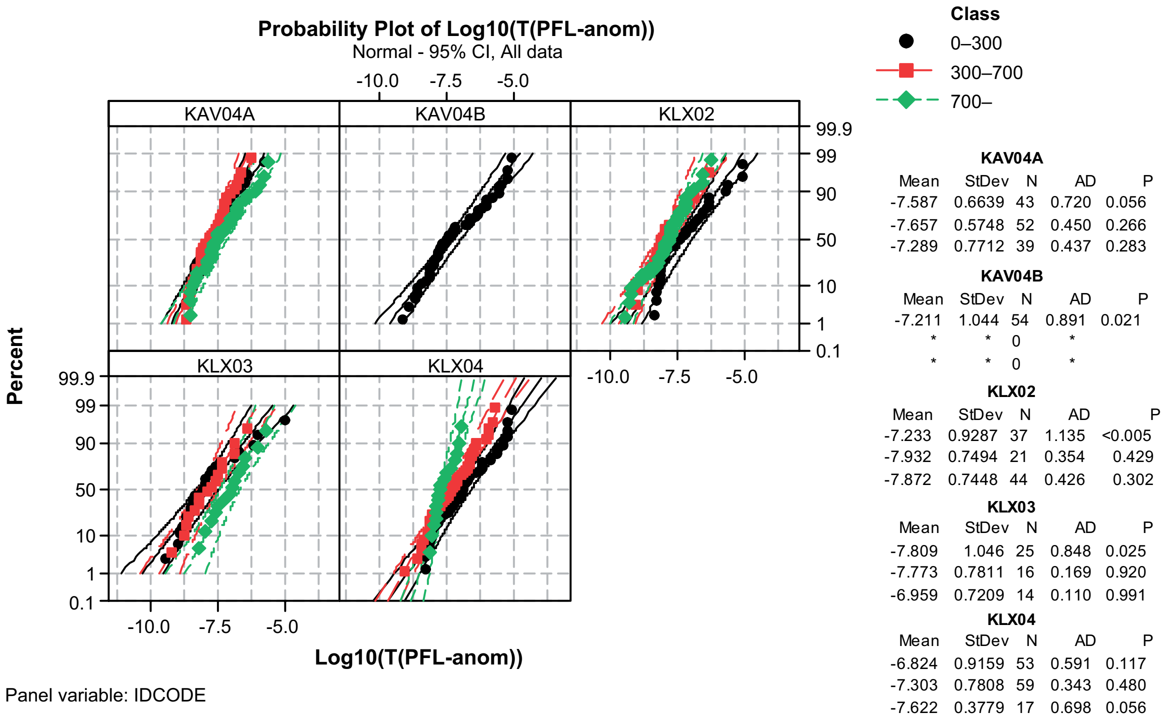


Figure A5-1. *Probability distribution plots of PFL flow anomaly measurements in KLX02, KLX03, KLX04 and KAV04 (A+B). Entire data set. (T: m²/s).*



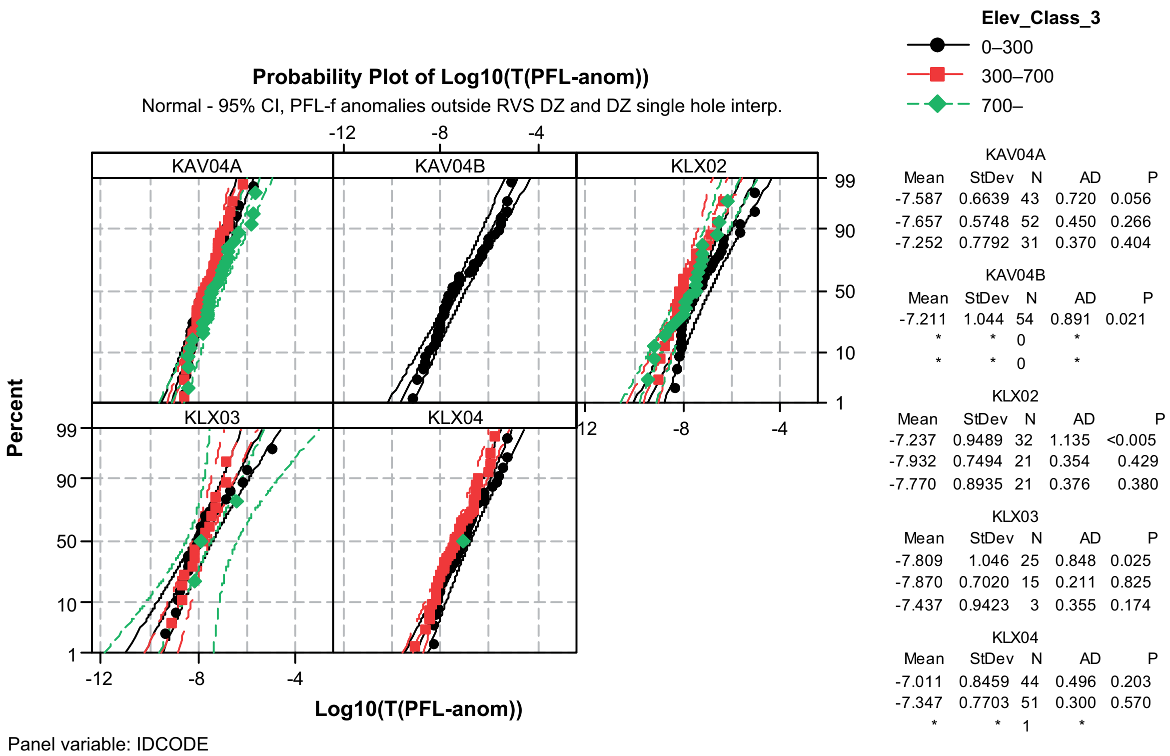
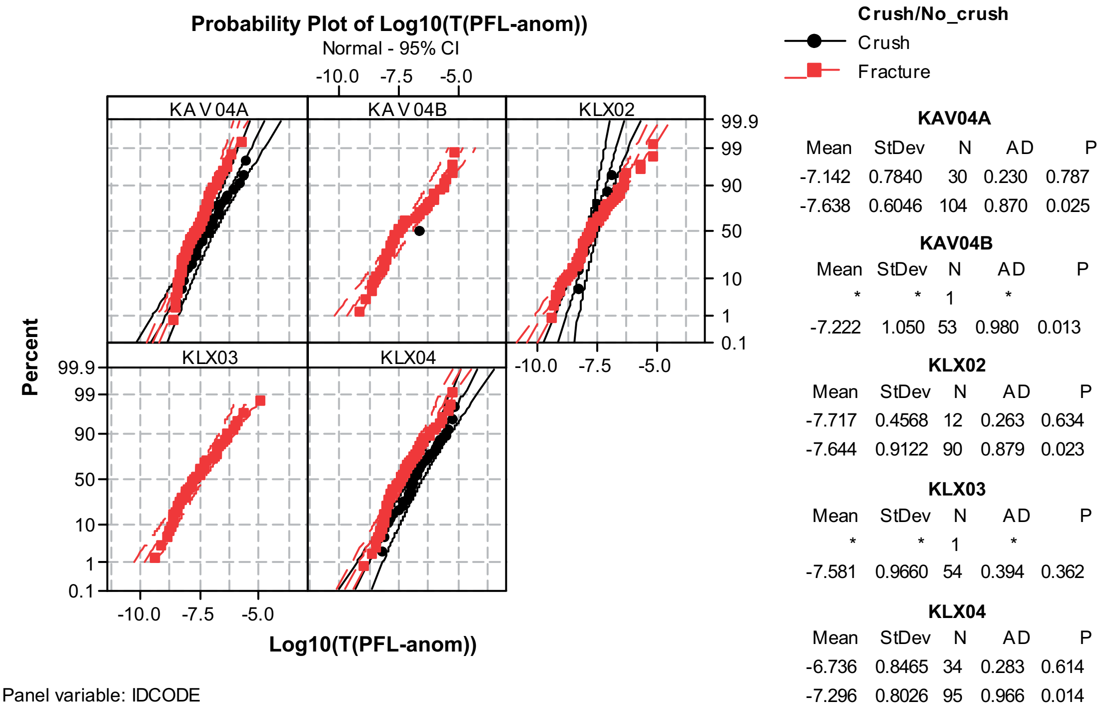


Figure A5-2. *Probability distribution plots of PFL flow anomaly measurements in KLX02, KLX03, KLX04 and KAV04 (A+B). Entire data set and data based on anomalies outside deformation zones defined in the geological single-hole interpretation and modelled deformation zones in RVS, for three elevation intervals. (T: m²/s)*



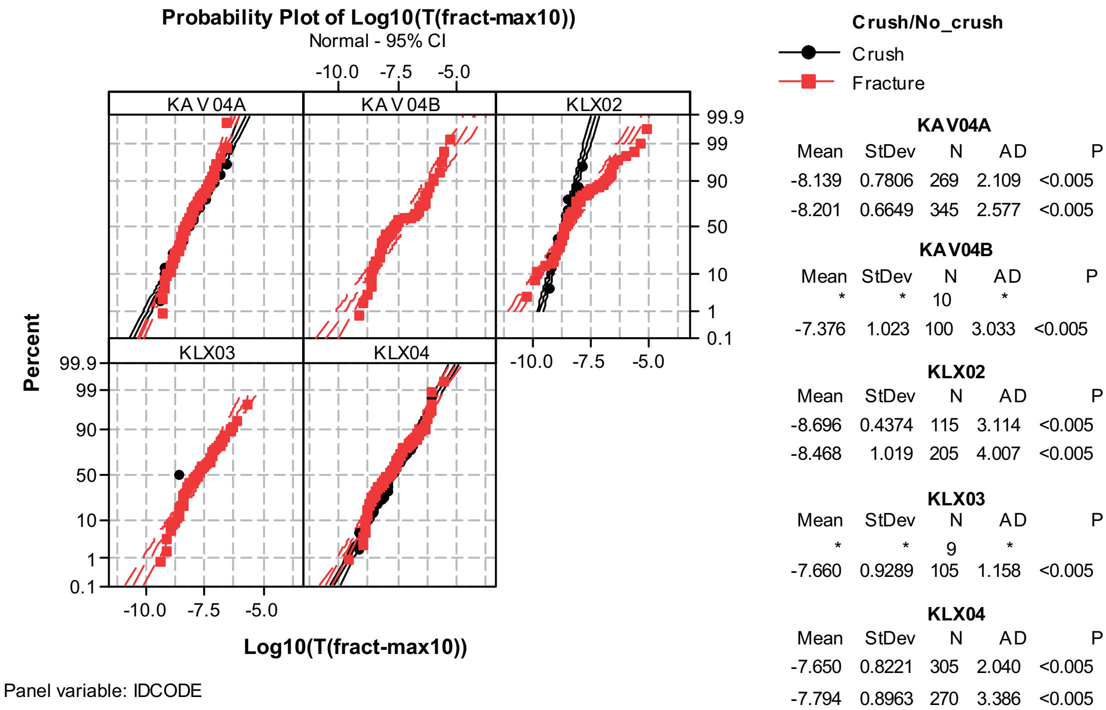


Figure A5-3. *Probability distribution plots of PFL flow anomaly measurements in KLX02, KLX03, KLX04 and KAV04 (A+B). Top: Data separated on flow anomalies found in core mapped as crush or fracture(s). Bottom: Data separated on flow anomalies found in core mapped as crush or fracture(s) but T-PFL anomaly has been dived by the No of possible fractures that form the anomaly, with a maximum of 10 fractures assumed. (T: m²/s).*

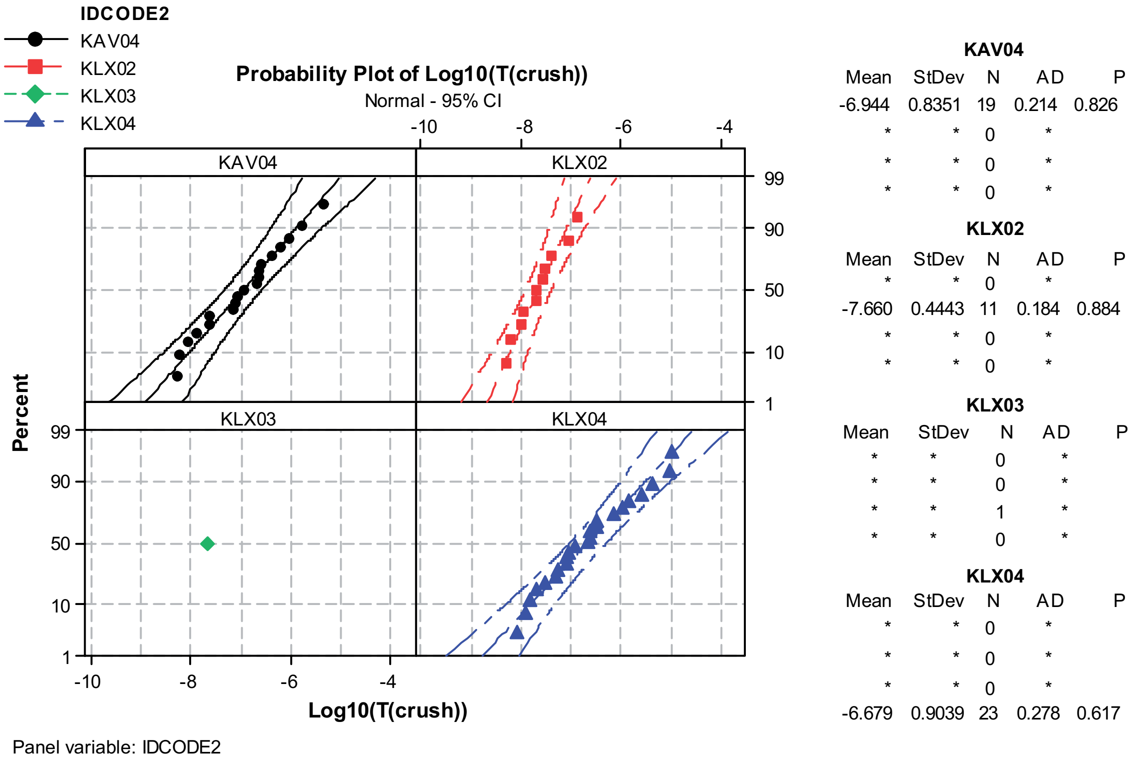


Figure A5-4. *Probability distribution plots of PFL flow anomaly measurements in KLX02, KLX03, KLX04 and KAV04 (A+B). Transmissivity of rock mapped as crush. The transmissivity is the sum of the individual flow anomalies found in a borehole section mapped as crush. (T: m²/s).*