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Formation factor logging in-situ by electrical methods in KLX03 and KLX04

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Formation factor logging in-situ by electrical methods in KLX03 and KLX04

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Abstract

This report presents measurements and interpretations of the formation factor of the rock surrounding the boreholes KLX03 and KLX04 in Laxemar, Sweden. The formation factor was logged in-situ by electrical methods. Formation factors could only be obtained in-situ below the borehole length 412 m due to possible errors caused by surface conduction in the upper low-saline parts of the rock mass. For KLX04, comparisons are made with formation factors obtained in the laboratory on samples from the bore core by electrical methods.

For KLX03, the in-situ rock matrix formation factors obtained range from 1.0×10^{-5} to 5.0×10^{-4}. The in-situ fractured rock formation factors obtained range from 1.0×10^{-5} to 6.8×10^{-3}. The formation factors appear to deviate somewhat from the log-normal distribution. The mean values and standard deviations of the obtained $\log_{10}$-normal distributions are –4.6 and 0.24, and –4.4 and 0.37 for the in-situ rock matrix and fractured rock formation factor, respectively.

For KLX04, the in-situ rock matrix formation factors obtained range from 8.8×10^{-6} to 2.1×10^{-4}. The in-situ fractured rock formation factors obtained range from 8.8×10^{-6} to 4.6×10^{-3}. The laboratory (rock matrix) formation factors obtained on bore core samples range from 9.7×10^{-5} to 4.3×10^{-4}. The formation factors appear to be fairly well log-normally distributed. The mean values and standard deviations of the obtained $\log_{10}$-normal distributions are –4.5 and 0.27, –4.2 and 0.46, and –4.1 and 0.45 for the in-situ rock matrix and fractured rock formation factor, and laboratory formation factor, respectively.

The rock type specific formation factor distributions presented in this report suggest that the in-situ formation factor within a rock type may range over one or two orders of magnitude.

Comparison between laboratory and in-situ values of resistivity indicates that the rock samples taken from the bore core and brought to the laboratory may be altered. The alteration could either be due to de-stressing or to mechanically disturbance induced in the sample preparation. The formation factors obtained in the laboratory may be overestimated by a factor of two or three.

The measurements in KLX03, and especially in KLX04, showed that results from in-situ groundwater chemistry measurements should be used with care. The reason is that the borehole in itself disturbs the groundwater chemistry situation by functioning as a hydraulic conductor. Shallow non-saline groundwater can quickly be brought to great depths in the borehole.

Sammanfattning

Denna rapport presenterar mätningar och tolkningar av bergets formationsfaktor runt borrhålen KLX03 och KLX04 i Laxemar, Sverige. Formationsfaktorn har loggats in-situ med elektriska metoder. Formationsfaktorn kunde endast erhållas under borrhålslängden 412 m in-situ beroende på potentiella fel orsakade av ytledning i det sötare vattnet i den övre delen av bergmassan. För KLX04 görs jämförelser med formationsfaktorn erhållen i laboratoriet på prov från borrkärnan med elektriska metoder.

För KLX03 varierar den erhållna in-situ formationsfaktorn för bergmatrisen från $1{,}0\times10^{-5}$ till 5.0×10^{-4}. Den erhållna in-situ formationsfaktorn för sprickigt berg varierar från $1{,}0\times10^{-5}$ till $6{,}8\times10^{-3}$. Formationsfaktorn verkar avvika något från den log-normala distributionen. Medelvärdena och standardavvikelserna för de erhållna $\log_{10}$-normal distributionerna är –4,6 and 0,24, samt –4,4 och 0,37 for in-situ formationsfaktorn för bergmatrisen respektive in-situ formationsfaktorn för sprickigt berg.

För KLX04 varierar den erhållna in-situ formationsfaktorn för bergmatrisen från $8{,}8\times10^{-6}$ till $2{,}1\times10^{-4}$. Den erhållna in-situ formationsfaktorn för sprickigt berg varierar från $8{,}8\times10^{-6}$ till $4{,}6\times10^{-3}$. Den erhållna laborativa formationsfaktorn (för bergmatrisen) varierar från $9{,}7\times10^{-5}$ till $4{,}3\times10^{-4}$. Formationsfaktorn verkar vara någorlunda väl log-normalt distribuerad. Medelvärdena och standardavvikelserna för de erhållna $\log_{10}$-normala distributionerna är –4,5 och 0,27, –4,2 och 0,46, samt –4,1 och 0,45 för in-situ formationsfaktorn för bergmatrisen, in-situ formationsfaktorn för sprickigt berg respektive den laborativa formationsfaktorn.

De bergartsspecifika formationsfaktordistributionerna som presenteras i denna rapport tyder på att formationsfaktorn inom samma bergart kan variera över en eller två tiopotenser.

Jämförelser mellan resistivitetsvärden från laboratorietester och in-situ indikerar att bergsproverna tagna från borrkärnorna till laboratoriet kan vara störda. Störningen kan antingen ha sitt ursprung i avlastning eller i mekanisk påverkan i samband med provförberedning. De erhållna laborativa formationsfaktorerna kan vara överskattade med en faktor två till tre.

Mätningarna i KLX03 och speciellt i KLX04 visar på att man måste använda resultat erhållna i grundvattenkemimätningar in-situ med försiktighet. Anledningen är att borrhålet själv stör grundvattenkemisituationen då det fungerar som en hydraulisk ledare. Ytnära och ickesalint grundvatten kan snabbt föras ner till större djup i borrhålet.

Contents

1 Introduction

This document reports data gained from measurements of the formation factor of rock surrounding the boreholes KLX03 and KLX04, located at Laxemar within the Oskarshamn site investigation area. The formation factor was logged in-situ by electrical methods. For KLX04, comparisons are made with formation factors obtained by electrical methods in the laboratory on samples from the bore core.

This work has been conducted according to the activity plan AP PF 400-05-026 (SKB internal controlling document). In Table 1-1 controlling documents for performing this activity are listed. Both activity plan and method descriptions are SKB's internal controlling documents.

Other contractors performed the field work and laboratory work, and that work is outside the framework of this activity. The interpretation of in-situ data and compilation of formation factor logs were performed by Chemical Engineering and Technology at the Royal Institute of Technology in Stockholm, Sweden.

Figure 1-1 shows the Oskarshamn site investigation area and the location of different boreholes. KLX03 and KLX04 are located in the Laxemar subarea on the left.

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

Activity plan	**Number**	**Version**
Bestämning av formationsfaktorn från in-situ resistivitetsmätningar i KLX03 och KLX04.	AP PS 400-05-026	1.0
Method descriptions	**Number**	**Version**
Formation factor logging in-situ by electrical methods – Background and methodology.	SKB TR-02-27	1.0

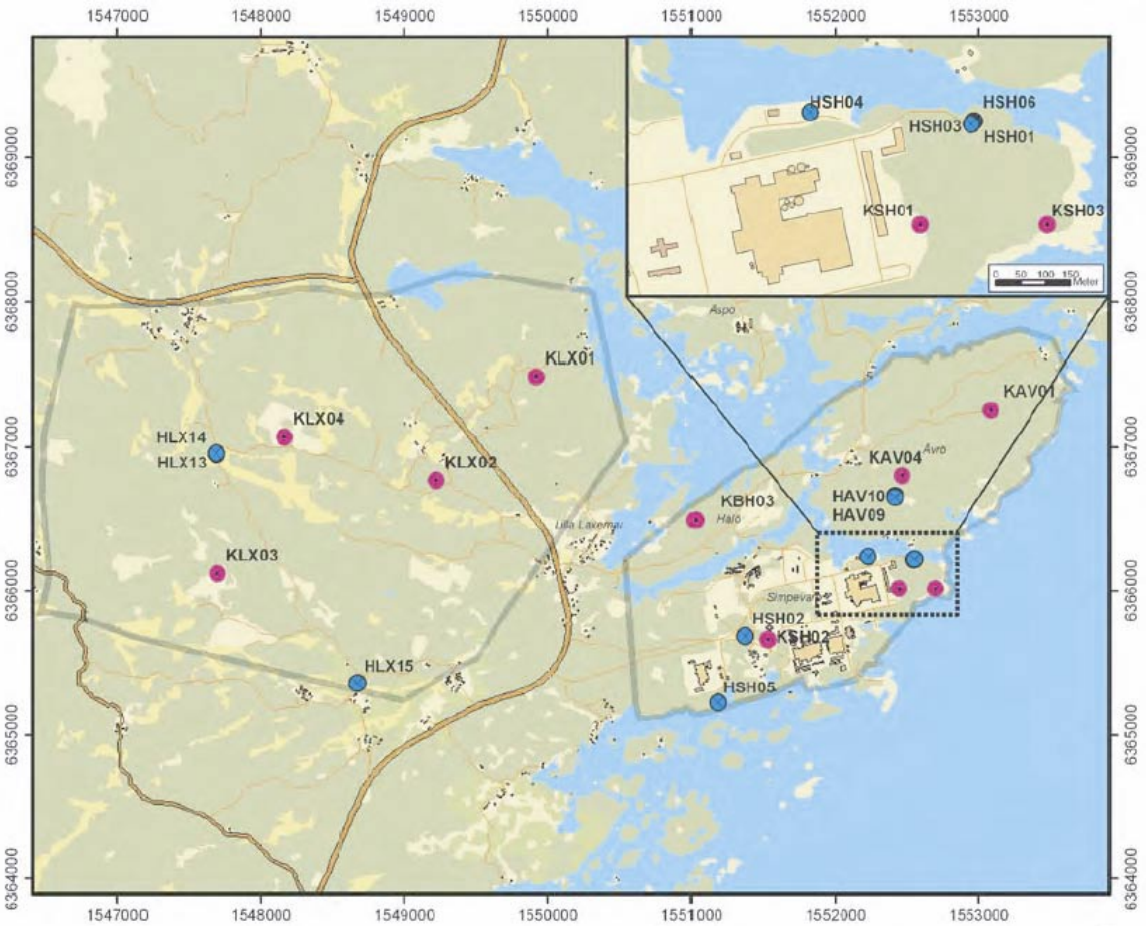


Figure 1-1. General overview of the Oskarshamn site investigation area.

2 Objective and scope

The formation factor is an important parameter that may be used directly in the safety assessment. The main objective of this work is to obtain the formation factor of the rock mass surrounding the boreholes KLX03 and KLX04. This has been achieved by performing formation factor loggings by electrical methods both in-situ and in the laboratory. The in-situ method gives a great number of formation factors obtained under more natural conditions than in the laboratory. To obtain the in-situ formation factor, results from previous loggings were used. The laboratory formation factor was obtained by performing measurements on rock samples from the bore core of KLX04. Other contractors carried out the field work and laboratory work.

3 Equipment

3.1 Rock resistivity measurments

The resistivity of the rock surrounding the boreholes KLX03 /1/ and KLX04 /2/ was logged in two separate campaigns using the focused rock resistivity tool Century 9072. The tool emits an alternating current perpendicular to the borehole axis from a main current electrode. The shape of the current field is controlled by electric fields emitted by guard electrodes. By using focused tools, the disturbance from the borehole is minimised. The quantitative measuring range of the Century 9072 tool is 0–50,000 ohm.m, according to the manufacturer. The rock resistivity was also logged using the Century 9033 tool. However, this tool is not suitable for quantitative logging in granitic rock and the results are not used in this report.

3.2 Groundwater electrical conductivity measurments

The EC (electrical conductivity) of the borehole fluid in KLX03 /3/ was logged using the POSIVA difference flow meter. The tool is shown in Figure 3-1.

When logging the EC of the borehole fluid, the lower rubber disks of the tool are not used. During the measurements, no drawdown is applied. Measurements were carried out before and after the difference flow logging in KLX03. The EC of the borehole fluid in KLX04 was logged as a part of the geophysical borehole logging using the Century 8044 tool /2/, before the difference flow logging.

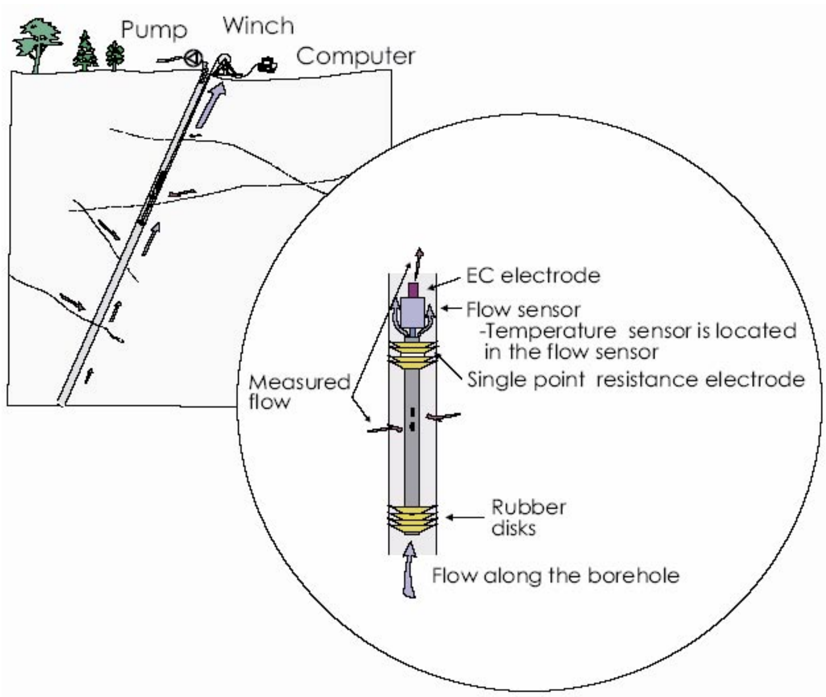


Figure 3-1. *Schematics of the POSIVA difference flow meter (image taken from /4/).*

When using both the upper and the lower rubber disks of the POSIVA difference flow meter, a section around a specific fracture can be packed off. By applying a drawdown at the surface, groundwater can thus be extracted from specific fractures. By also measuring the groundwater flow out of the fracture, it is calculated how long time it will take to fill up the packed off borehole section three times. During this time the EC is measured and a transient EC curve is obtained. After this time it is assumed that the measured EC is representative for the groundwater flowing out of the fracture. The measurements may be disturbed by leakage of borehole fluid into the packed off section and development of gas from species dissolved in the groundwater. Interpretations of transient EC curves are discussed in /5/. The quantitative measuring range of the EC electrode of the POSIVA difference flow meter is 0.02–11 S/m.

The EC, among other entities, of the groundwater coming from fractures in larger borehole sections is measured as a part of the hydrochemical characterisation. A section is packed off and by using a drawdown, groundwater is extracted from fractures within the section and brought to the surface for chemical analysis. A hydrochemical characterisations was performed in KLX03 /6/.

3.3 Difference flow loggings

By using the POSIVA difference flow meter, water-conducting fractures can be located. The tool, shown in Figure 3-1, has a flow sensor and the flow from fractures in packed off sections can be measured. When performing these measurements, both the upper and the lower rubber disks are used. Measurements can be carried out both with and without applying a drawdown. The quantitative measuring range of the flow sensor is 0.1–5,000 ml/min.

Difference flow loggings were performed in different campaigns in KLX03 /3/ and KLX04 /4/.

3.4 Boremap loggings

The bore cores of KLX03 /7/ and KLX04 /8/ were logged together with a simultaneous study of video images of the borehole wall. This is called boremap logging.

In the core log, fractures parting the core are recorded. Fractures parting the core that have not been induced during the drilling or core handling are called broken fractures. To decide if a fracture actually was open or sealed in the rock volume (i.e. in-situ), SKB has developed a confidence classification of open fractures expressed at three levels, “possible”, “probable” and “certain”, based on the aperture, weathering and fit of the fracture /9/.

As discussed in /10/, it is at present unclear if broken fractures that has been classified as sealed in-situ really can be treated as sealed when obtaining rock matrix formation factors by electrical methods. The reason is that in the core logging, the aperture is classified from 0.5 mm and larger. However, rock resistivity measurements are disturbed by fractures having an aperture of some tens of micrometers or larger. Therefore, until this has been properly investigated, all broken fractures recorded in the core logging were taken as potentially open in-situ, having a significant aperture.

In the boremap logging, parts of the core that are crushed or lost are also recorded, as well as the spatial distribution of different rock types.

4 Execution

4.1 Theory

4.1.1 The formation factor

The theory applied for obtaining formation factors by electrical methods is described in /11/. The formation factor is the ratio between the diffusivity of the rock matrix to that of free pore water. If the species diffusing through the porous system is much smaller than the characteristic length of the pores and no interactions occur between the mineral surfaces and the species, the formation factor is only a geometrical factor that is defined by the transport porosity, the tortuosity and the constrictivity of the porous system:

$$F_f = \frac{D_e}{D_w} = \varepsilon_t \frac{\delta}{\tau^2} \qquad \text{4-1}$$

where F_f (-) is the formation factor, D_e (m^2/s) is the effective diffusivity of the rock, D_w (m^2/s) is the diffusivity in the free pore water, ε_t (-) is the transport porosity, τ (-) is the tortuosity, and δ (-) is the constrictivity. When obtaining the formation factor with electrical methods, the Einstein relation between diffusivity and ionic mobility is used:

$$D = \frac{\mu RT}{zF} \qquad \text{4-2}$$

where D (m^2/s) is the diffusivity, μ ($m^2/V\times s$) is the ionic mobility, z (-) the charge number and R (J/mol×K), T (K) and F (C/mol), are the gas constant, temperature, and Faraday constant respectively. From the Einstein relation it is easy to show that the formation factor also is given by the ratio of the pore water resistivity to the resistivity of the saturated rock /12/:

$$F_f = \frac{\rho_w}{\rho_r} \qquad \text{4-3}$$

where ρ_w (ohm.m) is the pore water resistivity and ρ_r (ohm.m) is the rock resistivity. The resistivity of the saturated rock can easily be obtained by standard geophysical methods.

At present it is not feasible to extract pore water from the rock matrix in-situ. Therefore, it is assumed that the pore water is in equilibrium with the free water surrounding the rock, and measurements are performed on this free water. The validity of this assumption has to be discussed for every specific site.

The resistivity is the reciprocal to electrical conductivity. Traditionally the EC (electrical conductivity) is used when measuring on water and resistivity is used when measuring on rock.

4.1.2 Surface conductivity

In intrusive igneous rock, the mineral surfaces are normally negatively charged. As the negative charge often is greater than what can be balanced by cations specifically adsorbed on the mineral surfaces, an electrical double layer with an excess of mobile cations will form at the pore wall. If a potential gradient is placed over the rock, the excess cations in the electrical double layer will move. This process is called surface conduction and this additional conduction may have to be accounted for when obtaining the formation factor of rock saturated with a pore water of low ionic strength. If the EC of the pore water is around 0.5 S/m or above, errors associated with surface conduction are deemed to be acceptable. This criterion is based on laboratory work by /13/ and /12/. The effect of the surface conduction on rock with formation factors below 1×10^{-5} was not investigated in these works. In this report surface conduction has not been accounted for, as only the groundwater in the upper part of the boreholes has a low ionic strength and as more knowledge is needed on surface conduction before performing corrections.

4.1.3 Artefacts

Comparative studies have been performed on a large number of 1–2 cm long samples from Äspö in Sweden /13/. Formation factors obtained with an electrical resistivity method using alternating current were compared to those obtained by a traditional through diffusion method, using uranine as the tracer. The results show that formation factors obtained by the electrical resistivity measurements are a factor of about 2 times larger that those obtained by through diffusion measurements. A similar effect was found on granitic samples up to 12 cm long, using iodide in tracer experiments /14/. The deviation of a factor 2 between the methods may be explained by anion exclusion of the anionic tracers. Previously performed work suggests that the Nernst-Einstein equation between the diffusivity and electrical conductivity is generally applicable in granitic rock and that no artefacts give rise to major errors. It is uncertain, however, to what extent anion exclusion is related to the degree of compression of the porous system in-situ due to the overburden.

4.1.4 Fractures in-situ

In-situ rock resistivity measurements are highly disturbed by free water in open fractures. The current sent out from the downhole tool in front of an open fracture will be propagated both in the porous system of the rock matrix and in the free water in the open fracture. Due to the low formation factor of the rock matrix, current may be preferentially propagated in a fracture intersecting the borehole if its aperture is on the order of 10^{-5} m or more.

There could be some confusion concerning the terminology of fractures. In order to avoid confusion, an organization sketch of different types of fractures is shown in Figure 4-1. The subgroups of fractures that interfere with the rock resistivity measurements are marked with grey.

The information concerning different types of fractures in-situ is obtained from the interpretation of the boremap logging and in the hydraulic flow logging. A fracture intersecting the borehole is most likely to part the core. In the core log, fractures that part the core are either broken or operational (drill-induced). Unbroken fractures, which do not part the core, are sealed or only partly open. Laboratory results suggest that sealed fractures generally have no major interference on rock resistivity measurements. The water-filled void in partly open fractures can be included in the porosity of the rock matrix.

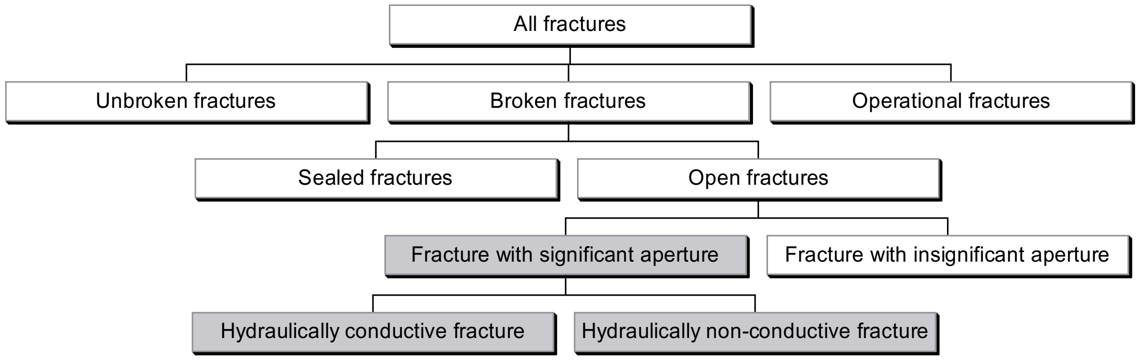


Figure 4-1. *Organization sketch of different types of fractures.*

Broken fractures are either interpreted as open or sealed. Open fractures may have a significant or insignificant aperture. With insignificant aperture means an aperture so small that the amount of water held by the fracture is comparable with that held in the adjacent porous system. In this case the "adjacent porous system" is the porous system of the rock matrix the first few centimetres from the fracture.

If the fracture has a significant aperture, it holds enough water to interfere with the rock resistivity measurements. Fractures with a significant aperture may be hydraulically conductive or non-conductive, depending on how they are connected to the fracture network and on the hydraulic gradients of the system.

Due to uncertainties in the interpretation of the core logging, all broken fractures are assumed to potentially have a significant aperture.

4.1.5 Rock matrix and fractured rock formation factor

In this report the rock resistivity is used to obtain formation factors of the rock surrounding the borehole. The obtained formation factors may later be used in models for radionuclide transport in fractured crystalline rock. Different conceptual approaches may be used in the models. Therefore this report aims to deliver formation factors that are defined in two different ways. The first is the "rock matrix formation factor", denoted by F_f^{rm} (-). This formation factor is representative for the solid rock matrix, as the traditional formation factor. The other one is the "fractured rock formation factor", denoted by F_f^{fr} (-), which represents the diffusive properties of a larger rock mass, where fractures and voids holding stagnant water is included in the porous system of the rock matrix. Further information on the definition of the two formation factors can be found in /5/.

The rock matrix formation factor is obtained from rock matrix resistivity data. When obtaining the rock matrix resistivity log from the in-situ measurements, all resistivity data that may have been affected by open fractures have to be sorted out. With present methods one cannot with certainty separate open fractures with a significant aperture from open fractures with an insignificant aperture in the interpretation of the core logging. It should be mentioned that there is an attempt to assess the fracture aperture in the interpretation of the core logging. However, this is done on a millimetre scale. Fractures may be significant even if they only have apertures some tens of micrometers.

By investigating the rock resistivity log at a fracture, one could draw conclusions concerning the fracture aperture. However, for formation factor logging by electrical methods this is not an independent method and cannot be used. Therefore, all broken fractures have to be considered as potentially open and all resistivities obtained close to a broken fracture detected in the core logging are sorted out. By examining the resistivity logs obtained by the Century 9072 tool, it has been found that resistivity values obtained within 0.5 m from a broken fracture generally should be sorted out. This distance includes a safety margin of 0.1–0.2 m.

The fractured rock formation factor is obtained from fractured rock resistivity data. When obtaining the fractured rock resistivity log from the in-situ measurements, all resistivity data that may have been affected by free water in hydraulically conductive fractures, detected in the in-situ flow logging, have to be sorted out. By examining the resistivity logs obtained by the Century 9072 tool, it has been found that resistivity values obtained within 0.5 m from a hydraulically conductive fracture generally should be sorted out. This distance includes a safety margin of 0.1–0.2 m.

4.2 Rock resistivity measurements in-situ

4.2.1 Rock resistivity log KLX03

The rock resistivity of KLX03 was logged on the 1st of October 2004 (activity id 13049533) /1/. The in-situ rock resistivity was obtained using the focused rock resistivity tool Century 9072. The borehole was logged between 103.6–1,000.2 m. In order to obtain an exact depth calibration, the track marks made in the borehole were used. According to /1/ an exact depth calibration was not obtained. The following deviations in the calibration with depth are reported.

The deviation is increasing with the borehole length. The borehole length reported in /1/ was corrected between 110–1,000 m by subtracting the deviation obtained by the polynomial equation shown in Figure 4-2.

In Figure 4-2 the borehole length is according to the reference marks. No correction in reported borehole length was made between 0–110 m.

Table 4-1. Deviation in borehole lengths. Data from /1/.

Reference mark (m)	110	150	200	250	300	350	399	400	450	500
Deviation (m)	0	0.03	0.08	0.09	0.14	0.17	0.21	0.22	0.28	0.32
Reference mark (m)	550	600	650	700	750	800	850	900	950	
Deviation (m)	0.36	0.42	0.5	0.56	0.62	0.76	0.8	0.94	1.09	

4.2.2 Rock matrix resistivity log KLX03

After adjusting the borehole length of the in-situ rock resistivity log, all resistivity data obtained within 0.5 m from a broken fracture detected in the core log were sorted out. In the core log (activity id 13059629), a total of 1,543 broken fractures are recorded between 101.5–998.2 m. Three crush zones but no zones where the core is lost are recorded.

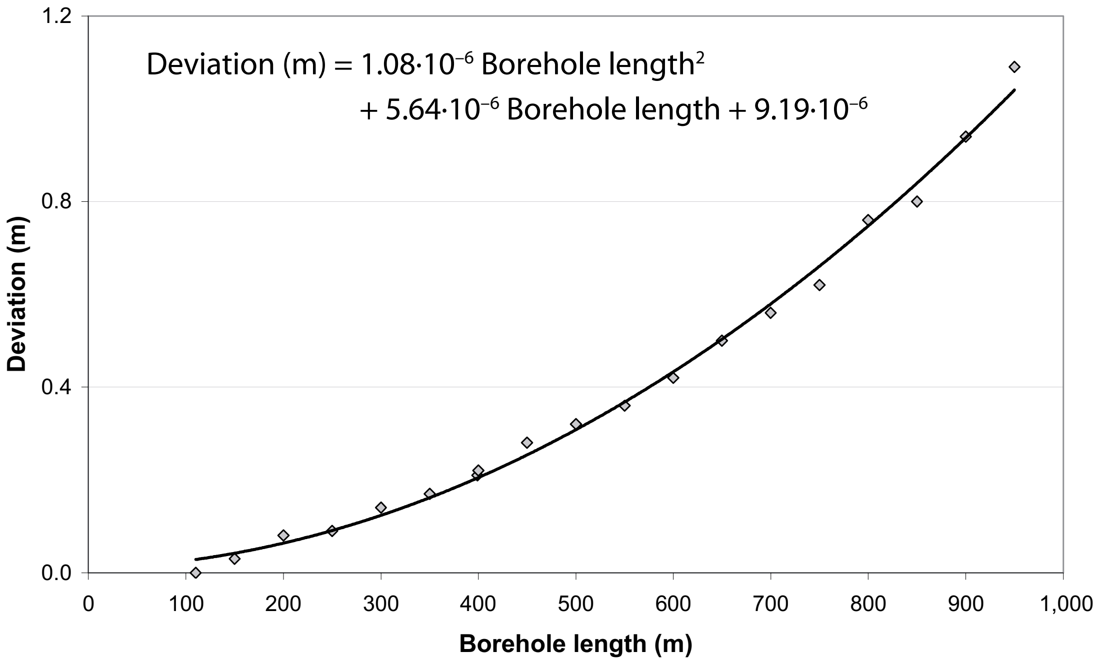


Figure 4-2. *Deviations in borehole length in KLX03.*

A total of 6.72 m of the core was crushed or lost. Broken fractures can potentially intersect the borehole in zones where the core is crushed or lost. Therefore, a broken fracture was assumed every decimetre in these zones. The locations of broken fractures in KLX03 are shown in Appendix B1. A total of 2,963 rock matrix resistivities were obtained between 102–998 m. 2,459 (83%) of the rock matrix resistivities were within the quantitative measuring range of the Century 9072 tool. The rock matrix resistivity log between 102–998 m is shown in Appendix B1.

Figure 4-3 shows the distribution of the rock matrix resistivities obtained between 102–998 m in KLX03. The histogram ranges from 0–100,000 ohm.m and is divided into sections of 5,000 ohm.m.

4.2.3 Fractured rock resistivity log KLX03

After adjusting the borehole length of the in-situ rock resistivity log, all resistivity data obtained within 0.5 m from a hydraulically conductive fracture, detected in the difference flow logging /3/, were sorted out. For the difference flow log, no correction in the reported borehole length was needed. A total of 55 hydraulically conductive fractures were detected in KLX03, although some were detected with uncertainty. The locations of hydraulically conductive fractures in KLX03 are shown in Appendix B1. A total of 8,459 fractured rock resistivities were obtained between 102–998 m. 7,608 (90%) of the fractured rock resistivities were within the quantitative measuring range of the Century 9072 tool. The fractured rock resistivity log between 102–998 m is shown in Appendix B1.

Figure 4-4 shows a histogram of the fractured rock resistivities obtained between 102–998 m in KLX03. The histogram ranges from 0–100,000 ohm.m and is divided into sections of 5,000 ohm.m.

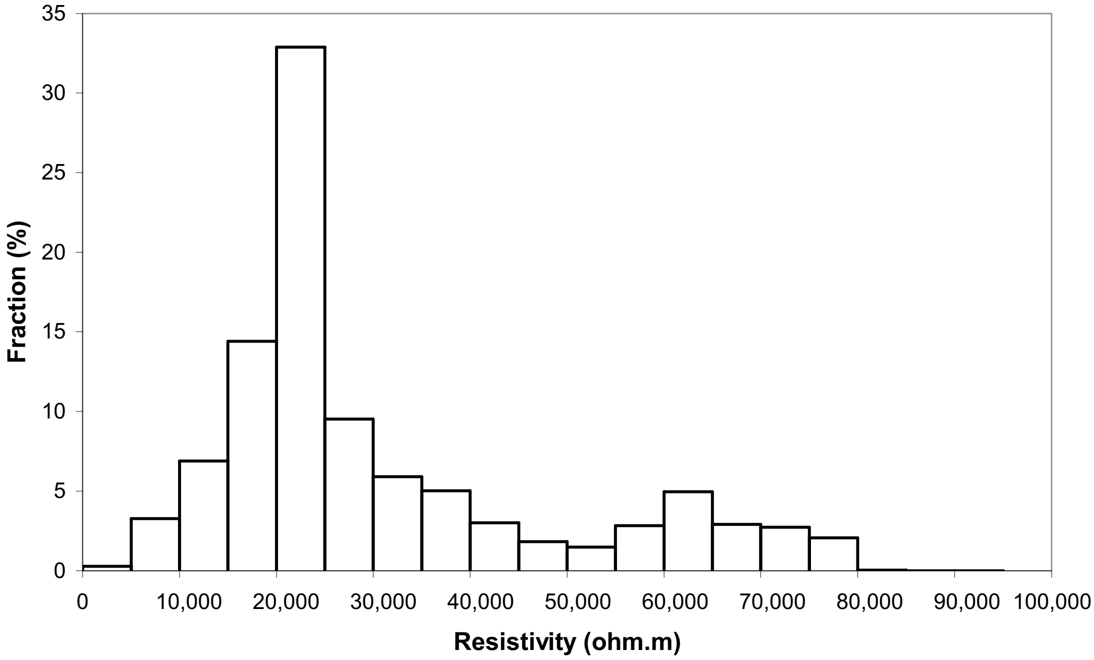


Figure 4-3. *Distribution of rock matrix resistivities in KLX03.*

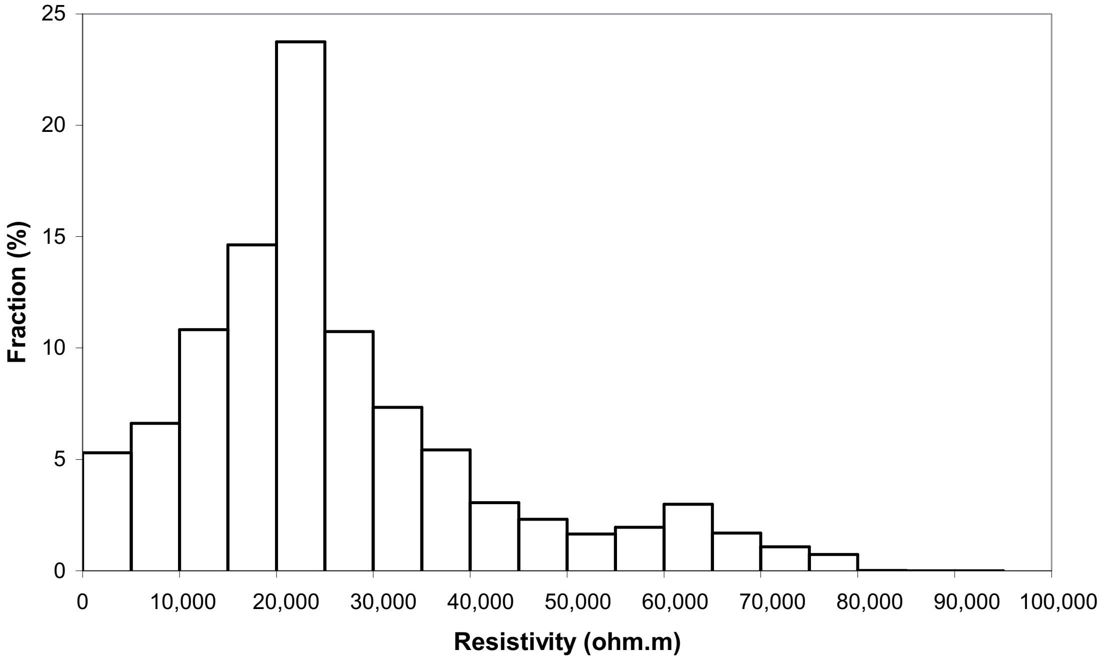


Figure 4-4. *Histogram of fractured rock resistivities in KLX03.*

4.2.4 Rock resistivity KLX04

The rock resistivity of KLX04 was logged on the 20th of October 2004 (activity id 13050191) /2/. The in-situ rock resistivity was obtained using the focused Century 9072 tool. The borehole was logged between 102.6–989.0 m. In order to obtain an exact depth calibration, the track marks made in the borehole were used. According to /2/ an exact depth calibration was obtained.

4.2.5 Rock matrix resistivity log KLX04

All resistivity data obtained within 0.5 m from a broken fracture, detected in the core log, were sorted out. In the core log (activity id 13062414), a total of 2,753 broken fractures are recorded between 101.5–991.2 m. In addition 53 crush zones and 41 zones where the core is lost are recorded. A total of 24.84 m of the core is crushed or lost. Broken fractures can potentially intersect the borehole in zones where the core is crushed or lost. Therefore, a broken fracture was assumed every decimetre in these zones. The locations of broken fractures in KLX04 are shown in Appendix B2. A total of 1,886 rock matrix resistivities were obtained between 102–989 m. 1,630 (86%) of the rock matrix resistivities were within the quantitative measuring range of the Century 9072 tool. The rock matrix resistivity log between 102–989 m is shown in Appendix B2.

Figure 4-5 shows a histogram of the rock matrix resistivities obtained between 102–989 m in KLX04. The histogram ranges from 0–100,000 ohm.m and is divided into sections of 5,000 ohm.m.

4.2.6 Fractured rock resistivity log KLX04

All resistivity data obtained within 0.5 m from a hydraulically conductive fracture, detected in the difference flow logging /4/, were sorted out. For the difference flow log, no correction in the reported borehole length was needed. A total of 129 hydraulically conductive fractures were detected in KLX04, although some were detected with uncertainty. The location of hydraulically conductive fractures in KLX04 are shown in Appendix B2. A total of 7698 fractured rock resistivities were obtained between 102–989 m. 7,330 (95%) of the fractured rock resistivities were within the quantitative measuring range of the Century 9072 tool. The fractured rock resistivity log between 102–989 m is shown in Appendix B2.

Figure 4-6 shows a histogram of the fractured rock resistivities obtained between 102–989 m in KLX04. The histogram ranges from 0–100,000 ohm.m and is divided into sections of 5,000 ohm.m.

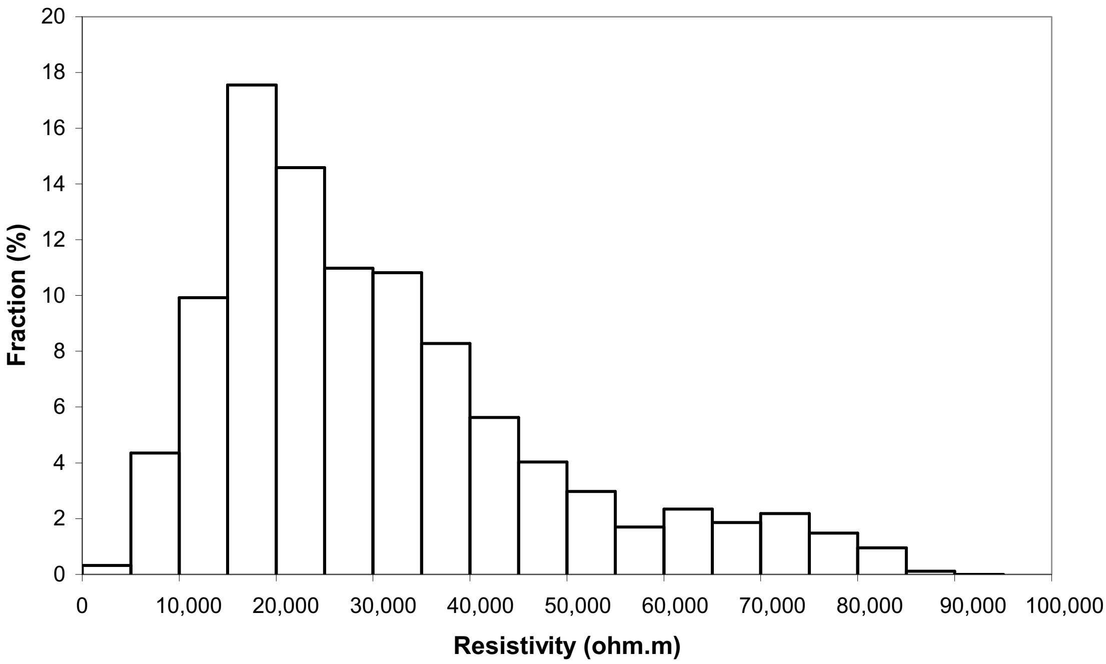


Figure 4-5. *Histogram of rock matrix resistivities in KLX04.*

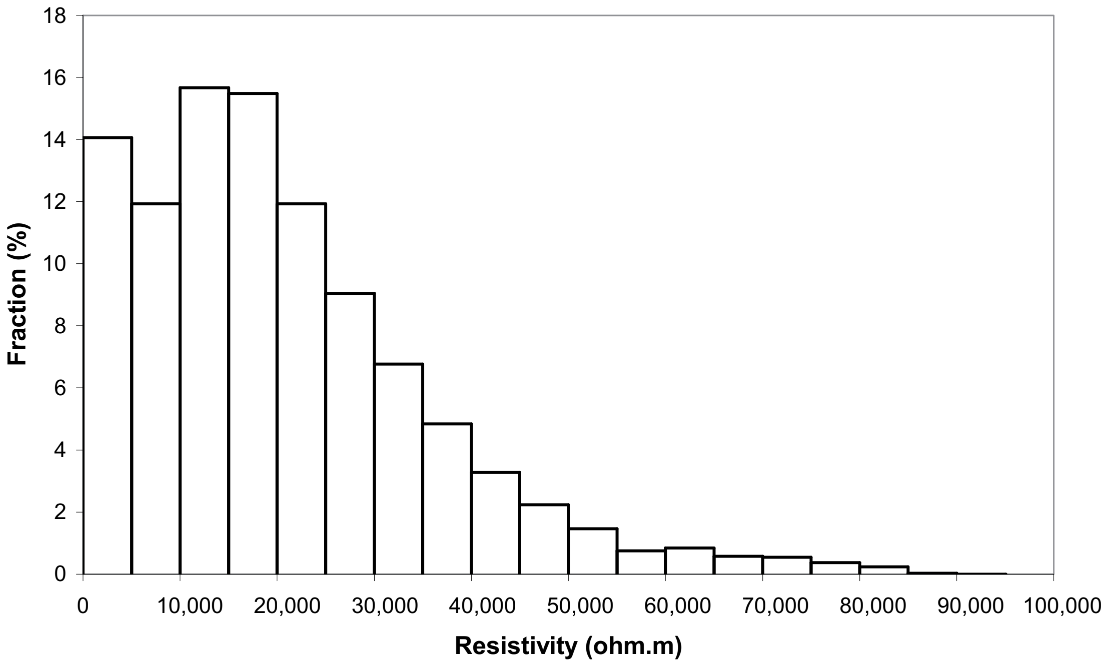


Figure 4-6. *Histogram of fractured rock resistivities in KLX04.*

4.3 Groundwater EC measurements in-situ

4.3.1 General comments

Some of the electrical conductivities presented in this section have been corrected for the temperature to conductivities at 25°C. Other electrical conductivities are uncorrected. The uncorrected value should be used for in-situ evaluations. However, as the corrections are insignificant (only a few percent) in comparison to other uncertainties, both corrected and uncorrected values have been used.

4.3.2 EC measurements in KLX03

The EC of the borehole fluid in KLX03 was measured as a part of the different flow logging campaign /3/. When performing the difference flow loggings, a drawdown is applied by pumping out of the borehole. Therefore, the composition of the borehole fluid will change during the campaign. The EC of the borehole fluid was measured both before and after the extensive pumping, on the occasions shown in Table 4-2.

Table 4-2. Measurements of borehole fluid EC, KLX03.

Measurment	Activity id	Start date
Before the pumping (1)	13056708	2004-11-05
After the pumping (2)	13056728	2003-11-16

By inspecting the activity log of KLX03 one can see that during the month preceding the difference flow logging camping, only geophysical and geological loggings, involving no pumping, were performed. The borehole fluid EC log obtained before starting the pumping is shown in Figure 4-7 by the solid black line. As one can see, the borehole fluid EC is low down to about 770 m. This is resulting from the fact that the borehole functions as a hydraulic conductor, where groundwater from shallower depths has flown to greater depth. As the borehole itself greatly disturbs the groundwater situation, one has to discuss whether the groundwater measured on, is representative for the original groundwater at that depth.

The grey solid line in Figure 4-7 shows the borehole fluid EC log obtained after the pumping. Here one can see that more saline water has been drawn from greater to shallower depth.

The EC of groundwater, extracted from a number of specific fractures between 195–970 m, was measured as a part of the different flow logging campaign between 2004-11-14 and 2004-11-16 /3/. The resulting fracture specific ECs are shown in Table 4-3.

The EC of groundwater extracted from a number of packed off sections in KLX03 was measured in the hydrochemical characterisation /6/. The hydrochemical characterisation was carried out between 2004-11-25 and 2005-04-13. The resulting fracture specific ECs are shown in Table 4-3.

The EC value obtained in the difference flow logging at 274 m appears to have been influenced by a major leakage of borehole fluid into the packed off section, which can be seen in the transient EC curve /3/. Therefore this value has been disregarded. The fractures specific ECs shown in Table 4-3 are shown in Figure 4-7, together with the borehole fluid EC logs. If there are more than one hydraulically conductive fracture in a packed off section, the mean value of the borehole lengths of the fractures is used. The numbers associated with the borehole fluid EC logs shown in Figure 4-7 are according to Table 4-2.

Table 4-3. Fracture specific ECs, KLX03.

Measurment	Borehole section (m)	Location of fractures (m)	EC (S/m)
Difference flow logging	195.1–195.6	195.3	0.14
Hydrochemical characterisation	193.5 –198.4	195.8, 197.7	0.14
Difference flow logging	266.5–267.0	266.8	0.30
Difference flow logging	274.2–274.7	274.7	(1.31)
Hydrochemical characterisation	408.0–415.3	409.9	0.45
Difference flow logging	453.2–453.7	453.4	1.27
Hydrochemical characterisation	600.0–670.7	619.4, 620.1, 660.2, 661.2, 662.4, 663.0, 666.7	1.20
Difference flow logging	619.2–619.7	619.4	1.36
Hydrochemical characterisation	735.5–748.0	740.8, 741.8, 742.3, 744.1, 746.4, 747.7	1.06
Hydrochemical characterisation	964.5–975.2	970.1, 970.5	2.80
Difference flow logging	969.9–970.4	970.1	2.87

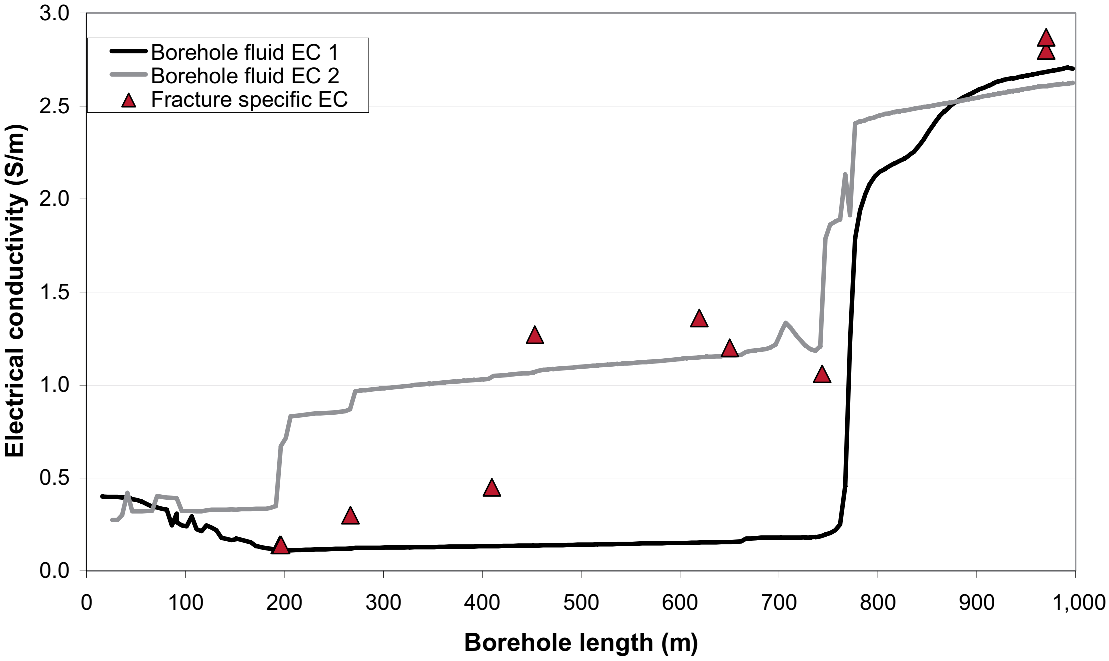


Figure 4-7. *Groundwater EC in KLX03.*

4.3.3 Assessing the validity of the groundwater EC measurements in KLX03

The borehole KLX03 functions as a hydraulic conductor, where groundwater from a shallow depth generally flows down the borehole and into hydraulically conductive fractures at a greater depth. By using a drawdown at the surface, the situation is reversed so that groundwater flows out of the fractures into the borehole. The EC of this groundwater is measured at specific fractures in the difference flow logging and in the hydrochemical characterisation. In the hydrochemical characterisation the uranin concentration of the groundwater is also measured. This is to assure that the fraction of uranin labeled cooling water, used when drilling the borehole, is low.

As stated before, it is important to discuss if the groundwater measured on, represents the groundwater existing at that depth before the drilling of the borehole. The red diamonds in Figure 4-8 show the groundwater flow in specific fractures when not using a drawdown /3/. A positive value means flow into the borehole and a negative value flow into the fracture.

Figure 4-8 also shows the flow down the borehole at different depth (solid grey line). In the upper 100 m, no difference flow logging was performed and therefore, it is assumed that all groundwater flowing into this section instead is introduced at the surface. A mass balance calculates the flow into the upper 100 m of the borehole. In doing this, it is assumed that no groundwater flows out of the borehole in the lower few meters of the borehole, where difference flow measurements were not performed. It is also assumed that there are no significant groundwater flows below the detection limit of the POSIVA flow meter used in the flow logging.

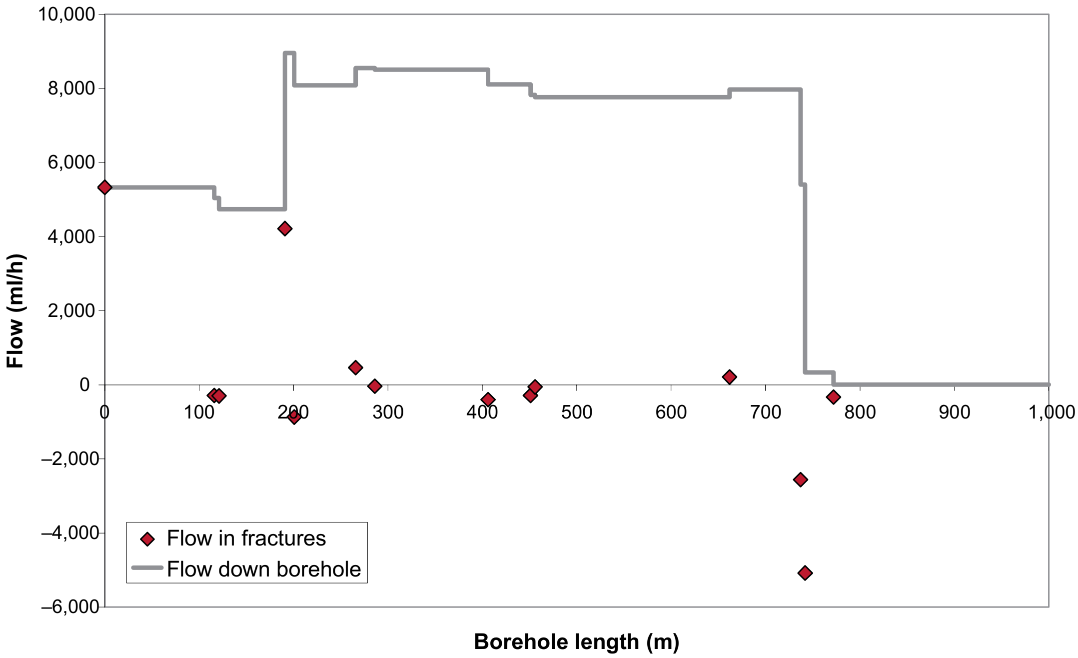


Figure 4-8. *Groundwater flow in KLX03.*

Taking the diameter of the borehole into account, a flow of 8,000 ml/h converts to a flow velocity of 1.8 m/h. The vertical turnover time of the borehole fluid can therefore be expected to be about a month. The exception is in the lower 200 m of the borehole, where there seems to be no major vertical flow. As only an insignificant concentration of uranin was found in the hydrochemical characterisation at the depth of 970 m, it is evident that the borehole fluid has been exchanged, possibly by a local horizontal flow. It seems reasonable to assume that the borehole fluid EC below 800 m is representative for the groundwater at that depth.

Below 200 m, there are two fractures with a groundwater flow into the borehole when not using a drawdown. These fractures are of special interest, as it is less likely that borehole fluid has flown directly into them. One fracture is at 266 m, where a fracture specific EC value of 0.30 S/m was obtained in the difference flow logging. The other fracture is at 662 m. Figure 4-9 shows the borehole fluid EC log obtained between 640–680 m, before starting the pumping.

From the increase in EC of the borehole fluid, one can suspect that the groundwater flowing out of the fracture is more saline than the borehole fluid. At 652 m depth, the borehole fluid EC is 0.156 S/m and at 672 m depth, the borehole fluid EC is 0.174 S/m.

If treating the borehole as a mixing reactor, one could suggest that the borehole fluid flowing down the borehole (7,759 ml/h) has mixed with groundwater flowing out of the fracture (207 ml/h) having an EC of approximately 0.85 S/m. Performing a similar exercise at 266 m, suggests a fracture specific EC of approximately 0.21 S/m. These values are in line with the values obtained in the difference flow logging and the hydrochemical characterisation at corresponding depths. Therefore, basing a groundwater EC profile on the data shown in Figure 4-7 seems reasonable.

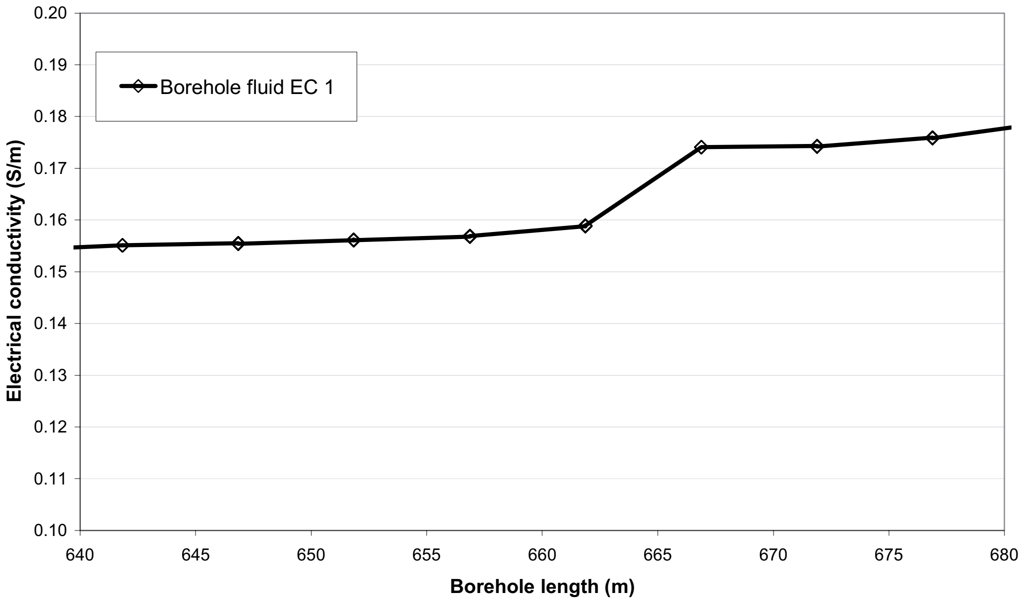


Figure 4-9. *Borehole fluid EC of KLX03.*

4.3.4 EC measurements in KLX04

The EC of the borehole fluid in KLX04 was not measured as a part of the different flow logging campaign. However, the borehole fluid EC was measured as a part of the geophysical borehole logging program using the Century 8044 tool on the 20th of October 2004 (activity id 13050190) /2/. By inspecting the activity log of KLX04, one can see that during the 20 days preceding the borehole fluid EC logging, no loggings involving pumping of groundwater out of the borehole were performed. The borehole fluid EC log is shown in Figure 4-10.

As one can see, the borehole fluid EC is low down to about 970 m. This is resulting from the fact that the borehole functions as a hydraulic conductor where groundwater from shallower depths has flown to greater depth. As the borehole itself greatly disturbs the groundwater situation, one has to discuss whether the groundwater measured on, is representative for the original groundwater at that depth.

The EC of groundwater, extracted from a number of specific fractures between 139–973 m, was measured as a part of the different flow logging campaign between 2004-08-04 and 2004-08-05 /4/. The resulting fracture specific ECs are shown in Table 4-4. No hydrochemical characterisation was performed in KLX04.

The fractures specific ECs shown in Table 4-4 are shown in Figure 4-10, together with the borehole fluid EC log.

Table 4-4. Fracture specific ECs, KLX04.

Measurment	Borehole section (m)	Location of fractures (m)	EC (S/m)
Difference flow logging	138.8–139.8	139.2	0.08
Difference flow logging	339.0–340.0	339.6	0.12
Difference flow logging	513.1–514.1	513.6	0.39
Hydrochemical characterisation	627.5–628.5	628.1	0.46
Difference flow logging	972.7–973.7	973.1	1.72

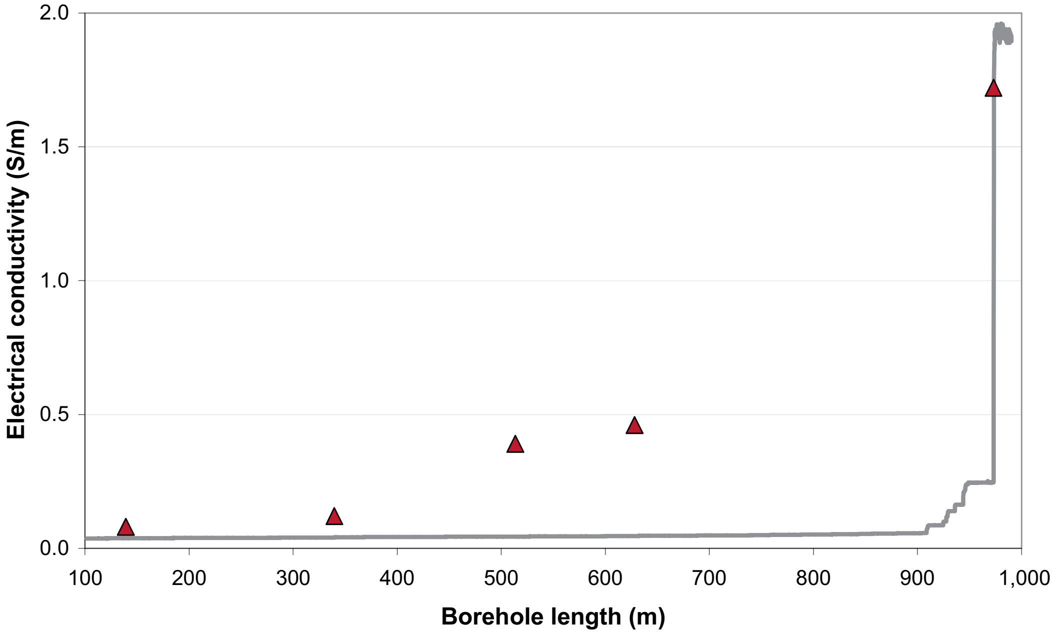


Figure 4-10. *Groundwater EC in KLX04.*

4.3.5 Assessing the validity of the groundwater EC measurements in KLX04

As for KLX03, the borehole KLX04 functions as a hydraulic conductor, where non-saline groundwater from a shallow depth can flow down to larger depth. The difference is that the vertical flow down the borehole KLX04 is much larger and that there is a vertical flow in essentially the whole borehole. The read diamonds in Figure 4-11 show the groundwater flow in specific fractures when not using a drawdown /4/. A positive value means flow into the borehole and a negative value flow into the fracture.

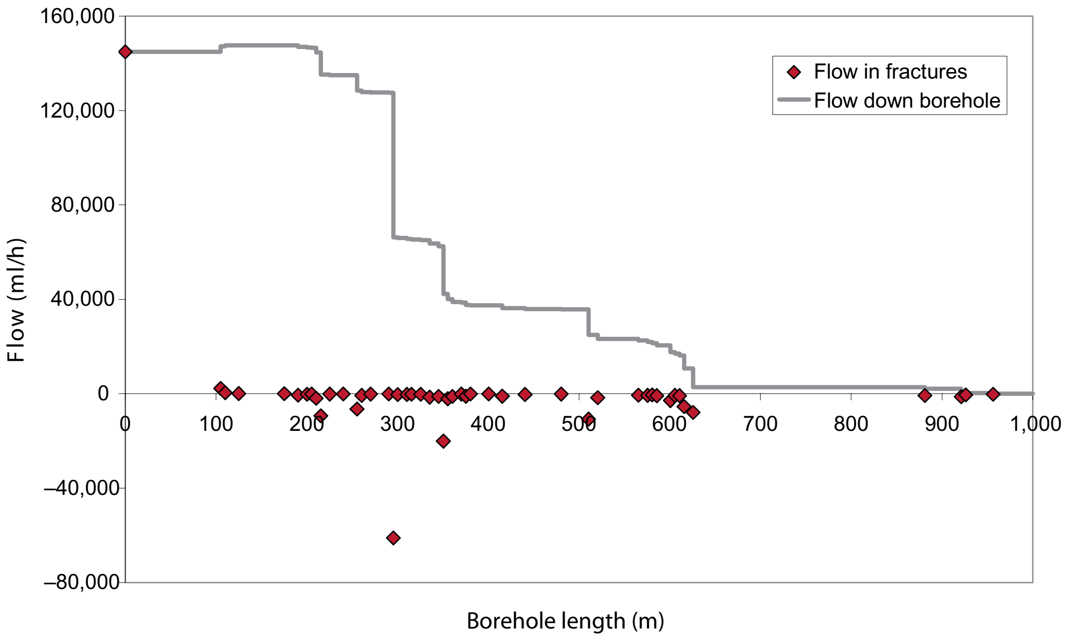


Figure 4-11. *Groundwater flow in KLX04.*

Figure 4-11 also shows the flow down the borehole at different depth (solid grey line). In the upper 100 m, no difference flow logging was performed and therefore, it is assumed that all groundwater flowing into this section instead is introduced at the surface. A mass balance calculates the flow into the upper 100 m of the borehole. In doing this, it is assumed that no groundwater flows out of the borehole in the lower few meters of the borehole, where difference flow measurements were not performed. It is also assumed that there are no significant groundwater flows below the detection limit of the POSIVA flow meter used in the flow logging.

Taking the diameter of the borehole into account, a flow of 140,000 ml/h in the upper part of the borehole converts to a flow velocity of 31 m/h. Figure 4-12 shows the flow in or out of fractures with (red stars) and without (blue diamonds) applying a drawdown. The image is taken from /4/.

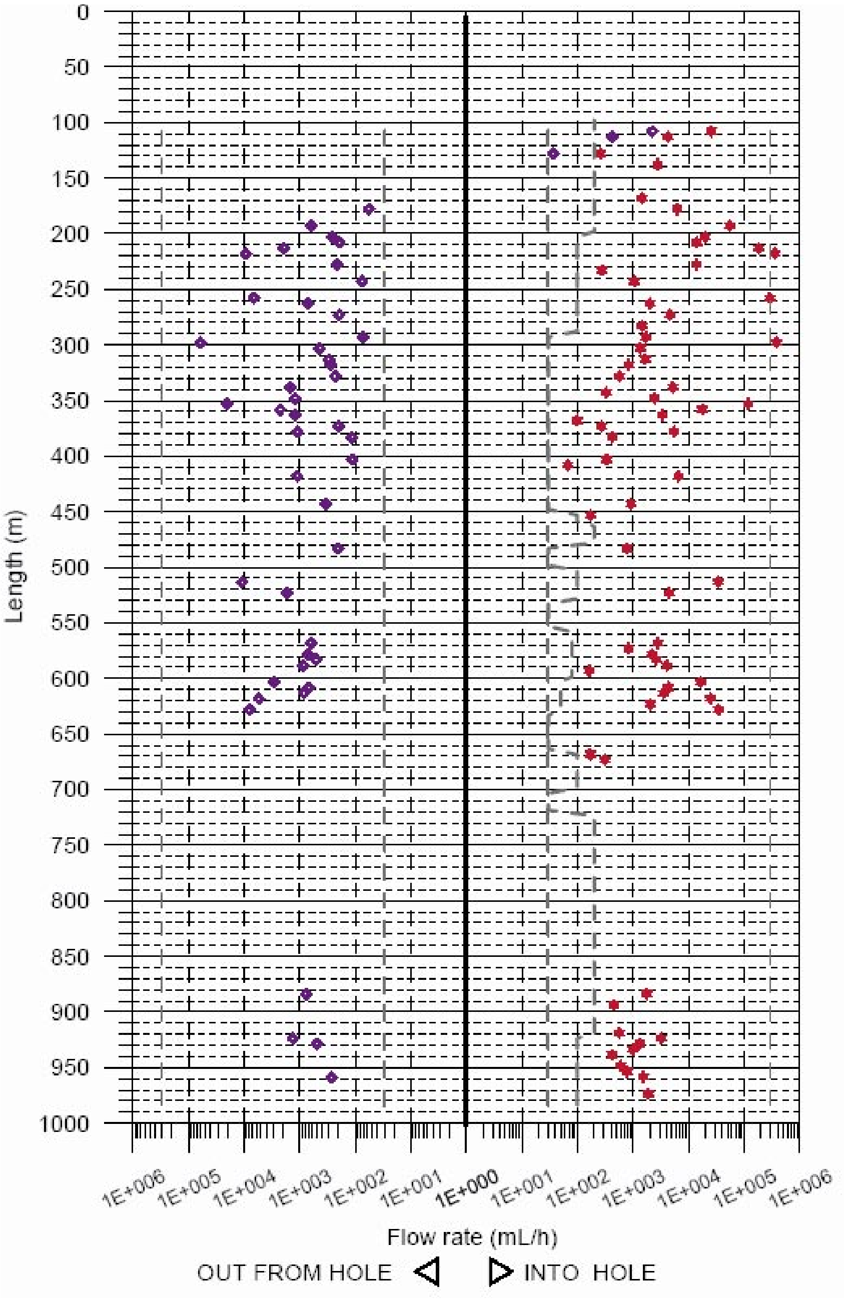


Figure 4-12. Fracture flow in and out of KLX04 with and without applying drawdown.

Below 300 m, the flow into the borehole when applying a drawdown is on the same order of magnitude as the flow out of the borehole when not applying a drawdown. Therefore one may suggest that the time applying the drawdown should be on the same order of magnitude as the time not applying the drawdown.

By inspecting the activity log of KLX04 one can se that the borehole was drilled between 2004-03-13 and 2004-06-28. It is very conceivable that during the drilling, non-saline groundwater naturally flowed down the borehole. As suggested by Figure 4-11, this flow may have been extensive. Between 2004-07-08 and 2004-07-29 no pumping was performed. A drawdown was then applied for only 6 days before obtaining the fracture specific EC. Therefore, one may suspect that a large fraction of the groundwater withdrawn from specific fractures originate from much shallower depths before the borehole was drilled. There are no measurements that may either confirm or contradict this suspicion. Unlike KLX03, there are no fractures with a natural flow into the borehole.

Because of this reasoning, the data shown in Figure 4-10 and Table 4-4 are deemed to be too uncertain and disregarded. The exception is the EC of 1.72 S/m at the depth of 973 m, which seems reasonable, as there appeared to be no vertical flow down the borehole KLX04 below 956 m.

4.3.6 EC extrapolations in KLX03 and KLX04

In KLX03, the groundwater EC is fairly well characterised as can be seen in Figure 4-7. As all data from KLX04 was deemed to be unreliable, except for at 973 m, it was decided to base the groundwater EC profile of KLX04 on values both from KLX03 and KLX04. The boreholes have similar inclinations. Figure 4-13 shows the fracture specific ECs and the assumed groundwater EC profiles of the boreholes.

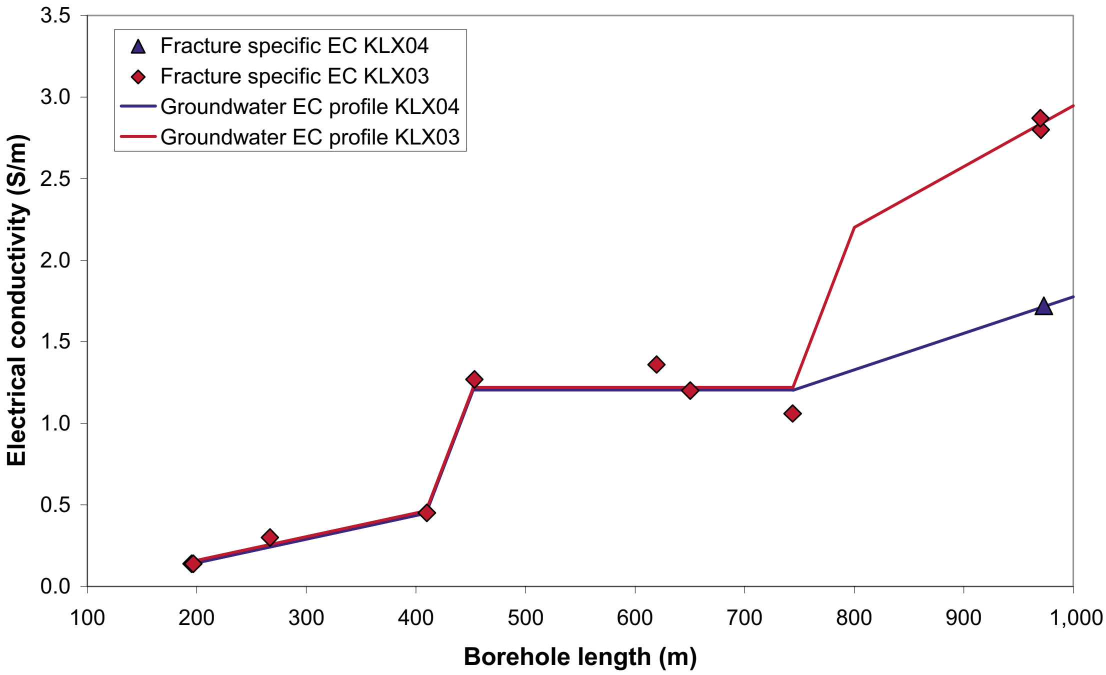


Figure 4-13. Assumed groundwater EC profiles in KLX03 and KXL04.

The following equations were used for the groundwater EC profiles of KLX03 and KLX04.

Borehole length 195–410 m, KLX03 and KLX04.

EC (S/m) = 1.45×10^{-3} × Borehole length (m) –0.13 4-4

Borehole length 410–452 m, KLX03 and KLX04.

EC (S/m) = 1.76×10^{-2} × Borehole length (m) –6.74 4-5

Borehole length 452–744 m, KLX03 and KLX04.

EC (S/m) = 1.22 4-6

Borehole length 744–800 m, KLX03.

EC (S/m) = 1.75×10^{-2} × Borehole length (m) –11.80 4-7

Borehole length 800–1,000 m, KLX03.

EC (S/m) = 3.73×10^{-3} × Borehole length (m) –0.78 4-8

Borehole length 744–1,000 m, KLX04.

EC (S/m) = 2.18×10^{-3} × Borehole length (m) –0.40 4-9

Above 412 m, the assumed groundwater EC is below 0.5 S/m. Therefore, in accordance with the criterion discussed in Section 4.1.2, in-situ formation factors were only obtained below this depth.

4.3.7 Electrical conductivity of the pore water

The rock surrounding KLX03 and KLX04 is in general highly fractured. In KLX03, on average 1.7 broken fractures per meter part the core. In KLX04, on average 3.1 broken fractures per meter part the core. The rock resistivity logs indicate that a substantial fraction of the broken fractures are open with a significant aperture. By using the POSIVA difference flow meter, groundwater could be withdrawn from most parts of the boreholes. By visual inspection of the rock resistivity logs, shown in appendix B1 and B2, one can see that the typical block of solid rock between open fractures with a significant aperture is a few meters wide or less. Even the centre of such a block would be fairly well equilibrated with non-sorbing solutes in a 1,000 years perspective. In general it seems reasonable to assume that the pore water of the rock matrix is fairly well equilibrated with the freely flowing groundwater at the corresponding depth at undisturbed conditions.

It is subjectively assessed that the errors, arising from the lack of knowledge in groundwater and pore water ECs, on average should not be more than a factor of 3.

4.4 Formation factor measurements in the laboratory

The laboratory work was performed by Geovista AB. The work was carried out between 2004-12-10 and 2005-04-01. Formation factors were obtained on 38 rock samples taken from the bore core of KLX04. The sample length was, in general, 3 cm. The obtained formation factors are tabulated in Appendix A1.

4.5 Nonconformities

None

5 Results

5.1 Laboratory formation factor

The formation factors obtained in the laboratory are tabulated in Appendix A1 for KLX04. The 38 laboratory formation factors obtained in KLX04 were treated statistically. By using the normal-score method, as described in /15/, to determine the likelihood that a set of data is normally distributed, the mean value and standard deviation of the logarithm ($\log_{10}$) of the formation factors could be determined. Figure 5-1 shows the distribution of the laboratory formation factors obtained in KLX04.

As can be seen in Figure 5-1 the obtained formation factors range over two orders of magnitude and deviates somewhat from the log-normal distribution. However, it should be kept in mind that only a few data points were used. The mean value and standard deviation of the distribution in Figure 5-1 are shown in Table 5-2. The laboratory formation factor log of KLX04 is shown in Appendix C2, as compared to the in-situ formation factor logs.

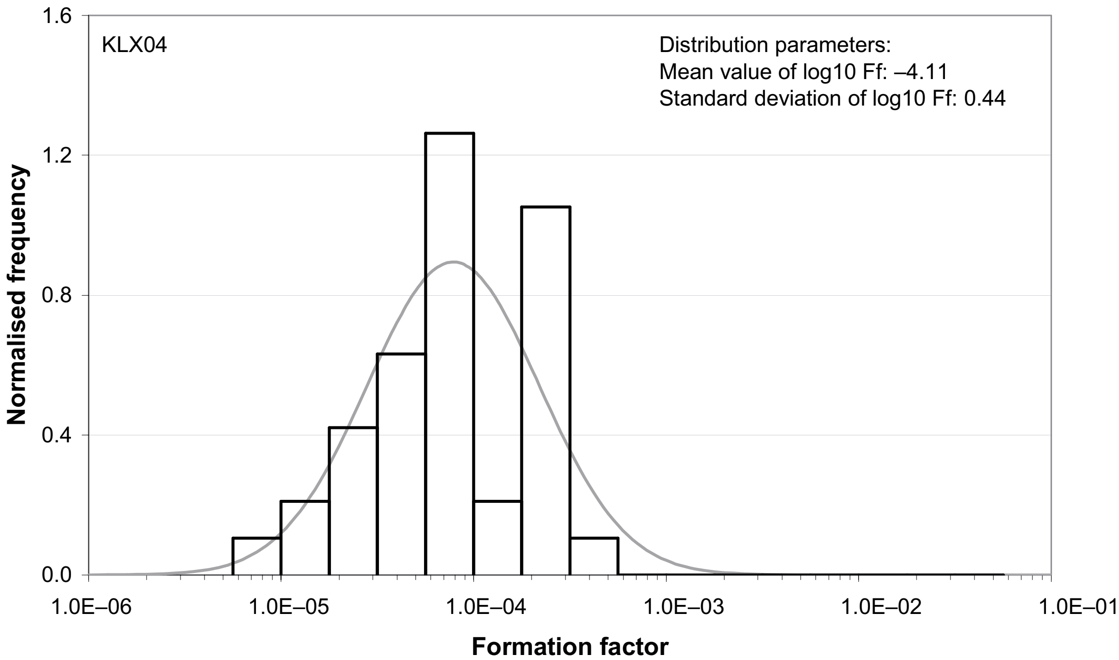


__Figure 5-1.__ Distribution of laboratory formation factors in KLX04.

5.2 In-situ rock matrix formation factor

Figure 5-2 shows the distributions of the rock matrix formation factors obtained in-situ in KLX03 and KLX04. As the groundwater EC was assessed to be below 0.5 S/m above the borehole length 412 m, rock matrix formation factors were only obtained in the lower parts of the boreholes.

The rock matrix formation factors deviates somewhat from the log-normal distribution in KLX03, while they are fairly well log-normally distributed in KLX04. The rock resistivity measurements may have been somewhat affected by the limited measuring range of the in-situ tool, which would give an overestimation of the formation factors in the lower formation factor range. This is more visible for KLX03. The mean values and

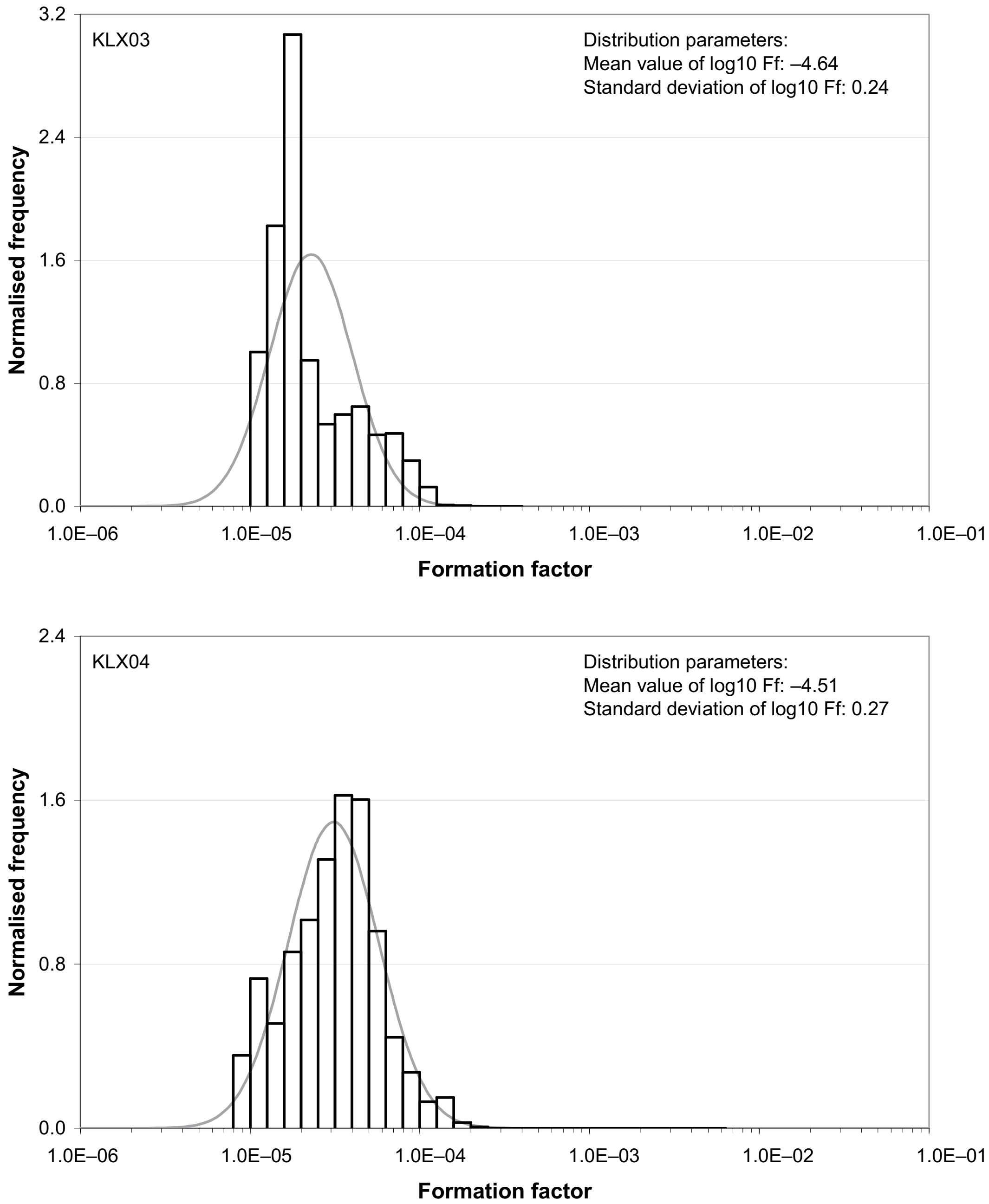
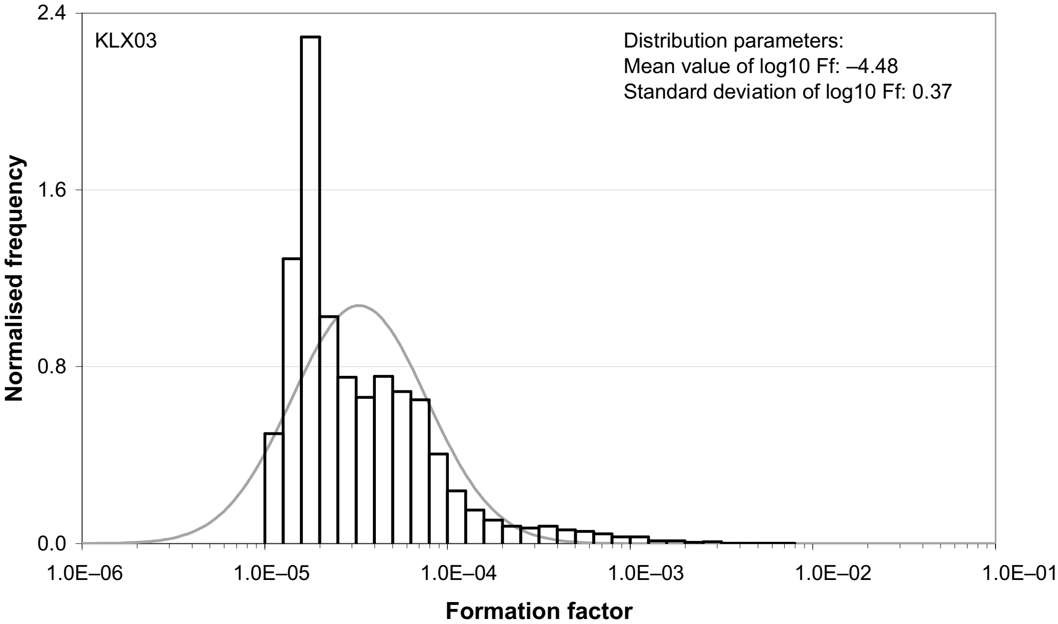


Figure 5-2. *Distributions of in-situ rock matrix formation factors in KLX03 and KLX04.*

standard deviations of the distributions in Figure 5-2 are shown in Table 5-1 and Table 5-2 for KLX03 and KLX04, respectively. The in-situ rock matrix formation factor logs of KLX03 and KLX04 are shown in Appendix C1 and C2, respectively. Rock type specific distributions of the rock matrix formation factor, for the two most abundant rock types, are shown in Appendix D1 and D3 for KLX03 and KLX04, respectively.

5.3 In-situ fractured rock formation factor

Figure 5-3 shows the distributions of the fractured rock formation factors obtained in-situ in KLX03 and KLX04. As the groundwater EC was assessed to be below 0.5 S/m above the borehole length 412 m, fractured rock formation factors were only obtained in the lower parts of the boreholes.



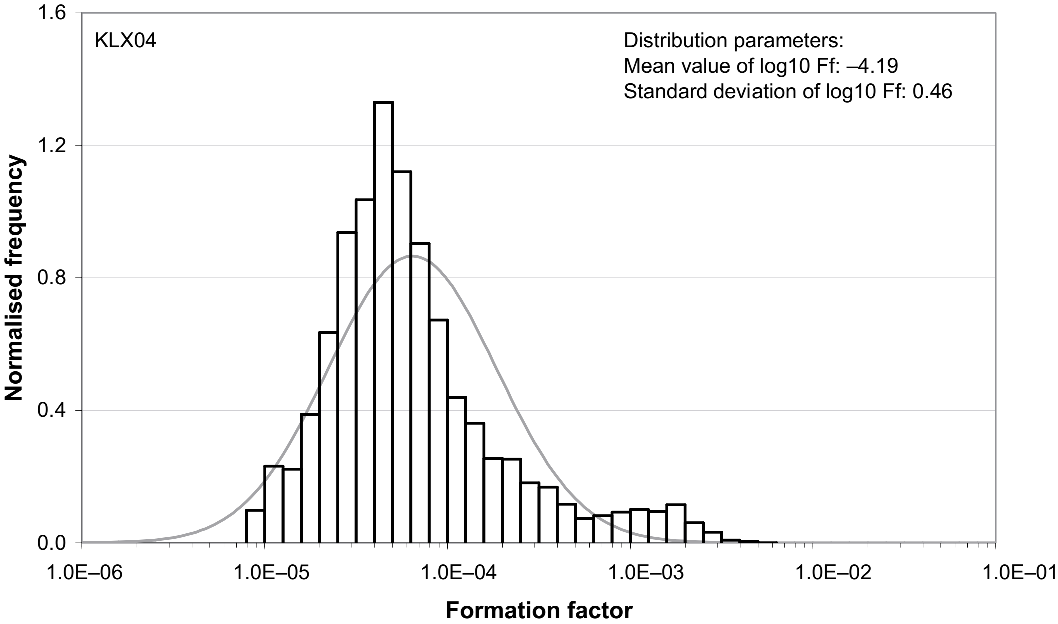


Figure 5-3. *Distributions of in-situ fractured rock formation factors in KLX03 and KLX04.*

Except for the deviations due to the limitations in the in-situ rock resistivity tool, a deviation from the log-normal distribution can be seen in the upper formation factor region. Here the obtained formation factors may have been affected by free water in hydraulically non-conductive fractures. The mean values and standard deviations of the distributions in Figure 5-3 are shown in Table 5-1 and Table 5-2 for KLX03 and KLX04, respectively. The in-situ fractured rock formation factor logs of KLX03 and KLX04 are shown in Appendix C1 and C2, respectively. Rock type specific distributions of the fractured rock formation factor, for the two most abundant rock types, are shown in Appendix D2 and D4 for KLX03 and KLX04, respectively.

5.4 Comparison of formation factors of KLX03

Table 5-1 presents mean values and standard deviations of the log-normal distributions shown in Figures 5-2 and 5-3 for KLX03. In addition, the number of data points obtained and the arithmetic mean values for the different formation factors are shown.

Table 5-1. Distribution parameters and arithmetic mean value of the formation factor, KLX03.

Formation factor	Number of data points	Mean $\log_{10}(F_f)$	Standard deviation $\log_{10}(F_f)$	Arithmetic mean F_f
In-situ Rock matrix F_f	2,193	–4.64	0.243	2.81×10^{-5}
In-situ Fractured rock F_f	5,650	–4.48	0.370	6.75×10^{-5}

It should be noted from Table 5-1 that the fractured rock formation factors are, on average, 2.4 times larger than the rock matrix formation factors.

5.5 Comparison of formation factors of KLX04

Table 5-2 presents mean values and standard deviations of the log-normal distributions shown in Figures 5-1, 5-2, and 5-3 for KLX04. In addition, the number of data points obtained and the arithmetic mean values for the different formation factors are shown.

Table 5-2. Distribution parameters and arithmetic mean value of the formation factor, KLX04.

Formation factor	Number of data points	Mean $\log_{10}(F_f)$	Standard deviation $\log_{10}(F_f)$	Arithmetic mean F_f
Laboratory F_f	38	–4.11	0.446	1.17×10^{-4}
In-situ Rock matrix F_f	1,466	–4.51	0.267	3.74×10^{-5}
In-situ Fractured rock F_f	5,313	–4.19	0.461	1.59×10^{-4}

As indicated in Table 5-2, the laboratory formation factors are, on average, 3.1 times larger than those obtained in-situ. This may be due to the fact that the rock samples are de-stressed in the laboratory. The laboratory samples may also have been mechanically damaged in the drilling process and sample preparation. In both these cases, results obtained in the laboratory may be non-conservative.

An alternative comparison could be made if comparing each laboratory formation factor with the in-situ rock matrix formation factor, obtained at a corresponding depth. Such a comparison is made in Appendix C3. The laboratory formation factor from a certain borehole length was compared to the mean value of the in-situ rock matrix formation factors taken within 0.5 m of that borehole length. In this comparison, the laboratory formation factors are, on average, 2.6 times larger than the rock matrix formation factors.

It should also be noted from Table 5-2 that the fractured rock formation factors are, on average, 4.3 times larger than the rock matrix formation factors.

6 Summary and discussions

The formation factors obtained in KLX03 and KLX04 range from 8.8×10^{-6} to 6.8×10^{-3}. The formation factors of KLX03 deviate somewhat from the log-normal distribution. The formation factors of KLX04 appear to be fairly well distributed according to the log-normal distribution. The obtained in-situ distributions, including the rock type specific distributions, have mean values for $\log_{10}(F_f)$ between –4.73 and –4.11 and standard deviations between 0.12 and 0.51. The arithmetic mean values range between 2.0×10^{-5} and 2.0×10^{-4}. In general, similar distributions were obtained.

The fractured rock formation factors were on average about two to four times larger than the rock matrix formation factors. This indicates that the retention capacity for non-sorbing species due to open, but hydraulically non-conductive, fractures may be larger than that of the intact rock matrix.

Judging from the obtained formation factor histograms, a significant fraction of the obtained in-situ rock resistivities may have been affected by limitations of the in-situ rock resistivity tool. However, these limitations have only minor effects on the obtained arithmetic mean values of the formation factor.

The formation factors obtained in the laboratory were two to three times larger than those obtained in-situ. This indicates either that the porous system is compressed in-situ or that the laboratory samples become mechanically damaged when brought to the laboratory. In both these cases the laboratory results would be non-conservative.

The measurements in KLX03, and especially in KLX04, showed that results from in-situ groundwater chemistry measurements should be used with care. The reason is that the borehole in itself disturbs the groundwater chemistry situation, by functioning as a hydraulic conductor. Shallow non-saline groundwater can quickly be brought to great depths in the borehole.

It would be valuable to obtain groundwater chemistry data that were as undisturbed by the presence of the borehole as possible. In KLX03, samples were taken from the bore core for leaching directly after drilling. Similar leaching experiments are described in /16/. These measurements may give valuable information on the pore water EC profile along the borehole. It is recommended to revisit the obtained formation factors when a more complete understanding of the groundwater chemistry of the area has evolved, to see whether the assumptions made in this report are reasonable.

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Appendix A

Laboratory formation factor for rock samples from KLX04

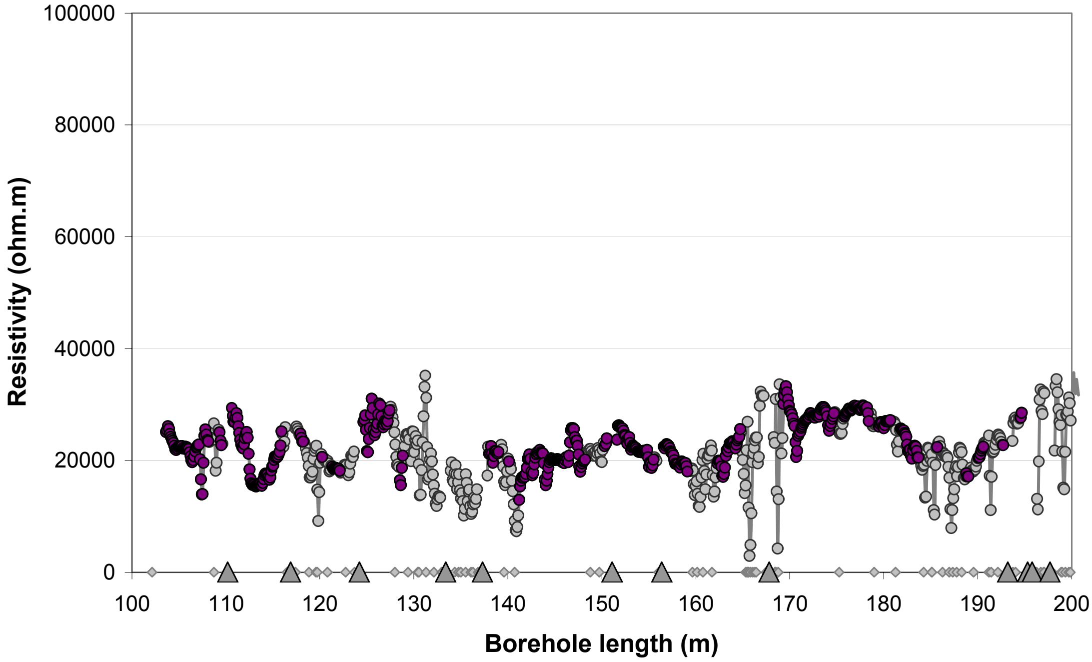
Secup (m)	Formation factor (–)	Secup (m)	Formation factor (–)
110.38	7.62E–05	559.67	6.75E–05
130.53	2.23E–04	579.70	2.38E–04
149.54	7.91E–05	600.35	5.36E–05
169.64	7.50E–05	620.00	5.09E–05
190.60	8.04E–05	640.00	5.76E–05
209.70	5.42E–05	659.79	4.17E–05
236.76	4.28E–04	680.75	1.35E–05
256.70	9.01E–05	700.18	9.71E–06
297.04	1.80E–04	740.38	1.04E–04
317.17	2.46E–04	759.81	6.72E–05
337.53	9.35E–05	780.71	2.92E–05
357.04	3.99E–05	800.00	7.88E–05
380.76	1.95E–04	820.89	1.89E–04
400.70	2.70E–05	840.15	9.58E–05
419.90	3.06E–04	860.19	1.94E–05
460.07	1.37E–05	880.23	2.74E–04
479.80	7.67E–05	889.87	2.91E–04
519.82	3.63E–05	939.75	2.53E–04
539.66	2.04E–05	978.70	1.76E–04

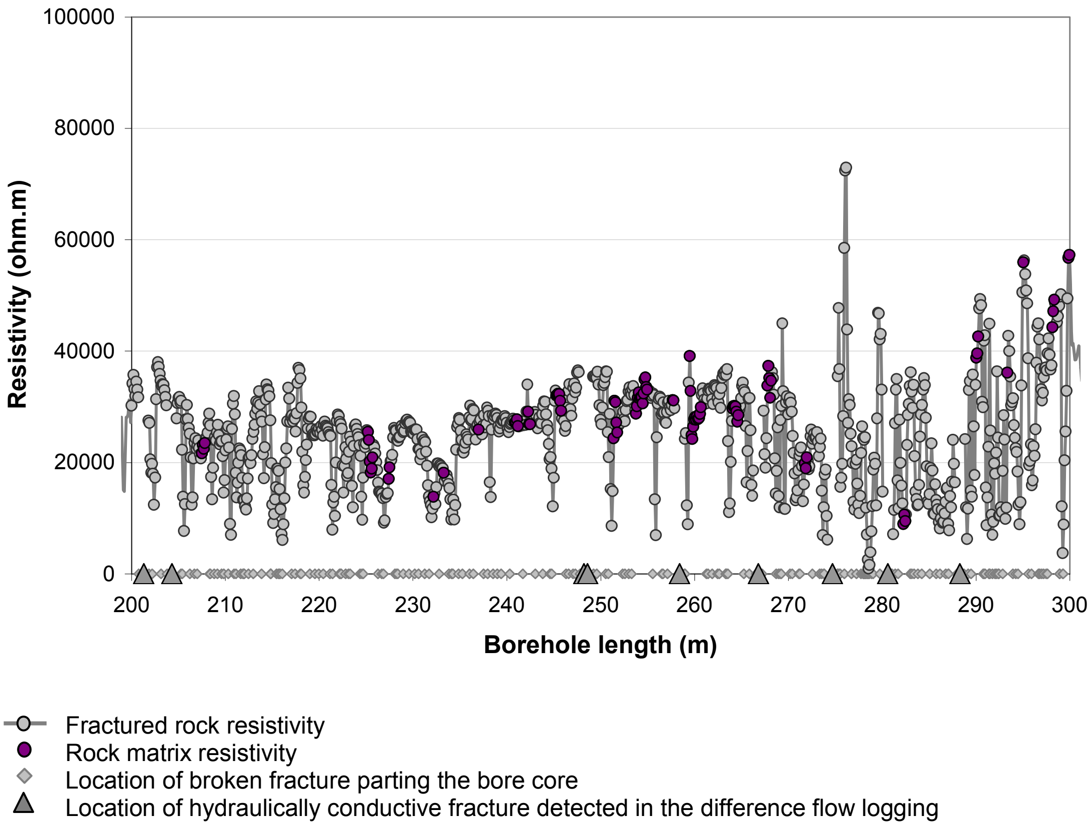
Secup = upper position in borehole for sample.

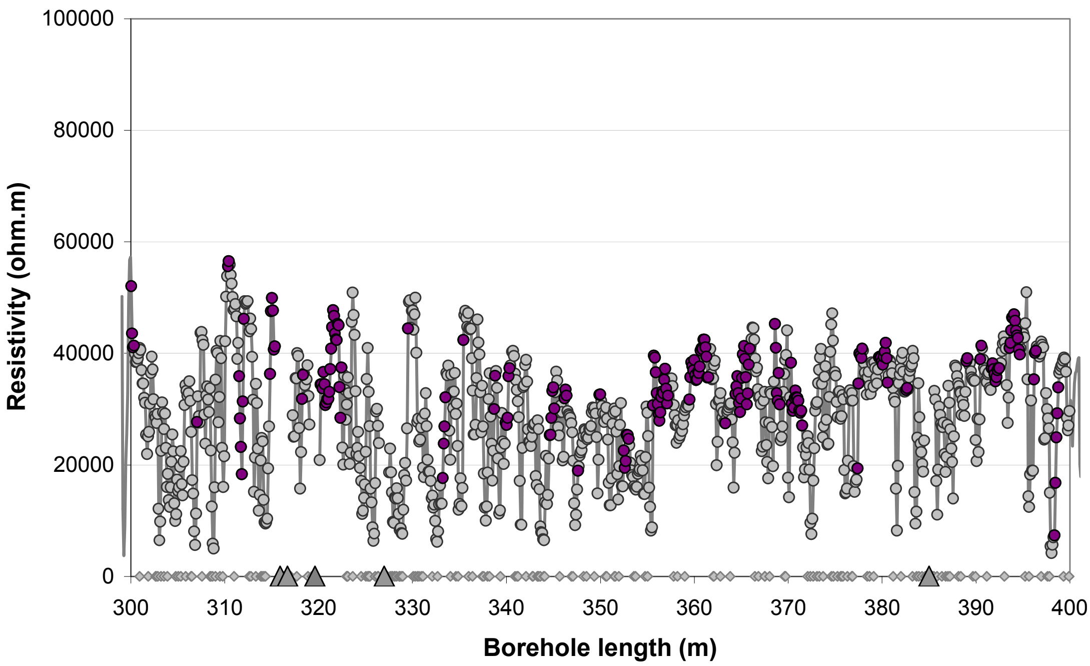
Appendix B

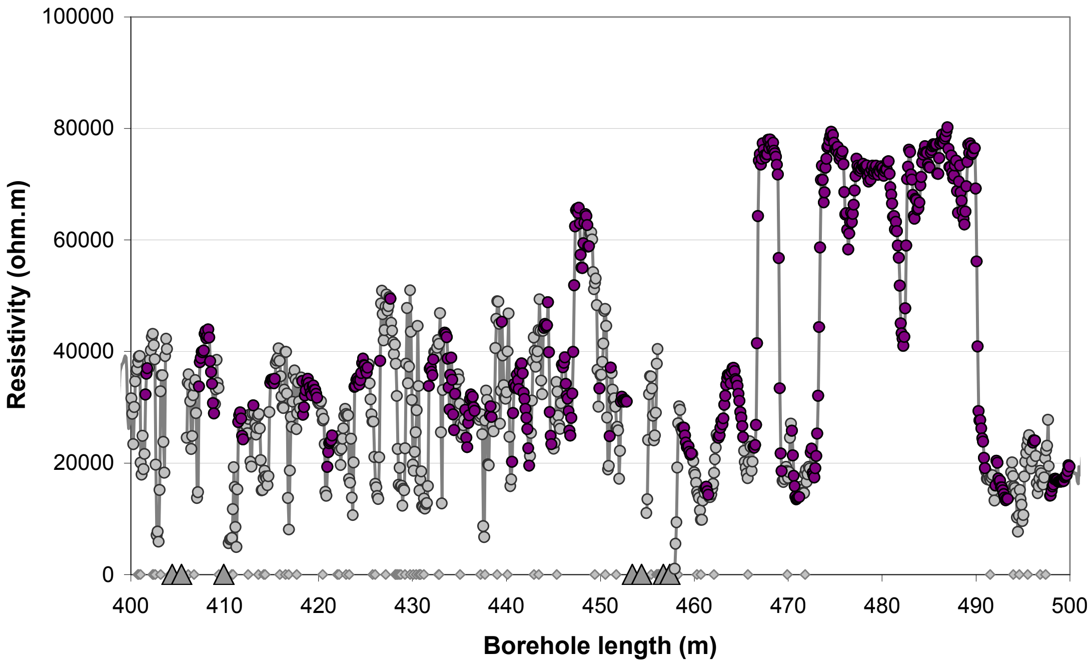
In-situ rock resistivities and fractures KLX03 and KLX04

In-situ rock resistivities and fractures KLX03

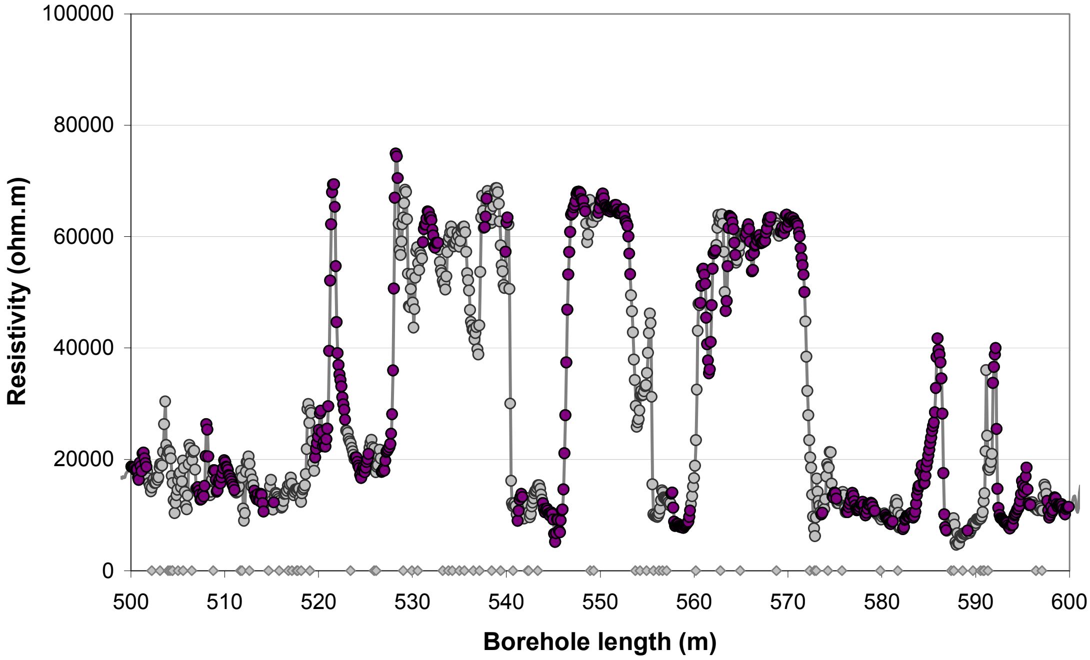




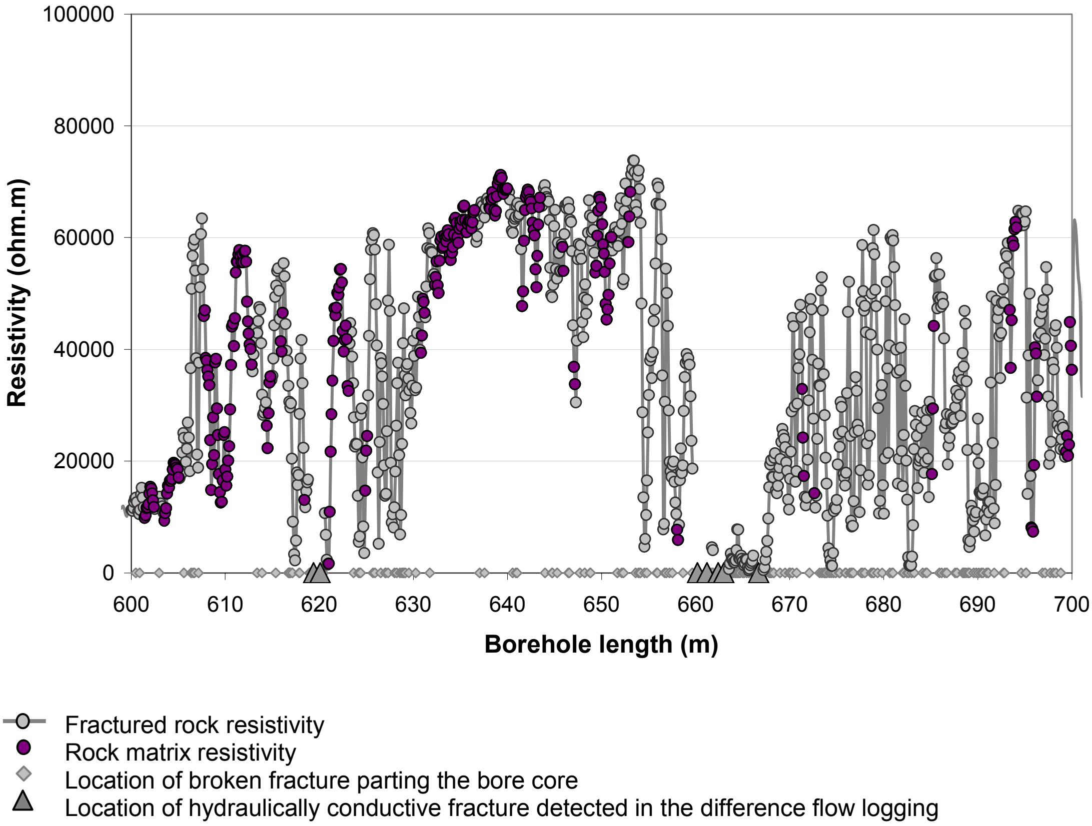




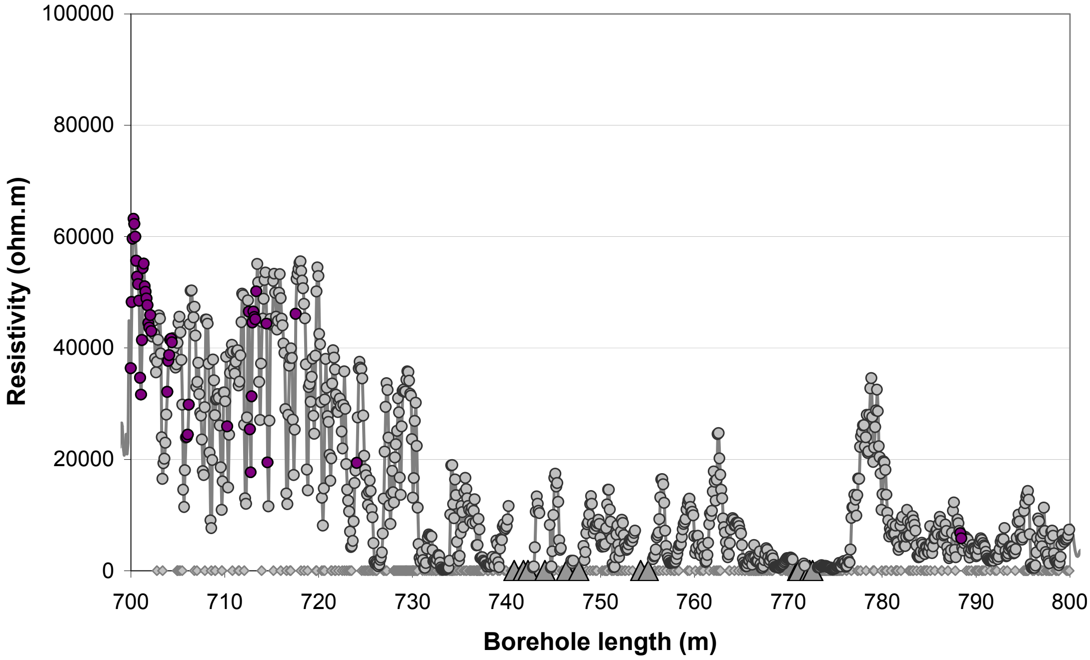
Fractured rock resistivity
Rock matrix resistivity
Location of broken fracture parting the bore core
Location of hydraulically conductive fracture detected in the difference flow logging

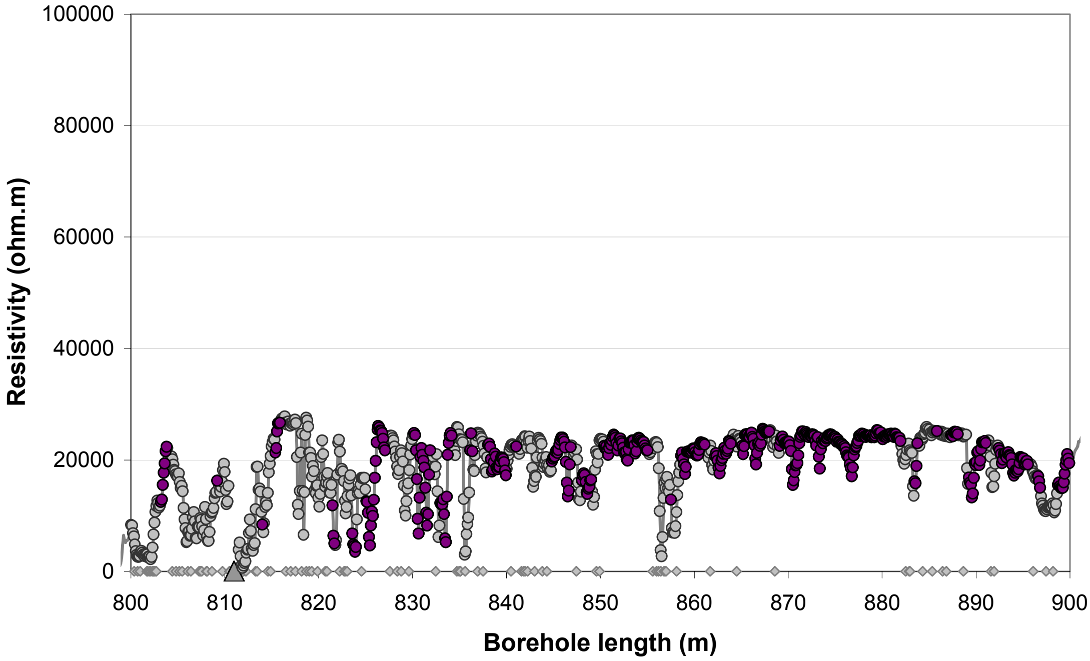


100000
80000
60000
40000
20000
0
Resistivity (ohm.m)
500
510
520
530
540
550
560
570
580
590
600
Borehole length (m)

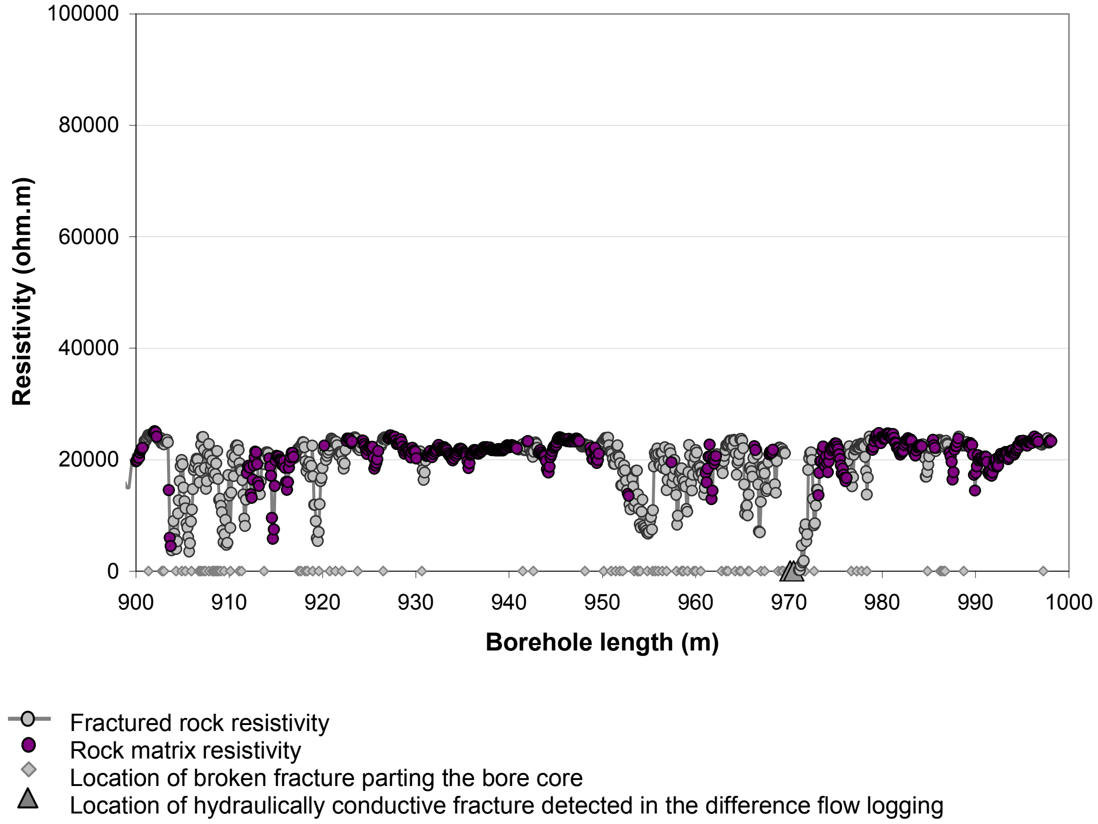


100000
80000
60000
40000
20000
0
Resistivity (ohm.m)
600
610
620
630
640
650
660
670
680
690
700
Borehole length (m)
Fractured rock resistivity
Rock matrix resistivity
Location of broken fracture parting the bore core
Location of hydraulically conductive fracture detected in the difference flow logging



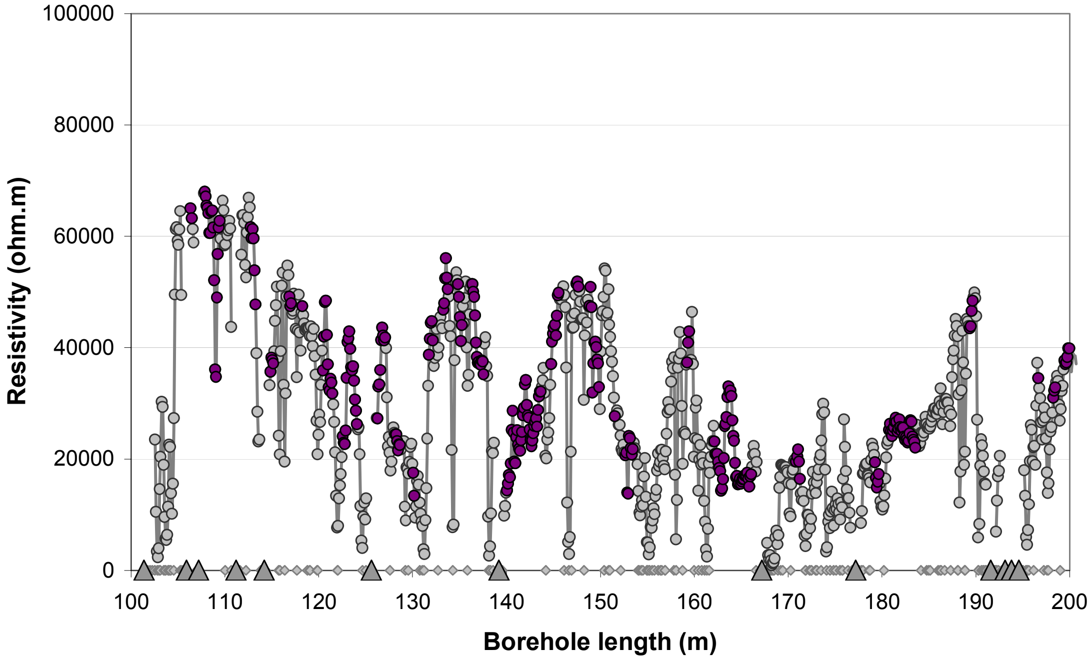


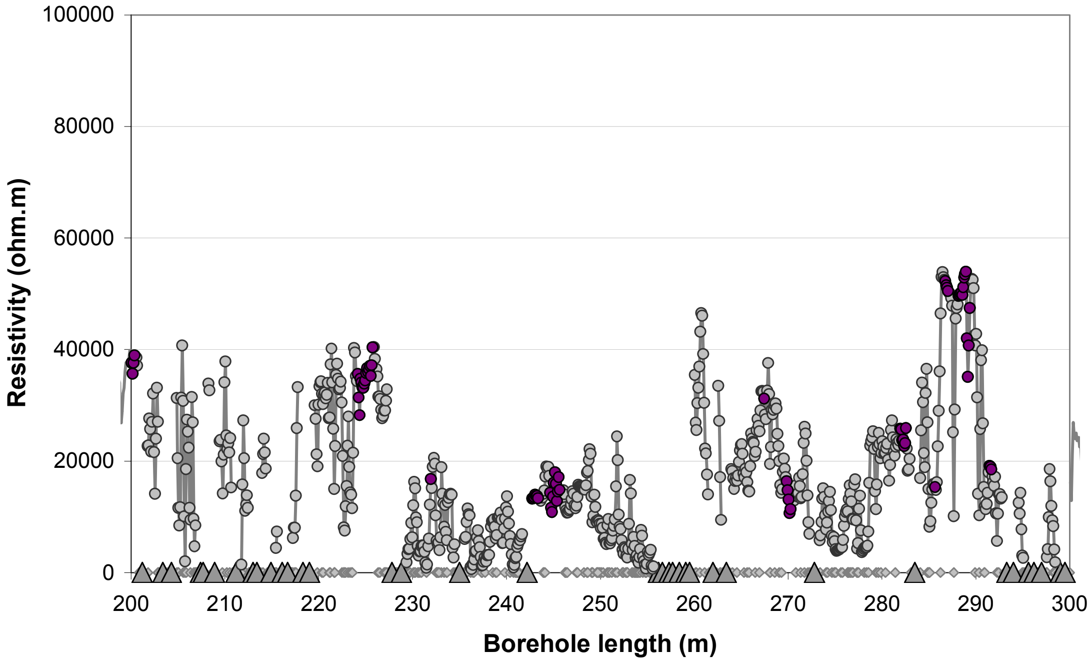
Fractured rock resistivity
Rock matrix resistivity
Location of broken fracture parting the bore core
Location of hydraulically conductive fracture detected in the difference flow logging



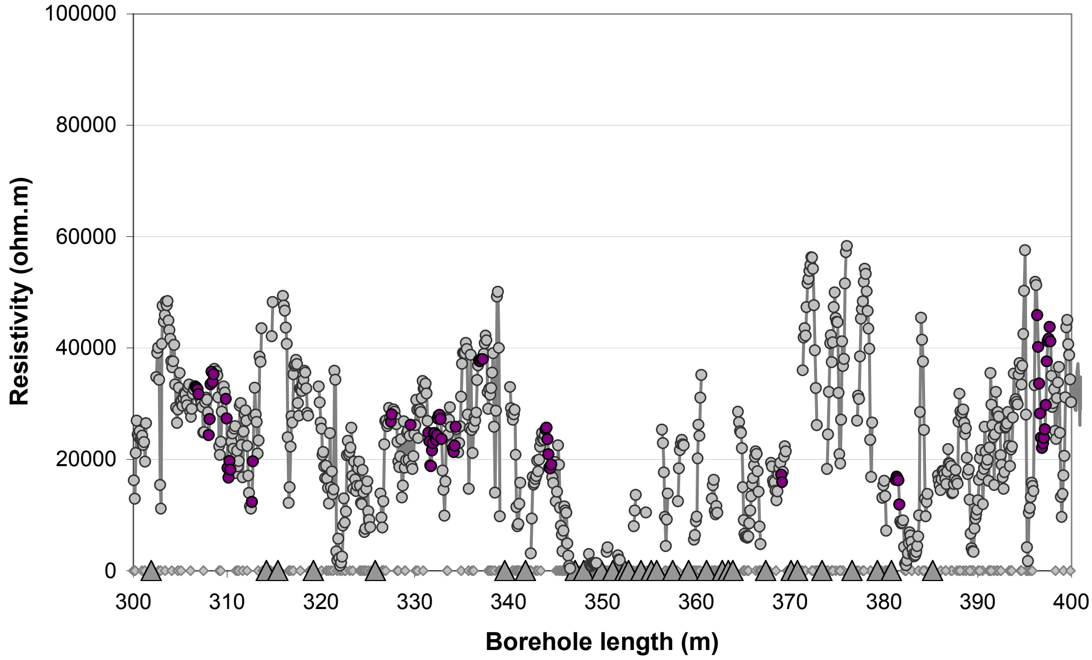
100000
80000
60000
40000
20000
0
Resistivity (ohm.m)
900
910
920
930
940
950
960
970
980
990
1000
Borehole length (m)
Fractured rock resistivity
Rock matrix resistivity
Location of broken fracture parting the bore core
Location of hydraulically conductive fracture detected in the difference flow logging

In-situ rock resistivities and fractures KLX04

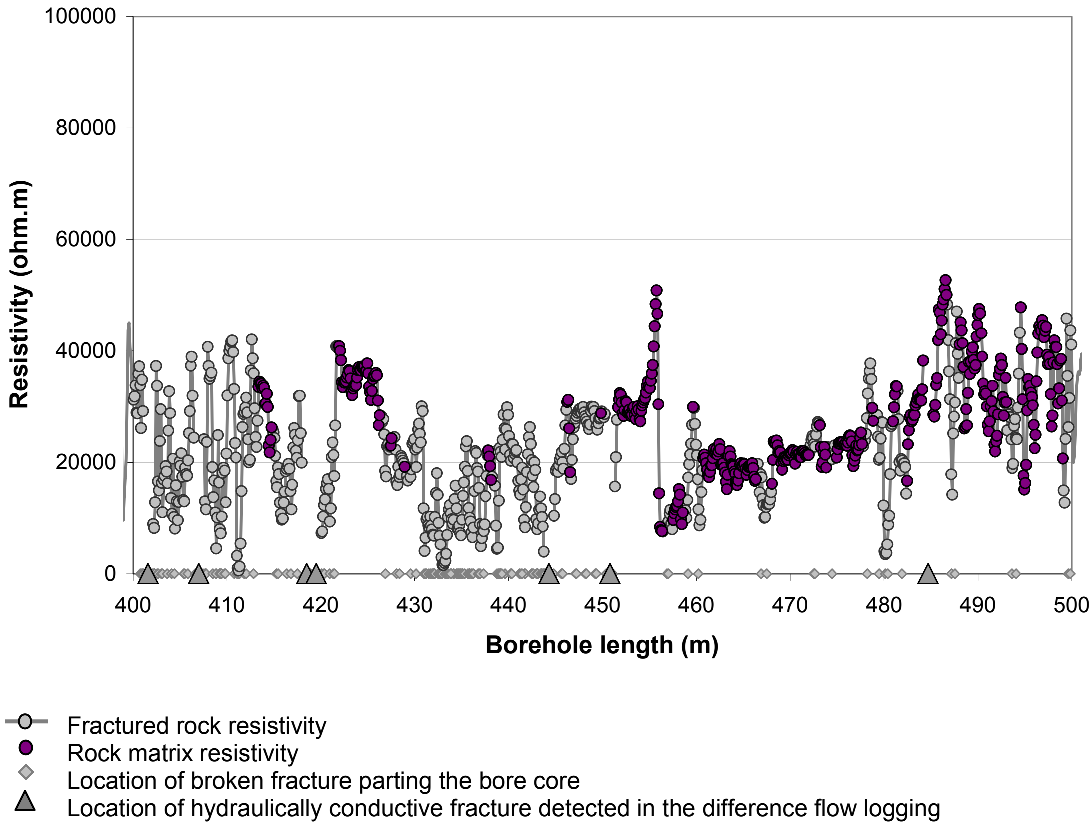




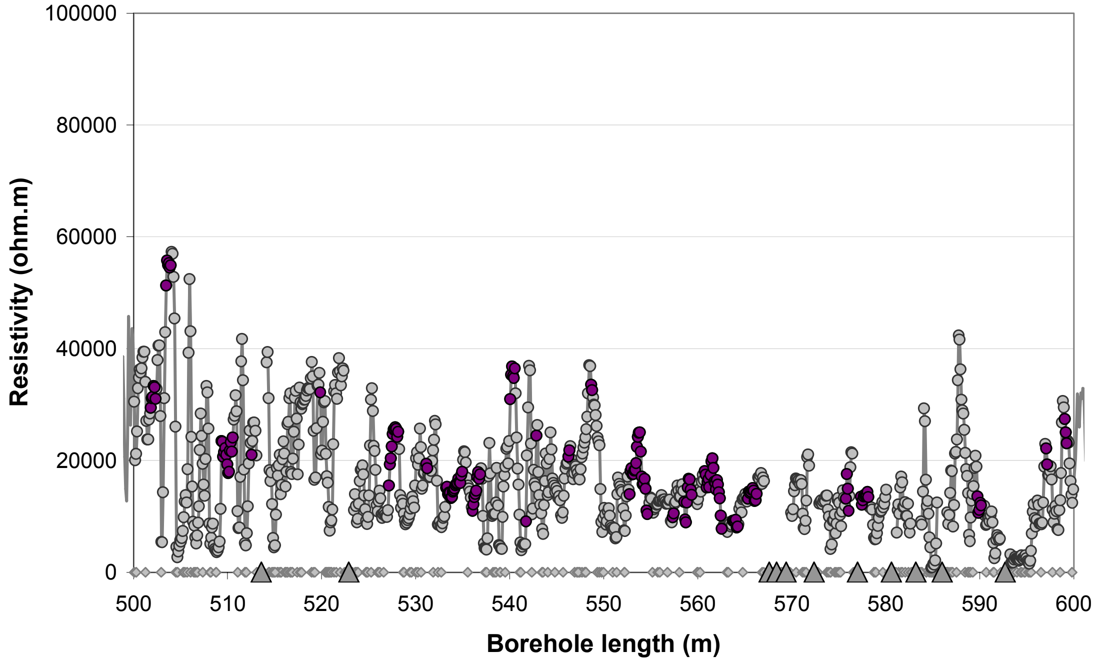
Fractured rock resistivity
Rock matrix resistivity
Location of broken fracture parting the bore core
Location of hydraulically conductive fracture detected in the difference flow logging

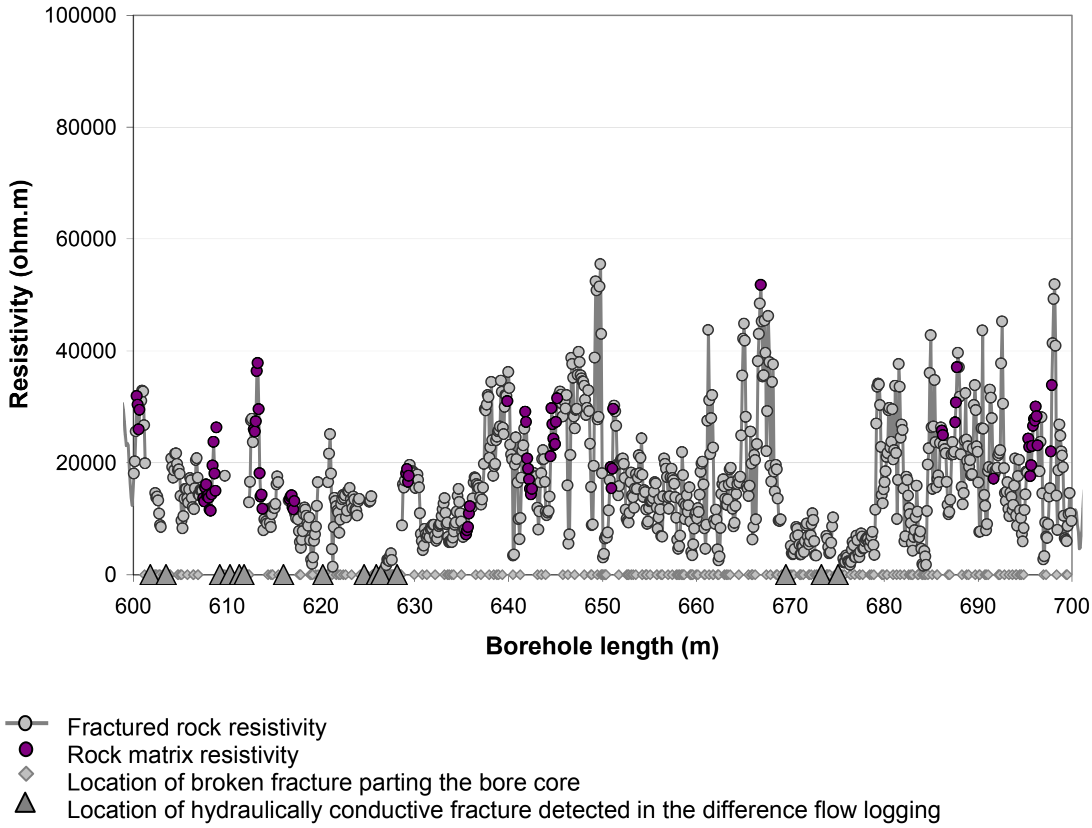


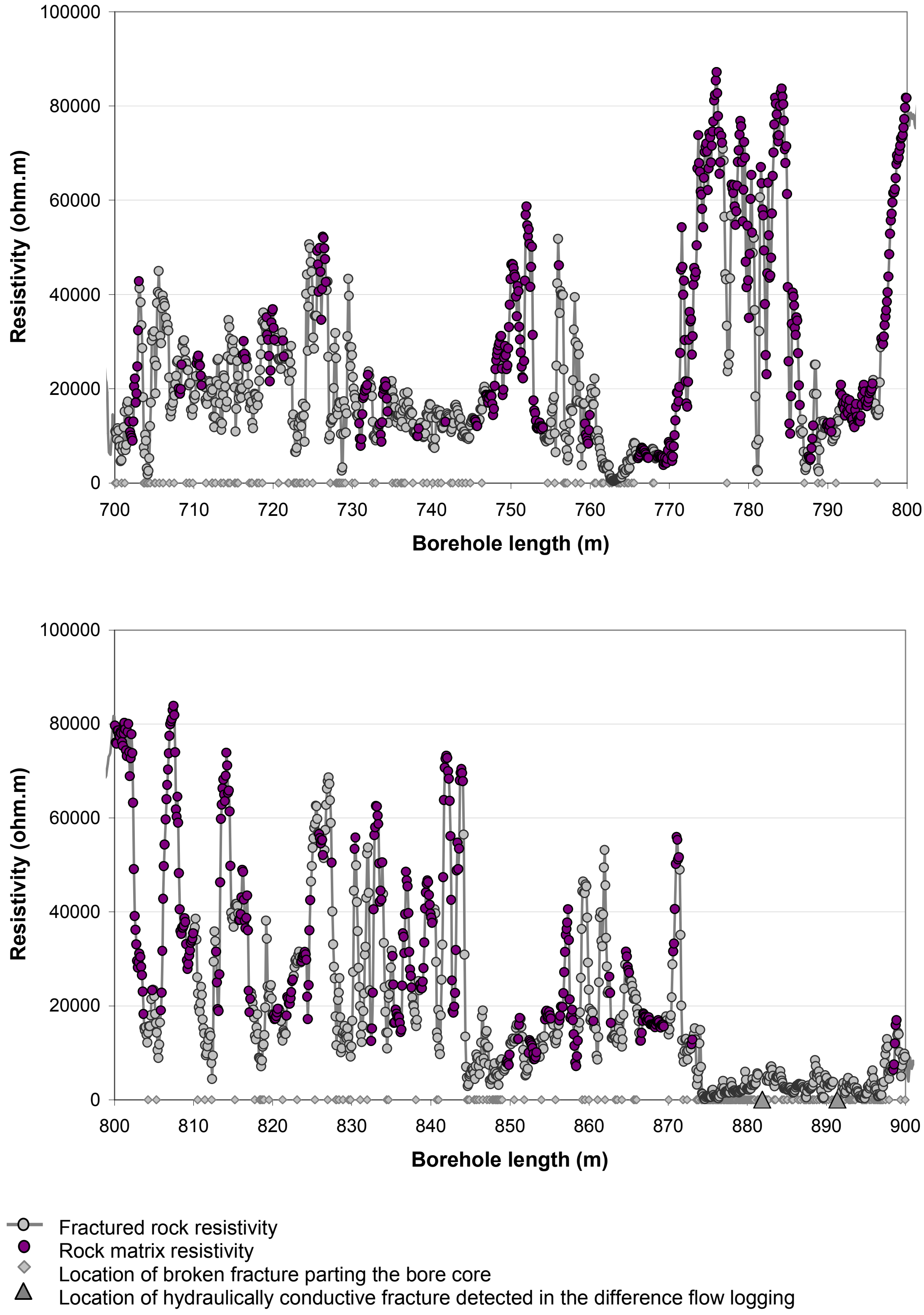
Resistivity (ohm.m)
Borehole length (m)



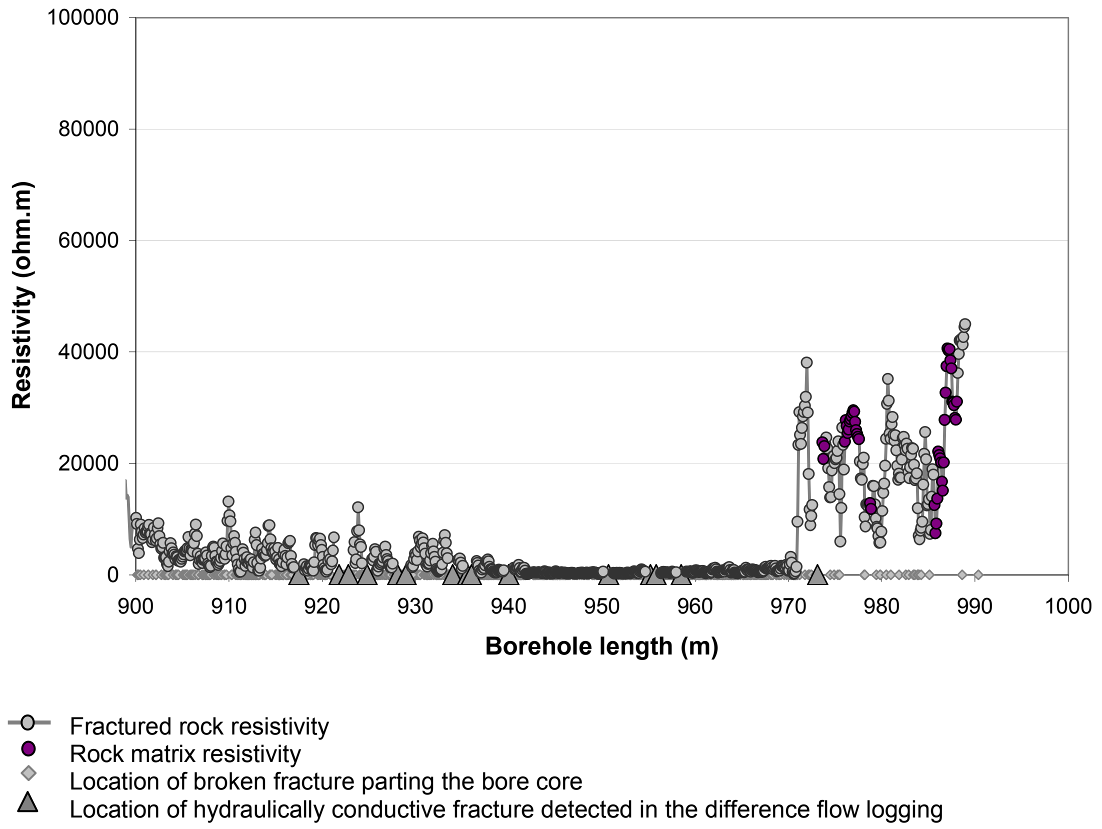
Resistivity (ohm.m)
Borehole length (m)
Fractured rock resistivity
Rock matrix resistivity
Location of broken fracture parting the bore core
Location of hydraulically conductive fracture detected in the difference flow logging


100000
80000
60000
40000
20000
0
Resistivity (ohm.m)
500
510
520
530
540
550
560
570
580
590
600
Borehole length (m)


100000
80000
60000
40000
20000
0
Resistivity (ohm.m)
600
610
620
630
640
650
660
670
680
690
700
Borehole length (m)
Fractured rock resistivity
Rock matrix resistivity
Location of broken fracture parting the bore core
Location of hydraulically conductive fracture detected in the difference flow logging

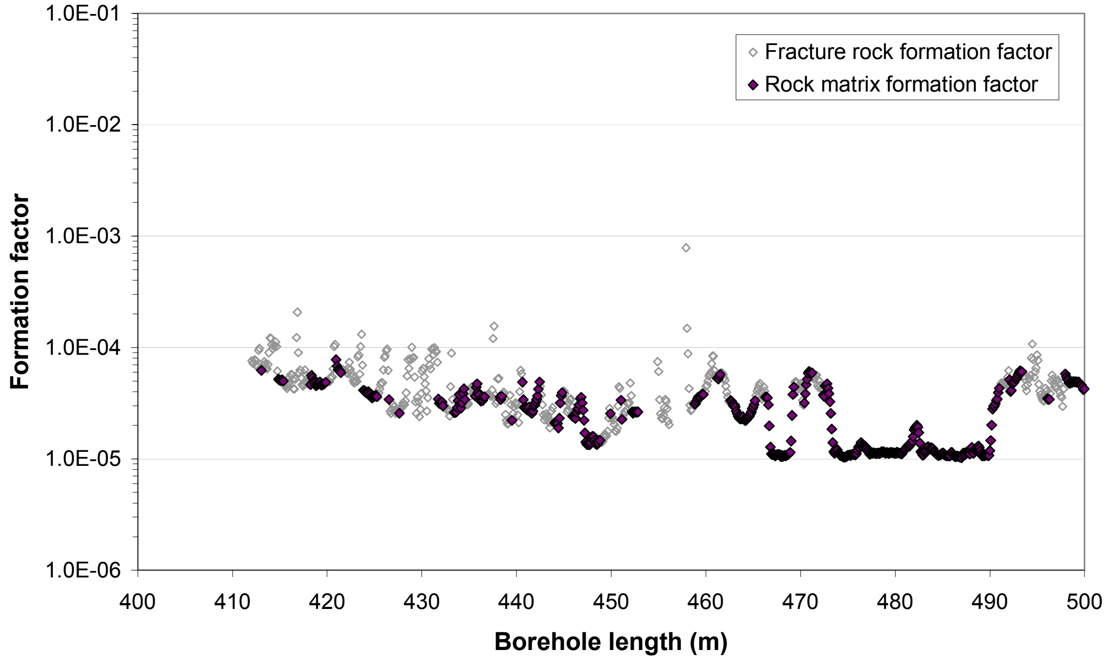


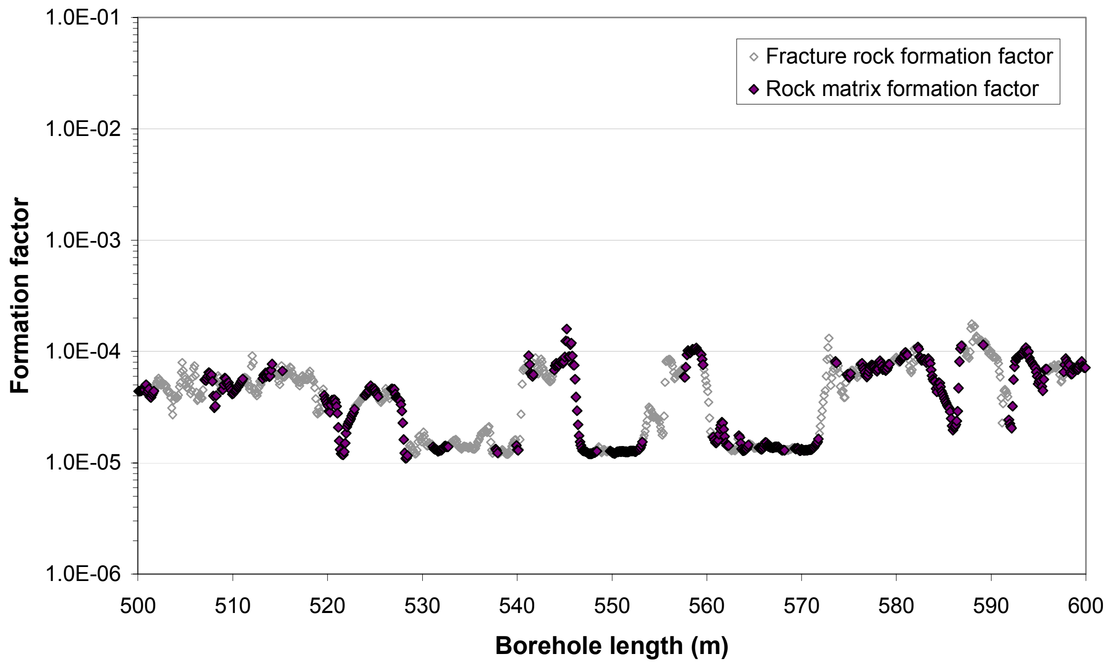
100000
80000
60000
40000
20000
0
Resistivity (ohm.m)
700
710
720
730
740
750
760
770
780
790
800
Borehole length (m)
800
810
820
830
840
850
860
870
880
890
900
Borehole length (m)
Fractured rock resistivity
Rock matrix resistivity
Location of broken fracture parting the bore core
Location of hydraulically conductive fracture detected in the difference flow logging

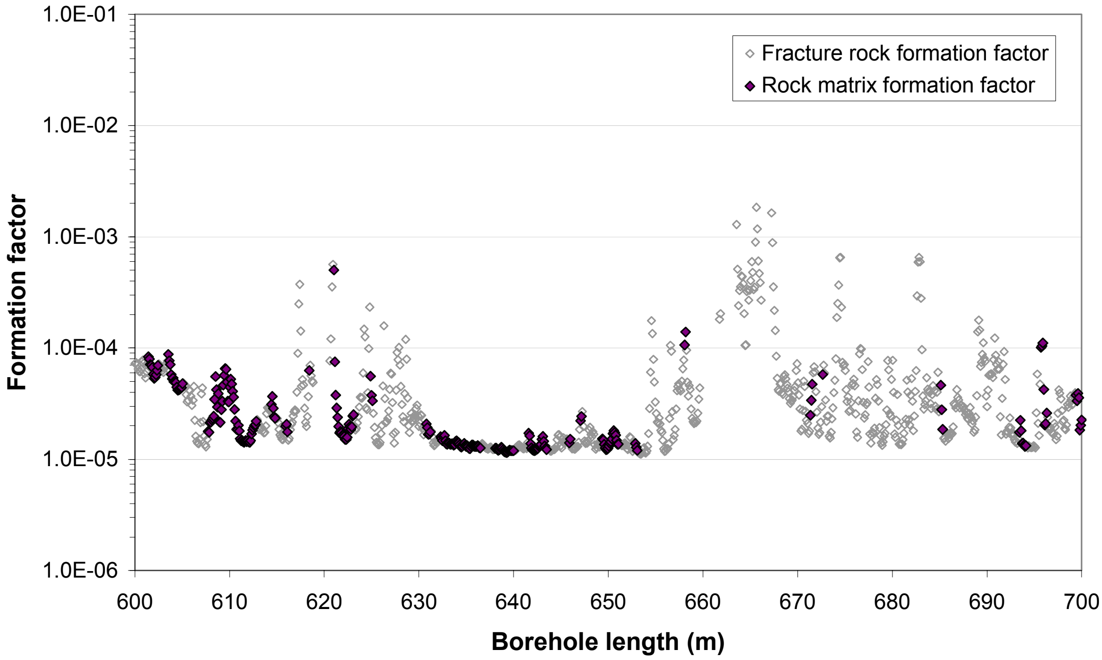

100000
80000
60000
40000
20000
0
Resistivity (ohm.m)
900
910
920
930
940
950
960
970
980
990
1000
Borehole length (m)
Fractured rock resistivity
Rock matrix resistivity
Location of broken fracture parting the bore core
Location of hydraulically conductive fracture detected in the difference flow logging

Appendix C

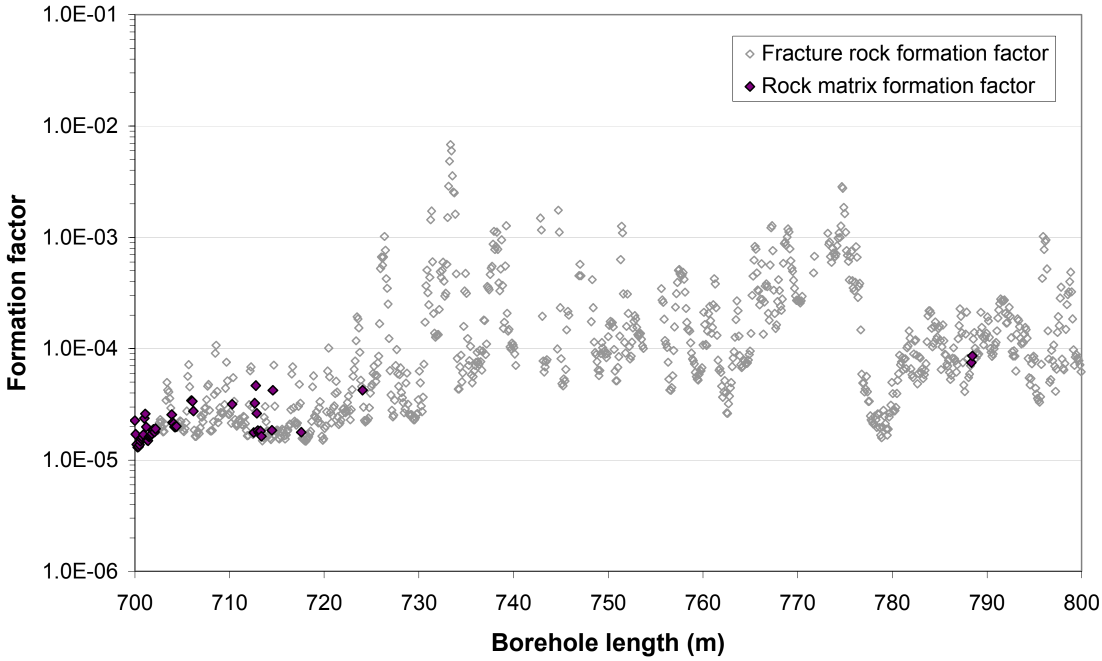
In-situ formation factors KLX03



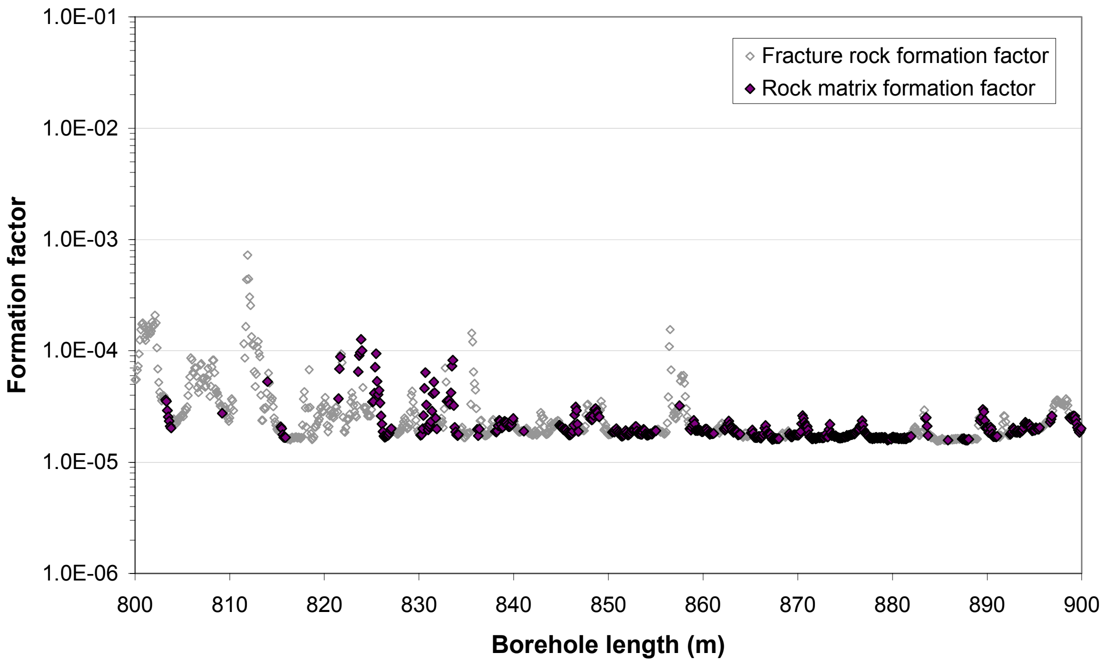


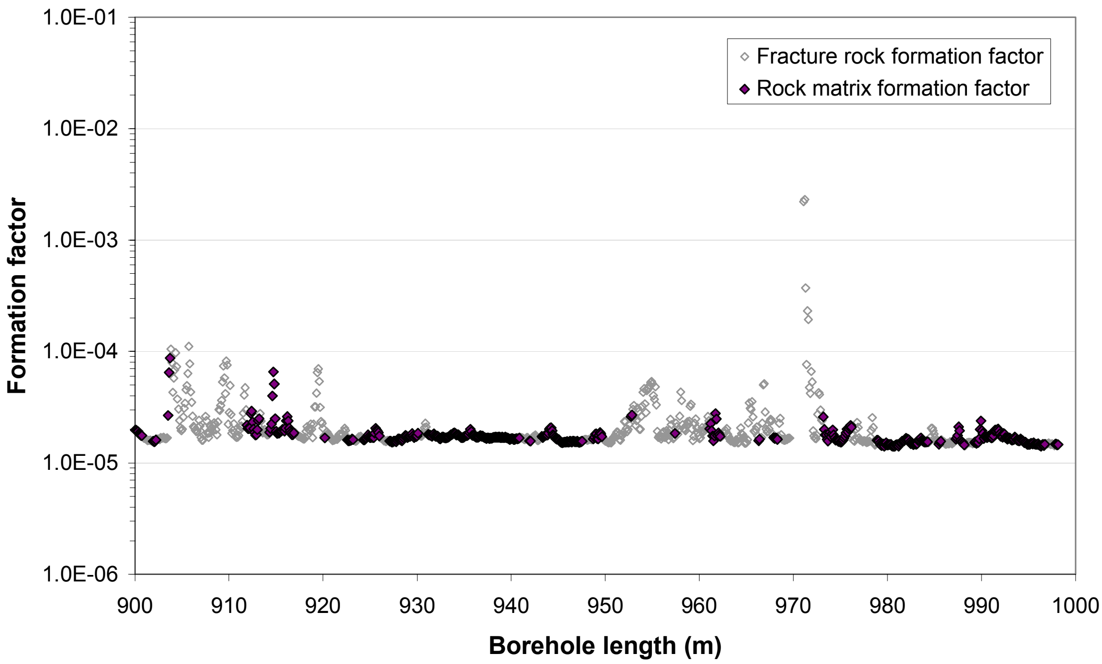


1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
Formation factor
600
610
620
630
640
650
660
670
680
690
700
Borehole length (m)
Fracture rock formation factor
Rock matrix formation factor

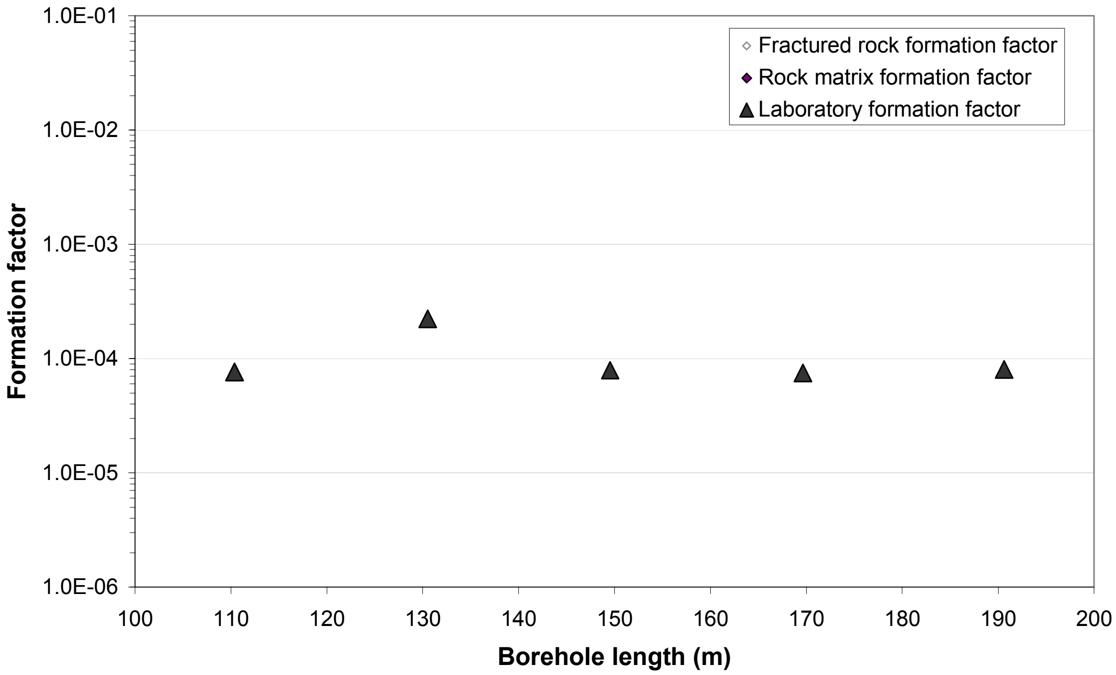


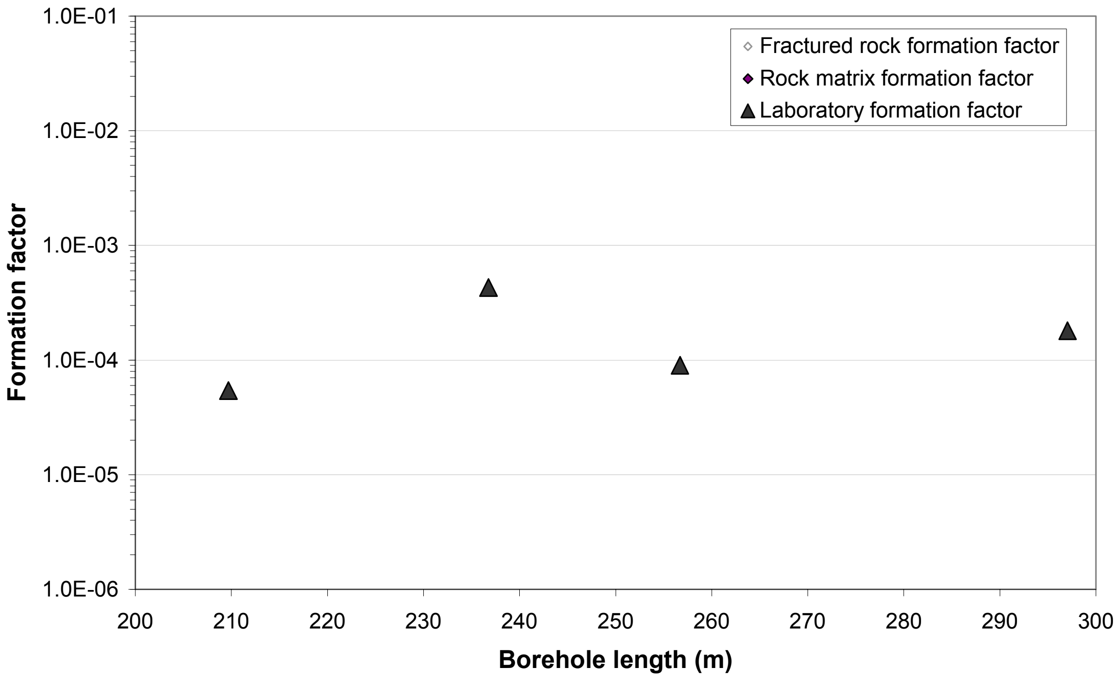
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
Formation factor
700
710
720
730
740
750
760
770
780
790
800
Borehole length (m)
Fracture rock formation factor
Rock matrix formation factor

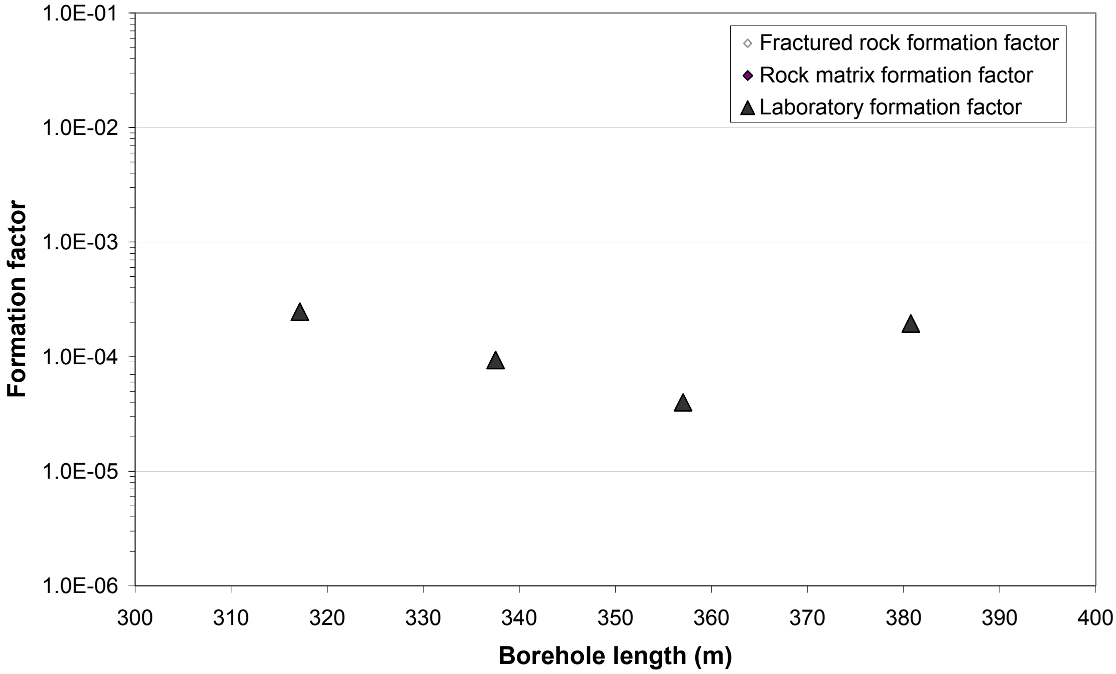

Fracture rock formation factor
Rock matrix formation factor
Formation factor
Borehole length (m)
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
800
810
820
830
840
850
860
870
880
890
900


Fracture rock formation factor
Rock matrix formation factor
Formation factor
Borehole length (m)
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
900
910
920
930
940
950
960
970
980
990
1000

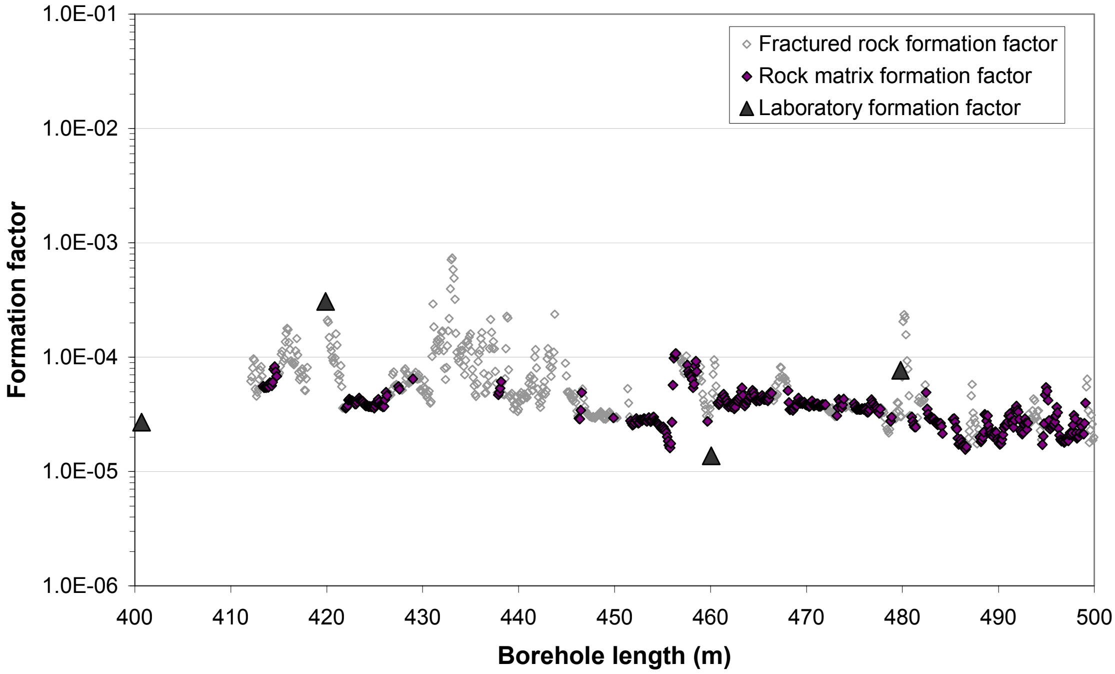
In-situ and laboratory formation factors KLX04



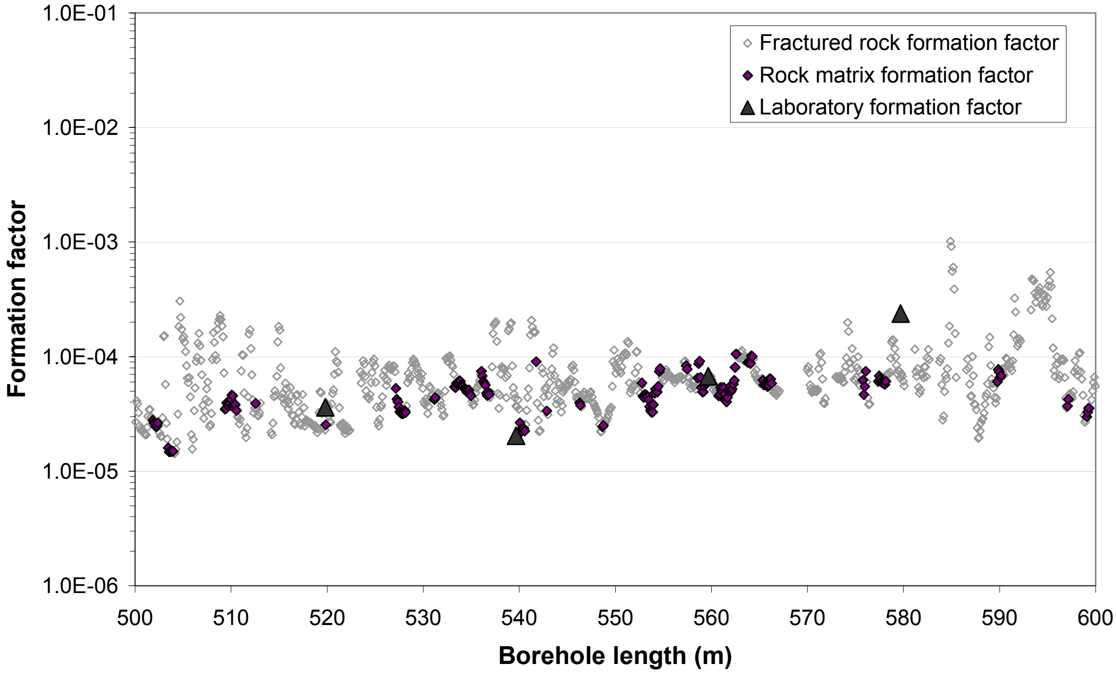




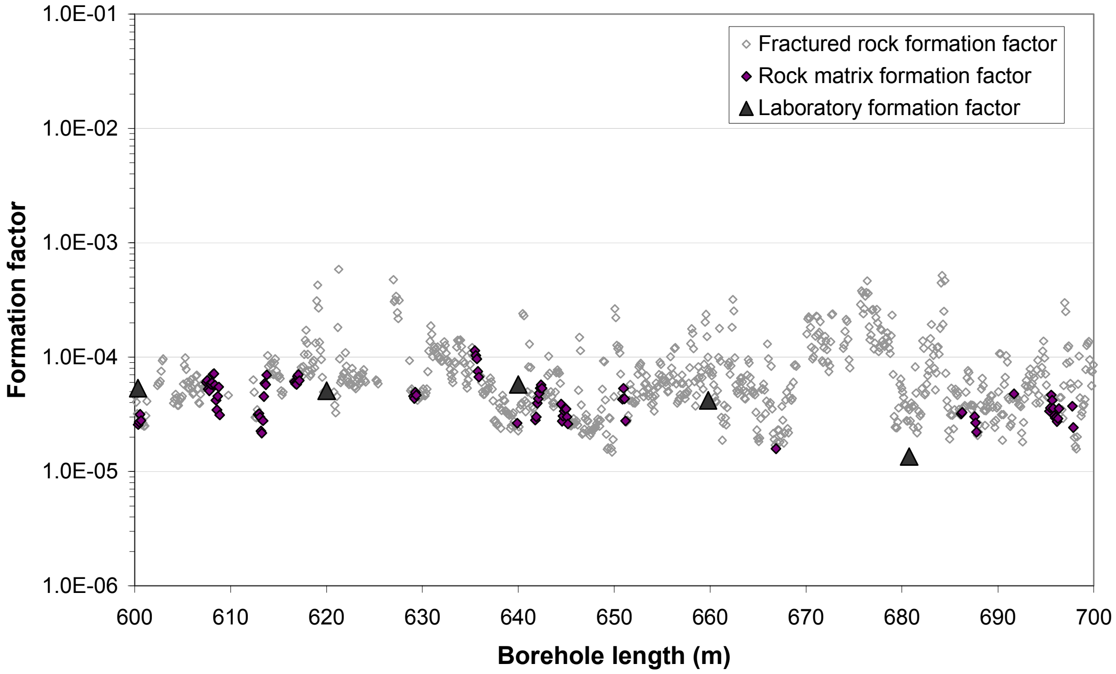
Fractured rock formation factor
Rock matrix formation factor
Laboratory formation factor
Formation factor
Borehole length (m)
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
300
310
320
330
340
350
360
370
380
390
400



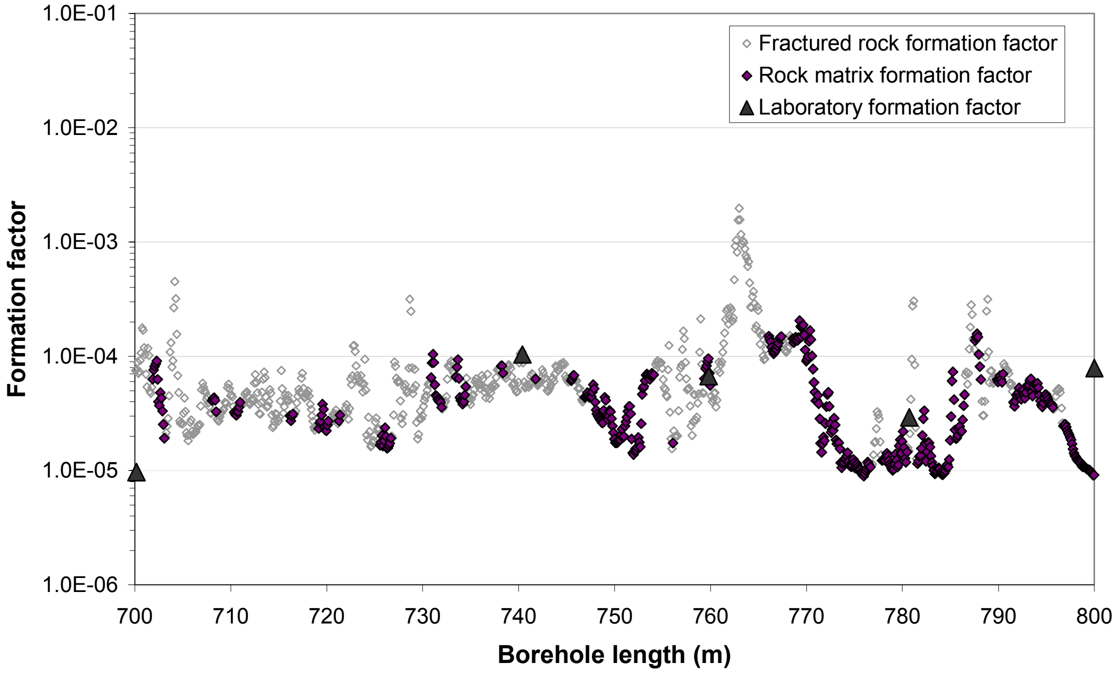
Fractured rock formation factor
Rock matrix formation factor
Laboratory formation factor
Formation factor
Borehole length (m)
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
400
410
420
430
440
450
460
470
480
490
500

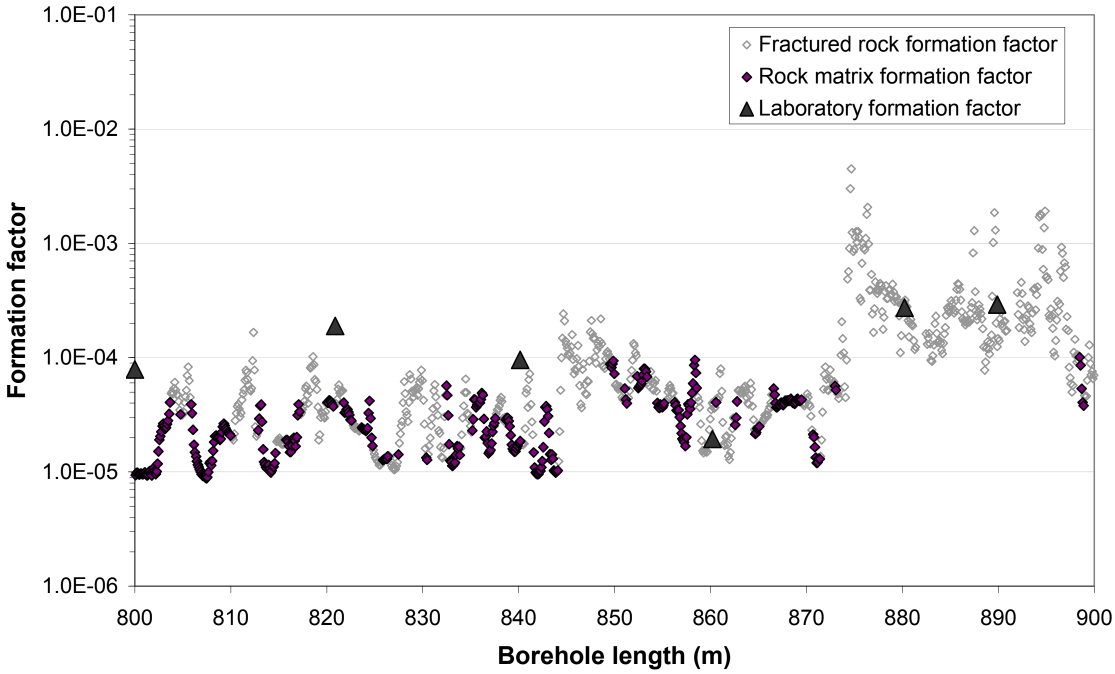


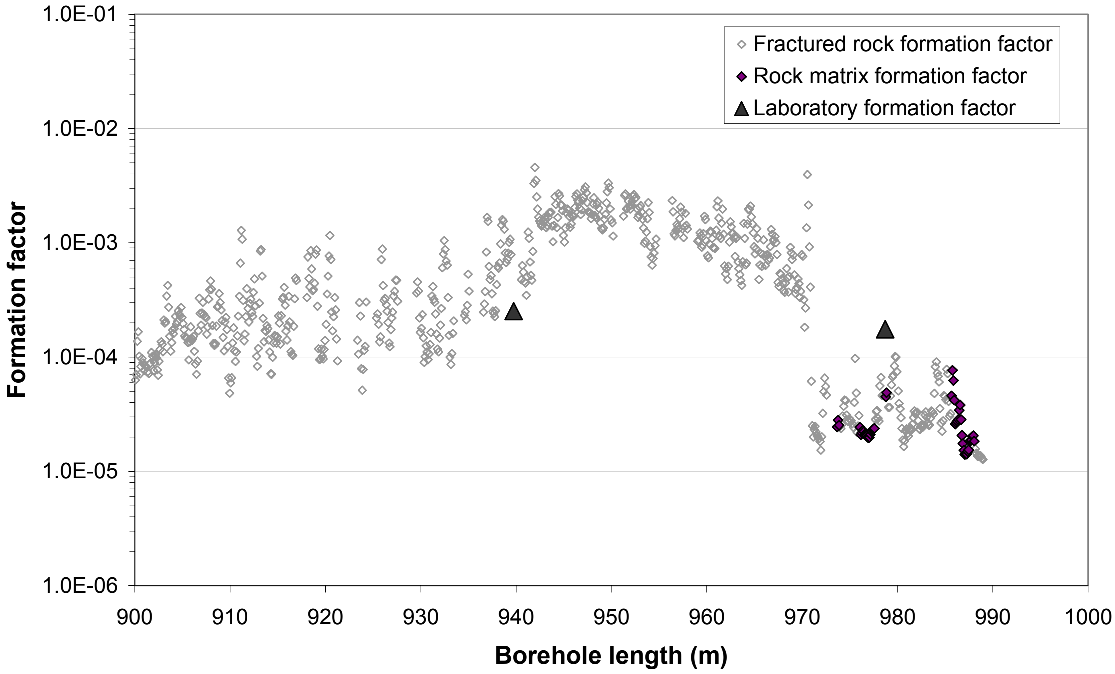
Fractured rock formation factor
Rock matrix formation factor
Laboratory formation factor
Formation factor
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
500
510
520
530
540
550
560
570
580
590
600
Borehole length (m)



Fractured rock formation factor
Rock matrix formation factor
Laboratory formation factor
Formation factor
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
600
610
620
630
640
650
660
670
680
690
700
Borehole length (m)


1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
Formation factor
700
710
720
730
740
750
760
770
780
790
800
Borehole length (m)
Fractured rock formation factor
Rock matrix formation factor
Laboratory formation factor


1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
Formation factor
800
810
820
830
840
850
860
870
880
890
900
Borehole length (m)
Fractured rock formation factor
Rock matrix formation factor
Laboratory formation factor


Fractured rock formation factor
Rock matrix formation factor
Laboratory formation factor
Formation factor
Borehole length (m)
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
900
910
920
930
940
950
960
970
980
990
1000

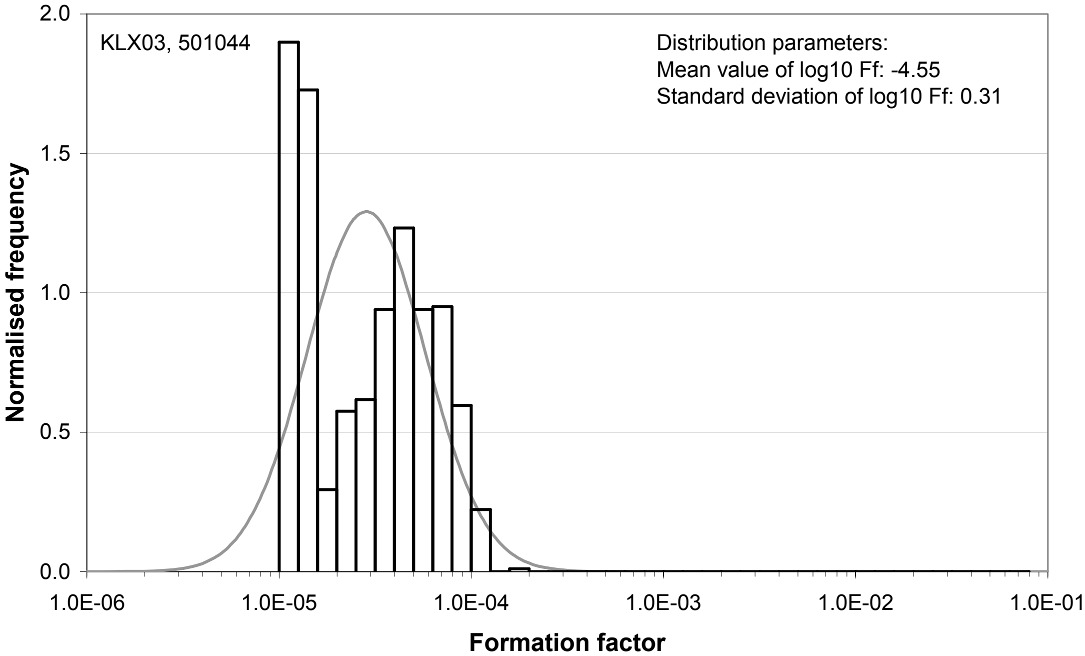
Comparison of laboratory and in-situ formation factors KLX04

Borehole length (m)	Laboratory F_f	Rock matrix F_f	Ratio Laboratory/ Rock matrix F_f
110.38	7.62E–05		
130.53	2.23E–04		
149.54	7.91E–05		
169.64	7.50E–05		
190.60	8.04E–05		
209.70	5.42E–05		
236.76	4.28E–04		
256.70	9.01E–05		
297.04	1.80E–04		
317.17	2.46E–04		
337.53	9.35E–05		
357.04	3.99E–05		
380.76	1.95E–04		
400.70	2.70E–05		
419.90	3.06E–04		
460.07	1.37E–05	2.74E–5	0.50
479.80	7.67E–05		
519.82	3.63E–05	2.55E–5	1.42
539.66	2.04E–05	2.65E–5	0.77
559.67	6.75E–05	5.47E–7	1.23
579.70	2.38E–04		
600.35	5.36E–05	2.80E–5	1.91
620.00	5.09E–05		
640.00	5.76E–05	2.64E–5	2.18
659.79	4.17E–05		
680.75	1.35E–05		
700.18	9.71E–06		
740.38	1.04E–04		
759.81	6.72E–05	8.01E–5	0.84
780.71	2.92E–05	1.30E–5	2.25
800.00	7.88E–05	9.52E–6	8.28
820.89	1.89E–04	3.89E–5	4.86
840.15	9.58E–05	1.71E–5	5.60
860.19	1.94E–05	4.06E–5	0.48
880.23	2.74E–04		
889.87	2.91E–04		
939.75	2.53E–04		
978.70	1.76E–04	4.69E–5	3.75

Laboratory F_f = Formation factor obtained in the laboratory.
Rock matrix F_f = Mean value of in-situ rock matrix formation factors from within 0.5 m of the borehole length.

Appendix D

Rock type specific distributions of rock matrix formation factors KLX03

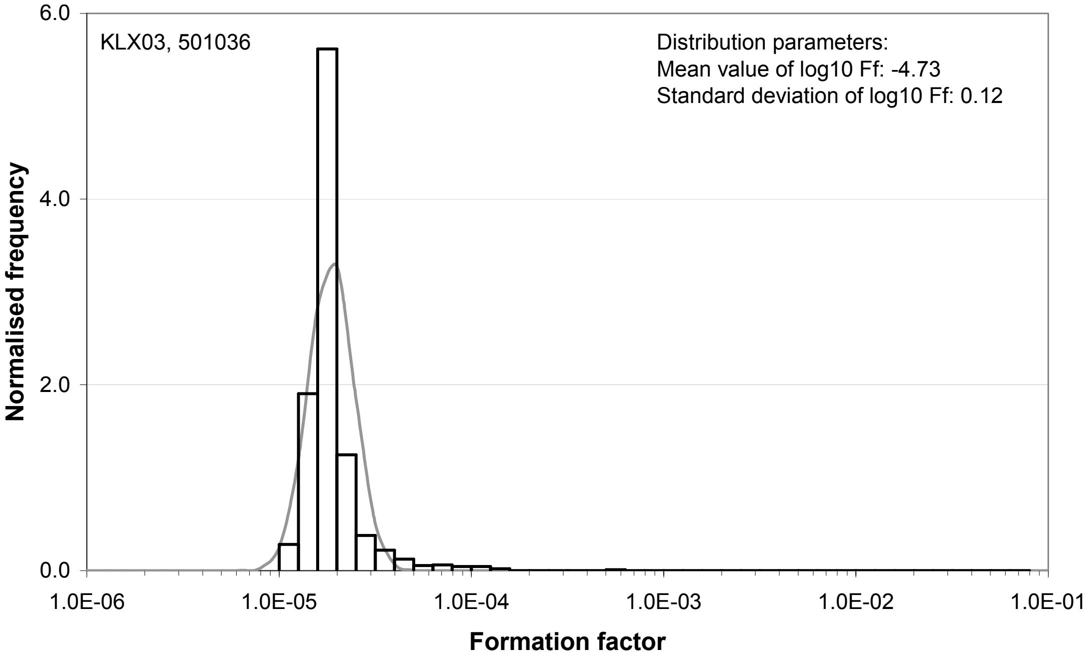


Rock type: 501044 = Granite to quartz monzodiorite, generally porphyritic

Length of core: 507 m (57%)

Number of data points: 990

Arithmetic mean: 3.70E-05



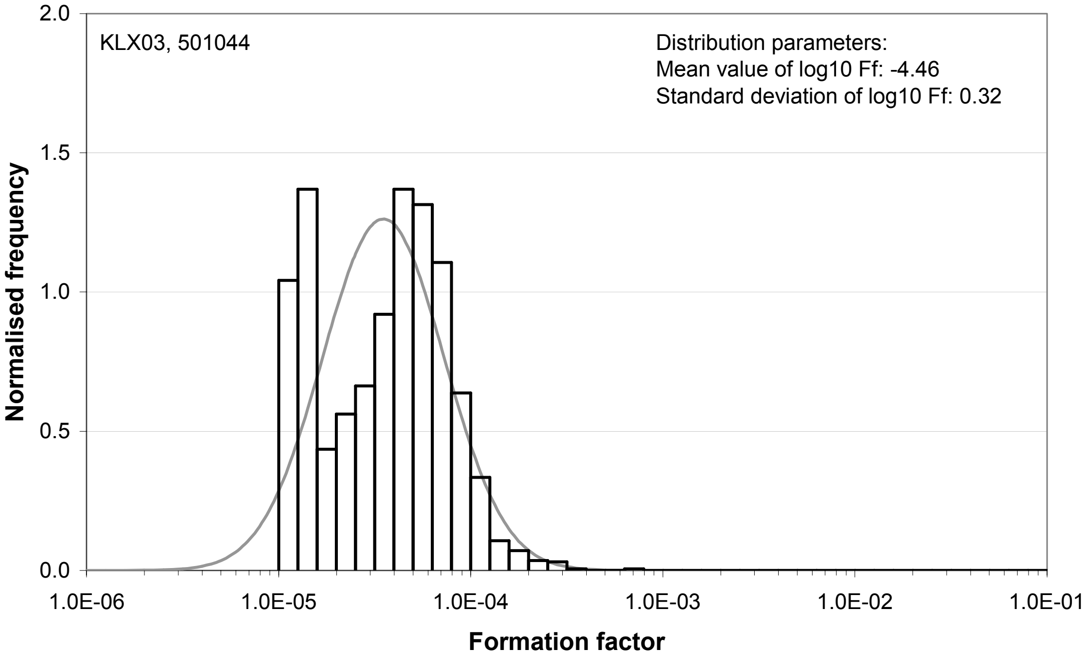
Rock type: 501036 = Quartz monzonite to monzodiorite, equigranular to weakly porphyritic

Length of core: 333 m (37%)

Number of data points: 1138

Arithmetic mean: 2.03E-05

Rock type specific distributions of fractured rock formation factors KLX03

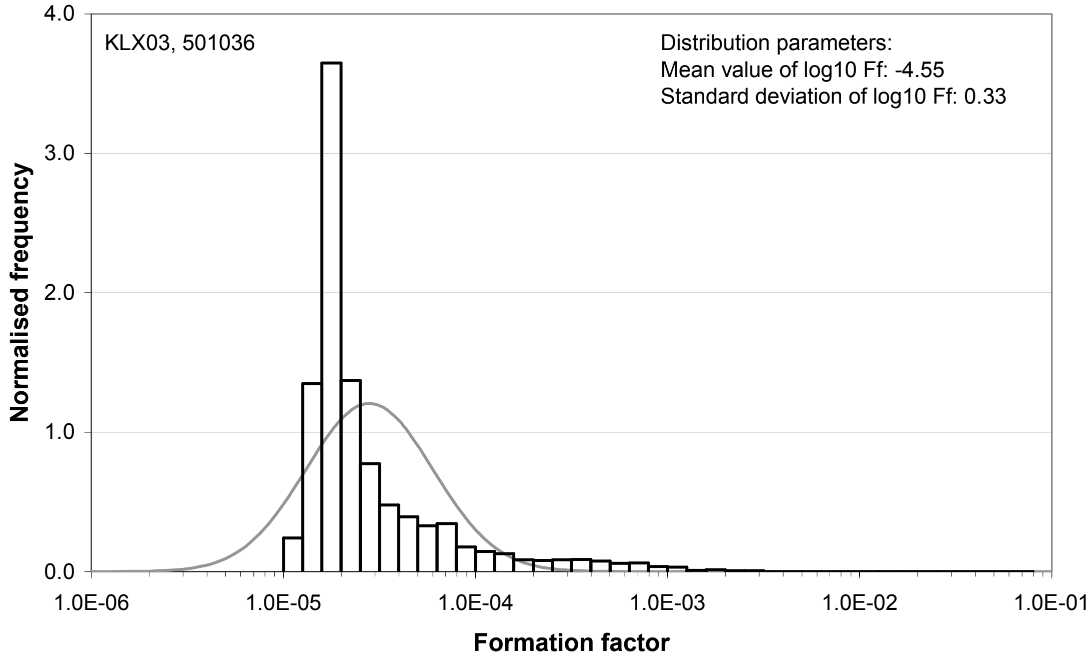


Rock type: 501044 = Granite to quartz monzodiorite, generally porphyritic

Length of core: 507 m (57%)

Number of data points: 1979

Arithmetic mean: 4.59E-05



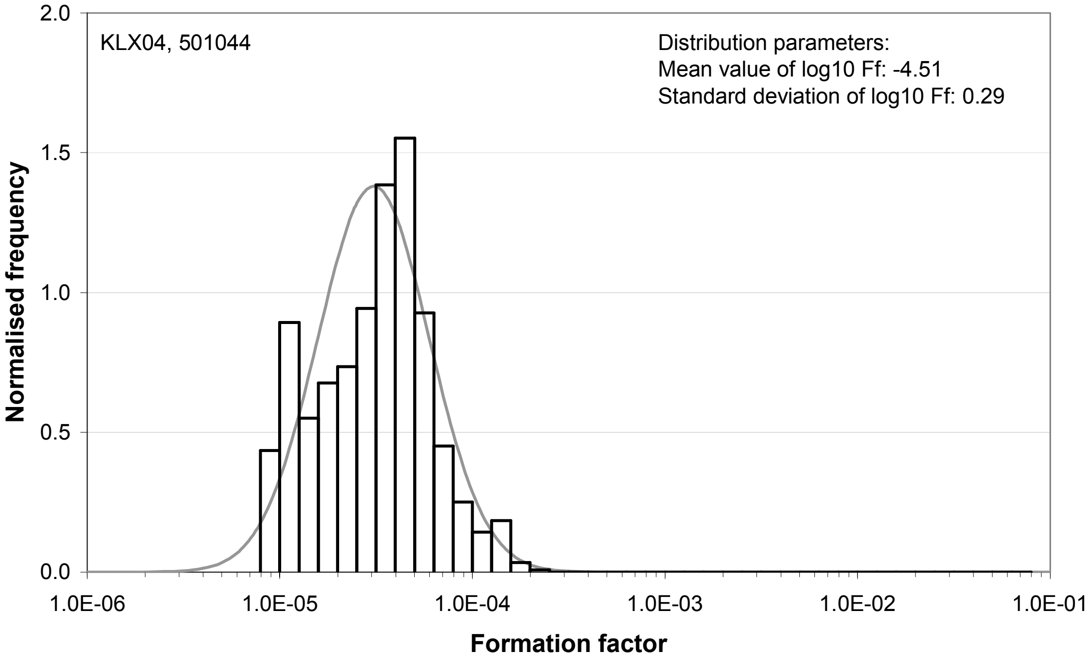
Rock type: 501036 = Quartz monzonite to monzodiorite, equigranular to weakly porphyritic

Length of core: 333 m (37%)

Number of data points: 3208

Arithmetic mean: 5.94E-05

Rock type specific distributions of rock matrix formation factors KLX04

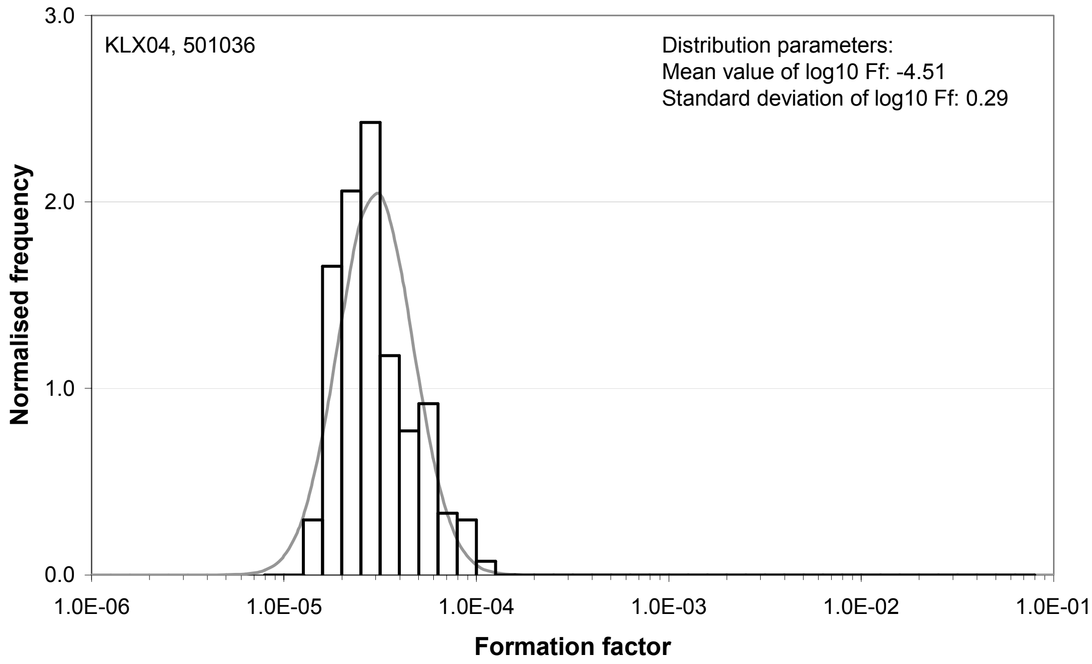


Rock type: 501044 = Granite to quartz monzodiorite, generally porphyritic

Length of core: 671 m (75%)

Number of data points: 1098

Arithmetic mean: 3.83E-05



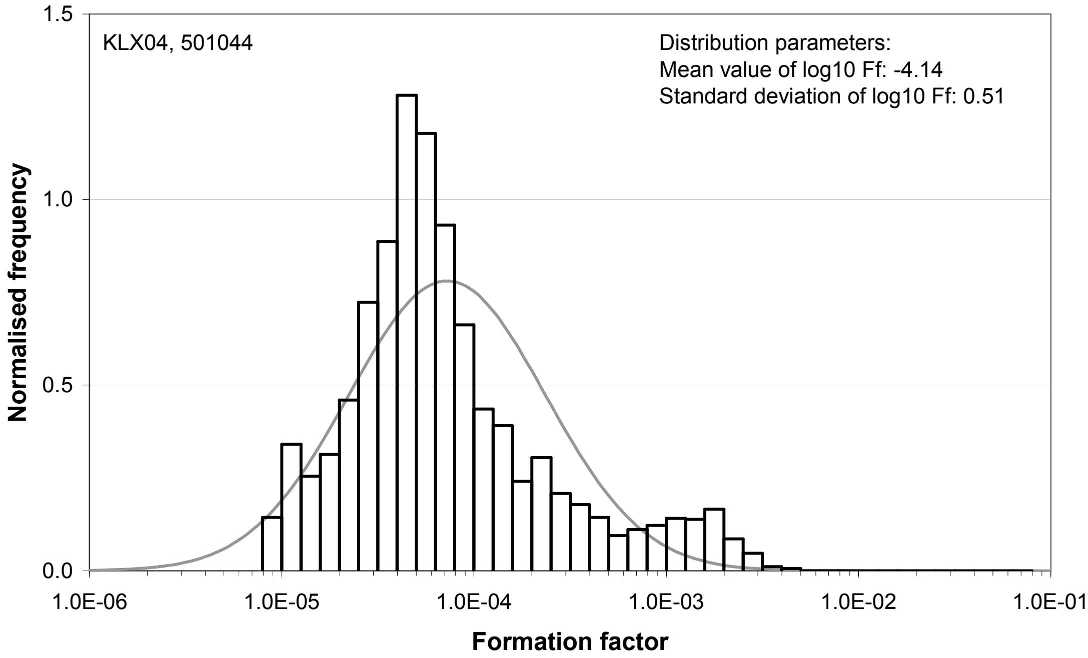
Rock type: 501036 = Quartz monzonite to monzodiorite, equigranular to weakly porphyritic

Length of core: 108 m (12%)

Number of data points: 272

Arithmetic mean:3.35E-05

Rock type specific distributions of fractured rock formation factors KLX04

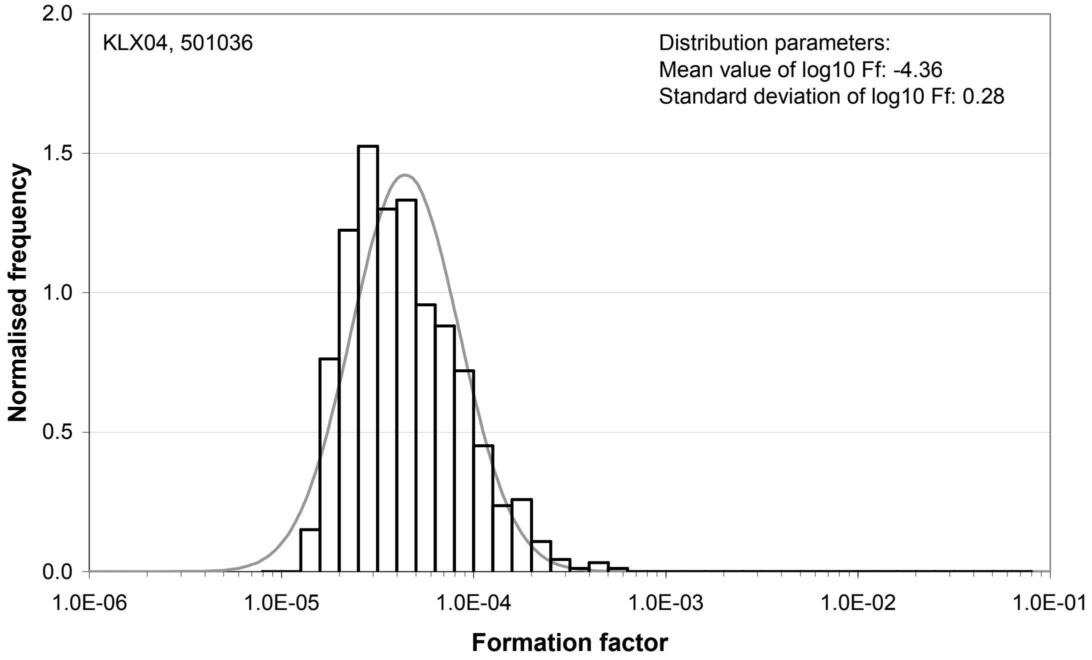


Rock type: 501044 = Granite to quartz monzodiorite, generally porphyritic

Length of core: 671 m (75%)

Number of data points: 3608

Arithmetic mean: 2.00E-04



Rock type: 501036 = Quartz monzonite to monzodiorite, equigranular to weakly porphyritic

Length of core: 108 m (12%)

Number of data points: 931

Arithmetic mean: 5.62E-05