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Oskarshamn site investigation

Formation factor logging in situ by electrical methods in KLX05 and KLX06

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October 2006

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Formation factor logging in situ by electrical methods in KLX05 and KLX06

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Keywords: AP PS 400-05-076, In situ, Formation factor, Rock resistivity, Electrical conductivity.

This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the client.

Abstract

This report presents measurements and interpretations of the formation factor of the rock surrounding the boreholes KLX05 and KLX06 in Laxemar, Sweden. The formation factor was logged in situ by electrical methods.

For KLX05, the in situ rock matrix formation factors obtained range from $4.7 \cdot 10^{-6}$ to $1.1 \cdot 10^{-4}$. The in situ fractured rock formation factors obtained range from $4.7 \cdot 10^{-6}$ to $5.6 \cdot 10^{-4}$. 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 –4.8 and 0.23, and –4.7 and 0.31 for the in situ rock matrix and fractured rock formation factor, respectively.

For KLX06, the in situ rock matrix formation factors obtained range from $4.9 \cdot 10^{-6}$ to $2.2 \cdot 10^{-4}$. The in situ fractured rock formation factors obtained range from $4.7 \cdot 10^{-6}$ to $2.4 \cdot 10^{-2}$. The formation factors are less well described by the log-normal distribution, possibly due to the fact that KLX06 is surrounded by a more heterogeneous rock mass than KLX05. The mean values and standard deviations of the obtained $\log_{10}$-normal distributions are –4.8 and 0.31, and −4.5 and 0.52 for the in situ rock matrix and fractured rock formation factor, respectively.

When obtaining the electrical conductivity profile of the groundwater in the boreholes, complementary data from other boreholes in the Laxemar subarea were used.

Sammanfattning

Denna rapport presenterar mätningar och tolkningar av bergets formationsfaktor runt borrhålen KLX05 och KLX06 i Laxemar, Sverige. Formationsfaktorn har loggats in situ med elektriska metoder.

För KLX05 varierar den erhållna in situ formationsfaktorn för bergmatrisen från $4{,}7 \cdot 10^{-6}$ till $1{,}1 \cdot 10^{-4}$. Den erhållna in situ formationsfaktorn för sprickigt berg varierar från $4{,}7 \cdot 10^{-6}$ till $5{,}6 \cdot 10^{-4}$. Formationsfaktorn verkar vara någorlunda väl log-normalt fördelad. Medelvärdena och standardavvikelserna för de erhållna $\log_{10}$-normal-fördelningarna är –4,8 och 0,23, samt –4,7 och 0,31 för in situ formationsfaktorn för bergmatrisen respektive sprickigt berg.

För KLX06 varierar den erhållna in situ formationsfaktorn för bergmatrisen från $4{,}9 \cdot 10^{-6}$ till $2{,}2 \cdot 10^{-4}$. Den erhållna in situ formationsfaktorn för sprickigt berg varierar från $4{,}7 \cdot 10^{-6}$ till $2{,}4 \cdot 10^{-2}$. Formationsfaktorn beskrivs mindre väl av en log-normal-fördelning, möjligen beroende av att KLX06 omges av en mer heterogen bergmassa än KLX05. Medelvärdena och standardavvikelserna för de erhållna $\log_{10}$-normal-fördelningarna är –4,8 och 0,31, samt –4,5 och 0,52 för in situ formationsfaktorn för bergmatrisen respektive sprickigt berg.

För att erhålla en profil över grundvattnets elektriska konduktivitet i borrhålen användes komplimenterande data från andra borrhål i delområde Laxemar.

Contents

1 Introduction

This document reports data gained from measurements of the in situ formation factor of rock surrounding the boreholes KLX05 and KLX06, within the Oskarshamn site investigation area. The work was carried out in accordance with activity plan AP PS 400-05-076. In Table 1-1 controlling documents for performing this activity are listed. Both activity plan and method descriptions are SKB's internal controlling documents.

The formation factor was logged in situ by electrical methods. No formation factor measurements were preformed in the laboratory. Other contractors performed the fieldwork, 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 Kemakta Konsult AB in Stockholm, Sweden.

Figure 1-1 shows the Oskarshamn site investigation area and the locations of different boreholes. Core drilled boreholes are marked by red dots. KLX05 and KLX06 are located in the southern and northern part of the Laxemar subarea, respectively.

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

Activity plan	Number	Version
Bestämning av formationsfaktorn från in situ resistivitetsmätningar i KLX05 och KLX06	AP PS 400-05-076	1.0
Method descriptions	**Number**	**Version**
Bestämning av formationsfaktorn med elektriska metoder	SKB MD 530.007	1.0

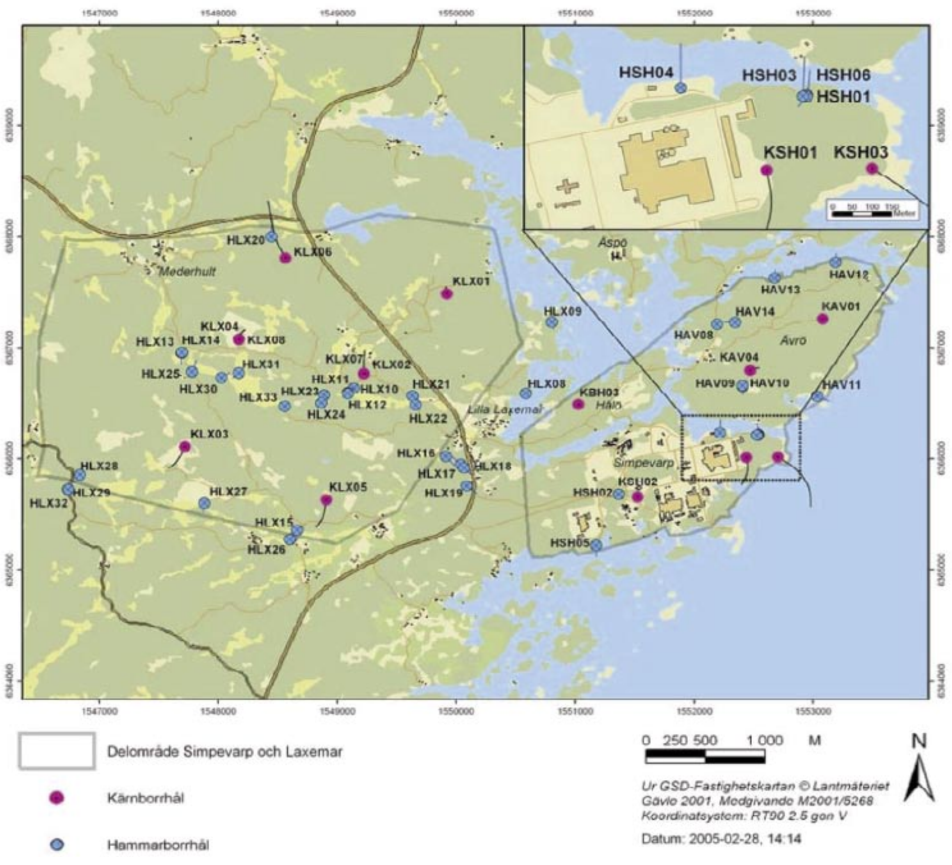


Figure 1-1. General overview of the Oskarshamn site investigation area.

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 KLX05 and KLX06. This has been achieved by performing formation factor loggings by electrical methods in situ. 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. Other contractors carried out the fieldwork.

3 Equipment

3.1 Rock resistivity measurments

The resistivity of the rock surrounding the boreholes KLX05 /1/ and KLX06 /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 KLX05 /3/ and KLX06 /4/ 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, a drawdown can either be applied or not. Measurements were carried out before and after the fracture specific EC measurements in each borehole.

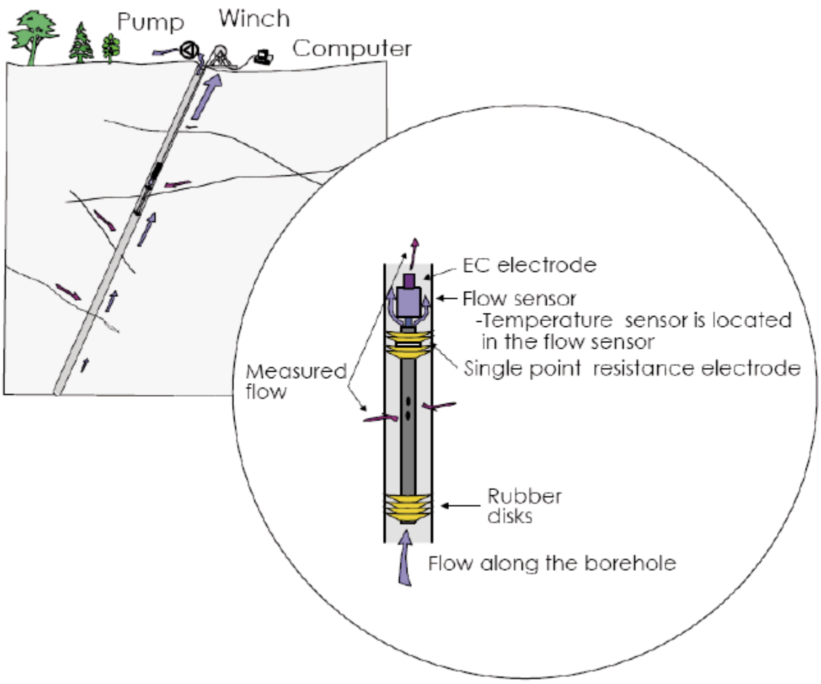


Figure 3-1. *Schematics of the POSIVA difference flow meter (image taken from /3/).*

When using both the upper and the lower rubber disks, 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. This is done in fracture specific EC measurements. 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.

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 two different campaigns in KLX05 /3/ and KLX06 /4/.

3.4 Boremap loggings

The drill cores of KLX05 /6/ and KLX06 /7/ 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 expressed at three levels, “possible”, “probable” and “certain”, based on the weathering and fit of the fracture. There is a strong uncertainty whether broken fractures were open before drilling or during/after drilling /8/. For this reason, it was decided to treat all broken fractures as potentially open in situ in this work.

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 /9/. 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:

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

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:

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

where D (m^2/s) is the diffusivity, μ ($m^2/V \cdot s$) 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 /10/:

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

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 groundwater 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 /11/ and /10/. The effect of the surface conduction on rock with formation factors below $1 \cdot 10^{-5}$ was not investigated in these works. In this report, surface conduction has not been accounted for, as more knowledge is needed on surface conduction before performing corrections. As the measured groundwater EC in KLX05 and KLX06, down to substantial depth, has an EC that is lower than this criterion, this restrains the applicability of the method at the site. This is further discussed in the Section 4.3 of this report.

4.1.3 Artefacts

Comparative studies have been performed on a large number of 1–2 cm long samples from Äspö in Sweden /11/. 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 /12/. 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 drill 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.

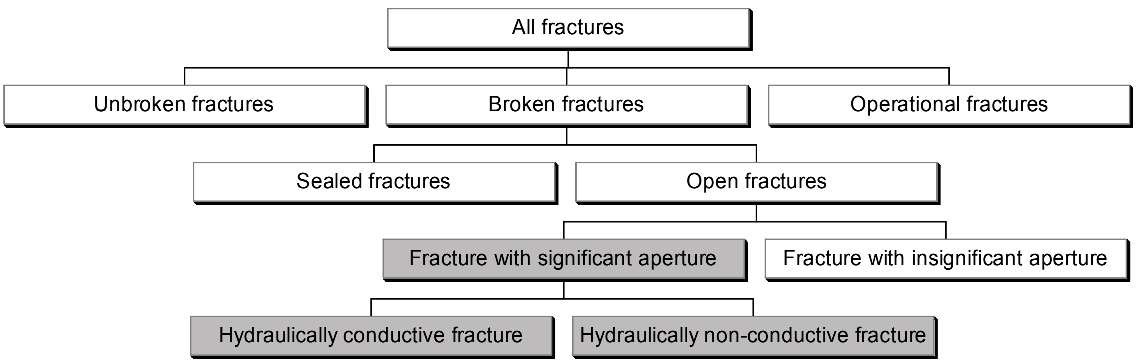


Figure 4-1. *Organization sketch of different types of fractures in situ.*

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 to 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 could 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 KLX05

The rock resistivity of KLX05 was logged on the 7th of April 2005 (activity id 13067448) /1/. The in situ rock resistivity was obtained using the focused Century 9072 tool. The borehole was successfully logged between 110–993 m. In order to obtain an exact depth calibration, the track marks made in the borehole were used. According to /1/ an accurate depth calibration was obtained.

4.2.2 Rock matrix resistivity log KLX05

All resistivity data obtained within 0.5 m from a broken fracture, detected in the core log, were sorted out from the in situ rock resistivity log. In the core log (activity id 13073322), a total of 1,265 broken fractures are recorded between 108–995 m. Three crush zones and one zone where the core has been lost are recorded. A total of 1.80 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 KLX05 are shown in Appendix A1. A total of 3,368 rock matrix resistivities were obtained between 110–993 m. Only 2,122 (63%) of the rock matrix resistivities were within the quantitative measuring range of the Century 9072 tool. The rock matrix resistivity log etween 110–993 m is shown in Appendix A1.

Figure 4-2 shows the distribution of the rock matrix resistivities obtained between 110–993 m in KLX05. 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 KLX05

All resistivity data obtained within 0.5 m from a hydraulically conductive fracture, detected in the difference flow logging /3/, were sorted out from the in situ rock resistivity log. For the difference flow log, no correction in the reported borehole length was needed. A total of 71 hydraulically conductive fractures were detected in KLX05. The locations of hydraulically conductive fractures in KLX05 are shown in Appendix A1. A total of 8,129 fractured rock resistivities were obtained between 110–993 m. 6,066 (75%) of the fractured rock resistivities were within the quantitative measuring range of the Century 9072 tool. The fractured rock resistivity log between 110–993 m is shown in Appendix A1.

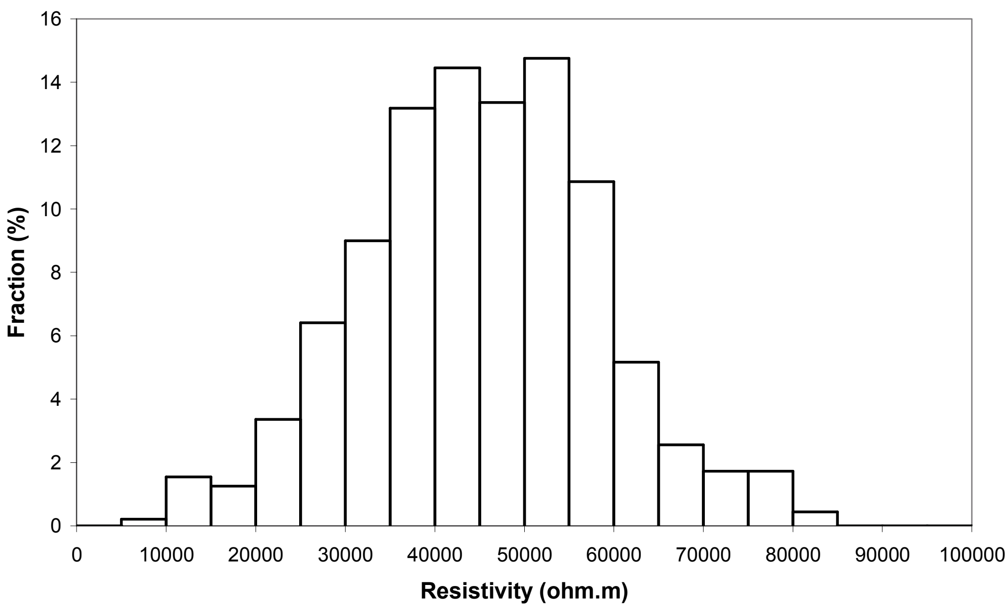


Figure 4-2. *Distribution of rock matrix resistivities in KLX05.*

Figure 4-3 shows a histogram of the fractured rock resistivities obtained between 110–993 m in KLX05. The histogram ranges from 0–100,000 ohm.m and is divided into sections of 5,000 ohm.m.

4.2.4 Rock resistivity KLX06

The rock resistivity of KLX06 was logged on the 5th of January 2005 (activity id 13061402) /2/. The in situ rock resistivity was obtained using the focused Century 9072 tool. The borehole was successfully logged between 103–990 m. In order to obtain an exact depth calibration, the track marks made in the borehole were used. According to /2/ an accurate depth calibration was obtained.

4.2.5 Rock matrix resistivity log KLX06

All resistivity data obtained within 0.5 m from a broken fracture, detected in the core log, were sorted out from the in situ rock resistivity log. In the core log (activity id 13064754), a total of 2,421 broken fractures are recorded between 101–965 m. In addition 56 crush zones and two zones where the core is lost are recorded. A total of 22.7 m of the core is crushed. 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 KLX06 are shown in Appendix A2. A total of 1,339 rock matrix resistivities were obtained between 103–965 m. 891 (67%) of the rock matrix resistivities were within the quantitative measuring range of the Century 9072 tool. The rock matrix resistivity log between 103–965 m is shown in Appendix A2.

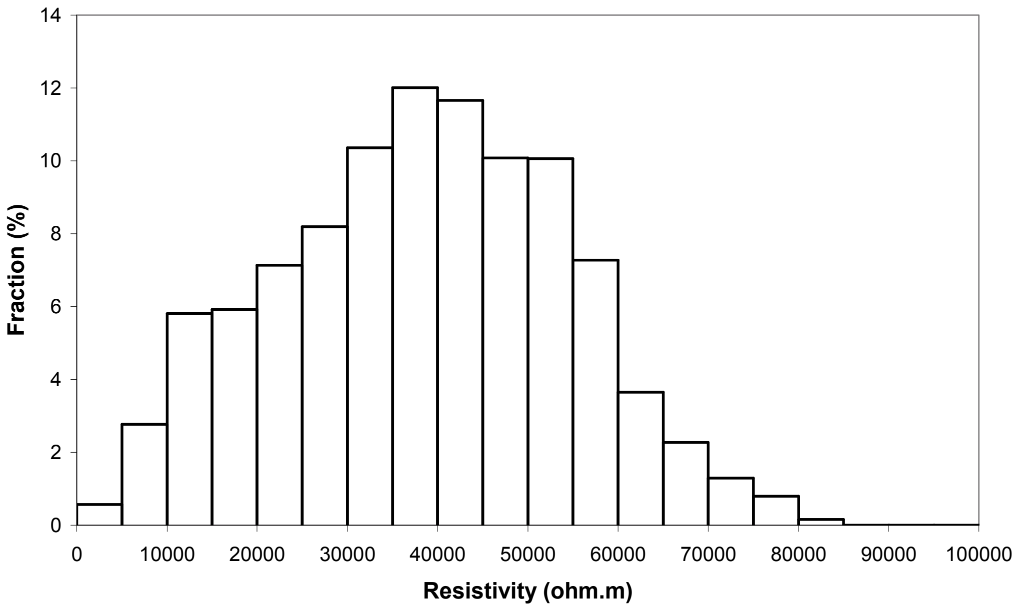


Figure 4-3. *Histogram of fractured rock resistivities in KLX05.*

Figure 4-4 shows a histogram of the rock matrix resistivities obtained between 103–965 m in KLX06. 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 KLX06

All resistivity data obtained within 0.5 m from a hydraulically conductive fracture, detected in the difference flow logging /4/, were sorted out from the in situ rock resistivity log. For the difference flow log, no correction in the reported borehole length was needed. A total of 186 hydraulically conductive fractures were detected in KLX06. The locations of hydraulically conductive fractures in KLX06 are shown in Appendix A2. A total of 7,242 fractured rock resistivities were obtained between 103–990 m. 6,019 (83%) of the rock matrix resistivities were within the quantitative measuring range of the Century 9072 tool. The fractured rock resistivity log between 103–990 m is shown in Appendix A2.

Figure 4-5 shows a histogram of the fractured rock resistivities obtained between 103–990 m in KLX06. The histogram ranges from 0–100,000 ohm.m and is divided into sections of 5,000 ohm.m.

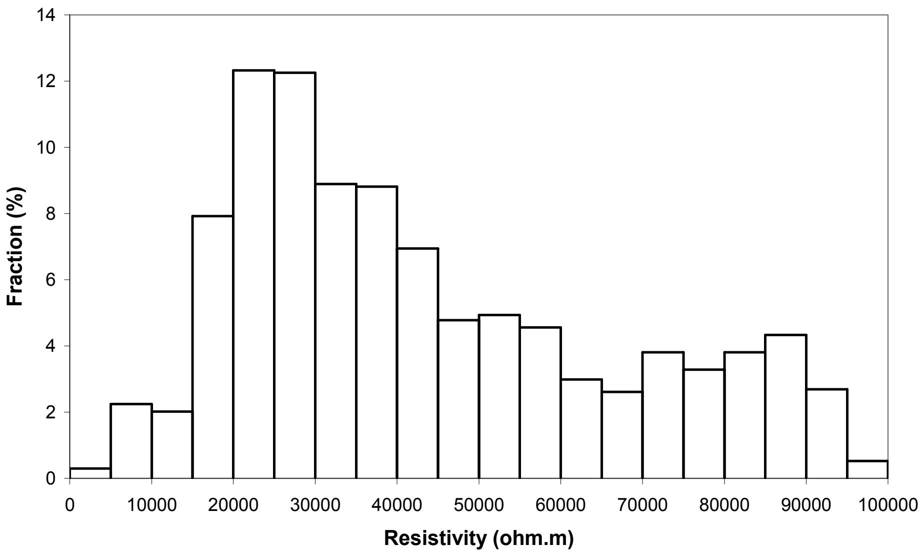


Figure 4-4. *Histogram of rock matrix resistivities in KLX06.*

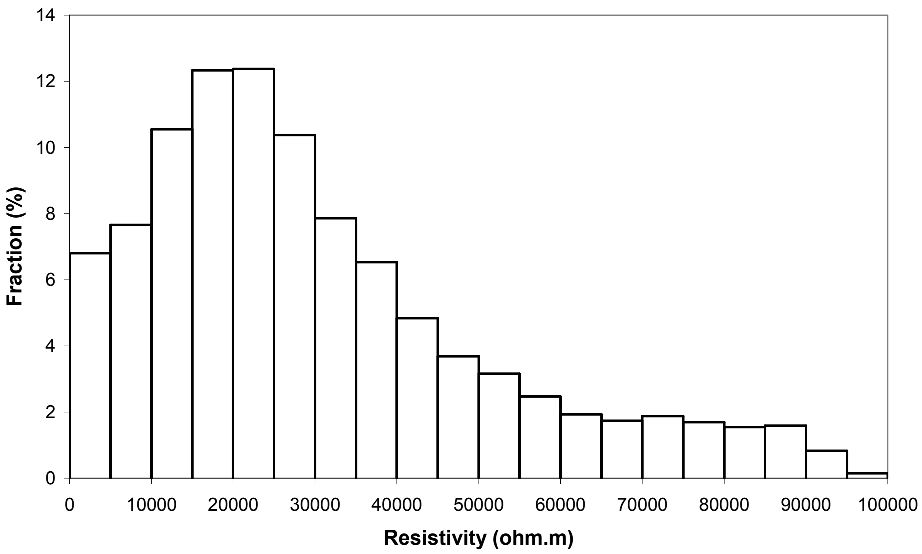


Figure 4-5. *Histogram of fractured rock resistivities in KLX06.*

4.3 Groundwater EC measurements in situ

4.3.1 General comments

In background reports concerning the EC of the groundwater, some data have been corrected for temperature, so that they correspond to data at 25°C. Other EC data are uncorrected. Data that correspond to the temperature in situ should be used in in situ evaluations. Even though these corrections are small in comparison to the natural variation of the formation factor, measures have been taken to use data that correspond to the in situ temperature. In some instances, EC data corrected to 25°C have been corrected once more so that they correspond to the in situ temperature.

4.3.2 Groundwater flow in KLX03–KLX07A

When performing chemical characterisations of the groundwater at depth at the Laxemar subarea, the representativeness of the data should be considered, due to the hydraulic situation of the site. When a borehole is drilled it functions as a hydraulic conductor, short-circuiting different hydraulic system that the borehole intersects. At Laxemar, the hydraulic gradients are relatively large and this results in large flows of groundwater in the boreholes. The fact that groundwater quickly flows from one depth to another in a borehole may affects the representativeness of the groundwater data obtained at a specific depth.

When measuring a fracture specific EC, by using the POSIVA difference flow meter or in the hydrochemical characterisations, a small section of the borehole is packed off. Water is then withdrawn from the fracture/fractures in the packed off borehole section and its EC is measured. However, if a large quantity of groundwater, representative for another depth, has flown along the short-circuiting borehole and into the fractures for weeks before the measurement, one can question the representativeness of the data obtained of that specific depth. It should be clarified that the measurements themselves may be accurate and still non-representative.

In measurements in KLX03 /13/, KLX04 /14/, KLX05 /3/, KLX06 /4/, and KLX07A /15/, 5-metre sections have been packed off and the flow in or out of the boreholes in these section has been measured by the POSIVA difference flow meter. This has been done without pumping in the borehole. The entire boreholes have been logged in this way by moving the tool stepwise. Based on these flow data, the flow along the boreholes without pumping can be assessed. When doing this, a few assumptions are made.

1) If the flow in a section is below the measurement limit of the tool, no flow is accounted for.
2) It is assumed that there is no flow in or out of the lower end of the borehole.
3) The flow in and out of the borehole should be equal. In many cases no flow measurements are performed in the upper 100 m. This may be due to a casing or to other reasons. This is handled by lumping the in- and outflows, distributed over the section, into an in- or outflow term at ground surface.

Figure 4-6 shows the flow situation in KLX03 /13/. The red diamonds show the flow, where one could be detected, in or out of the borehole in the packed off sections. A positive value is a flow into the borehole and a negative value a flow out of the borehole. The grey line shows the flow along the borehole required to feed the in- and outflows. A positive value represents a flow down the borehole and a negative value represents a flow up the borehole.

As one can see by the grey line in Figure 4-6, there is a substantial flow down the borehole down to about 750 m. The borehole diameter is 76 mm, which is the diameter of all the boreholes KLX03–KLX07A. A flow of $4.5 \cdot 10^3$ ml/h along the borehole corresponds to a plug flow velocity of about 1 m/h. In KLX03, water from the upper 200 m reaches down to the borehole length 750 m in about two weeks time.

Figure 4-7 shows the flow situation in KLX04 /14/. The legends are the same as in Figure 4-8.

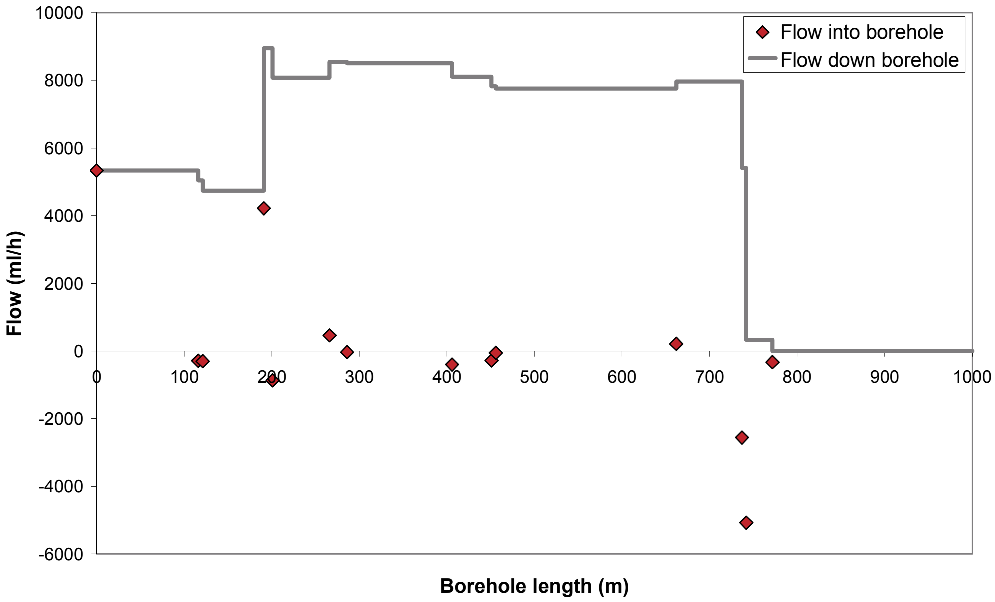


Figure 4-6. Flow into/out of and down/up borehole KLX03.

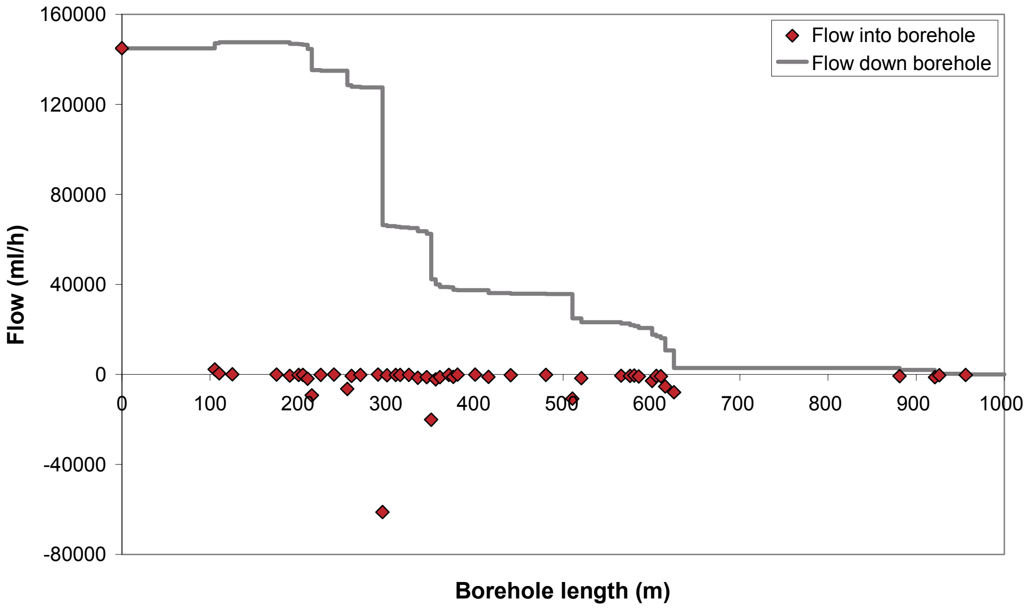


Figure 4-7. Flow into/out of and down/up borehole KLX04.

As one can see by the grey line in Figure 4-7, there is a major flow down the borehole down to about 625 m. In the upper 300 m, the plug flow velocity down the borehole is about 30 m/h. Below 625 m, the plug flow velocity down the borehole is about 0.5 m/h. Groundwater from the upper 200 m of the borehole could reach the 600 m level in a few days time and the 900 m level in a few weeks time.

Figure 4-8 shows the flow situation in KLX05 /3/.

In KLX05 there is a flow down the upper 100 m of the borehole. Between 100 and 150 m there is a flow out of the borehole. Furthermore, there is an flow into the borehole at a borehole length of about 250 m. Below 251 m there are no fractures with an in- or outflow above the measurement limit of the tool, without pumping. Therefore, the groundwater flowing into the borehole

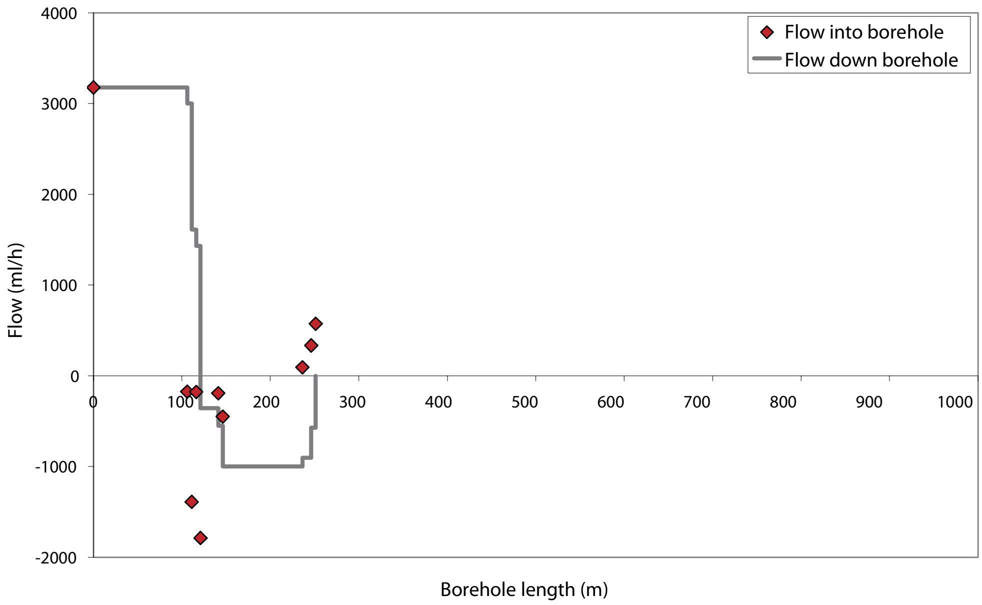


Figure 4-8. *Flow into/out of and down/up borehole KLX05.*

at about 250 m flows up the borehole. The groundwater flow at the borehole length 75 m was measured to be $4.0 \cdot 10^3$ ml/h down the borehole /3/. This should be compared to the assessed $3.2 \cdot 10^3$ ml/h. The deviation may be due to experimental errors and/or fractures with a flow below the measurement limit of the tool. Such fractures were detected when using a drawdown. In addition it is likely that the position of the tool somewhat affects the flow in the borehole. When measuring the flow in or out of a fracture, the small fracture aperture poses the largest resistance to the flow. When measuring in the borehole, the tool blocks a part of the borehole cross section (Figure 3-1), which should reduce the flow.

Figure 4-9 shows the flow situation in KLX06 /4/.

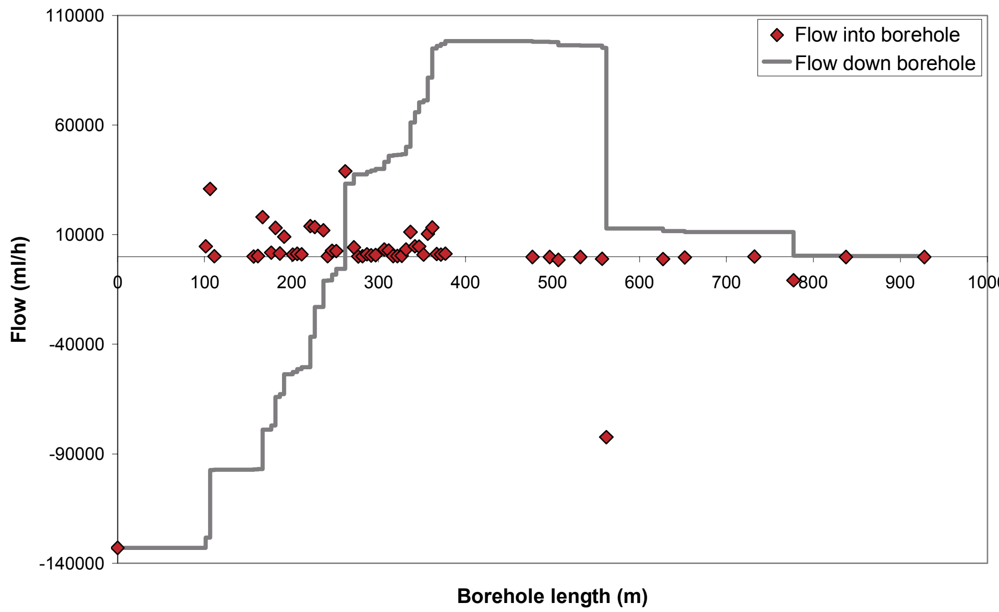


Figure 4-9. *Flow into/out of and down/up borehole KLX06.*

According to the flow measurements there is a substantially flow into the borehole between 100 and 380 m in KLX06. Below 380 m there are a few minor outflows in addition to the two major outflows at 562 m and 777 m. In the upper 262 m of the borehole there should be a flow up the borehole while below this borehole length, there should be a flow down the borehole. Groundwater from the fracture at 262 m should be able to reach down to 777 m in a less than two weeks time. The groundwater flow along the borehole was measured at the borehole length 100 m to be $8.0 \cdot 10^4$ ml/h up the borehole /4/. This should be compared to the assessed $1.3 \cdot 10^5$ ml/h. Even though this deviation is substantial, the measurement confirms that there is a major flow up the borehole.

Figure 4-10 shows the flow situation in KLX07A /15/.

As can be seen in Figure 4-10 there is a major flow down the borehole. The plug flow velocity at the borehole length 100 m should be about 80 m/h. Groundwater from the upper 100 m should reach down to the major outflow point at 762 m within a 24-hour period and down to 823 m within a week. The measured groundwater flow at the borehole length 102 m was $2.0 \cdot 10^5$ ml/h down the borehole /15/, while the flow assessed in this report is $3.7 \cdot 10^5$ ml/h.

4.3.3 EC measurements in KLX05

The EC of the borehole fluid in KLX05 was measured before and after performing extensive pumping in the borehole on the dates 2005-04-14 and 2005-04-25, respectively /3/. The EC of groundwater extracted from four specific fractures between 124 and 792 m was measured using the POSIVA difference flow meter, between the dates 2005-04-22 and 2005-04-25.

The turquoise and green lines in Figure 4-11 represent the borehole fluid EC logs obtained before (turquoise) and after (green) performing extensive pumping. The black crosses represents the obtained fractures specific ECs.

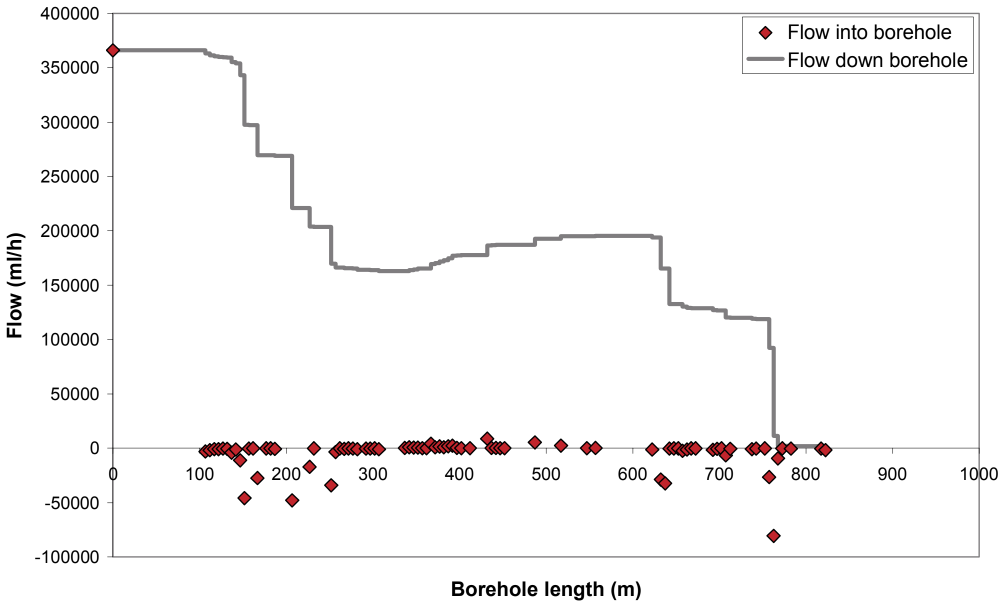


Figure 4-10. Flow into/out of and down/up borehole KLX07A.

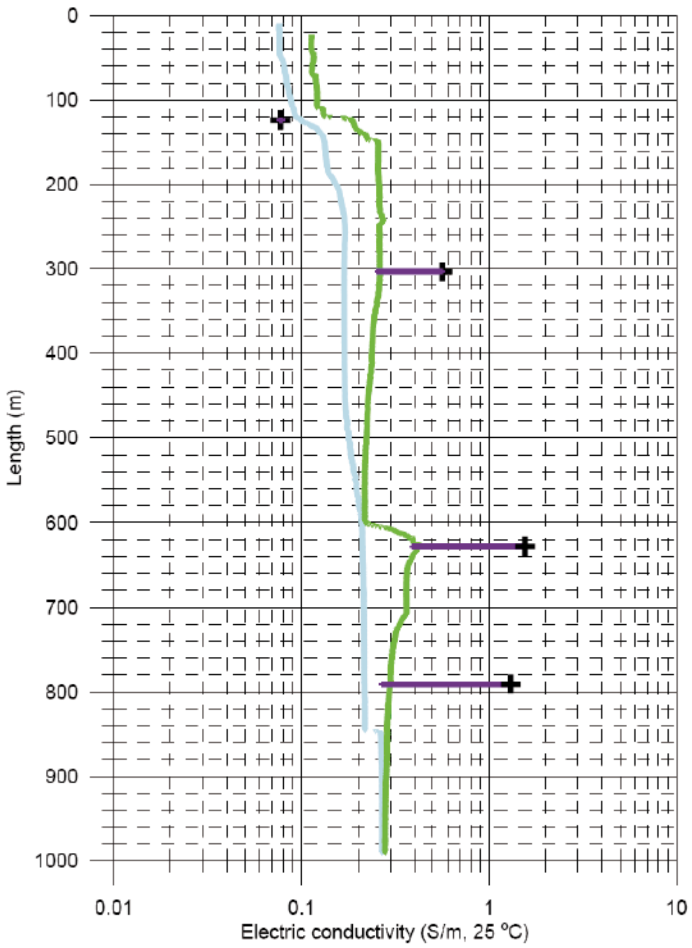


Figure 4-11. *Borehole fluid EC logs and fracture specific ECs in KLX05. Image taken from /3/.*

From the flow data available (Figure 4-8), it is hard to estimate whether there is a minute flow down or up the borehole below 251 m when not pumping. From EC data shown in Figure 4-11, however, one would suspect a flow down the borehole. As the flow down the borehole is assessed to be small, it is judged that the fracture specific ECs obtained at 303.8 m, 628.6 m, and 791.1 m should represent the groundwater at those corresponding depth reasonably well. As there is a large inflow into the fracture at 124 m when not pumping, the EC obtained here may be non-representative. The resulting fracture specific ECs in KLX05 are shown in Table 4-1. The data in parentheses are judged to be dubious.

Table 4-1. Fracture specific ECs, KLX05.

Measurment	Borehole section (m)	Location of fractures (m)	EC in situ (S/m)[1]	EC 25°C (S/m)[2]
Difference flow	123.76–124.26	124	(0.052)	(0.08)
Difference flow	303.47–303.97	303.8	0.40	0.56
Difference flow	628.55–629.05	628.6	1.3	1.56
Difference flow	791.01–791.51	791.1	1.1	1.31

[1]Data from /16/.
[2]Data from /3/.

4.3.4 EC measurements in KLX06

The EC of the borehole fluid in KLX06 was measured before and after performing extensive pumping in the borehole on the dates 2005-02-16 and 2005-02-26, respectively /4/. The EC of groundwater extracted from five specific fractures between 195 and 928 m was measured using the POSIVA difference flow meter, between the dates 2005-02-25 and 2005-02-26.

The blue and green lines in Figure 4-12 represent the borehole fluid EC logs obtained before (blue) and after (green) performing extensive pumping. The black crosses represents the obtained fractures specific ECs.

As can be seen from the flow data available (Figure 4-9), groundwater that is flowing into the borehole at the borehole length 262 m and below will flow down to the lower end of the borehole. This is consistent with what can be seen from the EC data. When not pumping in the borehole, groundwater flows into the borehole at 196 m and 377 m. Therefore these fractures should not be excessively contaminated by the borehole fluid. The ECs obtained at these depths are judged to be representative for the groundwater. When not pumping, groundwater flows out of the borehole at 562 m, 779 m, and 928 m. It is assessed that the groundwater in these fractures are highly affected by groundwater representing a shallower depth. In addition, when examining the transient fracture specific EC curve at 779 m /4/, the measurement does not seem to have been carried out for long enough time-period to have reached a stable EC value. The resulting fracture specific ECs in KLX06 are shown in Table 4-2. The data in parentheses are judged to be dubious.

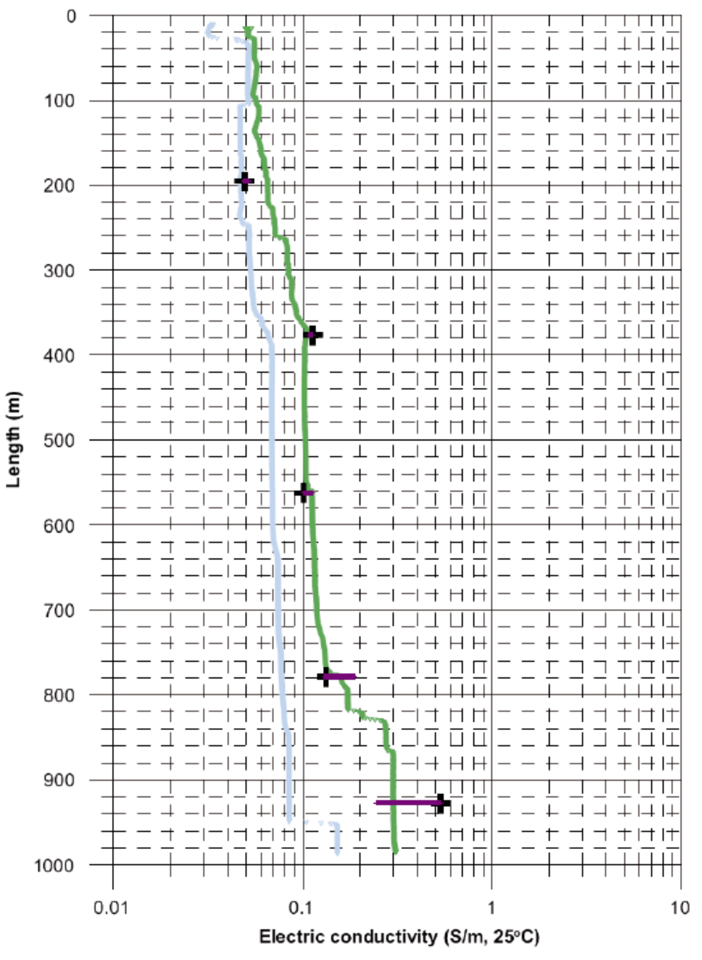


Figure 4-12. *Borehole fluid EC logs and fracture specific ECs in KLX06. Image taken from /4/.*

Table 4-2. Fracture specific ECs, KLX06.

Measurment	Borehole section (m)	Location of fractures (m)	EC in situ (S/m)[1]	EC 25°C (S/m)[2]
Difference flow	195.8–196.3	196.0	0.034	0.05
Difference flow	376.7–377.2	376.7, 377.0, 377.2	0.084	0.11
Difference flow	562.0–562.5	562.2	(0.080)	(0.10)
Difference flow	778.8–779.3	779.0	(0.11)	(0.13)
Difference flow	927.5–928.0	927.7	(0.47)	(0.53)

[1]Data from /16/.
[2]Data from /4/.

4.3.5 EC measurements in KLX03, KLX04, and KLX07A

EC measurements in KLX03 and KLX04 are described in /17/. In KLX03, groundwater from shallower depth penetrates the borehole down to a depth of 772 m. Below this depth there seems to be practically no flow down the borehole and it was assessed in /17/ that the borehole fluid EC obtained before performing pumping represents the groundwater EC below 800 m. In Table 4-3 the fracture specific ECs obtained by the POSIVA difference flow meter or in the hydrochemical characterisation are given. According to /17/ the fracture specific EC obtained at the borehole depth 275 m should be disregarded, as it was suspected that borehole fluid may have leaked into the packed off section when performing the measurement.

When not pumping, groundwater flows into the borehole KLX03 at 195–198 m and 267 m and out of the borehole at 409 m, 453 m, and 740–748 m. At the other depths, no flow was detected when not pumping. As the flow down the borehole is not excessive when not pumping, as in KLX04, KLX06, and KLX07A, fracture specific ECs obtained in sections with a flow into the borehole were judged as reasonable. In addition, ECs obtained at fractures that featured no flow when not pumping were judged as reasonable. The data in parentheses in Table 4-3 are judged to be dubious.

Table 4-3. Fracture specific ECs, KLX03.

Measurment	Borehole section (m)	Location of fractures (m)	EC in situ (S/m)[1]	EC 25°C (S/m)[2]
Difference flow logging	195.1–195.6	195.3	0.098	0.14
Hydrochemical characterisation	193.5 –198.4	195.8, 197.7	0.14	
Difference flow logging	266.5–267.0	266.8	0.21	0.30
Difference flow logging	274.2–274.7	274.7	(0.96)	(1.31)
Hydrochemical characterisation	408.0–415.3	409.9	(0.48)	
Difference flow logging	453.2–453.7	453.4	(0.99)	(1.27)
Difference flow logging	619.2–619.7	619.4	1.13	1.36
Hydrochemical characterisation	735.5–748.0	740.8, 741.8, 742.3, 744.1, 746.4, 747.7	(1.2)	
Hydrochemical characterisation	964.5–975.2	970.1, 970.5	2.6	
Difference flow logging	969.9–970.4	970.1	2.7	2.87

[1]Data from /16/.
[2]Data from /17/.

In KLX04, five fracture specific ECs were obtained by using the POSIVA difference flow meter /14/. When not pumping, groundwater flows out of the borehole at 340 m, 514 m, and 628 m. Due to the large flow down the borehole, the ECs obtained at these borehole lengths are judged to be dubious. No flow was detected at 139 m and 973 m when not pumping. At 139 m, the flow along the borehole is very large while at 973 m the flow should be minute. The former EC was judged to be dubious while the later was judged to be representative for the groundwater at that depth. The fracture specific EC values that were judged to be dubious are put in parentheses in Table 4-4.

In KLX07A, five fracture specific ECs were obtained by using the POSIVA difference flow meter /15/ on the date 2005-06-22. By inspecting the transient fracture specific EC curves /15/, all measurements seem to have been carried out without any problems. As seen by the flow data in Figure 4-10, there is a large flow down most of the borehole. Therefore, fracture specific ECs obtained at fractures where borehole fluid flows out of the borehole when not pumping, were judged as dubious. These values are put in parentheses in Table 4-5.

4.3.6 EC profiles in KLX05 and KLX06

In order to obtain groundwater EC profiles in the boreholes KLX05 and KLX06, fracture specific ECs obtained in the boreholes KLX03–KLX07A were used. As the boreholes have different inclinations, this was corrected for. The x-axis in Figure 4-13 represents the vertical borehole depth. Different altitudes of the drilling sites were not corrected for. The EC data in parentheses in Tables 4-1 to 4-5 were sorted out. In Figure 4-13 the EC values correspond to the in situ temperature. The values are tabulated in Appendix C.

The black line shown in Figure 4-13 is the linear fitting, by using the least square method, to the data shown in Appendix C. In this report, this fitting is used as the groundwater EC profile for KLX05 and KLX06. Obtaining such a profile is a somewhat subjective operation, due to lack of data. However, variations in groundwater EC are generally small in comparison to variations in the formation factor. It is recommended not to use the EC profile shown in Figure 4-13 in formation factor calculations at shallower depth than the borehole length 339 m, due to the criterion discussed in Section 4.1.2.

Table 4-4. Fracture specific ECs, KLX04.

Measurment	Borehole section (m)	Location of fractures (m)	EC in situ S/m)[1]	EC 25°C (S/m)[2]
Difference flow	138.8–139	139.2	(0.060)	(0.08)
Difference flow	339–340	339.6	(0.088)	(0.12)
Difference flow	513.1–514.1	513.6	(0.31)	(0.39)
Difference flow	627.5–628.5	628.1	(0.38)	(0.46)
Difference flow	972.7–973.7	973.1	1.6	1.72

[1]Data from /16/.
[2]Data from /17/.

Table 4-5. Fracture specific ECs, KLX07A.

Measurment	Borehole section (m)	Location of fractures (m)	EC in situ (S/m)[1]	EC 25°C (S/m)[2]
Difference flow	366.66–367.66	367.4	0.11	0.16
Difference flow	486.99–487.99	487.4	0.36	0.48
Difference flow	635.21–636.21	635.7	(0.14)	(0.17)
Difference flow	712.00–713.00	712.4	(0.20)	(0.25)
Difference flow	825.17–826.17	825.5	(0.71)	(0.86)

[1]Data from /16/.
[2]Data from /15/.

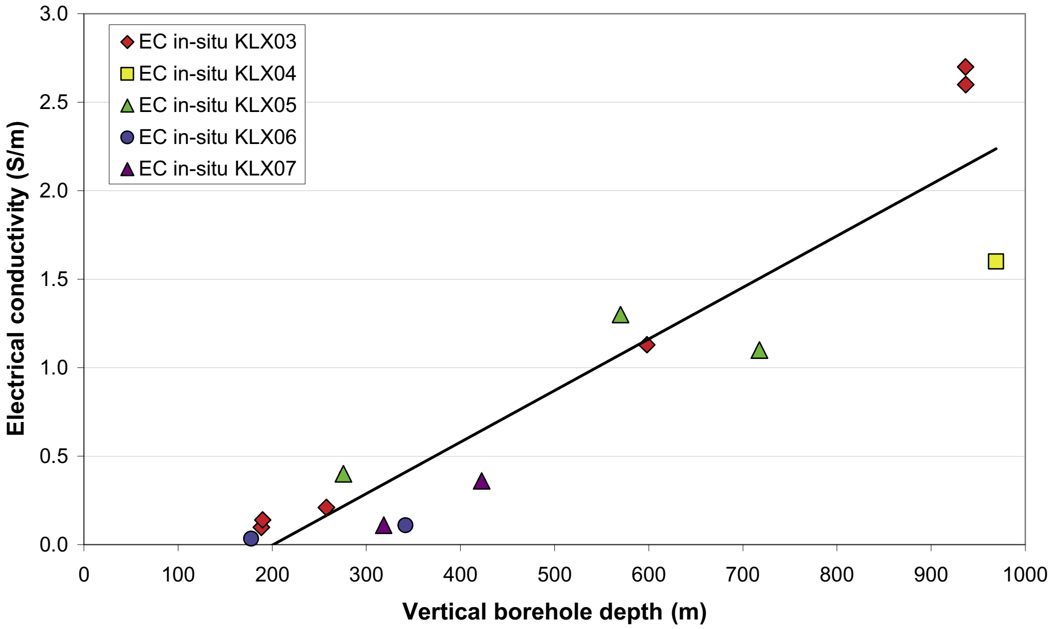


Figure 4-13. *Groundwater EC in KLX03–KLX07A.*

The equation for the EC-profile shown in Figure 4-13 is the following:

KLX05 and KLX06: borehole length 339–1,000 m,

EC (S/m) = 0.00321·borehole length (m)–0.586 4-4

4.3.7 Electrical conductivity of the pore water

The rock surrounding KLX05 and KLX06 is in general highly fractured. In KLX05, on average 1.4 broken fractures per metre part the core. In KLX06, on average 2.8 broken fractures per metre 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, even if the frequency of hydraulically conductive fractures decreases with depth. 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 metres 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

Formation factors have not been estimated in laboratory for KLX05 and KLX06.

4.5 Nonconformities

A significant number of obtained rock resistivities (26% for KLX05 and 15% for KLX06) are higher than the quantitative measuring range of the in situ rock resistivity tool.

5 Results

5.1 In situ rock matrix formation factor

The in situ formation factors obtained in KLX05 and KLX06 were treated statistically. By using the normal-score method, as described in /18/, 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 distributions of the rock matrix formation factors obtained in situ between 339–993 m in KLX05 and between 339–965 m in KLX06.

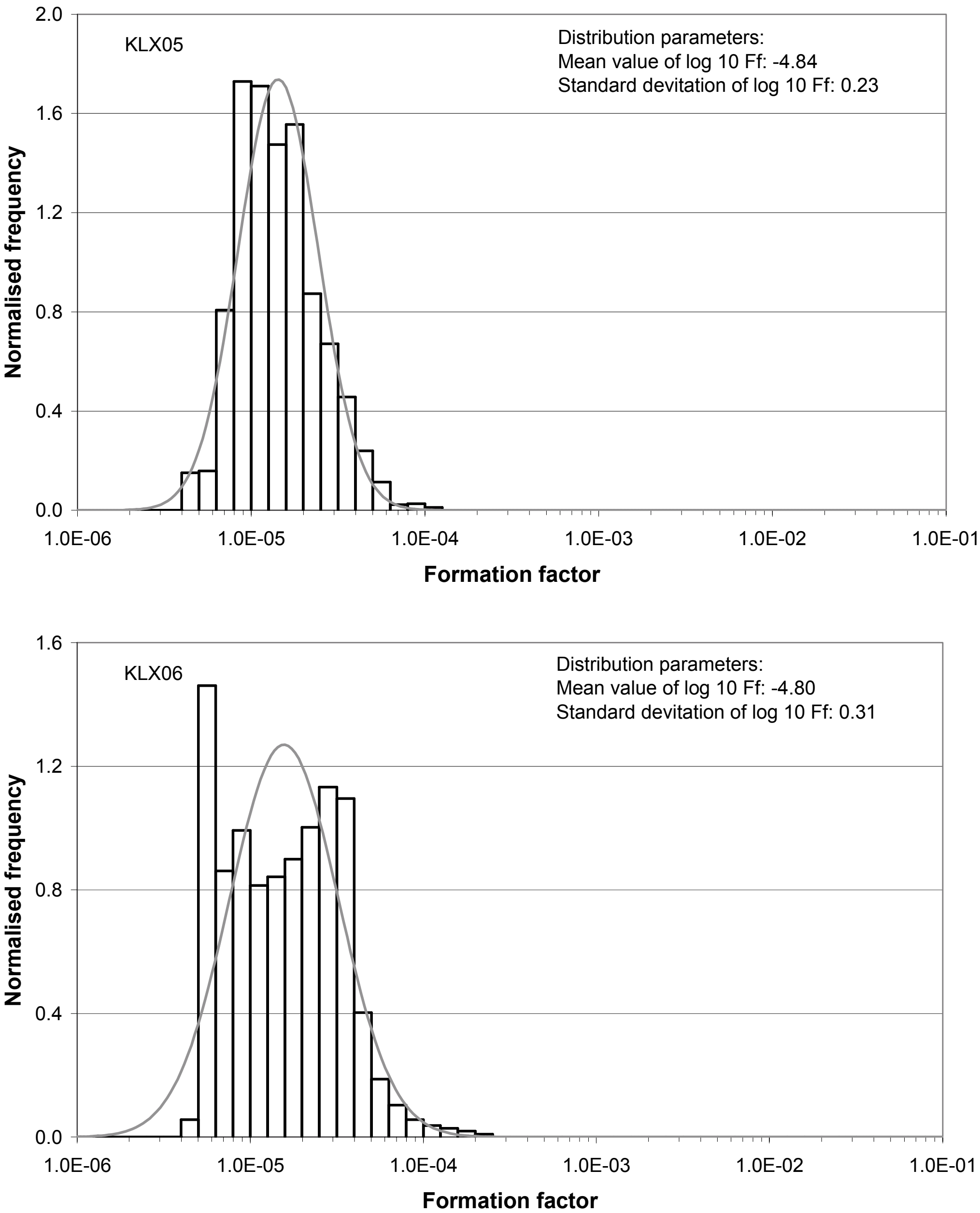


Figure 5-1. *Distributions of in situ rock matrix formation factors in KLX05 and KLX06.*

The rock matrix formation factors for KLX05 are fairly well log-normally distributed. For KLX06, the data deviates from the log-normal distribution. The rock surrounding KLX06 is more heavily fractured than that surrounding KLX05. Furthermore, the geology of KLX06 seems to be more complex with a larger component of fine-grained mafic rock. The rock resistivity measurements may have been somewhat affected by the limited measurement range of the in situ tool, which would give an overestimation of the formation factors in the lower formation factor range. This can especially be seen for KLX06. The mean values and standard deviations of the distributions in Figure 5-1 are shown in Table 5-1 and Table 5-2 for KLX05 and KLX06, respectively. The in situ rock matrix formation factor logs of KLX05 and KLX06 are shown in Appendix B1 and B2, respectively.

5.2 In situ fractured rock formation factor

Figure 5-2 shows the distributions of the fractured rock formation factors obtained in situ between 339–993 m in KLX05 and between 339–990 m in KLX06.

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, some of the obtained formation factors are affected by free water in hydraulically non-conductive fractures. The mean values and standard deviations of the distributions in Figure 5-2 are shown in Table 5-1 and Table 5-2 for KLX05 and KLX06, respectively. The in situ fractured rock formation factor logs of KLX05 and KLX06 are shown in Appendix B1 and B2, respectively.

5.3 Comparison of formation factors of KLX05

Table 5-1 presents mean values and standard deviations of the log-normal distributions shown in Figures 5-1 and 5-2 for KLX05. In addition, the number of data points obtained and the arithmetic mean values for the different formation factors are shown.

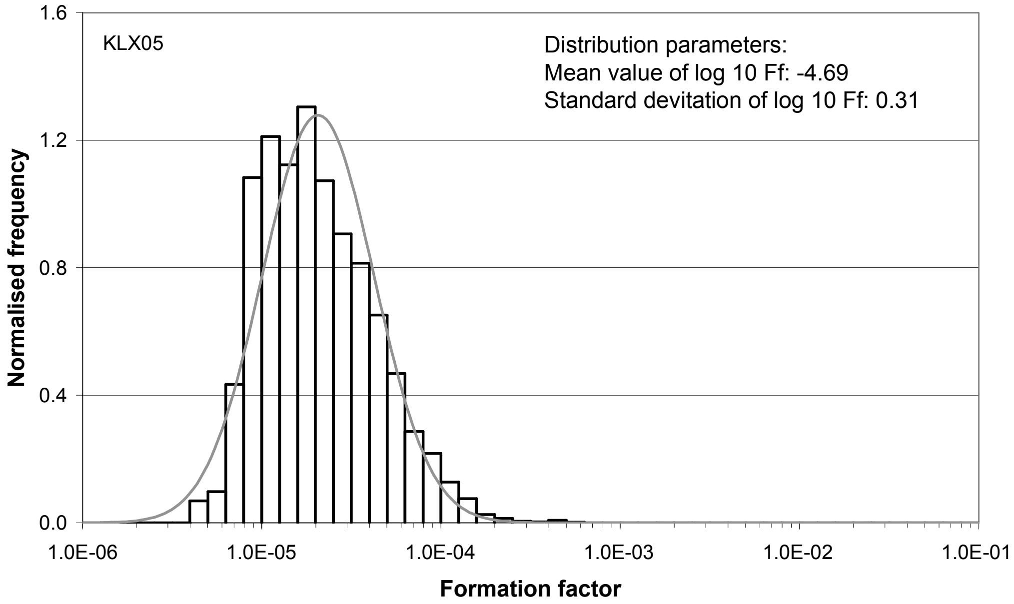
It should be noted from Table 5-1 that the fractured rock formation factors are, on average, 1.7 times as large as the rock matrix formation factors.

Table 5-1. Distribution parameters and arithmetic mean value of the formation factor, KLX05.

Formation factor	Number of data points	Mean log10(Ff)	Standard deviation $\log_{10}(F_f)$	Arithmetic mean F_f
In situ Rock matrix F_f	2,713	–4.84	0.23	$1.67 \cdot 10^{-5}$
In situ Fractured rock F_f	6,431	–4.69	0.31	$2.79 \cdot 10^{-5}$

Table 5-2. Distribution parameters and arithmetic mean value of the formation factor, KLX06.

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	1,068	–4.80	0.31	$2.08 \cdot 10^{-5}$
In situ Fractured rock F_f	5,870	–4.50	0.52	$2.14 \cdot 10^{-4}$



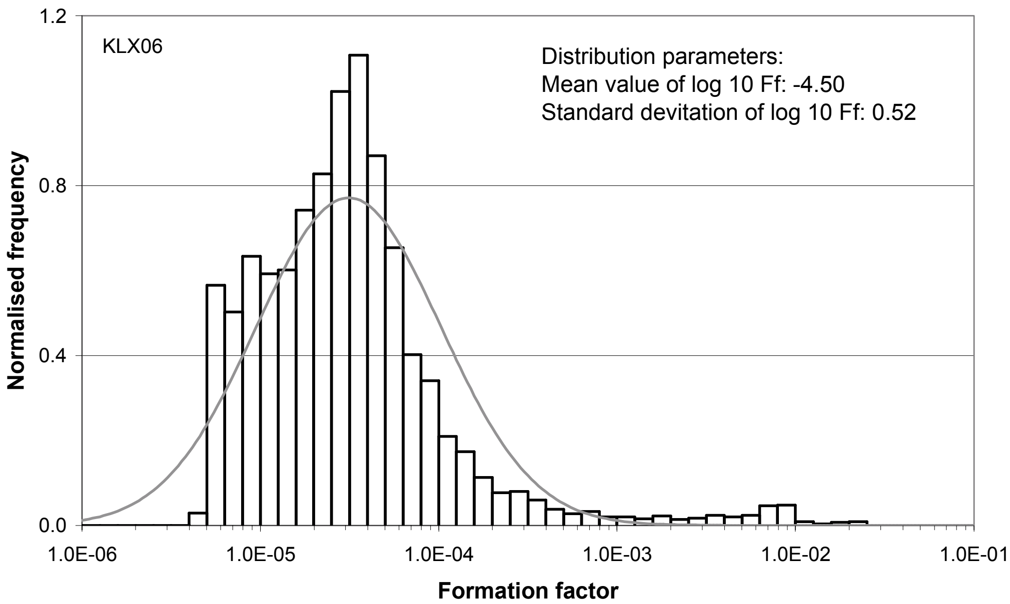


***Figure 5-2**. Distributions of in situ fractured rock formation factors in KLX05 and KLX06.*

5.4 Comparison of formation factors of KLX06

Table 5-2 presents mean values and standard deviations of the log-normal distributions shown in Figures 5-1 and 5-2 for KLX06. In addition, the number of data points obtained and the arithmetic mean values for the different formation factors are shown.

It should be noted from Table 5-2 that the fractured rock formation factors are, on average, one order of magnitude larger than the rock matrix formation factors.

6 Summary and discussions

The formation factors obtained in KLX05 and KLX06 range from $4.7 \cdot 10^{-6}$ to $2.4 \cdot 10^{-2}$. The formation factors appear to be fairly well distributed according to the log-normal distribution for KLX05. For KLX06, the formation factors are less well log-normally distributed. The rock mass surrounding KLX06 is both more fractured and potentially more complex in geology than the one surrounding KLX05. The obtained in situ distributions have mean values for $\log_{10}(F_f)$ between –4.8 and –4.5 and standard deviations between 0.23 and 0.52. The arithmetic mean values range between $1.67 \cdot 10^{-5}$ and $2.14 \cdot 10^{-4}$.

The fractured rock formation factors were on average 1.7 times as large for KLX05 and 10 times as large for KLX06 as 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 as large as, or even larger than, that of the intact rock matrix.

Judging from the obtained formation factor histograms, a fairly large fraction of the obtained in situ rock resistivities may have been affected by limitations of the in situ rock resistivity tool, especially in KLX06. However, these limitations have only minor effects on the obtained arithmetic mean values of the formation factor.

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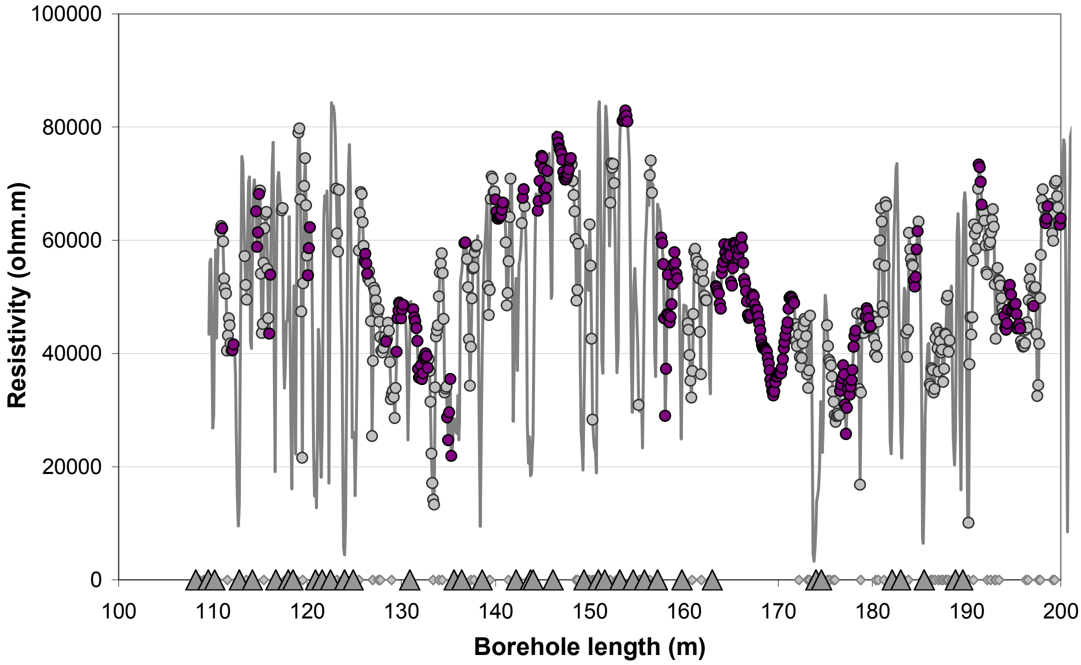
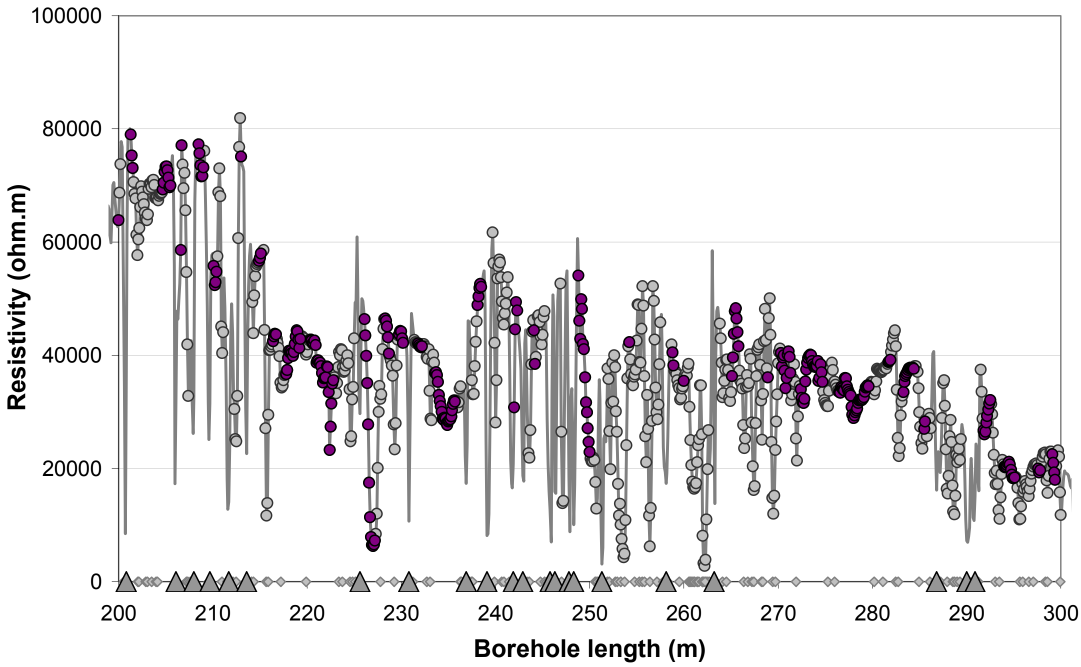
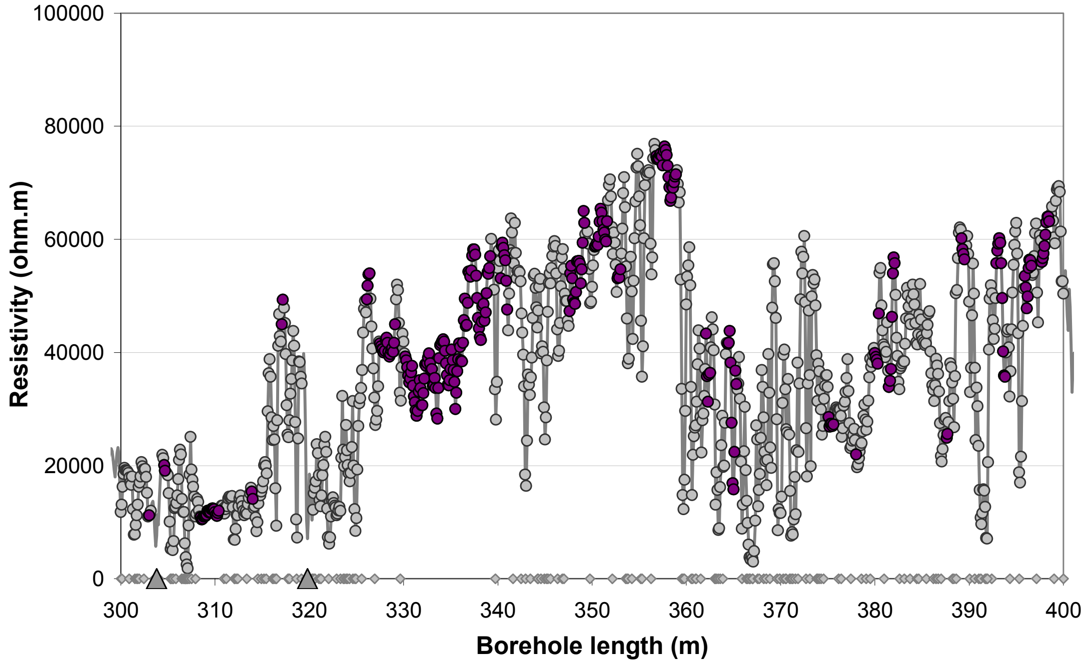
Appendix A1: In situ rock resistivities and fractures KLX05

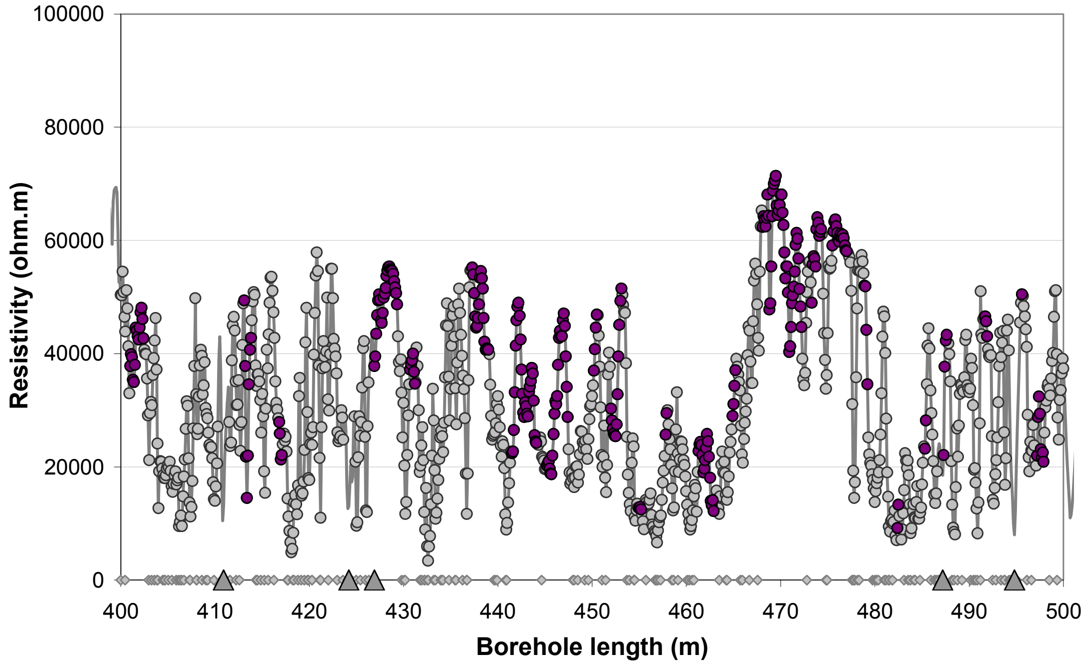




Rock resistivity
Fractured rock resistivity
Rock matrix resistivity
Location of broken fracture parting the drill core
Location of hydraulically conductive fracture detected in the difference flow logging

Appendix A1: **In-situ rock resistivities and fractures KLX05**





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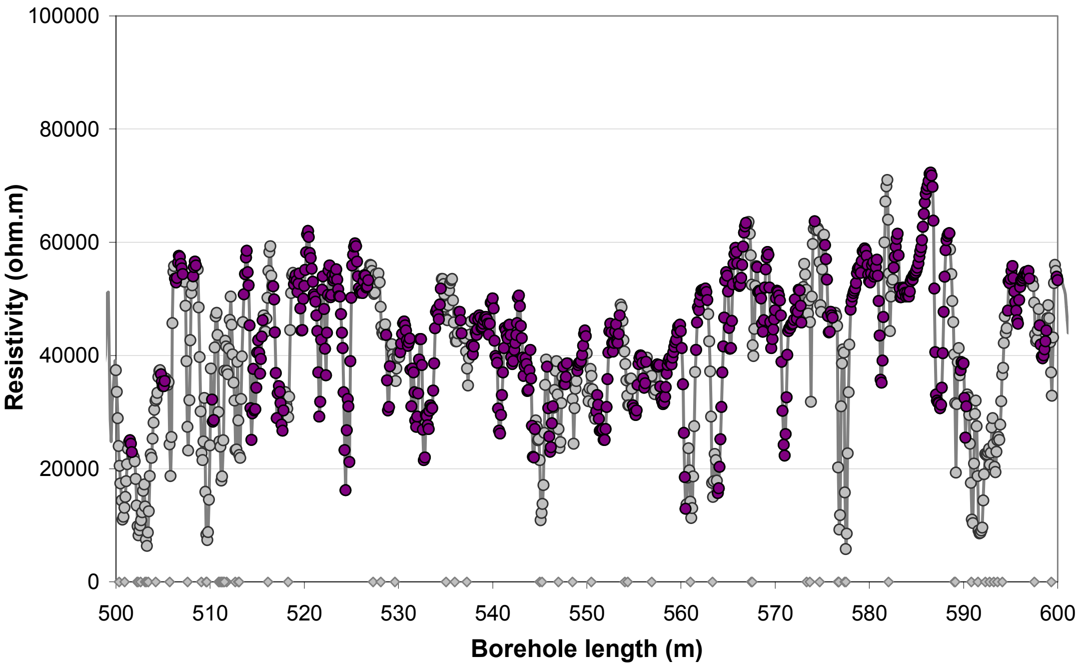

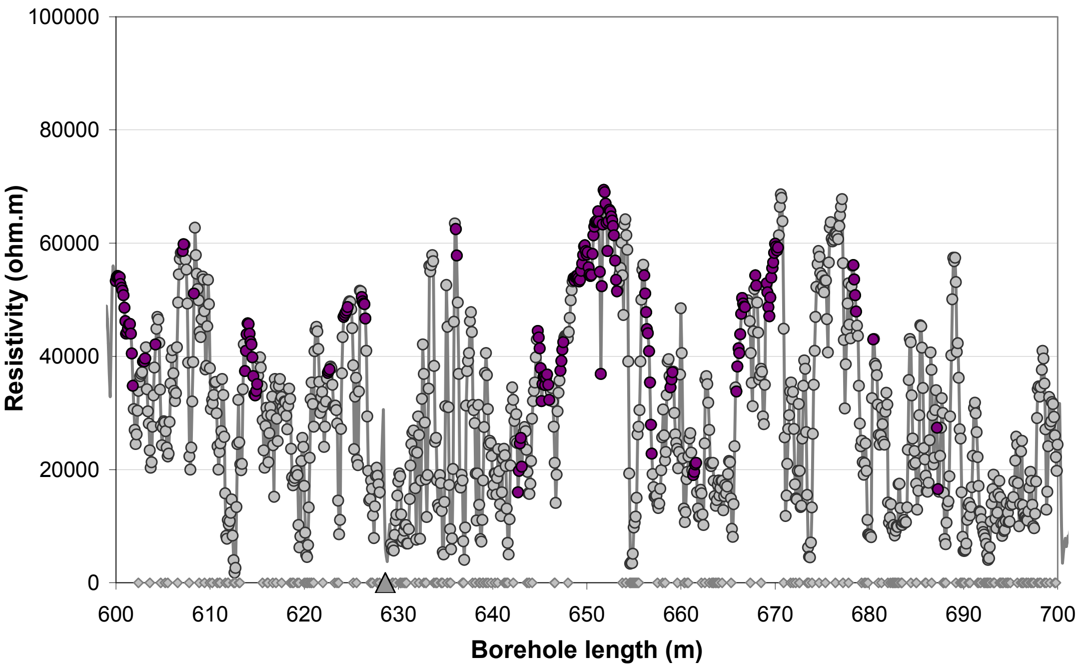

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Location of broken fracture parting the drill core
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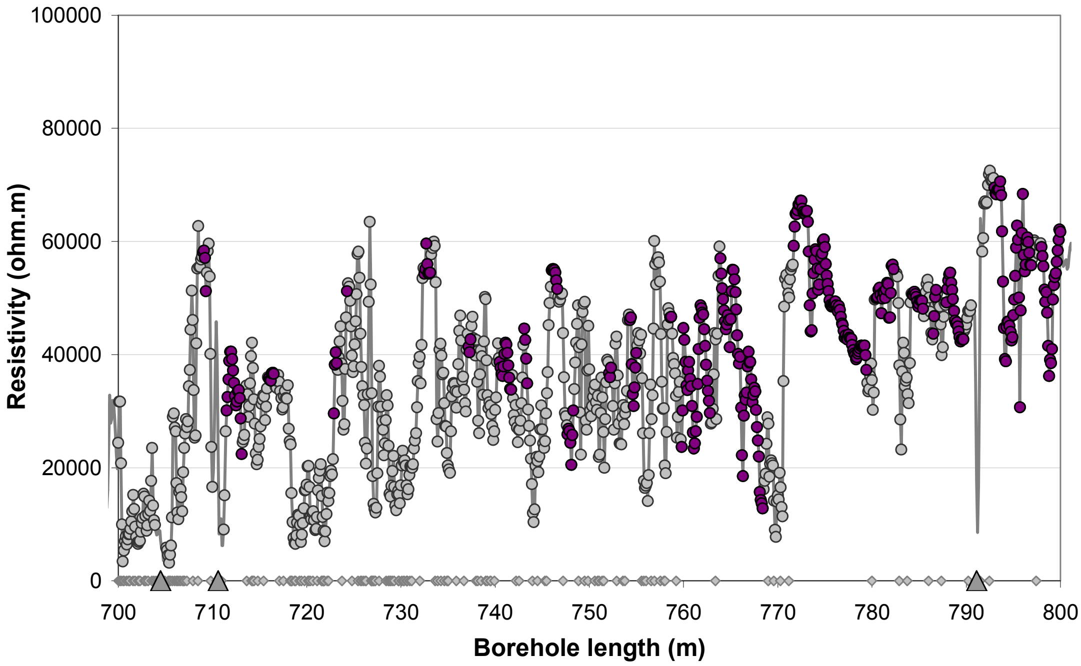
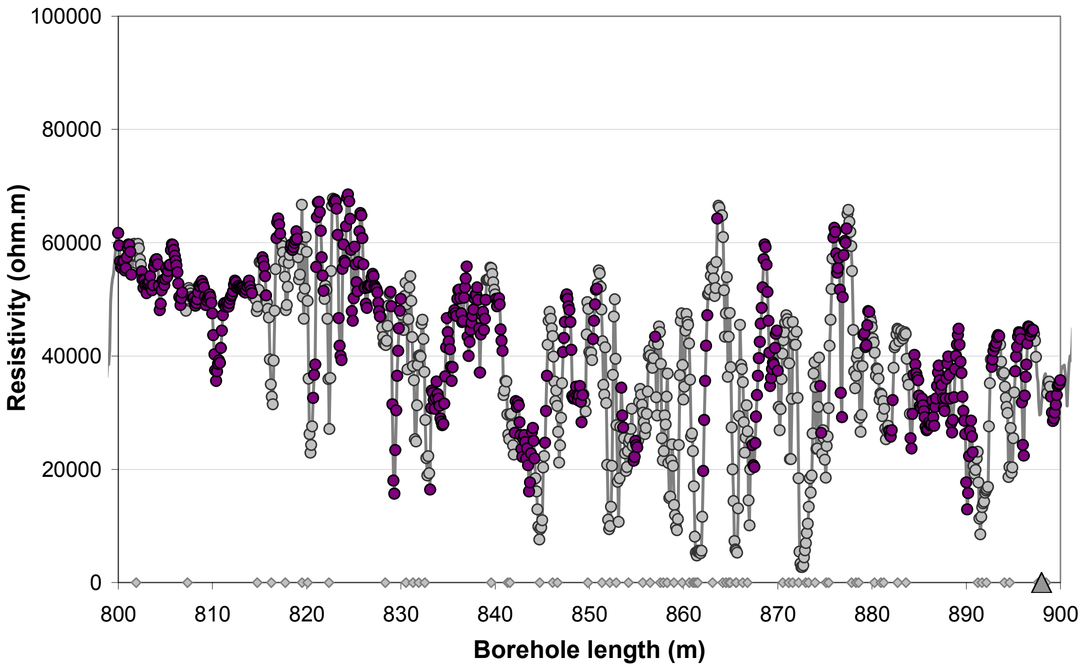
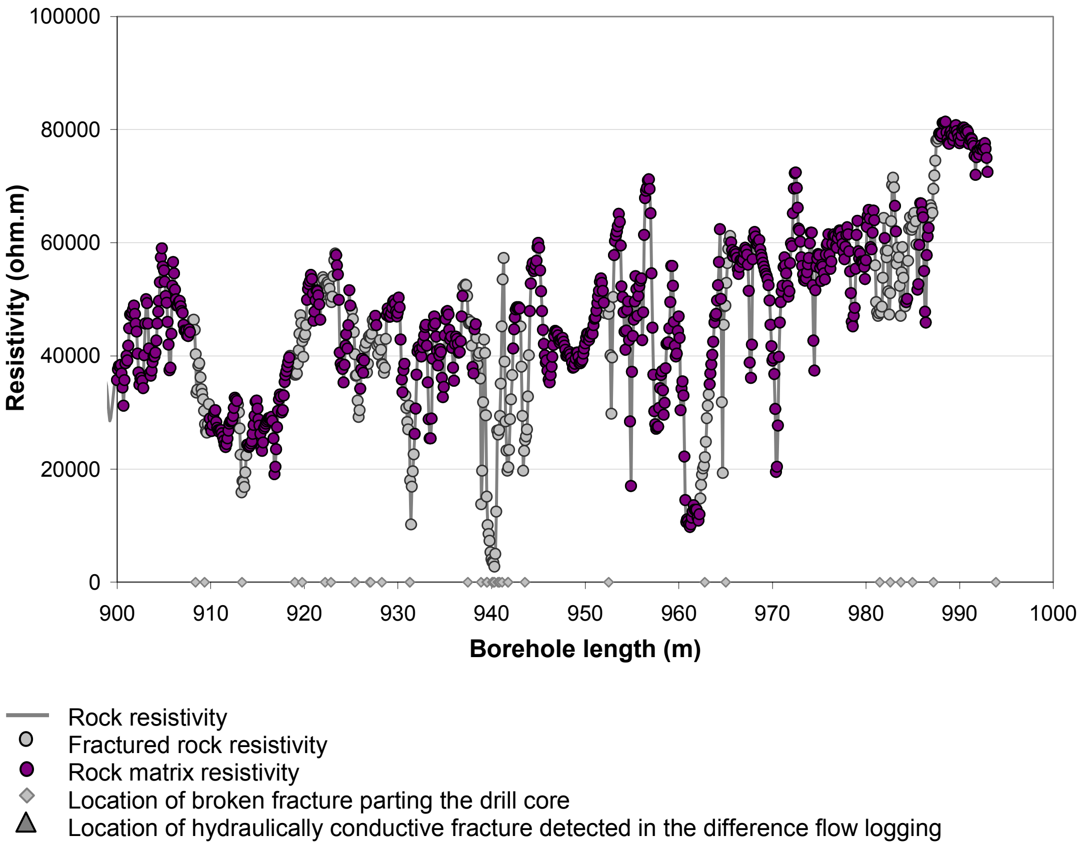
Appendix A1: **In-situ rock resistivities and fractures KLX05**



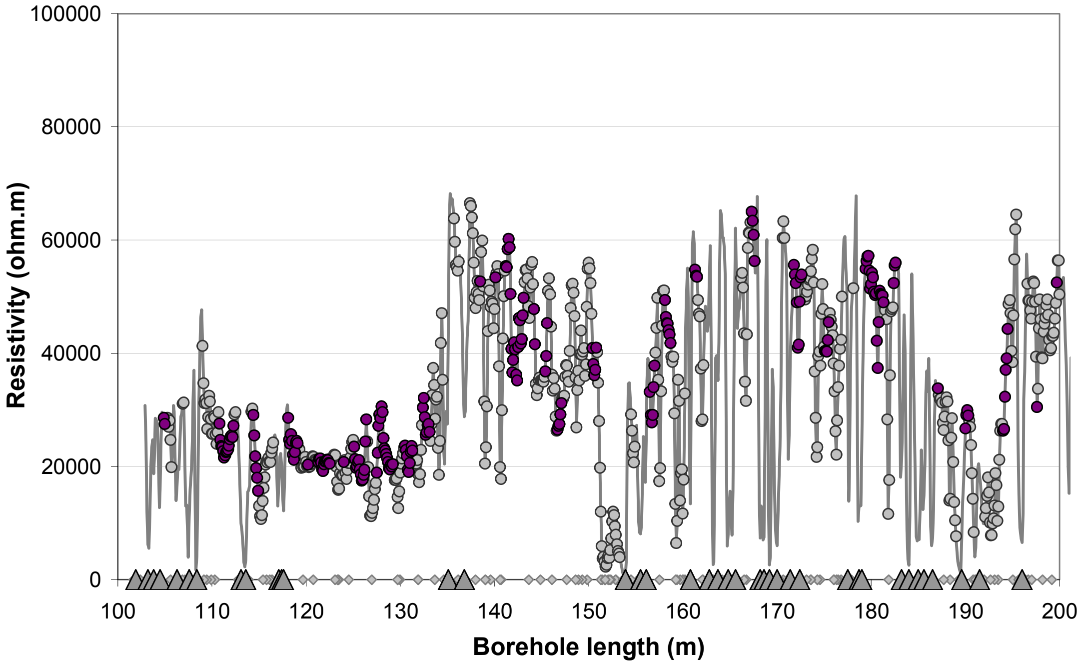


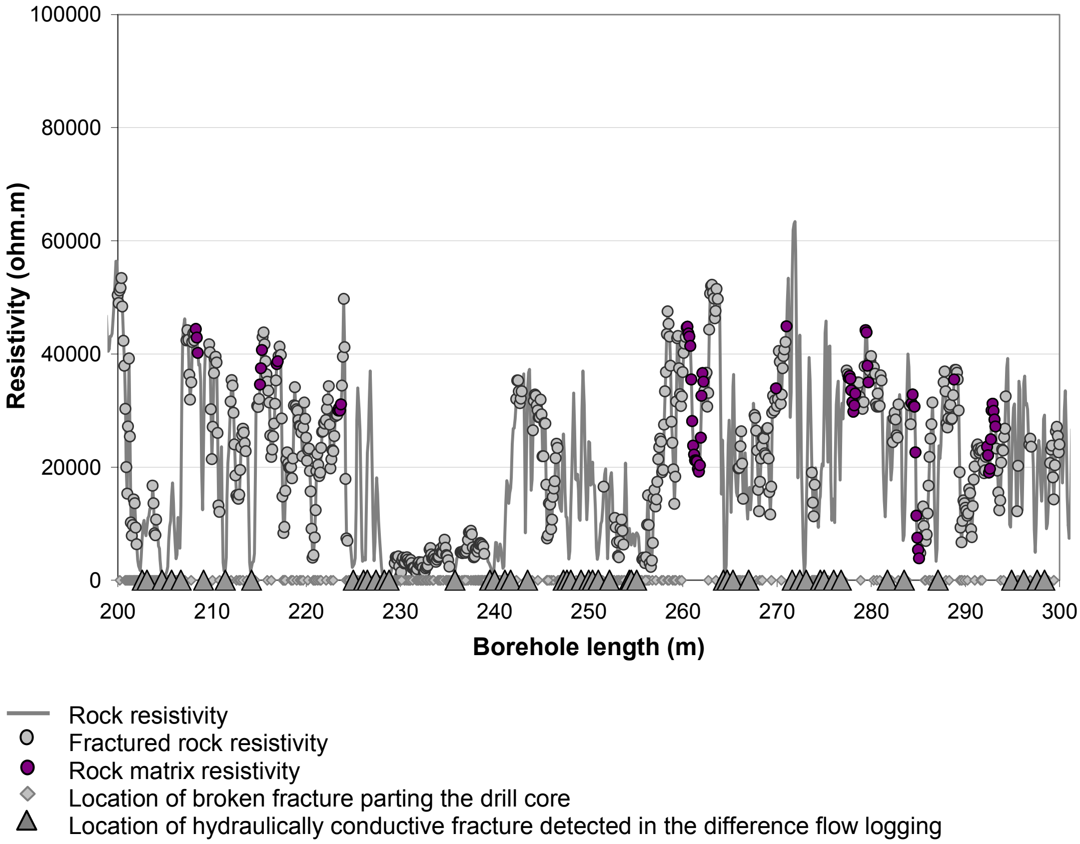
- Rock resistivity
- Fractured rock resistivity
- Rock matrix resistivity
- Location of broken fracture parting the drill core
- Location of hydraulically conductive fracture detected in the difference flow logging

Appendix A1: **In-situ rock resistivities and fractures KLX05**

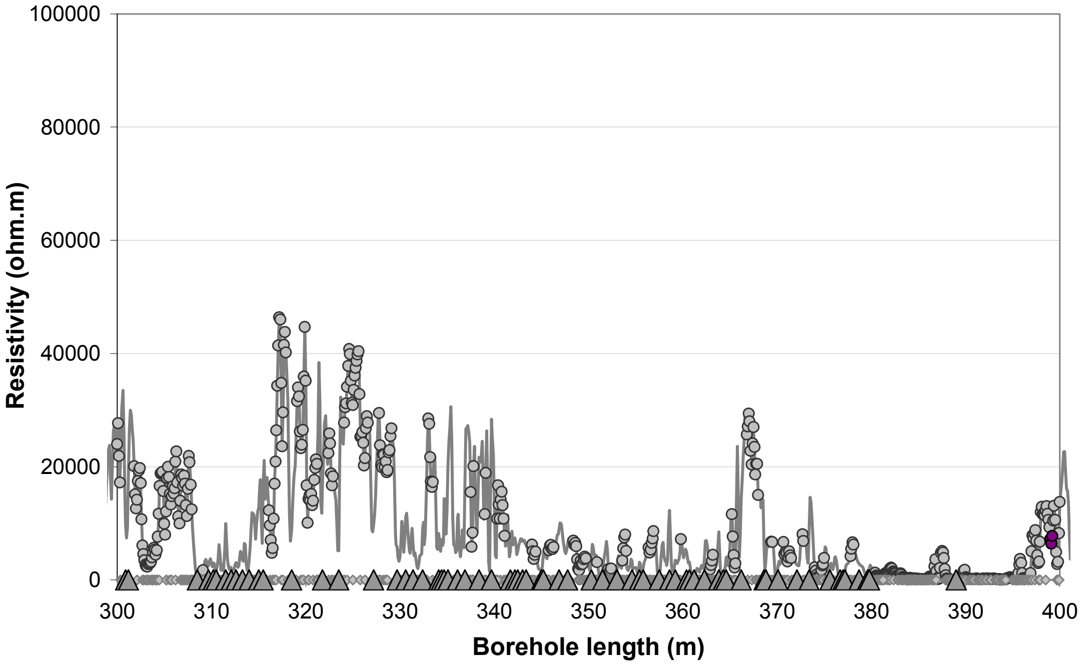


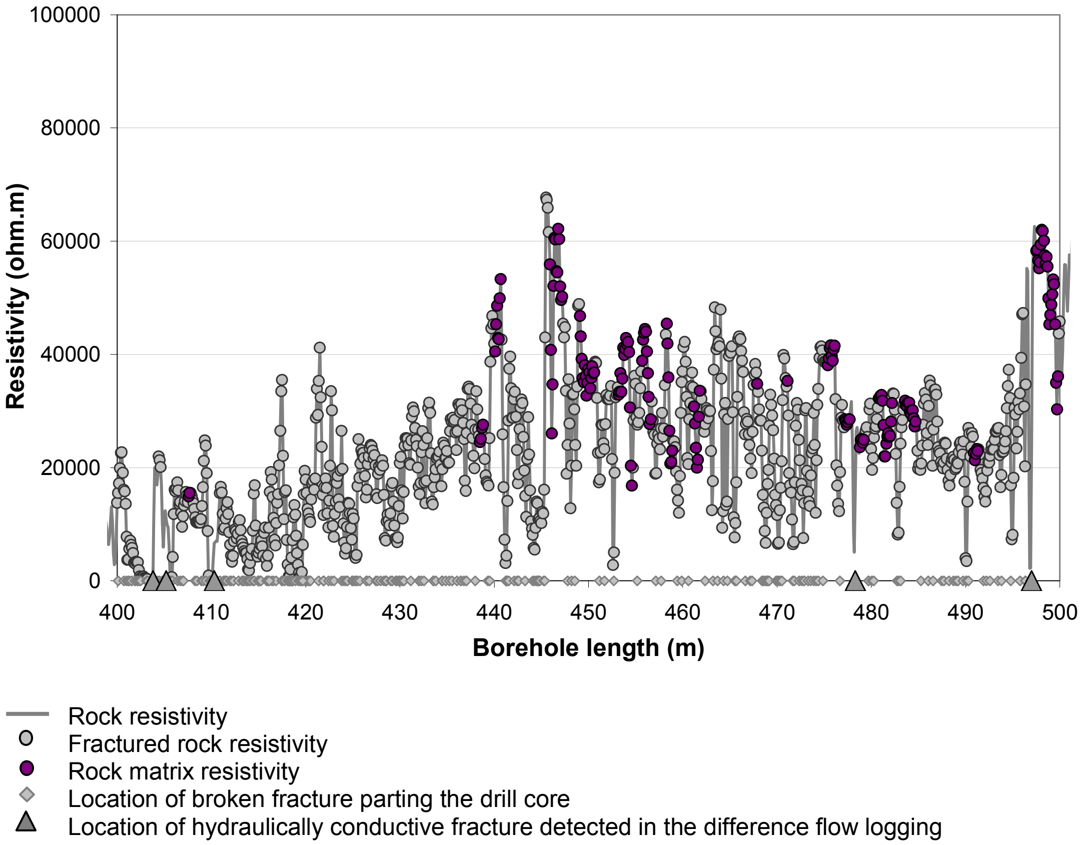
Appendix A2: In situ rock resistivities and fractures KLX06



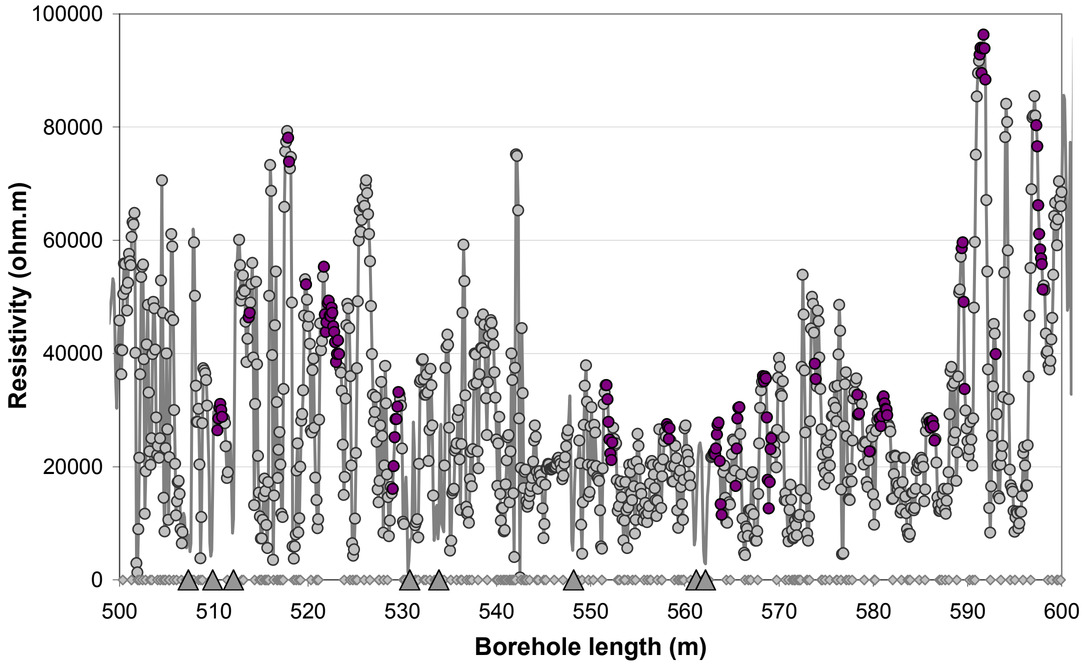


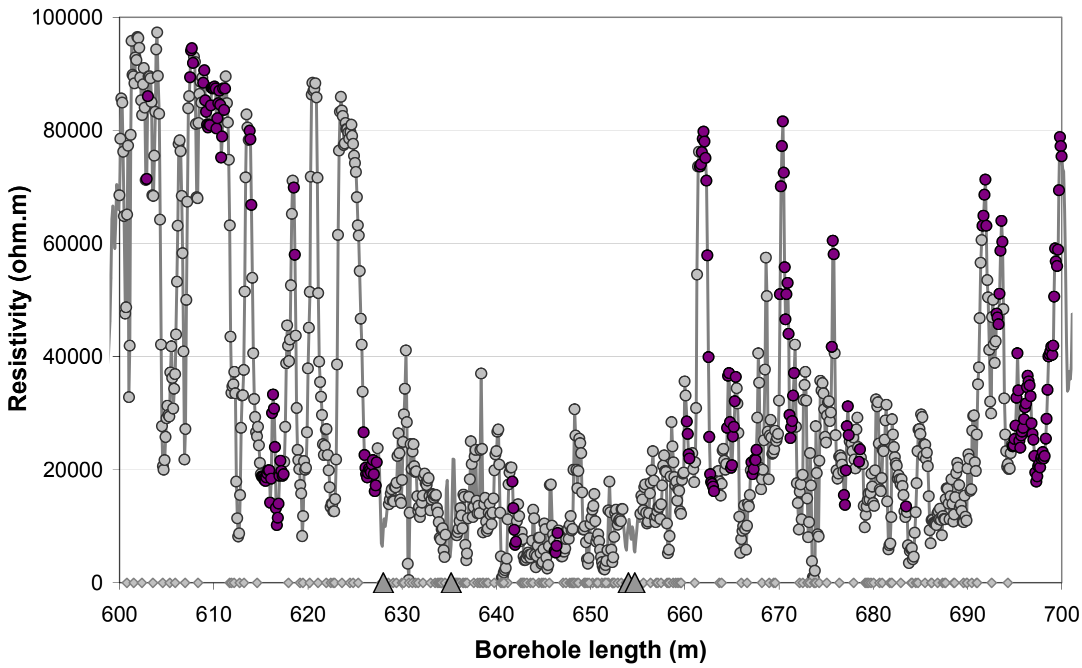
Appendix A2: **In-situ rock resistivities and fractures KLX06**





Appendix A2: **In-situ rock resistivities and fractures KLX06**





- Rock resistivity
- Fractured rock resistivity
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- Location of broken fracture parting the drill core
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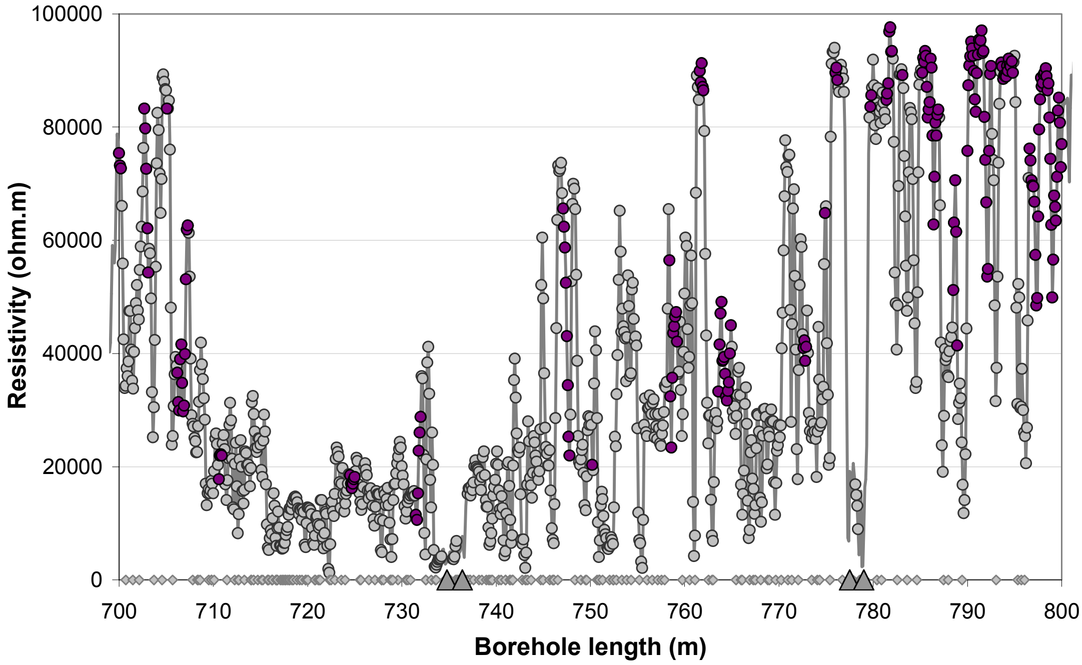
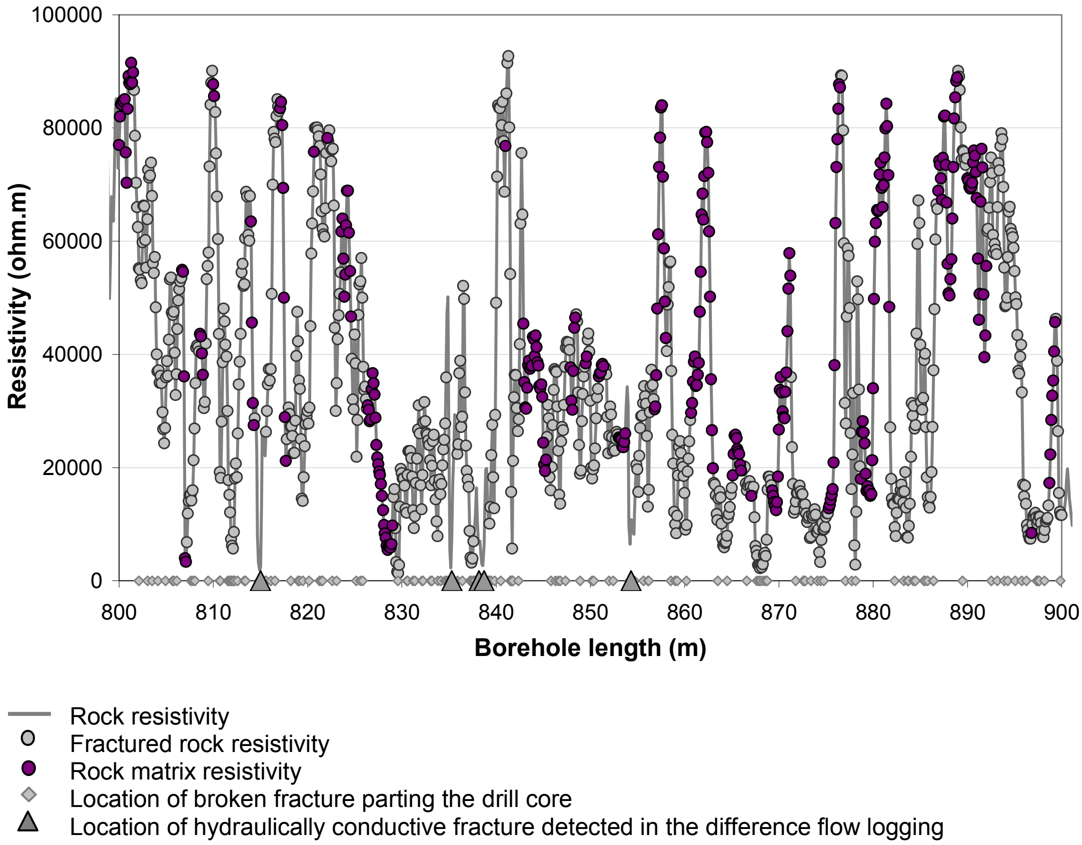
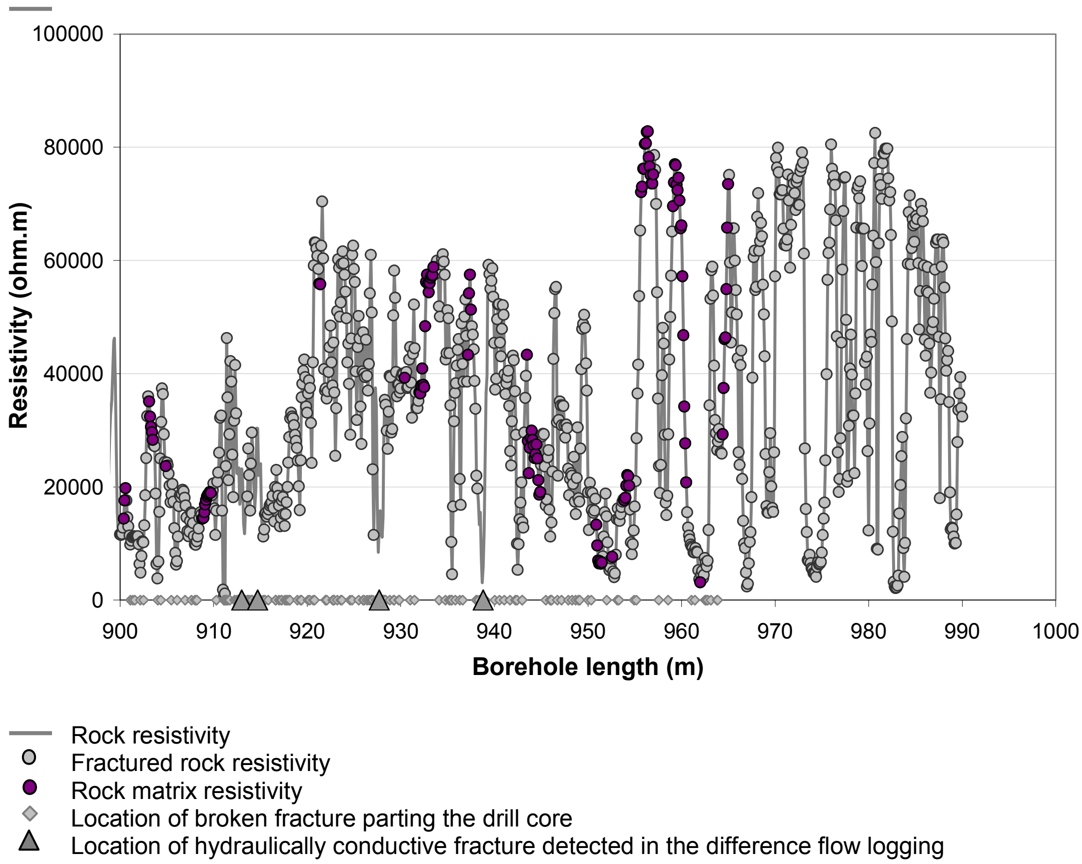
Appendix A2: **In-situ rock resistivities and fractures KLX06**



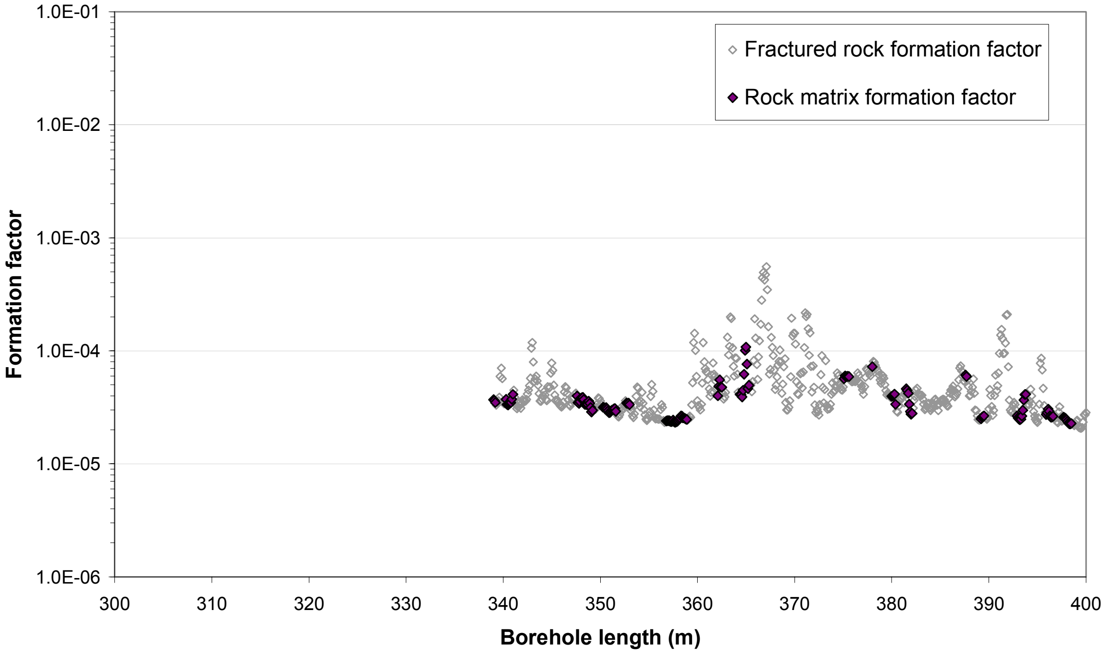


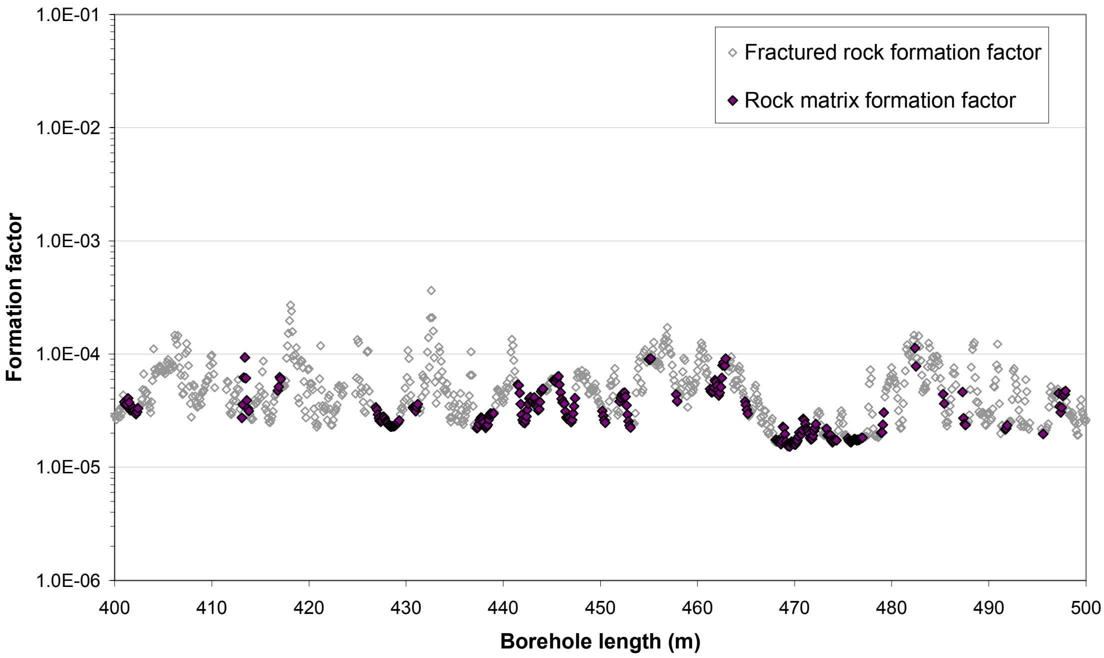
Appendix A2: **In-situ rock resistivities and fractures KLX06**



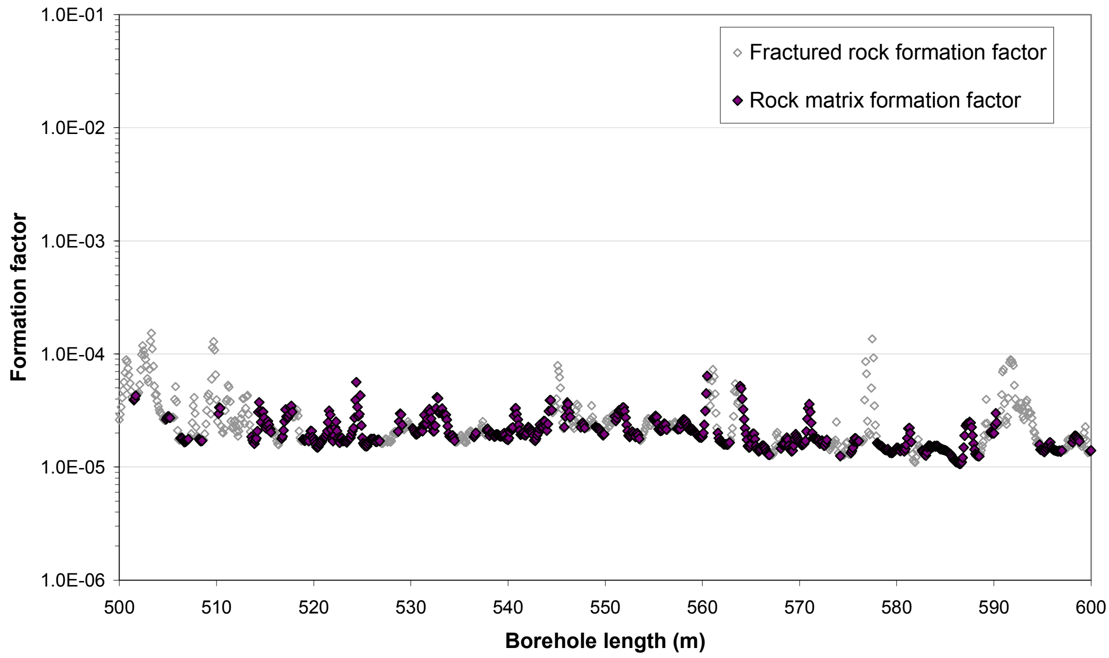
Appendix B

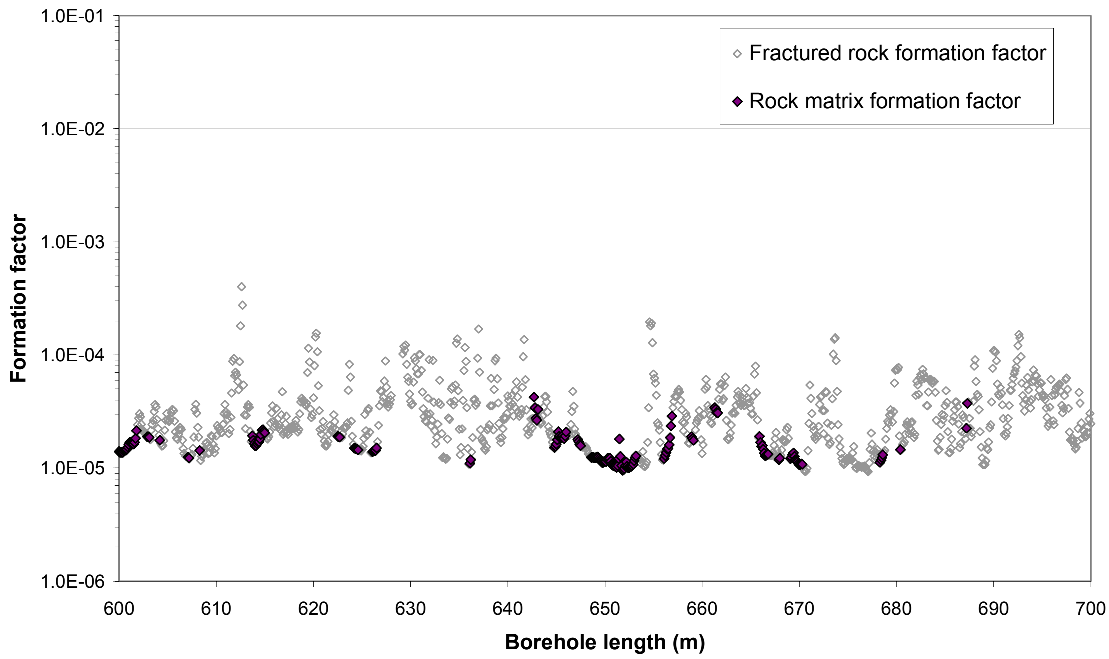
Appendix B1: In situ formation factors KLX05



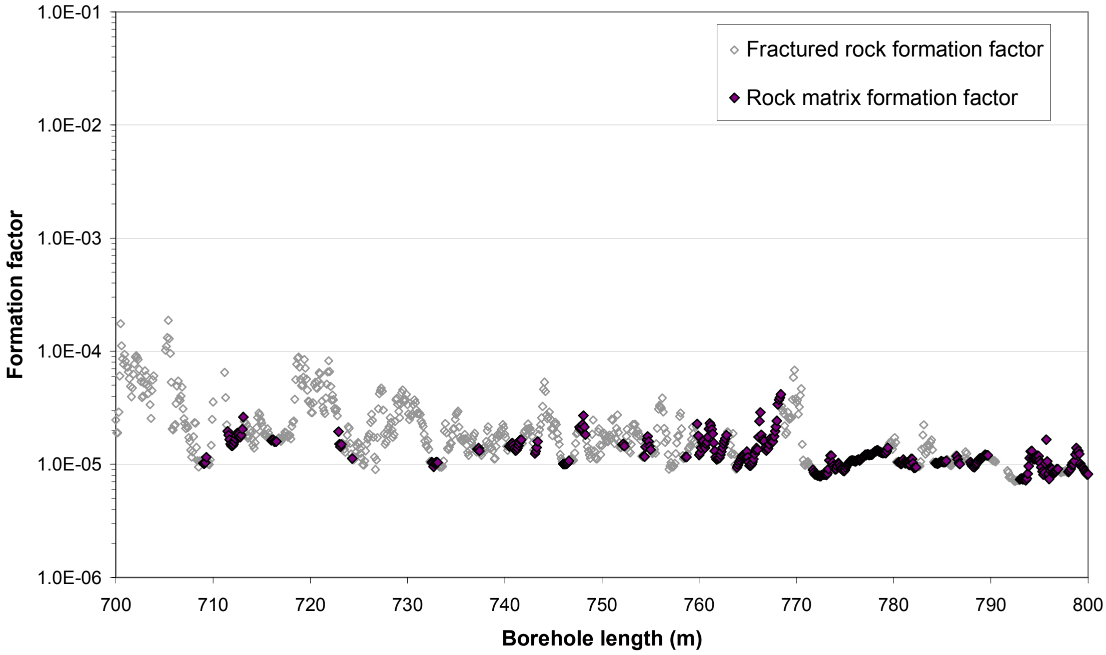


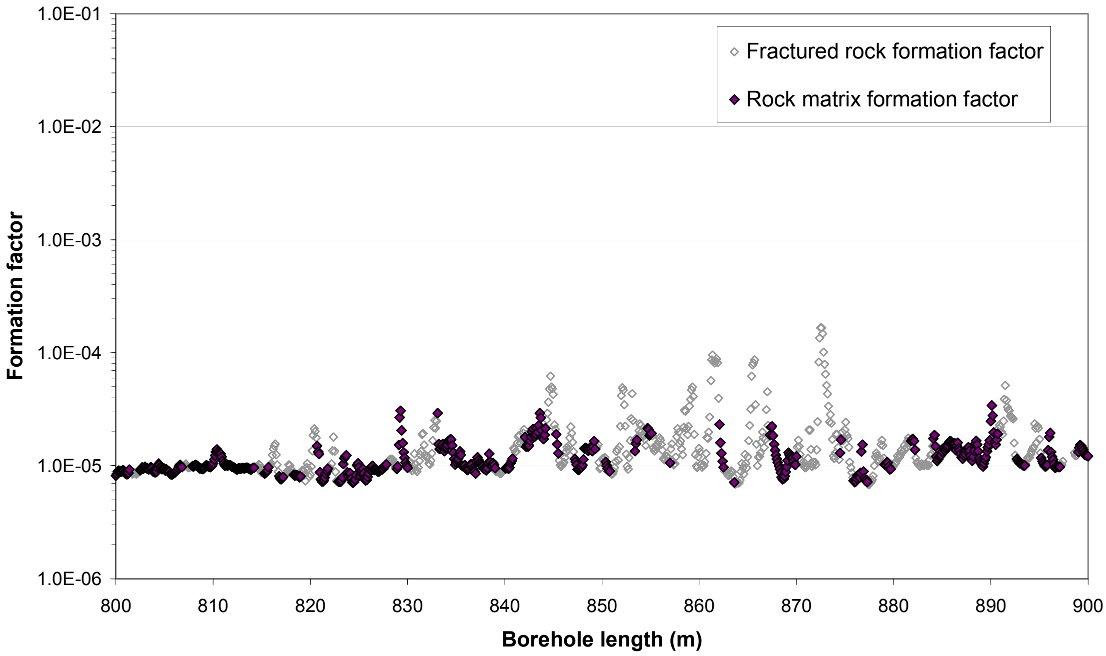
Appendix B1: **In-situ formation factors KLX05**



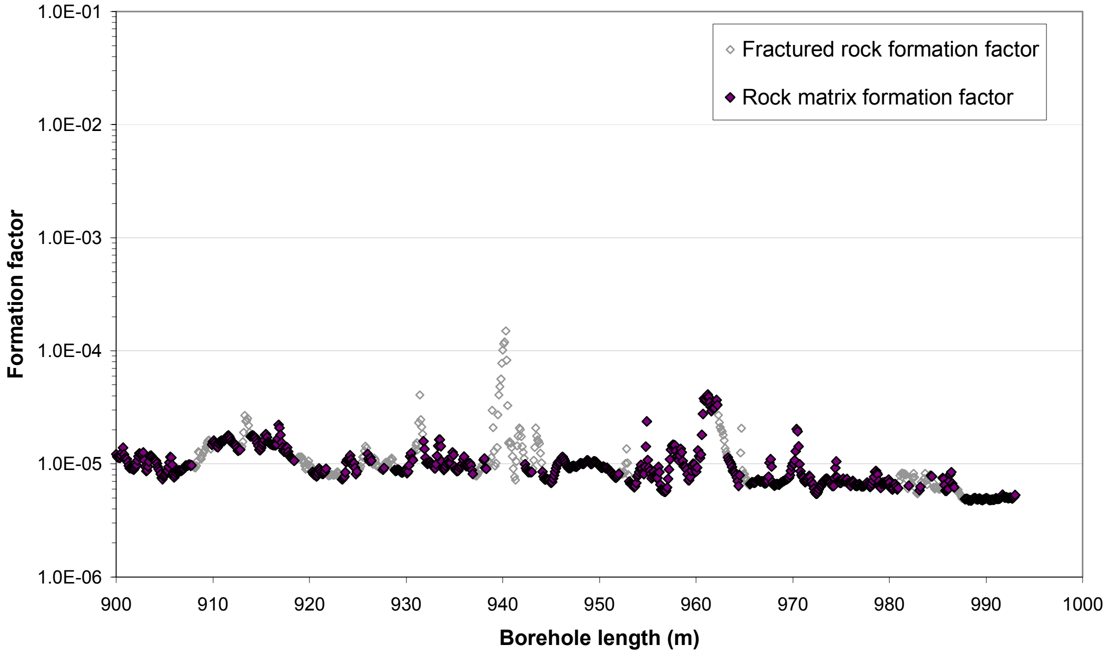


Appendix B1: **In-situ formation factors KLX05**

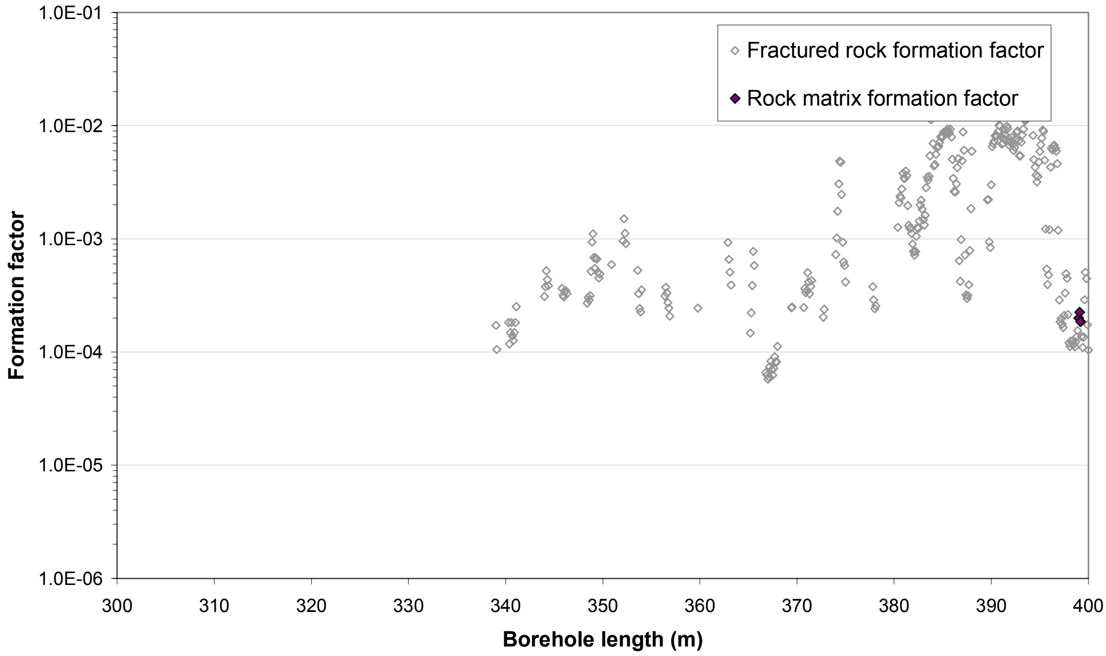


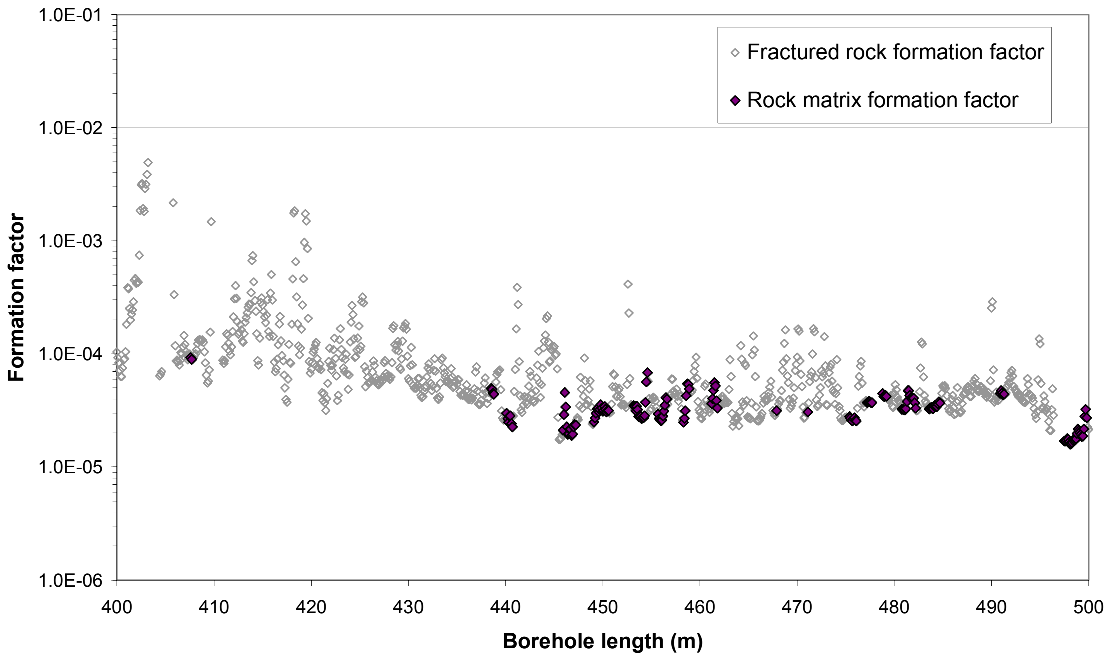


Appendix B1: **In-situ formation factors KLX05**

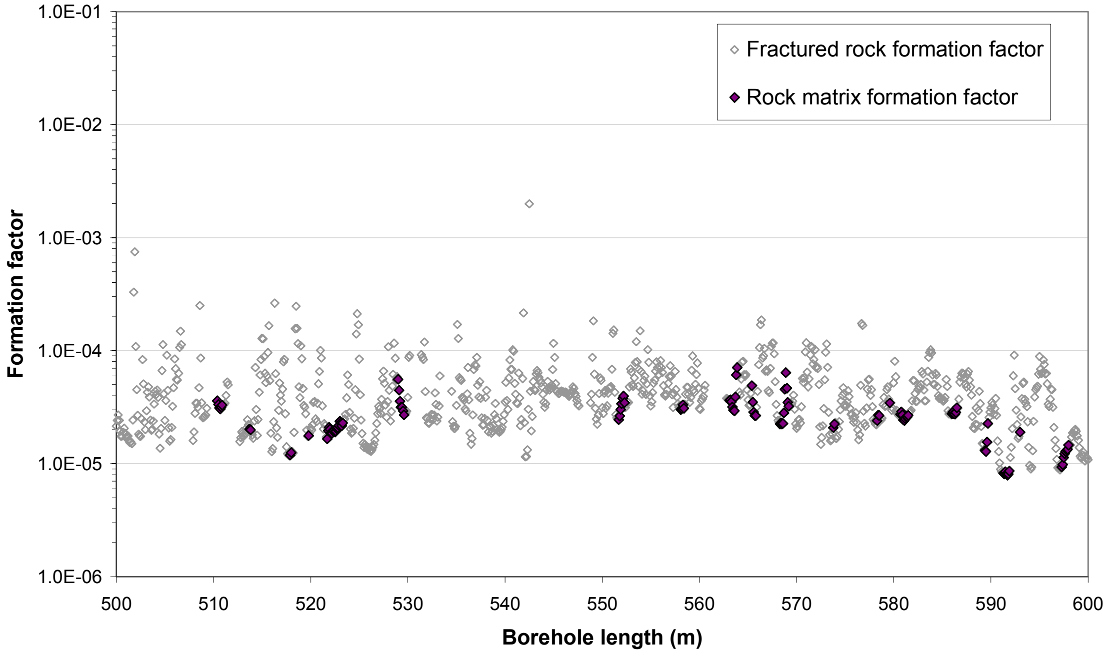


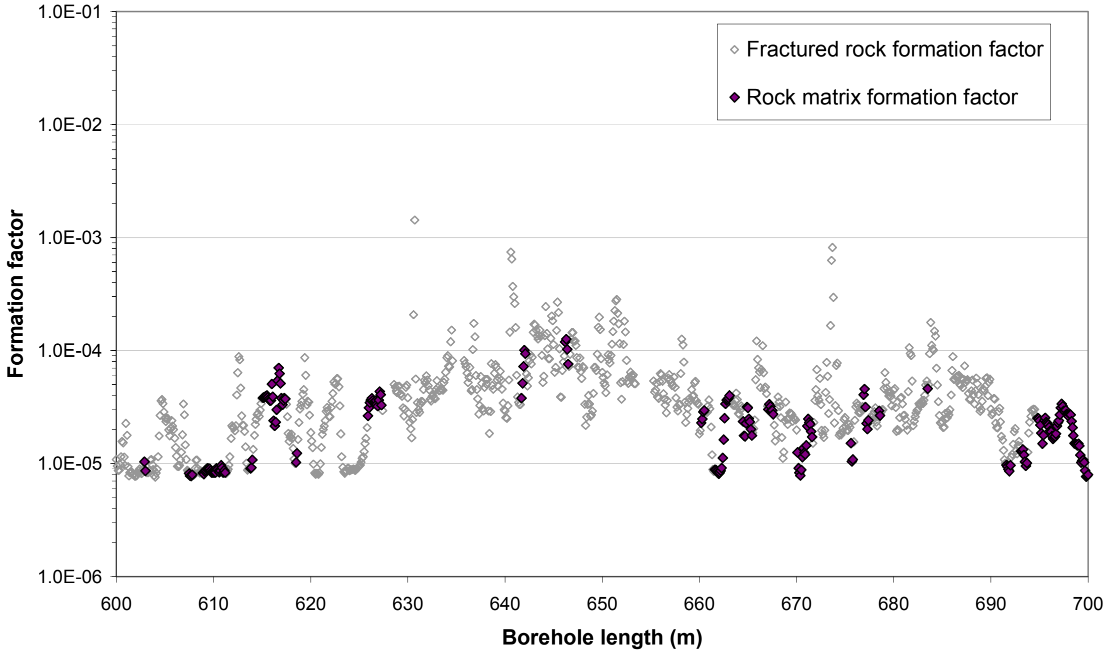
Appendix B2: In situ formation factors KLX06



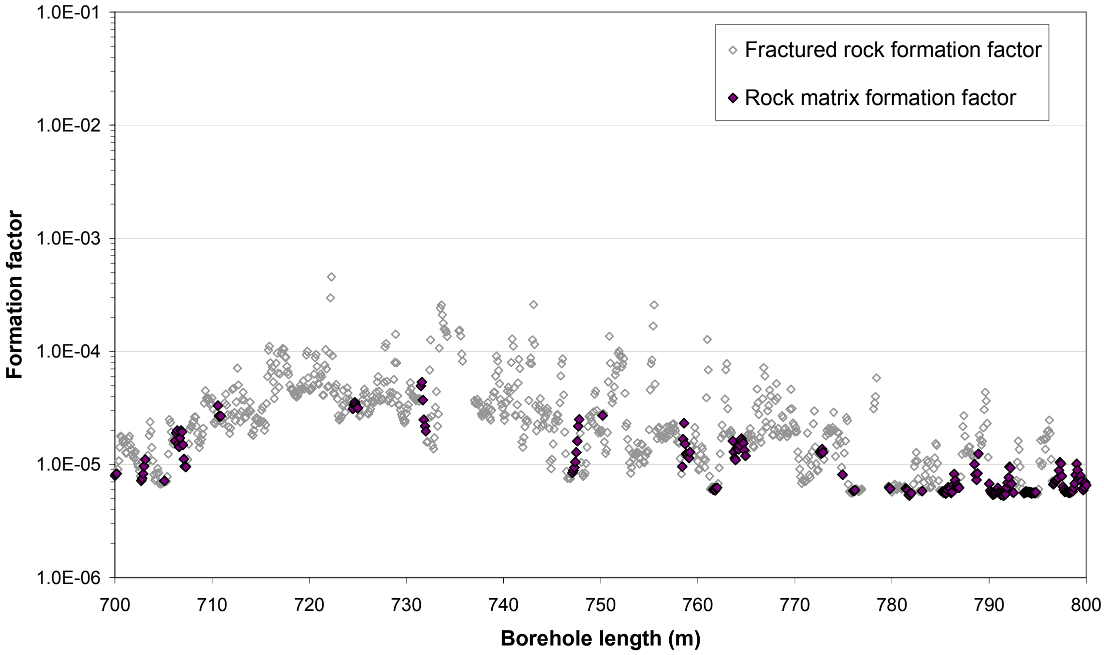


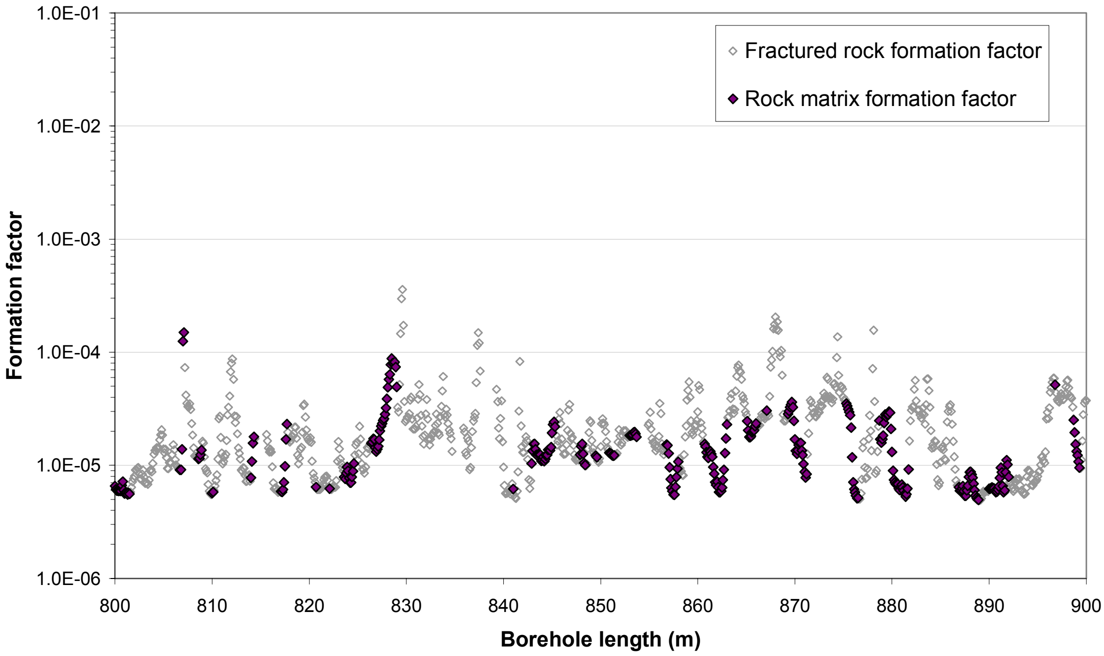
Appendix B2: **In-situ formation factors KLX06**



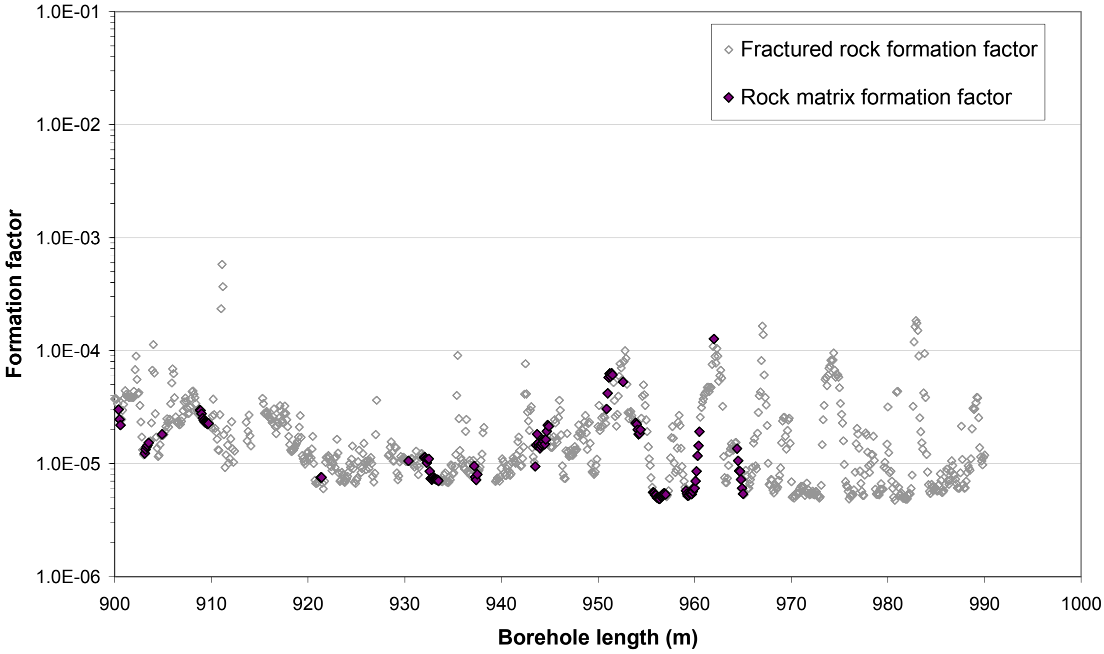


Appendix B2: **In-situ formation factors KLX06**





Appendix B2: **In-situ formation factors KLX06**



Appendix C

Groundwater EC data Laxemar

Borehole	Inclination	Borehole length	Borehole depth	EC 25°C	EC in situ	Method
KLX03	74.9°	195.3	188.6	0.14	0.098	Diff
		196.8	190.0		0.14	HC
		266.8	257.6	0.30	0.21	Diff
		619.4	598.0	1.36	1.13	Diff
		970.3	936.8		2.6	HC
		970.1	936.6	2.87	2.7	Diff
KLX04	84.7°	973.1	968.9	1.72	1.6	Diff
KLX05	65.1°	303.8	275.6	0.56	0.4	Diff
		628.6	570.2	1.56	1.3	Diff
		791.1	717.6	1.31	1.1	Diff
KLX06	65°	196.0	177.6	0.05	0.034	Diff
		377.0	341.6	0.084	0.11	Diff
KLX07A	60°	367.7	318.4	0.16	0.11	Diff
		488.0	422.6	0.48	0.36	Diff