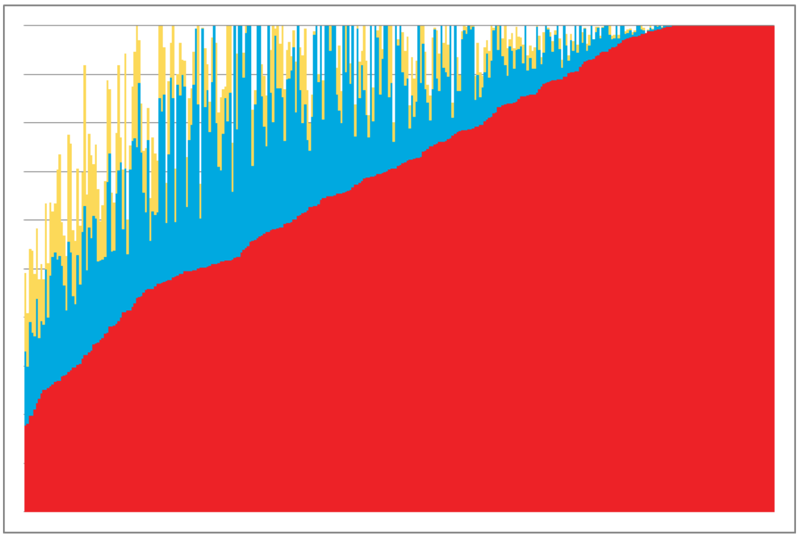

# Does one fracture dominate the borehole transmissivity?

## Investigation of fracture transmissivity in a crystalline rock mass

*Master of Science Thesis in the Master's programme Infrastructural and environmental engineering*


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Cover:
Diagram of transmissivity distribution for data used in the thesis

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## Abstract

When performing construction work in rock below the groundwater table hydrogeology is an important aspect to consider. To reduce inflow of water from the rock mass to an acceptable level sealing of fractures by grouting is needed. In order to make a good grouting design the aperture of the fractures has to be known. The actual fracture aperture varies along a fracture and cannot be measured and therefore the hydraulic aperture, which represents the open part of the fracture where flow can take place, is used. The hydraulic aperture is evaluated from hydraulic tests which are normally performed for sections of several meters at the time. The distribution of flow between the fractures within the tested section thus needs to be known to evaluate the hydraulic aperture.

In this thesis the distribution of transmissivity between the fractures within a section is investigated. The focus of the study is to investigate if the most water-bearing fracture can be considered to contribute to most of the flow. What can be considered to be most of the flow is a question of definition, here two different criterions have been used:

- The largest fracture contributes with 50 percent or more of the total flow in a section, $T_{largest} \geq 50$ %
- The largest fracture contributes with 80 percent or more of the total flow in a section, $T_{largest} \geq 80\%$

It has also been analysed if and how the transmissivity distribution is affected by section length, fracture frequency, borehole orientation, depth and size of total transmissivity.

The analysis is based on a large set of data for transmissivity in individual fractures retrieved from Posiva which is an expert organisation responsible for the final disposal of spent nuclear fuel in Finland. The data represents ungrouted crystalline rock from one test site.

In this study it was found that one fracture does not contribute to 80 percent or more of the total transmissivity. Most of the flow can however be assigned to the most water-bearing fracture for short section lengths if 50 percent or more is considered to be most of the flow. The transmissivity distribution is also found to vary with variations in section length, fracture frequency, borehole orientation, depth and size of transmissivity. All these factor do however not affect the likelihood that the most flowing fracture contributes to most of the total transmissivty even if the distribution of transmissivity is affected.

Key words: Borehole sections, fractures, hydraulic tests, largest fracture, transmissivity, transmissivity distribution.

## Sammanfattning

Nyckelord:

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Per Tengborg

Göteborg, May 2013

Víðir Einarsson and Anna Höglund

# Table of content

## List of Notations

### Roman letters

| | | |
|---|---|---|
| $A$ | [m$^2$] | area |
| $a$ | [-] | geometry constant |
| $b$ | [m] | hydraulic aperture |
| $dh/dl$ | [-] | hydraulic gradient |
| $g$ | [m/s$^2$] | the gravitational acceleration |
| $h$ | [m] | hydraulic head in borehole |
| $h_f$ | [m] | hydraulic head at radius of influence |
| $\Delta h$ | [m] | overpressure in hydraulic head |
| $I_{max}$ | [m] | maximum penetration length (of grout into a fracture) |
| $K$ | [m/s] | hydraulic conductivity |
| $k$ | [-] | shape factor for Pareto distribution |
| $L$ | [m] | section length |
| $\Delta p$ | [Pa] | the grouting overpressure |
| $r_w$ | [m] | radius of a borehole |
| $T$ | [m$^2$/s] | transmissivity |
| $T_{largest}$ | [m$^2$/s] | transmissivity of the most flowing fracture |
| $T_{max}$ | [m$^2$/s] | transmissivity of the most flowing fracture according to Gustafsson (2012) |
| $T_{f,i}$ | [m$^2$/s] | transmissivity from all fractures |
| $T_{tot}$ | [m$^2$/s] | total transmissivity |
| $Q$ | [m$^3$/s] | flow |

### Greek letters

| | | |
|---|---|---|
| $\mu$ | [Pa·s] | fluid viscosity |
| $\tau_0$ | [Pa] | yield strength of grout |
| $\rho$ | [kg/m$^3$] | fluid density |

# 1 Introuduction

Excavation of tunnels in rock can be constructed for various applications. Tunnels can, for example, be road or rail road tunnels, built for transporting water to a hydropower plants or for nuclear waste deposits. There are two main ways of excavating a tunnel in hard rock; the more common drill and blast method and using a tunnel boring machine (TBM).

When construction a tunnel in hard rock the hydrogeology of the area is an important aspect especially working in rock mass below the groundwater table (Hernqvist, 2009). Before a section of the tunnel is excavated, with either drill and blast method or a TBM, there is normally a need to grout the rock mass to reduce the inflow of water to the tunnel. Grouting is a method where grout is injected into the rock mass to seal fractures which reduces the flow of water into the tunnel. How large inflows that are acceptable varies from case to case, for road tunnels in Sweden the inflow requirements should be set so that there is no dripping or running water, the surrounding area is not affected from possible lowering of the groundwater table and so that there are no damages due to freezing (Vägverket, 2004). To fulfil these requirements the flow distribution of the conductive fractures needs to be known in order to find how small fractures that need to be grouted (Gustafson, 2012).

For the grouting to be successful and make the rock mass tighter the grout must be able to penetrate the water-bearing fractures. To be able to make a good grouting design and choose a grout that can penetrate the fractures the fracture aperture needs to be known (Warner, 2004). The fracture aperture varies along a fracture and to assign a theoretical aperture that the grouting can be based on is a complicated task (Gustafson, 2012). Hydraulic aperture can be calculated from the transmissivity which is found through hydraulic tests. The tests performed for infrastructural projects are made for sections of several meters at the time and does not give information about how the flow is distributed amongst the individual fractures. Gustafson (2012) however states that most of the flow from a section can be assigned to the most flowing fracture.

There is a rule of thumb saying that 80 percent of the flow from a tested section can be assigned to the fracture with the largest flow. In this thesis this rule of thumb is interpreted as; *at least* 80 percent of the total flow can be assigned to one fracture. The rule of thumb has not been explicitly stated in writing and therefore cannot be referred to however trying to find trends for transmissivity distribution is a task of hydrogeological interest.

This master thesis is aimed at analysing the distribution of flow within a borehole by looking at a large amount of transmissivity data of individual fractures. This type of data is produced by the hydraulic test method Posiva flow logging (PFL). The method has been developed by the Finnish organization Posiva, responsible for the handling of the Finnish nuclear waste, and can be used to measure the flow in sections as short as ten centimetres. With the assumption that there is not more than one fracture per ten centimetres the flow from each fracture in the tested borehole can thus be measured and the distribution of flow between the fractures can be evaluated.

Getting a better understanding of the transmissivity distribution in the rock mass can lead to a better basis for grouting design. An optimization of the grouting design can have economic gains if smaller volumes of grout can be used, better choice of grout for penetration in the fractures can be made, post grouting can be avoided and maintenance work can be minimized.

## 1.1 Aim and scope

The overall aim of this thesis work is to investigate the transmissivity distribution of individual fractures in boreholes. The investigation focuses on the contribution of the most water-bearing fracture to the total flow of a section.

The rule of thumb previously mentioned saying that 80 percent of the flow in a section can be assigned to the fracture with the highest flow, as well as the statement the largest fracture in a section has a transmissivity of the same order of magnitude as the total flow, will be analysed by using a large set of data.

What can be considered to be most of the flow is a question of definition. In this thesis the most water-bearing fracture is said to represent most of the flow if it contributes with at least 50 percent of the total flow.

The aim of the analysis carried out is to investigate if a trend can be found for the two statements:

- The largest fracture contributes with 50 percent or more of the total flow in a section, $T_{largest} \geq 50$ %
- The largest fracture contributes with 80 percent or more of the total flow in a section, $T_{largest} \geq 80\%$

The statements are analysed with respect to the following factors:

- Length of the tested sections.
- Fracture frequency.
- Borehole orientation; horizontal and vertical boreholes.
- Depth of the tested sections.
- Size of the total flow in the tested sections.

## 1.2 Limitations

This thesis considers crystalline rock only, as all the data as well as the Swedish bedrock is dominated by crystalline rock. Not crystalline rock in general.Only ungrouted rock mass is considered. The data used is from one test site and represents good quality rock why is it a drawback to have only one site.

The flow in a rock mass depends on the fracture system which is highly related to the geology. The type of bedrock of the individual boreholes is not considered, only the general geology of the area is presented.

Sections without flowing fractures were not included as they do not provide relevant data for the study.

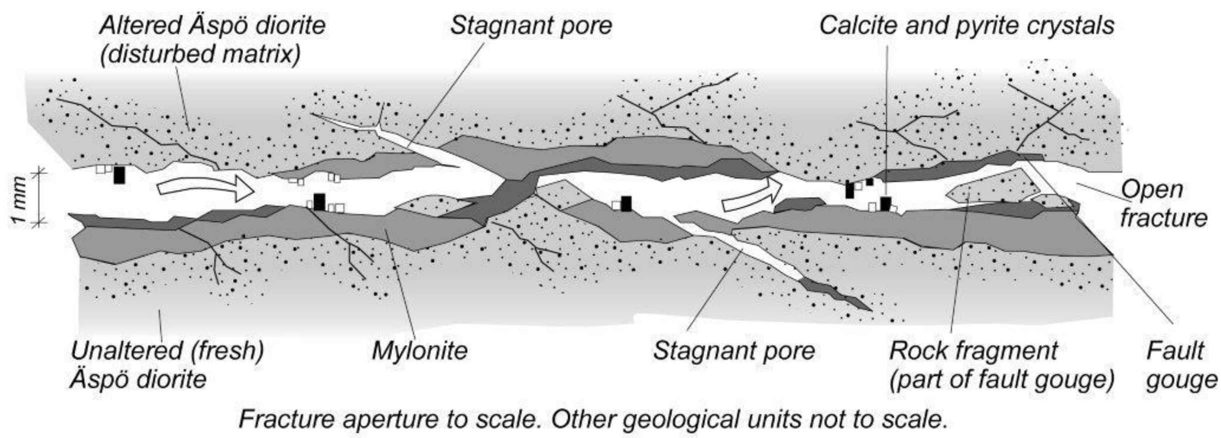
The independent flow of fracture.

# 2 The rock mass

The bedrock in Sweden is dominated by Precambrian crystalline rock formed between the formation of the Earth and about 545 million years ago. (SGU, 2008). Crystalline rock is typically hard and fractured (Gustafson, 2012) and consists of a matrix of blocks divided by fractures. The rock mass has been subjected to stress of different origin such as stress from tectonic movements, thermal stress due to cooling and lithostatic stress due to changes of weight of the overburden (NRC, 1996). When the stress is higher than the strength of the rock fractures are formed. Old rock usually has a complex deformational history since it has gone through many deformation events.

The porosity of a rock is of two kinds; primary and secondary porosity (NRC, 1996). The primary porosity is represented by the voids in the rock matrix while the secondary porosity is represented by the open fractures. The dense rock matrix of crystalline rock is largely impermeable and the primary porosity is low, hence the flow of water in the rock mass takes place in the fractures of the rock. Studying hydrogeology in crystalline rock is therefore largely about studying flow in fractures (Gustafson, 2012).

The stress fields a rock has been subjected to affect the orientation of the fractures to some extent and therefore fractures often occur in sets. The fractures in the same fracture set often have the same orientation (NRC, 1996). Geological origin of fractures influences the hydrological properties. The fracture surfaces are rough, hence the aperture varies along a fracture. There are contact points where stress can be transferred between the fracture walls. Fractures can be assumed to be partly filled by fracture fragments and minerals from when the fracture was formed as well as minerals precipitated from the groundwater (Gustafson, 2012). A schematic figure of a fracture can be seen in Figur 2-1. The openness of fractures also depends on the stress in the surrounding rock mass which increases with depth as the amount of overlying rock mass increases and on fracture orientation in relation to the orientation of the largest rock stress.




Figur 2-1: Schematic picture of a partly filled fracture with rough surfaces. Figure modified after Winberg et al. (2000).

To be of hydrogeological interest fractures must be conductive (Gustafson 2012). For a fracture to conduct water it needs to be connected to a fracture system in which water can flow (NRC, 1996). The fracture network has higher connectivity if the fracture frequency is high, fracture apertures are wide, fractures are large and their orientation is optimal (Singhal and Gaupta, 1999). To get accurate hydraulic property data the flow geometry of the fracture network needs to be considered (Fransson, 1999). Fracture orientation and connectivity are factors affecting the flow dimension in a rock mass. If the water flow is channelized within a fracture it is said to be one-dimensional whereas it if flows along a fracture plane it is said to be two-dimensional (Hernqvist, 2009). In a well-connected fracture network with fractures of varying orientation where the flow spreads spherically it is said to be three-dimensional.

To simplify calculations and modelling of fracture flow the fractures are assumed to be plane and have parallel surfaces. The hydraulic aperture, *b*, represents the open part of a fracture where flow can take place and is defined by the hydraulic properties of the fracture (NRC, 1996). Hydraulic aperture is used since the actual fracture aperture varies along the fracture and is not possible to measure (Gustafson, 2012). It is thus a simplification of the reality where the distance between the fracture surfaces is assumed to be the same as the mean aperture of the open part of the fracture.

In a homogeneous porous medium the flow can be described with hydraulic conductivity, *K*, and this is also used for rock mass in spite of inhomogeneous properties. The hydraulic conductivity describes the flux of unit gradient per unit of the cross section area. The conductivity can be found through equation 2.1.

$$Q = -KA \cdot \left(\frac{dh}{dl}\right) \qquad \text{(eq. 2.1)}$$

where $Q$ is the flow of water through the cross section $A$ and $dh/dl$ is the hydraulic gradient. The ability of a fracture to transmit water is described by the transmissivity, $T$, which can be used to obtain information about the hydraulic apertures of fractures (Hernqvist, 2009). Transmissivity is the product of the conductivity and the thickness of the aquifer, $b$, and is calculated according to equation 2.2.

$$T = K \cdot b. \qquad \text{(eq. 2.2)}$$

From the transmissivity the hydraulic aperture, *b*, can be calculated according to the cubic law (Snow, 1968, de Marsily, 1986, see Gustafson 2012).

$$T = \frac{\rho g b^3}{12\mu} \qquad \text{(eq. 2.3)}$$

where $g$ is the gravitational acceleration, $\rho$ is the fluid density and $\mu$ is the fluid viscosity.

In the rock mass big fracture zones can be found. These zones consist of many fractures and can have very different hydrological properties than the surrounding rock. Fracture zones can have two components a fault core surrounded by a damage zone (Caine, 1996). The damage zone is a fracture network usually with higher permeability than the surrounding rock mass. The fault core consists of a fault gouge, which reduces the permeability across the zone and can act like a fluid flow barrier. A fracture zone does not have to consist of both components and the extent of each component can vary. This means that different fracture zones can have very different characteristics. Due to the high water-bearing capacity fracture zones are an important hydrogeological issue when dealing with construction in rock below the groundwater table (Gustafson, 2012).

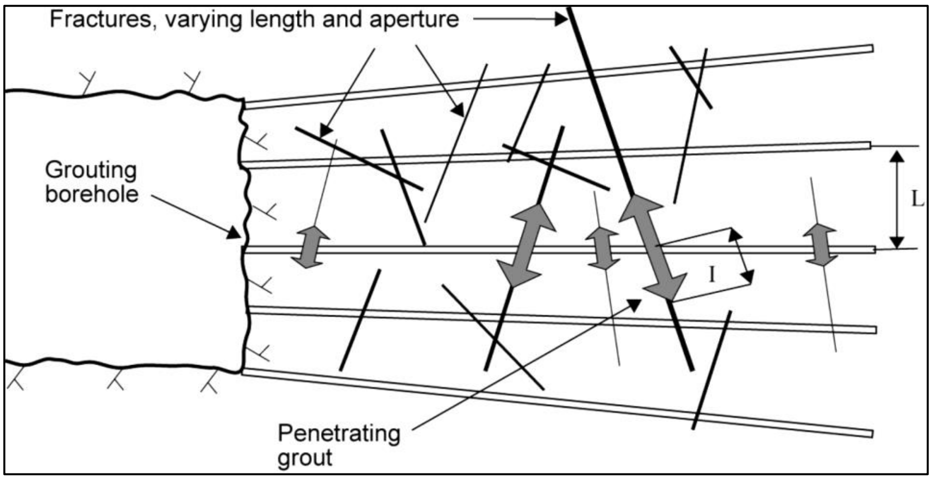
# 3 Tunneling and grouting

The drill and blast method has been used for a long time for underground excavation in hard rock. The drill and blast method is a continuous cycle that is divided into four major operations: drilling and charging, ventilation, loading and hauling and finally scaling and rock support (Zare and Bruland, 2007).

In tunnel constructions there are normally strict regulations regarding inflow of water. Inflow requirements are set with regards to the function of the tunnel, environmental restriction and to limit effects on the surrounding area (Vägverket, 2004). To fulfil these regulations sealing of fractures by grouting is necessary. In order to make a good grouting design and achieve a tight sealing it is crucial to understand the properties of the rock mass, such as the size and spacing of joint and fracture apertures (Warner, 2004).

The function of the grout is to fill the fractures and thereby hinder water flow (Warner, 2004). To achieve good grouting an appropriate grout must be chosen. There are two main types of grout, cementitious grouts and chemical solution grouts. The most commonly used is cementitious grout, which is a mixture of cement and water but may also contain chemical admixtures and fillers (Warner, 2004). Chemical solution grouts can be composed of different chemicals but common for these grouts is the absence of grains, which makes injection into small fractures possible. In selection of grout it is important to consider the fracture aperture since cementitious grout can only penetrate fractures with an aperture magnitude of three to five times the maximum grain size (Warner, 2004). The viscosity, $\mu$, and yield strength, $\tau_0$, of the grout are parameters affecting the penetrability and are thus important to describe.

For a rock mass to be sealed the grout must penetrate into the fractures to a sufficient length. The penetration length should be at least half the distance between the boreholes that are to be grouted, see Figur 3-1.




Figur 3-1: Grouting penetration with borehole distance L and penetration distance I. Figure after Gustafson and Stille (2005).

The maximum penetration length of a cement grout can be calculated according to equation 3.1 for steady state condition and plane- parallel fractures (Gustafson and Stille, 1996).

$$I_{max} = \frac{\Delta p}{2\tau_0} * b \qquad \text{(eq. 3.1)}$$

Where $I_{max}$ is the maximum penetration length, $\Delta p$ is the difference between the grouting pressure and water pressure, $\tau_0$ the yield strength of grout and $b$ the fracture aperture.

Knowing the maximum penetration length the actual penetration length can be calculated. The equations with which the actual penetration length is calculated are dependent on parameters such as grouting time and grout properties. The spacing of the grouting boreholes should not be too large as a large spacing requires a longer penetration length, which in turns prolongs the grouting time (Warner, 2004).

The assumption that the fractures are plane and parallel causes an underestimation of the necessary penetration length since fractures are in reality winding and have an irregular shape (Gustafson, 2012). It is also important to keep in mind that only fractures intersecting the grouting boreholes can be sealed, hence the orientation of the holes is of importance. In infrastructural projects where the possibility of selecting the stretch of the tunnel based on the fracture orientations is low and an optimization of borehole direction is not commonly done. Small adjustments of the direction could however improve the result (Warner, 2004).

Sealing efficiency can be evaluated by drilling a control hole between two grouted boreholes and measure the water inflow. If the flow of water exceeds the limits another grouting round is needed. Continuous evaluation and modification of the grouting design is needed since there are great variations at most sites (Warner, 2004).

Leakage improvement is not proportional to the cost of the work. The cost of reducing the last ten percent of the flow can be higher than for the first fifty percent (Warner, 2004). Due to this it is important that inflow requirements are not set stricter than necessary and to carefully decide how small fractures needs to be sealed. If the grouting design can be optimized there is a possible economical gain.

# 4 Evaluation of hydraulic tests

Hydraulic aperture can be calculated from the transmissivity which is found through hydraulic tests as presented in Chapter 2. The transmissivity is proportional to the cube of the aperture therefore there is a great difference in transmissivity between fractures of different size.

Hydraulic tests are normally performed for sections of several meters at a time and the transmissivity retrieved from these tests represents the sum of all fractures in that section. An assumption of how the transmissivity is distributed over the section is necessary in order to estimate the hydraulic aperture for single fractures.

Transmissivity measurements are often found to fit quite well to log-normal distribution, except for the higher values where there is normally a deviation from the distribution (Gustafson, 2012). Due to this quite good fit the transmissivity is often assumed to be log-normally distributed. However Gustafson (2012) has found the Pareto distribution to be more suitable. The Pareto distribution is useful when there are many small values and few large ones. According to Gustafson (2012) it can be assumed that the largest fracture in every interval largely dominates the transmissivity of that section which would support the choice of the Pareto distribution. Gustafson (2012) does point out that there might be other suitable distributions and that the Pareto distribution should not be regarded as the only one.

Based on statistical calculations using Pareto distribution Gustafson (2012) has drawn the following conclusions about the relationship between the transmissivity of a section, $T_{tot}$ and the flow from the fracture with the largest flow, $T_{max}$.

- If the shape factor for the Pareto distribution, $k$, and the number of fractures are known $T_{max}$ can be estimated from $T_{tot}$ reasonably well.
- There are few fractures in the section or $k<½$, $T_{max}$ is of the same order of magnitude as $T_{tot}$.
- In sections of heavily fractured rock where $k<½$, $T_{max}$ is still a significant proportion of $T_{tot}$.

In practice it is not feasible to perform thorough measurements and statistical calculations for all boreholes in a project, hence simplified methods of evaluations are needed. Gustafson (2012) states that the largest fracture in a section is responsible for a large part of the total flow. Fransson (2001) also found this to be the case in a field study at Äspö Hard Rock Laboratory. This was also found in Funehag (2009)

# 5 Data

Propose to make a connection to Ch 2 where the rock mass is described for Swedish conditions. However, the tests are made in Finland, Are the tests and results also relevant for Swedish conditions?

The data used in this study is retrieved from Posiva which is an expert organisation responsible for the final deposition of nuclear waste in Finland. The hydraulic tests from which the data is gathered were performed on the island Olkiluoto situated at the west coast of Finland. In this chapter the data and the site it originates from are described briefly and the test method used to collect the data, as well as a test method commonly used in infrastructural projects, are presented.

The study is based on data from hydraulic tests performed with Posiva flow logging (PFL) for boreholes of different orientation. In this data fracture transmissivity for all flowing fractures is given together with the depth of each fracture. Data from borehole image processing system (BIPS) is used to find the total number of fractures in vertical to subvertical boreholes.

## 5.1 Characteristics of the data

The data originates from surface boreholes OL-KR 1-57 and pilot boreholes OL-PH 1 and ONK-PH 2-14. The surface boreholes are vertical to subvertical, the location of the boreholes can be seen in Figur 5-1. They are mostly 300-1000 meters long with total length of over 30000 meters (Mönkkönen et al.,2012). The inclination of the surface boreholes range from 45° to 89° from horizontal with the deepest boreholes reaching over 800 meter down into the rock mass. The pilot boreholes are horizontal to subhorizontal, drilled along a tunnel profile during excavation, and vary in length from several tens of meters to couple of a hundred meters (Posiva Oy, 2003). The inclination of the pilot boreholes range from 4° to 6,5° from horizontal with depth down to 400 meters in to the rock mass.

## 5.2 Local geology of Olkiluoto

The crystalline bedrock of Finland is a part of the Precambrian Fennoscandinavian Shield. The bedrock of Olkiluoto consists mainly of gneiss, veined gneiss and migmatitic gneisses of varying mineral composition and texture (Mattila et al, 2007). The change from rather homogeneous gneisses to magmatic gneiss takes place gradually and no natural borders are identified. The gneiss is cut by narrow diabase dykes steeply dipping to NW (Mattila et al, 2007).


Figur 5-1: Surface boreholes KR 1 – KR 57 at Olkiluoto. The size of the grid squares is 500m x 500m. Figure from Toropainen (2007).

## 5.3 The tests

There are different types of tests used to find the hydraulic properties of rock. Most hydraulic tests are performed between two packers for sections of several meters at the time or a complete borehole and the results therefor represent the total section tested. Shorter sections, down to ten centimetres, can be measured with Posiva flow logging (PFL) which is a test method developed in Finland and that so far only has been used in investigations to find locations suitable for repository of nuclear waste. In this chapter Water pressure tests, which is a common way of measuring flow, and PFL will be described.

### 5.3.1 Water pressure tests (Injection tests)

The aim of the injection test is to determine the hydraulic characteristics of a rock mass adjacent to the tested borehole. Before the test can be carried out approximate steady state pressure should be present in the test section.  The test is then performed by injecting water into the borehole. A constant head is applied in the section and the decrease in flow rate is monitored. After the injection time the recovery time of the pressure is measured in the section (Ludvigson et al., 2007).

The test can be carried out as a single packer test, where the total section from the packer to the bottom of the borehole is measured, or as a double packer test, where a section isolated by two pacers is tested. A schematic picture for a double packer test is illustrated in Figure 5-2. The injection test can be carried out in different measurement scales (e.g. 100 m, 20 m and 5 m) and therefore provides a database of the hydraulic conductivity along the borehole on different scales (Ludvigson et al., 2007).

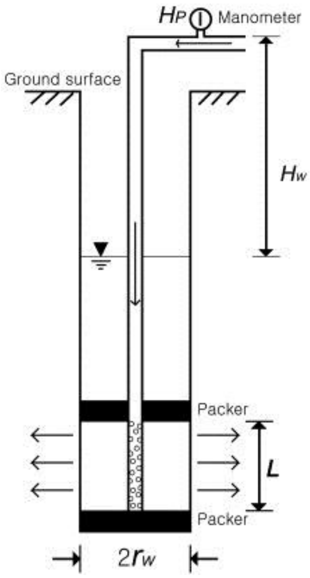



Figure 5-2: Illustration of a packer test from Hamm et.al. (2007)

The main parameter to be determined is the transmissivity. Other information that can be collected with the injection test is the identification of flow regimes and outer hydraulic boundaries (Hjerne et al., 2007).

If the ratio between $L$ and $r_w$ is small that is $L >> r_w$ which is the norm, then equation 5.1 can be used to calculate the transmissivity (Gustafson, 1986, see Gustafson, 2012).

$$T = \frac{Q}{2\pi\Delta h} * \ln(\frac{L}{r_w}) \qquad \text{(eq. 5.1)}$$

Where $T$ is the transmissivity, $Q$ is the flow rate by the end of the flow period, $\Delta h$ is the overpressure above groundwater pressure, $r_w$ the borehole radius and $L$ is the section length

For short duration water pressure test Fransson (2001) has shown that

$T \approx Q/dh$ (eq. 5.2)

is a good estimation of the transmissivity, $T$ where $Q$ is the flow rate and $dh$ is the hydraulic head.

### 5.3.2 Posiva Flow Logging

Posiva flow logging (PFL) is a geophysical logging device used to measure the flow of a borehole in small sections and is designed to detect individual fracture flows (Follin et al, 2011). Two different modes can be used for the PFL, sequential mode and overlapping mode. For location of conductive fractures the overlapping mode is used, which provides information about flow rate and transmissivity of the section. A detailed characterization of the total section is achieved as the device is moved stepwise, normally with a resolution of ten centimetres. When the measured section is small compared to the fracture intensity it can reasonably be assumed that there is no more than one fracture per section (Öhberg et al, 2006).

The device consist of two sets of rubber discs, normally four in the upper end and 6 in the lower end, that isolate the flow of the section of interest (Ludvigson et al., 2002). A schematic picture for a PFL test can be seen in Figure 5-3. To keep the hydraulic head in the borehole constant the flow along the borehole is allowed to pass the test section in a bypass tube without passing the flow sensor (Öhberg and Rouhiainen, 2000). Flow rates into or out of the test section are monitored using thermistors, which track both the dilution (cooling) of a thermal pulse and its transfer by the moving water. The thermal dilution method is used in measuring flow rates because it is faster than the thermal pulse method, and the latter is used only to determine flow direction within a given time frame. Both methods are used simultaneously at each measurement location (Väisäsvaara 2010).

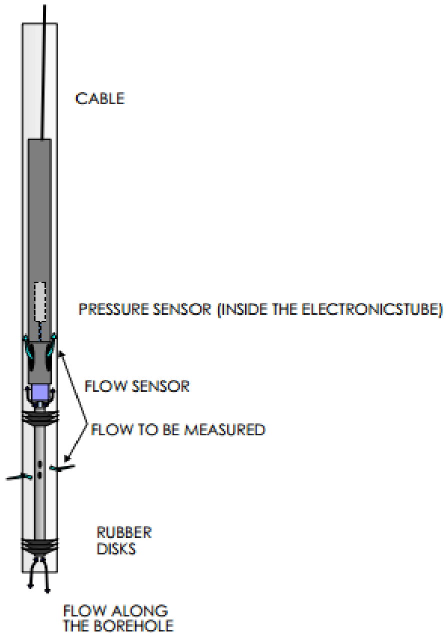



Figure 5-3: Illustration of a Posiva flow logging test from Sokolnicki and Heikkinene (2008)

When the test is performed in a borehole drilled from a tunnel below groundwater level a flow in the borehole will appear due to the pressure difference between the tunnel, with atmospheric pressure, and the pressure in the tested section. If a borehole is drilled from ground surface and down a pressure difference is achieved by lowering the groundwater level. The new groundwater level is kept constant by continuous pumping.

Data from PFL test can be interpreted with Thiem's formula, which assumes steady state and two dimensional radial flows (Thiem, 1906, see Gustafson, 2012).

$$h_f - h = \frac{Q}{T*a} \qquad (5.3)$$

Where $h$ is the hydraulic head in borehole, $h_f$, the hydraulic head at radius of influence, $Q$ is the flow rate, $T$, the transmissivity of the fracture and $a$ is a geometry constant explaine this constant!.

During investigations with the PFL method at Äspö hard rock laboratory in Oskarshamn, Sweden, the flow has been found to be radial most of the time according to Morosini[1]. It has also been found that the skin factor is higher the first meters close to the tunnel opening compared to deeper in the borehole. The skin factor takes the hydraulic communication to the surrounding rock into account (Fransson, 1999) and has to be taken into consideration when evaluating the test results.

Talk about measurement limit.

[1] Mansueto Morosini, Hydrogeologist at Swedish Nuclear Fuel and Waste Management Co (SKB), comunication April 18th 2013.

Talk about steady state time.

# 6 Method

Data was retrieved from Posiva in excel files for PFL measurements and Borehole image processing system (BIPS) data. In the excel files the transmissivity and the location of each flowing fracture is given. The location of the fractures is given in the data both in relation to the distance along the borehole and the depth in the rock mass in meters above sea level. Data that is questionable will be removed and not used, example of that is clusters of neighbouring fractures that have the exact same transmissivity and are located close together, which is regarded as effects of uncertain interpretation of complex data.

The data for vertical and subvertical boreholes is split up in the section lengths 100 m, 50 m, 20 m and 5 m and for horizontal and subhorizontal boreholes in 20 m, 5 m and 3 m. The reason why the boreholes of different orientation were split up in different section lengths is the variations in the data sets. The horizontal boreholes are shorter than the vertical and therefor the longer sections are not used, the 3 m sections are not used for vertical boreholes due to few sections with flowing fractures. Each section defined is seen as a random section and what borehole it originates from is not taken into account.

The cumulative transmissivity for the sections was found by summarizing the flow from each fracture in the PFL data, $T_{tot}=\sum T_{f,i}$. By summarizing the fracture flows an assumption of independent flow in the fractures is made. By comparing the transmissivity from each fracture with the total transmissivity from its section the contribution from every fracture in the section was found. The data was sorted by how large percentage of the transmissivity the largest fracture in each section is responsible for. Sections without flowing fractures were not included as they do not provide relevant data for the study.

To investigate the effects of different factors on the transmissivity distribution the data was split up in different data sets depending on the factors that is to be analysed.

- To investigate the effects of **section length** on the transmissivity distribution the data sets for sections of different lengths were compared, this was done for both vertical and horizontal boreholes.

- **Fracture frequency** was investigated by counting the total number of fractures, both flowing and non-flowing, from the BIPS data for the sections. The data was divided into groups according to the fracture frequency in each section.

- The effect of **borehole orientation** was investigated by comparing the data sets for vertical and horizontal boreholes.

- How the size of transmissivity affects the distribution was analysed by comparing **sections with large and small flows.** This was done by comparing data where all sections are included with data where all sections with a low total transmissivity are excluded.

- The effect of depth on the transmissivity distribution was investigated by dividing the data up after depth below sea-level. Only the sections at the depths 0-50, 50-100, 100-150 and 150-200 meters were analysed.

The analyses was not done for all data sets but only for the ones that had large enough sample size of sections for the respective factors.

When the different factors were investigated a graph was plotted for the largest, second largest and the third largest fracture from each section in a bar diagram, and the sections sorted by the contribution of the largest fracture in percentage. The different sections are presented in tables where sections were grouped after the contribution in percentage of the largest fracture in relation the total transmissivity.

Other factorss included in the analysis of the different data sets are the mean transmissivity and mean number of flowing fractures in the data sets and in the different percentage groups the sections are divided into.

The inclination of the boreholes, see Chapter 5.1, was obtained by using trigonometric formulas. The depth of the first and last fracture and the location of the fractures within the borehole were used for the calculations and the boreholes are thus assumed to be straight.

# 7 Results and discussion

In the following analysis the main focus is on how large share of the total transmissivity, $T_{tot}$, the most flowing fracture, $T_{largest}$, contributes to. Possible influence on number of factors; section length, fracture frequency, borehole orientation, depth and size of total section transmissivity on the transmissivity distribution of the most flowing fracture is studied in this chapter. The transmissivity distribution of the data sets for the respective factors is presented in diagrams and tables. The percentage of sections where one fracture contributes to 50 precent or more of the total transmissivity, $T_{largest} \geq 50\%$, 80 percent and more, $T_{largest} \geq 80\%$, and where one facture represents the total transmissivity, $T_{largest} = 100\%$, is of focus in the analysis.

The contribution to the total transmissivity in percentage from the fracture with the largest, 2$^{nd}$ largest and 3$^{rd}$ largest flow are presented in bar diagrams where each section is represented by one bar. The sections are sorted by percentage of transmissivity of the largest fracture, presented in red, which is of focus in this study. Some diagrams have an angular appearance, this is due to a lower number of sections and hence wider bars than in the smooth diagrams. All diagrams presented in figures in this chapter can be found in a larger version in Appendix, where for each diagram a table is also presented showing what data the diagram is based on. The tables presented in this chapter show the percentage of sections where the contribution from the most flowing fracture in the ranges $T_{largest} \geq 50\%$, $T_{largest} \geq 80\%$ and $T_{largest} = 100\%$ summarises all sections in the diagram for the respective range.

Looking at the diagrams showing transmissivity distributions for the fracture with the largest flow, for all studied factors, which are presented in Appendix 1 and Appendix 2 no general trend is found where one transmissivity percentage is more likely than another, except for the 100 percent which represents the sections with only one flowing fracture. The transmissivity percentage of the most water-bearing fracture ranges between 20 and 100 percent for most of the data sets in between which the distribution is more or less linear. The rule of thumb that exactly 80 percent of the transmissivity comes from the largest fracture cannot be confirmed based on this data.

## 7.1 Section length

The first studied factor is the length of the borehole sections and its effect on the transmissivity distribution. Four diagrams are presented in Figure 7-1, each showing the analysis of one section length. It can be seen that the percentages of sections with $T_{largest} = 100\%$ increase with shorter section length. The behaviour of the transmissivity distribution with variations in section length is similar regardless of borehole orientation, this can be seen by looking at the figures in Appendix 1.9, 1.16, 2.1, and 2.4. In the sections where $T_{largest} \geq 50\%$, $T_{largest} \geq 80\%$ and $T_{largest} = 100\%$ the percentage of sections increase with shorter section length. This is valid for both vertical and horizontal boreholes which can be seen in Table 7-1.

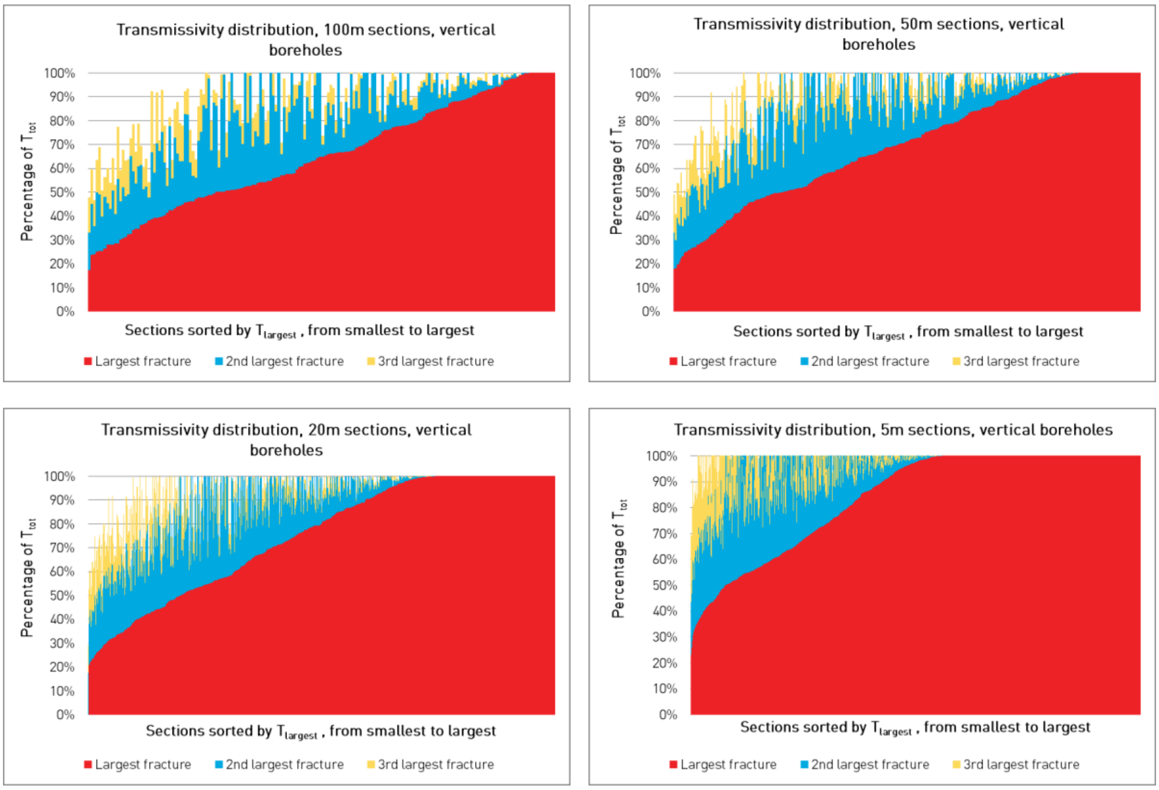



Figure 7-1: Transmissivity distribution for different section lengths, 100m, 50m, 20m and 5m, vertical sections (Appendix 1.1, 1.7, 1.9 and 1.16).

Table 7-1: Percentage of sections with $T_{largest}$ ≥ 50%, $T_{largest}$ ≥ 80% and $T_{largest}$ = 100% for different sections lengths, both for vertical and horizontal boreholes (Appendix 1.1, 1.7, 1.9, 1.16, 2.1, 2.4 and 2.7).

| **Percentage of $T_{tot}$** | **Vertical boreholes** | | | | **Horizontal boreholes** | | |
|---|---|---|---|---|---|---|---|
| | **100m sections** | **50m sections** | **20m sections** | **5 m sections** | **20m sections** | **5m sections** | **3m sections** |
| **$T_{largest}$ ≥ 50%** | 72,78% | 76,67% | 80,23% | 92,57% | 60,00% | 87,79% | 93,48% |
| **$T_{largest}$ ≥ 80%** | 28,89% | 38,79% | 50,15% | 65,28% | 20,00% | 51,91% | 64,13% |
| **$T_{largest}$ = 100%** | 5,56% | 13,33% | 25,44% | 44,18% | 8,89% | 29,77% | 40,76% |

The number of flowing fractures decreases with shorter section length in both vertical and horizontal sections, as can be seen in Table 7-2. This is an expected result since the sections originate from the same boreholes. The decrease in flowing fractures with section length together with the fact that the percentage of sections with $T_{largest} \geq 50\%$, $T_{largest} \geq 80\%$ and $T_{largest} = 100\%$ increase with section length indicates that it is more likely that one fracture is responsible for most of the flow when there are few flowing fractures.

As described in the Method, only the sections with detected flow are included in the data sets. This explains the deviation of the mean number of flowing fractures between different section lengths. Looking at the mean number of flowing fractures in 50 meter and 5 meter vertical sections it would be expected that it would be ten times more fractures in the 50 meter sections than in 5 meter sections if sections with no flow were included. Here the difference between the section lengths is only four times higher. This indicates that the flowing fractures are likely to be clustered together.

Table 7-2: Mean number of flowing fractures for different section lengths, both for vertical and horizontal boreholes (Appendix 1.1, 1.7, 1.9, 1.16, 2.1, 2.4 and 2.7).

| | **Vertical boreholes** | | | | **Horizontal boreholes** | | |
|---|---|---|---|---|---|---|---|
| | **100m sections** | **50m sections** | **20m sections** | **5 m sections** | **20m sections** | **5m sections** | **3m sections** |
| **Mean number of flowing fractures** | 15,38 | 9,1 | 5,01 | 2,2 | 7,67 | 2,86 | 2,09 |

## 7.2 Fracture frequency

Looking at the data presented in Table 7-3 which has been sorted by total fracture frequency it can be seen that the percentage of sections with $T_{largest} \geq 50\%$ is not greatly affected by fracture frequency. However the sections with $T_{largest} \geq 80\%$ and $T_{largest} = 100\%$ decrease with higher fracture frequency. This shows that the fracture frequency affects sections with $T_{largest} \geq 80\%$ and $T_{largest} = 100\%$.

Table 7-3: : Percentage of sections with $T_{largest} \geq 50\%$, $T_{largest} \geq 80\%$ and $T_{largest} = 100\%$ for 5m sections in vertical boreholes sorted by total fracture frequency (Appendix 1.18-1.21)

| **Percentage of $T_{tot}$** | **0-1 fractures / m** | **1-2 fractures / m** | **2-6 fractures / m** | **6-19 fractures / m** | **All sections** |
|---|---|---|---|---|---|
| **$T_{largest} \geq 50\%$** | 95,00% | 95,19% | 91,80% | 89,47% | 92,57% |
| **$T_{largest} \geq 80\%$** | 76,43% | 69,26% | 62,96% | 59,33% | 65,28% |
| **$T_{largest} = 100\%$** | 65,00% | 52,22% | 39,53% | 34,45% | 44,18% |

In Table 7-4 it can be seen that the frequency of total number of fractures and frequency of flowing fractures do not increase with the same intensity. The small changes in number of flowing fractures could be an explanation to the small variation in the sections with $T_{largest} \geq 50\%$.

Table 7-4: Fracture frequency of flowing fractures and total number of fractures for 5m sections in vertical boreholes sorted by total fracture frequency (Appendix 1.18-1.21)

| **Fracture frequency** | **0-1 fractures / m** | **1-2 fractures / m** | **2-6 fractures / m** | **6-19 fractures / m** |
|---|---|---|---|---|
| **Flowing** | 0,31 | 0,37 | 0,48 | 0,51 |
| **Total** | 0,7 | 1,62 | 3,62 | 8,25 |

## 7.3 Borehole orientation: horizontal and vertical boreholes

The boreholes from which the data is gathered are classified as vertical and horizontal where in reality they are subvertical and subhorizontal to some extent. The orientations of the boreholes affect which fractures they intersect, vertical boreholes are more likely to intersect sub horizontal fractures and vice versa. As has been described in Chapter 2 fractures or different origin can be expected to have different hydraulic properties. In the vertical and horizontal boreholes analysed there is a difference in size of transmissivity even though the mean number of flowing fracture is similar, this can be seen in Table 7-5. For 20 meter sections $T_{mean,V} \approx 7 \cdot T_{mean,H}$ and for 5 meter sections $T_{mean,V} \approx 4 \cdot T_{mean,H}$ . This indicates different hydraulic properties between the data sets of different orientation.

Table 7-5: Mean number of flowing fractures and mean transmissivity for 20m and 5 sections of different orientation (Appendix 1.9, 1.16, 2.1 and 2.4).

| | 20m sections | | 5m sections | |
|---|---|---|---|---|
| | **Vertical** | **Horizontal** | **Vertical** | **Horizontal** |
| **Mean number of flowing fractures** | 5,01 | 7,67 | 2,2 | 2,86 |
| **Mean $T_{tot}$** | 3,96E-06 | 5,60E-07 | 1,76E-06 | 4,42E-07 |

The transmissivity distribution of the fracture with the highest transmissivity in horizontal sections is lower than for vertical boreholes, this can be seen in Figure 7-2. When looking at the distribution for sections with $T_{largest} \geq 50\%$ and $T_{largest} \geq 80\%$ in

Table **7-6** it can be seen that the percentage of both ranges are higher for the vertical sections than the horizontal. It can also be seen that the precentage of sections with $T_{largest}$ = 100% is higher for vertical sections than for horizontal ones. The difference between vertical and horizontal sections decreases with shorter section length in sections with $T_{largest} \geq 50\%$, $T_{largest} \geq 80\%$ and $T_{largest}$ = 100%, which can be seen by comparing the results for 20 and 5 meter sections in

Table **7-6**.

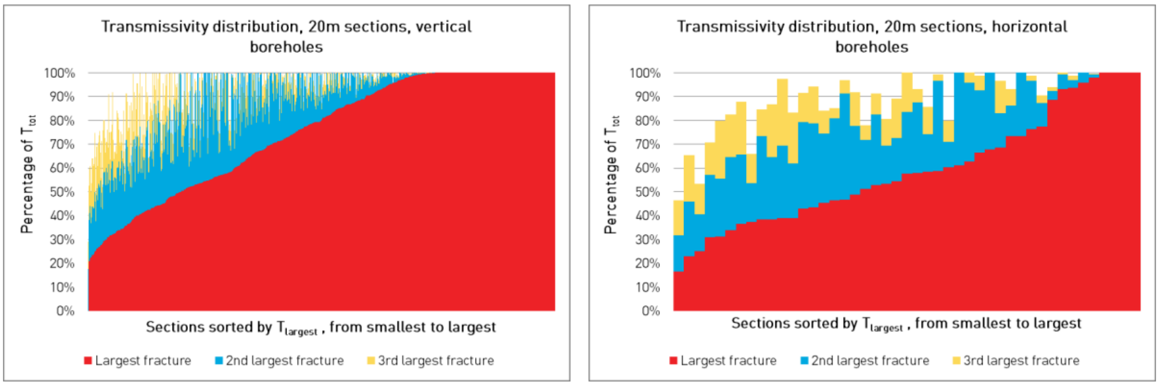



Figure 7-2: Transmissivity distribution for 20m sections with different orientation, vertical on the left and horizontal on the right (Appendix 1.9 and 2.1).

Table 7-6: Percentage of sections with $T_{largest}$ ≥ 50%, $T_{largest}$ ≥ 80% and $T_{largest}$ = 100% for different section lengths of different orientation (Appendix 1.9, 1.16, 2.1 and 2.4).

| **Percentage of $T_{tot}$** | **20m sections** | | **5m sections** | |
|---|---|---|---|---|
| | **Vertical** | **Horizontal** | **Vertical** | **Horizontal** |
| **$T_{largest}$ ≥ 50%** | 80,23% | 60,00% | 92,57% | 87,79% |
| **$T_{largest}$ ≥ 80%** | 50,15% | 20,00% | 65,28% | 51,91% |
| **$T_{largest}$ = 100%** | 25,44% | 8,89% | 44,18% | 29,77% |

## 7.4 Depth

In the data set for vertical boreholes where the sections are split up by depth the percentages of sections with $T_{largest} \geq 50\%$, $T_{largest} \geq 80\%$ and $T_{largest} = 100\%$ increase with depth. This trend is the same for sections of both 5 and 20 meters however the difference between the depths 100-150 and 150-200 meters is smaller than for the more shallow depths, especially for 5 meter sections where the values are more or less the same. This can be seen in the Table 7-7 and Table 7-8.

Rock mass of shallow depth is the most relevant for infrastructural projects as construction depths are normally low. Looking at Table 7-7 it can be seen that at 0-50 meter depth there is a lower percentage of sections with $T_{largest} \geq 50\%$, $T_{largest} \geq 80\%$ and $T_{largest} = 100\%$ than at a deeper depth. The data set for 0-50 meters has the lowest percentage of sections with $T_{largest} \geq 50\%$ of all data sets for vertical sections analysed and the trend is not as strong for one fracture representing most of the flow. This means that at shallow depth the contribution of $T_{tot}$ by smaller fractures is larger than at greater depth.

Table 7-7: Percentage of sections with $T_{largest} \geq 50\%$, $T_{largest} \geq 80\%$ and $T_{largest} = 100\%$ for 20m sections sorted by depth (Appendix 1.11-1.14).

| Percentage of $T_{tot}$ | Depth of 0-50m | Depth of 50-100m | Depth of 100-150m | Depth of 150-200m |
|---|---|---|---|---|
| $T_{largest} \geq 50\%$ | 60,44% | 72,17% | 75,56% | 83,64% |
| $T_{largest} \geq 80\%$ | 31,87% | 39,13% | 44,44% | 49,09% |
| $T_{largest} = 100\%$ | 0,00% | 12,17% | 12,22% | 29,09% |

Table 7-8: Percentage of sections with $T_{largest} \geq 50\%$, $T_{largest} \geq 80\%$ and $T_{largest} = 100\%$ for 5m sections sorted by depth (Appendix 1.22-1.25).

| Percentage of $T_{tot}$ | Depth of 0-50m | Depth of 50-100m | Depth of 100-150m | Depth of 150-200m |
|---|---|---|---|---|
| $T_{largest} \geq 50\%$ | 84,82% | 91,93% | 94,53% | 96,36% |
| $T_{largest} \geq 80\%$ | 44,44% | 62,25% | 70,65% | 70,00% |
| $T_{largest} = 100\%$ | 17,07% | 35,16% | 48,76% | 59,09% |

As found out in Chapter 7.1 the number of sections with $T_{largest} = 100\%$ can be expected to increase as the number of flowing fractures per section decreases and looking at Table 7-9 it can be seen that the number of flowing fractures per section is lower at deeper depth. The decrease in flowing fractures with depth can thus be an explanation to the increase in sections with $T_{largest} \geq 50\%$, $T_{largest} \geq 80\%$ and $T_{largest} = 100\%$.

Table 7-9: Mean number of flowing fractures for 20m and 5m sections sorted by depth (Appendix 1.11-1.14 and 1.22-1.25).

| Mean number of flowing fractures | Depth of 0-50m | Depth of 50-100m | Depth of 100-150m | Depth of 150-200m |
|---|---|---|---|---|
| 20m sections | 11,38 | 6,16 | 3,82 | 3,09 |
| 5m sections | 3,28 | 2,33 | 1,86 | 1,68 |

## 7.5 Sections with large and small total flow

Here the data with all sections is compared to data where the low transmissivity sections are excluded. For horizontal boreholes the limit of what is considered low transmissivity is lower than for the same comparison for vertical boreholes. This choice is made based on the fact that the horizontal boreholes have a lower transmissivity in general. Due to this the vertical and horizontal sections are dealt with separately as the numbers cannot be compared.

### 7.5.1 Vertical boreholes

Comparing the transmissivity distribution between the data set with all sections included and the data set with sections where $T_{tot} \geq 10^{-6}$ in vertical boreholes it can be seen that the distributions are similar in the two data sets. This can be seen in Figure 7-3 where the transmissivity distributions for 100 meter sections is presented as well as in Appendix 1.7, 1.8, 1.9, 1.10, 1.16, 1.17 for all section lengths.

Looking at the percentages of sections with $T_{largest} \geq 50\%$ and $T_{largest} \geq 80\%$ in both data sets they are also found to have similar values which can be seen in

Table **7-10**. This indicates that the size of the transmissivity does not affect these percentage ranges. However the ratio of the sections with $T_{largest} = 100\%$ decreases by excluding the sections with low transmissivity, as can be seen in

Table **7-10**.

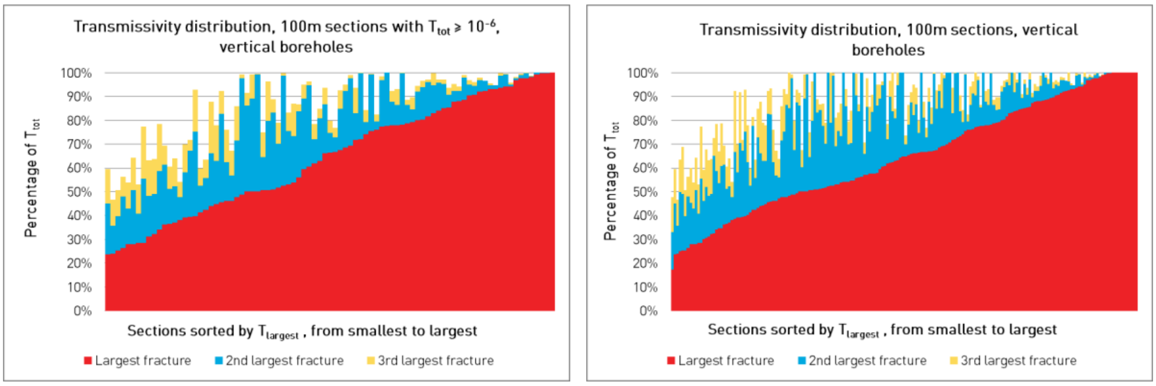



Figure 7-3: Transmissivity distribution for 100m sections for the data sets with all sections included on the right and sections with $T_{tot} \geq 10^{-6}$ on the left (Appendix 1.1 and 1.2).

Table 7-10: Percentage of sections with $T_{largest} \geq 50\%$, $T_{largest} \geq 80\%$ and $T_{largest} = 100\%$ for data set with all sections and data set with sections with $T_{tot} \geq 10^{-6}$ for all section lengths in vertical boreholes(Appendix 1.1, 1,2, 1.7, 1,8, 1.9, 1,10, 1.16 and 1,17).

| **Percentage of $T_{tot}$** | **100m sections** | **100m sections, $T_{tot} \geq 10^{-6}$** | **50m sections** | **50m sections, $T_{tot} \geq 10^{-6}$** | **20m sections** | **20m sections, $T_{tot} \geq 10^{-6}$** | **5m sections** | **5m sections, $T_{tot} \geq 10^{-6}$** |
|---|---|---|---|---|---|---|---|---|
| **$T_{largest} \geq 50\%$** | 72,78% | 68,97% | 76,67% | 74,14% | 80,23% | 79,89% | 92,57% | 94,31% |
| **$T_{largest} \geq 80\%$** | 28,89% | 29,89% | 38,79% | 39,66% | 50,15% | 48,91% | 65,28% | 72,76% |
| **$T_{largest} = 100\%$** | 5,56% | 1,15% | 13,33% | 4,31% | 25,44% | 9,24% | 44,18% | 20,33% |

The data set only including sections with $T_{tot} \geq 10^{-6}$ has higher mean value of flowing fractures than the data set with all sections included, as can be seen in Table 7-11. This indicates a relation between high transmissivity and large number of flowing fractures.

Table 7-11:Mean number of flowing fractures for all sections and sections with $T_{tot} \geq 10^{-6}$ in vertical boreholes (Appendix 1.1, 1,2, 1.7, 1,8, 1.9, 1,10, 1.16 and 1,17).

| | 100m sections | 100m sections, $T_{tot} \geq 10^{-6}$ | 50m sections | 50m sections, $T_{tot} \geq 10^{-6}$ | 20m sections | 20m sections, $T_{tot} \geq 10^{-6}$ | 5m sections | 5m sections, $T_{tot} \geq 10^{-6}$ |
|---|---|---|---|---|---|---|---|---|
| **Mean number of flowing fractures** | 15,38 | 24,8 | 9,1 | 16,58 | 5,01 | 9,15 | 2,2 | 3,14 |

### 7.5.2 Horizontal boreholes

Comparing the transmissivity distribution between the data set with all sections and data set with sections where $T_{tot} \geq 10^{-8}$ in horizontal boreholes it can be seen that the distributions are similar in the two data sets, just as for the vertical boreholes. This can be seen in Figure 7-4. Just as for the vertical boreholes the percentage of sections with $T_{largest} \geq 50\%$ and $T_{largest} \geq 80\%$ in both data sets have similar values, as can be seen in Table 7-12.

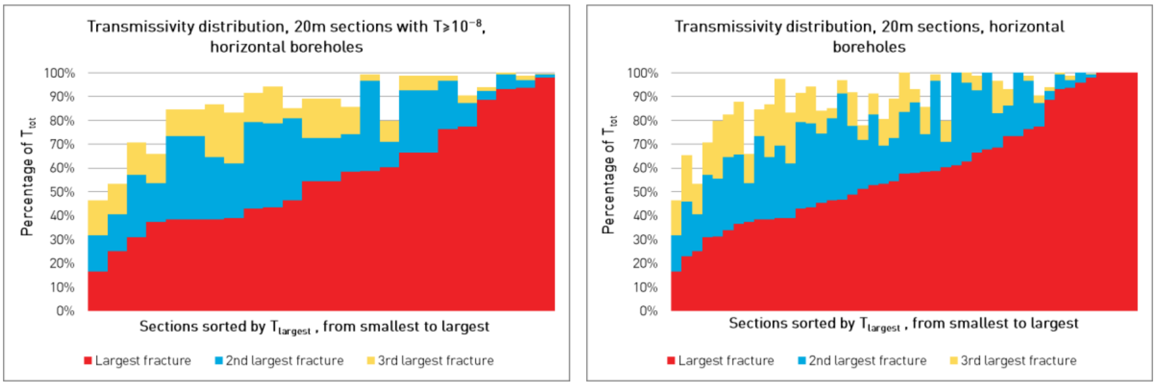



Figure 7-4: Transmissivity distribution for 20m sections for the data sets with all sections included on the right and sections with $T_{tot} \geq 10^{-8}$ on the left (Appendix 2.1 and 2.2).

Table 7-12: : Percentage of sections with $T_{largest} \geq 50\%$, $T_{largest} \geq 80\%$ and $T_{largest} = 100\%$ for data set with all sections and data set with sections with $T_{tot} \geq 10^{-6}$ for all section lengths in horizontal boreholes (Appendix 2,1, 2,2, 2,4, 2,5, 2,7 and 2,8).

| Percentage of $T_{tot}$ | 20m sections | 20m sections, $T_{tot} \geq 10^{-8}$ | 5m sections | 5m sections, $T_{tot} \geq 10^{-8}$ | 3m sections | 3m sections, $T_{tot} \geq 10^{-8}$ |
|---|---|---|---|---|---|---|
| $T_{largest} \geq 50\%$ | 60,00% | 54,17% | 87,79% | 86,44% | 93,48% | 92,68% |
| $T_{largest} \geq 80\%$ | 20,00% | 16,67% | 51,91% | 49,15% | 64,13% | 65,85% |
| $T_{largest} = 100\%$ | 8,89% | 0,00% | 29,77% | 22,03% | 40,76% | 36,59% |

As with the vertical sections the fracture frequency for the data set with sections with $T_{tot} \geq 10^{-8}$ has higher mean value of flowing fractures than the data set with all sections included, as can be seen in Table 7-13. This indicates a relation between high transmissivity and large number of flowing fractures, as was also seen for vertical sections.

Table 7-13: Mean number of flowing fractures for all sections and sections with $T_{tot} \geq 10^{-8}$ in horizontal boreholes (Appendix 2,1, 2,2, 2,4, 2,5, 2,7 and 2,8).

| | **20m sections** | **20m sections, $T_{tot} \geq 10^{-8}$** | **5m sections** | **5m sections, $T_{tot} \geq 10^{-8}$** | **3m sections** | **3m sections, $T_{tot} \geq 10^{-8}$** |
|---|---|---|---|---|---|---|
| **Mean number of flowing fractures** | 7,67 | 10,75 | 2,86 | 3,61 | 2,09 | 2,41 |

## 7.6 General discussion

How large percentage of sections that needs to fulfil the criterion $T_{largest} \geq 50\%$ and $T_{largest} \geq 80\%$ for the likelihood to be considered to be high is a question of definition. Here it is considered high if at least 80 percent of sections fulfil the criteria.

One fracture is not likely to have $T_{largest} \geq 80\%$ for any of the analysed data sets as less than 80 percent of the sections fulfil the criteria in all cases. This means that the 80 percent rule is not supported by this study.

For 100 meter, 50 meter vertical and 20 meter horizontal sections with $T_{largest} \geq 50\%$ is not found to have high likelihood of being fulfilled. Most of the flow can be considered to come from one fracture in 20 meter and 5 meter in vertical sections and 5 meter and 3 meter in horizontal sections. The only deviation from this is 20 meter vertical sections at depth 0-150 meters. This means that a 50 percent rule seems to apply to short borehole sections.

The total transmissivity for each section is obtained by summarising the transmissivity form all fractures within the section. Doing this, an assumption is made about independent flow in the fractures. This is probably not completely true, however without this assumption the analysis would not be possible as data from other hydraulic tests made in the same boreholes could not be compared to the PFL data because of uncertainty in depth.

The different data sets analysed in this thesis all have different number of sections. The amount of data needed to make a good analysis can be discussed but the more data used the more likely it is that the results are representative. The analyses based on a small amount of data can thus not be considered to have as high credibility as when a large amount of data is used.

Geology of the site where tests are performed is an important factor for the result as the properties of the fractures varies with geology. The fracture network can be expected to vary with e.g. rock type, geological formations and stress conditions and it has to be kept in mind that the data used for this analysis originates from one site.

The focus of the thesis is transmissivity distribution for the largest fracture since it is said to contribute to a large part of the total transmissivity. The distribution of the remaining fractures is also interesting to analyse, especially for the $2^{nd}$ and $3^{rd}$ largest fracture, to see if few large fractures contribute to a large part of the flow. Looking at the transmissivity distribution of the $2^{nd}$ and $3^{rd}$ largest fractures in the figures for all the data sets in Appendix 1 and Appendix 2 it seems like the three largest fractures contribute to most of the flow in a high percentage of the sections analysed. To analyse the distribution properly the relationship between these fractures would however have to be considered.

# 8 Conclusions

From looking at the data from the rock mass at Olkiluoto it was found that the likelihood that most of the transmissivity of a section can be assigned to the most flowing fracture is high in short sections and only valid for sections of 5 meter or shorter at shallow depth. This shows that the 80 percent rule is not supported by this study, however the 50 percent rule was found to apply for short boreholes sections.

It was also found that the transmissivity distribution is affected by section length, fracture frequency, borehole orientation, depth and size of total transmissivity. All these factor do however not affect the likelihood that the most flowing fracture contributes to most of the total transmissivty.

The likelihood that the largest fracture contributes to a large part of the total transmissivity increases with shorter section length, which is an expected result. There is an increase in sections with $T_{largest} \geq 50\%$, $T_{largest} \geq 80\%$ and $T_{largest} = 100\%$ when the sections get shorter and this is valid for both sections in vertical and horizontal boreholes. It was also found out that one fracture is more likely to be responsible for most of the flow when there were few flowing fractures.

With increasing fracture frequency the percentage of sections with $T_{largest} \geq 80\%$ and $T_{largest} = 100\%$ decrease while the percentage of sections with $T_{largest} \geq 50\%$ remains relatively unchanged. This means that the likelihood is not affected by the fracture frequency if a fracture is considered to contribute to most of the flow if $T_{largest} \geq 50\%$.

Comparing vertical and horizontal boreholes it was found that the percentage of sections with $T_{largest} \geq 50\%$, $T_{largest} \geq 80\%$ and $T_{largest} = 100\%$ is higher for vertical sections than horizontal. However the difference in these ranges decreases with shorter section length. The number of sections with only one flowing fracture is higher for vertical sections than for horizontal ones. This means that the likelihood of one dominating fracture is larger in vertical boreholes.

At shallow depth the contribution of $T_{tot}$ by smaller fractures is larger than at greater depth. It was found that percentage sections with $T_{largest} \geq 50\%$, $T_{largest} \geq 80\%$ and $T_{largest} = 100\%$ increase with depth and the data set for 0-50 meters has the lowest percentage of sections with $T_{largest} \geq 50\%$ of all data sets for vertical sections analysed.

The size of the transmissivity does not affect the percentage of sections with $T_{largest} \geq 50\%$ and $T_{largest} \geq 80\%$. However the percentage of sections with $T_{largest} = 100\%$ decreases in the higher transmissivity data set. There is also a larger number of flowing fractures in the data set with higher $T_{tot}$.

# 9 Suggestions for future research

Flow distribution within a rock mass is a complex topic as it is affected by many factors and varies with geology. This study only includes data from one site and as the flow distribution is highly connected to the geology of the site. Future research including data from several different sites is recommended to get a better understanding of how flow in rock mass behaves. If PFL data can be related to the geology of the borehole and variations with geological formations can be identified this could improve the understanding of variation between different sites.

The transmissivity distribution is of high interest in infrastructural projects as it could contribute to improvements of grouting design and thereby reduce problems with too large inflow of water into tunnels. To analyse a large set of PFL data from shallow depth would thus give a result more applicable to infrastructural construction.

The flow distribution depends on the fracture network in the rock mass and which fractures are intersected depends on the orientation of the boreholes. By looking further into the orientation of fractures and fracture zones in relation to borehole orientation a better understanding could be achieved of how fractures of different origin affect the distribution of fracture transmissivity.

Investigation of differences in transmissivity distribution between sections enclosing known hydrological zones, which have a high water-bearing capacity, and sections where no such zones are known to exist is an interesting aspect to consider for future research. From this comparison it can be analysed if the transmissivity distribution of these zones deviate from the surrounding rock mass.

If future research is conducted where data from boreholes is split up in sections it is recommended that the location of the sections in different boreholes is set at the same depth as this would make the data easier to handle.

For future research it is recommended to use data from boreholes where both PFL measurements and water pressure test have been conducted and the depth from the two measurements can be related with a high certainty. This could give a better evaluation of the total flow than $T_{tot}= \sum T_{f,I}$ as used in this study and it would make a better basis for evaluation of water pressure tests using flow distribution trends found from PFL data.

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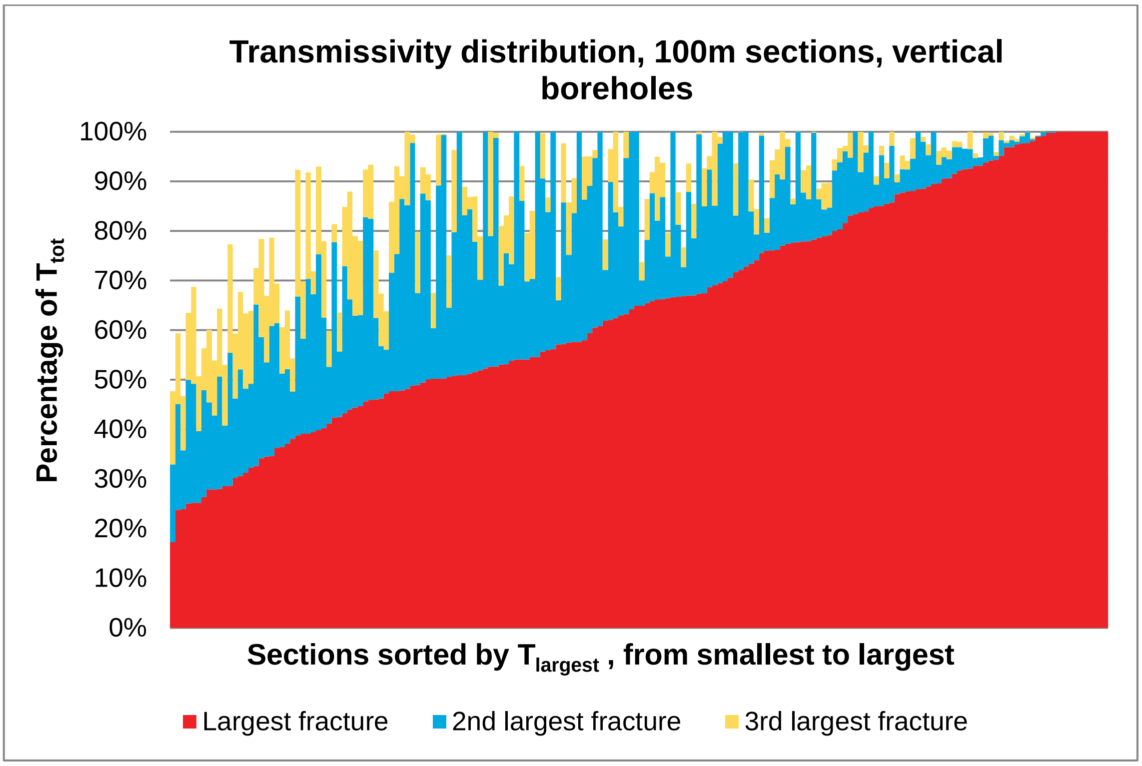
# List of Appendixces

## Appendix 1

## Appendix 2

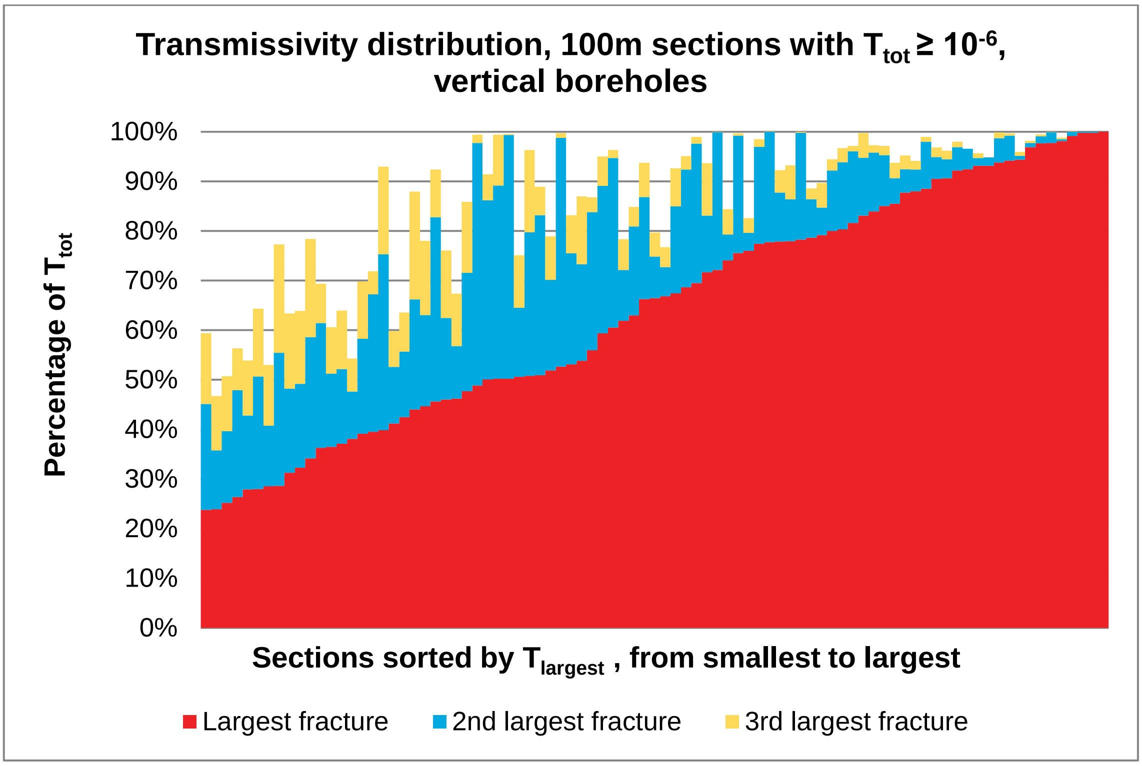
# Appendix 1: Vertical borholes

## 1.1 Transmissivity distribution, 100m sections, vertical boreholes



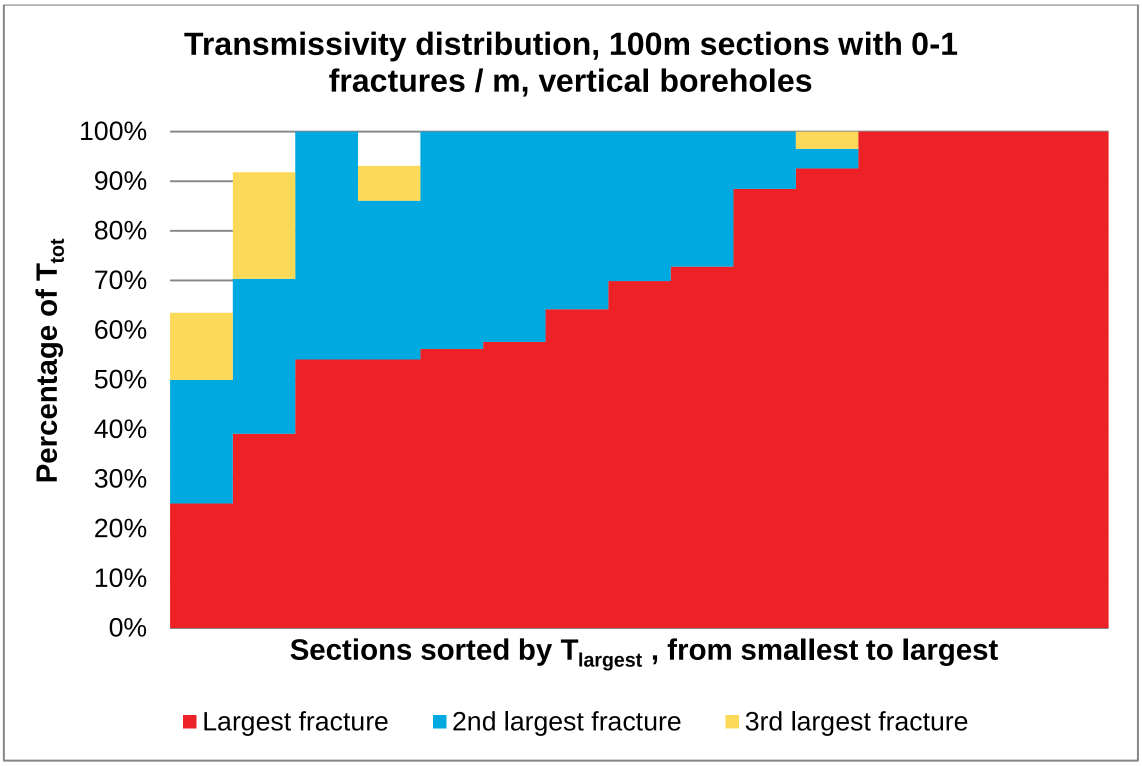

| Transmissivity distribution, 100m sections, vertical boreholes | | | | |
|---|---|---|---|---|
| Percentage of total transmissivity | Percentage of sections | Number of sections | Mean total transmissivity | Mean number of flowing fractures |
| 10-20% | 0,56% | 1 | 5,5E-07 | 28,00 |
| 20-30% | 6,11% | 11 | 1,32E-05 | 33,55 |
| 30-40% | 9,44% | 17 | 1,28E-05 | 24,18 |
| 40-50% | 11,11% | 20 | 1,06E-05 | 17,60 |
| 50-60% | 17,78% | 32 | 6,74E-06 | 12,66 |
| 60-70% | 14,44% | 26 | 8,89E-06 | 14,92 |
| 70-80% | 11,67% | 21 | 1,13E-05 | 16,52 |
| 80-90% | 11,11% | 20 | 1,46E-05 | 10,65 |
| 90-99,9% | 12,22% | 22 | 1,34E-05 | 11,14 |
| 100% | 5,56% | 10 | 1,32E-06 | 1,00 |
| | | 180 | 1,03E-05 | 15,38 |

## 1.2 Transmissivity distribution, 100m sections with $T_{tot} \geq 10^{-6}$ ,vertical boreholes



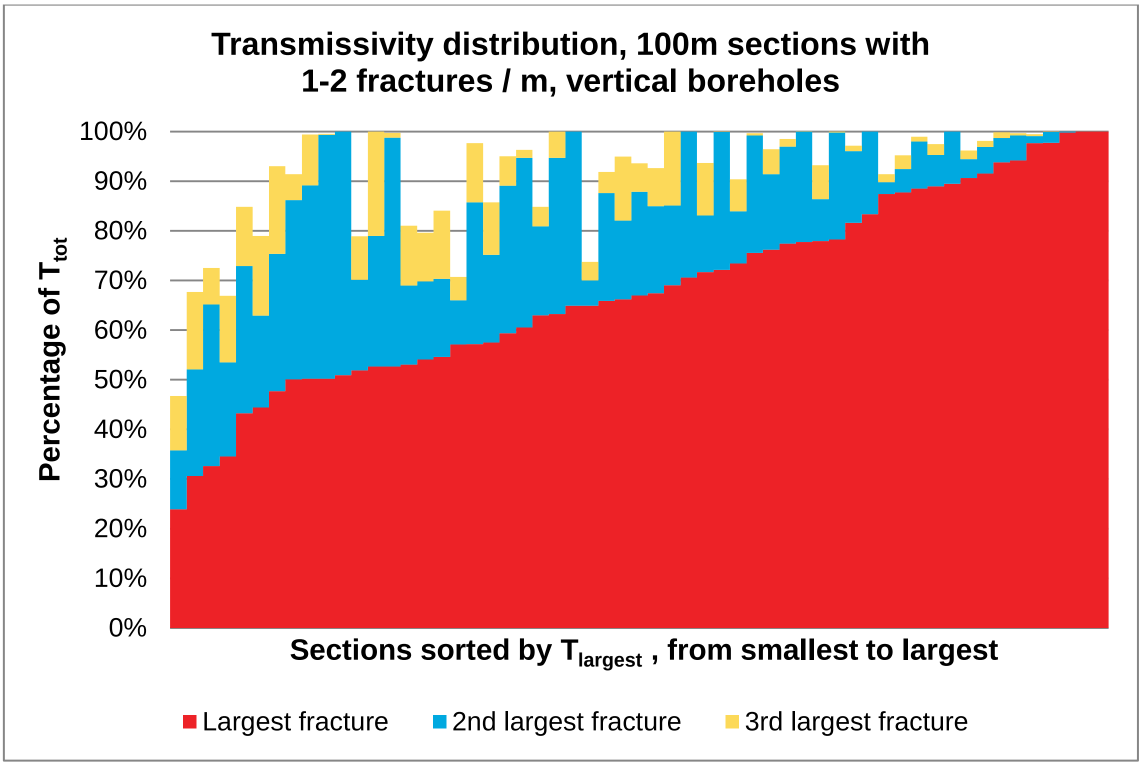

| Transmissivity distribution, 100m sections with $T_{tot} \geq 10^{-6}$,vertical boreholes | | | | |
|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 |
| 20-30% | 9,20% | 8 | 1,81E-05 | 43,25 |
| 30-40% | 11,49% | 10 | 2,17E-05 | 35,30 |
| 40-50% | 10,34% | 9 | 2,33E-05 | 27,44 |
| 50-60% | 13,79% | 12 | 1,77E-05 | 23,42 |
| 60-70% | 10,34% | 9 | 2,54E-05 | 31,89 |
| 70-80% | 14,94% | 13 | 1,82E-05 | 22,08 |
| 80-90% | 10,34% | 9 | 3,22E-05 | 16,89 |
| 90-99,9% | 18,39% | 16 | 1,82E-05 | 12,75 |
| 100% | 1,15% | 1 | 1,31E-05 | 1,00 |
| | | 87 | 2,12E-05 | 24,80 |

### 1.3 Transmissivity distribution, 100m sections with 0-1 fractures / m, vertical boreholes



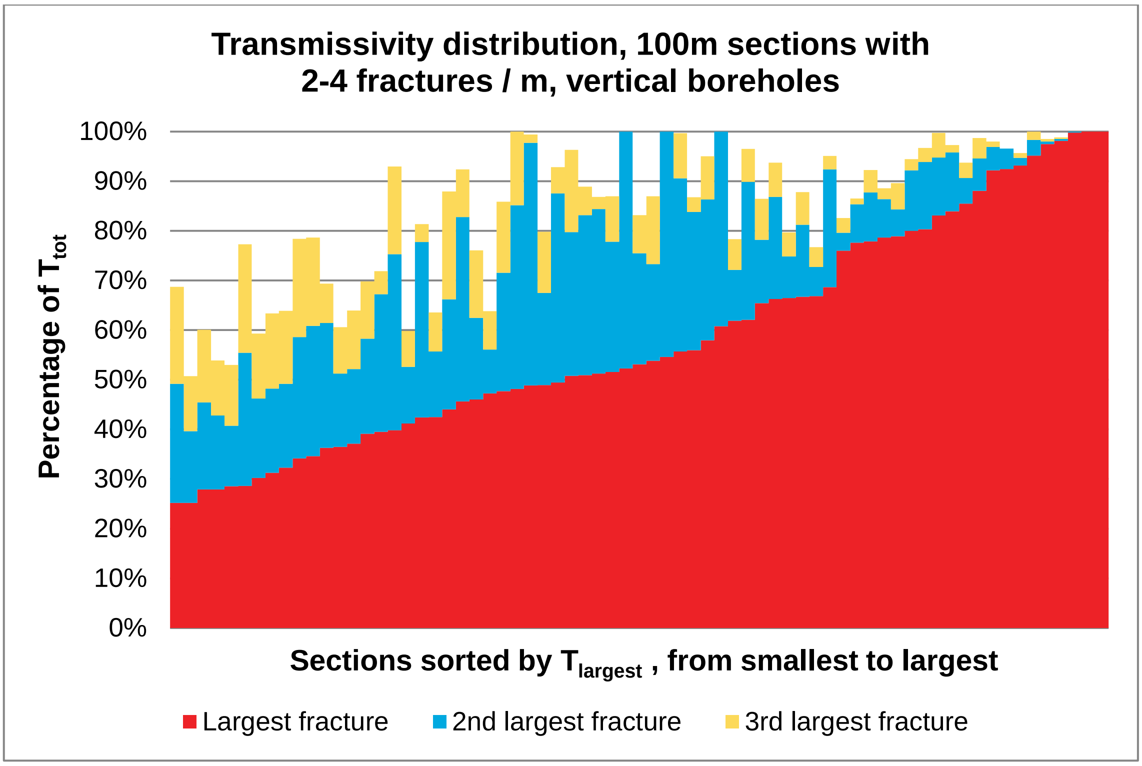

| Transmissivity distribution, 100m sections with 0-1 fractures / m, vertical boreholes | | | | | |
|---|---|---|---|---|---|
| Percentage of total transmissivity | Percentage of sections | Number of sections | Mean total transmissivity | Mean number of flowing fractures | Mean number of total fractures |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 | 0,00 |
| 20-30% | 6,67% | 1 | 2,80E-08 | 7,00 | 57,00 |
| 30-40% | 6,67% | 1 | 4,65E-09 | 4,00 | 68,00 |
| 40-50% | 0,00% | 0 | 0,00E+00 | 0,00 | 0,00 |
| 50-60% | 26,67% | 4 | 3,54E-08 | 3,00 | 70,50 |
| 60-70% | 13,33% | 2 | 1,42E-08 | 2,00 | 69,50 |
| 70-80% | 6,67% | 1 | 2,64E-07 | 2,00 | 66,00 |
| 80-90% | 6,67% | 1 | 2,21E-07 | 2,00 | 69,00 |
| 90-99,9% | 6,67% | 1 | 1,08E-07 | 3,00 | 83,00 |
| 100% | 26,67% | 4 | 2,13E-08 | 1,00 | 59,50 |
| | | 15 | 5,87E-08 | 2,53 | 66,80 |

## 1.4 Transmissivity distribution, 100m sections with 1-2 fractures / m, vertical boreholes



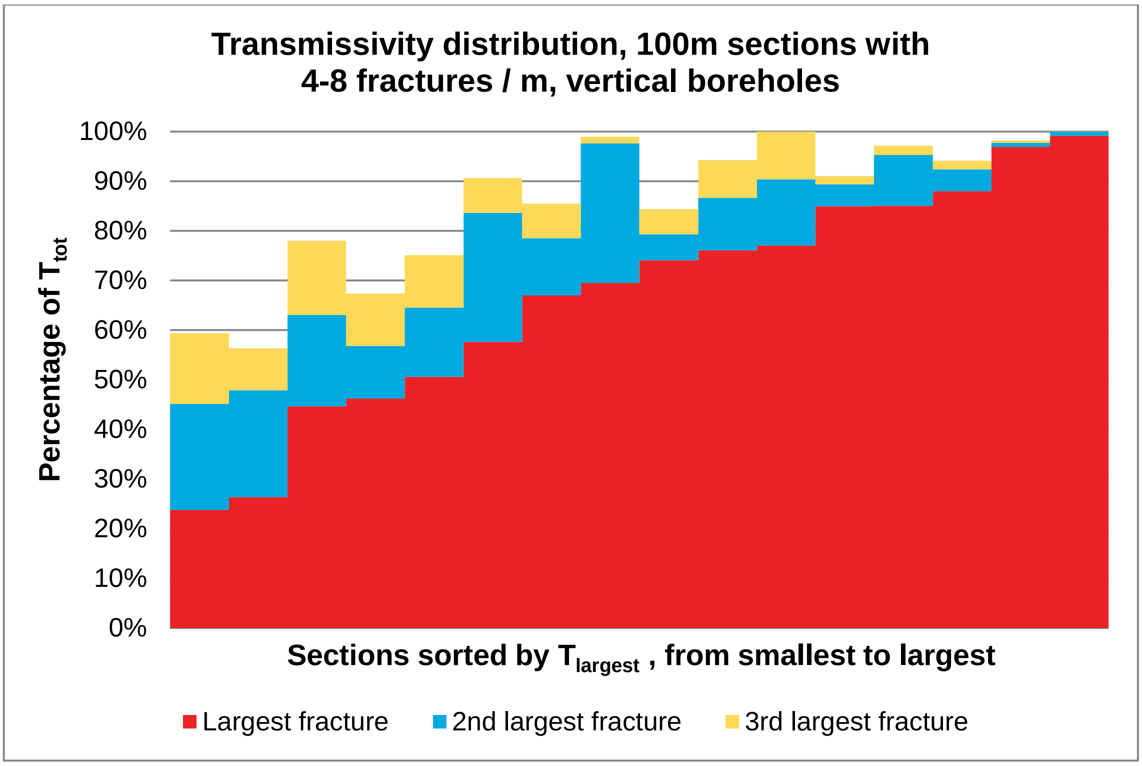

| Transmissivity distribution, 100m sections with 1-2 fractures / m, vertical boreholes | | | | | |
|---|---|---|---|---|---|
| Percentage of total transmissivity | Percentage of sections | Number of sections | Mean total transmissivity | Mean number of flowing fractures | Mean number of total fractures |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 | 0,00 |
| 20-30% | 1,75% | 1 | 2,95E-06 | 31,00 | 166,00 |
| 30-40% | 5,26% | 3 | 2,15E-07 | 10,33 | 130,00 |
| 40-50% | 5,26% | 3 | 1,11E-07 | 9,00 | 151,67 |
| 50-60% | 24,56% | 14 | 5,25E-06 | 13,79 | 153,71 |
| 60-70% | 17,54% | 10 | 1,76E-05 | 14,30 | 149,40 |
| 70-80% | 17,54% | 10 | 1,39E-05 | 5,70 | 150,30 |
| 80-90% | 12,28% | 7 | 2,23E-05 | 10,86 | 177,57 |
| 90-99,9% | 12,28% | 7 | 6,65E-06 | 6,57 | 146,71 |
| 100% | 3,51% | 2 | 6,55E-06 | 1,00 | 146,00 |
| | | 57 | 1,07E-05 | 10,63 | 153,02 |

## 1.5 Transmissivity distribution, 100m sections with 2-4 fractures / m, vertical boreholes



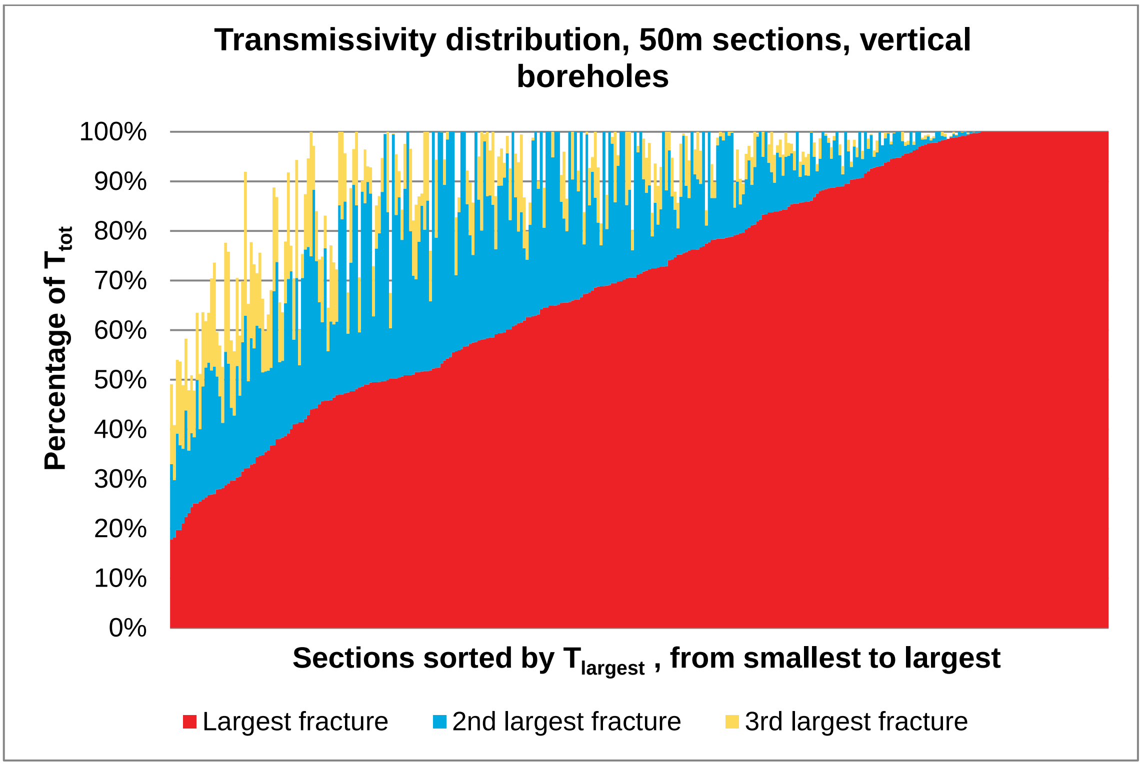

| Transmissivity distribution, 100m sections with 2-4 fractures / m, vertical boreholes | | | | | |
|---|---|---|---|---|---|
| Percentage of total transmissivity | Percentage of sections | Number of sections | Mean total transmissivity | Mean number of flowing fractures | Mean number of total fractures |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 | 0,00 |
| 20-30% | 8,70% | 6 | 1,69E-05 | 27,50 | 242,33 |
| 30-40% | 15,94% | 11 | 1,87E-05 | 29,09 | 298,73 |
| 40-50% | 17,39% | 12 | 1,72E-05 | 20,42 | 333,58 |
| 50-60% | 15,94% | 11 | 1,27E-05 | 12,73 | 267,09 |
| 60-70% | 13,04% | 9 | 5,78E-06 | 24,33 | 274,89 |
| 70-80% | 8,70% | 6 | 1,40E-05 | 36,33 | 287,17 |
| 80-90% | 7,25% | 5 | 3,40E-06 | 10,40 | 270,00 |
| 90-99,9% | 10,14% | 7 | 1,58E-05 | 15,86 | 298,43 |
| 100% | 2,90% | 2 | 2,80E-09 | 1,00 | 278,00 |
| | | 69 | 1,33E-05 | 21,33 | 288,01 |

## 1.6 Transmissivity distribution, 100m sections with 4-8 fractures / m, vertical boreholes



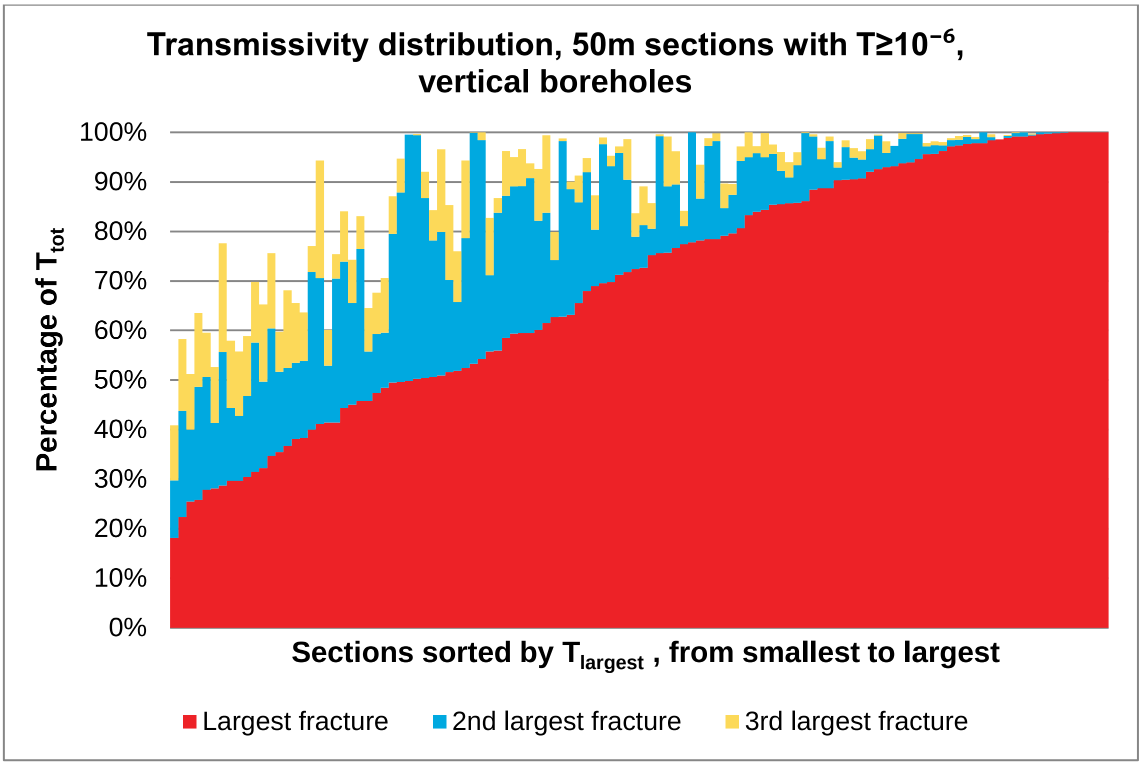

| Transmissivity distribution, 100m sections with 4- 8 fractures, vertical boreholes | | | | | |
|---|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** | **Mean number of total fractures** |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 | 0,00 |
| 20-30% | 12,50% | 2 | 1,53E-05 | 62,00 | 508,00 |
| 30-40% | 0,00% | 0 | 0,00E+00 | 0,00 | 0,00 |
| 40-50% | 12,50% | 2 | 2,17E-06 | 22,50 | 440,00 |
| 50-60% | 12,50% | 2 | 1,33E-06 | 23,50 | 479,50 |
| 60-70% | 12,50% | 2 | 1,16E-06 | 7,00 | 472,50 |
| 70-80% | 18,75% | 3 | 4,05E-06 | 18,00 | 459,00 |
| 80-90% | 18,75% | 3 | 3,95E-05 | 22,33 | 610,67 |
| 90-99,9% | 12,50% | 2 | 6,51E-05 | 8,50 | 415,50 |
| 100% | 0,00% | 0 | 0,00E+00 | 0,00 | 0,00 |
| | | 16 | 1,88E-05 | 23,00 | 485,67 |

## 1.7 Transmissivity distribution, 50m sections, vertical boreholes



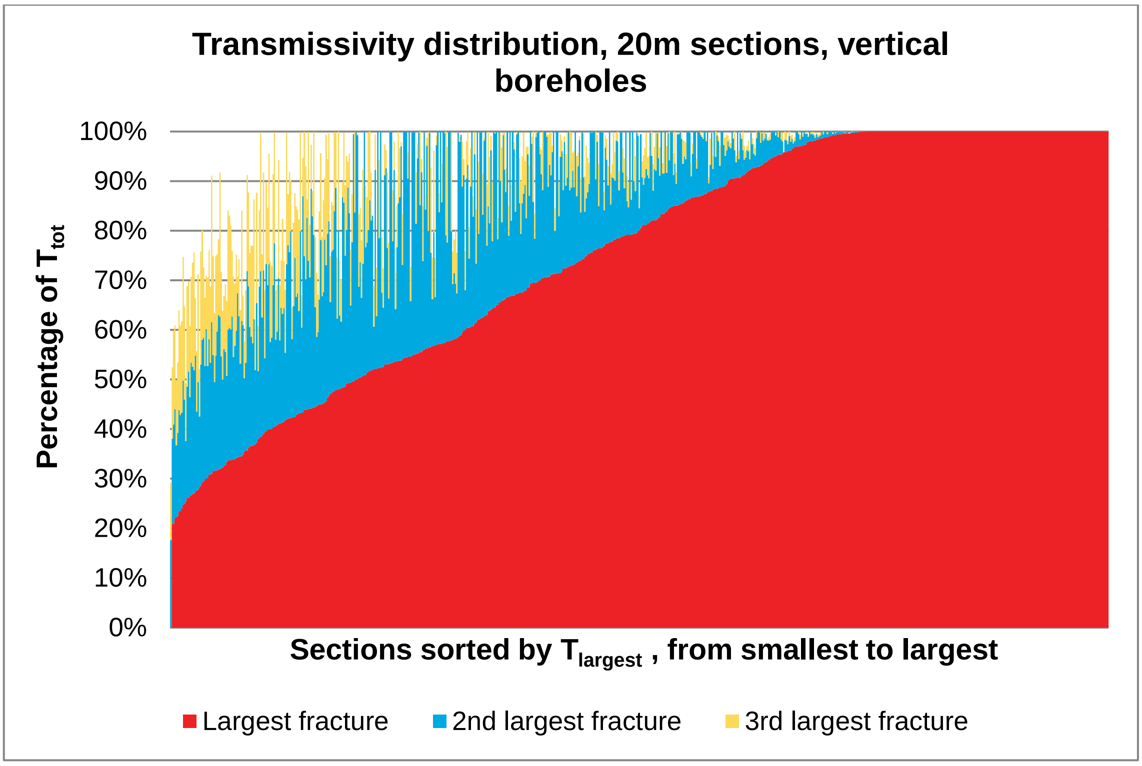

| Transmissivity distribution, 50m sections, vertical boreholes | | | | |
|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** |
| 10-20% | 1,21% | 4 | 5,3E-07 | 18,00 |
| 20-30% | 5,76% | 19 | 3,98E-06 | 21,37 |
| 30-40% | 5,76% | 19 | 1,29E-05 | 15,84 |
| 40-50% | 10,61% | 35 | 3,10E-06 | 13,26 |
| 50-60% | 12,42% | 41 | 6,22E-06 | 8,71 |
| 60-70% | 12,42% | 41 | 3,23E-06 | 7,05 |
| 70-80% | 13,03% | 43 | 9,92E-06 | 10,40 |
| 80-90% | 11,21% | 37 | 5,51E-06 | 8,05 |
| 90-99,9% | 14,24% | 47 | 1,41E-05 | 6,89 |
| 100% | 13,33% | 44 | 8,60E-07 | 1,00 |
| | | 330 | 6,51E-06 | 9,10 |

## 1.8 Transmissivity distribution, 50m sections with T≥$10^{-6}$ , vertical boreholes



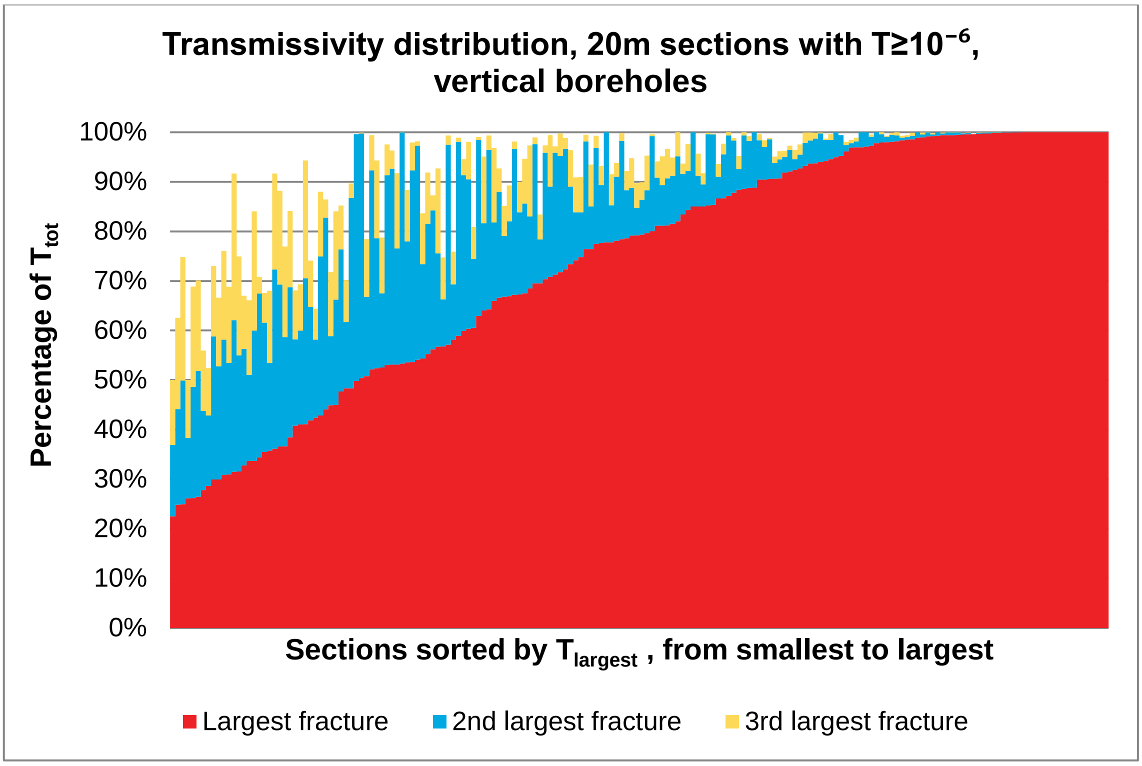

| Transmissivity distribution, 50m sections with T≥$10^{-6}$ ,vertical boreholes | | | | |
|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** |
| 10-20% | 0,86% | 1 | 1,9E-06 | 26,00 |
| 20-30% | 6,90% | 8 | 9,31E-06 | 33,75 |
| 30-40% | 6,90% | 8 | 3,04E-05 | 27,88 |
| 40-50% | 11,21% | 13 | 7,97E-06 | 22,46 |
| 50-60% | 12,93% | 15 | 1,68E-05 | 15,80 |
| 60-70% | 8,62% | 10 | 1,29E-05 | 15,90 |
| 70-80% | 12,93% | 15 | 2,80E-05 | 20,07 |
| 80-90% | 10,34% | 12 | 1,64E-05 | 13,25 |
| 90-99,9% | 25,00% | 29 | 2,26E-05 | 8,66 |
| 100% | 4,31% | 5 | 7,41E-06 | 1,00 |
| | | 116 | 1,82E-05 | 16,58 |

## 1.9 Transmissivity distribution, 20m sections, vertical boreholes



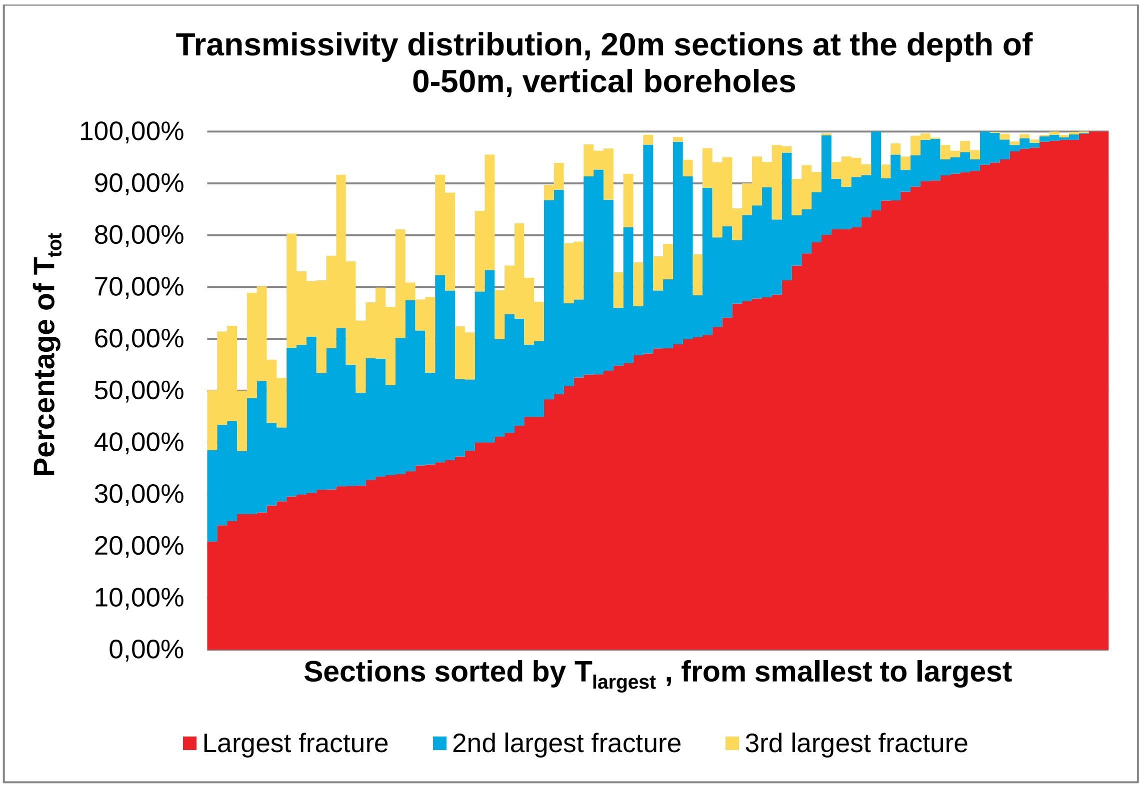

| Transmissivity distribution, 20m sections, vertical boreholes | | | | |
|---|---|---|---|---|
| Percentage of total transmissivity | Percentage of sections | Number of sections | Mean total transmissivity | Mean number of flowing fractures |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 |
| 20-30% | 3,78% | 26 | 2,22E-06 | 12,04 |
| 30-40% | 6,83% | 47 | 2,74E-06 | 9,64 |
| 40-50% | 9,16% | 63 | 1,58E-06 | 7,08 |
| 50-60% | 11,63% | 80 | 2,02E-06 | 6,41 |
| 60-70% | 7,99% | 55 | 3,81E-06 | 6,04 |
| 70-80% | 10,47% | 72 | 3,04E-06 | 5,43 |
| 80-90% | 9,74% | 67 | 7,17E-06 | 5,27 |
| 90-99,9% | 14,97% | 103 | 1,17E-05 | 4,59 |
| 100% | 25,44% | 175 | 9,28E-07 | 1,00 |
| | | 688 | 3,96E-06 | 5,01 |

### 1.10 Transmissivity distribution, 20m sections with $T \geq 10^{-6}$ , vertical boreholes



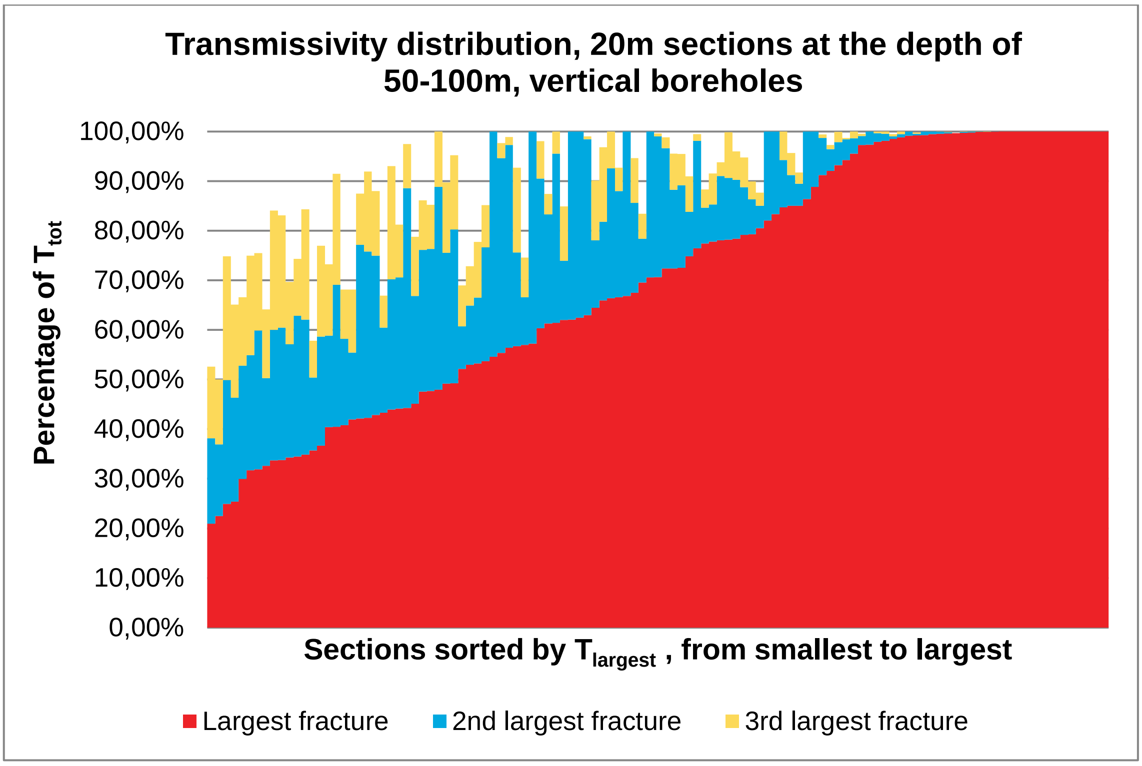

| Transmissivity distribution, 20m sections with $T \geq 10^{-6}$, vertical boreholes | | | | |
|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 |
| 20-30% | 5,43% | 10 | 5,52E-06 | 17,50 |
| 30-40% | 7,61% | 14 | 8,85E-06 | 15,36 |
| 40-50% | 7,07% | 13 | 7,12E-06 | 13,15 |
| 50-60% | 11,41% | 21 | 7,40E-06 | 10,76 |
| 60-70% | 8,15% | 15 | 1,35E-05 | 11,80 |
| 70-80% | 11,41% | 21 | 1,00E-05 | 9,19 |
| 80-90% | 11,41% | 21 | 2,02E-05 | 8,67 |
| 90-99,9% | 28,26% | 52 | 2,38E-05 | 6,31 |
| 100% | 9,24% | 17 | 9,25E-06 | 1,00 |
| | | 184 | 1,45E-05 | 9,15 |

### 1.11 Transmissivity distribution, 20m sections at the depth of 0-50m, vertical boreholes



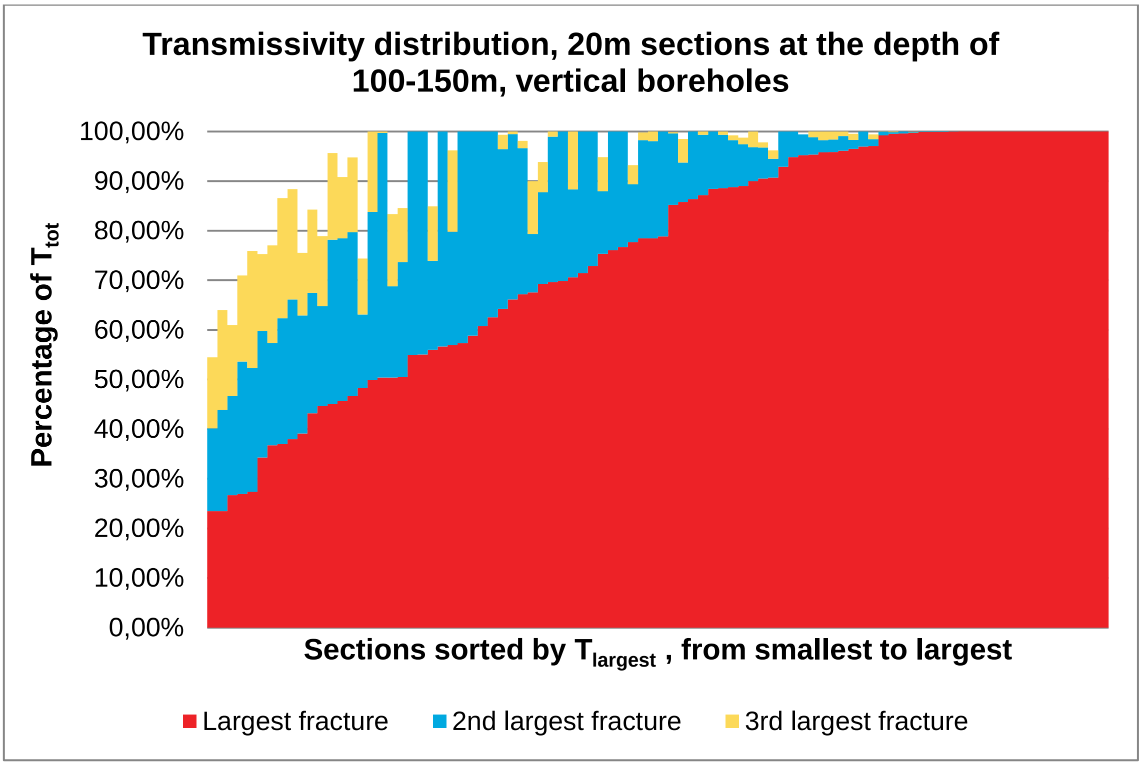

| Transmissivity distribution, 20m sections at the depth of 0-50m, vertical boreholes | | | | |
|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 |
| 20-30% | 10,99% | 10 | 4,49E-06 | 17,80 |
| 30-40% | 20,88% | 19 | 5,05E-06 | 12,84 |
| 40-50% | 7,69% | 7 | 3,43E-06 | 12,43 |
| 50-60% | 14,29% | 13 | 5,96E-06 | 11,54 |
| 60-70% | 9,89% | 9 | 9,20E-06 | 10,00 |
| 70-80% | 4,40% | 4 | 8,27E-06 | 12,25 |
| 80-90% | 10,99% | 10 | 1,09E-05 | 9,40 |
| 90-99,9% | 18,68% | 17 | 2,59E-05 | 8,35 |
| 100% | 2,20% | 2 | 4,08E-06 | 1,00 |
| | | 91 | 1,01E-05 | 11,38 |

## 1.12 Transmissivity distribution, 20m sections at the depth of 50-100m, vertical boreholes



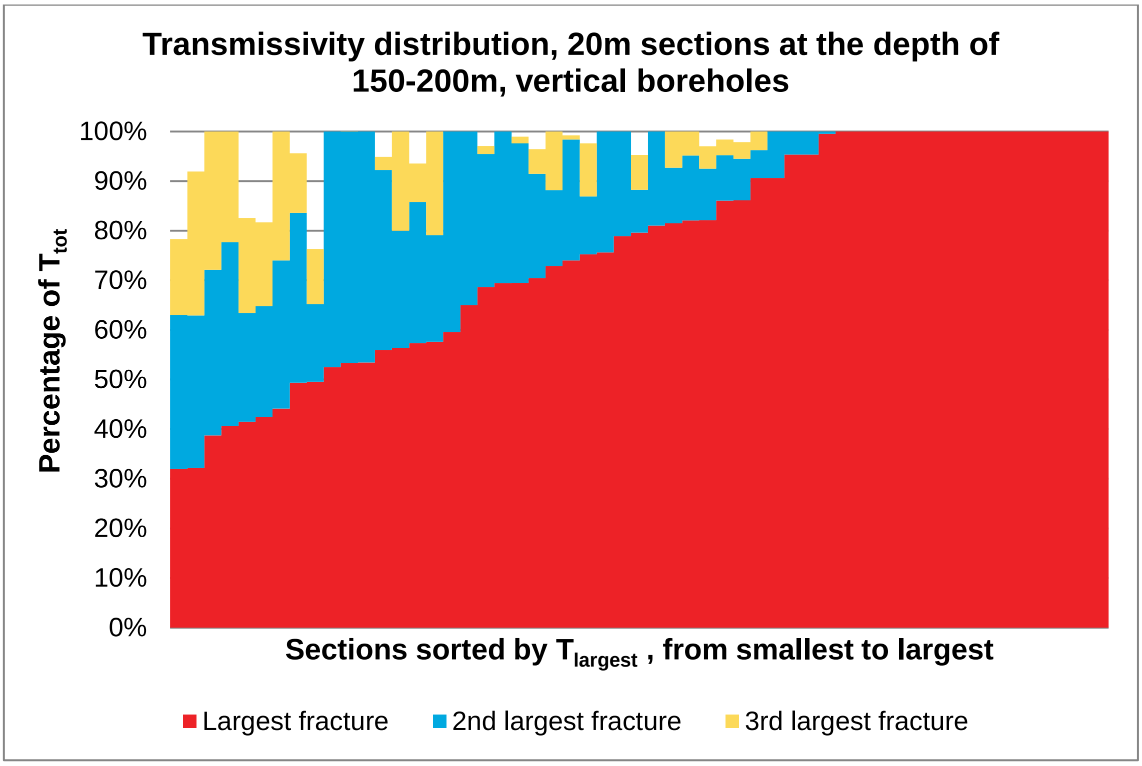

| Transmissivity distribution, 20m sections at the depth of 50-100m, vertical boreholes | | | | |
|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 |
| 20-30% | 4,35% | 5 | 2,38E-06 | 10,20 |
| 30-40% | 8,70% | 10 | 2,00E-06 | 7,90 |
| 40-50% | 14,78% | 17 | 6,45E-07 | 7,29 |
| 50-60% | 8,70% | 10 | 7,08E-07 | 7,90 |
| 60-70% | 12,17% | 14 | 3,47E-06 | 7,43 |
| 70-80% | 12,17% | 14 | 3,04E-06 | 7,64 |
| 80-90% | 7,83% | 9 | 1,53E-05 | 5,22 |
| 90-99,9% | 19,13% | 22 | 2,23E-05 | 4,68 |
| 100% | 12,17% | 14 | 3,75E-06 | 1,00 |
| | | 115 | 7,15E-06 | 6,16 |

### 1.13 Transmissivity distribution, 20m sections at the depth of 100-150m, vertical boreholes



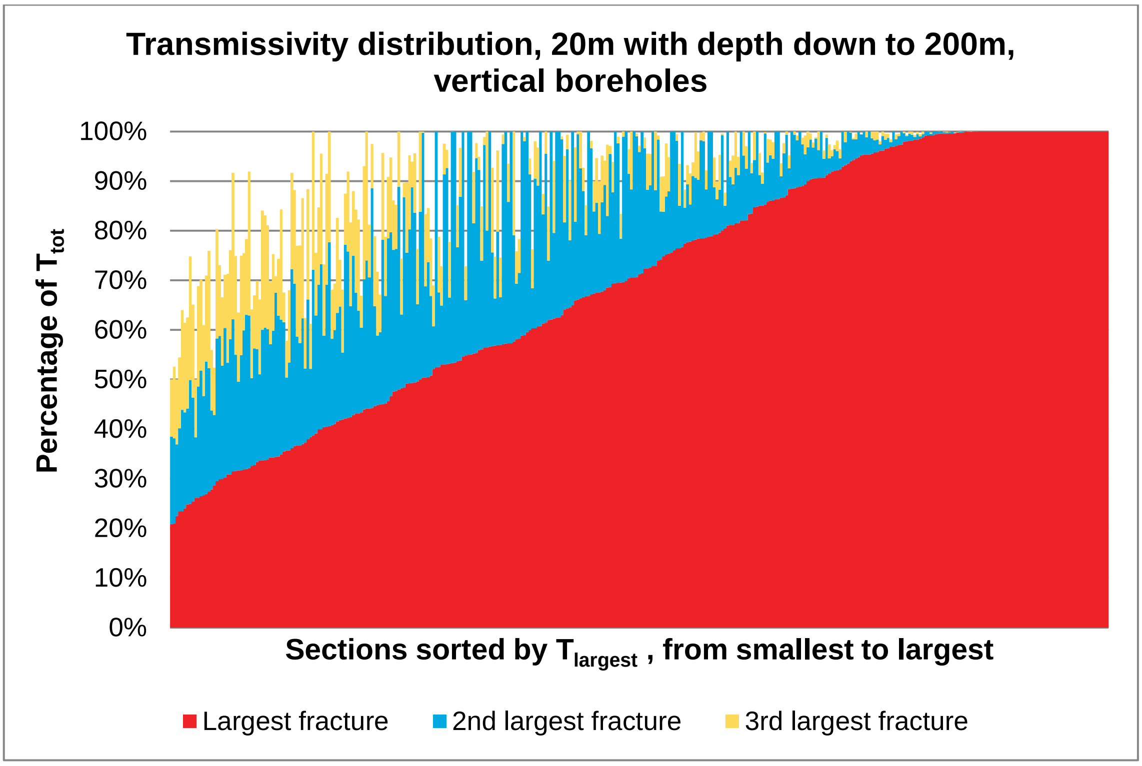

| Transmissivity distribution, 20m sections at the depth of 100-150m, vertical boreholes | | | | |
|---|---|---|---|---|
| Percentage of total transmissivity | Percentage of sections | Number of sections | Mean total transmissivity | Mean number of flowing fractures |
| 10-20% | 1,11% | 1 | 7,0E-08 | 9,00 |
| 20-30% | 5,56% | 5 | 5,87E-08 | 8,40 |
| 30-40% | 5,56% | 5 | 1,05E-07 | 5,20 |
| 40-50% | 7,78% | 7 | 8,19E-08 | 5,29 |
| 50-60% | 11,11% | 10 | 9,56E-07 | 4,60 |
| 60-70% | 10,00% | 9 | 7,86E-06 | 4,11 |
| 70-80% | 10,00% | 9 | 7,85E-06 | 4,00 |
| 80-90% | 10,00% | 9 | 7,92E-06 | 3,78 |
| 90-99,9% | 22,22% | 20 | 8,81E-06 | 3,65 |
| 100% | 12,22% | 11 | 3,59E-06 | 1,00 |
| | | 86 | 4,26E-06 | 3,82 |

## 1.14 Transmissivity distribution, 20m sections at the depth of 150-200m, vertical boreholes



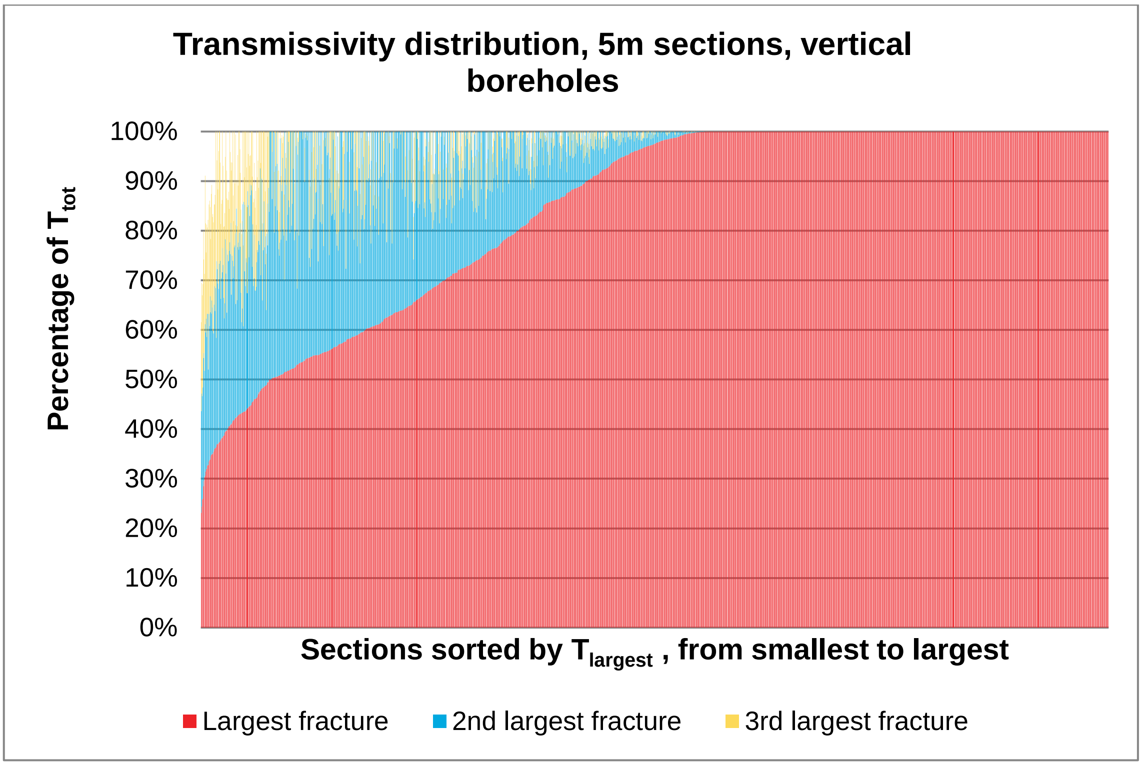

| Transmissivity distribution, 20m sections at the depth of 150-200m, vertical boreholes | | | | |
|---|---|---|---|---|
| Percentage of total transmissivity | Percentage of sections | Number of sections | Mean total transmissivity | Mean number of flowing fractures |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 |
| 20-30% | 0,00% | 0 | 0,00E+00 | 0,00 |
| 30-40% | 5,45% | 3 | 4,42E-08 | 4,67 |
| 40-50% | 10,91% | 6 | 1,35E-07 | 5,50 |
| 50-60% | 14,55% | 8 | 1,90E-06 | 3,25 |
| 60-70% | 7,27% | 4 | 5,42E-07 | 4,00 |
| 70-80% | 12,73% | 7 | 2,37E-07 | 4,14 |
| 80-90% | 10,91% | 6 | 2,88E-06 | 4,17 |
| 90-99,9% | 9,09% | 5 | 2,37E-07 | 2,20 |
| 100% | 29,09% | 16 | 2,42E-08 | 1,00 |
| | | 55 | 7,06E-07 | 3,09 |

### 1.15 Transmissivity distribution, 20m with depth down to 200m, vertical boreholes



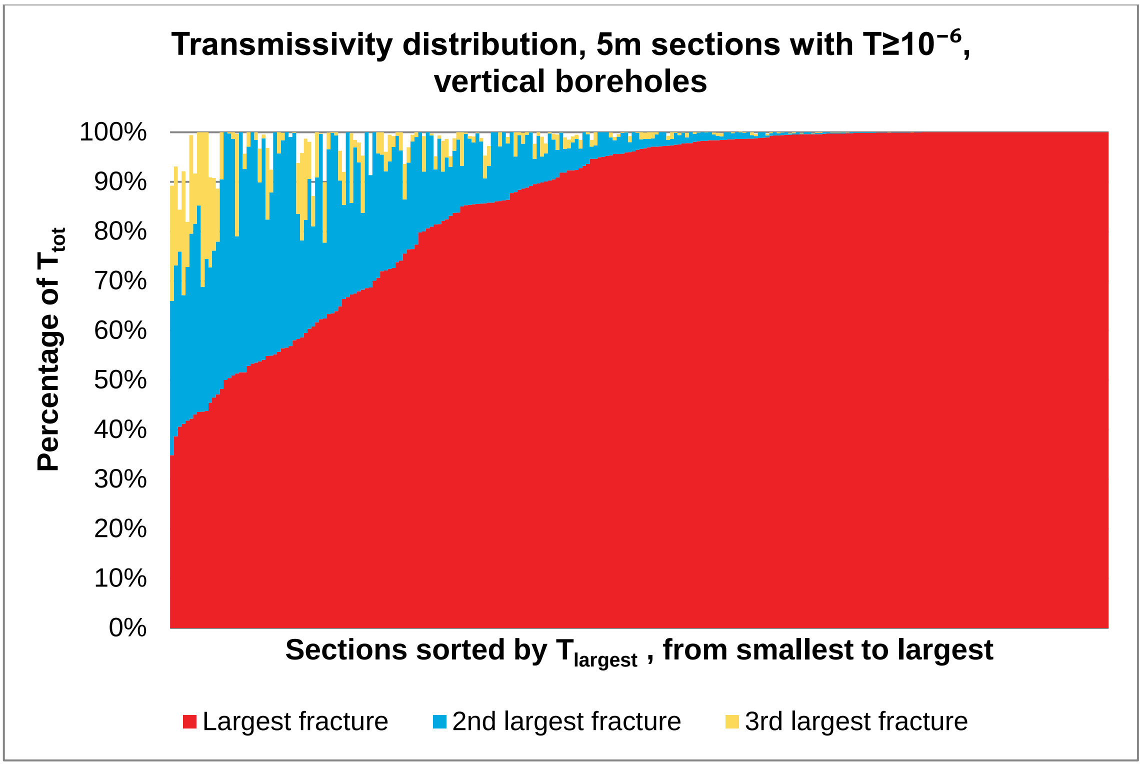

| Transmissivity distribution, 20m with depth down to 200m, vertical boreholes | | | | |
|---|---|---|---|---|
| Percentage of total transmissivity | Percentage of sections | Number of sections | Mean total transmissivity | Mean number of flowing fractures |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 |
| 20-30% | 6,10% | 20 | 2,86E-06 | 13,55 |
| 30-40% | 11,28% | 37 | 3,15E-06 | 9,81 |
| 40-50% | 11,28% | 37 | 9,82E-07 | 7,59 |
| 50-60% | 12,50% | 41 | 2,66E-06 | 7,34 |
| 60-70% | 10,98% | 36 | 5,67E-06 | 6,83 |
| 70-80% | 10,67% | 35 | 2,64E-06 | 6,29 |
| 80-90% | 10,06% | 33 | 1,02E-05 | 5,94 |
| 90-99,9% | 19,82% | 65 | 1,71E-05 | 5,12 |
| 100% | 14,33% | 47 | 2,14E-06 | 1,00 |
| | | 351 | 6,16E-06 | 6,43 |

## 1.16 Transmissivity distribution, 5m sections, vertical boreholes



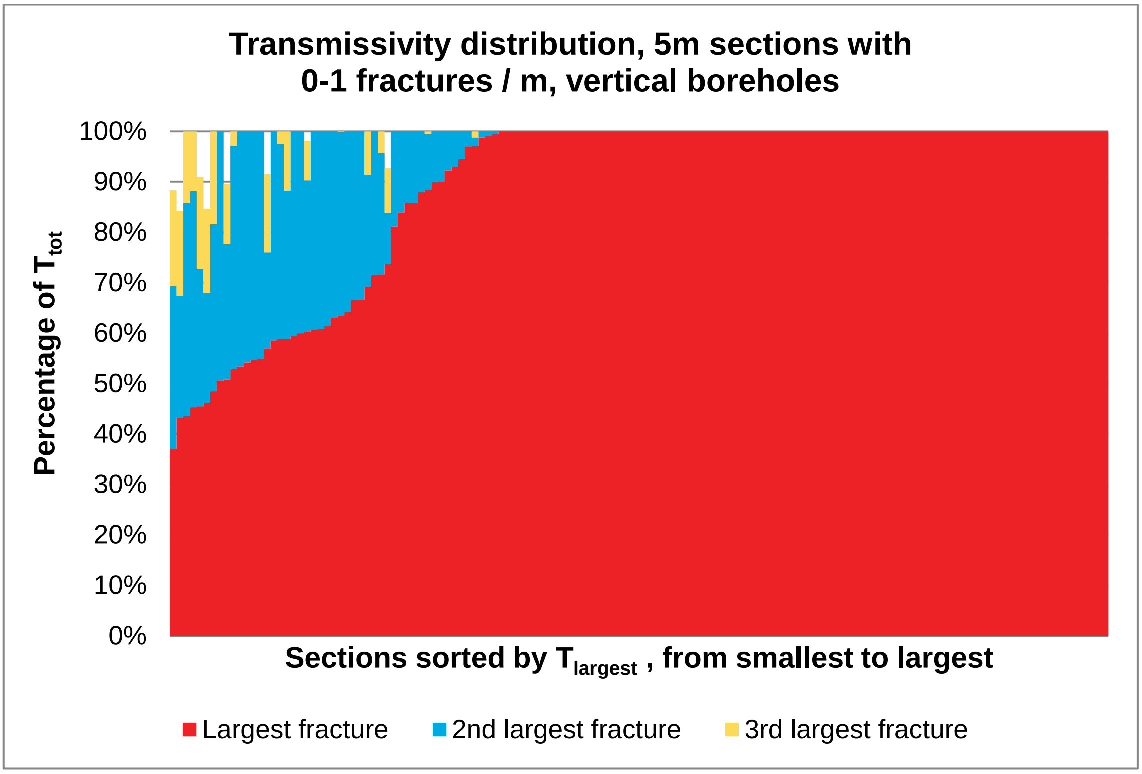

| Transmissivity distribution, 5m sections, vertical boreholes | | | | |
|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 |
| 20-30% | 0,37% | 6 | 2,50E-07 | 5,83 |
| 30-40% | 2,54% | 41 | 1,13E-06 | 4,41 |
| 40-50% | 4,64% | 75 | 6,75E-07 | 4,23 |
| 50-60% | 10,58% | 171 | 8,23E-07 | 3,08 |
| 60-70% | 8,73% | 141 | 8,43E-07 | 3,01 |
| 70-80% | 7,98% | 129 | 7,44E-07 | 2,91 |
| 80-90% | 7,61% | 123 | 3,19E-06 | 3,09 |
| 90-99,9% | 13,49% | 216 | 6,40E-06 | 2,76 |
| 100% | 44,18% | 714 | 8,56E-07 | 1,01 |
| | | 1616 | 1,76E-06 | 2,20 |

### 1.17 Transmissivity distribution, 5m sections with T≥10$^{-6}$ , vertical boreholes



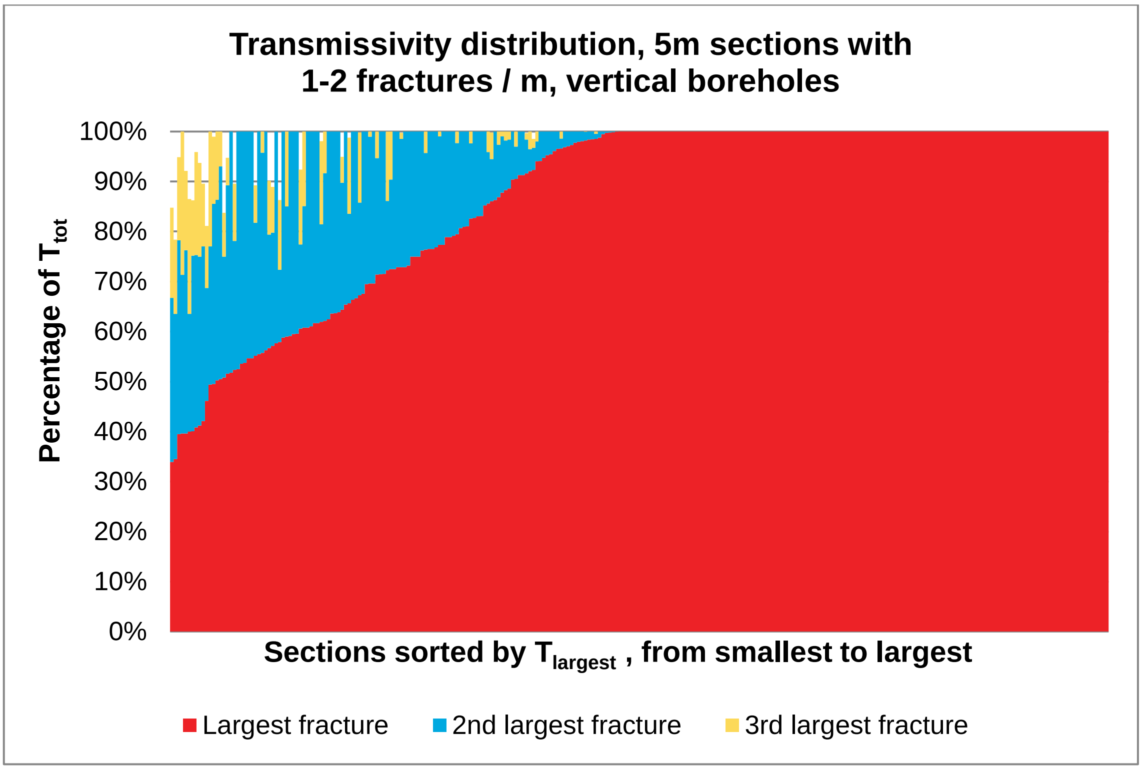

| Transmissivity distribution, 5m sections with T≥10$^{-6}$ , vertical boreholes | | | | |
|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 |
| 20-30% | 0,00% | 0 | 0,00E+00 | 0,00 |
| 30-40% | 0,81% | 2 | 2,04E-05 | 4,50 |
| 40-50% | 4,88% | 12 | 3,25E-06 | 4,92 |
| 50-60% | 8,94% | 22 | 5,64E-06 | 3,95 |
| 60-70% | 6,91% | 17 | 6,17E-06 | 4,82 |
| 70-80% | 5,69% | 14 | 5,79E-06 | 3,71 |
| 80-90% | 12,60% | 31 | 1,20E-05 | 4,10 |
| 90-99,9% | 39,84% | 98 | 1,38E-05 | 3,11 |
| 100% | 20,33% | 50 | 1,15E-05 | 1,02 |
| | | 246 | 1,09E-05 | 3,14 |

### 1.18 Transmissivity distribution, 5m sections with 0-1 fractures / m, vertical boreholes



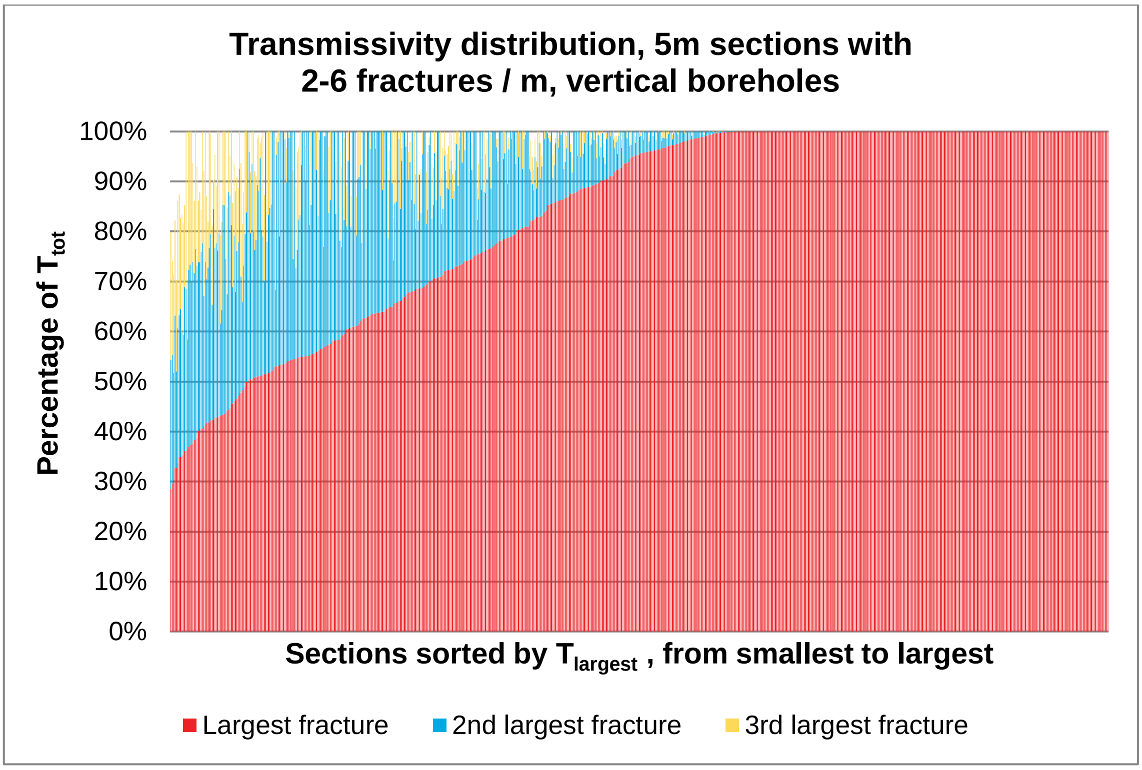

| Transmissivity distribution, 5m sections with 0-1 fractures / m, vertical boreholes | | | | | |
|---|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Total flow** | **Mean total transmissivity** | **Mean number of flowing fractures** |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 | 0,00 |
| 20-30% | 0,00% | 0 | 0,00E+00 | 0,00 | 0,00 |
| 30-40% | 0,71% | 1 | 2,36E-08 | 4,00 | 5,00 |
| 40-50% | 4,29% | 6 | 2,55E-07 | 3,50 | 3,83 |
| 50-60% | 9,29% | 13 | 1,36E-06 | 2,54 | 4,31 |
| 60-70% | 7,14% | 10 | 8,36E-07 | 2,40 | 4,10 |
| 70-80% | 2,14% | 3 | 9,29E-09 | 3,00 | 4,33 |
| 80-90% | 5,00% | 7 | 9,47E-07 | 2,14 | 4,00 |
| 90-99,9% | 6,43% | 9 | 1,00E-06 | 2,11 | 3,78 |
| 100% | 65,00% | 91 | 5,99E-07 | 1,00 | 3,19 |
| | | 140 | 6,99E-07 | 1,54 | 3,50 |

### 1.19 Transmissivity distribution, 5m sections with 1-2 fractures / m, vertical boreholes



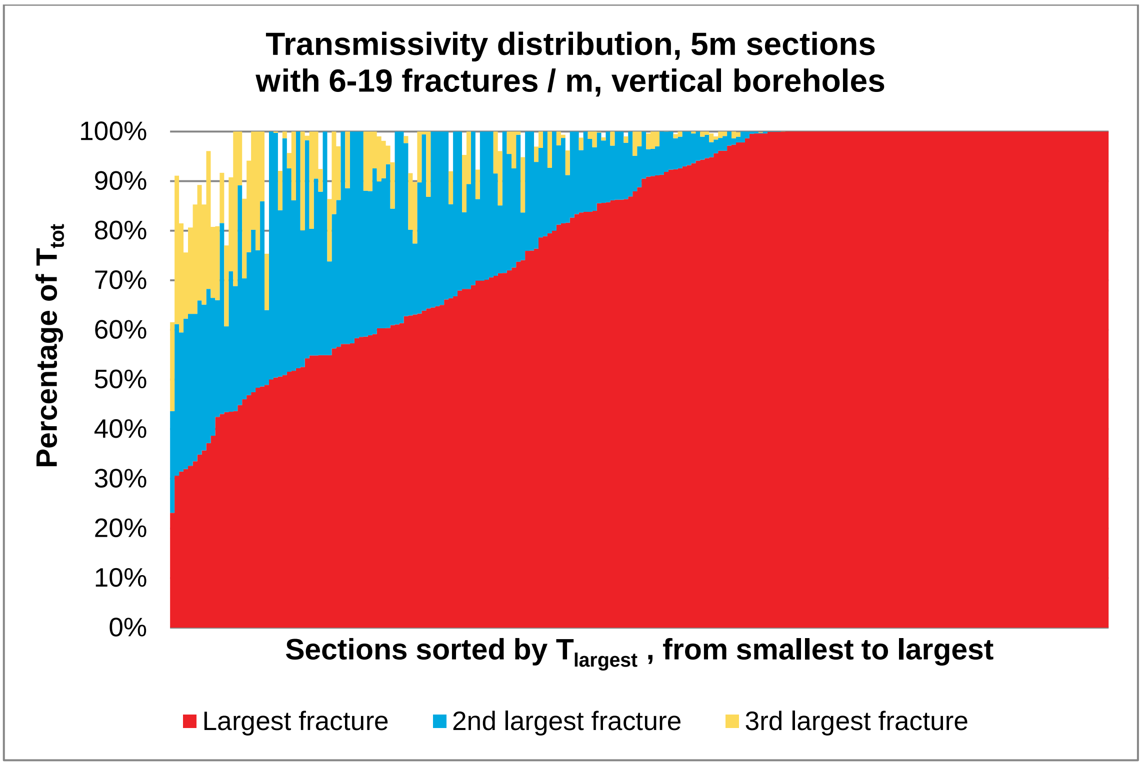

| Transmissivity distribution, 5m sections with 0-1 fractures / m, vertical boreholes | | | | | |
|---|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** | **Mean number of total fractures** |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 | 0,00 |
| 20-30% | 0,00% | 0 | 0,00E+00 | 0,00 | 0,00 |
| 30-40% | 2,22% | 6 | 1,18E-07 | 4,00 | 7,50 |
| 40-50% | 2,59% | 7 | 1,76E-07 | 4,71 | 8,71 |
| 50-60% | 8,89% | 24 | 1,84E-07 | 3,04 | 8,21 |
| 60-70% | 8,15% | 22 | 2,02E-07 | 2,68 | 8,41 |
| 70-80% | 8,89% | 24 | 1,94E-07 | 2,33 | 7,96 |
| 80-90% | 5,56% | 15 | 2,55E-07 | 2,53 | 8,40 |
| 90-99,9% | 11,48% | 31 | 1,50E-06 | 2,42 | 8,03 |
| 100% | 52,22% | 141 | 1,75E-07 | 1,00 | 8,05 |
| | | 270 | 3,35E-07 | 1,85 | 8,11 |

### 1.20 Transmissivity distribution, 5m sections with 2-6 fractures / m, vertical boreholes



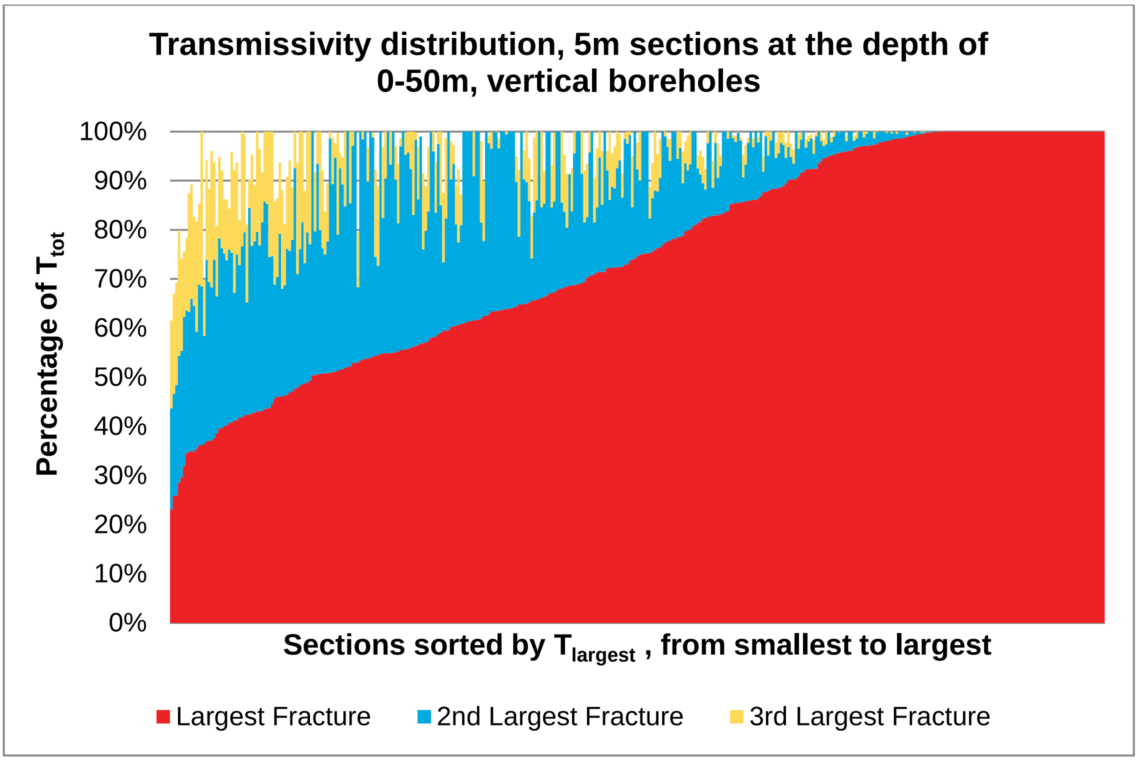

| Transmissivity distribution, 5m sections with 2-6 fractures / m, vertical boreholes | | | | | |
|---|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** | **Mean number of total fractures** |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 | 0,00 |
| 20-30% | 0,29% | 2 | 3,01E-07 | 5,00 | 17,00 |
| 30-40% | 2,64% | 18 | 2,24E-06 | 4,33 | 17,83 |
| 40-50% | 5,27% | 36 | 9,24E-07 | 4,39 | 18,83 |
| 50-60% | 10,40% | 71 | 1,29E-06 | 3,28 | 17,55 |
| 60-70% | 9,08% | 62 | 1,26E-06 | 3,21 | 18,85 |
| 70-80% | 9,37% | 64 | 5,98E-07 | 3,08 | 19,81 |
| 80-90% | 8,78% | 60 | 3,13E-06 | 3,43 | 19,20 |
| 90-99,9% | 14,64% | 100 | 8,52E-06 | 2,86 | 18,80 |
| 100% | 39,53% | 270 | 1,26E-06 | 1,01 | 17,03 |
| | | 683 | 2,43E-06 | 2,40 | 18,08 |

## 1.21 Transmissivity distribution, 5m sections with 6-19 fractures / m, vertical boreholes



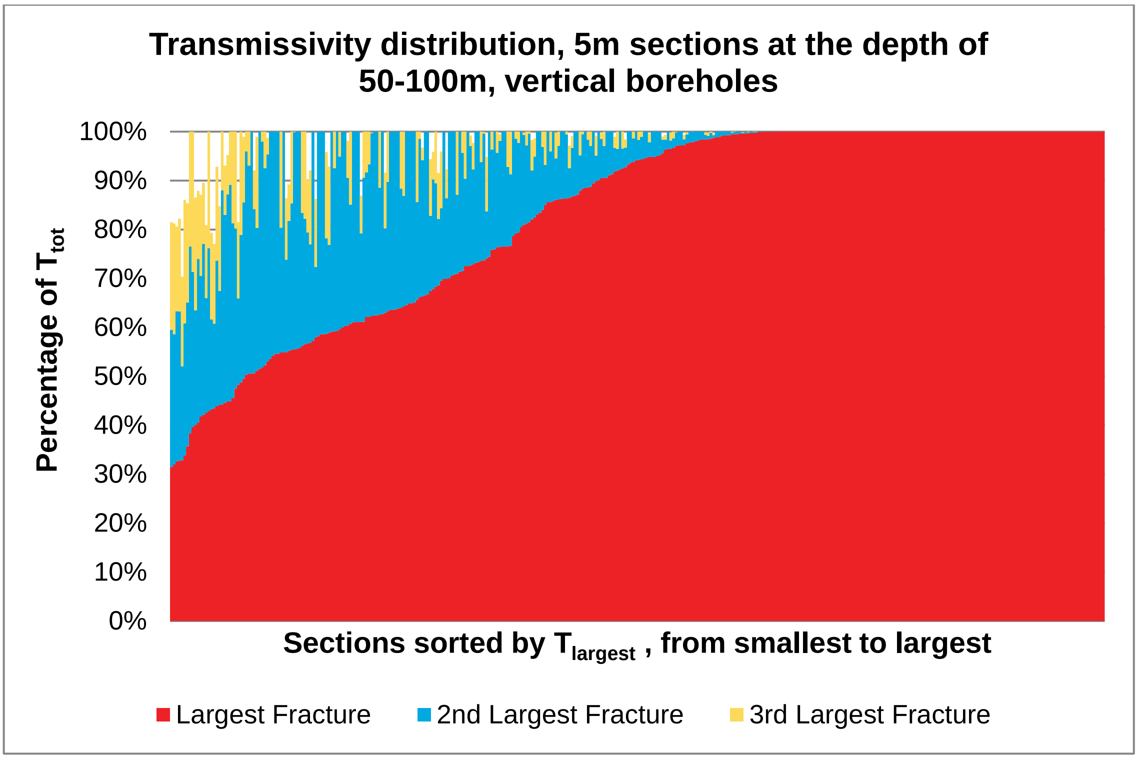

| Transmissivity distribution, 5m sections with 6-19 fractures / m, vertical boreholes | | | | | |
|---|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** | **Mean number of total fractures** |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 | 0,00 |
| 20-30% | 0,48% | 1 | 2,14E-07 | 7,00 | 42,00 |
| 30-40% | 4,31% | 9 | 5,17E-07 | 4,89 | 44,11 |
| 40-50% | 5,74% | 12 | 8,59E-07 | 4,50 | 38,17 |
| 50-60% | 11,48% | 24 | 9,55E-07 | 3,17 | 48,29 |
| 60-70% | 11,48% | 24 | 1,03E-06 | 3,38 | 41,75 |
| 70-80% | 7,18% | 15 | 3,08E-06 | 2,93 | 44,53 |
| 80-90% | 9,57% | 20 | 9,41E-06 | 3,30 | 36,40 |
| 90-99,9% | 15,31% | 32 | 6,62E-06 | 2,72 | 38,94 |
| 100% | 34,45% | 72 | 2,36E-06 | 1,00 | 40,64 |
| | | 209 | 3,25E-06 | 2,54 | 41,27 |

## 1.22 Transmissivity distribution, 5m sections at the depth of 0-50m, vertical boreholes



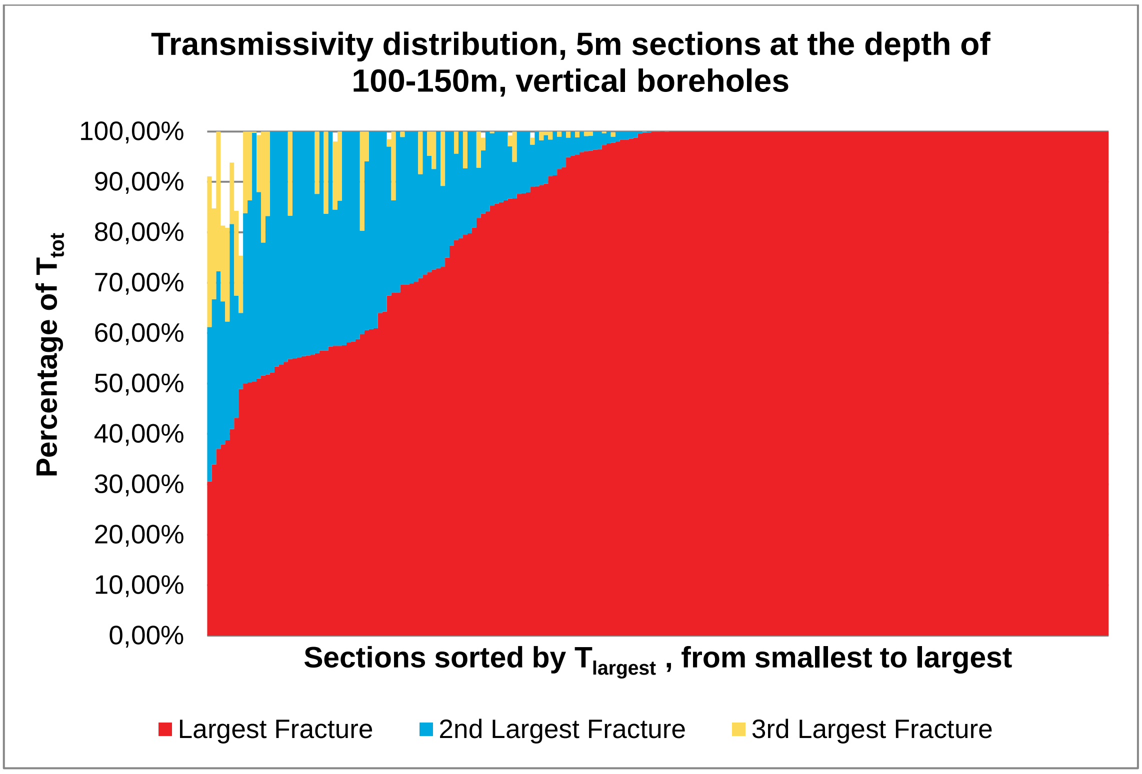

| Transmissivity distribution, 5m sections at the depth of 0-50m, vertical boreholes | | | | |
|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 |
| 20-30% | 1,36% | 5 | 2,98E-07 | 6,00 |
| 30-40% | 4,34% | 16 | 3,64E-07 | 4,75 |
| 40-50% | 9,49% | 35 | 1,04E-06 | 4,71 |
| 50-60% | 14,91% | 55 | 1,59E-06 | 3,69 |
| 60-70% | 14,63% | 54 | 9,92E-07 | 3,46 |
| 70-80% | 10,84% | 40 | 5,37E-07 | 3,58 |
| 80-90% | 10,57% | 39 | 4,42E-06 | 3,90 |
| 90-99,9% | 16,80% | 62 | 7,22E-06 | 3,05 |
| 100% | 17,07% | 63 | 1,97E-06 | 1,06 |
| | | 369 | 2,58E-06 | 3,28 |

### 1.23 Transmissivity distribution, 5m sections at the depth of 50-100m, vertical boreholes



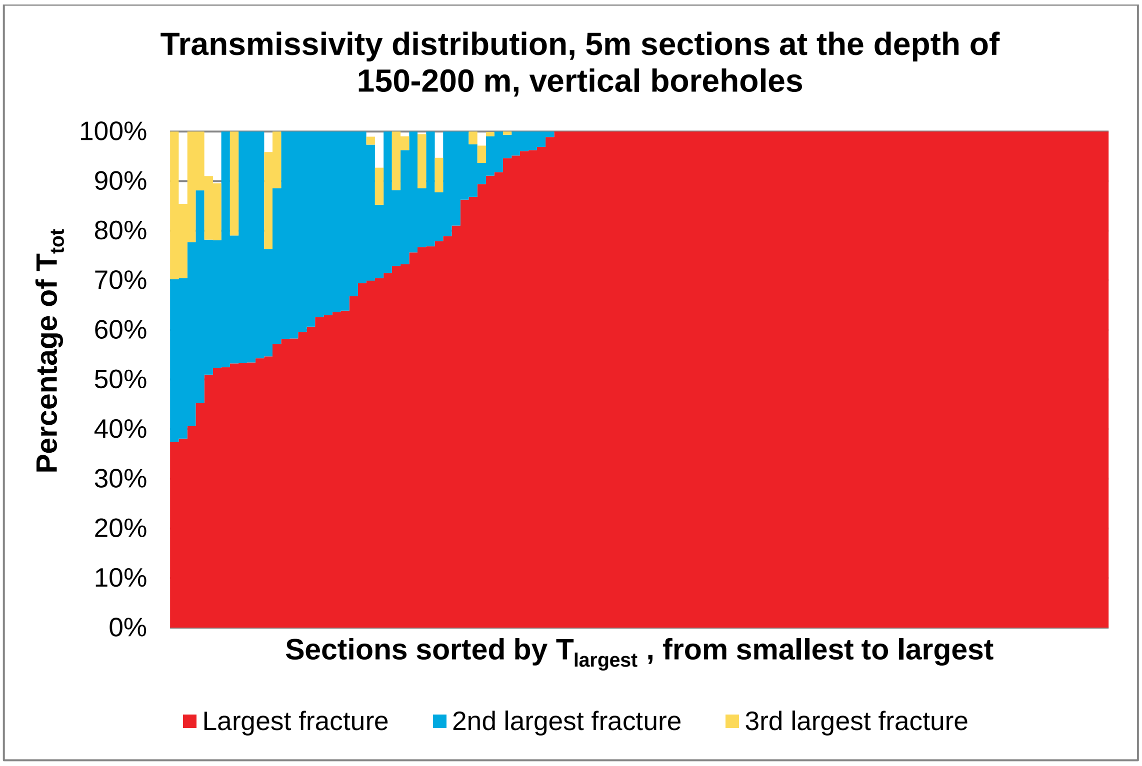

| Transmissivity distribution, 5m sections at the depth of 50-100m, vertical boreholes | | | | |
|---|---|---|---|---|
| Percentage of total transmissivity | Percentage of sections | Number of sections | Mean total transmissivity | Mean number of flowing fractures |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 |
| 20-30% | 0,00% | 0 | 0,00E+00 | 0,00 |
| 30-40% | 2,88% | 10 | 6,99E-08 | 4,30 |
| 40-50% | 5,19% | 18 | 2,19E-07 | 4,06 |
| 50-60% | 10,66% | 37 | 4,47E-07 | 3,05 |
| 60-70% | 11,24% | 39 | 4,63E-07 | 3,05 |
| 70-80% | 7,78% | 27 | 4,91E-07 | 2,74 |
| 80-90% | 8,36% | 29 | 2,07E-06 | 2,90 |
| 90-99,9% | 18,73% | 65 | 8,22E-06 | 2,75 |
| 100% | 35,16% | 122 | 1,95E-06 | 1,00 |
| | | 347 | 2,55E-06 | 2,33 |

### 1.24 Transmissivity distribution, 5m sections at the depth of 100-150m, vertical boreholes



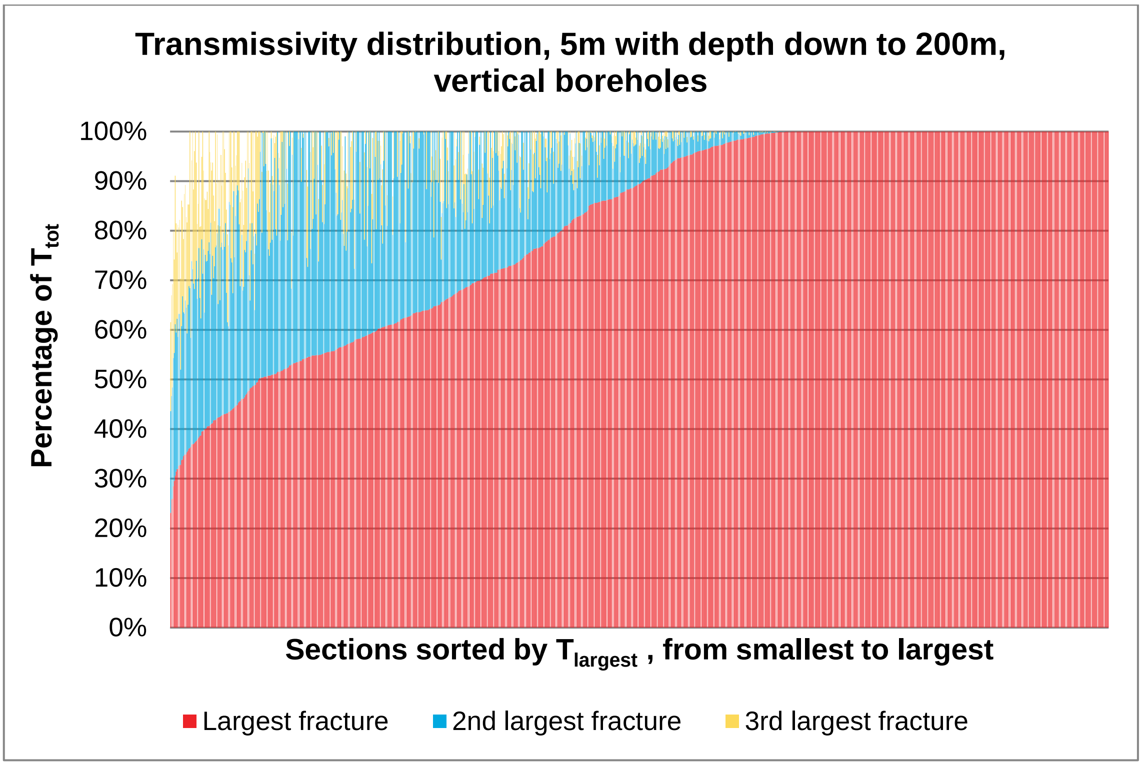

| Transmissivity distribution, 5m sections at the depth of 100-150m, vertical boreholes | | | | |
|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 |
| 20-30% | 0,00% | 0 | 0,00E+00 | 0,00 |
| 30-40% | 2,49% | 5 | 9,34E-08 | 4,40 |
| 40-50% | 1,99% | 4 | 6,02E-08 | 4,50 |
| 50-60% | 11,94% | 24 | 5,48E-07 | 2,50 |
| 60-70% | 5,47% | 11 | 3,53E-06 | 2,55 |
| 70-80% | 6,47% | 13 | 9,97E-07 | 2,46 |
| 80-90% | 8,46% | 17 | 4,34E-06 | 2,76 |
| 90-99,9% | 13,43% | 27 | 6,79E-06 | 2,37 |
| 100% | 48,76% | 98 | 6,17E-07 | 1,00 |
| | | 199 | 1,91E-06 | 1,86 |

### 1.25 Transmissivity distribution, 5m sections at the depth of 150-200 m, vertical boreholes




| Transmissivity distribution, 5m sections at the depth of 150-200m, vertical boreholes | | | | |
|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 |
| 20-30% | 0,00% | 0 | 0,00E+00 | 0,00 |
| 30-40% | 1,82% | 2 | 6,48E-08 | 3,50 |
| 40-50% | 1,82% | 2 | 2,13E-08 | 3,00 |
| 50-60% | 10,91% | 12 | 1,28E-06 | 2,83 |
| 60-70% | 7,27% | 8 | 2,73E-08 | 2,25 |
| 70-80% | 8,18% | 9 | 7,39E-08 | 2,78 |
| 80-90% | 3,64% | 4 | 3,95E-06 | 2,75 |
| 90-99,9% | 7,27% | 8 | 3,58E-07 | 2,38 |
| 100% | 59,09% | 65 | 5,61E-08 | 1,00 |
| | | 110 | 3,52E-07 | 1,68 |

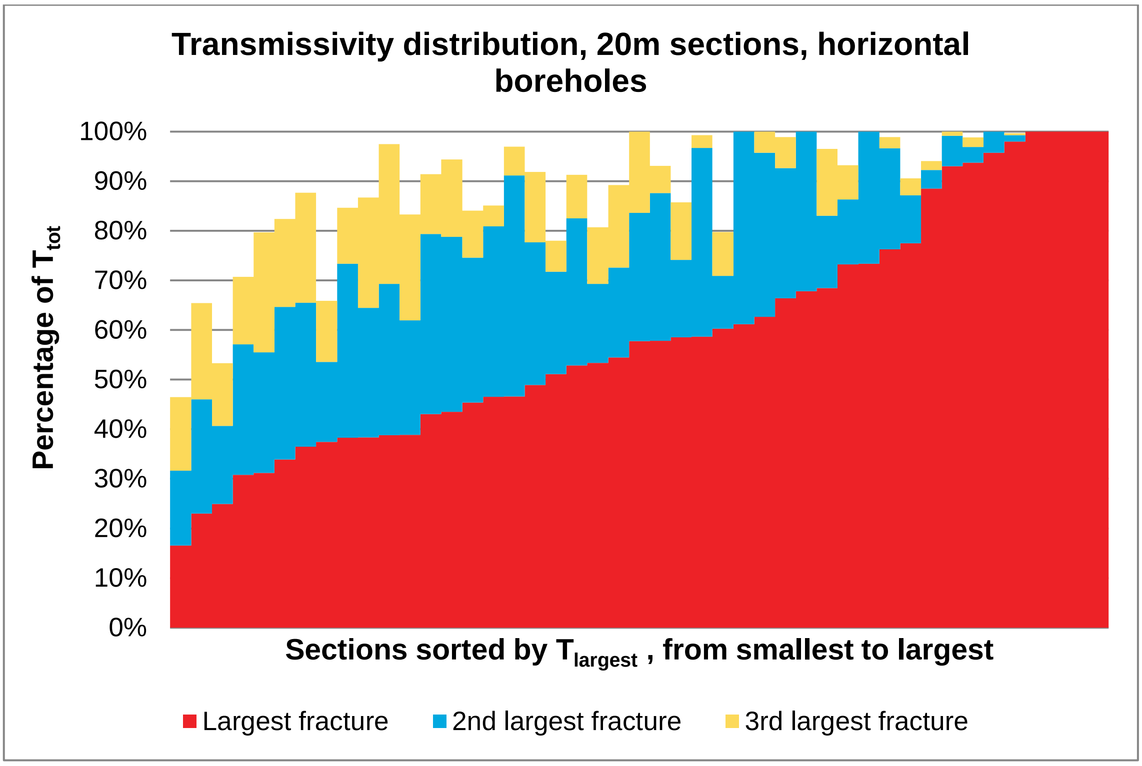
### 1.26 Transmissivity distribution, 5m with depth down to 200m, vertical boreholes




| Transmissivity distribution, 5m with depth down to 100m, vertical boreholes | | | | |
|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** |
| 10-20% | 0,00% | 0 | 0,00E+00 | 0,00 |
| 20-30% | 0,49% | 5 | 2,98E-07 | 6,00 |
| 30-40% | 3,21% | 33 | 2,16E-07 | 4,48 |
| 40-50% | 5,74% | 59 | 6,89E-07 | 4,44 |
| 50-60% | 12,66% | 130 | 1,02E-06 | 3,19 |
| 60-70% | 10,91% | 112 | 9,89E-07 | 3,14 |
| 70-80% | 8,67% | 89 | 5,44E-07 | 3,08 |
| 80-90% | 8,67% | 89 | 3,62E-06 | 3,30 |
| 90-99,9% | 15,77% | 162 | 7,21E-06 | 2,78 |
| 100% | 33,89% | 348 | 1,22E-06 | 1,01 |
| | | 1027 | 2,20E-06 | 2,51 |

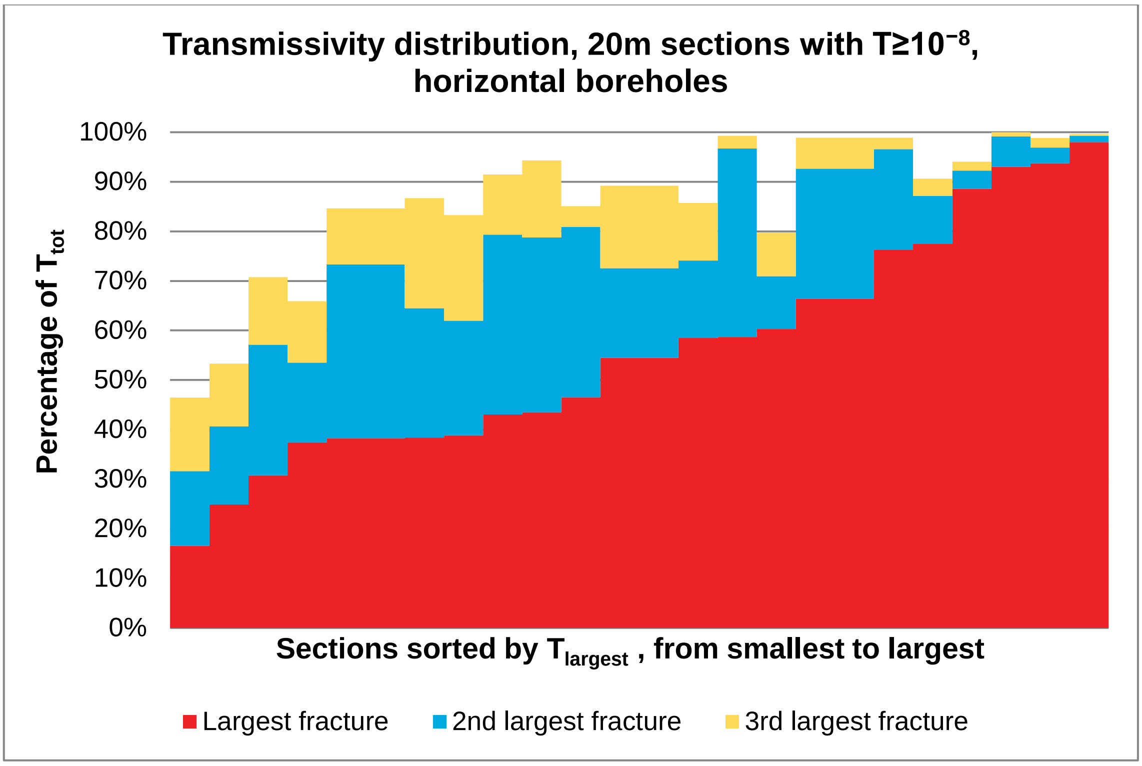
# Appendix 2: Horizontal boreholes

## 2.1 Transmissivity distribution, 20m sections, horizontal boreholes



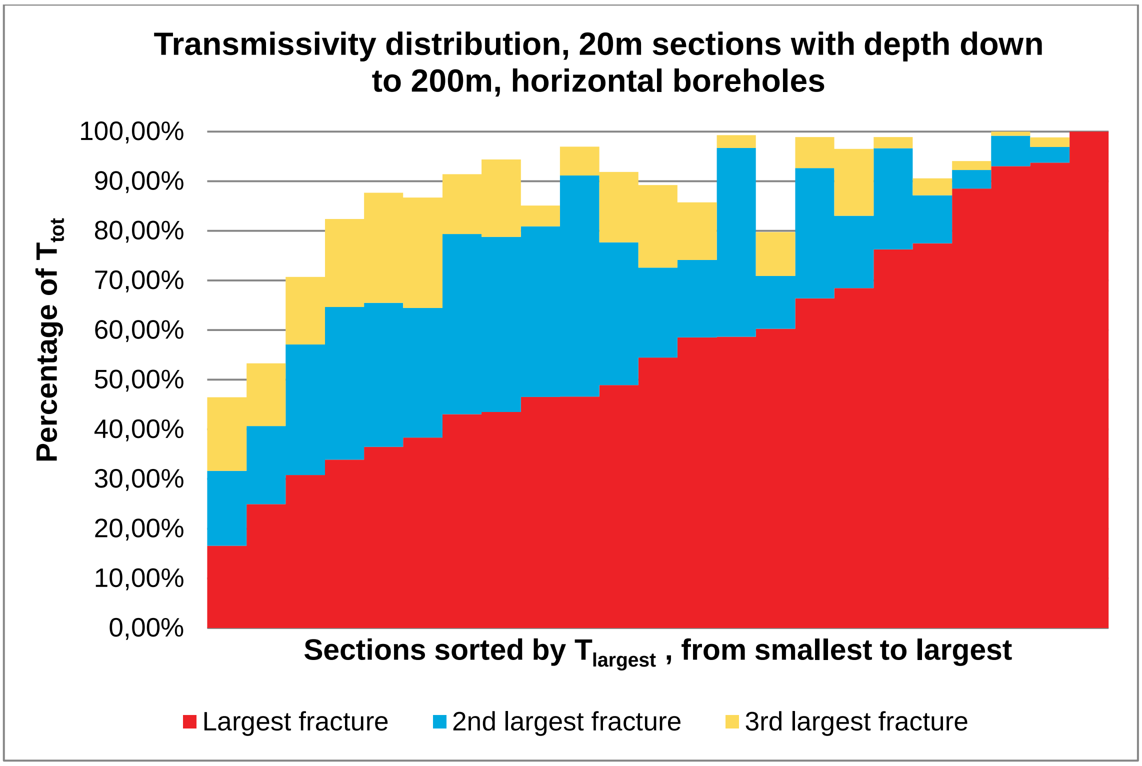

| Transmissivity distribution, 20m sections, horizontal boreholes | | | | |
|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** |
| 10-20% | 2,22% | 1 | 1,5E-07 | 20,00 |
| 20-30% | 4,44% | 2 | 2,91E-07 | 15,00 |
| 30-40% | 20,00% | 9 | 2,62E-07 | 11,44 |
| 40-50% | 13,33% | 6 | 1,52E-06 | 8,83 |
| 50-60% | 17,78% | 8 | 1,12E-06 | 7,38 |
| 60-70% | 13,33% | 6 | 2,28E-07 | 4,17 |
| 70-80% | 8,89% | 4 | 1,52E-07 | 5,00 |
| 80-90% | 2,22% | 1 | 1,55E-07 | 15,00 |
| 90-99,9% | 8,89% | 4 | 4,79E-07 | 4,00 |
| 100% | 8,89% | 4 | 1,16E-09 | 1,00 |
| | | 45 | 5,60E-07 | 7,67 |

## 2.2 Transmissivity distribution, 20m sections with with T≥10⁻⁸, horizontal boreholes



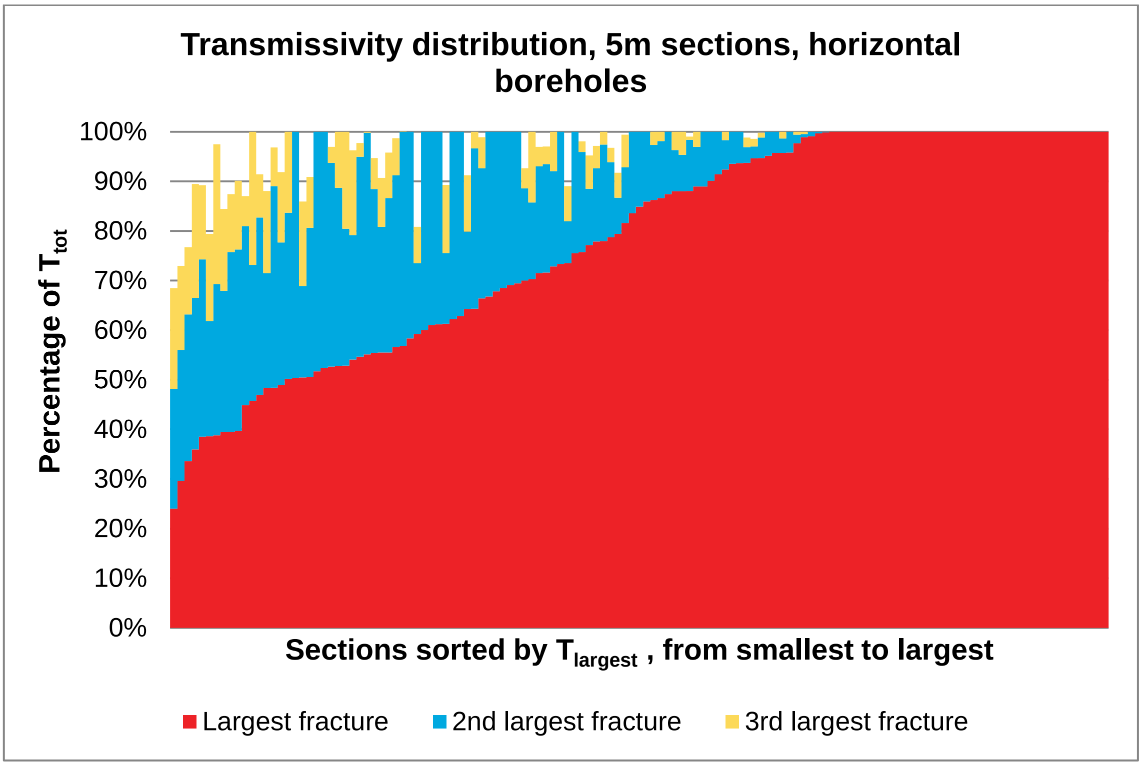

| Transmissivity distribution, 20m sections with with T≥10⁻⁸, ,horizontal boreholes | | | | |
|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** |
| 10-20% | 4,17% | 1 | 1,5E-07 | 20,00 |
| 20-30% | 4,17% | 1 | 5,82E-07 | 24,00 |
| 30-40% | 25,00% | 6 | 3,94E-07 | 14,67 |
| 40-50% | 12,50% | 3 | 3,03E-06 | 13,00 |
| 50-60% | 16,67% | 4 | 2,26E-06 | 6,50 |
| 60-70% | 12,50% | 3 | 4,68E-07 | 6,00 |
| 70-80% | 8,33% | 2 | 3,00E-07 | 7,00 |
| 80-90% | 4,17% | 1 | 1,55E-07 | 15,00 |
| 90-99,9% | 12,50% | 3 | 6,39E-07 | 4,67 |
| 100% | 0,00% | 0 | 0,00E+00 | 0,00 |
| | | 24 | 1,05E-06 | 10,75 |

## 2.3 Transmissivity distribution, 20m sections with depth down to 200m, horizontal boreholes



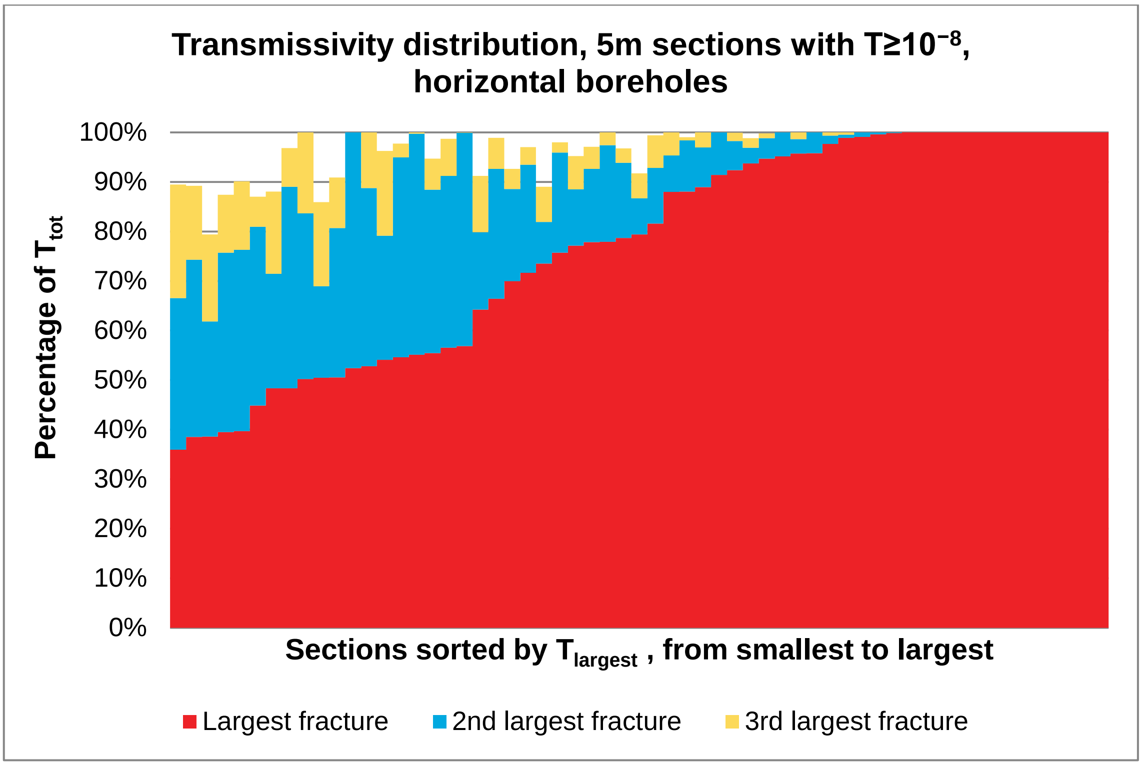

| Transmissivity distribution, 20m sections with depth down to 200m, horizontal boreholes | | | | |
|---|---|---|---|---|
| **Percentage of total transmissivity** | **Perecentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** |
| 10-20% | 4,35% | 1 | 1,5E-07 | 20,00 |
| 20-30% | 4,35% | 1 | 5,82E-07 | 24,00 |
| 30-40% | 17,39% | 4 | 3,18E-07 | 9,00 |
| 40-50% | 21,74% | 5 | 2,04E-06 | 10,00 |
| 50-60% | 13,04% | 3 | 2,99E-06 | 7,00 |
| 60-70% | 13,04% | 3 | 4,57E-07 | 6,00 |
| 70-80% | 8,70% | 2 | 3,00E-07 | 7,00 |
| 80-90% | 4,35% | 1 | 1,55E-07 | 15,00 |
| 90-99,9% | 8,70% | 2 | 8,59E-07 | 4,00 |
| 100% | 4,35% | 1 | 1,60E-10 | 1,00 |
| | | 23 | 1,04E-06 | 8,87 |

## 2.4 Transmissivity distribution, 5m sections, horizontal boreholes



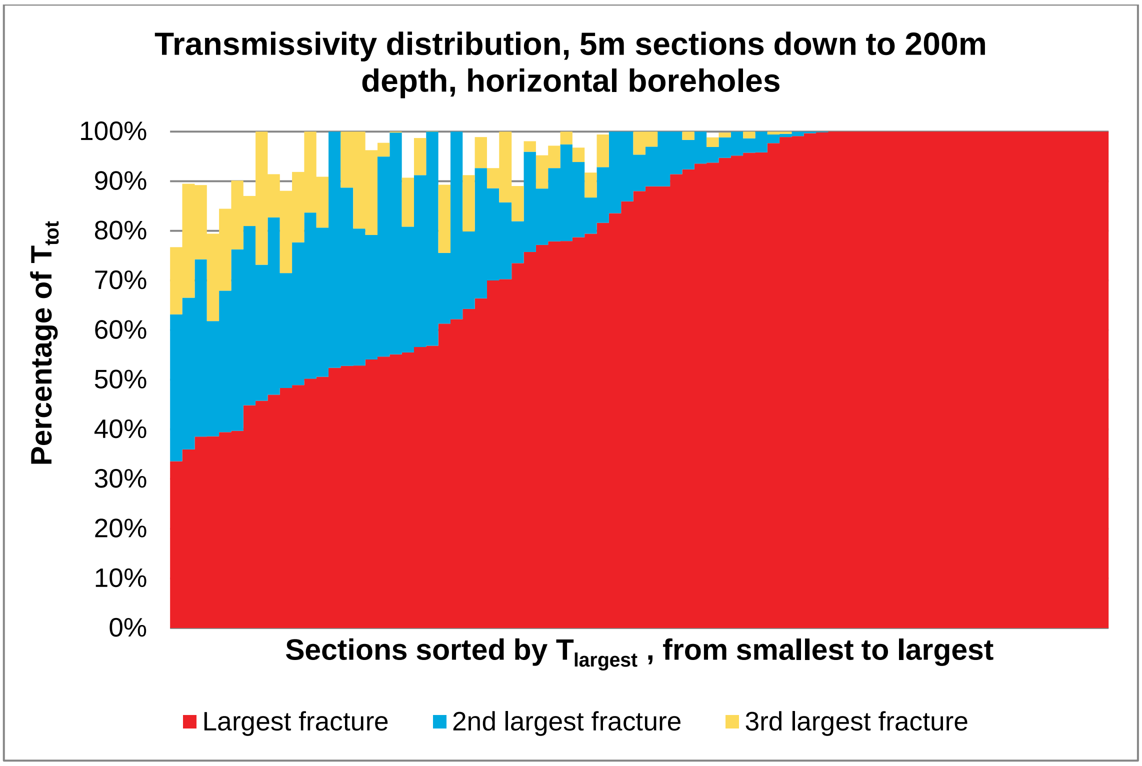

| Transmissivity distribution, 5m sections, horizontal boreholes | | | | |
|---|---|---|---|---|
| Percentage of total transmissivity | Percentage of sections | Number of sections | Mean total transmissivity | Mean number of flowing fractures |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 |
| 20-30% | 1,53% | 2 | 5,82E-10 | 5,50 |
| 30-40% | 6,11% | 8 | 3,06E-08 | 5,00 |
| 40-50% | 4,58% | 6 | 5,85E-08 | 5,17 |
| 50-60% | 14,50% | 19 | 5,28E-07 | 3,84 |
| 60-70% | 10,69% | 14 | 1,92E-08 | 2,64 |
| 70-80% | 10,69% | 14 | 7,70E-08 | 4,29 |
| 80-90% | 9,16% | 12 | 1,25E-07 | 3,00 |
| 90-99,9% | 12,98% | 17 | 5,42E-07 | 2,76 |
| 100% | 29,77% | 39 | 9,02E-07 | 1,03 |
| | | 131 | 4,42E-07 | 2,86 |

## 2.5 Transmissivity distribution, 5m sections with T≥$10^{-8}$, horizontal boreholes



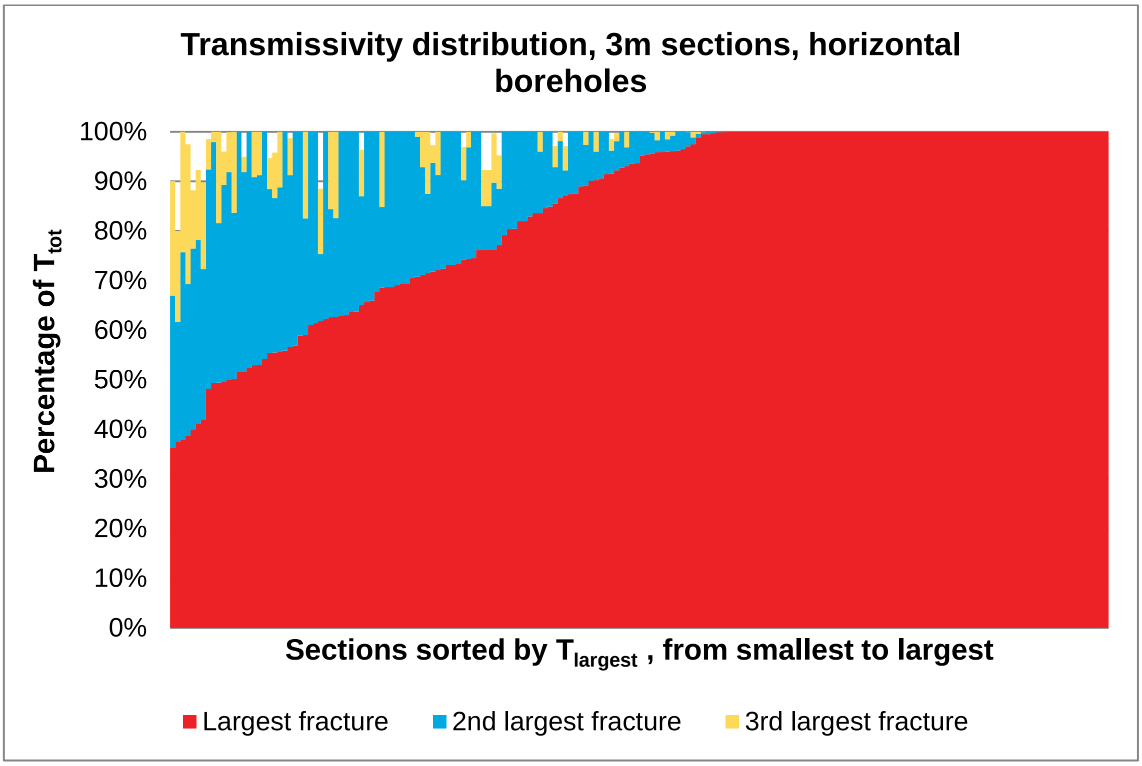

| Transmissivity distribution, 5m sections with T≥$10^{-8}$,horizontal boreholes | | | | |
|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 |
| 20-30% | 0,00% | 0 | 0,00E+00 | 0,00 |
| 30-40% | 8,47% | 5 | 4,67E-08 | 5,20 |
| 40-50% | 5,08% | 3 | 1,14E-07 | 6,67 |
| 50-60% | 18,64% | 11 | 9,10E-07 | 4,09 |
| 60-70% | 3,39% | 2 | 1,32E-07 | 5,00 |
| 70-80% | 15,25% | 9 | 1,19E-07 | 5,11 |
| 80-90% | 6,78% | 4 | 3,72E-07 | 4,25 |
| 90-99,9% | 20,34% | 12 | 7,67E-07 | 2,92 |
| 100% | 22,03% | 13 | 2,71E-06 | 1,08 |
| | | 59 | 9,79E-07 | 3,61 |

## 2.6 Transmissivity distribution, 5m sections down to 200m depth, horizontal boreholes



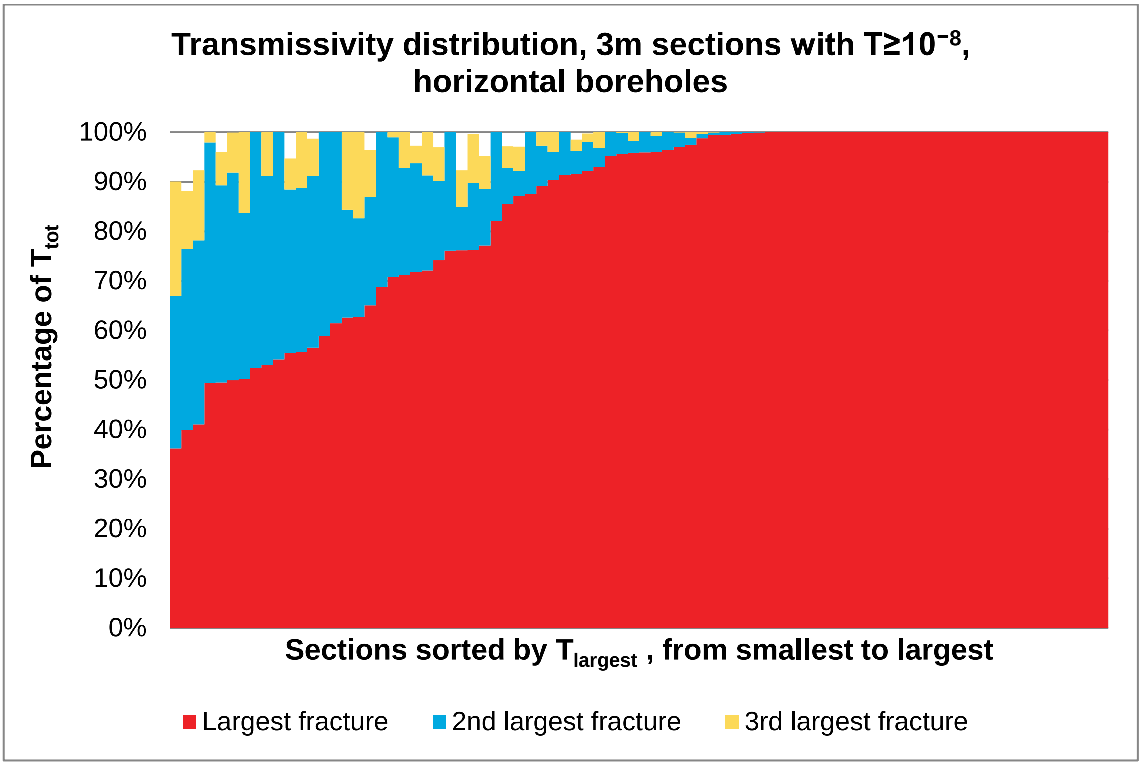

| Transmissivity distribution, 5m sections below 100m depth, horizontals boreholes | | | | |
|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 |
| 20-30% | 0,00% | 0 | 0,0E+00 | 0,00 |
| 30-40% | 7,79% | 6 | 3,8E-08 | 4,67 |
| 40-50% | 6,49% | 5 | 4,5E-08 | 4,80 |
| 50-60% | 14,29% | 11 | 8,6E-07 | 3,64 |
| 60-70% | 5,19% | 4 | 6,6E-08 | 4,00 |
| 70-80% | 11,69% | 9 | 1,0E-07 | 4,78 |
| 80-90% | 7,79% | 6 | 2,1E-07 | 2,83 |
| 90-99,9% | 16,88% | 13 | 7,1E-07 | 2,85 |
| 100% | 29,87% | 23 | 1,5E-06 | 1,04 |
| | | 77 | 7,35E-07 | 2,97 |

## 2.7 Transmissivity distribution, 3m sections, horizontal boreholes




| Transmissivity distribution, 3m sections, horizontal boreholes | | | | |
|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 |
| 20-30% | 0,00% | 0 | 0,00E+00 | 0,00 |
| 30-40% | 2,72% | 5 | 2,38E-08 | 4,60 |
| 40-50% | 3,80% | 7 | 5,23E-08 | 4,00 |
| 50-60% | 8,15% | 15 | 4,53E-08 | 3,13 |
| 60-70% | 10,87% | 20 | 1,64E-08 | 2,45 |
| 70-80% | 10,33% | 19 | 7,49E-08 | 2,84 |
| 80-90% | 8,70% | 16 | 1,26E-07 | 2,44 |
| 90-99,9% | 14,67% | 27 | 4,81E-07 | 2,56 |
| 100% | 40,76% | 75 | 5,56E-07 | 1,01 |
| | | 184 | 3,24E-07 | 2,09 |

## 2.8 Transmissivity distribution, 3m sections with T≥10$^{-8}$ horizontal boreholes




| Transmissivity distribution, 3m sections with T≥10$^{-8}$, horizontal boreholes | | | | |
|---|---|---|---|---|
| **Percentage of total transmissivity** | **Percentage of sections** | **Number of sections** | **Mean total transmissivity** | **Mean number of flowing fractures** |
| 10-20% | 0,00% | 0 | 0,0E+00 | 0,00 |
| 20-30% | 0,00% | 0 | 0,00E+00 | 0,00 |
| 30-40% | 2,44% | 2 | 5,90E-08 | 5,50 |
| 40-50% | 4,88% | 4 | 8,86E-08 | 4,25 |
| 50-60% | 9,76% | 8 | 8,29E-08 | 3,13 |
| 60-70% | 6,10% | 5 | 6,08E-08 | 3,00 |
| 70-80% | 10,98% | 9 | 1,56E-07 | 3,56 |
| 80-90% | 6,10% | 5 | 4,01E-07 | 3,00 |
| 90-99,9% | 23,17% | 19 | 6,82E-07 | 2,72 |
| 100% | 36,59% | 30 | 1,39E-06 | 1,03 |
| | | 82 | 7,25E-07 | 2,41 |