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Oskarshamn site investigation

Field measurements of thermal properties

Multi probe measurements in Laxemar

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Geo Innova AB

April 2007

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

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Preface

The data presented in this report is based on field measurements carried out during the fall of 2006. The locations for measurements were selected in cooperation with Carl-Henric Wahlgren, the Swedish Geological Survey, and John Wrafter, Geo Innova. The field measurements were conducted by Märta Ländell and Fredrik Mossmark, Geo Innova. Data analyses were carried out by Fredrik Mossmark and Jan Sundberg, Geo Innova.

Abstract

The primary objective of this investigation has been to measure thermal conductivity of shallow rock mass within the focused area within the Laxemar subarea. The measurements were conducted as a part of the Oskarshamn Site Investigation. The measurements were carried out in situ at outcroppings. Within the area 26 locations were selected, 24 of these represented the Ävrö Granite. Measurements were also conducted in diorite and in quartz monzodiorite. From the measurements, the heat capacity and thermal diffusivity was also evaluated. The evaluation method also allowed for analysis of anisotropic thermal properties, this evaluation was done for a few of the locations. Samples of rock cores were also taken from the field locations for analysis of density.

The distribution of thermal conductivity for the Ävrö granite is bimodal. The number of measurements in the two different parts of the distribution influences the mean value and causes the average thermal conductivity to be lower than in previous investigations, while the standard deviation is unchanged. Anisotropy of thermal conductivity was found at the three locations where this was investigated. The anisotropy factor was between 1.04 and 1.27.

Sammanfattning

Fältmätningar av primärt värmeledningsförmåga har genomförts i ytligt berg i Laxemar inom ramen för SKB:s platsundersökningar Oskarshamn. I Laxemars fokuserade undersökningsområde valdes 26 platser ut för mätningar, 24 av platserna hade bergarten Ävrögranit. En mätning gjordes även i vardera bergarten diorit och kvartsmonzodiorit. Från mätningarna utvärderades även bergets värmekapacitet och värmediffusivitet. Mätningsmetodiken har möjliggjort utvärdering av anisotropa egenskaper, vilket utförts i några fall. Prover togs på varje mätplats som sedermera analyserades i laboratorium avseende densitet.

För de 24 platserna med Ävrögranit erhölls mätresultat för värmeledningsförmåga mellan 2,17 W/(m·K) och 3,30 W/(m·K). Det aritmetiska medelvärdet för dessa platser var 2,49 W/(m·K). För värmekapacitet varierade resultaten mellan 1,99 MJ/(m^3·K) och 2,58 MJ/(m^3·K) med ett medelvärde på 2,24 MJ/(m^3·K). Anisotropa egenskaper för värmeledningsförmågan konstaterades för de tre mätningar som utvärderades med avseende på detta.

Contents

1 Introduction

SKB are performing investigations for the localisation of a deep repository for spent nuclear fuel at two sites, Forsmark and Oskarshamn. This document reports the results obtained by the measurement of thermal properties in the field in the focused area within the Laxemar subarea. The work was carried out in accordance with activity plan AP PF 400-06-063. For the field activities relating to the methods of measurement, the methods are described in Appendix 2. In Table 1-1, controlling documents for performing this activity are listed. Both activity plan and method descriptions are SKB's internal controlling documents.

The investigation included measurement of thermal properties in the Ävrö granite (mainly) and in quartz monzodiorite and diorite (one measurement each). Measurements of density of rock was also carried out, one sample was collected for laboratory density measurement at each location. The multi probe method makes it is also possibly to evaluate anisotropy in thermal conductivity. This has been done for three locations. The Ävrö granite in this area is weakly foliated, and anisotropy has been considered in the evaluation at only a few locations where measurements of Anisotropy of Magnetic Susceptibility (AMS) have indicated anisotropy /Mattsson et al. 2004/.

The rock outcroppings investigated are located within the Laxemar focus area, see Figure 1-1. For the locations, the ID numbers that have been used range from PSM001488 through PSM001513.

The field measurements were conducted during the period September through November of 2006. Laboratory measurements of density of collected rock samples were carried out by the Swedish National Testing and Research Institute (SP) in November, 2006. The results from the measurements presented in this report provide information concerning the thermal properties in the dominant Ävrö granite.

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

Activity plan	Number	Version
Fältmätning av termiska egenskaper	AP PS 400-06-063	1.0
Method descriptions	**Number**	**Version**
Density	/SKB MD 160.002/	2.0
Multi probe method	/Sundberg 2003/	
Method description: multi probe method	Appendix 2	

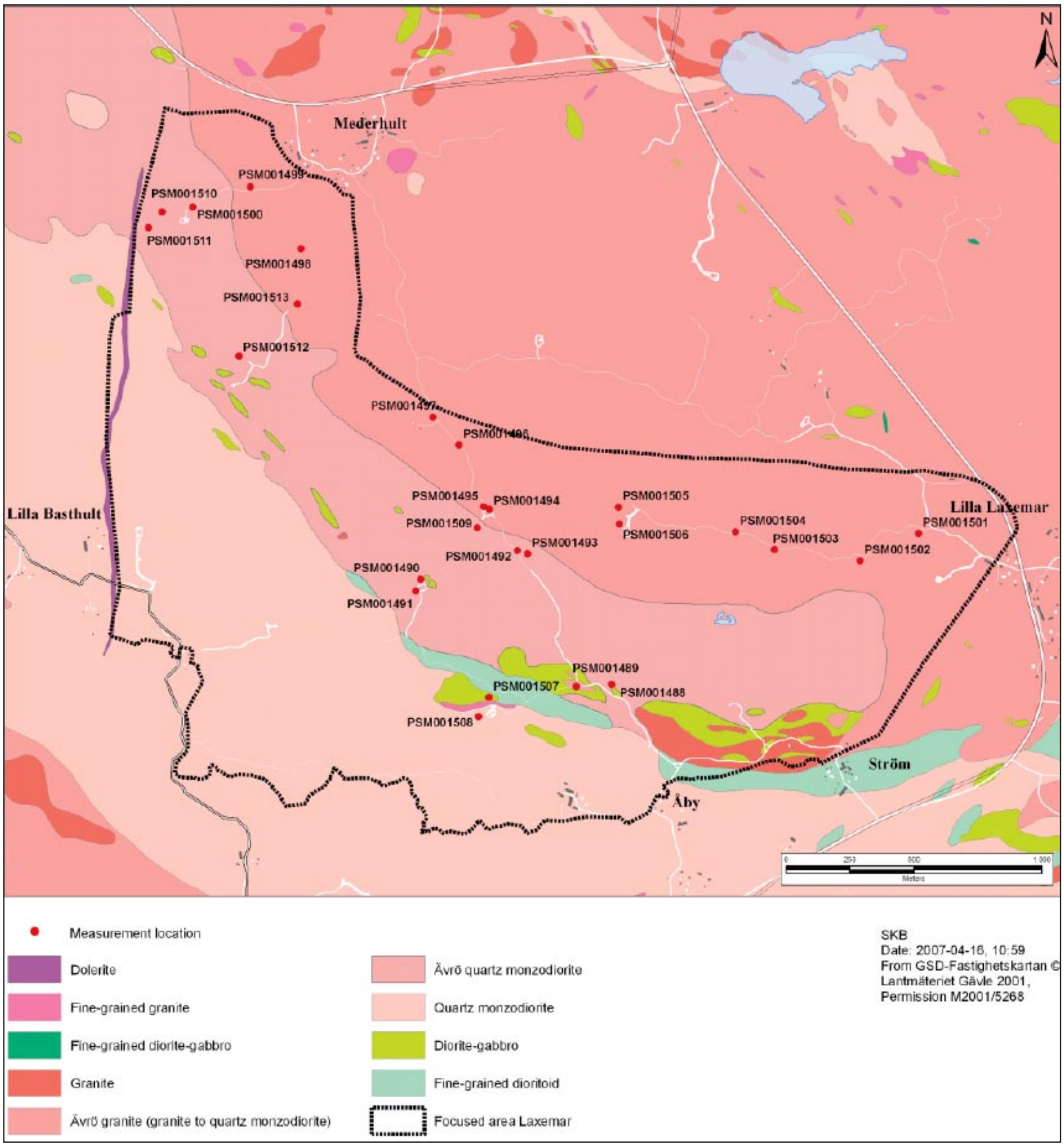

Figure 1-1. *The measurement locations and the rock types within the Laxemar subarea. In this report the Ävrö granite (granite to quartz monzodiorite) and Ävrö quartz monzodiorite are referred to as one rock type, Ävrö granite.*

2 Objective and scope

The primary objective of the investigations is to measure thermal conductivity of rock within the Laxemar area in the field, in a larger scale compared to laboratory measurements. Secondary objectives are to determine heat capacity and thermal diffusivity from the field measurements as well as density of collected samples in laboratory. A third objective is to evaluate possible anisotropy in thermal properties, for a couple of locations.

In previous investigations, a relation between density and thermal conductivity has been found for the Ävrö granite. The most recent developments for understanding of this relation has been presented in /Wrafter et al. 2006/ and /Sundberg et al. 2007a/. A validation of the method through repeated measurements at one location was also carried out.

Thermal properties have been determined using the multi probe and single probes methods. These methods are described in Appendix 2, see also /Sundberg 2003/ and in /Sundberg 1988/. Measurements have been carried out at a total of 26 locations, at 24 of these locations the rock type was Ävrö granite.

3 Equipment

3.1 Description of equipment/interpretation tools

The equipment used for the measurements comprised the following: one heating probe, four measurement probes, one constant current power supply, one data logger, one shunt and one gasoline driven electrical generator. The equipment is described in more detail in Appendix 2.

4 Execution

4.1 General

The first stage of the measurement comprised selection of suitable locations. A desk study was conducted to establish the locations of accessible outcroppings. This was followed by a field recognition that was carried out in collaboration with the Swedish Geological Survey (SGU). During the field recognition, the exact positions of the boreholes were decided based on accessibility, rock type and on fractures. Outcroppings where water saturated fractures could affect the thermal conductivity between boreholes were avoided.

The principle of the field measurements tests is as follows. The heating probe is placed in a centrally positioned borehole that is vertical. In two parallel boreholes, located at a short distance from the heater, probes for monitoring temperature during a measurement were installed. As a contact medium between the probes (both heating and temperature probes) and the rock, bentonite clay was used.

The central borehole was approximately 3.2 m long whereas the surrounding boreholes were drilled to a length of about 2.2 m. The work was carried out in accordance with activity plan AP PS 400-06-063 Measurement of thermal properties with the multi probe method (internal SKB document, in Swedish). The measurement procedure is described in more detail in Appendix 2.

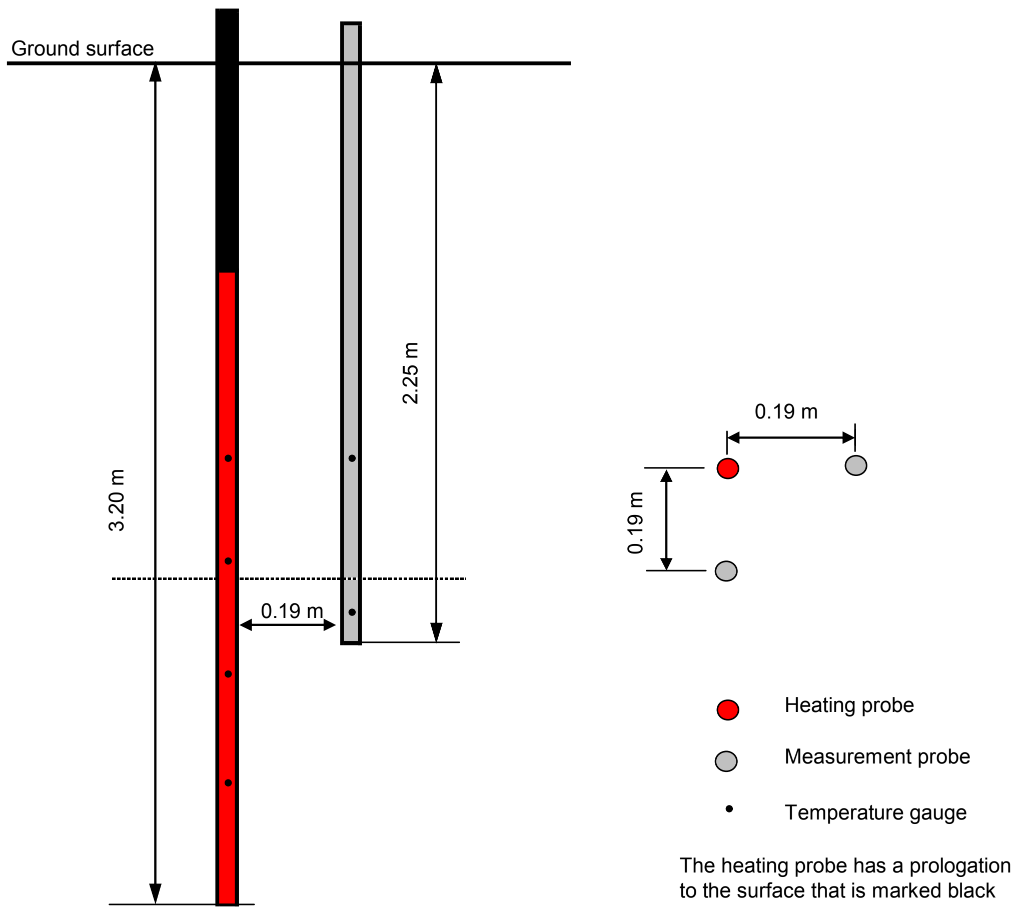

Figure 4-1. *Setup of measurement probes after installation for measurement, the extension rod for the heating probe is marked with black colour (the distances are approximate).*

At each location for measurement, a 10 cm long drill core was sampled for measurement of density in laboratory. The drill core was sampled close to the rock surface and not at the depth for measurement and at a horizontal distance of approximately 0.5 m from the measurement boreholes. The drill core (and the measured density) is therefore not fully representative for the measurement location.

The two measurement boreholes were oriented in a direction from the heating borehole in relation to the mean cardinal direction (102°) of the anisotropy of magnetic susceptibility (AMS) based on data presented in /Mattsson et al. 2004/. One measurement borehole was positioned in a direction from the heating probe that was parallel to the direction of the anisotropy while the other measurement borehole was positioned in a perpendicular direction. The direction from the heating borehole to the measurement borehole that was parallel to the anisotropy at each measurement location is presented in Appendix 4. For the boreholes PSM001492-PSM001495, PSM001503 and PSM001509 orientation of the three boreholes were made according to AMS measurements previously made on the same outcroppings.

According to /Mattsson et al. 2004/ the anisotropy of AMS in the southern Laxemar area has an inclination with moderate to steep dips. The boreholes were made vertical. A possible anisotropy of thermal conductivity could therefore be underestimated.

4.2 Preparations

The boreholes were drilled with a mobile drilling rig, Figure 4-2. The drilling rig used was a model that was mounted on wheels to limit damage to the vegetation when transporting it in the forest. For the drilling 25 mm drill bits were used. The boreholes were drilled with at a slow pace where the drill bit was slowly fed into the rock in order to achieve as parallel boreholes as possible. In the boreholes, stiff rods with slightly less diameter compared to the holes were inserted. The cc-distance between the rods was measured at different heights above the ground surface. From this information the distance between the heater and the sensor was calculated.

Figure 4-1. *Setup of measurement probes after installation for measurement, the extension rod for the heating probe is marked with black colour (the distances are approximate).*

Before each measurement the clay slurry was made in situ through adding of water and bentonite pellets into the boreholes. After the slurry had formed (and the small induced temperature change levelled out in the rock), the probes were inserted into the boreholes.

4.3 Execution of measurements

After installation of the equipment, temperature development of the probes was monitored. In a first step the probes reached the same temperature as in the surrounding rock. In a second step temperature drift of the rock was monitored to be used to correct the temperature during the following measurement.

After more than 20 minutes of monitoring the temperature of the rock mass, the measurement of thermal conductivity started. A constant heating effect of about 100 W/m was applied from the heating probe during a period of three to four hours. It was observed that a constant heat effect over time was achieved from the constant current power supply. Temperature in the probe and the heating effect was monitored with a data logger during the time when the equipment was installed (Figure 4-3). At the location PSM001496 installation and measurement was repeated at four different times to validate the measurement method and to evaluate uncertainties related to the installation. The temperature increase during the measurement period varied between 0.8 K and 2.5 K for the multi probe measurements and between 25 K and 35 K for the single probe measurements. The temperature decreases exponentially with the distance from the heating probe. The mean temperature increase in the measured volume is estimated to 5–10 K.

4.4 Data handling/post processing

After the completion of a measurement data was saved to a laptop computer as csv-files. The files included time, absolute temperature and current through the heating probe that had been measured every ten seconds. The temperature change was recalculated as temperature increase during the heating period and the current through the probe was recalculated to heating effect per metre. After this data processing the data was resaved in the Microsoft Excel format xls.

Figure 4-3. *Probes for measurements and heating, constant current power supply, data logger and laptop computer for monitoring of data.*

4.5 Analyses and interpretations

Two different analytical methods were used to analyze the measured data: one for the measurements of temperature in the heating probe and one for the measurement probes. The theories have previously been presented in, among others, /Sundberg 1988/.

4.5.1 Evaluation with multi probe theory

Evaluation of thermal properties with multi probe theory of data from the measurement probes determines not only the thermal conductivity but also thermal diffusivity (κ) and heat capacity (C). The method uses the analytical solution to temperature increase in a measurement probe presented in Equation 4-1. The equation uses time, radius, thermal conductivity and thermal diffusivity as variables /Carslaw and Jaeger 1959/.

$$T(r,t,\lambda,k) = \frac{q}{4\pi\lambda} \int_{\frac{r^2}{4\kappa t}}^{\infty} \left(\frac{e^{-x}}{x} \right) dx \qquad \text{Equation 4-1}$$

where

λ is thermal conductivity (W/(m·K))

κ is the thermal diffusivity (m^2/s)

q is the applied heating effect per metre (W/m)

r is the distance between the centre of the heating probe and the sensor at the measurement probe (m)

t is time (s)

T is temperature (K)

A fitting between measured data and the analytical method was made using the numerical conjugate gradient method with the software Mathcad. The heat capacity (C) will be determined according to Equation 4-2.

$$C = \frac{\lambda}{\kappa} \qquad \text{Equation 4-2}$$

where

κ is thermal diffusivity (m^2/s)

λ is thermal conductivity (W/(m·K))

C is heat capacity ($J/(m^3 \cdot K)$)

4.5.2 Evaluation for single probe measurements

The analysis of the temperature data from the heating probe was done with a simplified method based on the Equation 4-1. The simplified evaluation for the single probe method requires that $r^2/(4\kappa t)$ is small (if $r^2/(4\kappa t) < 0.01$ the error is < 1%). If this requirement is fulfilled, Equation 4-1 can be simplified as

$$T = \frac{q}{4\pi \cdot \lambda} \cdot (-\ln(r^2/4\kappa t) - \gamma) \qquad \text{Equation 4-3}$$

where γ = Eulers constant (0.5772….)

In a lin-log diagram, Equation 4-3 results in a straight line and the thermal conductivity can be evaluated from the slope of the asymptote.

This requirement needed to be fulfilled to use this simplified method means that the combination of measurement time and radius of thermal probe has to be considered, it is valid for long measurement time (t) and for small probe radius (r). For the evaluation Mathcad uses fitting with the numerical method Conjugate gradient to fit a logarithmic curve to the measured temperature data for the time period that is used for evaluation of thermal conductivity.

4.5.3 Evaluation of anisotropic thermal conductivity

The development of Equation 4-1 (developed by Claesson, 2006 and described in /Sundberg et al. 2007b/) has enabled evaluation of anisotropic thermal conductivity. The method used is described in Equation 4-4 considers a three dimensional grid and different thermal conductivity in two directions.

$$Td\left(x,y,z,t,\lambda_{.x},\lambda_{.y},C,q\right)=\frac{q}{4\cdot\pi\cdot\sqrt{\lambda_{.x}\cdot\lambda_{.y}}}\cdot\int_{H\cdot\sqrt{\frac{C}{4\cdot\lambda_{.x}\cdot t}}}^{\infty}e^{-\left(x^2+\frac{\lambda_{.x}}{\lambda_{.y}}\cdot y^2\right)\cdot\left(\frac{s}{H}\right)^2}\cdot\frac{1}{s}\cdot F(s,z)\,ds$$

$$F\ s,z) = \mathrm{erf}\left[\left(1-\frac{z}{H}\right)\cdot s\right]+\mathrm{erf}\left[\left(1+\frac{z}{H}\right)\cdot s\right] \qquad \text{Equation 4-4}$$

where,

H is the half the heater length (m)

λ_x, λ_y is the thermal conductivity in the principal directions ($\lambda_z = \lambda_x$ is assumed) (W/(m·K))

4.6 Comparison to approximation of thermal conductivity from density data

An empirical relationship has previously been developed to calculate thermal conductivity of Ävrö granite from density. The model is presented in /Sundberg et al. 2005b, 2006/ and /Wrafter et al. 2006/ and is based on laboratory measurements of thermal conductivity and density). The relation between density (ρ)and thermal conductivity (λ) is described in Equation 4-5.

$$\lambda = 3.739E{-}05\rho^2 - 0.2133655\rho + 306.344 \qquad \text{Equation 4-5}$$

4.7 Assessment of measured scale

An estimation of the measured scale has been carried out through a calculation of the influence of positive (infinite thermal conductivity) or negative (infinitesimal thermal conductivity) boundary. The impact from the boundary at the measurement probe is described in Equation 4-6. This impact is compared to the temperature increase in the measurement probe described in Equation 4-1. The division between Equation 4-7 and Equation 4-4 gives a relative impact on the temperature from the boundary. For the single probe method, the effect on the temperature rise in the heating probe is smaller than 0.5%, the distance to the boundary has to fulfil the criterion in Equation 4-7 /Sundberg 1988/.

$$T = \pm \frac{q}{4\pi\lambda} \int_{\frac{(2 \cdot r_b - r_t)^2}{4\kappa t}}^{\infty} \frac{e^{-x}}{x} \,\mathrm{dx}$$ Equation 4-6

$$r_b > 2 r_t \cdot \left(\frac{\kappa t}{r_t^2}\right)^{0.452}$$ Equation 4-7

where

r_b is the distance to the boundary (m)

r_t is the distance from the heating probe to the measurement probe (m) (In Equation 4-7 this distance is represented by the probe radius)

κ is the thermal diffusivity (m^2/s)

t is time (s)

4.8 Nonconformities

The measurements have been performed according to the activity plan. However, three planned locations for measurements were according to SKB not advisable to access due to difficulties to get approval from some of the landowners. For some of the measurements, failure of one or more of the sensors limited the number of data used for determination of thermal conductivity. A summary of what data that has been used in the results is presented in Appendix 1. In Appendix 2 the method is described. The description was written before the measurement in conformity with the activity plan. The measurements have been performed in conformity with the description. However, the used method to determine cc-distance had not such a high precision as planned.

5 Results

5.1 Measurement of thermal conductivity

The results from the measurements of thermal conductivity are presented in Figure 5-1. The two evaluation methods (single probe and multi probe) combined result in a total of eight different results for thermal conductivity for each location. A geometrical mean has been calculated for the four results from each method, this has been followed by the calculation of an arithmetical mean of the two methods. The complete set of results from the evaluation of the measurements is presented in Appendix 3.

The results for thermal conductivity varied between 2.17 W/(m·K) and 3.3 W/(m·K) for the 26 measured locations. For 24 of the locations the data presented in Figure 5-1 represent an arithmetic mean of data from the single probe and the multi probes method. For PSM001489 only results from the single probe method is included and for PSM001513 only multi probe method results are presented. Table 5-1, Table 5-2 and Table 5-3 present the results from the two methods and also for heat capacity and thermal diffusivity.

The highest thermal conductivity was measured in PSM001489 where it was determined to 3.3 W/(m·K). The lowest thermal conductivity of 2.17 W/(m·K) was determined for PSM001496 when considering both evaluation methods (Figure 5-1). For the Ävrö granite the mean thermal conductivity was slightly higher for the single probe method (2.52 W/(m·K)) compared to the multi probe method (2.43 W/(m·K)) (Table 5-3). If only locations where both evaluation methods have been used, were included the mean value for the single probe was 2.48 W/(m·K) compared to 2.41 W/(m·K) for the multi probe method. The evaluated thermal conductivity was hence 3% higher for the single probe method than for the multi probe method.

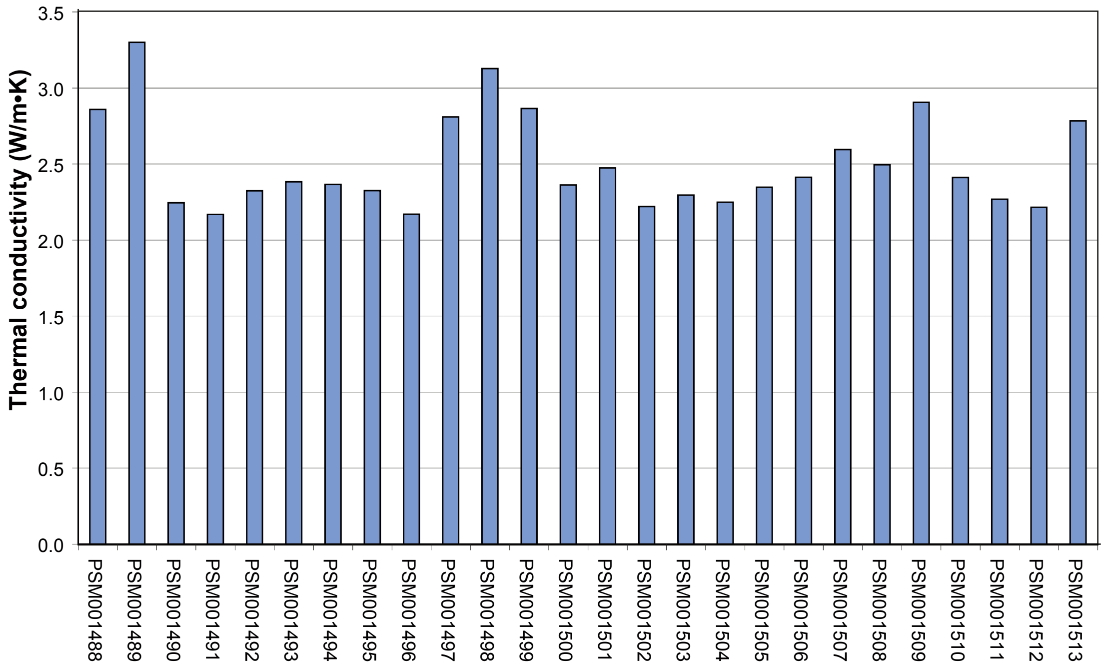

Figure 5-1. *Combined results of evaluated thermal conductivity from both the single probe method and the multi probe methods for the 26 locations where field measurements were carried out.*

Table 5-1. Results from the evaluation of thermal conductivity with the single probe and multi probe methods. Some measurements results are missing or have been excluded, see Appendix 3.

Measurement method Location ID	Thermal conductivity Combined results from both methods (W/(m·K))	Std. dev	Thermal conductivity Multi probe (W/(m·K))	Std. dev.	Thermal conductivity Single probe (W/(m·K))	Std. dev.	Rock type
PSM001488	2.86	0.08	2.83	0.12	2.88	0.05	Ävrö granite
PSM001489	3.30	0.05			3.30	0.05	Ävrö granite
PSM001490	2.24	0.06	2.26		2.23	0.06	Ävrö granite
PSM001491	2.17	0.08	2.11	0.05	2.23	0.10	Ävrö granite
PSM001492	2.32	0.08	2.29	0.03	2.36	0.11	Ävrö granite
PSM001493	2.38	0.07	2.34	0.05	2.43	0.05	Ävrö granite
PSM001494	2.37	0.08	2.33		2.41	0.08	Ävrö granite
PSM001495	2.33	0.06	2.27	0.03	2.38	0.01	Ävrö granite
PSM001496	2.17	0.09	2.10	0.04	2.24	0.06	Ävrö granite
PSM001497	2.81	0.07	2.79	0.06	2.83	0.07	Ävrö granite
PSM001498	3.11	0.06	3.15	0.05	3.08	0.05	Ävrö granite
PSM001499	2.87	0.08	2.81	0.04	2.93	0.05	Ävrö granite
PSM001500	2.36	0.19	2.31	0.11	2.42	0.23	Ävrö granite
PSM001501	2.47	0.05	2.44	0.05	2.51	0.05	Ävrö granite
PSM001502	2.22	0.09	2.26	0.09	2.18	0.07	Ävrö granite
PSM001503	2.30	0.05	2.25	0.02	2.34	0.02	Ävrö granite
PSM001504	2.25	0.07	2.21	0.08	2.29	0.05	Ävrö granite
PSM001505	2.35	0.04	2.32	0.02	2.38	0.03	Ävrö granite
PSM001506	2.41	0.05	2.33	0.05	2.49		Ävrö granite
PSM001509	2.91	0.10	2.87	0.05	2.94	0.04	Ävrö granite
PSM001510	2.41	0.05	2.38	0.05	2.44	0.05	Ävrö granite
PSM001511	2.27	0.07	2.20	0.02	2.34	0.03	Ävrö granite
PSM001512	2.22	0.06	2.17	0.02	2.26	0.06	Ävrö granite
PSM001513	2.78	0.06	2.78	0.06			Ävrö granite
PSM001507	2.60	0.06	2.60	0.08	2.59	0.06	Diorite
PSM001508	2.50	0.06	2.46	0.04	2.53	0.04	Quartz monzodiorite

The heat capacity varied between 1.99 MJ/m^3·K and 2.58 MJ/(m^3·K) for the Ävrö granite with an arithmetic mean of 2.24 MJ/(m^3·K). The thermal diffusivity ranged from 0.89 mm^2/s to 1.31 mm^2/s with a mean value of 1.05 mm^2/s. For eight of the measurement locations thermal diffusivity and heat capacity were not determined. The quality of these measurements was judged to be lower due to high variability in determinations of thermal diffusivity from individual sensors and unsatisfactory fit between measured and calculated temperature.

Table 5-2. Results from evaluation of thermal diffusivity and heat capacity. For eight of the measurement locations the quality of the measurements was judged to be lower and therefore not included. Some measurements results are missing or have been excluded, see Appendix 3.

Measurement method Location ID	Thermal diffusivity Multi probe (mm²/s)	Heat Capacity Multi probe (MJ/m³·K)	Rock type
PSM001488	1.22	2.33	Ävrö granite
PSM001489			Ävrö granite
PSM001490	0.98	2.30	Ävrö granite
PSM001491	0.89	2.36	Ävrö granite
PSM001492	1.05	2.19	Ävrö granite
PSM001493	1.03	2.27	Ävrö granite
PSM001494			Ävrö granite
PSM001495	1.11	2.04	Ävrö granite
PSM001496	1.06	1.99	Ävrö granite
PSM001497	1.24	2.25	Ävrö granite
PSM001498			Ävrö granite
PSM001499	1.31	2.14	Ävrö granite
PSM001500	1.05	2.21	Ävrö granite
PSM001501	1.07	2.29	Ävrö granite
PSM001502	1.02	2.21	Ävrö granite
PSM001503			Ävrö granite
PSM001504	1.01	2.18	Ävrö granite
PSM001505			Ävrö granite
PSM001506	0.91	2.58	Ävrö granite
PSM001509			Ävrö granite
PSM001510			Ävrö granite
PSM001511	0.97	2.26	Ävrö granite
PSM001512	0.96	2.27	Ävrö granite
PSM001513			Ävrö granite
PSM001507	1.05	2.49	Diorite
PSM001508	1.15	2.13	Quartz monzodiorite

Table 5-3. Summary of the measurement results of thermal properties for the Ävrö granite.

Measurement method	Thermal conductivity Combined from the two methods (W/(m·K))	Multi Probe (W/(m·K))	Single Probe (W/(m·K))	Heat Capacity Multi probe (MJ/(m³·K))	Thermal diffusivity Multi probe (mm²/s)
Mean	2.49	2.43	2.52	2.24	1.05
n	24	23	23	16	16
Std. dev.	0.32	0.29	0.31	0.13	0.12
Max	3.30	3.15	3.30	2.58	1.31
Min	2.17	2.10	2.18	1.99	0.89

5.2 Measurement of density

The results from the laboratory measurements of density are presented in Table 5-4. The wet density varied from 2,650 kg/m^3 to 2,788 kg/m^3 for the Ävrö granite. The wet density of diorite and of quartz monzodiorite was above 2,800 kg/m^3 (Table 5-4).

5.3 Correlation between density and thermal conductivity

The results from the laboratory analysis of density and the determined thermal conductivity for Ävrö granite were compared to the previously established relationship between these two parameters as described in Equation 4-5. Figure 5-2 illustrates that the thermal conductivity was lower than what would be assessed with Equation 4-5 for 21 of the 24 locations in Ävrö granite.

A division of the Ävrö granite into two subgroups has been defined that Ävrö granite with a higher density than 2,710 kg/m^3 constitutes one group and Ävrö granite with a lower density than 2,710 kg/m^3 constitutes another group /Wrafter, personal communication/. According to this density criterion, 16 of the measurement locations would represent the group with higher density while 6 would represent the group with lower density. The mean thermal conductivity and density for each group is presented in Table 5-5. The higher density group had a mean thermal conductivity of 2.36 (W/(m·K)) while the lower had a conductivity of 2.97 (W/(m·K)). The outliers PSM001496 and PSM001502 were not appointed to any of the groups.

Table 5-4. Wet and dry density of samples collected at the locations for measurements.

Location/ Sample ID	Dry density, ρd (kg/m^3)	Wet density (kg/m^3)	Rock type
PSM001488	2,721	2,728	Ävrö granite
PSM001489	2,644	2,650	Ävrö granite
PSM001490	2,784	2,788	Ävrö granite
PSM001491	2,727	2,734	Ävrö granite
PSM001492	2,730	2,738	Ävrö granite
PSM001493	2,703	2,712	Ävrö granite
PSM001494	2,705	2,715	Ävrö granite
PSM001495	2,729	2,737	Ävrö granite
PSM001496	2,701	2,712	Ävrö granite
PSM001497	2,676	2,685	Ävrö granite
PSM001498	2,649	2,661	Ävrö granite
PSM001499	2,669	2,677	Ävrö granite
PSM001500	2,720	2,732	Ävrö granite
PSM001501	2,744	2,751	Ävrö granite
PSM001502	2,668	2,675	Ävrö granite
PSM001503	2,723	2,732	Ävrö granite
PSM001504	2,734	2,739	Ävrö granite
PSM001505	2,712	2,723	Ävrö granite
PSM001506	2,706	2,719	Ävrö granite
PSM001509	2,680	2,689	Ävrö granite
PSM001510	2,723	2,732	Ävrö granite
PSM001511	2,720	2,726	Ävrö granite
PSM001512	2,717	2,725	Ävrö granite
PSM001513	2,662	2,673	Ävrö granite
PSM001507	2,853	2,858	Diorite
PSM001508	2,805	2,811	Quartz monzodiorite

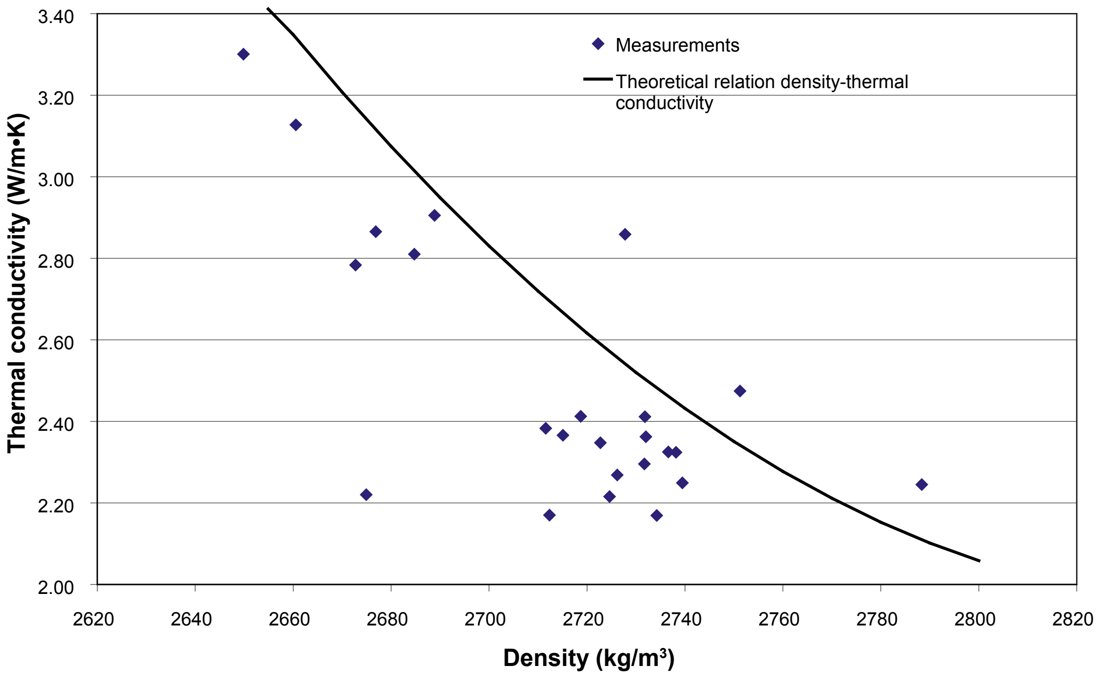

***Figure 5-2.** Thermal conductivity and wet density of the rock at the locations for measurements compared to the previously established relationship between the two parameters. See also text.*

Table 5-5. Mean density and thermal conductivity based on the density division of the Ävrö granite.

Division by density	Number of measurements n	Mean density kg/m³	Mean thermal conductivity (W/(m·K))	Standard deviation (W/(m·K))
> 2,710 kg/m³	16	2,733	2.36	0.16
< 2,710 kg/m³	6	2,672	2.97	0.20

5.4 Assessment of measurement scale

Data from the calculated arithmetic mean for thermal properties of Ävrö granite in Table 5-3 has been used with Equation 4-6 to assess the scale that has an impact on the results in the multi probe measurement. For insertion into the equation $r_{t,}$ the distance from the heating probe to the measurement probe has been estimated to 0.19 m and the time t to 10,800 s. For the thermal diffusivity, κ, three different values have been used from Table 5-3: the arithmetic mean ($1.05 \cdot 10^{-6}$ m²/s) the minimum ($0.89 \cdot 10^{-6}$ m²/s) and the maximum ($1.31 \cdot 10^{-6}$ m²/s).

After insertion of the data into Equation 4-1 and Equation 4-6 a calculated maximum distance to a fictive boundary that would affect the temperature increase by more than 0.5% is presented in Table 5-6. The impact of the 0.5% change in temperature increase for the entire measurement period was tested with data for location PSM001492. The regular evaluation resulted in the determined thermal conductivity of 2.29 W/(m·K), with a 0.5% change in temperature increase the evaluated conductivity was 2.36 W/(m·K). The difference is equal to 3%. Depending on what thermal diffusivity that is assumed, a distance to a fictive boundary would be in the range between 0.31 m and 0.34 m.

Table 5-6. Distance from the heating probe (multi probe method) to a fictive boundary positioned outside a measurement location that would affect the temperature increase by more than 0.5% in the measurement location.

	Thermal diffusivity κ (m^2/s)	Distance to boundary (m)
Min	$0.89 \cdot 10^{-6}$	0.31
Mean	$1.05 \cdot 10^{-6}$	0.33
Max	$1.31 \cdot 10^{-6}$	0.34

With the distance (radius) to a fictive boundary presented in Table 5-6 and with the known distance between the temperature gauges of the measurement probes a measured volume can be assumed. The vertical distance between the gauges is approximately 0.65 m. The volume of a measured cylinder of the rock with a 0.33 m radius and 0.65 m length is approximately 0.22 m^3. An assessment of the distance to a fictive boundary for the single probe measurement was also carried out using Equation 4-7. The distance would be approximately 0.17 m.

5.5 Anisotropy of thermal conductivity

At the locations PSM001492, PSM001495 and PSM001503 Anisotropy of Magnetic Susceptibility (AMS) had previously been measured /Mattsson et al. 2004/. The boreholes for the field measurements in this investigation had been oriented to measure thermal properties parallel and perpendicular to the anisotropy direction. One of the measurement boreholes was located parallel to the anisotropy direction from the heating probe and one was located in a perpendicular direction. For the three locations studied, a directional difference could be determined from the multi probe method as presented in Table 5-7. The thermal conductivity parallel to the anisotropy was between 4% and 27% higher than in the perpendicular direction.

Table 5-7. Thermal conductivity parallel and perpendicular to the anisotropy of magnetic susceptibility at locations where also measurements of magnetic susceptibility have been carried out.

Anisotropy	Thermal conductivity (W/(m·K))		
	Parallel	Perpendicular	λparallel/ λperpendicular
PSM001492	2.34	2.25	1.04
PSM001495	2.44	1.92	1.27
PSM001503	2.43	2.02	1.21

6 Assessment of uncertainties

6.1 Influence from contact medium and probe data

A calculation was made to evaluate the sensitivity of the evaluated results regarding the impact from the different thermal properties of the contact medium and the heating probe compared to the surrounding rock. Various properties of the contact medium and the probe were assumed and different measurement time was used for this purpose in a repeated evaluation. The method used for a calculated temperature increase is described in Equation 6-1 /Claesson 2006/. The values of the variables were assumed. In a second step, the exported temperature increase has been evaluated for thermal conductivity and heat capacity according to the method described in Section 4.5.1.

$$J(y) = \left(1 - \alpha \cdot \beta \cdot y^2\right) \cdot J1(y) - \alpha \cdot y \cdot J0(y)$$

$$Y(y) = \left(1 - \alpha \cdot \beta \cdot y^2\right) \cdot Y1(y) - \alpha \cdot y \cdot Y0(y)$$

$$T(t, a, \lambda) = \frac{q0}{\lambda} \cdot \frac{1}{\pi^2} \cdot \int_0^{100} \frac{1 - e^{-\frac{a \cdot t}{r0^2} \cdot y^2}}{y^2} \cdot \frac{Y0\left(\frac{r}{r0} \cdot y\right) \cdot J(y) - J0\left(\frac{r}{r0} \cdot y\right) \cdot Y(y)}{J(y)^2 + Y(y)^2} \, dy \qquad \text{Equation 6-1}$$

where

λ is thermal conductivity (W/(m·K))

T is the temperature increase (K)

q0 is the applied heating effect per metre (W/m)

β is the transition resistance (K/W)

α is the heat capacity of the heating probe (MJ/(m^3·K))

r is the distance between the centre of the heating probe and the sensor at the measurement probe (m)

r0 is the radius of the heating probe (m)

The transition resistance was calculated according to Equation 6-2 where the thickness of the contact medium is assumed to be 0.003 m.

$$\beta = 2\pi \cdot \lambda \cdot \ln\left(\frac{r0 + 0.003}{r0}\right) \cdot \frac{1}{2 \cdot \pi \cdot 0.6} \qquad \text{Equation 6-2}$$

The impact of the properties of the contact medium and the size and heat capacity of the measurement probe for different evaluation period is presented in Table 6-2. The assumptions that were made using three different cases as described in Table 6-1. The properties for the rock mass was assumed to 3.0 W/(m·K) for the thermal conductivity and to 2.43 MJ/(m^3·K) for the heat capacity for all cases.

Table 6-1. Assumptions made for calculation of impact on evaluated results from the heating probe and the contact medium.

	Radius of the heating probe (mm)	Distance from the heating probe to the measurement probe (mm)	Heat capacity of the heating probe, α (W/(m·K))	Contact resistance rock-probe, β (K/W)
Case 1	12.5	190	3.16	0.002
Case 2	1	190	2.43	0.03
Case 3	12.5	190	3.16	1.076

Table 6-2. Results from evaluation of thermal conductivity and heat capacity (multi probe method) in order to assess sensitivity to properties of the contact medium and the heating probe. The properties for the rock mass was assumed to 3.0 W/(m·K) for the thermal conductivity and to 2.43 MJ/(m³·K) for the heat capacity for all cases.

Evaluation period	1–2 hours Thermal conductivity (W/(m·K))	Heat capacity (MJ/(m³·K))	2–3 hours Thermal conductivity (W/(m·K))	Heat capacity (MJ/(m³·K))	3–4 hours Thermal conductivity (W/(m·K))	Heat capacity (MJ/(m³·K))
Case 1	3.00	2.44	3.00	2.44	3.00	2.44
Deviation (%)	0.0%	0.2%	–0.1%	0.2%	–0.1%	0.2%
Case 2	3.00	2.43	3.00	2.43	3.00	2.43
Deviation (%)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Case 3	2.89	2.42	2.94	2.44	2.96	2.45
Deviation (%)	–3.7%	–0.2%	–2.1%	0.5%	–1.4%	0.7%

For Case 3 a transitional resistance caused by the contact medium and a higher heat capacity of the heating probe than of the rock mass was assumed. For this approximation, the contact medium assumed was water with a thermal conductivity of 0.6 W/(m·K) instead of the used bentonite clay with a thermal conductivity of approximately 1–1.1 W/(m·K). This means, together with less thickness, that the calculated contact resistance at the field measurements is only 0.41–0.44 K/W. For case 3 the evaluated thermal conductivity from the multi probe method was 2.1% lower than the assumed value for the rock mass when the evaluation period between two and three hours was used. From evaluation with the single probe method the evaluated thermal conductivity was approximately 1% lower than the assumed conductivity of the rock mass. However, the more favourable conditions for the contact medium used in the field compared to the assumptions would decrease the impact on the results by more than half. The impact from the contact medium can therefore be regarded as insignificant.

It is also possible there is a small influence from the contact medium in the borehole with thermistors. The distance between the temperature gauge and the borehole wall is only about 2 mm. The influence on the evaluated rock thermal conductivity is assumed to be small. A conservative estimation is to use the harmonic mean equation which can be used as a value of the lower bound of the effective thermal conductivity. The influence from 2 mm bentonite clay (1 W/(m·K)) on the overall thermal conductivity is about –1.5%. The real impact should be smaller.

6.2 Influence from temperature drift

A significant temperature drift in the rock mass would have influence on the measured temperature data and the evaluated thermal conductivity. However, at the actual depth the influence from air temperature changes should be small during the short time of measurement. Before each measurement the temperature drift has been observed and has been consider small. In most cases no compensation for the actual drift has been needed. The uncertainties related to temperature drift are thus considered to be small and probably insignificant.

6.3 Uncertainty in cc-distance

Moderate errors in the determined cc-distance between the heating probe and the temperature sensor (multi probe method) has rather small impact on the evaluated thermal conductivity but may have a larger impact on the thermal diffusivity. An error of 10% in the distance results in an error of approximately 20% in the diffusivity value while the thermal conductivity is hardly affected /Sundberg 1988/.

At the present investigation the error in the cc-distance normally is estimated to be approximately ± 0.5 cm. The uncertainty is caused by the small gap between the measurement rods and the borehole walls and insufficient rigidity in the used steel pipes. However, fore some locations this error could be larger due to a small variation in borehole diameter. An additional uncertainty is caused by the slightly different diameter on sensor/heater and borehole (± 2 mm for each). For eight of the measurement locations thermal diffusivity determinations were excluded from the result due to high variability in evaluated thermal diffusivity from the individual sensors. The influence from the uncertainty on the evaluated thermal conductivity is judged to be insignificant or small.

6.4 Repeated measurement at one location

At the location PSM001496 installation and measurement was repeated at four different times to validate the measurement method and to evaluate uncertainties related to the installation Results are presented in Table 6-3. The data was the result of measurements between two hours and three hours of heating. The combined results from the two methods for thermal conductivity ranged 2.17 W/(m·K) to 2.24 W/(m·K) with a standard deviation of 0.03. The arithmetic mean of thermal conductivity was 2.11 W/(m·K) for the multi probe method and 2.27 W/(m·K) for the single probe method. The difference between the two results was hence larger than the mean difference for the ordinary measurement presented in Table 5-1 and may be explained by local inhomogeneities. The measurement number three had a lower quality than the other measurements and had a larger standard deviation for the eight individual evaluations (four for each method) than the other measurements. However, an exclusion of measurement number three did not change any of the mean values by more than 0.01.

Table 6-3. Repeated measurements at location PSM001496.

Measurement number	Thermal conductivity Both methods (W/(m·K))	Single probe (W/(m·K))	Multi probe (W/(m·K))	Heat capacity (MJ/(m³·K))	Thermal diffusivity (m²/s)
1	2.18	2.25	2.10	1.89	1.15
2	2.19	2.27	2.11	1.88	1.16
3	2.17	2.25	2.09	1.95	1.11
4	2.24	2.33	2.14	1.98	1.13
Mean	2.19	2.27	2.11	1.93	1.14
Std. dev.	0.03	0.04	0.02	0.05	0.02

It is possible that an earlier measurement could influence a repeated measurement. The time for recovery between the second and the third measurements was approximately 30 hours; the recovery time between the third and the fourth measurement was 15 hours. The cooling process after the second measurement should cause the temperature in the measurement probes to have a decreasing temperature of 0.005 K during the evaluation period of the third measurement. This gives a negligible influence on the evaluated thermal conductivity. For the fourth measurement the cooling process after the third measurement should cause the temperature to decrease approximately 0.015 K during the evaluation period (after between two and four hours of heating). When the temperature data for measurement number four was adjusted for the cooling process caused by the previous measurement, the mean thermal conductivity for the multi probe method was unaffected at 2.14 W/(m·K).

6.5 Other uncertainties

The locations for the in situ measurements were selected with a preference for rock volumes with few fractures. A true value of the groundwater level is not possible to determine at the different locations. The boreholes are drilled in solid rock without visible cracks. The drillholes could therefore be dry or influenced from rain at the time for measurement. The mean value of the ground water level in the area is judged to be about one meter below ground level according to data presented in /Johansson and Adestam 2004/. However, is some more elevated areas, the ground water level could be deeper, e.g. 2 m below ground level. Consequently, unsaturated conditions are possible for a part of the measurements.

The surface samples for density measurements have a larger porosity (causing a lower density) than for measurements on samples from deep boreholes. It is therefore possible that the measured densities are not representative for the measured thermal conductivity. This may have caused a potential bias in the relationship between density and thermal conductivity in Figure 5-2. It is also possible that the possible unsaturated conditions at the measurement sites (se above) and the above mentioned small contact resistance at the temperature gauge has a small influence on the relationship.

The used measurement equipment is of high quality and there are only small uncertainties in the measurement procedure. However, the equipment constitutes of a number of different component that may interact during measurement. The only way to analyse a potential bias is to calibrate the equipment in a medium with known thermal properties. Due to the dimensions of the probe, this has not been possible to perform.

7 Discussion and recommendations

The mean thermal conductivity for the Ävrö granite was 2.49 W/(m·K) with a standard deviation of 0.32 W/(m·K). Previous laboratory measurements with Transient Plane Source (TPS) on 59 samples of Ävrö granite has resulted in an arithmetic mean for thermal conductivity of 2.90 W/(m·K) /Wrafter et al. 2006/. The distribution of thermal conductivity for the Ävrö granite is bimodal /e.g. Wrafter et al. 2006/. The number of measurements in the two different parts of the distribution influences the mean value and causes the average thermal conductivity to be lower than in previous investigations, while the standard deviation is unchanged. Anisotropy of thermal conductivity was found at the three locations where this was investigated. The anisotropy factor was between 1.04 and 1.27.

A number of uncertainties have been evaluated. For the evaluated thermal conductivity the uncertainties are judged to be small. For the thermal diffusivity the uncertainty is significant mainly due to errors in the determined cc-distance. Uncertainties related to the whole measurement procedure, including installation, gave a standard deviation of 0.03 W/(m·K) for the evaluated thermal conductivity (based on 4 repeated measurements).

Comparison with earlier laboratory determination from the Laxemar area indicates systematic lower thermal conductivity results from the field measurement. This difference may be explained with bias in the density measurements and potential small underestimation of the measured thermal conductivity due to the contact medium in the boreholes.

It is recommended that the method is developed in order to decrease the measurement time with maintained quality. It is also recommended that further evaluation is made according to indicated anisotropic properties for the Ävrö granite.

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Appendix 1

Use of data for determination of thermal conductivity

Location ID	Multi probe Measurement probes				Single probe Heating probe sensors consecutively from the top			
	Probe 2 at bottom	Probe 2 at 65 cm	Probe 3 at bottom	Probe 3 at 65 cm	1	2	3	4
PSM001488	x	x		x	x	x	x	x
PSM001489					x	x	x	x
PSM001490	x				x	x	x	x
PSM001491	x	x	x	x	x		x	x
PSM001492	x	x	x	x	x	x	x	x
PSM001493	x	x	x	x	x	x	x	x
PSM001494			x		x	x	x	x
PSM001495	x	x	x	x	x	x	x	
PSM001496	x	x	x	x	x	x	x	x
PSM001497	x	x	x	x	x	x	x	x
PSM001498	x	x	x	x	x	x	x	x
PSM001499	x	x	x	x	x	x	x	x
PSM001500	x	x	x	x	x	x	x	x
PSM001501	x	x	x	x	x	x	x	x
PSM001502	x	x	x	x		x	x	x
PSM001503	x	x	x	x	x	x	x	x
PSM001504	x	x	x	x	x	x	x	x
PSM001505	x	x	x	x	x	x	x	x
PSM001506	x	x	x	x			x	
PSM001507	x	x	x	x	x	x	x	x
PSM001508	x	x	x	x	x	x	x	x
PSM001509	x	x	x			x	x	x
PSM001510	x	x	x	x	x	x	x	x
PSM001511	x	x	x	x	x	x	x	x
PSM001512	x	x	x	x	x	x	x	x
PSM001513	x	x						

Appendix 2

Description of measurement of thermal conductivity with the multi probe method in Laxemar

Date: 2006-09-01

Conducted by: Fredrik Mossmark and Jan Sundberg, Geo Innova AB

The equipment that will be used for the measurements is described in the following text. The heating probe will consist of a 2.4 m long stainless steel pipe with a 21 mm diameter and 3 mm wall thickness. Inside the steel pipe four temperature gauges (thermistors from Yellow Springs YSI 44006) installed at four different levels. The locations of the thermistors are at a distance from what would be the upper end when the probe is installed (not considering a prolongation that may be used) of 0.7 m, 1.1 m, 1.5 m, and 1.9 m. Inside the heating probe is a heating resistor of 15.4 ohms. The heating resistor was made of manganene, a material which resisting properties are marginally affected by heating ($6 \cdot 10^{-6}$ Ω/K). The remaining void of the probe consists of epoxy. A 1.14 m long prolongation will be provided for the equipment to be used with the heating probe to enable it to be installed in boreholes that are deeper than the probe length.

The four measurement probes consist of circular PVC pipes filled with epoxy that had a diameter of 21 mm. In each probe, close to the end of the bar that is to be installed to the bottom of the borehole, two temperature gauges have been installed that protrude through the surface of the bar (Figure 1). The temperature gauges comprise thermistors of type YSI 44006 from Yellow Springs, the same type that are used in the heating probe. The location of the two temperature gauges in each probe was at a distance from the end of the probe of 0.04 m and 0.65 m respectively.

Electrical power for the heat resistor (heating probe) is provided with a Delta Elektronika SM700 from which a constant current will be supplied. The constant current will mean an even heating effect provided by the heating probe over time during each measurement. The temperature and heat effect is to be measured with a logger model Datataker 500. The heating effect will be monitored through measuring electrical tension over a shunt (a constant resistor). A gasoline driven generator will supply electricity for the equipment.

The principle of the field work will be as follows. The boreholes will be drilled with a mobile drilling rig. In the boreholes, stiff rods with slightly less diameter compared to the holes will be inserted. The cc-distance between the rods will be measured at different heights above the ground surface. From these result the distance between the heater and the sensor at the actual depth were calculated. The measurement of the cc-distance will be repeated in order to ensure a good determination.

The 2.4 m long heating probe will be placed in a centrally positioned borehole that is vertical (Figure 1). In two boreholes located at a distance of approximately 0.19 m from the heater, the probes for monitoring temperature during a measurement are to be installed. These boreholes should be parallel to the central borehole and the temperature gauges were located close to the bottom of the borehole.

The configuration of the boreholes with installation is illustrated schematically in Figure 1. The central borehole will be approximately 3.2 m deep whereas the surrounding boreholes are to be drilled to a depth of about 2.2 m. The work will be carried out in accordance with activity plan AP PS 400-06-063 Mätning av termiska egenskaper i fält med flersondsmetod (internal SKB document). As a contact medium between the probe and the rock a slurry of bentonite clay will be used.

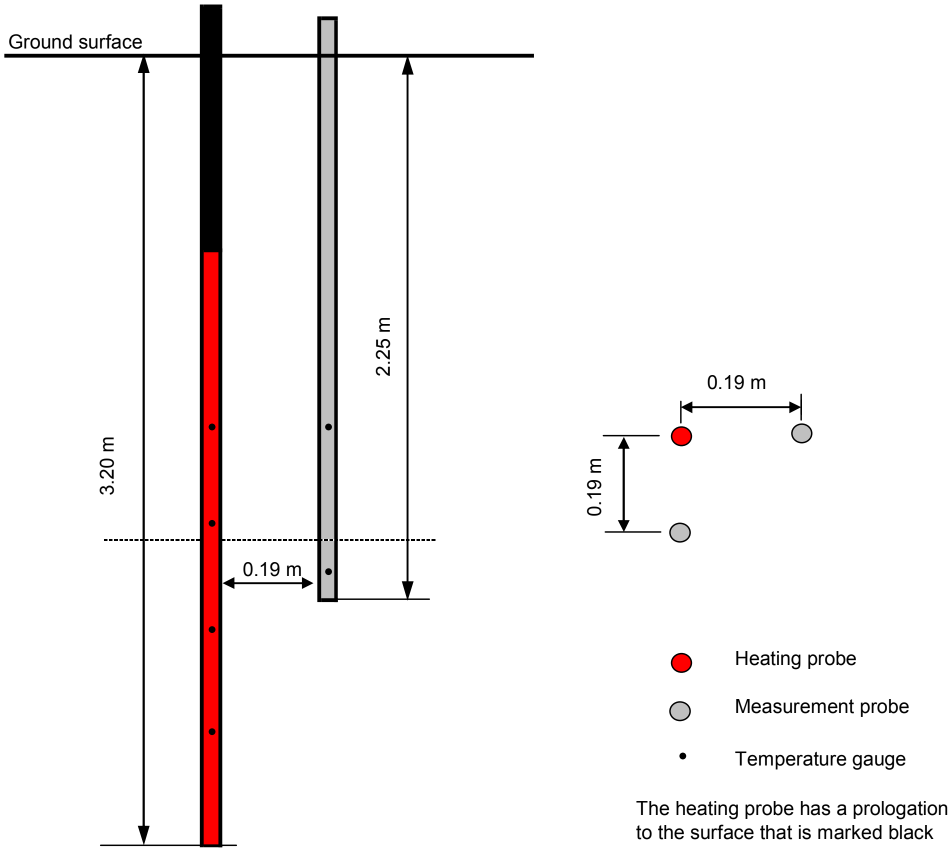

Figure 1. *Setup of measurement probes after installation for measurement, the extension rod for the heating probe is marked with black colour (the distances are approximate).*

Before each measurement, a clay slurry will be made in situ through adding of water and bentonite pellets into the boreholes. The bentonite will be let to absorb the water and swell to become a slurry for more than four hours before the probes are to be installed. This period will also let the slurry to reach a temperature similar to that of the surrounding rock. After the slurry has formed the probes will be inserted into the boreholes. At this time it will be carefully made sure by field personnel that air voids between the wall of the borehole and the probes do not occur.

After installation of the equipment, temperature development of the probes will be monitored. In a first step the probes should reach the same temperature as in the surrounding rock. In a second step temperature drift of the rock will be monitored to be used to correct the temperature during the following measurement.

After more than 20 minutes of monitoring the temperature of the rock mass, the measurement of thermal conductivity should start. A heating effect of about 100 W/m should be applied from the heating probe during a period of three to four hours. It will be observed that a constant heat effect over time is achieved from the constant current power supply. Temperature in the probe and the heating effect will be monitored with a data logger during the time when the equipment is installed.

Appendix 3

Complete results from the evaluation

Location ID	Multi probe Thermal conductivity (w/(m·K)) Measurement probes Probe 2 at bottom	Probe 2 at 65 cm	Probe 3 at bottom	Probe 3 at 65 cm	Single probe Thermal conductivity (w/(m·K)). Heating probe sensors consecutively from the top 1	2	3	4	Multi probe Heat capacity (MJ/(m³·K)) Measurement probes Probe 2 at bottom	Probe 2 at 65 cm	Probe 3 at bottom	Probe 3 at 65 cm
PSM001488	2.98	2.77	2.37	2.76	2.83	2.86	2.95	2.90	2.39	2.30	2.34	2.29
PSM001489	3	3	3	3	3.27	3.26	3.36	3.32	3	3	3	3
PSM001490	2.26	3	(2.02)[1]	(2.05)[1]	2.31	2.16	2.22	2.24	2.30	3	(2.64)1	(2.91)1
PSM001491	2.30	2.21	2.29	2.19	2.29	(1.72)[2]	2.23	2.43	2.57	2.40	2.37	2.32
PSM001492	2.33	2.29	2.29	2.26	2.21	2.36	2.48	2.37	2.22	2.07	2.27	2.18
PSM001493	2.27	2.33	2.36	2.38	2.41	2.37	2.43	2.50	2.29	2.28	2.22	2.30
PSM001494	(2.08)[1]	(1.927)[1]	2.33	(3.89)[1]	2.34	2.35	2.41	2.53	(4.527)[2,1]	(5.253)[2,1]	(1.274)[2]	(1.094)[2,1]
PSM001495	2.30	2.23	2.28	2.27	2.37	2.39	2.38	2.72	1.99	2.09	(1.55)[2]	(1.68)[2]
PSM001496	2.11	2.06	2.16	2.09	2.20	2.21	2.30	2.30	1.99	1.99	1	1
PSM001497	2.84	2.74	2.85	2.74	2.78	2.82	2.89	2.94	2.49	2.32	2.10	2.11
PSM001498	3.20	3.10	3.17	3.12	3.11	3.09	3.13	3.01	2.08	2.09	2.73	2.67
PSM001499	2.80	2.79	2.86	2.78	2.89	2.91	2.98	3.00	2.29	2.24	2.01	2.03
PSM001500	2.41	2.17	2.39	2.27	2.18	2.41	2.69	2.64	2.18	2.25	2.25	2.14
PSM001501	2.51	2.45	2.42	2.39	2.52	2.47	2.54	2.42	2.48	2.36	2.16	2.17
PSM001502	2.17	2.36	2.20	2.31	1	2.27	2.15	2.13	2.12	1.93	2.10	2.34
PSM001503	2.27	2.23	2.27	2.23	2.36	2.32	2.34	2.35	2.55	2.47	2.04	2.14
PSM001504	2.17	2.31	2.13	2.24	2.34	2.25	2.25	2.32	2.02	1.98	2.40	2.36
PSM001505	2.33	2.30	2.33	2.33	2.34	2.37	2.41	2.38	2.33	2.33	1.76	1.80
PSM001506	2.37	2.39	2.27	2.32	(2.58)[1]	1	2.49	1	2.50	2.43	2.75	2.65
PSM001507	2.69	2.50	2.59	2.62	2.56	2.65	2.62	2.53	3.04	2.61	2.52	2.34
PSM001508	2.49	2.41	2.50	2.44	2.50	2.53	2.56	2.58	2.27	2.16	2.03	2.07
PSM001509	2.90	2.81	2.91	(4.55)[1]	(2.98)[1]	2.89	2.96	2.97	(1.23)[2]	(1.54)[2]	(3.58)[2]	(2.72)[2]
PSM001510	2.40	2.37	2.44	2.33	2.44	2.38	2.43	2.51	2.46	2.36	1.84	1.92
PSM001511	2.19	2.21	2.23	2.22	2.33	2.31	2.33	2.38	1.84	1.87	2.87	2.64
PSM001512	2.18	2.18	2.18	2.14	2.20	2.23	2.26	2.35	2.25	2.20	2.41	2.23
PSM001513	2.74	2.82	3	3	3	3	3	3	2.91	2.68	3	3

[1] High noise in temperature measurement.

[2] Evaluated value outside of reasonable range or presenting a large variability for one location.

[3] Data series missing.

Appendix 4

Cardinal orientation of the measurement boreholes

Cardinal orientation of the anisotropy of magnetic susceptibility that was used for the orientation of the measurement boreholes. If local data has been available, these data has been used. Otherwise the mean cardinal direction (102°) has been used.

Location ID	Direction (°)
PSM001488	102
PSM001489	102
PSM001490	102
PSM001491	102
PSM001492	113
PSM001493	113
PSM001494	90
PSM001495	90
PSM001496	102
PSM001497	102
PSM001498	102
PSM001499	102
PSM001500	102
PSM001501	102
PSM001502	102
PSM001503	84
PSM001504	102
PSM001505	102
PSM001506	102
PSM001507	102
PSM001508	102
PSM001509	90
PSM001510	102
PSM001511	102
PSM001512	102

Principle for direction of the boreholes