D.T3.5.2 CALIBRATION REPORT BASED ON THE PILOT ACTIVITIES FOR TRANSFER OF KNOWLEDGE

Comparison and Validation report

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The involved GeoPLASMA-CE team

PP Acronym	**Person and task**
LP - GBA	Gregor Götzl () Martin Fuchsluger (reporting of temperature sensor calibration, TRT error estimation and calibration of TRT devices)
PP03 – geoENERGIE	Konstanze Zschoke (compilation and input for Thermal Response benchmark tests)
PP07 – GeoZS	Mitja Janža (reporting of comparison of TC measurements)
PP08 – PGI - NRI	Grzegorz Ryżyński (reporting of evaluation benchmark tests)

Content

1. Intruduction

Here will be the introduction and description of the aim of this report

The aim of this report is to show all performed calibration and validation tasks performed within the project GeoPLASMA-CE. The workings can be separated into three subtopics which are calibration of temperature sensors, comparison of thermal conductivity measurements and thermal response benchmark test.

First, the project partners LP-GB and PP06 calibrated their temperature sensors used to measure groundwater temperatures in the pilot areas Vienna and Bratislava-Hainburg. Chapter 2 shows the calibration method used and the results of all temperature sensors.

In the second subtopic representative rock samples from the pilot areas in Austria, Poland and Slovenia have been collected and their thermal properties have been measures. The used devices and methods by the project partners from Czech Republic, Austria, Slovenia, Slovakia and Poland are presented in chapter 3. A comparison between the obtained results and possible reasons for deviations are described.

The third section covers all comparison and benchmark tests involving thermal response test devices from the LP-GBA, PP03 and PP08. The report describes the field measurements carried out, the comparison of the evaluation routines and offers an approach of a proper error calculation for every single TRT measurement.

2. Calibration of temperature sensors

To fill the data gap of existing groundwater temperature data in the GeoPLASMA-CE pilot areas, additional field measurements has been done by the project team. The measurements were performed with different devices and different temperature sensors. Thus, each temperature sensor has a different deviation from the real value. Therefore, it is useful to calibrate all temperature sensors used inside a pilot area to a joint reference sensor with high precision. The calibration allows to correct the raw data values and make the measurements comparable to each other in a very accurate way. The calibration equipment is owned by LP-GBA, who offered all project partners to perform a calibration of temperature sensors with voluntary participation. The service was used by PP06 only. This chapter shows the method and the calibration results of all temperature sensors, used for PA Vienna and PA Bratislava-Hainburg.

2.1. Measuring temperature

Nowadays, temperature measurement is mostly done electronically via thermistor sensors. For environmental applications (-50°C to 100 °C) mostly RTDs (resistance temperature detectors) are used, which takes benefit of the temperature dependency of the electrical resistivity. In particular, Platin resistors are popular. Their nominal resistivity value at 0°C defines its name. A Pt-100 sensor, for example, has a resistivity of 100 Ohm at 0°C, but also Pt-25, Pt-500 and Pt-1000 sensors are produced with sensibilities from 0.1 Ohm/K (Pt-25) over 0.4 Ohm/K (Pt-100) to 4 Ohm/Kelvin (Pt-1000). This is defined in DIN EN 60751, inter alia, the approved tolerance value of the sensor, ranging from class AA to class C, see Figure 1. Special measurement devices with selected high precision Pt-100 sensors can reach up to 1/10 of class B and are used as factory calibration reference.

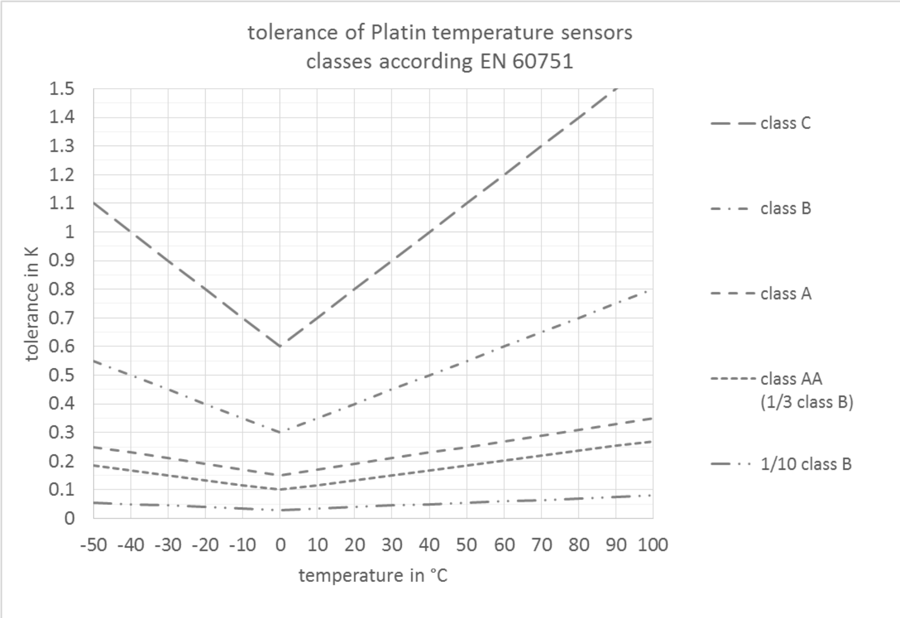

Figure 1: Tolerance classes according EN 60751 for Pt sensors (dotted lines); accuracy of selective Pt100 high precision sensors with appropriate

2.2. Calibration method

All used temperature sensors and devices in PA Vienna and PA Bratislava has been calibrated to a highly precise temperature sensor ("Hochpräziser Tauch-/Einstechfühler" with the handheld instrument 735-2 from Testo). This reference sensor itself is calibrated once a year in an accredited laboratory, according EN ISO/IEC 17025, at three points between 0 °C and 30 °C. The guaranteed accuracy of ±0.05 K in that range equals "1/10 class B", according to EN 60751.

Figure 2: calibration equipment: testo reference sensor with handheld device (left); Grant temperature regulated water bath (right), source: testo.com, labmerchant.com

The temperature calibration was done with the following equipment, see Figure 2:

- Temperature regulated water bath Type: GRANT Y14
- Testo 735-2 handheld device with high precision sensor as reference (accuracy < 0.05 K)

The following principles and workflow have been applied:

- 3- or 4-point calibration within 5 and 30°C within a regulated water bath
- Wait until stable temperature; per calibration point at least 30 minutes and 10 samples
- Determine the linear calibration function for each sensor by performing a linear fit of the measured temperature against the reference temperature
- The calibration function can be applied to the measured raw data

In PA Vienna 2 handheld temperature measurement devices and 10 permanent groundwater monitoring devices (WTFs) with overall 52 temperature sensors (4-6 sensors per device) were in use. In PA Bratislava-Hainburg the same 2 handheld devices of LP-GBA and 2 additional handheld devices of PP06-SGIDS were used. In total, 54 temperature sensors have been calibrated to the reference sensor.

2.3. Calibration results

Table 1 gives the calibration function of all calibrated temperature sensors as a result of the calibration procedure. The linear calibration function is defined by the slope (k) and the offset at zero (d).

The calibrated value T_K can be calculated from the measured value T_M by the following linear relation:

$$T_K = T_M \cdot k + d \quad \text{Eq. 2-1}$$

Figure 3 shows the deviation of the four used handheld groundwater temperature devices in comparison, before and after calibration at the three calibration points 5 °C, 15 °C and 25 °C. Three devices SGIDS#1, SGIDS#2 and GBA#1 show a deviation of the temperature values below 0.2 K in relation to the reference sensor. Noticeable is the deviation of device GBA#2 in the range of 0.5-0.6 K. After calibration and applying the calibration function to the raw data, the deviation of the four sensors are all below 0.025 Kelvin, see right hand side diagram in Figure 3.

Figure 4 shows the calibration results of all 52 temperature sensors (Type Maxim 18B20), used at the groundwater temperature monitoring devices. It is interesting, that there are two peaks at deviation to the absolute real value at 0 degC and 1 degC. That means, that 30 sensors have a deviation between -0.2 and +0.4 Kelvin and 22 sensors are in the range of 0.7 and 1.2 Kelvin deviation to the highly precise reference sensor. The reason is not clear now, as the accuracy of the datasheet gives ± 0.5 K. A repeated inspection of the sensors on a random basis in May 2019 could exclude a calibration mistake and confirms the result.

The summarised recommendation is, that a calibration of the temperature sensors is highly important, as the deviation of two sensors can be up to 1.2 Kelvin. Calibration and especially the application of the calibration function to the raw values is therefore recommended to have proper comparison of the measurement values.

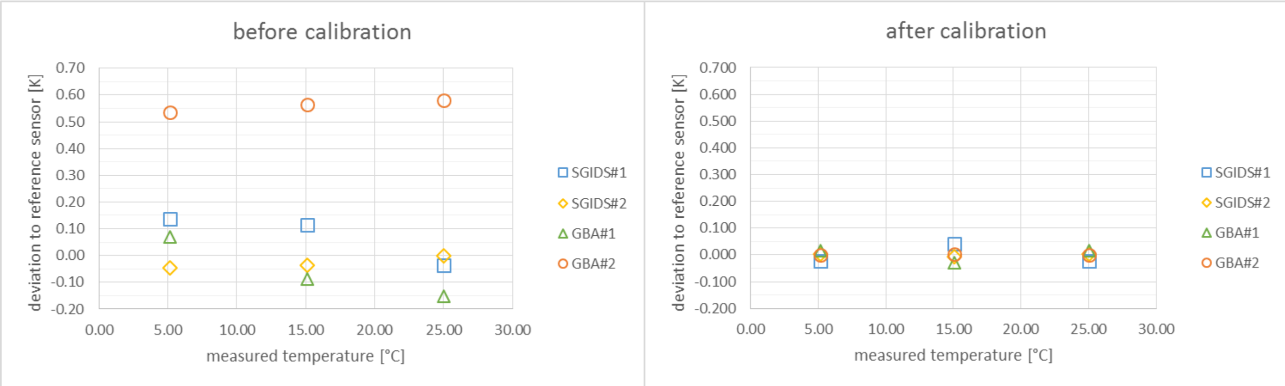

Figure 3: Deviation of all 4 handheld temperature sensor devices, used in PA Vienna and PA Bratislava, to the highly precise reference sensor, before (left) and after (right) three point calibration at 5 °C, 15 °C and 25 °C.

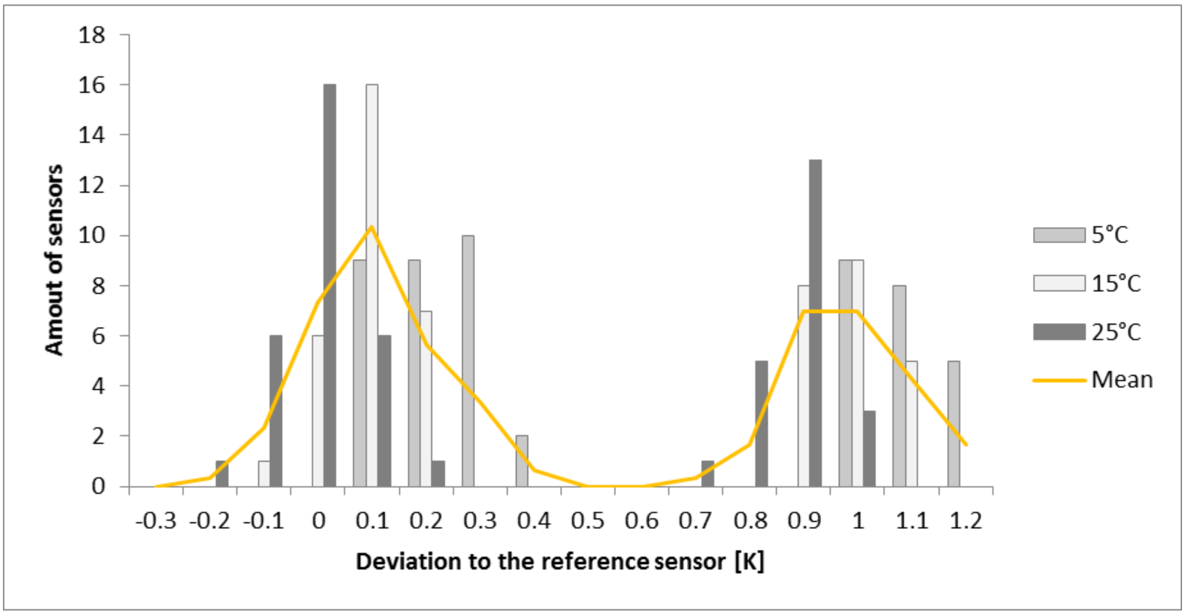

Figure 4: Histogram of the deviation of 52 temperature sensors of the temperature monitoring devices (short WTF) in relation to the reference sensor at three calibration points (5°C, 15 °C and 25 °C).

Table 1: Linear calibration function of all used temperature sensors as a result of calibration

short ID	full ID	Date of calibration dd.mm.yyyy	linear calibration function slope (k)	offset (d)
SGIDS#1	TLC_236662	30.01.2018	1.009	-0.20
SGIDS#2	WTW Cond 3310_14111281	30.01.2018	0.998	0.06
GBA#1	HT 110_110820 (150m)	30.01.2018	1.011	-0.11
GBA#2	HT 110_11000512 (50m)	30.01.2018	0.998	-0.53
GBA#3	22-4_T1	30.11.2017	1.010	-0.28
GBA#4	22-4_T2	30.11.2017	1.009	-0.25
GBA#5	22-4_T3	30.11.2017	1.013	-1.02
GBA#6	22-4_T4	30.11.2017	1.003	-0.95
GBA#7	EW-3_T1	30.11.2017	1.010	-1.02
GBA#8	EW-3_T2	30.11.2017	1.017	-0.30
GBA#9	EW-3_T3	30.11.2017	1.011	-0.23
GBA#10	EW-3_T4	30.11.2017	1.015	-0.33
GBA#11	22-223_T1	30.11.2017	1.010	-1.13
GBA#12	22-223_T2	30.11.2017	1.014	-0.40
GBA#13	22-223_T3	30.11.2017	1.011	-1.11
GBA#14	22-223_T4	30.11.2017	1.012	-0.21
GBA#15	22-114_T1	30.11.2017	1.009	-0.12
GBA#16	22-114_T2	30.11.2017	1.006	-0.12
GBA#17	22-114_T3	30.11.2017	1.002	-0.92
GBA#18	22-114_T4	30.11.2017	1.017	-0.24
GBA#19	22-114_T5	30.11.2017	1.008	-0.24
GBA#20	22-75_T1	30.11.2017	1.012	-1.13
GBA#21	22-75_T2	30.11.2017	1.009	-0.97
GBA#22	22-75_T3	30.11.2017	1.014	-0.29
GBA#23	22-75_T4	30.11.2017	1.010	-1.17
GBA#24	22-75_T5	30.11.2017	1.015	-0.26
GBA#25	22-75_T6	30.11.2017	1.014	-0.35
GBA#26	22.21/27_T1	30.11.2017	1.015	-0.32
GBA#27	22.21/27_T2	30.11.2017	1.014	-1.16
GBA#28	22.21/27_T3	30.11.2017	1.016	-0.32
GBA#29	22.21/27_T4	30.11.2017	1.014	-1.29
GBA#30	22.21/27_T5	30.11.2017	1.009	-1.04
GBA#31	22-263_T1	30.11.2017	1.009	-0.32
GBA#32	22-263_T2	30.11.2017	1.004	-0.04
GBA#33	22-263_T3	30.11.2017	1.005	-0.95
GBA#34	22-263_T4	30.11.2017	1.007	-0.10
GBA#35	22-263_T5	30.11.2017	1.009	-0.19
GBA#36	22-263_T6	30.11.2017	1.007	-1.04
GBA#37	22-264_T1	30.11.2017	1.008	-0.13

GBA#38	22-264_T2	30.11.2017	1.005	-0.06
GBA#39	22-264_T3	30.11.2017	1.003	-0.09
GBA#40	22-264_T4	30.11.2017	1.006	-0.15
GBA#41	22-264_T5	30.11.2017	1.007	-1.04
GBA#42	22-264_T6	30.11.2017	1.008	-0.94
GBA#43	S2-See_T1	30.11.2017	1.017	-0.15
GBA#44	S2-See_T2	30.11.2017	1.021	-0.40
GBA#45	S2-See_T3	30.11.2017	1.018	-0.35
GBA#46	S2-See_T4	30.11.2017	1.012	-1.19
GBA#47	S2-See_T5	30.11.2017	1.013	-1.20
GBA#48	S2-See_T6	30.11.2017	1.017	-1.18
GBA#49	22-246_T1	30.11.2017	1.008	-1.08
GBA#50	22-246_T2	30.11.2017	0.661	3.09
GBA#51	22-246_T3	30.11.2017	1.007	-0.97
GBA#52	22-246_T4	30.11.2017	0.662	3.10
GBA#53	22-246_T5	30.11.2017	1.012	-0.21
GBA#54	22-246_T6	30.11.2017	0.665	2.36

3. Comparison of thermal conductivity measurements

The following section presents devices and methods used to measure the thermal properties of 13 representative samples from the pilot areas in Slovenia, Austria and Poland.

A comparison between the obtained results and possible reasons for deviations are described. Measurements were carried out at the laboratories of the Geological Survey of Slovenia (GeoZS), Geological Survey of Austria (GBA), laboratory of thermophysics at Slovak Academy of Sciences (SAS) and at and at Institute of Geophysics of the Czech Academy of Science (PGI-NRI/CGS).

3.1. Description of the used methods

In general methods for measuring thermal conductivity of rock samples are divided into two groups, one dimensional linear steady-state methods and two dimensional cylindrical transient methods. The major difference between them is that steady-state methods need long measurement times (hours to days for single measurement), due to the requirement to establish and maintain the constant heat flow. On the other side transient methods are quicker, and measurements are carried out already during the heating process and temperature is measured with or without the contact. All the methods, presented below, are based on transient methods.

3.1.1. The Optical Scanning Method

The Optical Scanning Method is used in Thermal Conductivity Scanner (TCS) device, produced by TCS Lippmann and Rauen GbR (Popov et al., 2017). The method is based on scanning a flat, black coloured sample surface with a focused and continuously operated constant heat source in combination with a 2-channel hot and 1-channel cold temperature sensors. Temperature sensors move with a fixed distance between each other and with the same speed. When the samples are heated, electrical signals from the infrared sensors are processed with the computer and transformed into continuous thermal conductivity profiles, which allows analysing possible heterogeneity of a sample. Calculation of the maximum temperature rise is determined as (1):

$$\Theta = \frac{Q}{2\pi \times x \times \lambda} \qquad \text{Eq. 3-2}$$

Θ	Maximum temperature rise of unknown sample [°C]
Q	Heat source [Wm^{-2}]
x	Distance between heat source and sensor [m]
λ_R	Thermal conductivity of standard sample [$Wm^{-1}K^{-1}$]

The determination of λ values is based on the comparison of excessive temperatures of standard samples with excessive temperatures of unknown samples being heated. The expressed relation is (2):

$$\lambda = \lambda_R \left(\frac{\Theta_R}{\Theta}\right) \qquad \text{Eq. 3-2}$$

λ	Thermal conductivity of unknown sample [$Wm^{-1}K^{-1}$]
λ_R	Thermal conductivity of standard sample [$Wm^{-1}K^{-1}$]
Θ	Maximum temperature rise of unknown sample [°C]
Θ_R	Maximum temperature rise of standard sample [°C]

3.1.2. Dynamic Measurement Method

Dynamic measurement method, which is used in Applied Precision ISOMET 2104 is based on the analysis of a temperature response of the analysed material to heat flow impulses. Heat flow is generated in a resistor of probe by distributed electric power. Then the temperature is recorded and evaluated from the polynomial regression. The determination of thermal conductivity depends on constant heating power and is calculated as (3):

$$\lambda = \frac{2 \times q}{4\pi} \frac{\ln(t_2) - \ln(t_1)}{T_Q(t_2) - T_Q(t_1)} \quad \text{Eq. 3-3}$$

λ	Thermal conductivity of unknown sample [$Wm^{-1}K^{-1}$]
q	Heating rate [W]
T	Temperature [˚C]
t_1	Time at the beginning of measurement [s]
t_2	Time at the end of measurement [s]

Thermal diffusivity is estimated from the temperature change with time under a constant heating power and represents the ratio of the time derivative of temperature to its curvature. The equation is following (4):

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \quad \text{Eq. 3-4}$$

T	Temperature [˚C]
∇	First order derivative
T	Temperature [˚C]
t	Time [s]
α	Thermal diffusivity [$m2s^{-1}$]

After that volumetric heat capacity is derived as ratio between thermal conductivity and thermal diffusivity (5):

$$\rho C = \frac{\lambda}{\alpha} \quad \text{Eq. 3-5}$$

3.1.3. Pulse Transient Method

Pulse transient method, used in RTB 1.01, is based on the transient method performed in pulse and stepwise measurement regimes. The sample consists of three parts. Between the first and second part a plane heat source is fitted. Then a heat source is produced due to the joule heat in the planar electrical resistance. A thermocouple is fitted between the second and the third part to measure the temperature response to the heat pulse. From the temperature response the thermal diffusivity, specific heat and thermal conductivity are calculated as follows (6), (7), (8), (9):

$$\alpha = \frac{h^2}{2 \times t_m} \quad \text{Eq. 3-6}$$

$$\lambda = \lambda_R (\frac{\Theta_R}{\Theta}) \quad \text{Eq. 3-7}$$

	where $Q = R \times I^2 \times t_0$	Eq. 3-8

$$\lambda = \alpha \times c \times \rho \qquad \text{Eq. 3-9}$$

R	Electrical resistance of the planar heat source [Ω]
t_0	Duration of the heat pulse [s]
I	Hight of the current pulse [μm]
t_m	Time from start to the point of maximum temperature response [s]
ρ	Density [kgm^{-3}]
Q	Heat flow [Jm^{-2}]
h	Distance between planar heat source and thermocouple [m]
T_m	Maximum temperature response [°C]

This direct method operates on first principles and thus no calibration is necessary.

3.2. Description of the used devices

Thermal Conductivity Scanner (TCS) (Popov et al., 2017) uses optical scanning method and can measure thermal conductivity (λ) and thermal diffusivity (α) of compact rock samples. For measurements, samples need to have flat surface (+/- 0.5 mm), long at least 4 cm. Thickness and width depends on the assumed sample λ and can be therefore determined from the device instructions. Every sample also should be painted by a black enamel along scanning direction (a paint strip of cca 25-40 μm thickness and width of cca 2 cm). Measurement range and accuracy is given in Table 2.

Table 2: General information about precision of TCS device

Measurement range	***Thermal conductivity (λ) [$Wm^{-1}K^{-1}$]***	**0.2 - 25**
	Thermal diffusivity (α) [m^2s^{-1}]	$0.6 - 3.0 \times 10^{-6}$
Accuracy [%]		λ = 3; α = 5

Applied Precision ISOMET 2104 is portable hand-held device for measurements of thermal properties of rocks. Measurements depends on analysis of response of the rocks to heat flow impulses. The heat flow is induced in a resistor of the probe by a distributed electric power. The device is verified by special etalons with known values of thermal conductivity.

The device includes needle probe for soft materials and surface probe for hard materials. In our case surface probe was used, because research included flattened surfaces of hard rocks. This means that a smooth flat surface was required with minimum diameter of 60 mm and with thickness of at least 15 mm. In the Table 3 are presented general information about range and precision of device.

Table 3: General information about precision of ISOMET 2104 device

Measurement range	***Thermal conductivity (λ) [$Wm^{-1}K^{-1}$]***	**. 0.03 - 6**
	Volume heat capacity (c_v) [$Jm^{-3}K^{-1}$]	$4 \times 10^4 - 4 \times 10^6$
. Accuracy [%]		λ = 5; c_v = 15

A Chamber model RTB 1.01 was also used to perform measurements (Boháč et at., 2015). Thermophysical tester is designed for the laboratory research purposes and industrial measurements. Apparatus consists of the RTLab electronic unit and the specimen chamber model RTB 1.01 that supports various types of measurement methods. Device uses the Pulse Transient Method and allows performing measurements in variously defined atmosphere types (air, vacuum, inert) in a controlled temperature regime (isothermal, nonisothermal and in controlled uniaxial load). Device can perform any transient method measurement just by changing the external fitting procedures for different method like pulse, hot disk, stationary.

Measured properties can be thermal conductivity, thermal diffusivity and specific heat capacity. Device is suitable for solid rocks, non-solid plastic material (moisture clay, loam, soil) and liquids.

Sample preparation is essential. It is important to have three parts of sample in a form of cuboids. For our measurements dimensions of samples were square cross section 50 × 50 mm and thickness 1 × 15 mm and 2 × 30 mm (in average). In general samples can vary up to 150 × 150 × 350 mm. Samples were also polished and dry. Second part of sample with defined thickness represent the material property. Electronic unit perform the measurement in pulse as well as stepwise regime and this it is suitable for two-probe (pulse transient) as well as one-probe methods (plane hot disk). Basic information about measurement range and precision in presented in *Table 4*.

Table 4: General information about precision of RTB 1.01 device

Measurement range	***Thermal conductivity (λ) [$Wm^{-1}K^{-1}$]***	**0.01 - 70**
	Thermal diffusivity (α) [m^2s^{-1}]	10^{-8} - 10^{-6} × 10^{-6}
	Specific heat capacity (c_p) [$Jkg^{-1}K^{-1}$]	200 - 4000
Accuracy [%]		λ = 3 - 6; α = 3 - 5; c_p = 1 - 3

3.3. Comparison of thermal conductivity measurements on rock samples

In the study 13 rock samples from pilot areas (3 from Slovenia, 5 from Poland and 5 from Austria) were used. They were measured with 3 different methods: the optical scanning method, dynamic measurement method and pulse transient method. Below (Table 5) are listed institutions and associated methods.

Table 5: Table of devices and methods, used by individual partners.

Project partner	Location of measurements	Used device and method	Abbreviation
Institute of Geophysics of the Czech Academy of Science (GFU)	Institute of Geophysics of the Czech Academy of Science (GFU)	**TCS** Optical Scanning Method	PGI - NRI/CGS
		Hot Disc Dynamic Measurement Method	PGI - NRI/CGS (HD)
Geological Survey of Slovenia	Geological Survey of Slovenia	**TCS** Optical Scanning Method	GeoZS
Geological Survey of Austria	Geological Survey of Austria	**ISOMET 2104** Dynamic Measurement Method	GBA
	Slovak Academy of Sciences	**RTB 1.01** Pulse Transient Method	GBA (SAS)

Below, the results of the measurements and their comparisons are presented. More detailed information (age, lithology, location, all measurements) on all the mentioned samples is provided in Appendix 1.

3.3.1. Measurements on Slovenian samples (GeoZS_34a, GeoZS_25b, GeoZS_3b)

Slovenian samples were measured with three methods. In GeoZS laboratory with TCS and at GFU (Czech Republic) laboratory with TCS and with hot disc (dynamic method). Methods are similar except that in case of measurement with TCS the temperature is determined without contact (infrared), while hot disc uses contact (thermocouple).

Average values of thermal conductivity (λ) and diffusivity (α) measured on samples GeoZS_34a, GeoZS_25b and GeoZS_3b are presented in Table 6 and Figure 5. Two differences are given, maximal difference between the measurements and the standard deviation between them.

Table 6: Comparison of measurements of thermal conductivity (λ) and thermal diffusivity (α) on Slovenian samples.

	GeoZS		PGI-NRI/CGS		PGI-NRI/CGS (HD)		Maximal difference [%]		Standard deviation [%]	
	$\lambda_{average}$	$\alpha_{average}$	$\lambda_{average}$	$\alpha_{average}$	$\lambda_{average}$	$\alpha_{average}$	$\lambda_{average}$	$\alpha_{average}$	$\lambda_{average}$	$\alpha_{average}$
GeoZS_34a	3.84	1.52	3.81	1.51	3.90	1.45	±2	±1	±4	±2
GeoZS_25b	3.23	1.19	3.11	1.31	3.14	1.38	±3	±11	±5	±8
GeoZS_3b	1.83	0.64	1.65	0.44	1.64	0.51	±11	±10	±9	±8

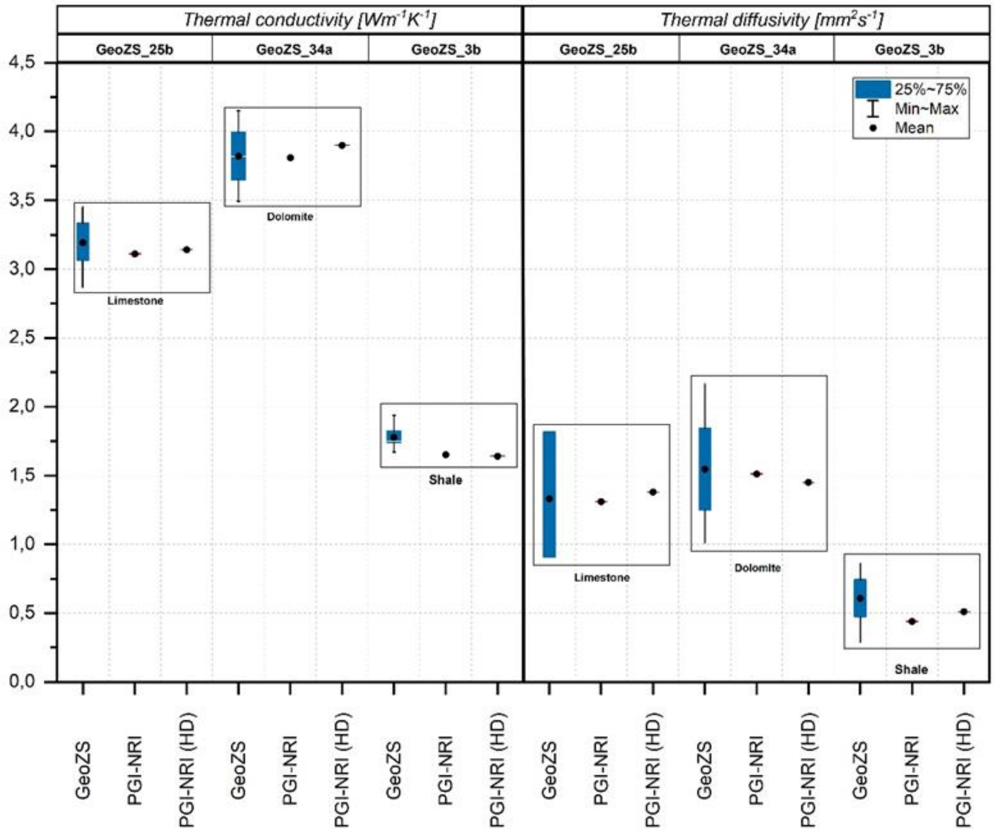

Figure 5: In black squares are measured values of the samples, compared between the laboratories. In case of a larger set of repeated measurements (GeoZS) results of measurements are displayed with minimum and maximum values, while in other cases the average values of the measured parameter are presented with points.

The measured thermal conductivity and diffusivity on Slovenian samples are comparable, considering the accuracy of the instrument. Dimensions of samples were the same for all the devices, therefore there were no errors due to the preparation of the sample. A slight deviation between TCS measurements could be caused due to the choice of different standard samples that were used in calibration process.

3.3.2. Measurements on Polish samples (GH16, GH4, GH11, GH5N, GH10)

Polish samples were measured with three methods. In GeoZS laboratory with TCS, at GFU (Czech Republic) laboratory with TCS and in GBA laboratory with ISOMET 2104. Like before temperature is determined with TCS without contact and with ISOMET by contact.

Average values of thermal conductivity (λ) and diffusivity (α) measured on samples GH16, GH4, GH11, GH5N and GH10 are presented in Table 7 and Figure 6.

Table 7: Comparison of measurements of thermal conductivity (λ) and thermal diffusivity (α) on Polish samples.

	GeoZS		PGI-NRI/CGS		GBA		Maximal difference [%]		Standard deviation [%]	
	$\lambda_{average}$	$\alpha_{average}$	$\lambda_{average}$	$\alpha_{average}$	$\lambda_{average}$	$\alpha_{average}$	$\lambda_{average}$	$\alpha_{average}$	$\lambda_{average}$	$\alpha_{average}$
GH16	3.18	0.87	3.07	/	3.05	1.50	±4	±72	±6	±32
GH4	2.86	0.85	2.75	/	/	/	±4	/	±5	/
GH11	2.98	1.19	2.76	/	/	/	±8	/	±11	/
GH5N	3.08	1.33	2.88	/	2.78	1.68	±7	±23	±12	±18
GH10	2.99	1.26	2.81	/	2.62	1.46	±8	±9	±15	±10

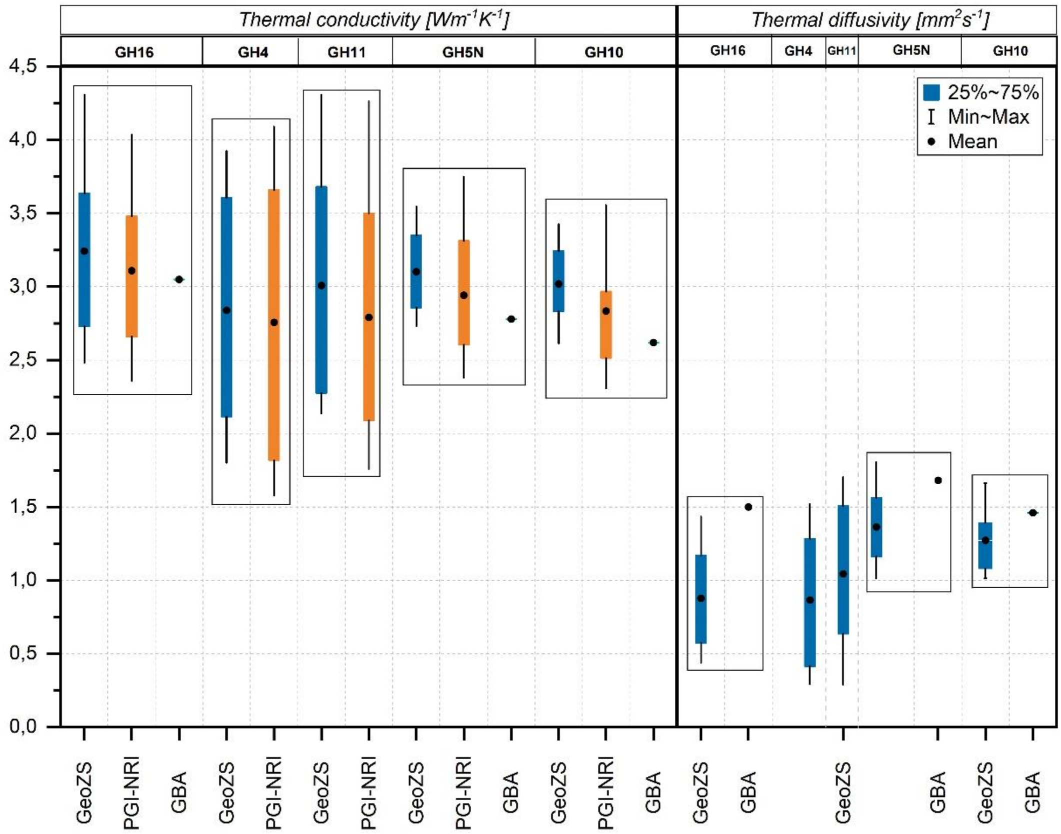

Figure 6: In black squares are measured values of the samples, compared between the laboratories. In case of a larger set of repeated measurements (GeoZS, PGI-NRI/CGS) results of measurements are displayed with minimum and maximum values, while in other cases the average values of the measured parameter are presented with points (GBA).

The measured thermal conductivity values are within the range of the accuracy of the devices. Results of measurements with ISOMET 2104 show the largest deviation, however they are in similar range. Deviations observed due to unequal measurement conditions (e.g. ambient temperature).

On the other side measurements of diffusivity show quite large deviation between the average measured values (for example for sample GH16 (Figure 6). The reason for such a large deviation could be related to the heterogeneity of the sample or could be caused due to use of different direction of measurement (regarding the bedding plane).

As already mentioned, Polish samples were measured twice using the same method (TCS), which allows us a comparison of measured λ in different directions depending on heat flow. The same polish samples were measured perpendicular and parallel to the bedding plane, two or three times. This gave us the coefficient of anisotropy of samples on thermal conductivity. Anisotropy is a property that relates to the structure and texture of a rock. For quantification of anisotropy λ is measured parallel (λ_{II}) and perpendicular ($\lambda_{\perp}$) to bedding or schistosity. Defined is as ratio between:

$$A = \frac{\lambda_{II}}{\lambda_{\perp}} \quad \text{Eq. 3-10}$$

From the analysis of anisotropy, we can see two groups of values (Figure 7). One group fits well with a black line (black line corresponds to value A = 1) and that indicates similar λ on both scanning lines. We can conclude that are both samples quite isotropic with values GH5N = 1,01 ± 0,03 W/mK and

GH10 = 0,94 ± 0,00 W/mK. On the other side, other three samples show anisotropies with values GH16 = 0,77 ± 0,02 W/mK, GH4 = 0,54 ± 0,05 W/mK and GH11 = 0,62 ± 0,00 W/mK.

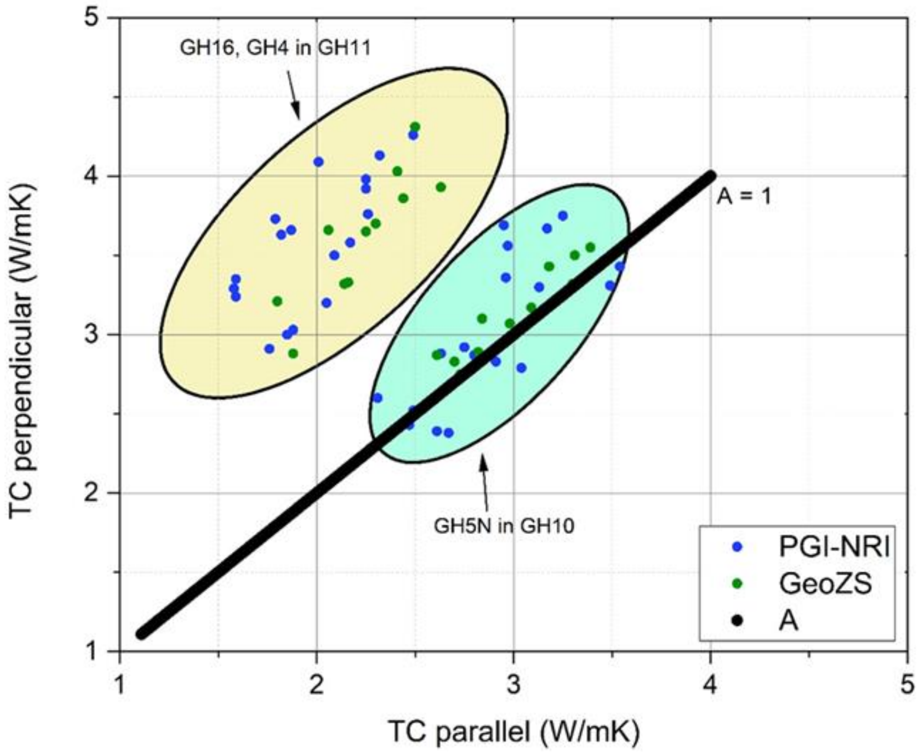

Figure 7: Measurements of thermal conductivity (λ) parallel and perpendicular to bedding or schistosity.

From the box and whisker plots below (Figure 8) we can see difference between λ on the same sample because of the different orientation of scanning lines. As discussed above difference is seen on samples GH16, GH4 and GH11, where values for parallel λ are much lower than the ones for perpendicular λ according on direction of heat flow. For samples GH5N and GH10 measured λ values in both directions are quite similar, which indicates on isotropic rocks.

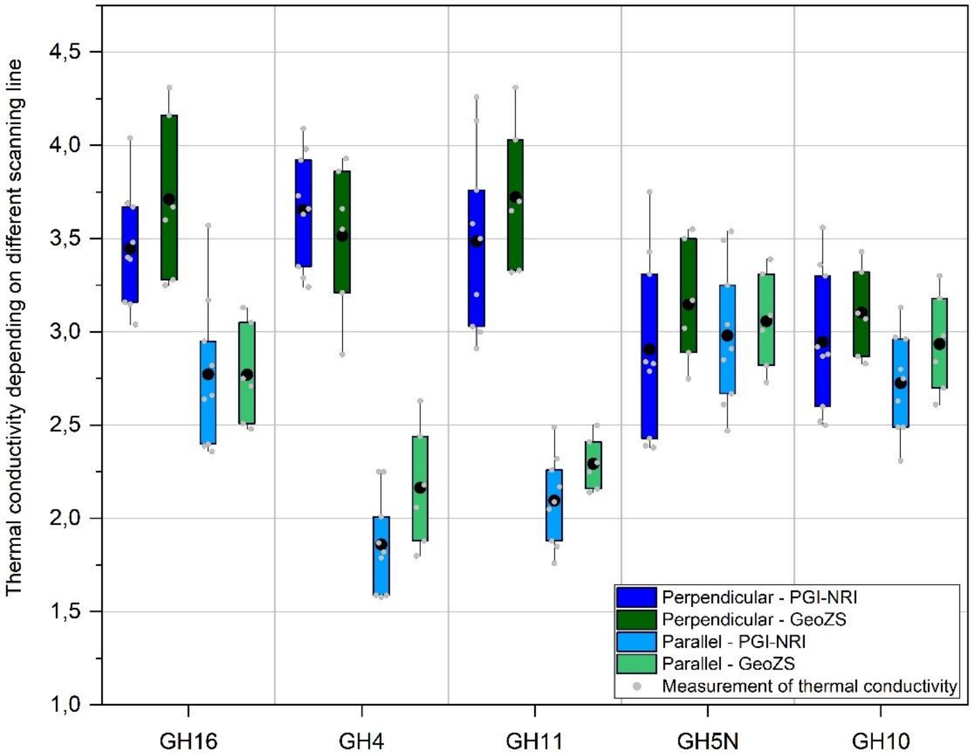

Figure 8: Comparison of whole set of measurements of thermal conductivities (λ), measured parallel and perpendicular *to bedding or schistosity*. Boxes whiskers represent minimum and maximum measured values.

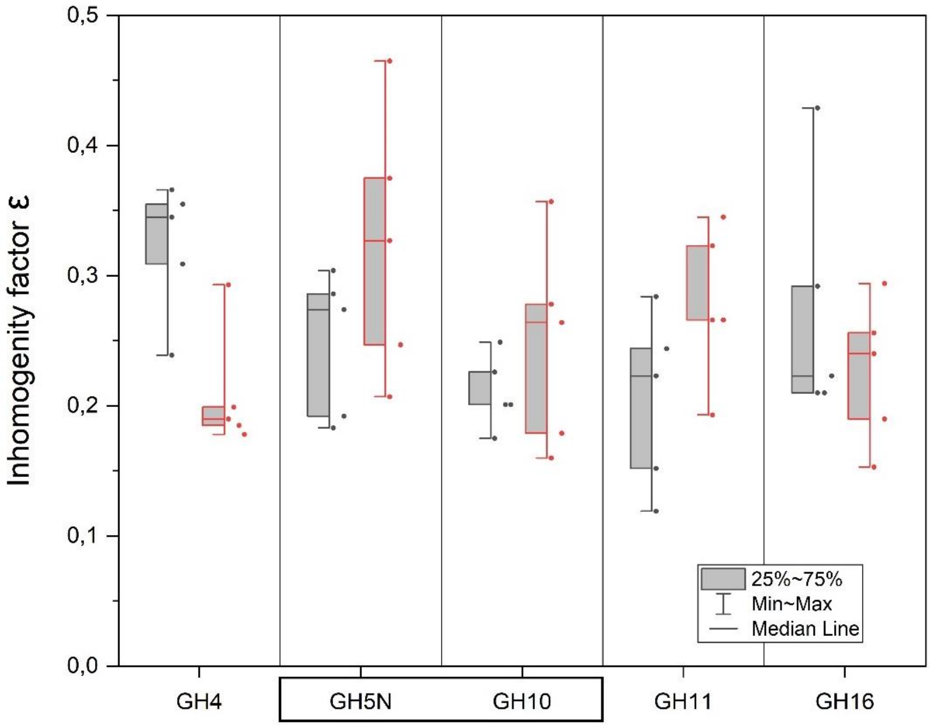

Figure 9: Presentation of inhomogeneity factor.

From the thermal conductivity profile of individual samples TCS scanner also determine the inhomogeneity factor ε (Figure 9). It is defined as the maximum difference in conductivity along the scanning line divided by the average thermal conductivity. If the sample is big enough it is important to measure more than one scanning line in every direction with the aim to determine TC distribution within the inhomogeneous sample and therefore obtain representative average values. Inhomogeneity for optical scanning method is defined as:

$$\varepsilon = \frac{\lambda_{max} - \lambda_{min}}{\lambda_{average}} \quad \text{Eq. 3-11}$$

Measured inhomogeneity was higher for scanning lines oriented perpendicular to bedding or schistosity. This is because scanning line travels through the layers of variable mineral. Exception is sample GH4, where is inhomogeneity higher for parallel scanning line.

3.3.3. Measurements on Austrian samples

Austrian samples were measured with three methods. In GeoZS laboratory with TCS, at SAS (Slovakia) laboratory at the request of the GBA with RTB 1.01 and in GBA laboratory with ISOMET 2104. Temperature was determined with TCS without contact and with ISOMET and RTB 1.01 by contact.

Average values of thermal conductivity (λ) and diffusivity (α) measured on samples H3, L1-D, BB2, Wolf and BDA4 are presented in Table 8 and Figure 10.

Table 8: Comparison of measurements of thermal conductivity (λ) and thermal diffusivity (α) on Austrian samples.

	GeoZS		GBA		GBA [SAS]		Maximal deviation [%]		Standard deviation [%]	
	$\lambda_{average}$	$\alpha_{average}$	$\lambda_{average}$	$\alpha_{average}$	$\lambda_{average}$	$\alpha_{average}$	$\lambda_{average}$	$\alpha_{average}$	$\lambda_{average}$	$\alpha_{average}$
H3	2.21	0.95	/	/	2.31	1.18	±5	±24	±5	±12
L1-D	3.66	1.34	4.32	2.04	5.21	1.83	±24	±41	±64	±29
BB2	3.76	1.35	3.31	2.01	4.94	1.65	±36	±27	±69	±27
Wolf	2.39	0.99	2.20	1.37	2.86	1.28	±21	±31	±28	±16
BDA4	2.86	1.20	3.14	1.54	2.73	6.17	±10	±380	±17	±230

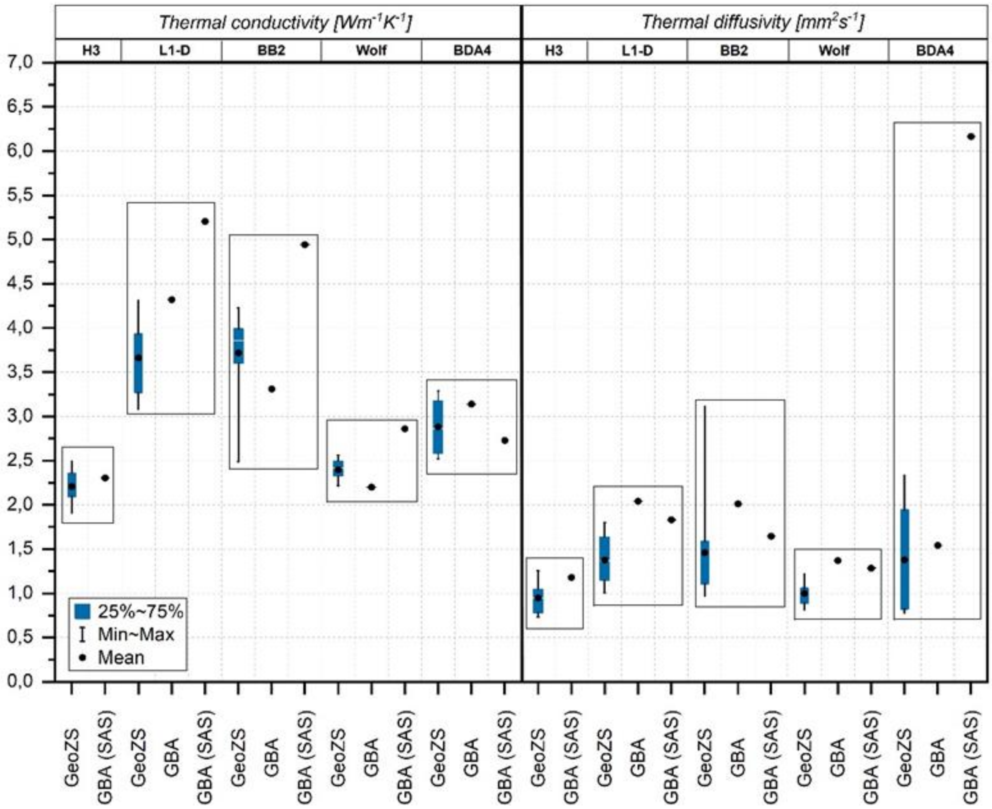

Figure 10: In black squares are measured values of the samples, compared between the laboratories. In case of a larger set of repeated measurements (GeoZS) results of measurements are displayed with minimum and maximum values, while in other cases the average values of the measured parameter are presented with points (GBA and GBA(SAS)).

Comparison of measured thermal conductivity and diffusivity shows the largest deviations comparing to other measurements. The possible cause of this is related to the use of devices, which are based on different methods. Also, the sample dimension is important. RTB 1.01 requires a special square shape of the sample, which is not so appropriate for measurements with TCS. Samples were too thin, which probably led to deviations from other values. Also, measurements with RTB 1.01 were performed on non-flat surface of a sample, so on sample BB2 bentonite was used as a heat contact agent. This agent was used to help but there is still some difference in thermal conductivity which need to be calibrated. Other samples also didn't have planar surfaces, therefore measurements will need to be evaluated again at different condition, like flattening the surface or to use bentonite.

4. Thermal Response benchmark test

4.1. Aim of the benchmark test, calibration of TRT devices

Thermal response test (TRT) devices and TRT measurements are nowadays well studied. There exist some guidelines (see deliverable D.T3.5.1), which all emphasize the importance of giving the uncertainty of the measurement to the evaluated results. In practice, not many performed TRT reports can be found, which give indication of the uncertainty. This may be, because no guideline for error estimation exits.

Initially, attempts were made to find a calibration opportunity for a TRT device as a whole. We tried to find a BHE with an exactly known effective thermal conductivity and its uncertainty, where we can plug our devices and compare the evaluated values to the known value. In practice, it is not possible to find such a BHE due to the fact that underground conditions may change over time and the thermal conductivity cannot be tied up on an exact value in the needed accuracy. A project at ZAE Bayern[1] is currently developing a test facility to simulate the thermal response of a BHE under adjustable conditions. This facility would be interesting to calibrate our TRT devices, but the completion date of the project comes too late for GeoPLASMA-CE.

The project team decided to focus on a benchmark test of all TRT devices, which are available in the project team. Therefore, the requirements for a benchmark BHE (borehole heat exchanger) were defined in the report of D.T3.5.1. Two BHE location could be identified: One BHE in Vienna and one BHE in Krakow. A third BHE, located in Węgrzce near Krakow, was also measured by two project partners. It turned out during GeoPLASMA-CE that this location does not fulfil the requirement for a benchmark TRT due to a high groundwater flow and no possibility for measuring a downhole temperature profile.

At the BHE in Vienna, three TRT devices and at the BHE Krakow, two devices were participating the benchmark. The evaluation of all TRTs was done by one person, to avoid differences in the evaluation process. Additionally, two datasets were evaluated by all benchmark participants to compare the individual evaluation routine.

The results of the benchmark test emphasize the importance of a proper error calculation for every single TRT. Especially, the use of accurate flow and temperature sensors for the TRT device and their calibration can reduce the total error significantly.

4.2. Benchmark location and TRT devices

For the benchmark test two borehole heat exchanger (BHE) were available, one in Vienna and one in Krakow. The drilling log and the temperature log for the two BHE are illustrated in Figure 11. A picture of the involved TRT devices is shown in Figure 12.

For the detailed requirements of choosing the BHE location, see D.T3.5.1. For detailed specification of the TRT devices, see ANNEX A.

1 https://www.interreg-central.eu/Content.Node/GeoPLASMA-CE/6-TRT-WS-GeoPLASMA-CE-Reuss-testing-of-TRT-devices-2.pdf

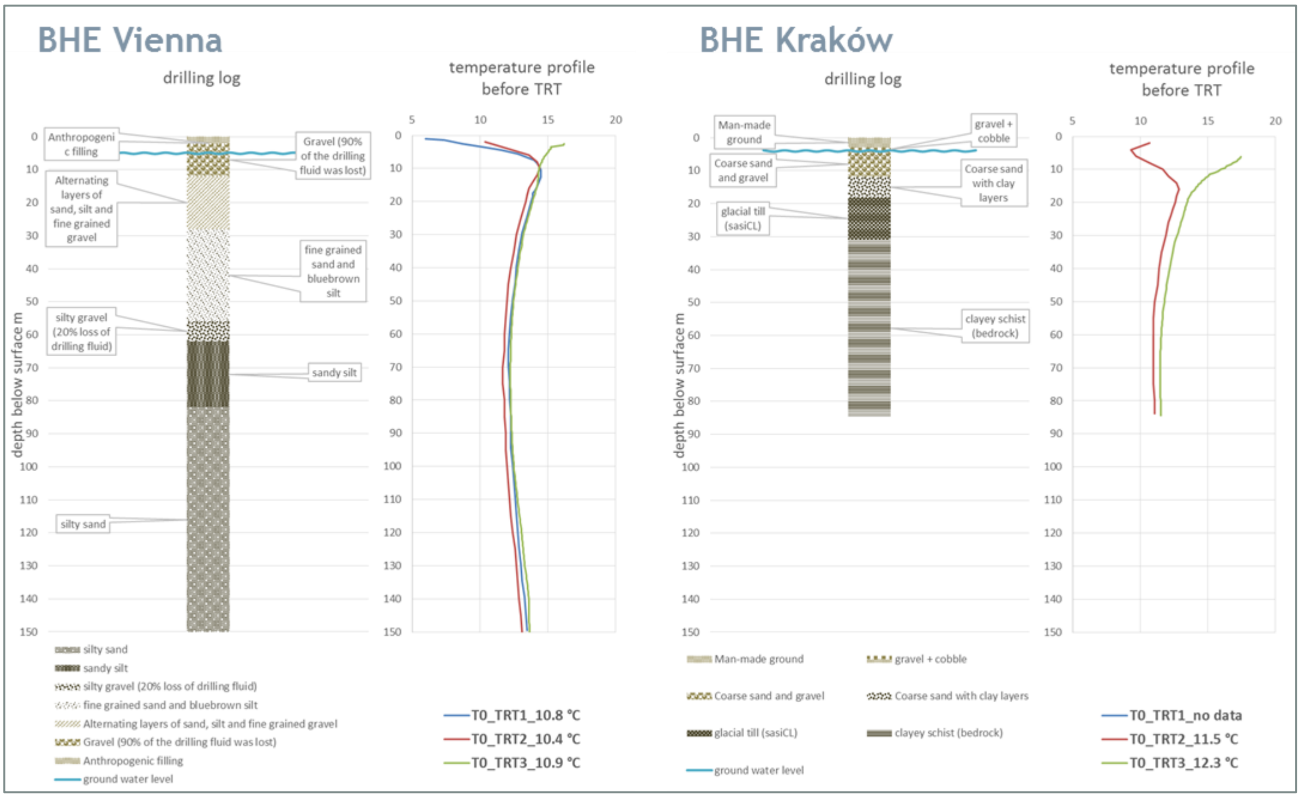

Figure 11: Two test sites were available for the benchmark test; drilling log and undisturbed temperature profiles of BHE Vienna (left) and BHE Krakow (right)

Figure 12: Three TRT devices were participating the benchmark test

4.3. Performance, evaluation and joint standard of the TRT benchmark

For the performance and processing of the TRT, we defined joint standards in GeoPLASMA-CE (see deliverable D.T3.5.1). A summary of the most important criteria and the compliance at the benchmark test is given in Table 9. Most defined quality criteria were fulfilled, while some are not complied like the minimum duration of TRT measurements of two tests in Krakow or the appropriate sampling interval at TRT#3. The waiting time of the second temperature profile after the TRT did not comply at all tests with the defined quality criteria and should be reconsidered as it turned out to be too time-consuming for the executers of the TRT measurements.

The joint GeoPLASMA-CE standard for evaluating TRT measurements also includes a common evaluation sheet with all relevant parameters of the TRT procedure. The evaluation was done by one person for all benchmark TRTs to avoid differences in the evaluation aproach. The common evaluation sheet for all TRT devices can be found in ANNEX B.

Table 10 shows the most important parameters of all 5 benchmark tests in comparison. The thermal conductivity, representing the main result, varies around 0.11 W/m/K (5.8 %) at BHE Vienna for the three devices and 0.09 W/m/K (5 %) at BHE Krakow for TRT#2 and TRT#3. The scattering of the results does not directly indicate the uncertainty of the individual measurements as the real value is not known. The decision in D.T3.5.1 to round the evaluated thermal conductivities to one digit, has to be reconsidered, as shown in Figure 13: Due to the rounding the scattering increased to a value of 0.2 W/m/K (10.5 %) for the benchmark tests at the BHE site in Vienna.

The variation of the thermal resistance, a side result, is around 0.02 K/W/m (15 %). The resistance is in a reasonable range of a single U-tube BHE with low conductive backfilling.

Noticeable is the difference of the measured mean underground temperature below 10 m depth at BHE Krakow. This difference is shown in the temperature profile in Figure 11.

Table 9: Summary of criteria for performing TRT tests, defined as joint standard in GeoPLASMA-CE

		BHE Vienna			BHE Krakow	
		TRT#1	TRT#2	TRT#3	TRT#2	TRT#3
criterion title	**target value**	**criterion fulfilled**				
waiting time after drilling	7 d	OK	OK	OK	OK	OK
waiting time after filling the pipes	1 d	OK	OK	OK	OK	OK
length of the BHE	25 m	OK (150 m)	OK (150 m)	OK (150 m)	OK (84.5 m)	OK (84.5 m)
duration of the TRT test	t min + 48 h	OK (120 h)	OK (96 h)	OK (68 h)	too short (45 h)	too short (46 h)
specific power load	30 W/m	OK (53 (W/m)	OK (46 W/m)	OK (34 W/m)	OK (67 W/m)	OK (60 W/m)
turbulent flow	3000 Reynolds	OK (17000)	OK (12000)	OK (11000)	OK (13000)	OK (14000)
sampling interval	1 min	OK	OK	too low (10 min)	OK	too low (10 min)
temperature profile before TRT	1	OK	OK	OK	OK	OK
temperature profile after TRT with delay 12-24h	12 h	too low (5h)	too low (2h)	too low (2h)	no T-log after TRT	too low (2h)

Table 10: Evaluation parameter and results of the benchmark TRTs

TRT location:		BHE Vienna			BHE Krakow	
TRT device:		TRT#1	TRT#2	TRT#3	TRT#2	TRT#3
evaluation parameter						
TRT date		Mar. 18	Jan. 18	Sep. 17	Apr. 18	Sep. 18
TRT run time	h	120	68	96	46	45
mean flow rate	l/h	2004,0	1289,9	1398,9	1588,4	1558,7
mean temperature difference	K	3,5	3,5	4,3	2,8	3,1
mean drilling diameter	mm	133	133	133	125	125
vol. heat capacity earth	$MJ/m^3/K$	2,3	2,3	2,3	2,3	2,3

minimum time criterion	h	15	13,6	12,5	15	13
evaluation results						
effective thermal conductivity	W/m/K	1,92	1,84	1,95	1,76	1,85
mean underground temperature below 10 m	°C	12,8	12,4	12,9	11,5	12,3
thermal borehole resistance	K/W/m	0,12	0,14	0,13	0,13	0,12

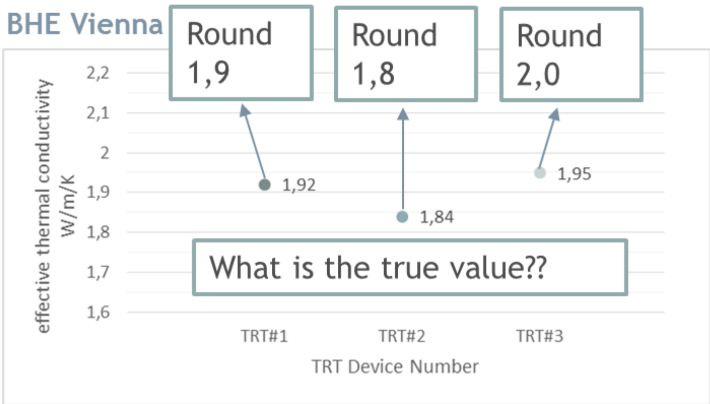

Figure 13: Evaluated thermal conductivity of the three TRT devices for BHE Vienna

The evaluation of the benchmark test shows the importance of determining the uncertainty of the TRT measurement for every single measurement. At the GeoPLASMA-CE core team meeting in Praha in November 2018, the decision was done to develop a proposal for a joint procedure for TRT error estimation.

4.4. TRT error estimation

A measurement is just useful if the accuracy and precision is known or at least can be estimated. While a random error influences the precision (spread of results is small at good precision), a systematic error influences the accuracy of a measurement (offset to the real or accepted value), cf. Hughes et al, 2010[2]. Hereafter, the systematic error is treated, as they can be improved by calibration.

The existing standards and guidelines (described in deliverable D.T3.5.1) propose to indicate the error in all TRT reports. In practice, only very few TRT performer issue the error and if doing so, the given error is mostly just a fraction of the total error like only indicating the line source approximation error as it is easy to derive.

The comprehensive estimation of the accuracy of a TRT measurement is rather complex. The following proposal for error estimation combines the error related from the sensors of the device themselves in combination with the error due to inhomogeneity of parameters during the TRT run and due to inhomogeneity of underground parameters. In addition, the line source approximation error remains as a bottom limit of the error estimation.

[2] Ifan Hughes, Thomas Hase; 2010: Measurements and Their Uncertainties: A Practical Guide to Modern Error Analysis; 136 pages; Oxford University Press

Proposal to estimate the total error (e) of a TRT by three factors:

> Device error (e1): Calculated from the accuracy of the flow meter and the temperature sensors

> Slope stability (e2): evaluated from the stepwise evaluation curves. The slope stability is dependent on different factors like the homogeneity of operational parameters during measurement (electric power or heat input rate, underground conditions, air temperature influence). In addition, it corresponds to inhomogeneities in the subsurface and BHE parameters (subsurface temperature, groundwater influence, heat capacity and conductivity, geometric inhomogeneity of the U-tubes).

> Line source approximation (e3): The value describes the remaining error of the approximation of Kelvin's line source theory in comparison to the exact solution.

Another parameter, which can play a major role in accuracy, is the volumetric heat capacity of the circulating fluid during the measurement. Especially if antifreeze is used, a calorimeter should be used to determine the real heat capacity of the fluid. The heat capacity of the fluid is needed to calculate the power input to the BHE during the TRT. However, this topic will not be addressed in this document.

4.4.1. Device error e1

During the performance of a TRT, two values have to be measured and monitored to calculate the thermal power input to the BHE:

- temperature difference, directly at the BHE head
- volumetric fluid flow.

The accuracy of the TRT results is strongly dependent on the accuracy of the temperature and flow sensors. The accuracy of the absolute temperature is not as important, as the accuracy of the temperature difference between inlet and outlet senor. Therefore, it is essentially to pair the temperature sensors. Pairing should be done once a year, by calibration and adjustment of both sensors. Pairing means that both sensors have to show the same value in the temperature range of the TRT (~ 10-40 °C), at least up to a precision of one digit.

The calculation of λ is proportional to the flow rate and the temperature difference of the fluid:

$$\lambda = c \cdot Q \cdot \Delta T \qquad \text{Eq. 4-3}$$

Hence, with Gaussian error propagation the device error e1 can be calculated by:

$$e1 = \lambda \cdot \frac{\Delta\Delta T}{\Delta T} + \lambda \cdot \frac{\Delta Q}{Q} \qquad \text{Eq. 4-4}$$

λ	Thermal conductivity of the earth
ΔT	Temperature difference between inlet and outlet of the BHE
Q	Volume flow rate of the circulating fluid
$\Delta\Delta T$	Absolute measurement error of ΔT
ΔQ	Absolute measurement error of Q
c	Constant factor $c = \frac{c_{VW}}{L_{BHE} \cdot 4 \cdot \pi \cdot k}$

c_{VW}	Volumetric heat capacity of fluid (depending on fluid properties)
L_{BHE}	Length of BHE
k	Logarithmic slope of the temperature rise

Table 11 shows the calculation of device error for the benchmark TRT with all necessary input parameters. TRT#1 has a good accuracy as the temperature sensors are paired and calibrated and a very accurate magnetic-inductive (MID) flow meter is used. TRT#3 uses temperature sensors without calibration and turbine flow sensor with the consequence that the device error is 4-5 times higher. TRT#2 has paired and calibrated temperature sensors and an ultrasound flow sensor. The accuracy is moderate to good.

Table 11: Results of device error calculation for the benchmark test, with all needed parameters, as an example

			BHE Vienna			BHE Krakow	
sensor accuracy of the TRT device			TRT#1	TRT#2	TRT#3	TRT#2	TRT#3
max. deviation of temperature sensors	ΔΔT	K	0,05	0,05	0,2	0,05	0,1
accuracy of flow meter	ΔQ	L/h	10	50	70	50	70
measurement parameter							
mean flow rate	Q	l/h	2004,0	1289,9	1398,9	1588,4	1558,7
mean temperature difference	ΔT	K	3,5	3,5	4,3	2,8	3,1
results of TRT measurements							
effective thermal conductivity	λ	W/m/K	1,92	1,84	1,95	1,76	1,85
device error	*e1*	W/m/K	0,04	0,10	0,19	0,09	0,14

4.4.2. Slope stability error e2

The slope stability is determined in the evaluation process, by calculating the stepwise prograde and retrograde lambda evaluation. An explanation, how to do this is explained in deliverable D.T3.5.1. The stability is dependent on different factors, e.g. constancy of parameters during measurement (electric power or heat input rate, underground conditions, air temperature influence) or inhomogeneity in earth and BHE parameters (earth temperature, groundwater influence, heat capacity, thermal conductivity as well as the geometric inhomogeneity of the U-tubes).

To determine the slope stability uniform, the decision was done to apply the last 12 hours of the stepwise prograde evaluation curve and inside the time frame of 8 to 24 hours of the stepwise retrograde evaluation. In each timeframe, the difference of the maximum and minimum lambda-value has to be determined. The greatest difference defines the slope error e2.

Procedure of determining the slope stability error:

1. determine prograde stability = variation of λ at last 12 h of stepwise prograde evaluation

2. determine retrograde stability = variation of λ between 8-24 h of stepwise retrograde evaluation
3. The greatest value defines the slope stability e2:

$$e2 \equiv MAXIMUM\ (prograde\ stability\ , retrograde\ stability) \qquad \text{Eq. 4-5}$$

Figure 14 demonstrates the determination of the slope stability at the three benchmark tests at BHE Vienna and Figure 15 at BHE Krakow.

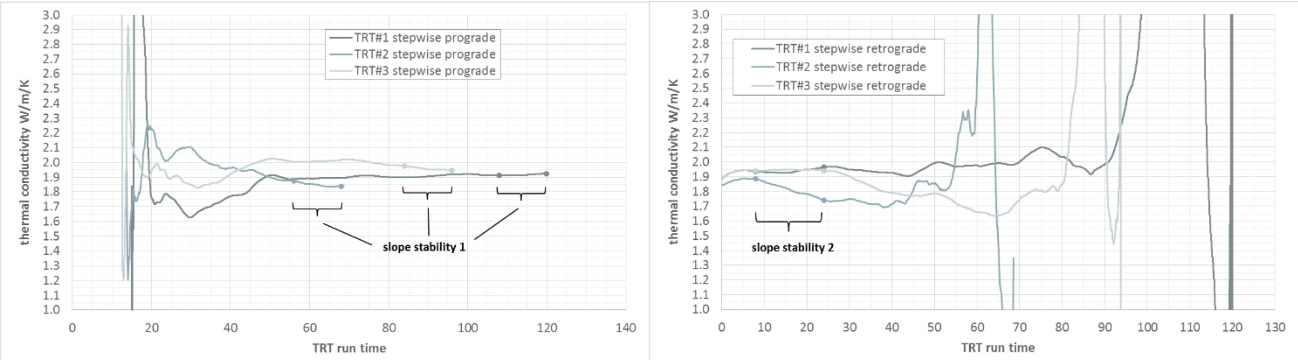

Figure 14: Slope stability evaluation for the benchmark TRT at BHE Vienna; stepwise forward evaluation with prograde stability frames on the left; stepwise backward evaluation with retrograde stability on the right;

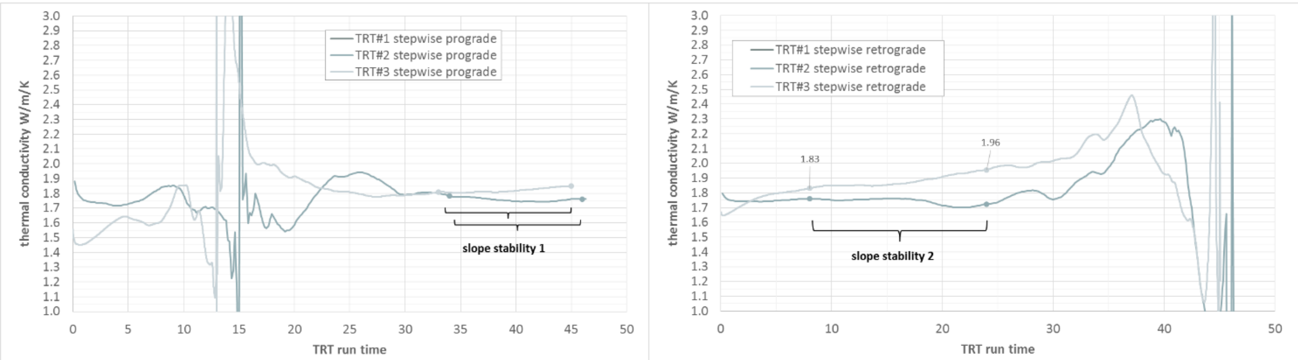

Figure 15: Slope stability evaluation for the benchmark TRT at BHE Krakow; stepwise forward evaluation with prograde stability frames on the left; stepwise backward evaluation with retrograde stability on the right;

The results of the slope stability values of the benchmark tests are expressed numerically in Table 12. The lowest slope stability error was determined at the BHE site in Vienna at the device TRT#3 showing an error of 0.03 W/m/K. The same device at the BHE site in Krakow showed an error of 0.13 W/m/K. The reason for this is not clear but may be linked to the short TRT runtime, groundwater movement, air temperature influences or variations of the electrical power supply during the TRT measurement. The high error can be determined graphically as shown in the right diagram of Figure 15. The stepwise retrograde curve rises from 1.83 W/m/K to 1.96 W/m/K and leads to the following conclusion:

Dependent on the value of t_{MIN}, chosen at TRT evaluation, the result of the conductivity will be in the range of 1.83 to 1.96 W/m/K. The highest error in slope stability for the benchmark can be observed at BHE Vienna with TRT#2 (see also Figure 14).

Table 12: Results of slope stability error evaluation for the benchmark TRT

			BHE Vienna			BHE Krakow	
			TRT#1	TRT#2	TRT#3	TRT#2	TRT#3
slope stability	e2	W/m/K	0,04	0,15	0,03	0,06	0,13

4.4.3. Line source approximation error e3

This component has to be considered, if the evaluation is done with the line source approximation of Kelvin's line source theory. It is a theoretical value and describes the remaining error of using his approximation in comparison to the exact solution.

Based on formula (14) in VDI 4640 Vol.5 (draft), 2016:

$$t_{min} \geq \frac{p \cdot r_b^2}{\alpha} \quad \text{Eq. 4-6}$$

And considering the reciprocal function fit between p and the error, and the thermal diffusivity:

$$p \cong \frac{0{,}53}{e3} \cdot \lambda \quad \text{Eq. 4-7}$$

the device error e3 can be calculated by:

$$e3 = \frac{0{,}53 \cdot c_v \cdot r_b^2}{t_{min}} \quad \text{Eq. 4-8}$$

p parameter, defined in VDI 4640 Vol.5 (draft), 2016, as a function of the approximation error
r_b drilling radius [m]
α thermal diffusivity $\alpha = \lambda / c_v$ [m²/s]
λ thermal conductivity of the earth [W/m/K]
c_v volumetric heat capacity of the earth [J/m³/K]
t_{min} chosen evaluation starting time [s]

The value of e3 is mainly dependent on the chosen start time of the TRT (t_{min}). The line source approximation error will mark the minimum possible error and is just considered, if the device error e1 and the slope stability is very low or the chosen evaluation time t_{min} is very low.

Table 13 gives the results of the calculation of e3 for the benchmark tests. The volumetric heat capacity was estimated equally, since the influence of this parameter is low.

Table 13: Result of line source approximation error for the benchmark TRTs

		BHE location:	BHE Vienna			BHE Krakow	
		TRT device name:	TRT#1	TRT#2	TRT#3	TRT#2	TRT#3
Input parameter for e3							
mean drilling diameter	d	mm	133	133	133	125	125
vol heat capacity	cv	MJ/m³/K	2.3	2.3	2.3	2.3	2.3
minimum time criterion	t_{min}	h	15	13.6	12.5	15	13
line source approximation error	*e3*	W/m/K	0.09	0.10	0.10	0.08	0.09

4.4.4. Total error

The calculation of the total error e of a thermal response test is based on the assumption, that e1 and e2 are independent and not correlated. Thus, the combination of e1 and e2 can be combined with the root mean square formula. Considering e3 as the lower limit of the error value, the formula for the total error is given as the maximum error related to either e3 or the root mean square of e1 and e2.

$$e = max\left(\sqrt{e1^2 + e2^2}; e3\right) \quad \text{Eq. 4-9}$$

4.5. Results of the TRT benchmark test with error estimation

Figure 16 and Table 14 are showing the results of the benchmark TRT with error estimation. The results of the devices TRT#1 and TRT#3 at the BHE site in Vienna are quite converging considering that device TRT#1 obtains a very good total accuracy. Hence, the most likely conductivity value is in the range from 1.87 to 1.93 W/m/K, considering all three results with error estimation. At the BHE site in Krakow, only two devices participated during the project. The most likely conductivity value is therefore determined by the upper value of TRT#2 and the lower value of TRT#3, between 1.75 and 1.81 W/m/K (see Figure 16).

The deviation between device TRT#2 and TRT#3 is rather significant at both locations showing values of 0.09 and 0.11 W/m/K. This might be related to a systematic offset between the two devices.

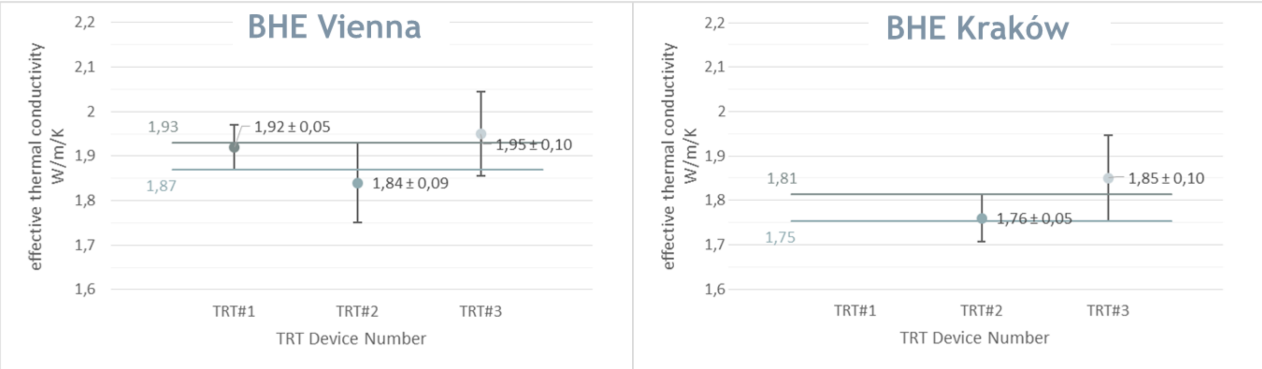

Figure 16: Thermal conductivity with error estimation bars of the benchmark tests in comparison.

Table 14 shows the summary of all TRT benchmark results. The estimated total error, as proposed by the GeoPLASMA-CE team is a combination of the three error components e1, e2 and e3. The accuracy of the TRT benchmark tests are in the range of 5.2 % to 10.4 %. The main factor of the error estimation is highlighted in red colour. At the BHE site in Vienna, TRT#1 showed a low error of the device (e1) and related to the slope stability (e2). For that reason, the error related to the line source approximation prevailed. The device TRT#2 shows a moderate device error (e1) and a poor slope stability (e2) while the device TRT#3 shows a significant device error (e1) but a very good slope stability (e2).

The goal defined in the deliverable D.T3.5.1 in reaching an accuracy of 5 % could not be achieved in the benchmark TRT measurements performed in GeoPLASMA-CE.

Table 14: Main results of the benchmark test; red values indicating main factor for high error values

		BHE Vienna			BHE Krakow		
		TRT#1	TRT#2	TRT#3	TRT#1	TRT#2	TRT#3
mean underground temperature below 10 m	°C	12,8	12,4	12,9	No data	11,5	12,3
thermal borehole resistance	K/W/m	0,12	0,14	0,13	No data	0,13	0,12
effective thermal conductivity	**W/m/K**	**1,92**	**1,84**	**1,95**	**No data**	**1,76**	**1,85**
estimated total error e	**%**	**5,2**	**9,7**	**9,8**	No data	**6,0**	**10,4**
estimated total error e	**W/m/K**	**0,10**	**0,18**	**0,19**	No data	**0,11**	**0,19**
device error e1	W/m/K	0,04	0,10	0,19	No data	0,09	0,14
slope stability e2	W/m/K	0,04	0,15	0,03	No data	0,06	0,13
line source approximation error e3	W/m/K	0,10	0,11	0,12	No data	0,09	0,10

4.6. Results of the benchmark of TRT processing routines

Benchmark of TRT processing routines is intended to verify the impact of the evaluator and the processing workflows on the TRT results. To achieve this, two datasets were selected (from the test runs done within the GeoPLASMA-CE project), processed and interpreted by three independent evaluators, each using a different routine and calculation tools. The details of the used benchmark datasets are presented in Table 8.

Three processing routines were applied. The first two are Excel calculations based on standard formulas used to perform the benchmark in chapter 4.2. These processing workflows are used by the Austrian Geological Survey, for this benchmark it is referred as “GBA routine”, and the private company geoENERGIE Konzept GmbH, referred as “geoENERGIE”.

The third processing routine is performed by the GeRT CAL software. For this benchmark this routine is referred as “GERT CAL”.

The GeRT-CAL software allows the evaluation of the data collected during a geothermal-response-test in order to calculate the thermal conductivity of the ground (λ_{eff} [W / (m · K)]) and the thermal borehole resistance (R_b [K / (W · m)]).

The evaluation-algorithm is based on the line source theory and automatically calculates and considers the lower time criterion.

The software was developed by UBeG GmbH & Co. KG and is provided with the TRT device GeRT manufactured by UBeG (TRT device #2 according to chapter 4.2).

The software GeRT CAL calculates the thermal conductivity (λ) and the borehole resistance (R_b) with the specified temperature data and basic data using Kelvin’s line source theory. The software also performs a stepwise evaluation and displays the result in form of a stepwise evaluation chart (see figures 13 and 17).

The GeRT CAL software works after the following formulas based on the line source theory (according to Users Guide to GeRT, Copyright by UBeG GmbH & Co. KG, Germany, 06.02.2015):

Calculation of thermal diffusivity α [m²/s]:

$$\alpha = \frac{\lambda_{est}}{\rho c_p} \quad \text{Eq. 4-9}$$

Lower time criterion t_{b1} [sec]

$$t_{b1} = \frac{5r_0^2}{\alpha} \qquad \text{Eq. 4-10}$$

λ_{est}	Estimated thermal conductivity [W/(m K)]
α	Thermal diffusivity [-]
ρC_p	Volumetric heat capacity [MJ/m³/K]
r_0	Radius of borehole [m]
t_{b1}	Lower time criterion [sec]

Calculation of thermal conductivity

$$\lambda = \frac{Q}{4 \cdot \pi \cdot H \cdot k} \qquad \text{Eq. 4-11}$$

Q	Heating output [W]
H	Length of BHE [m]
K	Gradient [-]
λ	thermal conductivity [W/(m K)]

Calculation of thermal borehole resistance for each time step and sensor.

$$R_b = \frac{H}{Q} \cdot (T_f - T_0) - \frac{1}{4\pi\lambda} \cdot \left(\ln(t) + \ln\left(\frac{4\alpha}{r_0^2}\right) - 0{,}5772\right) \qquad \text{Eq. 4-12}$$

Q	Heating output [W]
H	Length of BHE [m]
T_0	Undisturbed ground temperature [°C]
Λ	thermal conductivity [W/(m K)]
α	Thermal diffusivity [m²/s]
r_0	Radius of borehole [m]
t	Time [sec]
T_f	Fluid temperature at time t [°C]

In Table 8 the processing routines benchmark results are presented. The results of thermal conductivity for all routines and datasets are very similar. The difference ranges from 0.01 to 0.05 W/m*K. Also, the results for the borehole resistance are very concordant, with differences between the routines of 0.01 K/W/m

The presented figures (Fig. 11-13 and Fig. 15-17) show the GeRT CAL software interface and TRT charts and evaluation. For comparison purpose the stepwise evaluation charts were presented for all three used routines.

Table 8: Table of results of TRT processing routines benchmark.

TRT Benchmark dataset:		Dataset 1	Dataset 2
Evaluation parameter:			
TRT date		24th April 2018	7th March 2018
TRT run time	h	46.3	120
mean flow rate	l/h	1532.9	2003.7
mean temperature difference	K	2.57	3.43
mean drilling diameter	mm	125	133
vol. heat capacity earth	MJ/m³/K	2.3	2.3

BHE length	m	84.5			150		
starting temperature	ºC	12.40			12.85		
Processing routine:		**GBA routine**	**geoENERGIE**	**GERT CAL**	**GBA routine**	**geoENERGIE**	**GERT CAL**
minimum time criterion	h	16.7	8.1	7.13	14.9	10.0	7.55
Evaluation results:		**GBA routine**	**geoENERGIE**	**GERT CAL**	**GBA routine**	**geoENERGIE**	**GERT CAL**
effective thermal conductivity	W/m/K	**1.76**	**1.75**	**1.75**	**1.93**	**1.93**	**1.88**
thermal borehole resistance	K/W/m	**0.11**	**0.11**	**0.11**	**0.12**	**0.12**	**0.12**

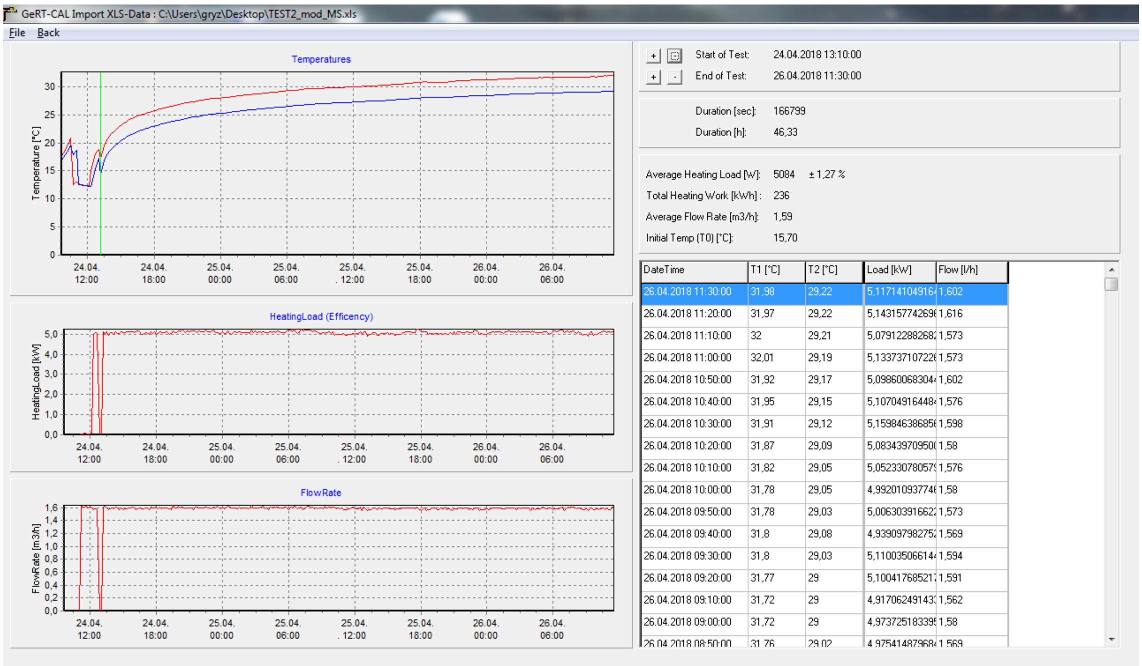

Figure 17: Raw data imported to GERT CAL software. Dataset 1

Figure 18: Thermal conductivity evaluation in GERT CAL software. Dataset 1.

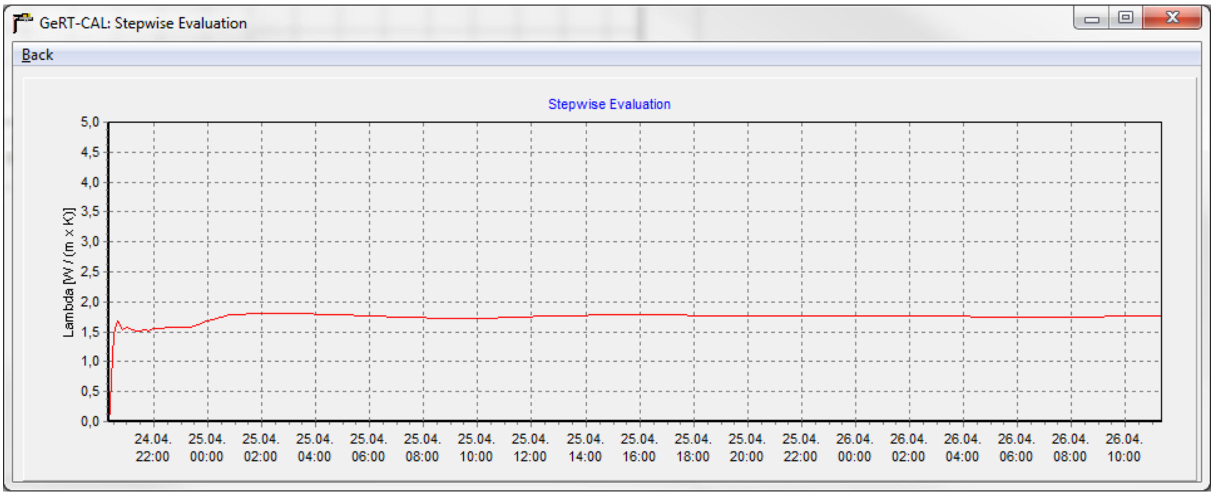

Figure 19: Stepwise evaluation in GERT CAL software. Dataset 1.

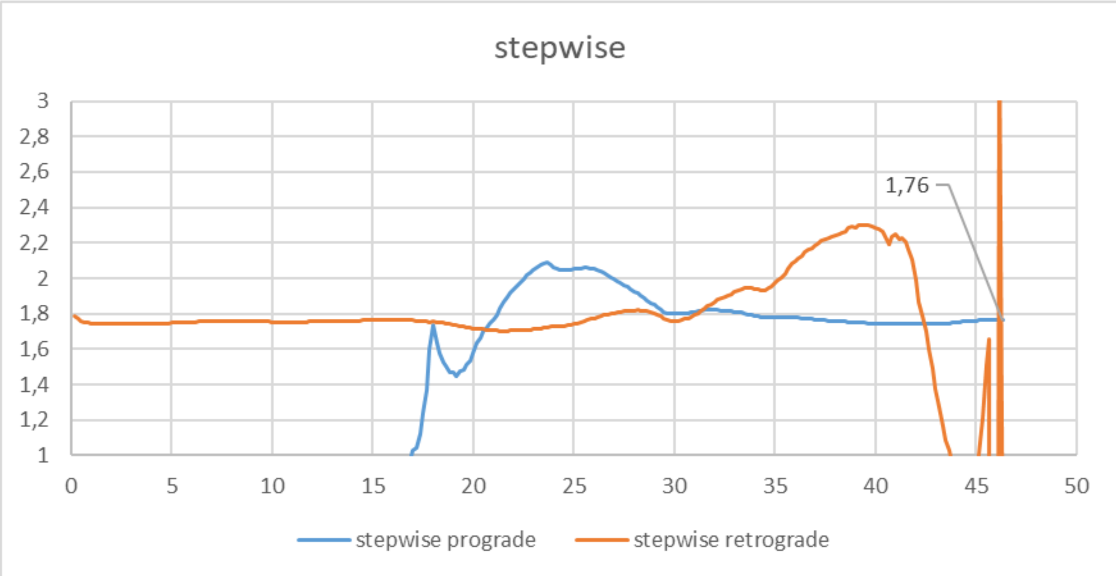

Figure 20: Stepwise evaluation according to GBA routine. Dataset 1.

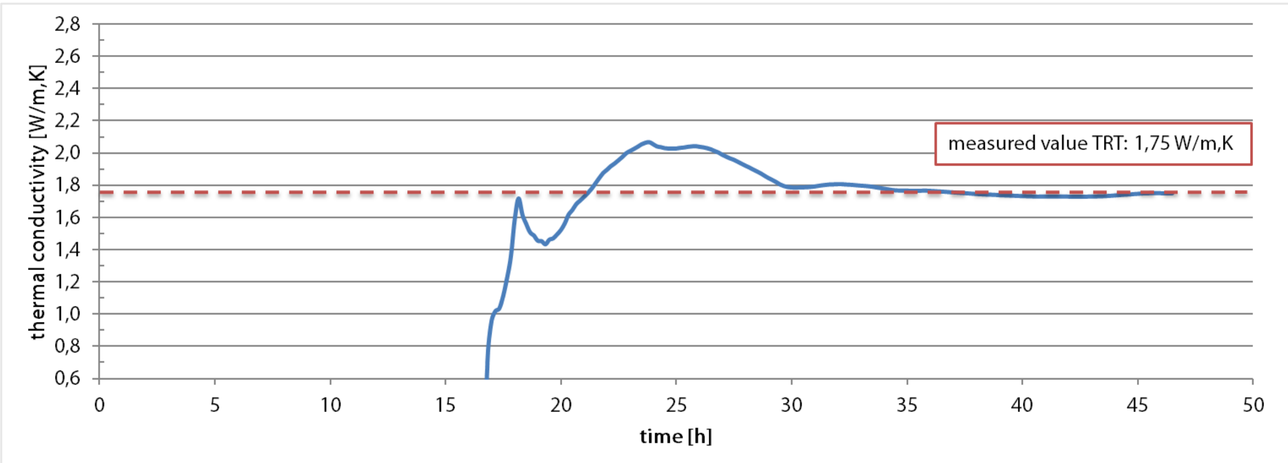

Figure 21: Stepwise evaluation according to geoENERGIE. Dataset 1.

The TRT interpretation software (such as GeRT CAL) facilitates the processing workflow and allows the user to efficiently generate reports that can be delivered to clients/designers. The software interface is simple and user friendly. Due to this, the user should be a trained geologist, skilled in manual interpretation of TRT runs. Otherwise there is a danger of using the software as a "black box".

Most of the errors can result not directly from the software workflow and used calculation algorithms, but from erroneous import of raw the TRT data from datalogger or a lack of training and experience from the software user (black box case).

GeRT CAL software contains two modules of curve fitting algorithms – parameter variation and superposition methods. These functions are very useful in interpretation of disturbed TRT runs (due to electrical grid instability or interruption by short term power loss). Curve fitting features are very useful during commercial TRT workflow, where tests are carried out in real construction site conditions, under tight schedules and deadlines and often there is no opportunity to repeat the disturbed TRT run. The unskilled user can also generate errors in TRT evaluation using this curve fitting features without detailed knowledge and experience.

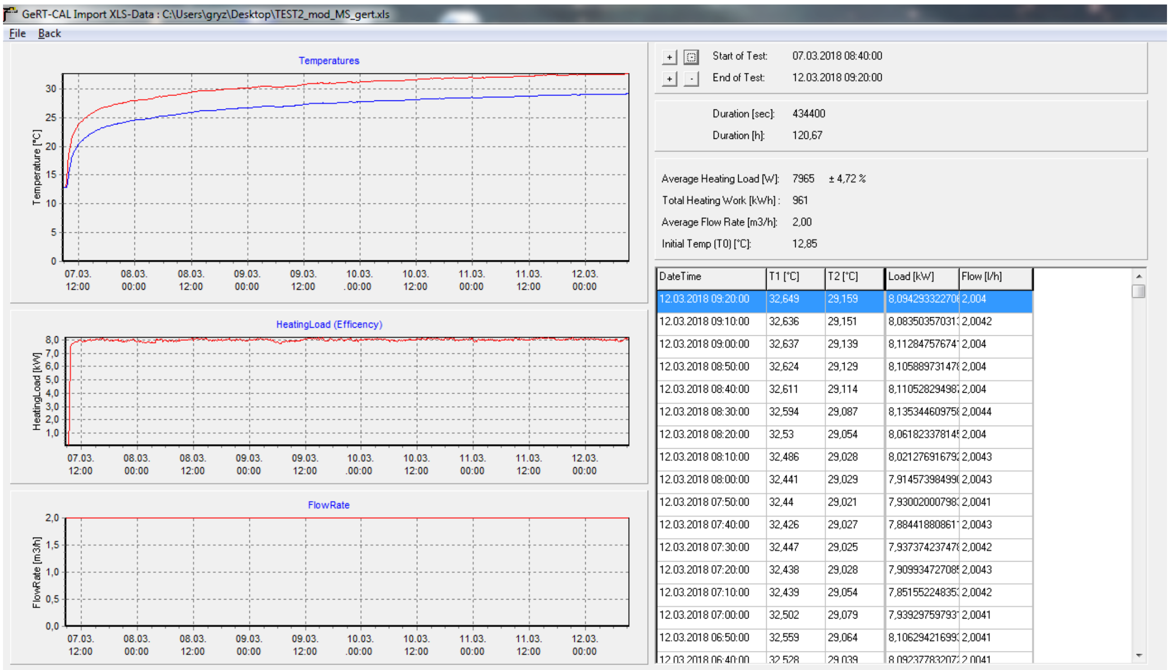

Figure 22: Raw data imported to GERT CAL software. Dataset 2.

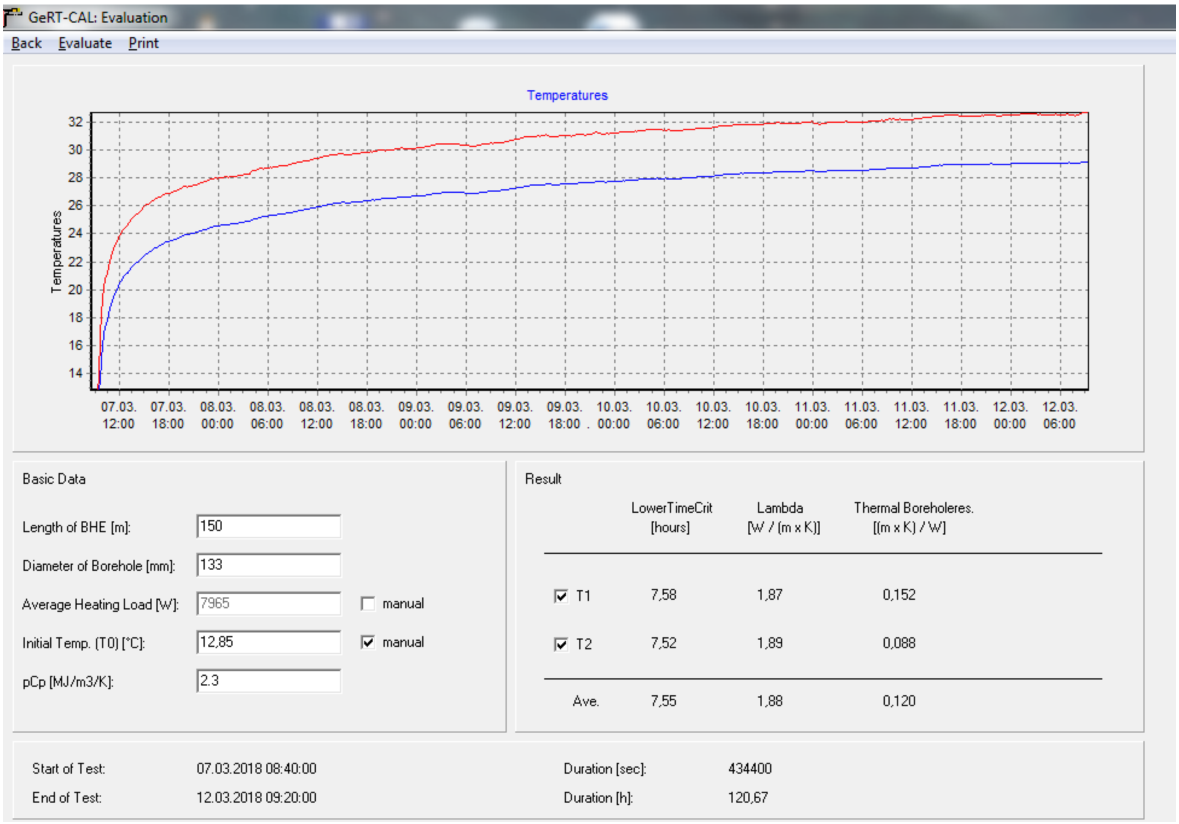

Figure 23: Thermal conductivity evaluation in GERT CAL software. Dataset 2.

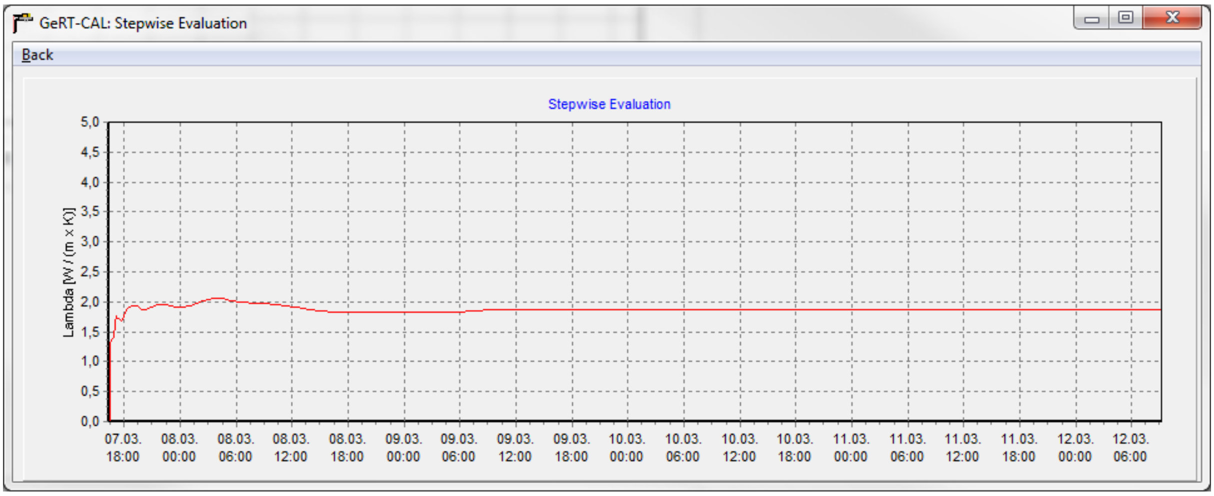

Figure 24: Stepwise evaluation in GERT CAL software. Dataset 2.

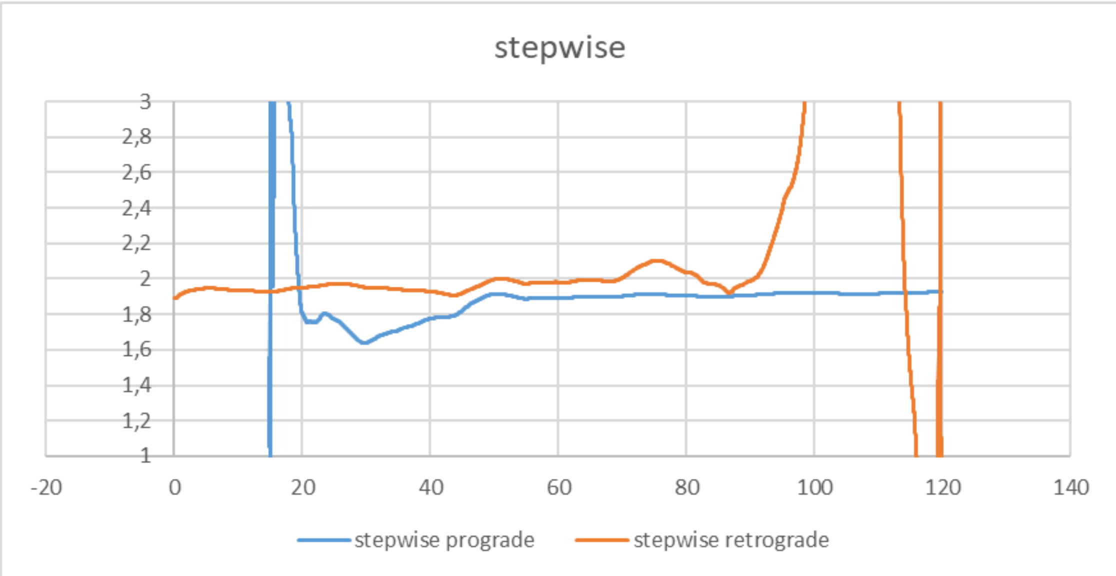

Figure 25: Stepwise evaluation according to GBA routine. Dataset 2.

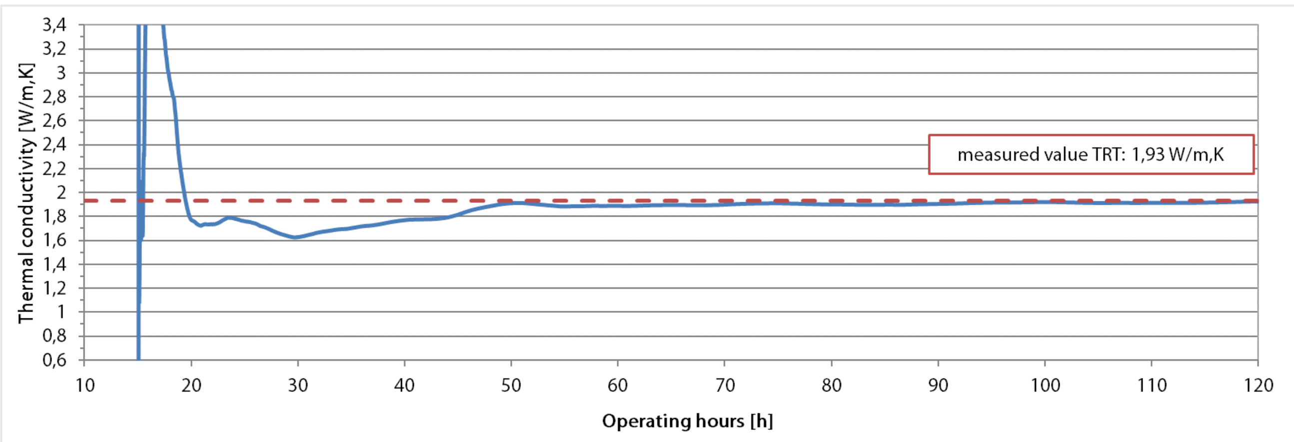

Figure 26: Stepwise evaluation according to geoENERGIE. Dataset 2.

5. Conclusion

5.1. Calibration of temperature sensors

If various temperature sensors are used for one joint investigation area, a calibration is urgently recommended. The calibration of the four handheld groundwater devices showed, that three of the sensors were converging well (deviation <0.2 K) while one device showed an offset of around 0.6 K. Around 60 % of all 52 temperature sensors used in groundwater monitoring were coinciding with the reference sensor (deviation < 0.4 K) while the remining 40 % had an offset of around 1 K. This is a significant deviation, if the groundwater temperature is used for the calculation of resources linked to open loop systems. Calibration and especially the application of the calibration function to measured raw values is therefore recommended if values from different devices are combined in maps.

5.2. Conclusions of the TC comparison measurements

The comparison of thermal conductivity and diffusivity measurements showed deviations between devices used. Taking into account the accuracy of the devices relatively comparable measurements were obtained with TCS, hot disc and ISOMET 2104, while deviations of measurements obtained with RTB 1.01 are more significant.

Deviation among measurements could be caused, beside the different method used, also from other potential reasons:

1. Measurements were performed under different conditions (e.g. ambient temperature).
2. Measured samples weren't in the same condition, as they were measured over a long-time span (water saturation, temperature).
3. Different methods require different sample sizes (e.g. Samples for RTB 1.01 device are thinner than needed for TCS measurements, so the effect of heat flow absorption is not the same.).
4. Devices accuracy influences on obtaining results (between 1 and 15 % of error).
5. The choice of different standards for same device can affect the deviations between the measurements (e.g. TCS).
6. Methods, like ISOMET and RTB 1.01, require good contact between probe and sample, so if sample surface is not smooth enough, deviations can occur. Bentonite mortar was used as a heat contact agent for improvement of contact between probe and sample. But this approach is still under research.
7. Deviation can appear if samples weren't measured in the same direction (according to bedding plane). Because of that is important that samples are measured in different directions. In this case we can make analysis of anisotropy (like for polish samples).

Heterogeneity of the sample is also very common, therefore multiple sample measurements are highly recommended, as this gives us the most realistic average. Then factor of heterogeneity ε can be calculated and samples evaluated.

5.3. TRT benchmark measurements

The benchmark test revealed the following:

The results of a TRT measurement is not very sensitive to the evaluator as the processing workflows are well explained and rather harmonized in literature. It is more sensitive to the accuracy of the TRT device itself and the quality of the test performance. Especially the introduction of the device error shows the importance of the usage of accurate temperature and flow sensors in the TRT device. In particular, a proper calibration and pairing of the temperature sensors of the TRT device can reduce the total error significantly. In addition, a frequency-controlled circulation pump (feedback loop of the flow meter to the circulation pump) can enhance the slope stability. However, the slope stability can be poor due to inhomogeneity effects related to the subsurface, which cannot be controlled by the TRT operator.

In any case it is recommended to execute an appropriate error estimation for every TRT measurement following the proposals developed in GeoPLASMA-CE. The existing guidelines for thermal response tests should include instructions how to calculate the error for a TRT measurement. In addition, national or international quality certificates are recommended to decouple the quality of TRT measurements from the devices used.