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A portable borehole temperature logging system using the four-wire resistance method

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Abstract

High-quality temperature–depth information from boreholes with a depth of 100 m or more is used in geothermal studies and in studies of climate change. Electrical wireline tools with thermistor sensors are capable of measuring borehole temperatures with millikelvin resolution. The use of a surface readout mode allows analysis of the thermally conductive state of a borehole, which is especially important for climatic and regional heat flow studies. In this study we describe the design of a portable temperature logging tool that uses the four-wire resistance measurement method. The four-wire method enables the elimination of cable resistance effects, thus allowing millikelvin resolution of temperature data at depth. A preliminary two-wire model of the system is also described. The portability of the tool enables one to collect data from boreholes down to 300 m, even in locations with limited accessibility.

Keywords: borehole temperature logging, geothermal gradient, four-wire method

(Some figures may appear in colour only in the online journal)

1. Introduction

Precision temperature versus depth (T–D) measurements in boreholes with a depth of 100 m or more have a variety of interesting applications including determination of crustal heat flow, geothermal development and the study of recent climate change. In thermally stable boreholes, the amount of information increases with the accuracy of the T–D data (Chapman and Harris 1993). For example, in paleoclimatic studies, the precision of the T–D data directly affects the extent of the reconstructed surface temperatures back in time, as surface temperature effects decay exponentially with depth (Pollack 1993). As a result, a temperature logging tool with high resolution (1–10 mK) enables one to detect deeper climatic perturbations within a borehole, eventually going further back in climatic history.

Electrical wireline techniques are widely used in borehole temperature logging (Blackwell and Spafford 1987, Wisian *et al* 1998, Beardsmore and Cull 2001). In these systems, a temperature-sensitive electrical resistor is sent down into the borehole and changes in the resistance with temperature of the environment are acquired. The sensor itself is completely isolated from the borehole environment, and the entire electrical measurement is performed in a closed loop. In surface readout mode, the changes in resistance within the borehole are monitored and recorded at the same time. With accurate temperature readings, this enables one to understand *in situ* thermal conditions of the borehole, i.e. whether the heat transfer is conductive, convective or hydrologic. The surface readout capability is especially useful for precision T–D measurements where both depth and temperature information must be accurately obtained.

One of the most commonly used sensor type for precision temperature logging is a thermistor, due its high temperature coefficient of resistance (Blackwell and Spafford 1987). Using a high-resolution resistance meter, temperature differences of ~1 mK can be resolved by a thermistor sensor. Another advantage of thermistors is their high room temperature resistance (1–100 kΩ) which reduces the cable resistance effects during measurements.

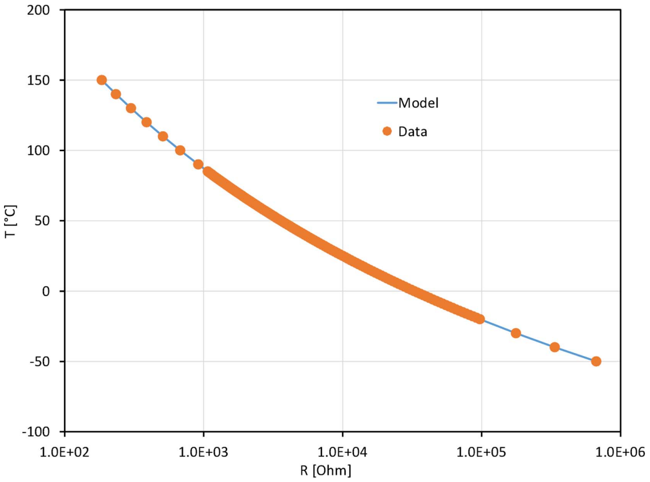

Figure 1. Thermistor calibration curve. Note that the *x*-axis is in a logarithmic scale.

In surface readout tools, the logging cable is used both for transmitting data to the surface and for lowering the probe into the borehole. As a result, the cable must have both desirable electrical and mechanical properties. The most important electrical effect is the possible interference of the resistance of the cable between the resistance meter unit on the surface and the probe within the borehole. The four-wire resistance technique (Kelvin method) allows us to eliminate cable resistance effects (Clow *et al* 1996, Clow 2008). In this study, we present the development of a low-cost portable T–D system based on the four-wire method for applications in shallow boreholes.

2. Design of the system

2.1. Temperature probe

In the system we used a negative temperature coefficient (NTC) thermistor by Datanab LLC with 10 kΩ resistance at room temperature. The range of measurement for the sensor is −50 °C to 150 °C, which is suitable for moderate-temperature boreholes. For a typical NTC thermistor, the temperature sensitivity is given by

$$\Delta T \approx \frac{\Delta R}{\alpha_T R_s}$$

where α_T and R_s are sensor temperature coefficient and sensor resistance, respectively. For typical values of $\alpha_T = 0.05\ \mathrm{K}^{-1}$ and $R_s = 10\ \mathrm{k}\Omega$ for a thermistor, a resolution of $\Delta R = 1\ \Omega$ in the resistance meter corresponds to a resolution of $\Delta R = 2\ \mathrm{mK}$ in the temperature readings. Commercial resistance meters are nowadays capable of milli-ohm sensitivity; this enables us to make millikelvin temperature measurements using the thermistor sensor in an economical way. Figure 1 shows the calibration points provided by the manufacturer (blue dots) along with the curve (orange curve) fitted to these points. For the fitting function, a modified version of the Steinhart–Hart equation is used (Clow *et al* 1996):

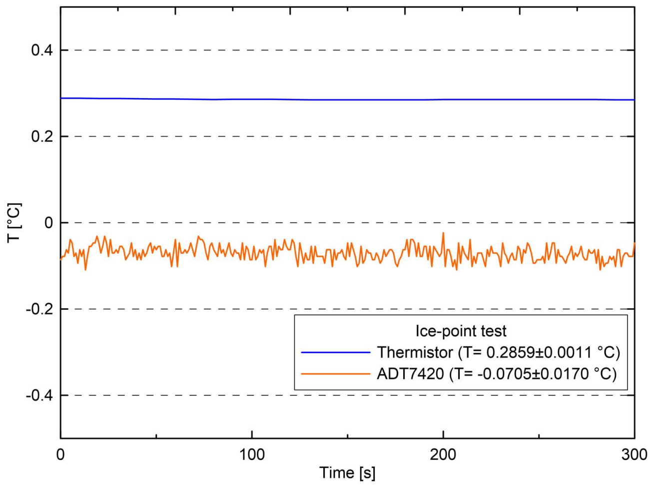

Figure 2. Ice-point test for the thermistor probe (blue curve). In the test, a pre-calibrated digital temperature sensor (ADT7420) was also used for comparison (orange curve).

$$\frac{1}{T} = A + B[\ln R] + C[\ln R]^2 + D[\ln R]^3$$

where T and R represents temperature (in kelvin) and resistances (in ohm), respectively. The coefficients A, B, C, D are specific to the sensor, and were determined by applying least-squares regression to the calibration points. The steep change of resistance with temperature is evident from the figure.

The temperature probe consists of a single-bead sensing element placed in a stainless steel tube with a thermally conductive epoxy filling. An air-tight epoxy filling enables faster thermal response of the probe. The overall probe diameter is less than 1 cm, which allows access to boreholes even with small openings on their heads.

The performance of the probe was tested in the laboratory environment by applying an ice-point test. In this test, the probe was immersed into a bucket filled with a mixture of ice pellets and water. The ice content of the bucket was kept as great as possible to obtain conditions near 0 °C in the environment. For comparison, a second thermometer, a digital output temperature sensor (ADT7420), developed by Analog Devices, was used. The temperature resolution of the ADT7420 is lower than the thermistor due to strong white noise characteristics but it can be improved by a longer data acquisition time and averaging. Most importantly, the ADT7420's output is pre-calibrated and has a very reliable long-term accuracy of ~0.1 K.

The result of the ice-point test is shown in figure 2. The resolution of the thermistor probe is basically limited only by the R-meter resolution which is better than 1 Ω, and corresponds to 1 mK in the current case. The resolution of the ADT7420 depends on the length of the measurement. For a time interval of 300 s in the current experiment we obtained a resolution of 0.017 °C. Temperatures are 0.286 °C and 0.071 °C for the thermistor and ADT7420, respectively. It should be noted that due to the possible impurity of the ice/

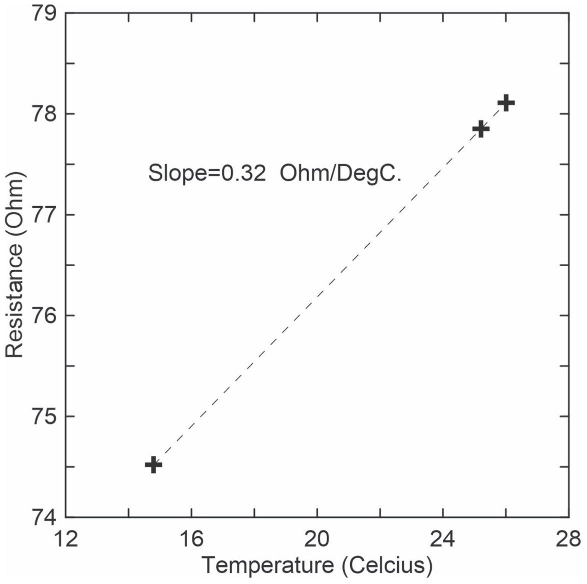

Figure 3. Cable resistance versus temperature.

water mixture, there might be a slight shift from the 0 °C conditions in the environment.

2.2. Electrical design

Two different resistance measurements methods were applied in the design of the T–D system. In the first method, a two-wire method was used, where the sensor resistance is measured directly with a high-sensitivity digital multi-meter (DMM) with two terminals. We used a Fluke 289 DMM which has a 4.5 digit resolution (corresponding to 1 Ω resolution for our system) as well as a data recording capability. Its other advantage is that it is battery operated. In this design, a two-wire logging cable with a length of 300 m is used. Such a system is desirable due to the durability of the logging cable (electrical insulation is needed only for two wires) and the light weight of the cable, and hence of the overall T–D system. For the two-wire cable, 26 AWG with nickel plated copper (NPC) conductors with a perfluoroalkoxy (PFA) coating are used. The overall diameter of the cable is 2.1 mm and it weighs only 2.2 kg for its 300 m length. In a two-wire T–D system a systematic error arises due to cable changes in resistance during logging. In order to understand this effect, the cable (one-way) resistance was measured for three different temperature conditions (figure 3). The rate of change for the cable resistance is measured to be $0.32\,\Omega\,^{\circ}\mathrm{C}^{-1}$. The temperature changes on the cable during measurements directly contaminate the borehole measurement. For temperatures changes of $2\text{–}5\,^{\circ}\mathrm{C}\ 100\,\mathrm{m}^{-1}$ in the borehole, the cable resistance changes impose an error of 4–10 mK in the temperature data. Such an error may be acceptable for geothermal gradient measurements but is undesirable for climate studies. We also measured the capacitance of the cable as $23\,\mu\mathrm{F}$ which was interpreted to have a negligible effect on resistance measurements.

Our field experience (discussed in the following section) showed that the main drawback of a two-wire system is not changes in cable resistance but other problems during data acquisition. We observed that resistance readings show too much fluctuation during measurement at a certain depth. Such fluctuations cannot be explained by any changes within the borehole and must be caused by some external field. These fluctuations result in difficulties with recording the data and also obscure the fine details of the *in situ* thermal conditions (i.e. hydrological effects).

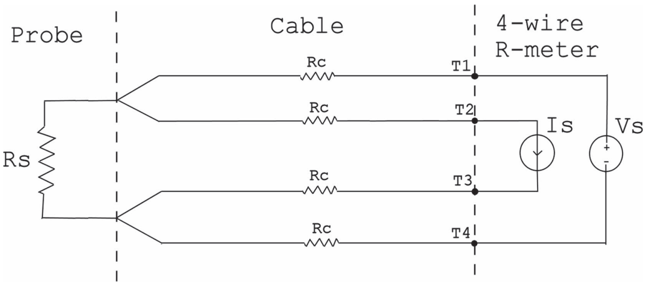

Figure 4. Circuit schematics for the four-wire measurement method.

Due to practical problems with the two-wire system, the resistance measurement has been replaced by the four-wire method. The working principle of the four-wire method is shown in figure 4. As shown in the figure, two terminals are used for the current source while the other two terminals are used for reading the voltage on the sensor. The resistance is determined by the ratio of the voltage and the current readings. We used GW-Instek GOM 802 DC milli-ohm meter which has four-wire measurement capability. It has a rated resolution of 1 Ω within the 3–30 kΩ range. The meter uses AC power so it is necessary to have an AC source. Our experience is that using a noisy AC source (such as a gas generator) for powering the meter can corrupt resistance measurements, so a voltage regulator and/or a proper grounding for the circuit may be necessary for better data quality.

The four-wire cable chosen for the new system has the same conductor properties as the two-wire cable mentioned above but it is additionally shielded with a steel armor braid. This steel armor can both protect the cable against mechanical damage and shield the cable against external electric fields. The overall diameter of the four-wire cable is 3.1 mm and it weighs 8.2 kg for a length of 300 m.

2.3. Mechanical design

Mechanical integration of the system was carried out by Atikol FT. The surface unit consists of a manually operated drum, a four-wire slip-ring system at the center of the drum, and a depth reading unit in front of the drum. Depth readings are made optically by a disc where its rotations per second are recorded and converted into depth information. The accuracy of depth measurements has been tested by two-way measurement in a borehole, and determined to be 0.06% (6 cm per 100 m). The general view of the T–D logging system is shown in figure 5. The overall weight of the system is about 25 kg. Ideally the system should be used by two people, but

Figure 5. General view of the T–D logging system.

one person can use it for shallow (less than ~200 m deep) boreholes.

3. Field tests

Field tests of the system tend to be quite challenging because both electrical and mechanical performances of the entire system with all of its components are rated. For field tests, we selected water-filled boreholes with a depth of at least 100 m. Because of the faster thermal response in water, holes filled with a high water table are more suitable for T–D measurements. In water-filled sections, it takes less than 30 s for the probe to equilibrate. We also sampled the air-filled sections above the water table, but the results do not represent equilibrium temperatures due to the much longer time needed for the probe to equilibrate. Although there is no lower limit for the depth interval, we used 5 m intervals for air-filled sections, and 1 m or 5 m intervals for water-filled sections of a borehole. For a total depth of 300 m, the logging time is 1–3 h depending on the depth interval chosen.

The field results for a 115 m deep borehole in Çeşme/İzmir are shown in figure 6. This measurement was made by the two-wire measurement method. The overall behavior of the T–D curve shows the expected conditions of a thermally conductive borehole. At the $z = 0$ level,it shows the surface ground temperature and the annual temperature cycle almost diminishes within the first 5 m of the borehole. Below this depth, in the 5–40 m interval, a characteristic disturbance curve (deviations from the red line) of a long-term change in the surface temperature conditions are observed, which is interpreted as being the effect of climate change in this area. Below this interval, static geothermal conditions are observed towards the bottom of the borehole. By extrapolating the static curve (red line) towards the surface we observe that there is a significant calibration error in the measurements. That is, the annual surface temperature is 17°C–18 °C in this area while the T–D data extrapolates to about 20.5 °C at the surface. This is an expected problem if the cable resistances are not properly removed from the readings with the two-wire mode.

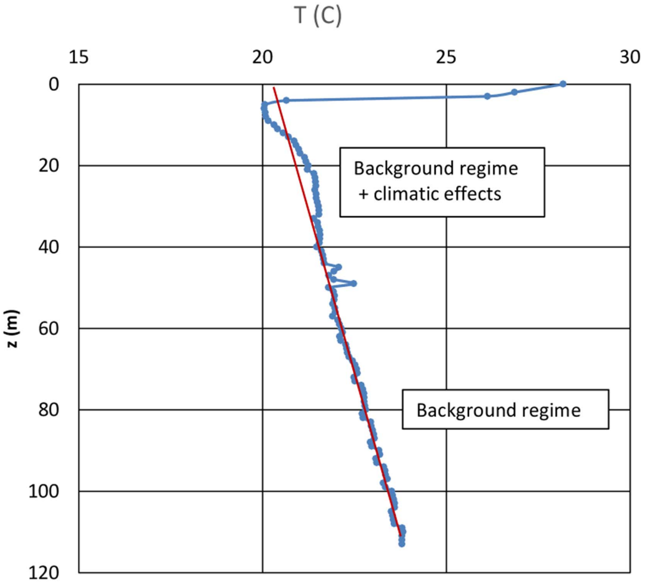

Figure 6. T–D curve obtained from a borehole in Çeşme/İzmir. This measurement was taken by a system with two-wire cable. The red curve shows the expected undisturbed geothermal gradient.

The results of the test in figure 6 shows that reliable T–D measurements are possible even with the use of a two-wire logging system. However, there is also a significant short-range deviation in temperatures that cannot be explained by thermal conditions in the borehole. For example, the spikes at depths of 45 m and 49 m, and discontinuities of magnitude ~0.1 °C in multiple depths below 50 m, are likely to be due to external effects. This noise is interpreted as being mostly due to the transient changes in cable resistance due to environmental effects (e.g. electromagnetic radiation in the air, magneto-telluric effects, and triboelectric effects on the cable) during the measurement. These small changes in the cable resistance were evident in the system during the measurement by the rapid fluctuations in resistance readings. These transient changes in resistance readings caused difficulties in the field in terms of recording the data, as well as monitoring the *in situ* thermal state of the borehole. Another disadvantage was not being able understand whether the probe had become stuck at some depth or had reached to the bottom of the hole because of fluctuating resistance readings.

Another T–D measurement made in a borehole in Salihli/Manisa is shown in figure 7. This measurement was made after the T–D tool had been modified to use the four-wire measurement method. When compared with the T–D log in figure 6 we observe that short-range fluctuations are significantly smaller. Also, as a result of removing the cable resistances, the T–D curve does not show calibration error as the undisturbed temperatures project to the expected surface temperatures in this area ($T = 17.5$ °C at $z = 0$ for the red line). Also in figure 7, a lithological and single-point resistance (SPR) log for this hole is shown on the left of the figure.

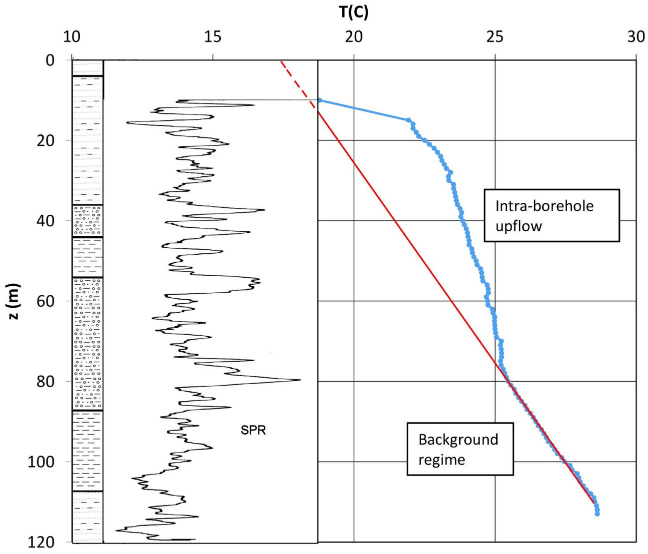

Figure 7. T–D data collected from a borehole in Salihli/Manisa. The measurement was made by the four-wire system. The red curve shows the background geothermal gradient. Other well data are shown for comparison on the left of the figure (lithology and SPR logs).

According to this, below ~80 m the borehole is clay dominated whereas above this there is a section of gravel. Gravel is expected to have high water permeability whereas clay is usually known to have very low permeability. When combined with the behavior of the T–D curve, we interpret that there is an intra-borehole upflow starting at 80–85 m up to the water table at ~15 m within the borehole. Below 80 m, T–D curves indicate a conductive (linear) gradient which is expected for the clay-dominated lithology.

The final stage of the field tests consists of comparing the new T–D system with a commercial one by using them at the same borehole. For this purpose, two previously logged boreholes, one in Manisa province and one in Usak province in Turkey were revisited, and new T–D data were collected with the new tool.

T–D data for comparison were collected previously as part of a research project (İlkışık *et al* 1996, 1997) in Turkey. The data acquisition was made by the General Directorate of Mineral Research and Exploration (MTA) of Turkey (Karlı *et al* 2006). The tool used by MTA is a ‘Mount Soupris’ brand commercial logging system. This tool also works in surface readout mode and prints depth and temperature information on a log paper during measurement. During the field study, the MTA team initially measured the depth of the well using a sinker; then, T–D data were collected from bottom to top. A more detailed discussion of the wider dataset with interpretations may be found in Erkan (2015).

T–D curves for Boyali (figure 8(a)) show a general agreement between the two tools in terms of obtaining the geothermal gradient of the borehole. The offset between T–D curves may be due to calibration differences between the tools. By comparison with the data from neighboring holes and the meteorological data in this area, Erkan (2015) argued that there may be a systematic positive shift for the temperatures in the MTA data. A second difference is the fluctuations in temperature with the MTA tool whereas relatively steady gradients are obtained with the new tool. We interpret the fluctuations as being due to the measurement strategy and not representing the true conditions within the borehole. As mentioned above, with the MTA tool the borehole was accessed twice prior to temperature logging which may have resulted in disturbance of the steady thermal conditions. With the new tool, logging was performed at the beginning from top to bottom to minimize thermal disturbances in the borehole (Blackwell and Spafford 1987). The disadvantage of this procedure is the ambiguity of the total depth information for the hole at the time of logging.

The T–D curves for the second hole (figure 8(b)) also shows similar characteristics, and the geothermal gradient of the hole is obtained properly by both tools. In particular, relatively lower gradients below 100 m in the hole were detected by both instruments. Excluding the small offset between two measurements, the difference in the top 50 m of the hole can be explained by the climate change between the measurement times. That is, a ground warming trend from 1996 to 2016 would be observed as curving of the T–D curve toward positive temperatures at depth, which is profound in the 2016 log.

4. Discussion

The field tests returned successful results for the present T–D logging system. The tests also show that the system is robust for working in a variety of field conditions. One of the obstacles experienced in the field was tangling of the logging cable when the probe became stuck at the rim of a borehole. Such a condition can be realized during the measurements by constant temperature readings despite increasing depth but with a loss of tension on the cable at the head. However, the tension drop on the cable may still not be noticed if probe gets stuck at great depths (e.g. more than 200 m). This condition is indistinguishable from the possibility that the probe has encountered an isothermal section. In such cases, it is inevitable that one will encounter tangling issues of the logging cable in the borehole. In old boreholes drilled for water production (e.g. drilled before the year 2000) we had several issues of tangling. Secondly, boreholes with historic issues during drilling (such as lost circulation of the drill mud) seem to have a greater chance of deformation at their rim and have greater potential for tangling issues with the T–D tool.

In order to keep the system in a good condition, electrical isolation for the whole of the logging cable must be maintained at all times. The tangling issues discussed above can cause electrical leakage between the conductors, so the system must regularly be tested for leakages. Possible leakages between wires can be checked in the system by measuring the resistances of different combinations of the terminals in figure 4. In the absence of a leakage the resistances shown in table 1 must be read between different terminals.

In a system where leakage occurs between any two wires the apparent resistances can be below the expected value. The

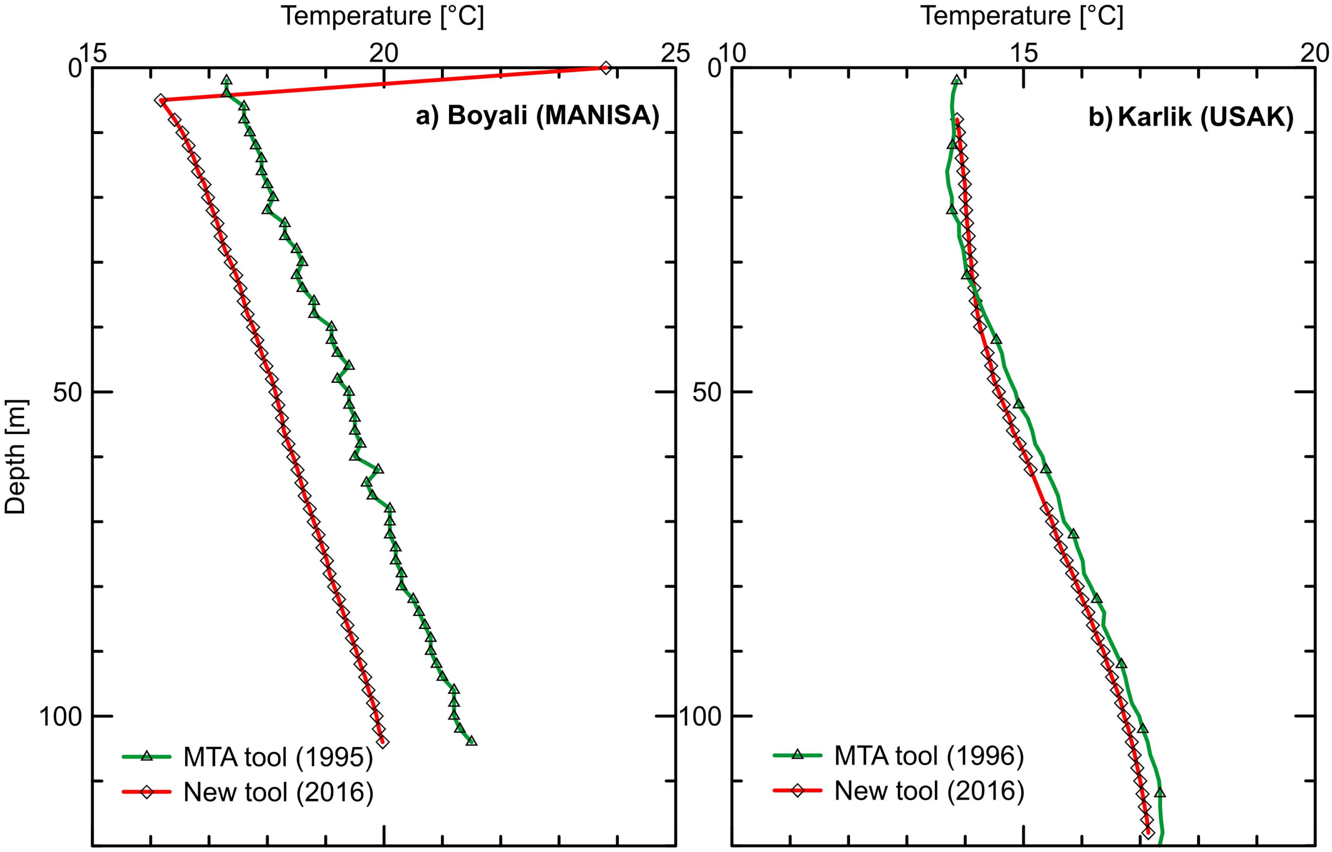

Figure 8. The comparison of a commercial tool (MTA tool) with the new T–D tool at selected boreholes in (a) Manisa and (b) Usak.

Table 1. Expected resistances between different terminals in the absence of inter-conductor leakage.

Terminals (see figure 4)	Expected resistance
T1–T2	$2R_c$
T1–T3	$R_s + 2R_c$
T1–T4	$R_s + 2R_c$
T2–T3	$R_s + 2R_c$
T2–T4	$R_s + 2R_c$
T3–T4	$2R_c$

amount of deviation would depend on the severity of a leakage. In the limiting case of contact between the wires the meter would zero resistance.

5. Conclusions

The T–D system designed and developed here uses a thermistor sensor and is capable of obtaining high-resolution borehole temperatures with depth. By using the four-wire resistance measurement method it is possible to remove the cable effects. The system works in surface readout mode which enables one to analyze the thermal conditions of the borehole during the measurement. The system is portable with an overall weight of about 25 kg, and allows easy access to most borehole sites. The fast thermal response of the thermistor also allows rapid measurements at boreholes less than 300 m deep.

Acknowledgments

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References

Beardsmore G R and Cull J P 2001 *Crustal Heat Flow, a Guide to Measurement and Modeling* (Cambridge: Cambridge University Press)

Blackwell D D and Spafford R E 1987 Experimental methods in continental heat flow *Methods Exp. Phys.* **24** 189–226

Chapman D S and Harris R N 1993 Repeat temperature measurements in borehole GC-1 northwestern Utah: towards isolating a climate change signal in borehole temperature profiles *Geophys. Res. Lett.* **20** 1891–4

Clow G D, Saltus R W and Waddington E D 1996 A new high-precision borehole-temperature logging system used at GISP2, and Taylor Dome, Antarctica *J. Glaciol.* **42** 576–84

Clow G D 2008 USGS polar temperature logging system, description and measurement uncertainties. *US Geological Survey Techniques and Methods* 2–E3 US Geological Survey

Erkan K 2015 Geothermal investigations in western Anatolia using equilibrium temperatures from shallow boreholes *Solid Earth* **6** 103–13

İlkışık O M *et al* 1996 Ege Bölgesi'nde ısı akısı araştırmaları, TÜBITAK Project No: YDABÇAG- 233/G (report in Turkish)

İlkışık O M, Yenigün H M, Şardar S, Oğuz S, Yalçın M N, Sar C, Okay N and Bayrak M 1997 Ege Bölgesi'nde jeotermak araştırmalar, TÜBITAK Project No: YDABÇAG- 430/G (report in Turkish)

Karlı R, Öztürk S and Destur M 2006 Türkiye ısı akısı projesi raporu *General Directorate of Mineral Research and Exploration (MTA) Report* 10937 Ankara (in Turkish)

Pollack H 1993 Climate change inferred from borehole temperatures *Glob. Planet. Change* **7** 173–9

Wisian K W, Blackwell D D, Bellani S, Henfling J A, Normann R A, Lysne P S, Förster A and Schrötter J 1998 Field comparison of conventional and new technology temperature logging systems *Geothermics* **27** 131–41