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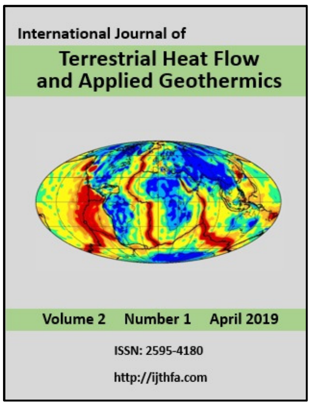

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The history of the surface temperature at Ajameti/Georgia as extracted from long-term temperature records in the subsurface

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Abstract

The transient temperature component was determined from long-term highly resolved temperature records in a borehole at Ajameti near Kutaisi in Western Georgia during the period between July 2017 and September 2018. Temperatures were recorded at depths of 100, 175 and 250 m with a resolution below the Millikelvin range and a recorded measurement frequency of 3 per hour, resulting in 72 individual measurements daily. At the depth of 100 m, a linear temperature increase of 0.0036 K/year was observed during those 15 months of measurement. At both larger depths, a precise linear trend could not be estimated. Additional impacts of water flow in the subsurface, penetrating from the surface or ascending from deeper layers during the time of measurements, superpose the transient component. The linear trend at 100 m can be understood as an increasing surface temperature at a rate of 0.015 K/year since 80 to 90 years. Two models agree with the data, i.e. a fast rise of the temperature as well as a continuous increase at a temperature diffusivity of $\kappa = 0.9*10^{-6}$ m²/s of the subsurface. The result coincides with the history of the Ajameti village which was founded in 1935, a period in which the settlement trees were probably cut to obtain a larger area of cultivated land, continuously increasing the surface temperature.

1. Introduction

Changes of the temperature at the Earth's surface penetrate into the subsurface superposing the steady temperature distribution which is caused by the heat flow from the Earth's interior with an exponentially decreasing amplitude and a depth depending phase shift. It can be estimated that the diurnal temperature variation reaches theoretically a depth of approximately 1.5 m with amplitude of 0.001 K. The seasonal variation penetrates down to 30 m with the same amplitude, if no additional effect like precipitation superposes the theoretical temperature field. Also temperature changes which are caused by deforestation, afforestation, urbanization or climate changes induce transient temperature components. These changes of the surface coverage cause also a difference between the temperature of the air and of the soil which has already been discussed since a long time when Kupffer (1829) concluded that the mean annual temperature of the air does not generally coincide with the soil temperature near the Earth's surface. The effect of growing vegetation to the subsurface temperature was discussed by Buntebarth et al. (2019 - this volume).

The study of the climate change has a long history and was reviewed e.g. by Weart (1998). It is revealed from tree-rings, pollen in ancient see sediments, coral reefs and so forth. In geothermics, an early study of the effect of temperature changes at the Earth's surface to the temperature of the subsurface has been presented by Čermák (1971). During the recent decades several works have been published to recover the surface temperature history by temperature logging in boreholes (e.g. Čermák et al. 1999, Hamza & Vieira 2011, Majorowicz 2002, Shen et al. 1995) or long-term measurements at shallow depths (e.g. Čermák et al. 2000). As a general result, the measurements reveal that a high geographical variety of the temperature history has been found which supports a constant surface temperature as well as a recent climate warming of 2 or more degrees per 100 years (Hamza & Vieira, 2011). Most of the geothermal results are based on temperature measurements in dependence on depth. The analysis of single or multiple temperature logs means that every temperature log is a snap-reading log which can include fast variations at depth. They can be caused by water flow induced by different impacts, e.g. seasonal precipitation which moves along faults and fractures, tectonic activity, hydrothermal water migration and usage of groundwater.

2. Study Area

The study area considered in this work is a sedimentary basin of the Caucasus intramontane and sub-montane depressions which are characterized by a simple structure with flat folded layers and steep faults. Exploratory drilling revealed at the region low-angle overthrusting and overlapping structures (Adamia et al., 1989). Ajameti borehole was drilled in the central part of West Georgia down to 1339 m. The Ajameti well penetrates in the uppermost 14 m a Quaternary Alluvial layer of gravels. Lithologic sequences of marl of Miocene age were encountered in the interval between the depth of 14 m and 300 m, and down to 520 m complex layering of clay, mergel and limestone of Eocene age occur. Below 520 m depth, a Lower Cretaceous limestone complex exists which is composed by massive dolomitized fractured and karstic limestones, similar to the main regional aquifer. The recharge area of this aquifer is located at quite high hypsometric elevations (1200-2200m above sea level) of the South Caucasian slope and its water impermeable roof is of Aptian-Cenomanian age which extends within a large area in Western Georgia (Tsertsvadze et al., 1998). The seismicity is weak in the region so that the tectonic activity is low.

3. Models of heat transport into the subsurface

Several earlier studies subjecting boundary conditions at the surface to solve the heat conduction equation were employed (e.g. Tautz, 1971). In this work, in order to evaluate the effects of changing surface temperature into the subsurface, a spontaneous temperature step and a continuous increase/decrease at Earth's surface temperature were applied as boundary conditions (Carslaw & Jaeger, 1959; Tautz, 1971). Both problems can be solved analytically.

A spontaneous temperature step can be presumed for example during both a deforestation and afforestation. One when a sudden temperature step occurs due to a cut down forest, allowing total solar energy reaching directly the free Earth's surface, and the other when cooling takes place due to the increasing absorption of solar energy by the leaf canopy, respectively. This pattern can also be presumed due to other human activities concerning to land usage. A continuous increase/decrease at Earth's surface temperature can be observed during a climate change. The heat conduction equations were solved for a half space of constant temperature with constant temperature diffusivity.

The solution of the heat conduction equation applying a temperature step as a boundary condition (Carslaw and Jaeger, 1959; Tautz, 1971) is expressed as:

$$T(z,t) = \pm T_0\left(1 - erf\left(\frac{z}{2\sqrt{(at)}}\right)\right) \tag{1}$$

Its temporal derivative is:

$$\left(\frac{\partial T}{\partial t}\right)_{z=const} = \pm T_0\frac{z}{2\sqrt{(\pi a t^3)}}exp\left(\frac{-z^2}{4at}\right) \tag{2}$$

Consider a climate change in which the temperature continuously increases or decreases at the Earth's surface at a rate of e.g. T_o= ±2 K within time interval 'k' of 100 years. Applying this boundary condition, the solution of the heat conduction equation (Tautz, 1971) is:

$$T(z,t) = \pm T_0\frac{z^2}{ka}\left[\left(\frac{at}{z^2}+\frac{1}{2}\right)erfc\left(\frac{z}{2\sqrt{(at)}}\right) - \frac{1}{\sqrt{(\pi)}}\sqrt{\left(\frac{at}{z^2}\right)}exp\left(\frac{-z^2}{4at}\right)\right] \tag{3}$$

Its temporal derivative is:

$$\left(\frac{\partial T}{\partial t}\right)_{z=const} = \pm T_0\frac{1}{k}erfc\left(\frac{z}{2\sqrt{(at)}}\right) \tag{4}$$

Applying Eq. (2) and Eq. (4), the fact is neglected that the meteorologically measured air temperature is possibly not equal to the geothermally determined surface temperature. It is presumed that the heat transfer coefficient (h) is very large as per Newton's cooling law:

$$-K\left(\frac{\partial T}{\partial z}\right)_{z=0} = h(T_{air} - T_0) \tag{5}$$

4. Methodology

The aim of this investigation has been to record the temperature with a resolution below the millikelvin range during a long time in order to decipher the impacts from superposed signals. For this propose, field measurements were carried out at a borehole at Ajameti, near Kutaisi in Western Georgia during the period between July 2017 and September 2018. The selected borehole reaches a depth of 1339 m and has a diameter of 14.6 cm. Temperature were recorded at depths of 100, 175 and 250 m. The recorded measurement rate was 3 per hour, resulting in 72 individual daily measurements.

For the temperature measurement the LogBox microT temperature recording equipment of geotec-instruments was installed in the well. LogBox microT is a high precision thermometer with a resolution of 0.0002 K. The instrument is protected by a metallic hut which has a size of a few square meters and a height of 2 m. The three individually calibrated temperature sensors are protected in waterproof stainless-steel housing. The precipitation was determined on the basis of records at the meteorological station of Kutaisi which is ca. 20 km distant from the study area.

5. Results

Instead of incremental temperature log, the measurements were carried out during a long time at several depths and the temporal derivative of the temperature determined. The advantage of this method is that high frequency temperature variations are excluded, and the steady heat flow component needs not be determined. The disadvantage is that only a few depths can be considered. However, the sensors can be placed at depths below 150 m at which temperature logging cannot resolve the transient component (Hamza & Vieira 2011). Environmental parameters i.e. surface temperature and precipitation are also taken into account.

The temperature of the device is close to the surface temperature. Fast variations, however, undergo damping effects, so that the diurnal surface variations might differ slightly. Based on the calculated impacts from superposed signals, six diagrams were plotted. The daily mean values are displayed at Figures 1 and 2.

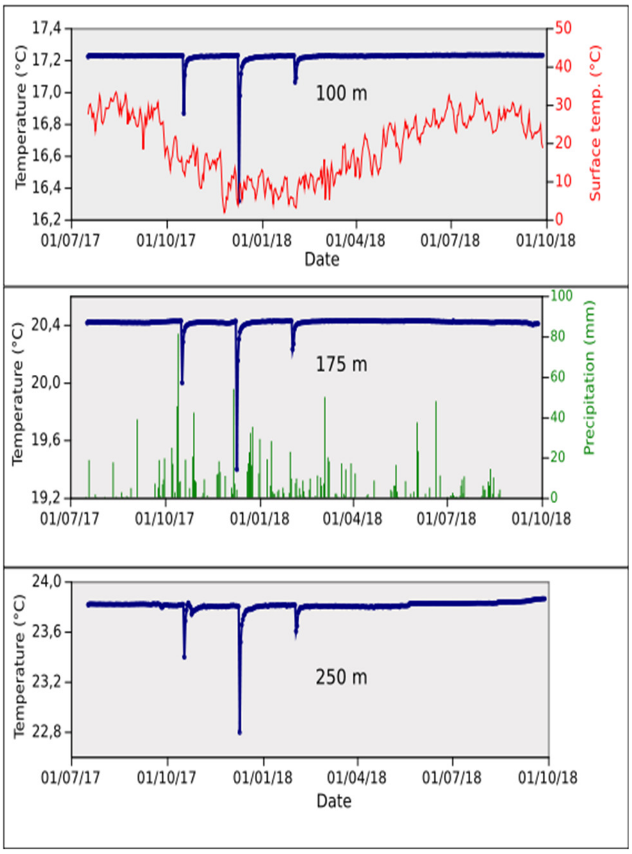

Figure 1 - The temperature records as daily average at Ajameti/Georgia at several depths as well as the surface temperature and the regional precipitation from July 2017 until September 2018 (Jimsheladze et al. 2019).

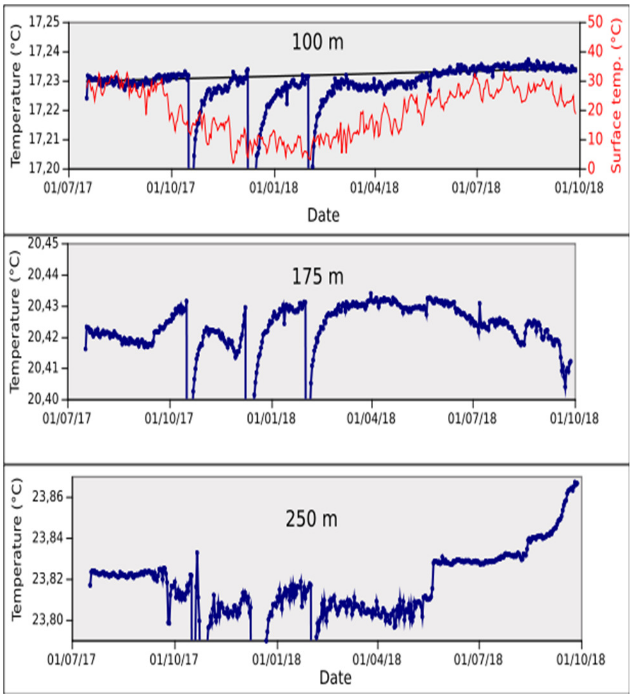

Figure 2 - Temperature records as daily mean values at Ajameti/Georgia at several depths as well as the surface temperature from July 2017 until September 2018. A linear trend is estimated at depth of 100 m.

The temperature variations reveal that several notable changes occurred during the time of registration which are related to strong rainfalls. The curvature of recovery signal demonstrates that much time is necessary to reach again the temperature equilibrium with the surrounding rocks. Differences might occur between the rainfall at Kutaisi and that at the location of the well. This fact does not allow the quantification of this impact. Nevertheless, Figure 1 shows the coincidence between the recorded temperature and the precipitation.

Very heavy rain waters probably invaded directly from the surface to depths in the borehole. Because of its lower temperature and the increased hydrostatic pressure, the water moves down within the borehole. Table 1 shows further details. Even though the borehole was cased down to 460 m, hydraulic connections can be perceived between the surface and 100 m depth as well as between 100 m and 175 m. Meteoric water can flow directly into the borehole at these depth intervals, probably along fractures. The temperature drop is higher at 175 m. This anomaly hardly decreases down to 250 m. A further peculiarity appeared end of May 2018 when the temperature rose more or less suddenly by 0.02 K at 250 m.

Table 1 - Maximum Temperature decrease within the borehole during strong rainfall.

Depth (m)	16. Oct. 2017 ΔT (K)	8. Dec. 2017 ΔT (K)	1. Feb. 2018 ΔT (K)
100	1.0	1.3	0.6
175	1.3	1.3	0.8
250	1.1	1.2	0.8

The temperature gradient between the sensors is determined and shown in Figure 3. It is calculated from daily mean values. The curvature of the interval between 175 m and 250 m indicates an increase of the gradient, whereas the gradient decreases between 100 m and 175 m. The average results indicate a net increase, because the decrease in the upper interval is smaller.

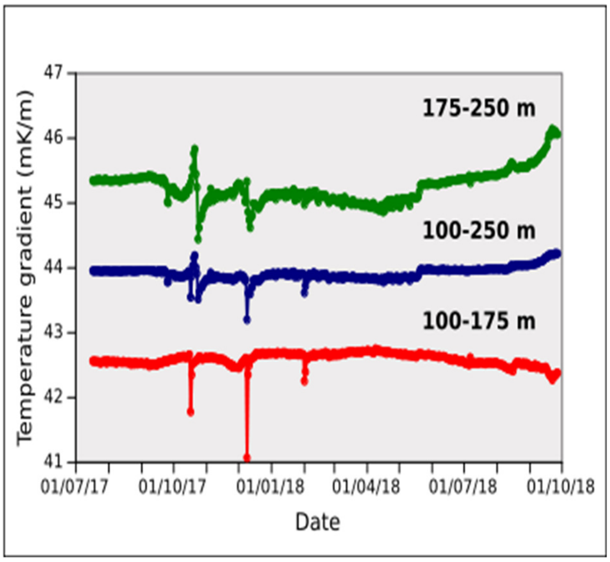

Figure 3 - Daily average of the temperature gradient between the temperature sensors, red: upper interval, green: lower interval and blue: average.

Figure 4 displays the individual measurements and shows that a continuous increase occurred which lasts for 1.5 days. This rise happened also at 175 m with half of the amount and during half of the time after a preceding drop. An additional excursion of ca. 0.001 K can be realized at 250 m on 20th May which is documented by 7 individual measurements and persists, therefore, only 2 hours.

Applying Eq.2, an event can be assumed which occurred between 60 and 130 years ago depending on the presumed parameters of the model (Figure 5). If deforestation is the reason of the sudden increase of the surface temperature, a change of 1.5 K or 2 K is realistic (Čermák, 1971; Buntebarth et al., 2019 - this volume). The elapsed time depends on the temperature diffusivity. If a value of thermal diffusivity (κ) of $1.0*10^{-6}$ m²/s is assumed, the time interval ranges from 60 to 125 years. The low value of κ of $0.8*10^{-6}$ m²/s yields an elapsed time between 90 to 130 years.

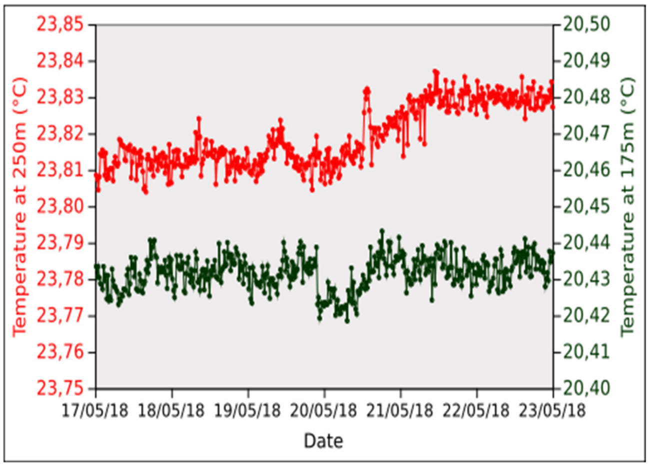

Figure 4 - Individual measurements at depths of 175 m (in red color) and 250 m (in green color) during the second half of May 2018.

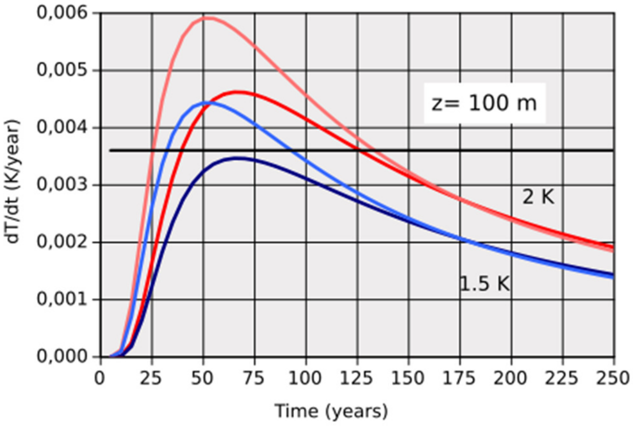

Figure 5 - The temperature changes in dependence on the elapsed time at the depth of 100 m after a temperature step of 1.5 K (blue) and 2 K (red). The curve in orange color represents the case for a temperature diffusivity κ of $1.0*10^{-6}$ m²/s and the curve in dark blue color for κ of $0.,8*10^{-6}$ m²/s. The black line shows the present trend of the temperature variation at depth of 100 m.

Applying equation (4) a continuous temperature increase of the surface temperature is assumed which is ongoing since 60 or more than 250 years (Figure 6), depending on the transient temperature of 0.01 K/year, 0.015 K/year or 0.02 K/year as well as on the temperature diffusivity. At the slow temperature increase at the surface of 0.01 K/year, the present determined temperature increase coincides with an elapsed time between 170 years and more than 250 years, if the temperature diffusivity ranges from κ= $0.8*10^{-6}$ m²/s to $1.0*10^{-6}$ m²/s. The slightly increased rate of warming of 0.015 K/year yields elapsed times of 80 to 120 years. The maximum warming up of 0.02 K/year explains an ongoing process since 65 to 85 years.

6. Discussion and Conclusions

Considering all models, a realistic estimation is that a temperature increase of ca. 1.5 K can be realized since about 100 years. More precise temperature diffusivity could distinguish whether a temperature step or a continuous increase coincides with the recorded temperatures.

On the other hand, 100 years is a short time what allows to consider the history of the near settlement. Ajameti is mentioned for the first time in the second half of the 11th century as a place for hunting, where the winter was warm and the summer very hot. The village has been founded in 1935 and people settled near the well ca. 80 to 90 years ago. The assumption is realistic that the people needed cropland and continuously cut the forest, a process which outlasted for years.

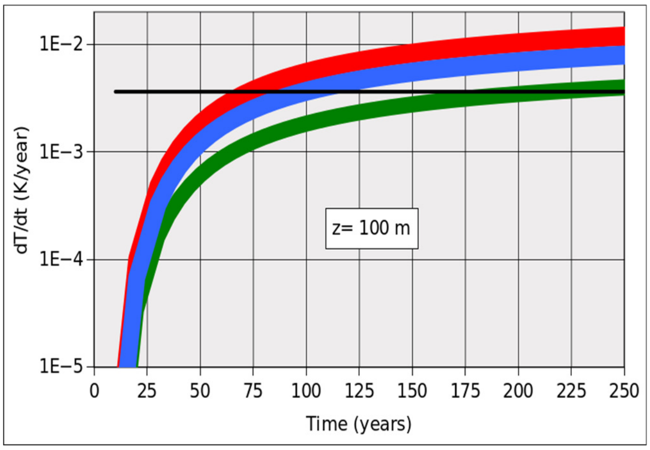

Figure 6 - The temperature changes in dependence on the elapsed time at the depth of 100 m after a continuous temperature change of 0.01 K/year (green), 0.015 K/year (blue) and 0.02 K/year (red). The band width represents an interval of the temperature diffusivity κ between $0.8*10^{-6}$ m²/s and $1.0*10^{-6}$ m²/s. The black line shows the present trend of the temperature variation at depth of 100 m.

Taking in consideration these facts for understanding the model calculations, the ambiguity of possible results can be narrowed down. The step change of temperature as well as its continuous rise coincide with the temperature change of 0.0036 K/year at the depth of 100 m, if a surface temperature increase of 1.5 K started 80 to 90 years ago and outlasted for decades. The Figures 5 and 6 demonstrate that an average temperature diffusivity κ of $0.9*10^{-6}$ m²/s agrees with these assumptions.

In order to distinguish between both models, the knowledge of the heat transfer coefficient is necessary. The heat flows from greater depth through the surface and this heat flow is proportional to the temperature difference at the surface as per equation (5). The temperature difference at the earth's surface depends not only on time, e.g. the diurnal and seasonal variation, but also on the land usage, the type of vegetation and on meteorological components. When temperature logging is applied, the temperature depth function can be influenced at shallow depths according to equation (5), if the heat transfer coefficient h is not very large. Depending on the surface temperature difference and a realistic value of h, the heat flow from the earth‘s interior can be reduced or even heat flows into the subsurface. The value of h varies at air between 10 and 100 W/m²K which is far away from a very large value. If a temperature difference occurs, the terrestrial heat flow density from the Earth’s interior amounts a few percent of the heat flow passing the surface.

As a consequence, the temperature difference in equation (5), may cool down the uppermost surface layer or warm it up. The surface albedo determines the amount of solar energy which reaches the Earth’s surface (e.g. Buntebarth et al., 2019 - this volume) and therefore, the albedo influences the temperature difference in equation (5). A surface which is free of forest absorbs directly the solar energy and change its temperature which penetrate into the subsurface. A change in the air temperature, however, does not change immediately the surface temperature at the same proportion, because the heat transfer coefficient between air and solid is limited and for this reason the heat transfer from the air into the subsurface is damped and delayed. The determination of the heat transfer coefficient is necessary for establishing a model of climate change. The impacts of vegetation which can be caused by e.g. deforestation, afforestation or urbanization are also reflected in subsurface temperature variations and superpose a possible effect of climate change at shallow depths.

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