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THE MAXIMUM EFFECT OF DEEP LAKES ON TEMPERATURE PROFILES – DETERMINATION OF THE GEOTHERMAL GRADIENT

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ABSTRACT

Understanding the climate change processes on the basis of geothermal observations in boreholes is an important and at the same time high-intricate problem. Many non-climatic effects could cause changes in ground surface temperatures. In this study we investigate the effects of deep lakes on the borehole temperature profiles observed within or in the vicinity of the lakes. We propose a method based on utilization of Laplace equation with nonuniform boundary conditions. The proposed method makes possible to estimate the maximum effect of deep lakes (here the term "deep lake" means that long term mean annual temperature of bottom sediments can be considered as a constant value) on the borehole temperature profiles. This method also allows one to estimate an accuracy of the determination of the geothermal gradient.

Key words: Geothermal gradient, Reduced temperature, Laplace equation, Lake

RESUMEN

El entendimiento de los procesos de cambio climático basado en las observaciones geotérmicas en pozos es importante y a la vez un problema intrincadamente complejo. Muchos efectos no climáticos podrían causar cambios en las temperaturas de la superficie terrestre. En este estudio investigamos el efecto de los lagos profundos sobre los perfiles de temperatura registrados en pozos, al interior o en las inmediaciones de los lagos. Proponemos un método basado en el uso de la ecuación de Laplace con condiciones de frontera no uniforme. El método hace posible estimar el máximo efecto de los lagos profundos (el término "lago profundo" significa que

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la temperatura media anual de los sedimentos del fondo, evaluada sobre un largo período, puede ser considerada como un valor constante) sobre los perfiles de temperatura en los pozos. Este método también permite estimar la precisión en la determinación del gradiente geotérmico.

Palabras clave: gradiente Geotérmico, temperatura Reducida, ecuación Laplace, Lago.

I. Introduction

At present many efforts are made to determine the trends in ground surface temperature history (GSTH) from geothermal surveys. In this case accurate subsurface temperature measurements are needed to solve this inverse problem – estimation of the unknown time dependent ground surface temperature (GST). The variations of the GST during the long term climate changes resulted in disturbance (anomalies) of the temperature field of geological formations. Thus, the GSTH data could be evaluated by analyzing the present precise temperature-depth profiles. The effect of surface temperature variations in the past on the temperature field of formations is widely discussed in the literature (e.g., Lachenbruch and Marshall, 1986; Beltrami et al., 1992; Shen and Beck, 1992; Bodri and Cermak, 1995; Harris and Chapman, 1995; Huang et al., 1996; Guillou-Frottier et al., 1998; Huang and Pollack, 1998; Huang et al., 2000; Pollack and Huang, 2000; Majorowicz and Safanda, 2005; Eppelbaum et al., 2006; Hamza et al., 2007; Hopcroft et al., 2007; Rath and Mottaghy, 2007; Gonz´alez-Rouco et al., 2008; Kooi, 2008).

II. Previous investigations: Some research background

Earlier the forward calculation approach (FCA) was used for the analysis and interpretation of borehole temperatures in terms of the GSTH (Eppelbaum et al., 2006). Three groups based on the geographical proximity were formed. Fifteen borehole temperature profiles from Europe (5), Asia (4) and North America (6) were selected (Huang and Pollack, 1998; www.geo.lsa.umich.edu/~climate). The objective of this study was the estimation of the warming rates in the 20th century by the FCA method and comparing with those obtained by the few parameter estimation (FPE) technique (Huang et al., 1996; Huang and Pollack, 1998). It was reasonable to assume that for close spaced boreholes, the values of the warming rates obtained by the two inversion methods, should vary in narrow limits. The results of inversions (FCA) have shown that for boreholes in North America the current warming rates vary in the 0.41- 2.45 K/100a range. The wide range for the warming rate of 0.33-2.48 K/100a was also determined for boreholes in Europe. Interesting results were obtained for four boreholes in Asia (China) (Eppelbaum et al., 2006). In this case the warming rate varies in relatively narrow limits (1.16-1.59 K/100a.). The warming rate estimated by the FPE technique (Huang and Pollack, 1998) varied in wide ranges: 0.38-2.49 K/100a (North America); 0.21-3.75 K/100a (Europe), and 0.30-2.53 K/100a (Asia). Thus, we can conclude that for boreholes in North America and Europe both approaches provide practically the same ranges of warming rates. For Asian boreholes the FCA approach gives a more consistent (narrow) range of warming rates (1.16-1.59 K/100a).

The results of temperature inversion by both techniques indicate that probably some of non-climatic effects (vertical and horizontal water flows, steep topography, lakes, vertical variation in heat flow, lateral thermal conductivity contrasts, thermal conductivity anisotropy, deforestation, forest fires, mining, wetland drainage, agricultural development, urbanization, *etc*.) may have perturbed the borehole temperature profiles. Influence of these factors has been studying by many authors (e.g., Carslaw and Jaeger, 1959; Lachenbruch, 1965; Kappelmeyer and Haenel, 1974; Blackwell et al., 1980; Majorowicz and Skinner, 1997; Guillou-Frottier et al., 1998; Lewis and Wang, 1998; Kohl, 1999; Safanda, 1999; Pollack and Huang, 2000; Cermak and Bodri, 2001; Gosselin and Mareschal, 2003; Gruber et al., 2004; Bodri and Cermak, 2005; Mottaghy et al., 2005; Nitoiu and Beltrami, 2005; Allen et al., 2006; Taniguchi, 2006; Chouinard and Mareschal, 2007; Hamza et al., 2007; Safanda et al., 2007). At the same time exact calculation of all these factors is a complex physical-mathematical problem, which obviously will be completely solved in a future by the method of successive approximations.

The temperature regime of sedimentary formations is influenced by many environmental and geological factors (local relief, sedimentation, erosion, lateral conductivity contrasts, underground water movement), past climate, and by the heat flow from the Earth's interior – terrestrial heat flow. Most of temperature surveys are conducted in boreholes. In many cases the drilling sites of boreholes are located within or outside of deep lakes (we employ the term "deep lake" to designate that long term mean annual temperature of bottom sediments could be considered as a constant value). The objective of this study is to evaluate to what extent the proximity of deep lakes can affect the temperature profiles of wellbores. In 1974 Balobayev and Shastkevich published results of their analytical study which can be used to determine the configuration of the steady temperature field of formations beneath the lakes of an arbitrary contour (Balobayev and Shastkevich, 1974). Taking into account that this publication is not easily accessible to researchers, we present below a brief summation of the results of this study (Balobayev and Shastkevich, 1974). Authors assumed that the lake existed for an infinitely long period of time. In this case the solution of Laplace equation with non-uniform boundary conditions can be used to describe the steady temperature field of formations beneath the lakes and estimate the maximum effect (due to assumption that the lake existed for an infinitely long period of time) of lakes on borehole temperature profiles.

III. Climate reconstruction methods: Some typical disturbances and restrictions

We should note that all climate reconstruction methods are based on one-dimensional heat conduction equation. It is assumed that a uniform boundary condition is applied on a plane surface, the formation is a laterally homogeneous medium, and the thermal properties can depend only on a depth. For this reasons any subsurface temperature variations arising from conditions that depart from that theoretical model have the potential to be incorrectly interpreted as a climate change signature (Pollack and Huang, 2000). To demonstrate the well selection procedures we briefly present two examples. In the study conducted by Guillou-Frottier et al. (1998), only 10 from 57 temperature profiles were selected for inversion of past ground surface temperatures. As was mentioned by Nitoiu and Beltrami (2005) from over 10,000 borehole temperature logs worldwide (The International Heat Flow Commission global geothermal data set), only about 10% of these data are currently used for climate studies because a number of known non-climatic energy perturbations are superimposed on the climatic signal.

Therefore, an extreme caution should be used in selection of temperature-depth profiles for inferring the ground surface temperature histories.

The following criteria were considered in rejecting boreholes from the study: steep topography, proximity of lakes, water circulation, instrumental problems, other identifiable terrain effects (such as heat refraction, permafrost effects), and recent changes in surface conditions (clearing of trees). For most of the boreholes that were discarded, the shallowest part of the temperature profile is perturbed. As was mentioned by co-authors these perturbations are often similar to the perturbations due to changes in surface temperature. If the terrain conditions had not been considered, warming would have been inferred for 25 boreholes. Ten boreholes show apparent cooling, and only one shows no difference. To screen out borehole temperature data from Eastern Brazil with indications of possible perturbations arising from non-climatic effects, the following quality assurance conditions (we basically agree with these criteria) were imposed (Hamza et al., 2007):

1. The borehole is sufficiently deep that the lower section of the temperature-depth profile allows a reliable determination of the geothermal gradient, presumably free of the effects of recent climate changes. Order of magnitude calculations indicate that surface temperature changes of the last centuries would penetrate to depths of nearly 150 m,
2. The time elapsed between cessation of drilling and the temperature log is at least an order of magnitude large compared to the duration of drilling,
3. The temperature-depth profile is free from the presence of any significant non-linear features in the bottom parts of the borehole, usually indicative of advection heat transfer by fluid movements, either in the surrounding formation or in the borehole itself,
4. The elevation changes at the site and in the vicinity of the borehole are relatively small so that the topographic perturbation of the subsurface temperature field at shallow depths is not significant,

   and
5. The lithologic sequences encountered in the borehole, have relatively uniform thermal properties, and are of sufficiently large thickness that the gradient changes related to variations in thermal properties do not lead to systematic errors in the procedure employed for extracting the climate related signal.

Out of a total of 129 temperature logs only 17 were found to satisfy the above set of quality assurance conditions (Hamza et al., 2007). Corrections can be applied, for example, to correct borehole temperature profiles for the effect of topography (Lachenbruch, 1965; Blackwell et al., 1980; Safanda, 1994, 1999). However, this is rarely done because the amplitude of the climatic signals is often smaller than the uncertainty on these corrections (Chouinard and Mareschal, 2007). Safanda et al. (2007) presented interesting results of repeated temperature logs from Czech, Slovenian and Portuguese borehole climate observatories within a time span of 8-20 years. The repeated logs revealed subsurface warming in all the boreholes amounting to 0.2-0.6 °C below 20 m depth. The warming rate of 0.05 °C/yr. at the Czech observatory (located in a park within the campus of the Geophysical Institute in Prague) was estimated. This warming rate is two times more than the simulated value (using the surface air temperature as a forcing function). It was assumed that subsurface temperature at the station is influenced by new structure built within the campus of the Geophysical Institute within the last 10-20 years and/or by other components of infrastructure built 40-50 years ago. The authors (Safanda et al., 2007) conducted a quantitative analysis of these effects by solving numerically the heat conduction equation in a 3D geothermal model of the borehole site. It was found out that the mentioned anthropogenic structures influence the temperature in the borehole quite strongly.

Nitoiu and Beltrami (2005) attempted to correct borehole temperature data for the effects of deforestation. The authors simulated the ground surface temperature changes following deforestation by using a combined power exponential function describing the organic matter decay and recovery of the forest floor after a clear-cut (Covington, 1981). The presented examples demonstrate that application of this correction could allow incorporate many borehole data into the borehole climatology database (Nitoiu and Beltrami, 2005).

IV. Working equations

Let's assume that the well site is located within or outside of a deep lake. As it was mentioned above, we consider the long-term mean annual temperature of bottom sediments as a constant value (for the first time this problem was shortly outlined in Balobaev et al. (2008)). We will assume that $z = 0$ is the vertical coordinate of the lake's bottom. The temperature regime of geological formations in this area (within and outside of the lake) is subjected to the thermal influence of the lake. The extent of this influence depends mainly on the lake's dimensions, on the current depth, the distance from the lake, and on the difference between the long term mean annual temperature of bottom sediments and the long term mean annual temperature of surrounding lake formations (at $z = 0$). We will assume that the lake existed for an infinitely long period of time. The following designations will be used below:

ρ, φ, z are cylindrical coordinates (ρ is the distance from the z axis, φ describes the angle from the positive xz-plane to the point, and z is depth); T_{is} is the long term mean annual temperature of bottom sediments; and T_{ot} is the long term mean annual temperature of surrounding lake formations at $z = 0$. Firstly, let consider a lake of an arbitrary contour (Figure 1).

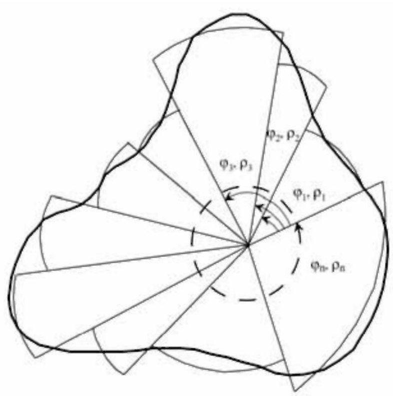

Figure 1. Division of an arbitrary contour lake into sectors (after Balobayev and Shastkevich, 1974).

The Laplace equation for the semi-infinite solid area is

$$\frac{\partial^2 T}{\partial \rho^2} + \frac{1}{r}\frac{\partial T}{\partial \rho} + \frac{1}{\rho^2}\frac{\partial^2 T}{\partial \varphi^2} + \frac{\partial^2 T}{\partial z^2} = 0 \qquad (1)$$

The boundary conditions are

$T(\rho, \varphi, z = 0) = T_{is}$ within the lake area.
$T(\rho, \varphi, z = 0) = T_{ot}$ outside the lake area
$T(\rho = \infty, \varphi, z) = T_{ot} + \Gamma z$

where Γ is the regional (outside the lake area) geothermal gradient.

The solution of Laplace equation is possible by division of an arbitrary contour lake into sectors. However, the solution is expressed through a complex Poisson integral and fairly elaborate and time-consuming computations are needed (Balo- bayev and Shastkevich, 1974). Let's ρ_{max} be the maximum value of the set $\rho_1, \rho_2, \ldots, \rho_n$. By introducing a safety factor (the maximum thermal effect of the lake on temperature profiles) we can assume that the lake has a circular shape with a radius $R_i = \rho_{max}$. Now the Laplace equation and boundary conditions are

$$\frac{\partial^2 T}{\partial \rho^2} + \frac{1}{r}\frac{\partial T}{\partial \rho} + \frac{\partial^2 T}{\partial z^2} = 0 \qquad (2)$$

$T(\rho, z = 0) = T_{is} \quad \rho \le R_i$
$T(\rho, \text{öz} = 0) = T_{ot} \quad \rho \text{ £ } R_i$
$T(\rho = \infty, z) = T_{ot} + \Gamma z$

The solution eq. (2) is (Balobayev and Shastkevich, 1974):

$$T(\rho, z) = T_{ot} + \Gamma z + M(T_{is} - T_{ot} \qquad (3)$$

$$M(p,z) = 1 - A_1[A_2 \Pi(\alpha_1^2, k) + A_3 \Pi(\alpha_2^2, k)] \qquad (4)$$

$$A_1 = \frac{z}{\pi\sqrt{z^2 + (R_i + \rho)^2}}; \quad A_2 = \frac{\sqrt{z^2 + \rho^2} - R_i}{\sqrt{z^2 + \rho^2} + \rho} \qquad (5)$$

$$A_3 = \frac{\sqrt{z^2 + \rho^2} + R_i}{\sqrt{z^2 + \rho^2} + \rho}; \quad \alpha_1^2 = \frac{2\rho}{r + \rho}; \quad \alpha_2^2 = \frac{2\rho}{r - \rho} \qquad (6)$$

$$r^2 = \rho^2 + z^2; \quad k^2 = \frac{4\rho R_i}{z^2 + (R_i + \rho)^2} \qquad (7)$$

where $\Pi(\alpha_1^2, k)$ and $\Pi(\alpha_2^2, k)$ are the complete elliptical integrals of the third order (Abramowitz and Stegun, 1965).

For the center of the island ($\rho = 0$)

$$M(z) = 1 - \frac{z}{\sqrt{z^2 + R_i^2}} \qquad (8)$$

The temperature gradient for the well drilled at the center of the lake ($\rho = 0$) can be determined from eqs. (3) and (8).

$$\Gamma^* = \frac{\partial T(0,z)}{\partial z} = \Gamma - (T_{is} - T_{ot}) \left[\frac{R_i^2}{(z^2 + R_i^2)^{3/2}} \right] \quad (9)$$

$$\Delta\Gamma = \Gamma^* - \Gamma = -(T_{is} - T_{ot}) \left| \frac{R_i^2}{(z^2 + R_i^2)^{3/2}} \right| \quad (10)$$

For distances $\rho > 0$ from eq. (3) we obtain

$$\Gamma^* = \frac{dT(\rho,z)}{dz} = \Gamma + (T_{is} - T_{ot}) \frac{dM}{dz} \quad (11)$$

or

$$\Delta\Gamma = \Gamma^* - \Gamma = (T_{is} - T_{ot}) \cdot \frac{dM}{dz} \quad (12)$$

Introducing the reduced temperatures, $T_R(\rho, z)$ from eq. (3), we can write

$$T_R(\rho,z) = T(\rho,z) - T_{ot} - \Gamma z = M(T_{is} - T_{ot}) \quad (13)$$

V. Example of calculations

Let's consider a 30 m deep lake with a radius of R_i = 100 m and T_{is} = 10 °C. The regional geothermal gradient is Γ = 0.0300 °C/m and T_{ot} = 20 °C. The drilling site of a 3000m wellbore is located at a distance of 150m from the center of the lake (Table 1).

Table 1. The functions dM(z,0)/dz and M(z, ρ)

z, m	-d*M*/dz, 10^{-6} 1/m, ρ = 0	The function $M(z, \rho)$ — Distance from the center of the lake (ρ), m						
		0	50	100	150	200	300	400
20	9429	.8039	.7612	.3828	.0525	.0168	.0042	.0017
50	7155	.5528	.4937	.2815	.0950	.0370	.0100	.0091
100	3536	.2929	.2606	.1787	.0985	.0518	.0174	.0076
150	1707	.1679	.1538	.1189	.0805	.0512	.0212	.0101
200	894.4	.1056	.0991	.0827	.0628	.0450	.0222	.0116
250	512.3	.0715	.0683	.0598	.0488	.0379	.0215	.0122
300	316.2	.0513	.0496	.0449	.0384	.0315	.0198	.0122
400	142.7	.0299	.0292	.0275	.0249	.0219	.0159	.0111
500	75.43	.0194	.0119	.0184	.0172	.0157	.0125	.0095
600	44.43	.0136	.0135	.0131	.0125	.0117	.0099	.0080
700	28.28	.0100	.0100	.0098	.0094	.0090	.0079	.0066
800	19.08	.0077	.0077	.0076	.0073	.0071	.0064	.0056
900	13.47	.0061	.0061	.0060	.0059	.0057	.0052	.0047
1000	9.852	.0050	.0049	.0049	.0048	.0047	.0044	.0040
1100	7.421	.0041	.0041	.0041	.0040	.0039	.0037	.0034
1200	5.727	.0034	.0034	.0034	.0034	.0033	.0032	.0030
1400	3.617	.0025	.0025	.0025	.0025	.0025	.0024	.0023
1600	2.427	.0019	.0019	.0019	.0019	.0019	.0018	.0018
1800	1.707	.0015	.0015	.0015	.0015	.0015	.0015	.0014
2000	1.245	.0012	.0012	.0012	.0012	.0012	.0012	.0012
2200	.9362	.0010	.0010	.0010	.0010	.0010	.0010	.0010
2400	.7215	.0009	.0009	.0009	.0009	.0009	.0008	.0008
2600	.5677	.0007	.0007	.0007	.0007	.0007	.0007	.0007
2800	.4547	.0006	.0006	.0006	.0006	.0006	.0006	.0006
3000	.3698	.0006	.0006	.0006	.0006	.0006	.0006	.0005

What are the magnitudes of the formation temperature perturbations (expressed through the reduced temperatures) caused by the lake? The results of calculations after eqs. (4) and (8) are presented in Table 1 and Figure 2. We have to note that bottom of the lake has a coordinate $z = 0$ and because of this the actual depth is $z^* = z + 30$ m. In our case $T_{is} - T_{ot} = -10$ °C and the lake has a cooling effect on the temperature profiles. The values of $T_R(\rho, z)$ are decreasing with depth and practically can be neglected for radial distances of 550-600 m from the center of the lake (Figure 2).

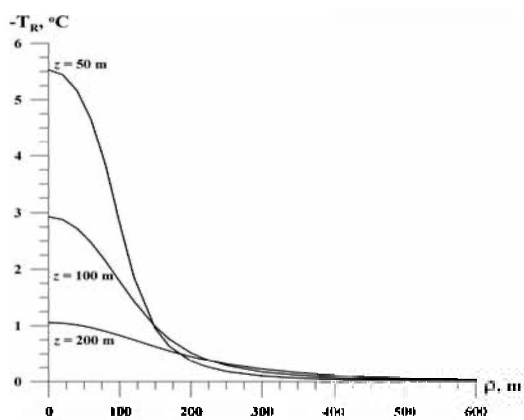

Figure 2. The reduced temperatures versus radial distance for three depths.

Let's now assume that we have to determine the maximum values of $T_R(\rho, z)$ and $\tilde{A}\Gamma(\rho, z)$ for the 300-500 m section of the wellbore. The values of $T_R(\rho, z)$ can be estimated directly from eq. (13) and Table 1:

$$T_R(150{,}300) = -10^{\circ}\mathrm{C}\cdot 0.0384 = -0.384\ ^{\circ}\mathrm{C};$$
$$T_R(150{,}500) = -10^{\circ}\mathrm{C}\cdot 0.0172 = -0.172\ ^{\circ}\mathrm{C}$$

To determine the values of $\Delta\Gamma(\rho, z)$ for this case we suggest to approximate the function M by a quadratic polynomial (Table 2, eq. (14)).

$$M^* = a_0 + a_1 z + a_2 z^2 \qquad (14)$$

$$\frac{dM^*}{dz} = a_1 + 2a_2 z \qquad (15)$$

$$a_0 = 0.1126 \qquad a_1 = -0.3341\cdot 10^{-3} \qquad a_2 = 0.2872\cdot 10^{-6}$$

Then the values of $\Delta\Gamma(\rho, z)$ can be determined from eqs. (12) and (15):

$$\Delta\Gamma(150{,}300) = 1{,}6174\bullet 10^{-3}\ ^{\circ}\mathrm{C/m};$$
$$\Delta\Gamma(150{,}500) = 0.4684\bullet 10^{-3}\ ^{\circ}\mathrm{C/m}$$

For the 300-500m section of the well the values of $T_R(\rho, z)$ and $\Delta\Gamma(\rho, z)$ are presented in Figure 3. In our example the value of the regional geothermal gradient (Γ) is 0.03 °C/m. Thus, the accuracy of the determined geothermal gradient is somewhere between

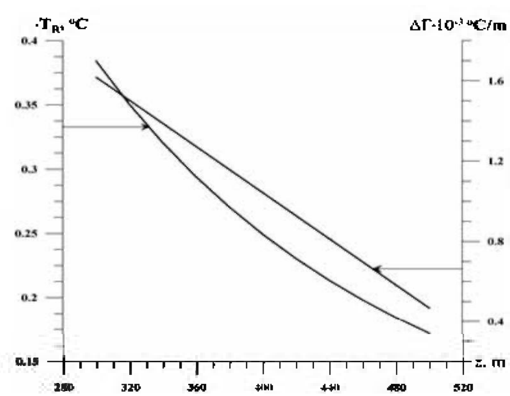

Figure 3. The reduced temperature and the value of $\Delta\Gamma$ versus depth for $\rho = 150$ m.

Table 2. The approximation of the function *M* by a quadratic polynomial (eq. (14))

z, m	*M*	*M**	*(M- M*)/M ·100, %*
300	0.03842	0.03822	0.51
320	0.03505	0.03510	-0.15
340	0.03207	0.03221	-0.45
360	0.02941	0.02955	-0.49
380	0.02705	0.02712	-0.27
400	0.02494	0.02492	0.07
420	0.02304	0.02295	0.38
440	0.02135	0.02121	0.65
460	0.01982	0.01970	0.60
480	0.01844	0.01842	0.12
500	0.01720	0.01737	-0.97
The average squared deviation = 0.50%			

$$(0.4684 \cdot 10^{-3}/0.03) \cdot 100\% = 1.56\% \text{ and}$$
$$(1.6174 \cdot 10^{-3}/0.03)\ ) \cdot 100\% = 5.39\%$$

At the same time for a wellbore located at the center of the lake the values T_R and $\Delta\Gamma$ are maximal (Table 1, eqs. (12) and (13)):

$$T_R(0{,}300) = -10^{o}C \cdot 0.0513 = -0.513\ °C;$$
$$T_R(0{,}500) = -10^{o}C \cdot 0.01942 = -0.194\ °C,$$

$$\Delta\Gamma(0{,}300) = 3.16 \bullet 10^{-3}\ °C/m$$
$$\Delta\Gamma(0{,}500) = 0.754 \bullet 10^{-3}\ °C/m$$

A commercially available software, Maple 7 (Waterloo Maple, 2001), was utilized to compute the function $M(\rho, z)$.

VI. Conclusions

It is shown that borehole paleoclimate investigations are complicated by many disturbing factors, exact calculation of which is a complex physical-mathematical problem. Proposed method allows ***to estimate*** the maximum effect of deep lakes on the borehole temperature profiles observed within and outside of the lakes. Authors assumed that the lake existed for an infinitely long period of time. In this case the solution of Laplace equation with nonuniform boundary conditions can be used to describe the steady temperature field of geological formations beneath the lakes and estimate the maximum effect (due to assumption that the lake existed for an infinitely long period of time) of lakes on the borehole temperature profiles. A numerical example to estimate the effect was explained in detail. Presented example of calculations testifies to what extent the proximity of a deep lake affects the borehole temperature profiles. An accuracy of the determination of the geothermal gradient is also estimated.

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