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Assessment of Ice Borehole Temperature Conditions at Interface with Subglacial Lake Vostok (Antarctica)

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Abstract
Borehole 5G drilled at Vostok Russian Research Station in Antarctica is currently the deepest ice hole ever drilled in the ice shields of Greenland and the Antarctic continent. This drilling project produced data that predetermined research trends for decades to come. The ice core recovered from Borehole 5G was used for palaeoclimatic reconstruction that covers over 420,000 years [7, 10, 13]. This made it possible to reconstruct the history of the Earth climate and atmosphere throughout the four recent glacial and five interglacial periods including the current one. It will provide an insight into the oncoming natural tendencies in climate change.

The discovery of the largest sub-glacial lake on the Earth, Lake Vostok in Antarctica, was confirmed in 1996. Borehole 5G reached the interface between the atmospheric and congelation (lake) ice at the depth of 3538 m. This congelation ice was formed as the result of lake water freezing over the glacier subface. This gave a start to indirect investigations of Lake Vostok focusing on its properties and characteristics as well as ice formation patterns. Subsequently, the borehole reached a zone near the lake surface, where the ice temperature was close to the melting point and ice crystals were characterized with huge sizes of around 1.5 m.

Our perception of Lake Vostok is based on the information obtained with remote sensing techniques (e.g. areal and ground radar soundings, seismic surveys, satellite radar altimetry) as well as on calculations using field data and available simulations. Further surveys will provide new information on the lake configuration and depths as well as the thickness and structure of its bottom sediments. This will help to carry out additional simulations of thermodynamic properties of the glacier-subglacial lake system. However, these investigations will neither be able to produce reliable information on the lake water composition nor confirm or dispel the assumption that some life forms exist in the lake. Therefore, sampling of the lake water is a key task to secure significant progress in research of this unique natural object [5].

Solution of this problem is a primary objective of further investigations in Borehole G5 that include water sampling from Lake Vostok and studies of the ice cores, which are expected to provide an insight into the origin and historical composition of lake water as well as possible existence of life in the lake.

Unsealing Lake Vostok for a short time and collecting water samples from its surface layer helps to obtain source information about its current condition. Besides its intrinsic value, this data is also critical for developing technologies and technological tools for further direct investigations of the lake, collection of bottom samples as well as adjustment of remote investigation and simulation results.

This paper presents results of time freezing calculations for the lake water with 'positive' temperature that entered the borehole once the subglacial lake was unsealed. These calculations were made using independent techniques.

The paper studies temperature conditions in the borehole at the interface with the subglacial lake.

Keywords: Antarctica, deep drilling, ice sheet, ice core, borehole, unsealing, lake water, heat transfer, Subglacial Lake Vostok

METHOD

Unique technologies developed at St. Petersburg Mining University made it possible for the Russian specialists at Vostok Research Station in Antarctica to unseal the world's largest Subglacial Lake Vostok using the KEMS-132 electromechanical drilling assembly. The lake was unsealed on February 5, 2012, at the depth of 3769.3 m below the ice sheet surface, which sparked keen interest in the global academic community [15,16].

The lake unsealing was preceded by research activities to fine-tune ice drilling technology to be applied at and near the phase-transition temperature.

The final stage of unsealing Lake Vostok with Borehole 5G was to freeze the lake water that entered the borehole at a specified depth, which was part of the drilling and penetration process. Subsequent re-drilling of the borehole produced an ice core of the frozen lake water. This clean technology helps to keep the subglacial lake environment intact. Figure 1 shows scheme of borehole 5G.

In order to successfully implement the developed technology of Lake Vostok unsealing, we need to forecast dynamics of lake water freezing inside the borehole. Difficulties concerned with experimental studies of this process ask for theoretical research into the water freezing process in the borehole-lake near-contact zone.

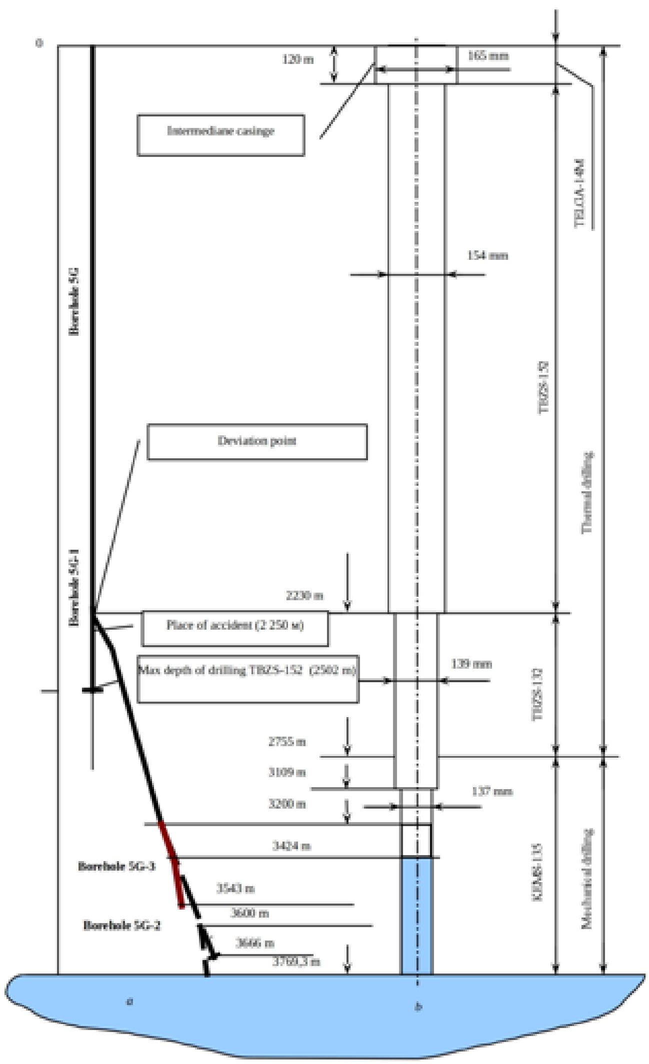

Figure 1: Scheme of borehole 5G: a - vertical projection; b - borehole construction.

Let us consider the steady-state process of heat-transfer from the lake water that entered the borehole to the low-temperature cylindrical walls of the ice mass around the borehole. In this case, the differential equation of heat-transfer through a cylinder wall takes the following form [1]:

$$dQ = \frac{2 \cdot \pi \cdot \lambda \cdot (t_w - t_i) \cdot L}{lnr} \cdot d\tau, \tag{1}$$

where L is the length of the borehole section concerned starting from its bottom (*10 metres*), which is equal to the column height of the lake water that entered the borehole, *m*; t_w – lake water temperature, *°C*; t_i – ice temperature, *°C*; λ – thermal conductivity coefficient of ice, *W/m·°C*; r – radius of isothermic cylindrical borehole surface, *m*; τ – time, *minutes*.

The differential equation of heat transmission balance for the cooling water may be written as:

$$dQ = \frac{\pi \cdot D_h^2}{4} \cdot L \cdot \rho_w \cdot C_w \cdot dt_w, \tag{2}$$

where D_h is borehole diameter, *m*; ρ_w – water density, *kg/m*^{3}; C_w – specific heat capacity of water, *J/kg·°C*.

By making the right hand sides of equations (1) and (2) equal, separating variables and performing integration using the time parameter, we obtain the following expression:

$$\tau_w = \left(\frac{\rho_w \cdot C_w \cdot D_h}{8 \cdot \lambda}\right) \cdot lnr \cdot ln\left(\frac{t_{wi} - t_i}{t_{wf} - t_i}\right), \tag{3}$$

where t_{wi} is the initial water temperature, *°C*; t_{wf} is the final water temperature,*°C*.

Let us determine the freezing time for the whole water volume present in the borehole at the wall temperature of *2.87°C*, (thermal gradient – *0.02Degrees/metre*) [2].

The heat-transfer differential equation (1) is converted to:

$$Q_f = \frac{2 \cdot \pi \cdot \lambda \cdot (t_w - t_i) \cdot L}{lnr} \cdot \tau_f, \tag{4}$$

where Q_f is the amount of heat transferred from the water lake to the ice mass through the cylindrical borehole walls, J, while the heat balance equation for the freezing water (2) will take the following form:

$$Q_f = \frac{\pi \cdot D_h^2}{4} \cdot L \cdot \rho_w \cdot q_i, \tag{5}$$

where $q_л$ is heat of ice melting, *3.34 ·10*^{5} *J*/kg.

Equation (4) still stands for the case when the heat flows in the opposite direction, i.e. if $t_w < t_i$.

In the state of thermal equilibrium, the amount of heat lost by the 'warm' lake water and received by the cold ice mass through the borehole wall should be the same.

Simultaneous solution of equations (4) and (5) produces the following formula to calculate the freezing time of all the lake water in the borehole:

$$\tau_f = \frac{\rho_w \cdot q_i \cdot D_h^2}{8 \cdot \lambda \cdot (t_w - t_i)} \cdot lnr, \tag{6}$$

As during the heat exchange process the temperature of liquid is changing, its physical properties will be changing too. Therefore, it is important to agree on a certain defining temperature that could be used for calculation of the required values. Mean temperature of the liquid throughout the tube (borehole) length is calculated using the following equation:

$$\acute{t}_l = t_{hw} \pm \Delta t.$$

where t_{hw} is the hole wall temperature at the cross-section concerned, *°C*; Δt is the average temperature head value,*°C*. Positive sign "+" is used if the liquid is cooled, while negative sign "–" is used for liquid heating. The temperature differences (temperature head) between the wall and the liquid in contact with the wall is

$$\Delta t = t_{tw} - t_l.$$

Hence, in this case

$$\Delta t = t_i - t_w = -2.87 - (-1.8) = -1.07°C$$

$$\acute{t}_w = t_i + \Delta t = -2.87 + (-1.07) = -3.94°C$$

Let us replace t_w in equation (6) with $\acute{t}_w$.

Subsequently, the total time for water cooling down to the temperature of *–°C* and its complete freezing can be expressed as

$$\tau_c = \tau_w + \tau_f, \tag{7}$$

The calculated parameters of water cooling and freezing in the borehole are shown in the table below:

$D_{hole, mm}$	140
$T_{w, days}$	1.6
$T_{f, days}$	10.3
$\tau_{c, days}$	11.9

Let us assess the time for freezing of an assumed water portion at which the stresses inside the ice wall become equal to the admissible stresses in the ice mass.

Now let us assess the stresses inside the borehole wall due to freezing of the entire water volume.

The entire volume of frozen water in the borehole with the account for its volumetric expansion coefficient due to change in the aggregative state in water-to-ice transition β can be calculated with the following equation:

$$V_i = (1+\beta)\cdot\frac{\pi D_{hole}^2}{4}\cdot L, \quad (8)$$

Relative perimeter extension of the borehole section due to freezing of the entire water volume will lead to relative deformation.

Volumetric gain due to water freezing:

$$\Delta V_i = V_i - \frac{\pi D_{hole}^2}{4}\cdot L,$$

or, with the account for the previous equation:

$$\Delta V_i = \beta\cdot\frac{\pi D_{hole}^2}{4}\cdot L.$$

In this case, borehole diameter D_{hole}would increase and would equal D_i. Then

$$\Delta V_i = \frac{\pi D_i^2}{4}\cdot L - \frac{\pi D_{hole}^2}{4}\cdot L,$$

or upon algebraic transformation with the account for the previous equation:

$$D_i^2 - D_{hole}^2 = \beta\cdot D_{hole}^2, \quad (9)$$

Perimeter extension of the borehole section due to freezing of the entire water volume will equal

$$\Delta = \pi\cdot(D_i - D_{hole}),$$

while the relative extension will be expressed in the following way:

$$\varepsilon = \frac{(D_i - D_{hole})}{D_{hole}}, \quad (10)$$

The following algebraic expression can be obtained taking into account equation (9):

$$\varepsilon = (2+\varepsilon) = \beta, \quad (11)$$

where relative deformation will be determined as

$$\varepsilon = \sqrt{-1+\beta} - 1, \quad (12)$$

With due account for numerical value of the volumetric expansion coefficient in water-ice transition (*β=0.11*) at °C, relative deformation equals

ε =0.0004

Subsequently, following Hook's law of elastic stress-strain relations, stresses inside the borehole walls will amount to:

$$\sigma_{hw} = E\cdot\varepsilon = 9000\cdot 0{,}0004 = 3.6MPa, \quad (13)$$

which significantly exceeds the admissible stresses for ice $[\sigma]$.

It is required to find the share of water frozen in the borehole α at which the actual stresses start to exceed the admissible ones.

Equation (8) to calculate the share of water frozen inside the borehole $[\propto]$ will take the following form

$$V_\alpha = (1+\alpha\cdot\beta)\cdot\frac{\pi\cdot D_i^2}{4}\cdot L.$$

Then upon mathematical manipulation, equation (11) will look in the following way:

$$\varepsilon\cdot(2+\varepsilon) = \alpha\cdot\beta, \quad (14)$$

Inserting the admissible stresses $[\sigma]$ in the Hook's law (10) we will obtain an equation for the admissible relative deformation[3,4]:

$$[\varepsilon] = \frac{[\sigma]}{E} = \frac{3200}{9000} = 0.36$$

Then, the admissible share of frozen water inside the borehole, at which the stresses inside the borehole wall become equal to the admissible stresses, is controlled by the following expression (with account for equation (14)):

$$[\propto] = \frac{[\sigma]/E\cdot\left(2+\frac{[\sigma]}{E}\right)}{\beta} = 7.7 \quad (15)$$

Which means that even with 7.7% of water turned into ice, stresses inside the borehole walls get equal to admissible stresses $[\sigma]$.

The heat balance equation for the share of water frozen inside the borehole $[\propto]$ will take the following form:

$$Q_\propto = \propto\cdot\frac{\pi\cdot D_{hole}^2}{4}\cdot L\cdot\rho_c\cdot r, \quad (16)$$

Which solution together with equation (4) produces the following expression:

$$\tau_\alpha = \frac{\alpha\cdot\rho_w\cdot q_i\cdot D_{hole}^2}{8\cdot\lambda\cdot(t_w - t_i)}\cdot lnr = 12.8314days, \quad (17)$$

i.e. the time needed for freezing of the admissible water share at which stresses in the borehole walls get equal to the admissible stresses. Ice that is formed on the borehole walls will squeeze non-frozen water out, which will decrease stresses inside the borehole walls and will increase the time required for admissible stresses to form in the borehole.

CONCLUSIONS

The data obtained with two independent data (7) and (17) are characterized with close quantitative match. It may turn out to be even closer at lower temperature gradients, which could be actually lower than the ones used in calculations.

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