

Thermobaric Conditions at Ice-Water Interface in Subglacial Lake Vostok, East Antarctica

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Abstract

Thermobaric conditions of subglacial Antarctic environment remain poorly understood, despite recent advances in radar and seismic surveying. The direct accessing to the largest subglacial lake, Lake Vostok, was carried out twice by Russian scientists in February 2012 and January 2015, opening new opportunities for assessing the thermobaric conditions at ice-water interface. According to the assumption that ice sheet is "floating" on the lake, it was predicted that the water would rise 30 - 40 m in the bottom part of the borehole, but in fact the water rose from the lake to a height of more than 500 m. To explain this phenomenon we assume that the pressure in Lake Vostok results from the external pressure of the entire mass of ice above it and the pressure of the water column that is overlaid above the point being considered. Extrapolation of temperature measurements from the deep bore-holes drilled at Vostok Station also confirmed that the bed of the ice sheet is at pressure melting point. As a result of accessing Lake Vostok, the pressure in the lake is reduced that would lead to the formation of a new additional layer of accretion ice on the lower ice sheet surface.

Keywords

Subglacial Lake, Ice Drilling, Hydrostatic Pressure, Borehole Temperature

1. Introduction

It is now generally recognized that a vast network of lakes, rivers, and streams exists thousands of meters beneath Antarctic Ice Sheet. As of 2010, 387 subglacial lakes have been identified; this will increase as surveys improve spatial coverage [1]. Prediction of the thermobaric conditions in Antarctic subglacial reservoirs is one of the most important challenges in relation to studies of gas hydrate formation, water circulation, unique habitat for life and accretion processes on the underside of the ice sheet. Estimation of the thermobaric conditions is especially important in a view of the ongoing projects to access and to directly sample subglacial lakes [2]-[4].

With dimensions of 280 km by 50 km, Lake Vostok is largest subglacial lake in Antarctica. It is located under the similarly named Russian station, Vostok Station (78°28'S, 106°48'E, 3488 m a.s.l.) in the central part of East Antarctica (**Figure 1**). The area of Lake Vostok is about 15,790 km², and the thickness of the ice sheet in the region of Lake Vostok varies within 1950 - 4350 m [5]. The total ice volume above the lake without factoring in the islands is near 64,600 km³. True altitude of the ice-water interface relative mean sea level range from -600m on the northern part to -150 m in the southern part. Lake Vostok is at least 1000 m deep in the south and relatively shallow in the north and extreme southwest. The volume of water is about 6100 km³ and the average depth is about 400 m. It has been shown that subglacial melting occurs in the north of Lake Vostok and freezing takes place in the south [6].

Drilling a deep Hole 5G started in February 1990 six years before the large subglacial lake under Vostok station was officially recognized [7]. Finally, after 22 years Russian team made contact with the Lake Vostok water February 5, 2012 at a depth 3769.3 m (Figure 2). The borehole liquid level rapidly raised, and visible outflow of drilling fluid form the mouth of the borehole was continued during $\sim 5 \min [8]$ [9]. The drill was immediately recovered, but upon reaching the surface the whole drill was filled and coated with refrozen water ice. It was predicted that the water would rise up the near-bottom part of the borehole, by 30 - 40 m, but in fact the water rose far above. On January 2013, the drill deployment found the first signs of frozen lake water (cork of bright white hard material) at the depth of 3181.9 m at distance of ~ 587 m from the bottom of ice sheet [10].

The frozen subglacial water was re-drilled and the first crescent-shaped fragments of frozen water ice were got from the depth of 3367 m. At a depth of 3397 m, the first "ice core" consisting of a white substance, clath-rate hydrate mixture of lake gases and densifier, HCFC-141b, was retrieved. Deeper than 3406.1 m the drill be-gan to recover the continuous full diameter core composed from outside frozen water ice and hydrate core. However, the Hole 5G-1 is inclined from the vertical by ~6°, and during re-drilling the drill moved away from the axis of the main hole. That is why the crescent-shaped segment of glacial ice appeared in the core shortly after, and the proportion of glacial ice increased steadily with depth. Totally 34.1 m long core with frozen lake water was recovered.



Figure 1. Vostok station and other deep ice coring sites on Antarctica



Figure 2. Schematic drawing of deep Hole 5G. Photo: G. Talalay (January, 2011).

Drilling was continued to the depth of 3765 m [11]. Then pressure logging of the hole revealed the underbalanced state of the drilling fluid column, and 800 L of densifier was added to the near-bottom part of the hole. Drilling was resumed, and on January 25, 2015 subglacial Lake Vostok was accessed for the second time at the depth of 3769.15 m (15 cm less than in 2012). Recovered drill was coated by frozen water almost in the same manner as after the first penetration. Before last run the liquid level was at the depth of 95.5 m, but after pulling the drill level raised to 46 m. Four days after penetration the drilling was again continued through fresh-frozen water starting from the depth of 3696.6 m. It means that lake water raised to the height of \sim 73 m.

Clearly, the pressure in the Lake Vostok is much higher than expected. To explain this phenomenon we as-

sume that the pressure in Lake Vostok results from the external pressure of the entire mass of ice above it and the pressure of the water column that is overlaid above the point being considered. The following considerations attempt to give explanations for uncontrolled blowout happened at Vostok Station.

2. Pressure at Ice Sheet-Lake Vostok Interface

According to available data [12] and its extrapolation, hydrostatic pressure of the drilling fluid column at the bottom of the Hole 5G-2 at the moment of the first accessing of Lake Vostok was equal to 33.515 MPa. The drilling fluid consisting of a mixture of kerosene and HCFC 141b, which is less dense than lake water, began to rapidly rise up the borehole. As a result, about $1.5 - 2.5 \text{ m}^3$ of this fluid poured out through the mouth of the borehole to special trays, installed in the drilling building [8].

The Hole 5G and its upper part are practically vertical to the depth of 2400 m, below this depth the angle is $6.3^{\circ} \pm 0.9^{\circ}$ [13]. It means that true vertical depth of the Hole 5G-2 is ~3761 m that can be taken as the ice thickness at Vostok station.

Surface topography above Lake Vostok, determined from satellite altimetry, showed that the ice surface above the Lake Vostok is very flat, an along-lake north-south slope is prominent, tilting 60 m over a horizontal distance of ~250 km [14]. 90% of the surface of the ice-water contact can be approximated by a plane slightly inclined towards the north with an angle of not more than 0.1° [5]. Simulations of ice sheet dynamics above Lake Vostok assumed that the overlying ice is in hydrostatic equilibrium [15] [16], and the ice/lake interface is considered to be a stress-free surface [17]. Thus, the shear stress in ice sheet due to surface slope is insignificant (less than 0.01 MPa).

The small amount of superincumbent under-stress ice is located in the down warping coastal area. The evaluation of the coastal topography shows that the south and west coastal area with length of coastal line of ~200 km is inclined to the center of the lake at distance of ~5 km with the angle 3.5° and occupies an area of less than 6% of the entire surface of Lake Vostok. 4% of the lake surface, located along the northern part with length of coastal line of ~75 km, is inclined to the center of the lake at a distance of ~9 km with an angle of 2° . Almost entire eastern of Lake Vostok has no up warping because the ice flow is beset by bedrock hillside. Therefore, we assume that the influence of shear stress in the coastal area of Lake Vostok on the vertical component of the gravity force of the whole ice mass is quite small and in a first approximation can be neglected.

In the assumption that the ice sheet is "floating" on the lake and is, hence, in hydrostatic equilibrium with the lake, the pressure on the ice-water interface was estimated to be equal to the local lithostatic pressure of the ice sheet at the point of drilling [18] [19]:

$$P_{I} = \rho_{i} g \left(Z_{V} - z_{f} \right) \cdot 10^{-6} \approx 33.747 \text{ MPa}, \qquad (1)$$

where ρ_i is the average ice density, kg/m³ (average ice density through the section vertically in the region of Vostok station can be taken equal to 923 kg/m³ [20]); g is the acceleration of gravity, 9.81 m/s²; Z_V is the thickness of the ice sheet at Vostok station, m; z_f is the firn correction accounting for the air content in the upper snow-firn zone (for Vostok $z_f = 34$ m [21]).

According to this hypothesis the differential pressure, which is the difference between hydrostatic pressure of the drilling fluid in the borehole and the lake pressure, is approximately -0.231 MPa (Table 1), and the rise of the water level in the borehole would be 23.6 m, which is far less than the observations. This means that the theoretical assumption that water in the Lake Vostok is equal to lithostatic pressure at the point of drilling is wrong.

Assuming Lake Vostok is totally isolated from the Antarctic subglacial drainage system, is sealed along its entire perimeter and forms a reservoir of water in which the pressure is hydrostatic. Then according to the Pascal's Law, full pressure P at any point inside an isolated reservoir in homogenous field of the force of gravity consists from two components [22]:

$$P_{II} = P_i + P_w \,, \tag{2}$$

where P_i is the external lithostatic pressure of ice sheet, MPa; P_w is hydrostatic pressure of the water column, MPa.

External lithostatic pressure P_i is determined by the integral of the total weight of superincumbent ice over the entire area of the lake (on Figure 3 the area between vertical lines S and N). This pressure is uniform for any

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Parameters	Notation	Version I	Version II
Lake pressure under Vostok Station, MPa	Р	33.747	38.090
Differential pressure at the bottom of Hole 5G-2, MPa	ΔP	-0.231	-4.574
Estimated rise of upwelling water in the borehole, m	-	23.6	3 883
Temperature at ice-water interface (pressure melting point), °C	t_m	-2.68	-3.06
Depth of pressure melting point due to extrapolation of temperature profile, m	-	3776.7	3758.3





Figure 3. Schematic cross-section of Lake Vostok from south to north (using data from [5] [23]).

point at the ice-water interface and is determined with the equation:

$$P_i = \rho_i g \frac{V_0}{S_0} \cdot 10^{-6}$$
, or (3)

$$P_i = \rho_i g\left(\overline{Z} - z_f\right) \cdot 10^{-6}, \tag{4}$$

where V_0 is the entire ice volume above the lake's surface, m³; S_0 is the horizontal area of the surface of ice-water interface, m²; \overline{Z} is the average ice thickness above subglacial lake, m (according to data published in [5] $\overline{Z} = 4091$ m).

Hydrostatic pressure P_w is created inside lake's volume by the action of gravity force of water column, the height of which is determined by the difference of height from the selected point to the point with maximum absolute altitude at the entire water-ice boundary:

$$P_w = \rho_w g Z_w \cdot 10^{-6} \,, \tag{5}$$

where ρ_w is the lake's water density, kg/m³, Z_w is the height of water column, m.

The height of water-column Z_w can be estimated according to ice thickness as following (Figure 4):

$$Z_w = Z - Z_{hw} \pm \Delta H , \qquad (6)$$



Figure 4. How to estimate height difference from the selected point to the point with maximum absolute altitude: (a) if surface of selected point is lower than high-water point; (b) if surface of selected point is higher than high-water point.

where Z is the ice thickness at selected point, m; Z_{hw} is the thickness of ice at the high-water point with maximum absolute altitude at the entire water-ice boundary, m; ΔH is the elevation difference between these points, m.

The height of water-column between bottom of the hole 5G-2 and highest point of ice-water interface (height between points *B* and *A* on Figure 3) is estimated due:

$$Z_{w}^{B-A} = Z_{V} - Z_{hw}^{A} - \Delta H^{B-A} \approx 138 \,\mathrm{m} \,, \tag{7}$$

where Z_{hw}^{A} is the minimal ice thickness above Lake Vostok (3600 m [5]); ΔH^{B-A} is the altitude different between Vostok station and ice sheet surface with minimal ice thickness $(\Delta H^{B-A} = 3488 - 3465 = 23 \text{ m})$.

So, assuming that the pressure in the Lake Vostok is composed of the external pressure of the entire mass of ice above the lake and the pressure of the water column that is overlaid above the point being considered, we obtain:

$$P_{II} = \rho_i g \left(\overline{Z} - z_f \right) \cdot 10^{-6} + \rho_w g Z_w^{B-A} \cdot 10^{-6} \approx 38.09 \text{ MPa} \,. \tag{8}$$

In this case, the rise of water level in the borehole is greater than the 3761 m vertical height of the Hole 5G-2. This means that even if the entire borehole is filled with subglacial water, the excessive pressure in the Lake Vostok would not be compensated, and the outflow of the water through the borehole mouth would continue like artesian well until the water freezes in the borehole. Such artesian supraglacial fountains are well known phenomenon and were observed in valley glaciers, e.g. at Trapridge Glacier, Yukon, Canada [24], John Evans Glacier, Ellesmere Island, Canada [25], Vatnajökull Ice Cap [26] and others. We assume that the upwelling of subglacial water at Vostok Station in the Hole 5G has stopped not due to equalization of the pressure in the lake and drilling fluid, but because of freezing of the lake's water in the hydraulic fracturing cracks between borehole bottom and lake.

There is good reason to believe that the real interface between the ice sheet and the subglacial water lies a few meters below the bottom of the hole, and that lake water rose into the hole through intergranular cracks formed secondary to the large pressure difference between the lake and the fluid in the borehole. This phenomenon is widely known in geology and mining as fracturing, and it occurred in Greenland in 2004, when subglacial water rose into the hole although the ice sheet bed was about 6 m beyond the bottom of the borehole [27]. During the Antarctic summer season of 2006-2007, in a deep borehole at the Dome Fuji Station, subglacial water began to leak into the borehole a few meters above the ice sheet bed [28].

Radar profiling has recorded a chain of subglacial water layers at 30 km west of the Vostok Station with elevations that are up to 850 m higher than the edge of the Lake Vostok (point *C* on **Figure 3** [23]). It could be speculated that this subglacial aquatic system is interconnected and includes Lake Vostok. It is quite probable that the connecting channels are not detected by the radar due to complex surface relief or as a result of their small thickness. If so, the pressure at the ice-water interface should be much higher as has been noted above.

When a subglacial lake is accessed by a borehole with negative differential pressure, the pressure in the lake is reduced to some extent, and as a result the accretion ice would be formed at least in the area around the bottom of the drill-hole. In this way, the accessing of subglacial lake would lead to significant change of the system's condition, which has existed for hundreds of thousands of years without external influences.

3. Temperature at the Ice-Water Interface

Temperature measurements in deep boreholes at Vostok Station were regularly carried out since beginning of 1970-s [13] [29] [30]. R.N. Vostretsov (personal communication, 1999) compared data obtained in different expeditions and in different holes drilled at Vostok Station and tabulated the summary sheet. Fitting a polynomial to these data gives the following approximation for temperature profile at Vostok Station in the lower part of the ice sheet at depths range from 1806 to 3606 m:

$$t = -48.832 - 5.9529 \times 10^{-3} Z + 7.4421 \times 10^{-6} Z^2 - 6.965 \times 10^{-10} Z^3 .$$
⁽⁹⁾

This equation gives the opportunity to predict the temperature at the bed of ice sheet taking into account the temperature of the ice-water interface which is equal to the pressure melting point. As the pressure P [in MPa] increases, the melting temperature t_m [in K] of ice decreases as follows (modified from [31]):

$$P = 611.66 \times 10^{-6} \left\{ 1 + \sum_{i=1}^{3} a_i \left[1 - \left(\frac{t_m}{273.16} \right)^{b_i} \right] \right\}.$$
 (10)

Using the pressure from Equation (8), ice temperature at the bed of the sheet would be equal to -3.06 °C. Extrapolation and solving of Equation (9), gives the depth of 3758.3 m at pressure melting that is in close proximity to the true vertical depth of Lake Vostok accessing (~3761 m).

The temperature gradient up to the depth of 2500 m is close to linear, and in lower part of the ice sheet it decreases to 0.02206° C/m as the ice-water interface is approached (**Figure 5**). Extrapolation of temperature measurements below 3606 m gives estimates of geothermal heat flux at the ice sheet base as 46.2 mW·m⁻² that is lower than it was obtained by modeling [32].



Temperature gradient, °C/m

Figure 5. Measured temperature gradient in ice sheet at Vostok Station revealed from deep bore holes and predicted temperature gradient in air, subglacial Lake Vostok, sediments and Earth's crust within allowable limits (marked by more dark color).

4. Conclusions

The estimation of the pressure at ice-water interface in isolated subglacial reservoirs being equal to the local lithostatic pressure of the ice at the drilling point does not account the hydrostatic features of subglacial environment. Repercussion of Lake Vostok showed that the pressure difference between hydrostatic pressure of drilling fluid and lake pressure was incorrectly calculated, and the pressure in the Lake Vostok is much higher than expected. Perhaps, the assumption that the ice sheet is simply "floating" on the lake, is only appropriate for active subglacial lakes which are draining into other lakes or into isolated pathways that connect to the ocean [33] or a few ice thickness away from grounded lake margins.

Our most probable scenario assumes that the pressure in this totally isolated reservoir which has a complex ice-water interface, results from the external pressure of the entire mass of ice above it and the pressure of the water column that is overlaid above the point being considered. It is possible that rising subglacial water rising into the borehole could, and, outflows through the mouth similar to artesian aquifer flow if the borehole does not freeze closed.

When Lake Vostok was accessed by a borehole with negative differential pressure, subglacial water inevitably upwells into the borehole and the condition of thermobaric equilibrium is disturbed to some extent. At this point thermobaric conditions in the lake changed, leading to the freezing-on of additional accreted ice to the ice sheet base. These assumptions should be considered for future subglacial lakes exploration.

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