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Unsealing Subglacial Lake Vostok: Lessons and implications for future full-scale exploration

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Abstract. The deep holes drilled at Vostok Station by the Russian Antarctic Expedition reached the surface of Subglacial Lake Vostok twice — on February 5, 2012 and January 25, 2015. Two unsealings of the largest subglacial water body on Earth, led by Nikolay Vasiliev, have become remarkable events in the history of Antarctic science. To preserve all the twists and turns of this pioneering work for the ice-drilling community, we have compiled and carefully analyzed all the available drilling, geophysical, and glaciological observations made prior to, during, and after the lake piercings. Based on that information, in this paper we have pieced together a detailed narrative of these two unprecedented drilling operations in the hope that the lessons learned may prove useful for future environmental stewardship, scientific investigations, and technological developments related to the exploration of Lake Vostok.

Keywords: subglacial lake, deep drilling, access borehole, breakthrough, re-drilling, HCFC-141b hydrate

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1. Introduction

The decades-long deep-drilling project at Russia's Vostok Station, which has made an outstanding contribution to the study of past climate change [1], has, in recent years, increasingly been linked to the exploration of Lake Vostok, the largest subglacial water body on Earth, which was discovered in East Antarctica at the end of the 20th century [2].

In 1998, scientists drilling through the Antarctic ice sheet at Vostok reached, via borehole 5G-1 and at a depth of 3539 m, a stratum of congelation ice that was accreted from the lake water [3]. This event marked a new stage in research into Subglacial Lake Vostok (SLV), when the core of accreted ice became the main source of experimental data on the environments and hydrological regime of the lake [4–9].

The next prize on the horizon was the unsealing of Lake Vostok. Researchers at the Arctic and Antarctic Research Institute and the St. Petersburg Mining University proposed a conservative approach that was both relatively simple and associated with a minimal risk of lake contamination [10]. Their idea was to maintain a small pressure difference between the drilling fluid in the borehole and the subglacial water immediately before accessing the lake, so that after the drill pierced the bottom of the ice sheet, the lake water could enter the borehole and rise several dozens of metres above the lake's surface. It was assumed that due to the relatively rapid freezing of the water in the hole, accompanied by the trapping of dissolved impurities and gases, the newly formed ice would provide data on the original properties of the lake water that would be easier to interpret than data from ice that had slowly accreted over thousands of years to the bottom of the ice sheet.

The primary concern when planning the unsealing of SLV was to avoid chemical and biological contamination of the water entering the hole, and potentially the lake itself, with the drilling fluid (a mixture of aviation kerosene and Freon HCFC-141b) that is used to fill the hole in order to prevent its closure. The initial plan, therefore, was to replace the drilling fluid in the lower 100-metre section of the hole with an environmentally friendly hydrophobic liquid that is heavier than drilling fluid but lighter than water (e.g. polydimethylsiloxane). In addition, researchers intended to use a coreless electrothermal drill to penetrate the bottommost 30-metre layer of ice [10, 11]. However, for a number of reasons, the decision was made that it was not possible to implement these technological proposals, as may have been preferred, and they were eventually omitted during the first (February 5, 2012) and second (January 25, 2015) unsealings of Lake Vostok [12].

Since 2012, several publications have appeared that discuss some aspects of drilling and borehole operations during the first unsealing of Lake Vostok [12–15], but nothing has been reported so far about the second unsealing, which took into account the experience and corrected the miscalculations of the first one.

The aim of our paper is to give, for the first time, a comprehensive description of the two unsealings of SLV based on a complete dataset, which includes all available drilling, geophysical, and glaciological observations collected prior to, during, and after the lake piercings. Ultimately, we attempted data-consistent reconstructions of the subglacial water and drilling fluid movements in the hole during these events. We hope that the data and lessons learned from these two endeavours may prove to be useful in terms of guiding future environmental stewardship, scientific investigations, and technological developments associated with the exploration of Lake Vostok.

2. Methods

The drilling of borehole 5G, which later on became a multibranch hole (Fig. 1), began at Vostok Station in February 1990. At first, the TELGA-14M, TBZS-152M, and TBZS-132 thermal drills were used in succession to reach a depth of 2755 m in hole 5G-1. Below this depth, drilling operations continued with the cable-suspended electromechanical drill KEMS-132 [11]. With only minor changes in its assembly, the KEMS-132 drill was used both for routine ice coring and sidetracking to bypass the drill abandoned inside the 5G-1 hole, as well as for unsealing the lake and then re-drilling the frozen lake water that filled the hole following the breakthrough. Due to the use of different drills in the early years of 5G drilling and owing to hole reaming, the borehole diameter varies stepwise with depth from 165 mm in the upper 120 m cased section of the hole to ~155 mm between 120–2230 m and to 139–135 mm in its deeper section [16].

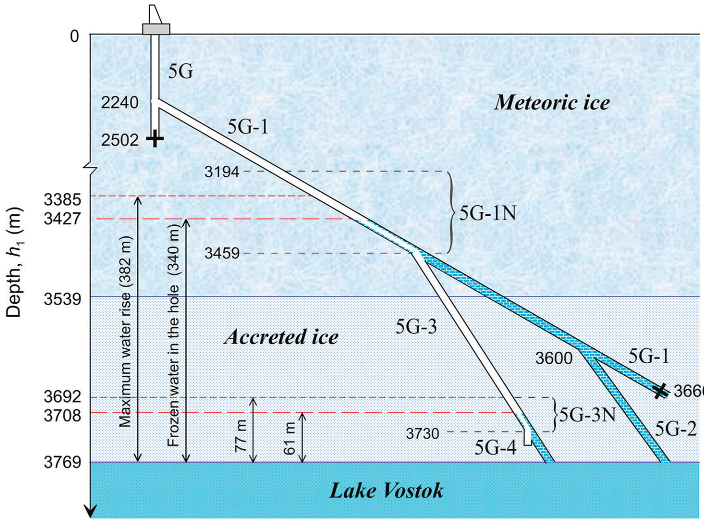

Fig. 1. Schematic of the multibranch borehole 5G at Vostok Station as of January 2018.

Depths shown here at an arbitrary scale are from the ice core length measurements. The inclination of the boreholes is exaggerated: in reality, their deviation from the vertical does not exceed 6°. Lost drills are shown by crosses. The vertical heights of the maximum water (and/or water-drilling fluid emulsion) rises and of the frozen water columns in the boreholes after the first and second unsealings of the lake are indicated. 5G-1N and 5G-3N are the intervals of boreholes 5G-1 and 5G-3 re-drilled after the unsealings. The lower sections of boreholes 5G-1, 5G-2, and 5G-3 remain filled with frozen Lake Vostok water. See text for further explanation

Рис. 1. Схема скважины 5Г на станции Восток по состоянию на январь 2018 г.

По оси ординат дана глубина скважин по керну (в произвольном масштабе). Наклон скважин преувеличен — в реальности их отклонение от вертикали не превышает 6°. Буровые снаряды, оставленные в скважинах, показаны крестиками. На схеме показаны уровни максимального подъема воды (и/или эмульсии воды и заливочной жидкости) и высоты столбов замерзшей в скважинах озерной воды после первого и второго вскрытий озера. 5Г-1N и 5Г-3N — интервалы скважин 5Г-1 и 5Г-3, из которых в результате повторного бурения были подняты керны замерзшей воды и гидратного материала. Нижние участки скважин 5Г-1, 5Г-2 и 5Г-3 остались заполнены замерзшей озерной водой. Более подробные пояснения даны в тексте

The data acquisition module designed and manufactured by the AMT company (St. Petersburg) to control and record drilling parameters was put into operation at the final stage of the 5G-2 hole boring, starting from a depth of 3720 m. In this study we use only three of all the measured parameters for further analysis: instantaneous depth of the drill, its lowering/hoisting speed, and weight on bit.

In the practice of ice drilling with cable-suspended drills, three types of depths are usually distinguished: the drillers' depth obtained from the cable depth counter (h_2), the ice core logging depths obtained from the core length measurements (h_1), and the vertical depth (h). In its upper part, up to a depth of 2400 m, the 5G hole is almost vertical; here the empirical relationship applies: $h \approx 0.9992 \cdot h_1 \approx 1.0042 \cdot h_2$. Below 2400 m, the average inclination angle of holes 5G-1, 5G-2 and 5G-3 is close to 6°, and depths h, h_1 and h_2, expressed in metres, are related to each other by the relationship $h - 13.70 \approx 0.9935 \cdot h_1 \approx 0.99852 \cdot h_2$ [17]. In what follows, along with h_1, which is the official depth of the hole, we also use h_2 when discussing drilling and borehole survey data or h when calculating ice and fluid pressures.

The two-component drilling fluid used at Vostok is a mixture of kerosene-based aircraft fuel (TS-1 or similar) with the dichlorofluoroethane HCFC-141b (CFC-11 was used when drilling the upper 2270 m of the borehole). We used two methods to estimate the hydrostatic pressure of the fluid in the borehole: (i) calculation of the fluid pressure based on the density of the fluid samples collected from different depths in the hole [18] (see SOM for details), and (ii) direct measurements of the fluid pressure using a downhole pressure gauge. In-situ pressure measurements were carried out with the aid of two KMT downhole loggers, which were manufactured and calibrated in SPE Grant (Ufa). Manufacturer's stated accuracy of these loggers is 0.25% of the reading. The results obtained by the two methods coincided, as a rule, within 0.1 MPa.

Differential pressure in the borehole is defined as $\Delta p = p_f - p_i$, where p_f is the hydrostatic pressure of the drilling fluid and p_i is the ice pressure at depth h. To calculate Δp, we used the linear dependence $p_i(h)$ obtained from accurate ice core density data [19], which is valid at depths greater than 120 m with an accuracy of approximation of about 0.01 MPa (see SOM):

$$p_i(\text{MPa}) = 9.068 \cdot 10^{-3} \cdot (h(\text{m}) - 32.4). \quad (1)$$

An important innovation introduced before the second unsealing of the lake was the use of an acoustic level meter (Sigma-ART), which allowed real-time monitoring of the fluid level in the hole during drilling operations.

3. A narrative of the first unsealing of Lake Vostok

After reaching the stratum of SLV accretion ice in 1998, drilling activity in the 5G-1 borehole was suspended for eight years; it resumed only in December 2005. The drilling of this hole continued in the following years until the drill got stuck and eventually abandoned at 3666 m in November 2007. The drilling of new branch hole 5G-2, started in January 2009 to bypass the lost drill by deviation from parent hole 5G-1 [20], was then continued to the surface of Lake Vostok (Fig. 1).

By the end of the 2010/11 austral season, borehole 5G-2 had reached a depth of 3720 m which made it possible to plan the lake piercing for the next field season, 2011/12. The main uncertainties and associated risks that complicated preparations for the first SLV unsealing were as follows.

1. Uncertainty in ice-thickness estimate. A borehole temperature logging performed in December 2011 showed that the ice temperature at a depth of 3720 m was about –3.2 °C. The pressure melting temperature of ice at the ice sheet bottom depends, among other things, on the actual concentration of gases dissolved in the uppermost layer of lake water, and can range between –2.85 and –2.52 °C at the drilling site [21]. Given these data and their uncertainties, we calculated that with 95 % probability the lake surface would be reached within a depth interval of 3750–3782 m (h_1), and most probably at depth h_1 = 3767 m (h = 3756 m), i.e. at an only slightly shallower depth than that predicted by the combined RES data (h = 3770±11 m, h_1 = 3781±11 m [22]). Indeed, the first indications of the presence of liquid water at the hole bottom were encountered when the hole reached a depth of 3766 m (h_1). The surface of an 80-centimetre ice core recovered from the hole was eroded by water, the core was frozen to the core barrel and the core barrel was covered with water ice. It was suggested that a small (~3 litres) amount of subglacial water could have entered the borehole by seepage through hydraulic cracks that appeared along the weakened (pre-melted) boundaries of ice crystals during the core breakoff [13]. However, during the subsequent 5 drilling runs preceding the breakthrough, no further indications of significant water in the borehole were observed.

2. Accurate estimation of subglacial water pressure was hampered by the fact that the drilling site is located in the transition zone between grounded and freely floating ice where a deviation from the hydrostatic equilibrium condition was observed [23].

3. Because of the high total dissolved air content expected in SLV (up to 2.5–2.7 litres (STP)) of gas per kg of water [21, 24]), there was a certain risk of uncontrolled degassing of the lake water if it was allowed to rise in the hole too high above the ice-water interface [25, 26].

Finally, given the experience of previous drilling operations that ended with subglacial water flooding into the hole (see e.g. [27]), we were well aware that, once breakthrough occured, our ability to control the movements of liquids in the borehole would be limited.

3.1. Borehole condition prior to breakthrough

The last drilling run in borehole 5G-2, which culminated with the unsealing of Lake Vostok, was conducted on 5 February 2012. It so happened that the last fluid sampling and density measurements were carried out on 15 January, a whole three weeks before the unsealing, when the bottom of the hole was still 31 m above the lake surface. Based on the results of these measurements it was decided to inject 350 kg of HCFC-141b densifier into the borehole, in the 3300-3630 m depth interval, in order to increase the mean density of the fluid column [13]. During the completion of the 5G-2 drilling, as the hole deepened, the desired level of fluid in the borehole was maintained by the addition of pure kerosene. Finally, in the course of the last drilling run on 5 February, when the drill was already lowered into the hole, another 250 litres of kerosene were added to the top of the fluid column.

Taking all these operations into account, we reconstructed the hydrostatic pressure of the drilling fluid, p_f, and the differential pressure, Δp, in the borehole on the evening of 5 February, prior to the lake's unsealing (see Fig. 2*a*, curves 1 and 2). Before the unsealing run began, the fluid level in the hole was 50 m, and when the drill reached the bottom of the hole it rose up to 20 m below the top of the casing due to displacement of the fluid by the submerged drill and cable. The mean (effective) density of the fluid column $\langle\rho_f\rangle$ is defined as $\langle\rho_f\rangle = P_f/(gl_f)$, where l_f and P_f are, respectively, the height of the fluid column and the hydrostatic pressure at its bottom, and g is the local gravity acceleration. We estimate that during the last drilling run in borehole 5G-2, the mean density of the drilling fluid was $\langle\rho_f\rangle = 916$ kg·m^{-3}.

Using the similarly defined mean densities of ice $\langle\rho_i\rangle$ and subglacial water $\langle\rho_w\rangle$, and assuming equality between the ice overburden and the subglacial water pressure, the following expression for the expected water rise in the hole due to the lake unsealing can be obtained (see SOM):

$$l_w = \left(\frac{\langle\rho_i\rangle}{\langle\rho_f\rangle}H_i - l_f\right)\left[\frac{\langle\rho_w\rangle}{\langle\rho_f\rangle} + \left(\frac{d_w}{d_f}\right)^2 - 1\right]^{-1}. \quad (2)$$

Here l_w is the expected height of water column above the lake surface, H_i is the ice sheet thickness at the drilling site, d_f and d_w are the diameters of the borehole in its upper, cased part and in its bottom part filled with water, respectively. The corresponding fluid-level rise in the hole, Δh_f, is then defined as

$$\Delta h_f = -l_w\,(d_w/d_f)^2. \quad (3)$$

Using Eqs. (2) and (3) with the data gathered in the Table, and taking $d_f = 165$ mm, and $d_w = 138$ mm, we calculated that immediately after the breakthrough, with the drill still at the bottom of the hole, the water should rise 20 m above the surface of the lake, which would cause the fluid level to rise from 20 m to just 6 m below the top of the casing. During hoisting of the drill to the surface, the water level should rise to 59 m above the lake, while the level of the drilling fluid should drop to the 11 m mark. (The latter estimate accounts for a 2-metre drop in the fluid level due to fluid drained from the hole by the cable.)

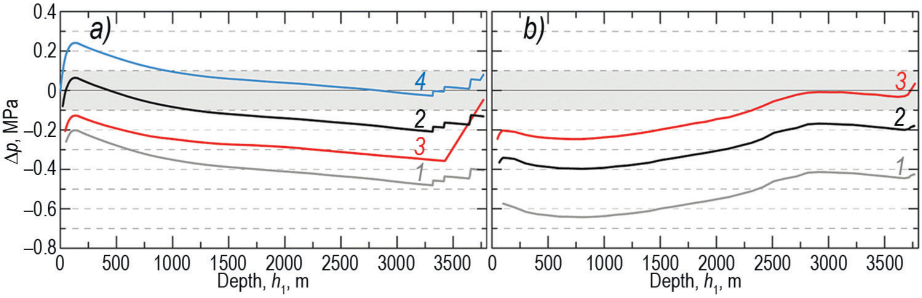

Fig. 2. Differential pressure (Δ*p*) in the borehole prior to and in the course of the first (*a*) and second (*b*) unsealings of Lake Vostok.

1 — immediately before lake unsealing (the drill is out of the hole); *2* — same as 1, but the drill is at the bottom of the hole; *3* — after equilibration of the drilling fluid and sub-ice water pressure in the hole; *4* — the moment when the drilling fluid first rose to the hole's mouth during the first unsealing of the lake.
The shaded band shows the typical uncertainty range for determining Δ*p* (±0.1 MPa). See text for various methods that were used to obtain Δ*p*

Рис. 2. Дифференциальное давление (Δ*p*) в скважине до и во время первого (*a*) и второго (*b*) вскрытий озера Восток.

1 — непосредственно перед вскрытием озера (буровой снаряд на поверхности); *2* — то же, что и 1, но снаряд на забое скважины; *3* — после выравнивания давления бурового раствора и озерной воды в скважине; *4* — момент начала излива буровой жидкость из устья скважины во время первого вскрытия озера.
Серая полоса — типичный диапазон погрешности определения Δ*p* (±0,1 МПа). Методы определения Δ*p* см. в тексте

Table

Summary of borehole observations immediately before and after Lake Vostok unsealings

Таблица

Результаты скважинных наблюдений непосредственно до и после вскрытий озера Восток

Characteristic	First unsealing	Second unsealing
Measurements and predictions before lake unsealing		
Level of drilling fluid in the hole, h_f (m)*	50 (20)	96 (66)
Mean density of drilling fluid, $\langle\rho_f\rangle$ (kg m^{-3})	916	926
Height of drilling fluid column, l_f (m)*	3709 (3739)	3663 (3693)
Differential pressure at the borehole bottom, Δ*p* (MPa)*	–0.41 (–0.14)	–0.46 (–0.19)
Mass of drilling fluid in the hole (t)**	59.53 (58.64)	58.37
Expected height of water column in the hole after lake unsealing, l_w (m)*	59 (20)	67 (26)
Expected level of drilling fluid after lake unsealing, h_f (m)*	11 (6)	51 (47)
Measurements and observations after lake unsealing		
Borehole depth at breakthrough, h_1 (m)	3769.3	3769.2
Water height in the hole estimated from measurements of the drilling fluid level, l_w (m)	–	60
Water height according to re-drilling results, l_w (m)	340	61
Level of drilling fluid after pressure equilibration, h_f (m)	43	48
Height of drilling fluid column, l_f (m)	3376	3650
Mean density of drilling fluid, $\langle\rho_f\rangle$ (kg m^{-3})	915	925
Mismatch between subglacial water pressure and ice overburden pressure, $(P_w - P_i)$ (MPa)	–0.05	–0.02
Mass of drilling fluid in the hole (t)	54.04	58.41
Mass of lost drilling fluid (t)**	5.49 (4.60)	–0.04

Note:
* The base values refer to the case when the drill is out of the hole, while the values in brackets refer to the position of the drill at the bottom of the hole.
** The value in brackets does not account for the mass of fluid in the abandoned section of hole 5G-1 (0.89 t). We assume that this fluid was displaced by subglacial water shortly after the first unsealing of Lake Vostok.
The estimates presented in the table are calculated for the following conditions: the vertical ice-sheet thickness H_i = 3758.6 m, the ice overburden pressure (inclusive atmospheric pressure) at the bottom of the ice sheet P_i = 33.85 MPa, the mean density of ice $\langle \rho_i \rangle$ = 915 kg m^{-3}, the mean density of subglacial water in the hole $\langle \rho_w \rangle$ = 1015.5 kg m^{-3} (adapted from [28]).

Примечание.
* Основные значения относятся к случаю, когда буровой снаряд находится на поверхности, значения в скобках — снаряд на забое скважины.
** Значения в скобках не учитывают массу буровой жидкости в аварийной части ствола скважины 5Г-1 (0,89 т). Мы предполагаем, что эта жидкость была вытеснена подледниковой водой вскоре после первого вскрытия озера.
Оценки, представленные в таблице, рассчитаны для следующих условий: вертикальная мощность ледникового покрова H_i = 3758,6 м; давление льда у подошвы ледника с учетом атмосферного давления P_i = 33,85 МПа; средняя плотность льда $\langle \rho_i \rangle$ = 915 кг·м$^{-3}$; средняя плотность подледниковой воды в скважине $\langle \rho_w \rangle$ = 1015,5 кг·м$^{-3}$ (адаптировано из [28]).

Given all the uncertainties of the input data, our post factum analysis seems to indicate that on the evening of 5 February 2012, the borehole condition was not unequivocally favourable for unsealing the lake. In particular, the level of the drilling fluid in the hole was probably too high, and its mean density too low, to ensure that the inflow of the lake water would be counterbalanced by the fluid rise in the casing and that there would not be any uncontrolled surface release of fluid.

3.2. Description of the last drilling run in borehole 5G-2

Drilling parameters during this run are shown in Fig. 3, where the moment in time when the drill was placed at the bottom of the hole is designated by number 1, and the moment of breakthrough is designated by number 2. According to the record, it took about 25 minutes to penetrate the remaining 85 cm of ice that had separated the bottom of the borehole from the lake since the previous drilling run was completed. The drill bit struck the surface of Lake Vostok at 11:21 pm local time at a depth of h_1 = 3769.3 m (h = 3758.6 m), as manifested by an unusually large increase in weight on bit (time point 2 in Figure 3) with a simultaneous loss of antitorque moment (not shown). The pressure deficit in the borehole was estimated to be only 0.14 MPa (see Table), but the hydraulic shock on breakthrough was strong enough to smash the drilled ice core and press its fragments against the top of the core barrel (see SOM for the ice core description).

The hoisting of the drill was initiated at 4 seconds following breakthrough, with a maximum available at this depth speed (~0.3 m s^{-1}). After approximately 1 min, drilling fluid began to flow out of the borehole mouth (Fig. 4*a*). It was estimated that 1.5 to 2.5 m^3 of drilling fluid was released through the top of the casing column, and only a small part of it was collected to a barrel [13]. The outflow lasted for 4.5 min, after which the fluid level fluctuated slightly near the top of the casing for 1 min and then slowly went downward. No signs of lake water degassing, such as gas bubbles reaching the top of the fluid column, were observed.

Apparently, the end of the fluid outflow from the hole mouth coincided in time with the moment when the drill broke off the water rising in the hole, which was recorded by a sharp decrease in weight of bit (time point 3 in Fig. 3). Another 4.5 min later, the water began to catch up with the drill again (time point 4). During the next 13 min, the

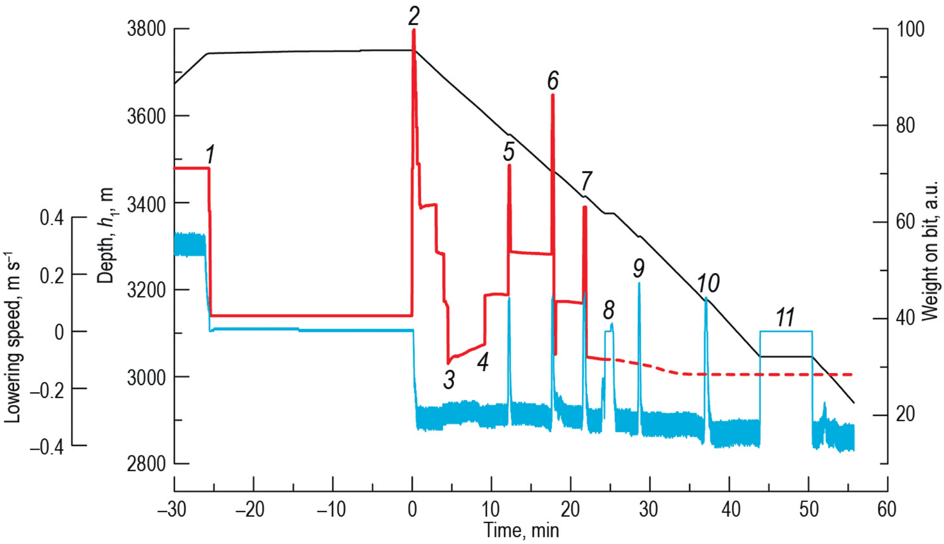

Fig. 3. Instantaneous depth of the drill (black), lowering/hoisting speed (light blue), and weight on bit (red) as recorded in the course of the first unsealing of Lake Vostok.

Time is counted from the moment the lake was breached. Numbers *1–11* mark the time points of the record discussed in the text. The dashed part of the red curve shows the readings of the weight-on-bit sensor after it has frozen

Рис. 3. Записи текущей глубины бурового снаряда (черная кривая), скорости его спуска/подъема (голубая кривая) и нагрузки на забой (красная кривая) в ходе первого вскрытия озера Восток.

Время отсчитывается от момента вскрытия озера. Цифрами *1–11* обозначены точки на кривых, которые обсуждаются в тексте. Пунктирная часть красной кривой отражает показания датчика нагрузки на забой после его замерзания

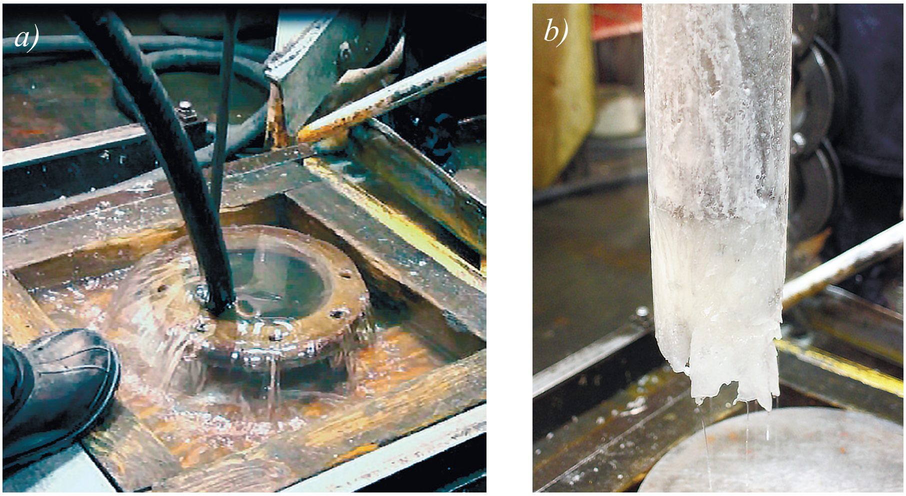

Fig. 4. Overflow of drilling fluid from the borehole mouth during the first unsealing of Lake Vostok (*a*), and the drill bit covered with frozen lake water after removing the drill from the hole (*b*)

Рис. 4. Излив буровой жидкости из устья скважины во время первого вскрытия озера Восток (*a*) и буровая коронка снаряда, покрытая замершей озерной водой, после подъема снаряда из скважины (*b*) effect of rising water on the weight-on-bit sensor readings was particularly strong when the drill lifting was paused several times to fix the winch spooling errors near the winch flanges (time points 5–7). Judging from the weight-on-bit record in Fig 3, the drill had finally cleared off the water soon after time point 7, at a depth of h_2 = 3410 m (h_1 = 3427 m), so that the subsequent episodes of stopping the drill lifting (time points 8–11) went unnoticed by the weight-on-bit sensor, which quickly froze after leaving the warm water into the cold drilling fluid.

At 02:00 am the next day, the drill, coated with ice, was retrieved from the borehole (Fig. 4*b*); traces of frozen water on the cable were observed up to at least 15 m above the cable termination.

Observations and measurements made during the subsequent austral winter showed that 1) the level of drilling fluid became stabilized at 43 m below the casing top, 2) the mean density of the fluid was 915 kg·m^{-3} based on measurements of 31 samples collected from between 50 and 3190 m depths, and 3) the new bottom of the hole appeared to be at a depth (h_1) of 3200 m.

3.3. Evidence from the re-drilling of borehole 5G-1 after first LV unsealing

The re-drilling of borehole 5G-1, filled with frozen subglacial water, began in the 2012/13 austral season from a depth of 3194 m, at which a drilling torque was recorded for the first time. Despite all measures taken to ensure that the drill would not deviate from the slant parent hole, sidetracking could not be avoided, and eventually a new 5G-3 branch hole was formed at a depth of 3459 m (Fig. 1). Re-drilling revealed that what was originally thought to be the hole bottom at a depth of 3200 m turned out to be a 60-cm long lump of solid white material, observed for the first time in the Vostok holes.

From this depth and down to 3385 m, the borehole diameter was only slightly smaller than it was before the lake unsealing, so re-drilling was reduced to reaming the hole with a conventional core head, without taking material from the hole into the core barrel. The chips collected after these reaming runs contained much of the white material similar to that observed in the lump discovered above.

Re-drilling revealed a gradual narrowing of the borehole between 3385 and 3427 m, caused by accretion of ice from subglacial water on the cold walls of the hole (Fig. 5*a*). The thickness of crescent-shaped fragments of congelation ice (frozen lake water) found in the chip chamber and core barrel increased with drilling depth. Concurrently, in the interval 3385–3427 m, the amount of solid white material in the hole increased. At first it came to the surface as a discontinuous core (Fig. 5*b*) until, finally, a full-diameter core consisting of an inner core of white material embedded in congelation ice began to be taken from a depth of 3424 m (Fig. 5*c*, *d*).

A preliminary study of the white material in the field showed that its density amounts 927±5 kg·m^{-3} and, in contrast with congelation ice, it degasses intensely when placed in warm water. Further investigation by X-ray powder diffraction and Raman spectroscopy showed that the white substance recovered from the Vostok borehole was an ice-hydrate mixture consisting of sII clathrate HCFC-141b hydrate (20–40 mass%), kerosene (37–39 mass%) and ice Ih [29]. Thus, it was confirmed that the subglacial water entering a borehole tends to react with the drilling fluid to form HCFC-141b hydrate, possibly mixed with air hydrate, as it was first observed in the EPICA borehole drilled in Dronning Maud Land, where HCFC-141b was also used as a drilling-fluid densifier [30].

In the 3424–3427 m depth (h_1) interval, the inner core of the ice-hydrate mixture was completely wedged out, so that below 3427 m the drilled ice core comprised only

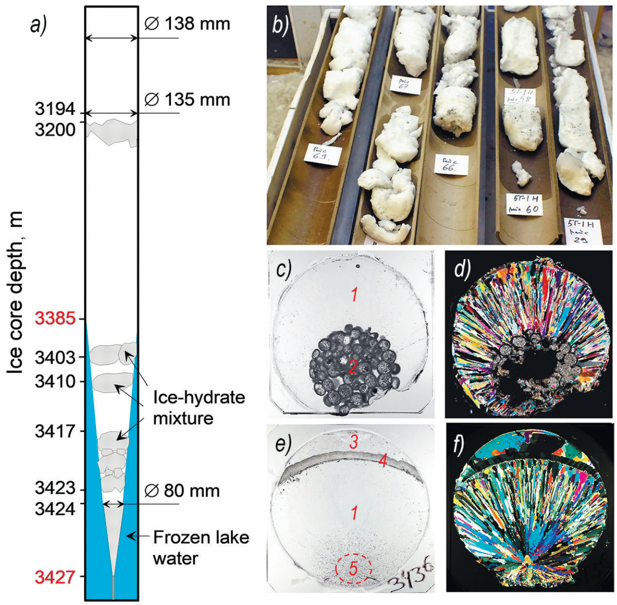

Fig. 5. Evidence from the re-drilling of borehole 5G-1 after the first unsealing of Lake Vostok (photos *c-f* adapted from [15]).

a — schematic representation of the borehole section 3194-3427 m partially filled with frozen subglacial water and white solid material that is a mixture of ice and HCFC-141b hydrate; *b* — discontinuous core of the ice-hydrate mixture from the depth interval 3417–3423 m; *c*–*f* — thin cross sections of the core at depths of 3426 m (*c*, *d*) and 3436 m (*e*, *f*), photographed in plain transmitted light (*c*, *e*) and between crossed polarizers (*d*, *f*)

On microphotographs *c, e*: *1* — frozen lake water; *2* — ice-hydrate mixture; *3* — host meteoric ice; *4* — layer of ice-hydrate mixture coating the wall of borehole 5G-1 which appeared in the core due to deviation of the drill from the parent hole; *5* — area around the central canal, which approximately coincides with the axis of borehole 5G-1

Рис. 5. Результаты повторного бурения скважины 5Г-1 после первого вскрытия озера Восток (фотографии *c-f* взяты из [15]).

a — схематическое изображение участка скважины 3194–3427 м, частично заполненного замерзшей подледниковой водой и белым твердым материалом, представляющим собой смесь льда и гидрата HCFC-141b; *b* — прерывистый гидратно-ледяной керн из интервала глубин 3417–3423 м; *c*–*f* — поперечные шлифы керна с глубин 3426 м (*c*, *d*) и 3436 м (*e*, *f*) в проходящем естественном (*c*, *e*) и поляризованном (*d*, *f*) свете.

На микрофотографиях *c*, *e*: *1* — замерзшая озерная вода; *2* — гидратно-ледяная сердцевина керна; *3* — вмещающий ледниковый лед; *4* — гидратно-ледяной слой, покрывающий стенку скважины 5Г-1, которая попала в керн в результате отклонения бура от основного ствола; *5* — область вокруг центрального канала, положение которого примерно совпадает с осью скважины 5Г-1

frozen lake water and an outer crescent-shaped segment of meteoric ice (Fig. 5*e*, *f*). Based on this, we conclude that the pressure equalization at the point of water inflow occurred when the water in the hole rose to a depth h_1 of 3427 m (which corresponds to a water level of 340 m above the ice-water interface) and the level of drilling fluid stabilized at 43 m below the casing top.

Texture and fabric studies performed on cross thin sections of ice cores showed that the congelation ice has a radial texture (Fig. 5*d*, *f*) with the preferred orientation of *c*-axes normal to the elongation axis of the ice crystals. This kind of ice fabric is consistent with the classical law of geometric selection, which implies that crystals exposing their fast growth direction (the prism plane) to the ice-water interface are preferentially developed.

Accretion of freezing lake water began from the cold wall of the borehole and proceeded at a slowing rate towards the borehole axis. Water freezing in the proximity of the central canal located near the hole axis occurred last of all, and was accompanied by entrapment of gas and liquid impurities rejected by growing ice crystals and pushed toward the hole axis (Fig. 5*e*). Some of these impurities may have flowed down the canal into the warmer, still unfrozen part of the borehole. In some cases, concentric layers differing in the size of ice crystals were observed in the thin sections of frozen water (Fig. 5*f*). Such layering indicates the stadiality in the ice accretion, and may serve as evidence of fluctuations in the water level in the borehole during the time elapsed from the lake's unsealing to the complete freezing of the water.

Chemical analyses of the frozen lake water confirmed that the concentration of liquid inclusions (drilling fluid) trapped by congelation ice during water freezing increases towards the hole axis and decreases from top downward as the sampling depth increases [15]. Interestingly, this study also revealed a kind of fractionation of organic compounds comprised in the drilling fluid that occurred as the water froze. The bulk of the frozen water (region 1 in Fig. 5*c*, *e*) was mainly contaminated with kerosene constituents (aliphatic, naphthenic, and aromatic hydrocarbons), but in the inner core of the ice-hydrate mixture (region 2 in Fig. 5*c*) and in the area around the central canal (region 5 in Fig. 5*e*) the concentration of HCFC-141b increased twofold. Moreover, near the central canal, where almost no organic compounds associated with kerosene were detected, the analysis showed relatively high concentrations (~30 $mg \cdot L^{-1}$) of phenol congeners that are usually added to kerosene in very small amounts to prevent oxidation. It was suggested that phenols, which, unlike other components of drilling fluid, have a high solubility in water, tend to be excluded, along with other dissolved impurities and gases, from the growing congelation ice and concentrate near the central canal that freezes last [15].

Unfortunately, the overall high organic contamination of the analyzed samples (≈15 % by volume) [15] and the possible biological and technogenic contamination of the congelation ice by drilling fluid, cable armour and drill [8, 31] rendered it essentially irrelevant for studying the chemical, gas, and biological properties of the lake water from which this ice was formed.

3.4. Reconstructing water and drilling fluid movements in the borehole during the first LV unsealing

Even in the absence of a fluid level record, the data reported above enables us to piece together an aggregate picture of what happened in the borehole on the night of February 5–6 2012, which led to an unexpectedly high water rise in the hole.

According to our calculations, if the drill had not been lifted up from the bottom of the hole directly after the breakthrough, pressure equalization at the point of water inflow would have occurred when the height of the water in the hole reached 20 m above the lake surface, and the rise in the fluid level would have stopped at 6 m below the top of the casing.

In reality, however, this 6-metre margin (equivalent to a pressure of 0.05 MPa, which is less than uncertainties of our estimates) was reached and surpassed within the first minute following breakthrough, resulting in the surface release of the fluid. Because the unfilled part of the casing was too short to allow for balancing the water head by increasing the height of the fluid column, complete pressure equalization at the point of water inflow could now only be achieved by replacing the relatively light drilling fluid in the hole with the heavier lake water. And since the height of fluid column was limited from above, every 100 metres of water rise resulted in an increase in pressure at the base of the borehole by only 0.1 MPa.

Based on the data in hand, the average rate of water upsurge during the first minute following breakthrough (0.5 $m \cdot s^{-1}$) exceeded the speed of drill hoisting (0.3 $m \cdot s^{-1}$), so that the water had outrun the 12-metre long drill by the time the fluid reached the top of the casing. Judging from the traces of frozen water on the cable, the water slug above the drill could be up to 15 m long. The decrease in the rate of water rise, as the equilibrium pressure approached, was partially compensated by a strong swabbing effect due to the high speed of drill hoisting.

Water was still rising in the hole when the fluid overflow ended at 4.6 min following the breakthrough. This clearly indicated the existence of lateral outflow (loss) of fluid from the borehole. Another minute later, the fluid level began to drop, indicating that the rate of the water rise had become less than the rate of the lateral fluid outflow. This, in turn, led to an increase in the pressure imbalance in the hole and, consequently, to a temporary, slight acceleration of the water rise.

Shortly after passing time point 4 (Fig. 3), at 10 min following breakthrough, the rate of the water rise slowed down again as the drill reached the junction between boreholes 5G-2 and 5G-1 at a depth of 3600 m (Fig. 1) and the rising water began to replace the drilling fluid in the abandoned part of the 5G-1 hole.

Eventually, at 22 min following breakthrough, the water rise almost ceased at a depth (h_1) of 3427 m. In the 3427–3385 m depth interval, the drill kept pushing the water slug above it. Water gradually ran down through the annulus between the drill and the borehole walls, forming an inverted-cone-shaped icy shell on the walls (Fig 5*a*), while the remaining water inside the drill froze, disabling the weight-on-bit sensor.

Most likely, displacement of the drilling fluid with water in the abandoned hole was accompanied by an upward slug flow of two-component (water-in-drilling fluid) emulsion which further complicated the dynamics of water-fluid interaction, forming a disperse system that promoted the formation of HCFC-141b hydrate. As a result, the entire water column frozen in borehole 5G-1 between 3666 and 3427 m was contaminated with drilling fluid components. The re-drilling data (Fig. 5*a*) suggest that the dispersed water reached well above the maximum water rise and contributed to the formation of a hydrate layer on the borehole walls and lumps of hydrate-ice mixture inside the borehole up to 572 m above the lake surface (h_1 = 3194 m).

Our estimates of the mass of drilling fluid in the borehole before and after the lake unsealing (see Table) show that a total of about 5.5 t of fluid was lost during the unsealing operation. Assuming that the surface release accounts for 1.4 to 2.3 t [13], the remaining 3.2–4.1 t of fluid must have seeped out of the hole laterally.

Hydraulic fracturing in the borehole was first invoked to explain this lateral fluid outflow [12–14]. Although hydrostatic overpressure in the Vostok borehole before and during the lake unsealing (Fig. 2) was well below the hydraulic fracture pressure for an intact borehole walls [32], such fracturing could have developed in the brittle ice zone observed at Vostok between depths of 250 and 750 m [19]. Crack nuclei in the borehole walls could have been formed here due to the thermal drill used in this depth range, and also due to the low level of drilling fluid maintained during the drilling of hole 5G in the 1990s [33].

The alternative, and perhaps the most plausible, explanation for the significant lateral fluid loss from the borehole is the casing leakage. Indeed, recent tests which involved changing the fluid level indicated that the casing is likely to be leaking at about 40 m below its top, and in 2018, casing damage at that depth was recorded by a downhole video camera.

The experimental data gathered in the Table allow us to calculate a mismatch between subglacial water pressure, P_w, and the ice overburden pressure, P_i, at the ice sheet sole as:

$$P_w - P_i = g(l_f \langle\rho_f\rangle + l_w \langle\rho_w\rangle - H_i \langle\rho_i\rangle), \quad (4)$$

where H_i is the ice-sheet thickness at the site of drilling, and l_f and l_w are the heights of the drilling fluid and water columns, respectively, after pressure equilibration. The obtained pressure mismatch (–0.05 MPa) is considerably less than the uncertainty of our estimate of ~0.1 MPa. This implies that within this uncertainty, the ice sheet is in hydrostatic equilibrium at the drilling site, and the hypothesis that the pressure in the lake is much higher than the ice overburden pressure [34] can be safely ruled out.

Summarizing the above, we have to admit that a number of mistakes were made during the first unsealing of SLV, which led to a high water rise in the hole. The most important of these include: the low density of the drilling fluid, a high fluid level in the casing prior to the unsealing, and the high speed of the drill lifting following the breakthrough, which caused a strong swabbing effect. The subsequent surface release of the drilling fluid, along with the casing leakage, resulted in water rising above the junction with the abandoned hole 5G-1 and in the onset of the upward slug flow of water-fluid emulsion, thus making it impossible to foresee what would happen next.

Fortunately, the water rise stopped well below the critical depth (~1500 m [21, 25]) above which explosive degassing of SLV with unpredictable consequences would have been possible.

The knowledge and experience gained during the first unsealing of Lake Vostok came in handy when preparing and conducting the second unsealing of the lake in 2015.

4. The second unsealing of Lake Vostok

Drilling of the 5G-3 branch hole continued for the next three austral seasons until finally in January 2015, the borehole approached the surface of the lake for the second time. Provided that during the first lake unsealing we had indeed reached and broached the ice-sheet bottom, and that the water entered the hole directly from the lake and not through intergranular cracks in the ice massive as could also be assumed [35], it was possible to accurately predict the depth of the second breakthrough and anticipate the drilling run during which it would occur. We planned and conducted the second unsealing of SLV based on the above assumption.

4.1. Borehole condition prior to breakthrough

In December 2014 to January 2015, a total of over 1.8 t of HCFC-141b densifier was injected into the borehole to depths ranging from 500 to 3,720 m to increase the mean fluid density as required. After reaching a depth (h_1) of 3764.6 m, which is ~4.5 m above the expected ice-water interface, a series of borehole activities (hole reaming, fluid density and pressure measurements and adjustments) were carried out on 15–22 January. The resulting profile of differential pressure in the borehole prior to the second unsealing of the lake is shown in Fig. 2*b*. Before the unsealing run began, the mean fluid density in the hole was 926 kg·m^{-3} and the fluid level was set at 96 m, which, according to Eqs. (2) and (3), meant that following breakthrough, the water should initially rise 26 m above the surface of the lake, resulting in an increase in the drilling fluid level to 47 m below the casing top. Final pressure equilibration in this case should have been expected at l_w = 67 m and h_f = 51 m (compare with similar estimates for the first lake unsealing in the Table). Based on previous experience, it was concluded that the borehole conditions were now favourable to proceed with the second unsealing.

4.2. Description of the unsealing run in borehole 5G-3

The introduction of an acoustic level meter (Sigma-ART) into the practice of borehole activities at Vostok was instrumental for the securing smooth running of the second SLV unsealing.

After calibration against a float level gauge, the acoustic meter allowed near real-time monitoring of the fluid level, h_f, with an accuracy of ±1.5 m and a fairly accurate assessment of the water level changes in the hole prior to and following breakthrough. Assuming zero lateral liquid outflow from the hole below a depth of 40 m, and neglecting thermal-expansion and compressibility effects, the current water height in the hole, l_w, was estimated from the fluid level data:

$$l_w = (h_f^* - h_f)\,(d_f/d_w)^2, \qquad (5)$$

where h_f is the measured level of drilling fluid and h_f^* is the fluid level which would be observed in a routine drilling run with no water entering the hole. The h_f^* values for different depths of the drill were obtained from the time-lapse data on the fluid level

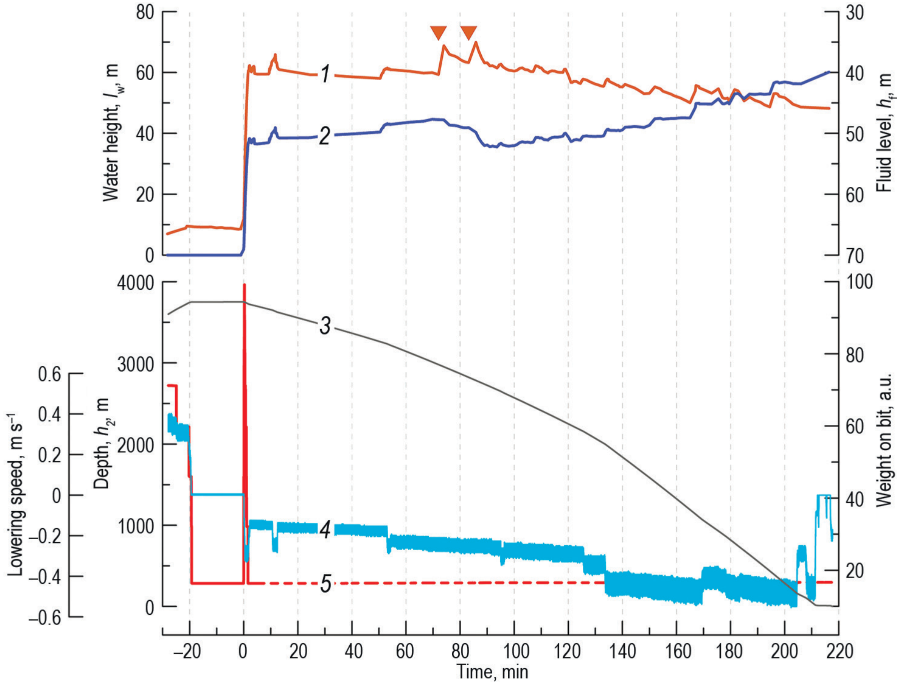

Fig. 6. Drill and liquid control records from the second unsealing of Lake Vostok.

1 — depth of the drilling fluid level below the top of the casing, h_f (the ordinate is inverted); *2* — estimated water height above the lake surface, l_w; *3* — depth of the drill; *4* — lowering/pulling speed of the drill; *5* — weight on bit (the dashed part of the curve – readings of the sensor after it has frozen).

The triangles mark the moments when we began to pour kerosene (2×100 litres) into the borehole through its mouth. Time is counted from the moment the lake was breached

Рис. 6. Записи контроля бурения и жидкости при втором вскрытии озера Восток.

1 — расстояние от уровня заливочной жидкости в скважине до верха обсадной колонны, h_f (ось перевернута); *2* — расчетная высота подъема воды в скважине, l_w; *3* — глубина снаряда; *4* — скорость спуска/подъема снаряда; *5* — нагрузка на забой (пунктирная часть кривой — показания замершего датчика нагрузки).

Треугольниками отмечены моменты начала заливки керосина в скважину (2×100 литров). Время отсчитывается от момента вскрытия озера change while the drill was being lowered into the hole. These data were corrected for the fluid drained from the hole by the cable and for the addition of 200 litres of kerosene to the top of the fluid column after the breakthrough (see below).

The second unsealing of Lake Vostok was accomplished on 25 January 2015. The drill reached the surface of the lake during the drilling run in which this was expected, and at virtually the same depth (h_1= 3769.2 m) as three years earlier. The records of h_f and l_w during the unsealing run are shown in Fig. 6 along with other drilling parameters. The plots presented here give immediate and reliable information on the liquid movements in the hole following breakthrough.

As with the first lake unsealing, the subglacial water rushing into the hole outran the drill by ~3 metres in the first minute after the drill lifting started. This time, however, the rise of drilling fluid column in the hole was not limited by the top of the casing and the rate of water upsurge rapidly decreased as it approached the current (for a given drilling depth) pressure equalization at the point of water inflow. Therefore, although the drill hoisting speed was halved compared to the first lake unsealing in order to reduce the swabbing effect, already at the 4th minute of hoisting (at a depth h_1 of ~3724 m) the drill broke away completely from the water column rising behind it. At the same time, the drill could, for a long time, continue to push a slug of water and water-fluid emulsion above it. Judging by the traces of ice and ice-hydrate mixture on the cable, the length of this plug could initially reach 10–12 m, but it then decreased as it was washed downward during the drill lifting. Shortly after the drill came out of the water, the weight-on-bit sensor froze and stopped working.

Attempts to increase the speed of drill lifting made at 11 and 53 min following breakthrough resulted in an increased swabbing effect and a sharp rise in the fluid and water levels (see Figure 6), so they were abandoned.

To reduce the water rise caused by a decrease in the height of the overlying fluid column as the cable emerged from it, pure kerosene was added into the hole twice, at 72 and 83 min following breakthrough (100 litres each time). The resulting rise in the drilling fluid level and the drop in water level can be clearly seen in the h_f and l_w curves in Fig. 6. A temporary fluid rise slightly above the level of the casing leakage (40 m) did not, apparently, significantly affect the calculated values of l_w, because the initial (excluding added kerosene) mass of fluid in the borehole remained unchanged within the uncertainties of its estimate (see Table).

The subsequent gradual rise of water in the borehole was due to a drop in the fluid level as the cable and the drill were pulled out of the borehole. The short-term fluctuations of h_f and l_w seen in Fig. 6 are mainly related to the uneven speed of the hoisting, which was eventually increased when the drill entered the wider part of the borehole at a depth of 2200 m.

Fluid level observations continued for some time even after the drill was brought to the surface, until the level was completely stabilized at h_f = 48 m (l_w = 60 m). The measured values coincided reasonably well with the predictions (see Table) considering the addition of 200 litres of kerosene into the hole during the drill hoisting. Measurements made by a KMT downhole logger four days after the lake unsealing showed that up to the borehole bottom encountered at h_1 = 3696 m the mean density of the drilling fluid was 925 kg·m^{-3}, i.e. practically the same as measured before the unsealing run began.

4.3. Evidence from the re-drilling of borehole 5G-3 after the second LV unsealing

It was decided to start re-drilling hole 5G-3 just 5 days following breakthrough, when, according to preliminary calculations, the water in the hole should have already frozen. Eleven drilling runs were conducted from January 30 through February 3, yielding core

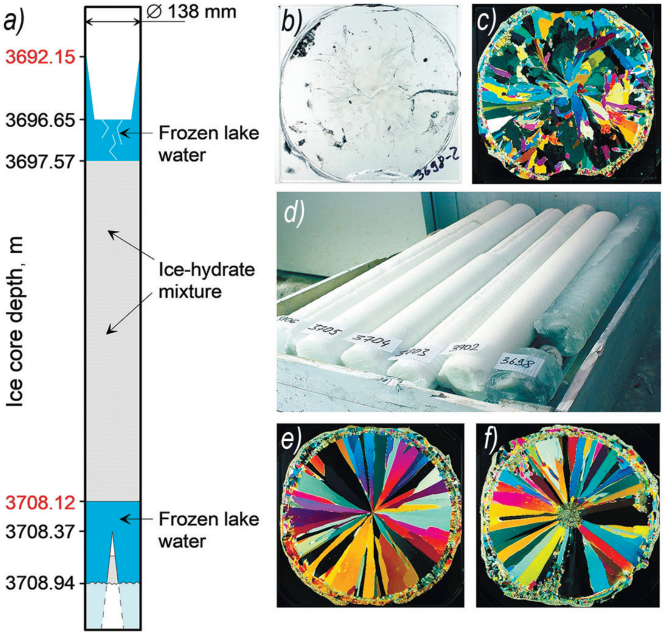

Fig. 7. Evidence from the re-drilling of borehole 5G-3 after the second unsealing of Lake Vostok (*a*, *c*, *f* are from [36]).

a — schematic representation of the borehole section 3692–3709 m filled with frozen lake water and ice-hydrate mixture; *b*, *c* — thin cross section of the core at a depth of 3696.75 in plain transmitted light (*b*) and between crossed polarizers (*c*); *d* — continuous solid core of ice-hydrate mixture from the depth interval 3697.57–3708.12 m; *e*–*f* — thin cross sections of the core at 3708.20 m (*e*) and 3708.92 m (*f*) between crossed polarizers

Рис. 7. Результаты повторного бурения скважины 5Г-3 после второго вскрытия озера Восток (*a, c, f* взяты из работы [36]).

a — схематическое изображение участка скважины 3692–3709 м, заполненного замерзшей озерной водой и гидратно-ледяным материалом; *b, c* — поперечный шлиф керна с глубины 3696,75 м в проходящем естественном (*b*) и поляризованном (*c*) свете; *d* — непрерывный гидратно-ледяной керн из интервала глубин 3697,57–3708,12 м; *e–f* — поперечные шлифы керна с глубин 3708,20 м (*e*) и 3708,92 м (*f*) в поляризованном свете

from a depth interval of 3692.15–3708.94 m (Fig. 7). Drilling was halted when subglacial water entered the hole for the second time during this field season.

Re-drilling revealed that a 10-metre plug composed of an ice-hydrate mixture had formed above the freezing water and completely filled the borehole volume in the depth interval 3697.57–3708.12 m (Fig. 7*a*, *d*). A 92 cm thick layer of fractured congelation ice containing traces of unfrozen water was found immediately above the plug (Fig. 7*b*, *c*). The volume of this layer was about 15 litres, which roughly corresponds to the amount of water that may have drained out of the drill's compartments after the drill emerged from the water rising in the hole. The fact that liquid water accumulated on the top of the plug indicates that the latter began to solidify while the water was still rising in the hole behind the drill.

Deeper than the hydrate plug, in the 3708.12–3708.94 m depth interval, the core was composed of congelation ice with a radial texture characteristic of water frozen in the hole (Fig. 7*e*, *f*). The lower part of this core had a still unfrozen central canal (Fig. 7*f*), through which the lake water began to seep into the hole when the drill reached it. The top of the frozen water column appeared at a depth of 3708.12 m, or 61 m above the lake surface, which agrees well with both the fluid level monitoring data and the initial targets.

The data obtained during the second SLV unsealing confirmed a difference of virtually zero between subglacial water pressure and ice overburden pressure at the drilling site, as established during the first unsealing (see Table). Calculations based on the estimated volume and mean density of the drilling fluid showed no loss of fluid mass during the unsealing operation.

To summarize the above, the second SLV unsealing went as planned, without major drilling surprises or miscalculations.

5. Summary and outlook

The first two unsealings of Lake Vostok, masterminded by Nikolay Vasiliev, were important (and indispensable) pioneering steps on the challenging road to full-scale exploration of the biggest subglacial lake on Earth.

The invaluable experience and knowledge gained during the first unsealing of the lake was fully taken into account when preparing and conducting the second. In particular, the miscalculations made during the first attempt to unlock SLV were recognized and corrected, and monitoring of the liquid movements in the borehole was introduced. These changes made it possible to eventually achieve good compliance of the actual results of the whole operation with the set targets.

During the two SLV unsealings, the most accurate data to date on ice sheet thickness (3758.6±3 m) and ice overburden pressure (33.85±0.05 MPa) at the drilling site were obtained and revalidated. It was shown that the mismatch between subglacial water pressure and ice overburden was very close to zero (within uncertainty of 0.1 MPa), which means that the ice sheet is most likely in hydrostatic equilibrium at this site.

Unfortunately, hopes that the subglacial water frozen in the borehole would be useful for studying the original properties of SLV's water were not fully realized. Severe organic, biological and technogenic contamination of the congelation ice core, recovered before the drills deviated from the parent boreholes, has largely rendered them unsuitable for studying most subglacial water properties except for isotopic composition [37]. The rare exception so far has been the congelation ice sample obtained after the second lake unsealing, which provided, through rigorous decontamination and control procedures, evidence that the lake surface water that entered the borehole does not contain microbial DNA [38]. On the positive side, important new insights into both the conditions of accreted ice formation, and the environments and the hydrological regime of Lake Vostok were obtained by studying two replicate cores from holes 5G-2 and 5G-3, which both reached the surface of the lake (see e.g., [9, 39, 40]).

The re-drilling of the Vostok boreholes that were filled with frozen lake water showed that in all cases a solid white substance, a mixture of ice and HCFC-141b hydrate, is formed in the drilling fluid-lake water interaction zone. Hydrate formation was found to occur almost instantaneously, even before the completion of the drilling run in which the lake was unsealed. The solid substance that forms partially or completely fills the borehole and prevents any attempt to sample the liquid lake water. The latter means that the existing deep borehole filled with a mixture of kerosene and the dichlorofluoroethane HCFC-141b cannot be used as an access hole for investigating SLV. The previously proposed replacement of the currently used drilling fluid in the bottomhole zone with a fluid that does not react with water (e.g., organosilicon fluid) [29] may, in our opinion, only further complicate the interaction between different fluids in the hole and create as yet unknown technological problems, while not addressing the existing environmental concerns.

However further investigations might proceed, the undying scientific and public interest in exploration of subglacial Antarctic environments and, in particular, Lake Vostok give us hope that the work started by Nikolay Vasiliev's team will be continued. The next grand challenge ahead is sampling and in-situ investigations of SLV's water column and bottom sediments.

The experience of two unsealings of Lake Vostok shows conclusively that there is a need to develop new technology, or adapt those previously devised [see e.g., 41, 42] to the extreme conditions of Vostok, in order to access and study subglacial environments, which would enable us to obtain uncompromised scientific data.

Preparing and carrying out the full-scale exploration of Lake Vostok will require significant financial and human resources. We would like to believe that with the commissioning of the new wintering complex at Vostok station, the time for this new Antarctic venture will come.

Supplement. Supplementary material related to this article is available online at: http://cerl-aari.ru/index.php/lv

Competing interests. The authors declare that they have no conflict of interest.

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Вскрытие подледникового озера Восток: уроки и выводы для будущих полномасштабных исследований

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Расширенный реферат

Два вскрытия крупнейшего на нашей планете подледникового озера Восток, осуществленные под руководством профессора Санкт-Петербургского горного университета Николая Ивановича Васильева, стали выдающимися событиями в истории антарктической науки. Бесценный опыт и знания, полученные во время первого вскрытия озера 5 февраля 2012 г., были полностью учтены при планировании и проведении второго вскрытия подледникового водоема, которое было выполнено 25 января 2015 г. с минимальными отклонениями от заданных параметров.

В ходе этих уникальных буровых операций были получены самые точные на сегодняшний день оценки мощности ледникового покрова (3758,6 ± 3 м) и давления льда на контакте ледника с подледниковым водоемом (33,85 ± 0,05 МПа) в пункте бурения. Было установлено, что разница давлений воды и льда на границе раздела близка к нулю и, следовательно, ледниковый щит на этом участке находится в гидростатическом равновесии с озером.

К сожалению, надежды на то, что поднявшаяся в скважину подледниковая вода окажется полезной для изучения среды озера Восток, оправдались не в полной мере. Сильное органическое, биологическое и техногенное загрязнение керна замерзшей воды озера, который был получен до выхода бурового снаряда из материнской скважины, сделало его практически непригодным для изучения большинства свойств подледниковой воды, кроме ее изотопного состава. Редким исключением стала проба конжеляционного льда, полученная после второго вскрытия озера, которая, благодаря строгим процедурам деконтаминации и контроля загрязнения, позволила сделать вывод о том, что поверхностная вода озера, попавшая в скважину, скорее всего, не содержит микробную ДНК (см. Bulat et al. в этом номере). Вместе с тем исследования двух параллельных кернов из скважин 5Г-2 и 5Г-3, достигших поверхности озера, позволили получить новые данные как об условиях формирования нарастающего на нижнюю поверхность ледника озерного льда, так и о среде и гидрологическом режиме озера Восток (Ekaykin et al. в этом номере).

Повторное бурение скважин, заполненных замерзшей озерной водой, показало, что во всех случаях в зоне взаимодействия заливочной жидкости и подледниковой воды образуется твердое белое вещество — смесь льда и гидрата фреона HCFC-141b. Было установлено, что образование гидрата происходит практически мгновенно, еще до завершения бурового рейса, в котором производилось вскрытие озера. Образующееся твердое вещество частично или полностью заполняет скважину и препятствует любым попыткам взять пробу жидкой озерной воды. Последнее означает, что существующая глубокая скважина, заполненная смесью керосина и дихлорфторэтана HCFC-141b, не может быть использована в качестве скважины доступа для проведения прямых исследований подледникового водоема. Предложенная ранее замена используемой в настоящее время буровой жидкости в призабойной зоне скважины на жидкость, не реагирующую с водой (например, кремнийорганическую), может, на наш взгляд, лишь еще больше усложнить взаимодействие различных жидкостей в скважине и создать пока неизвестные технологические проблемы, не разрешив при этом существующих экологических озабоченностей.

По какому бы пути ни пошли дальнейшие исследования озера, неугасающий научный и общественный интерес к изучению подледниковой среды Антарктиды вообще и озера Восток в частности дает нам надежду на то, что работа, начатая командой Н.И. Васильева, будет продолжена. Следующая грандиозная задача — проникновение в подледниковый водоем с целью проведения отбора проб и прямых исследований водной толщи и донных осадков озера Восток. Подготовка и осуществление проникновения в озеро потребуют создания новых буровых и исследовательских технологий, а следовательно, значительных финансовых и человеческих ресурсов. Хочется верить, что с вводом в эксплуатацию нового зимовочного комплекса станции Восток придет время и для этого нового масштабного антарктического проекта.

Ключевые слова: подледниковое озеро, глубокое бурение, скважина доступа, вскрытие, повторное бурение, гидрат фреона HCFC-141b

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