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Contents

Содержание

Dedicated to the memory of Nikolay Vasiliev,
who for many years led the deep drilling project at Vostok Station

Editors' Preface

Lake Vostok and other subglacial lakes emerged as an important new frontier in Antarctic science at the end of the last century. Today, the exploration of subglacial Antarctic environments, which are thought to affect ice sheet dynamics, house unique microbial ecosystems, and hold yet unmatched sedimentary records of past climate change, is one of the priorities for Antarctic research set by the 1st SCAR Horizon Scan in 2014 for the next two decades and beyond.

With an area exceeding 15000 km^2 and water depth reaching 1200 m, Lake Vostok, buried beneath the 4 km thick East Antarctic ice sheet, is the largest subglacial water body on our planet. The origin and the contemporary state of Subglacial Lake Vostok (SLV) are closely related to the geologic evolution, climatic history, and development of ice cover of the Antarctic continent. As an old, deep tectonic lake isolated from the open atmosphere and surface biota for millions of years, Lake Vostok has great potential for harbouring exotic life. A success in the search for life in the lake's environments (accreted ice, lake water, and sediments) would yield exciting microbiological and biogeochemical findings, which might provide new insights into development of life on Earth and have important methodological and motivational implications for the exploration of extraterrestrial icy ecosystems.

SLV is located in the traditional area of scientific and logistic activity of the Russian Antarctic Expedition. Vostok Station was established in 1957, long before the discovery of Lake Vostok. By a happy coincidence, it was built at the southern end of the lake, which not only favours Russian efforts to explore the lake, but also makes such efforts almost mandatory.

In 1999–2013, including the International Polar Year 2007/08, Russian exploration at Lake Vostok was carried out as part of a special project within the framework of the long-term "World Ocean" Federal Targeted Programme, sub-programme "Antarctica". This project was implemented by a consortium of eight Russian research institutions led by the Arctic and Antarctic Research Institute (AARI) of Roshydromet.

During this period, geophysical, geodetic, and glaciological traverses were carried out all over the lake and its surroundings. The main output of this large-scale field activity was a series of 1:1 000 000 maps of the lake water table limits, the ice and water body thickness, and the bedrock relief. Coordinated field and modelling efforts yielded improved estimates of the contemporary distribution of the accreted (lake) ice thickness, its age, and freezing rates along the Vostok flow line. The laboratory analyses of accreted ice, extracted as a core from the deep boreholes drilled at Vostok, provided the first important insights into the environments and hydrological regime of the subglacial water body. Biological and chemical studies performed using state-of-the-art decontamination procedures led to a preliminary conclusion that the lake water from which this ice was

formed may have a very low microbial content, suggesting that the main water body of SLV may also be an extremely dilute biological solution, and that life in the lake, if any, is restricted to the bottom sediments.

Drilling of deep borehole 5G began at Vostok Station in February 1990 and reached the surface of Lake Vostok only after more than two decades of complex operations. In 1999–2001, researchers at the AARI and St. Petersburg State Mining Institute proposed an environmentally friendly approach to the unsealing of SLV. However, the chance to put the technology that was developed into action came only in 2012, when, on February 5, borehole 5G-2, the second deviated branch borehole at Vostok, broached the surface of the subglacial lake for the first time. This landmark milestone in the history of Antarctic research reverberated around the world, and in the December 2012 issue of *Nature*, the first unsealing of Lake Vostok was listed among the biggest scientific breakthroughs of the year.

The pre-entry phase of SLV's exploration has been completed. The results of research into accreted ice and lake water frozen in the hole after the lake's unsealing often led to ambiguous (and sometimes conflicting) evidence about life in the lake, the biogeochemistry of the lake water, and the possible influence of hydrothermal activity in SLV. The general consensus is that existing discrepancies will not be resolved until water and sediments are collected *in situ* and analyzed in laboratories under clean conditions. The next grand challenge ahead is to develop technologies and tools that will allow clean entry into the lake, conduct *in situ* studies, and sample the SLV water column and bottom sediments. We hope that with the commissioning of the new wintering complex at Vostok station, the time for this new Antarctic venture will come.

This special issue of *Arctic and Antarctic Research* was originally conceived to mark the tenth anniversary of the first unsealing of Lake Vostok. But we ran over time, and it so happens that it will now be published a decade after the second successful unsealing of the lake on January 25, 2025. The papers presented here cover most areas of research related to the exploration of SLV and other Antarctic subglacial lakes: ice drilling technology, accreted ice analyses, molecular biological and mineralogical studies, and the geophysical survey of the lake.

The authors of this special issue dedicate it to the memory of Nikolay Vasiliev (1948–2021), a renowned professor at the St. Petersburg Mining University. His name is inextricably linked to the most exciting achievements in the legendary venture to drill through the ice at Vostok Station. For many years he was the key person leading this project, which played a vitally important role in the study of past climate change on our planet. It is under his leadership, and with his direct participation, that Lake Vostok was unsealed for the first time, making it possible to study the core of accreted ice and opening the door to further exploration of this unique under-ice water body.

Vladimir Lipenkov, Pavel Talalay

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A scientific journey: Nikolay Vasiliev's quest to perfect the tools to drill into deep Antarctic ice

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Abstract. Since the early 1950s, when extensive exploration of Antarctica began, drilling has become an integral part of many large-scale scientific projects carried out on the sixth continent. Thanks to the rapid development of drilling equipment and technology, numerous scientific discoveries have been made in the fields of paleoclimatology, geology, glaciology, and other natural sciences. Since 1968, the St. Petersburg Mining University has played a leading role in this area's development, and several generations of ice drilling specialists were trained within its walls. One of the most outstanding was Nikolay Vasiliev, who led Antarctic research at the university from 2002 to 2021. His contribution to the development of ice core drilling in Antarctica cannot be overestimated. Professor Vasiliev's extensive and highly creative work laid the foundation for many achievements in this field over the past 30 years. His path is a brilliant example of hard work and dedication to one's cause. This article is a tribute to Professor Vasiliev, who is cherished by his friends and colleagues who had the good fortune to work and study with this talented person and scientist.

Keywords: Antarctica, glacier drilling, electromechanical drill, warm ice drilling, Lake Vostok

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The main thing, in my opinion, is a spark in the soul, personal motivation, belief in success, the desire to go forward despite difficulties, and the ability to never give up.

Nikolay Vasiliev (1948–2021)

Introduction

Professor Nikolay Vasiliev was, for many years, the permanent leader of the deep core drilling project at the Russian Antarctic Vostok Station. Under his direct supervision, the deepest ice borehole (3769.3 m) [1] was drilled, and the largest subglacial water body on our planet — Lake Vostok [2] — was penetrated twice. Vasiliev spent two wintering periods (lasting over a year each) and 12 field seasons (two to three months at

Professor Vasiliev at the Mining University

Профессор Горного университета Н.И. Васильев

a time) at Vostok Station, as well as five field seasons on the glaciers of the Severnaya Zemlya archipelago, as part of the high-latitude expedition A-162 and the international PEGAIS project "Global Arctic Climate Change" [3].

Vasiliev's achievements in the field of deep ice drilling have made him famous as an outstanding specialist both in Russia and abroad. He contributed to the development of international scientific and technical cooperation in the polar regions and was one of the key participants in the Russian-French-American project on ice core drilling and research at Vostok Station (1989–1998), as well as in long-term Russian-French collaboration on ice core research and paleoclimate studies (2001–2019). Professor Vasiliev was a regular participant in numerous international events dedicated to ice drilling techniques and technology, such as ice drilling symposia, Russian-French seminars, competitions, and engineering exhibitions.

Vasiliev successfully combined his scientific work with teaching. He taught at the well drilling department of St. Petersburg Mining University for over 20 years, 13 of which he served as head. He is the author of 120 published works and patents for inventions, and supervised three doctors of science who participated in drilling operations at Vostok Station.

During his career, Professor Vasiliev received a number of awards, including the Order "For Merit to the Fatherland" (fourth class) and the Award of the Government of the Russian Federation in the field of science and technology.

In this article, we would like to discuss Vasiliev's life, his key scientific achievements, and the significance of his work for the development of Russian science.

The beginning of the journey

Nikolay Vasiliev's admission to the Leningrad Mining Institute in 1966, specializing in mining machines and complexes, marked the beginning of his development as an engineer and inventor. While still a student, young Nikolay became involved in the scientific life of the Department of Mining Machine Design; his first scientific article was on the development of gearing theory [4]. After qualifying as a mining mechanical engineer in 1971, Vasiliev started working at his university department as a laboratory assistant, focusing on problems related to upgrading vibratory conveyors. The results of

Graduation photograph of Nikolay Vasiliev, aged 23, at the Leningrad Mining Institute, now the St. Petersburg Mining University (1971)

Фотография 23-летнего Николая Васильева из выпускного альбома 1971 года Ленинградского горного института (ныне Санкт-Петербургский горный университет) his work, carried out between 1971 and 1978, were reflected in scientific publications, copyright certificates, and patents. Vasiliev's successes in designing mining machines and equipment attracted the attention of the management of the Mining Thermophysics Laboratory, which included the Antarctic Research Department (ARD).

Beginning in 1967, scientists from the Antarctic Research Department and their colleagues from the Arctic and Antarctic Research Institute (AARI) carried out deep drilling and ice core research in Antarctica. The result of a decade of cooperation was a 'dry' borehole drilled at Vostok Station to a depth of 952.8 m, which is still the deepest borehole drilled in ice without using drilling fluid [5]. Vasiliev received an invitation to take up the position of senior engineer at the Antarctic Research Department. The romance of Antarctic research quickly captivated him, and from that moment on, Vasiliev's entire life was inextricably linked with polar science.

The origins of mechanical ice drilling technology

At the initial stages of his work in the ARD, Vasiliev worked on improving the theory of thermal and, subsequently, mechanical ice destruction, which became a priority for him. Anticipating the huge potential of electromechanical ice drilling technology, under the guidance of his mentor, Professor Boris Kudryashov, he took over the baton in the development of this area from his colleague, Gennady Stepanov, who developed the first version of a core cable-suspended electromechanical drill (KEMS).

Vasiliev improved the design of KEMS [6], and the changes he made increased the reliability of the drill and reduced the chances of complications and accidents during drilling. With the help of this modernized drill, in 1988, as part of the A-162 expedition, a borehole was drilled to a depth of 459 m on Severnaya Zemlya. This was the first time that the bedrock under the glacier had been reached and 4.4 m rock cores had been recovered using a core cable-suspended electromechanical drill [7]. In the same year, Vasiliev successfully defended his PhD thesis entitled "The electromechanical drill and the technology of drilling boreholes in ice and subglacial rocks".

At that time, drilling at the Vostok station was conducted in borehole 4G-2 at depths exceeding 2,000 m using the thermal drilling method. This process was accompanied by occasional complications due to imperfections in the drilling rig design [8].

Nikolay Vasiliev and Vladimir Zubkov carrying out maintenance work on the drill at Vostok Station, 2011

Николай Васильев и Владимир Зубков во время технического обслуживания бурового снаряда на станции Восток, 2011 г.

Successful testing of the upgraded KEMS drill on Severnaya Zemlya made it possible to switch to electromechanical drilling technology at Vostok station at a depth of 2428.5 m, during the 34th Soviet Antarctic Expedition (SAE) in 1989 — Vasiliev's first Antarctic expedition. Improvement of deep ice core drilling technology continued in the newly drilled 5G borehole in early 1990.

Developing a standard for deep ice drilling

Drilling the 5G-1 hole at Vostok with an electromechanical drill was carried out at a high rate of penetration (with a run length of 2.8 m) up to a depth of 2 930 m. This success was largely due to Vasiliev developing a telemetry and drilling control system, which was capable of operating in temperatures up to –70 °C and with a drilling fluid pressure of up to 40 MPa.

Subsequent drilling was accompanied by some complications and a significant reduction in the rate of penetration due to changes in the ice structure and its physical and mechanical properties with depth. Individual ice crystals were found to have increased in size (up to 1 m) and the temperature increased as the drill approached Lake Vostok. This type of ice is known as warm ice in the scientific community, and many researchers have sought to improve the efficiency of drilling it [9, 10].

The professor at work

Профессор за работой

At that time, there were no specific guidelines for ice drilling at great depths, so the drilling team led by Vasiliev had to take on the role of pioneers and inventors. The deep modernization of the drill included improvements to the geometry of the drill head [11, 12], the development of new designs for filters [13] and an anti-torque system; extensive theoretical research also had to be undertaken [14]. These efforts enabled the team to continue drilling work.

The results of this work were summarized in Vasiliev's doctoral dissertation, 'Rational technology of drilling boreholes in ice using a core cable-suspended electromechanical drill', which he successfully defended in 2004.

The last 100 m to the surface of subglacial lake Vostok were especially challenging: the drill got stuck at the bottom twice. In the first instance, the accident was resolved by a special fishing tool, designed by Vasiliev and reproduced in wintering conditions by Alexander Krasilev and Vladimir Zubkov [15]. The second time the drill got stuck proved fatal, and after numerous attempts to retrieve it, it was decided to divert

The vivid outcome of Vasiliev's innovations – a perfect quality ice core recovered from the super-deep hole at Vostok.

Наглядный результат инноваций Н.И. Васильева – керн отличного качества, поднятый из сверхглубокой скважины на станции Восток.

the borehole, bypassing the drill left at the bottom. For the first time, Vasiliev's technology for deviating from the parent hole was applied [16], allowing branch holes to be drilled without significant changes to the design of the electromechanical drill.

A new world record of 3769.3 m was set for drilling boreholes in ice when Subglacial Lake Vostok was finally unsealed on February 5th, 2012. This technology was developed by a team of scientists from the Mining Institute and AARI in 2000 [17]. In anticipation of the lake's unsealing, large-scale preparatory works were carried out. Together with the perseverance and consistency of the drilling crew, these efforts made it possible to reach Lake Vostok just one day before the team had to leave Vostok Station on the last plane at the end of the field season [18].

Professor Vasiliev's personal qualities, such as his attention to detail and intuition, were particularly important for the success of this project. These innate characteristics were well complemented by his deep understanding of the downhole processes involved in drilling.

An in-depth analysis of the hydrodynamic process of water rising into the borehole during the first unsealing of the lake in 2012 allowed for a more controlled second unsealing in 2015 [19]. The result of these two operations was the recovery of samples of congelation ice, which formed as a result of the freezing of lake water that entered the borehole.

Vasiliev shared his accumulated knowledge and experience through monographs, scientific articles, and textbooks. His contributions have enabled the following: deepening fundamental understanding of the complex processes that occur in ice when it is drilled; establishing the main patterns of changes in the structural and physical properties of the Antarctic ice sheet with depth, which determines mechanical and rheological properties that affect borehole drilling and maintenance; and creating safe and competitive technologies for drilling through ice and environmentally friendly techniques for accessing subglacial water bodies. He is rightfully considered to be the creator of modern international standards for deep ice drilling.

Conclusion

A friendly cartoon by a colleague depicting Professor Vasiliev hard at work

Дружеский шарж, изображающий профессора Васильева за работой

Professor Vasiliev was an outstanding scientist and researcher who made a significant contribution to the history of Antarctic research. His work continues to be the foundation for the development of technology and tools for drilling into Antarctic ice. The technology he created, using the KEMS-135 drill, which he painstakingly developed and improved, serves as a model for best practices in deep ice drilling. The professor himself said that this achievement was the most significant result of his creative activity.

His reverent attitude to his work, perseverance, and ability to dream, which are inherent in many outstanding scientists, became the defining features of his personality

Vasiliev's friends and younger colleagues: staff of the Mining University and AARI during the 67th Russian Antarctic Expeditions

Друзья и последователи Н.И. Васильева: сотрудники Горного университета и ААНИИ в составе 67-й Российской антарктической экспедиции

and the key to his success. Even during periods of insufficient funding, Vasiliev was able to make scientific progress.

As a leader, Professor Vasiliev has inspired and continues to inspire others to achieve results. His colleagues, including the polar researchers at the Vostok station, remember him with warmth and respect. They affectionately call him 'professor'. His close friends call him *Kolya-golova* ('Kolya the brain'), due to his extensive knowledge and far-reaching abilities.

It is thanks to Vasiliev that a strong, experienced, and effective drilling team was established at Vostok station. He was passionate about everything new and promising in science and technology. He gave all his strength and time to his work. He was democratic in approach, kind, accessible, benevolent, and friendly. He had an unflagging sense of humour. He was honest in his judgments and exacting in business.

His work lives on through his students. They rely on the knowledge he left behind, and continue to explore the Antarctic continent.

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Творческий путь Николая Васильева – создание современной технологии бурения глубоких скважин во льду

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Аннотация. С начала 50-х гг. XX в., когда началось активное изучение Антарктиды, бурение стало неотъемлемой частью многих масштабных научных проектов, осуществляемых на ледяном материке. Благодаря стремительному развитию техники и технологий бурения было сделано множество научных открытий в области палеоклиматологии, геологии, гляциологии и ряда других естественных наук. С 1968 г. и по сей день одну из ведущих ролей в развитии данного направления играет Санкт-Петербургский горный университет. В его стенах было воспитано несколько поколений специалистов по бурению льда. Особое место среди них занимает бессменный руководитель направления антарктических исследований в период с 2002 по 2021 г., профессор, доктор технических наук Николай Иванович Васильев. Его вклад в развитие отечественного бурения в Антарктиде невозможно переоценить. Многолетняя творческая деятельность Н.И. Васильева заложила основу для многих достижений в этой области за последние 30 лет. Его путь является ярким примером трудолюбия и преданности своему делу на протяжении всей жизни. Эта статья — дань уважения и памяти профессору Н.И. Васильеву, которую хранят его друзья, последователи и коллеги, имевшие счастье работать с этим талантливым человеком и ученым и учиться у него.

Ключевые слова: Антарктида, бурение ледников, электромеханический буровой снаряд, бурение теплого льда, озеро Восток

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Mineral inclusions in the accretion ice above Lake Vostok

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Abstract. The paper is based on additional studies of mineral inclusions in the accretion ice sampled by deep drilling at Vostok Station in central Antarctica. The studies include X-ray microtomography of two mineral inclusions with identification of their mineral composition; analysis of clay minerals in the soft aggregate of the largest inclusion; and geochronological study of zircon grains. X-ray microtomography shows intact morphology of the inclusions in the ice core and their internal texture. The soft aggregate of the largest inclusion is characterized by the dominance of illite, intermediate concentrations of chlorite and small amounts of kaolinite. A notable feature is the absence of mixed-layer minerals typical of Antarctic coastal areas. The most valuable information is derived from new geochronological data and their integration with previous dating data. The detrital zircon U-Pb ages show strong probability peaks between 900 and 1100 Ma, while the detrital monazite ages are clustered between 1250 and 1450 Ma. Both of these age intervals correspond to the Rayner Orogeny.

Keywords: central Antarctica, subglacial Lake Vostok, accretion ice, rock clast, clay minerals, zircon, monazite, geochronology

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1. Introduction

The ice borehole at Vostok Station passed through the 3769 m-thick East Antarctic ice sheet above Lake Vostok with complete sampling of ice cores, which provided very valuable information on ice properties, palaeoclimate, subglacial environments and other

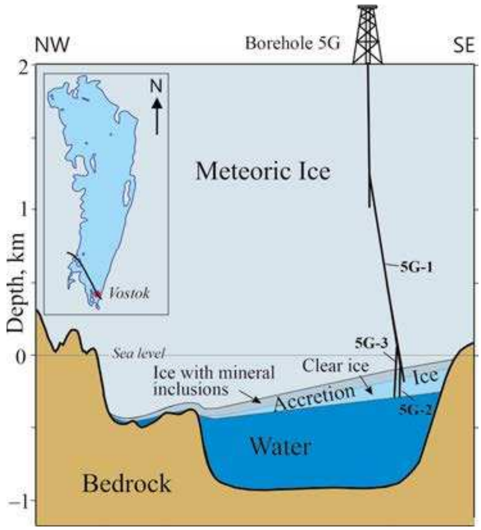

Fig. 1. Ice-water-bedrock section along the ice flow line and across Vostok Station (modified from [3] and borehole 5G with branches 5G-1, 5G-2 and 5G-3; the inset at top left shows the contours of subglacial Lake Vostok (from [9] and the position of the section

Рис. 1. Разрез ледовой толщи, воды и коренного ложа вдоль линии тока льда и через станцию Восток (по [3] с изменениями) и скважину 5Г с ответвлениями 5Г-1, 5Г-2 и 5Г-3; на вставке вверху слева показаны контуры подледникового озера Восток (из [9]) и положение разреза

areas of scientific knowledge [1–3]. Ice core studies show that the ice at this site is divided into 2 main layers according to its origin: the upper one (3537 m thick), formed from atmospheric precipitation, and the lower one (232 m thick), frozen from the water of subglacial Lake Vostok, i. e. accreted from below [4] (Fig. 1). The upper 81 m of accretionary ice (between 3537 and 3618 m), sampled by three borehole branches [5], contains small mineral inclusions, generally less than 1 mm in size, although several intervals contain larger (> 2 mm) inclusions, and the depths of 3606–3608 m are characterized by the presence of the largest inclusions up to 1 cm across [6] (Fig. 2).

Previous studies of 11 inclusions (from depths 3548, 3549, 3550, 3556, 3559, 3561, 3582, 3607, 3608 m) have shown that most of them are represented by soft aggregates consisting mainly of clay matrix, mineral grains ranging in size from 5 to 150 mkm (mainly quartz grains) and rock clasts [3, 7]. Larger inclusions (found mostly in the 3606–3608 m layer) contain rock clasts up to 6–8 mm in diameter. Two inclusions (from 3550 and 3559 m) contain sulfide minerals: pyrite, molybdenite, sphalerite, which may be evidence of hydrothermal activity in Lake Vostok [3].

Lake Vostok is the largest subglacial freshwater reservoir in Antarctica and one of the largest in the world with a water layer up to 1000 m thick [9], but only its southern part provides conditions for water freezing [8] (Fig. 1). The ice sheet drilled at the Vostok station came from the shallow lake area with an island as the site of the present grounded ice [3, 9] (Fig. 1). It is evident that mineral inclusions were trapped in the 81 m thick accreted ice at the time when the ice sheet was flowing over this shallow part of the lake, either from suspension [10] or directly from the lake bottom during ice grounding episodes, which provided grabs of relatively large rock clasts [6] (Fig. 2).

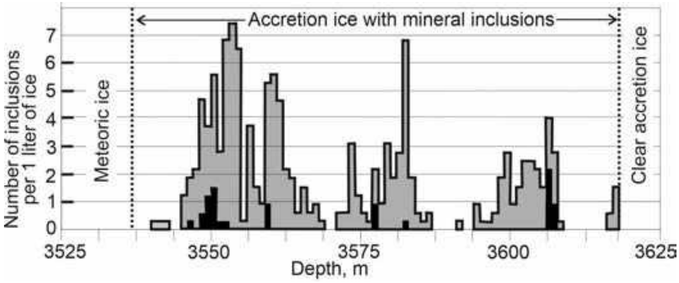

Fig. 2. Calculated concentration of mineral inclusions in the ice cores of accreted ice (borehole 5G-1); the blak shading shows the concentration of relatively large (> 2 mm) inclusions captured from the lake bottom (after [6] with modifications)

Рис. 2. Подсчет концентрации минеральных включений в кернах аккреационного льда (скважина 5Г-1); черной закраской показана концентрация относительно крупных (> 2 мм) включений, захваченных со дна озера (по [6] с изменениями)

Petrographic research, scanning electron microscopy and microanalysis of rock clasts found in the accreted ice (within soft inclusions) allow us to identify these clasts as consolidated, unmetamorphosed quartzose siltstones and sandstones. The bottom sediments trapped in frozen water and incorporated into the ice sheet are thought to be products of ice erosion of the bedrock upstream of southwestern Lake Vostok. The sedimentary nature of this region, known as the Vostok Subglacial Highlands, is also supported by magnetic, gravity and seismic data [3, 11].

All sedimentary rock clasts contained detrital zircon and monazite grains, which were detected by energy dispersive X-ray microanalysis and dated by secondary ion mass spectrometer SHRIMP-II. A total of 31 zircon and 5 monazite grains were dated [3]. Within 7 years since the last publication [3], new data on mineral inclusions in the accreted ice have been obtained. The aim of this paper is to present the results of this additional research. New research includes: 1) X-ray microtomography of two mineral inclusions from a depth of 3606.9 m (branch G-3); 2) examination of rock clasts from a depth of 3606.9 m (branch G-3) with identification of their mineral composition; 3) analysis of clay minerals in the largest soft clast from the 3608 m depth (branch G-1) and, for comparison, in samples from coastal lakes of the Larsemann Hills, Vestfold Oasis (Princess Elizabeth Land) and Banger Hills (western Wilkes Land); 4) geochronological study of 10 zircon grains from the largest (8 mm long) rock clast from the 3608 m depth (branch G-1) and 6 zircon grains from the 4.5 mm long rock clast from a depth of 3607 m (branch G-1).

2. Methods

X-ray computed microtomography was used for the first time to study intact (situated in ice cores) mineral inclusions. The aim of this technology was the recognition of their internal structure and original external morphology. This research was performed at Saint Petersburg State University on a SkyScan 1172 microCT scanner equipped with a cooling stage (Bruker, Belgium).

The rock clasts were studied in the Center of Isotopic Research of the All-Russia Geological Institute (CIR VSEGEI) using a scanning electron microscope (SEM) CamScan MX 2500 equipped with an energy-dispersive X-ray spectrometer Pentafet 10 mm^2 (Oxford Instruments, UK) and SEM TESCAN VEGA3 (TESCAN, Czech Republic) with an energy-dispersive X-ray spectrometer Aztec Ultim 100 mm^2 (OXFORD Instruments, UK).

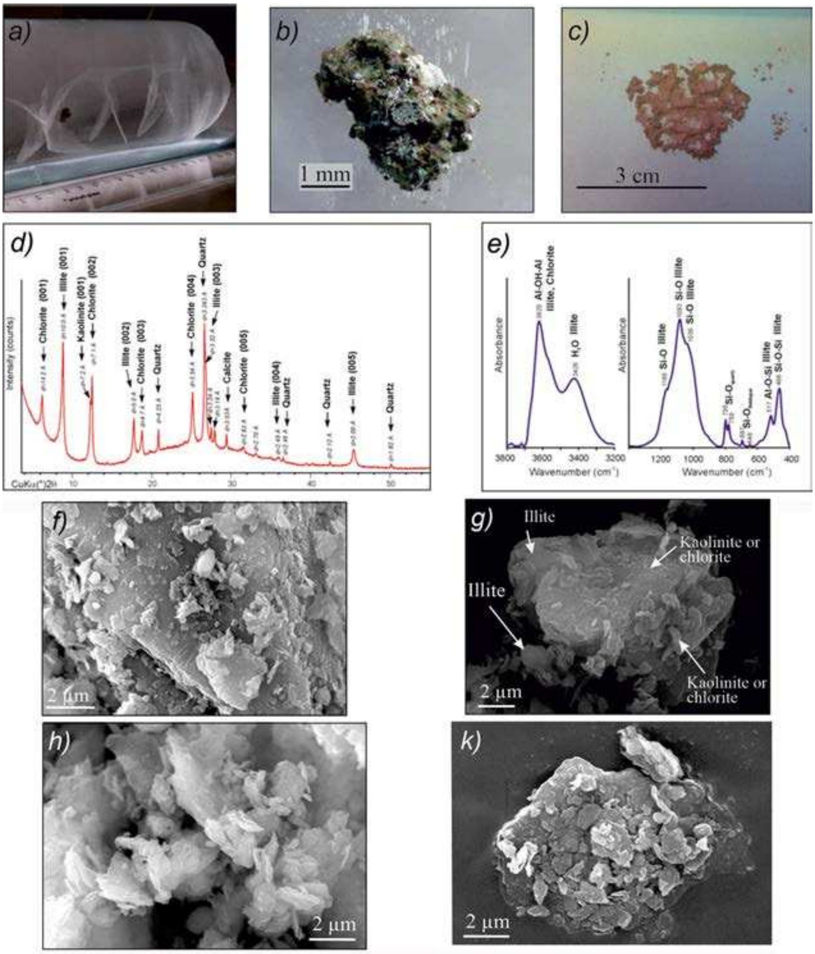

Fig. 3. Study of clay minerals in the largest mineral inclusion from a depth of 3608 m (borehole branch 5G-1).

a — photograph of ice core with the largest mineral inclusion inside; *b* — photograph of the largest intact mineral inclusion (soft aggregate); *c* — dry fine-grained (mostly clayey) residue after drying, which was used for the study of clay minerals; *d* — X-ray diffractogram of the oriented preparation in air-dry state (in brackets are orders of basal reflections for clay minerals); *e* — part of infrared spectra and identification of absorption bands; *f*–*k* — micrographs obtained with a scanning electron microscope: clay minerals on the surface of the feldspar grain (*f*), aggregate of different clay minerals (*g*), aggregate of illite particles (*h*), aggregate of kaolinite particles (*k*)

Рис. 3. Результаты изучения глинистых минералов в самом крупном минеральном включении с глубины 3608 м (скважина 5Г-1).

a — фотография ледяного керна с крупнейшим минеральным включением внутри; *b* — фотография самого крупного ненарушенного минерального включения (агрегат); *c* — сухой тонкодисперсный (преимущественно глинистый) остаток после высушивания, использованный для изучения глинистых минералов; *d* — рентгеновская дифрактограмма ориентированного препарата в воздушно-сухом состоянии (в скобках указаны порядки базальных отражений для глинистых минералов); *e* — часть ИК-спектров и идентификация полос поглощения; *f*–*k* — микрофотографии, полученные на сканирующем электронном микроскопе: глинистые минералы на поверхности зерна полевого шпата (*f*), агрегат различных глинистых минералов (*g*), агрегат частиц иллита (*h*), агрегат частиц каолинита (*k*)

The study of clay minerals was carried out in the Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry and the Geological Institute (Russian Academy of Science) by powder X-Ray diffraction, electronic microscopy and infrared spectrometry using X-Ray diffractometer "Ultima-IV" (RIGAKU, Japan) with a semiconductor detector "DTex/Ultra", SEM LEOSupra 50 VP (Carl Zeiss, Germany) and a FTIR spectrometer "VERTEX 80v" with a DTGS detector and a KBr beamsplitter (Bruker, Germany), respectively.

Infrared spectroscopy (spectra acquisition) was performed in the mid-IR spectral region (4000–400 cm^{-1}) under vacuum pumping conditions with a resolution of 4 cm^{-1}. In order to obtain the most accurate information in the absorption region of the OH-groups, the sample was additionally heated at 150 °C for 20–24 hours. The results obtained were processed using the OPUS 7.0 program. The use of infrared spectroscopy allowed us to correctly apply methods of mathematical modelling of X-ray diffraction patterns from oriented preparations, to calculate the quantitative ratio of clay minerals, and to determine the composition of the amorphous phase. Before the analysis, a fine-grained fraction was extracted from the largest soft aggregate (3608 m; Fig. 3*a*, *b*) and a dry specimen with a weight of approximately 0.5 g was prepared (Fig. 3*c*).

The geochronological study was carried out at CIR VSEGEI using the Sensitive High Mass-Resolution Ion Microprobe (SHRIMP-II, ASI; Australia) following the *in situ* uranium-lead method described by Williams [12]. Zircon grains were preliminarily identified using a SEM CamScan MX 2500 in a cut and polished rock clast mounted in a special preparation for microprobe analysis. Additional zircon grains were found by re-polishing previously cut rock surfaces. Repeat measurements were carried out on two grains to statistically increase the data set.

The intensity of the primary beam of negatively charged molecular oxygen ions was 3 nA with a spot diameter of approximately 20 μm at a depth of up to 2 microns. $^{206}Pb/^{238}U$ ratios in zircon samples were normalised to the Temora-2 zircon standard (416.8 Ma, [13]). Concentrations of lead, uranium and thorium in measured zircon grains were obtained using zircon standard 91500 with a known uranium content of 81.2 ppm [14]. Measured Pb/U ratios of monazite were corrected using reference monazite from the Thompson Mine with a known age of 1766 Ma and U content of 2000 ppm, using the energy filtering technique to reduce the isotopic overlap. The correction for common lead was applied to the value of the measured ^{204}Pb isotope. In some cases where the measured grain size was comparable to or slightly smaller than the analytical spot, the surrounding matrix was analysed to ensure the absence (or insignificant content) of lead, uranium and thorium components. Errors of individual analyses (ratios and ages) are reported at the one sigma level. Raw data were processed using SQUID-1 software [15]; plots of concordia and probability of age distribution were generated using the Isoplot-3 program [15]. The probability density plot consists of ages calculated from the $^{206}Pb/^{238}U$ isotopic ratio for the concordant data and $^{207}Pb/^{206}Pb$ for the few discordant values.

3. Results

3.1. X-Ray microtomography

Two mineral inclusions from a depth of 3606.9 m (branch G-3) were studied using X-ray computed microtomography in ice cubes cut from ice cores (i.e. in intact conditions). The inclusions as a whole have a fanciful shape and consist of relatively large elongated

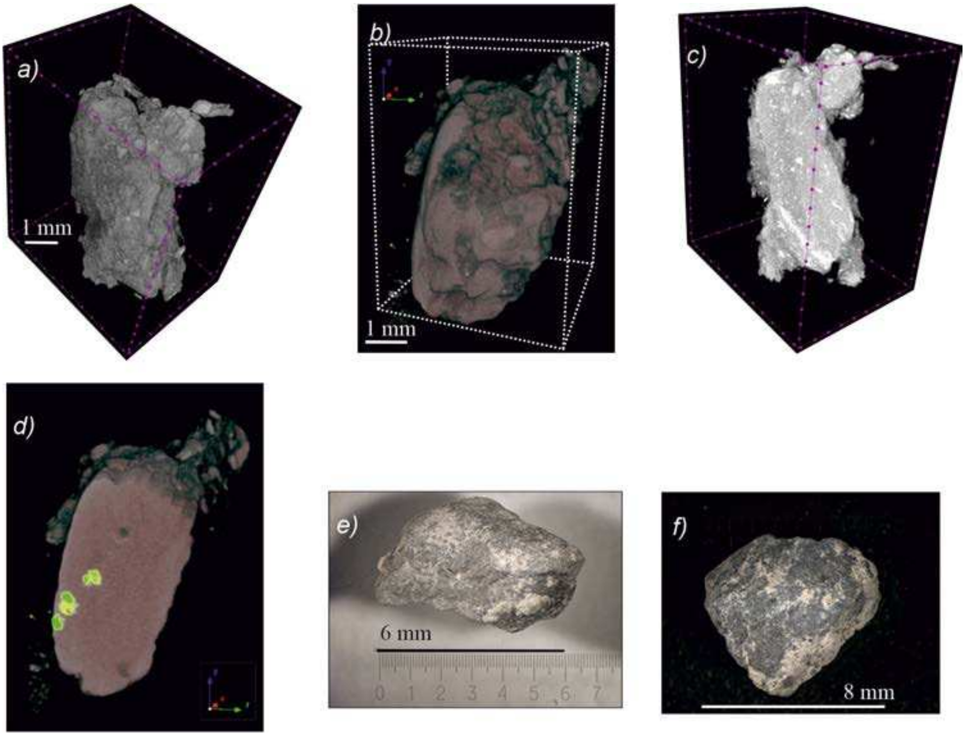

Fig. 4. Images of two inclusions from a depth of 3606.9 m (borehole branch 5G-3).

a, b — Three-dimensional image of mineral inclusions in the ice obtained using of X-ray computed microtomography showing their surface morphology; *c, d* — Three-dimensional images of mineral inclusions in the ice obtained using of X-ray computed microtomography showing sections in the XZ plane (the bright spots are denser mineral grains); *e, f* — photographs of rock clasts after their thawing from the ice and clearing from fine-grained material. The dimensions of 3606.9-3 (1) are 6.3×5.5×2.3 mm, the dimensions of 3606.9-3 (2) are 7.7×5.8×3.5 mm

Рис. 4. Изображения двух включений с глубины 3606,9 м (скважина 5Г-3).

a, b — трехмерное изображение минеральных включений во льду, полученное с помощью рентгеновской компьютерной микротомографии, показывающее морфологию их поверхности; *c, d* — трехмерные изображения минеральных включений во льду, полученные с помощью рентгеновской компьютерной микротомографии, показывающие сечения в плоскости XZ (яркие пятна — более плотные минеральные зерна); *e, f* — фотографии обломков пород после их вытаивания ото льда и очистки от мелкозернистого материала. Размеры 3606,9-3 (1) — 6,3×5,5×2,3 мм, 3606,9-3 (2) — 7,7×5,8×3,5 мм

bodies and numerous small satellites (Fig. 4*a*, *b*). The study shows that the large bodies are rock clasts covered by fine-grained material ranging in thickness from 150 μm to 1.2 mm. Analysis of this material and substance of small satellites using the SEM CamScan MX 2500 revealed a predominance of layered silicates (probably of the hydromica group) and, to a lesser extent, the presence of quartz grains, feldspars and accessory minerals up to 20–30 μm in size. After the ice melted, the cover was almost completely disintegrated exposing the rock clast (Fig. 4*c*).

3.2. Identification of clay minerals

Comprehensive analysis of the fine-grained fraction from the largest soft aggregate (3608 m) showed that the total content of clay minerals is 70–75 % and the other part of the fraction is represented by small grains of quartz, amorphous silica, feldspars and calcite. Infrared spectroscopy showed that the main peaks of the spectra obtained belong to vibrations of Al-OH-Al bonds of illite and chlorite in the region of 3620 cm^{-1}, Si-O bonds of illite in the region of 1165, 1083, 1036 cm^{-1}, and strain vibrations of Al-O-Si (517 cm^{-1}) and Si-O-Si (466 cm^{-1}) of illite.

The clay minerals identified are illite (69 %), chlorite (24 %) and kaolinite (7 %) of terrigenous origin (Figs 3). Illite forms large but thin particles and microaggregates (Fig. 3*h*), while kaolinite is characterized by thicker particles with a pronounced hexagonal shape (Fig. 3*k*). Most of the clay minerals are of terrigenous origin, although authigenic clay minerals have also been detected on the surface of feldspars (Fig. 3*f*). Terrigenous illite is represented by relatively large but thin particles and ultramicroaggregates, while terrigenous kaolinite is characterized by thicker particles with a pronounced hexagonal morphology. In contrast, authigenic clay minerals have much finer particles and a relatively isometric morphology.

Examination of oriented samples in the air-dry state and after saturation with ethylene glycol did not reveal the presence of swelling phases (smectites or mixed-layer formations of the illite-smectite, kaolinite-smectite or chlorite-smectite series). Furthermore, a specific feature of the inclusion in the Vostok ice core is the complete absence of mixed-layer (illite/smectite) clay minerals, which are typical of Antarctic coastal regions (e. g. Shirmacher Oasis, Prince Charles Mountains [16, 17], including those investigated in this study (Larsemann Hills, Vestfold Oasis and Banger Hills).

3.3. Study of rock clasts

Figure 5 shows some of the previously and recently examined rock clasts [2, 3, 7], most of which are quartzose siltstones and sandstones. The largest, 8 mm long, rock clast from the 3608 m depth (Fig. 5, 3608-1) was examined using the SEM CamScan MX 2500S in addition to the petrographic analysis previously performed. It was found that this clast is characterized by very low porosity (1.5 ± 0.5 %) and consists of quartz grains (0.03–0.17 mm across; 69 %), potassium feldspar grains (0.03–0.17 mm across; 18 %) and cement of probable chlorite composition (10 %); the accessory minerals (apatite, garnet, monazite, zircon, iron hydroxides and others (about 1 %). The integral density of the clast, calculated from the distribution of the minerals, their average density and porosity, is estimated to be about 2.6 g/cm^3. Four zircon grains (one 15 μm and three 40 μm in size) were additionally identified in this largest rock clast for for further isotopic analysis.

Two new clasts from a depth of 3606.9 m (branch G-3; Fig. 4*c*; Fig. 5, 3606.9) have been studied by X-ray microtomography and electronic microscope. The first clast (Fig. 5, 3606.9-3(1)) is composed of layered silicates (less than 10 μm in size; about 75–80 %), quartz (30–50 μm in size; 15–20 %), feldspar (about 5 %) and accessory minerals (apatite, rutile, ilmenite, hematite, monazite, zircon; 5–20 μm in size, less than 1 %;). Several well-rounded oval-shaped quartz grains (up to 1 mm in size) are present in the rock mass (Fig. 4*b*). The rock can be defined as silty mudstone. The second clast (Fig. 5, 3606,9-3(2)) is different in its mineral composition and consists mainly of quartz (60–65 %), feldspars (about 30 %), layered silicates (3–5 %) and accessories, but a part of the rock (about 15 % in the section studied) is occupied by a wedge of layered silicates.

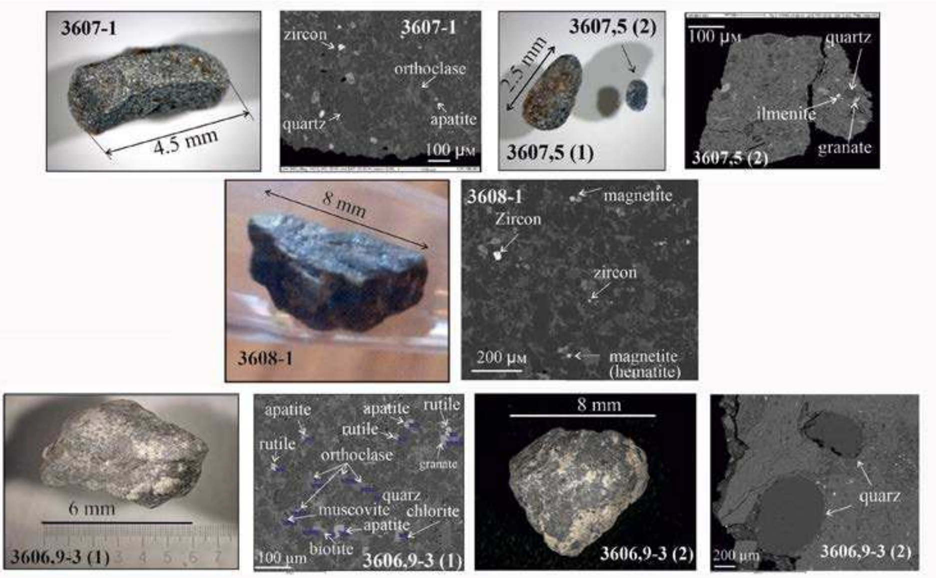

Fig. 5. Photographs of some of the rock clasts studied and backscatter SEM images with identified minerals. Numbers on the images are borehole depths; the number after the hyphen is the hole branch; the number in brackets is the sample number

Рис. 5. Фотографии некоторых изученных обломков пород и изображение их фрагментов в обратно-рассеянных электронах на сканирующем электронном микроскопе

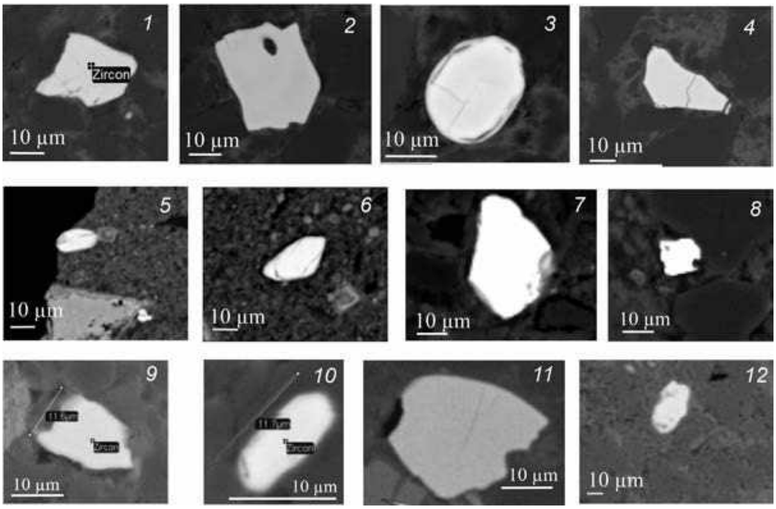

Fig. 6. Backscatter SEM images of zircon and monazite grains showing their type morphology. 1–8: zircon grains (1–7) and monazite grain (8) identified in clast 3608-1 (sandstone); 9–10: zircon grains identified in clast 3606.9-3 (1); 11–12 zircon grains identified in clast 3607

Рис. 6. Изображения зерен циркона и монацита в обратно-рассеянных электронах на сканирующем электронном микроскопе, демонстрирующие их типовую морфологию. 1–8: зерна циркона (1–7) и монацита (8), идентифицированные в обломке 3608-1 (песчаник); 9–10: зерна циркона, идентифицированные в обломке 3606,9-3 (1); зерна циркона, идентифицированные в обломке 3607

3.4. Dating of detrital mineral grains and integration of age data

In addition to the previously dated 31 zircon and 5 monazite grains [3], 10 detrital zircon grains were found in the rock clast from a depth of 3608 m and 6 zircon grains in the rock clast from a depth of 3607 m. Moreover, five age determinations of monazite grains were added from previous studies (not considered in [3]). The size of all the detrital zircon and monazite grains identified ranges from 10 to 50 μm and predominantly from 30 to 40 μm. The zircon grains examined by electron microscopy in sample mounts do not show the primary crystal forms and most of them are rounded in shape, though some of the grains have an angular morphology (Fig. 6).

The zircon U-Pb ages show strong probability peaks at 900, 1000 and 1100 Ma with the latter being the most prominent; the minor but reliable (not less than 5 analyses) peaks are characterized by ages of 900 and 800 million years; and peaks at 760, 1300, 1600, 1750, 2500 Ma (2–3 analyses) can also can be considered as statistically significant (Fig. 7). The monazite age distribution is less reliable due to the relatively small number of analyses. These ages are mainly clustered between 1250 and 1450 Ma and one probability peak falls at 1100 Ma. Isotope ratios of zircon grains suggest that they may be of both magmatic and metamorphic origin.

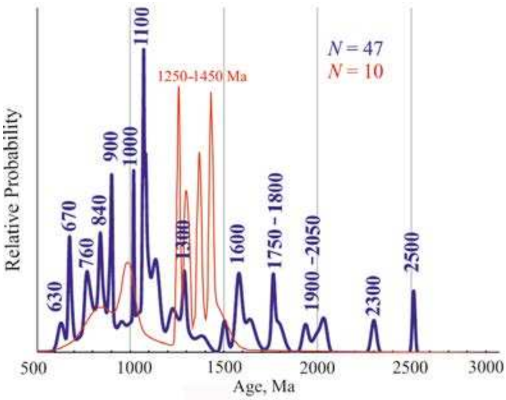

Fig 7. Probability age distribution for zircon ($^{206}Pb/^{238}U$; blue line) and monazite ($^{208}Pb/^{232}Th$; red line) grains. The age peaks (in millions of years) of the zircon grains are shown

Рис. 7. Вероятностное распределение возраста зерен циркона ($^{206}Pb/^{238}U$; синяя линия) и монацита ($^{208}Pb/^{232}Th$; красная линия). Показаны пики возрастов (в миллионах лет) зерен циркона

4. Interpretation and Discussion

4.1. Mineral inclusions

The accretion ice contains several layers of relatively large (>2 mm) mineral inclusions (Fig. 1). The inclusions were extracted from two layers (at depths of 3582 m and 3607–3608 m), and their examination revealed the presence of rock clasts within the soft aggregates (Fig. 5). It can be assumed that all the other large inclusions (or at least most of them) also contain rock clasts.

Royston-Bishop with coauthors [18] suggested that the particles composing the inclusions may have been incorporated into the accretion ice by growing ice crystals and/or by rising frazil ice crystals with upward water circulation. These mechanisms are suitable for fine-grained particles, but relatively large (up to 8 mm long) and heavy (tens to more than hundred milligrams) particles cannot be suspended in the freshwater of the lake, and so entrapment of rock clasts must have occurred during occasional contacts of the accreting ice with the lake bed at several ice grounding points. The ragged morphology of the lake floor in a shallow bay, which defines different conditions at the bottom of the ice sheet (floating or grounded state), is confirmed by radio-echo sounding [19].

The freezing process was quite slow, with the possible presence of water pockets in the already formed accreted ice, where a suspension of fine-grained material was present. This material was evenly distributed over the surface of the clasts (Fig. 4*a*,*b*).

4.2. Clay minerals

Illite, chlorite and kaolinite, identified in the soft aggregate (inclusion) from a depth of 3608 m are common in Antarctic seas, coastal lakes and outcropped glacial deposits [17, 20]. Illite is the dominant clay mineral and is the product of physical weathering of magmatic and high-grade metamorphic assemblages typical of East Antarctica. However, sedimentary rocks can also be considered as a source of illite, thus, for example, Devonian to Triassic sedimentary succession (Beacon Supergroup) developed in the Transantarctic Mts. is considered to be a source of illite in the Ross Sea Basin [21].

Chlorite is also a widespread mineral, mostly derived from low-grade metamorphic, mafic and sedimentary rocks, and it is not resistant to weathering and long transportation. Kaolinite is a very resistant mineral and is a product of chemical weathering of feldspar and is more characteristic of temperate and tropical latitudes, but can occur in polar regions due to the weathering of older, kaolinite-bearing sediments [20]. The relatively high chlorite content and the presence of kaolinite in the samples studied (Fig. 3) are related to the weathering of the sedimentary rocks underlying the ice, and most likely their cement. The absence of mixed-layer (illite/smectite) clay minerals in the soft aggregates studied suggests that the environmental and weathering conditions in the subglacial environment of central Antarctica and the outcropping regions of the Antarctic margins are significantly different.

4.3. Provenance of detrital zircons

East Antarctica is characterized by a variety of tectonic provinces with ancient metamorphic and magmatic complexes, which are outcropped within coastal regions and well-studied in terms of rock composition, geochronology and geodynamic settings [22, 23] (Fig. 8). Major tectonic subdivisions of East Antarctica are Archean cratons and Proterozoic orogens of different ages (Fig. 8). Crystalline complexes of Archean cratons are unique due to the abundance of tonalite-trondhjemite-granodiorite suites and high- (mostly) to medium-grade metamorphic rocks. The ages of the cratons range between 3.9 to 2.4 Ba, but some parts of them were reworked by younger tectonic processes during the Proterozoic.

The major Proterozoic orogens generally become younger from east to west and are known as the Wilkes, Rayner and Coats-Maud Orogens [23] (Fig. 8). The Wilkes Orogen is thought to underlie the coastal region of Wilkes Land. Exposed rocks include high-grade ortho- and paragneiss and magmatic rocks of varying composition. The dominant age peaks of detrital zircons are ca. 1800–1700 Ma, ca. 1595 Ma and ca. 1380 Ma. Sedimentary protoliths were deposited during the interval 1350–1300 Ma and then intruded during three magmatic events at ca. 1325–1315 Ma, ca. 1250–1210 Ma and ca. 1200–1130 Ma.

The Rayner Orogen is located between Dronning Maud Land and Queen Marie Land, but is best exposed and studied in the Lambert Rift area, where it is composed of high-grade tonalite- and granite orthogneisses, paragneisses and schists, quartzites, metavolcanics, as well as post-kinematic felsic and mafic intrusions. Magmatic and

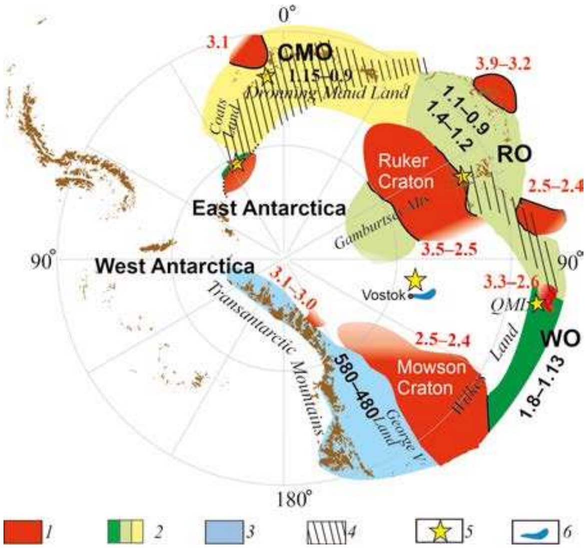

Fig. 8. Major Tectonic provinces of East Antarctica (modified from [23].

1 — Archean Cratons; *2* — Proterozoic Orogens; *3* — Neoproterozoic — Early Paleozoic Ross Orogen; *4* — Early Paleozoic (550–500 Ma) tectono-thermal event (recycling of pre-existing crust); *5* — Late Neoproterozoic — Early Paleozoic sedimentary basins; *6* — Lake Vostok. The red and black numbers (bold font) are the ages of major magmatic and metamorphic rocks of tectonic provinces. Abbreviations: WO — Wilkes Orogen, RO — Rayner Orogen, SMO — Coats-Maud Orogen, QML — Queen Marie Land

Рис. 8. Основные тектонические провинции Восточной Антарктиды (по [23] с изменениями).

1 — архейские кратоны; *2* — протерозойские орогены; *3* — неопротерозойский — раннепалеозойский ороген Росса; *4* — раннепалеозойское (550–500 млн лет) тектоно-термальное событие (переработка ранее существовавшей коры); *5* — поздненеопротерозойские — раннепалеозойские осадочные бассейны; *6* — озеро Восток. Красные и черные цифры (жирный шрифт) — возраст основных магматических и метаморфических пород. Сокращения: WO — ороген Уилкса, RO — Рейнерский ороген, RO — ороген Котса-Мод, QML — Земля Королевы Мэри

metamorphic crystallization events are recorded during two major time intervals: ca. 1400–1250 and 1100–800 Ma [24].

The Coats-Maud Orogen is generally traced in bedrock outcrops from Coast Land to Enderby Land, and its crust was formed during two phases of accretion. The older one is recorded in the western part of the orogen and consists mainly of high-grade complexes dated within 1150–1050 Ma; while the second one is typical of the eastern part of the orogen and is interpreted as the Tonian Oceanic Arc Super Terrane (TOAST), emplaced within 1000-900 Ma interval [26]. Coats-Maud and Rayner orogens experienced Late Neoproterozoic — Early Paleozoic (600–500 Ma) reactivation (orogeny?) involving magmatism of mainly granitoid composition and high- to medium-grade metamorphism [23, 25, 26].

The distribution of tectonic terranes beneath the ice in the Antarctic interior is interpreted from geophysical, mainly magnetic data, which show marked differences in the magnetic field patterns within the cratons and orogens [23]. For instance, magnetic data [26] allow us to identify the tectonic provinces underlying the Gamburtsev Mts. in central Antarctica — the Archean Ruker Craton, which is characterized by an unstructured mosaic field, and the orogenic terrane showing curved linear, extended anomalies similar to those developed within the Rayner Origen (Fig. 8).

Detrital zircon and monazite geochronology is a useful tool for reconstructions of source regions, paleodrainage patterns and paleogeograpy, especially in Antarctica, which is almost entirely covered by ice. The zircon population in the rock clasts studied shows a wide range of ages from Late Neoarchean to Late Neoproterozoic (Fig. 7), reflecting a diversity of Precambrian source terrains. The zircon grains studied are dominated by 900 to 1100 Ma ages, which are typical of the well-studied Rayner Orogen (Fig. 8). This region can therefore be considered as the likely provenance for the majority of the detrital zircon grains found in the rock clasts, though the orogen identified in the southern Gamburtsev Mts. may be a closer and therefore more appropriate source region.

A small population of zircon grains between ca. 1600 and 2050 Ma is thought to be derived from complexes of the Wilkes Orogen bordering the Mawson Craton. Similar zircon U-Pb ages have been obtained from a suite of granitoid clasts collected in glacial catchments draining central East Antarctica from the Transantarctic Mts. to the Gamburtsev Mts. [28]. The oldest (single) peaks of 2300 and 2500 Ma may correspond to the nearby cratonic terrains (Fig. 8).

Of particular interest is the group of well-defined ages between 600 and 800 Ma. The basement outcrops of these ages have not been found in the coastal regions of East Antarctica but may be present in the ice-covered regions of central Antarctica and may record magmatism associated with the crustal extension prior to the break-up of the Rodinia supercontinent. Detrital zircon grains of similar ages have been found in sediments off George V Land, with the proposed provenance located to the south of the Ross Orogeny, whose complexes are outcropped in the Transantarctic Mts [28].

Detrital monazite grains show a predominance of ages between 1450 and 1250 Ma, demonstrating marked differences in age distribution compared to detrital zircon, and minor peaks at ca. 840 and 1000 Ma (Fig. 7). The discrepancies in the age spectra are explained by differences in the physical and petrogenetic characteristics of minerals and because monazite is formed in a broader range of metamorphic conditions, so it can record a wider variety of events than zircon [29]. In our case, the age interval of 1450–1250 Ma corresponds well with the early phase of the Rayner Orogeny, though similar ages are also typical of the Wilkes Orogen (Fig. 8).

Conclusion

Additional studies of mineral inclusions from cores of accretion ice provide new information on their initial (intact) morphology and clay mineralogy, the rock clast they contain, the geochronology of detrital zircon and monazite grains in rock clasts and the provenance of detrital minerals.

1. X-Ray microtomography of ice cores containing rock clasts shows that the clasts are covered with a thin film of fine-grained clayey material. Based on this observation we suggest that the rock clast was captured within the ice grounding zone from the bottom of a shallow bay, located upstream from Vostok Station, and then spent some time in a water pocket with a fine-grained suspension that deposited on the clast surface.

2. Clay minerals, illlite (69 %), chlorite (24 %) and kaolinite (7 %), were identified in fine-grained material of largest mineral inclusion in the accretion ice. The sample studied (as an analogue of lake sediments) is characterized by the absence of mixed-layer (illite/smectite) clay minerals typical of Antarctic coastal regions, which is probably a peculiarity of subglacial weathering in central Antarctica.

3. The detrital zircon U-Pb ages show strong probability peaks at 900, 1000 and 1100 Ma and minor peaks at 760, 800, 900 1300, 1600, 1750 and 2500 Ma, while the detrital monazite ages are mainly clustered between 1250 and 1450 Ma with one probability peak at 1100 Ma. The dominant age group for the detrital zircons between 900 to 1100 Ma corresponds well with the main phase of the Rayner Orogeny manifested in East Antarctica between Dronning Maud Land and Queen Marie Land, though the Gamburtsev Mts with orogenic assemblages of similar ages can be considered as a more probable source region. Detrital monazite grains show a different age distribution compared to detrital zircon, with a predominance of age population between 1450 and 1250 Ma, and these ages are thought to correlate with the early phase of the Rayner Orogeny.

Competing interests. The authors declare no conflict of interest.

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Минеральные включения в аккреационном льду озера Восток

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Аннотация. Статья основана на дополнительных исследованиях минеральных включений в кернах аккреационного льда скважины 5Г на станции Восток в Центральной Антарктиде. Исследования включают рентгеновскую микротомографию двух минеральных включений с определением их минерального состава, анализ глинистых минералов в агрегате крупного включения и геохронологическое изучение зерен циркона. Рентгеновская микротомография показывает неповрежденную морфологию включений в ледяном керне и их внутреннюю текстуру. На основании анализа микрофотографий можно предположить, что обломок породы был захвачен в зоне налегания льда на мелководном участке озера Восток, расположенном выше по течению льда от станции Восток, и затем некоторое время находился в водном кармане с мелкозернистой взвесью, которая оседала на поверхности обломка. Агрегат крупного включения характеризуется преобладанием иллита (69 %), промежуточными концентрациями хлорита (24 %) и относительно небольшим количеством каолинита (7 %). Примечательным является отсутствие смешаннослоистых глинистых минералов, характерных для прибрежных районов Антарктики. Наиболее ценная информация получена из новых геохронологических данных и их интеграции с предыдущими данными датирования. U-Pb возраст детритовых зерен циркона показывает лавные пики на рубежах 900, 1000 и 1100 млн лет, в то время как возраст зерен монацита в основном сгруппирован между 1250 и 1450 млн лет с одним пиком вероятности на рубеже 1100 млн лет. Доминирующая возрастная группа зерен циркона между 900 и 1100 млн лет хорошо согласуется с главной фазой рейнерской орогении, проявленной в Восточной Антарктиде между Землей Королевы Мод и Землей Королевы Мэри, хотя подледные горы Гамбурцева можно рассматривать как более вероятный источник сноса. Зерна монацита, вероятно, отвечают ранней фазе рейнерской орогении.

Ключевые слова: Центральная Антарктида, подледниковое озеро Восток, озерный лед, обломки горных пород, глинистые минералы, циркон, монацит, геохронология

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The formation conditions of subglacial Lake Vostok's accreted ice based on its stable water isotope composition

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Abstract. In this paper, we present a new dataset on the stable water isotopic composition (δD and $\delta^{18}O$) in a sequence of subglacial Lake Vostok's accreted ice (3538–3769 m) measured along three parallel ice cores. The high precision of the new data has allowed us to characterize the formation conditions of different sections of the ice. The whole lake ice interval may be divided into 3 zones: 1) "zone 0", 3538.8–3549.8 m, is under the strong influence of the local water formed from melted meteoric ice likely entering from under the glacier on the lake's west coast; 2) "zone 1" (accreted ice 1), 3549.8–3607.4 m, is experiencing significant variability due to the slightly different effective fractionation coefficient in the course of "water inclusions" in the ice matrix during the freezing process; 3) "zone 2" (accreted ice 2), 3607.4–3768.8 m, is under the influence of glacial melt water from the northern part of the lake and the hydrothermal flux from the lake's bottom. We defined the exact boundary between the accreted ice 1 and ice 2, which corresponds to a sharp isotopic excursion at a depth of 3607.4 m. In this work, we present for the first time data on the "^{17}O-excess" parameter in the lake ice and water, which allowed us to make a direct calculation of the equilibrium fractionation coefficient for oxygen 17 during water freezing.

Keywords: Lake Vostok, accreted ice, hydrology, water isotopes

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Introduction

April 2023 marked the 30th anniversary of the publication of Jeff Ridley's work with co-authors "Identification of subglacial lakes using ERS-1 radar altimeter" [1]. The publication of this article in 1993 ended the long history of the discovery of subglacial Lake Vostok. After three decades of first remote geophysical [2] and then direct comprehensive studies of lake ice and water samples [3], it still remains one of the least studied objects on our planet. The reason for this is, firstly, the impossibility of direct penetration into the lake from the currently operating 5G borehole [4], and secondly, the need to develop environmentally and biologically clean methods of accessing the lake and sampling lake water, which in terms of technical complexity and financial costs will be comparable to space missions.

Due to the current impossibility of direct studies of the lake, at this stage, the efforts of specialists are aimed at extracting all possible information from already available samples of accreted (i.e. frozen from the lake) ice (Fig. 1), as well as from the few (and partially contaminated with drilling fluid) samples of lake water. One of the main methods in this area has been and remains the analysis of the isotopic composition of hydrogen and oxygen. One of the first works summarizing the data available at that time

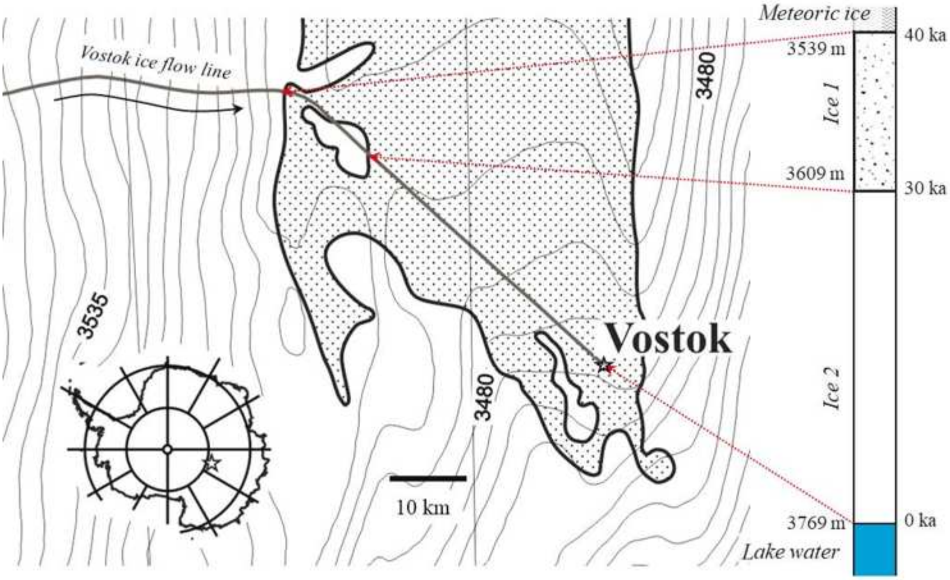

Fig. 1. Scheme of the formation of accreted ice in subglacial Lake Vostok.
The glacier crosses the southern part of the lake valley from northwest to southeast. While moving over the lake, a layer of ice freezes onto the base of the glacier, the entire thickness of which is divided into two intervals: 1) "lake ice 1" (3539–3609 m), formed in the strait between the western shore of the lake and the island (and, possibly, above the island) and containing visible mineral inclusions, as well as a relatively large amount of gas and chemical impurities; 2) "lake ice 2" (3609–3769 m), formed over the deep-water part of the lake and practically free of impurities. Adapted from [5] with small modifications.

Рис. 1. Схема формирования конжеляционного льда подледникового озера Восток.

Ледник пересекает южную часть озерной котловины с северо-запада на юго-восток. Во время движения над озером на подошву ледника намерзает слой льда, вся толща которого делится на два интервала: 1) «озерный лед 1» (3539–3609 м), сформированный в проливе между западным бортом озера и островом (и, возможно, над самим островом) и содержащий видимые минеральные включения, а также относительно большое количество газовых и химических примесей; 2) «озерный лед 2» (3609–3769 м), сформированный над глубоководной частью озера и практически не содержащий примесей.

on the isotopic composition of lake ice was the publication of Ekaykin and co-authors [5], in which a simple isotopic model of the lake was developed and it was shown that hydrothermal circulation plays an important role in the lake's hydrological regime. Further, in [3, 6], the isotopic composition of water was directly measured (which coincided with the results of calculations performed in [5]) and it was shown that ice formation generally occurs under equilibrium conditions, but at the same time the isotopic composition of ice experiences small fluctuations associated with the mechanism of ice formation and with variations in the isotopic composition of the water itself. The detailed reconstruction of these factors at that time was limited by the insufficient accuracy of the values of the isotopic composition profile of lake ice.

In this article, we present a new, most accurate to date stacked (based on 3 parallel cores) vertical profile of the isotopic composition of the accreted ice of subglacial Lake Vostok and analyze it from the point of view of the conditions of its formation. In addition to oxygen 18 and deuterium, we are also publishing data on the concentration of oxygen 17 in lake ice for the first time and discussing the prospects for using this parameter in future studies of the hydrological regime of the lake.

Methods

To construct a stacked profile of the isotopic composition of lake ice lying in the basal part of the glacier under the Vostok station in the depth range of 3538–3769 m, 10 cm samples were used from the cores of parallel hole branches 5G-1 (in the depth range of 3538–3611 m), 5G-2 (3601–3769 m), and 5G-3 (3538–3608 m and 3715–3769 m).

Isotope measurements were performed in the Climate and Environmental Research Laboratory of the AARI using Picarro L2120-i and L2140-i laser analyzers according to the methodology developed by us and previously published [7]. As a working standard, the VOS-4 standard was used, which was made from surface snow collected near Vostok station and calibrated relative to the IAEA standards VSMOW-2, SLAP and GISP. The isotopic values of VOS-4 are –439.7±0.3 ‰ for δD, –56.81±0.02 ‰ for $\delta^{18}O$ and –30.41±0.01 ‰ for $\delta^{17}O$. The working standard is measured every 5 samples. About 10 % of randomly selected samples are measured repeatedly in order to determine the reproducibility of measurements. For a single sample measurement, the random measurement error is 0.046 ‰ and 0.21 ‰ for, respectively, $\delta^{18}O$ and δD.

To construct a stacked series for all cores, the depths of cores 5G-2 and 5G-3 were reduced to a depth of 5G-1, and the values of the isotopic composition of ice for all three cores were reduced to the values of the isotopic profile of lake ice to a depth of 3611 m, obtained at the Laboratoire des Sciences du Climat et de l'Environnement (Saclay, France) based on 1 m samples and published in [8].

The standard error of the values of the stacked series of isotopic composition of lake ice was determined as the standard deviation of the values of the isotopic composition of ice at a given depth in individual cores, divided by the square root of the number of observations, and amounting to 0.038 ‰ and 0.17 ‰ for, respectively, $\delta^{18}O$ and δD.

Oxygen measurement 17 is performed using a different technique on the Picarro L2140-i device. For one measurement cycle, which lasts 3 days, only 5 samples are measured. Each sample is poured into 3 vials, and the resulting 15 vials are randomly placed on the tray. At the beginning, in the middle and at the end of the series, the VOS-4 standard is set. First, the first standard is measured 20 times to stabilize the device, and then each vial is measured 20 times. The first 5 measurements are ignored, and the last

15 measurements are averaged. Thus, for each sample we obtain 3 independent values of isotopic composition, each of which, in turn, is obtained by averaging 15 measurements. These three values are compared to make sure that the standard deviation of the ^{17}O-excess values (^{17}O-excess = (ln(δ^{17}O/1000+1) – 0.528 ln (δ^{18}O/1000+1))$\cdot 10^6$) does not exceed the limit of 5 per meg (5 units per million). If the sample meets this criterion, the average value of its isotopic composition is calculated; if not, it is sent for additional measurement.

Results

In Fig. 2*a* the profile of the isotopic composition (δ^{18}O) of lake ice is shown. Unlike atmospheric ice, accreted ice is characterized by extremely low variability of isotopic values in depth: 1 standard deviation of oxygen 18 values in the upper part of the profile (in the so-called "lake ice 1" [3], up to a depth of 3608 m) is 0.2 ‰, and in the lower part of the profile it is 3 times less (0.06 ‰). Despite such low variability of the isotopic composition, its fluctuations in the upper part of the profile are significant. In the lower part of the profile ("lake ice 2"), the variability of isotopic values is only 1.6 times higher than the measurement error. Apparently, there are no significant short-period fluctuations in the isotopic composition.

Figure 2*b* shows the profile of the dxs parameter (which is defined as dxs = δD – 8δ^{18}O [9]). This parameter is widely used in interpreting the isotopic composition of atmospheric ice as an indicator of the intensity of kinetic isotopic processes during evaporation of water in a moisture source and during precipitation from ice clouds [10]. It is not convenient for studying isotopic fractionation during the freezing of water, since the regression coefficient of the "freezing line" (the line connecting the points of the isotopic composition of water and the formed ice) in typical Earth conditions is always less than 8.

Because of this, in [5] we proposed using the parameter dxs4 = δD – 4.02δ^{18}O (Fig. 2*c*). The coefficient 4.02 is the slope (regression coefficient) of the "freezing line" (i.e., the line connecting the points corresponding to water and ice formed by freezing this water in the diagram δD *vs* δ^{18}O) for water having an isotopic composition that is the same as the water in the subglacial Lake Vostok. The regression coefficient of the freezing line k can be calculated using the following formula:

$$k = [(\delta D_w + 1000)/(\delta^{18}O_w + 1000)]\cdot[(\alpha_D - 1)/(\alpha_{18} - 1)], \qquad (1)$$

where w stands for the isotopic composition of water, and α_D and α_{18} are the coefficients of isotopic fractionation during the freezing of water for deuterium and oxygen 18, respectively. The equilibrium values of α_D and α_{18} are 1.0208 and 1.003 [8], but their real (effective) values may be lower. However, no matter how the fractionation coefficients change, they change in parallel for deuterium and oxygen 18 — thus, the value of the right part in formula (1) – and therefore the value of the coefficient k — always remains unchanged. At a very high freezing rate, the fractionation coefficients are equal to 1 — in this case, the isotopic composition of ice is equal to the isotopic composition of water, and equation (1) does not make sense.

Thus, a notable feature of the dxs4 parameter is that it does not change during the freezing process of water (i.e. it is the same for water and for the ice formed from it) and, moreover, its value does not depend on effective fractionation coefficients, but only on the isotopic composition of the freezing water.

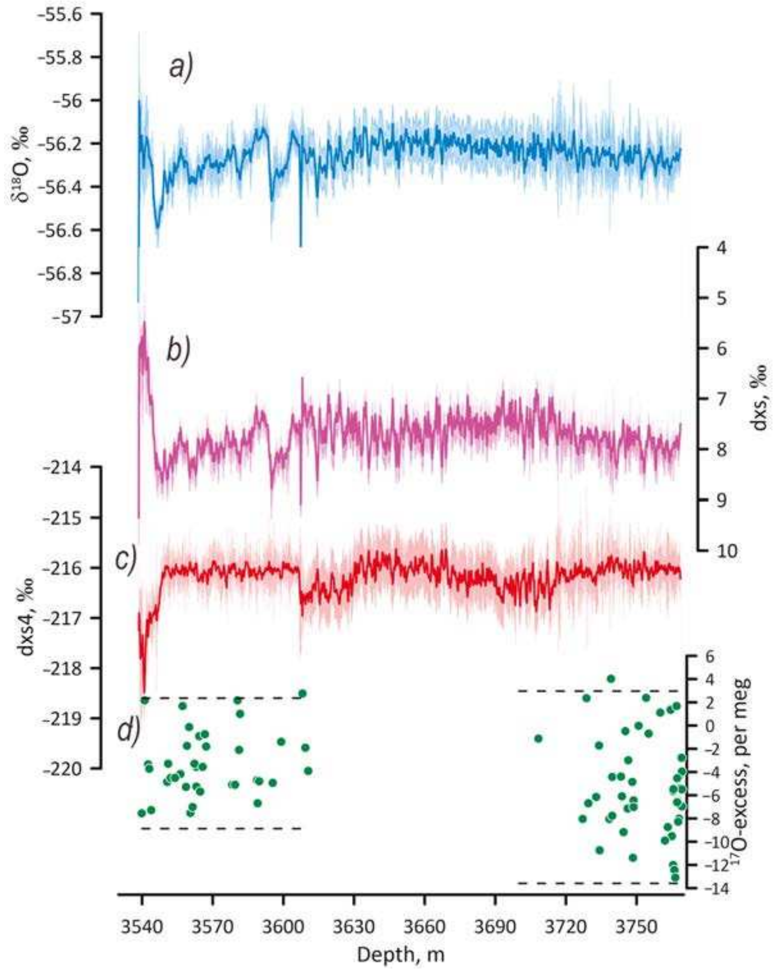

Fig. 2. Stacked isotopic profile of the subglacial Lake Vostok's accreted ice: *a)* — concentration of oxygen 18; *b)* — dxs parameter (dxs = δD – 8δ^{18}O); *c)* — dxs4 parameter (dxs4 = δD – 4.02δ^{18}O); *d)* — ^{17}O-excess parameter (^{17}O-excess = (ln(δ^{17}O/1000 + 1) – 0.528ln (δ^{18}O/1000 + 1))·10^6).

In Figs. 2*a–c*, the shading shows the uncertainty (±2σ). In Fig. 2*d* the dash lines show 96 % of the ^{17}O-excess values distribution (±2σ)

Рис. 2. Сводный изотопный профиль конжеляционного льда подледникового озера Восток: *a)* — содержание кислорода 18; *b)* — параметр dxs (dxs = δD – 8δ^{18}O); *c)* — параметр dxs4 (dxs4 = δD – 4,02δ^{18}O); *d)* — параметр ^{17}O-excess (^{17}O-excess = (ln(δ^{17}O/1000 + 1) – 0,528·ln(δ^{18}O/1000 + 1))·10^6).

На рис. 2*a–c* заливкой показаны пределы погрешности (±2σ). На рис. 2*d* пунктиром показаны пределы значений ^{17}O-excess, в которые укладывается 96 % распределения (±2σ)

Accordingly, if the value of dxs4 changes in the lake ice, this indicates that the isotopic composition of the water from which this interval of lake ice was formed is changing.

Figure 3*b* shows the values of deuterium concentration (δD) as a function of δ^{18}O, and Figure 4 shows a diagram of the dependence of dxs4 on δ^{18}O for lake ice.

Fig. 2*d* shows the values of the ^{17}O-excess parameter. 42 measurements were performed in Lake ice 1, the average value of this parameter was –4.2±0.6 per meg (a confidence interval equal to ± 2 errors of the average is given). 59 measurements were performed in Ice 2, the average value of ^{17}O-excess was –4.8±0.7 per meg. Thus, lake ice of both types does not differ in terms of relative concentration 17. It is obvious that the variability of this parameter in depth (if any) is significantly less than the measurement error. Therefore, it is not possible to establish a connection between this parameter and other characteristics of the lake ice.

We also measured the oxygen 17 content in the "icicle" frozen on the drill bit during the first opening of the lake (see Fig. 2 in [6]), the isotopic composition of which corresponds to the isotopic composition of the surface water layer in the southern part of Lake Vostok. The value of ^{17}O-excess in this sample is –15±2 per meg.

Discussion

Characteristics of the conditions of lake ice formation in various sections of the ice flow line passing through the borehole at Vostok station.

In order to characterize the conditions of lake ice formation at different depth intervals, we divided the isotope profile into homogeneous sections based on data on the ratio of oxygen 18 and deuterium isotopes (Fig. 3*b*) and on the variability of the dxs4 parameter (Fig. 2*c* and Fig. 4), see Table.

The obtained results show, first of all, that the traditional division of lake ice into 2 layers ("ice 1", with mineral inclusions, presumably formed over the strait near the western shore of the lake, and "ice 2", without mineral inclusions, presumably formed over the deep part of the lake (Fig. 1)) is too simplified, at least in terms of isotopic composition. At least we can talk about three layers, two of which, in turn, are also divided into sections that differ in isotopic composition.

The upper 11 m of lake ice (adhering to the accepted classification, we will call this layer "lake ice 0") differ very much from the underlying ice thickness by a large range of isotopic values and an unusual ratio between oxygen 18 and deuterium (red, orange and yellow sections in Fig. 3*a*, 3*b* and 4). We believe that in this zone there is the influence of local glacial meltwater (and probably hydrothermal waters) coming from under the glacier near the western side of the lake.

To illustrate this hypothesis, in Fig. 3*c* we have shown the isotopic composition of the main components of the hydrological system of Lake Vostok — the isotopic composition of the water freezing under the Vostok station (determined by the isotopic composition of the above-mentioned "icicle"), the isotopic composition of glacial melt water coming from the northern part of the lake (according to [5]), as well as the probable isotopic composition of meltwater, which could come from under a glacier near the western shore of the lake (corresponds to the average isotopic composition of atmospheric ice core 5G in the range 3500–3530 m).

Regarding the isotopic composition of the lake water, it is vital to distinguish between the isotopic composition of water freezing under a glacier in the area of Vostok station (this is shown in Fig. 3*c*) and the isotopic composition of "resident" lake water. The difference between them is due to the fact that the melted glacial water coming from the northern part of the lake does not completely mix with the resident (lying deeper) lake water [5]. Whereas the isotopic composition of the freezing water was measured directly from the isotopic composition of the water sampled after the unsealing of the lake [6], the isotopic composition of the resident water, on the contrary, is not known and can only be

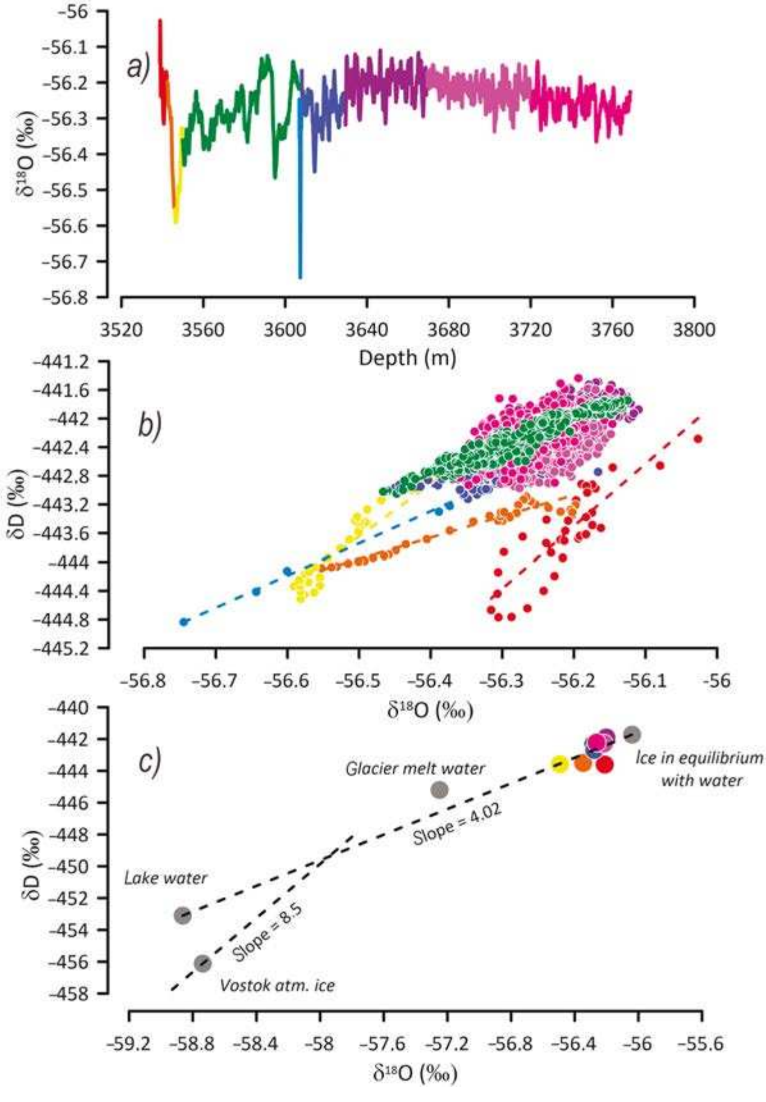

Fig. 3. Uniform segments of the lake ice's isotopic profile and the relationship between different components of Lake Vostok.

a — uniform segments of the lake ice thickness defined on the base of the oxygen 18/deuterium relationship (Fig. 3*b*) and the dxs4 parameter (Figs. 2*c* and 4); *b* — the relationship between oxygen 18 and deuterium; *c* — the isotopic composition of the different components of Lake Vostok's hydrological cycle: the coloured circles are the mean values of the different segments isotopic profile of lake ice; the grey circles are the isotopic composition of the lake water; the isotopic composition of ice in the equilibrium with this water (the slope of the line connecting these two points is 4.02); the isotopic composition of the melt glacier water entering the lake in its northern part according to [5]; the isotopic composition of the lower part of the meteoric ice in the 3500–3530 m interval of the 5G ice core; and the local Meteoric Water Line with a slope of 8.5.

The same colours in Figs. 3*a*, 3*b* and 3*c* depict the same segments of the isotopic profile

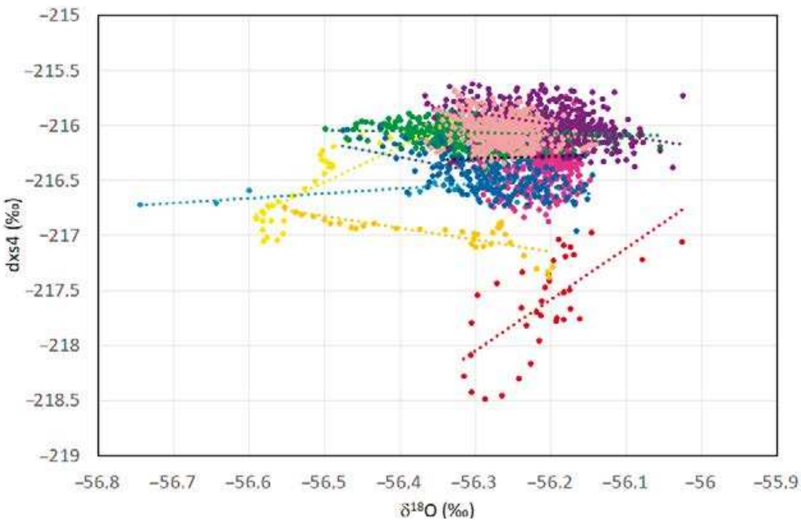

Fig. 4. The dxs4/δ^{18}O for the lake ice. The colours of the segments correspond to the colours in Fig. 3

Рис. 4. Диаграмма dxs4/δ^{18}O для озерного льда. Цвета интервалов соответствуют аналогичным цветам на рис. 3

estimated approximately based on existing ideas about the hydrological regime and the mass balance of Lake Vostok.

Figure 3*c* does not show the isotopic composition of the hydrothermal waters – its value is not known for certain, but, in any case, in this diagram the corresponding point is located to the right of the isotopic composition of the lake water [5].

The isotopic composition of the freezing lake water may change 1) due to a change in the ratio of resident lake water and glacial/hydrothermal melt water, and 2) due to a change in the isotopic composition of glacial/hydrothermal melt water. In the first case, the oxygen 18 / deuterium ratio in the freezing lake water will be close to 4 for meltwater coming from the northern part of the lake (see Fig. 3*c*). In the case of the arrival of local meltwater from under the western shore of the lake, the oxygen 18 / deuterium ratio can be almost any due to the proximity of its isotopic composition to the lake water. In the second case, the oxygen 18 / deuterium ratio in the freezing lake water will be close to 8. In the case of the influence of hydrothermal waters, this ratio should be significantly less than 4 [5].

Рис. 3. Однородные сегменты изотопного профиля озерного льда и соотношение между различными изотопными компонентами озера Восток.

a — изотопно однородные участки толщи озерного льда, выделенные на основе данных о соотношении кислорода 18 и дейтерия (рис. 3*b*) и параметра dxs4 (рис. 2*c* и 4); *b* — зависимость между концентрацией кислорода 18 и дейтерия; *c* — изотопный состав различных компонент гидрологического цикла озера Восток: цветные кружки — средние значения изотопного состава однородных участков показанных на рис. 3*a* и 3*b*; серые кружки — изотопный состав озерной воды, определенный по «сосульке», намерзшей на буровой снаряд после первого вскрытия озера; изотопный состав льда, который находится в равновесии с этой озерной водой (эта точка соединена с предыдущей линией с коэффициентом регрессии равным 4,02); изотопный состав талой ледниковой воды, поступающей в озеро в его северной части по [5]; изотопный состав нижней части атмосферного льда керна 5Г в интервале 3500–3530 м и локальная линия метеорных вод с коэффициентом регрессии 8,5.

Одинаковые цвета на рис. 3*a*, 3*b* и 3*c* показывают одни и те же участки изотопного профиля

Table

Characteristics of homogeneous sections of the vertical profile of the isotopic composition of the Lake Vostok accreted ice

Таблица

Характеристики однородных интервалов вертикального профиля изотопного состава конжеляционного льда озера Восток

Zone	Depth interval, m		δD, ‰	$\delta^{18}O$, ‰	dxs4, ‰	Slope (regression coefficient)	
	Top	Bottom				$\delta D/\delta^{18}O$	dxs4/$\delta^{18}O$
0–1	3538.8	3542.3	–443.6	–56.22	–217.65	**8.5±0.9**	**4.5±0.9**
0–2	3542.3	3545.8	–443.5	–56.35	–217.0	**3.0±0.2**	**–1.1±0.2**
0–3	3545.8	3549.8	–443.6	–56.49	–216.5	**7.3±0.3**	**3.3±0.3**
1	3549.8	3606.8	–442.3	–56.28	–216.1	**3.92±0.05**	–0.1±0.05
"Peak 3608"	3606.8	3608.1	–443.3	–56.39	–216.6	**4.2±0.3**	0.1±0.3
2–1	3608.1	3629.3	–442.7	–56.28	–216.4	**2.2±0.2**	**–1.8±0.2**
2–2	3629.3	3693.3	–442.0	–56.20	–216.1	**2.7±0.2**	**–1.3±0.2**
2–3	3693.3	3720.3	–442.4	–56.23	–216.3	**3.9±0.4**	–0.1±0.4
2–4	3720.3	3768.8	–442.2	–56.26	–216.0	**3.5±0.1**	**–0.6±0.1**

Note. Bold text highlights statistically significant regression coefficients.
Примечание. Жирным шрифтом выделены статистически значимые коэффициенты регрессии.

Taking this into account, let's consider in more detail each of the sections of the isotope profile (the specified colour refers to the colour with which the sections are painted in Fig. 3; isotopic characteristics for each section are shown in the Table).

The interval 3535.8–3549.8 m ("lake ice 0") differs from the underlying ice column, first of all, by a very strong change in the parameter dxs4 (Fig. 2*c*), which indicates a significant change in the isotopic composition of freezing water during the formation of this ice column. Another notable difference between this interval is that the values of its isotopic composition in the diagram δD *vs* $\delta^{18}O$ (Fig. 3*b*) have a large spread and lie away from the array of points of the isotopic composition of ice below 3549.8 m. At the same time, according to the slope between δD and $\delta^{18}O$, this interval is clearly divided into 3 zones (Fig. 3*b*):

Zone 0–1 (red, 3538.8–3542.3 m):

A strong change (by more than 2 ‰) in the values of dxs4 (Fig. 4) indicates an intensive change in the isotopic composition of the freezing water. The ratio of oxygen 18 and deuterium is $\delta D = 8.5\ \delta^{18}O + 44.8$. This is very close to the local meteoric water line for the lower part of the atmospheric ice at Vostok (3500–3530 m), and in general we interpret the variability of the isotopic composition of the ice in this zone as a manifestation of the strong influence of local glacial melt water, which can dominate the freezing mixture.

The average isotopic values of ice in this zone are –56.22 ‰ for oxygen 18 and –443.6 ‰ for deuterium (Table).

Zone 0–2 (orange, 3542.3–3545.8 m):

Dxs4 is also noticeably changing here (by almost 1 ‰, Fig. 4), but at the same time $\delta D = 3.0\delta^{18}O - 276.5$. Such a low regression coefficient of the oxygen 18 / deuterium line may indicate the influence of hydrothermal waters, but, apparently, this section of ice is simply a transition between zones 0–1 and 0–3.

Zone 0–3 (yellow, 3545.8–3549.8 m):

This section is similar to ice 0–1, but with a noticeably lighter (by 0.27 ‰) isotopic composition of oxygen 18. The ratio between oxygen 18 and deuterium is $\delta D = 7.3\delta^{18}O - 31.7$.

It can be assumed that the influence of resident lake water is greater in the freezing mixture. On the other hand, the shift of section 0–1 relative to section 0–3 and the underlying ice thickness in oxygen 18 with a constant deuterium content (Fig. 3*b*) may also indicate that there is more hydrothermal water admixture in zone 0–1 compared to all the other ice sections.

Zone 1 (green, 3549.8–3606.8 m):

This section, in fact, is "lake ice 1". The isotopic composition varies quite widely, but dxs4 remains unchanged (Fig. 2*c* and 4). The freezing line is described by the equation $\delta D = 3.92\delta^{18}O - 221.8$. This section of ice is the only one whose isotopic composition's formation mechanism is known for certain. It is formed from lake water that is homogeneous in composition, and variations in isotopic composition are due to changes in the effective fractionation coefficient due to different volumes of trapped water inclusions ("pockets" [3]). Since aqueous inclusions freeze after being incorporated into the ice matrix, their isotopic composition does not change after freezing. Thus, the larger the proportion of these pockets, the lower the effective fractionation coefficient, and the closer the isotopic composition of ice is to the isotopic composition of the freezing water.

The available isotope data make it possible to calculate the volume of these water pockets fairly accurately. In particular, the maximum decrease in the values of the isotopic composition at a depth of 3595.1 m can be explained by the volume fraction of aqueous inclusions, which is 11 %.

The average isotopic values of ice in this zone are –56.28 ‰ for oxygen 18 and –442.3 ‰ for deuterium.

Further, the blue colour in Figures 3 and 4 shows the "isotopic peak of 3608 m", which will be discussed in more detail in the next section.

Ice below 3608.1 m ("lake ice 2") is characterized by the apparent absence of short-period fluctuations in isotopic composition (Fig. 2*a*), as well as by low values of the regression coefficient of the freezing line (< 4, Fig. 3*b* and Table). At the same time, according to the nature of the dxs4 variability (Fig. 2*c* and 4), this section can be divided into several zones:

Zone 2–1 (blue, 3608.1–3629.3 m):

This interval is characterized by a low dxs4 value compared to the above and below ice layers (Fig. 2*c*). The ratio between oxygen 18 and deuterium is $\delta D = 2.1\delta^{18}O - 322$. Such a low regression coefficient may indicate a change in the proportion of hydrothermal waters in the freezing mixture. At the same time, the isotopic composition of ice within a given area first decreases, then increases – this may be due to a change in the volume of water pockets, which are practically not found in the underlying ice layers [3].

Zone 2–2 (purple, 3629.3 – 3693.3 m):

Starting from this section, significant short-period variations in isotopic composition are completely absent. According to the ratios of δD *vs* $\delta^{18}O$ and dxs4 *vs* $\delta^{18}O$, this zone is similar to the previous one (Table), but at higher (respectively, by 0.08 and 0.3 ‰) values of $\delta^{18}O$ and dxs4 (Fig. 2*c*, 3*b* and 4), which indicates a slight change in the proportion of hydrothermal waters in the freezing mixtures.

Zone 2–3 (magenta, 3669.3 – 3720.3 m):

The dxs4 parameter practically does not change here, despite the fact that the isotopic composition of the ice decreases markedly with depth. The immutability of the dxs4 values is explained by the fact that the regression coefficient between oxygen 18 and deuterium is close to 4 here (3.9, Table). This could be explained by a change in the fractionation coefficient, but this is unlikely, since there are practically no water pockets in this zone. It follows from Figure 3*c* that such an isotopic composition may be due to a change (decrease with depth) in the proportion of glacial melt water from the northern part of the lake.

Zone 2–4 (pink, 3720.3–3768.8 m):

This section is characterized by a weak (but significant) negative correlation between dxs4 and $\delta^{18}O$ (a slight increase in dxs4 with a decrease in the values of $\delta^{18}O$), and the ratio between oxygen 18 and deuterium is $\delta D = 3.5\delta^{18}O - 247.3$. The isotopic composition of this zone is similar to the previous one in deuterium, but slightly lighter (by 0.03 ‰) for oxygen 18. All this generally suggests that the proportion of meltwater from the northern part of the lake continues to decrease in this area, but the contribution of hydrothermal waters is also slightly lower than in the previous section.

In Fig. 5, we have shown the average values of the isotopic composition of different sections of ice, as well as the isotopic composition of ice, which is in isotopic equilibrium with the freezing lake water.

This figure confirms the strong difference between zone 0, on the one hand, and zones 1 and 2, on the other. The regression coefficient of the line connecting the average values of sections 1 and 2 is 5.44. That is, the difference between different sections of the profile is explained by both a change in the effective fractionation coefficient (the proportion

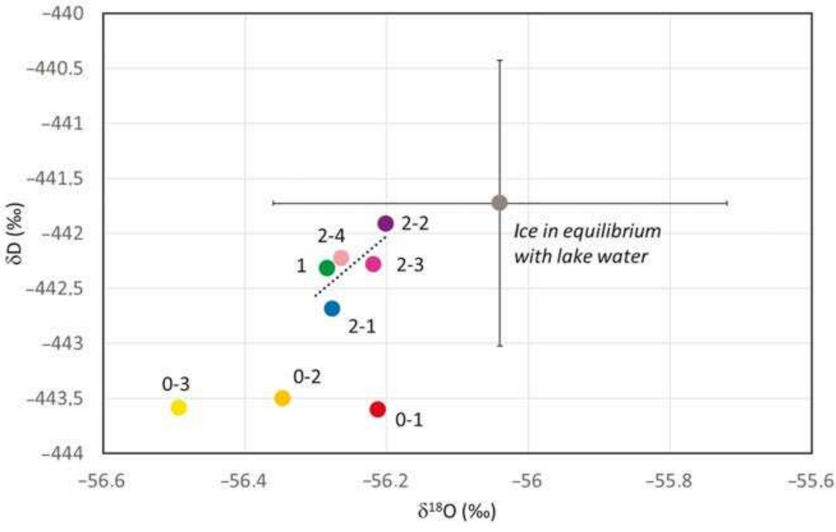

Fig. 5. The isotopic composition of the different lake ice segments, as well as the isotopic composition of the ice in equilibrium with the freezing lake water.

The error bars are ± 2 standard errors of mean. The colours of the points correspond to different ice segments in Figures 3 and 4. The dotted line denotes the linear regression for the isotopic composition of lake ices 1 and 2

Рис. 5. Изотопный состав различных участков озерного льда, а также изотопный состав льда, который находится в изотопном равновесии с замерзающей озерной водой. Пределы погрешности показывают ±2 ошибки среднего.

Цвет точек соответствует цвету разных участков льда на рис. 3 и 4. Пунктирной линией показана линейная регрессия для изотопного состава озерного льда 1 и 2 of water inclusions) and the influx of glacial melt water (and, possibly, a change in the isotopic composition of the latter).

Figure 5 also suggests that the lake ice may not be in complete equilibrium with the freezing lake water (the fractionation coefficient is 90–95 % of the equilibrium one). However, given the relatively large error in our estimates of the isotopic composition of the freezing lake water, and therefore ice in equilibrium with this water, we cannot judge this reliably.

If we assume that the lower part of the ice is in equilibrium with the lake water, then the isotopic composition of zone 2–4 can determine the isotopic composition of the water freezing directly under Vostok station: it is equal to –59.09 ‰ for oxygen 18 and –452.61 ‰ for deuterium.

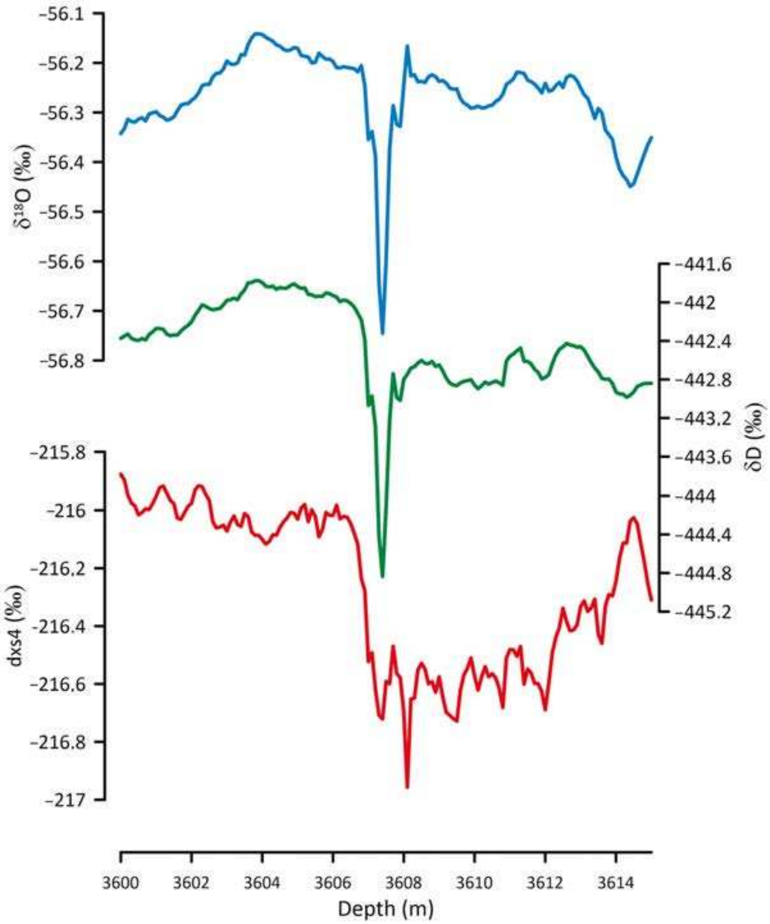

Fig. 6. The isotopic composition of lake ice in the interval 3600–3615 m.

From top to bottom: concentration of oxygen 18, concentration of deuterium and the dxs4 parameter

Рис. 6. Изотопный состав озерного льда в интервале 3600–3615 м.

Сверху вниз: содержание кислорода 18, содержание дейтерия и параметр dxs4

The nature of the unique peak of the isotopic composition of lake ice discovered at a depth of 3608 m

Figure 6 shows the isotopic composition of lake ice in the interval 3600–3615 m.

At a depth of 3607.4 m (or rather, in the range 3606.9–3608.0 m) we see a strong decrease in the values of the isotopic composition, which has been called the "isotopic peak 3608". We strongly believe that this peak is not an artefact associated with measurement problems, as it occurs in all three cores (5G-1, 5G-2 and 5G-3).

Within this peak, $\delta^{18}O$ changes by 0.75 ‰ and drops to the minimum values for the entire lake ice (Fig. 3*a*). The regression coefficient of the regression line for the ice interval containing the peak is 4.5 (Fig. 3*b* and Table). This clearly indicates a sharp change in the effective fractionation coefficient, which could be caused either by a large water inclusion or a change in the freezing rate of water (a lower fractionation coefficient corresponds to a higher freezing rate).

At the same time, a sharp change in the dxs4 parameter is also observed in this section of ice (Fig. 2 and Fig. 6), which indicates that the isotopic composition of the freezing water was different above and below the peak. Surprisingly, the isotopic composition was approximately the same in oxygen 18, but differed in deuterium (Fig. 6). This behaviour can only be explained by a change in the proportion of hydrothermal water in the freezing mixture (it is higher below the peak), since all other processes would lead to a parallel change in both isotopes.

The peak width is 110 cm, but taking into account molecular diffusion, it can be assumed that the initial peak width (before diffusion smoothing) was significantly smaller, the first tens of centimetres. This suggests that the event that caused the occurrence of this peak was extremely abrupt — very short in time and/or very small in space.

We consider the most likely explanation of the observed pattern to be the contact of lake ice with the water of the deep-water part of the lake after passing over the island (Fig. 1). In this case, it is "peak 3608" that can be considered to be the boundary between lake ice 1 and lake ice 2, and we can also assume a break in ice formation at the end of section 1.

It is interesting to note that the layer of large mineral inclusions previously found in the core of 5G-1 [11] lies at a depth of 3606.3–3606.5 m, i.e. almost at the very bottom of zone 1, approximately 1 m above the isotope peak. These inclusions could not be captured by ice except through direct contact between the glacier and the underlying rock. This generally does not contradict the idea that the isotope peak was formed after the passage of the glacier over the island (Fig. 1).

Oxygen 17 in the lake ice and the lake water

^{17}O-excess is a relatively new parameter that has only recently entered the practice of isotope studies [12, 13]. It has already been successfully used in paleoclimatic reconstructions based on ice core data [14, 15], but its application in hydrology is still limited by insufficient understanding of oxygen 17 fractionation during processes such as water freezing [16] and isotope exchange between water and rocks.

In this paper, for the first time, we present data on the value of ^{17}O-excess in the ice (4.8±0.7 per meg) and in the water (–15±2 per meg) of Lake Vostok. Since, as shown in the previous sections, this water and ice are likely to be in isotopic equilibrium, this gives us the opportunity for the first time to determine the equilibrium fractionation coefficient for oxygen 17 when water freezes.

Fractionation coefficient for oxygen 17:

$$\alpha_{17} = \alpha_{18}{}^{m}, \quad (2)$$

where α_{18} is the fractionation coefficient for oxygen 18, and *m* is the exponent equal to 0.529 for equilibrium processes and 0.518 for kinetic processes [13]. Since the freezing of water in Lake Vostok occurs under equilibrium conditions, it can be expected that the value of *m* will be close to 0.529, and in this case the ^{17}O-excess of ice would be equal to –12.5 per meg. In order to get a value of ^{17}O-excess in the lake ice equal to –5 per meg, the value of *m* must be equal to 0.5315.

The same conclusion was drawn earlier when measuring the isotopic composition of water frozen in the 5G-1 borehole after the first unsealing of the lake in 2012 (the data have not been published).

The value of *m* obtained by us significantly exceeds 0.529, but it nevertheless fits into the range of 0.501–0.553 obtained in other experimental studies [16].

Conclusion

As a result of the research that was conducted, we were able to characterize in detail the ratio of various factors that played a role in the formation of different sections of the accreted ice of the subglacial Lake Vostok. It is shown that the division of ice into two zones — "ice 1", with mineral inclusions, and "ice 2", without mineral inclusions — is too simplified. At least 3 zones should be distinguished, two of which, in turn, are divided into shorter homogeneous sections. The isotopic composition of these sections is determined by a different ratio of four different factors: 1) a change in the effective fractionation coefficient due to the capture of water pockets; 2) the contribution of local melted atmospheric waters from the western shore of the lake; 3) the contribution of melted atmospheric waters from the northern part of the lake; 4) the contribution of hydrothermal waters.

For the first time, we were able to measure the value of the ^{17}O-excess parameter in lake ice and in lake water and, thus, experimentally determine the equilibrium fractionation coefficient for oxygen 17 during the freezing of the lake water.

In the future, we plan a more comprehensive analysis of the lake ice, taking into account all available data on isotopic, gas, mineral and chemical compositions. It is also necessary to continue theoretical and experimental studies on the geochemistry of oxygen 17 during processes such as freezing/melting and isotope exchange with rocks, which will clarify the contribution of various sources of Lake Vostok water to its mass balance.

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Условия формирования конжеляционного льда подледникового озера Восток по данным о его изотопном составе

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Аннотация. Представлен новый набор данных по составу стабильных изотопов воды (δD и $\delta^{18}O$) в толще конжеляционного льда подледникового озера Восток (3538–3769 м), измеренных по трем параллельным ледяным кернам. Высокая точность новых данных позволила охарактеризовать условия формирования различных участков этого льда. Весь интервал озерного льда можно разделить на три зоны: 1) «зона 0», 3538,8–3549,8 м, находится под сильным влиянием местных вод, образованных растаявшим атмосферным льдом, вероятно, поступающим из-под ледника на западном берегу озера; 2) «зона 1» (озерный лед 1), 3549,8–3607,4 м, испытывает значительные колебания изотопного состава вследствие различий эффективного коэффициента фракционирования при замерзании водных включений в ледяной матрице; 3) «зона 2» (озерный лед 2), 3607,4–3768,8 м, находится под влиянием талых ледниковых вод, поступающих из северной части озера, и гидротермального потока со дна озера. Впервые определена точная граница между озерным льдом 1 и льдом 2, которая соответствует резкому изотопному выбросу на глубине 3607,4 м. Приводятся данные о параметре ^{17}O-excess в озерном льду и воде, что позволило провести прямой расчет равновесного коэффициента фракционирования кислорода 17 при замерзании воды.

Ключевые слова: изотопный состав, гидрология, конжеляционный лед, озеро Восток

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Remote sensing and mathematical modelling of Lake Vostok, East Antarctica: past, present and future research

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Abstract. The paper presents a review of the studies carried out in the area of the subglacial Lake Vostok (East Antarctica) to date. They include geophysical, glaciological, geodesic, and geological investigations. The most important geophysical investigations were carried out by the Polar Marine Geosurvey Expedition. They included reflection and refraction seismic, and also radio-echo sounding. The major contribution to the study of this region was made by American researchers, who in the 2000/01 field season performed a complex airborne geophysical survey on a regular network. Their work included magnetometric, gravimetric, and radio-echo sounding measurements. All the research conducted found that the water surface area is 15 790 km², and its altitudinal height changes from –600 to –150 m. The average depth of Lake Vostok is 400 m, and the maximum marks reach 1 200 m. The water body volume is estimated at 6 100 km³. There are 11 islands in the lake, and their total area is 365 km². In addition, 56 isolated subglacial water bodies were found around the lake. A special section is devoted to a review of mathematical models of heat and mass transfer processes in the glacier and water movement in Lake Vostok.

Keywords: Lake Vostok, glacier dynamics, multidisciplinary studies, review of mathematical models

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Introduction

The interest in the study of the subglacial Lake Vostok is related to the uniqueness of this natural object. Today, it has no analogues on our planet. The hypothesis of the existence of a large subglacial water body buried under an ice sheet to the north of the Vostok Station was suggested based on the analysis of satellite data published in the well-known article [1]. In addition to these data, the article discussed radio-echo sounding (RES) data, which allow detecting with a very high degree of probability the existence of water under an ice sheet [2]. Further geophysical studies made by Russian scientists confirmed the initial hypothesis. However, this issue was finally resolved by the first penetration of Lake Vostok. This momentous event took place on February 6, 2012, at 0:24 local time, which corresponds to February 5, 20:25 Moscow time [3].

In retrospect, it is clear that as early as the mid-1970s there was enough information to suggest that a large subglacial water body exists to the north of the Vostok Station. Even at the dawn of Antarctic studies, I.A. Zotikov suggested the existence of such objects. He attributed their formation to basal melting and the filling of the negative forms of subglacial relief with meltwater [4–6]. In general, one can say that this was the first large-scale study, which resulted in building a one-dimensional mathematical model based on an analytical solution of the thermal conductivity equation, taking into account the vertical movement of the ice sheet. This model was a development of an earlier and simpler version of the glacier heat transfer model [7]. Less than ten years after I.A. Zotikov's model was published, in December 1967, new data indicating the existence of a subglacial water body were obtained in conducting RES around the Sovetskaya Station [8]. Subsequent studies of Antarctica's interior led to the discovery of a large number of similar objects. At present, their revealed number is 675 [9], but Lake Vostok stands out among them for its truly grandiose size [10]. The first comprehensive review of Lake Vostok can be found in a monograph written by I.A. Zotikov [11]. It discusses many important issues, including the formation of the lake and the existence of life isolated from the rest of the world.

The present work is an attempt to summarize the main geophysical, glaciological, and geodesic results obtained in the years of study of the Lake Vostok region. The next step in the study, in the opinion of the authors, should be related to penetration into Lake Vostok with the aim of studying directly its water column and bottom sediments. This is the only proper way to get reliable data about the composition of the lake water, the processes taking place in the lake, the microorganisms living in the lake, etc., in other words, about the entire environment and its evolution. At the same time, mathematical modelling of processes in the lake is equally essential. For this reason, the authors have prepared an overview of the main results of modelling associated with Lake Vostok. The final part of the article describes how the authors see the next step in the study of this unique natural object, primarily in terms of remote sensing and mathematical modelling.

Main results of research before 1993

The first reliable geophysical data on the Lake Vostok area were obtained in 1958–1964 in the course of seismic sounding and gravimetric observations performed by A.P. Kapitsa and O.G. Sorokhtin [12–14]. However, in the process of data interpretation, the layer located directly under the ice sheet was mistakenly taken for a sedimentary cover. Subsequent works were mostly related to airborne RES. In particular, in the airborne RES of 1971–1978 reflections typical of water objects were registered to the north of the Vostok Station [2, 15]. In the 33rd Soviet Antarctic Expedition (SAE) field season on November 7 1987, Russian scientists made a regional flight from the Molodezhnaya Station to the Vostok Station, along the line of which complex airborne RES was performed. Reflections similar to those observed over ice shelves were registered in the area of the Vostok Station. However, this fact was not given due attention [16, 17]. Scientists returned to geophysical studies only after the publishing of the paper, in which the geographical name Lake Vostok first appeared [1].

In addition to several geophysical studies, meteorological, geomagnetic, ionospheric, glaciological, drilling works, and also observations of cosmic rays were carried out at the Vostok Station during this period. Meteorological observations started on December 16, 1957, on the day the station opened [18], and almost never stopped. The highest priority was probably given to glaciological studies. These also began in 1957 with the setting up of a snow profile and the first core drilling down to a depth of 12 metres. At that time, a wide range of measurements, including thermometry [18], was carried out in this borehole. Subsequently, the glaciological studies were significantly expanded and supplemented with observations at glaciological testing sites and in the ITASE traverses. In particular, during the 15th SAE (1970) along the route Komsomolskaya Station — Vostok Station snow stakes were installed every 3 km. In the same year deep drilling began at the Vostok Station, which continued 20 years later, on February 20, 1990 (the 35th SAE), when the borehole 5G was started [19], through which in the following years penetration into Lake Vostok was performed. The study of the ice core made it possible to form a reasonable hypothesis on how the climate of Antarctica has changed over the past nearly half a million years. In addition, the ice core data showed that the lower part of the ice sheet, starting from a depth of 3 538 m, consists of accreted ice formed as a result of lake water freezing [20]. This is very important information, especially for mathematical modelling of the heat-mass transfer processes both in the ice sheet and Lake Vostok. There is another important point: the upper part of the accretion layer in the depth range of 3 538–3 608 metres contains solid (mineral) unevenly distributed (from 2–3 to 25 particles per metre of the ice core) inclusions, 1–2 mm in size. They were probably captured by the glacier as it crossed the shallow coastal area of the lake. Thus, these particles may reflect the composition of the sediments, providing unique information on the geological structure of the subglacial environment [20, 21]. In addition to these works, geodesists from East Germany made measurements of the velocity of near-surface ice flow, which was estimated to be about 3 m/year [22]. These figures were subsequently refined by their colleagues [23].

Main results of research after 1993

The discovery of Lake Vostok and interest in this natural phenomenon resulted in the need for a thorough study of this area. For obvious reasons, Russian scientists were the first to step up their activities. In order to study the lake in detail by remote methods reflection seismic surveys were started around the Vostok station in 1995, and from 1998 they were complemented with ground-based RES. Specially for these purposes, the Polar Marine Geosurvey Expedition (PMGE) developed a unique ice-penetrating radar (RLS-60-98), which was subsequently modified (RLS-60-06) to have greater power and depth [16, 17]. At the initial stage, experimental and methodological works aimed at improving the research methodology and increasing its accuracy were performed. The latter was necessary for penetrating Lake Vostok, which became feasible as there was only about 130 metres left to drill, and the remaining ice thickness had to be calculated with maximum accuracy.

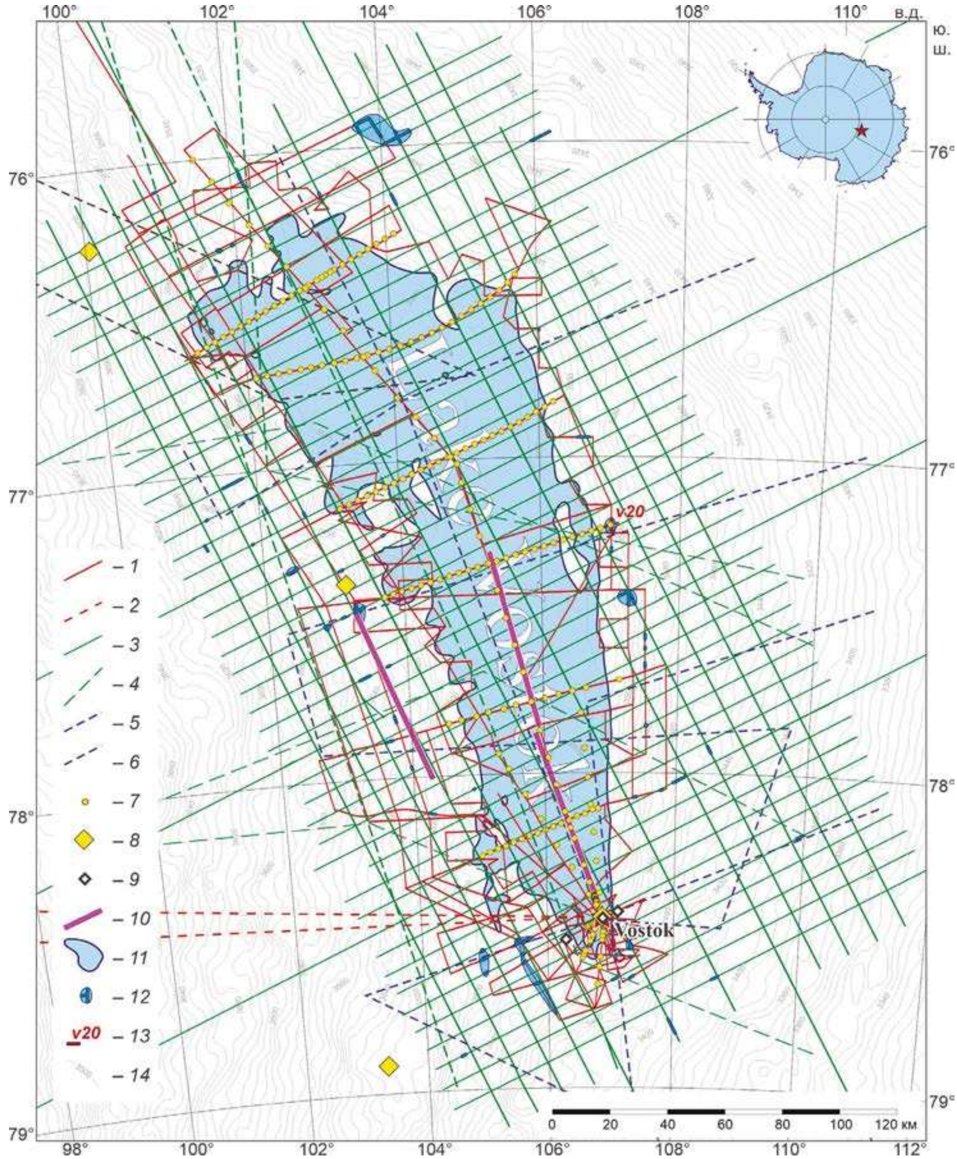
For this purpose, specialized seismic and RES works were carried out, which allowed the researchers to determine that directly at the point of drilling the average velocity of elastic wave propagation in the glacier body and in the pure atmospheric ice (the layer velocity) is 3 810 ± 20 m/s and 3 920 ± 20 m/s, respectively; the average electromagnetic wave propagation is 168.4 ± 0.5 m/μs [10]. On the basis of the data, the thickness of the ice sheet in this area was determined: the average value for both remote methods was 3,768 m, which is only a quarter of a percent less than the value 3 758.6 ± 3 m obtained from drilling after penetrating the lake [24]. The total length of the ground-based radar routes followed during the Russian surveys was 5.190 linear kilometres, and the total number of reflective seismic sounding points was 318 [16,17]. They are shown in Fig. 1.

Seismic and radio-echo sounding was completed in 2008. This research method was replaced by seismic refraction experiments, which were carried out between 2009 and 2013 to determine the bedrock velocities and crustal structure of Lake Vostok and its western coast. During these studies, two lines were acquired with direct and reversed observation using explosives as a source of seismic waves (Fig. 1) [25]. This survey shows that seismic velocities at the lake bottom are in the range of 6.0 to 6.2 km/s, and definitely correspond to the crystalline basement. The data obtained, however, do not exclude the presence of a thin (100 to 200 m) low-velocity (less than 3.8 km/s) layer representing the sedimentary cover. On the seismic profile on the western side of the lake, the velocity of elastic waves was 5.4–5.5 km/s, which corresponds to consolidated sedimentary rocks [25].

In the 1999/2000 season, Italian scientists made 12 separate geophysical survey flights over the water area of Lake Vostok [26]. In the 2015/16 season, three routes crossed the northern end of the lake during comprehensive airborne geophysical investigations by Chinese scientists [27–29]. However, the major contribution to the study of this region was made by American researchers, who in the 2000/01 field season performed a complex airborne geophysical survey on a regular network. Their work included magnetometric, gravimetric and RES measurements [30, 31]. The Russian and American data complemented each other well and made it possible to plot an integrated diagram of the ice sheet thickness and of the heights of the under-ice relief, and to map the shoreline of Lake Vostok with high accuracy (Fig. 1). The ice thickness above the Lake Vostok basin varies between 3 600 and 4 350 m. The ice sheet has a distinctive layered structure, correlating with the ice core data from the borehole 5G [32]. RES data analysis of the ice sheet stratification (isochrones) allowed drawing ice flow lines practically through its entire thickness: from 900 to 3 750 metres over three layers [33].

It was found that the water surface area is 15 790 km², and its altitudinal height changes from –600 to –150 m. The average depth of the lake is 400 m, and the maximum marks reach 1 200 m. The water body volume is estimated at 6 100 km³ [34]. There are 11 islands in the lake, and their total area is 365 km². In addition, 56 isolated subglacial water bodies were found around the lake [10], one of which (*v20*) is active (Fig. 1), i. e. the height of the ice sheet above it changes with time, which indicates a change in the volume of water, which, in turn, indirectly points to possible drainage [9, 35]. On the basis of the map of the natural relief a geomorphological analysis was done [10], whose results, when interpreted, helped to more precisely identify the features of the bedrock and to draw the first orographic diagram of the area [36].

The results of the US complex RES made it possible to substantiate the earlier assumption that the basin of Lake Vostok is a long-term rift graben filled with sediments of the Late Mesozoic to Cenozoic age [21, 37, 38]. These conclusions about the deep structure were confirmed by seismological earthquake converted-wave method observations made in the 2002/03 season along a 20.7 km profile passing through the Vostok station (the observation points are shown in Fig. 1). They showed that the western and eastern



sides of the Lake Vostok basin are divided by a distinct crustal-through rupture zone, the boundary of which is clearly traced up to 50 km. The crust thickness to the west and east of the Vostok basin is 34 km and 36 km, respectively. In addition, the data obtained indicate that an elevated geothermal flux may exist directly beneath the basin [39].

The conclusions about the tectonic nature of the Vostok basin and the neo-tectonic processes taking place in the region are also confirmed by biological studies. The thermophilic bacteria *Hydrogenophilus thermoluteolus* were found in the borehole G5 ice core at a depth of 3 607 m [40]. It is known that 50 °C is the optimal temperature for their growth and development. The hydrothermal activity may be caused by the rise of hot waters through the deep faults [21]. Moreover, these waters are probably mineralized and, therefore, the water mass may be stratified. This is extremely important for understanding the processes at the bottom of Lake Vostok and modelling the lake water circulation.

Important information for the mathematical modelling of heat-and-mass transfer in the ice and water mass/column has been obtained by geodetic methods. This work was carried out in ITASE traverses by researchers from the Institute of Planetary Geodesy of Dresden Technical University (Technische Universität Dresden — Institut für Planetare Geodäsie). In particular, the near-surface velocity of the ice flow above and beyond Lake Vostok was instrumentally determined to be 2.00 ± 0.01 m/year [41]. Another important result for mathematical modelling was the detection of tides in Lake Vostok and instrumental determination of variations in the ice surface heights associated with them. It was shown in [42, 43] that they are about 40 mm, and the resulting redistribution of the lake water from the tides forms an additional component of the general circulation. The geodetic data and modelling showed, among other things, that the water of Lake Vostok cannot flow out, it only can flow in, for example, as a result of drainage from the surrounding small water bodies [44].

Mathematical models of processes in Lake Vostok

The main results presented above do not in themselves answer the question of what processes occur in Lake Vostok and in the contact zone of its surface with the ice sheet, and how exactly these processes occur. Meanwhile, they are certainly important not only

Fig. 1. Location of geophysical investigations in the Lake Vostok area.

1 — Russian ground-based RES; *2* — Russian regional complex airborne geophysical survey route (1987); *3* — American complex airborne geophysical survey (magnetometric, gravimetric, RES, and laser altimetry, 2000/01); *4* — Italian complex airborne geophysical survey (magnetometric, gravimetric and RES, 1999/2000); *5* — Danish-American-British airborne RES; *6* — Chinese Airborne (CHINARE) studies (magnetometric, gravimetric and RES measurements, 2015/16); *7* — Russian reflection seismic (1995–2008); *8* — Russian reflection seismic (1950–1960s); *9* — Russian sounding by the earthquake converted-wave method; *10* — Russian refraction seismic; *11* — Lake Vostok coastal line; *12* — stable subglacial water bodies; *13* — active subglacial water body *v20*; *14* — ice surface elevation contours in metres

Рис. 1. Схема расположения геофизических работ в районе озера Восток.

1 — отечественные наземные радиолокационные исследования; *2* — региональные маршруты комплексной аэрогеофизической съёмки СССР (1987 г.); *3* — комплексные аэрогеофизические работы США (магнитометрические, гравиметрические и радиолокационные измерения, а также лазерная альтиметрия; 2000/01 г.); *4* — комплексные аэрогеофизические работы PNRA (магнитометрические, гравиметрические и радиолокационные измерения; 1999/2000 г.); *5* — аэрогеофизические маршруты комплексной датско-американо-британской аэрогеофизической съемки 1971, 1974–1975 гг.; *6* — работы CHINARE (магнитометрические, гравиметрические и радиолокационные измерения; 2015/16 г.); *7* — отечественные сейсмические зондирования МОВ (1995–2008 гг.); *8* — отечественные сейсмические зондирования МОВ (1950–1960-е гг.); 9 — отечественные зондирования МОВЗ; *10* — отечественные профили МПВ; *11* — береговая линия озера Восток; *12* — стабильные подледниковые водоемы; *13* — активный подледниковый водоем *v20*; *14* — изогипсы высот дневной поверхности в метрах from the theoretical point of view, but also from the applied perspective, e. g. prediction of probe behaviour in the process of sampling lake water or bottom sediments. But any remote sensing methods cannot answer this or other questions. Among the many theoretical and applied issues related to Lake Vostok, the moving of lake water is the most interesting and important. To some extent, it can only be resolved by mathematical modeling, which, of course, should be based on in situ data [45]. Despite the fact that Lake Vostok is covered by a thick ice sheet, currents may exist in it, as in other subglacial water bodies. Water circulation is a result of the indirect effects of endogenous and exogenous processes. The former lead to the vertical movement of water masses due to convection associated with the Earth's heat flow. The latter are related to the geomorphological and subglacial processes of freezing–melting, glacier movement, tides, water and glacial erosion, and a number of others. In addition, the drainage of subglacial water bodies [46, 47] is also an additional source of the inlake advection and turbulent diffusion.

Even small density gradients, which in turn depend on pressure, temperature and mineralization, can cause water circulation in isolated and unstable subglacial water bodies. The latter parameter is the most uncertain for these objects. As mentioned above, the water column of Lake Vostok may well be stratified: fresh at the top and mineralized at the bottom. The water pressure in a subglacial reservoir should be close to that of the ice sheet above it. In this case, if it exceeds 28.4 MPa (which corresponds to a thickness of 3 170 m), the maximum density of fresh water at its freezing temperature is reached. These conditions occur in Lake Vostok, which is under 3 700–4 300 m of ice [10]. Because the thickness of the ice sheet above the lake is not constant, but changes by a few hundred metres, there is a temperature gradient. For example, for Lake Vostok the difference in ice thickness between its northern and southern parts is 460 m. This creates a temperature difference of 0.31 °C, which, according to model estimates [48], results in the horizontal movement of the water at a rate from 0.3 to 0.6 mm/s (i. e. up to 20 km per year). The strength of this horizontal circulation will depend on the heat flow at the ice-water interface, the inclination of the lake surface, and the Coriolis force. Subsequently, similar calculations were made using a numerical 3D model of the ocean circulation, and the results confirmed that Lake Vostok has a weak circulation across the entire area with local variations in the velocity field determined by bathymetry [49].

One of the methods to study the specific features of water circulation in lakes is physical simulation in specially designed test apparatuses. Undoubtedly, this is the most obvious way to get an idea of the true course of natural processes, which, in turn, can help develop mathematical models. However, physical modelling has its drawbacks, which are primarily related to the impossibility to simulate the whole set of similarity parameters, such as the Reynolds, Rayleigh, Taylor, Rossby and Prandtl coefficients, characteristic of natural basins, in a laboratory environment. Nevertheless, a number of researchers have been able to obtain very interesting and promising results in their experiments [50, 51]. The authors of these works modelled the convection process in laboratory experiments with water put in rotating tanks. In particular, the study [50] provides a brief overview of vortex movements, their genesis, the evolution of vortex structures and their role in the ocean and atmosphere dynamics. Special attention was given to the influence of vortices upon small-scale turbulence and water circulation. On the whole, the paper presents general results of the laboratory and numerical modelling of phenomena associated with vortices in stratified and rotating liquids, as well as their values in convective flows.

Wells and Wettlaufer moved from more general questions to more specific ones and carried out laboratory experiments specifically to study the circulation in subglacial Lake Vostok [51]. Their experimental tank was made of transparent double-glazed units and had the following dimensions: length 91.4 cm, width 30.4 cm, and depth from 14.5 to 24.5 cm. In order to account for the effects of the boundary heat fluxes due to ice melting/freezing and the geothermal heat fluxes, a cooling element was connected to one half of the structure and a heating element to the other half. The near-bottom part also had constant heating, simulating the flow of geothermal heat. The entire cell was mounted on a precision-controlled rotating platform in order to account for the influence of the Coriolis force on the forming circulation currents. By performing a series of experiments under different initial and boundary conditions, the researchers obtained two fundamentally different results. The nature of the convective motions was largely dependent on whether the tank was rotating or not. In the non-rotating experiment, overturning circulation arose. When the horizontal scale of the eddies >1, a small stratified domain was formed under the roof, while the deeper region had an overturning circulation. When the horizontal scale of the eddies <1, a similar overturning circulation occurred, with sinking beneath the cold region, rising in the deep region, without the presence of a stratified domain. In the rotating experiment, columnar eddies dominated in the water body, transferring the heat directly from the base to the top. The horizontal movement of the particles 100 μm in size added to the water occurred predominantly in the thin top and bottom boundary layers. The action of the stronger rotation changed the flow dynamics dramatically so that the columnar vortices rapidly stirred passive tracers, but the exchange between the parts of the tank was weak. On this basis, it was concluded that the water exchange between the northern and southern parts of Lake Vostok might also be small, and thus their chemical and biological compositions would be different. According to the authors, in both the experiment and in Lake Vostok, rotation plays a dominant role in controlling the nature of the convective motions, and compensatory water exchange between the base and the roof of Lake Vostok takes about 20–30 days, with minimal lateral mixing.

In theoretical works [48, 52], to describe the water circulation in Lake Vostok, various balance ratios were used, which have a clear physical meaning and with some simplifications allow one to estimate this process. The advantage of this approach was that it made cumbersome calculations redundant; however, avoiding the equations of thermodynamics and hydrodynamics, it is often possible to answer only a small number of questions. In particular, Jean-Robert Petit formulated the concept of an empirical model of the water cycle and the energy balance of Lake Vostok and made the following simplified diagram of water circulation in it [52]. He did not take into account the Coriolis force deviation. The circulation consisted of two closed structures (loops) in the near-surface and deep parts of the water body. The currents formed at the surface were thermohaline structures in which the water temperature and mineralization changed. The cycle began with the formation of water as a result of melting of the lower edge of the ice cover and this melt water mixing with the lake water. The flow was directed from the melting area to the freezing area, where the ice condensed, and the salt, impurities and gases were expelled. Deeper than this layer was a warmer and more mineralized downward water loop with a temperature of –2.5 °C. The flow recirculated, returning to the melting area and mixing heat and salt with the lower layers. The lower water masses cooled, forcing the water to sink to the bottom of the lake. There it was heated again by geothermal heat and rose to the surface. This formed a second circulatory structure, the development of which was supported solely by the Earth's heat flow. Thus, according to [52], this circulation of water from deep layers probably generates additional heat, which increases the thermal flux to 170 mW/m² (compared to the geothermal flux of ~53 mW/m²), of which almost 2/3 is used for ice melt and 1/3 is released through the glacier/ice sheet. Similar conclusions were also presented in [48], which was used by Jean-Robert Petit and other researchers to further study the circulation in Lake Vostok [51, 53, 54].

An alternative and more relevant approach to studying water circulation in subglacial lakes is numerical modelling based on hydrodynamic equations. This approach was applied in two studies [49, 53], which used various modifications of the 3D hydrodynamic model originally developed for calculations of ocean circulation [55–57]. In the first research [49], two calculations were made using an adapted model, in one of which the depth of the lake was made constant, and in the other the author used what little information he had about the bathymetry and topography of the Lake Vostok basin and assumed the water mineralization to be equal to zero. Undoubtedly, those assumptions affected the modelling results. In the first case, he obtained the result that the horizontal circulation in the lake was predominantly barotropic and accompanied by a single vortex. In the second case, the horizontal circulation was baroclinic. In general, there was upwelling in the western part of the lake and downwelling in the eastern one, with vertical speeds of about 0.01 cm/s. There were also other difficulties caused by the lack of data for studying water circulation in Lake Vostok [48, 58]. However, the researchers who carried out later assessments no longer faced this kind of problems, as Lake Vostok had already been well studied by geophysical methods [10].

For instance, more recently, using the 3D Hydrodynamic model ROMBAX, Malte Thoma and co-authors concluded that a barocline circulation is dominant in Lake Vostok [53]. A weak counter-clockwise circulation was formed in the northern basin of the reservoir, while two more strong vortices (one clockwise and one counter-clockwise) were observed in the southern depression. Also, in the southern part of the lake, where the freezing area is located, an anticyclonic water circulation was observed closer to the surface, and a cyclonic circulation in the deeper layers. In general, the anticyclonic circulation was more dominant with respect to the overall mass transfer. The upwelling was concentrated in the east and the downwelling in the west. The only exception was the southern part, where freezing led to vertical stratification of the water column and upwelling concentrated in the western part. The researchers assumed that initially the lake was in stationary state, its water was fresh, and its temperature was –2.6 °C (the phase transition temperature at the pressure created by the ice column). The simulation time was chosen to be 150 years, this period was sufficient to reach a stationary state [53]. In 2010, Malte Thoma and co-authors complicated the problem and used both the RIMBAY ice-dynamics model and the ROMBAX circulation model, as well as their combination in the RIROCO model to assess the interaction of the two systems: the lake and the glacier [59].

Russian researchers have also attempted to characterize the circulation in the subglacial Lake Vostok. For instance, papers [60, 61] present a specially developed 3D non-hydrostatic model. The authors concluded that the previously used hydrodynamic models with hydrostatic approximation have their limitations. The reason for the insufficient adequacy of the hydrostatic approximation, in their opinion, is that the horizontal and vertical components of the water velocity moduli differ by only one order of magnitude in the estimates of Lake Vostok circulation parameters made in [48, 49, 52, 53, 62]. Publications [60, 61] present the results of calculations for the hydrodynamic model of convective circulation, which is based on 3D equations of hydrodynamics in the variables "vortex" — "vector potential" (Helmholtz equations) and the heat-balance equation. Refusal to use the hydrostatic approximation entailed limitations on time and computational resources. For this reason, during the calculations, the model equations were integrated in time for only two years, a period insufficient for reaching a stationary state of the circulation system, and due only to the limited computer resources available to the author's team. The temperature distribution in the water column of Lake Vostok and the zonal and meridional velocity of the currents in it were estimated based on the modelling results. Undoubtedly, the non-hydrostatic model has the advantage of allowing one to reproduce meso- and small-scale vertical vortex structures, however, that was not possible within the framework of this work.

Thus, numerical estimates and application of mathematical modelling methods [48, 49, 53, 54, 58, 63, 64] gave the first ideas about the currents both in Lake Vostok and other subglacial water bodies. In addition, an analysis of the influence of subglacial lakes on the overlying ice sheet was given [33, 65–70], which is important for further studies of subglacial hydrological and geomorphological processes in these unique natural objects.

Conclusion: plans for the future

Plans for further research of Lake Vostok, as well as any other site, are determined by the results achieved, which logically leads to setting new tasks. In the previous studies, a variety of data from different branches of science were obtained. However, there are important questions that remain unanswered. How, when, and why was Lake Vostok formed? Was it formed before or after the glaciation? In other words, is the lake water relic water that existed millions of years ago, or is the basin filled with melt glacial water? Of course, there are opinions on this issue. They are, in particular, outlined in [70], which suggest that Lake Vostok is a relic lake. This theory also appeals to the authors of this paper, but well-grounded answers to these questions can be obtained only based on the results of the next stage, which, as mentioned above, involves studying the lake itself as a water body and taking bottom samples. This will allow inferring how the lake was formed and how it developed. The next question concerns the deep structure of the Lake Vostok area. The already available geophysical data are still insufficient for unambiguous classification of the lake basin as rift graben. In the opinion of the authors, this issue requires further geophysical work, and, first and foremost, deep seismic sounding and earthquake converted-wave method profiling. These works will help to define the structural features of the Earth's crust and determine the Mohorovičić discontinuity. Besides, the important issue is the thickness and stratification of the lake bottom sediments. Unfortunately, the recent investigations described above cannot characterize it. This is a matter for future research, e. g. by high-resolution common-depth-point reflection profiling.

And finally, the third question. What is happening in the lake itself? What is happening in the area of its contact with the ice sheet? A separate issue concerns the behaviour of small subglacial water bodies surrounding the lake, and a particularly active water body *v20*, which seems to drain into Lake Vostok. Part of the answer to these questions may be a subsequent in situ study of the lake water and basal sediments. However, the borehole is not the whole lake, and without mathematical modelling it is impossible to build a correct, complete, and reasonable picture of these processes. Modelling will require, among other things, studies of the glacier dynamics, i. e. geodetic and glaciological studies over a large area of the lake and beyond, as well as systematic satellite observations. Geodetic measurements are important not only for modelling the moving of the lake water but also for better understanding of the glacier behaviour both inside and outside the lake. In addition, ground-based RES and satellite observations can certainly shed light on the processes taking place in the active subsurface water body *v20*. Particularly, a series of satellite altimeters, such as ICESat, CryoSat, and ICESat-2, CryoSat-2, could be used to see and show how the glacier surface over this small lake has changed in height from 2003 until now.

Thus, the authors see the new stage of research at the renovated station as large-scale multidisciplinary work based on the results of research in the borehole 5Г (including bottom sampling) [71], and its ultimate goal is to describe the deep structure and evolutionary stages of the region, as well as a mathematical model of heat-and-mass transfer processes in the glacier and lake water.

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Study of Lake Vostok is an absolute priority of Russian research in Antarctica, which is stated in the “Strategy for the Development of Russia’s Activities in Antarctica until 2030” approved by the Government of the Russian Federation on 19.08.2020. The “Plan of Measures for the Implementation of the Strategy for the Development of the Activity of the Russian Federation in Antarctica until 2030”, approved by the Government of the Russian Federation 30.06.2021 No1767-р, contains Action 21 “Complex research of subglacial Lake Vostok and the Earth’s paleoclimate near the Russian Antarctic Station Vostok”, included in “Strategy…”. Large-scale construction of new buildings, including scientific ones, is currently under way at the Vostok Station. And the planned work follows the path of our country’s priority scientific objectives in Antarctica.

Competing interests. The authors have no conflicts of interest to declare.

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Дистанционные исследования и математическое моделирование озера Восток, Восточная Антарктида: прошлое, настоящее и будущее

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Расширенный реферат

В статье представлен обзор исследований, выполненный к настоящему времени в районе подледникового озера Восток (Восточная Антарктида). Они включают в себя геофизические, гляциологические, геодезические и геологические исследования. Наиболее важные геофизические исследования были проведены Полярной морской геологоразведочной экспедицией. Они включали в себя сейсмические исследования методом отраженных и преломленных волн, а также радиолокационное профилирование. Значительный вклад в изучение этого региона внесли американские исследователи, которые в ходе летнего полевого сезона 2000/01 г. провели комплексную аэрогеофизическую съемку по регулярной сети маршрутов. Она включала в себя магнитометрические, гравиметрические и радиолокационные измерения. В результате этих работ установлено, что площадь водной поверхности составляет 15 790 км^2, а ее высота над уровнем моря изменяется в пределах от –600 до –150 м. Средняя глубина озера Восток составляет 400 м, а максимальные отметки достигают 1200 м. Объем воды озера составляет 6100 км³. На его акватории насчитывается 11 островов, а их общая площадь составляет 365 км². Кроме того, вокруг озера было обнаружено 56 изолированных подледниковых водоемов, один из которых активный. На начальном этапе проводились специализированные работы, направленные на совершенствование методики исследований и повышения их точности. Они позволили установить, что непосредственно в пункте бурения скважины 5Г средняя скорость распространения упругих волн в теле ледника и в чистом атмосферном льду (пластовая скорость) составляет 3810 ± 20 м/с и 3920 ± 20 м/с соответственно; средняя скорость распространения электромагнитных волн составляет 168,4 ± 0,5 м/мкс. На основе этих данных была определена мощность ледника в этом районе, которая составила 3768 м. Специальный раздел посвящен обзору математических моделей, которые описывают процессы тепло- и массопереноса в леднике и движения воды в озере Восток. Новый этап исследований на обновленной станции видится авторам как масштабные мультидисциплинарные работы с опорой на результаты бурения скважины, включая донное опробование. Конечным результатом может стать описание глубинного строения и этапов развития региона, а также математическая модель процессов тепломассопереноса в леднике и озерной воде. Изучение озера Восток является безусловным приоритетом отечественных исследований в Антарктиде. Это нашло свое отражение в «Стратегии развития деятельности Российской Федерации в Антарктике до 2030 года», утвержденной Правительством РФ 19.08.2020. В этом основополагающем документе, регламентирующем все научные исследования в южной полярной области, имеется Мероприятие № 21 «Комплексные исследования подледникового озера Восток и палеоклимата Земли в районе российской антарктической станции Восток», и планируемые работы следуют в фарватере приоритетных научных задач нашей страны в Антарктике.

Ключевые слова: озеро Восток, динамика ледника, комплексные исследования, обзор математических моделей

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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].

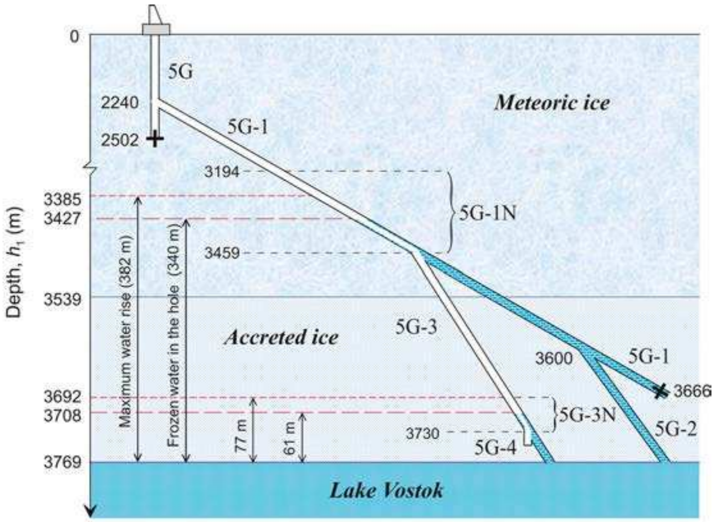

Fig. 1. Schematic of the multibranch borehole 5G at Vostok Station as of January 2018.

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):

$$p_i(\text{MPa}) = 9.068\cdot10^{-3}\cdot(h(\text{m}) - 32.4). \qquad (1)$$

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):

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

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

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

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.)

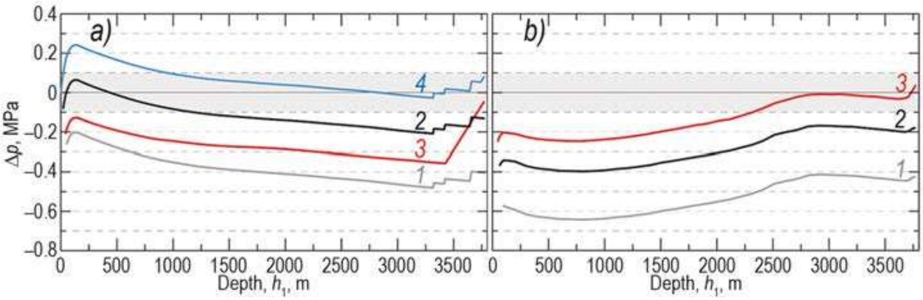

Fig. 2. Differential pressure (Δp) in the borehole prior to and in the course of the first (*a*) and second (*b*) unsealings of Lake Vostok.

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 Δp (±0.1 MPa). See text for various methods that were used to obtain Δp

Рис. 2. Дифференциальное давление (Δp) 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 Δp (±0,1 МПа). Методы определения Δp 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, Δp (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

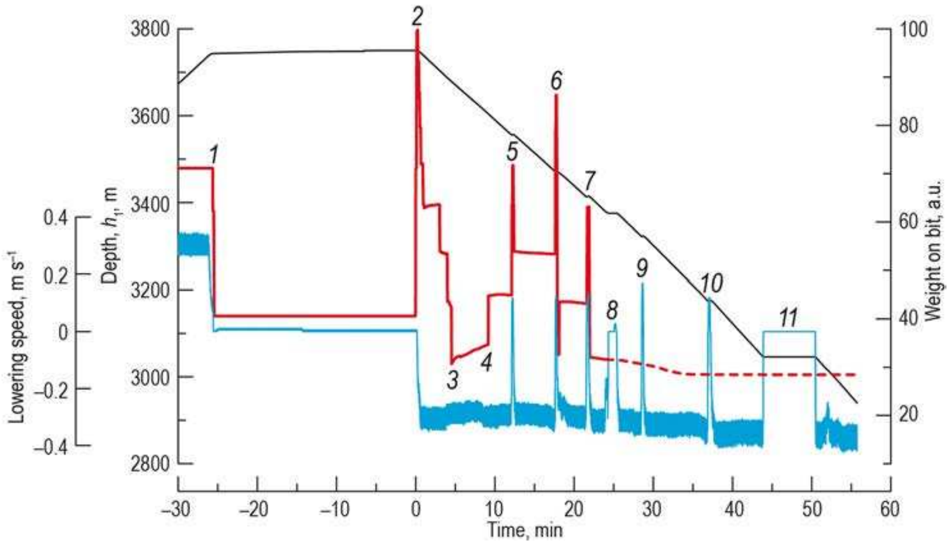

Fig. 3. Instantaneous depth of the drill (black), lowering/hoisting speed (light blue), and weight on bit (red) as recorded in the course of the first unsealing of Lake Vostok.

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

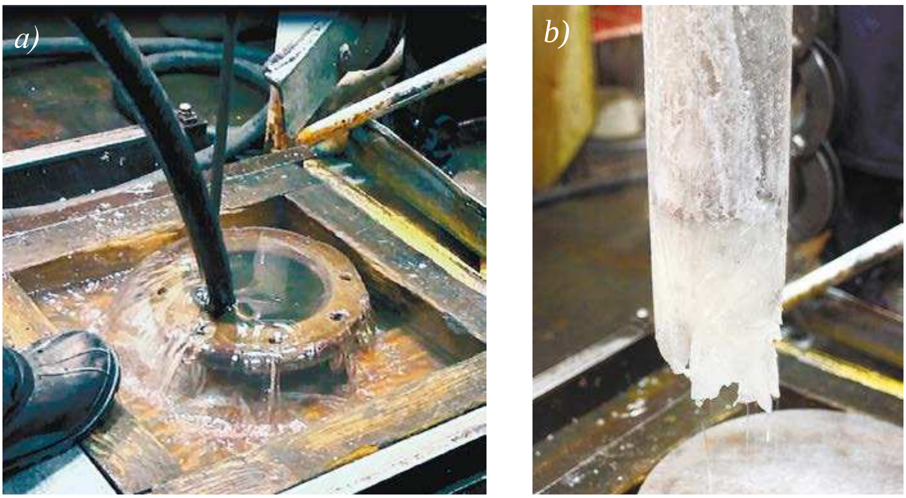

Fig. 4. Overflow of drilling fluid from the borehole mouth during the first unsealing of Lake Vostok (*a*), and the drill bit covered with frozen lake water after removing the drill from the hole (*b*)

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

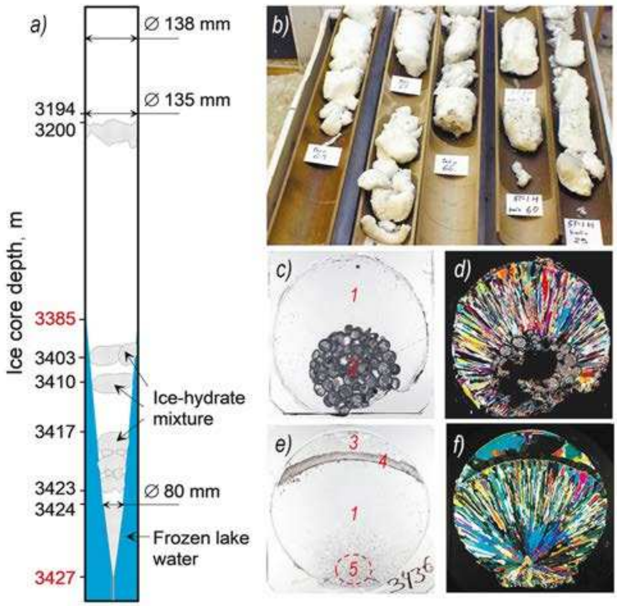

Fig. 5. Evidence from the re-drilling of borehole 5G-1 after the first unsealing of Lake Vostok (photos *c-f* adapted from [15]).

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:

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

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

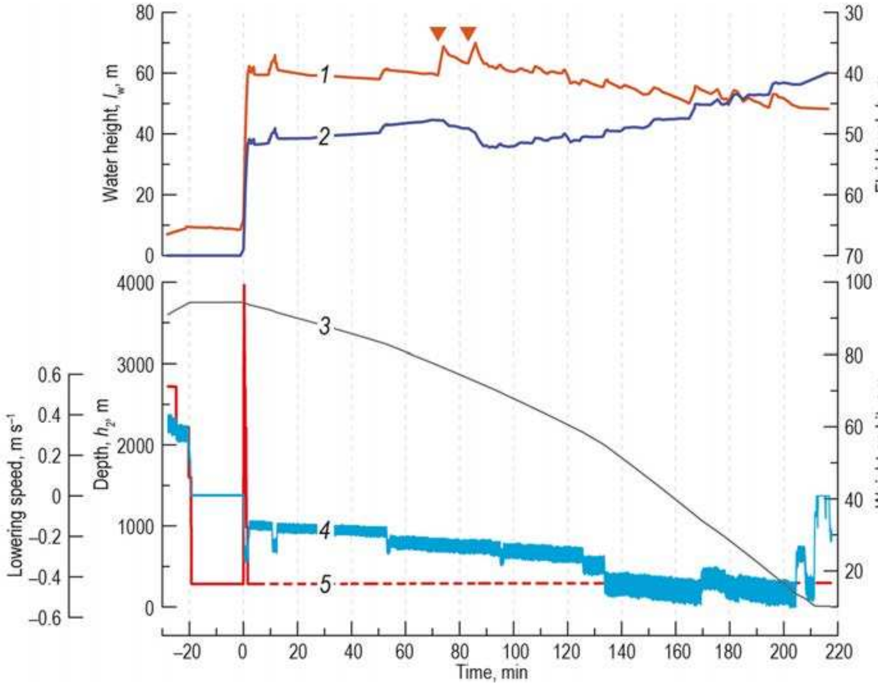

Fig. 6. Drill and liquid control records from the second unsealing of Lake Vostok.

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

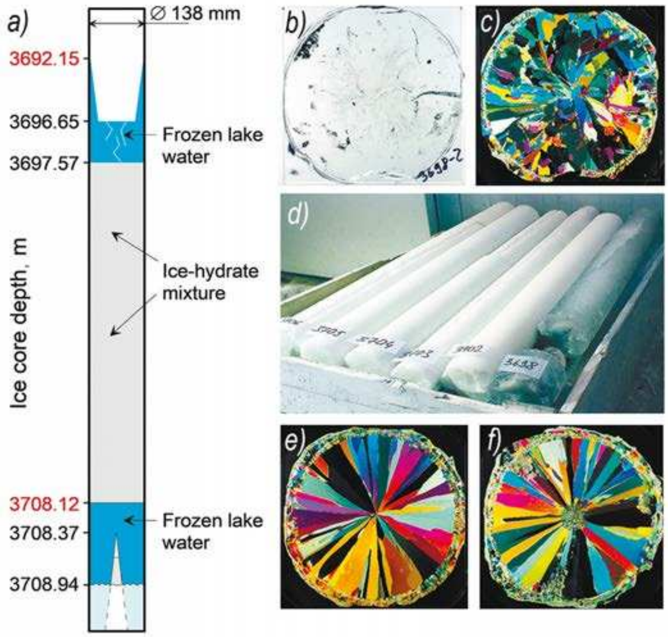

Fig. 7. Evidence from the re-drilling of borehole 5G-3 after the second unsealing of Lake Vostok (*a*, *c*, *f* are from [36]).

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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Дополнительные материалы. Относящиеся к этой статье дополнительные материалы доступны на сайте http://cerl-aari.ru/index.php/lv

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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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Alternative clean approaches to accessing subglacial Lake Vostok

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Abstract. A study of the subglacial Lake Vostok requires clean accessing and sampling technologies. The paper presents four potential options — three types of hot-points and a hot-water drilling system — which can be considered as environmental-friendly technologies and could be used in the cold ice of East Antarctica. The description contains only general ideas and a brief estimation of the main parameters of the technologies suggested and does not include any detailed analysis. All the methods proposed have their own advantages and disadvantages. The final decision about a method's applicability should be made following careful development and engineering work, including theoretical studies, modelling, laboratory testing, taking into account the available funds and logistics opportunities.

Keywords: borehole, hot-point, hot-water drilling system, thermal drill

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1. Introduction

With an area of about 15 500 km^2, excluding 70 km^2 covered by islands, Lake Vostok is the largest subglacial lake in Antarctica [1, 2]. The volume of the water is ~6 100 km^3 and the average depth is ~400 m. The thickness of the ice sheet over the lake is nonuniform and increases from 3 600 m in the south to 4 350 m in the north. A slight thinning of the ice sheet down to approximately 3 250 m was recorded near the eastern shore of the lake, 135 km to the north of the Vostok Station.

Sealed from the Earth's atmosphere for millions of years, the subglacial Lake Vostok may provide unique information about microbial evolution, the past climate of the Earth, and the formation of the Antarctic ice sheet. Although modern observations widely employ remote-sensing instruments to provide indirect indications of subglacial environment phenomena, direct observation and sampling by drilling are still much needed for hydrological, chemical and microbiological studies. The subglacial water is very likely to contain life, which must adapt to the total darkness, low nutrient levels, high water pressures and isolation from the atmosphere. It is obvious that in situ investigations should not contaminate this subglacial aquatic system. This consideration makes the sustainability of subglacial environment a factor of chief importance. So far protocols for minimizing the contamination and thermodynamic disturbance of subglacial aquatic environments have not been established, although a few initiatives to protect them have been launched [e. g., 3].

In February 2012, Lake Vostok was accessed by an electromechanical drill suspended on a cable at a depth of 3769.3 m [4]. The borehole was filled with two-component kerosene-based fluid composed of fuel Jet A1 and dichlorofluoroethane HCFC-141b as a densifier. The operations allowed the lake water to enter and freeze within the lower part of the borehole, from which further coring recovered a frozen sample of the lake water. Unfortunately, when subglacial water entered the borehole, it was contaminated by the toxic drilling fluid [5]. Thus, alternative conceptions and technologies for clean accessing and sampling of the subglacial Lake Vostok are still urgently needed.

In this paper, we present potential options — hot-points and a hot-water drilling system — which can be considered, for the moment, as the cleanest technologies for accessing and sampling of the subglacial Lake Vostok. The description contains only general ideas and a brief estimation of the main parameters of the technologies suggested and does not include any detailed conceptions.

2. Ice drilling potentials

For one to be able to drill deep holes in extreme environmental conditions, which include low temperatures, glacier flows, an absence of roads and infrastructure, intense winds and snowfall, purpose-built drills have to be designed or conventional equipment needs to be heavily modified. Depending on the nature of ice disintegration at the borehole bottom, the techniques that can be used for accessing and sampling subglacial environment are divided into two large categories: mechanical and thermal drilling methods (Fig. 1). Mechanical drilling tools most commonly utilize cutting or hammering, while thermal drilling tools use heat to melt ice [6, 7].

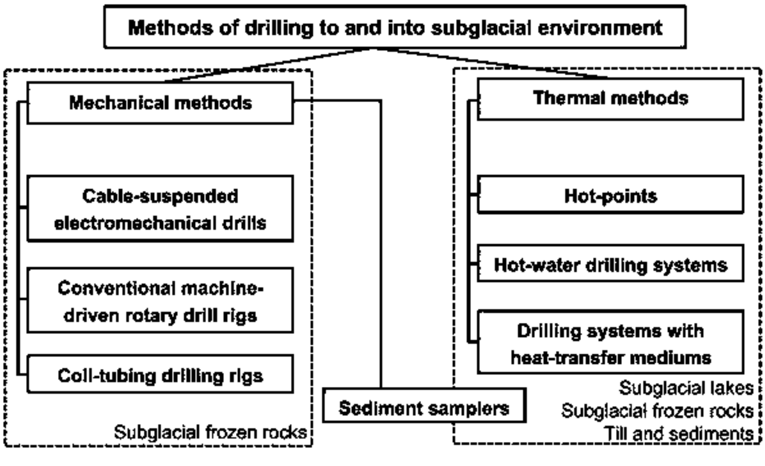

Fig. 1. Classification of drilling methods for accessing subglacial environments

Рис. 1. Классификация методов бурения для изучения подледниковой среды

2.1. Mechanical drilling

All mechanical deep ice drilling methods — cable-suspended electromechanical drills [8–10], conventional machine driven rotary drills [11] and coil-tubing drilling rigs [12–14] — utilize environmentally hazardous drilling fluids (two-component kerosene-based fluids with density additives or ester compounds) to prevent borehole closure and to remove borehole products when cutting the ice [15].

Currently synthetic-based drilling fluid based on the aliphatic synthetic ester ESTISOL™140 is identified as the most suitable low-temperature drilling fluid for drilling in cold ice [16]; however, actual use showed that ESTISOL™140 also has toxic effects [17]. Low-molecular-weight dimethyl siloxane oils [18–20] and low-molecular-weight fatty acid esters [21] can be considered as good alternatives to low-temperature drilling fluids but need to be further investigated for environmental compatibility.

Besides environmental hazard, low-temperature drilling fluids are difficult to clean and filter off because of the high viscosity and oiliness. In addition, downhole equipment like electromechanical cables, drill pipes, motors, etc. are not easy to decontaminate microbiologically or chemically. Therefore, we hold the opinion that mechanical deep ice drilling methods are not suitable for clean accessing of subglacial environment and can be used only in areas with a frozen bed where the rocks are considered impermeable and contamination is less likely.

2.2. Thermal drilling

The same considerations can be applied to thermal drilling systems with intermediate heat-transfer mediums in which the drilling fluid that fills the borehole is heated in the downhole or surface heaters and is used as a source of heat to melt the ice at the bottom of the hole. Zakharov suggested using hot dimethyl siloxane oil as a medium for melting ice [22]. This will allow one to use the borehole for a long time because the fluid does not freeze in the borehole, and its hydrostatic pressure prevents borehole closure. As mentioned above, microbiological, chemical and mechanical cleaning of dimethyl siloxane oil would be extremely difficult. Drilling a borehole with a diameter of 200 mm will require about 150 m^3 of the quite expensive (4.5–25 EUR/kg) fluid [19]. In addition, the heat capacity of dimethyl siloxane oil is 2.3 times lower than that of water. This means that to obtain a penetration rate equal to that of hot water, the temperature or flow rate of dimethyl siloxane oil should be much higher than in the case of water circulation.

Boreholes drilled with hot-points or hot-water drilling systems are filled with water that is currently considered as the most environmentally friendly drilling fluid. However, meltwater refreezing is a significant issue for the safe retrieval of the drill stem and other instrument conveyance into and out of the hole. A borehole filled with melted water begins to cool/refreeze immediately upon creation. Boreholes completely refreeze within 4–23 h at an ice temperature of –25 °C and an initial diameter of 100–240 mm [23].

When a lake is accessed by thermal drills, the number of microbial cells contained in the meltwater should not exceed the minimum concentration of microbes in the basal glacial ice being passed through (~10^2 cells/ml) [3]. Thus, downhole tools should be thoroughly cleaned at the surface prior to deployment for the collection of microbial samples from subglacial zones. Hot points might drag native microbes immured in the ice as they melt to subglacial targets at depth; however, this occurs in a predictable manner [24]. In the context of hot-water drilling, water has to be filtered and UV-treated at the surface. Such cleaning technology was well proven in the case of the subglacial lakes

Whillans and Mercer, hydraulically active lakes at the coastal margin of West Antarctica, which were successfully accessed by US teams with hot water circulation in early 2013 and in the season of 2018–2019 [25, 26].

3. Hot-points

Hot-points are non-coring drills equipped by an electrically heated tip to melt ice (different designs of hot points are reviewed in [7]). In general, electric-heated hot-points are used in temperate glaciers, which are at their melting point throughout the year from their surface to their base. However, there are several options to drill in cold ice: (1) using a heating power cable that prevents the refreezing of the meltwater in the borehole; (2) antifreeze assisted drilling, in which a hydrophilic liquid is added into the hole and mixed with the meltwater; (3) freezing-in hot-points which are able to drill downward while the meltwater refreezes behind the unit (Fig. 2).

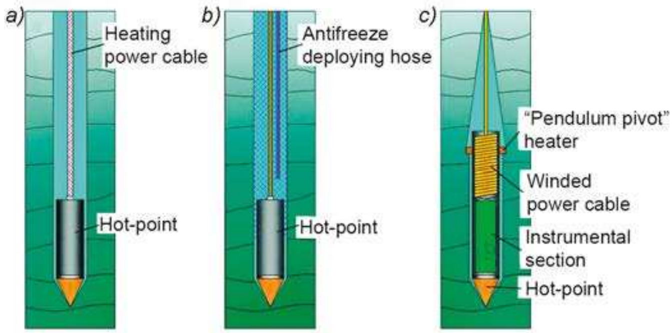

Fig. 2. Potential options of hot-points for drilling in cold ice: (*a*) with a heating cable; (*b*) by adding antifreeze; (*c*) freezing-in hot point with an on-board tethering cable (modified from [27])

Рис. 2. Возможные варианты термоигл для бурения в холодном льду: (*a*) с помощью нагревательного кабеля; (*b*) путем добавления антифриза; (*c*) термоигла с расположенной в снаряде лебедкой и вмораживаемым кабелем (рисунок переработан из [27])

3.1. Hot-points with a heating power cable

The design of hot-point systems includes an electromechanical cable with a winch to provide power to the downhole heaters and retrieving the drill. The electromechanical cable can be a small-diameter armored cable or a lighter-weight reinforced tough-rubber or plastic-sheathed cable. All of them dissipate some heat as a result of power losses during electric power transmission to the downhole unit. This heat prevents partial refreezing of the meltwater. Classen was the first to suggest increasing the resistance of the power cable in order to improve dissipating heat and reduce the hole closure [28].

Suto with colleagues [29] proposed a hot-point that can penetrate through thick ice using a heating cable which would provide power and also heat the surrounding area to completely protect the borehole from refreezing. According to theoretical assumptions, the required power supply for the heaters in the drill and for the heating cable greatly increased with depth. To penetrate through 3,000 m of cold ice with a temperature of –55 °C at the surface and 0 °C at the bottom, the hot-point would require 19 kW plus 140–235 kW to heat the cable. However, the heating cable is a matter of careful design to avoid overheating, especially in air. A simple dissipation experiment of 10 W in 1 m of an ordinary electromechanical cable hung in air shows the melting of the electrical insulation (Victor Zagorodnov, personal communication, 2023).

3.2. Antifreeze assisted hot points

Of the different antifreeze additives to meltwater that are used (ethylene glycol [30]; methanol [31]; ethanol [32]) only ethanol can be considered as a more or less environmentally friendly material. Ethanol is an easily biodegradable, natural and widely occurring product. On the other hand, ethanol is a well-known antiseptic material used as a bactericide and fungicide. It kills microorganisms by denaturing their proteins and dissolving their lipids, and is effective against most bacteria and fungi and many viruses [33].

To avoid any effect on subglacial microorganisms, Doran and Vincent [3] suggested not using biodegradable materials. Some other researchers (e. g. [34]) are of the opinion that the ethanol-water solution would reduce the possible environmental impact on subglacial lakes. Talalay and colleagues [15] suggested that ethanol would be rapidly consumed by the microbiota (if it exists) in the subglacial water body into which it might flow, and the

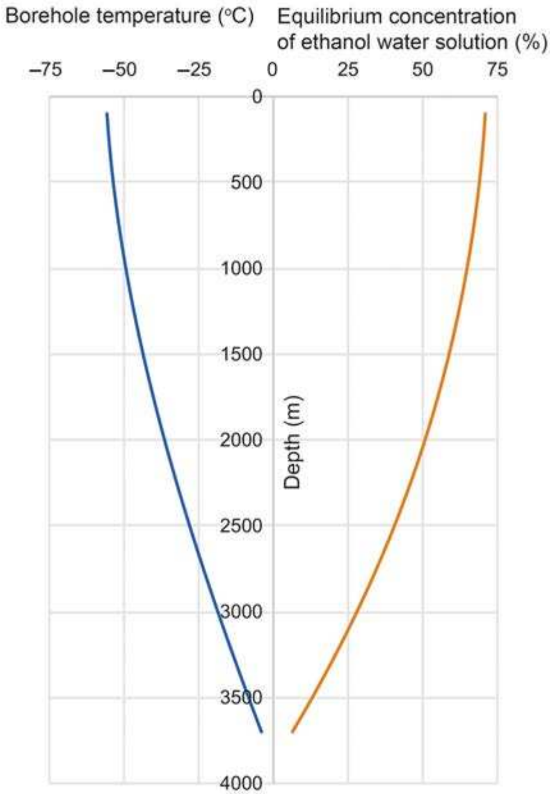

Fig. 3. Smoothed measured temperature profile in a 5G deep borehole at the Vostok Station [37] and equilibrium concentration of ethanol-water solution corresponding to in-depth temperature [38]

Рис. 3. Сглаженный измеренный температурный профиль в глубокой скважине 5Г на станции Восток [37] и равновесная концентрация водноспиртового раствора, соответствующая температуре на глубине [38] harmful effect depends on the pollutant concentration. Thus, the possibility of ethanol-water solution's use as a drilling fluid for accessing subglacial lakes is still under discussion.

From the technological point of view, the main bottleneck of ethanol-water solution use is that it dissolves ice from the borehole walls down to equilibrium concentration [35]. The equilibrium concentration of the ethanol water solution is the mass of the solvent contained in the solution in a state of thermodynamic equilibrium, i.e., the state of a system that is simultaneously in mechanical, thermal and chemical equilibrium. This means that the thermodynamic variables (temperature, pressure and thermodynamic potentials) are constant throughout the system. In the case of changing borehole conditions (for example, the temperature changes due to heat dissipating from the cable or convection processes in the borehole), the water from the aqueous solution freezes and forms slush in the borehole.

The equilibrium concentration of the ethanol water solution can also be considered as the concentration of the solvent at the freezing point. It increases with the decreasing freezing point (in the range down to –67 °C, based on the data from Industrial Solvents Handbook [36]):

$$C_M = -1.619t - 6.2 \cdot 10^{-3} \cdot t^2, \quad (1)$$

where C_M is the mass concentration of ethanol, %; t is the freezing point of the ethanol-water solution, °C.

Antifreeze-assisted drilling involves removing some of the meltwater from the borehole and careful adding of ethanol such that the equilibrium (or slightly higher) concentration of the ethanol-water solution must be preserved at every depth (Fig. 3) [37]. The equilibrium concentration in the bottom part of the borehole is quite small and, thus, the potential harmful effect is also small.

3.3. Freezing-in hot-points

Freezing-in hot-points are able to move towards the ice sheet base while the melted water refreezes behind the drill. One of the first freezing-in hot-point drills, a subglacial wireless autonomous station, was supposed to use nuclear energy for melting through the ice sheet, but it was never realized owing to technical challenges and environmental considerations [39].

A freezing-in hot point with an on-board tethering cable was proposed by Phillberth [40] to study the temperature distribution in ice sheets. The most notable characteristic of the drill is that the wires used for receiving and transmitting electrical power moved out of the advancing drill and became fixed in the refreezing meltwater above it, hence the drill only travelled one way. In the summer of 1968, the Philberth probe reached the remarkable depth of 1,005 m at the Jarl-Joset station in Greenland.

In the following years, nine similar freezing-in thermal hot-points were designed in different conceptual and testing phases, but all of them travelled one way (drills are reviewed in [7]). It is likely that non-recoverable hot-points would not pass through the Environmental Impact assessment designated by the Protocol on Environmental Protection to the Antarctic Treaty. A drill that is worked-out or dead after penetration into a subglacial lake is considered as solid non-combustible waste that must be removed from the Antarctic Treaty area.

The newly developed hot-point — RECoverable Autonomous Sonde (RECAS) — allows one to drill ice downward and upward and to sample subglacial water while the subglacial lake remains isolated from the surface [41]. RECAS is equipped with two electrically powered melting tips located at the upper and lower ends of the sonde, an inner cable recoiling mechanism, and a sampling/monitoring section (Fig. 4). The sonde was successfully tested in East Antarctica during the 2021–2022 field season: it reached the ice sheet base at the depth of 200.3 m, sampled meltwater from basal ice and recorded the parameters (pressure, temperature, pH, and conductivity) of the melted water [42, 43]. Then the sonde returned to the ice surface. The average downward penetration rate was 1.85 m/h, and the average upward penetration rate was 2.94 m/h. The borehole inclination was in the range of 1.1–1.6°. After the sonde passed through, the meltwater in the borehole behind the sonde froze and closed the borehole, verifying the potential of this technology for clean subglacial exploration.

In view of the drilling requirements for Lake Vostok with an ice thickness of 3 250–3 800 m, many improvements still need to be made to the RECAS working prototype with a 500 m cable inside. According to preliminary estimations, for one to drill with a penetration rate of at least 1.5 m/h, the outer diameter of RECAS with a maximum drilling capacity of 3 800 m needs to be increased from 180 mm to 216 mm, the overall length — from 7.27 m to 13.22 m, and the surface power consumption — from 10.11 kW to 31.07 kW. The specific parameters are shown in the Table.

To maximize the benefits of a single subglacial lake access, the scientific payload carried by the sonde can also be improved by adding dissolved oxygen and methane detectors, camera observation in the lake, etc. The increased RECAS diameter offers a possibility for such improvements.

Two concepts similar to RECAS were proposed by Stone Aerospace, a US engineering company [44], and Aachen University, Germany [45]. The stone Aerospace system, the Subglacial Polar Ice Navigation, Descent and Lake Exploration (SPINDLE) probe, uses two servo-controlled tether spoolers: a dedicated strong spooler for descent and ascent, and a dedicated power/communications spooler. The initial prototype was designed with cables required for a 2500-m-deep Antarctic subglacial exploration mission.

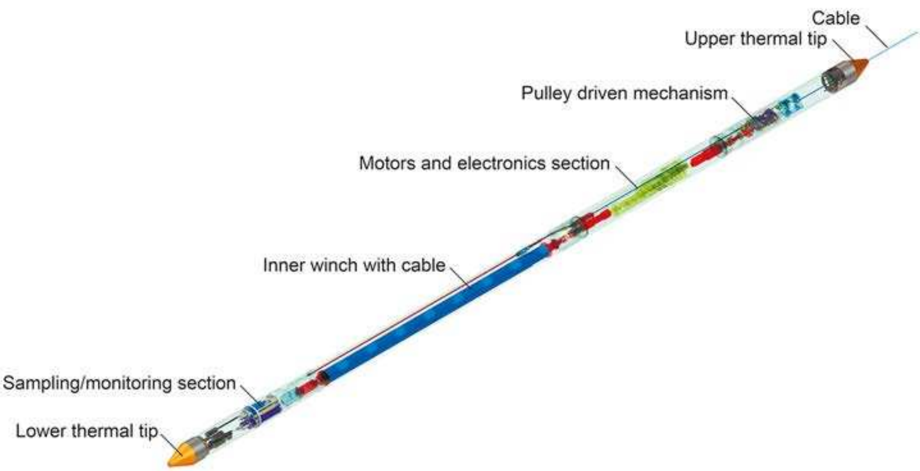

Fig. 4. 3D-model of the RECAS working prototype with a 500 m cable inside (the sonde body is shown transparent)

Рис. 4. 3D-модель рабочего прототипа теплового зонда RECAS с кабелем длиной 500 м внутри (для наглядности корпус зонда показан прозрачным)

The Aachen University probe was designed using the Technologies for the Rapid Ice Penetration and subglacial Lake Exploration (TRIPLE) project line initiated by the German Aerospace Center (DLR). The TRIPLE-IceCraft melting probe can penetrate several kilometres of glacial ice at a speed of up to 5 m/h. A demonstration of the TRIPLEIceCraft with a maximum melting depth of 500 m was carried out at the Ekström Ice Shelf in Antarctica in February 2023 [46]. The main problem found was that the cable has slipped through the drive wheel and the probe could not move upward.

Table

RECAS parameters with different drilling capacity

Таблица

Параметры теплового зонда RECAS с различной предельной глубиной бурения

Maximum drilling capacity (m)	Outer diameter (mm)	Overall length (m)	Power of thermal tips (kW)	Surface power consumption (kW)	Weight (kg)
3250	216	11.96	10.18	29.14	670
3500	216	12.53	10.18	30.02	690
3800	216	13.22	10.18	31.07	730

4. Hot-water drilling system

A hot-water drilling system can provide rapid and clean access to Lake Vostok for the deployment of different samplers and corers. During drilling, hot water is pumped at high pressure through a drill hose to a nozzle that jets hot water to melt the ice. The water from the nozzle uses the melted hole as the return conduit and then reuses it at the surface. This method is very quick (penetration rates can reach 120–200 m/h), allowing the drilling of deep holes in a number of days. The components of the drilling system and circulating water can be cleaned to provide sufficient purity for penetration into the subglacial lake.

The main parameters of hot-water drilling systems are flow rate, pumped pressure, and the temperature of the water delivered [47]. The controlled outcome variables are the diameter of the drilled borehole, the rate of penetration, and the refreezing rate of the borehole. The minimal flow rate of hot water Q_{min} [m^3/s] for drilling can be estimated according to:

$$Q_{min} = \frac{\pi \rho_i v D^2 (l_i + \varepsilon |T_i| C_i)}{4 \rho_w C_w T_b}, \qquad (2)$$

where ρ_i is the density of the ice, kg/m^3; v is the desired rate of penetration, m/s; D is the mean diameter of the borehole, m; l_i is the latent heat of the melted ice, J/kg; ε is the coefficient accounting for the lateral conductive heat losses in the ice masses outside the borehole; T_i is the ice temperature, °C; C_i it the specific heat capacity of the ice, J/(kg·K); ρ_w is the density of the water, kg/m^3; C_w is the heat capacity of the water, J/(kg·K); T_b is the bottom temperature of the drilling water that sprays out of the nozzle, °C.

Estimating the bottom temperature of the drilling water is a complicated task because it depends itself on the flow rate, the diameter of the borehole, the ice temperature, the initial temperature of the hot water, the inner/outer diameters of the hose and the material/thickness of the hose. For precise estimations, it is necessary to establish the additively closed modelling system (e. g. [48]).

The initial diameter can be estimated as:

$$D = \sqrt{\frac{4\rho_w Q C_w T_b}{\pi \rho_i v(l_i + \varepsilon |T_i| C_i)}}. \tag{3}$$

Here we present two estimations. The option A includes the required minimal hot water flow rate at a constant rate of penetration (40 m/h) and the initial borehole diameter (300 mm). The option B includes estimation of the initial diameter at a constant rate of penetration (40 m/h) and the flow rate (210 L/min). In the options, we assume the following parameters and coefficients: ρ_i = 917 kg/m^3; v = 0.0111 m/s = 40 m/h; l_i = 336000 J/kg; ε = 1.1; C_i = 2108 J/(kg K); ρ_w = 1000 kg/m^3; the heat capacity of water C_w = 4184 J/(kg·K); T_{bs} = 90 °C. The ice temperature T_i at the Vostok station was taken according to the polynomial approximation as a function of the true vertical depth [37]. If the required initial borehole diameter is constant and equal to 300 mm, the minimal flow rate increases from 53.4 L/min to 253.1 L/min (Fig. 5). If the flow rate is constant and equal to 210 L/min, the initial borehole diameter decreases from 594 mm to 457 mm. It is most likely that the desirable ranges of the required flow rate and the initial diameter are in between these boundary options.

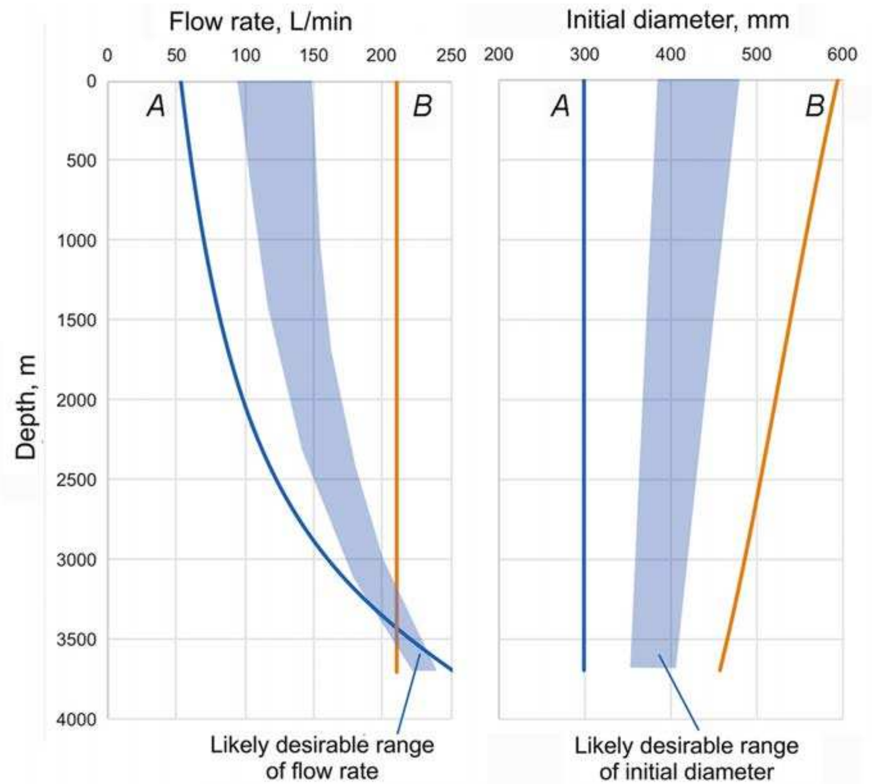

Fig. 5. Estimations of the required hot water flow rate and initial borehole diameter (explanations are given in the text)

Рис. 5. Оценочные графики требуемого расхода горячей воды и начального диаметра скважины (пояснения даны в тексте)

The critical point of the hot-water drilling technology is the refreezing of the meltwater in the hole. How long the borehole will remain sufficiently open should be considered at the beginning of the project design because the hole cannot be left to refreeze until its diameter becomes less than the size of the drill stem or the instrumentation lowered through the hole. This consideration is especially important in the cold ice above Lake Vostok. Safety accessing of the lake would require a series of reaming operations. Greenler et al. [48] suggested a comprehensive method to predict the ultimate size and freezing back rates based on the water flow rate and temperature, the rate of penetration, ice temperature and reaming parameters. This model proved to be very successful in the course of the IceCube project at the South Pole.

5. Discussion

We presented several potential options (three types of hot-points and a hot-water drilling system) for accessing and sampling the subglacial Lake Vostok. Accessing the lake using a hot-point with a heating cable seems to be the task of the distant future because the proposed system would require a careful design of a heating power cable of high strength and with an internal heating element. Currently, no existing cables satisfy both of these requirements [29].

The carefully prepared technology involving antifreeze-assisted thermal drilling is quite realistic but its success will depend on the possibility of keeping the right concentration of ethanol in the borehole. Antifreeze-assisted thermal drilling requires a large amount of ethanol (25–30 m^3 in the case of a 120-mm diameter hot-point) that should be delivered to the drilling site.

We believe that the RECAS sonde deployment could be one of the most promising options to access and study Lake Vostok. Successful tests in Antarctica have proved the reliability of the new ‘spider’ drilling approach for subglacial lake measurement and sampling. The biggest challenge of using RECAS for such deep subglacial lake exploration is ensuring its long-term working reliability. Damage to any heating element or mechanical part during drilling may lead to the failure of the whole project. Adding backups and careful pre-checking of the most important components may be an effective solution.

Deep hot-water drills, with their inherent speed, offer a feasible alternative for rapid accessing of Lake Vostok. To ensure clean accessing, the drilling water should be ultra-filtered, UV-treated, and pasteurized before being used to melt the access hole. Thus, it should contain significantly less microbial and particulate content than the surrounding ice. Nevertheless, deep hot-water drilling involves considerable technical and logistical challenges. First of all, these systems are extremely heavy and power hungry.

The UK project to access the subglacial Lake Ellsworth, ~3000 m beneath the surface of the West Antarctic ice sheet, can serve as an example of impossibility to overcome the challenges associated with deep hot-water drilling [49]. The main reason for the failure relates to a subsurface cavity of water 300 m beneath the ice surface that could not be connected to the main drill hole. The circulation failure consequently resulted in insufficient water supply to continue the drilling deeper. Thus, reliable drill instrumentation, communication and monitoring systems are essential for safe and successful deep hot-water drilling.

Overall, drilling with hot-points is relatively cheap: it is estimated to be 8–10 times less expensive than penetration with a hot-water drilling system, while the installation and operation require only four-five specialist staff. Due to the slow penetration rates, the time of accessing Lake Vostok with hot-points would be 3–4 months. RECAS requires double the time (6–7 months) to complete the downward drilling and go back. Thus, continuous drilling operations should be organized by overwintering personnel or on an automatic basis.

Another problem regarding ice melting with hot-points is the intrusion of components that cannot be melted, such as dust or rock particles. Mineral inclusions and dust are always present in glacial ice, and their size and content depend on the site's location. Although a decrease in the rate of penetration was observed when drilling in dusty ice, the thermal head can drill through tephra layers in the ice sheet [50]. This is because solid particles or dust can be pushed aside from the tip and flushed out from the borehole bottom by water convection. A simple dust collector can partially collect the suspended solid particles during drilling. However, penetration through ice containing large-size rocks (the largest rock intrusion in the Vostok ice core from 3 608 m is 8 mm in length [51] would be problematic).

A final decision about a method's or methods' applicability should be made based on detailed development and engineering work, including theoretical studies, modelling, laboratory testing, taking into consideration the available funds and logistics opportunities.

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Альтернативные решения экологически чистого вскрытия подледникового озера Восток

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Аннотация. Озеро Восток площадью около 15500 км^2 является крупнейшим подледниковым озером в Антарктиде. Задача проникновения в озеро может быть решена только путем использования экологически чистой технологии бурения, исключающей попадание в водоем современной микрофлоры и обеспечивающей сохранение жизнеспособности реликтовых организмов. К сожалению, вскрытие озера Восток, проведенное российскими исследователями в феврале 2012 г., не позволило, отобрать «чистые» пробы озерной воды, поскольку они оказались контаминированы токсичной буровой жидкостью. В статье представлены четыре потенциальных варианта вскрытия подледникового озера Восток — три типа термоигл (с нагревательным кабелем, с антифризом и с расположенной в снаряде лебедкой и вмораживаемым кабелем) и система бурения горячей водой, которые можно рассматривать как экологически чистые технологии бурения и которые могут быть использованы в холодных льдах Восточной Антарктиды. Описание включает в себя только общие идеи и краткие оценки основных параметров предлагаемых технологий и не содержит детальных концепций. Все предложенные методы имеют свои преимущества и недостатки. Окончательное решение о применимости того или иного метода вскрытия должно приниматься в результате детальных научно-исследовательских и проектных работ, включающих теоретические исследования, моделирование, лабораторные и полевые испытания на основе имеющихся возможностей финансирования и логистики.

Ключевые слова: система бурения горячей водой, скважина, термическое бурение, термоигла

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General concept of a deep hot water drilling system and drilling strategy to access Subglacial Lake Qilin, East Antarctica

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Abstract. Deep Antarctic subglacial lakes represent physically unexplored aquatic environments, the investigation of which may provide unique information about microbial evolution, past climate of the Earth, and formation of the Antarctic ice sheet. Subglacial Lake Qilin identified in the middle part of the Princess Elizabeth Land is recognized as one of the ideal lakes for upcoming exploration. Currently, R&D work to develop a deep hot water drilling system to access this lake has been started in China, and the paper presents a general concept of the system and the brief description of the drilling strategy. Access drilling to the lake is planned for the season 2026/27.

Keywords: clean access, hot-water drilling system, subglacial lake

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1. Introduction

About 99 % of Antarctica is covered by an ice sheet, on average, 2126 m thick [1]; yet it has been proved theoretically and experimentally that there is liquid water at the base. According to a hybrid ice-sheet–ice-stream model, approximately 80 % of the Antarctic ice sheet is likely to be at the pressure-melting point [2]. It is now accepted that subglacial hydrological environment is similar to water distribution elsewhere on the Earth surface and includes a vast network of lakes, rivers, and streams existing thousands of metres beneath the Antarctic ice sheet. As of 2022, 675 subglacial lakes have been identified in Antarctica [3].

Some subglacial lakes, so-called active subglacial lakes, are prone to sudden discharges of water, which can flow hundreds of kilometres and also connect with other lakes and the ocean [4]. Other lakes are confined within topographic valleys and some are thought to be isolated, potentially for hundreds of thousands of years, and may provide unique information about the microbial evolution, the past climate of the Earth and the formation of ice sheet and glaciers [5, 6].

The next stage of exploration requires direct sampling of these aquatic systems. The subglacial water most likely contains life, which must adapt to total darkness, low nutrient levels, high water pressures and isolation from atmosphere. It is obvious that *in situ* investigations should not contaminate these subglacial aquatic systems. This criterion makes sustainability of subglacial environment of key importance. Currently, protocols for minimizing contamination and thermodynamic disturbance of subglacial aquatic environments have not been established, although a few initiatives to protect them have been formulated [7].

Hot-water drilling systems currently offer the cleanest way of accessing the base of polar ice sheets. These systems are one of the fastest ice drilling systems with penetration rates reaching 120–200 m/h [8]. Hot water drills have two main functions: (1) to convey heat to the bottom of the hole to melt the ice and (2) to recover the drill and melt water to the surface.

Two US clean hot-water drilling projects succeeded in accessing subglacial lakes Whillans and Mercer in early 2013 to the depth of about 800 m [9] and during the season of 2018–2019 to the depth of 1067 m [10]. Both lakes are hydraulically active and located near the coastal margin of West Antarctica. A UK project to access deep subglacial Lake Ellsworth approximately 3 000 m beneath the surface of the West Antarctic ice sheet failed in 2012 [11]. The main reason for the failure relates to a subsurface cavity of water 300 m beneath the ice surface that could not be connected to the main drill hole. Another joint UK–Chile collaborative project to explore subglacial Lake Centro de Estudios Científicos (CECs) at a depth of almost 2 650 m also in West Antarctica was terminated because of the COVID19 pandemic issues [12, Keith Makinson, personal communication, 2021).

For now, the deepest holes with hot-water drilling systems were drilled to the depth of 2 500 m within the IceCube Project at the South Pole [13]. However, this system did not include water and hose cleaning devices and, thus, did not meet the requirements for minimizing contamination of subglacial aquatic environments [7]. Makinson and coauthors, speculated that with a reliable hot-water drilling system and an optimized drilling strategy to attain minimum drill fuel usage, it would be possible to drill a clean 36-cm 3 500-m deep access hole [14]. Such a system has not been built physically. So, the challenge of clean sampling of deep subglacial lakes is still unresolved.

In this paper, we briefly introduce the concept of a new deep hot water drilling system aimed at accessing Subglacial Lake Qilin in East Antarctica. The required set of instrumentation and samplers to study the lake water and sediments remains under discussion.

2. Potential drill site

In the middle of the 2010s, interpretation of radio-echo sounding revealed a series of subparallel, narrow, and long subglacial canyons in Princess Elizabeth Land, East Antarctica, which individually extend to 545 km in length and are up to ~10 km wide [15]. The existence of a large subglacial lake in one of the canyons was suggested on the basis of subglacial hydraulic flatness, elevated basal reflectivity, and high basal specularity [16]. The lake is estimated ~42 km in length and 370 km^2 in area, making it one of the largest subglacial lakes in Antarctica (Fig.1). The lake is overlain with an average ice thickness of about 3 600 m. The estimated maximal water thickness from gravity inversion in the central part of the lake is ~240 m. The average ice temperature at the surface is assumed to be near –45 °C [17].

Subglacial Lake Qilin was chosen as a candidate for our exploration because the lake is (a) logistically accessible through Chinese scientific field operations (~400 km from the Chinese Zhongshan Station); (b) much deeper and more isolated than lakes Whillans and Mercer, greatly increasing the likelihood of finding unique microorganisms and sedimentary climate record; (c) representative of many other continental interior deep subglacial Antarctic lakes, in terms of pressure and temperature conditions.

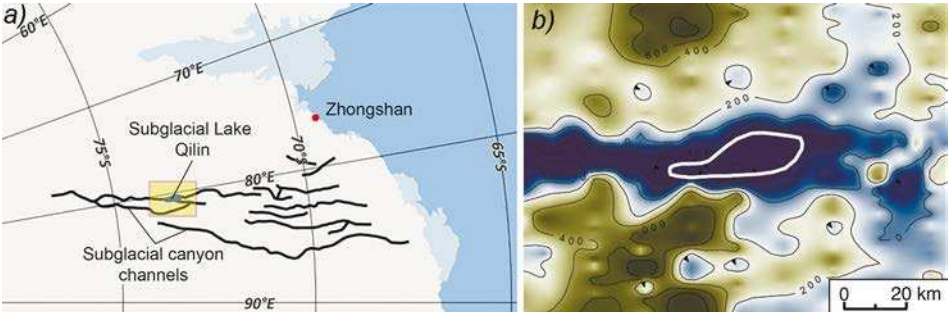

Fig. 1. Location of Subglacial Lake Qilin: (*a*) map of Princess Elizabeth Land, solid dark lines indicate location of canyon channels; (*b*) bedrock topography with estimated contour of the lake, area is marked as a yellow rectangle on the map leftward (modified from [16])

Рис. 1. Местоположение подледникового озера Цилинь: (*a*) карта Земли Принцессы Елизаветы, сплошные темные линии указывают расположение каналов каньона; (*b*) рельеф коренных пород с предполагаемым контуром озера, область отмечена желтым прямоугольником на карте слева (изменено по [16])

3. General concept

3.1. System components

The concept of the system is based on previous clean hot water drill designs [11, 12, 18]. The proposed drilling system includes eight subsystems (Fig. 2): (*1*) primary heating system, (*2*) secondary heating system, (*3*) cleaning system, (*4*) hoisting system of the main hole, (*5*) downhole drill-nozzle, (*6*) return water system, (*7*) electrical generators (not shown in Fig. 2), and (*8*) control system (the diagram shows the position of the proposed sensors).

The *primary heating system* consists of a circulation tank, a pump, a boiler and a heat exchanger. The system works in a closed loop mode. A heat exchanger conducts

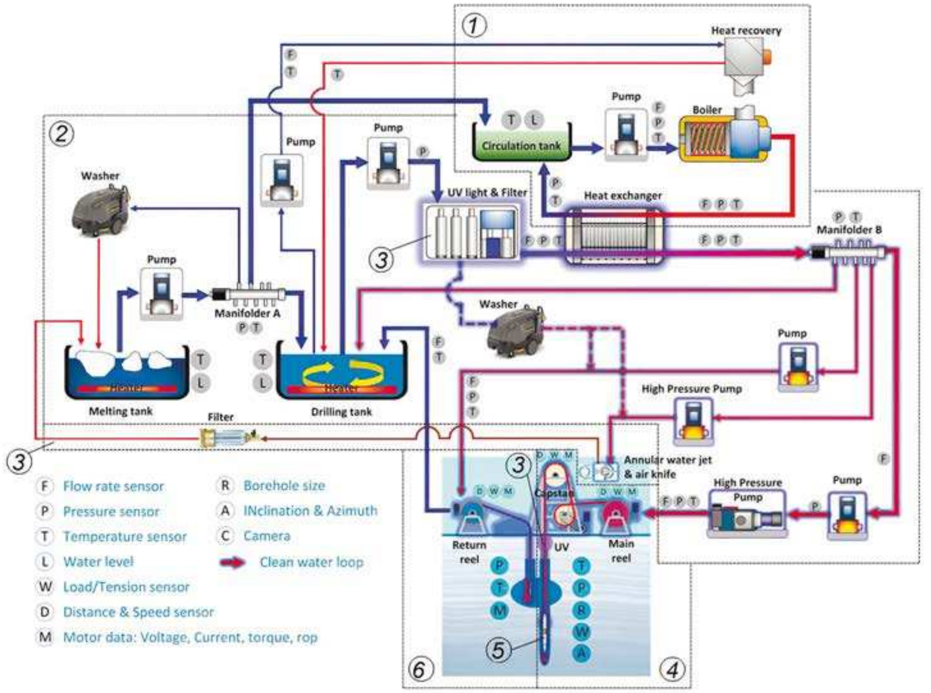

Fig. 2. Schematic diagram of the hot-water drilling system to access Subglacial Lake Qilin, East Antarctica: (*1*) primary heating system, (*2*) secondary heating system, (*3*) cleaning system, (*4*) hoisting system of the main hole, (*5*) downhole drill-nozzle, and (*6*) return water system

Рис. 2. Принципиальная схема системы бурения скважины доступа горячей водой к подледниковому озеру Цилинь, Восточная Антарктида: (*1*) первичный контур нагрева горячей воды, (*2*) вторичный контур нагрева горячей воды, (*3*) система механической и биологической очистки горячей воды, (*4*) спуско-подъемное оборудование, (*5*) забойное оборудование с гидравлической насадкой и (*6*) система рециркуляции воды

the heat from the hot antifreeze in the primary heating system to the cold water circulating through the secondary heating system. Separating heating system on two loops reduces the risks of drill water contamination and allows almost the entire circulation system to operate at low pressure, enhancing operational safety.

The *secondary heating system* consists of a melting tank, a water storage (drilling) tank, a heat exchanger, and high-pressure pumps. The max hot water supply temperature depends on drill site elevation and boiler capacity. At 3 000 m in elevation (expected elevation of the drill site), water boils at 89.8 °C. Given the heat losses in the exchanger, the temperature of the water delivered is assumed to be ~85 °C. The secondary heating system has two additional branches for water delivery into the return hole and for hose cleaning (annular water jet and air knife).

The *cleaning system* includes a unit with UV lights and filters for water cleaning, an annular water jet, an air knife and main borehole entry UV lights for hose cleaning. The particle size of the solid phase impurity filtration is not greater than 0.1 μm; the microbial killing rate is 99.99 %.

The *hoisting system* of the main hole includes a reel with a hose and a tower. The reel uses an electrical variable-frequency drive. The traction drive allows increased precision of the winching process and reduces the load on the main hose reel.

The *downhole drill-nozzle* includes a drill stem, consisting of a 10-m long ten-piece brass tube with a replaceable nozzle at the bottom, a downhole measuring system, and a reamer. Alternative spray nozzles, which could be fitted with the drill stem, would include: (1) a forward-pointing full core cone spray nozzle (15° to 30°) to form the initial hole through the porous firn until solid ice is reached; (2) a horizontal spray nozzle tip to melt the cavity and to aid the interconnection of the main and return holes; (3) a forward-pointing single spray nozzle (0°) to maximize hole formation in front of the drill stem in solid ice.

The exit water velocity is expected to be in the range of 30–40 m/s with the pressure drop of 0.5–1.0 MPa resulting in a rate of penetration of 20–60 m/h. The downhole measuring system consists of five pressure tubes located around a central tube. The downhole measuring parameters include the borehole diameter through a leaf-spring caliper and ultrasonic sensors, borehole inclination and azimuth, water temperature and pressure.

To ensure that the hole is sufficiently large during the pulling out of the drill, the drill-nozzle includes a reamer. A spring-loaded valve of the reamer is activated when contact is made as the hole is narrowed while the drill is going up. Upon activation, hot water flows through a network of channels and sprays over the surface of the reamer cone.

The *return water system* includes a submersible return reel with an umbilical and submersible pump. The umbilical has two hoses and electric lines: (1) to deliver water from the cavity to the surface; (2) to supply hot water from the surface to the cavity to prevent refreezing; (3) to provide electrical power to the submersible pump; and (4) to get signals from the downhole sensors.

The *electrical generators* provide electrical power for the reels, electric pumps, control systems, and other equipment. The total rated capacity of the generators is >150 kW.

The *control system* collects and monitors the drill data during the whole operating process, and sends and receives the control instructions and feedback signals. The entire system is composed of the surface, borehole and software subsystems. The parameters chosen for control and monitoring are shown in Fig. 2 by a legend of symbols.

3.2. Proposed drilling technology

The proposed concept includes the drilling of two holes. One hole — *return hole* — is the supplementary borehole to be drilled for the water to be returned to the surface and to be used as the main water supply for the drilling of the second *main hole*. A water recirculation system is established for the drilling system to avoid the need for continuous snow melting.

3.2.1. Drilling to the first cavity

The first pilot hole (main hole) is drilled to the depth ~50 m, slightly deeper than the water pooling depth (Fig. 3). The hose and nozzle are lowered slowly to form a straight hole because gravity is used as the steering mechanism. At the bottom the cavity is initiated using a horizontal spray nozzle tip. After completion of the first hole, the drill-nozzle is lifted and moved to a new position ~1 m from the first hole. A submersible pump is deployed into the first hole and water is recovered to the surface storage tank. The second hole (return hole) is drilled to the same depth of ~50 m. At the bottom of the second hole, the cavity is initiated with a horizontal spray nozzle tip and a connection between the cavities is established. The excess of water (5–7 m^3) is recovered to the surface storage tank.

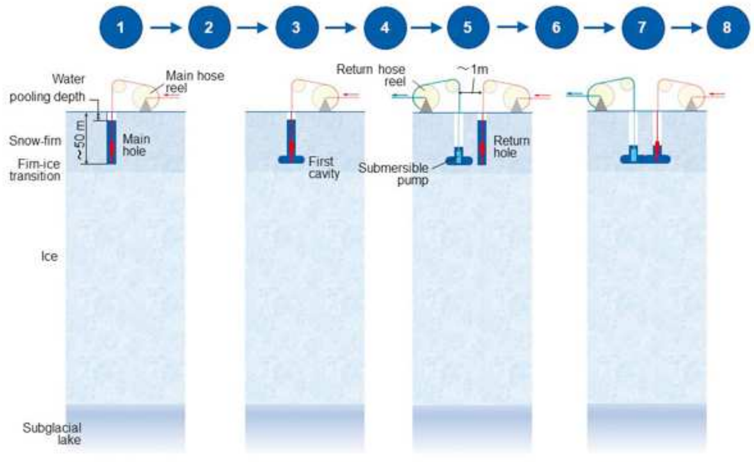

Fig. 3. Proposed sequence of drilling operations to the first cavity (adapted from [19]): 1 — firn drilling of the main hole; 2 — lifting, changing nozzle; 3 — forming first cavity; 4 — moving of the main hose reel; 5 — pumping out, firn drilling of return hole; 6 — lifting, changing nozzle; 7 — first cavity connection; 8 — lifting, changing nozzle

Рис. 3. Предлагаемая последовательность операций бурения до первой каверны (адаптировано по [19]): 1 — бурение основной скважины; 2 — подъем, замена гидравлической насадки; 3 — формирование первой каверны; 4 — перемещение подъемника шланга основной скважины; 5 — откачка воды, бурение дополнительной скважины для рециркуляции воды; 6 — подъем, замена гидравлической насадки; 7 — соединение первой каверны; 8 — подъем, замена гидравлической насадки

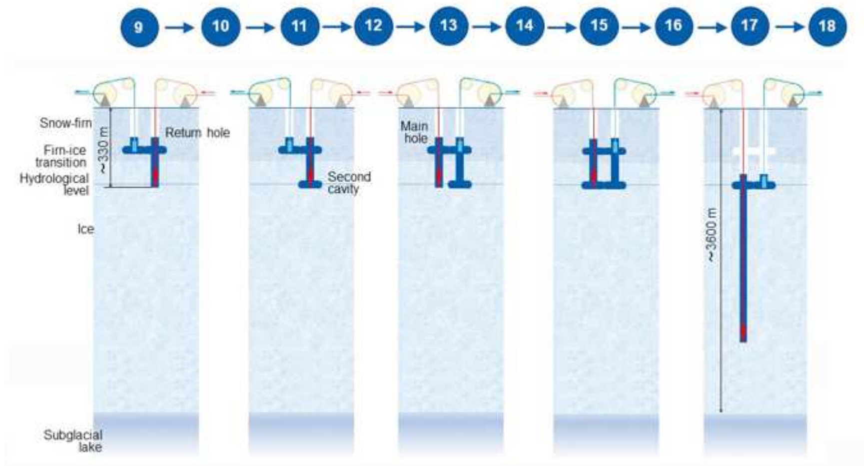

Fig. 4. Proposed sequence of drilling operations to the second cavity and further down (adapted from [19]: 9 — drilling of return hole; 10 — lifting, changing nozzle; 11 — forming of second cavity; 12 — changing positions of the main and return reels; 13 — drilling of main hole; 14 — lifting, changing nozzle; 15 — second cavity connection; 16 — lifting, changing nozzle; 17 — drilling of the main hole to the target depth; 18 — upward reaming

Рис. 4. Предлагаемая последовательность операций бурения до второй каверны и далее вниз (адаптировано по [19]: 9 — бурение дополнительной скважины для рециркуляции воды; 10 — подъем, смена гидравлической насадки; 11 — формирование второй каверны; 12 — изменение положения основного и вспомогательного подъемников; 13 — бурение основной скважины; 14 — подъем, замена гидравлической насадки; 15 — соединение второй каверны; 16 — подъем, замена гидравлической насадки; 17 — бурение основной скважины на заданную глубину; 18 — расширение скважины при подъеме забойного оборудования

3.2.2. Drilling to the second cavity

The return hole has to be drilled slightly deeper than the hydrological level, which is estimated at the depth of 315–320 m. Thus, the depth of the return hole is suggested to be ~330 m (Fig. 4). Upon completion, the second cavity is created near the bottom of the hole. The position of the drill nozzle and submersible pump has to be changed and drilling of the main hole is continued to the same depth of ~330 m. At the bottom, the cavity is made using the horizontal spray nozzle tip and a connection between the cavities is established. The submersible pump is lowered down to the second cavity and the excess of water (30–40 m^3) is gradually recovered to the surface storage tank.

3.2.3. Drilling to the target depth

Drilling of the main hole is continued with the single straight nozzle tip (0°) to the base of the ice sheet. The refreezing of meltwater is a significant problem for the safe retrieval of the drill stem and conveyance of other instruments into and out of the hole [20, 21]. Thus, in operations with the risk of losing the drill in the hole because of refreezing, two drilling methods might be considered. The first method involves periodic reaming

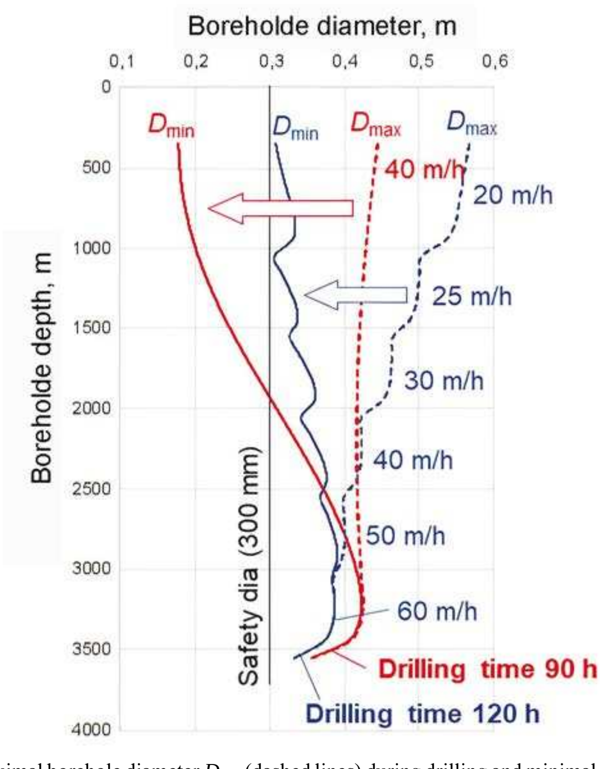

Fig. 5. Modeled maximal borehole diameter D_{max} (dashed lines) during drilling and minimal diameter after drilling completion D_{min} (solid lines) under different drilling scenarios: drilling at a continuous speed of 40 m/h (red lines) and drilling with stepped acceleration of speed from 20 to 60 m/h (blue lines); minimal safe diameter (300 mm) is shown by the vertical black thickened line

Рис. 5. Смоделированный максимальный диаметр скважины D_{max} (штриховые линии) во время бурения и минимальный диаметр после завершения бурения D_{min} (сплошные линии) при различных сценариях бурения: бурение с постоянной скоростью 40 м/ч (красные линии) и бурение со ступенчатым увеличением скорости от 20 до 60 м/ч (синие линии); минимальный безопасный диаметр (300 мм) показан вертикальной черной утолщенной линией using hot-water sprays; the second one calls for a carefully controlled drilling speed that ensures that the hole has a minimum safety diameter. Both methods can be implemented in our project but, at the moment, the second method takes priority. Based on the melting-refreezing theory developed by Greenler [22], the final diameter of the borehole after drilling completion with a constant speed of 40 m/h would be less than the minimum safe diameter of 300 mm (red lines in Fig. 5). However, a stepped acceleration of the drilling speed from 20 to 60 m/h would ensure that the final diameter is slightly larger than the minimum safe diameter (blue lines in Fig. 5). An additional hole enlargement will be provided by upward reaming after penetration into the subglacial lake. It is expected that creating the main hole using this method will take about 120 hours. After completion, the main hole can be kept open with the required diameter by regular reaming.

4. Plans for the future

Currently, all the drilling components are in the intensive design stage. According to the proposed schedule, project joint tests are to be carried out at the drilling facility of Jilin University in Changchun, China at the end of 2024 — beginning of 2025. The system should be ready for shipping to Antarctica before October 2025. During the 2025/26 season, the hot-water drilling system will be assembled near the Zhongshan Station, likely within 40 km of the station, and a trial drilling will be conducted by drilling to the ice sheet base. During the same season, field radar and seismic investigations are planned above Subglacial Lake Qilin in order to determine the optimal location of the drill site. Access drilling to the lake is planned in the season 2026/27.

Competing interests. No conflict of interest involved.

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Общая концепция системы глубокого бурения с горячей водой и стратегия бурения скважины доступа к подледниковому озеру Цилинь, Восточная Антарктида

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Аннотация. Глубокие подледниковые озера Антарктики представляют собой фактически не исследованную водную среду, изучение которой дает возможность получить уникальную информацию об эволюции микроорганизмов, климате Земли в прошлом и формировании антарктического ледяного покрова. Подледниковое озеро Цилинь, обнаруженное средствами дистанционного зондирования в центральной части Земли Принцессы Елизаветы в Восточной Антарктиде, является одним из идеальных объектов для предстоящих исследований. Длина озера оценивается в 42 км, а площадь — в 370 км^2, что делает его одним из крупнейших подледниковых озер в Антарктиде. Озеро предположительно является изолированным и покрыто льдом средней толщины около 3600 м. В настоящее время в Китае начаты научно-исследовательские работы по разработке системы глубокого бурения с горячей водой для экологически чистого доступа к этому озеру. Предлагаемая буровая система включает в себя восемь подсистем: (1) первичный контур нагрева горячей воды, (2) вторичный контур нагрева горячей воды, (3) систему механической и биологической очистки горячей воды, (4) спуско-подъемное оборудование, (5) забойное оборудование с гидравлической насадкой, (6) систему рециркуляции воды, (7) электрические генераторы и (8) систему контроля и управления. В статье представлены общая концепция системы экологически чистого глубокого бурения с горячей водой и краткое описание стратегии бурения. Бурение скважины доступа к озеру запланировано на сезон 2026/27 г.

Ключевые слова: подледниковое озеро, скважина чистого доступа, система бурения горячей водой

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Main aspects of constructing snow foundations for the new buildings of the Russian Vostok Station, East Antarctica

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Abstract. The present buildings of the Russian station Vostok (East Antarctica) began to operate in 1963 and have been under snow for many years. In connection with the extensive plans to study the subglacial Lake Vostok, it was decided to build a new wintering complex. Since there is a thick snow-firn layer in the construction area, the building of the complex requires solid foundations measuring 200×120 m. It was decided to build them by means of layer-by-layer snow compaction. Based on the approximate weight of the complex of 2 500 tons, its operation time of about 30 years, and the estimated pressure of the station supports on the snow cover of 100 kPa, the foundations slab must have a density of at least 550 kg/m³, and the hardness of the coating of more than 0.5 MPa. In developing the methodology of constructing the slab for the new wintering complex, the method of layer-by-layer snow compaction was taken as the basis, developed for the construction of airfields on deep snow and suitable for taking heavy aircraft on wheeled landing gear. Experimental snow compaction was carried out using various caterpillar tracks, after which stamp tests of snow surfaces with different initial snow characteristics were performed. The bearing capacity of the foundations was assessed by calculating the vertical mechanical stresses on their lower surface, which are formed by the pressure of the station supports. The strength characteristics of the snow were assessed by direct measurements using the Brinell method and with the help of a mechanical press based on the samples taken and a penetrometer. Ultimately, the density of the snow layers in the upper part of the foundations reached 650 kg/m³. In addition to the base layer, 9 additional layers were formed. The first eight were formed in the summer of 2019/20, and the last one in January 2022. The total thickness of the foundations exceeded 3 metres. Upon their construction, the average surface excess relative to the natural snow cover was 210 cm. Based on the rate of snow accumulation, as well as the subsidence of the station supports and foundations into the snow mass, the foundations surface will equal the level of natural snow cover in approximately 30 years.

Keywords: Vostok Station, new wintering buildings, snow compaction technique

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Introduction

During the Second Comprehensive Antarctic Expedition, the domestic inland Vostok Station was opened near the South Geomagnetic Pole on December 16, 1957. In addition to many multidisciplinary, primarily glaciological research programmes, core drilling began in 1970 [1]. After the discovery of a unique natural phenomenon — the subglacial Lake Vostok [2, 3] — studying this Antarctic area became especially important and relevant. Russia undertook systematic research with the great advantage of having a wintering station and annual logistic traverse. The main emphasis was on remote geophysical work, which included the seismic-reflection method and radio-echo sounding. The results made it possible to identify the features of the glacier structure, subglacial relief, and depth structure of the Vostok Lake area, as well as to measure the water layer thickness [4–6]. The penetration into Lake Vostok on February 5, 2012 [7] was the greatest event in the study of Antarctica and allowed the investigation of the body of water by direct methods, i.e., a direct study of the lake water [8, 9], with the study of the bottom sediments in sight. A general overview of the studies performed and planned is given in our paper, this issue [10].

The current Vostok Station housing complex has been under a layer of snow up to 6 metres thick for many years. These buildings were constructed between January and June 1963 [11]. The materials used for the construction are in a gradually deteriorating condition. The station operates all the year round, including winter, when access is virtually impossible. However, with the forthcoming intensification of research work, which is planned following Measure No. 21, “Comprehensive studies of the subglacial Lake Vostok and paleoclimate of the Earth in the area of the Russian Antarctic Vostok Station”, “Action Plan for implementing the Strategy for Development of Activities of the Russian Federation in the Antarctic until 2030”, approved by the Russian Government on June 30, 2021, No. 1767-r, the lack of modern living and laboratory facilities becomes evident. Therefore, it was decided to build a new wintering complex (NWC) at the Vostok Station, which will be close to the buildings of the currently operating station and eventually replace it (Fig. 1).

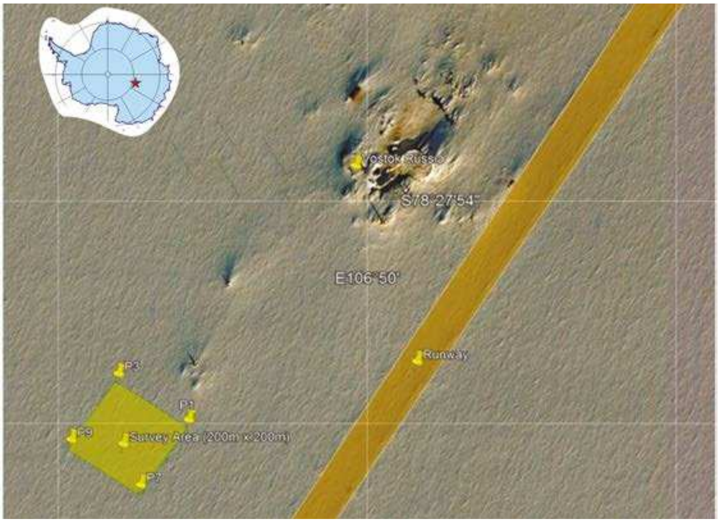

Fig. 1. Location of the new buildings of the Vostok Station [12]

Рис. 1. Схема расположения новых корпусов станции Восток [12]

The main difficulty is that the Vostok Station is located in central Antarctica. This region, according to the classification of glaciers [13], is a zone of dry snow with a snow-firn thickness of about 100 m [14] and a total glacier thickness of more than 3 700 m [5]. The density of the surface snow layer averages 350 kg/m³ [15, 16]. The thickness of the snow-firn strata at the construction site is also significant, due to which, at the stage of the NWC Vostok project development, the question arose of constructing preliminary foundations. In choosing the material, various options were considered, including construction from frozen ice through layer-by-layer pouring of water and from reinforced concrete structures. All of these methods were rejected as they required enormous resources. In the end, it was decided to build the foundations of the station from compacted snow [12] since this method was thought to be the most reliable and economical, especially considering the difficulties of transporting materials and equipment to central Antarctica. Similar stations — Amundsen-Scott (USA) and Concordia (Italy-France) are built on compacted snow. Based on the authors' knowledge, this will be the first attempt to construct such special foundations for a capital structure in Antarctica.

This work aims not only to communicate to the scientific community the main aspects of the construction of the NWC Vostok foundations, but also to present the results of experimental tests and characteristics of the snow cover and foundations for possible use in the future.

Methodology for the construction of the NWC Vostok foundations

In developing the methodology for building the NWC Vostok foundations slab (FS), the layer-by-layer snow compaction method developed for constructing airfields on deep snow, suitable for taking heavy aircraft with wheeled landing gear, was taken as the basis [17]. It is used to build snow-ice runways with a density of snow-firn material over 600 kg/m³ and a hardness of more than 1 MPa. The technique of building such runways was adapted for coastal Antarctic stations, where the surface temperature of the snow during the warm period is close to the phase transition temperature. However, the snow surface temperature in the Vostok Station area does not exceed –25 °C, even in the summer months. During the 2006–2008 field seasons, experimental and methodological work was carried out to determine the possibility of compacting the cold snow to create an airfield suitable for taking wheeled aircraft. The work was carried out in the area of the existing airfield, which can only take aircraft with ski landing gear. Experimental snow compaction was carried out using the tracks of different tractors, followed by stamping tests of snow surfaces with different initial snow characteristics. The results obtained [18] formed the basis for developing a technique for constructing the NWC foundations. In particular, dependencies of the snow density on the impact on the snow cover were obtained. They are shown in Fig. 2. The uniaxial compression strength of the snow was measured using a mechanical press. A total of 50 plate load tests were conducted. The hardness of the compacted snow was measured with a penetrometer with a fracture energy of 8.5 J [17]. Its strength was measured on cylindrical specimens 9 cm in diameter and 16 cm long on a hydraulic press with a dynamic range of 0.2 to 1.5 MPa. The press was calibrated with a precision DOSM-3-1 dynamometer with a dynamic range from 0.1 to 10 kN. A total of 300 measurements were made on the samples. Their accuracy is estimated to be no worse than 2 %. Fig. 2 shows the averaged data for different initial snow characteristics.

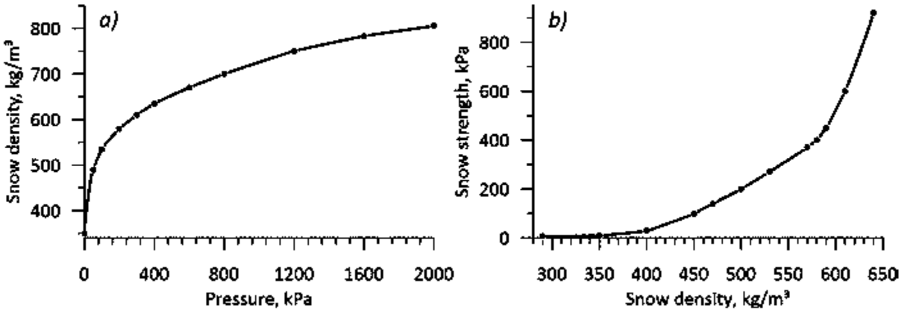

Fig. 2. Dependencies of the density of the compressed snow on the pressure (*a*) and the snow strength on density (*b*)

Рис. 2. Зависимости плотности образующегося снега от оказанного на него давления (*a*) и прочности снега от его плотности (*b*)

The density of the natural snow cover was measured using the VS-43 weight snow meter, and the density of the compacted snow was measured using samples obtained from the core samples. The density variation of the natural snow cover did not exceed 10 %.

Fig. 3 shows the dependence of the depth of impact on the snow cover of the applied stamp pressure P for different snow densities ρ and its hardness σ, obtained as a result of the plate load tests. The depth of impact refers to the depth of the snow layer in which the physical and mechanical characteristics of the snow changed after the mechanical impact. The experiments were carried out on the snow airfield of the Vostok Station, designed for planes with ski landing gear, where the snow is of varying densities. The impact depth was measured for compacting devices, and the impact time on the snow cover was several tens of seconds. The experiments aimed to examine the possibility of compacting cold snow to a certain density and, consequently, strength.

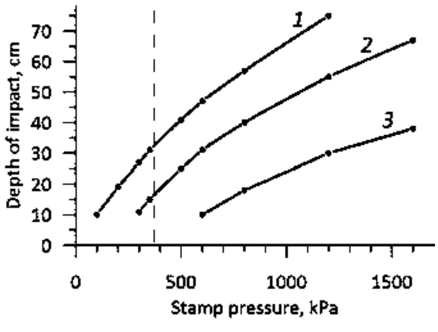

Fig. 3. Depth of impact on the snow depending on stamp pressure for various initial snow characteristics: *1* — ρ = 420 kg/m³, σ = 0.045 MPa; *2* — ρ = 500 kg/m³, σ = 0.2 MPa; *3* — ρ = 580 kg/m³, σ = 0.45 MPa.

The vertical dotted line shows the maximum possible pressure (P = 0.35 MPa) on the surface exerted by the sealing devices

Рис. 3. Глубина воздействия на снежный покров в зависимости от давления штампа для различных исходных характеристик снежного покрова: *1* — ρ = 420 кг/м³, σ = 0,045 МПа; *2* — ρ = 500 кг/м³, σ = 0,2 МПа; *3* — ρ = 580 кг/м³, σ = 0,45 МПа.

Вертикальной пунктирной линией показано максимальное возможное давление (P = 0,35 Мпа) на формируемую поверхность, оказываемое уплотняющим устройством, имеющимся в распоряжении строительного отряда

Based on the compactor capabilities, the maximum thickness of the snow layer to be compacted was selected. A mandatory condition was sealing the layer over the entire thickness, which means the thickness of the layer should not exceed the exposure depth. The FS snow layers were applied using the Kässbohrer Pisten Bully Polar 300 (Fig. 4*a*). After that, due to mixing the snow, its density increased from the initial value of 350 kg/m³ to 420 kg/m³. The main device to compact the FS snow layers was a compaction platform designed and built to create snow aerodromes suitable for heavy-wheeled aircraft. It received a patent for invention [19].

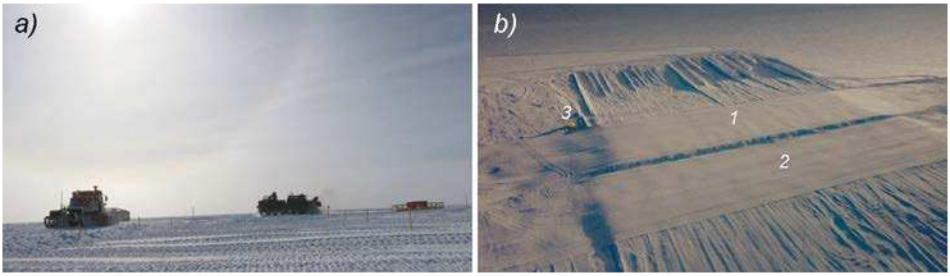

Fig. 4. Fragment of the foundations slab for the new buildings of the Vostok Station (a) and the top view (b).

The compaction of the snow layer by a special platform towed by a heavy artillery tractor is shown in the background of section a. In section b: 1 — the eastern part of the foundations (intended directly for the new buildings); 2 — the western part of the foundations; 3 — the temporary glaciological laboratory. The photos are by K.A. Ovchinnikov

Рис. 4. Фрагмент создания плиты фундамента НЗК Восток (a) и вид сверху на нее (b).

Уплотнение нанесенного снежного слоя специальной платформой, буксируемой артиллерийским тяжелым тягачом (АТТ), представлено на заднем плане секции а. На секции б: 1 — восточная часть ПФ размером 200×60×3 м (предназначена непосредственно для расположения модулей НЗК); 2 — западная часть ПФ, размером 200×60×2 м (для дополнительной инфраструктуры НЗК); 3 — временная гляциологическая лаборатория. Фото К.А. Овчинникова

Foundations slab construction technology and main results

The horizontal dimensions of the FS were determined by the design dimensions of the NWC, as well as the accompanying infrastructure (fuel storage, etc.). In addition, we considered the possibility of working on it with construction equipment on the entire perimeter of the NWC under construction. The horizontal dimensions of the FS were 200×120 m. The FS thickness was calculated based on the main functions of the foundations: to withstand the load from the plant supports and to ensure a higher position of the NWC relative to the surrounding natural snow cover over a long period (about 30 years). Several factors cause the gradual deepening of the NWC over time: (1) natural snow accumulation in the area, which is about 7.2 cm/year [15, 16]; (2) sinking of the station supports into the FS body, due to the compression creep of the snow material under prolonged exposure to mechanical stress and (3) sinking of the FS into the underlying snow cover, also due to compression deformation of the snow under prolonged mechanical impacts of the total weight of the FS and NWC.

At the initial stage of construction, after selecting the FS location, the natural snow cover was compacted by heavy artillery tractor (HAT) caterpillars, with their pressure on the snow at about 45 kPa. Compaction was carried out on the entire site of the prospective FS. As a result, the snow surface lowered by about 50 cm relative to the surrounding terrain, and the density of the snow surface of the site to a depth of 40 cm increased from 350 kg/m³ to 470 ± 20 kg/m³. Below 40 cm, the density of the snow changed insignificantly. Thus, a basic FS layer was created. Further, the snow layers applied to the foundations site were compacted by HAT tracks and the compacting platform. When the snow layers were applied, geodetic control of their thickness and horizontality was carried out. The ground control of the marks was carried out by a Trimble R10-2 GNSS receiver (Trimble Inc., USA) in real time over a 10×15 m network. The height mark was taken on the calculation of +30 cm from the average height of the previous compacted layer. The snow layers were applied with the Kässbohrer Pisten Bully Polar 300 (PB-300). In one trip, it could take up to 4 m³ of snow, which was evenly distributed at the FS construction site. Snow was taken from the surrounding area at 50 to 150 m from the construction site. One transporter PB-300 took 7 days to apply a snow layer of 30 cm thickness on the entire area of 200×120 m. The work was carried out only during the daytime because the air temperature dropped below –30 °C at night, which was unacceptable for the operation of the blade's hydraulic system. In general, according to the NWC design, the foundations surface was to consist of two sites located at different levels. The western part of the 200×60 m FS is one metre lower than the eastern part of the same size FS (Fig. 4). Given the dispersion of vertical stresses with depth under the station supports, the lower FS layers were not compacted as thoroughly as the upper ones. The lower FS layers were compacted once, at most twice, unlike the upper layers, which were compacted repeatedly.

The FS surface in the first construction phase was divided into two equal parts measuring 200×60 m to save time and for more efficient use of the technology. On one of the FS sites, the compacted snow layer was applied and on the other already compacted layer, another snow layer was applied. Fig. 4*a* shows a photo of the snow layer compaction section with a platform weighing 9 tons, towed by a HAT with simultaneous application of the next snow layer by the conveyor blade on the other half of the FS.

In the second phase of construction, after the FS reached a thickness of two metres, the application of snow layers and their subsequent compaction was carried out only on the eastern half of the FS. All the foundations work was done during the two summer field seasons of 2019/20 and 2021/22. No work was performed during the 2020/21 season for technical reasons.

During the work, the maximum pressure exerted by the compaction platform on the snow surface was 0.35 MPa. As follows from Fig. 3, the maximum depth of impact on the snow cover at a snow density of 420 kg/m³ is 30 cm. Based on this value, the maximum thickness of the applied snow layer was selected, which should not be exceeded. It took 10 to 12 hours for the HAT caterpillars to compact the newly applied snow layer over the entire FS area once. It took at least 14 hours to compact the snow layer with a platform towed by an PB-300 transporter over the entire FS area. In compacting, the speed of the towed device should not exceed 5 km/hour because any increase above this speed may destroy the snow cover [20], i. e., the compacted snow may be thrown out from under the skids of the compacting platform. Eventually, the density of the snow layers in the upper part of the FS reached 650 kg/m³ to a depth of 2.5 m. In addition to the base layer, 9 layers were formed. The first eight were formed in the summer of 2019/20, and the last one in January 2022. The total thickness of the FS, including the base layer, under the NWC modules exceeded 3 m.

A temporary glaciological laboratory was organized near the construction site to obtain the main characteristics of the resulting FS snow material. The density and uniaxial compressive strength were measured using cores taken from the FS body. The hardness of FS snow layers was measured using a penetrometer directly on the FS. Fig. 5 shows the averaged vertical distribution of the density and the uniaxial compressive strength of the snow material inside the FS body on its eastern part, which is intended directly for the location of the Vostok Station modules.

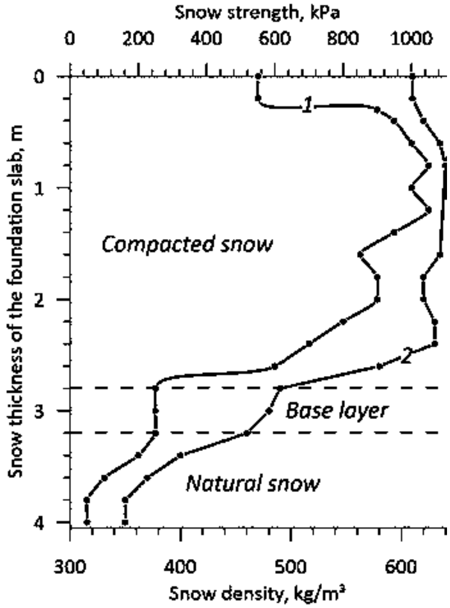

Fig. 5. Density and strength distribution of the compacted snow in the eastern part of the foundation slab.

1 — strength of the compacted snow layer for uniaxial compression, *2* — snow density

Рис. 5. Распределение плотности и прочности снежного материала в восточной части плиты фундамента НЗК.

1 — прочность снежного покрова на одноосное сжатие, *2* — плотность снега

The measurement data presented in Fig. 5 were obtained from cores sampled at the FS in early February 2022. The uppermost ninth layer, formed in January 2022, has much less strength due to the short time that has passed since its formation. The strength of the compacted snow layer increases gradually over a long period, which is due to the slow process of diffusion sintering of the compacted snow granules [21]. In constructing the FS, an experiment was conducted to measure changes in the strength of the compacted snow layer over time. At the western FS site, where no additional layers were applied after the completion of the first phase of construction, the hardness of the compacted snow layer was measured daily with a penetrometer. The density of the layer investigated increased immediately after compaction and reached 640 kg/m³, and the hardness actually initially decreased. Fig. 6 shows the change in the hardness of the compacted layer over time. Measurements were taken daily for 15 days in January 2020. Further measurements were not carried out because the seasonal work at the Vostok Station finished. In the following year, no work was carried out in the Vostok Station area for technical reasons. After two years, the work resumed and the measurement of the hardness of the FS was carried out

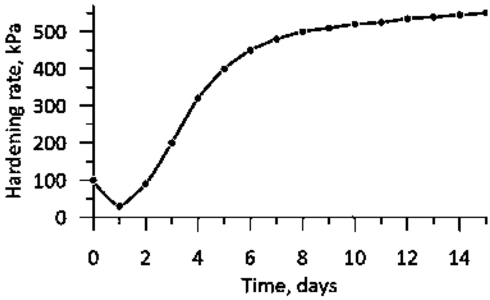

Fig. 6. The hardening rate of the compacted snow.

The average snow temperature during the measurement period was –32 °C.

Рис. 6. Результаты эксперимента по скорости затвердевания уплотненного снега.

Средняя температура снега за период измерений составила –32 °C

again in the same place with the same penetrometer. It was found that after two years the hardness of the compacted snow material almost doubled and reached 1 MPa. The hardness of the layer was measured once at 30 points evenly across the FS surface. The variation did not exceed 5 %.

Bearing capacity of the foundations slab

The FS bearing capacity was assessed by calculating the vertical mechanical stresses on its lower surface, formed by the pressure of the station supports. If the dissipation of the mechanical stresses on the lower surface of the FS does not exceed the carrying capacity of the natural snow cover on which it rests, then the FS bending deformation will not occur, and, as a consequence, its destruction will not follow. This calculation method is an upper estimate of the sufficient thickness of the FS to withstand the NWC load. The estimated pressure of the station supports on the snow cover is 100 kPa. The hardness of the snow material that makes up the FS must be at least higher than the pressure of the station supports. The dispersion of the vertical mechanical stresses in the FS body with depth will depend on the strength characteristics of the material forming the FS. They are shown in Fig. 5.

A rough estimation of the dissipation of the vertical mechanical stresses was made from the results of a plate load test on compacted snow [18]. A stamp with a different pressure impacted the pre-compacted snow cover with known mechanical characteristics. In this case, the depth of the impact on the snow cover studied was measured. In particular, at its density of 500 kg/m^3 and the corresponding uniaxial compressive strength of 0.2 MPa, a pressure of 0.8 MPa was exerted on the snow. The impact depth was 40 cm. This means that at a depth of 40 cm, the mechanical stress from the stamp fell to the strength of the snow cover studied and amounted to 0.2 MPa. Fig. 3 shows the dependencies of the impact depth on the applied stamp pressure for some snow cover characteristics. These tests were conducted between 2006 and 2008. The FS was stronger since the coating density was higher than in the stamp tests. By conducting about 50 experiments with different stamp pressures, a curve of mechanical stress dissipation with depth was obtained for certain snow cover characteristics. For example, Fig. 7 shows the vertical stress dispersion curve for a snow cover with a density of 500 kg/m^3 under the stamp at a surface pressure of 100 kPa.

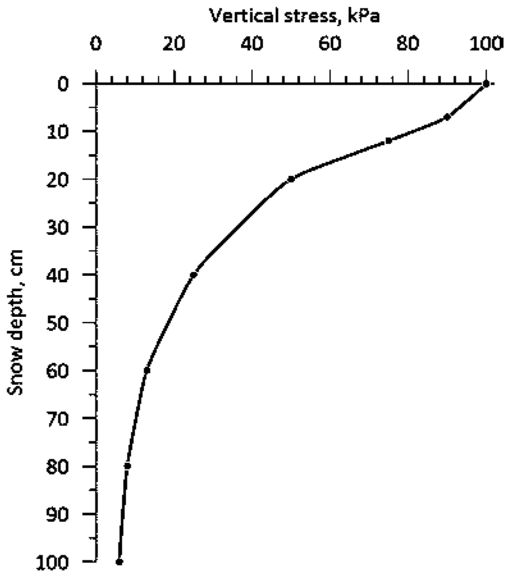

Fig. 7. Stress relaxation with depth for snow density of 500 kg/m³ based on the data collected in 2006–2008

Рис. 7. Ослабление вертикальных механических напряжений с глубиной для снежного покрова плотностью 500 кг/м³ по данным 2006–2008 гг.

The results of the experiments presented in Fig. 7 were obtained in 2006–2008 at the airfield of the Vostok Station, where there were snow layers of different densities and thicknesses. The values presented on the graph agree well with similar data on the dissipation of vertical stresses under the IL-76 landing gear, given in [17]. The greater the strength of the snow material investigated, the faster the vertical stresses under the stamp dissipate with depth. If one imagines an FS of infinite thickness, then at a certain depth, the vertical stresses from the station supports will reach their minimum value, equal to the ratio of the station's weight to the FS area, and will be 1 kPa for NWC Vostok. If the FS thickness is not less than the calculated depth where the vertical stresses will be less than the strength of the natural snow cover on which the FS rests, the latter is safe against collapse. The strength characteristics of the natural snow cover in the NWC construction area were evaluated by direct measurements using the Brinell method [22]. Fig. 8 shows a diagram of the experiment.

The measurements were made by embedding spherical objects of two different diameters into the natural snow cover. The force applied to the objects and the size of the spherical indentation imprint were measured. The hardness of the snow layer tested was calculated using the Brinell formula [23]:

$$\sigma = \frac{P}{\pi D h},$$

where σ is the Brinell hardness of the snow cover, P is the impact force on the sphere, D is the sphere diameter, h is the sphere immersion depth in the snow cover. The minimum hardness of the natural snow cover, measured at 30 points by pressing a spherical object into the natural snow cover at the construction site, was 10 kPa. The measurement points

Fig. 8. Scheme of the experiment measuring the strength characteristics of natural snow cover by the Brinell method. The photos are by S.P. Polyakov

Рис. 8. Схема эксперимента по измерению прочностных характеристик естественного снежного покрова методом Бринелля. Фото С.П. Полякова

were chosen evenly. Previously, the density of snow on the surface was measured at 20 points evenly on the site using VS-43. The average value was 350 kg/m³, with no more than 10 % variation. This value was used to calculate the bearing capacity of the NWC FS. In general, the measurements were carried out according to the standard methodology.

As follows from Fig. 7, tenfold weakening of the mechanical stresses applied to the upper surface of the FS will occur at a depth of about 0.7 metres. Given that the initial pressure on the surface from the station supports is 100 kPa and considering the scale effect of the difference in the size of the test stamp and the station supports, the minimum FS sufficient thickness with a snow material density of 500 kg/m³ will be about one and a half metres. In the case under consideration, the density of the upper layers of the FS exceeded 600 kg/m³, and the FS thickness was more than 3 m. Thus, such an FS is certain to be sufficient to withstand the load of the NWC supports.

Creep of the snow material of the foundations slab under the impact of the NWC Vostok supports

One of the important processes that can lead to a decrease in the height of the NWC location relative to the surface of the surrounding natural snow cover is the plastic deformation of the FS snow material under the NWC supports. Calculations of the creep of snow material of different densities were carried out to assess the degree of influence of this process. The snow material begins to deform under the pressure of the NWC supports. The calculation of the deformation was carried out according to the relation

$$\tau = \eta_k \dot{\varepsilon}\,, \qquad (1)$$

where τ is the mechanical stress in the snow (in the case considered, the pressure on the snow from the NWC supports), η_k is the compression viscosity factor of the FS snow material, $\dot{\varepsilon}$ — the rate of relative deformation.

Considering the one-dimensional case of only the vertical deformation of the FS under the action of the NWC supports, the formula for calculating the vertical deformation can be presented in the form:

$$\frac{dh}{dt} = \dot{\varepsilon} h\,,$$

where h is the thickness of the FS layer studied. Accordingly,

$$dh = \dot{\varepsilon} h \cdot dt\,. \qquad (2)$$

The compression viscosity coefficient η_k was calculated using Bader's formula [19]:

$$\eta_k = \frac{a_\eta \rho_S}{\rho_I - \rho_S} exp\left(b_\eta \rho_S\right), \qquad (3)$$

where ρ_I is the density of fresh ice, ρ_S is the snow density, a_η, and b_η are empirical coefficients. At the Berd station [24], unique experiments were conducted to measure the compression viscosity coefficient of snow of different densities at temperatures T = –28 °C, similar to the surface layer temperature of snow in the summer near the Vostok station. According to the experimental data obtained by Bader [20] at the Berd station, at temperature T = –28 °C: $\eta_k = 10^{11}$ Pa·s at ρ = 450 kg/m³; $\eta_k = 10^{12}$ Pa·s at ρ = 500 kg/m³; $\eta_k = 10^{13}$ Pa·s at ρ = 650 kg/m³.

Given the relation (2), the compression deformation (creep) of the FS snow material under the NWC supports, ΔH, for the entire FS of thickness H for the time t_0 will be

$$\Delta H = \int_0^{t_0}\int_0^{H} \dot{\varepsilon} \cdot dh \cdot dt\,.$$

Substituting into it the value for the relative strain rate taken from (1), one can obtain:

$$\Delta H = \int_0^{t_0}\int_0^{H} \frac{\tau}{\eta_k} dh \cdot dt\,.$$

This formula was used to calculate the subsidence of the station supports for a given time period t_0 for different strength characteristics of the snow material of which the FS is composed.

The calculations were performed numerically with a depth step Δh = 5 cm and a time step Δt = 10 hours for an FS of thickness H = 3 m. The values of vertical mechanical stresses inside the FS, $\tau(h)$, were taken from experimentally obtained stamp test data for different snow characteristics. In particular, Fig. 6 shows the distribution of vertical stresses for a snow density of 500 kg/m³. The compression viscosity coefficient ηk values were calculated using Bader's formula (3). It depends on the snow density and its temperature and increases as the density increases as the snow material is compacted under the station supports. The compression viscosity coefficient also depends significantly on the snow temperature and increases as it decreases. In the calculations, a correction multiplier was introduced for the temperature of the snow layers inside the FS according to the relation [25]:

$$\eta_k = k\,exp\left(\frac{Q}{RT_0}\right), \tag{4}$$

where Q is the activation energy of snow; R is the gas constant; T_0 is the absolute temperature; k is a constant coefficient for a given snow type. The snow temperature in the calculations was set as the average monthly temperature of the upper snow layers in the area of the Vostok Station [15, 16].

Fig. 9 shows the results of calculations of the compression creep of the snow material under the station supports for different density characteristics of the snow material. If one substitutes the real distribution of snow density in the FS, shown in Fig. 5, the subsidence of the station supports in the FS body will be 12 cm, 28 cm, and 33 cm for 1 year, 10 years, and 30 years, respectively.

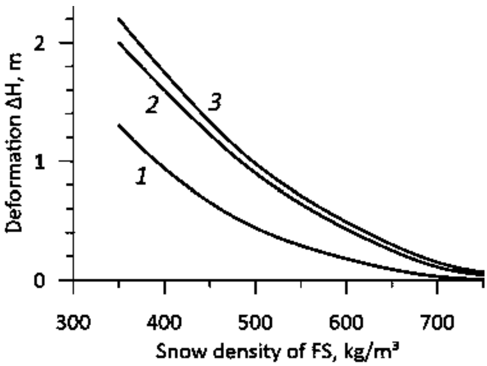

Fig. 9. Calculated compressive creep of the foundations under the station supports for various densities of the initial snow material for various periods

Рис. 9. Результаты расчетов компрессионной ползучести ПФ под опорами станции для различной плотности исходного снежного материала за различные периоды времени

Another process leading to the lowering of the Vostok NWC location is the compression deformation of the natural snow cover on which the station foundations rest. The total weight of the FS, on which the station rests (200×60×3 m), will be about 20 thousand tons. At the same time, the weight of the NWC itself is 2 500 tons. Thus, given the size of the FS, the pressure on the underlying snow layer from the FS side will be about 20 kPa. The deformation of the underlying snow layers was calculated according to the same scheme as the creep of the FS snow material under the station supports, presented above. As a result, for the initial density of the natural snow cover of 350 kg/m³, the FS decrease will be 9 cm in 1 year, 16 cm in 10 years, and 20 cm in 30 years.

Discussion of the results

During the whole period of FS construction, geodetic control of the excess of the FS surface relative to the surrounding natural snow cover was carried out. Thus, at the end of the 2019–2020 seasonal works, the excess of the FS surface position relative to the natural snow cover was 200 cm. The unevenness of the height of the FS surface itself did not exceed 10 cm. At the beginning of the 2021/22 construction season, geodetic measurements of the excess position of the FS surface were repeated. In fact, over 2 years, the average immersion of the FS into the snow strata was about 8 cm, which agrees well with the theoretical calculations presented above. A slightly overestimated result of the calculations of the FS immersion into the snow strata compared to the actual data can be explained by the increased density of the underlying snow layers, on which the FS rests after the first phase of construction in 2019/20. At the end of FS construction, the average excess of its surface relative to the natural snow cover was 210 cm.

Due to the severe climatic conditions in the area of the Vostok Station, only 2 months are suitable for work: December and January, when the air temperature rises to –30 °C. Nevertheless, with two PB-300s and one HAT, the entire 3 m thick snow base could be created in just one summer field season.

Yet, it should be noted that the performed analysis of experimental data and detailed numerical estimates do not take into account a possibility that the supports of the new station buildings could somewhat additionally sink not only due to the one-dimensional compression of the underlying snow-firn layer but also due to 3D deformational upward flow of snow and firn around the columns. Another submerging effect can be related to the fact that the new station area (~ 60×200 m^2) in both directions is comparable or even larger than the snow-firn layer thickness (~80–100 m) in the Vostok region. As a result, the load of the station, not being dissipated within the firn thickness, could lead to further increase in the total compression rate.

Conclusions

With the technical equipment available to the construction team that built the FS, namely: one HAT and one PB-300, the construction of the FS took 2 years. Each year the work was carried out only in the summer period from late November to early February. The main mechanism for lowering the height of the station location relative to the surrounding snow cover is natural snow accumulation on the surrounding NWC surface, which is about 7.3 cm/year [15, 16]. Accordingly, over 30 years, the height of the natural snow cover will increase by about 2 m relative to its original position. The total lowering of the lower part of the station supports relative to the surface of the natural snow cover, given the compression deformation of the FS under the station supports and the deformation of the natural snow cover on which the FS rests, will be about 240 cm in 30 years. Thus, it will take about 30 years for the height of the natural snow cover to reach the height of the bottom of the station supports. Consequently, the work performed has shown that the new buildings of the Vostok Station will last satisfactorily for at least thirty years and given that the height of the station piers themselves is 4 metres, the new buildings could last much longer.

Competing interests. The authors declare no conflict of interest.

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Основные аспекты строительства снежного фундамента для новых корпусов российской станции Восток, Восточная Антарктида

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Расширенный реферат

Имеющиеся на сегодняшний день корпуса российской станции Восток (Восточная Антарктида) начали эксплуатироваться в 1963 г. и уже многие годы находятся под снегом. В связи с обширными планами по изучению подледникового озера Восток было принято решение о возведении нового зимовочного комплекса. Поскольку в районе строительства имеется мощная снежно-фирновая толща, установка комплекса требует наличия твердого фундамента. Его размеры, исходя из конфигурации нового зимовочного комплекса, составляют 200×120 м. Строительство фундамента было решено осуществлять путем послойного уплотнения снега. Исходя из ориентировочного веса комплекса в 2500 тонн, времени его эксплуатации около 30 лет и предполагаемого давления опор станции на снежный покров в 100 кПа, плита фундамента должна иметь плотность не менее 550 кг/м³, твердость покрытия более 0,5 МПа. При создании метода ее формирования за основу была принята методика послойного уплотнения снега, разработанная для строительства снежных аэродромов на глубоком снегу, пригодных для приема тяжелых самолетов на колесном шасси. Экспериментальное уплотнение снега осуществлялось с помощью гусениц различных тягачей, после чего выполнялись штамповые испытания снежных поверхностей с различными исходными характеристиками снега. Оценка несущей способности фундамента осуществлялась методом расчета вертикальных механических напряжений на его нижней поверхности, образующихся от давления опор станции. Оценка прочностных характеристик снега производилась как прямыми измерениями по методу Бринелля, так и с помощью механического пресса по отобранным образцам и пенетрометром. В конечном итоге плотность снежных слоев в верхней части фундамента достигла 650 кг/м³. В общей сложности, помимо базового слоя, было сформировано еще 9 дополнительных слоев. Первые восемь — летом 2019/20 г., а последний — в январе 2022 г. Общая толщина фундамента превысила 3 метра. При нанесении снежных слоев осуществлялся геодезический контроль за их толщиной и горизонтальностью. Разброс неровности высоты самой поверхности фундамента не превышал 10 см. Для экономии времени и более эффективного использования техники его поверхность на первом этапе строительства делилась на две равные части размером 200×60 м. На одной из площадок фундамента проводилось уплотнение нанесенного снежного слоя, а на другой, уже уплотненной, наносился очередной снежный слой. По окончании его строительства среднее превышение поверхности относительно естественного снежного покрова составило 210 см. Исходя из скорости аккумуляции снега, а также погружения опор станции и фундамента в снежную толщу, поверхность нижней части опор станции сравняется с уровнем естественного снежного покрова примерно через 30 лет. Фактическое среднее погружение плиты фундамента за два года в снежную толщу составило около 8 см, что неплохо согласуется с теоретическими расчетами. Таким образом, новые корпуса станции Восток удовлетворительно просуществуют на протяжении по крайней мере тридцати лет, а с учетом того, что высоты самих ее опор составляют 4 метра, значительно дольше.

Ключевые слова: станция Восток, новый зимовочный комплекс, методика уплотнения снега

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Conceptual project of a center for testing technologies and technical devices for glacier drilling

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Abstract. The implementation of drilling projects in Antarctica requires comprehensive research and development work to study the processes of interaction between drilling equipment and ice and test devices designed for ice drilling. Testing facilities with artificial ice are essential for conducting this type of research. The article presents an analysis of the existing experimental stand projects, which identified a common drawback — inability to recreate a structure of atmospheric ice and thermobaric conditions similar to those in boreholes drilled in Antarctica. The authors propose the conceptual project of a center for testing technologies and technical devices for glacier drilling. The center is to be located on two sites: the first — on the "Sablino" educational and scientific testing ground of Saint-Petersburg Mining University in the Leningrad Region (Russia), the second — at the drilling complex of 5G borehole at Vostok station in Antarctica. The implementation of the project will allow conducting experimental research and testing, using both shallow artificial ice wells and deep boreholes in the Antarctic glacier. In addition, it will allow maintaining the drilling complex and 5G borehole in a good technical condition.

Keywords: Antarctica, artificial ice borehole, borehole 5G, drilling process, drilling technologies and equipment, testing center

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1. Introduction

Since the mid-20th century, the world's leading countries, including the Russian Federation, have been engaged in active research in Antarctica. Many of the research projects involve drilling into glaciers to collect ice cores or access subglacial water bodies and rocks for geological, paleoclimatic, and biological studies [1]. In the former case, scientists obtain ice core material, which is a unique source of information about the climatic processes that have occurred on the sixth continent over the past few million years [2, 3]. In the latter case, scientists get quick access to subglacial reservoirs and bedrock to conduct geological, paleo-climatic and biological research [4–6].

St. Petersburg Mining University, in collaboration with the Arctic and Antarctic Research Institute (AARI), has been conducting scientific research at Vostok Station for over five decades. This work involves drilling deep boreholes into glaciers and studying the resulting cores. In this time, technologies and technical devices have been developed and applied, which made it possible to set several world records in glacier drilling [7, 8] and to unseal subglacial Lake Vostok twice [9, 10].

The testing of the technologies and equipment developed was often carried out directly during the process of deep ice drilling, which led to increased risks of emergency situations and prolonged project duration. The mechanical and thermal destruction of ice differs significantly from the processes occurring during the destruction of rocks [11, 12]. This necessitates the adaptation of the existing drilling technologies and the development of new ones, taking into account the mining, geological, and physic-geographical conditions of the Antarctic [13]. These activities require comprehensive research and development, including experimental studies on the interaction of drilling tools with ice and the testing of the technical devices developed [14, 15].

A solution to these problems can be worked out on experimental stands that use various methods for modeling ice masses:

– using single ice blocks (artificial or natural);
– using ice towers;
– using ice wells.

Each of the methods listed has its own advantages and disadvantages, which are discussed below.

Projects using single ice blocks

In the early 1980s, an experimental setup was developed at Leningrad Mining Institute (now St. Petersburg Mining University) to simulate the operating conditions of an ice core electromechanical drill (KEMS) attached to a carrying cable using single ice blocks [16]. The experimental stand was used at Vostok station. This enabled research on the drilling equipment of the 5G borehole complex with the circulation of the drilling fluids used. The main disadvantage of the setup was the artificial model of the bottom hole with limited dimensions, which did not allow for the required run length, as well as the difference in the physical and mechanical properties between the ice block and the glacier.

In 1988, a team of Japanese researchers conducted a study on ice cutting, collection and transportation and tested the electronics used in the drilling equipment (Tachikawa, Tokyo, Japan) [17]. The research was conducted on a 20 m tall derrick with a refrigeration chamber at the base, which provided circulation of cooled kerosene and housed an ice block measuring 0.2 × 0.6 × 0.9 m. The chamber had a window for observing the drilling process. The main disadvantages of the experimental setup include: the cooling system did not allow the temperature of the ice and kerosene to be lower than –5 °C; the dimensions of the ice block limit the number of tests (to three).

In 1994, a group of Japanese scientists developed a more advanced experimental stand for studying the ice cutting process [18], with pressure ranging from 0.1 to 30 MPa at temperatures of up to –62 °C. The stand's disadvantage was that its working chamber was too small to accommodate a drill.

In 2015, Chinese scientists conducted research to determine the relationships between the geometric parameters of ice cuttings and the drilling parameters of an electromechanical auger drill [19]. A special experimental setup was made, including a mechanical part and an ice block measuring 0.7×0.6×0.5 m, prepared from lake ice at a temperature of no more than –5 °C. The mechanical part of the setup contained a 2 m high mast with a drill suspended on it. The drill was equipped with a single-cutter bit. The parameters of the drilling modes and the temperature of the ice were recorded by sensors. The main disadvantages of the experimental stand include the lack of an anti-torque system, which causes significant vibration during projectile operation and distortion of the results obtained; and the characteristics of the lake ice not corresponding to those of the atmospheric ice in Antarctica.

Projects using ice towers

The arrangement of ice blocks in the form of towers provides an increased depth for experimental drilling and testing of full-scale drilling equipment.

The first experimental complex for studying the ice drilling process was built during the times of the Russian Empire at the Tomsk Technological Institute in the winter of 1909 [20].The author of the project was Boris Petrovich Weinberg, a famous Russian physicist and glaciologist, who proposed the theory of ice movement along an inclined channel, and studied the movement of Arctic ice and its physical and mechanical properties. The complex consisted of a tower 10 m high, where ice was frozen naturally by gradually moving a box of steel sheets and adding water. This complex was used to test the first thermal drill designed for drilling boreholes in ice.

One of the most significant international ice tower projects was the research conducted by Japanese scientists between 1992 and 1993. This research aimed to test drilling systems with fluid in polar conditions. In Rikubetsu city, which is located in the coldest region of Japan, a 30-meter-high testing facility was built, with a 15-meter-tall ice tower made of 1 × 1 m ice blocks. Before beginning the experiments, pilot holes with a depth of 8 m were drilled in the ice tower and filled with drilling fluid to a height of 7 m. The tower's cross-sectional area was sufficient to drill nine holes, with a total drilling depth of 63 m. However, despite the low air temperatures in winter (down to –25 °C), the experimental conditions were insufficiently similar to those in which drilling was carried out in Dome F, Antarctica.

An example of modern experimental research experience using an ice tower is the testing of the RECAS (RECoverable Autonomous Sonde) thermal probe [Pavel Talalay, personal communication]. In the winter of 2021, a 15 m high tower made of lake ice blocks was constructed on Hongqi Lake in Changchun, China. The lake's depth of 3 m made it possible to conduct successful experiments on collecting water samples from a reservoir using a probe. However, during the equipment testing, meltwater leaked between the ice blocks, leading to overheating of the probe's elements.

Ice wells projects

Another glacier modeling method is to use ice wells. This method was first used in 1964 in Hanover (USA) to test drilling tools developed by the Cold Regions Research and Engineering Laboratory (CRELL). The ice was formed in a special structure with a diameter of 1.22 m and a depth of 63 m. The structure consisted of pipe sections and an internal coolant circulation system. However, during the research, the well was depressurized, and the drilling fluid polluted the environment [21].

Another example of an artificial ice well where equipment was tested is the Laboratory of Glaciology and Geophysics of Environment in Grenoble (France). To test drilling technologies, researchers created an 8 m deep pit, in which ice was frozen. The shallow depth of this structure made it impossible to test a full-size drill, so the final stages of equipment testing were carried out in Antarctica [22].

A distinctive feature of the ice well created in 2015 at the University of Minnesota (USA) was the principle of ice freezing due to the circulation of a coolant in the annular channel between the casing and a pipe simulating a well. The working depth of the well was 152 m with a diameter of 124.2 mm. Liquid coolant CO_2 circulated through the annular space of the well, providing an ice temperature in the range from –25 to –40°C. However, the small diameter of the well caused frequent contact between the drilling tool and the wall of the pipe, resulting in damage. During the tests, difficulties were observed in supplying the coolant to the annular space, leading to difficulties in the process of ice freezing. A lack of refrigerant flow in the well prevented its use as a permanent testing facility. After the completion of the testing program for a mechanical drilling rig, the facility was decommissioned [23].

One of the significant projects currently using ice wells is the ice drilling test facility at the Polar Research Center of Jilin University in China [21]. In this project, artificial ice is frozen in a pipe with an internal diameter of 1 m and a wall thickness of 10 mm, which is installed in a shaft at a depth of 12.5 m. The shaft has a diameter of 2.6 m and is covered by a waterproof casing. The annular space between the ice well and the walls of the shaft contains evaporator coils and thermal insulation, which also serves as a space for equipment maintenance and repairs. The ice well can be used to test technical devices for glacier drilling and its main advantages include:

– the ability to simulate various environments and geological conditions;

– the ability to regulate the temperature of ice over a wide range;

– high technological efficiency of the design allowing one to perform a series of tests under identical conditions.

Some disadvantages of this structure include the complexity of installation works, high requirements for the quality of the underground part, and the complexity of maintaining cryogenic equipment [24]. Of all the methods of glacier modeling, the most universal is the creation of artificial ice wells. These models are part of testing facilities that allow year-round testing of drilling techniques and equipment. However, like other methods, this method of modeling ice mass cannot recreate the structure of atmospheric ice or the thermobaric conditions at boreholes in Antarctica, which directly affects the design features of drilling tools and the drilling process.

2. Glacier drilling technology and equipment testing center

The Center for testing technologies and technical devices for glacier drilling is to be located on two sites:

1) on the “Sablino” educational and scientific testing ground of Empress Catherine II Saint-Petersburg Mining University in the Leningrad region (Russia);

2) at the drilling complex at Vostok station in Antarctica, where a 5G deep borehole has been drilled.

At the first site, drilling equipment will be tested in an artificial ice well. At the second location, the tests will be conducted in conditions of a deep borehole in the glacier.

The possibility of constructing a complex with two ice wells, similar to the design of the Jilin University Polar Research Center, is being investigated on the “Sablino” testing ground. The complex will be housed in a building measuring 18 m long, 15 m width, and

Fig. 1. Complex with two ice wells: *a* — main hall; *b* — climate equipment (*1* — drilling mast; *2* — tested drilling tools; *3* — hydraulic manipulator; *4* — collar of ice well; *5* — refrigeration and compressor equipment; *6* — hydro-heat-insulated pit; *7* — climate chambers; *8* — evaporators; *9* — ice well)

Рис. 1. Комплекс с двумя ледовыми скважинами: *а* — основной зал; *б* — климатическое оборудование (*1* — буровая мачта; *2* — испытываемые буровые снаряды; *3* — гидравлический манипулятор; *4* — устья ледяных скважин; *5* — холодильно-компрессорное оборудование; *6* — гидро-теплоизолированный котлован; *7* — климатические камеры; *8* — испарители; *9* — ледяная скважина)

13 m tall (Fig. 1). Below the building’s zero level a 6 m deep hydro- and heat-insulated pit will be located. The building will include engineering and technical systems such as:

– power supply: power consumption up to 250 kW;

– water supply: centralized cold and hot water supply, with a flow rate of 5 to 10 m^3/h, through individual treatment facilities;

– ventilation system: supply and exhaust ventilation system, with heating of the air supplied in cold seasons;

– heating system: central heating system with a possibility to install heaters in lifting gates, entrance vestibules and mechanical workshops.

The complex is to be equipped with the following main equipment: ice wells, mounted in climate chambers installed in a hydro- and heat-insulated pit; refrigeration and compressor equipment; a drilling rig on a mobile platform; a hydraulic manipulator on a movable platform; process fluid tanks, and pumping equipment.

One climate chamber is designed to be able to maintain a constant operating temperature throughout the entire volume in the range from –2 °C to –70 °C, the second – with the ability to change the temperature in gradient in the heat-insulated sections of the chamber, allowing temperature control from +5 °C to –70 °C.

The chambers will be equipped with service hatches, ladders and local lighting for servicing the climate control equipment. The cooling system is individual for each chamber and built by using ozone-safe freons R404A and R23. Innovative technology for regulating the performance of refrigeration-compressor equipment enables smooth temperature regulation over a wide range.

Each climate chamber has its own autonomous power supply and control system, complete with an individual touch panel. The software allows saving test programs on a PC and uploading them to a controller, as well as using convenient functions for displaying information on the screen and printing. Remote access to the climate chambers is available, enabling real-time control of their settings from any user device.

The climate chambers' design and technical specifications were developed in collaboration with specialists at NPF REOM LLC in St. Petersburg. The drilling rig will be mounted on a platform with the possibility of longitudinal and transverse movement, making efficient use of the entire cross-sectional area of the ice well. The design of the drilling rig allows the use of two types of technologies: with cable-suspended drilling, and rotary drilling, depending on the research objectives.

The ice well complex fulfills the following tasks:

– study of ice destruction processes using mechanical and thermal drilling methods;

– conducting tests of technologies and technical devices for drilling glaciers and subglacial bedrock, as well as unsealing subglacial reservoirs and sampling water and sediments;

– testing geophysical equipment for ice boreholes;

– approbation of control systems for ice drilling;

– training of specialists for scientific research in Antarctica.

It should be noted that the establishment of a test center will address scientific and practical issues not only in Antarctica, but also in the Arctic region, allowing one to:

– investigate the processes related to permafrost thawing to ensure the stability of civil and industrial infrastructure foundations [25, 26];

– test permafrost drilling equipment to obtain undisturbed samples;

– conduct tests on mobile drilling equipment to sample core material from Arctic glaciers, icebergs and shelf ice to assess the safety of Northern Sea Route navigation and drilling platform operation [27, 28].

At the drilling complex of 5G borehole at Vostok station, modernization is planned, which involves replacing the main and auxiliary equipment.

The drilling complex was constructed during the 27th Soviet Antarctic Expedition on May 29, 1983 to drill borehole 4G, and later relocated to the site of borehole 5G. Since the start of its operation, the complex has undergone numerous modifications and now includes the following main components (Fig. 2):

– a drilling building, which consists of two mobile wagon-type units, installed on sleds and covered with heat-protective panels;

– a welded 12 m high drilling mast made of metal pipes, equipped with a system of blocks for tripping and drilling operations on a carrying cable;

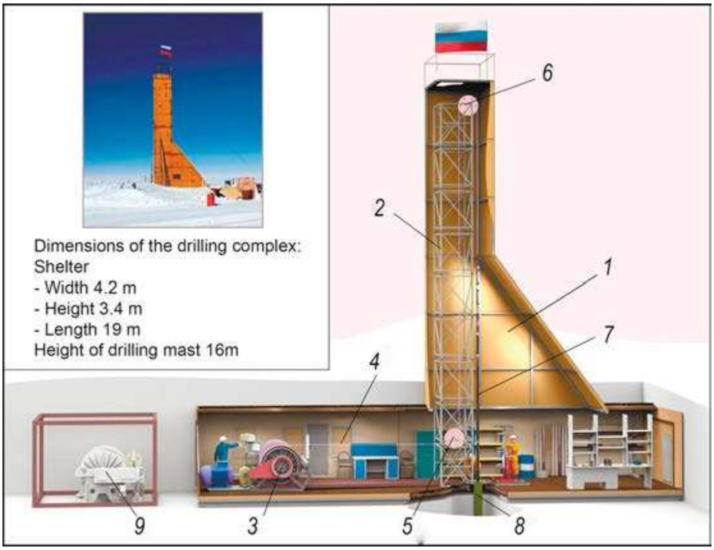

Fig. 2. Drilling complex of well 5G: *1* — drilling building; *2* — drilling mast; *3* — drilling winch with control panel; 4 — carrying cable; 5 — deflection roller; 6 — crown block roller; 7 — electromechanical drill KEMS-135; 8 — casing column; 9 — rewinder

Рис. 2. Буровой комплекс скважины 5Г: *1* — буровое здание; *2* — буровая мачта; *3* — буровая лебедка с пультом управления; *4* — грузонесущий кабель; *5* — отклоняющий ролик; *6* — кронблочный ролик; *7* — электромеханический колонковый снаряд КЭМС-135; *8* — обсадная колонна; *9* — перемоточное устройство

– a drilling winch with an 18,2 kW DC electric drive. On the winch drum a seven-core armored carrying cable is wound up, 4,100 m long and 17.5 mm in diameter. For equable laying of the cable on the winch drum, a cable layer on an endless screw is used with the possibility of manual adjustment;

– power supply system for working and auxiliary equipment;

– a control and monitoring system for tripping and drilling operations, including the main control panel (manufactured by Leningrad Mining Institute, 1984) and a special data collection module MSD-A (manufactured by AMT CJSC, St. Petersburg, Russia).

The borehole 5G consists of five branches (Fig. 3). Branch 5G-5 intersects several of the glacier layers studied, which differ in their structural and physical-mechanical characteristics:

– snow-firn layer (up to 100 m), represented by permeable layers of compacted snow turning into ice [29];

– meteoric ice (100 – 3539 m), the crystal size of which increases with depth [9]. This layer includes brittle ice (250 – 600 m), consisting of fragmented crystals [30], and ancient ice (3310 – 3539 m), the structure of which has been disrupted by ice flow anomalies;

– accreted (lake) ice with mineral inclusions (3539 – 3769.3 m) [31].The borehole is filled with a non-freezing drilling fluid – a mixture of Jet-1 aviation kerosene and F-141b freon, which has a density that compensates for the glacier pressure. The temperature and pressure of the drilling fluid change with the borehole depth [32]. According to caliper measurements of branch 5G-5, performed during the 69th Russian Antarctic Expedition (RAE), it was found that equipment with a diameter of 135 mm can be tested along the

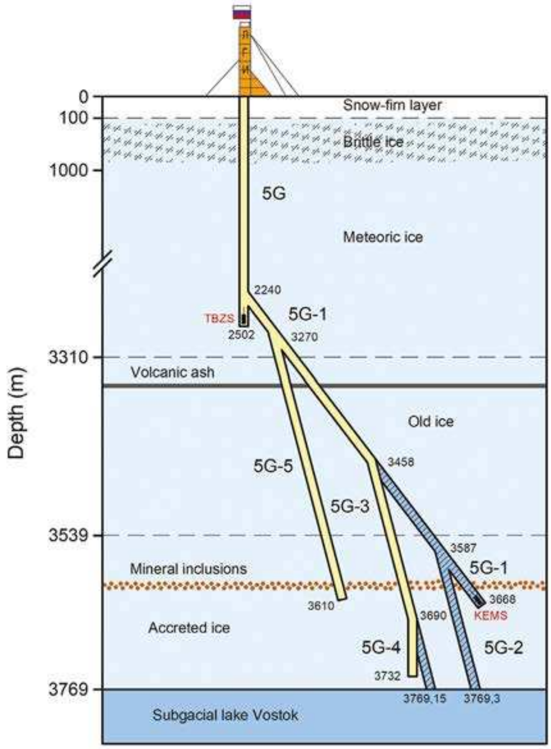

Fig. 3. Schematic representation of 5G multibranch borehole configuration. The shaded branches are filled with frozen lake Vostok water. The names of lost drills are shown by red inscriptions (adapted from [33])

Рис. 3. Схематическое представление конструкции многоствольной скважины 5Г. Заштрихованные участки заполнены замерзшей водой из озера Восток. Красные надписи обозначают наименования снарядов, оставленных в скважине (актуализировано из [33])

entire depth of the branch. Access to the other branches can only be gained by using a drilling tool with a controlled deviation in zenith and azimuth angles.

The deep drilling project at the 5G-5 branch was completed during the 69th RAE season, reaching a depth of 3610 m. Consequently, the borehole can be used to test technologies and technical devices for drilling glaciers in unique thermobaric conditions. However, the drilling complex main and auxiliary equipment is significantly worn out, necessitating modernization. This is the goal of the project “Comprehensive studies of subglacial Lake Vostok and paleoclimate around the area of Russian Antarctic station Vostok”.

The modernization includes the replacement of:

– drilling winch and control system;
– carrying cable;
– deflection and crown block rollers of the drilling mast;
– rewinding the cable device;
– auxiliary equipment;

– inspection and repair of electrical supply systems.

The updated drilling winch with a capacity of 4 000m for a 17.5 mm carrying cable differs from the installed one in: a greater traction force (at least 80 kN); an improved electromechanical drive with a frequency control (40 kW power); automated control and monitoring systems for tripping operations and cable laying. For transpooling the carrying cable, a productive rewinder (winding speed 2 km/h) with a maximum pull force of 20 kN is to be used. The design and technical specifications of the winch and rewinder were provided by experts from of the Oktyabrsky Plant of Logging Equipment "VNIIGIS" LLC.

The new carrying cable for downhole equipment is KG (4 × 0.75 + 3 × 2 × 0.20) – 90 – 17, with a significant breaking force (at least 90 kN). It consists of four cores with a cross-section of 0.75 mm^2 and three twisted pairs with a cross-section of 0.20 mm^2. The carrying element of the cable is an UHMPE (ultra-high modulus polyethylene) thread, which is more resistant to mechanical impacts at low temperatures and in aggressive environments, has a higher strength and a lower specific gravity than cables wrapped in steel. The design and technical parameters of the carrying cable were provided by specialists from SKT Group LLC.

The proposed modernization will allow testing in the borehole:

– mechanical and thermal drills on a load-carrying cable at any depth interval, including equipment with a directional drilling control system;

– mechanical and thermal borehole reamers;

– technical devices for unsealing subglacial lakes from a borehole filled with a non-freezing fluid;

– drilling fluids;

– geophysical equipment for ice boreholes exploration;

– equipment for determining the physical and mechanical properties of ice;

– equipment for drilling new boreholes;

– delivery modules for research equipment of subglacial reservoirs;

– equipment for cleaning boreholes from mechanical impurities;

– equipment for eliminating accidents in boreholes;

– telemetry systems, sensors, etc.

3. Conclusions

Drilling operations on Antarctic glaciers necessitate extensive research and development aimed at understanding the processes of interaction between a drill and a glacier and testing the technical devices developed for drilling glaciers. For this purpose, teams of researchers from different countries create experimental stands with artificial ice. The primary distinction between these designs is the method used to model the glacier. Each method has advantages and disadvantages, but they all share one limitation: it is impossible to recreate the structure of atmospheric ice and thermobaric conditions in Antarctic boreholes.

The authors propose the conceptual project of a center for testing technologies and technical devices for glacier drilling. The Center will be located on two sites: on the educational and scientific testing ground "Sablino" of Saint-Petersburg Mining University in the Leningrad Region (Russia) and at the drilling complex 5G borehole at Vostok station in Antarctica. The realization of this project will allow conducting experimental research and testing, using both shallow artificial ice wells and deep borehole 5G in the Antarctic glacier.

The first stage of testing drilling equipment and technologies will be validating the proposed solutions on experimental stands that simulate future operating conditions under certain assumptions. The location of the stands at "Sablino" will allow conducting research all-year-round, as well as rapid adjustments to the designs of the devices and methods developed for conducting experiments.

In the second stage of the tests, the drilling equipment and technologies will be tested in a deep 5G borehole. This will enable testing the equipment's operability under thermobaric conditions and the specific ice structure of the Antarctic glacier.

The proposed approach to the realization of the project "A Center for testing technologies and technical devices for glacier drilling" will enable the most efficient and safe implementation of drilling operations in Antarctica.

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Концептуальный проект центра испытаний технологий и технических средств бурения ледников

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Расширенный реферат

Реализация буровых проектов в Антарктиде требует проведения комплексных научно-исследовательских работ, направленных на изучение процессов, протекающих при бурении ледников. Важную роль в данных исследованиях играют экспериментальные стенды с искусственным ледовым массивом.

В результате проведенного обзора было установлено, что в большинстве случаев экспериментальные стенды и сооружения имеют ограничения в габаритах и функциональных возможностях и не могут воспроизвести реальных условий эксплуатации (низкие температуры, высокое давление, физико-механические свойства атмосферного льда) разрабатываемого уникального оборудования. Начало эксплуатации оборудования без проведения испытаний в реальных скважинных условиях повышает риски возникновения осложнений и аварий в процессе работ, вызванных недостатками в конструкции оборудования. Данные недостатки могут быть обнаружены только при проведении буровых работ непосредственно в Антарктиде, что может отрицательно сказаться на сроках реализации научно-исследовательских проектов.

Решением обозначенной проблемы является выстраивание новой последовательности испытаний работоспособности скважинного оборудования для условий Антарктиды:

1) Апробация концептуальных решений для технологий и технических средств в рамках малых экспериментальных стендов с использованием ледяных блоков.

2) Испытание полноразмерных рабочих прототипов в условиях ледяных скважин, на базе учебно-научного полигона «Саблино» Санкт-Петербургского горного университета (Ленинградская область, Россия). Конструкция скважин и их технологические возможности разработаны с учетом достоинств и недостатков предшествующих проектов. Климатические камеры, в которых расположены скважины, рассчитаны на регулирование температур в скважине в диапазоне от –2 °C до –70 °C. Предложенное в работе экспериментальное сооружение позволит проводить широкий комплекс испытаний оборудования для полярных условий.

3) Предварительные испытания оборудования в скважинных условиях на базе модернизированного бурового комплекса им. Б.Б. Кудряшова на станции Восток, Антарктида. Испытание разработанного оборудования в условиях скважины 5Г позволит оценить работу устройств в реальных условиях перед их внедрением в рабочую эксплуатацию.

Данный комплекс средств по испытанию оборудования будет способствовать решению множества научных и практических задач, связанных не только с исследованиями в Антарктиде, но и проектами, реализуемыми в арктических регионах.

Ключевые слова: Антарктида, бурение ледников, буровые технологии и оборудование, ледяные скважины, скважина 5Г, экспериментальный стенд

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Dedicated to Nikolay Vasiliev —
a brilliant person who unsealed Lake Vostok

The uppermost water horizon of subglacial Lake Vostok could be microbial DNA-free, as shown by Oxford Nanopore sequencing technology

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Abstract. The research aimed to search for microbial life in subglacial Lake Vostok. This was done by examining the uppermost layer of water that entered the borehole and froze after the lake was accessed. The sample was collected from a depth of 3721 m and consisted of water-frozen re-cored ice. It underwent thorough decontamination and was melted successively in cold and cleanroom facilities. Genomic DNA was then isolated and amplified using v3-v4 16S rRNA bacterial gene region-specific degenerate primers. The Sanger method and high-throughput Oxford Nanopore sequencing were used to sequence the amplicons generated. The Sanger DNA analysis revealed 16 bacterial phylotypes, and only one of them, 3721v34-24, met all the contamination criteria. This phylotype was the dominant one, making up 41.4 % of the clones and consisting of three allelic variants. However, it remained unclassified and showed 87.7 % similarity to the closest GenBank entry, *Mucilaginibacter daejeonensis* NR_041505 of *Bacteroidota* (family *Sphingobacteriaceae*). The Oxford Nanopore technology generated 21067 reads for the 3721m sample and 3780 for the control one. Among these, 7203 (34 %) and 1988 (53 %) reads for the ice sample and the control one were classified with 93 % accuracy. For the 3721m sample, 21 bacterial phylotypes were identified with an abundance above 0.5 %. Fifteen were identical to the Sanger findings and identified as contaminants. The remaining six were different, either found in the control Nanopore trial or were apparent contaminants. The discovery of phylotype 3721v34-24 in the lake water by Sanger sequencing was unexpected. However, it was later detected in the 3721m sample and control experiments using nanopore sequencing, indicating it was also a contaminant. Thus, the research suggests that the topmost water layer in Lake Vostok may not contain any microbial DNA. Additional frozen-water samples are currently being analyzed to investigate the issue further.

Keywords: Antarctica, contamination, deep ice coring, frozen lake water, lake unsealing, microbial communities, nanopore sequencing, subglacial Lake Vostok

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Introduction

Lake Vostok is a giant (270 × 70 km, 15800 km^2 area), deep (up to 1.3 km) freshwater liquid body buried in a graben beneath a 4-km thick East Antarctic Ice Sheet with the temperature near the ice melting point (around –2.5 °C) under 400 bar pressure. It is exceptionally oligotrophic and poor in primary chemical ions (compared with the surface snow), under high dissolved oxygen tension (in the range of 320–1300 mg/L), with no light, and sealed from the surface biota about 15 Ma ago [1, 2]. Lake Vostok has a breathtaking history of discovery [3] — starting from assumptions in the 1960s and finishing with complete certainty [4].

Regarding microbiological studies, only our team has worked on 'borehole-frozen' lake water following several cases of lake unsealing. In addition, we are the first to use high-throughput sequencing technologies to recover possible microbial communities in Lake Vostok. Nevertheless, cell concentrations and Sanger finds were reported a decade or more ago. However, regrettably, these studies on natural accretion ice did not adequately address the issue of "foreign" contamination, which is crucial when analyzing such pristine low-biomass samples [5, 6]. At the same time, there are papers by the S. Rogers team [7–9] that reported data (cell counts and DNA study) that appear to be misleading because of contamination issues linked to the limitation of optical microscopy (number of fields to scan) and inappropriate methods implemented (e. g., for DNA isolation, MinElute Virus Spin Kits (QIAGEN, Valencia, CA) were used, which, however, cannot break down all the bacteria). This applies to a recent paper [10], which used an unclear ice sample source and flawed methodology (again, for DNA isolation, MinElute Virus Spin Kits (QIAGEN, Valencia, CA) were employed). Anyway, it would be incorrect to compare studies performed on natural accretion lake ice (due to the features of ice formation—about 1cm per year, and consequent matter fractionation). Those of "borehole-frozen" lake water speedily flow into a borehole from the upper-most water horizon (as with our sample 3721).

Water-frozen (in a borehole) samples have been shown to feature very dilute cell concentrations — from 167 to 38 cells per ml. So far, the 16S rRNA gene Sanger sequencing has yielded three bacterial phylotypes, all meeting numerous contamination criteria. Two phylotypes were reported earlier [11] — the still unidentified and phylogenetically unclassified phylotype w123-10, likely belonging to *Parcubacteria Candidatus Adlerbacteria*, and 3429v3-4, which shows below-genus level (93.5 %) similarity with *Herminiimonas glaciei* of *Oxalobacteraceae* (*Betaproteobacteria*). The third find (phylotype 3698v46-27) has proved to be conspecific with several species of *Marinilactobacillus* of *Carnobacteriaceae* (*Bacillota*), featuring very similar 16S rRNA genes. Among them is *M. piezotolerans*, isolated from a 4.15 m deep sub-seafloor sediment core collected at 4790.7 m deep Nankai Trough [12].

Our purpose was to search for microbial life in the subglacial Antarctic Lake Vostok by analyzing the uppermost layer of the water that entered the borehole following the lake unsealing at a depth of 3769 m from the surface [13]. The current study aims to re-evaluate microbial finds in a 3721 m borehole-frozen lake water sample obtained with Sanger sequencing applying the high throughput Oxford Nanopore sequencing technology. This technology is now regarded as an attractive tool for studying microbial communities (metataxonomics), even in field conditions [14 and references within], including Antarctica [15].

Materials and methods

The water sample studied was 3721 m deep borehole-frozen re-cored ice (Fig. 1). It was thoroughly decontaminated and melted in cold and cleanroom facilities [16], and the genomic DNA extracted [16] was amplified with 16S rRNA bacterial gene v3-v4 region-specific degenerate primers Merk-341F and Merk-805R [17] for 31+26 cycles using FastStart polymerase (Roche, USA) at 53 °C annealing temperature. The amplicons generated were sequenced by the Sanger technique (Beagle, Saint-Petersburg, Russia). The negative PCR was used as a control.

It is worth noting that the ice segment was rather clear/transparent but had a faint smell of kerosene.

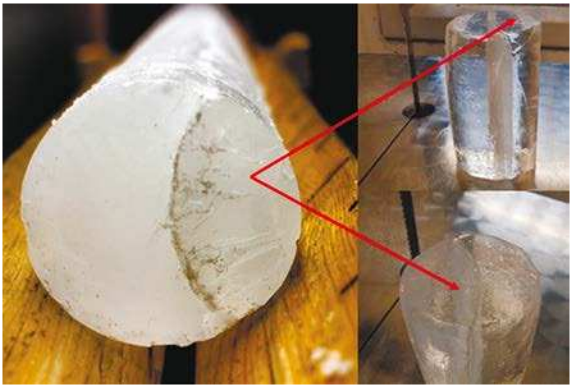

Fig. 1. 5G-3N borehole frozen lake water sample (3720.32–3720.75) as a moon-shape segment. The arrows point to the same ice segment (frozen water)

Рис. 1. Керн льда замерзшей воды (3720,32–3720,75 м) из скважины 5Г-3Н. Видна «полулунная» структура в результате отклонения скважины при повторном бурении. Стрелки указывают на сегмент льда замершей воды

The MinION device equipped with Flow Cell R9.4 was used for nanopore sequencing. The sequencing run was operated by MinKNOW software (Oxford Nanopore, UK). The sequencing was performed with libraries prepared for 16S rRNA gene v3-v4 region amplicons (about 485 bp). The corresponding kits were implemented — to repair amplicon ends (NEBNext Ultra II End repair/dA-tailing Module reagents E7546), ligate barcodes (Native Barcoding Expansion 1-12 EXP-NBD104), and then sequencing adapters (Adapter Mix II AMII). All these and further steps (like loading the libraries in a flow cell, etc.) followed instructions provided by Oxford Nanopore Technologies. The sequencing was run for 72 hours. The Fast5 files obtained were basecalled under the "high accuracy" option with trimming barcodes using MinKNOW software. The resulting FastQ files were processed with EPI2ME software (Oxford Nanopore, UK). The Min similarity score was settled at 88 % (given the PCR primers comprise about 9 % of the total amplicon length). Further work was performed on classified reads using GenBank entries.

Results and discussion

Sanger sequencing

The DNA analyses revealed 16 different bacterial phylotypes with a low gene library coverage of 55.2 %, indicating significant biodiversity (Table 1). Of these, only one phylotype, 3721v34-24, met all the contamination criteria [16], including the Contaminant Library, which consists of 329 16S rRNA gene phylotypes.

Phylotype 3721v34-24 was the dominant one, making up 41.4 % of the clones and consisting of three allelic variants. It was taxonomically unclassified — showed 87.7 % similarity (below the family level) with *Mucilaginibacter daejeonensis* NR_041505 of *Bacteroidota* (family *Sphingobacteriaceae*). Some DNA clones with identical sequences were found in GenBank, such as uncultured unidentified *Bacteroidetes* DQ316809 from uranium-contaminated sediment in the USA. Additionally, more sediment clones were found with only a single mismatch, for example, KC431957 and DQ404664, both unidentified. As a result, the new lake-water phylotype was identified as an unclassified "sediment-loving" bacterium and was assigned to the new *Bacteroidota* phylum for the lake inhabitants. Therefore, the newly discovered bacterial phylotype [18] and the three previously recorded phylotypes may represent indigenous cell populations in Lake Vostok.

Table 1

3721 m sample vs. Control amplicons in Sanger vs. Nanopore sequencing

Таблица 1

Образец льда 3721 м в сравнении с контролем нанопорового секвенирования и результатом секвенирования по Сэнджеру

No.	Sanger 3721 m	NANOPORE Control (reads/%)	Taxa classified (closest by DNA similarity)	NANOPORE 3721m (reads/%)	Conclusion Status
1	Cont_+2_3721v34-63 (-12)	15 0.85	*Hyphomicrobium denitrificans*	844 12.70	Cont
2	Cont_+2_3721v34-60 (-19)	136 7.69	*Sphingobium yanoikuyae*	839 12.62	Cont
3	Cont_3721v34-30	172 9.73	*Sphingomonas echinoides*	822 12.37	Cont
4	Cont_3721v34-86	235 13.29	*Cloacibacterium normanense*	784 11.79	Cont
5	Cont_3721v34-105	26 1.47	*Novosphingobium gossypii*	303 4.56	Cont
6	Cont_3721v34-111	1 read	*Corynebacterium tuberculostearicum*	300 4.51	Cont
7	Cont_3721v34-122	ND	*Psychrobacter cibarius* Fermented seafood	246 3.70	Cont
8	Cont_3721v34-29	13 0.74	*Acinetobacter junii*	141 2.12	Cont

End of Table 1

Окончание табл. 1

No.	Sanger 3721 m	NANOPORE Control (reads/%)	Taxa classified (closest by DNA similarity)	NANOPORE 3721m (reads/%)	Conclusion Status
9	95.5 %* Cont-drill_3721v34-17	8 reads	*Novosphingobium Naphthalenivorans* (Genus level)	120 1.81	Cont
10	Cont_3721v34-117	24 1.36	*Cutibacterium acnes*	99 1.49	Cont
11	Cont_3721v34-1	50 2.83	*Diaphorobacter polyhydroxybutyrativorans (1546149)*	94 1.41	Cont
12	Cont_3721v34-89	12 0.68	*Phenylobacterium koreense*	88 1.32	Cont
13	Cont_3721v34-114	1 read	*Methylobacterium jeotgali*	87 1.31	Cont
14	ND	6 reads	*Sphingobium scionense*	79 1.19	Cont
15	Cont_excSK24	ND	*Staphylococcus warneri*	68 1.02	Cont
16	ND	ND	*Psychrobacter immobilis* Human clinical, infection	66 0.99	Cont
17	Cont_w22-59 Cont_+16_w23-22	17 0.96	*Rothia amarae*	54 0.81	Cont
18	ND	8 reads	*Cloacibacterium rupense*	46 0.69	Cont
19	ND	23 1.30	*Acinetobacter tjernbergiae*	43 0.65	Cont
20	ND	11 0.62	*Sphingomonas kyungheensis*	40 0.60	Cont
21	ND	ND	*Veillonella rogosae* Human oral microbiome	37 0.56	Cont
	87.7 %* +12_3721v34-24	ND	*Mucilaginibacter daejeonensis* Rice straw	3 (88.8%*) 0.04	Cont
	85.6 %* +12_3721v34-24	5 reads (88.8%*)	*Mucilaginibacter jinjuensis* Rotten wood	14 (89.4%*) 0.2	Cont

Note. Blastn data (classified reads above 0.5% abundance). Nanopore Control — control trial (sham DNA isolation/negative PCR, etc); Cont — contaminant (‘Cont_’ in the ‘Sanger’ column means the phylotype is in our Contaminant Library); ND — not detected; * — similarity score (%); if there is no indication, the percentage is 98 % or more. Despite the very low similarity score, the Epi2Me Oxford Nanopore software classified these reads as *Mucilaginibacter ssp.*

Примечания. Ампликоны классифицированы с использованием программы NCBI Blastn. Данные приведены для встречаемости таксонов 0.5 % и выше. В предпоследней колонке приведен окончательный статус таксонов. Нанопоровый контроль — «холостая» экстракция ДНК/негативная ПЦР; Cont — контаминант (‘Cont_’ в первой колонке “Sanger 3721 m” означает, что данный филотип присутствует в нашей библиотеке контаминантов); ND — не обнаружено; * — сходство (%); если нет указаний, то значение 98 % и выше; несмотря на очень низкое сходство (ниже уровня семейства); программа для классификации (Epi2Me Oxford Nanopore) с использованием данных в GenBank, классифицировала нанопоровые прочтения как *Mucilaginibacter ssp*.

Nanopore sequencing

To clarify the latest finding, phylotype 3721v34-24 from the ice-frozen water core 3721 m was re-tested using high-throughput nanopore sequencing with the same amplicon for the v3-v4 region of the 16S rRNA gene. This study included nanopore controls (sham DNA isolation/negative PCR and 'carry-over' contamination during nanopore library preparation) for the first time (see Fig. 2).

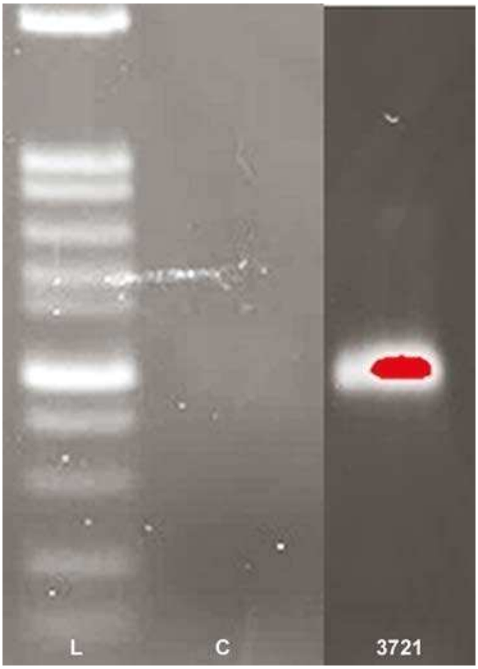

Fig. 2. True signal vs. Control in Nanopore sequencing.

1.7 % composite agarose gel stained with Ethidium Bromide. L — 100 bp ladder (bright band below — 500 bp in size); C — sham DNA isolation followed by negative PCR (Ambient RNA-free water); 3721 m sample amplicon. The recording was performed with ChemiDoc (Thermo Fisher Scientific, USA), which allowed us to highlight the band intensity (in red — overexposure) in trying to detect a signal in the control lane

Рис. 2. «Истинный» сигнал ампликона образца 3721 м в сравнении с сигналом контроля (фактически его отсутствием) в нанопоровом секвенировании.

Использовали 1,7 % композитный агарозный гель с окрашиванием этидием бромидом. L — 100 п. о. (пар оснований) маркер молекулярный весов (яркий фрагмент снизу — размер 500 п. о.); C — контрольный ампликон («холостая» экстракция ДНК в ПЦР); ампликон образца 3721 м. Детекция сигнала выполнена с использованием прибора ChemiDoc (Thermo Fisher Scientific, USA) с переэкспозицией сигнала (красный цвет) с целью выявить какой-либо сигнал в контроле

After performing "high accuracy — trim barcodes" basecalling, we obtained 21067 reads for the 3721 m sample and 3780 for the control one (no visible amplicon). Of these, 7203 reads (34 %) for the ice sample and 1988 reads (53 %) for the control sample were classified with 93 % accuracy. For the 3721 m sample, we identified 21 bacterial phylotypes above 0.5 % abundance (Table 1). Among these, 15 phylotypes matched Sanger's findings, while the remaining six phylotypes were unique to nanopore sequencing and were found in the control Nanopore trial, indicating contamination. One phylotype unique to nanopore sequencing, *Psychrobacter immobilis*, was also considered a contaminant due to its known origin from a human clinical source [19]. The same was true with *Veillonella rogosae* [20]. Therefore, all the 21 phylotypes discovered in nanopore sequencing above 0.5 % abundance were identified as contaminants (identical to either Sanger contaminants or control findings). In terms of accuracy, nanopore sequencing (> 97.69 similarity) was found to be superior compared to Sanger readings (100 % accuracy) for our amplicons (Fig. 3).

Phylotype 3721v34-24 was identified in Sanger sequencing with 12 clones, which may indicate a population of living cells. This phylotype was detected in the 3721 m sample with three nanopore reads (0.04 % abundance) and approximately 20 reads for all the three closely related species. Additionally, it was found in the control sample studied with five

1: +12_3721v34-24_87.68-Mucilaginibacter_daejeonensis	100.00	99.04	99.52	99.28	99.28
2: da6fc4b1-3b6a-4293-98ec-d1545f8f087b_CONTROL	99.04	100.00	98.64	97.69	97.95
3: r-c_b89629ae-7402-420b-8fee-de2c8de0573a_CONTROL	99.52	98.64	100.00	98.15	98.19
4: f9cd4690-d61c-476f-a134-9ce78793252a_NANO-LV3721	99.28	97.69	98.15	100.00	97.91
5: 56d03a9b-24fa-42a9-8dcf-b62f580d4599_NANO-LV3721	99.28	97.95	98.19	97.91	100.00

Fig. 3. Distance matrix of Nanopore reads (sequences) related to Sanger clone 3721v34-24.

+12_3721v34-24 — Sanger phylotype sequence from 3721 m sample; CONTROL — Nanopore reads from the control; NANO-LV3721 — Nanopore reads from 3721 m sample; r-c — reverse complement strand

Рис. 3. Матрица дистанций (%) последовательностей нанопоровых прочтений в сравнении с клоном по Сэнждеру 3721v34-24.

+12_3721v34-24 — филотип по Сэнждеру образца 3721 м; CONTROL — нанопоровые прочтения контрольного апликона; NANO-LV3721 — нанопоровые прочтения ампликона образца 3721 м; r-c — «обратно-комплементарная» нить ДНК

reads, although this species was not identical but only closely related to M*ucilaginibacter jinjuensis.* Even when using the “super-accurate” option for basecalling, the 3721 m sample yielded only five reads.

In contrast, when seven additional nanopore controls from other sequencing experiments were examined for *Mucilaginibacter spp.*, these species were represented by significantly higher read numbers, with 23 reads for *Mucilaginibacter daejeonensis* and 424 reads for the closely related *Mucilaginibacter jinjuensis* (Table 2). This suggests that they may be contaminants.

Table 2

***Mucilaginibacter spp.* — related phylotypes in Sanger and Nanopore sequencing, including control trials**

Таблица 2

Филотипы, сходные с *Mucilaginibacter spp.*, в секвенировании по Сэджеру и нанопоровом секвенировании, включая нанопоровый контроль

Controls Max reads	Taxa	LV3721 Nanopore reads	LV3721 Sanger finds
23	*Mucilaginibacter daejeonensis**	3 (88–91 % similarity)	87.7 % + 12_3721v34-24
424	*Mucilaginibacter jinjuensis**	14 (88–91 % similarity)	85.6 % + 12_3721v34-24

*— Despite a very low similarity score (below family level), the Epi2Me Oxford Nanopore software classified these reads as *Mucilaginibacter ssp.*

* — Несмотря на очень низкое сходство (ниже уровня семейства), программа для классификации (Epi2Me Oxford Nanopore) с использованием данных GenBank классифицировала нанопоровые прочтения как *Mucilaginibacter ssp.*

Phylotype 3721v34-24, linked to *Mucilaginibacter daejeonensis*, was discovered in Sanger sequencing [18]. However, it cannot represent findings from Lake Vostok. The lake’s uppermost water layers may be free of microbial DNA [21]. Additional frozen water samples, 16S rRNA gene regions, and other Sanger findings are currently being processed through nanopore sequencing to resolve this issue.

The assumption that the Lake Vostok water body, especially its uppermost layers, could be free of microbes is not as unusual as many people might think. The belief that microbes inhabit the Earth in all possible places may not apply to exceptional cases such as Lake Vostok. The only factor that can prevent microbes from living there is the extremely high oxygen levels, which have been calculated but not yet measured. If the estimated values of around 800 mg/L [22] are accurate, then no life as we know it, including environmental DNA, should be expected to be found there. The lake could be considered a "cold oxygen reactor" (quoting Chris McKay). Despite life's ability to adapt quickly to environmental changes (e.g., the lake's ice cover), it may not withstand them and could become extinct following the Gaian bottleneck hypothesis [23].

Conclusions

Interpreting the findings carefully when analyzing ice/snow samples for microbial content with very low biomass is essential. The high throughput Oxford Nanopore sequencing technology allows one to more precisely identify previously discovered phylotypes. Thus, our research has revealed that phylotype 3721v34-24, previously recovered by the Sanger technique and thought to be related to organisms from the lake, has turned out to be a contaminant. The study also suggests that the status of three bacterial phylotypes identified earlier (100 % — *Marinilactobacillus sp*. of *Bacillota*, family *Carnobacteriaceae*) (< 86 % known taxa, *Parcubacteria* Candidatus *Adlerbacteria*), 3429v3-4 (93.5 % — *Herminiimonas* sp. of *Betaproteobacteria*, family *Oxalobacteraceae*) and thought to represent native cell populations in Lake Vostok [11, 12] is unclear and needs to be further investigated.

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Возможная стерильность верхнего водного горизонта подледникового антарктического озера Восток по данным нанопорового секвенирования

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Аннотация. Целью исследования был поиск микробной жизни в подледниковом антарктическом озере Восток путем изучения верхнего слоя воды, попавшей в скважину и замерзшей в ней после того, как озеро было вскрыто. Образец был получен из скважины на глубине 3721 м и состоял изо льда замерзшей озерной воды. Он был тщательно деконтаминирован, расплавлен в чистом помещении, и выделенная геномная ДНК была амплифицирована с использованием вырожденных праймеров, специфичных для области v3-v4 бактериальных генов 16S рРНК. Для секвенирования полученных ампликонов использовали метод Сэнджера и технологию высокопроизводительного секвенирования Oxford Nanopore. Анализ ДНК по методу Сэнджера выявил в общей сложности 16 бактериальных филотипов, из которых только один филотип, 3721v34-24, прошел все критерии на контаминацию. Этот филотип был доминирующим и включал 41,4 % клонов с тремя аллельными вариантами, но остался неклассифицированным, показав 87,7 % сходства с ближайшим таксоном в GenBank *Mucilaginibacter daejeonensis* NR_041505 из филума *Bacteroidota* (семейство *Sphingobacteriaceae*). Технология Oxford Nanopore секвенирования дала 21067 прочтений для образца 3721 м и 3780 прочтений для контроля. Из них 7203 (34 %) и 1988 (53 %) прочтений для образца льда и контроля, соответственно, были классифицированы с аккуратностью 93 %. Для образца 3721 м был идентифицирован 21 бактериальный филотип с численностью таксонов выше 0,5 %. Пятнадцать из них оказались общими с находками по Сэнгеру, а остальные шесть были уникальными, но присутствовали в нанопоровом контроле или оказались очевидными контаминантами. Пятнадцать филотипов, совпадающих с таковыми по Сэнджеру, были определены как контаминанты. Филотип по Сэнджеру 3721v34-24, который считался истинной находкой для воды озера, в нанопоровом секвенировании был обнаружен как в образце льда 3721 м, так и контроле, т. е. был также отнесен к контаминантам. Таким образом, самый верхний горизонт воды в озере Восток может не содержать микробной ДНК. Для прояснения этого вопроса проводятся дальнейшие исследования замерзших в скважине проб воды.

Ключевые слова: Антарктида, вскрытие озера, глубокое бурение во льду, загрязнение, замерзшая озерная вода, микробные сообщества, нанопоровое секвенирование, подледниковое озеро Восток

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