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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].

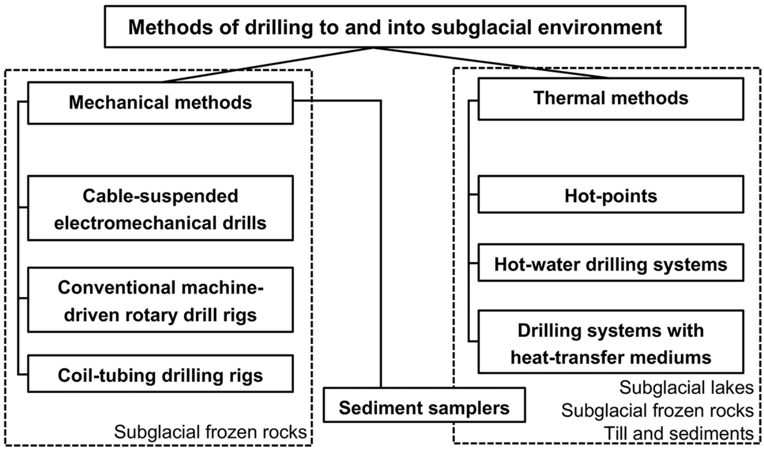

Fig. 1. Classification of drilling methods for accessing subglacial environments

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).

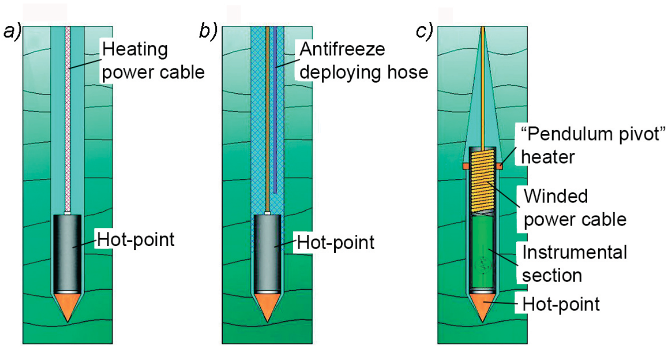

Fig. 2. Potential options of hot-points for drilling in cold ice: (*a*) with a heating cable; (*b*) by adding antifreeze; (*c*) freezing-in hot point with an on-board tethering cable (modified from [27])

Рис. 2. Возможные варианты термоигл для бурения в холодном льду: (*а*) 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

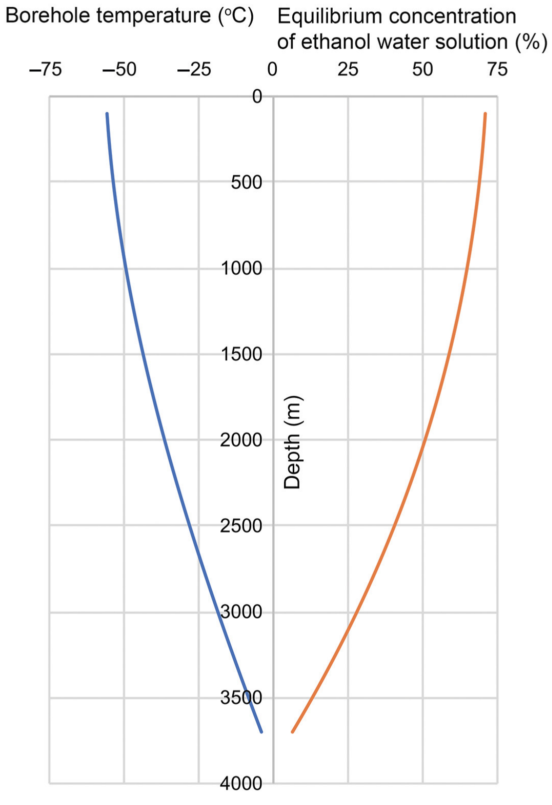

Fig. 3. Smoothed measured temperature profile in a 5G deep borehole at the Vostok Station [37] and equilibrium concentration of ethanol-water solution corresponding to in-depth temperature [38]

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]):

$$C_M = -1.619t - 6.2\cdot10^{-3}\cdot t^2, \quad (1)$$

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.

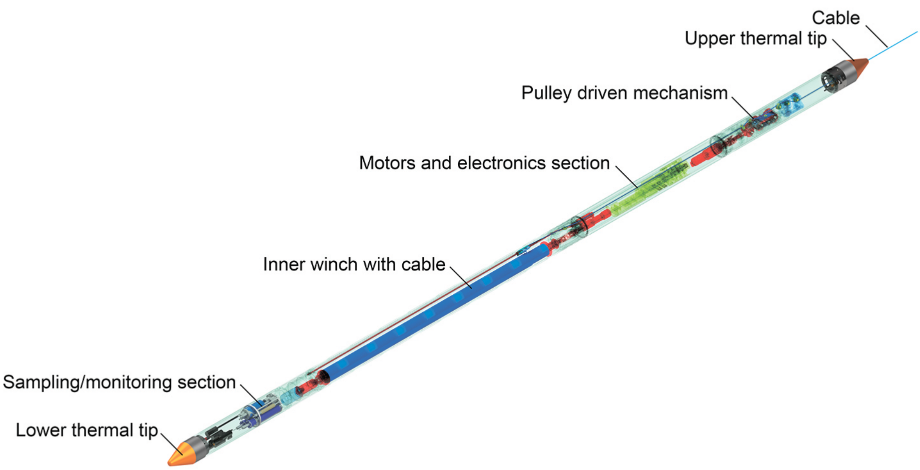

Fig. 4. 3D-model of the RECAS working prototype with a 500 m cable inside (the sonde body is shown transparent)

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:

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

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:

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

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.

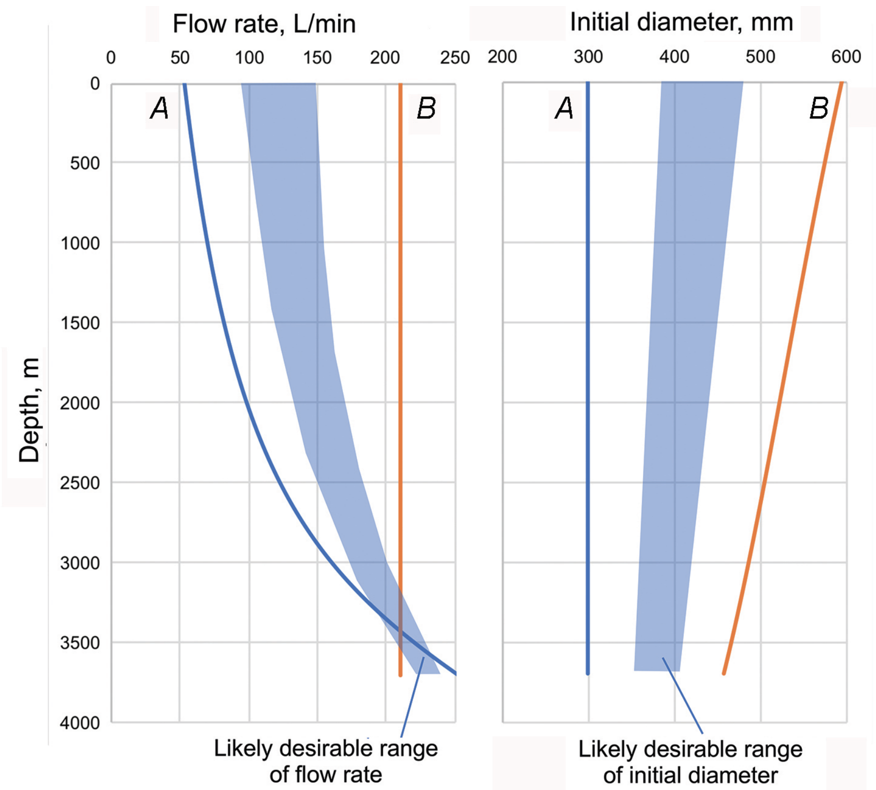

Fig. 5. Estimations of the required hot water flow rate and initial borehole diameter (explanations are given in the text)

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.

Competing interests. No conflict of interest involved.

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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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