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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 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.

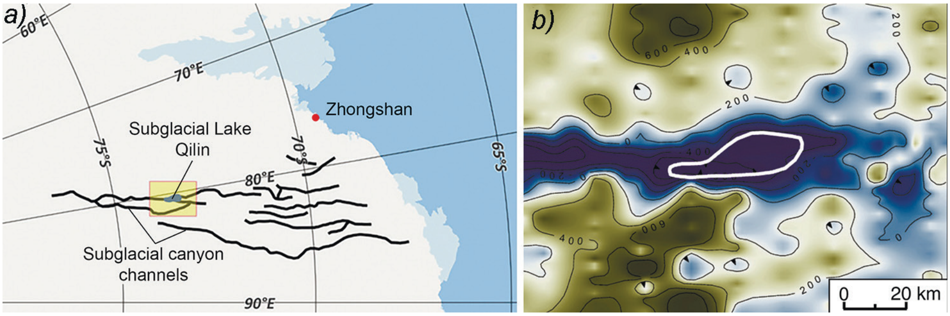

Fig. 1. Location of Subglacial Lake Qilin: (*a*) map of Princess Elizabeth Land, solid dark lines indicate location of canyon channels; (*b*) bedrock topography with estimated contour of the lake, area is marked as a yellow rectangle on the map leftward (modified from [16])

Рис. 1. Местоположение подледникового озера Цилинь: (*а*) 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

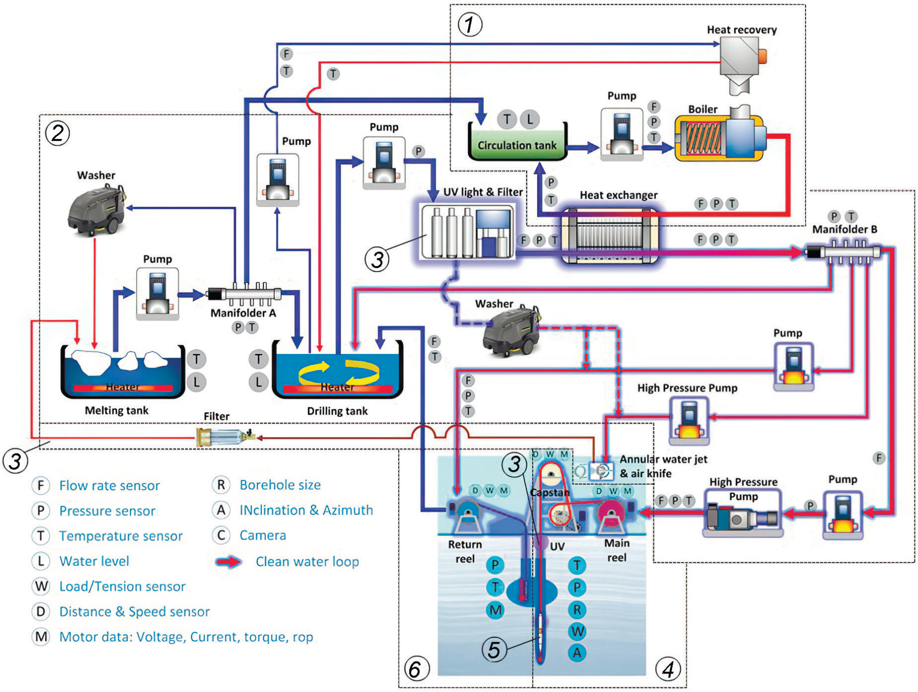

Fig. 2. Schematic diagram of the hot-water drilling system to access Subglacial Lake Qilin, East Antarctica: (*1*) primary heating system, (*2*) secondary heating system, (*3*) cleaning system, (*4*) hoisting system of the main hole, (*5*) downhole drill-nozzle, and (*6*) return water system

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.

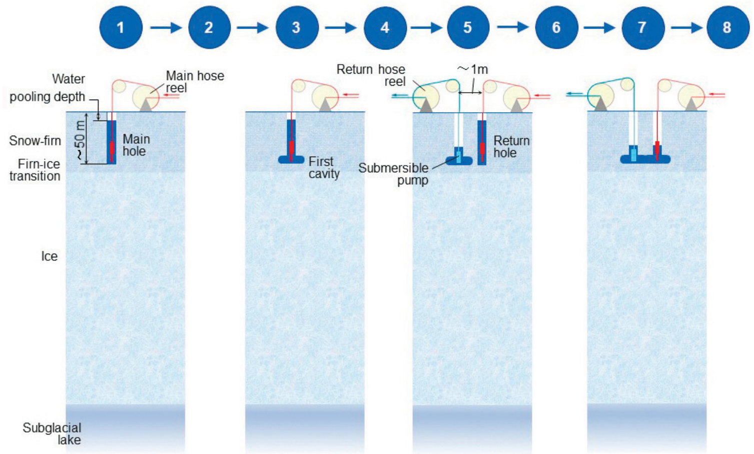

Fig. 3. Proposed sequence of drilling operations to the first cavity (adapted from [19]): 1 — firn drilling of the main hole; 2 — lifting, changing nozzle; 3 — forming first cavity; 4 — moving of the main hose reel; 5 — pumping out, firn drilling of return hole; 6 — lifting, changing nozzle; 7 — first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

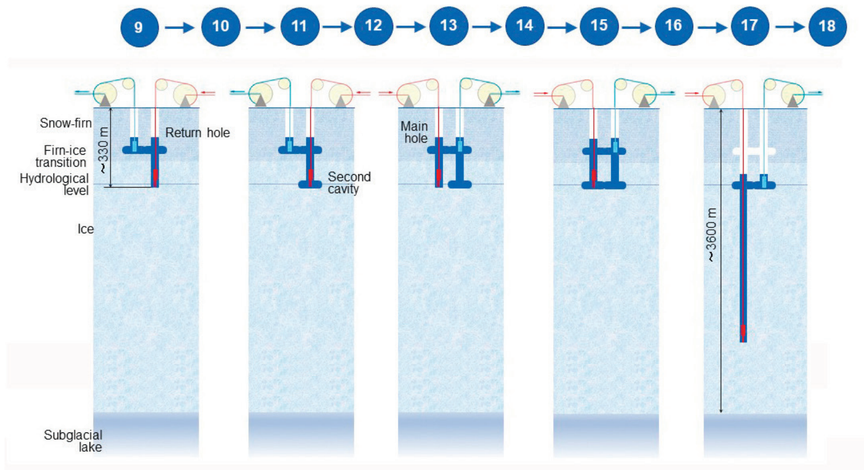

Fig. 4. Proposed sequence of drilling operations to the second cavity and further down (adapted from [19]: 9 — drilling of return hole; 10 — lifting, changing nozzle; 11 — forming of second cavity; 12 — changing positions of the main and return reels; 13 — drilling of main hole; 14 — lifting, changing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

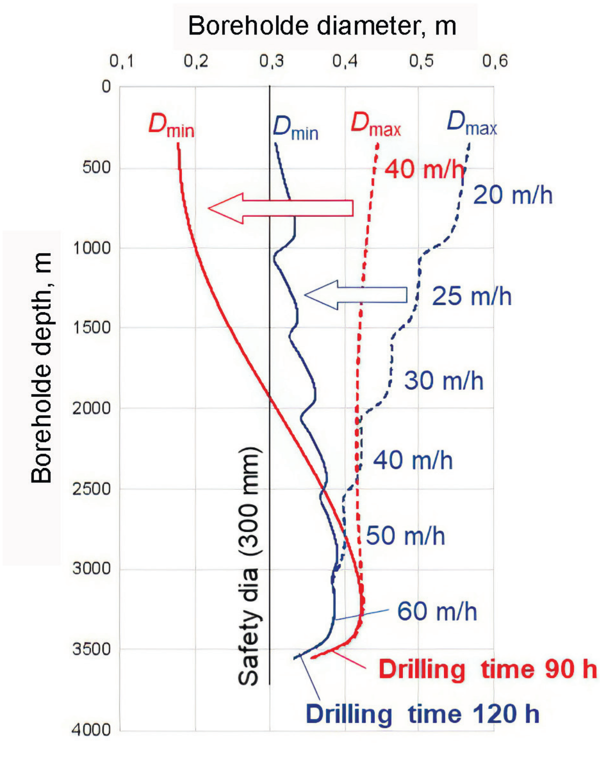

Fig. 5. Modeled maximal borehole diameter D_{max} (dashed lines) during drilling and minimal diameter after drilling completion D_{min} (solid lines) under different drilling scenarios: drilling at a continuous speed of 40 m/h (red lines) and drilling with stepped acceleration of speed from 20 to 60 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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