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Russian researchers reach subglacial Lake Vostok in Antarctica

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Abstract Opening a new scientific frontier lying under the Antarctic ice, Russian researchers have drilled down and finally reached the surface of the gigantic freshwater lake, Lake Vostok. The mission chief likened the achievement to placing a man on the moon. Drilling in the area of the lake began 22 years ago in 1990, but progressed slowly as a result of funding shortages, equipment breakdowns, difficulties of drilling in the "warm" ice, and environmental concerns. In 1996, six years after drilling was started, a group of Russian and British scientists discovered the lake believed to be one of the largest fresh water reservoirs on the planet. This lake is among the last unexplored places on Earth. Sealed from the Earth's atmosphere for millions of years, it may provide vital information about microbial evolution, the past climate of the Earth, and the formation of the Antarctic ice sheet. Russian experts waited several years for international approval of their drilling technology before proceeding. As anticipated, lake water under pressure rushed up the borehole, pushing the drilling fluid up and away, then froze, forming a protective plug that prevented contamination of the lake. In December of the next Antarctic season, 2012—2013, researchers plan to re-drill the frozen sample of subglacial water for analysis.

Keywords **Lake Vostok, Antarctic subglacial environment, ice drilling**

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0 Introduction

The Soviet Antarctic research station, Vostok, was established at the center of the East Antarctic Ice Sheet (78°28'S, 106°48'E, 3 488 m a.s.l.) in 1957 (Figure 1). The first drilling was carried out in 1958 when four boreholes were drilled with a hot point thermal drill to a maximum depth of 52 m[1]. Deep ice core drilling at Vostok Station began in 1970, and during the 1970s a set of open uncased holes were drilled using a thermal drill system suspended on cables. The deepest dry hole in the ice reached 952.4 m (Hole #1, May 1972). For drilling at greater depths it was necessary to prevent hole closure by filling the borehole with a low-temperature fluid. Therefore, from 1980 new thermal and electromechanical drill systems working in fluid were used. Two boreholes reached depths of more than 2 000 m. Hole #3G-2 was extended to 2 201.7 m in 1985, and Hole #4G-2 to 2 546.4 m in 1989[2]. Drilling of a new deep hole, Hole #5G, started in February 1990[3–4], six years before the large subglacial lake under Vostok Station was officially recognized[5]. Twenty-two years later, on February 5, 2012, Russian researchers made contact with Lake Vostok water, at a depth 3 769.3 m.

1 Lake Vostok

Lake Vostok, with dimensions of 280 km × 50 km, is the largest among more than 400 subglacial lakes identified by radar and seismic surveys in Antarctica. The area of Lake Vostok is about 15 790 km^2, and the thickness of the ice sheet in the region of Lake Vostok varies from 1 950 m to 4 350 m[6]. Absolute heights of the water table range from −600 m at the northern part of the lake to −150 m at the south. Lake Vostok is at least 1 000 m deep at the southern end (Figure 2), and relatively shallow to the north and extreme southwest. The volume of water in the lake is about 6 100 km^3, and the average depth is about 400 m. There may be several hundred meters of glacial sediment depos-

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ited over its floor.

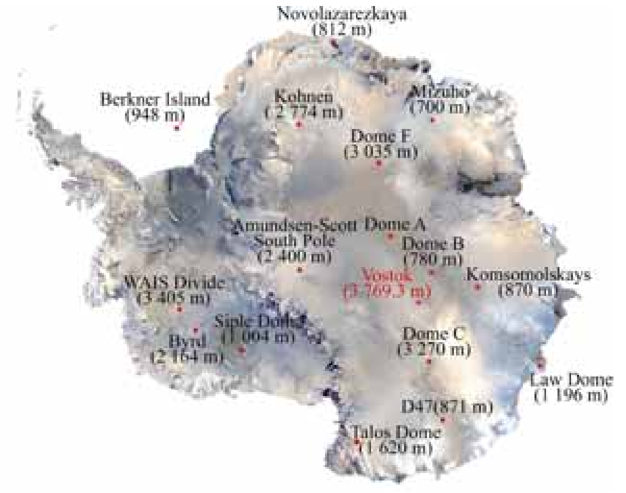

Figure 1 Vostok Station and other deep ice coring sites in Antarctica.

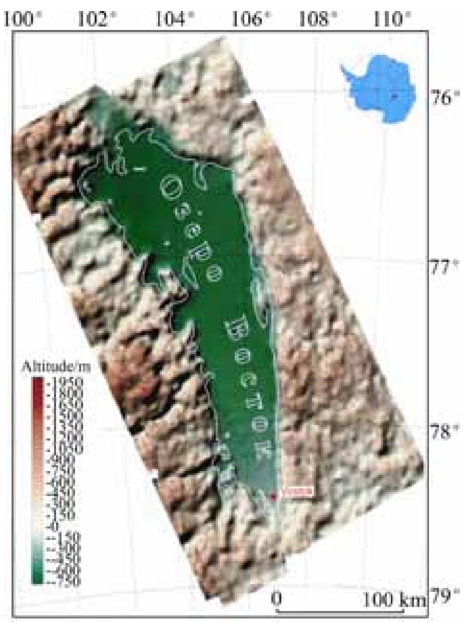

Figure 2 Bedrock topography in the region near Lake Vostok[6].

The origin, evolution, and the present-day state of the Lake Vostok system are closely related to the tectonic evolution, the climatic history, and the development of the Antarctic ice sheet. The lake represents an old (Late Jurassic—Early Cretaceous) rift structure bounded by deep faults and, as an ancient and deep tectonic lake isolated from the surface biota for millions of years, it has great potential for harboring prehistoric life.

Samples of water from Lake Vostok are required for the investigation of physical and chemical processes, and for the identification of life within the lake. Researchers elected to use the existing deep hole, Hole #5G, to gain access to the lake to collect samples of subglacial water[7].

2 Drilling

Drilling of the deep Hole #5G started in February 1990, using a TELGA-14M thermal drill for dry coring to a depth of 120 m[8], and a TBZS-152M thermal drill for fluid-filled holes down to 2 502.7 m. However, this drill became stuck during tripping out, at a depth of 2 259 m, as a result of hole closure caused by insufficient fluid pressurization. Recovery attempts failed, and the cable was pulled out of the top of the drill. About 35 m of artificial core was then dropped on top of the stuck drill, creating a base for a new offset hole. A TBZS-132 thermal drill was used to sidetrack and drill Hole #5G-1 (Figure 3). In 1993, Hole #5G-1 reached 2 755.3 m in depth, a new record for thermal drilling in ice.

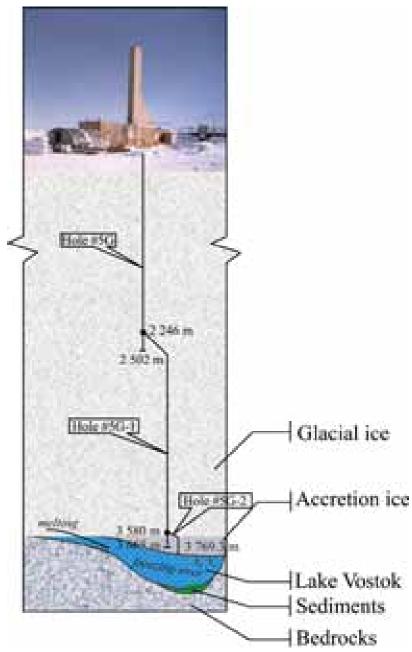

Figure 3 Schematic drawing of deep Hole #5G (showing #5G-1 and #5G-2).

In November 1994, drilling operations in Hole #5G-1 resumed with a KEMS-135 electromechanical drill, reaching 3 350 m by January 1996. From 1996—1997 the drilling operations were limited by the short Antarctic summers but drilling of Hole #5G-1 continued until January 1998, reaching a depth of 3 623 m.

After an eight-year hiatus, Hole #5G-1 was reopened in the summer of 2005—2006, and was deepened to 3 658 m in January 2007, but at this depth the drill became stuck at the bottom of the hole. A drill team that remained at Vostok Station over winter filled the lower hole with 80 L of an antifreeze agent. The drill was captured with an overshot gripper and was lifted to surface on the first attempt, and then the water-glycol solution was removed from the hole.

In May 2007 drilling continued to a depth of 3 668 m. Unfortunately, during enlargement of the hole in October

2007, the core barrel suddenly dropped to the bottom. All attempts to recover it failed, and operations did not resume until December 2008. Starting at a depth of 3 580 m, a new deviated hole was drilled using a KEMS-135 electromechanical drill with a special drill head and cutters. In the summers of 2009—2010 and 2010—2011 drilling at Vostok continued, and Hole #5G-2 was deepened to 3 720.5 m (Figure 4). According to radar and seismic observations, the ice-water interface at Lake Vostok was at a depth of 3 755 ± 15 m[9], and the remaining ice thickness was estimated to be about 35 m.

Figure 4 Drilling complex at Vostok Station, January 2011 (Photograph: G. P. Talalay).

3 Reaching Lake Vostok

In December 2011 the drilling complex at Vostok Station was reopened, and all surface and bottom drilling equipment was rechecked and maintained. Logging of the borehole showed that the inclination of the hole at depths deeper than 3 590 m varied from 4.6° to 5.7°, and the liquid level in the hole was stable at 54 m. Temperature measurements in the hole (Table 1) enabled the prediction of temperature conditions at the bed of the ice sheet, taking into account that the basal ice temperature above the subglacial lake is equal to the pressure melting value.

Table 1 Temperature and pressure measurements in Hole #5G (5G-1, 5G-2), December 6, 2011

Depth/m	Temperature/℃	Hydrostatic pressure/bar
1 000	- 49.26	—
1 600	- 42.05	—
2 200	- 32.93	189.78
2 600	- 25.74	230.92
3 000	- 18.10	266.33
3 510	-7.66	311.95
3 550	-6.84	315.54
3 610	-5.61	320.89
3 650	-4.79	324.49
3 700	-3.76	328.96

Based on extrapolation of the temperature profile, the ice thickness at Vostok Station should range from 3 751–3 757 m with the temperature at the ice-water boundary ranging from –2.9℃ to –2.75℃. The small variation is caused by different estimations of the Clapeyron temperature-pressure slope. The hydrostatic pressure of the drilling fluid column at a depth of 3 700 m was measured as 328.96 bar, 2.64 bar less than the overburden pressure of ice at this depth.

Drilling of Hole #5G-2 resumed on January 2, 2012. The drilling was conducted on a three-shift, twenty-four-hour cycle, with an average progress rate of 1.75 m per day. The first water entry occurred at a depth of 3 766.3 m on February 4, and about 30–40 L of the water was pumped into the inner part of the drill by a down-hole pump. No cracks or capillaries in the ice core were observed at this time. The drilling continued, recovering the core with a length of 0.3–0.9 m per run, and the next day, February 5, the subglacial water finally entered into the hole at a depth of 3 769.3 m.

The drilling fluid consisted of a mixture of kerosene and Freon 141b, which is less dense than lake water, and it began to rise rapidly up the borehole. As a result, about 1.5 m^3 of this fluid poured out through the mouth of the borehole into special trays, installed in the drilling building. The pulling of the drill started after 4 s, when the sensors came into action, and 2.5 h later the drill was recovered to the surface (Figure 5). Russian scientists reached the lake just before they had to leave the station at the end of the Antarctic summer, when plunging temperatures put a halt to all travel to the region (Figure 6). On February 6, several hours after the historical event, the summer's last flight of the DC-3 BT 67 "Turbo Basler" departed, and the drilling team left Vostok Station.

Figure 5 The refrozen Lake Vostok water recovered from the last run, February 5, 2012 (Photograph: N. I. Vasiliev).

Figure 6 Russian researchers at Vostok Station pose for a picture after reaching subglacial Lake Vostok, February 5, 2012 (http://www.aari.nw.ru).

It is symbolic that, on February 4, Vostok Station was visited by Yuri Trutnev, Minister of Natural Resources and Ecology of the Russian Federation. Yuri Trutnev took the first water sample from subglacial Lake Vostok and delivered it to Moscow. On February 10, he presented Vladimir Putin, Prime Minister of the Russian Federation, with a small glass canister containing the first sample of the prehistoric water, a yellowish liquid with the inscription “Lake Vostok, aged more than 1 million years” (Figure 7).

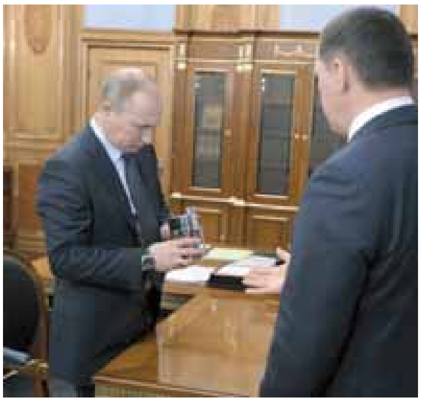

Figure 7 Russia’s Natural Resources Minister, Yuri Trutnev, presented Prime Minister Putin with a canister containing the first sample of water from Lake Vostok (http://www.1tv.ru/news/social/198799).

4 Discussion and plans for the future

Researchers predicted that the water would rise in the near-bottom part of the borehole, up to 30–40 m from the water table. In fact, because of the volume of fluid that filled the empty space inside the casing and effused through the mouth of the borehole, the water rose from the lake to a height of about 600 m. The pressure difference between the hydrostatic pressure of the drilling fluid and the lake pressure had been calculated incorrectly, and the pressure in Lake Vostok was much higher than expected. This will need to be taken into consideration for future exploration.

The next stage of Lake Vostok sampling is planned for the 2012—2013 Antarctic summer season, and will be conducted after confirmation that freezing in the hole has finished. Coring of the frozen lake ice will be carried out with a KEMS-135 electromechanical drill. It is likely that it will only be possible to re-drill the upper 10–15 m of the frozen water because the main hole is inclined from the vertical by several degrees, and the re-drilled hole will deviate rapidly from the previous direction. This occurred in the North Greenland Ice Core Project (NGRIP) borehole in 2003–2004. Subglacial water was reached at a depth of 3 085 m, and the water replaced the drilling fluid and rose to a height of 43 m[10]. The NGRIP borehole had a slight inclination from the vertical, and during re-drilling the drill moved away from the axis of the main hole, and the proportion of pure ice core increased steadily with depth. The subglacial refrozen water was completely gone from the core after the first 14 m of re-drilling.

Unfortunately, the technology used for the Lake Vostok access did not comply with the draft Comprehensive Environmental Evaluation “Water Sampling of the Subglacial Lake Vostok” submitted to the Committee for Environmental Protection (CEP), and considered by the XXV Antarctic Treaty Consultative Meeting (ATCM), in Warsaw, Poland, from 10–20 September, 2002[11]. According to the proposal submitted for evaluation, a liquid such as silicon oil would be delivered to the bottom of the borehole using a special device[7]. It was anticipated that, being heavier than the drilling fluid and lighter than the water, this hydrophobic liquid would create a 100 m-thick “buffer-layer” of ecologically friendly fluid at the bottom of the hole. In fact, Lake Vostok was accessed without this “buffer-layer”, using a mixture of kerosene and Freon 141b. Kerosene is a material that poses a significant risk to the environment[12], and the concentration of aromatics in kerosene-like turbine fuel is 20%–25%. Aromatics are the most hazardous hydrocarbons, and in aquatic environments concentrations of aromatics greater than 1 $mg \cdot m^{-3}$ can be toxic to microorganisms.

When the subglacial water first entered the borehole, it contacted and mixed with the toxic drilling fluid. The subglacial water was almost certainly contaminated by the drilling fluid, and it is likely that it will be of no use for the investigation and identification of new forms of life within it. This concern is supported by microbiological studies of frozen subglacial water recovered from the NGRIP borehole in Greenland in July 2004[13], and from the EPICA borehole at Base Kohnen, in January 2007[14]. The subglacial water samples that had contacted drilling fluid similar to the Vostok drilling fluid were totally contaminated.

There is good reason to believe that the real interface between the ice sheet and the subglacial water lies a few meters below the bottom of the hole, and that lake water rose into the hole through intergranular cracks formed secondary to the large pressure difference between the lake and the fluid in the borehole. This phenomenon is widely known in geology and mining as fracturing, and it occurred in Greenland in 2004, when subglacial water rose into the hole although the ice sheet bed was about 6 m beyond the bottom of the borehole[10]. During the Antarctic summer season of 2006—2007, in a deep borehole at the Dome Fuji Station, subglacial water began to leak into the borehole a few meters above the ice sheet bed[15].

Despite the difficulties and challenges, reaching the surface of Lake Vostok, the crown jewel of Antarctic lakes, came after more than two decades of drilling, and was a major achievement avidly anticipated by scientists around the world. Although the samples collected were likely contaminated by the drilling fluid, contamination of the lake was avoided as the subglacial water entered into the borehole and froze. For the future exploration of Lake Vostok it is essential that researchers focus on developing new methods and protocols to minimize the risk of contamination.

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