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A proposed sterile sampling system for Antarctic subglacial lakes

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Abstract: In recent years, many subglacial lakes beneath the Antarctic Icecap have been discovered (M.J. Siegert *et al*., Antarct. Sci., **8**, 281, 1996). It is presumed that these lakes have been isolated from the greater terrestrial and marine environment for a long period of time (P. Barrett, SCAR International Workshop on Subglacial Lake Exploration, Vol. 2, 17, 1999). As a result, there is considerable interest in the geochemical and biological makeup of these lakes.

International efforts are ongoing to determine the best methodology to study and/or sample the ice, water, and sediments associated with these lakes. The authors propose a sterile drill to penetrate and sample subglacial lakes without contamination. The system uses a hot-water access drill to reach the vicinity of the lake, followed by insertion of an electrically-heated completion drill and sample retrieval system. The operation of the system is such that no open conduit exists between the lake and the surface at any time, thereby preserving the isolation, and hopefully the integrity, of the lake.

An appendix describes an alternative sampling technology.

1. Introduction

It is possible to categorize approaches to investigating subglacial lakes as conservative or ambitious. The latter have the advantage of increasing the amount of information that can be retrieved, but at the cost of greater technological risk. Nevertheless, we must keep in mind that we only have one opportunity to enter a given lake when we are guaranteed that it is pristine. Subsequent investigations of a lake will always have a shadow of doubt as to whether the lake environment has been compromised, so it can be argued that we must try to obtain as much information as possible on the first encounter with a lake. The design described below would be classed as ambitious and is not without considerable technological risk. The authors feel that with appropriate testing of the various components in analogous environments (*e.g*., Arctic lakes, ice shelves, etc.), these risks can be managed.

A wish list for the characteristics of a sampling system for subglacial lakes might include the following: retrieval of lake water and sediment samples, preservation of these samples in their *in-situ* state (*i.e*., temperature and pressure), the absence of an open conduit between the lake and the surface, and no introduction of contaminating materials into the lake. The sterile sampling system proposed in this paper fulfills many of these objectives. The system consists of four components: (1) an access drill, (2) a deployment bus, (3) a hole completion drill, and (4) a sampling sonde. The system has three functions: (1) penetrate into the lake, (2) insert and operate the sampling sonde, and (3) recover uncontaminated samples. All three functions are to be performed while preventing contamination of the lake.

The design of the access drill will not be discussed here except to note that it would be a hot water drilling system. Using water as the drilling fluid (rather than kerosene, fluorocarbons, or other compounds) minimizes potential contamination of the lake. Recovery of the samples will require the use of the hot water drill to drill/ream along the sterile drill's power cable.

The dimensions of the proposed drill are a 20-cm diameter, by approximately 5.5 m long, cylinder.

2. Deployment method

A 20-cm diameter access hole is required to within 10 m of the ice/water interface. This hole should terminate in a vertical orientation and should be drilled in an under-balanced mode (*i.e.* $P_{water} < P_{ice}$) in order to prevent contamination of the lake through infiltration or hydro-fracture. Under-balanced drilling could be achieved by pumping water out of the access hole at depth, possibly via a secondary hole located beside the main hole. Ideally, the use of makeup water would be avoided. Termination of the access hole at the appropriate height above the ice—water interface would be monitored using a forward-looking sonar system on the hot water drill.

The sampling system will be lowered to the bottom of the hole on its control cable (Fig. 1, Panel 1) and sealed in place. Borehole closure, assisted by strong under-balanced borehole pressure, will seal the drill system in place. At the location of the system, the high ice temperature (at the pressure melting point) and high stress should make for rapid closure.

Although the system will have been sterilized and cleaned of foreign material at the factory, contamination during deployment is inevitable. As borehole closure occurs, the water in the vicinity of the system will be sterilized (see below for a further discussion). Once closure is complete, the system will release the completion drill (Fig. 1, Panel 2). The completion drill uses an electrical hotpoint to melt a 20-cm diameter hole into the lake. Once the lake has been penetrated, the completion drill drops off the bus (cable detaches inside bus) and falls to the lake bottom or floats to the ice—lake interface (Fig. 1, Panel 3). The completion drill is designed such that the hydrodynamic shape ensures that it will glide off to the side, leaving an unobstructed "view" of the lake bed below the bus and drop sonde. This design concept is predicated on the depth of the lake being sufficient to allow the completion drill and its trailing cable to get out of the way.

In the absence of any efficient thermal sink, it is expected that the hole created by the completion drill will remain open indefinitely. Processes of ice accretion, which have been observed in Lake Vostok, are of a time scale that will not interfere with the described sampling mission (Siegert *et al.*, 2000).

The sampling sonde is then deployed on its water-sampling program (Fig. 1, Panel 4). The sonde is suspended on a cable from a winch inside the deployment bus. The sonde is lowered slowly through the undisturbed water column while taking readings and

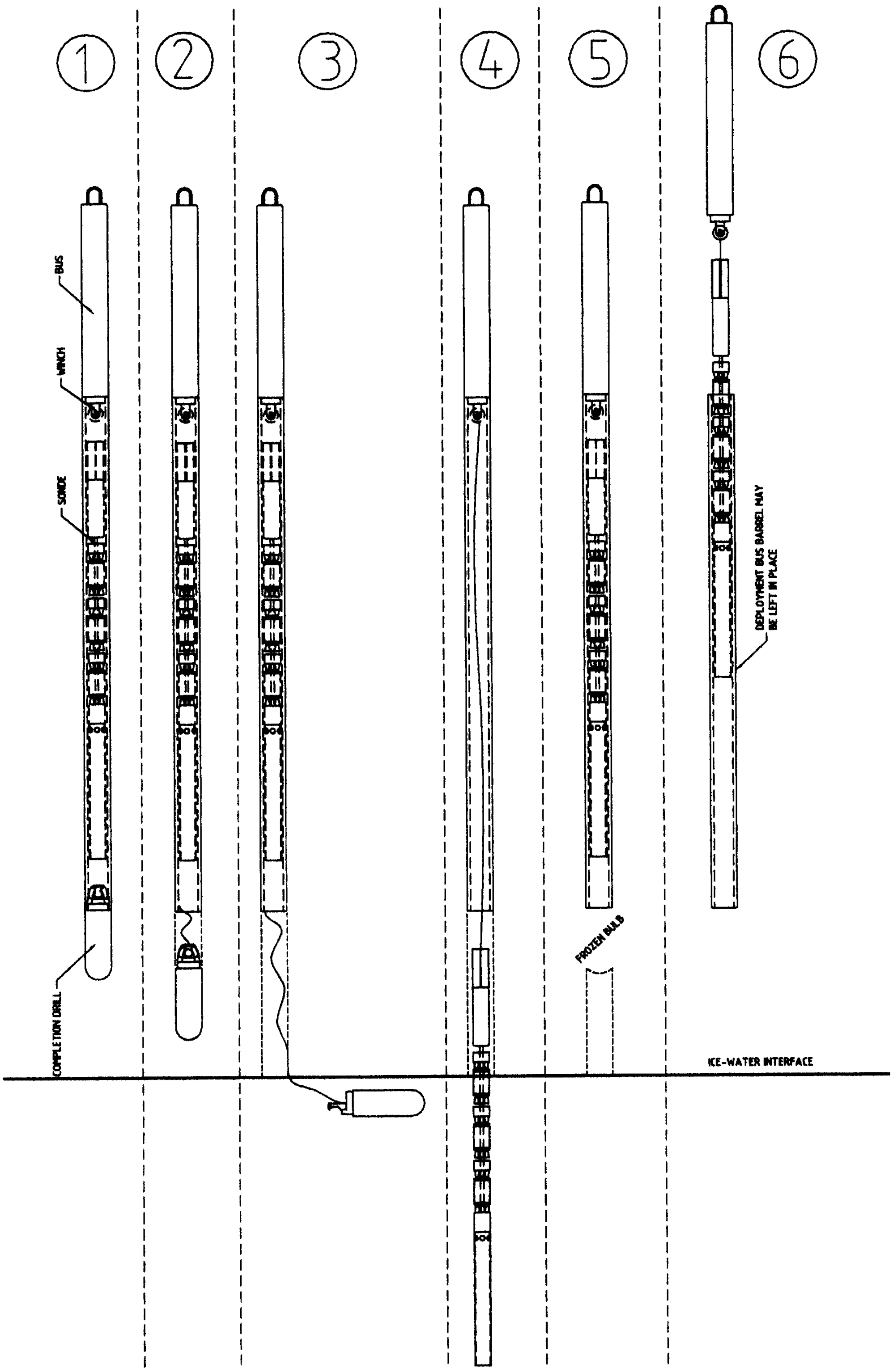

Fig. 1. *Deployment procedure for the sterile sampling system: (1) Insertions and freezing-in, (2) Initiation of completion drilling, (3) Completion drilling complete, (4) Sampling program begins, (5) Sampling program complete, re-sealing of completion hole, (6) Recovery of sampling system (showing option of outer barrel being left in place).*

samples. The sensors and samplers contained on the sonde are described below. When this sampling program is completed, the sonde is dropped in free-fall from a suitable height above the water—sediment interface by releasing cable stored inside the sonde.

Once the sonde impacts the lake bottom (taking a core sample), the winch inside the bus raises the sampling sonde. Should the core barrel become stuck in the sediment, the core barrel is designed to separate from the upper section of the sonde.

In all phases of the sampling, data are transmitted to the surface and stored in the sonde and bus computers. Redundant data storage is used to ensure that communications failure does not result in loss of data.

Finally, a refrigeration system (or other scheme) on board the deployment bus causes the hole below the bus to close off (Fig. 1, Panel 5). Since there are no thermal sinks available to freeze the water, an active method is required to effect the desired phase change. Waste heat from the freezing process would be released at the top of the drill. A recovery reamer then drills along the cable and releases the bus from the ice (Fig. 1, Panel 6).

Alternatively, if it is decided that complete isolation of the sub-glacial lake is not required (*i.e.*, if the hole need not be sealed below the drill prior to recovery and fluid from the lake is permitted to enter the access hole), then multiple entry of the sampling drill/sonde is possible. Nevertheless, the initial penetration into the lake will involve no transfer of fluid or gas into or out or the lake owing to the drill being sealed off from the surface. If the winch fails to raise the sampling sonde, samples can still be recovered by the standard reaming technique, although this will open a conduit between the lake and the access hole.

3. Details of subsystems

3.1. Deployment bus

This subsystem delivers the completion drill and the sampling sonde to the bottom of a 20-cm hole drilled to within 10 m of the lake. The bus is connected to the surface via an 8-conductor power/communications link (4 for power (10 AWG) and 4 for communications—redundant circuits for both). Data are transmitted bi-directionally using a current loop or differential protocol. Supply voltage is approximately 600 VAC with maximum power consumption approximately 20 kW (for hotpoint drilling). Power is supplied at surface using standard 115/230 VAC generators with step-up transformers. The hotpoint uses 600 VAC directly; other systems (*e.g.*, winch, control circuits) use down-hole step-down transformers and power conditioning, as required. The cable might also contain a vent hose, as is discussed below.

The deployment bus contains a dock for the completion drill, a winch for the drop sonde, and a control unit. The control unit is capable of communicating with the surface, communicating with the drop sonde, storing data on-board, operating the drill on a pre-planned mission should communications with the surface fail (using battery power), and operating the completion drill. The bus computer would be a compact IBM-PC computer equipped with a large capacity hard disk. Waste heat from the computer (and the ensuing melting of surrounding ice) would be minimized by shutting off high-power peripherals when they are not required. All electronics are potted or otherwise sealed to prevent fluid intrusion.

The winch is capable of storing a considerable length of 2.5 mm (0.1″) armoured single-conductor counter-wound cable. A horizontal-axis winch drum would store 120 m this cable, but a vertical-axis drum could have a much larger capacity. This cable is readily available in a galvanized steel form. Since the winch has, by necessity, a small drum diameter, synthetic-fibre or fibre-optic telemetry cables having restricted bend radii are not recommended.

The bus has two additional features relating to retrieving samples. In order to preserve the environmental seal between the lake and the surface, it is necessary to reseal the hole created by the completion drill. We will not have a pressure differential or strong temperature gradient available to close the hole. One possibility is to equip the bus with a refrigeration system to carry heat from the bottom of the bus (where the completion drill is mounted) to the top of the drill—when operating, this would create a bulb of ice beneath the drill that would seal the hole. The bulb of water created at the top of the drill, and resulting volume expansion could be vented up through the cable and/or down through the body of the drill—the heat input would also serve to clear the top of the drill in preparation for sample retrieval.

Refrigeration (especially using compressors and coolant) is a rather complex solution to this problem—better solutions may be found. Other possibilities include recovering the completion drill and using it as a plug. The completion drill could be equipped with thermoelectric coolers to create the frozen bulb or to freeze it to the borehole wall.

The exterior of the bus is covered with film heaters in order to assist with releasing the drill from the ice. Since the ice temperature will be very near the melting point, any heat input will cause melting.

The bus is also designed to separate at the top of its barrel should the recovery reamer and heaters fail to release the entire bus (Fig. 1, Panel 6). This will allow the computer, winch, and sample sonde to be pulled out of the barrel and up the hole to the surface. The presence of a coolant circulation system would complicate this maneuver.

3.2. *Completion drill*

The completion drill is a bull-nosed hotpoint drill equipped with a forward-looking sonar sounder capable of detecting the ice—water interface. Communication between the depth sounder and the bus computer is via a current loop on the power supply. The completion drill produces a 20-cm diameter hole for up to 20 m. Drilling rate is estimated at 5.5 cm/min (the power level available at the hot point is 10 kW, but approximately 10 kW will be lost via resistance heating in the power cable for a total power draw of 20 kW). The cable for the completion drill spools out of a coiled reservoir at the top of the completion drill.

The excess water volume created by the completion drill could be vented through the cable or relieved by hydrofracturing into the lake. The former would be the preferred method (since it maintains the integrity of the ice surrounding the drill), but venting of water through the cable is problematic at depths where the temperature is sub-freezing. Perhaps the vent tube could be designed so that resistive heating in the cable will keep the vent tube above freezing. The pressure sensor on the sampling sonde can be used to monitor water pressure above the completion drill.

Once the hole is completed, the completion drill drops off. The cable connection to the bus can be broken manually or by command from the bus computer.

3.3. Sampling sonde

The sampling sonde is the heart of the drill. It consists of four main sections: (1) core sampler, (2) water samplers, (3) instrument package, and (4) control computer (Fig. 2).

The core sampler is a simple drop core sampler with a 10 cm (4″) inside diameter. The length of the core barrel, the method to retain core (piston or spring fingers), and the desired mass of the sonde will be determined when more information is available concerning the characteristics of the lake (*e.g.*, from detailed seismic studies).

Above the core sampler is a spindle to which are attached three electrically-actuated water samplers (modified Niskin-type or sampling bags). Each sampler holds approximately 2 *l* of fluid and is equipped with a vent to allow dissolved gas to escape (it will be difficult to reliably seal a vessel against several hundred atmospheres of internal pressure in a remote operation). In addition, a smaller (500 m*l*) sampling chamber will be provided which can provide a gas-tight seal for the sample. A 500 m*l* sample will also be providing before hole completion as a control for studying sterilization effectiveness.

At the top of the spindle are the instrument package, computer module, cable reservoir, and stabilizing fins. The instrument package contains sensors suitably modified for the high-pressure environment. Sensors include pressure, temperature, redox potential, pH, conductivity, and biofluorescence. Other possible sensors include dissolved gas sensors (*e.g.*, oxygen and carbon dioxide). A pump and 0.2 μm filter will be provided to sample particulate matter, including microbes, in bulk water. The sonde will also have a high-magnification still camera (with a resolution of approximately 50 μm) and possibly a wide-field camera.

The sonde computer triggers the water samplers. This computer takes commands from the surface, via the bus computer, and also has available data from a pressure sensor to determine depth in the lake. Should communications be lost, the sonde computer can operate from a local battery and take samples and readings according to a pre-established schedule. Other sensors may also be mounted (*e.g.*, pH, conductivity, and temperature).

Note that the design current concept does not isolate the core sample from the environment of the drill and borehole during recovery. Gases dissolved in the core will also exsolve as the sonde is raised, thereby likely disturbing the stratigraphy.

3.4. Recovery reamer

The recovery reamer is a hot water drill that creates a 20-cm minimum diameter hole as it threads along the power cable to the drill location. When the drill is reached, the sampling unit, and control computer could separate from the deployment bus barrel, or the refrigeration system could be reversed to release the entire deployment bus and contents.

In order to prevent tangling of the sterile drill cable and the reamer hose, the reamer should be fitted with anti-torque skates to prevent rotation. Care should also be used in selecting the water hose such that it has counter-wound wraps and will not tend to twist under axial loading. Additional anti-tangle fixtures (Fig. 3) may be added to the reamer hose at intervals (*e.g.* cable stabilizers that keep the reamer hose and drill cable separated and prevent rotation/twisting).

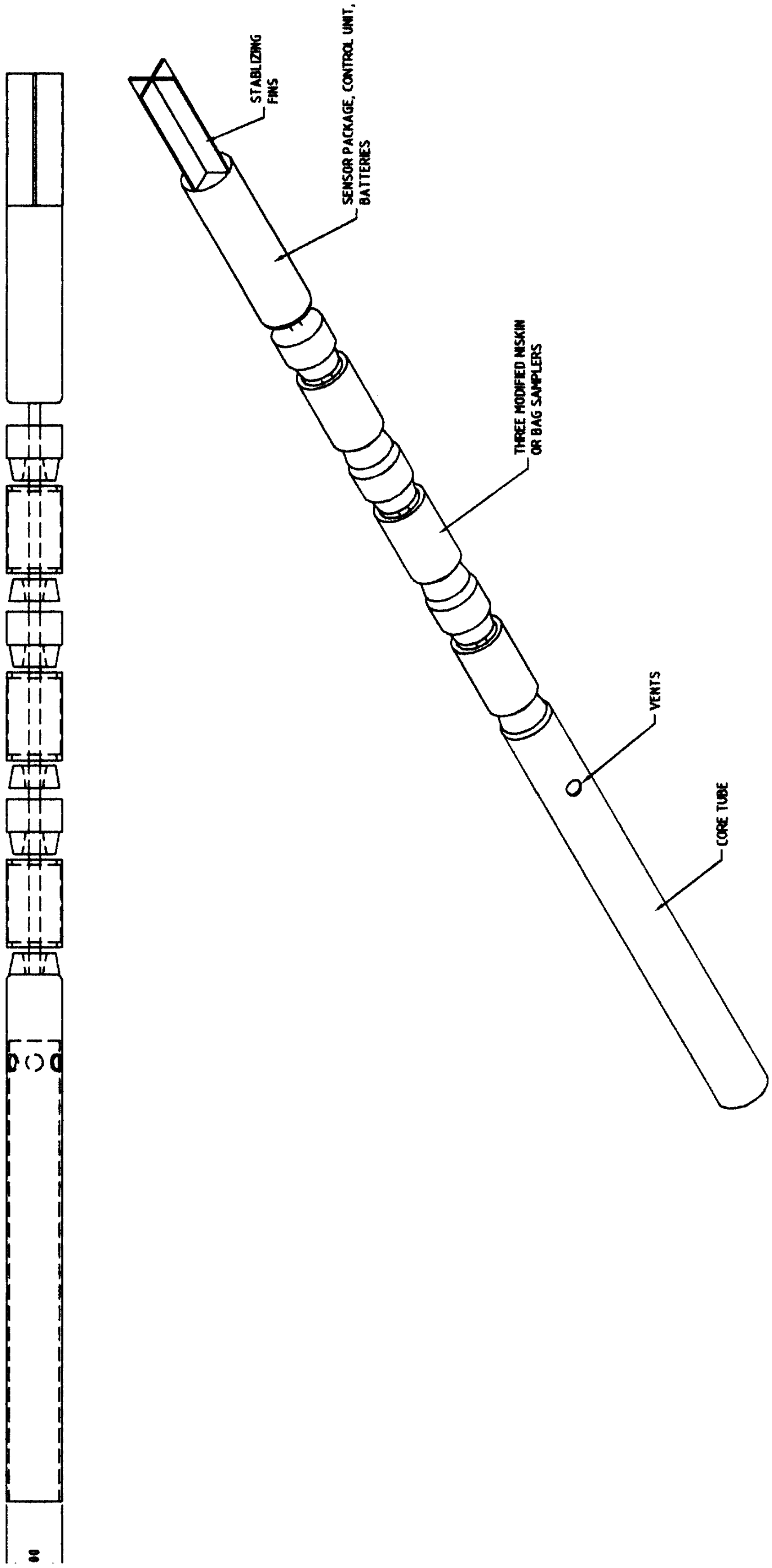

Fig. 2. Detail view of the sampling sonde.

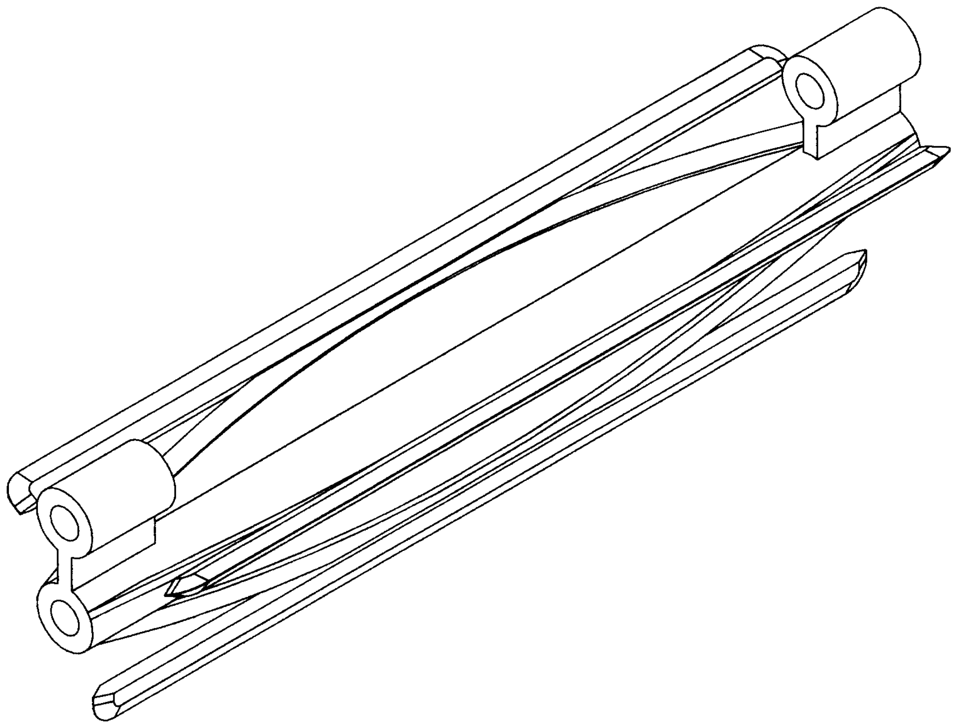

Fig. 3. Schematic of an anti-wrap fixture used to keep the recovery drill hose and sampling system cable from tangling.

Water pressure at the sterile drill can be monitored to gauge the risk of overpressure in the hole (and thereby contamination of the lake through cracks in the frost plug).

Once the components are freed, they are hauled to the surface.

4. Sterilization

Sterilization of the drill is proposed to occur in two stages: first at the factory, and second at the site. Ideally, the sterilization procedure will not only kill microorganisms on the drill, but will also remove them. This would ensure that there are no organic carbon, proteins, DNA, or other similar compounds on the drill. Possible in-situ and factory sterilization methods include steam cleaning, immersion or swabbing with alcohol or H_2O_2, and irradiation. These sterilization methods are not ideal: irradiation is environmentally risky, alcohol introduces a contaminant in relation to organic carbon measurements, and H_2O_2 is not an effective agent against all microorganisms.

5. Discussion

The system described above meets many of the desired objectives: it will retrieve water and sediment samples in an unfrozen state (albeit not all at *in-situ* pressure) and, if operations go as planned, it will ensure that no open conduit exists between the lake and the surface. Nevertheless, there are several major technological advancements required before this system should be deployed on an Antarctic Lake. Each of these problems must be overcome and the solutions tested to ensure a high degree of certainty that the system will operate as desired in Antarctica.

- **Access drill**: The technology to drill a 20-cm access hole to within 10 m of a lake surface at 3500 m+depth does not exist. It may be possible to adapt the technology developed for the AMANDA project for this task.
- **Under-balanced drilling**: The proposed system calls for under-balanced pressure conditions during access drilling, emplacement, and recovery. For a 3500-m hole, this will require that the water level in the hole be maintained about 500 m below the surface. This will require a large, reliable, multi-stage deep well pumping system, probably located in a dry secondary hole adjacent to the main hole.
- **Freezing in**: When freezing-in the sampling system, the hole will likely freeze shut at the water level (500 m below the surface) before borehole closure can take place. This is problematic because the volume of water between the sampling system and a frozen plug above will expand as it freezes, thereby causing potential leakage or hydro-fracture. The access drill could be kept in place and operated at a reduced flow rate to keep the hole open, or a vent tube in the cable could release excess water to the surface.
- **Re-sealing the completion hole**: Once the sampling program has been completed, it will be necessary to re-seal the hole beneath the drill. This will require an active method to seal the hole.
- **Recovery**: Keeping a cable (from the sampling system) and a hose (from the cable-following recovery drill), both over 3500 m long and moving against each other, from tangling will be difficult. We have proposed a method by which this problem might be solved, but this must be thoroughly-tested.

Given the fact that pristine sampling can only be ensured for the first penetration of a lake, initial sampling should probably be done on one or more smaller lakes before tackling the largest, and arguably the most scientifically-interesting, lake: Lake Vostok. Any sampling should occur only after extensive testing of the technology in analogue environments.

It is our hope that the ideas presented in this proposal will stimulate thought and discussion on possible methodologies and technologies that might be used to investigate Antarctic subglacial lakes.

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Appendix: Alternative technologies

A.1. The problem with a normal hot water drill

As outlined by Clow and Koci (2002), a standard hot water drilling technology capable of producing 20 cm holes to depths on the order of 3700 m would be huge and energetically impractical. Nevertheless, the coiled tubing (CT) drilling technology outlined in their paper would permit a sampling scheme related to that proposed above.

A.2. An alternative: waterlock technology

An enlarged CT drill having a nominal tubing size of 7 cm would be used to drill an access hole to within 50 m or so of the lake-ice interface. Hot water would be used as the drilling fluid. The drilling bottom hole assembly (BHA) would then be replaced by a "waterlock" assembly. Power and communications for the waterlock assembly would be provided by wires embedded in the wall of the coiled tubing.

The waterlock consists of three major components, listed from the top down: (1) a 10-m long "downpipe" whose dimensions match that of the coiled tubing, (2) a 16.5-cm diameter body containing a central cylindrical passage whose diameter is greater than the inner diameter of the coiled tubing (in this case approximately 5.2 cm), and (3) a completion drill similar in concept to that described above.

The waterlock body would have two electrically-operated ball valves located at the top and bottom of the central passage, separated by perhaps 5 m. Between these ball valves would be located a cylindrical winch equipped with a cradle which can drop through the lower ball valve. The drum storing the winch cable is concentric with the central passage and could hold 1000 m of 2.5 mm, single-conductor wireline.

In operation, the access hole would be maintained in an underbalanced condition (meaning that the pressure in the hole is less than that in the lake). Once the waterlock assembly is in place, hot water would continue to circulate down through the coiled tubing, returning through the annulus outside the tubing. Water would enter the annulus through one or more diverter valves, the lowest one being located at the top of the downpipe. Given the ice temperature profile at Lake Vostok (J.R. Petit, pers. commun.), it is estimated that 750 kW of heat would be required to keep the interior of the coiled tubing free from ice buildup.

Since no water circulates around the downpipe, the ice in this area will close around the pipe through freezing and borehole closure processes. The ice would also close in around the waterlock body. This closure produces an external seal for the passage of water between the lake and the borehole. A packer could be used to supplement this seal.

The completion drill (which might itself consist of a sampling system such as a cryobot (F. Carsey, pers. commun.)) would then finish the hole into the lake.

By judicious use of the ball valves and waterlock winch, sampling and/or measurement instruments of varied design and objective could be introduced to the lake through the waterlock without opening a direct conduit between the lake and the borehole. Instrument retrieval would be effected using an industry-standard "overshot" lowered through the coiled tubing from the surface.

A.3. Advatages and disadvantages

The waterlock system permits multiple entries into the lake while maintaining isolation of the lake. There are no concerns with pairs of cable twisting or with the structural strength of drilling hose as is the case with traditional hot water drilling. The system uses locally-derived water as a drilling fluid.

The small inner diameter of the coiled tubing (approximately 5.2 cm) restricts the diameter of instrumentation, although instruments can be long. Conversely, the larger size of coiled tubing as compared to the system proposed by Clow and Koci (2002) means that the drill would not be transportable by air. A continuous heat source, albeit smaller than that required for any standard deep hot water drill, is necessary during the drilling and experiment phases.

A.4. Isolation and safety considerations

In order to ensure that the isolation of the lake from fluids in the borehole is maintained, the access hole is kept in an underbalanced condition through the use of a relief well. Nevertheless, the degree of underbalancing is small enough that should a leak from the lake to the hole develop, the fluid from the lake cannot rise high enough to cause a geyser effect through the exsolution of dissolved gas. Sterilization could be an ongoing effort by sterilization of the circulating water and in situ mechanisms within the waterlock.