Mem. Natl Inst. Polar Res., Spec. Issue, **56**, 5–37, 2002

A fast mechanical-access drill for polar glaciology, paleoclimatology, geology, tectonics and biology

Gary D. Clow[1] and Bruce Koci[2]

[1] *U.S. Geological Survey, Federal Center, Denver, CO 80225-0046, U.S.A.*
[2] *Ice Coring and Drilling Services (ICDS), University of Wisconsin-Madison,*
1225 West Dayton Street, Madison, WI 53706, U.S.A.

Abstract: We propose that a new type of drill, alternately known as a Fast Mechanical-Access Drill, or Coiled Tubing Drill for Ice (CTDI), be developed for polar research. The proposed drill is similar in concept to the latest coiled tubing (CT) drills used for commercial oil and gas development. CT drills use a metal or advanced-composite tube to deliver fluid downhole to a hydraulic motor that drives a cutting bit. This technique should permit drilling rates of ~40 m·hr^{-1} in polar ice. The bulk of the components are commercially available. The CTDI would be: a) capable of drilling through 3–4 km of ice in 6–8 days, including setup time, b) aircraft (LC-130) transportable and sled-mounted for rapid mobilization/demobilization, c) able to drill an array of deep boreholes in a single season, d) able to produce semi-permanent uniform-diameter holes with minimal thermal disturbance, e) capable of acquiring rock cores, frozen sediment cores, and short ice cores, f) sufficiently modular and flexible by design that new tools can be added to satisfy future research needs. The capabilities of the CTDI would fill the void between existing deep ice-core drills and hot-water drills. It is believed the new drilling system would greatly enhance several lines of current research, as well as allow the pursuit of new scientific investigations that are not currently feasible. The CTDI could be used by the research community to help address outstanding questions concerning the Earth's climate system, the history and dynamics of ice sheets, the geology and tectonics of polar regions, and the biology within and beneath polar ice sheets. Finally, we discuss access drills for investigating conditions within Antarctic subglacial lakes.

1. Introduction

The polar research community currently has two types of ice drills that can penetrate at least a kilometer of ice, ice-coring drills (ICD) and hot-water drills (HWD). These drilling systems are optimized for recovering high quality ice and for gaining quick access to depths of 1 km or more, respectively. As a by-product, ice-coring drills also produce semi-permanent boreholes in which various properties of the surrounding ice can be determined using geophysical logging methods; the uniform hole diameter produced by ICDs facilitates these measurements. Geophysical measurements in ICD holes currently include borehole 'tilt' and closure (*e.g.* Hansen and Gundestrup, 1988), high-precision temperature (Clow *et al.*, 1996), sonic velocity (G. Lamorey, pers. commun.), and optical scattering/absorption (Bay *et al.*, 2001). Borehole imaging done thus far in HWD holes is also possible in ICD boreholes. These logs provide valuable information about how horizontal velocities, shear-strain rates, temperature, ice fabric, dust concentration, and entrained sediment vary from the bed to the surface of an ice sheet. This information can in turn be used to improve our understanding of ice rheology (Fisher and Koerner, 1986; Dahl-Jensen and Gundestrup, 1987), regional ice dynamics (Dahl-Jensen, 1985), ice-bed interactions (Engelhardt *et al.*, 1990), climate history (Cuffey *et al.*, 1995; Johnsen *et al.*, 1995), and geothermal heat flow. Short bedrock cores have also been obtained with ICDs (*e.g.* Mayewski *et al.*, 1994), although ICDs were not really designed with this in mind. At the present time, ICDs are both slow and expensive to operate, limiting our ability to obtain these types of glaciologic, geologic, and paleoclimatic data to just a few sites in the polar regions. In addition, the sites selected for ICD holes are rarely the best locations for geologic and many other studies. Finally, conditions in and around ICD boreholes are not ideal for some types of geophysical measurements such as high-precision temperature[1].

Many research projects do not require continuous ice core. In this case, hot-water drills can provide rapid access to depths of 1.0–1.5 km. Although HWDs can be scaled to drill deeper, the energetics are such that they become enormous if depths beyond 1.5 km are desired. The new Wotan HWD should be capable of reaching 3 km, but it will weigh at least 227000 kg (Koci, 2002). Obviously, the portability of such a drill is limited. HWDs in the 1-km class are relatively portable and can be used to drill an array of holes in a single season (Engelhardt *et al.*, 1990). These drills are excellent tools for investigating conditions at the base of an ice sheet where it is relatively thin, providing short-term access to the oceanographic environment beneath an ice shelf, and for installing sensors that need to be frozen into ice at depth (*e.g.* stress sensors, vertical strain gauges, photomultiplier tubes). HWDs have recently been used to acquire short ice cores (Gow and Engelhardt, 2000) as well as subglacial sediment samples (Tulaczyk *et al.*, 1998). Although the fact that hot water holes generally freeze shut in 2–3 days is an advantage for some experiments, it is a distinct disadvantage for others. Sensors cannot be recovered for periodic recalibration; expensive instruments cannot be moved to acquire data at different depths or recovered for use in other boreholes. Geophysical experiments that require repeat logs over several years in a semi-permanent access hole (*e.g.* borehole tilt) cannot be done. In addition, the large thermal disturbance imposed by drilling a HWD hole eliminates the possibility of making temperature measurements at the level of precision required for paleoclimate reconstruction using borehole paleothermometry (Clow, 1992). The variable diameter that is intrinsic to HWD holes also makes it extremely difficult to obtain measurements before hole closure that require a smooth borehole wall (*e.g.* downhole DiElectric Profile measurements).

The limitations inherent in current deep drilling systems suggest that a third type of drill could greatly benefit certain aspects of polar research. Given the needs of the research community, we suggest that such a drilling system be optimized for providing rapid access to depths of 3–4 km. The new drilling system should be able to produce arrays of semi-permanent, uniform-diameter holes with minimal thermal disturbance, allowing a wide range of experiments to be conducted within each borehole over a number of years.

---

[1] The drilling process for an ICD borehole generally produces a large thermal disturbance that persists for a number of years. In addition, the diameter of most ICD boreholes is large enough that the fluid within these holes naturally convects, producing thermal noise (Hansen and Gundestrup, 1988).

The new system should also be capable of acquiring short ice cores and of sampling sub-ice basal materials. The system should be both modular and flexible so that new tools can be easily added to satisfy future research needs.

A fast mechanical 'access' drill based on commercial coiled tubing (CT) technology appears to satisfy these requirements. Coiled tubing technology has undergone very rapid development since its first operational use in 1991 (Sas-Jaworsky and Bell, 1996; Connell *et al.*, 1999; Gaddy, 2000). This stems from a number of advantages that CT drills have over traditional rotary rig drills for a wide range of commercial applications. While coiled tubing drills (CTDs) can penetrate rock at the same rate as rotary drills, CT drilling systems are much more compact, require smaller drilling crews, can be mobilized and demobilized much faster, and offer a higher degree of safety and control. The advantages are so great that by 2001, ~70% of all oil-drilling in northern Alaska was being performed with CTDs (R. Whitlow, pers. commun.; see also Gantt *et al.*, 1998); the cost of these wells was about half that of rotary-rig produced wells. The Alaskan experience clearly demonstrates that coiled tubing is a viable technology and that CTDs are very capable of efficiently drilling through 2.5–4.6 km of sedimentary rock under arctic operating conditions. These drills are now commonly used to produce slimhole wells (diameters <13 cm), drill horizontal sidetracks out to 900 m from the main wellbore, install completion tubing, log high-angle boreholes, and deliver sophisticated treatment fluids to specific zones downhole (Bigio *et al.*, 1994). Given their advantages and flexibility, it is anticipated CTDs will see even wider commercial use in the near future.

As with a commercial CTD, the mechanical-access drill we propose for polar research (CTDI, Coiled Tubing Drill for Ice) would utilize a high-pressure pump and coiled tubing to deliver fluid to a steerable downhole hydraulic motor that drives a cutting bit (Fig. 1). An 'injector' would be used on the surface to guide the tubing into and out of the hole and to maintain the correct pressure on the bit. Nearly all the components are commercially available, although they would in some cases need modification and testing to satisfy polar environmental conditions and logistics. A CTDI could operate using any number of environmentally sound drilling fluids, ranging from non-freezing hydrophobic fluids (*e.g.* n-butyl acetate) that would allow a borehole to remain open for years, to hot water and possibly air. Almost any experiment deemed practical could be mated to the front end of a CT drill due to its modular design and the availability of downhole mechanical power, electrical power, and communications. Thus core barrels for the acquisition of rock cores, frozen sediment cores, or short ice cores could be easily attached to the front end of a CTDI. Since CT drills are designed for drilling rock, the tubing has ample tensile strength for acquiring either rock or ice cores.

We estimate a CTDI should be able to achieve effective drilling rates of $40\,\mathrm{m\cdot hr^{-1}}$ in polar ice, allowing a 3–4 km deep borehole to be drilled in 6–8 days, including setup time and downtime; this figure pertains to holes along a transect. A modular 3.5-km CTDI could be designed to fit on five sleds, each of which would fit in an LC-130 aircraft; the first hole along a transect may require an additional 3–4 days to assemble items too large to fit in an LC-130 in their field-ready form. Once delivered to a field area by an LC-130, a sled-mounted CTDI could be pulled hundreds of kilometers along an array transect using a tracked vehicle. Thus, a CTDI would be capable of drilling an array of deep boreholes in a single season. The holes would remain accessible for years if drilled with a non-

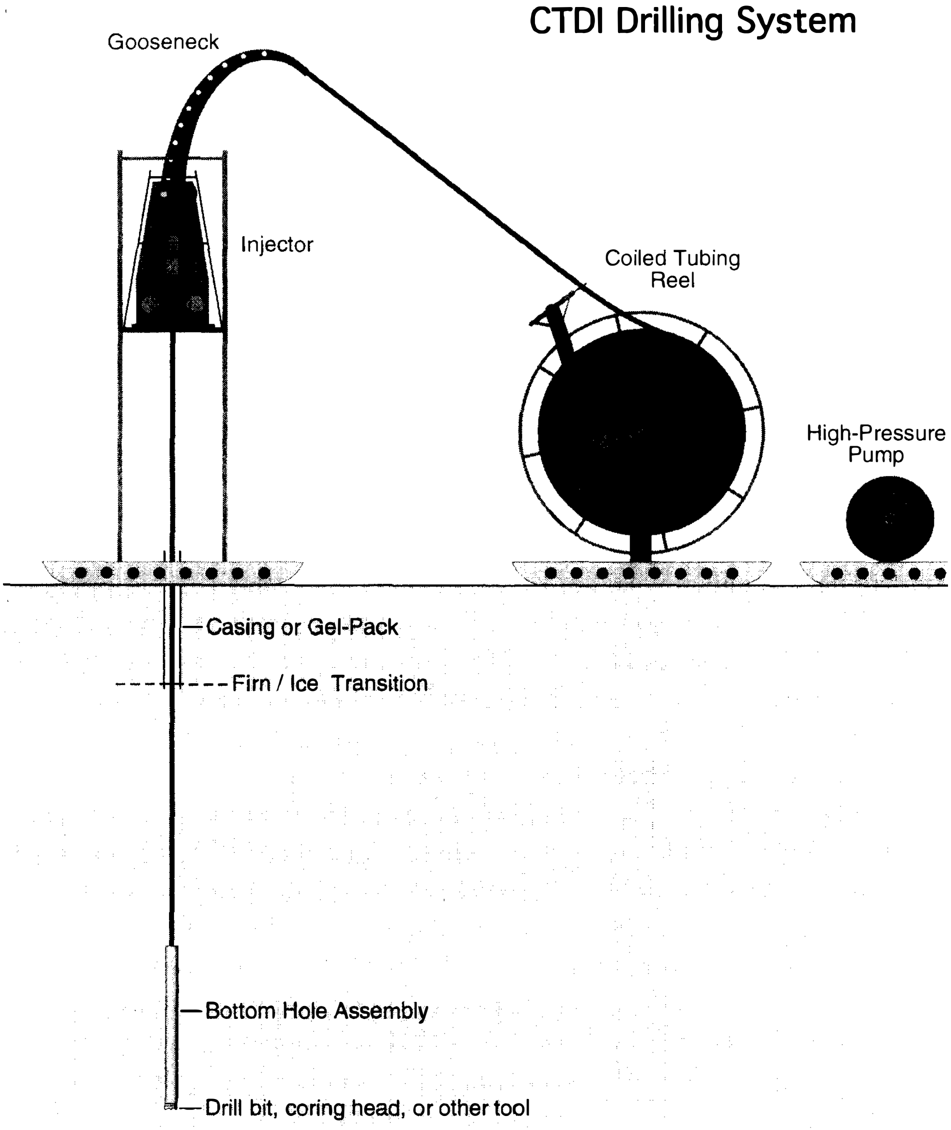

Fig. 1. Primary components of the CTDI (fast access) drilling system.

freezing hydrophobic fluid. In addition, they would have a uniform diameter and would return to thermal equilibrium much faster than ICD-produced boreholes[2], facilitating certain types of geophysical measurements. A wide range of scientific investigations could

---

[2] The primary source of thermal disturbance for an ICD hole is the addition of relatively warm drilling fluid to the hole. The bulk of this excess heat is transferred to the ice surrounding the upper few hundred meters of the borehole. In contrast, a CTDI borehole uses only 1/5 as much drilling fluid and the associated excess heat is transferred to a much larger ice volume by fluid circulation along the entire length of the hole. Thus, the thermal disturbance caused by the input of drilling fluid to the hole is relatively small. The greatest source of thermal disturbance for a CTDI hole would be due to the advection of heat along the hole by the circulating fluid. However, circulation would be limited to just a few days. Scaling the results from oil wells in northern Alaska, we estimate that CTDI

then be done in each hole over the course of several years, if desired.

The proposed CTDI drilling system does bare some similarities to a hot-water drill. The primary difference is that the chips are drilled mechanically rather than using heat to melt the ice. This allows a CTDI to drill much deeper than a HWD while remaining relatively compact and portable. In addition, the CTDI is specifically designed to drill rock as well as ice. Both types of drills require a drilling fluid to be pumped through a

Table 1. Strengths and limitations of various deep drilling systems.

Drill	Strengths	Drawbacks
Ice Coring	• maximizes recovery of high-quality ice • leaves a semi-permanent access hole • uniform borehole diameter	• slow, expensive • holes are thermally disturbed • holes too large for some experiments • large quantity of drilling fluid required
Hot Water	• fast access to 1–2 km • relatively portable (1-km drills)[†] • can drill array of holes in single season • sensors can be frozen in place (e.g. stress, vertical strain, PMTs) • can obtain short ice cores	• holes refreeze in 2–3 days • deployed sensors cannot be recovered for calibration checks or redeployment • repeat geophysical logs cannot be done (e.g. borehole 'tilt') • holes significantly disturbed, thermally • variable hole diameter • large quantity of fuel required
Coiled Tubing	• fast access to 3–4 km • relatively compact & portable • fast mobilization & demobilization • leaves a semi-permanent access hole • uniform hole diameter • minimal thermal disturbance • can drill array of holes in single season • sensors can be repositioned within hole or recovered for periodic recalibration • can obtain short ice cores • can obtain rock & frozen sediment cores • variety of drilling fluids can be used	• firn layer must be sealed • holes too small for some experiments • moderate volume of drilling fluid required

[†] 1-km class hot-water drills are relatively portable while HWDs capable of drilling deeper are not.

---

boreholes will approach thermal equilibrium an order of magnitude faster than ICD holes. Preliminary modeling suggests CTDI holes should be within ~1 mK of equilibrium within 12 months of hole completion. More detailed analysis will be needed to verify this result.

hose or coiled tubing to provide the energy for either melting or mechanically removing ice. With a CTDI, the ice chips are transported to the surface with the drilling fluid where the two must be separated.

Table 1 lists the strengths and limitations of the ICD, HWD, and CTDI drilling systems. In many ways, these three systems provide complementary capabilities. Thus, one, two, or all three systems potentially could be used on any given project, depending on the scientific objectives. In the remainder of this paper we attempt to provide some of the scientific motivation for developing a CT drill for polar research as well as a brief technical description of a CTDI.

2. Scientific motivation for drill development

We envision the CTDI as a tool that could be used by the research community to help address outstanding questions concerning the Earth's climate system, the history and dynamics of polar ice sheets, the geology and tectonics of polar regions, and the biology within and beneath the ice sheets. At present, the time and cost required to make deep boreholes in polar ice sheets with existing drills severely limits our ability to acquire data pertinent to these questions. Given the speed, relative portability, and modularity of a 3–4 km CT drill, we foresee not only a great enhancement of several lines of current research, but also the emergence of new lines of research that are not currently feasible.

Data acquired in arrays of deep access holes could vastly improve our ability to answer a broad range of scientific questions, including:

1) Did the West Antarctic Ice Sheet (WAIS) persist through the last interglacial period?
2) What has been the range of natural climate variability in the polar regions during the Holocene? Are current climate conditions beyond the range of natural variability?
3) How cold was Antarctica during the last ice age?
4) What is the phasing of climate changes between different regions of Antarctica, and between Antarctica and the Northern Hemisphere?
5) How does the geothermal flux vary throughout Antarctica? What is the impact of this distribution on the dynamics of the ice sheets? What is the relationship between the crustal heat flow distribution and seismic velocities in the upper mantle?
6) To what extent is the West Antarctic Rift System still active?
7) What is the composition and age of rocks underlying the polar ice sheets?
8) What specific conditions allow lakes to exist beneath the ice sheets?
9) Does biological activity presently occur within the ice sheets or in the basal materials?

Data acquired through the use of an access drill cannot unambiguously answer all of these questions. Rather, these data would be used in conjunction with data acquired by other means, such as space-based sensors, airborne geophysics, seismology, ice-penetrating radar, deep ice coring, and hot-water drilling. Still, the data acquired in deep access holes would be essential to our understanding in many cases. Below are a few examples of how data acquired in deep access holes potentially could improve our understanding of a wide range of topics.

2.1. Paleoclimatology

2.1.1. Deep Ice Coring Projects

Without doubt, deep ice coring is the best way to obtain high-resolution paleoclimate information in the polar regions. Deep ice coring obviously takes time, is very expensive, and requires the commitment of substantial human and material resources. Data obtained using a polar CT drill could maximize the investment made in a deep ice coring project. For example, a fast CTDI could be used as part of the site selection process: 1) Temperature measurements in an access hole could be used to quickly verify whether the bed is presently frozen at a proposed core site. These data can also be used to determine the likelihood that the bed remained frozen throughout the last glacial/interglacial cycle and thus how old the ice is likely to be at depth. Although ice-penetrating radar has been used to assess whether the bed is presently frozen, recent work by Gades *et al.* (2000) shows that the radar signal can give ambiguous results in this regard; the reflection from frozen till and wet till can be very similar. 2) Ice divides are favorite targets for deep ice cores due to the absence of complicating horizontal ice flow and because older ice will be further off the bed where it will be less distorted. The mapping of 'internal' layers using an ice-penetrating radar can often reveal whether an ice divide has migrated over time, thus complicating the interpretation of a deep ice core. Since this issue is so critical to interpreting an ice core, an additional method of establishing the divide history is desirable. Basal temperatures are expected to be elevated beneath a stationary ice divide. Similarly, a migrating ice divide is expected to leave a trail of warm basal ice in its wake (Nereson and Waddington, 2002). Thus, temperature measurements near the bottom of a few access holes could be used to determine whether an ice divide has been migrating, and if so, at what rate (Fig. 2). 3) Ice dynamics models are used to predict how old the ice is at each depth at a proposed core site. A means for verifying the model predictions prior to committing a deep ice coring drill to a specific site is desirable. This could be done by running a suite of geophysical logs (*e.g.* sonic velocity, optical scattering/absorption, DEP[3]) in an exploratory access hole. With the correct combination of logs, chances are

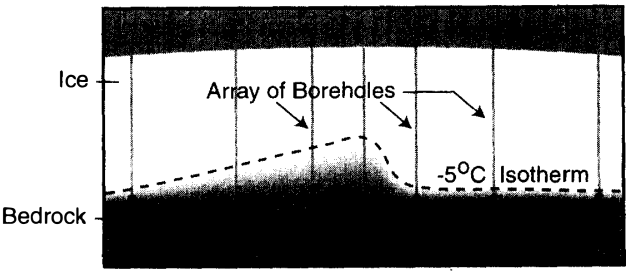

Fig. 2. Basal temperatures indicate the direction and magnitude of divide migration.

---

[3] DiElectric Profiling (DEP) measures the capacitance of ice which is related to the concentration of ions, particularly salts. While Electrical Conductivity Measurements (ECM) require two probes that contact the ice, DEP is a non-contact measurement reducing the requirements for how smooth the wellbore must be. Still, with an ice penetration depth of only 0.5 mm, borehole wall irregularities must be less than 0.2 mm at all scales less than the plate separation (~5 mm) in order for DEP to work properly. Hence, this technique will require wall polishing. Based on laboratory tests, downhole DEP measurements are expected to detect annual layers, at least to depths where the plate separation is a fraction of the annual layer thickness (K. Taylor, pers. commun.).

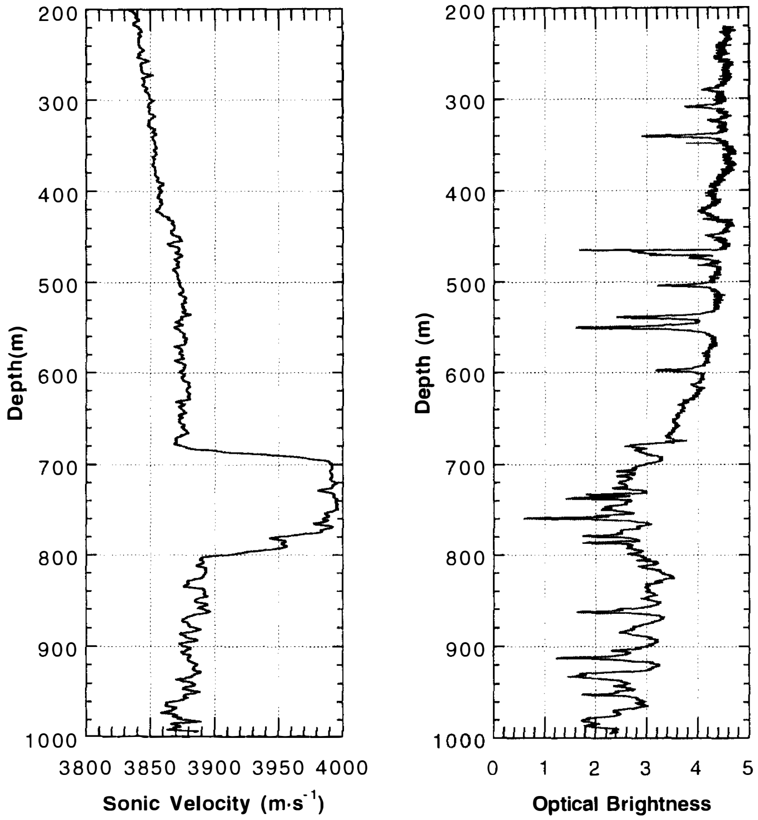

Fig. 3. Sonic velocity and optical logs obtained in the 1-km deep Siple Dome borehole. An abrupt change in properties occurs at 677 m in both logs. 35 prominent volcanic ash layers are apparent in the optical log as well as climate-related dust variations (Bay et al., 2001). Cross-correlation of such features between widely spaced boreholes would provide a depth-age scale for the corresponding sites. A downhole DEP log (not available at this time) would also contribute extremely valuable information. The sonic velocity log was acquired by Gregg Lamorey.

very good that specific age markers could be detected (Fig. 3). For example, 35 prominent volcanic ash bands were identified in the optical log recently acquired in the 1-km deep Siple Dome borehole (Bay *et al.*, 2001). The availability of the Siple Dome ice core allows these ash layers to be dated. A depth-age scale can now be established for future access holes throughout West Antarctica by cross-correlating optical (and other) logs from these holes with Siple Dome.

In addition to site selection issues, a polar CT drill could contribute to ice coring projects in a number of other ways. 1) A fast CTDI could reach the brittle-ice zone well ahead of a deep ice-coring drill. Thus, the CTDI could be used to test the effect of cutter geometry in the brittle-ice zone. These experiments could be done without the pressure to produce core, or the fear that core would be lost during the tests. Short brittle-ice cores could also be retrieved allowing the mechanical properties of the ice to be evaluated in a laboratory. Thus, information critical to obtaining high quality core would be available before the ICD reached the brittle-ice zone. 2) If an access hole is drilled in parallel with an ice-coring operation, high-precision temperature measurements from the access hole could be used to determine the calibration constants for the high-resolution stable-isotope paleothermometers ($\delta^{18}O$ and δD) as soon as the isotope data become available. At present, the borehole temperatures necessary for this calibration do not become available until 3 years after a deep ice core hole has been completed due to the large thermal disturbance caused by the drilling operations. In contrast, thermally equilibrated data could be obtained from a CTDI-produced hole within ~12 months of borehole completion and this could be done while deep ice coring operations are still under way. 3) There never seems to be enough ice from interesting sections of an ice core. A steerable CTDI would allow a core-hole (*e.g.* Byrd, Taylor Dome, Vostok) to be re-entered to acquire short ice cores at desired depths, providing additional ice for analysis. Thus, a polar CT drill has the potential to make significant contributions to deep ice coring projects.

2.1.2. Magnitude of long-term temperature changes

The history of temperature changes on millennial time scales is important for understanding the Earth's climate system and its capacity for change. At present, major aspects of Antarctica's temperature history for the last 50 kyr are still very poorly known. Although detailed stable isotope ($\delta^{18}O$ and δD) histories have been retrieved from sites in both East and West Antarctica (Jouzel *et al*., 1993; Petit *et al*., 1997), it's unclear how to convert these histories to temperature without utilizing high-precision borehole temperature measurements to provide the calibration constants, as was done for central Greenland (Cuffey *et al*., 1995; Johnsen *et al*., 1995). The calibration constants needed to establish the warming at the termination of the Wisconsin Ice Age have not yet been determined for any site in Antarctica.

A more direct way to quantify the magnitude of long-term temperature changes in the polar regions is through the use of 'borehole paleothermometry'. This involves the inversion of high-precision borehole temperature measurements to reconstruct a regional temperature history. Borehole paleothermometry results have shown that central Greenland was 21 K colder than present during the Last Glacial Maximum (Dahl-Jensen *et al*., 1998; Clow, 1999), demonstrating the Northern Hemisphere's large capacity for change. Similar work needs to be done in Antarctica. This requires access holes with minimal thermal disturbance where the ice is at least 2.5-km thick. Although there are a couple ICD holes of this depth either in the planning stages or currently underway, it will be many years before they are completed. In addition, these boreholes will be thermally disturbed so it will be even longer before reliable high-precision temperatures become available. The availability of a fast CTDI would allow borehole paleothermometry experiments to be conducted much sooner and at many more sites. Data from multiple sites are desirable given the spatial complexity of Antarctica's climate (King and Turner, 1997; Mayewski and Goodwin, 1999).

2.1.3. Natural climate variability, the last 2 kyr

Documenting the range of natural climate variability during the Holocene, especially during the last 2 kyr when the Earth's orbital parameters have been similar to present, is important for ascertaining whether current climate conditions are beyond the range of natural variability. Thus far, the magnitude of temperature variations over the last 2 kyr has only been determined at two sites in Antarctica, Law Dome and Taylor Dome. The results from these two sites, one on the coast and one in the climatic transition between the polar plateau and the Ross Sea, are not surprisingly quite different. Due to the spatial complexity of Antarctica's climate, we need to establish the magnitude of temperature variations at many sites before we can understand the true range of natural variability in Antarctica over this crucial period. Borehole paleothermometry utilizing high-precision temperature data from arrays of access holes is well suited for this task on multi-century time scales. Stable isotope measurements on short ice cores from a set of sample depths in the same array of access holes, can provide the range of variability on shorter time scales.

2.1.4. Phasing of climatic changes within Antarctica and between hemispheres

Establishing the phasing of climatic changes between various regions of Antarctica, and between these regions and the Northern Hemisphere is important for deciphering the cause(s) of millennial and sub-millennial climate changes. Stable isotope measurements on ice samples from specific target depths in access holes could help establish the relative timing of climate events at key sites. A suite of geophysical logs could be run in each access hole to establish the depth-age scale needed to determine the depths at which to obtain the ice samples. A low-resolution stable isotope log could also be acquired by making isotope measurements on the ice chips produced by the access drill, contributing additional information to the depth-age scale; stable isotope measurements can be successfully made using just 2 cm^3 of ice, although 10 cm^3 is better. These samples can be in form of chips that were once coated in n-butyl acetate (B. Vaughn, pers. commun.) and possibly other drilling fluids. The depth resolution for a chip-derived isotope log could be improved by drilling incrementally and flushing all the chips to the surface at the end of each drilling pulse.

Once the target depths have been established, ice for detailed isotope measurements could be obtained with a CTDI in three ways: 1) Use a 'sidewall sampler' to acquire strips of ice along the wall. 2) Use the directional drilling capability of the CTDI to drill short ice cores off to the side of the main wellbore at the desired depths. 3) Since the CTDI is fast, short vertically-oriented ice cores could be obtained at the desired depths while drilling a second nearby access hole.

2.1.5. Climate prior to 420 ka

Polar ice cores currently provide the best resolved records of atmospheric composition and climate variation for the last few glacial/interglacial cycles. The oldest paleoclimate records obtained thus far from polar ice date back to 420 ka (Petit *et al*., 1999). Older ice most certainly exists in East Antarctica; in principle, million-year-old ice could still exist at low accumulation sites. Ice of this age would be of great interest since the 100-kyr cycle that has dominated the Earth's climate for the last few glacial/interglacial cycles, did not do so prior to about 800 ka. One explanation for this is that the Earth's climate system crossed a critical threshold at ~800 ka, driven by a general decline in atmospheric CO_2 levels. Extending the high-resolution record to 800 ka and beyond would improve our understanding of the degree to which various internal and external forcing factors control the Earth's climate system. Geophysical logs in exploratory access holes would quickly reveal if ice older than 420 ka exists at a given site and thus is a candidate for a deep continuous ice core; dust and ion concentrations change so much between a glacial period and an interglacial that the number of glacial/interglacial cycles present at a site should be easily discernible in optical and DEP logs.

2.2. *Physical glaciology*

2.2.1. Physics of ice flow

Glaciologists need access to deep ice at many locations to better establish the flow laws for ice. To properly interpret ice cores for past climatic conditions, the physics of ice flow must be thoroughly understood. In addition, the ice dynamics models used to predict the stability of the West Antarctic Ice Sheet and the contribution that ice sheets make to sea level change in response to climate change, rely on our understanding of how ice flows in response to stress. At this time, the flow laws for ice throughout large ice sheets are only partly established. To better understand the physics of ice flow, and thus the dynamics of polar ice sheets, multi-axis stress and strain measurements need to be made under a wide range of conditions. Sites for these measurements should include not only unusual places such as ice divides, ice streams, and flow lines entering prominent subglacial lakes, but also *average* places that are more representative of large areas of the ice sheets. The required vertical strain and multi-axis stress data can be obtained by freezing sensors into deep ice, utilizing either a HWD or a CTDI. In the later case, water could be injected into the bottom of a CTDI-produced access hole and allowed to freeze. Alternately, a CTDI potentially could use hot water as the drilling fluid from the surface to the target depth. As for the required horizontal strain data, they are probably best obtained through repeat borehole inclination logs as was done at Dye 3 and GISP2 in Greenland (*e.g.* Hansen and Gundestrup, 1988). This requires semi-permanent access holes as would normally be produced by a CTDI.

2.2.2. Site-dependent factors affecting ice flow

In addition to stress, the rate of ice flow depends on the orientation of the ice crystals (fabric), on impurity concentrations, exponentially on temperature, and perhaps on other factors. These factors are expected to vary greatly not only with depth, but also from site-to-site. At this time, we have scant knowledge of the actual values for these factors within the Antarctic ice sheets. In West Antarctica, we have data from only two sites, Bryd and Siple Dome. To realistically model the dynamics of the West Antarctic Ice Sheet, measurements of these site- and depth-dependent factors should be made at multiple locations. The situation is similar in East Antarctica. Ice fabric can be established through sonic velocity measurements (Thorsteinsson *et al*., 1999), ion concentrations potentially can be determined through downhole DEP, dust concentrations can be evaluated through optical logging (Fig. 3), and temperature can be measured using standard techniques. Short ice cores could be obtained for verification. Thus, an array of deep access holes would allow the distribution of ice fabric, dust and ion concentrations, and temperature to be mapped using economical geophysical logging methods. The availability of a CTDI drilling system would encourage the further development of geophysical logging tools specifically for polar research.

2.2.3. Basal conditions

Ice flow rates also depend on conditions at the bed of an ice sheet. Important controls include the composition of the underlying material (bedrock or soft sediment) and whether the ice/bed interface is frozen or at the pressure melting point. The temperature at the bed is partly controlled by the geothermal heat flow. These factors are expected to have a great deal of spatial variability. Bed samples from key locations, guided by the results of airborne geophysics, would vastly improve our understanding of the underlying geology. This knowledge would in turn improve our ability to model the dynamics of the ice sheets. The ability to rapidly drill arrays of access holes would also allow basal conditions to be more thoroughly investigated in specific critical areas, such as the heads of the ice streams.

2.2.4. Ice flux measurements

A critical link between climate change and the changes in ice sheet volume that affect sea level, is the rate at which ice flows from the interior of the ice sheets to the coast. At present, there are no measurements of the ice flux from interior Antarctica. Instead, we rely completely on estimates from ice dynamics models. There are measurements of the horizontal surface velocities, but not of the horizontal velocities from the bed to the surface which are necessary to calculate ice flux. Horizontal velocity profiles and the resulting ice fluxes can be obtained from repeat borehole inclination logs in semi-permanent access holes (*e.g.* Gundestrup and Hansen, 1984). Although these measurements cannot be done everywhere, they should be done at several key sites to test the ice flux estimates produced by ice dynamics models.

2.2.5. History of the West Antarctic Ice Sheet

To what extent has the surface elevation of the West Antarctic Ice Sheet (WAIS) varied over the last glacial/interglacial cycle? Did the WAIS persist through the last warm interglacial (MIS-5e)? Answers to these questions can help establish the sensitivity of the WAIS to climate change and whether the WAIS is stable under current or somewhat warmer conditions. One way to establish the extent of the WAIS during Marine Isotope Stage 5e and/or earlier, warm interglacial periods involves 'exposure dating' of bedrock cores obtained from deep access holes. Cosmogenic isotope measurements can be used to estimate the time since a basal bedrock surface was last free of ice, and the duration of its last exposure. Although the method can only be applied to sites that stood above sea level when they were last ice-free, this includes significant areas of central West Antarctica and several recently discovered sub-glacial mountains in the vicinity of the West Antarctic ice streams. This exposure dating approach could be applied to cores obtained along presently buried bedrock slopes, allowing us to track past ice thickness changes. With suitable core samples it might be possible to date deglaciation and re-burial of nunataks at key sites in West Antarctica. For sites that were below sea level, marine diatom assemblages and ^{10}Be concentrations obtained from sediment cores may be used to determine when the sites were last free of ice. Using this method, Scherer *et al.* (1998) found that the WAIS had partially or completely collapsed at least once during the last 750 kyr. Additional subglacial cores are required to determine exactly when this happened. Thus, the availability of a rapid access drill capable of acquiring bedrock or sediment cores could contribute to our understanding of the West Antarctic Ice Sheet's elevation history and its sensitivity to climate change.

The history of ice-divide migration is also important for understanding the dynamics of an ice sheet. An ice divide can migrate in response to changes in the configuration of the margins of the ice sheet or to changes in the pattern of snow accumulation. Both factors are likely to have been important in West Antarctica. High-amplitude magnetic anomalies with little topographic expression have been observed along the Sinuous Ridge that underlies the present ice divide in West Antarctica. Behrendt *et al.* (2001) argue that these anomalies are volcanic in origin and that flowing ice has eroded away the volcanic edifices, producing the gentle topography. This suggests that the ice divide has migrated a significant distance since little erosion should occur beneath an ice divide (basal shear stresses are too low). However, the timing of glacial removal of the volcanic edifices and subsequent migration of the ice divide to its current position are highly uncertain. The volcanic activity that produced the edifices could have occurred very recently, *i.e.* during the Holocene, but this remains speculative. Samples of subglacial material from the sources of the magnetic anomalies would help test whether the anomalies are indeed associated with volcanic intrusions. If they are volcanic, dating the samples would not only establish when the volcanic activity occurred, but also would constrain when the glacial erosion and subsequent ice-divide migration occurred.

2.2.6. History of the late-Tertiary East Antarctic Ice Sheet

A bedrock drilling program could also help resolve the controversy concerning the age of the late-Tertiary (<35 Ma) Sirius Group glacial deposits. Webb *et al.* (1984) and Webb and Harwood (1991) believe the Sirius Group was deposited by glacial ice overriding marine sequences in the Wilkes-Pensacola Basins. This scenario of a dynamic ice sheet is difficult to reconcile with the alternative hypothesis that the East Antarctic Ice Sheet (EAIS) has been stable since the mid-Miocene (Denton *et al.*, 1993; Kennett and Hodell, 1993). Bedrock samples from key sites in East Antarctica may help resolve the nature of the EAIS during the late-Tertiary. Again, exposure age dating could be utilized to help determine the development and evolution of the ice sheet.

2.3. Geology and tectonics

More than 97% of the Antarctic continent is presently covered with ice. Consequently, very little is known about its bedrock geology. The sparse rock outcrops are confined to the coastal and near-coastal areas, the Transantarctic Mountains, and the Ellsworth Mountains. Everywhere else, the nature and evolution of the bedrock geology has by necessity been inferred through extrapolation of the outcrop data and from limited geophysical data. Bedrock drilling would provide a direct means for obtaining information about Antarctica's geologic history. Indeed, bedrock drilling is the only way to test the geologic composition of the rocks beneath the Antarctic ice sheets. Thus, an access drill capable of acquiring rock cores through ice up to 3–4 km thick would greatly benefit geologic studies.

2.3.1. Crustal composition and tectonic history

Examples of geologic issues that could be addressed with a fast access drilling system include: 1) *Recent Volcanic Activity in West Antarctica.* Hundreds of volcanic centers have been identified in West Antarctica based on the interpretation of shallow-source magnetic anomalies (Behrendt *et al.*, 2001). Although some volcanic exposures are as old as ~30 Ma, most of the volcanic activity is believed to have occurred within the last 15 Myr. Behrendt *et al.* (2001) suggest that the 400-km long Sinuous Ridge underlying the present WAIS ice divide is volcanic in origin and that its uplift provided a nucleation point for the development of the West Antarctic Ice Sheet. Although it is not known to what extent the inferred volcanic centers are still active in West Antarctica, ice thickness, gravity, and aeromagnetic data do suggest the presence of an active subglacial volcano at 111°5′W, 81° 50′S (Blankenship *et al.*, 1993). If true, the major ice streams in this area may be related to the high geothermal heat flow associated with an active tectonic rift zone. Drilling could test the existence and age of the inferred volcanics, which is important for understanding one of the potential controls for the West Antarctic Ice Sheet. 2) *Nature of the Byrd Subglacial Basin*. The Byrd Subglacial Basin is one of the lowest parts of West Antarctica with depths exceeding −2000 m. The crust must be relatively thin in this region. Behrendt *et al*. (1994) have suggested the presence of a late Cenozoic flood basalt province in this region as part of the West Antarctic Rift System. Acquisition of rock cores from the central portion and margins of the basin should provide valuable information regarding the composition of the bedrock as well as the nature and timing of any rifting. 3) *Nature of the Gamburtsev Mountains*. These are the highest subglacial mountains in East Antarctica with elevations reaching 3000 m. The mountains may have originated by shortening of a Carboniferous intracratonic basin (Veevers, 1994) or through volcanic activity during the mid- to late-Cenozoic as an inland extension of the Amery Graben (Elliot, 1994). The nature and age of the Gamburtsev Mountains have major implications for the tectonic and glacial history of East Antarctica. Retrieval of bedrock samples would help resolve the controversy concerning its origin.

2.3.2. Geothermal heat flow

The largest void in the global heat flow database (International Heat Flow Commission, 2001: Global Heat Flow Database. http://www.geo.lsa.umich.edu/IHFC/index.html.) is Antarctica. Of the nine continental Antarctic heat flow values in the global database, all are from the Ross Island/McMurdo Dry Valleys region. Yet geothermal heat flow is one of the most important controls on the dynamics of the Antarctic ice sheets. The geothermal flux is also very important for determining the thermal state of the crust and for assessing the age of regional tectonic activity. Surrounded by divergent plate boundaries, some regions of the Antarctic Plate are expected to be in a state of extensional stress. Active rift systems with high heat flow may be associated with these regions. Geophysical data and the presence of mapped alkaline volcanic rocks of Cenozoic age (Behrendt *et al*., 1996; LeMasurier, 1990) do suggest the existence of a large rift system in West Antarctica. However, we do not know the extent to which the West Antarctic Rift System is still active. Geothermal flux measurements would contribute substantially to our knowledge of this rift system. Such measurements should be made at multiple sites as the heat flux is expected to have large spatial variations, especially near active volcanos and normal faults; hot water often percolates up normal fault planes in active rift systems. Examining the relationship between the crustal heat flow distribution and upper-mantle seismic velocities may also improve our understanding of the Earth's upper mantle beneath Antarctica.

To better understand the tectonic environments within Antarctica, crustal heat flow measurements should be made at a large number of sites across the continent. The heat flow can be easily obtained from temperature measurements in arrays of access holes drilled through the ice sheets at sites where the ice is frozen at the bed. The access holes should be at least 2-km deep to uniquely determine the geothermal flux; for shallower holes, the temperature gradient at the base of an ice sheet is still strongly perturbed by the large temperature change at the termination of the Wisconsin ice age. The CTDI drilling system is well-suited for this endeavor.

2.4. *Biology*

Under the right conditions, microorganisms can survive at temperatures as low as −50°C (Barghoorn and Nichols, 1961). To do this, microbes have adopted a variety of strategies. While some simply slow their metabolic levels to accommodate low temperature and/or nutrient levels, others shut down nearly all forms of energy consumption. Still others form spores that allow them to become completely dormant until conditions improve, at which time mechanisms are activated to repair cell damage. What is not known is how long microorganisms can remain viable under extremely cold temperatures and low nutrient levels. This question is of great interest to both microbiologists and exobiologists. Price (2000) has argued that nutrient levels are high enough within acidic liquid veins in deep ice that a few microbes per cm^3 could remain biologically functional for hundreds of thousands of years. Ancient microorganisms stored in polar ice are also of interest for what they might reveal about the evolution of bacteria and their resistance to antibiotics (Handfield *et al.*, 1994).

Microbes have indeed been found within deep ice (1500–2750 m) at Vostok, East Antarctica (Abyzov *et al.*, 1998), within the Greenland Ice Sheet at GISP2 (Willerslev *et al.*, 1999; Ma *et al.*, 2000), and within the Agassiz Ice Cap on Ellesmere Island (Wuethrich, 1994; Handfield *et al.*, 1994). Since these cells have the same size range (∼0.1 to ∼1 μm) as dust particles found in polar ice, and their concentration tends to correlate with the dust concentration, it is likely these microorganisms were transported with dust by high winds during colder climate periods, were deposited into polar snow, and then died or became dormant as they were incorporated into the ice sheets. At least at Vostok, most of the cells are of spore-forming organisms but in a vegetative state. Although the vast majority (∼99%) of the organisms cannot be cultivated, at least some of the microbes appear to still be viable. At this time, it is not known whether a small fraction of the aeolian-deposited microbes found in deep polar ice remain biologically functional within acidic veins as postulated by Price (2000).

Microbes have also been found in the ice accreted to the base of the East Antarctic Ice Sheet above Lake Vostok (Karl *et al.*, 1999; Priscu *et al.*, 1999). These microorganisms, some of which revive in the presence of liquid water, reflect the organisms that live in the lake beneath the ice sheet. Based on the cell concentrations found in the accreted ice, Priscu *et al.* (1999) estimate the microbial concentration in Lake Vostok may be as high as 10^6 cells·$\mathrm{m}l^{-1}$. Finally, viable microorganisms and microfossils (diatoms, radiolarians) are likely to exist in sediments beneath the polar ice sheets.

An access drill capable of acquiring short ice cores from biologically interesting depths and frozen sediment cores from beneath the ice sheets, would allow the investigation of biological activity in these extreme environments. Ice samples from accreted ice above subglacial lakes would reveal what organisms live in the lakes. Even without direct sampling, it may be possible to detect microbial activity in deep ice by looking for autofluorescence (B. Price, pers. commun.). Living cells emit weak fluorescent radiation at 450 nm when excited by 360-nm light. Dead cells do not do this. Rather, they fluoresce intensely at 530 nm in response to 460-nm light. Thus, it may be possible to construct a 'microbe' logging instrument that could rapidly detect both dead and living cells within deep polar ice by lowering it in an access hole.

Biological investigations in both deep ice and subglacial environments would expand our knowledge of the range of conditions under which life can or cannot exist. It would also improve our understanding of how long microorganisms can remain viable under extreme conditions and potentially of bacterial evolution. In addition, any microfossils found in the course of these investigations would provide important information regarding the geologic and climatic history of Antarctica. The ability of the CTDI drilling system to provide access holes for biologically interesting measurements (*e.g.* autofluorescence), to acquire biologically targeted cores, to deploy instrument packages at great depth, and to utilize a variety of drilling fluids, offers the possibility of investigating biological activity in deep polar environments that are not currently accessible.

3. Technical description

3.1. Overview

There may be several ways to construct a fast mechanical-access drill for polar research. Of these, we recommend a design based on 'coiled tubing', the latest technology used for a wide variety of commercial drilling applications. This has the advantage of building on extensive research and development by the oil and gas industry. It also appears to provide the most cost-effective and capable design. The proposed CTDI drilling system would have four primary functions:

- Provide rapid access to deep ice and the basal environment beneath polar ice sheets.
- Acquire rock cores, frozen sediment cores, and short ice cores.
- Provide arrays of small-diameter semi-permanent boreholes suitable for geophysical measurements.
- Obtain additional ice samples from previously drilled core holes or access holes through 'directional' or 'sidetrack' drilling.

The tremendous advancements made in coiled tubing technology over the last decade have resulted from the technical advantages that CT drills have over conventional rotary drills in many situations, and from simple economics. CT drilling systems are more compact than rotary drills, can be mobilized and demobilized much more quickly, can be operated by half the normal drill crew, and offer a greater degree of safety and control. These advantages lead to well production costs that are half that of rotary-produced wells. Small sub-surface targets that were previously inaccessible, can now be reached due to the higher degree of control that is available with CT drills. Technological advancements during the last decade include the development of larger diameter high-strength tubing, the use of advanced composites for tubing, the introduction of small diameter downhole motors, orienting tools, new cutting bits, and CT heads that accept geophysical logging tools. There is now a high level of operational efficiency due to improved equipment reliability and a much greater understanding of the overall CTD process. Although coiled tubing has traditionally been made of high-quality steel, advanced-composite CT has recently become available. Advanced-composite tubing is 1/3 the weight of steel, has two orders of magnitude greater fatigue resistance, has excellent chemical resistance, and is available with copper and/or fiber-optic conductors embedded in the walls of the tubing for data and electrical power transmission (Fowler *et al*., 1998; JPT, 1999); composite tubing with embedded conductors has been successfully manufactured in lengths as long as 7.3 km. Because of the reduced weight, a smaller injector can be used with composite tubing than with traditional steel tubing. These developments now make CT drilling possible in the polar regions.

A schematic of a polar CT drill is shown in Fig. 1. Drilling fluid is pumped downhole through composite tubing using a high-pressure pump located on the surface. An 'injector' provides control for the drill string, maintaining the correct weight on the bit at all times. Fluid passing through the tubing under pressure drives a downhole hydraulic mud motor, which in turn drives the drill head. Standard drill bits, core barrels, or other tools can be attached to the drill head. The chips and fluid return to the surface outside the coiled tubing, using the space between the tubing and the borehole wall as the conduit. A slurry pump at the firn/ice transition can be used (if necessary) to return the chip-fluid slurry to the surface through a separate hose. The hole is sealed through the firn layer to prevent drilling fluid from leaking into the surrounding firn, which is permeable. This can be accomplished by installing fiberglass casing or by injecting a gel into the borehole wall in the firn layer. In either case, the chips are separated from the drilling fluid at the surface before the fluid is pumped back down the hole. Chip separation would involve running the chip-fluid slurry through vibrating screens in a device known as a 'shaker'.

Figure 4 shows the bottomhole assembly (BHA) that contains the actual drill. Optional torque reaction skates could be located at the top of the BHA to prevent drill

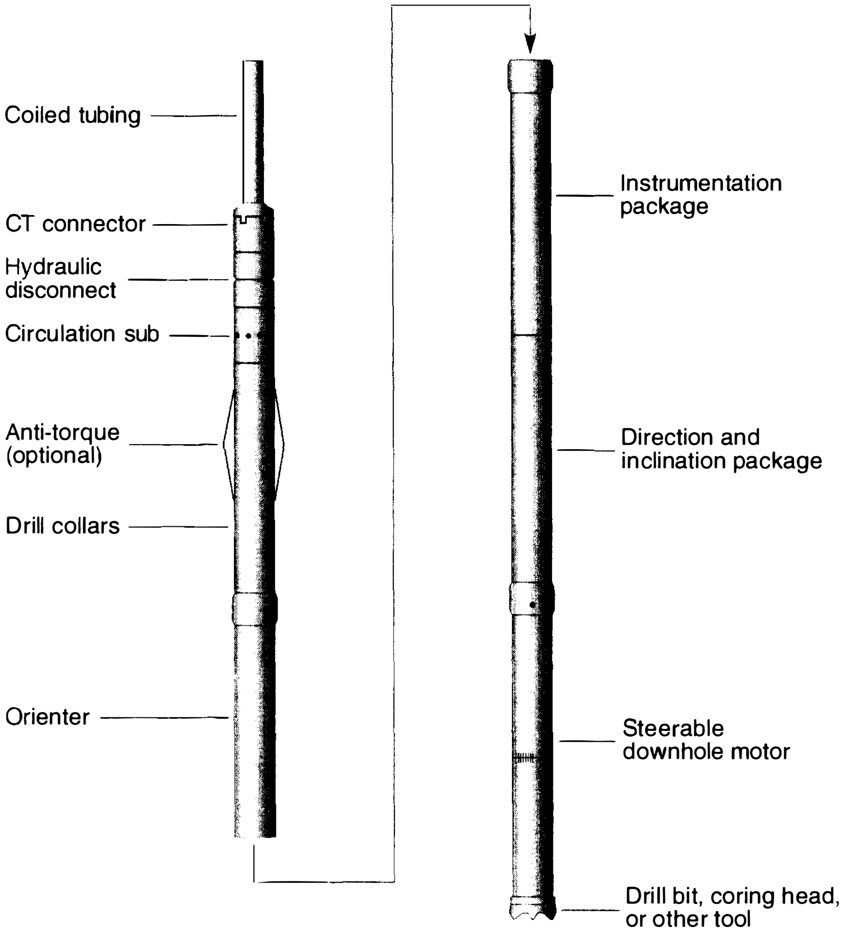

Fig. 4. Detail of the bottomhole assembly (BHA).

rotation. Although the coiled tubing will resist drilling torque, the tubing can wind up quite a bit before much reaction develops. Torque reaction skates would provide much faster reaction times. A positive-displacement hydraulic motor provides the power to drive the drill bit, coring head, or other tools.. Most commercial applications utilize high-speed small-diameter (5.4, 6.0, 7.3, 7.9, 9.5-cm) motors. These motors currently yield rock penetration rates comparable to those of rotary drills, but with much less weight on the cutting bit. New high-power slimhole motors developed on behalf of the U.S. Department of Energy effectively double current CT penetration rates (Cohen *et al.*, 2000). A wide range of drill and coring bits are presently available for CT drills, depending on application. These bits are specifically designed to reduce motor stalls and reactive torques (Feiner, 1995) when drilling through a variety of materials, including various rock types, cement, and steel tubing; PDC (polycrystalline diamond compact) and natural diamond cutters are used in the bits. The CTDI system would utilize commercial bits for cutting rock. However, new bits may need to be designed to provide optimal penetration rates through ice. Downhole instrumentation and navigation packages would be located above the motor.

Past experience suggests that only ~100 kg of weight will be needed on the bit while drilling ice. This is probably best achieved through the use of drill collars near the top of the bottomhole assembly (Fig. 4). Drill collars would keep the CT under tension, making weight control on the bit more precise. Drilling rock will require significantly more weight on the bit (1000–2000 kg). Again this weight is probably best achieved through the use of drill collars, although the injector can also produce this weight as it pushes the tubing into the wellbore. In either case, the use of computer control would maximize the penetration rates by optimizing the weight on the bit. Computer control relies on monitoring the pressure on the cutters. This information, which is indicative of the torque required to rotate the bit, would be transmitted to the surface through the copper or fiber-optic conductors embedded in the composite tubing. As the injector advances the tubing into the hole, the weight on the bit increases. When the bit pressure reaches a preset upper limit, the computer stops the movement of the tubing downhole. The pressure then drops as the motor continues drilling ahead. When the pressure drops below a preset lower limit, the computer re-engages the injector and again advances the tubing into the hole. This system would provide the maximum penetration rates possible with a CTDI.

All commercial CT drills are fully steerable, allowing them to access small targets at great depths. We recommend the CTDI be steerable as well for three reasons: 1) Relying on gravity has never proven to be a reliable means for drilling straight holes. Borehole deviations of up to 20° have occurred on past deep drilling projects. In contrast, a steerable drill would provide a high degree of control over the hole direction, greatly simplifying drilling operations. 2) A steerable drill adds the ability to do 'directional' or 'sidetrack' drilling. With these drilling techniques, short ice cores could be obtained to the side of a vertical wellbore in order to augment interesting sections of ice core or to replace missing sections (Fig. 5). This could be done in an access hole or by re-entering a previously drilled core-hole (*e.g.* Byrd, Siple Dome, Vostok). These cores could be obtained at low- or high-angles relative to the wellbore, or even horizontally. 3) Basal conditions and rock types are expected to vary on short spatial scales beneath polar ice

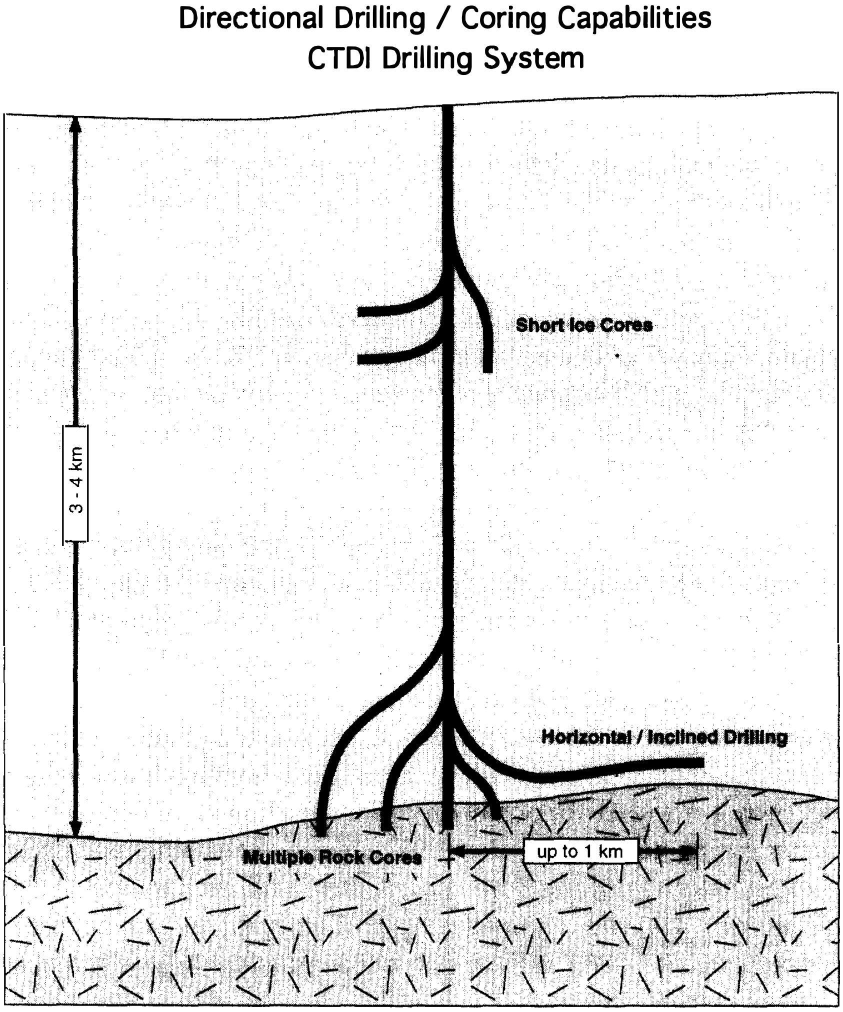

Fig. 5. *The CTDI drilling system would be fully steerable, allowing it to acquire short ice cores at low- or high-angles in previously drilled ICD holes or in newly drilled access holes. The CTDI would also be capable of acquiring multiple rock or frozen sediment cores from a single primary wellbore. With present technology, the CTDI would be able to drill horizontally out to ~1 km from the main wellbore. Inclined drilling at angles up to 110° would be possible.*

sheets. Directional drilling would provide the means for obtaining multiple rock or frozen sediment cores from a single wellbore (Fig. 5). Commercial CT drills are generally steered using an 'orienter' (Fig. 4) in combination with a steerable motor. The orienter, located above the instrument and navigation packages, typically rotates or indexes the lower section of the BHA to the desired azimuth in 20° increments in response to cycling the fluid pressure in the wellbore. Steerable CT motors have an adjustable bend in their mid-section that can generally be set anywhere between 0° and 3°. Given the significant additional capabilities provided by having a fully steerable drill, the CTDI should incorporate an orienting tool and a steerable motor. The expense is expected to be less than 5% of the total drill cost.

3.2. *Safety features*

A number of safety features are inherent in the CTDI design to prevent it from becoming permanently stuck in a borehole: 1) A circulation subassembly (Fig. 4) is located within the BHA above the orienter. If there's concern the chip concentration is becoming too high anywhere within a wellbore, the circulation sub can be activated, directing the drilling fluid radially through side exit ports in the BHA rather than to the motor. This increases the circulation rate in the borehole by eliminating the pressure drop and flow rate restrictions through the BHA, resulting in improved removal of chips. Enhanced circulation to the surface is then possible without bit or motor damage since the bit doesn't rotate while the circulation sub is open. 2) The most likely place for a CTDI to become stuck is at the bottomhole assembly. Glycol or hot water can be pumped directly to the BHA through the tubing to melt the ice surrounding the BHA. 3) Composite tubing has a high tensile strength (>100 MPa for 4.4-cm tubing). Thus, a great deal of force can be applied to the tubing in an effort to pull it free from an obstructed wellbore. 4) A hydraulic disconnect at the top of the BHA provides the option of releasing the bottomhole assembly should it become stuck. At the very least, the entire coiled tubing string can then be recovered in one piece. Considering the high cost of polar logistics, the CT string is worth considerably more than the BHA.

A CTDI drill is also safer to operate than other drills in several respects: 1) The CTDI uses an injector rather than a drill tower; an injector is much easier and thus safer to assemble and disassemble in the field. 2) Since the communication lines are embedded in the tubing, there's no need for someone to be standing over the borehole, physically attaching ('tie-wrapping') a separate electrical cable to the tubing as it is injected into a hole. 3) If a non-freezing drilling fluid is used, there's no need to heat the operating fluid to high temperatures. 4) With a non-freezing drill fluid, there's also no need to rush when something inevitably goes wrong as there's no danger that the hole will quickly freeze shut.

3.3. *CTDI options*

Several characteristics of modular CT drills allow them to be easily adapted to multiple tasks. This is indicated by the fact that they are presently used to drill slimhole wells, drill 1-km long horizontal sidetracks, install completion tubing, make access holes in steel casing using speed-mill attachments, detonate guns at depth to perforate steel tubing, log high-angle wellbores, and deliver fluid treatments at specific depths in commercial wells (Bigio *et al*., 1994). The CTDI drilling system shares these characteristics.

With the availability of mechanical power, electrical power, and communication lines at the bottomhole assembly, a wide variety of options are possible with a CTDI. New circulation, navigation, instrumentation, and other subassemblies can be incorporated into the modular BHA. Tools requiring rotation can be easily added to the drill head in place of standard drill bits. An example is a coring head for rock or ice. Standard commercially available (small diameter) coring equipment for CT drills produce 3-m long rock cores; the core barrels can be doubled or tripled up to produce 6 or 9-m long rock cores if desired. Acquisition of a core would involve bringing the BHA to the surface, replacing the drill bit with coring equipment, 'tripping' the CT downhole, drilling the core, and tripping the CT back to the surface. Typical trip rates for commercial CT drills are 30 $\mathrm{m{\cdot}min^{-1}}$ downhole and 40 $\mathrm{m{\cdot}min^{-1}}$ uphole. While coring rates depend on the type of material being drilled, rates of at least 3 m·hr^{-1} can be achieved in sandstones and carbonates. Thus, we expect the CTDI would normally be able to acquire a 3-m rock core at depths of 3 km in 4 hours, including the trip times. Commercial rock coring equipment is unlikely to produce high-quality ice core. Thus, ice-coring equipment would need to be custom made. Considering the trip times, 3–6 m long ice cores might be a reasonable objective. In addition to coring equipment, other tools that could be attached to the front end of the BHA include a wall 'polisher' to prepare a wellbore for geophysical measurements requiring a smooth wall (*e.g.* DEP), and high-speed horizontal or vertical mills. A 'continuous sidewall sampler' that would cut long strips of ice for isotopic analyses is yet another possibility.

The BHA can also be completely removed to allow the attachment of various tools directly to the coiled tubing head (CTH). Thus, geophysical logging tools could be attached to the tubing in order to log high-angle or horizontal sections of a wellbore; the rigidity of CT allows these tools to be pushed into high-angle sections. Wellbore 'packers' and/or instrument packages could be attached to the CTH and then hydraulically released at depth. If desired, an instrument could be frozen into a wellbore at a specific depth by deploying the packer/instrument combination at that depth and then using the CTDI to inject water around the instrument package. An additional tool that would be useful for some applications is a 'sonic transponder' that would allow the drillers to know exactly how far the bottom of the borehole is from potentially unfrozen sediments or the upper surface of a lake. This would allow a borehole to be drilled to within a few meters of these unfrozen environments and then stopped if desired. An instrumented cryobot could then be launched into a lake, for example. As with other logging tools, the sonic transponder could be attached directly to the CTH.

3.4. *CTDI implementation and logistics*

Large portions of the polar ice sheets are 3–4 km thick. To meet various scientific objectives, we recommend the CTDI be constructed to reach these depths. This is well within the technical ability of CT drilling systems. A primary issue in the design specifications is provided by the logistical constraints. While CT drills are presently capable of drilling holes as large as 32 cm, we recommend the CTDI drilling system be designed to produce small-diameter (7–8 cm) holes in the interest of portability. A small-diameter drilling system minimizes the logistics impact primarily by reducing the size of the tubing reel and the amount of drilling fluid required to fill the borehole. We believe nearly all the scientific objectives discussed in this paper can be satisfied with a small-diameter drilling system. Based on commercial availability, we recommend the use of 4.4-cm composite tubing, 5.4-cm or 6.0-cm steerable motors, and drill bits in the 7.0–7.9 cm size range. For the purpose of coring, the 6.0-cm motor and 7.9-cm drill bits are probably the better choice.

On-bottom drilling rates for commercial CT drills vary tremendously with the hardness of the rock being drilled. During the 1990s, rates of penetration (ROP) were about 24 m·hr^{-1} in low-strength glauconite (JPT, 1997), 9-21 m·hr^{-1} in sandstone, 7 m·hr^{-1} in moderately hard dolomite, and less than 2 m·hr^{-1} in hard limestone. 'Effective' ROPs, which include the additional time taken to clean the wellbore, survey the hole, and adjust equipment, can be about 75% of the 'true' ROP. Field tests with new high-power slimhole motors double these drilling rates (Cohen *et al*., 2000). With recent improvements, CT drills now regularly achieve ROPs of 45 m·hr^{-1} in sandstones in northern Alaska (R. Whitlow, pers. commun.). In contrast to rock, relatively little power is required to mechanically drill ice. Past experience suggests that ice can be mechanically drilled at about 60 m·hr^{-1}. The actual penetration rate for a CTDI drill operating in ice may be more a function of how quickly the ice chips can be pumped to the surface. To prevent a wellbore blockage, the chip concentration should be kept below 5% in the chip-fluid slurry. Estimated CT pumping rates indicate the chip concentration can be kept below 5% while drilling at 60 m·hr^{-1}. However, this assumes everything is working perfectly. A more realistic effective drilling rate may be 2/3 the peak rate, or 40 m·hr^{-1}.

A possible field layout for a 3.5-km CTDI drilling system is shown in Fig. 6. All components would fit on five sleds to facilitate mobilization and demobilization. Each sled would be transportable by an LC-130 aircraft, although the flanges may need to be removed from the tubing reel. Once in the field, the CTDI drilling system could be moved hundreds of kilometers along array transects using a large tracked vehicle such as a Challenger. Alternatively, the drilling system could be flown between research sites that are too far apart or are separated by crevasse fields. Estimated weights of the major system components are given in Table 2. The total weight of a CTDI drilling system would be ~26000 kg, including sleds. This is half the weight of deep ice-coring drills and less than 12% of the weight of hot-water drills capable of reaching the same depth (Table 3).

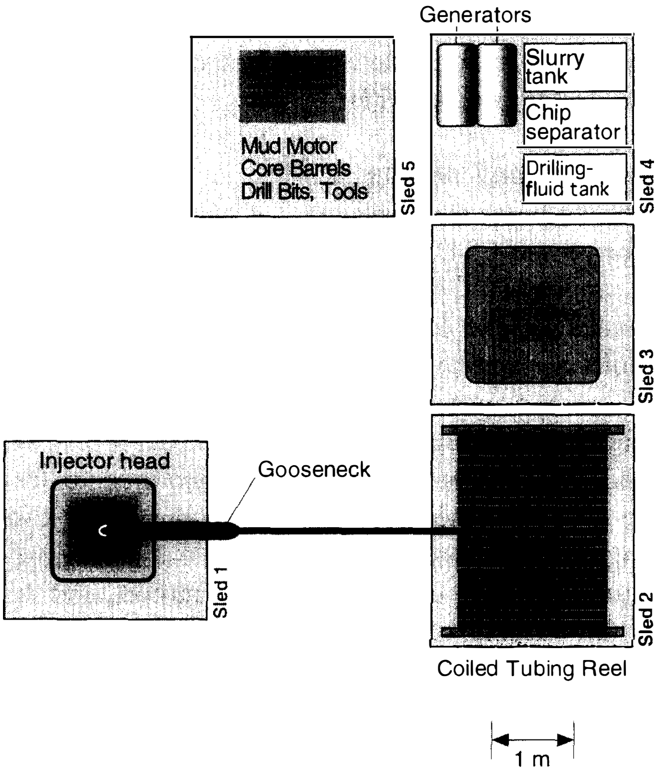

Fig. 6. Field layout for a sled-mounted 3.5-km CTDI drilling system. The system would consist of five sleds, each of which would be transportable by an LC-130 aircraft. Once in the field, the sleds could be pulled to new drilling sites by a large tracked vehicle.

Table 2. Weights of major components for a 3.5-km CTDI drilling system. Sled weights are included with the associated components.

Item	Weight (kg)
High-pressure pump	2000
Composite coiled tubing (4.4 cm)	5250
Tubing reel/winch	11300
Injector (including tower)	4300
BHA[†]	500
Chip separator	1000
Drilling-fluid holding tank	800
Generators[‡]	600
Total	~25750

[†] Includes drill collars for drilling ice.

[‡] Assumes the use of Microturbine generators; diesel generators would be 1500 kg heavier. Total power required is 50–60 kW.

Table 3. Comparison of the weights and times required to drill a 3.5-km borehole through ice using ice-coring, hot-water, and CTDI drilling systems.

	ICD[†]	HWD[‡]	CTDI
Drill weight (kg)	45000	227000	26000
Drilling fluid (kg)	91000	0	17000
Fuel (kg)	5000	45000	3000
Total weight, drill+fluids (kg)	141000	272000	46000
Field portability	no	limited	yes
Hole diameter (cm)	18	~30	7.9
Effective drilling rate ($m \cdot hr^{-1}$)	1.7	30	40
Total drilling times[§] (days)	$\geq 10^3$	10–12 *(30)*	6–8 *(4)*
Time hole remains open	indefinite	2–3 days	indefinite

[†] Based on USA's 13-cm ice-coring drill.

[‡] Based on the new Wotan hot-water drill (Koci, 2002); the existing AMANDA hot water drill does not have the power to reach 3.5 km.

[§] Total borehole production time including rigging-up and rigging-down, on-bottom drilling time, downtime, and miscellaneous activities. Numbers in parentheses indicate the number of additional days needed to setup for the first hole of an array.

Upon arrival at a field site, the CTDI sleds would be moved into position. All hydraulic and electrical connections would then be made-up and tested and the coiled tubing fed through the injector. Connecting the BHA is the next step. As BHAs for commercial CT drills are often ~18-m long, this step normally requires a crane. Although the BHA for a CTDI may not be quite 18-m long, it may very well be ~12-m in length. Rather than lift the injector 12–18 m above the surface to install the BHA, it would be far better to drill a 'starter' hole deep enough to accommodate the BHA. The BHA could then be lowered into the starter hole, the injector slid over the hole, and the BHA connected to the coiled tubing head. This procedure minimizes how far the injector must be raised and the height of the associated tower (used in lieu of a crane). To create the starter hole, we recommend lifting the injector just high enough (perhaps 2 m) to connect a jetting tool to the coiled tubing head. The CTDI could then be used to rapidly 'jet' a hole to the firn/ice transition. The next task is to seal the borehole walls through the firn layer in preparation for recirculating the drilling fluid back to the surface. This can be accomplished by installing fiberglass casing or by using the CTDI to inject a gel into the borehole walls above the firn/ice transition. Polymerizing gel injected into porous rock formations and/or fractures has been very successful at preventing the infiltration of pressurized water or gas into wells. This technique should also be capable of preventing the leakage of drilling fluid from a borehole into the surrounding firn. Now that the borehole has been prepared through the firn layer, the BHA can be installed as described above. The CTDI would then be ready for deep drilling.

By 1998, CT technology had improved to the point that 49% of the total time required to develop a new well in Arctic Alaska was actually spent drilling, liner operations took 9%, downtime consumed 9%, perforating well casing took 7%, rigging up/down took 7%, waiting on cement took 5%, and miscellaneous activities consumed 14% (Gantt *et al.*, 1998). If we can use the commercial experience as a guide, then of the total time spent creating a new borehole with the CTDI drilling system, about 55% will be on-bottom drilling time, 10% will be spent rigging-up and breaking-down the drill, 10% will involve drilling and sealing the firn layer, 10% will be downtime, and 15% will be used for miscellaneous activities. With an effective drilling rate of 40 $m \cdot hr^{-1}$, the total time needed to drill through 3–4 km of polar ice would be 6–8 days, including setup and breakdown time. The first hole along an array transect may require an additional 3–4 days to assemble items that are too large to fit in an LC-130 in their field-ready form. These items may include the tubing reel, the injector tower, and the chip separator. Still, with this speed it's unlikely a multi-season support camp would ever be required for CTDI drilling projects. Rather, we expect the drill would be moved to new drill sites several times per season. Commercial CT drills are typically operated by a crew of five but some of these people are involved in well-production aspects that would be irrelevant for CTDI drilling projects. We expect a CTDI could be operated by a very small crew (3 people). Without a multi-season camp, the support staff could be very small as well.

Total logistics requirements must include the transport of necessary drilling fluids and fuels to a drill site. Table 3 compares the weights, speeds, and other characteristics of the CTDI drilling system with hot-water drills and ice-coring drills capable of reaching similar depths (*i.e.* 3–4 km). The total weight of a CTDI drilling system plus fluids needed to create a 3.5-km borehole is 1/3 of the ICD+fluids weight and 1/6 of the HWD+fluids weight.

Although we advocate the development of a 3–4 km CTDI, there is an entire class of research problems that only require drilling to about 1 km. Drilling arrays of holes near ice streams is an example. Since a 1-km CTDI would utilize all the same components as a 3–4 km CTDI except for the amount of tubing, it may be advantageous to have a single CTDI drilling system with two tubing reels, one with 3–4 km of tubing and another with only 1.0–1.5 km of tubing. This takes advantage of the inherent modularity of the CTDI system. The CTDI drilling system doesn't have the same scaling issues as hot-water drills;

the situation is more analogous to an ice-coring drill. For a CTDI to drill deeper, the only thing that changes is the amount of tubing needed and the size of the associated winch; a slightly larger high-pressure pump may also be needed to overcome additional friction.

3.5. Special considerations for a polar CT drill

Although the bulk of commercial CT technology should be readily adapted to the CTDI drilling system, there are a number of issues that will require consideration. The minimum operating temperature for composite tubing is currently −40°C. At colder temperatures, the tubing liner becomes too brittle. For much of the East Antarctic Ice Sheet, temperatures are below −40°C in the upper 500 m of the ice. This problem could be solved by switching to a different tubing liner or by heating the drilling fluid to −40°C while drilling the upper 500 m where required in East Antarctica. Once the drill penetrates below 500 m, the circulating fluid will be warmed by passage through the warmer ice at depth. Heating would then no longer be necessary. The coldest subsurface temperatures on the Alaskan North Slope where much CT experience has accrued are about −11°C. Polar ice sheets are 20–40 K colder. Therefore, the long-term performance of composite tubing and other subsurface components (*e.g.* mud motors, circulation subassemblies, orienting tools) at very low temperatures and repeated drilling cycles should be evaluated. Component modification may be required in some cases.

Drilling fluids provide several critical functions for CT drills. These include: providing the pressure and flow rate needed to drive the mud motor, providing chip transport and suspension in the wellbore annulus, reducing the friction between the CT and the wellbore, stabilizing the borehole wall, and providing an environment in which to make accurate geophysical logs. For the polar regions, drilling fluids must also satisfy stringent environmental concerns. Thus, the U.S.A. for example has adopted n-butyl acetate as its primary drilling fluid. N-butyl acetate and other polar drilling fluids can be very chemically active. Commercial composite tubing and bottomhole assemblies are specifically designed to work in corrosive environments. Still, the long-term effect of exposure to chemically active polar drilling fluids on composite tubing and other components should be tested. Whether a proposed drilling fluid can satisfy the critical functions for a CT drilling system also needs consideration before the fluid is adopted.

Possibly the most critical area for CTDI development is finding a way to efficiently separate the chips from the drilling fluid once the slurry reaches the surface. This process may ultimately limit how fast the CTDI can penetrate ice. The separation process must be fast enough that the drilling fluid can be pumped back down the hole at the rates required to drive the mud motor and transport the chips back to the surface. Chip separation for commercial CT drills is accomplished through the use of a shaker table and high-speed centrifuge. These systems may need some modification to work properly with the CTDI drill.

Commercial cutting bits for CT drills are designed to optimize penetration rates and reduce reactive torques while drilling rock. New bits may need to be designed to optimize drilling rates in ice with a CTDI. Penetration rates also critically depend on the weight on the bit. The weight needed to provide optimal penetration rates in ice with the CTDI will need to be determined. This data is critical for deciding how much weight to incorporate into the drill collars, which influences the total length of the BHA, and for the computer software used to control the injector.

The ice cores that can be obtained with a CTDI would be perhaps 3–6 m long. Thus, depth must be known to within a meter when acquiring these targeted cores. Coiled tubing normally forms a helix in a wellbore making it difficult to accurately know the depth based on the amount of tubing spooled into the hole. This effect will still occur to some extent even with the use of drill collars, particularly if they only weigh about 100 kg. In addition, CT tubing can stretch as much as 1.2 m during a 3000 m roundtrip. To solve this problem, commercial CT drills use real-time gamma-ray data for accurate depth control. Some other method would need to be used with the CTDI. A real-time optical log (Fig. 3) may have the necessary depth resolution in ice although the area where the optical data are acquired would need to be free of suspended ice chips. It may be possible to achieve this by opening the circulation subassembly, stopping the bit rotation, and pumping clean fluid around the annulus surrounding the BHA.

One of the primary scientific objectives of the CTDI drilling system is the acquisition of rock cores. While it is believed advanced-composite tubing has adequate tensile strength to break rock cores free, this issue should be looked at more thoroughly. Commercial composite tubing has a tensile strength greater than 100 MPa. By comparison, sedimentary rocks (shales, sandstones) typically have a tensile strength less than 10 MPa while granites and diorites generally have tensile strengths less than 20 MPa (Lockner, 1995). However, rock strength is quite variable. Individual specimens of granite, diorite, gabbro, basalt, and amphibolite have been found with tensile strengths as high as 55 MPa, or half that of advanced composite tubing. If it is determined greater tubing strength is needed to obtain core from the harder rock types, stainless steel coiled tubing is available with tensile strengths as high as 700 MPa. Since CT drills are specifically designed to drill rock, there is nothing to prevent the CTDI drilling system from continuing to drill to great depths once rock is encountered.

4. Summary and conclusions

A number of outstanding polar research problems cannot be adequately addressed using current deep drilling systems. The limitations inherent in these drilling systems suggest that a third type of drill be developed for polar research. Given the needs of the research community, we suggest that such a drilling system be optimized for providing rapid access to depths of 3–4 km.

A fast mechanical-access drill based on commercial coiled tubing technology appears to provide the most capable and cost-effective way to obtain rapid access to great depths. This solution takes advantage of extensive coiled tubing research and development already done by the oil and gas industry. Commercial coiled tubing drills are presently used for a wide range of commercial applications and they are now extensively used in the Arctic. The bulk of the components needed to build a CTDI for polar research are commercially available, although they would in some cases need modification and testing to satisfy polar operating conditions and logistics.

The proposed drill (CTDI, Coiled Tubing Drill for Ice) is projected to achieve effective drilling rates of 40 $m \cdot hr^{-1}$ in ice. Thus, a 3–4 km deep hole could be drilled in 6–8 days, including setup time and downtime. With this speed, a CTDI could produce an array of deep boreholes in a single season. The LC-130 transportable CTDI drilling system would be sled-mounted for rapid mobilization and demobilization; the system could be pulled hundreds of kilometers along array transects using a large tracked vehicle such as a Challenger. The drill could utilize a number of environmentally sound drilling fluids, ranging from non-freezing hydrophobic fluids (*e.g.* n-butyl acetate) to hot water. We expect the drill would normally be operated with a non-freezing fluid, allowing the holes to remain accessible for years. A wide range of scientific investigations could then be done in each borehole (*e.g.* geophysical logging, long-term monitoring, ice sampling, rock coring). Deep access holes produced in this manner would rapidly recover from the thermal disturbance caused by drilling and have a uniform diameter, which is ideal for many types of geophysical measurements.

This type of drill has a great deal of modularity and flexibility inherent in its design. Since mechanical power, electrical power, and downhole communications are all available at the bottomhole assembly, the drill head can serve as a platform for a wide variety of tools, including core barrels, wellbore polishers, and side-wall samplers. Various tools and instruments can also be attached directly to the coiled tubing head by removing the BHA. Thus, geophysical measurements could be made in low- or high-angle sections of boreholes, packers and/or monitoring instruments could be deployed at any depth in a wellbore, instruments could be frozen into the ice at great depth, and cryobots could be launched into subglacial lakes. Given the flexibility of the CTDI design, new tools could be easily added to satisfy future research needs. The basic drill would be capable of acquiring rock cores, frozen sediment cores, and short ice cores. The proposed drill is also fully steerable, providing positive control over the drilling direction and giving it the capability of doing directional drilling in either access holes or previously drilled ice-core holes. Additional ice samples could then be obtained from interesting depths for further analysis. Multiple rock cores could also be obtained from a single vertical wellbore. The CTDI would be capable of drilling great distances into rock, although a blow-out protection system would be required in sedimentary environments.

Given the speed and flexibility of the CTDI drilling system, it could truly be thought of as an 'exploration' tool for polar research. It would provide rapid access to environments that are presently unreachable. If built, the CTDI drilling system would greatly enhance several lines of current research, as well as allow the pursuit of new scientific investigations that are not currently feasible. The CTDI drilling system could be utilized by a number of polar research disciplines, including: climatology, glaciology, geology, geophysics, and biology.

Acknowledgments

Many individuals generously contributed to the access drill concept. We especially thank Ted Stagg, Rick Whitlow, Jesse Colins, Anne Grunow, David Elliot, Ed Waddington, Kurt Cuffey and John Stone. David Fisher, Richard Jarrard, and John Behrendt provided thoughtful reviews that helped improve the manuscript. Thanks also to Gregg Lamorey and Ryan Bay who provided the sonic velocity and optical logs, respectively, shown in Fig. 3. Support for a portion of this investigation was provided by the U.S. Geological Survey's Global Change and Climate History Program.

References

Abyzov, S.S., Mitskevich, I.N. and Poglazova, M.N. (1998): Microflora of the deep glacier horizons of central Antarctica. Microbiology, **67**, 451–458.

Barghoorn, E.S. and Nichols, R.L. (1961): Sulfate-reducing bacteria and pyritic sediments in Antarctica. Science, **134**, 190.

Bay, R.C., Price, P.B., Clow, G.D. and Gow, A.J. (2001): Climate logging with a new rapid optical technique at Siple Dome. Geophys. Res. Lett., **28**, 4635–4638.

Behrendt, J.C., Blankenship, D.D., Finn, C.A., Bell, R.E., Sweeney, R.E., Hodge, S.M. and Brozena, J.M. (1994): CASERTZ aeromagnetic data reveal late Cenozoic flood basalts(?) in the West Antarctic rift system. Geology, **22**, 527–530.

Behrendt, J.C., Saltus, R., Damaske, D., McCafferty, A., Finn, C.A., Blankenship, D.D. and Bell, R.E. (1996): Patterns of late Cenozoic volcanic and tectonic activity in the West Antarctic rift system revealed by aeromagnetic surveys. Tectonics, **15**, 660–676.

Behrendt, J.C., Blankenship, D.D., Morse, D.L., Finn, C.A. and Bell, R.E. (2001): Removal of subglacially erupted volcanic edifices beneath the divide of the West Antarctic Ice Sheet interpreted from aeromagnetic and radar ice sounding surveys. Proceedings Volume 8th International Symposium on Antarctic Earth Sciences, ed. by J.A. Gamble *et al.* Wellington, N.Z., 6 p.

Bigio, D., Rike, A., Christensen, A., Collins, J., Hardman, D., Doremus, D., Tracy, P., Glass, G., Joergensen, N.B. and Stephens, D. (1994): Coiled tubing takes center stage. Oilfield Review, October 1994, 9–23.

Blake, E.W. and Price, B. (2002): A proposed sterile sampling system for Antarctic subglacial lakes. Mem. Natl Inst. Polar Res., Spec. Issue, **56**, 253–263.

Blankenship, D.D., Bell, R.E., Hodges, S.M., Brozena, J.M., Behrendt, J.C. and Finn, C.A. (1993): Active volcanism beneath the West Antarctic ice sheet and implications for ice-sheet stability. Nature, **361**, 526–529.

Clow, G.D. (1992): The extent of temporal smearing in surface-temperature histories derived from borehole temperature measurements. Paleogeogr., Paleoclimtol., Paleoecol., **98**, 81–86.

Clow, G.D. (1999): Quantification of natural climate variability in central Greenland and East Antarctica using borehole paleothermometry. International Union of Geodesy and Geophysics-99, Birmingham, England, B.249.

Clow, G.D., Saltus, R.W. and Waddington, E.D. (1996): A new high-precision borehole temperature logging system used at GISP2, Greenland and Taylor Dome, Antarctica. J. Glaciol., **42**, 576–584.

Cohen, J.H, Leitko, C.E and Long, R.C. (2000): Slimhole drilling system doubles penetration rates. Oil & Gas J., **98** (15), 67–69.

Connell, M., Isennock, C. and Headrick, D. (1999): Coiled tubing: applications for today's challenges. Pet. Eng. Int., **72**(7), 18–21.

Cuffey, K.M., Clow, G.D., Alley, R.B., Stuiver, M., Waddington, E.D. and Saltus, R.W. (1995): Large arctic temperature change at the Wisconsin-Holocene glacial transition. Science, **270**, 455–458.

Dahl-Jensen, D. (1985): Determination of the flow properties at Dye 3, South Greenland, by bore-hole-tilting measurements and perturbation modeling. J. Glaciol., **31**, 92–98.

Dahl-Jensen, D. and Gundestrup, N.S. (1987): Constitutive properties of ice at Dye 3, Greenland. The Physical Basis of Ice Sheet Modelling, ed. by E.D. Waddington and J.S. Walder. Wallington, IAHS, 31–43 (IAHS publ. 170).

Dahl-Jensen, D., Mosegaard, K., Gundestrup, N., Clow, G.D., Johnsen, S.J., Hansen, A.W. and Balling, N. (1998): Past temperatures directly from the Greenland ice sheet. Science, **282**, 268–271.

Denton, G.H., Sugden, D.E., Marchant, D.R., Hall, B.L. and Wilch, T.I. (1993): East Antarctic ice sheet sensitivity to Pliocene climate change from a Dry Valleys perspective. Geogr. Ann., **75A**(4), 155–204.

Elliot, D.H. (1994): The Late Mesozoic and Cenozoic history of Antarctica: some implications for sediment basin history, sediment provenance, and paleoclimate. Terra Antarct., **1**, 445–457.

Engelhardt, H., Humphrey, N., Kamb, B. and Fahnestock, M. (1990): Physical conditions at the base of a fast moving Antarctic ice stream. Science, **248**, 57–59.

Feiner, R.F. (1995): Bit selection increases coiled tubing and slimhole success. Pet. Eng. Int., **68**(7), 37–41.

Fisher, D.A. and Koerner, R.M. (1986): On the special rheological properties of ancient microparticle-laden northern hemisphere ice as derived from bore-hole and core measurements. J. Glaciol., **32**, 501–510.

Fowler, S.H., Feechan, M. and Berning, S.A. (1998): Development update and applications of an advanced-composite spoolable tubing. 1998 Offshore Technology Conference paper 8621, Houston, TX, 4-7 May, 6 p.

Gaddy, D.E. (2000): Coiled-tubing drilling technologies target niche markets. Oil & Gas J., **98**(2), 29–34.

Gades, A.M., Raymond, C.F., Conway, H. and Jacobel, R.W. (2000): Bed properties of Siple Dome and adjacent ice streams, West Antarctica, inferred from radio-echo sounding measurements. J. Glaciol., **46**, 88–94.

Gantt, L.L., Oba, E.M., Leising, L., Stagg, T., Stanley, M., Walker, E. and Walker, R. (1998): Coiled tubing drilling on the Alaskan North Slope. Oilfield Rev., **10**(2), 20–35.

Gow, A.J. and Engelhardt, H. (2000): Preliminary analysis of ice cores from Siple Dome, West Antarctica. Physics of Ice Core Records, ed. by T. Hondoh. Sapporo, Hokkaido University Press, 63-82.

Gundestrup, N.S. and Hansen, B.L. (1984): Bore-hole survey at Dye 3, South Greenland. J. Glaciol., **30**, 282–288.

Handfield, M., Koerner, R.M., Jones, H.G. and Guay, R. (1994): The recovery and culture of microorganisms from deep ice cores of the Agassiz Ice Sheet (80°N, 70°W), Ellesmere Island, Canadian Arctic Archipelago. Abstracts of the 94th General Meeting of the American Society for Microbiology, Las Vegas, Nevada, 329.

Hansen, B.L. and Gundestrup, N.S. (1988): Resurvey of bore hole at Dye 3, South Greenland. J. Glaciol., **34**, 178–182.

Johnsen, S.J., Dahl-Jensen, D., Dansgaard, W. and Gundestrup, N. (1995): Greenland palaeotemperatures derived from GRIP bore hole temperature and ice core isotope profiles. Tellus, **47B**, 624–629.

Jouzel, J., Barkov, N.I., Barnola, J.M., Bender, M., Chappellaz, J., Genthon, C., Kotlyakov, V.M., Lipenkov, V., Lorius, C., Petit, J.R., Raynaud, D., Raisbeck, G., Ritz, C., Sowers, T., Stievenard, M., Yiou, F. and Yiou, P. (1993): Extending the Vostok ice-core record of paleoclimate to the penultimate glacial period. Nature, **364**, 407–412.

JPT (1997): High-penetration-rate drilling with coiled tubing. J. Pet. Technol., **49**(6), 590-591.

JPT (1999): Advanced-composite spoolable tubing. J. Pet. Technol., **51**(5), 58-60.

Karl, D.M., Bird, D.F., Björkman, K., Houlihan, T., Shackleford, R. and Tupas, L. (1999): Microorganisms in the accreted ice of Lake Vostok, Antarctica. Science, **286**, 2144–2147.

Kennett, J.P. and Hodell, D.A. (1993): Evidence for relative climatic stability of Antarctica during the early Pliocene: a marine perspective. Geogr. Ann., **75A**(4), 303-330.

King, J.C. and Turner, J. (1997): Antarctic Meteorology and Climatology. Cambridge, Cambridge University Press, 409 p.

Koci, B. (2002): Wotan: a drill for ice cube. Mem. Natl Inst. Polar Res., Spec. Issue, **56**, 209-216.

LeMasurier, W.E. (1990): Late cenozoic volcanism on the Antarctic Plate: an overview. Volcanos of the Antarctic Plate and Southern Oceans, ed. by W.E. LeMasurier and J.W. Thomson. Washington, D.C., Am. Geophys. Union, 1–17 (Antarct. Res. Ser., **48**).

Lockner, D.A. (1995): Rock failure. Rock Physics and Phase Relations: A Handbook of Physical Constants, ed. by T. Ahrens. Washington, D.C., Am. Geophys. Union, 127–147.

Ma, L-J, Rogers, S.O., Catranis, C.M. and Starmer, W.T. (2000): Detection and characterization of ancient fungi entrapped in glacial ice. Mycologia, **92**, 286-295.

Mayewski, P.A., Wumkes, M., Klinck, J., Twickler, M.S., Putscher, J.S., Taylor, K.C., Gow, A.J., Waddington, E.D., Alley, R.B., Gibb, J.E., Grootes, P.M., Meese, D.A., Ram, M., Whalen, M. and Wilson, A.T. (1994): Record drilling depth struck in Greenland. EOS: Trans., **75**, 113-124.

Mayewski, P. and Goodwin, I. (1999): Antarctica's role pursued in global climate change. EOS: Trans., **80**, 398-400.

Nereson, N.A. and Waddington, E.D. (2002): Isochrones and isotherms beneath migrating ice divides to be published in J. Glaciol.

Petit, J.R. and 18 others (1999): Climate and atmospheric history of the past 420000 years from the Vostok ice core, Antarctica. Nature, **399**, 429-436.

Petit, J.R., Basile, I., Leruyuet, A., Raynaud, D., Lorius, C., Jouzel, J., Stievenard, M., Lipenkov, V.Y., Barkov, N.I., Kudryashov, B.B., Davis, M., Saltzman, E. and Kotlyakov, V. (1997): Four climate cycles in Vostok ice core. Nature, **387**, 359-360.

Price, P.B. (2000): A habitat for psychrophiles in deep Antarctic ice. Proc. Natl. Acad. Sci. U.S.A., **97**, 1247-1251.

Priscu, J.C., Adams, E.E. and Lyons, W.B. (1999): Geomicrobiology of subglacial ice above Lake Vostok, Antarctica. Science, **286**, 2141-2144.

Sas-Jaworsky, A. and Bell, S. (1996): Innovative applications stimulate coiled tubing development. World Oil, **217**(6), 61-69.

Scherer, R.P., Aldahan, A., Tulaczyk, S., Possnert, G., Engelhardt, H. and Kamb, B. (1998): Pleistocene collapse of the West Antarctic Ice Sheet. Science, **281**, 82-85.

Siegert, M.J., Dowdeswell, J.A., Gorman, M.R. and McIntyre, N.F. (1996): An inventory of Antarctic sub-glacial lakes. Antarct. Sci., **8**, 281-286.

Thorsteinsson, T., Waddington, E.D., Taylor, K.C., Alley, R.B. and Blankenship, D.D. (1999): Strain rate enhancement at Dye 3, Greenland. J. Glaciol., **45**, 338-345.

Tulaczyk, S., Kamb, B., Scherer, R.P., Engelhardt, H.F. (1998): Sedimentary processes at the base of a West Antarctic ice stream: constraints from textural and compositional properties of subglacial debris. J. Sediment. Res. A, **68**, 487-496.

Veevers, J.J. (1994): Case for the Gamburtsev Subglacial Mountains of East Antarctica originating by mid-Carboniferous shortening of an intracratonic basin. Geology, **22**, 593-596.

Webb, P.N. and Harwood, D.M. (1991): Late Cenozoic glacial history of the Ross Embayment, Antarctica. Quat. Sci. Rev., **10**, 215-223.

Webb, P.N., Harwood, D.M., McKelvey, B.C., Mercer, J.H. and Stott, L.D. (1984): Cenozoic marine sedimentation and ice-volume variation on the East Antarctic craton. Geology, **12**, 287-291.

Willerslev, E., Hansen, A.J., Christensen, B., Steffensen, J.P. and Arctander, P. (1999): Diversity of Holocene life forms in fossil glacier ice. Proc. Natl. Acad. Sci. U.S.A., **96**, 8017-8021.

Wuethrich, B. (1994): Ancient bacteria are frozen in time. New Sci., **143**(1934), 16.

(*Received March 13, 2001; Revised manuscript accepted September 27, 2001*)

Appendix: Access drills for exploring subglacial lakes

Ice-penetrating radar surveys and modeling studies suggest there may be many subglacial lakes beneath the Antarctic Ice Sheets (see Siegert *et al*., 1996). Lake Vostok is but one example, albeit an extraordinary one. Given the isolation of the Antarctic subglacial lakes, biologists are understandably very interested in investigating the environmental conditions within these intriguing lakes and any organisms that might be living there. However, strict preservation of the lakes' environmental isolation is a prime concern. Any experiments designed to probe or sample the lakes must be well-conceived to avoid contaminating either the lakes or the samples themselves. To this end, two systems have been proposed for entering subglacial lake environments. Both systems require an access hole be drilled to within 10–20 m of the ice/water interface. The first system involves launching a probe known as a cryobot from the bottom of an access hole into a lake (F. Carsey, pers. commun.); the cryobot melts its way through the 10–20 m of ice with the hole refreezing behind itself. Information from various sensors is transmitted to the surface through a communications cable. The second system utilizes an electrically-heated completion drill to deploy a sterile sampling system into a lake (Blake and Price, 2002). In this case, samples are returned to the surface. There are only two types of drills, hot-water drills and CT drills, that potentially can create the access holes required to explore the subglacial lakes with either of these technologies in a reasonable amount of time.

Using hot water for the access-hole drilling fluid has a distinct advantage in this application in that it minimizes the risk of contamination. However, a hot-water drill capable of reaching 3700 m (using Lake Vostok as an example) would be truly enormous. Even the new Wotan drill (Koci, 2002) would be unable to reach these depths in its present design configuration. A larger version of Wotan could probably reach 3700 m if the water pressure is increased from 6.9 MPa to 10.3 MPa and the flow rate increased to 950 $l\cdot\mathrm{min}^{-1}$. The weight of such a drill would exceed Wotan's 227000 kg. In addition, we estimate 50000–60000 kg of fuel would be needed to power the drill. Although a Wotan-type HWD would be capable of drilling the access holes, the shear size of this drilling system would limit the number of subglacial lakes that could be explored using this technology.

A coiled-tubing drill can also use hot-water as the drilling fluid. However, the energy requirements are much more modest than with a traditional HWD. A CT drill utilizing hot-water would still use mechanical energy to do the actual drilling. Thus, much less heat needs to be delivered to the drill head. The hot-water is simply used to drive the hydraulic downhole motor and drill bit, transport the chips to the surface, and maintain the hole. Once an access hole is drilled, the CT drill can be tripped to the surface, the BHA removed, the sterile sampling system or cryobot connected to the CT head, and the CT tripped back down the hole where the sampling system or cryobot would be released. The coiled tubing could then be left in the hole continuing to circulate hot water and providing communications to the sampling system or cryobot. Should the hole refreeze to the point that the CT string cannot be retrieved, the coiled tubing would at least provide a conduit through which samples could be returned to the surface. Coiled tubing has a high collapse resistance. Thus, it should be able to withstand freeze-back pressures.

Alternatively, a CT drill could utilize a non-freezing fluid such as n-butyl acetate to drill an access hole for subglacial lake investigations. The advantage of this approach is that the access hole would remain open indefinitely and thus would be available for sample retrieval or subsequent experiments. Without the danger of imminent borehole freeze-back, the process of cryobot deployment or sample acquisition could proceed in a very controlled methodical manner. We believe each step of the experiment can be designed so that there is a safe fall-back position from the standpoint of preventing contamination. A possible scenario is as follows: 1) An access hole would be drilled with pure n-butyl acetate or some other non-freezing fluid. As with commercial CT drilling, the hole would be drilled in an underbalanced manner. This will greatly reduce the likelihood that the drilling fluid could infiltrate the surrounding ice *via* any fractures and thereby possibly contaminate the lake as the borehole nears the ice/water interface. The BHA's instrument package could include a video camera, an optical logger, and a sonic logger to continuously monitor conditions in the surrounding ice. If it appears the drilling fluid is leaking into the surrounding ice, hot water could be quickly pumped through the CT to flood the lower section of the hole where it would be allowed to freeze while a new approach is devised. Another possibility is to use the coiled tubing to coat the borehole walls with a polymerizing gel to stop any leakage. 2) If the hole is successfully drilled without any leakage, the coiled tubing would be used to deploy the cryobot or sampling system at the bottom of the hole. 3) The outer surface of the cryobot or sampling system will be coated with drilling fluid while it is being installed. To sterilize the outer surface of these instruments, the CT can be used to flood the lower section of the hole with hydrogen peroxide. Intense ultraviolet light could also be used to sterilize the equipment. Once sterilization is complete, the lower section of the hole can be flooded with water and a packer installed to isolate the water-filled section from the drilling fluid above. The packer probably isn't necessary but would offer greater protection. With the packer in place, it is unlikely that drilling fluid could get into the lake even if the bottom of the access hole is breached into the lake. A double packer surrounding 10 m of water that refreezes to form an ice plug would offer even greater protection. 4) The cryobot or sampling system would now be free to melt its way into the lake. 5) Sample return would proceed in reverse order utilizing the existing access hole. CT drills offer such a wide range of capabilities that other workable scenarios probably can be devised.

The size of the coiled tubing needed for a subglacial CT drill will depend on the dimensions of the probes or sampling systems to be deployed. Current cryobot designs have an outer diameter of 10–12 cm while the diameter of the sterile sampling system proposed by Blake and Price (2002) is 20 cm. Holes as large as 13 cm can probably be drilled with the CTDI drilling system proposed in the bulk of this paper. However, creating holes large enough to accommodate a 20-cm sampling system would require the use of tubing at least 6.0 cm in diameter. The tubing reel for this size CT would not fit in any existing ski-equipped aircraft and thus would need to be moved between drilling sites using a large traverse vehicle. The weight of a CT drill needed to create 13-cm holes would be about 28000 kg while that for a drill capable of drilling 22-cm holes would probably be 52000–77000 kg. The weight of the fluids would depend on whether the holes are being drilled with hot water or a non-freezing fluid.

Although either a hot-water drill or a CT drill could be used to create the access holes needed to investigate conditions within the Antarctic subglacial lakes, we believe a CT drill has a number of advantages over a traditional HWD for this application: 1) coiled tubing is strong enough to support its entire weight, 2) coiled tubing can operate at much higher pressures than can HWD hoses, 3) electrical and/or fiber-optic conductors can be embedded in the tubing so there's no need to strap (*i.e.* 'tie-wrap') a separate cable to the tubing in order to provide downhole communications, 4) it is fully steerable, providing greater control, 5) mechanical power is available downhole, 6) the CT drill can be used to deploy instrument packages and packers at depth, 7) either hot water or non-freezing fluids such as n-butyl acetate can be used for the drilling fluid, 8) if the CT drill uses hot-water as the drilling fluid, its energy requirements are much less than those of a traditional HWD, 9) other fluids such as hydrogen peroxide or polymerizing gels can be delivered downhole, 10) the coiled-tubing can be used as a conduit to return samples to the surface, and 11) the inherent flexibility of the CT design and the wide range of available options suggest that a CT drilling system could be used to successfully respond to a wide range of unexpected situations.