Instruments and Methods

Portable system for intermediate-depth ice-core drilling

V. Zagorodnov, L. G. Thompson, E. Mosley-Thompson

Byrd Polar Research Center, The Ohio State University, 1090 Carmack Road, Columbus, Ohio 43210-1002, U.S.A.

ABSTRACT. A lightweight, portable drilling system for coring up to 500 m depths has been developed and field-tested. The drilling system includes four major components: (1) an electromechanical (EM) dry-hole drill; (2) an ethanol thermal electric drill; (3) a drill set-up with a 500 m cable capacity; and (4) a controller unit. The system may be switched quickly from a dry-hole EM drill to an antifreeze thermal electric drill. This lightweight system makes ice-core drilling more cost-efficient, and creates a minimal environmental impact. The new EM drill, which recovers 100 mm diameter, 1 m long pieces of ice core, is 3.2 m long and weighs 35 kg. This drill and the drilling set-up were recently tested at the Raven (former Dye 2) site, southern Greenland, where a core was recovered to 122 m. The thermal drill is 2.9 m long and weighs 25 kg. It produces 100 mm diameter, 2.1 m long pieces of ice core, and was tested to 315 m in Franz Josef Land, Eurasian Arctic. The drilling set-up with a 250 m cable weighs about 100 kg (or 128 kg for 500 m of cable). After minor adjustments this drill system retrieved cores of better quality than those recovered by other drill systems under similar glaciological conditions. After adjustments to optimize its performance, the drill retrieved 5.25 m of core per hour over the depth range 0–21 m.

INTRODUCTION

Since our first high-elevation drilling on the Quelccaya ice cap in a remote region of Peru in 1983 we have used various versions of electromechanical (EM) and thermal drills (TD) to retrieve cores from >4500 m a.s.l. (Table 1). The deepest such core, 308 m to bedrock on the Guliya ice cap, China, was obtained using an EM drill to 198 m and an ethanol TD from 198 to 308 m. This project demonstrated the need for both types of drill, as each has advantages. The EM drill penetrates faster than the TD and operates in a fluid-free (dry) hole. Where the ice is warmer and rapid hole closure is possible, the slower-penetrating TD provides good quality core and the ethanol mixture slows closure of the borehole. Additionally, ethanol has a lower environmen-

tal impact than other commonly used drilling fluids (Gosink and others, 1991).

Conventional thermal and mechanical drills, developed for ice-coring in the Arctic and Antarctic, are not suited for drilling on high-elevation glaciers. The EM drills for 100 mm ice-coring are heavy and require a tall (5–6 m) hoisting mast. Although portable TDs produce smaller-diameter (80–85 mm) cores, they also require a heavy drilling set-up. Here we summarize our development of a reliable, portable, lightweight and cost-effective drilling system capable of retrieving ice cores to 500 m depths from glaciers with temperatures ranging from 0° to −30°C. Particular attention was focused on designing a system that requires less human effort to deliver, assemble and operate at high elevation. Low power requirements and minimal environmental impact were also considered important improvements for the new drilling system. This paper describes a new EM drill and a lightweight 500 m drilling set-up developed for high-elevation, intermediate-depth ice-coring. The results of three field tests of this EM drill on high-elevation glaciers and at the Raven (former Dye 2) site, southern Greenland, are presented. The new ethanol TD is described in a separate paper (Zagorodnov and others, 1998).

Table 1. High-elevation ice-coring operations in support of the Ohio State University Ice Core Paleoclimate Program

Site	Year	Elevation	Drill	Depth	Temperature
		m a.s.l		m	°C
Quelccaya, Peru	1983	5670	TD PICO	163.6	temperate
Dunde, China	1987	5325	EM PICO	139.8	−4.7 (base)
Guliya Ice Cap, China	1992	6200	EM PICO	198	−6 (200 m)
			TD ATED	198–308	−2 (at base)
Huascaran, Peru	1993	6048	TD ATED	160, 166	−5 (82 m)
Sajama, Bolivia	1997	6542	EM BPRC	39	−10.3
			EM PICO	132, 132.5	
Dasuopu, China	1997	7190	EM BPRC	27	−14
			EM PICO	140, 140, 160	

Notes: TD, thermal drill; EM, electromechanical drill; PICO, Polar Ice Coring Office; ATED, antifreeze thermal electric drill; BPRC, Byrd Polar Research Center.

A BRIEF REVIEW OF DRY-HOLE EM ICE-CORE DRILL DEVELOPMENT

The first dry-hole EM drills were field-tested in 1973 (Rand, 1976; Rufli and others, 1976). After several modifications, the first 100 m deep core from a dry hole was taken at Dye 2 in September 1974 (Rand, 1976), followed by two more 100 m cores in Antarctica using the same drill (Rand, 1975). Several shallow cores were recovered in central Greenland in 1974 with the University of Bern drill (Rufli and others, 1976).

Since then several different versions of these EM drills have been developed and successfully used to recover cores from various glaciers. The specifications for most of these drills are presented in Table 2.

All EM drills consist of the following principal components: a coring head equipped with cutters and core catchers; a core barrel with spiral flights; an outer jacket; a geared motor; an anti-torque; and a cable connection. In addition, most drills have a slip-ring device which prevents cable damage when the anti-torque fails. To detect an anti-torque failure during penetration, some drills have a rotation sensor. Some drills are equipped with a hammer which assists in breaking the ice core and freeing it when it is stuck (Johnsen and others, 1980). Torque limiters (friction clutch) were included in some drill designs (Rufli and others, 1976); Holdsworth, 1984). Four types of anti-torque devices have been used: hinged friction blades (Ueda and Garfield, 1969), leaf springs (Rand, 1976), skates (Rufli and others, 1976) and side cutters (Suzuki and Takizawa, 1978). Small-diameter (5.6 mm) electromechanical cables were used with dry-hole EM drills (Johnsen and others, 1980). However, the high loop resistance of these cables does not allow their use with TDs, which require more power (>3 kW).

Johnsen and others (1980) found experimentally that three cutters in the coring head produce the best-quality core. Experiments confirmed that a cutting speed of 0.5–2.0 m s^{-1} by cutters with 45° rack and 15° relief angles was optimal. The most efficient chip removal was achieved with 4–5 mm thick nylon flights mounted at a 45° angle (Johnsen and others, 1980; Litwak and others, 1984; Suzuki and Shimbori, 1984).

Originally, these drills were developed for 100 m depth firn- and ice-coring. Field experience and modifications allowed routine ice-coring down to 140–150 m and in rare instances to 350 m. Generally, ice-core quality diminished below 100 m, and below 150 m the ice-core production rate slowed down (Gillet and others, 1984; Litwak and others, 1984; Clausen and others, 1989; Schwander and Rufli, 1994).

Most of these drilling systems were developed to operate in polar regions where airborne and ground transportation support are available. Shallow and intermediate-depth ice-coring systems were designed to operate specifically on high-elevation glaciers (Zhu and Han, 1994; Blake and others, 1998). The basic technical information necessary for development of our drill system is available in the papers cited.

BYRD POLAR RESEARCH CENTER EM DRILL

The Byrd Polar Research Center (BPRC) EM drill meets three major requirements: (1) lightweight, (2) short length and (3) simple operation. The EM drill produces 100 mm diameter core in up to 1.1 m length pieces and is fully compatible with our recently developed and field-tested ethanol TD (Zagorodnov and others, 1998). To construct the lightweight, short drill the S-type schema was chosen (Arnason and others, 1974; Suzuki and Shimbori, 1985, 1986). S-type drills have the advantage of a relatively short chip-storage compartment that is easily and quickly emptied. Schematics and specifications of the drill are shown in Figure 1 and Table 2.

As an S-type drill the BPRC EM drill has a core barrel attached to the central shaft (5 in Fig. 1), and the space above the core barrel is used as a chip-storage compartment. In the past, similar chip-removal systems, including core barrel, auger flights and booster auger, were used only in fluid-ice-core drills (Arnason and others, 1974; Tanaka and others, 1994). In order to lift chips between the core barrel and jacket without fluid, 18 longitudinal grooves, 6.5 mm wide, 1 mm deep and 1200 mm long, are machined in the lower section of the jacket. To provide chip transport above the core barrel, two booster augers are attached to the main shaft. The shaft and core barrel, and shaft and gear are coupled with quick-removal pins. The perforated-disk sweeper, which prevents chips from falling out of the drill, is attached to the top of the shaft. To remove the ice core and chips when

Table 2. Specifications of the cable-suspended dry-hole EM ice-core drills

Drill[*]	Maximum drilled depth	Ice temp.	Length of drill/core	Diameter of hole/core	Weight of drill/core	Penetration rate	Core production rate	Power	Cable diam./ weight (100m)	Source
	m	°C	m	mm	kg	mm s^{-1}		kW	mm/kg	
CRREL	100	−14; −49	3.60/1	142/100	65/7.2	17	max. 6.6 m h^{-1}	1	9.5/35[†]	Rand (1976)
PIUB	50 to	−14 to 30	4.0[†]/0.9	115/75	<50/4	10–20	10 m h^{-1}	0.5	17/39	Rufli and others (1976);
	304.8	−30	–	143/105	–	–	<20 m d^{-1}	–	–	Schwander and Rufli (1989, 1994)
UCPH	325	−32	3.50/1	104/78	40/4.4	–	75 m d^{-1}	0.45	5.6/12.3	Johnsen and others (1980); Clausen and others, (1989); Gundestrup and others, (1989)
RU	73.6	–	4.70/1[†]	117/75	–	–	52 m d^{-1}	0.45	10/27	Jessberger and Dörr (1984)
NHRIE	202	−51	3.70[†]/1	144/100	55[†]/6.9	–	40 m d^{-1}	0.74	8/24[†]	Holdsworth (1984)
PICO	350	−49	4.70[†]/1	142/102	80[†]/7.3	5	40 m d^{-1}	1	11/42	Litwak and others (1984); Mosley-Thompson and others (1990)
BZXJ	90	–	1.60/0.35	91/67	11/1.12	10	50 m d^{-1}	0.37	–	Zhu and Han (1994)
JARE	143	−45	2.54/0.5	146/105	65/7.9	5	30 m d^{-1}	1	10[†]/36	Suzuki and Shiraishi (1982)
LGGE	203	−32	4.20/1.2[†]	144/100	120/8.6	–	–	1	–	Gillet and others (1984)
HILDA/ ECLIPSE	350/161.6	−22/−?	3.60/1	112[†]/82	50/4.9	11	30 m d^{-1}	0.180	4.8/9.1	Blake and others (1998)
BPRC	122	−14	3.24/1.05	129/100	35/7.2	5–14	3–6 m h^{-1}	0.60	8.1/11.8	This work

[*] CRREL, Cold Regions Research and Engineering Laboratory; PIUB, Physikalisches Institut, Universität Bern, Switzerland; UCPH, University of Copenhagen; RU, Ruhr-Universität, Bochum, Germany; NHRIE, National Hydrology Research Institute, Environment Canada; PICO, Polar Ice Coring Office; JARE, Japanese Antarctic Research Expedition; LGGE, Laboratoire de Glaciologie et Géophysique de l'Environnement; BPRC, Byrd Polar Research Center.

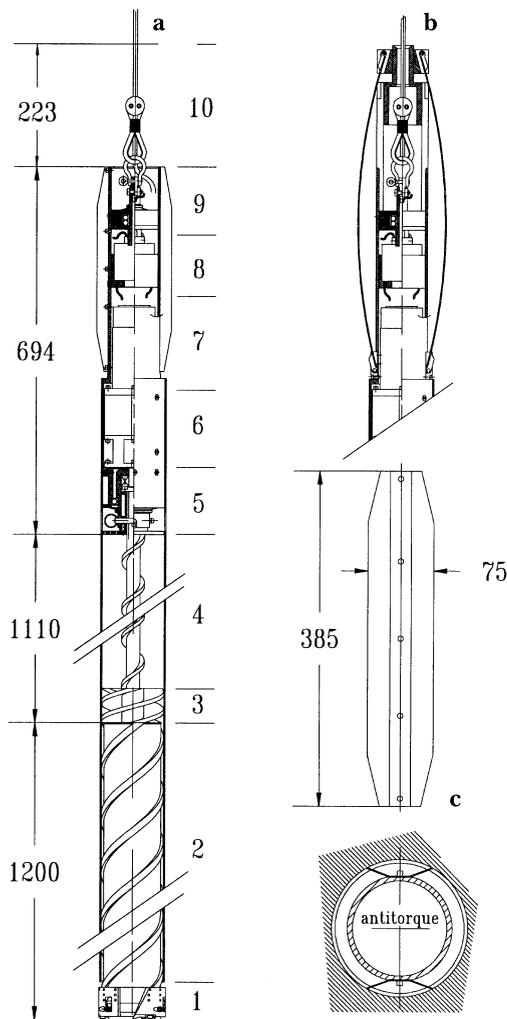[†] Value not presented in source(s): authors' estimation.

Fig. 1. BPRC EM drill with U-blade anti-torque (a) (1, coring head; 2, core barrel; 3, booster auger; 4, chip compartment; 5, coupling; 6, gearbox; 7, motor; 8, slip ring; 9, swivel, 10, cable termination), conventional anti-torque (b) and U-blade anti-torque (c); dimensions in mm.

Two anti-torque units were developed: (1) a U-blade anti-torque made of 0.20 and 0.38 mm thick spring stainless steel (C in Fig. 1), and (2) the conventional anti-torque made of four leaf springs (B in Fig. 1).

The BPRC drill can be transported completely assembled in a fiberglass tube (which also serves as the hoisting mast) or partially disassembled in five sections: (1) outer jacket, (2) core barrel, (3) auger–shaft, (4) motor–gearbox and (5) anti-torque housing. The longest section of the drill is the outer jacket (2540 mm), and the heaviest (11.2 kg) is the motor–gearbox, which includes a ball-bearing support and top coupling unit.

DRILLING SET-UP

The newly developed coaxial, Kevlar cable, 8.1 mm in diameter, has two conductors. The 500 m length cable has a loop resistance of 5.5 Ω, and weighs 56 kg. This cable was used for both EM and TD drilling operations. A molded plastic jacket on the cable prevents uplifting of the drilling fluid out of the borehole.

The use of a small-diameter cable significantly reduces the weight and size of the hoisting winch. The drilling set-up (Fig. 2) includes a winch, a base frame, a fiberglass mast, a top sheave, a tilting table and a controller. The winch is powered with a 1.5 kW permanent magnet d.c. motor directly coupled to a 56:1 planetary gearbox. The winch drum is attached to the gearbox output shaft, and the drum–motor assembly is attached to an aluminum frame. The motor–gearbox–drum–frame assembly weighs 35 kg. For an 8 mm diameter cable, the maximum drum capacity is 500 m. The pulling capacity of the winch is about 400 kg with an empty drum, and about 200 kg with a full drum. The maximum raising speed is 0.52 m s^{-1} with an empty drum, and 0.9 m s^{-1} with a full drum. The maximum gravity-lowering speed of the EM drill in a dry hole is about 1.5 m s^{-1}. The rear shaft of the winch motor has a square socket which allows movement of the drill up and down with either a crank handle or an auxiliary or "penetration-drive" motor. This motor feeds the cable at a constant speed during penetration.

The base frame is constructed of three aluminum channels bolted together. The hoisting mast consists of a 3.35 m long fiberglass tube, which also serves as a drill-shipping container. On top of the mast is a 0.3 m diameter pulley coupled to a bidirectional shaft encoder (1024 ppr) and fixed to a platform, which is supported by two load cells. The mast is fixed in a tilted (2–3°) position by thin-wall aluminum tubes. This support structure also serves as a ladder which the operator can climb up if adjustments are needed. Standard slip-on fittings allow fast assembly of the drilling rig. The drilling set-up is vertically stable without additional support. The entire system can be unpacked and assembled by one person in about 4 hours. The system can be pre-assembled into four components (winch with cable, drilling mast, drill and controller) that are easily transportable by either sled or Twin Otter and that can be assembled by one person in about 20 min.

To increase efficiency and avoid heavy lifting, a tilting table (TT) has been developed. The TT is made of a standard aluminum channel rotated on a horizontal shaft (Fig. 2) and is normally in a vertical position. To position the drill horizontally, it is moved over the TT and lowered to rest on the removable base support. With the cable free, the drill
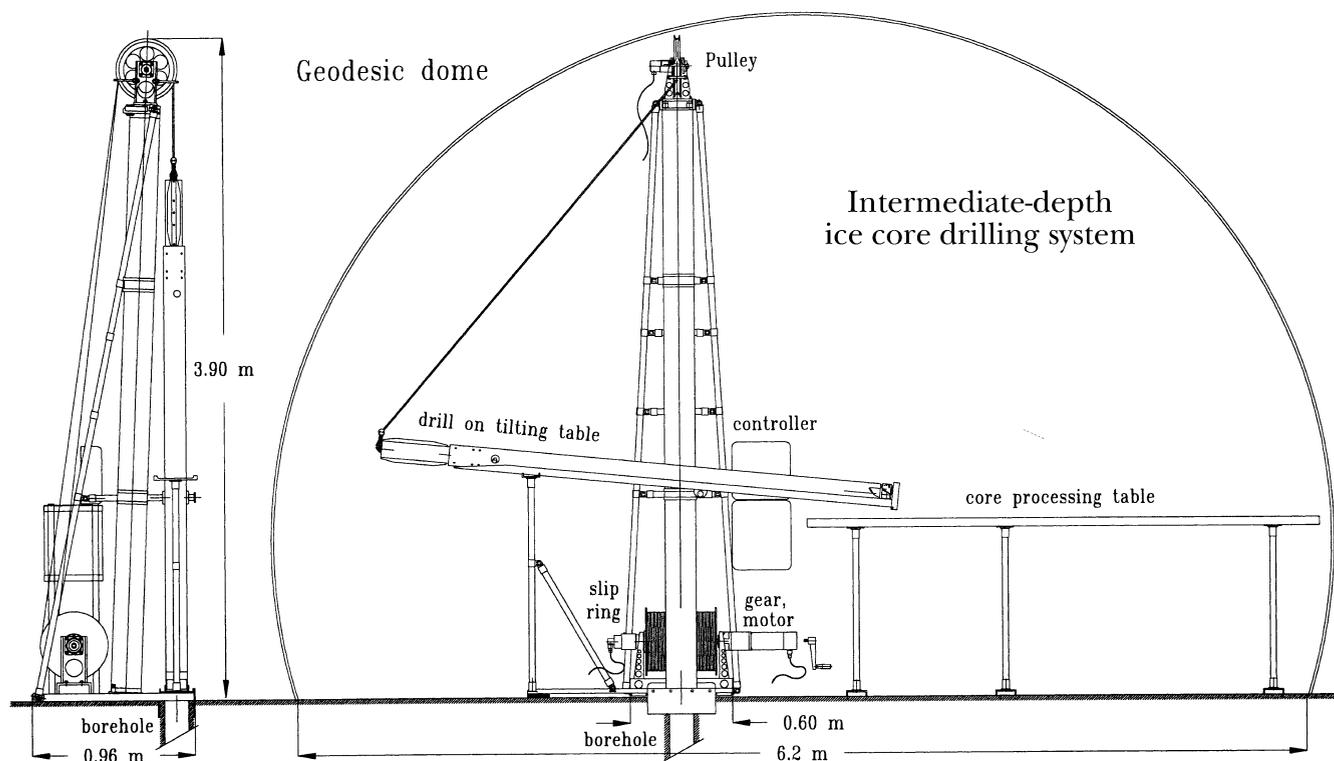
the drilling run is completed, the drill is placed horizontally on the tilting table (described below), where the shaft is separated from the gear shaft and the core-barrel–shaft assembly is removed from the jacket. Simultaneously a sweeper moves all the chips from the storage compartment. Once the core barrel is disconnected from the shaft, the core is removed from the top end of the core barrel.

The coring head is equipped with three cutters and three "bird beak"-shaped core catchers. The head is attached to the core barrel with screws. Originally cutters had 25° rack and 15° relief angles, but during the 1998 field test the relief angle was increased to 20°. Cutters and core catchers are made of stainless steel heat-treated to 50–55 Rockwell hardness. Three flange-head screws serve as adjustable penetration limiters. The cutting pitch can be changed by adding or removing flat washers. For penetrating ice with the described cutter geometry the optimal experimental clearance was found to be about 1mm. The drill is powered with a 0.57 kW d.c. motor. Because the drill is cutting a narrow kerf (14 mm), the specific energy available for ice-cutting and chip transport is close to or higher than that of some of the heavy prototype drills (Table 2) equipped with a 1 kW motor but which have a wider kerf. For high-elevation glaciers, enough power must be used to penetrate thick layers of dust and particle-laden ice.

Fig. 2. Portable intermediate-depth ice-core drilling system.

and TT may be turned by gravity to a slightly inclined position, where the top of the TT rests firmly on a support. Now the core barrel–shaft can be easily disconnected and removed from the jacket. The TT enables one person to operate the TD or the EM drill, and provides a rigid base for assembling the drills or making adjustments. This drilling set-up was designed to operate either in the open air or inside a geodesic dome (Fig. 2).

The EM drill controller provides two (drill and winch) adjustable 120 V d.c. outputs with a maximum current of 15 A. It also monitors the depth (1 mm resolution) up to 999 m in a digital format, as well as the cable tension (0.1 kg resolution). A thyristor-type drill controller supplies ±0–120 V d.c. for the EM drill and 0–350 V d.c. for the TD. The same controller can be used with a winch for hoisting operations. During penetration the winch motor is controlled by a servo-amplifier with a load-cell feedback. Three control options for the winch motor have been tested: (1) manual speed control (hoisting up/down), (2) manual torque control (hoisting up/down) and (3) auto-constant torque mode (penetration with constant cable tension or constant drill-kerf pressure). The cable tension and winch- or drill-motor current are constantly logged on a data acquisition system; a sample of these data is shown in Figure 3. The total weight of the drilling equipment including shipment containers, two EM drills, tools, spare parts for drill and winch (motors, gearboxes) and spare controller is 356 kg; the shipment volume is about 1 m^3.

DRILLING-SYSTEM PERFORMANCE

The EM drill was first tested in July 1997 on the Sajama ice cap, Bolivia. A snow–firn–ice core 40 m in length was taken during 15 working hours. The drill performed well except for the anti-torque system: the thin (0.2 mm) U-blades were bent almost every drilling run. Thicker U-blades (0.38 mm)

were prepared for a second drill test on the Dasuopu glacier, China (September 1997). Here a 27 m ice–firn core was taken in 10 hours. It was found that in layered firn–ice sequences thicker U-blades offered substantial resistance when the drill was lowered in the borehole. Otherwise, the drill performed well.

The final test and tuning of the new EM drill was conducted at the Raven site in May 1998, where two boreholes 122 and 21 m deep were drilled during 6 days. Here the drill was set inside a dome shelter, where air temperature was often slightly above the melting point. Measured borehole temperatures were in the range $-14.6°$ to $-15.4°$C. Drill performance specifications during the Raven test are shown in Table 3 and Figure 3.

Much of the drill-test effort was focused on optimization of the angle of U-shaped anti-torque blades to allow penetration of the layered firn–ice sequences. Instead of four, a single pair of 0.38 mm thick U-blades was mounted on the drill, which allowed coring from the surface down to 110 m,

Table 3. Drill performance specifications

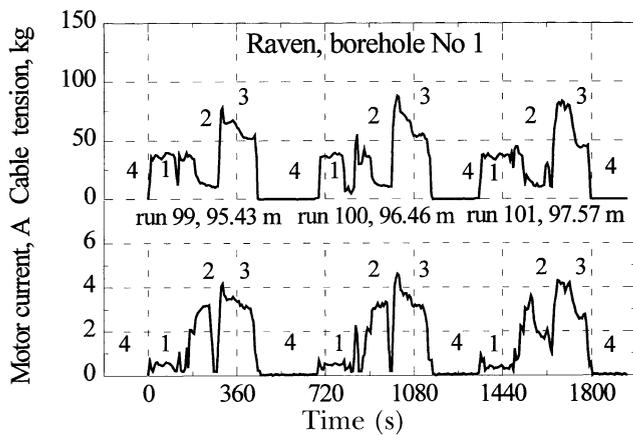| Date (1998)	Depth	Drilling time	Penetra-tion rate	Core pro-duction rate	Lowering/raising rate
	m		mm s^{-1}	m d^{-1}	m s^{-1}
Core 1					
13 May	0–5.0	3 h 00 min	–	5 (1.67)	–
14 May	5.0–43.46	10 h 20 min	8.7	38.46 (3.73)	0.29/0.37
15 May	43.46–79.76	12 h 15 min	5.0	36.3 (2.96)	0.54/0.57
16 May	79.76–109.76	8 h 10 min	5.3	30.0 (3.67)	0.61/0.68
17 May	109.76–112.36	2 h 00 min	–	2.6 (1.3)	–
18 May	112.36–122	3 h 10 min $\Sigma = 39$	6.0	9.64 (3.04)	0.79/0.65
Core 2					
18 May 98	0–21.0	4 h 00 min	14	21 (5.25)	0.25/0.44

Fig. 3. Fragment of drilling log data: 1, drill lowering; 2, penetration; 3, drill raising; 4, chips and ice-core recovery.

at which point a conventional anti-torque was mounted (Fig. 1b). The anti-torque was changed in order to test and compare performance of these different devices. The second borehole was drilled using only conventional anti-torque. Although the U-shaped anti-torque blades worked satisfactorily, the drill performed better with the conventional anti-torque system. The conventional anti-torque increased the weight of the drill by 5 kg, which contributed to smoother passes between ice and firn layers.

The results of the drill test indicate that ice layers interbedded with the firn present major difficulties for drilling. We found that the penetration rate of the EM drill is much higher in the firn than in the ice; in addition, ice-coring requires a higher bottom pressure. The U-blade anti-torque contributes vertical drag depending upon the specific properties of ice–firn sequences. When the anti-torque is in an ice layer the drag substantially increases. Therefore, if the anti-torque blades are in contact with an ice layer and the drill bit is penetrating an ice layer, the pressure on cutters is reduced, causing the cutters to slip. This effect was not observed when the drill penetrated firn layers. When the blades were arranged to provide lower wall pressure and lower vertical drag, respectively, the anti-torque tended to slip in the firn layers.

A conventional, leaf-spring anti-torque provided less vertical drag and smoother motion between ice and firn layers. It improved drill performance and core quality. However, wall-pressure adjustments became necessary at 4–6 m and below 15 m. The depth of these adjustments depends on both firn density and the frequency and thickness of ice layers. The denser the firn and more frequent the ice layers, the less tension is required on the anti-torque springs. During the second borehole drilling, we found that the constant-speed penetration drive also improved the overall drill performance. It provided cable feeding of 14 mm s^{-1}, which was found to be optimal for the given properties of the ice–firn sequence at Raven site.

Below 80 m the cutters tended to slip more frequently. To avoid this, the relief angle of the cutters was increased and the anti-torque springs were relaxed. Both adjustments increased bit pressure and improved drill performance. The first sign of stress in the ice appeared near 85 m where longitudinal fractures occurred in some ice-core sections. However, the quality of the core was quite good along the entire 122 m of core, and none of the core sections drilled exhibited wafering. Up to 83 m the drill produced 1.03–1.08 m long sections of core, and at greater depths the lengths of the core sections varied between 0.4 and 1.02 m, with an average length of 0.83 m.

The maximum inclination of the first borehole, 2.5°, was measured at 10 m depth. Below 33 m the borehole inclination was in the range 0.5–1.5°. The second borehole was vertical from top to bottom. The larger inclination of the upper part of the first borehole resulted from numerous experiments with the penetration drive and anti-torque system. The drilling-log data (Fig. 3) show that most of the penetration was conducted with the cable tension too low, which permits the drill to deviate from vertical. Since both boreholes were very close to vertical, we suggest that the pendulum steering resulted from the anti-torque drag.

Based on field data and drill dimensions, the density of the chips in the storage compartment is about 500 kg m^{-3}. This is 15–20% less than the density achieved with the S-type drill under laboratory conditions (Suzuki and Shimbori, 1985). Although the length of the chip-storage compartment could be shortened by 15–20%, field testing indicated that below 85 m the long drilling runs (1.05 m) were sometimes associated with difficulties in removing the core barrel from the drill. The potential difficulties in removing the core barrel under higher compression, or with warmer ice or ambient air temperature, lead us to conclude that the chip-storage compartment should not be shortened.

BPRC EM drill-core production rate was slower in the first than in the second borehole (Table 3). The relatively slow drilling was related to the initial adjustments of the anti-torque, penetration drive, controller and cutters. Subsequent ice-core production reached a maximum rate of 6 m h^{-1} (Fig. 3) with an average of 3.67 m h^{-1}. The second hole was drilled with adjusted anti-torques, cutters and optimal penetration speed, and as a result the average core–production rate increased from 3.5 to 5.25 m h^{-1}. The relatively slow core-production rate at Raven was due in part to the time consumed removing the core from the core barrel. The top of the core barrel has a reinforcement ring which creates a wedging effect when the core is extracted. Thus, most of the core was removed from the core barrel through the coring head-end. This added an extra 1.5–2 min to each drilling run. Without the reinforcement ring the core-removal procedure should take 1–2 min, increasing the average core-production rate to about 6 m h^{-1}.

CONCLUSIONS

The new EM drill and 500 m drilling set-up worked well, without mechanical failures. Two anti-torque systems were tested. Both proved simple and reliable, and provided pendulum drill steering, which resulted in a vertical borehole. The small-diameter, lightweight coaxial cable exhibits low power losses and is suitable for both EM drills and TDs. This cable allows the design of a portable, lightweight drilling set-up suitable for up to 500 m ice-coring using a suite of new EM and thermal ethanol drills. The field test demonstrated that the new EM drill produces good quality snow, firn and ice cores to 120 m depth, about 80 m below the ice–firn transition. No wafering or cracking of ice core was noticed, although longitudinal fractures were intermittent. After adjustments were made, an ice-core production rate of 5.25 m h^{-1} was achieved. These experiments demonstrated that better-quality ice-core and vertical boreholes result when a constant speed of penetration is maintained.

Constant-speed penetration may be accomplished by the use of an auxiliary winch motor which would involve simpler electronics and thus be more reliable. For faster ice-core drilling on high-elevation, low-latitude glaciers, which often contain high concentrations of dust, sand and rock fragments, carbide tip cutters should be available. More extensive tests and fine adjustments must be performed to determine how the drill will perform at depths of 150–200 m. For high-elevation glaciers and ice caps it is essential to have a drill capable of coring dust-laden ice at temperatures between −3° and −14°C.

ACKNOWLEDGEMENTS

REFERENCES

Arnason, B., H. Björnsson and P. Theodórsson. 1974. Mechanical drill for deep coring in temperate ice. *J. Glaciol.*, **13**(67), 133–139.

Blake, E. W., C. P. Wake and M. D. Gerasimoff. 1998. The ECLIPSE drill: a field-portable intermediate-depth ice-coring drill. *J. Glaciol.*, **44**(146), 175–178.

Clausen, H. B., N. S. Gundestrup, S. B. Hansen and S. J. Johnsen. 1989. Performance of the UCPH shallow- and hand augers. *In* Rado, C. and D. Beaudoing, *eds. Ice core drilling. Proceedings of the Third International Workshop on Ice Drilling Technology, Grenoble — France, 10–14 October 1988.* Grenoble, Centre National de la Recherche Scientifique. Laboratoire de Glaciologie et Géophysique de l'Environnement, 14–20.

Gillet, F., D. Donnou, C. Girard, A. Manouvrier, C. Rado and G. Ricou. 1984. Ice core quality in electro-mechanical drilling. *CRREL Spec. Rep.* 84-34, 73–80.

Gosink, T. A., J. J. Kelley, B. R. Koci, T. W. Burton and M. A. Tumeo. 1991. Butyl acetate, an alternative drilling fluid for deep ice-coring projects. *J. Glaciol.*, **37**(125), 170–176.

Gundestrup, N. S., S. B. Hansen and S. J. Johnsen. 1989. Refinements of the UCPH shallow drill. *In* Rado, C. and D. Beaudoing, *eds. Ice core drilling. Proceedings of the Third International Workshop on Ice Drilling Technology, Grenoble — France, 10–14 October 1988.* Grenoble, Centre National de la Recherche Scientifique. Laboratoire de Glaciologie et Géophysique de l'Environnement, 6–13.

Holdsworth, G. 1984. The Canadian Rufli–Rand electro-mechanical core drill and reaming device. *CRREL Spec. Rep.* 84-34, 21–32.

Jessberger, H. L. and R. Dörr. 1984. Recent experiences with a modified Rufli ice drill. *CRREL Spec. Rep.* 84-34, 45–49.

Johnsen, S. J., W. Dansgaard, N. Gundestrup, S. B. Hansen, J. O. Nielsen and N. Reeh. 1980. A fast light-weight core drill. *J. Glaciol.*, **25**(91), 169–174.

Litwak, J., L. Kersten and K. Kuivinen. 1984. The PICO intermediate drill system. *CRREL Spec. Rep.* 84-34, 41–44.

Mosley-Thompson, E., L. G. Thompson, P. M. Grootes and N. Gundestrup. 1990. Little Ice Age (neoglacial) paleoenvironmental conditions at Siple Station, Antarctica. *Ann. Glaciol.*, **14**, 199–204.

Rand, J. H. 1975. 100-meter ice cores from the South Pole and the Ross Ice Shelf. *Antarct. J. U.S.*, **10**(4), 150–151.

Rand, J. H. 1976. The USA CRREL shallow drill. *In* Splettstoesser, J. F., *ed. Ice-core drilling.* Lincoln, NB, University of Nebraska Press, 133–137.

Rufli, H., B. Stauffer and H. Oeschger. 1976. Lightweight 50-meter core drill for firn and ice. *In* Splettstoesser, J. F., *ed. Ice-core drilling.* Lincoln, NB, University of Nebraska Press, 139–153.

Schwander, J. and H. Rufli. 1989. Electromechanical drilling in dry holes to medium depths. *In* Rado, C. and D. Beaudoing, *eds. Ice core drilling. Proceedings of the Third International Workshop on Ice Drilling Technology, Grenoble — France, 10–14 October 1988.* Grenoble, Centre National de la Recherche Scientifique. Laboratoire de Glaciologie et Géophysique de l'Environnement, 32–37.

Schwander, J. and H. Rufli. 1994. Electromechanical drilling of a 300-m core in a dry hole at Summit, Greenland. *Natl. Inst. Polar Res. Mem., Spec. Issue* 49, 93–98.

Suzuki, Y. and K. Shimbori. 1984. Mechanical drill systems for the 25th Japanese Antarctic Research Expedition. *Natl. Inst. Polar Res. Mem., Special Issue* 34, 188–196.

Suzuki, Y. and K. Shimbori. 1985. Ice core drills usable for wet ice. *Natl. Inst. Polar Res. Mem., Special Issue* 39, 214–218.

Suzuki, Y. and K. Shimbori. 1986. Development of an ice core drill for liquid-filled holes. *Natl. Inst. Polar Res. Mem., Special Issue* 45, 86–92.

Suzuki, Y. and K. Shiraishi. 1982. The drill system used by the 21st Japanese Antarctic Research Expedition and its later improvement. *Natl. Inst. Polar Res. Mem., Special Issue* 24, 259–273.

Suzuki, Y. and T. Takizawa. 1978. Outline of the drilling operation at Mizuho Station. *Natl. Inst. Polar Res. Mem., Special Issue* 10, 1–24.

Tanaka, Y. *and 6 others.* 1994. Development of a JARE deep ice core drill system. *Natl. Inst. Polar Res. Mem., Special Issue* 49, 113–123.

Ueda, H. and D. E. Garfield. 1969. Core drilling through the Antarctic ice sheet. *CRREL Tech. Rep.* 231.

Zagorodnov, V., L. G. Thompson, J. J. Kelley, B. Koci and V. Mikhalenko. 1998. Antifreeze thermal ice core drilling: an effective approach to the acquisition of ice cores. *Cold Reg. Sci. Technol.*, **28**, 189–202.

Zhu Guocai and Han Jiankang. 1994. BZXJ super light ice core drill. *Natl. Inst. Polar Res. Mem., Special Issue* 49, 87–92.