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V. Zagorodnov, L.G. Thompson, P. Ginot, V. Mikhalenko. Intermediate-depth ice coring of high-altitude and polar glaciers with a lightweight drilling system. *Journal of Glaciology*, 2005, 51 (174), pp.491 à 501. 10.3189/172756505781829269 . insu-00375203

HAL Id: insu-00375203

<https://insu.hal.science/insu-00375203v1>

Submitted on 22 Nov 2021

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Instruments and Methods

Intermediate-depth ice coring of high-altitude and polar glaciers with a lightweight drilling system

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ABSTRACT. A total of 11 ice cores to a maximum depth of 460 m have been obtained over the past 3 years from high-altitude glaciers on the saddle of Mount Bona and Mount Churchill in Alaska (designated B–C), and on Quelccaya ice cap and Nevado Coropuna in Peru. Ice coring was conducted using an intermediate-depth drilling system. The system includes an electromechanical drill (EMD) and an ethanol thermal electric drill (ETED). The EMD permitted an average ice-core production rate (ICPR) of 7.0 m h⁻¹ down to 150 m. An average ICPR of 2 m h⁻¹ to 460 m depth was possible with the ETED. The quality of the B–C ice cores is better than that of cores previously drilled with an EMD and ETED system. A new cutter design, drilling with a lubricant/cutting fluid and a new anti-torque assembly were tested in the laboratory and in glacier boreholes. We examine the performance of the drills in cold and temperate ice and in clean and particle-laden ice. The influence of the ethanol drilling fluid on ice-core isotopic, ionic and dust composition is discussed.

INTRODUCTION

Personnel safety, environmental impact, ice-core quality and the cost of field operations have been the primary emphases in the development and enhancement of deep ice-core drilling systems over the past 30 years. Thousands of meters of ice core have been obtained and significant experience in the design of drilling systems has been acquired. However, relatively few intermediate-depth (ID) operations have been conducted using equipment specifically designed for ID operations (e.g. shallow-depth dry-hole drills (Clausen and others, 1989; Schwander and Rufli, 1994), a shortened electromechanical deep drill (S. Johnsen, unpublished information), a full-size deep-hole electromechanical drill (EMD) (Taylor Dome, Antarctica, 1994; Siple Dome, Antarctica, 2000) and an ethanol thermal electric drill (ETED; Zagorodnov and others, 1998)).

Ice thicknesses up to 1000 m are common in polar and high-latitude glaciers, and only on rare occasions are these glaciers accessible with surface vehicles that can carry heavy equipment. Use of heavy aircraft is not possible at most mountain sites and significantly increases the cost of ice-coring operations on polar ice sheets. Economical ID ice coring of these glaciers is achievable only with portable lightweight drilling systems delivered by small aircraft. Ideally an ID ice-core drilling system will have a 1000 m or more depth capability, a high ice-core production rate, low power consumption and the capability to operate in a fluid-filled borehole. The borehole fluid needs to be safe for the drill operators, to present a minimal environmental impact and not to contaminate the ice core. In some cases, the borehole fluid and fuel make up >50% of the total field operation cargo. Reducing borehole-fluid and fuel requirements minimizes contamination of drill sites, and transportation costs. One economical approach in ID ice coring is to

only partially fill the borehole with fluid. Unless the stability of the borehole is compromised, drilling of a dry hole as deep as possible reduces drill fluid requirements. Thus, enhancement of dry-hole drill techniques is an important part of ID development.

The accessibility of most ID drill sites is limited, not only by the total weight of the equipment, but also by the weight of each single piece of equipment. For example, 1000 m of electromechanical, steel-armored cable suitable for thermal drills weighs about 300 kg. Special equipment is needed to handle this cable at the drilling site. To overcome this problem, a lighter Kevlar[®] (Dupont polymer) coaxial cable has been developed for Byrd Polar Research Center (BPRC) ID drilling systems.

At the drilling site, short set-up and equipment disassembly times allow personnel to dedicate more time to drilling. Shorter surface times for drill servicing increase the ice-core production rate (ICPR). All the above factors have been considered in the development of a 500 m ID ice-core drilling system (Zagorodnov and others, 2000). Recent modifications to the system have increased the depth capabilities to 1000 m. Using this system in May–June 2002, a 460 m long ice core to bedrock and a few shallow (116, 12.4, 11.8, 11.5 and 11.3 m) ice cores were obtained from the saddle of Mount Bona and Mount Churchill (B–C), Alaska, USA (4200 m a.s.l.; 10 m depth temperature: –24°C). In 2003 three ice cores (168, 29 and 129 m) were obtained at two summits of Quelccaya ice cap, Peru (5670 m a.s.l.; temperatures close to the melting point), and a further three cores (34, 34 and 146 m) were retrieved from Nevado Coropuna, Peru (6450 m a.s.l.; 10 m depth temperature: –6°C).

This paper analyzes the performance of a 500 m ID drilling system in the context of polar and high-altitude ice core drilling operations and describes recent improvements

Table 1. Specifications of BPRC electromechanical, coaxial Kevlar[®] cables

Cable type	Diameter	Resistance	Weight* (air)	Breaking strength
	mm	$\Omega \text{ km}^{-1}$	$\text{kg} (100 \text{ m})^{-1}$	kN
A	7.9	16	11.3	10
B	8.9	5.7	17.3	30
C [†]	8.5	10	13.0	20

*Shipping weight 35–45% higher. [†]Projected values.

that have led to the development of a more sophisticated 1000 m lightweight ID ice-core drilling system. The influence of thermal drilling and of using an ethanol/water solution (EWS) as a drilling fluid on the analyses of ice cores in the laboratory is investigated.

DRILLING SET-UP AND SUPPORT SYSTEMS

Ice-core drilling systems include ice-core drills, winches, controllers, power systems and shelters. The design and specifications of a dry-hole EMD were presented in Zagorodnov and others (2000). The performance of the surface equipment affects the ice-core quality, the ICPR and the physical effort required by the drill operators. The BPRC ID drilling system is provided with a tilting table that reduces the physical effort for the drill operators. The table makes it possible to rotate the drill from a vertical to a horizontal position and back using a winch. A penetration drive auxiliary motor controls the cable feed during drilling runs. It provides the fine adjustment needed to control the penetration speed. The systems are equipped with either a 200 V (2 kW) d.c. controller for the EMD or a 400 V (6 kW) d.c. controller for the ETED. Either can be used with the drill or winch motor. Depth and weight readouts are incorporated in a separate unit. Specifications of the major components of the BPRC 500 and 1000 m ID ice-core drilling systems are shown in Tables 1–3.

The use of lightweight drills and a coaxial Kevlar[®] cable allows for the design of a winch that weighs just 35 kg including the frame, drum, gearbox and d.c. brush motor. A heavier cable (B in Table 1) was developed for deep thermal drilling and was field-tested with an ETED in ID boreholes. After 3000 cycles in a flex test, cable B lost 25% of its strength. The residual strength (22.5 kN) is acceptable for deep (3000 m) ice-core drilling. The mast, winch and drill controllers together weigh 64 kg. At a maximum raising

speed of 0.68 m s^{-1} , the average power consumption is about 1.5 kW. With the same mast controller system equipped with a larger drum and a depth capability of up to 1000 m (cable B in Table 1) the weight increased by 65 kg (Table 3). Despite the advantages of the Kevlar[®] cable, its vulnerability to wear and the relatively low breaking strength could be considered drawbacks. The additional cost of cable replacement every 1000 m (shallow ice coring) is the price paid for a lightweight system. However, >2800 m of ice cores have been drilled with cable A (Table 1), and 700 m with cable B, with no problems. The reduction in transportation costs and the operational advantages compensate for the cable-replacement cost.

Weight, fuel consumption and reliability are the major criteria considered when power systems are chosen for ice-coring operations. Currently 4, 7 and 10 hp (3.0, 5.2 and 7.5 kW) air-cooled diesel generators have been used up to 6550 m a.s.l. Zagorodnov and others (2002b) showed that air-cooled diesels have the best weight/power ratio when compared to gasoline generators and solar panels. Two-stroke gasoline engines are lighter than the diesels, but about 50% less fuel-efficient. They therefore require more fuel and are less environmentally friendly than diesel engines. Low (0.5–1.5 kW) and high (3.0–6.0 kW) power requirements for EMD and ETED, respectively, eventually led to the development of a distributed power system that includes one, two or three small-size (1–5 kW) generators that operate with one load. The concept of a distributed power system was field-tested and found practical for drilling sites with logistical limits of 30–40 kg for each item. The operation of a few generators in parallel achieved a high total power output with lightweight components.

The drilling system utilizes permanent magnet (PM) alternators, which are 20% more power-efficient, 70% lighter, and more reliable than conventional alternators, therefore providing a substantial reduction in fuel consumption. Flexible solar panels are heavier than the combined weight of an air-cooled diesel generator and the fuel necessary for 500 m of ice coring. They also require significantly more time to assemble and dismantle. While solar energy is a pollution-free power source, daylight and weather limitations can lead to an extended drilling campaign. Therefore, the low environmental impact of drilling operations with solar panels is questionable.

Protection of the drill operators and equipment from harsh environments improves core quality and ICPR. Three types of shelter have been tested over multiple field operations: (1) sturdy structure Pacific Domes design (Pacific Domes Inc. and custom-made Ohio State University dome), (2) lightweight Mountain Hardware, Space

Table 2. Specifications of the EM and ETED ice-core drills

Drill	Length drill/core	Weight* drill/core	Optimal depth	Power (optimal)	Diameter borehole/core	ICPR
	m	kg	m	V/A/kW	mm	m h^{-1}
BPRC-EM3.2	3.2/1.05	35/7.6	200	90/5.0/0.45	129/102	2.5...15
BPRC-EM2.8 [†]	2.8/1.0	25/7.5	200	180/3.0/0.44	129/102	2.4...18
ETED-2.5	2.5/2.1	40/15.2	500	390/9.8/3.82	125/102	2.0 [‡]
ETED-3.7 [†]	3.7/3.15	68/22.8	1500	450/11.5/5.2	127/102	3.0 [‡]

*Shipping weight 35–45% higher. [†]Projected values. [‡]500 m depth.

Station dome and (3) fishing shelters and service tents. Sturdy Pacific Domes are suitable for relatively long-lasting ID ice coring and heavy snowfalls. Service tents are significantly lighter, require short set-up times and are reasonably priced.

It is assumed that ID ice coring does not require an upper casing for the borehole. Depending on the configuration, the average installation and teardown time for camp and equipment are 60 and 40 man-hours, respectively. At some drilling sites, additional time is needed to excavate ice-core storage trenches. Six-person teams appear to be optimal for single-shift operation to 500–600 m drilling depth, and 12-member teams in two–three shifts for drilling in the 1000–1500 m range.

ELECTROMECHANICAL DRILLING

The most difficult conditions for dry-hole drilling occur when the surface or borehole temperatures are close to the melting point. This causes the ice cuttings to stick to the drill parts, block the passageways and accumulate in the kerf and inside the core barrel. This can result in jammed core barrels, fractured ice cores and shortened drilling runs. In severe cases, the drill can be stuck at the bottom of the hole. The drilling of shallow (<100 m) boreholes in cold firn and ice with high-pitch cutters does not usually have the above complications, while deeper coring leads to low-pitch cutting, fine-chip production and inevitable core barrel jams. To improve the EMD performance below 100 m, three options have been investigated: (1) lubrication of the chip passageways, (2) lubrication of the cutters and (3) cutting of coarser chips.

The first option consists of coating the coring head, exterior of the core barrel and interior of the outer jacket with antifreeze (96% polypropylene glycol – commercial automobile antifreeze). With this option the ice core is not in contact with the lubricant. Applying the antifreeze with a plastic brush before each drilling run adds 2–3 min to the drill surface time. Polypropylene glycol is a viscous fluid that stays on the drill parts during drill lowering, provides lubrication for the cuttings and significantly improves drill performance in warm or cold ice below 100 m. Lubrication efficiently prevents chip jams when the drill is operated at air temperatures above the melting point or during sunny days when the drill is heated by solar radiation (Zagorodnov and others, 2002c). The glycol also prevents the freezing of a warm drill lowered into a cold borehole and improves drill performance when a small amount of water exists in the kerf. Approximately 1200 m of ice cores have been obtained with the use of lubricants at different air/ice temperatures in

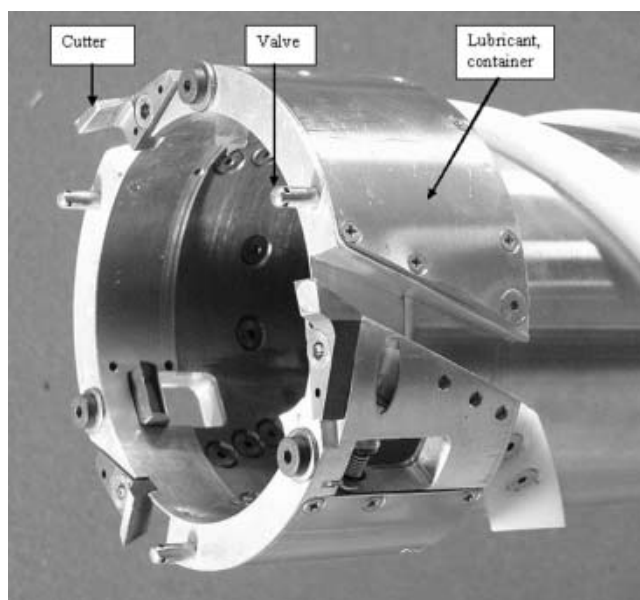


Fig. 1. Coring head with lubricant containers and step cutters.

polar and high-altitude glaciers. The average use of glycol is about 40 mL per drilling run for a 108 mm outer diameter and 1.15 m long core barrel. Since the application of glycol in cold ice is mainly below 80 m, just 4 L of lubricant is enough to complete a 180 m deep borehole. Drilling in a warm environment may require the use of glycol at shallow depths as well. This procedure was tested with the BPRC EMD only and may not be suitable for other EMDs.

It has been noted (personal communication from S. Hansen, B. Koci and S. Johnsen, 2000) that when EM dry-hole coring continues below 150 m in a fluid, the quality of retrieved ice cores is greatly improved until the brittle ice zone is reached below 400 m. Assuming the core quality enhancement resulted from cutting with a lubricant, tests were conducted with a new coring head equipped with containers that carried a cutting lubricant (Fig. 1). The new coring head had three 17.5 mL containers and three valves that opened when the drill touched the bottom of the hole. An optimal viscosity mixture of glycol and ethanol (2 : 1) was used. No significant differences in penetration rate or improvement in core quality were noted when dry and lubricated cutters were alternated in the B–C borehole. Possibly the lubricant quantities were not sufficient to change the drill performance and it is likely that the lubricant was absorbed by the cuttings. More information on ice coring with cutter lubrication is presented below.

Table 3. Specifications of the ice-core drilling set-ups

Depth capability m	Dimensions* m	Weight† kg	Power (optimal) V/A/kW	Hoisting speed up/down m s ⁻¹	Pulling force N
200‡	0.94/1.05/3.2	90	90/11/1.0	0.6/1.8	700–1400
550	0.94/1.05/4.2	155	150/10/1.5	0.8/1.8	700–1400
1000	0.94/1.05/4.2	220	150/10/1.5	0.5/1.8	1000–2000
1000‡	0.94/1.05/4.2	280	150/20/3.0	0.8/1.8	1500–2500

*Length/width/height. †Minimal configuration; shipping weight 35–45% higher. ‡Projected values.

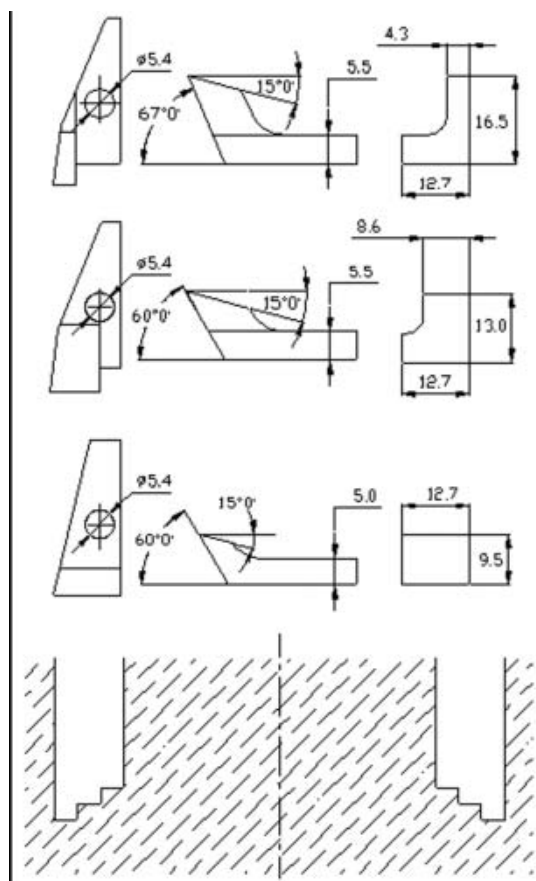


Fig. 2. Step cutters and kerf cross-section (dimensions in mm).

Numerous field observations have shown that drilling with a high cutting pitch does not compromise drill performance or ice-core quality. However, drilling below 100–150 m deep requires a substantial reduction of the cutting pitch that results in the generation of fine cuttings and problems in their transport. This, in turn, reduces the penetration depth during a drilling run and diminishes the core quality. Attempts to drill with a high (>3 mm) pitch below 100–150 m result in increased torque on the cutting head and slippage of the anti-torque assembly. In order to reduce the torque on the cutting head and at the same time generate coarse cuttings, a head with special cutters was designed (Figs 1 and 2). Each of the three new cutters covers only one-third of the width of the kerf. Moreover, the height of each cutter is different. The outer cutter is the highest (deepest cut) the second is 3.5 mm shorter and the third is 7 mm shorter. The incremental height of the cutters creates a stepped kerf (Fig. 2) that possibly provides a more gradual change in the stress relief within the subsurface layer of the ice core. Conventional and step cutters cut the same volume of ice per revolution and require approximately the same torque, but step cutters generate coarser cuttings. Each step cutter penetrates three times deeper per revolution than conventional cutters which follow each other and therefore cut one-third of the depth of the pitch. Laboratory test drilling in artificial ice with step-cutter lubrication produced excellent-quality ice cores at 50% of the motor current compared with conventional cutters. Motor-current reduction was achieved by the improved transport of the coarse cuttings. However, field tests of the same configuration coring head in the B–C borehole did not demonstrate the same improved drill performance. The

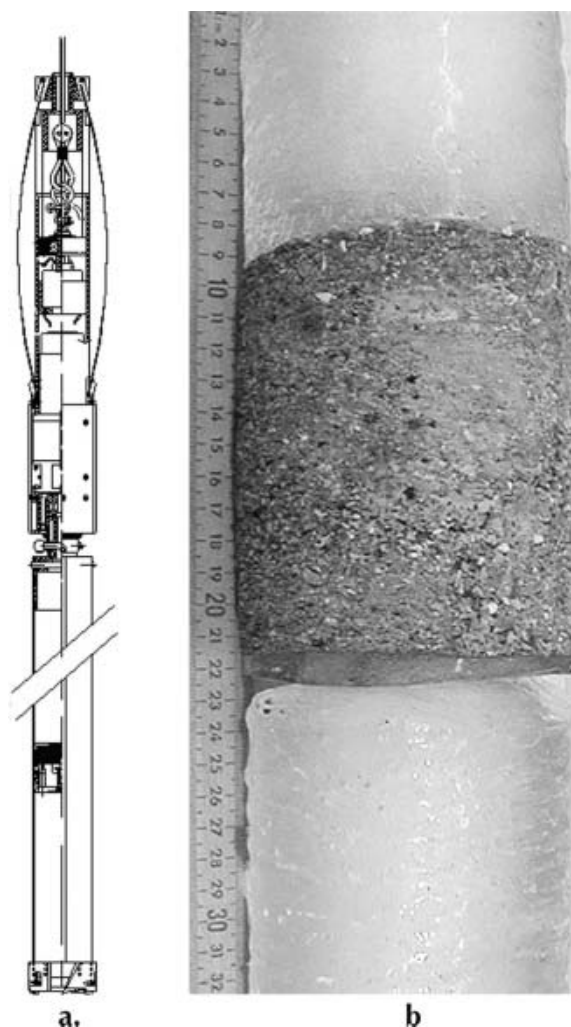


Fig. 3. (a) Schematic of submersible EMD sampler. (b) Core with limestone particles; details in text.

discrepancy between the laboratory drilling tests and glacial drilling can be explained, first, by the stressed ice conditions below 145 m depth in the B–C borehole, yet insignificant stresses in the artificial ice, and, second, by the B–C borehole temperature being considerably lower than the laboratory temperature. Laboratory results seem to be in agreement with the drilling of the Quelccaya borehole, where temperatures were close to the melting point and the step cutters performed significantly better than conventional cutters in the depth range 76–126 m. More information on step cutters is presented in the EMD performance section below. Another characteristic of step cutters is their performance under low bit pressures. In the B–C borehole, conventional cutters required 6–8 kg of bit loading, while step cutters perform with 2 kg loading. Often in temperate ice, step cutters performed with a ‘negative bit pressure’; cutters actually pull the drill down instead of acting under the pressure, due to the gravitational pull of the drill suspended by the cable. Possibly the low bit pressure can be explained by the smaller (one-third) contact area of the step cutters that resulted in the same specific bit pressure as conventional cutters during penetration. Low cutter load permits significantly improved vertical steering of the drill and it is an important improvement for lightweight drills.

Below 150 m, conventional leaf spring anti-torque assemblies often slip. A more reliable and simple

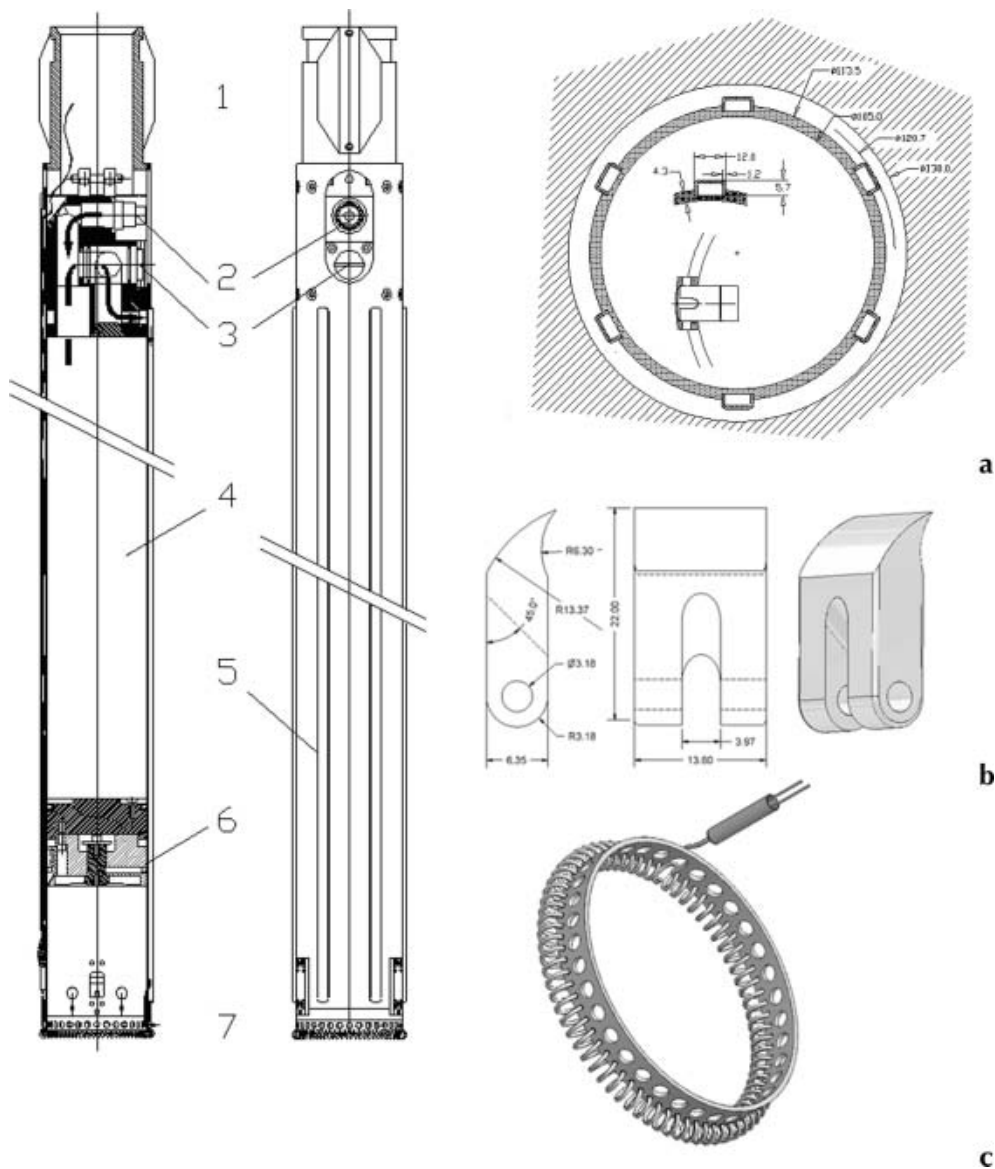


Fig. 4. ETED: 1. stabilizer; 2. nipple; 3. valve; 4. core barrel; 5. channels; 6. piston; 7. coring head. (a) ETED cross-section. (b) Core catchers. (c) Coring head. All dimensions in millimeters.

anti-torque assembly was developed and field-tested. To prevent bending of the blades, described in Zagorodnov and others (2000), the blades were reinforced with additional 1.6 mm thick edge skates. The new anti-torque assembly is only 12 cm long, requires about 10 mm radial space and performs well in cold and temperate firn and ice, essentially with no adjustments and no slippage. On several occasions the new anti-torque assembly was exchanged with a conventional leaf spring anti-torque assembly, and the former demonstrated its superiority. The absence of any anti-torque assembly slip eliminates the need for slip rings in the EMD design and results in a 5–10% shorter drill.

Experimental drilling of ice with a submersible EMD sampler (Fig. 3a) and an EWS was completed in the laboratory and in the Quelccaya borehole. The sampler has two parts: (1) a submersible version of the EMD motor section and (2) an ETED core barrel, but, instead of a heating ring, it is fitted with a coring head with cutters (conventional or step cutters). To reduce torsional force on the ice core, a swivel was mounted at the lower end of the piston. During the

drilling process the ice core pushes the piston up and the EWS is injected at the lower end of the core barrel which sweeps the cuttings from the kerf. A full-size, excellent-quality ice core (0.9 m long and 102 mm diameter) was drilled under the following conditions: ice temperature -7°C , EWS 33% at -10°C ; penetration rate started at 2 mm s^{-1} and continued at 7.5 mm s^{-1} ; power 0.21 kW. A small fraction (estimated at 10–20%) of the cuttings were dissolved during the drilling run. The ice core was smooth, with cutting marks clearly visible and no signs of ice-core dissolution. The ice core was not in contact with the EWS for long enough to show marks of dissolution. In the Quelccaya borehole, a similarly configured drill, with new anti-torque assembly, no piston and no manifold (Fig. 4), was tested below 124 m depth. The step cutters were not as efficient with this dry-hole EMD. The penetration was slow, probably due to the absence of fluid circulation at the kerf.

Drilling of a frozen layer of ice containing crushed limestone particles (Fig. 3b) was also conducted with an EMD sampler equipped with carbide-tipped cutters. To minimize cutter wear, the rake and relief angles were chosen to be

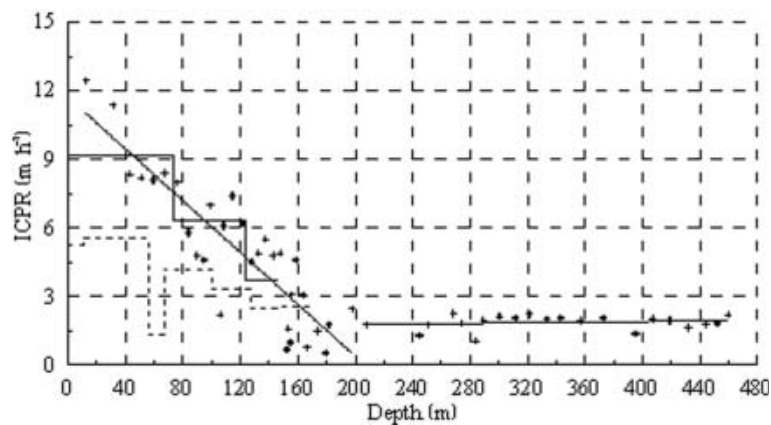


Fig. 5. Performance of dry-hole EMD and ETED. Crosses and solid line: B–C borehole; thick solid line: Coropuna; dashed thick line: Quelccaya ice cap.

20° and 5°, respectively. A layer of compacted, crushed limestone particles was filled with water and frozen on top of an ice block, then another layer of pure ice was frozen on top of the limestone layer. With the given cutter geometry, the maximum penetration rate in pure ice was 1.6 mm s^{-1} , while the layer with the limestone particles was penetrated at 2 mm s^{-1} and 0.26 kW of power.

PERFORMANCE OF DRY-HOLE EMD

The B–C drilling down to 180 m depth was done in 4.5 working days or 41 working hours, and down to 460 m with ETED (Fig. 5). An ICPR of $\sim 13 \text{ m h}^{-1}$ was achieved during the first hour. This linearly decreased with depth and at 180 m it was down to 1 m h^{-1} . Several factors affected the ICPR (e.g. lowering and raising time, the penetration rate, the surface time and the time spent freeing a stuck drill). A few short episodes of a stuck drill (each of which lasted about 3 hours and required changing the cutters), which occurred mainly below 150 m, made up most of the non-core production time. The average ICPR in the 180 m deep borehole was about 4.4 m h^{-1} . A depth of 150 m was reached in 22 hours with an ICPR of 6.8 m h^{-1} . That is 40% faster than drilling in Greenland with the same drill (Zagorodnov and others, 2000). We attribute the improved EMD performance to the use of a better machined and anodized outer jacket and to lubrication of the core barrel.

The 146 m long ice core from Nevado Coropuna was obtained in 2.5 working days, approximately 20 working hours, at an average ICPR of 7.3 m h^{-1} (Fig. 5). Near the surface the ICPR was close to 12 m h^{-1} and at the bottom, about 3.73 m h^{-1} . The performance of the drill was close to that at the B–C borehole.

The top of Quelccaya ice cap consisted of temperate firn with water at the firn–ice transition (24–26 m depth). A small amount of meltwater constantly ran into the borehole. In the course of drilling, water was removed with the cuttings and only a small amount ($< 3 \text{ L}$) accumulated at the borehole bottom between drilling runs. However, over the second, third and fourth night non-drilling periods, 20–30 L of water accumulated in the hole and had to be bailed out each morning. The presence of capillary water in the firn complicated drilling. The water partly washed out the lubricant and wet the metal surfaces. Then wet ice particles stuck to the core barrel and eventually formed a thick layer that jammed the core barrel. If the core barrel rotation was stopped before the core break, the drill became stuck at the bottom. Forward and reverse rotation would normally free the drill, otherwise jerking and hammering were necessary. The removal of compressed cuttings from the core barrel and the bailing of water required extra effort and time. All these additional activities during the first 2 days of drilling reduced the ICPR to 5.5 m h^{-1} , which is about 38% of the ICPR at the same depth in cold ice. On the third day of drilling, the ICPR dropped to 1.34 m h^{-1} , mainly due to frequent sticking of the

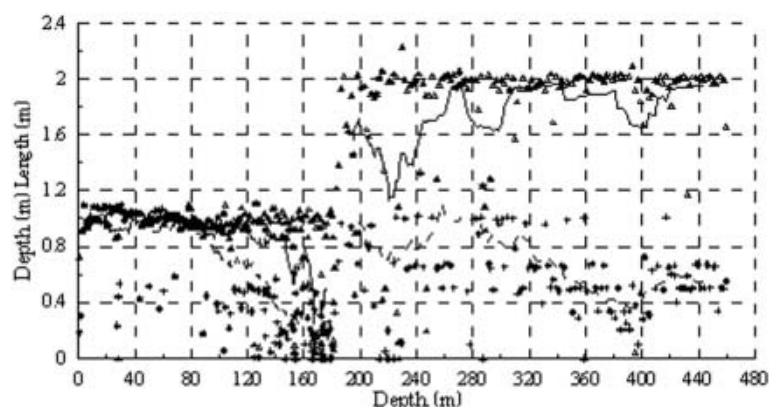


Fig. 6. Penetration depth (triangles, solid line) and length of ice-core pieces (crosses, dashed line) in the B–C borehole.

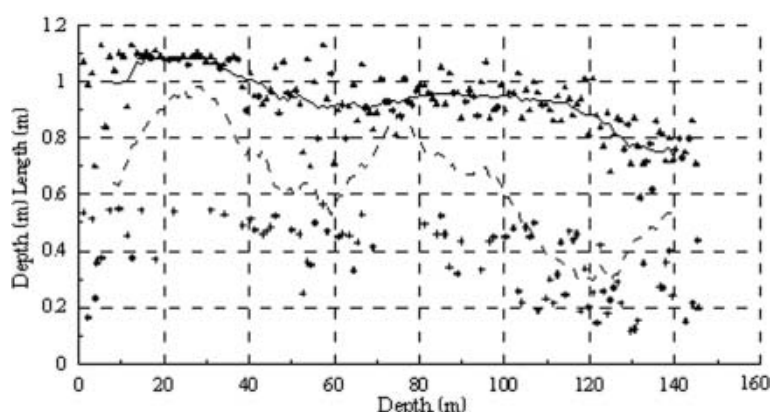


Fig. 7. Penetration depth (triangles, solid line) and length of ice-core pieces (crosses, dashed line) in the Coropuna borehole.

drill. On the fourth day the performance of the drill was significantly improved (ICPR of 4.2 m h^{-1}) when step cutters were introduced below 76 m. Here the ICPR was 60% of normal (cold ice) conditions. Down to 100 m depth, the penetration depth per drilling run practically doubled and sticking events were less frequent. However, from 100 to 124 m the average penetration depth diminished to 0.1 m for each run and drilling was continued with a thermal drill (Fig. 5). Empty drilling runs, i.e. no penetration, were more frequent in this borehole than in any other holes drilled with this drill. This is attributed mainly to ice formation behind the cutters.

The quality of ice cores from the B–C borehole (Fig. 6) was significantly better than that of previous cores taken in a cold environment and in the same depth intervals. Down to 100 m depth, the penetration depth and the average length of core pieces was close to 1 m. At 150 m depth, the penetration depth and the length of core pieces were as short as 0.75 m and 0.35 m, respectively. However, the penetration depth here was significantly greater than that for the Greenland boreholes drilled with the same drill equipped with the older design outer jacket and without lubrication.

On the Nevado Coropuna ice cap, the penetration depth and the length of the core pieces gradually decreased with borehole depth (Fig. 7). Since the borehole did not reach the critical depth ($\sim 150 \text{ m}$), both parameters were high, down to the borehole bottom. The difference between the

penetration depth and the length of ice-core pieces can possibly be explained by stresses in the ice or, more likely, it can be attributed to air temperature and solar exposure of the drill during the daytime. The depth interval 40–64 m was drilled at the time of highest air temperatures and without lubrication. The depth interval 76–122 m was drilled with lubrication and the deepest part of the borehole was drilled during the next day and was possibly affected by the air temperature and solar radiation. The final 25 m were drilled in cold weather that helped to improve core quality again. The dependence of core quality on the air temperature had been noticed while coring in Greenland (Zagorodnov and others, 2002c). (A similar correlation between the time of day and core quality was observed in the Purogangri (Tibetan Plateau) borehole (depth 214.7 m). There a sharp decline in ice-core quality was noted below 125 m, which was probably due to ice stresses, and a smaller pitch used in the drilling. Then the ice temperature from 125 to 214.7 m increased from -3°C to -0.8°C , possibly making drilling conditions more complex. The Purogangri borehole was drilled with conventional cutters and an unknown, non-glycol-based automobile antifreeze. It was significantly less viscous than the antifreeze used elsewhere, and possibly ran off the surfaces before the drill reached the bottom. As a rule, the core quality decreased after 1300 h and increased over the evening hours after 1600.) Unlike Nevado Coropuna, the quality of the B–C and Quelccaya ice cores did not show any correlation with air

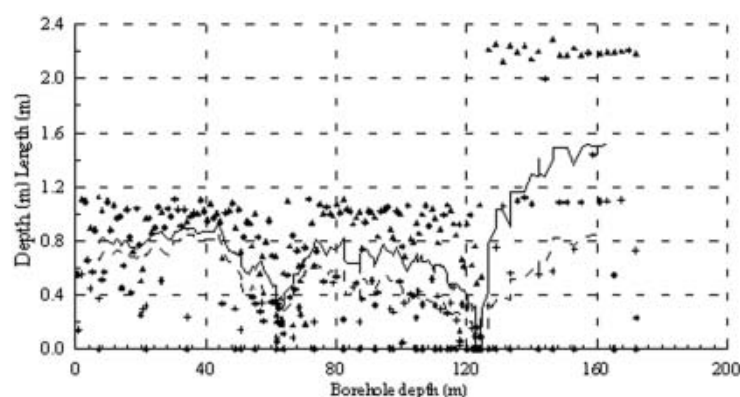


Fig. 8. Penetration depth (triangles, solid line) and length of ice-core pieces (crosses, dashed line) in the Quelccaya borehole.

temperature. It is possible that the air temperatures at noon were lower during the B–C drilling. Drill performance in temperate ice (Quelccaya) did not depend upon the drill temperature.

The average penetration depth and length of core from Quelccaya ice cap (Fig. 8) closely follow each other from the surface to 122.5 m depth, with some declining values towards the bottom. Apparently good-quality cores correlated with limited penetration. Probably the shorter drilling runs and less brittle temperate ice contributed to the retrieval of better cores.

THERMAL DRILLING

The major drawbacks of the prototype ETED (Zagorodnov and others, 1998) included a thin-walled core barrel that was considered vulnerable during operation, a slow descent time in a fluid-filled borehole and a limited ability to control the bit pressure due to its light weight. A new core barrel was made of a thick-walled (4.3 mm) stainless-steel tube (Fig. 4a). This increased the weight of the drill by 48 kg and made the drill more robust. Six channels for the flow of the EWS were machined into the tube and covered with segments of 1.2 mm thick-walled stainless-steel square tubing. A low-power laser was used to seal the channels, minimizing thermally induced distortions of the core barrel during welding. Specifications of the new ETED are presented in Table 2.

A new type of coring head consisting of a coiled tube with an imbedded heating wire (Fig. 4c) was designed. Thirty-six 6.35 mm holes are located just above the single, interchangeable, heating element. This results in better heat distribution and a 4.3 m h^{-1} penetration rate in clean, temperate ice at 2.25 kW. The new coring head consists of a 32Ω heating element that dissipates the same power as the prototype coring head at a 56% lower current. The latter allows the use of a small-diameter electromechanical cable with low power losses. The new coring head requires a high-voltage (450 V d.c.) controller and an adequate power source (Zagorodnov and others, 2002a, b). Operating the new ETED is easier with the thick-walled core barrel. The increased weight permits a faster lowering rate and makes it easier to maintain a vertical borehole, but it also makes controlling the bit pressure more sensitive. With a slack cable the drill tends to tilt from the vertical and jam itself to the point where it cannot penetrate further, creating a step or 'false bottom' in the wall of the hole. Several such steps were experienced in the B–C borehole. Each time the drill is lowered rapidly down the hole, encountering a step can damage the coring head. Also a few coring-head burnouts were experienced in the B–C borehole. Usually the coring heads drilled 40–80 m or more of ice before requiring replacement. Damaged coring heads, usually bent coils, were repairable with commonly available tools and could be replaced in about 15 min.

High-resistance (up to 100Ω) coring heads with a shielded electric return were tested. This option makes it possible to run the ETED with a steel-armored electromechanical cable, using the cable shield as an electrical return and eliminating the use of a bulky transformer. These coring heads were tested in the laboratory under hydrostatic pressure up to 586 bar for 48 hours. However, in the North Greenland Icecore Project borehole at 286 bar (3000 m), all six experimental coring heads burned out. During lowering

of the drill, the power to the coring heads was turned on at several depths as well as at the borehole bottom for significant periods, and everything performed as designed. Only upon contact with the kerf or hole bottom did the heaters fail. A possible explanation is dielectric breakdown due to the change in heater geometry under the high hydrostatic and superimposed contact pressures.

In a newer version of ETED a hand-operated valve was added to the manifold (Fig. 4). The function of the valve is to disconnect the inner space of the core barrel (EWS container) from the channels while filling the drill with the EWS, enabling the drill to be filled in a horizontal position while removing the core. The valve is returned to the drilling position when hanging vertically before descent.

To incorporate the closed framed core catchers (Fig. 4a) in the 8 mm radial space, 6.25 mm thick core catchers were designed. A few core catchers were broken during the B–C drilling. New, stronger, field-tested core catchers are shown in Figure 4b. The new core catchers were tested during the Peru ice coring and performed well. For more information about core catchers see below.

The performance of any thermal drill has to be examined from the point of view of the power available at the coring head. The ice-coring operations described above were conducted with 3–4 kW generators. We found this power range to be optimal for high-altitude operation. As a back-up option, ice coring with the low-power (2 kW) ETED is possible, but for 500 m and deeper coring, 5–6 kW is desirable.

The ICPR of the ETED in the B–C borehole (Fig. 5) was very steady down to the borehole bottom and was about 2 m h^{-1} . The stability of the ICPR in the B–C borehole was achieved by the reduction of surface time and the increased lowering rate. In the process of drilling, a few core catchers were broken. To solve the problem, a neck was melted at the bottom of each ice core. To melt a neck, the ETED was held for 40 s slightly above the bottom after the end of penetration, before breaking the core. The new core catchers (Fig. 4b) break the core without a neck. Another procedure which decreased the ICPR was the use of a hand pump to fill the drill with the EWS. This time can be reduced by at least 2 min with an electrically powered pump.

Close to the bottom of the B–C borehole, a few (5–10 mm thick) layers containing small (4–6 mm) pebbles were penetrated without a noticeable reduction in the penetration rate. This we attributed to the small effective cross-section of the coiled tube type of coring head and the low concentration of pebbles.

The design of the ETED and the drilling protocol with the EWS has been described by Morev and Yakovlev (1984) and Zagorodnov and others (1994, 1998). The B–C coring with an ETED clearly demonstrated that, in order to avoid the formation of hard slush in the core barrel, higher than equilibrium concentrations of ethanol must be used in the bottom part of the borehole, which results in the partial dissolution of the ice core and borehole wall. The maximum loss of ice core is about 2% of the core volume. The positive effect of using an excess ethanol concentration is the increased borehole diameter, which results in a higher lowering rate. In temperate ice (Quelccaya ice cap), drilling was done without any EWS. Furthermore, the piston and manifold were removed from the drill, which significantly increased the drill lowering rate and drilling-run penetration depth. In general, the ICPR at Quelccaya ice cap was 25%

higher than for the B–C borehole with about the same power provided to the coring head.

The differences in the ice core obtained with ETED (Figs 6 and 8) are longer pieces and the absence of shattered sections. Horizontal and longitudinal cracks, mainly in the middle of the ice-core cross-sections, dominate thermally drilled cores. These breaks are usually present in the upper half of the core. Longitudinal cracks appeared below 300 m in the B–C cores and became more frequent towards the bottom. A possible cause of the longitudinal and some of the perpendicular core fractures is the thermal–elastic stresses originating from the heat released when the EWS freezes between the core and core barrel as the drill is raised. In Figures 6 and 8, at 180 and 124 m depth, respectively, the average length of core pieces obtained with an ETED is almost twice that of the cores obtained with an EMD. ETED cores are slightly eroded due to the dissolution of the core surface.

INFLUENCE OF THERMAL DRILLING AND EWS ON ISOTOPIC COMPOSITION AND IONIC AND DUST CONCENTRATION OF ICE-CORE SAMPLES

Here we sketch the potential problems of EWS contamination of the ice core and provide data relevant to the context of this paper. A paper with detailed statistical analyses of data from different boreholes is in preparation.

To study the influence of the borehole fluid on ice-core composition, two questions have to be answered: (1) How deep does the fluid penetrate into the ice-core interior? and (2) Could small amounts of fluid alter the isotopic, ionic and dust measurements? The answers are related to the type of drilling fluid (hydrophobic or hydrophilic), method of drilling (thermal or mechanical), duration of the ice-core contact with the fluid, core quality, crystal size, ice temperature, core-processing protocol (relaxation/fluid evaporation time), time in storage of the core at a given temperature, sample preparation protocol and other conditions.

Gosink and others (1993) presented the only available data on ethanol and butyl acetate penetration into the interior of an electromechanically drilled ice core (150 m deep, Summit, Greenland). After 3 months of cold storage, the ice core was sampled and analyzed. Most of the ethanol (with concentrations >10 000 ppm) was found in the outer 1–2 mm of the core, while concentrations at 5 mm penetration were in the range 10–200 ppm, at 10–15 mm they were about 4 ppm, and at 20 mm they were 0.1 ppm (the detection limit is 0.1 ppm). The ice core was packed wet, following standard procedure, immediately after recovery (personal communication from B. Koci, 1993). Another section of the ice core was immersed in butyl acetate. This section demonstrated that butyl acetate concentrations declined sharply from 2 ppm at 0.5 mm depth to 0.3 ppm at 2 mm. Such large differences between ethanol and butyl acetate concentrations result from the hydrophobic nature of butyl acetate and its extreme volatility. In contrast, ethanol is a hydrophilic fluid and low concentrations of EWS are significantly less volatile than butyl acetate. Unfortunately the compositions of the experimental sections of the Greenland Summit ice core were not analyzed and the effect of either fluid is not known.

The B–C ice core was packed wet immediately after recovery. Short-term storage at the drilling site and subsequent transportation were at temperatures below -15°C ,

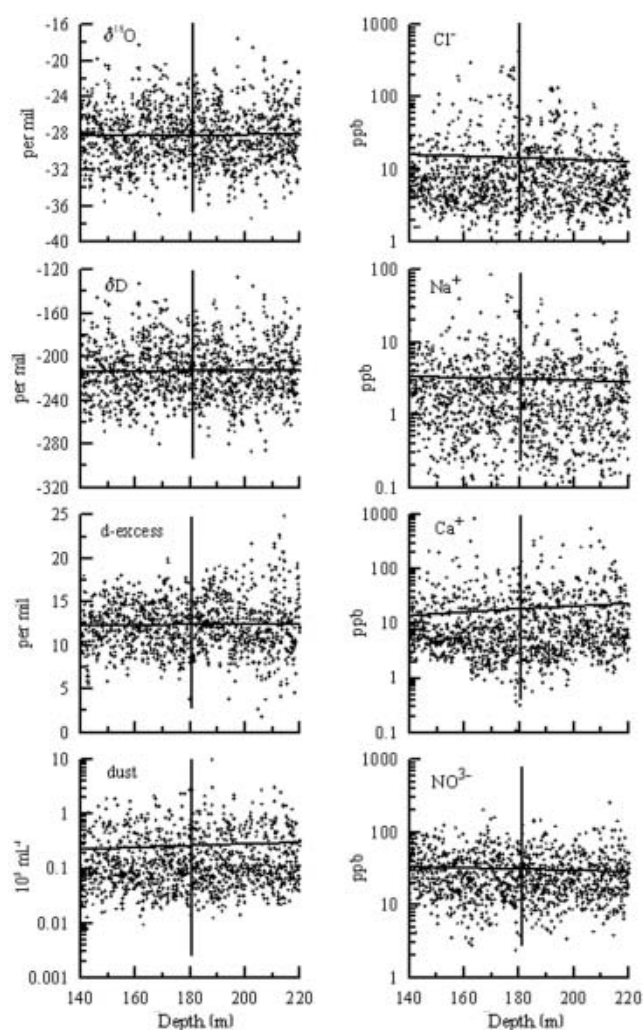


Fig. 9. Ice-core composition at transition between dry and EWS-filled borehole; vertical line is dry–wet borehole transition depth (180.76 m).

while long-term storage was below -30°C . The top section of the ice core (180.76 m), drilled without EWS, was analyzed within 1 year of recovery and the bottom part (460.9 m) within 2 years. The temperature of this section of the ice core was -24°C at the top, gradually increasing to -7°C at the bottom. The upper part of the core (from 180.76 m) was in contact with 40% EWS, and the bottom part with 25%. Due to the depth difference, the average contact time of the top core section with EWS during one run was 45–55 min, while for the bottom of the same section it was 5–15 min.

To study the influence of ethanol on the isotopic composition and the ionic and dust concentrations in the ice core, the mean values of 10 m intervals (~ 10 years each) above and below the transition between dry and EWS-filled sections of the borehole were analyzed using a *t*-test. In Figure 9, individual chemical species (1165 samples) and linear approximation lines are shown in intervals 40 m above and 40 m below transition depth. Statistically and visually there is no difference between profiles above and below the 180.76 m transition depth. The mean values for both stable isotopes are not significantly different, although the deuterium excess (d-excess) of the bottom part of the ice core is higher. Magnesium and nitrates do not show significant difference in means, although magnesium is not

normally distributed and the *t* test is therefore not legitimate. Long-term trends of Ca^+ , Na^+ and Cl^- lead to differences in mean value for these chemical species.

To determine the radial effects of contamination, a series of samples were cut from the surface of the core down to 12 mm depth. None of the ions examined show significant differences in their individual values below 12 mm. Only chloride, potassium and sodium demonstrate high values in subsurface (8 mm) samples, with no difference below 12 mm. These three ions have the highest differences in their means at transition depth. Calcium, magnesium, nitrate, sulfate and ammonium ions did not change significantly with depth. Thus it appears that these ions are not sensitive to the presence of ethanol in low concentrations.

In the bottom part of the borehole (410–460 m) the influence of ethanol results in significant changes in d-excess and δD values for 22% of the 2959 samples in this interval. The frequency of abnormal d-excess values increases from 0.05 m^{-1} in the 180–90 m depth interval to 90 m^{-1} in the 450–460 m interval, with a maximum of 170 m^{-1} in the 380–390 m interval where the core quality was poor (Fig. 6). This indicates d-excess and δD values are impaired by core quality and contact time with fluid. The criterion for separation of adequate (normal) and altered (abnormal) δD values is contingent upon d-excess values that exceed deviations typical for dry-hole samples. Normal values of $\delta^{18}\text{O}$ and δD were measured in both surface and interior samples; here only interior samples were analyzed. The abnormal values of δD are 20‰ heavier than the normal values. Average abnormal d-excess values are 16‰ higher than the normal average. No changes of $\delta^{18}\text{O}$ values have been found.

DISCUSSION, CONCLUSIONS AND FUTURE DEVELOPMENT

Economical and low-environmental-impact ice-core drilling is possible with ID systems such as the dry-hole EMD and the ETED. The development of the ID lightweight ice-core drilling system was made feasible through the use of the lightweight Kevlar[®] electromechanical cable, the air-cooled diesel PM power generators and lightweight shelters. Low-resistance electrical cables allowed the use of the dry-hole EMD and the low-power ETED. The combination of these drills makes it possible to drill boreholes partially filled with EWS. The logistical burden and environmental impact at the B–C drilling site were significantly reduced with the use of EWS. Less than 1000 L of ethanol were used to make 3640 L of EWS to fill the lower 280 m of the borehole. The use of a conventional fluid EMD system, as an alternative to the ETED system, would require at least 3640 L of hydrophobic borehole fluid at the drilling site. The use of EWS is not harmful to the personnel and it requires little fuel to make the meltwater from the snow to mix with the ethanol. Thus, two to three people can operate the drill and power generators and prepare the EWS. A one-shift drilling operation including core processing is possible with five to six people. Field time could be halved with a two-shift operation, but requires a field party of 12.

Experimental drilling with a submersible EMD sampler showed that mechanical drilling with a EWS is possible without significant ice dissolution. Since only a small portion of the cuttings can be dissolved in the kerf, the circulation of the EWS and removal of the cuttings are necessary. Electromagnetic drilling with EWS can be

considered in the future for low-contamination drilling at the bottom of ice caps. Carbide-tipped cutters allow low-power recovery of frozen material with particles.

Ice-core quality and performance of EMD in dry boreholes below 100 m were improved with lubrication of the passageways for cuttings and the use of step cutters. Lubrication permits the operation of EMD at air temperatures above the melting point and in temperate ice. An average ICPR of 7.0 m h^{-1} is possible in a 150 m deep borehole. Improvement in the shallow-drilling technique can be seen in the improved quality of the ice cores, the higher ICPR, an increased maximum depth, the reduction in system weight and the decrease in installation and teardown time. A further reduction in the total equipment weight of the dry-hole 200 m system can be achieved with a 15–20% lighter and shorter (2.8 m, 20–25 kg) EMD and a 25% lighter winch.

The coiled tube type of thermal electric coring head is power-efficient and has a low effective cross-section. The latter produces low hydraulic drag during drill lowering and has less interference when penetrating low-concentration pebble layers than conventional thermal coring heads. The experimental high-resistance coring head can be used with low current and a light, strong electromechanical cable (C in Table 1). High-resistance coring heads eliminate the need for a step-down transformer in the drill design. The coaxial, Kevlar[®], lightweight, low-resistance cable is suitable for 3000 m ice coring with a low-power thermal drill. The environmental and logistical advantages of ETED technology for ice coring down to 1000 m can be realized with available, field-tested equipment. Conservative estimates show that a 1000 m borehole can be cored in 560 hours or 28 days (20 effective drilling hours per day). As estimated, 7 days is sufficient for the assembly and teardown of the field camp. With 7 reserve days, the total operational time is estimated to be about 6 weeks. The estimated total weight of a 1000 m drilling operation including life support and drilling systems, ethanol, fuel and core boxes (3500 kg) is about 12 t.

Ice cores drilled with EWS have radial distribution of ethanol concentrations, with highest values at the surface layer (up to 10 000 ppm) and concentrations below the detection limit (0.10 ppm) at 20 mm depth. Abnormal d-excess values are presumably associated with ethanol contamination occurring in approximately 22% of the samples; frequency of abnormal d-excess values increases with the depth and peaks within a depth interval of low core quality, 50 m above the bottom. In samples with abnormal d-excess, average δD values are 20‰ heavier.

Experiments show that five of the eight commonly measured ions are not sensitive to the presence of ethanol, even with presumably high concentrations. Sodium, potassium and chloride contamination was detected in samples cut 8 mm from the surface of the ice core, but there is no reason to suspect that these samples were contaminated in any way by ethanol. Analysis of presumably ethanol-contaminated (2640 abnormal and 10 000 normal) samples through the whole length of the ice core drilled with EWS did not show any significant influence.

In order to reduce or exclude ethanol contamination the following changes in drill design and core-processing protocol are proposed: (1) use immersion hydrophobic fluid to isolate the ice core from EWS, which would reduce contact time to only 10–15 s; (2) blot and evaporate EWS residues from the ice-core surface before packing.

ACKNOWLEDGEMENTS

The technical and operational success of the ice-coring operations relies heavily on the equipment constructed at BPRC. We thank D. Lape and F. Hoffman for their high-quality work. Analyses of B–C core were made by P.-N. Lin, M. Davis and T. Mashiotta. Their efforts and valuable discussions allowed us to clarify some interpretation questions. We thank the University of Copenhagen (Geophysical Institute), Denmark, for contributing to the design and field testing of the new ETED coring heads. B. Koci and H. Ueda took part in numerous discussions that ultimately resulted in the design and construction of the ID system. J. Martin (Martin Diesels, Inc.) contributed ideas and resources for diesel generator development for high altitudes, and donated two units to BPRC. E. Kline and Pacific Domes (<http://www.pacificdomes.com/contact.html>) helped to develop a custom dome and provided a quality product. Anonymous reviewers provided useful suggestions that improved the paper. We thank friends who have been involved in ice-coring operations. This work was supported by the US National Science Foundation and the Ohio State University.

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MS received 4 April 2004 and accepted in revised form 6 May 2005