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Performance of intermediate depth portable ice core drilling system on polar and temperate glaciers

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Abstract: A portable ice core drilling system was developed at the Byrd Polar Research Center (BPRC) and tested during four field seasons on both polar and temperate ice fields. The prime features of the new drilling system include its low power requirement, light weight, depth capability of 500 m, quick setup, easy ice core handling, and high ice core production rate (ICPR). Since 1997, more than 1200 m of ice cores has been recovered with the BPRC dry hole electro-mechanical (EM) drill. After modifications described in this paper, the drill achieved the following performance characteristics: (1) drilling from the surface to 15 m in one hour in cold firn; (2) drilling to 30 m within 2.5 hours and (3) drilling to 100 m within 14 hours, with an average ICPR of 7.15 m/h.

Six boreholes in the temperate ice on the summit of Mt. Kilimanjaro (5985 m a.s.l.) totaling 200 m were drilled to bedrock. The deepest hole was drilled down to 51 m. High concentrations of dust and thick layers of volcanic ash were common features in the Mt. Kilimanjaro ice, where the average ICPR was 8–10 m/h.

A new version of the antifreeze-thermal-electric drill (ATED) has been developed and laboratory tested. The paper presents a comprehensive examination of the EM and ATED drill performances based on quantitative data regarding drill design and conditions at drilling sites. The optimal protocol for coring in polar and temperate ice at air temperatures above the melting point is examined.

1. Introduction

The concept of a portable ice core drilling system resulted from the demand for cost efficient field ice coring operation. An efficient field operation requires a low transportation burden with short setup and drilling time. Both requirements are especially important for high altitude ice coring operations. Over the past 25 years a few portable drilling systems have been developed which use dry hole EM drills (Blake *et al.*, 1998; Johnsen *et al.*, 1980; Zhu and Han, 1994). Depth capability of these drilling systems is limited to about 350 m in polar glaciers and to 200 m in subpolar glaciers.

Major components of the BPRC portable ice coring system are listed in Table 1. The system can be delivered to the drilling site partly or completely assembled by small aircraft, helicopter, snow machine, animal, or by man. In order to conduct ice coring in different environments the system includes drilling setup, two power supplies and two shelters, one

Table 1. Specifications of BPRC ice core drilling system.

1. EM drill:	Length core/drill	1.05/3.24 m
	Diameter core/hole	102/129 mm
	Penetration rate (max) in solid ice	∼72 m/h
	Power requirements (max/optimal)	1.0/0.5 kW
	Weight: item/shipment	35/50 kg
2. TE drill:	Length core/drill	2.1/2.58 m
	Diameter core/hole	102/129 mm
	Power requirements	1.5–3 kW
	Penetration rate (solid ice)	2.3–4.0 m/h
	Weight: item/shipment	38/50 kg
3. Winch:	Hoisting speed	0.5–0.9 m/s
	Pulling capacity	700–1400 N
	Power requirements	0.5–1.5 kW
	Weight: item/shipment	35/50 kg
	Frame	35/55
	Cable (500 m)/shipment	56/65 kg
	Tower and pulley/shipment	20/58 kg
	Control box/shipment	18/35 kg
4. Power system:	EM drilling, portable diesel, 1 kW	70/100 kg
	TE drilling, gasoline generator 5 kW	70/110 kg
5. Shelter:	Drilling	200/250 kg
	Power	45/45 kg
6. Miscellaneous:	Spare parts, tools,	50/65 kg
	EM drill (spare)	35/50 kg
	TE drill controller	35/35 kg

for drilling and core processing and another one for the power generator. No single component of the drilling system exceeds 30 kg in weight, except for drilling cables longer than 300 m. Longer cables can be delivered to the drilling site as one piece but in two or more skeins. Total shipping weight of the portable drilling system does not exceed 1100 kg. Shipping containers are 38% of this weight. Shelters, second power generator, and a set of two spare drills make up almost 50% of the total shipment weight. A minimal configured system powered with a portable diesel generator for EM drilling down to 200 m in open air weighs about 250 kg with tools and a minimal set of spare parts included. The optimal configuration of the system can be specified depending on desired maximum depth, ice temperature and expected weather conditions.

Thermal drilling requires drilling fluid and a bigger power system. The BPRC drilling system is described in Zagorodnov *et al.* (1998, 2000) in greater detail and includes compatible EM and thermal electric (TE) drills capable of retrieving 100 mm diameter ice cores. Alternating an EM drill with an ethanol thermal drill permits deep ice coring in subpolar and temperate glaciers and low usage of a borehole fluid (Koci and Zagorodnov, 1994). Therefore, this new drilling system differs from others by the option to use a TE drill with fluid in subpolar and temperate glaciers down to the depth of 500 m (Zagorodnov *et al.*, 1998), where most of the conventional dry hole EM drills encounter difficulties. Substitution of an EM drill for a TE drill bellow 200 m depth is possible by use of a lightweight, low electrical resistance coaxial drilling cable (Zagorodnov *et al.*, 1998). The other reasons for farther development of ATED technology are the environmental safety of ethanol-water solution (EWS) as a borehole fluid, option of the multiple ice coring using directional drilling technique (Zagorodnov *et al.*, 1994b) and long term stability of EWS filled boreholes (Zagorodnov *et al.*, 1998). These aspects of ice coring are specifically important for the study of sub-glacial lakes and shelf glaciers. At high ice temperatures at the bottom of shelf glaciers and above the sub-glacial lakes the ethanol concentration is as low as a few percent and many meters of ice above the interface can be drilled without ethanol.

The BPRC EM drill has the advantage of a relatively short chip storage compartment that can be emptied easily and quickly. This is an S-type drill that was invented by Arnason *et al.* (1974) and was suggested for dry hole ice coring by Suzuki and Shimbori (1985, 1986). S-type drills have separate compartment for storage of cuttings and core, U-type drills store cuttings and core in the same unit (Suzuki and Shimbori, 1985, 1986). Specifications of the drill are presented in Tables 1, 2 and in Table 2 in Zagorodnov *et al.*

Table 2. Specifications of cable suspended dry-hole electro-mechanical ice core drills.

Drill[†]	Length drill/ core	Area (cm^2) borehole/ core	Weight, drill/ core	Specific power[‡], W cm^{-2}	Ice core production rate	Reference
CRREL	3.6	158/79=2.0	9	12.53	6.6 m/h	Rand, 1975, 1976
PIUB	4.4* -	104/44=2.36 161/87=1.85	6.9 -	8.38 -	10 m/h <20 m/day	Rufli *et al.*, 1976; Schwander and Rufli, 1989, 1994
UCPH	3.5	85/48=1.77	9.1	6.08	75 m/day	Johnsen *et al.*, 1980; Clausen *et al.*, 1989; Gundestrup *et al.*, 1989
RU	4.7*	108/44=2.45	-	7.11	52 m/day	Jessberger and Dorr, 1984
NHRIE	3.7*	163/79=2.06	7.6	8.78	40 m/day	Holdsworth, 1984
PICO	4.7*	158/82=1.93	10.9	13.05	40 m/day*	Litwak *et al.*, 1984; Mosley-Thompson *et al.*, 1990
BZXJ	4.6	65/35=1.86	9.8	12.42	50 m/day	Zhu and Hun, 1994
JARE	5.1	167/87=1.92	8.2	12.37	30 m/day	Suzuki and Shiraishi, 1982
LGGE	3.5*	163/79=2.06	13.9	11.86	-	Gillet *et al.*, 1984
HILDA/ ECLIPS	3.6	99*/53=1.87	10.2	10.93	30 m/day	Blake *et al.*, 1998
INVENTOR	3.2	83/47=1.76	10.8	6.76	3-5 m/h	Stampfli and Stampfli, 2000[§]
BPRC	3.1	131/79=1.66	4.9	11.50	2.5...15 m/h	This work

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

[†] Name are from the organization which developed the drill and can be inferred from the reference.

[‡] Rated motor power and kerf area ratio.

[§] Simplified ice core drilling at high-altitude-glaciers down to bedrock. http://www.icedrill.ch/index.html#Ice_Core_Drills

(2000). According to data in Table 2 the BPRC EM drill has the smallest drill/core length and weight ratio and close to the highest value of specific bit power compared to other EM drills. The short length of the BPRC EM drill permits to confine the drilling operation to a relatively small dome shelter. The drilling setup is equipped with a tilting table, which allows for horizontal positioning of the drill, which reduces the physical load on the drill operators as well as drill preparation time.

The ICPR of the BPRC drill is close to the highest reported value, achieved by the PIUB drill (Table 2). Compared to the PIUB drill the BPRC drill has almost twofold more specific power, produces 60% bigger cross-section ice core, 30% lighter and 20% shorter. High power drills, such as PICO and BPRC are able to core sand laden and ash layered ice that require high torque to cut though a particle-ice mixture and to transport cuttings.

Ice coring of polar glaciers deeper than 100 m is often associated with core fracture and chip jams. Ice core drilling in Polar Regions at air temperatures close or above the melting point also causes chip sticking and chip jam. These problems have been recognized in the past and changes in drill design and drilling protocol have been made (Johnsen *et al.*, 1980; Schwander and Rufli, 1994). Similar problems were observed with the BPRC EM drill during ice coring in Greenland and on Mt. Kilimanjaro.

In this paper, field performance of BPRC EM drill in Greenland at three sites (D1, D2 and D3) and on three ice fields on Mt. Kilimanjaro is analyzed. After ice coring in Greenland in 1998 (Zagorodnov *et al.*, 2000) performance of the drill was significantly improved by the modifications of drill design and drilling protocol. Special attention in this paper is given to the operation of EM drill at air temperatures above the melting point, in cold and temperate ice.

2. EM drill performance and ice core quality

The conditions at the drilling sites in Greenland can be characterized by density and temperature profiles (Fig. 1a, b). The ice-firn transition is in the depth interval from 75 m to 90 m, and borehole temperatures range from −17°C to −24°C. Glaciers on Mt. Kilimanjaro do not have a firn sequence. Solid infiltration- and/or congelation ice (Shumski, 1964) was drilled from the surface to bedrock. Ice temperatures there were −1.4°C in the coldest part of the glacier and was melting point (water saturated ice) in warmest. Thus, the ice temperatures and densities at these sites represent a wide range of drilling conditions.

Experimental drilling at Raven site in Greenland (Zagorodnov *et al.*, 2000) to the depth of 122 m was performed with the BPRC EM drill with a relatively steady ICPR ranging from 2.5 m/h to 5.0 m/h (Fig. 2). After modification of the core barrel coupling, drilling at D1, D2, and D3 sites in the same depth interval was conducted at ICPR ranging from 3.0 m/h to 15 m/h. The ICPR is close to that of the U-type UCPH (Johnsen *et al.*, 1980) and CRREL drills (Rand, 1975, 1976) and surpasses performance of other drills (Table 2, Fig. 3). Real comparisons of different drills can be accomplished only if ice coring is conducted at the same site under similar conditions.

The daily ICPR was reduced due to the need for drill adjustments and repair (Zagorodnov *et al.*, 2000). Two major difficulties were found: (1) ice cuttings clogging

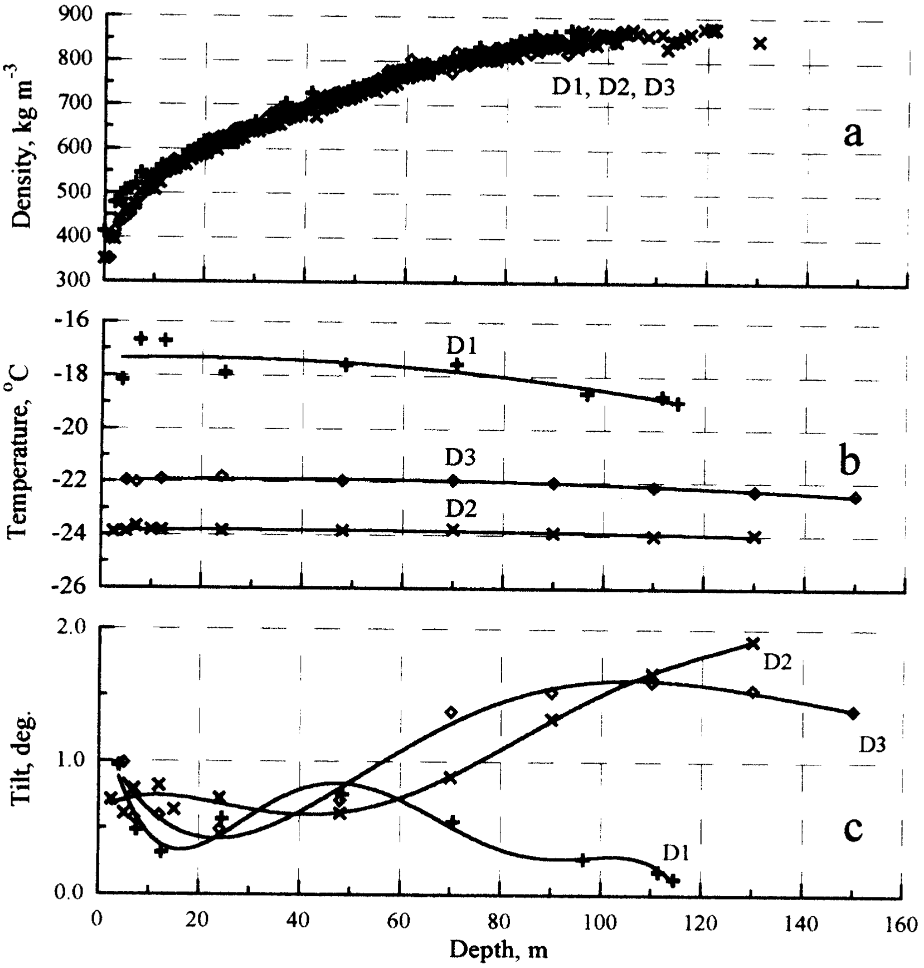

Fig. 1. Ice core density (a), borehole temperature (b) and borehole inclination (c) at D1, D2 and D3 drilling sites in Greenland.

the passageways and (2) ice cuttings sticking to the ice core surface. The first problem occurs below 60–80 m, usually after 2–3 p.m. when the air temperature inside the drilling shelter rises above the melting point. The first sign of the problem appears when cuttings stick outside of the coring head and core barrel. The space between flights gets narrower, and eventually chip passages are clogged with compressed ice particles. The second problem was observed at depths below 100 m. The consequences of cuttings deposited on the core surface are short drilling runs and jammed core inside of the core barrel. In order to conduct drilling with restricted ability to transfer ice cuttings from the kerf to the storage compartment, the drill motor was frequently overpowered. Sticking of cuttings to the ice core surface also causes high motor current and jamming of the ice core inside of the core barrel. As the depth increases, the layer of cemented cuttings gets thicker and harder. Eventually the core sticks to the bottom of the coring head. Both problems lead to short drilling runs and core fracture. In Fig. 4 depth intervals with mediocre drill performance appear as short penetration runs. A combination of factors such as ambient air temperature, size and shape of cuttings, penetration rate, drill design and quality of drill surfaces make it difficult to separate the contribution of each factor.

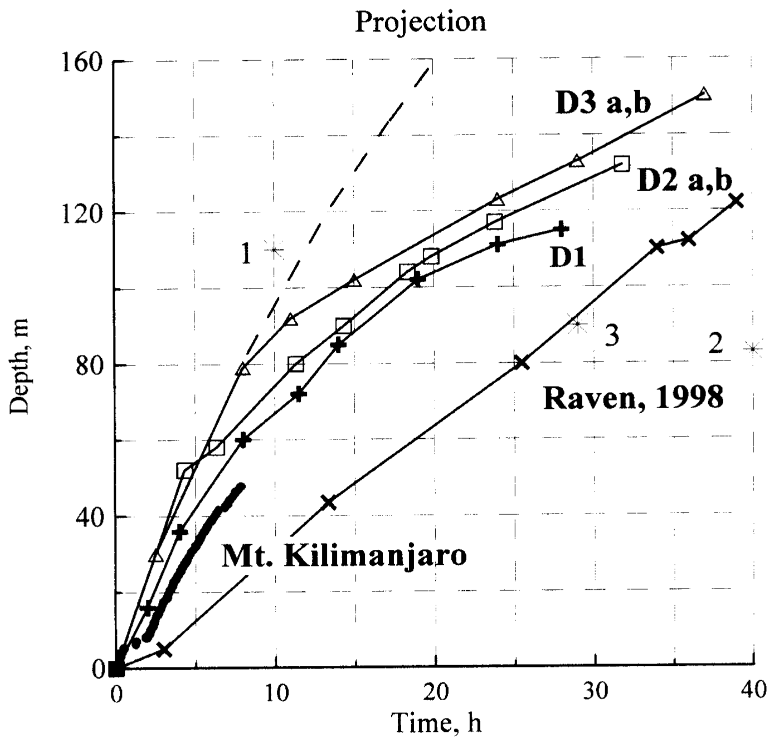

Fig. 2. *Progress of D1, D2, D3, Raven and Mt. Kilimanjaro boreholes; stars are progress of UCPH (1, Gundestrup et al., 1989), BZXJ (2, Zhu and Hun, 1994) and NHRIE (3, Holdsworth, 1984) drills.*

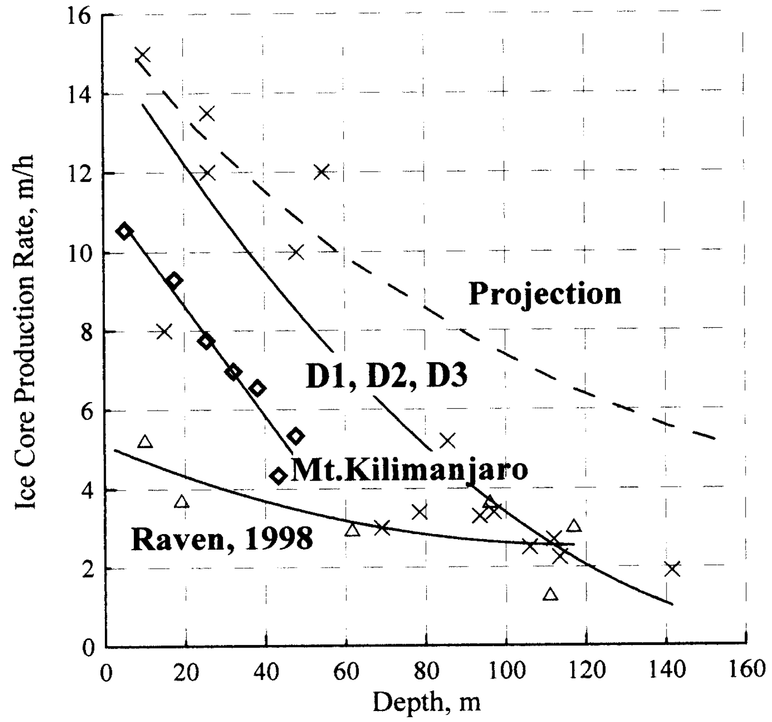

Fig. 3. *Ice core production rate versus depth.*

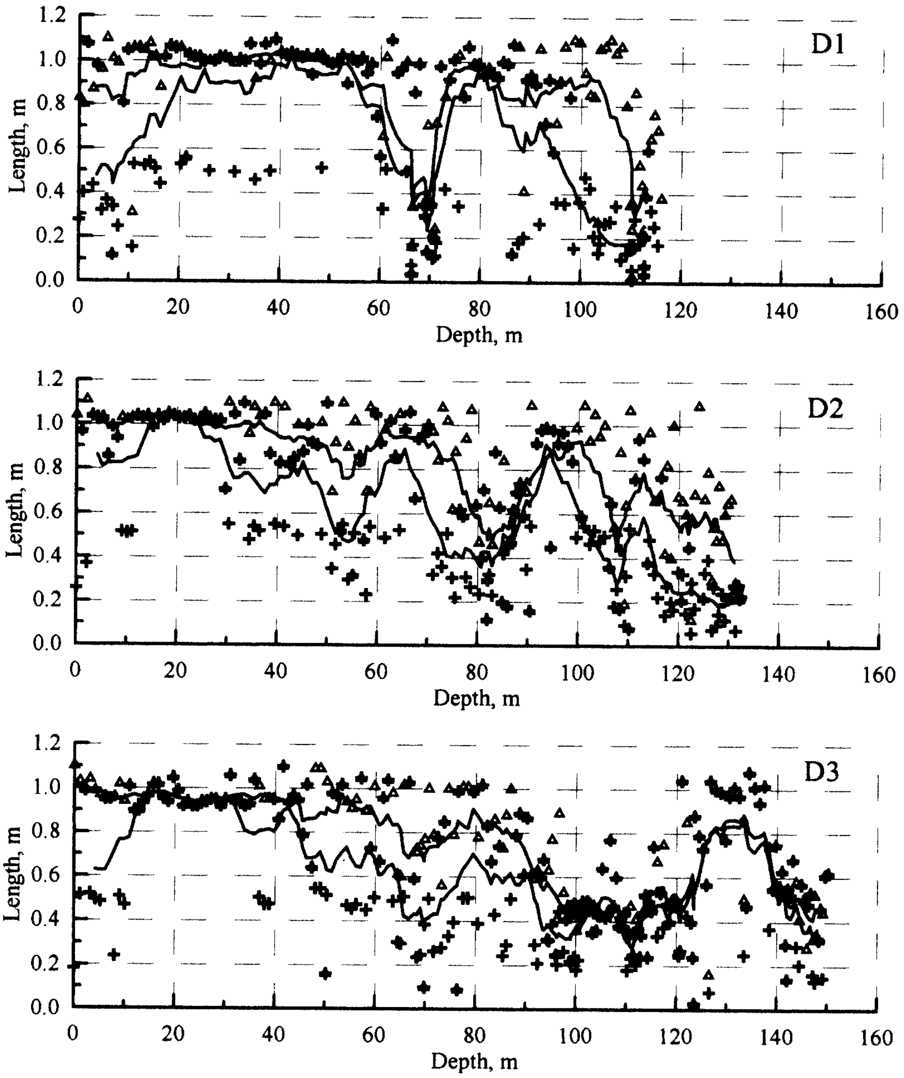

Fig. 4. Penetration depth (triangles) and length (crosses) of an ice core pieces per drilling run at D1, D2, and D3 sites versus borehole depth; solid lines are running average at 9 : 1 window.

Partial chip removal resulted in reducing the ICPR and reduction depth of penetration. Sometimes the problem can be solved with a set of sharp cutters as it was done at D1 at depth 70 m and at D2 at 60 m (Fig. 4, D1). The most effective way to avoid chip jam was to brush the outside surface of a core barrel and the inside surface of a jacket before every drilling run. That procedure allowed us to obtain good quality ice cores down to 100–110 m depth. Drilling to the greater depths requires further reduction of chip friction. To follow the idea to lubricate chip passageway (Schwander and Rufli, 1994), the outside surface of the core barrel and the inside surface of the outer jacket were treated with auto-antifreeze. It was found that a thin layer of such lubricant applied after brushing off the chip considerably improved drill performance. It should be stated that the inner surface of the core barrel was not in contact with antifreeze and ice core was not contaminated during drilling.

At the D3 site brushing was used below 50 m and lubrication below 120 m. At D3 (Fig. 4), one can see that with brushing only the penetration depth and core section length are gradually decreasing to 0.4 m at 120 m depth. At a depth interval from 120 m to 138 m lubrication was used on each drilling run. That resulted in increased length of core and ICPR. However, below 138 m penetration depth gradually decreased from 0.7 m to 0.3 m. Penetration at that depth was possible only at low (3–5 mm/s) rates and resulted in production of fine cuttings that stick to the core surface. It was clear that after the treatment of the core barrel and jacket, that reduction of penetration depth was due to jammed core inside the core barrel. Attempt to close the core catcher's windows in order to restrict chips influx to the core barrel did not give positive results.

Comparison of Schwander and Rufli (1994) and Johnsen *et al.* (1980) drills performance led us to the conclusion that the BPRC EM drill is less capable to transfer cuttings from the kerf to the storage compartment. The most likely reason for that is longitudinal roughness of the inside surface of the outer jacket. A new jacket of the same design has been built with smoother surfaces. Moreover a hard-anodized coating inside the jacket and the coring head has been applied. The outcome of these modifications is presented below.

Strong winds and powerful solar radiation, reaching 1200–1300 W/m^2 in the middle of the day (K. Mountain pers. commun.), are common to most high altitude tropical glaciers including Mt. Kilimanjaro. To deal with such conditions a geodesic dome with a solar radiation reflective cover has been constructed on the first drilling site at Mt. Kilimanjaro. At air temperatures inside the drilling shelter below freezing (−2°C) and glacier surface temperature of −1.4°C, the first ice core was drilled down to bedrock at 50.5 m depth. Without a reflective cover air temperatures inside drilling shelter would reach 10°C or higher. Brushing of the core barrel was a standard procedure and the antifreeze was not used here. In general, drilling runs were short (0.3–0.6 m), and the average ICPR was about 5 m/h. Ice core quality ranged from good to poor. It was also difficult to remove the core barrel from the drill because compressed cuttings obstructed it. Compressed ice cuttings were almost as hard as ice and filled the space between flights. With little effort the cuttings would flake off the barrel in big pieces. Such chip behavior is the result of ice being close to melting point (−0.4°C at the bottom) and relatively high air temperatures inside the shelter.

The second borehole was drilled under the same conditions, but brushing and antifreeze lubrication of the core barrel and the inside surface of the outer barrel were used from surface to the bottom. Drill performance improved substantially and the ICPR reached 10 m/h. Core length was increased to the maximum core barrel capacity with occasional short runs. Four other ice cores at two different ice fields were drilled without shelter at ice temperatures close to the melting point. Drill performance and ice core quality was excellent. Drilling was periodically slowed down by the necessity to change cutters when thick layers of volcanic ashes were encountered. Under such conditions a new set of cutters performed well over 20 m of drilling. When dullness of the cutters is visually obvious then short (5–6 mm) cracks from surface down to 4 mm depth are frequently observed in ice cores. Probably, performance of the drill and quality of sand laden ice core can be improved with carbide tip cutters.

One borehole on Mt. Kilimanjaro was drilled to 9.5 m depth in water-saturated ice.

Excellent quality ice core was obtained. The borehole was filled with water all the time. Drilling in water filled borehole resulted in slow lowering of the drill and 3–5 mm smaller core diameter. Drilling of water-saturated ice indicates a possibility to design an intermediate depth EM drill to operate in the borehole filled with an ethanol-water solution. Fluid EM drill would have the advantages of dry hole EM drill such as low power requirements, small disturbances of ice temperature, and high ice core production rate. It seems feasible to attempt intermediate depth ice coring in partially filled boreholes - to drill top 200 m with dry hole EM drill and deeper with fluid EM drill. Use of an ethanol-water solution makes it possible to dissolve cuttings in the borehole as it was done in CRREL deep drill (Ueda and Darfield, 1968). Such design makes possible to exclude two parts of conventional ice core drills: (1) the cuttings transport mechanism and (2) cuttings storage compartment. It resulted in short length and simple design drill. The fluid EM drill of the same length as the BPRC EM drill (3.2 m) with core barrel capacity of 2.1 m is designed and will be tested. New fluid EM drill can be used with the existing winch system and shelters. Drilling of water-saturated ice on Mt. Kilimanjaro shows that EM drill has 5-fold faster penetration rate compared to ethanol thermal drill and 30–50% slow lowering and raising rates. Without of outer-jacket borehole wall-drill clearance in new EM drill is almost three times bigger comparing to dry hole drill. Projected lowering rate of new fluid EM drill is slightly higher compared to that of the ethanol ET drill (Zagorodnov *et al.*, 1998). Based on performance data of ethanol ET and the BPRC EM drills expected ICPR of new EM drill in 200–500 m depth interval is 3–6 m/h.

Ice coring at the summit of Mt. Kilimanjaro was performed either inside the dome shelter or in open air with brushing and lubrication and was conducted below the rated motor power and without adjustments of cutters or antitorque. Therefore, a high daily ICPR was achieved mainly because of improved chip's passageways, core barrel brushing and lubrication.

3. Optimization of drilling protocol

Optimization of drilling protocol has three objectives: (1) minimization of field time, (2) reaching maximum depth with dry hole EM drill, and (3) reduction of physical effort by operators during drilling and core handling. The optimization of the drilling protocol also requires a reliable, efficient, lightweight, and easy to setup power system and shelters that are discussed in separate paper presented in this volume.

In order to develop optimal drilling protocol timing of major drilling procedures such as drilling run, drill descent, penetration, drill raise, core removal, and drill preparation, were recorded. The last two operations include drill placement on the tilt table, its horizontal positioning, core barrel and cuttings extraction from the drill, core extraction, brushing and application of antifreeze to the core barrel, brushing and lubrication of the inner surface of the jacket, drill assembly, turning drill vertically and taking it out of the tilt table. Timing of these operations as a function of a borehole depth is presented in Fig. 5. All measured data are approximated by a linear function of depth.

Lowering and raising the drill at very shallow depths required extra time to dampen the drill oscillation before placing it in the borehole, to reset the depth counter, to turn on and accelerate the winch motor, to couple the penetration drive, and then repeat the same

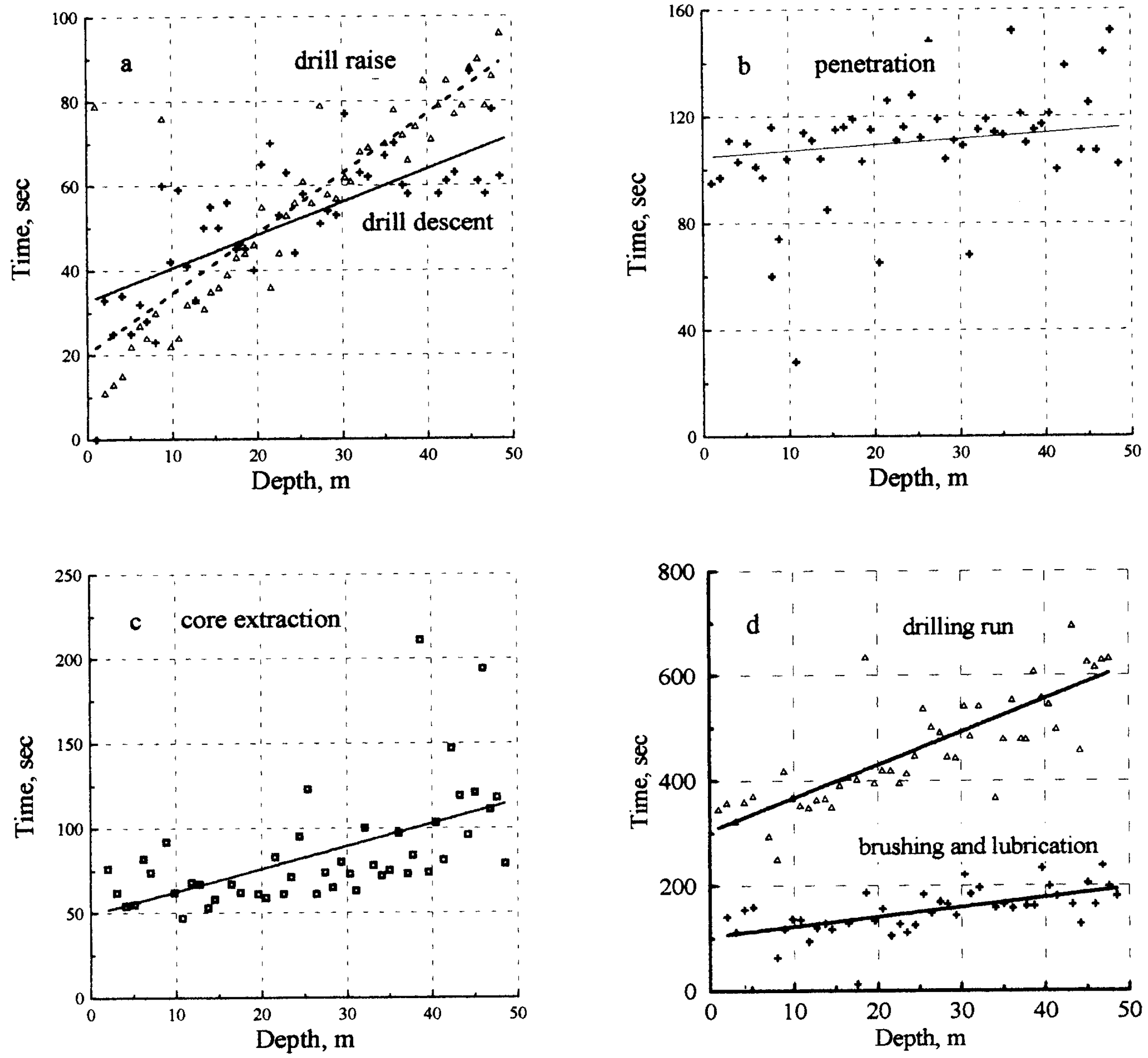

Fig. 5. Timing of ice core drilling procedures at Mt. Kilimanjaro; borehole 2.

steps in reverse order to finish the drilling run. Thus, the initial time for drill descent is about 32 s, for drill rise—about 20 s, and for core extraction—50 s. Drill preparation (brushing and lubrication) required 100 s. Therefore the total initial time needed to conduct the first drilling run at the surface is about 180 s. Normally, time of all operations linearly increased with depth. That seems logical for lowering, raising and penetration, but is also true for the ice core removal, brushing and lubrication. The late activity takes more time because chip are getting finer and exhibit better adhesion to the drill surfaces.

Drilling of polar firn does not require brushing and lubrication, and the use of a penetration drive. Therefore, if these operations can be excluded from the drilling protocol the initial time per drilling run will be one third of what was achieved at Mt. Kilimanjaro, and the ICPR achieved in firn at D1, D2 and D3 sites would be consistent with that at Mt. Kilimanjaro sites (Fig. 2). The option to use a second core barrel, which can be prepared (core removed, core barrel brushed and lubricated) during drill lowering, penetration and raising, could save up to 30% of drilling run time. Simple calculations show that depth of 100 m can be reached in 8.5 hours at an average ICPR of about 12 m/h. Projected time for 160 m ice coring is about 20 drilling hours.

High quality ice cores obtained on Mt. Kilimanjaro show that the modifications described above not only increase ICPR but also reduce cutting and torsion stresses on the ice core. Considering the above modifications effect on ICPR and ice core quality we expect that in cold glaciers good quality ice core can be obtained up to 250–350 m depth using a dry hole EM drill.

4. Borehole inclination

Ice core drills have a center of gravity above the coring head and have a tendency to produce inclined boreholes. Verticality of boreholes drilled with the BPRC EM drill was measured. Inclinations of D1, D2, and D3 boreholes are shown in Fig. 1c. From 0 to 60 m inclination of holes ranged from 0.5° to 1°. That inclination represents the initial tilt of the drill and tilt of the logger inside of core barrel. Below 60 m borehole tilt increased to 2°. Depending on the technique used to control penetration the tilt would either continue to increase or decrease. D1 and D2 boreholes were drilled mostly with 'off hand' technique, while D3 was done with the penetration drive - an auxiliary slow motor that provide slow cable feeding and limited penetration rate. The 'off hand' technique assumes free cable feeding and employs the operator's hand to sense cable tension and drill's bottom pressure. In practice, during routine operation the penetration rate is governed by the penetration shoes and very little is controlled by holding the cable to activate the pendulum steering (Aamot, 1967). Another way to achieve pendulum steering is to increase the antitorque blades lateral pressure and thereby achieve a top hanging point. Below 90 m depth one cannot sense the weight of the drill during penetration without special equipment. In conjunction with the chip sticking problem it is more difficult to control bit pressure. Although heavy drills with an efficient chip removal system may allow the operator to sense cable tension without sensors. Pendulum steering with the cable feed (penetration drive technique) is the most effective way to produce a vertical borehole. This technique requires a slow winch motor controller and a sensor to measure cable tension (Zagorodnov *et al*., 1998) or a penetration drive and a cable tension sensor. The first device has simpler mechanics and a faster start up procedure but relatively complex electronics. The second device is more robust, but has more mechanical parts and needs an additional 15 s to engage and disengage it each drilling run. D3 borehole below 90 m was drilled with the penetration drive. At depths below 100 m the tilt of the borehole decreases. All of the Mt. Kilimanjaro cores were drilled using the penetration drive. The two surveyed Mt. Kilimanjaro boreholes had no tilt.

5. Antifreeze-thermal-electric drill (ATED)

Field application of the BPRC ATED drill (Zagorodnov *et al*., 1998) shows the following drawbacks: (1) vulnerability, (2) lightweight, (3) relatively slow penetration. This 2.1-m capacity drill is made of thin wall (1.6 mm) stainless steel tube and weighs 25 kg; outside tubes used for EWS circulation have wall thickness 0.15 mm. Under field conditions the drill was vulnerable to damage during operation and harsh transportation.

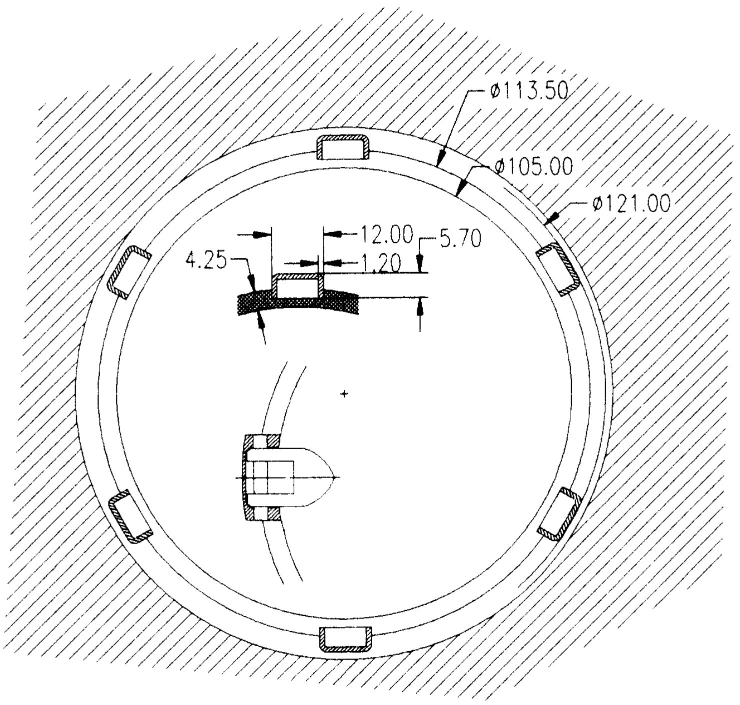

Fig. 6. Cross section of ATED: fluid circulation channels and core catcher are shown; dimension are in mm.

However, 315 m of ice core was taken without drill damage. A new more robust and heavy drill was made of stainless tube with a 4.25 mm thick wall (Fig. 6). In order to circulate EWS square groves have been machined along the core barrel; 1.25 mm thick channel covers the grooves. The new drill is more rugged and heavier, and with the same capacity of core barrel it weighs almost 38 kg. The core barrel-borehole wall clearance of the new drill is smaller compared to the light one. However, the projected lowering rate should be higher compared with the prototype due to increased weight. By the same reason it is expected that the verticality of the borehole will be maintained with less effort.

During production drilling the penetration rate of coring head was almost 45% slower than that at laboratory tests due to circulation of drilling fluid through the coring head (Zagorodnov *et al.*, 1998). To improve the performance of the coring head, 6 mm diameter holes were drilled trough a holding ring above the heating element. Now the EWS flow will not extract heat from the kerf as it did in the prototype coring head (Zagorodnov *et al.*, 1998). Penetration rate of new coring head is shown in Fig. 3 in Zagorodnov *et al.* (1998). As a result of faster penetration the borehole diameter is smaller and it could decrease lowering rate by about 30% (Zagorodnov *et al.*, 1994b), but increased weight will compensate for the smaller clearance.

The new drill is considered to be as a second drill available for the portable intermediate depth ice core-drilling system described above. However, the drill has potential for cost efficient ice coring down to the depths greater than 1000 m. The prototype drill was successfully used for deep drilling in central Antarctica almost 20 years ago (Zagorodnov *et al.*, 1998) to depths of 800 m and recovered good quality ice cores. The new version of ATED has better heat distribution and according to our theoretical investigations

(Nagornov *et al*., 1994) induces less thermo-elastic stress that is prime cause of the ice core fracture.

6. Conclusions

The major technical difficulty of dry hole ice coring is chip removal. A reliable chip removal mechanism guarantees fast drilling and good quality ice core. The BPRC EM drill performance has been significantly improved with properly machined, polished and coated inner- and outer surfaces of the coring head, the core barrel and the outer jacket. Brushing of chip pathways before each drilling run led to fewer chip sticking and clogging of passageways.

Ice cuttings melting and clogged passageways are common problems during ice coring at air temperatures above melting point. One tested solution is to treat chip passageways with auto-antifreeze. This procedure also improved drill performance and quality of ice cores drilled below 130 m in a cold environment (−15... −30°C). Use of a chemically active lubricant as an auto-antifreeze also permits drilling of temperate ice at air temperatures above melting point. Ice cores are not in contact with lubricant and therefore are not contaminated. This procedure was tested only with the BPRC (S-type) drill and may not be suitable for the conventional EM drills.

The BPRC EM drill achieved a maximum ICPR of 15 m/h in cold firn and 10 m/h in temperate ice at shallow depths. It is estimated that alternate use of two core barrels below 30 m would reduce drill preparation time and maintain an average ICPR of 9–10 m/h down to 100 m. On the other hand, the physical load on drill operators and core processors will be tangibly increased compared to a drilling protocol with one core barrel.

Drilling of sand laden ice and ash layers required more attention to cutters compared to drilling of pure ice. Often one set of cutters performed well over 20 m. Penetration of only one 0.1 m thick ash layer dulled the cutters. Probably carbide tip cutters could last longer, but brittle carbide may require more frequent sharpening than steel cutters. Because of the brittle nature of carbide, non-aggressive cutting angles would have to be found.

If verticality of the borehole is imperative then the initial borehole tilt can be controlled with a guidance system incorporated into the drilling setup. To achieve vertical drilling from surface to a desired depth a penetration drive and the electronic cable tension sensor have to be used. Without these special measures borehole inclination from 1.5° to 3° can be routinely maintained by pendulum steering with adjustable antitorque blades.

Experimental drilling of water-saturated ice indicates a possibility to design an intermediate depth EM drill to operate in fluid filled borehole. This type of drill could yield the advantages of dry hole EM drills such as low power requirements, small disturbances of ice temperature, and high ICPR. It is also worth consideration of the use of an ethanol-water solution as a borehole liquid to benefit from its small environmental impact and low transportation burden (Gosink *et al*., 1991).

An improved version of antifreeze-thermal-electrical drill was designed and laboratory tested. It is expected that field operation of the drill will permit a higher ICPR. The drill will allow cost-efficient ice coring to depths of 1500–2000 m. The drill is suitable for sub-bottom multiple ice coring with minimal environmental impact on sub-glacier areas.

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