7th INTERNATIONAL WORKSHOP

ON

ICE DRILLING TECHNOLOGY

Pyle Center, University of Wisconsin, Madison, WI, USA
9-13 September 2013

Co-sponsored by:
Ice Drilling Program Office – Ice Drilling Design and Operations (IDPO-IDDO)
International Partnerships in Ice Core Sciences (IPICS)
International Glaciological Society (IGS)

Conveners:
Mary Albert (Ice Drilling Program Office, USA)
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PROGRAM

Monday, 9 Sep 2013			
	16:00		Icebreaker/Registration
	20:00		*End of day*
Tuesday, 10 Sep 2013			
	08:00		Registration
		OPENING SESSION	
	08:30		Opening of workshop
	08:35	Hansen	Sigfús Jóhnsen memorial
	08:45	Severinghaus	Some scientific goals for ice drilling over the next decade (keynote lecture)
Session 1		**CHALLENGES & EMERGING TECHNOLOGIES**	
	09:45	Talalay	Recent problems of ice drilling technology: A discussion
	10:05	Wilhelms	Present drill developments at the Alfred Wegener Institute (AWI)
	10:25	Wang	Rapid ice drilling concept with air continual transporting of cuttings and cores
	10:45		*Coffee break*
	11:15	Alemany	The new subglacior drilling probe
	11:35	Triest	Down borehole sampling and analysis design solutions for the SubGlacior Ice&Lasers project
	11:55	Zagorodnov	Thermodynamics of access boreholes in Ross Ice Shelf studied with DTS sensors
Session 2		**LOGISTICS & DRILL CAMP OPERATIONS**	
	12:15	Steffensen	The NEEM deep ice core drilling camp as a test site for new ideas in camp construction
	12:35	Mulvaney	The James Ross Island and Fletcher Promontory ice core drilling projects
	12:55	Pyne	Intermediate Coring at Roosevelt Island: Logistics and lessons
	13:15		*Administrational stuff*
	13:20		*Lunch break*
	14:20		**POSTER SESSION**
	18:00		*End of day*
Wednesday, 11 Sep 2013			
Session 3		**SHALLOW & HIGH-ALTITUDE DRILLING**	
	08:30	Kuhl	Blue Ice Drill — Design and applications
	08:50	Matoba	Alpine ice core drilling at the northern North Pacific region
	09:10	Schwikowski	A new thermal drilling system for high-altitude or temperate glaciers
	09:30	Hong	Discrete element modeling of cuttings transportation by ice coring auger
	09:50	Leonhardt	Buildup, advancement and field test of a 200 meter shallow core system based on the classic Hans Tausen Drill
	10:10		*Coffee break*
Session 4		**INTERMEDIATE DEPTH ICE DRILLING**	
	10:40	Sheldon	A new Danish intermediate depth ice core drilling system
	11:00	Johnson	Next generation of an intermediate depth drill
	11:20	Triest	Technical innovations and optimization for intermediate ice core drilling
	11:40	Mandeno	Ice coring at Roosevelt Island: Drill design, performance and refrigeration solutions at a low altitude "warm coastal" Antarctic location
	12:00		*Administrational stuff*
	12:10		*Lunch break*
	13:15		**FIELD EXCURSION**
Thursday, 12 Sep 2013			
Session 5		**HOT WATER DRILLING**	
	08:30	Cherwinka	The Enhanced Hot Water Drill (IceCube — South Pole)
	08:50	Benson	The ARA Hot Water Drill (Askaryan Radio Array — South Pole)
	09:10	Anker	The BAS ice shelf hot water drill: current design and drilling methods
	09:30	Makinson	Hot water drilled sub-ice access required: what are the best options?
	09:50	Hill	A review of the subglacial Lake Ellsworth 2012/13 field campaign
	10:10		*Coffee break*
	10:40	Rack	Developing a hot-water drill system for the WISSARD Project
	11:00	Duling	Techniques for clean access drilling of subglacial lakes
Session 6		**SPECIAL ASPECTS OF ICE DRILLING TECHNOLOGY**	
	11:20	Duling	Traction drives to improve hose and cable spooling

	11:40	Burnett	Instrumentation and control systems for the WISSARD hot water drill
	12:00	Mortensen	Precision cable winch level wind for deep ice coring systems
	12:20	Fan	Design and test of anti-torque system of cable-suspended electromechanical drill
	12:40	Zhang	Control system of IBED electromechanical drill
	13:00		*Lunch break*
Session 7		**DRILLING FLUIDS**	
	14:00	Xu	Theory and experiment of ester drilling fluids for ice coring in Antarctica
	14:20	Sheldon	Promising new borehole liquids for deep ice core drilling on the high Antarctic plateau
Session 8		**DIRECTIONAL DRILLING & REPLICATE SAMPLING**	
	14:40	Podoliak	The technology of directional drilling in ice via drill on carrying cable
	15:00	Shturmakov	DISC Drill and Replicate Coring System — New era in deep ice drilling engineering
	15:20		*Coffee break*
	15:50	Gibson	Replicate Ice Coring System architecture — Mechanical design
	16:10	Mortensen	Replicate Ice Coring System architecture — Electrical, electronic, and software design
	16:30	Johnson	DISC Drill and Replicate Ice Coring System testing
	16:50	Dahnert	Production drilling at WAIS Divide
Session 9		**FUTURE DRILLING PROJECTS**	
	17:10	Steffensen	A new Greenland drill site, NEGIS
	17:30		*Administrational stuff*
	18:00		**BANQUET DINNER**
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Session 10		**DEEP ICE DRILLING**	
	08:30	Popp	Experience from the NEEM deep drilling
	08:50	Vasilev	The method for maintaining the differential pressure in boreholes drilled in ice and the effect of ice hydrofracturing
	09:10	Vasilev	Results and peculiarities of the 5G borehole drilling
	09:30	Motoyama	Analysis of shallow/deep ice core drilling data, and the future plan of intermediate depth drilling
Session 11		**RAPID ACCESS & IN-SITU PROBES**	
	09:50	Dachwald	Design and field tests of a maneuverable clean subsurface ice exploration probe
	10:10	Heinen	Acoustic in-ice navigation in the Enceladus Explorer project
	10:30		*Coffee break*
	11:00	Goodge	Progress toward a rapid access ice drill for deep drilling of basal ice sheets and sub-ice bedrock in Antarctica
	11:20	Schwander	RADIX: A minimal resources rapid access drilling system
Session 12		**WARM ICE, SUBGLACIAL PENETRATION & SAMPLING**	
	11:40	Lipenkov	What have we learned from the first unsealing of Lake Vostok?
	12:00	Graly	Pulley operated, suction-powered subglacial sediment extractor successfully employed to depths of 825 meters
	12:20	Siegel	Project VALKYRIE: Development of a laser powered autonomous ice penetrator
	12:40		*Lunch break*
	13:40	Zagorodnov	Mechanical ice core drilling at temperatures close to the pressure melting point
	14:00	Sun	Bedrock drilling project at Gamburtsev Subglacial Mountains in East Antarctica
	14:20	Cao	The diamond drilling bits test for subglacial bedrocks sampling
	14:40		**CLOSING SESSION & WRAP-UP**
	15:00		*Coffee break*
	15:30		Spontaneous session on hot topics
	18:00		Latest end of workshop

Recent problems of ice drilling technology: A discussion

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More than 170 years ago, in 1841 Louis Agassiz, one of the creators of glacial theory, made his first attempt to drill to the bed of Unteraargletscher, Alps. Since that time, various thermal and mechanical ice drilling systems were specially built for this job as well as some conventional drill rigs were adapted for ice coring. Although the recent ice drilling technology is at the high, there are still many problems to be solved by future development engineering. Some of these difficulties were identified at the first International Partnerships in Ice Core Sciences (IPICS) workshop in 2004 as the main challenges of ice drilling technology. That is improving of drilling fluids, core quality of brittle ice, drilling efficiency in the "warm" ice, and replicate coring methods. Even some of approaches have been found, these problems still are not solved completely. In addition, other specific challenges related to improvement of the old drilling methods and developing of the new emerging technologies may be determined as follows: rapid ice drilling with air continual transporting of cuttings and cores; sidewall coring; identification of safety maximal depth of dry drilling in ice; penetration into subglacial rocks; environmental-friendly accessing of subglacial lakes; core breaking of the "warm" ice and subglacial rocks; designing of reliable fishing tools; casing construction and sealing of casing shoe; adjusting of the conventional drilling rigs for glacial exploration; improving of the control system and some others. Recent problems of ice drilling technology are discussed, and possible solutions are given.

Present drill developments at the Alfred Wegener Institute (AWI)

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The presentation will give an overview about the drill design and manufacturing technology aspects we tackled while building the 200 m ice core drill and the inter-mediate depth and deep drilling system.

The presentation will cover e.g. a new winch design, a new drill tower concept, new motor sections, manufacturing technology for EPICA/NorthGRIP drill parts and design modifications to the EPICA/NorthGRIP drill design.

Some of the special aspects we will present in more detail on posters, where this talk will present the overall concept.

Rapid ice drilling concept with air continual transporting of cuttings and cores

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Compressed air as the drilling fluid has many advantages: low environmental pollution, high drilling efficiency, low cost, high penetration rate, etc. At present, air drilling technology is recognized as the contemporary drilling technique that is applied widely and has the most developmental potential. The ice drilling technology with air cuttings removing by conventional normal circulation was previously proposed and tested. However, because of loose state of shallow ice near drilling wellhead, the compressed air is leaked and compressed air flow rate dramatically decreases. Thus, the ice cuttings will not be discharged from the borehole bottom, and repeated fragmentation will happen, which results in low drilling efficiency and even in stoppage of penetration. In general, drilling depth can reach only 100 m. Casing of the permeable snow-firn zone can improve penetration process but requires applying of complicated drilling technology with under-reaming operations and sealing of casing shoe. Proposed rapid ice drilling technology with air continually transporting cuttings and cores produces dry hole using air reverse circulation technology. Two options are considered to obtain ice cores without stopping of drilling. When double-wall drill pipe is used, air goes down to the bottom of the hole from the gap between the inner and outer tube, and then carrying ice core and ice chips back to the surface from the drill pipe center channel. When single wall drill pipe and vacuum pump are used, air goes down to the borehole bottom from the circle gap between the borehole wall and the outer of the drill pipe, and then transports the cuttings and cores from the center of pipe with suction-function of the vacuum pump. Calculations of the airflow rate and pressure are presented on the base of flow required for continually transporting the ice core with the most length and diameter.

The new subglacior drilling probe

Alemany O. (1), Chappellaz J. (1), Kerstel E. (2), Romanini D. (2), Cattani O. (3), Falourd S. (3), Calzas M. (4), Triest J. (1), Lefebvre E. (1), Possenti P. (1), Duphil R. (1) and Piard L. (1)

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The aim of the French ANR SUBGLACIOR (and European ERC ICE&LASERS) projects to be implemented during the coming 5 years is to design, construct and implement a revolutionary ice drilling system able to measure geochemical signals in situ (measurements performed simultaneously with the drilling) using an embedded laser spectrometer in the probe. Here, we do not speak anymore about ice core drilling. We plan a true probing of the ice sheet, part of the ice being used for the online measurements. The drilling system will include: i) the drilling tool itself, embedding an OFCEAS laser system patented by LIPhy at Grenoble (for measuring water isotopes and greenhouse gases), and its electronics to transmit information at the surface, ii) a hosepipe and cable to drive the probe, to provide power, to get the electronic information, and to circulate the drilling fluid and ice chips from the borehole to the surface, iii) a winch. This ensemble should be able to drill down to 3000-4000 m of depth within a single field season in Antarctica, i.e. in less than 90 days. The instrument will be carried on site by traverse vehicles or relatively small aircrafts (like Dash 7 or BT67). This revolutionary system will then be key to ascertain the validity of future potential Antarctic sites for accessing ice older than 1 million years. Its long-term impact will also include many glaciological and biogeochemical applications.

We will present here the current status of the probe design and we will discuss the solutions envisaged to circumvent several technical challenges related with such design.

Down borehole sampling and analysis design solutions for the SubGlacior Ice&Lasers project

Triest J. (1), Alemany O. (1), Chappellaz J. (1), Romanini D. (2), Grilli R. (2), Desbois T. (2) Guillerm C. (3), Cattani O. (4) and Falourd S. (4)

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Using significant technological breakthroughs and unconventional approaches, the ANR SubGlacior and ERC Ice&Lasers projects aim to advance ice core research by inventing, constructing and testing an in-situ probe to evaluate if a target site is suitable to recover ice as old as 1.5 million years. The probe will drill down into the ice and measure, in real time, the depth profiles of the ice δD and/or $\delta^{18}O$ water isotopes, as well as the trapped gas CH_4 concentration, using innovative embedded laser technology. The probe, anticipated to have a diameter of around 120mm, will electromechanically drill down the ice sheet to a maximum depth of 3500m and sample continuously using a melting device. In this talk, we will present the challenges and related design evaluations and solutions for the water sampling and laser analysis systems that are housed inside the SubGlacior probe.

We will cover:
- overall probe design and section layout
- high pressure sample inlet and outlet solutions
- continuous gas and vapor extraction
- miniaturization of the OFCEAS laser spectrometer
- instrument control from embedded mini PC
- temperature and vibration control
- FEA analysis for optimal thermal and mechanical design
- drill fluid evaluations

Thermodynamics of access boreholes in Ross Ice Shelf studied with DTS sensors

Zagorodnov V. (1), Tyler S. (2), Holland D. (3), Stern A. (3), Thompson L.G. (1), Sladek C. (2) and Kobs S. (2)

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We present a new method of shelf glacier access borehole drilling emphasizing a light-weight, environmentally friendly, portable and low logistic burden drilling technique. This presentation describes a drilling technique that was successfully developed for multiple sensors installation under the Ross Ice Shelf (RIS) at the Windless Bight (WB) site, Antarctica, in November-December 2011. The technique was developed for small sensor (d<40 mm) installation. Combination of dry borehole electromechanical drill (EMD) and thermal-electric hot point drill (HPD) made possible penetration through 193 m ice shelf and into the ocean below in ~34 hours of drilling effort. Data collected during drilling and access at Windless Bight showed that access (40 mm sensors) to the subglacial cavern was possible during 3-4 hours after penetration to the ocean in spite of strong freezing conditions within the borehole. Total weight of EMD and HPD equipment including power system and fuel is ~400 kg. Two team members from a party of four drilled two access boreholes at WB 2011 site. This new drilling technique does not require drilling fluid and therefore has minimal environmental impact when compared with other ice drilling techniques.

Three fiber optic Distributed Temperature Sensing cables (DTS) were installed in two boreholes, allowing continuous, high temporal (2.5 min first 42 h; 6 h during following 6 month) and spatial (1 m) resolution monitoring of the borehole and sub-glacier sea temperature (Stern et al., 2013; Tyler et al, 2013). The DTS data from the borehole during and after freeze in, laboratory experimental data on borehole freezing rate and theoretical estimates were used to study borehole closure rate due to seawater freezing and temperature relaxation after boreholes were frozen.

The experiences and data from Windless Bight will permit modifications of the drilling equipment and current drilling protocol that make possible: 1) installation of sensors up to 110 mm in diameter; 2) logging, water and/or sediments sampling in sub-glacier cavern and following small diameter (40 mm) sensors installation within 3 hours (ice temperature -25°C); 3) rapid (18-22 work hours) penetration time through up to 200 m ice, and 4) installations through 400 m thick ice shelf after 65 hours of drilling.

The NEEM deep ice core drilling camp as a test site for new ideas in camp construction

Steffensen J.P., Larsen, L.B., Hansen, S.B., Sheldon S.G., Popp T., Hilmarsson S. and Dahl-Jensen D.

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The NEEM camp was constructed in 2008 on the Greenland ice sheet (77.5 N 51 W, 2450 m a.s.l) to facilitate ice core drilling and analysis and to support associated programs. In 2009 and 2010 a 2540 m ice core to bedrock was retrieved and in 2011 and 2012 samples of basal material were collected before the camp was packed down on site. 12500 man-days were spent at NEEM by 260 persons: 51% young scientists, 21% senior scientists, 20% logistics and 8% associated project members. Several new construction features have been introduced at NEEM to reduce the overall carbon emissions of ice drilling operations, to reduce the impact on local environment and to fulfill the environmental conditions laid out by Greenland Authorities. Among the new features are: Extensive use of modular freezer units as 'warm' cabins for power plant, workshops and laboratories, a mounted ski frame under the 4-storey, 45 ton main dome building, central heating of the main dome using waste heat from the power plant and frames that allow for lifting and moving garages in one piece. Finally, a full size sub-surface test science trench was constructed with the use of a balloon, eliminating future need for any roofing material except snow. The bulk of NEEM camp assets have now been stowed on heavy sleds for a future move by traverse train, including the main dome to a new drill location on the Greenland ice sheet.

The James Ross Island and Fletcher Promontory ice core drilling projects

Mulvaney R. (1), Triest J. (1, 2) and Alemany O. (2)

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Following on from the successful multi-season project to recover an ice core to bedrock on Berkner Island (948 m), the UK-French collaboration went on to drill two further bedrock ice cores from James Ross Island (JRI) situated close to the northern-most extent of the Antarctic Peninsula in 2008 and the Fletcher Promontory (FP) to the south-east of the Peninsula in 2012. Each of the new ice cores penetrated to the bedrock (364 m at JRI; 654 m at FP), and each contains ice from the last glacial period and, in the case of FP, possibly even the previous interglacial. Briefly we will discuss the scientific motivation for drilling these cores, and our experiences in the field.

Remarkably, each of the two new ice cores were recovered in single seasons, starting and finishing with clear equipment-free sites, with teams of just seven personnel at the site. Here we discuss how we took the experience from Berkner Island, and refined it to enable rapid input and setup of the drilling infrastructure, and the successfully recovery of intermediate bedrock ice cores with a minimal team. Each of the cores was drilled in fluid filled borehole, and the fluid recovered from the borehole at the end of the drilling and flown out of the field. At the end of each of these drilling projects, the entire drilling infrastructure was uplifted and retrograded from the field in the same season.

Intermediate coring at Roosevelt Island: Logistics and lessons

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Roosevelt Island is a coastal ice rise embedded in the north eastern corner of the Ross Ice Shelf about 750 km from the McMurdo airfields. The island divide (drill site) has a 'coastal climate' with a mean annual temperature of –23°C, elevation of 560 m and accumulation ~20 cm/yr. Mid- summer surface air temperatures rise above zero during the warmest part of the day, and in combination with high humidity means that low cloud/fog is common and has been a major constraint to regular air operations. For the three seasons of operation so far (2010–2013) approximately 63,000 kg of personnel and equipment has been flown to site in 34 DC3-T (Basler) and one LC130 airlifts. Approximately 28,000 kg of equipment remains on site for recovery in 2013–14.

Intermediate depth ice coring has been carried out over the last two summer-seasons 2011-2013 reaching bedrock at 765 m depth. Drilling and core processing was carried out in a bespoke tunnel tent covering a firn trench floored with interlocking polyethylene 'pavement' normally used for soil stabilization. The tent/trench successfully allowed two summer seasons of drilling but is a constraint to multi-year deeper drilling operations or at sites of very high snow accumulation.

Equipment delivered to site is limited in size and weight compatible with Twin Otter/Basler aircraft operations. This has limited 'man moveable' equipment units to ~430 kg and mobile plant to snow mobiles which have been used for all surface operations including rudimentary grooming of the skiway.

A camp operation for up to 12 personnel has been in operation to support drill shifts and provided shower, laundry and kitchen, water from snow melting using electrical and generator waste heat. Secure power generation for camp and drilling operations has been problematic and generator improvements would be considered for the future that could improve waste heat recovery but still remain within the equipment handling restrictions for aircraft.

Blue Ice Drill — Design and applications

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The Blue Ice Drill (BID) is an agile drill system designed by the Ice Drilling Design and Operations (IDDO) group of the University of Wisconsin-Madison to produce clean, high quality 241 mm diameter ice cores quickly from near surface. The entire drill system is transportable by one helicopter load. The system consists of a down-hole motor/gear reducer rotating a coring cutter and core barrel inside an outer barrel for efficient cuttings transport in solid ice. A variable frequency drive (VFD) and a custom-made control box regulate electrical power to the drill. Torque reaction is accomplished on the surface via handles attached to a torsion stem. Core recovery is achieved with either core dogs in the sonde or with a separate core recovery tool (CRT). All down-hole tools are suspended on a collapsible tripod via ropes running on a capstan winch. The BID is operated by a minimum of two people and has been used successfully during two seasons of coring on a Blue Ice area of Taylor Glacier in Antarctica.

A new generation of the drill system, BID-Deep, has been designed to increase the coring depth to 200 meters. The BID-Deep coring system incorporates a traditional winch with steel, electromechanical cable and a redesigned crown sheave assembly. The addition of anti-torque skates and a strengthened, load-triggered slide-hammer to the sonde improve coring efficiency at depth. Components of the BID-Deep coring system were tested near Summit Station in Greenland in 2013. The full system is scheduled for completion in 2014.

Alpine ice core drilling at the northern North Pacific region

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Institute of Low Temperature Science (ILTS), Hokkaido University carried out ice core drillings at alpine glaciers in the northern North Pacific region to reconstruct climate change for a few hundreds years in this region. We obtained two ice cores from Kamchatka Peninsula. An ice core of 211m long was drilled at the summit caldera of Mount Ushkovsky in the Vostok Range. The other of 115m long was drilled at the summit caldera of Mount Ichinsky in the Sredny Range in 2006. The drilling was successfully carried out until bedrock. Three ice cores were obtained from two sites of Alaska. Two ice cores of 50m long and 212m long were drilled from the summit caldera of Mount Wrangell in the Saint-Elias Range. Another ice core was obtained from the ice divide of three glaciers; Black Rapids, Trident, and Sustina Glaciers in Alaska Range. The ice cores were drilled with several types of electro-mechanical drills made by Geo Tech Ltd Japan and the technical division of ILTS. In this presentation, we introduce specifications of the drilling systems including types of cutters, core catcher, anti-torque, winch, motor and so on with data of drilling operations and conditions of drilling sites. We also show preliminary data of ice core analysis.

A new thermal drilling system for high-altitude or temperate glaciers

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For ice core drilling on high-elevation glaciers, lightweight and modular electromechanical (EM) drill systems are used to allow for transportation by either porters or pack animals. However, the application of EM drills is constrained to glaciers with temperatures well below the ice melting point. When drilling into temperate ice, liquid water accumulates in the borehole, filling the chip barrel and finally blocking the drill. Drilling into or near temperate ice is also problematic since pressure induced melting during drilling can cause refreezing of melt water on the drill which then easily gets stuck in the borehole. Additionally the drill chips freeze together and ice forms on the cutters. Another disadvantage of EM drilling is its susceptibility to ice core fracture. Especially in the deepest part just above bedrock, which is under highest shear stress comparable to the brittle ice zone, small pieces of ice are often produced instead of good quality ice cores. Fractured ice cores cannot be used for the analysis of most trace species, since the standard decontamination techniques cannot be applied.

We developed a new thermal drill (TD) which can be easily combined with the EM drill FELICS (Fast Electromechanical Lightweight Ice Coring System). It produces a borehole diameter of 103 mm compatible with FELICS and ice cores with a length of 70 cm and a diameter of 80 mm, minimal 75 mm. The melting element consists of a hotspring coil heater of 3.3 mm diameter and 610 mm heated length. Nominal power is 650 W at 230 V, actual power is 2000 W at 400V. The heater is placed in an aluminum crown with cooling fins. With the combined drill we obtained a 101 m long surface-to-bedrock ice core from temperate Silvretta glacier, Swiss Alps (2927 m a.s.l.). The borehole temperature was around 0°C and it was filled with melt water. Power was supplied by two 2-kW gasoline generators, with a total consumption of 70 l of alkylate fuel for the 89 m drilled with the TD drill. Drilling speed was about 1.8 m/h. The drill produced excellent quality, none-fractured ice cores.

Discrete element modeling of cuttings transportation by ice coring auger

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Electromechanical auger drilling technology is widely used in shallow ice core drilling either on mountain glaciers or polar ice caps and sheets. Generally, these drills have light weight, can be easily transported to remote drilling site and conveniently installed there, and drill with relatively high rate of penetration and low power consumption. Nowadays at least 14 types of auger electromechanical drills were designed and tested in glaciological laboratories all over the world, however, auger options were usually determined by experience, and the main parameters (helix angle of the fights and rotational speed) are varied in a wide range from drill to drill. In order to improve the efficiency of cuttings removal and to choose the optimal parameters, auger transportation of ice cuttings was simulated using EDEM Software Platform. The cuttings transportation was modeled for the auger with certain helix angle (15°; 20°; 25°; 30°; 35°; 40°; 45°) at five different rotation speed (50 rpm; 75 rpm; 100 rpm; 125 rpm; 150 rpm) and constant cuttings production rating at penetration of 20 m/h. The efficiency of ice cuttings removal was considered from two points of view: average particles velocity and height of cuttings transportation. As the result, the optimal helix angle was determined.

Buildup, advancement and field test of a 200-meter shallow core system based on the classic Hans Tausen Drill

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Many challenges need to be overcome by drilling ice cores in polar areas. The construction of a drill system is by no means a simpler task. Our engineering department faced this challenge over the last 3 years and will continue in the future.

Following the footsteps of earlier developments, the Alfred-Wegener-Institute decided to build a shallow core drill based on the classic Hans Tausen Drill. Looking to the future and on a very likely subsequent implementations of an intermediate or deep drill system, further developments took place and where already integrated in the system. Great attention was paid to build an overall compatible system throughout the different ice core drill depths and its different requirements.

Our aim was to test a gearless-drive-system for the bottom section. This so called "Direct-drive-high-torque-motor" offers interesting possibilities for future developments and changes the way of the general ice coring drill process. Besides this the motor is more energy efficient and proofed to be very reliable at cold temperatures.

Another task was the assembling of a lightweight, transportable and automated tower system for the shallow core drill. This was a far more challenging cause than expected. But finally we got a very interesting tower system running that deserves further discussions.

The presentation will present the buildup process of the whole system. In more detail we will show the new developments like the torque motor and drill tower. Furthermore we will show video footage from the successful test expeditions that took place close to Kohnen-Station Antarctica 2012/13.

A new Danish intermediate depth ice core drilling system

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Ice cores have provided a great wealth of scientific data relating to the past climate and environment. Recovery of this valuable material has required innovative and reliable solutions, carefully designed to cope with harsh polar environments, and yet very precise to recover continuous good quality ice core. Over the past 40 years Denmark has developed several ice core drilling systems that have successfully recovered more than 10km of deep ice core and many thousands of meters of shallow ice core from Greenland alone. These drilling systems can be fitted into 4 general categories involved with drilling depth, weight, and support.

i. 3" Hand Auger - drilling depths from 0m to 15m - boxed weight of 75Kg - can be used by 1 or 2 in an open field environment.
ii. 3" Shallow Drill with Shallow Winch & Tower - Drilling depths from 1.1m to circa 120m - boxed weight 400Kg - can be used by 2 or more operators in a open field environment.
iii. 4" HT Drill with Shallow Winch & Tower - Drilling depths from 2.2m to 425m - boxed weight 550Kg - can be used by 2 or more operators in a small camp environment.
iv. 4" Deep Drill with Deep Winch & Tower - Drilling depths from 100m to an excess of 3,300m - boxed weight over 6,000Kg - normally used by 3 or more personnel in a large well equipped camp environment.

Several recent projects have demanded the recovery of ice core to depths in excess of 600m, such as at the Flade Isblink (2006) and the Renland ice cap (2015). These projects require that the overall system weight is low, that the ability to setup and operate is within the limitations of a small camp environment, that the drilling should be completed within a summer season, and that the overall logistical and transportation costs are kept to a minimum. Using these criteria a new drilling system capable of drilling in excess of 600m drill depth was seen as useful future development.

Here we report on a new intermediate depth drilling system designed for recovering 4" ice cores from 2.2m to depths of 1,000m by 2 or more operators in a small sized camp environment. The weight of the system when packed is less than 650Kg, of which the intermediate winch is the single heaviest component at 320Kg with 1,000m of useable cable. The entire system consists of,

i. Denmark's successful HT Drill - setup initially in dry mode, followed by reamer mode, and then wet mode
ii. A highly modified low weight AusLog 2000 Winch with the ability to hold a up to 1,400m of cable,
iii. A newly built tilting tower,
iv. A new fully integrated drill & winch controller.

The new intermediate depth drilling system includes the ability to be setup directly on the snow surface or be mounted and moved on a Nansen sled, can be transported by Twin Otter or Basler Turbo 67, has many drill and operator safety features, allows fast drill ascent speeds, has high pulling force capabilities, has an integrated descent speed control and load cell display, and more generally, the design and construction of many parts are inter-operable and inter-changeable with the other Danish drill & winch systems.

Next generation of an intermediate depth drill

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Many of the ice coring objectives in the Ice Drilling Program Office (IDPO) Long Range Science Plan, such as those in the IPICS 2k array and 40k network, are attainable in many locations with an Intermediate Depth Drill (IDD) that can collect core from a fluid-filled hole down to a depth of 1500 meters. With consultation from the Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen, and the Science Drilling Office, Antarctic Research Centre, Victoria University of Wellington, New Zealand, Ice Drilling Design and Operations (IDDO) designed and is in the process of building of an agile Intermediate Depth Drill to meet this objective. The drill tent, power distribution, and core processing system are an integral part of the IDD, which can be deployed by small aircraft and assembled by hand to minimize logistic requirements. The new drill system will be ready for testing in Greenland beginning the late spring of 2014. The first production drilling is scheduled for 2014-15 field season at South Pole.

Technical innovations and optimization for intermediate ice core drilling

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We present the technical aspects that were a key part of the efficient operation of two successful British Antarctic Survey/NERC led ice core drilling projects on James Ross Island (364m depth) and Fletcher Promontory (640m depth).

The talk will cover:

- Light-weight and rapid drill infrastructure setup; surface drilling without a trench, lightweight floor construction and tent modifications.
- New ultra compact cable tensioning device for spooling on and off the drum
- Drill setup; impact of drill length and setup on efficiency, drill head design modifications
- Evaluation of drilling with no casing and minimum fluid column
- Ice core packaging improvements for shipment
- Drill fluid recovery and environmental impacts

Ice coring at Roosevelt Island: Drill design, performance and refrigeration solutions at a low altitude "warm coastal" Antarctic location

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Recently completed ice coring of Roosevelt Island to 763 meters used a New Zealand built intermediate drill based on the proven Danish Hans Tausen design. Modifications to the drill design included a 2 meter barrel, high volume perforated chips chamber similar to JARE and NEEM deep drills but the system also incorporates a hydraulically powered mast providing a mechanical solution for drilling rate control, controlled core breaks and mast tilting.

The drill and mast was used for all aspects of drilling operations; dry drilling to 130 meters, reaming to 205 mm diameter, casing installation to 65 meters, and wet drilling to final depth using an Estisol 240 and Coasol drill fluid mix. Despite the brittle zone ice, high core quality with 2 meter length, single piece core recovery was consistently achieved.

The Roosevelt Island summit drill site, at an elevation of 560 meters msl and close proximity to the ocean environment, has a mean annual temperature of -23°C however summertime temperatures greater than 0°C have been measured for parts of the day. Warm temperatures experienced previously at coastal Antarctic sites have been a problem for ice coring but also planned experiments on core gases required storage of cores at site below -18°C. This was achieved using forced air refrigeration developed from a commercially available system that maintained the ice cores below -23°C in the unlined firn storage cave 3 meters below the surface.

The Enhanced Hot Water Drill (IceCube — South Pole)

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During the austral summer seasons 2004-05 to 2010-11, the IceCube Neutrino Observatory was constructed at the South Pole. IceCube utilizes 86 strings of optical sensors buried deep beneath the surface to transform the surrounding ice into a 1 cubic-kilometer (1 billion ton) particle astrophysics detector. Each string required drilling a hole 60 centimeters in diameter to a depth of 2500 meters. The 5 megawatt, 1M lb. Enhanced Hot Water Drill (EHWD) was designed and built specifically for this task, capable of producing the required holes at a rate of 1 hole per 48 hours. Hot water drilling on this scale presented unique challenges and was rich with lessons learned, yielding a collection of notable developments and takeaways (e.g. fuel-saving measures, thermal modeling, hose design, firn drilling, closed-loop computer control). More recently, considerations have been made for resurrecting the EHWD in support of the Precision IceCube Next Generation Upgrade (PINGU), a 20- to 40-string in-fill of optical detectors being designed to be co-located within the IceCube array. These considerations include equipment replacement and upgrades for improving hole ice quality. Lessons learned from IceCube construction and recent EHWD resurrection topics will be presented.

The ARA Hot Water Drill (Askaryan Radio Array — South Pole)

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An innovative new hot water drill system was successfully deployed in the 2012-13 austral summer season at the South Pole to support early construction of the Askaryan Radio Array (ARA). ARA is a neutrino detector that uses in-ice antennas to pick up the radio signatures of neutrino collisions with ice. The proposed full detector will span an area of approximately 100 square-kilometers in close vicinity to South Pole Station. The detector array will consist of 37 stations, each requiring six dry holes 16 centimeters in diameter to a depth of 200 meters. The ARA Hot Water Drill is a mobile system packaged onto a 3-sled train that drills these holes at a rate of 1 hole per 10 hours, using hot water to create a dry hole. Central to the drill's operation is its ability to pump the hole dry as it drills, eliminating freezeback concerns and producing a steady surplus of water. The ARA drill is a standalone system, tethered only to electrical generators, and must operate with limited direct support from the South Pole Station. Drill system design, techniques, operations, performance, and proposed enhancements following its first season in the field will be presented.

The BAS ice shelf hot water drill: current design and drilling methods

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The 2011/12 Antarctic field season saw the first use of a new British Antarctic Survey ice shelf hot water drill system on Larsen C and George VI ice shelves. Delivering 90 l min-1 at 80°C, a total of five holes >30 cm in diameter at three locations were successfully drilled through almost 400 m of ice to provide access to the underlying ocean, including the first access beneath Larsen C Ice Shelf. These access holes enabled the deployment of instruments to measure seawater conductivity, temperature, depth, and microstructure, the collection of 6.2 l water samples and up to 2.9 m long sediment cores using a simple hammer assisted gravity corer, before long term oceanographic moorings were deployed. Whilst the drilling methodology has remained relatively unchanged over the last 20 years, this latest design eliminates or reduces past equipment failure modes and exploits developments in three phase power motor control systems. The simple modular design allowed for Twin Otter aircraft deployment, rapid assembly and commissioning of the system, which proved highly reliable, requiring minimal supervision once the appropriate drilling parameters were set. The 15 KVA three-phase petrol generator enabled the use of more compact motors and control systems, reducing the demands on field logistics. An acoustic housing for the generator and entirely submersible pumping system also provided quiet working conditions. A number of novel solutions to various operational sub-ice shelf profiling and mooring deployment issues were successfully employed through the hot water drilled access holes to aid the positioning, recovery and deployment of instruments. These simple solutions include a catch for accurate positioning of mooring cables with respect to ice base and a cable deployed tool to release profiling instrumentation trapped against the ice base. Also, a drill nozzle with a highly flexible 1 m diameter brush was used to partially seal and then enlarge the hole only at the ice shelf base to prevent profiling instruments from becoming trapped at the ice base. With future activities now focusing on Filchner-Ronne Ice Shelf, the drill is currently being upgraded from its current 500 m capability to 1000 m with an additional 1" hose and further generator, pumping and heating modules.

Hot water drilled sub-ice access required: what are the best options?

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As scientific interest in sub-ice environments continues to grow the demand to access these poorly sampled environments is also increasing. Beneath the floating ice shelves, which can range in thickness from 100 m to 2500 m, direct observations are needed to understand ice-ocean processes and how the global ocean interacts with polar ice sheets. Beneath the grounded ice sheet where ice thickness can exceed 4000 m, samples of water, sediment and rock are needed to understand ice sheet dynamics, glacial history, biogeochemistry and sub-ice ecosystems for example. Consequently, more groups are initiating or expanding their hot water drilling programs. The wide-ranging requirements for sub-ice access mean that no single drilling system can efficiently meet all of the demands and drills have tended to be very project specific with the drill components not easily transferable between projects. However, a more modular approach to hot water drill design offers the possibility of reducing the equipment pool diversity, while preferably minimizing things like financial costs, logistic demands, equipment complexity, maintenance, and staff training.

With a need to provide at least 30 cm diameter sub-ice access holes, ranging in depth from a few hundred meters to over 3000 m, through ice as cold as -32°C, British Antarctic Survey (BAS) is attempting to adopt greater modularity and commonality within its hot water drilling systems that span the 300-2300 m range. For greater depths, the benefits of multiple small modules begin to diminish and larger modules are required to extend the drilling range to deeper and colder ice. Based on BAS hot water drills past and present, and those in planning, an overview of the basic hot water drilling power calculations, together with some of the available equipment and modular options will be presented.

A review of the Subglacial Lake Ellsworth 2012/13 field campaign

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If you are involved in ice drilling, you cannot fail to be familiar with the Subglacial Lake Ellsworth program and the recent 2012/13 field campaign to access and directly sample the lake. Unfortunately, despite 15 years of careful planning, 3 years of intense equipment development and navigating a long and complex logistics chain, the campaign was unsuccessful. Even more unfortunate was the success of the media campaign, which meant that the whole world was witness to this event.

In the months that followed the field campaign, much analysis was done to determine the causes of the various problems and to learn lessons for any future campaign. The program was also subject to a formal external review.

This presentation, from the program's Expedition Leader, aims to give the following information:

a. An overview of the Hot Water Drilling equipment and the drilling process used in the program

b. A step-by-step account of the problems encountered that eventually led to the campaign being halted

c. The key lessons learned from this experience, which can hopefully be carried forward to the next campaign

It is hoped that this presentation will inform and contribute greatly to the global collective knowledge on ice drilling and will help those who have closely followed the progress of the program to understand more clearly the events of the 2012/13 field campaign.

Developing a hot-water drill system for the WISSARD project

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The WISSARD (Whillans Ice Stream Subglacial Access Research Drilling) Project is a multidisciplinary research project funded by the U.S. National Science Foundation through three primary grants: (1) Lake Ice Stream Subglacial Access Research Drilling (LISSARD) based at the University of California-Santa Cruz (UCSC), (2) Robotic Access to Grounding-zones for Exploration and Science (RAGES) based at Northern Illinois University (NIU), and (3) Geomicrobiology of Antarctic Subglacial Environments (GBASE) based at Montana State University (MSU). The Science Management Office at the University of Nebraska-Lincoln (UNL-SMO) established subawards with each of these institutions in June 2011 to design, build, test and deploy a hot water drill system (HWDS) capable of making holes of various diameters through 800 meters of ice for the WISSARD Project in Antarctica. The WISSARD HWDS is comprised of the following primary modules: (1) a Melt Tank (MT), (2) a 3700 gallon capacity Water Supply Tank (WST), (3) a Water decontamination and Filtration Unit (WFU), (4) two Heater-Pump Units (HPU-1, HPU-2), (5) a Hose Reel Unit (HRU), and (6) a Command and Control Module (CCM). Several auxiliary modules transferred from the IceCube Project Enhanced HWDS have been integrated into the WISSARD HWDS, including: (1) two containerized 225 kV generators, (2) a Power Distribution Module, and (3) a Day Fuel Tank (DFT). Additional modules provided by either UNL or the USAP include: (1) a Storage Traverse Unit (STU), (2) an expandable container (known as a MECC) used as the MECC Workshop Module (MWM), and a series of 3000 gallon mobile steel fuel tanks (FT). Eight UNL staff assembled and tested the hot water drill system from October through December 2012 and remained in Antarctica to operate the system through mid-February 2013. From late December 2012 through January 2013, the HWDS was traversed by USAP tractors more than 625 miles over the ice shelf to the Subglacial Lake Whillans deep field site and was used to provide access holes through the 800 meters of ice to enable WISSARD Project science operations. The drill system worked as designed, providing up to 72 gallons per minute (gpm) of hot water at 95°C and pressures up to 2500 pounds per square inch (psi) thereby enabling the science team to collect samples of water, sediment and microbiology and achieve most of the primary project objectives.

Techniques for clean access drilling of subglacial lakes

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Techniques and problems that were developed to enable clean access hot water drilling into Subglacial Lake Whillan are reviewed. The primary hot water drilling requirement was to develop an initial bore hole and carry out subsequent reaming operations without introducing contaminants or compromising water quality that would jeopardize the geological and biological science objectives. Maintenance of a minimum borehole diameter was required for science tool deployment.

To attempt to accommodate the clean requirements we located our return water pump within one meter of the main bore hole outside of a sterilizing UV collar, which allowed us to melt through to main drill hole and also act as a source for extra drill water. The main borehole drilling was done to 700 meters then the drill recovered for logging the hole for depth and diameter then drilling was continued. At 750 meters the return water pump was lowered to 110 meters, to reduce hydraulic head in the drill hole so lake water would come up the drill hole, with the drill hot water flow reduced to 13 GPM and the drill speed slowed down to 0.5 m/minute to slowly melt into the lake. Upon breaking through into the lake the drill dwelled for 30 minutes at break through area then reamed up at 2 meters per minute and flow at 30 gallons per minute.

The WISSARD drill's clean access drilling techniques are in the right general direction. We have proven that we can access a lake with reasonable results. But the WISSARD drilling project also showed that that it is essential at minimum to have a system for logging the hole after drilling, or ideally, an instrumented drill head with real time capabilities to give a clear idea of drill hole shape and lifetime, especially the final 10 meters of the drill hole and the breakthrough area so we can accurately develop drilling models.

Traction drives to improve hose and cable spooling

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This paper introduces the custom design and development of a linear traction device for hot water drill hose handling that was designed to solve the need for a smaller physical foot print, avoid imparting rotational toque into the drill hose while still avoiding hose slippage, and use industry standard parts to avoid long lead time for field repairs. By using variable frequency motor controllers powering electrical motors driving a system of spring loaded urethane belts, two on top and two on the bottom, we are able to control the drill hose with less slippage while keeping the hose on a linear path reducing hose strain and minimizing the chance of the hose jumping off a pulley, plus, eliminating the need for a large capstan style drive system. This new system of linear traction system has a place in hot water drilling, and can easily be adapted to cable tool operations with its ability to do linear pulling, avoiding twisting of the hose or cable while supplying tremendous traction with minimal pressure on the hose or cable which allows for greater flexibility in reel and traction device placement.

Instrumentation and control systems for the WISSARD hot water drill

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The WISSARD (Whillans Ice Stream Subglacial Access Research Drilling) traversable hot water drill system was designed to create various diameter holes to a depth of 800 meters with most major components being controllable from a single user interface. The core of this control system utilizes an industrial safety rated PLC module, enabling system wide emergency stop capabilities which conform to industrial safety standards without additional network cable routing. The network was arranged in a ring architecture to provide a redundant communication path for seamless operation in the event of a cable break. The ring connects each of the major subsystems, which received individual Input/Output (I/O) aggregation panels with local battery backup modules. Each I/O connection made to these panels uses a connector and mating bulkhead, rather than being hardwired into the controller inputs, to enable rapid removal of the panel for DNF storage. Motor control was achieved by way of vector drive AC motors coupled with variable frequency drives (VFDs). The addition of a torque-limiting module on the reel/winch controlling VFD units allows for an uncharacteristically large fleet angle to exit the level wind while still maintaining proper wrap layering. This module also provides a key safety feature as reels can be stopped with only moderate pressures applied to oppose rotation. The drill system in total consists of four low-pressure pumps, six high pressure pump & diesel burner units, three reels (one with automated level wind), a four motor linear traction device, and over 100 digital and analog I/O points to ensure proper operation and system cleanliness. The control system design was focused on utilizing commercial-off-the-shelf components while being highly modular, easily expandable, and rapidly deployable. There was additional emphasis placed on redundant manual operator controls and maintaining a low degree of system automation to avoid dependence on software control loops. The result of this design paradigm was a control system, which was taken from concept to full operation in six months, whereby it successfully performed in field without insurmountable problems.

Precision cable winch level wind for deep ice coring systems

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In deep Ice drilling a large amount of time is spent winching the down-hole assembly in and out of the borehole. Therefore time-savings can be achieved if higher winching speeds are possible. To obtain high winching speeds it is desired to have the cable drum properly wound at all times without the need for any adjustments. Traditionally level wind mechanisms have used mechanical, or more recently electronic, methods to control the winding of the drum. Often continuous adjustment has been required to ensure that the drum is properly wound. To successfully wind a drum orthocyclically (or perfect layer winding), a level wind mechanism is required. The level wind serves the purpose of maintaining appropriate fleet angle (the angle that the cable has with the drum) such that the cable is not forced, by excessive fleet angle, away from its natural position on the drum. This paper describes a technology that permits a controlled fleet angle leading to accurate and reliable winding of the drum. The technology utilizes a feedback control system to ensure an appropriate fleet angle such that the cable is always permitted to wind correctly. Detail on the electronic controller is provided.

Design and test of anti-torque system of cable-suspended electromechanical drill

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The anti-torque system which can provide high reactive static torque is one of the key requirements to electromechanical drilling technology especially to bedrock drilling process where torque transmission to the drill bit is 6-8 times higher than in superincumbent glacier ice. Different types of anti-torque systems were analyzed, and a new skate-type anti-torque system with six-bar mechanism and double blades was designed. The mathematical model for calculation of pressing radial force depending on the shape and design of the anti-torque system was build up, and the dependence of radial force versus torque was investigated. Finally, the parameters of anti-torque system that can provide high reactive static torque were obtained. The special test stand to measure the reactive static torque and the moving vertical force was constructed. According with results of experiments, the minimum reactive torque was 103.5 N·m, and the highest force for moving of anti-torque system was 440 N. These parameters are in the acceptable range and can meet the requirement of armored cable-suspended electromechanical subglacial bedrock core drilling.

Control system of IBED electromechanical drill

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A new Ice and Bedrock Electromechanical Drill 'IBED' has been developed in Polar Research Center at Jilin University, China. In many cases, efficiency and safety of the drilling depends on the reliability of the control system as the process is going on without visual access of the operator. The IBED control system is composed of three subsystems: surface subsystem, borehole subsystem and host computer software subsystem. The surface control subsystem has five functions: data registration (cutter load, cutter rotation speed, penetration depth and speed, loading weight, drilling directional angle, drilling fluid flow rate, borehole pressure, motor current and voltage, winch motor power, borehole and surface temperature, wind speed, etc.), signal conversion, communication with host computer, drill motor and winch motor control, and power supply modulation control. The borehole subsystem measures borehole parameters, sends sensors signal, and receives motor control signal. CAN bus has been used for communication between the borehole subsystem and surface subsystem. The host computer software subsystem can display and store all the parameters in form of digital and dynamic curves. All the parameters can be read and print out during any run time. The monitoring and control system includes hand and semi-automatic levels to adjust parameters by manipulating of the system according to the work conditions in the borehole and running conditions of all the equipment. Overrun alarm function has been designed in software subsystem. When the parameters exceed the limited value, the system will send an alarm signal to the annunciator, and the alarm information will be display in the computer interface. The testing and control system has a momentous effect.

Theory and experiment of ester drilling fluids for ice coring in Antarctica

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The identification of the new environmentally friendly drilling fluid with predictable performance characteristics has become one of the most pressing problems of ice core drilling technology. Based on the deep analysis on the data of drilling fluids used in Polar Regions, a theoretical study on the influence of the molecular structure, molecular weight size, molecular inter-atomic forces of esters on the viscosities and densities of drilling fluids was carried out, according to the characteristic of Antarctic ice core drilling and the requirements for the properties of drilling fluids. The following properties of the common esters and the selected esters were considered: environmental protection, biodegradability, good inter-miscibility, low temperature resistance, density compliance, low viscosity, etc. The viscosities and densities of the Low Molecular Fatty Acid Esters 'LOFAME' were tested under different temperature and their variation mechanism with temperatures was studied. The principles for the selection of the drilling fluids for deep ice coring in Antarctica have been confirmed. The experimental results showed that the dynamic viscosities and densities of the drilling fluids, which are composed of the selected 5 kinds single substance of LOFAME esters and their compounds, are in the ranges of 8.7-15.2 mPa·s and 937-942.5 kg/m3, respectively, at temperature of -60 C. The required properties of the drilling fluids can be adjusted according to the actual needs at any time.

Promising new borehole liquids for deep ice core drilling on the high Antarctic plateau

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The successful recovery of good quality ice core at depths greater than 100m depends critically on a well-lubricated drill head, and on stabilizing the borehole from collapse due to the increase in iso-static pressure with depth.

Finding a suitable liquid for drilling deep ice cores at very cold sites, such as found on the Eastern Antarctic high plateau, is not an easy task. There are multiple considerations, such as: Health issues, toxicity levels, general environmental issues, changing temperatures at specific drill sites, compatibility with ice and water, and contamination of ice cores. Further considerations involve the liquids impact on drill performance, drill design, ice core quality, working environment, ease of logistical transport, and overall costs.

A choice of drilling liquid always depends on a careful evaluation of preferences and trade-offs. Historically, most drilling liquids were chosen purely with a focus on the physical and chemical characteristics, and less consideration of toxicity, safe working environment, and general environment impact.

Here we report on 2 new promising candidate drill liquids. Firstly, a primary drill liquid for singular use at extremely cold drill locations, secondly, an additive drill liquid for density fine-tuning at warmer drill locations or at warmer drilling depths. We have focused our investigations not only on the drilling performance, or the physical and chemical characteristics, but also on environmental, safety, health, logistical, availability, and cost issues. These 2 new liquids will incur slightly higher purchase costs compared to some of the past drill liquids that were suitable to such cold environments. We believe these purchase costs are relatively small when compared to the overall costs when the liquids are transported to distant isolated drill sites and also can be easily compensated by minor changes in overall project budgets. We see the positive characteristics of these new liquids far outweigh the drill liquid currently available.

The technology of directional drilling in ice via drill on carrying cable

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We present construction of the borehole 5G, the data of the Lake Vostok unsealing and the results of glaciological-drilling group at the Vostok station in the 58th season of the Russian Antarctic Expedition (December 2012- February 2013) for starting branch hole.

The technology of directional drilling for rounding of accident zones and for additional sampling, also technological characteristics of starting the branch hole are discussed. Theoretical base of borehole flexures and changing of drill spatial position at deviation zone are presented.

The angle of divergence between boreholes 5G-2 and 5G-3 is calculated on the base of measuring the thickness of crescent-shaped core, formed during starting branch hole.

Provides theoretical base of borehole deviations and changing of drill spatial position at deviation zone. The experience of using and effectiveness of drill on the carrying cable for directional drilling in ice sheets.

DISC Drill and Replicate Ice Coring System — New era in deep ice drilling engineering

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The Deep Ice Sheet Coring (DISC) Drill and Replicate Coring System were designed and manufactured by Ice Coring and Drilling Services (ICDS), which later became Ice Drilling Design and Operations (IDDO) group of the University of Wisconsin-Madison under contract with the US National Science Foundation. Throughout the entire project, ICDS/IDDO worked together with numerous subcontractors, the US science community, the European ice drilling community, and polar logistical support organizations to achieve all engineering and science goals. DISC/Replicate Coring Drill is a complex electromechanical system designed to take 122 millimeter diameter ice cores from the main borehole and 108 millimeter diameter replicate ice cores to depths of 4,000 meters. Detailed design of the DISC Drill began in 2003. The Drill was manufactured and tested in Greenland in 2006. During five consecutive field seasons at West Antarctic Ice Sheet (WAIS) Divide, 3,405 meters of ice core were drilled, setting the US deep ice drilling record. The Replicate Coring System, which utilizes the DISC Drill as its basis, was developed and built by IDDO in 2010-11and tested during 2011-12 WAIS Divide field season and at the IDDO testing facility in Madison, WI during summer-fall of 2012. During the 2012-13 field Antarctic season, the system produced five azimuth and depth controlled deviations at four target depth levels. A total of 285 meters of replicate core was recovered in the first coring of its kind in drilling history. The entire ice core from the main and replicate boreholes, including ductile, brittle, and warm ice, had excellent quality and satisfied needs of the ice science community.

Replicate Ice Coring System architecture — Mechanical design

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The Replicate Ice Coring System has been developed by Ice Drilling Design and Operations (IDDO) group under a Cooperative Agreement with the U.S. National Science Foundation. The mechanical architecture of the Replicate Ice Coring System leverages the existing infrastructure of the Deep Ice Sheet Coring (DISC) Drill to create a steerable drill capable of recovering replicate core at any targeted depth in an existing bore hole. Critical requirements of the system include: collecting an ice core on the high-side of an open hole allowing future access to the entire bore hole for passive logging tools, collecting up to 4 cores at a single depth, operation to depth of 4000m at -55°C and 5000psi. To meet these requirements, the Replicate Coring System includes the integration of several new mechanical sub-systems developed and tested from 2010 through 2012. Two electro-mechanical actuators were developed with specialized levers capable of exerting a force of more than 1kN to push the sonde to any targeted azimuth while providing anti-torque for coring and deviation operations. New core and screen barrels were designed and implemented using off-the-shelf casing tube with a reduced diameter to facilitate deviation while maintaining the ice chip capacity of the larger DISC drill. Several new cutting heads, including broaching, milling and coring heads, were designed, tested and optimized for the multiple stages of the replicate coring procedure. Changes to the motor section to improve radial load capacity were among several modifications to DISC drill sub-systems also implemented. The system was successfully deployed at the WAIS Divide site in Antarctica in the 2012-2013 field season recovering 285m of core from 5 deviations at 4 target depths.

Replicate Ice Coring System architecture — Electrical, electronic, and software design

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The Replicate Coring System was introduced as an addition to the existing Deep Ice Sheet Coring (DISC) Drill system. The purpose of the Replicate Coring System is to enable the DISC Drill to deviate from an existing parent borehole and create a deviation bore from it. A challenging requirement is that the Replicate Coring System needed to perform the deviation on the parent bore's "uphill" side. To do this, a system using six actuators was designed which could push the drill in any desired direction. The six actuators are controlled synchronously by an electronic control system comprising servo amplifiers, computer control, navigation, and several feedback variables from the actuators and their servo amplifiers. The architecture of the overall system is presented and additional detail is provided on the various electronic and software system members and their roles are explained. The idea behind the system's navigational function is also explained.

DISC Drill and Replicate Ice Coring System testing

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Drilling the WDC06A borehole at WAIS Divide with the DISC Drill began in January 2008 and was successfully completed in December 2011 to a depth of 3405 meters. Replicate coring was conducted at WAIS Divide during the 2012-2013 field season. 285 m of replicate ice core were successfully recovered from 5 separate deviations at four depth intervals between 1963 m and 3100 m. Extensive testing and consequent system modifications at WAIS Divide and at the IDDO testing facility in Madison, WI were an integral part of the project and largely contributed to the entire project success. As a result, the base equipment and drilling processes and procedures evolved each season, which improved system reliability and efficiency.

Production drilling at WAIS Divide

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The Deep Ice Sheet Coring (DISC) Drill was used for production ice core drilling at WAIS Divide in Antarctica for six field season between 2007 and 2013. Continuous ice core samples were obtained between the snow surface and 3,405 meters depth. During the 2012-2013 austral summer, the DISC Drill's newly designed Replicate Ice Coring System was utilized to collect 285 meters of additional high quality core samples at depths of high scientific interest. Annual progress graphs are described as well as milestones achieved over the course of the project. Drilling operations, challenges encountered, drill fluid usage, drilling results, and the drill crew's experiences with the DISC Drill and Replicate Ice Coring System during production drilling are described and discussed in detail. Core processing operations are described briefly as well the logistical undertaking of the DISC Drill's deployment to Antarctica.

A new Greenland drill site, NEGIS

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We plan to drill an ice core in the large North East Greenland Ice Stream (NEGIS) at a site where the surface velocity is of the order 100m/yr (75.61 N, 35.91 W). The goals of such a project is to learn about ice stream sliding and deformation by observing the ice structure and deformation especially near the base. Deep ice cores have never been drilled in an ice stream and one from such a dynamic area would give new insight into the study of ice sheet dynamics, which we have an urgent need to understand to predict future ice loss from the Greenland ice sheet. In addition, radar measurements show that we will be able to achieve an undisturbed climate record reaching at least 50 kyr back in time. This will allow detailed studies of the D-O events and our present interglacial. Ice from early Holocene (present interglacial), which was warmer than today and serves as an important analogue for future Earth, will be analyzed with a high time resolution using modern advanced technology, which was not possible at recent Greenland drill sites as early Holocene ice was in the brittle zone.

The NEGIS ice stream is very well suited for such a project because the ice stream reaches deep into the Greenland ice sheet to a point that is far from crevasses in the marginal zones. In addition to the climatic and ice stream dynamics reasons, the project also involves the challenge of developing tools to observe the basal ice stream behavior, such as logging tools to detect sliding, deep hole cameras to observe dynamics, and drills that do not get stuck in layers with the high shear.

Experience from the NEEM deep drilling

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The drill used for the NEEM ice core drilling is based on a design that goes back more than 3 decades to the DYE-3 deep drilling in South Greenland. The NEEM drill most resembles the basic design of the NGRIP and Hans Tausen drills described in Johnsen et al. (2007). Since its inception this design has been replicated in various forms for use throughout the international ice drilling community. Modifications specific for the NEEM drilling were made in order to account for a new drilling liquid - a 2:1 mixture of Estisol-240 and Coasol - which has a much higher viscosity than typically had been used for deep drilling. These design features together with the new liquid were a categorical success. By the end of the first season of deep drilling the bore-hole depth reached more than 1750 meters. With one season more bottom sediments had been reached at more than 2400 meters, and finally the sediment laden ice was itself collected in a separate campaign with an adapted rock drill. As expected, these accomplishments didn't come without challenges. We present here the details of the NEEM drill and examine its performance characteristics over the NEEM field seasons. We also share our experiences of the NEEM drilling, which in many ways resembled an international drilling academy hosting many groups, engineers, and students who contributed and gained experience using our system, including experiments with directional drilling, warm ice drilling, and sediment-rock drilling.

The method for maintaining the differential pressure in boreholes drilled in ice and the effect of ice hydrofracturing

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Maintenance and control of the drilling fluid pressure in a borehole drilled in ice is an important component of the drilling technology. The ability to adjust the fluid density at all depths in the borehole allows the prevention of hole closure by maintaining the desired pressure of the drilling fluid.

The experimental data obtained in borehole 5G since 1994 suggest the development of the horizontal fractures in the surrounding ice at different depths where the fluid pressure exceeds the pressure of ice. It is shown that the hydrofracturing may occur even at very low differential pressures. For instance, at depths greater than 1000 m the pressure difference that may allow hydrofracturing was estimated to be less than 0.01 MPa.

Based on this inference we attempt to explain the process of water rise in the borehole after unsealing of subglacial Lake Vostok.

Results and peculiarities of the 5G borehole drilling

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We present here a brief description of the drilling operations in the deep 5G hole at the Russian Vostok Station with more detailed account of the final stage of this long-term project successfully ended on February 5, 2012 with the first Lake Vostok unsealing. Relevant information on the borehole design and the technical characteristics of the downhole and surface drilling equipment is given. The peculiarities of the drilling process are discussed in connection with changing properties of the penetrated ice. The data analysis allows defining the main factors that influence the efficiency of the electromechanical drill system at great depths. It is shown that the elevated temperature of ice and its coarse-crystalline texture are mainly responsible for the significant slowing-down of ice coring in the bottom sections of ice sheets observed at Vostok and at another drilling sites in Antarctica and Greenland as well. Based on the large amount of experimental data obtained in the course of the deep drilling at Vostok, we discuss the processes, which occur in the borehole during the ice drilling and unsealing the sub-ice water bodies. Finally we formulate the drill equipment requirements and process specifications that would ensure the best performance of an electromechanical drill and trouble-free drilling operations at different depths in a borehole up to the bottom of ice sheet.

Analysis of shallow/deep ice core drilling data, and the future plan of intermediate depth drilling

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We carried out a lot of ice core drilling of glaciers and ice sheets at the Arctic and Antarctic using our developed shallow ice core drill systems. We recorded detailed drilling information and it will become the hint of the improvement of drill system. For example, the shape of core cutter, core catcher and cutter mount, angle and thickness of spiral with core barrel, rotation speed of the core barrel, the shape of anti-torque, lightweight of winch, and so on.

Our deep ice core drill using Dome Fuji station has many sensors. For example, core barrel rotation speed, drill inclination, cutter load, drill motor current, cutting speed, cutter break and cable tension, and so on. We analyze these data.

The deep drilling became very difficult below 3,000 m. The temperature of ice sheet near bedrock was a pressure melting point. So the cutting chips became ice easily during chip transportation. We will consider the drilling difficulties near bedrock.

We plan the intermediate depth drilling (about 500m) near the coast of the Antarctic ice sheet in austral summer of 2015-2016. The specification of drill system will be reported.

Design and field tests of a maneuverable clean subsurface ice exploration probe

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We describe the design of IceMole, a maneuverable subsurface ice exploration probe that is currently developed at FH Aachen University of Applied Sciences for clean in-situ analysis and sampling of subsurface materials, and report the results of our first field tests between 2010 and 2012. The IceMole design is based on the novel concept of combined melting and drilling. The probe has the shape of a rectangular tube (15cm x 15cm cross section) with a ~3-kW melting head and a rotating hollow ice screw at its tip. The required electric power is generated by a surface aggregate and transmitted via a cable that can be uncoiled from the probe. Communications and data transfer to the surface is also via this cable. The driving force of the ice screw presses the melting head firmly against the ice, thus leading to good conductive heat transfer. The IceMole can change direction by differential heating of the melting head, which generates a torque that forces the IceMole into a curve. In 2010, the first IceMole prototype was successfully tested on the Swiss Morteratsch glacier and demonstrated horizontal, upward and downward melting capabilities. It also drove a curve with a radius of ~10m and penetrated artificial layers of dirt that was found on the glacier. Tests of an enhanced second prototype on the Morteratsch glacier and on the Icelandic Hofsjökull glacier in 2012 demonstrated enhanced attitude determination capabilities and an increased melting velocity (~1m/hr). The main advantage of IceMole for clean sampling is that it does not utilize drilling fluids and can be sterilized prior to deployment. The currently built third-generation probe has been named Enceladus Explorer (EnEx). Being funded by DLR and being built by a consortium of 6 German universities, it offers a sophisticated system for obstacle avoidance, target detection, and navigation in deep ice. We intend to use the EnEx probe for clean access into a unique subglacial aquatic environment and an extraterrestrial analog in the McMurdo Dry Valleys, known as Blood Falls, with subsequent sample return from this subglacial brine. The IceMole-technology is currently also evolved to demonstrate the capability to penetrate ice under simulated Mars conditions with a miniaturized probe (MarsMole project) and to harvest micrometeorites from Antarctic firn at a depth of about 20m (Marvin project).

Acoustic in-ice navigation in the Enceladus Explorer project

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The Enceladus Explorer project is a preparatory study for a future space mission to the Saturn moon Enceladus. Its ultimate goal is to probe liquid water pockets below the icy surface. A potential rover could be based on the IceMole which is a melting probe combined with an ice screw for forward thrust. Partial heating of the IceMole head allows navigating curved trajectories through the ice. The Enceladus Explorer project will develop a specialized IceMole probe for a terrestrial test scenario. The goal of this exploratory study is to probe water from a liquid crevasse close to the "Blood-falls" at the Taylor glacier in the Antarctica.

To navigate such a rover the actual position and the monitoring of the performed trajectory are essentially needed. Part of the navigation system is the acoustic positioning system (APS) for the localization of the rover in the ice. For this, the head of the rover is equipped with acoustic sensors, which receive signals emitted from acoustic emitters that are placed on the ice surface. The generation of the surface signals and the acquisition of received signals inside the rover need to be synchronized to determine the propagation time. Based on the measured propagation times, the speed of sound of the ice and the positions of emitters at the surface the position can be determined by triangulation techniques.

We present the design of the acoustic positioning system, which is currently in development. The system is designed to track the in-ice melting probe IceMole within a 100m trajectory in the Taylor Glacier, Antarctica. Results from tests in water and a first field test on the Morteratsch Glacier, Switzerland, will be shown.

The Enceladus Explorer project is initiated and funded by the German Space Agency DLR.

Progress toward a rapid access ice drill for deep drilling of basal ice sheets and sub-ice bedrock in Antarctica

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We are designing a new rapid access ice drill (RAID) for use on the ice sheets of Antarctica. Our goal is to rapidly drill to deep ice (drilling penetration up to 3300 m depth), followed by coring of ice, ice-sheet bed interface, and bedrock substrate below. This novel drilling technology will provide an entirely new way to obtain in situ measurements and samples of ice, glacial bed, and rock for interdisciplinary studies in geology, glaciology, paleoclimate, microbiology, and astrophysics. The RAID drilling platform will give the scientific community access to a rich record of geologic and climatic change on a variety of timescales, from the billion-year rock record to thousand-year ice and climate histories.

The RAID drilling platform will be mobile, logistically autonomous, and capable of drilling quickly to deep ice. Once a borehole is created, drilling of ice and rock cores will follow, and the hole will be kept open to facilitate reentry for down-hole optical logging and heat flow measurement. Drilling will only be done in frozen-bed conditions to avoid contaminating the subglacial hydrologic environment. The platform will enable a drilling crew to be onsite, drilled, cored and rigged-down in <250 hrs, so that multiple holes may be completed per field season in Antarctica. Once built, the drilling system will be established as an NSF-sponsored facility operated by the University of Minnesota. We plan to complete construction of the RAID drill rig in 2014 and make a winter field test in early 2015, followed by deployment to and testing in Antarctica by late 2016. Initial scientific use of RAID is expected in the 2017-18 austral summer.

Our current design for RAID is based on modification of a standard rotary diamond-coring rig as used in the mineral exploration industry, operated in a flooded reverse-circulation mode with composite drill rods. After setting a firn casing, a 3.25 in-diameter ice borehole will be cut quickly using polycrystalline diamond (PCD)-impregnated face-centered bits. Ice chips created by the boring process will be carried to the surface by reverse circulation using ESTISOL 140 and separated, allowing for recirculation of the drilling fluid. Ice, till and rock cores (1.50-1.875 in diameter) will then be retrieved into an inner core barrel using a wireline bottom-hole assembly utilizing a thin-kerf diamond rotary bit. The entire cutting and coring operation will be completed with only one trip of the main drill string.

RADIX: A minimal resources rapid access drilling system

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Rapid drilling of an access hole has been reflected for many years for prospecting potential deep drilling sites and investigating the deeper layers of an ice sheet. For the IPICS "Oldest Ice Project", a project with the goal of retrieving the longest continuous ice core record in Antarctica, these rapid access drillings suggest themselves in view of the high costs that would arise by missing an optimal drilling site. The RADIX design aims to develop a system using minimal resources and logistics support. The main parameter determining weight and price of the project is the diameter of the drilled hole. RADIX is based on a coiled drilling system. The practical lower limit of the hole size is given by the flow resistance through the hydraulic tubing and is in the range of 20 to 25 mm. We present the theoretical basis of the drill and hydraulics design as well as results of a 30 mm prototype drill test on a temperate glacier in Switzerland. The drilling speed is about 10 mm/s, resulting in less than 4 days of continuous drilling for a 3000 m hole. The hole can be used for temperature and other downhole measurements. The drilled ice chips and/or core samples from specific depths will be available for analysis.

What have we learned from the first unsealing of Lake Vostok?

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The deep hole drilled at Vostok Station by the Russian Antarctic Expedition reached the surface of subglacial Lake Vostok at 3769 m depth on February 5, 2012. As a result of lake unsealing, subglacial water flooded into the hole and rose to several hundred meters above the base of ice sheet.

In the next (2012-2013) austral season the hole was re-drilled in order to recover refrozen lake water. The first signs of the presence of refrozen water in the hole were found at a depth of 3194 m (i.e. 575 m above lake surface), but it was much deeper, at a depth of 3424 m, that the drill finally met the surface of the 'solid' water ice. The hole just above this ice was partly filled with the bright white material preliminary identified as mixed clathrate-hydrate of the lake gases and hydrochloroflurocarbon (HCFC-141b) densifier of the drilling fluid. This material was estimated to fill up about 30% of the hole volume in the depth interval from 3415 to 3424 m.

Here we present an extensive set of data obtained from the hole surveys and ice core studies performed in the 2011–2012 and 2012–2013 field seasons at Vostok. Based on these data, we attempt a reconstruction of the chain of processes occurred in the hole during and after Lake Vostok unsealing.

Pulley operated, suction-powered subglacial sediment extractor successfully employed to depths of 825 meters

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For use in a hot-water drilling program in the ablation zone of the Greenland Ice Sheet, we designed and deployed a sediment extractor that can efficiently retrieve up to a kilogram of subglacial sediment from a water-filled borehole. The extractor is a suction device, operated manually from the surface by means of a 3/32nd inch stainless steel support wire rope. The core of the extractor is a brass weight that is lifted and dropped within a stainless steel tube. Stainless flap valves and o-rings draw water from the bed rapidly into the sample chamber. Water is then slowly expelled, allowing settled sediment to remain. The extractor can be operated once, or repeatedly to thoroughly scour the borehole bottom. Deployment used a powered cable winch to lower and raise the extractor through the borehole; though moving the down-hole brass weight and valve can be performed manually (with gloved hands). We have used several types of sediment samplers in previous borehole studies, but this version is notably the most efficient.

Extraction of sediment depends on the entrainment and settling of the material sucked into the sampler by the induced water flow, therefore some bias is expected. Medium and course pebbles may not be well mobilized by the input water flow, and particles larger than the ½-inch inlet will be excluded. Particles with low settling velocities (clays, silts) may be under sampled as they can be flushed out with the evacuating water.

The extractor was employed 9 times during the summers of 2011 and 2012 in boreholes of depths of 100 to 825 m. Recovered sediment volumes ranged from a few grams to over a kilogram, likely reflecting variability in debris cover at the ice sheet's base. Most material recovered was in the sand sized fraction, though silts, clays, and fine pebbles were also recovered. The grain size distribution varies considerably between the borehole samples, with various samples being dominated by coarse sand and pebbles, fine sand, or very fine sand and silt. This variability mirrors conditions at the ice sheet's outlets, where moraines are dominated by coarse sand and pebbles, outwash plains by fine and medium sand, and low-flow outwash regions by finer material. These results suggest that, despite the bias inherent in the sampling method, the composition of sediment retrieved by the extractor approximately reflects the composition of sediment at the bed.

Project VALKYRIE: Development of a laser powered autonomous ice penetrator

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Project VALKYRIE (Very-deep Autonomous Laser-powered Kilowatt-class Yo-yoing Robotic Ice Explorer) is a novel NASA-funded research project aimed at developing the first laser-powered cryobot — a self-contained intelligent ice penetrator capable of delivering science payloads through ice caps to sub-glacial lakes. Although the long range objective is to enable a Europa lander mission, the mission readiness testing will involve a full-scale sub-glacial lake cryobot sample return through kilometers of ice cap thickness. If successful, VALKYRIE will make possible direct access to sub-glacial lakes without the multi-year environmental protection process and will eliminate the need for complicated, heavy on-site sterilization equipment: the vehicle can be sterilized to internationally accepted protection levels prior to deployment. The melt path freezes behind the vehicle, preventing forward contamination. Because the power source remains on the surface, multi-month missions within sub-glacial lakes are possible.

Testing at Stone Aerospace between 2010 and 2013 has already demonstrated high power optical energy transfer over relevant (kilometer scale) distances as well as the feasibility of a vehicle-deployed optical waveguide (through which the power is transferred). The test vehicle is equipped with a forward-looking synthetic aperture radar (SAR) that can detect obstacles out to 1 kilometer from the vehicle. The initial ASTEP test vehicle will carry a science payload consisting of a DUV flow cytometer and a water sampling sub-system that will be triggered based on real-time analysis of the cytometer data. Results of laboratory test data and details of planned field campaigns will be discussed.

Mechanical ice core drilling at temperatures close to the pressure melting point

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Surface air temperature, precipitation rate, ice thickness and geothermal heat flux determine the thermodynamic state of a glacier. At annual air temperatures on glacier surfaces above -12°C to -10°C snow melting takes place, and melt water percolates to the snow-firn interface before refreezing and raises the temperature close to the pressure melting temperature (PMT). However, because of glacier dynamics and melt water runoff, identical conditions do not exist across of whole glacier and some areas remain below the PMT. The thermodynamic state of a glacier also depends on the climatic history of the glacier surface, and temperatures at depth do not reflect present climatic conditions. Polythermal glaciers are those that have ice layers that exist below freezing temperatures and at the PMT. In the tropics polythermal glaciers exist up to 6000 m above sea level. They are also common in the sub-Arctic up to 3000 m a.s.l. Ice at the PMT has been observed at the bottom of the Greenland and Antarctica Ice Sheets. Thus, the PMT conditions at both tops and bottoms of glaciers are common.

Firn and ice at the PMT contain water in the forms of veins, lenses and bottom reservoirs. Mechanical drilling causes the temperature at the cutter tips to rise up to a few degrees. If ice temperatures are close to the PMT, small amounts of water are released by the cutting action and can result in cutters and coring heads icing over. This wet cutting creates aggregates, which adhere to the core barrel and eventually block fluid circulation in deep boreholes. Similar processes also take place in shallow dry hole mechanical drilling.

Most reported dry hole drilling operations in temperate glaciers ceased just below the firn/ice transition. The primary causes of the termination of drill penetration involved the icing of the coring head behind the cutters and the blockage by compressed cuttings of conduits that facilitate chip removal. There are few polythermal glaciers on which the Byrd Polar Research Center (BPRC) electro-mechanical ice core drill (EMD) has been used successfully in dry and semi-wet boreholes. The greatest depth in a temperate glacier through which a semi-wet borehole has penetrated is 195 m. In this presentation we discuss drilling operations in polythermal glaciers with a dry hole EMD and deep ice coring in polar ice sheets close to the glacier bed.

Bedrock drilling project at Gamburtsev Subglacial Mountains in East Antarctica

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The Gamburtsev Subglacial Mountains is a subglacial mountain range located in Eastern Antarctica, near Dome A. It is approximately 1,200 km long, and the mountains are believed to be about 2,700 m high, although they are completely covered by over 600 m of ice and snow. The range has become the subject of great scientific interest because the mechanism driving uplift of the young-shaped Gamburtsev Mountains in the middle of the old Antarctic Plate is absolutely unknown. Drilling to bedrock offers the unique opportunities to research not only subglacial geology and tectonics processes but also to get new findings for paleo-climatic and paleo-environmental recording and basal sliding studies. Retrieving bedrock samples under ice sheets and glaciers is a very difficult task. Drilling operations are complicated by extremely low temperature at the surface of, and within glaciers, and by glacier flow, the absence of roads and infrastructures, storms, winds, snowfalls, etc. According to indicative terms and conditions drilling equipment should be able to penetrate through the Antarctic ice sheet up to the depth of at least 1000 m and to pierce the bedrock to the depth of several meters from ice–bedrock boundary. All drilling equipment (two 50-kW diesel generators, winch, control desk, etc.) is installed inside a movable sledge-mounted warm-keeping and wind-protecting drilling shelter that has dimensions of 8.8×2.8×3.0 m. Mast has two positions: horizontal for transportation and vertical working position (mast height is 12 m). Drilling shelter is transported to the chosen site with crawler-tractor, and all equipment is ready to start drilling immediately upon arrival to the site. Total weight of drilling equipment (without drilling fluid) is near 15 tons. To drill through ice and bedrock a new, modified version of the cable-suspended Ice and Bedrock Electromechanical Drill 'IBED' is designed and tested. The expected average daily production of ice drilling would be not less than 25 m/day. The lower part of the drill is adapted for coring bedrock using special tooth or bionic diamond bit. The new approaches of subglacial bedrock drilling technology are connected with utilization of environmental friendly, low-toxic materials, e.g. low-molecular dimethyl siloxane oils or ester type. They have suitable density-viscosity properties, and can be consider as a viable alternative for drilling in glacial ice and subglacial bedrock.

The diamond drilling bits test for subglacial bedrocks sampling

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The electromechanical drilling technology is one of the most promising methods for subglacial bedrock drilling, but the potential drilling parameters (load and torque transmission to the drill bit) are limited by the design of the drill, armored cable, hoisted winch, etc. In order to determine the minimal drilling parameters of the electromechanical drill for subglacial bedrock drilling and choose of the optimal construction of the diamond drill bit with minimal load and low power consumption, a special testing stand has been constructed, and several types of standard and specifically developed diamond bits have been tested including surface set diamond bits, impregnated diamond bits, teeth shape diamond bits, biotic diamond bits. All experiments were done in granite with hardness of 4400-5500 MPa. The standard surface set and impregnated diamond bits had very low rate of penetration (less than 0.15 m/h) at the load not exceeding 5 kN. The best results were obtained with teeth shape bit: average drilling speed ≈ 3.18 m/h and torque moment ≈ 28.77 N m with the drilling load of 3 kN and the rotation speed of 500 rpm, comparing with 'number two' biotic diamond drilling with speed of 1.69 m/h and torque moment of 38.12 N m at the same conditions. However, the life of teeth shape bits was only about 3 m, which is much lower than that of the biotic diamond drilling bit.

Low temperature, high precision pressure-temperature logger

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High-accuracy measurements in boreholes with extremely low temperatures less than -35°C are substantially complicated because of the limitation of the minimum operating temperature for electronic components. Developed pressure-temperature logger was designed for precise measurement of temperature down to −60°C and pressures up to 35 MPa due to local heating of the chips inside pressure chamber. To prevent the influence of the local heating of the chips on the accuracy of temperature measurements the following design decisions were incorporated: 1) pressure chamber was thermally isolated and temperature-stabilized; 2) temperature sensor was remote from the heat source using extension tube; 3) extension tube was produced from Caprolon®, material with a low thermal conductivity. As the result, the logger can measure temperature with accuracy of 0.01°C and pressure within ± 0.23% error.

Deep borehole logging at Dome Fuji Station, Antarctica

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The deep ice core drilling in depth of 3,035m was succeeded at Dome Fuji Station, Antarctica in January 2007. It is almost the depth of the bedrock. We used butyl acetate as borehole liquid. The liquid level was approximately 120m from the surface. We carried out borehole logging observation from surface to bottom in January 2007, 2011 and 2013. Measurement items were liquid temperature, ice temperature, liquid pressure and borehole diameter. The resolution of temperature was 0.05 degree Celsius. The one order of magnitude smaller resolution was necessary for the study of the temperature gradient. The film-shaped temperature sensor with the small time constant was used for the ice temperature measurement. It was pushed to the borehole wall. But it was destroyed in the depth of hundreds of meters for the vibration with the wall. The direction of largest inclination could not be measured. We report the result of borehole logging, problems and future improved points.

DISC Drill and Replicate Coring Systems research and development

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The Deep Ice Sheet Coring (DISC) Drill is a drilling system designed to retrieve ice core to a depth of 4000 meters. The detailed DISC Drill design was first started in 2003, and has since evolved to become a scientific tool producing ice cores of excellent quality. With the addition of the Replicate Coring System the capabilities of the DISC Drill have been expanded to allow deviation drilling from the parent borehole. In this manner additional ice core is retrievable and allows scientists to study climatically significant events without the need to drill an entirely new bore. Research and Development activities of the DISC and Replicate Coring Systems, along with laboratory and field testing at the West Antarctic Ice Sheet Divide (WAIS) Divide are presented on this poster.

Thermal simulations of the maneuverable ice exploration probe IceMole

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We present a computational model for the maneuverable subsurface ice exploration probe IceMole (IM) that is currently developed at FH Aachen University of Applied Sciences. The probe has been developed for clean in-situ analysis and sampling of subsurface materials. It combines conventional melting with drilling and hence allows for arbitrary ice penetration directions, even horizontally and upwards. Future deployment plans include drilling through temperate and non-temperate glaciers on Earth, as well as extraterrestrial deployment on the solar system's icy moons Europa and Enceladus in the far future. The computational model of the IM system supports design decisions such as the choice of materials, geometry, and control strategy. Furthermore, environmental conditions can be easily altered and systematically evaluated for future mission planning.

The underlying physical model considers heat transfer within the probe and the surrounding ice, as well as energy loss due to phase change. Two- and three-dimensional full-scale simulations are performed with the open source finite element simulation software Elmer. Consideration of the energy loss due to melting of ice is essential to get a realistic view on temperature evolution during the penetration process and ultimately the IM motion. We incorporate this by using the so-called Effective Heat Capacity Method on a fixed IM-centered grid. The meshes are assembled with Salome that provides both, interfaces to standard CAD software, and to the simulation software Elmer.

In this contribution we consider two case studies: At first we look at a laboratory test setup in which a brick-like IM-head dummy has been melted into a -20°C ice block. The experiments showed that installation of a sensor (a piezo-array for ultrasonic forefield exploration) deteriorates the melting properties significantly. We present corresponding simulation results that further investigate the influence of the sensor on the melting performance and discuss possible implications. A second study looks at the IM in motion. Here, we calculated melting velocities for different IM working modes. Simulated results are compared to recent data from a field campaign at Morteratsch glacier, Switzerland, and extrapolated to the environmental conditions found in the McMurdo Dry Valleys, Antarctica.

NEEM drill liquids — The investigation and experience using ESTISOL 240 and COASOL

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Good quality deep ice cores can be used to provide excellent scientific data in a continuous past climate record for more than 800,000 years. At depths below 100m smooth well lubricated ice drilling and overall borehole stability are critical issues that affect the successful recovery of several thousand meters of good quality ice core.

Finding a suitable liquid for drilling deep ice cores at sub zero sites, such as found in the arctic and Antarctic regions, is not an easy task. In the past 60 years or so many liquids have been used to varying degrees of success, but for various reasons are either un-available, considered un-safe and dangerous, or are so environmentally damaging to be not permissible.

Here we report on our investigation into suitable drill liquids, information concerning the candidate liquids, the rationale behind the re-design of our successful NGRIP Drill, the further knock-on effect of those changes, and on our actual field experience of this liquid combination at Flade Isblink in 2006 and at NEEM during 2009-2012.

A current update of silicone oil as drilling fluid

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For the SubGlacior Ice&Lasers project we require a suitable drill fluid to reach depths of up to 3500m in the Antarctic ice sheet in a single season. In addition to the challenging drilling conditions it will also need to meet the requirements for in-situ analysis by laser spectrometry.

Following a detailed literature review of existing and potential drill fluids we have focused on the evaluation of Estisol and a range of silicone oils.

We present an update on the following aspects:

- silicone oil manufacturers, available grades and cost
- implications of subtle differences in physical properties from synthesis
- viscosity measurements
- ice chips behavior testing
- material compatibility testing
- latest toxicology and ecology reports
- suitability for laser spectrometry

Modeling of drilling fluid contamination at the ice drilling sites

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Formerly utilized drilling fluids are considered as very harmful agents for Polar Regions environment because nature recovery takes much longer time than in regions with temperate and open climate. Drilling fluids can contaminate in large quantities air, surface and near-surface snow-firn layers, ice cuttings, and subglacial water resources. Interactions of the drilling at inland on the Antarctic and Greenland ice sheets with surface or air biota are impossible or unlikely, but the possibility of impacts to subglacial water biota from drilling fluid can occur almost at any inland drilling site. In order to estimate influence of drilling fluids evaporation and spilling on the Polar Regions environment, Visual MODFLOW and EIAProA2008 software were used to simulate air pollution, snow-firn contamination and foulness of subglacial reservoirs. The different drilling fluid types and external conditions were looked over and analyzed that allowed to establish good practice for minimizing pollution of the Polar environment.

Improvements of the drilling fluid processing for cable-suspended electromechanical drills

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Drilling process and especially drilling fluid processing is very harmful for environment in Polar Regions where nature recovery takes much longer time than in regions with temperate and open climate. Used at present drilling fluid circulation systems are specified by very high fluid wastes during processing. Measurements in deep drilling projects in Antarctic and Greenland ice sheets showed that 25%-40% of the drilling fluid, pumped into the hole, is retrieved to the surface with cable and drill, and up to 45% of retrieved fluid goes to waste. This leads not only to increasing of the fluid consumption and cost of the project in general but also to severe contamination of air, surface and near-surface snow-firn layers at the drilling site. Efforts to minimize environmental impacts from drilling fluid should be focused on air contamination, spill prevention and control, and ice cuttings handling. In order to reduce wastes and environmental impact it is proposed to modify drilling fluid processing system by avoiding of evaporation and leakages of fluid as far as practicable. Drilling fluid is prepared and pumped into the hole according to predetermined program on semiautomatic mode, and volume and density of the drilling fluid blended and pumped into the hole are measured continuously. Components of the drilling fluid are stored and mixed in the special closed containers equipped by pressure relief valves. Separation of drilling fluid from ice cuttings is carried out by two steps: firstly, fluid is separated with hydro extractor and then with thermal separator. To reduce the amount of removed drilling fluid with cable special squeezing collar is installed on the borehole mouth. All these arrangements are able to decrease drilling fluid wastes in many times.

CLIMCOR, PaleoCLIMatic CORing, High Resolution and Innovations

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Global climate changes have been evidenced in various ways since the start of paleoclimatology in the 70s. The access to past atmosphere conditions in the air bubbles trapped in ice-cores gave an important impulse as it made the green-house gases concentrations accessible a prerequisite for climate modelers. Indeed since the publication of CO_2 and CH_4 variations over the last climate cycle in Vostok ice-cores, our knowledge of the past climate conditions has improved tremendously. However, improvements in technical equipment and approaches indicate that more is still to come inducing expected new findings in terms of mechanisms. The IMAGES program yielded very good quality and long marine cores that permitted to compare marine and ice-core records with high confidence. Moreover they permitted to improve the knowledge of past oceans dynamics, especially those linked to the massive discharges of icebergs in the oceans, impacting the Atlantic meridional overturning circulation. On the continent, various environments are drilled and cored to provide also comparable and reliable records of past climate: lakes, peatbogs, speleothems and loess. These records are complementary yielding important dataset to feed the earth system models necessary for a better understanding of past climate dynamics.

Technical limitation of the present equipments does not allow such important jump in the quality of the data, and therefore in the knowledge of i, past climate variations at extremely high resolution and ii, of the behavior of the different domains as studied in IPCC experiments while societal requirements are more and more expressed by policy makers. C2FN initiative at CNRS gathers the present coring equipments located in labs or at the technical division of INSU, and coordinates the different efforts provided by the concerned communities (ocean, ice and continent). Valorization of the results obtained are published in high ranked scientific journals and presented in scientific meetings. Moreover the technological improvements and developments in coring activities are likely to result in patent applications that the DT INSU realizes in the framework of its activities and duties. CLIMCOR project intends to provide the French scientific community, the top-level technological support, complementary to the funded ASTER-CEREGE Equipex for top-level analytical support. CLIMCOR place the French scientific community in a competitive position at the international level while potential societal requirements are not put aside in case of emergency requirements by policymakers. Although C2FN cells gather renowned technician in their respective fields, strong interactions with French companies is a daily routine.

IBED ice and bedrock electromechanical drill

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The new multipurpose Ice and Bedrock Electromechanical Drill 'IBED' suspended on armored cable was designed to solve three different tasks: 1) dry core drilling of upper snow-firn layer with bottom-air reverse circulation; 2) fluid core drilling of glacial ice with bottom-fluid reverse circulation; 3) bedrock core drilling. IBED drill has modulus construction, and different sections of the drill for different tasks are replaced as all of them have the same bayonet joint. The upper part is the same for all variants; it includes four sections: cable termination, slip rings section, antitorque system, electronic pressure chamber. The moto-gear sections are differed by rotation speed of the output shaft of the gear-reducer. All modulus contain 3 kW AC3~380 V submersible motor of Grundfos MS4000 type. The motor is pre-lubricated and can keep outer pressure up to 15 MPa. Gear-reducer for drilling in ice lowers the drill bit rotation speed to 100 rpm; gear reducer for subglacial drilling lowers the drill bit rotation speed to 500 rpm. In addition, module for dry core drilling contains vacuum pump for near bottom air reverse circulation instead of liquid-driven pump that is installed into other two variants. The rotation speed of air-driven pump is the same as rotation speed of the motor and the shaft from the motor connects through the inner space of the gear directly to fans. In modules for drilling with liquid the shaft from the motor connects with two gear-reduces: one for rotation of the core barrel and drill bit, and another one for driving of the pump. The pump is the Rotan CD33EM-3U332 pump with an internal idler gear. The capacity of the pump is 38–41 L/min with maximal pumping pressure of 0.2 MPa. IBED lower part for drilling in ice consists from two parts: chip chamber for filtration of drilling fluid and collecting chips, and core barrel with the drill bit. The outer/inner diameter of the drill bit is 134/110 mm. Length of the core barrel is 2.5 m. Lower part of the bedrock variant contains standard 2-m length core barrel borrowed from conventional diamond drill string, chip chamber for gravity separation of rock cuttings and dead weights (appr. 200 kg) for increasing of the load on the diamond drill bit. The outer/inner diameters of the diamond bit are 57/41 mm.

CosmoDrillWAIS: Proposed drilling project to recover cosmogenic isotopes from subglacial bedrock

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The West Antarctic Ice Sheet (WAIS) is an important control on global sea level but is thought to be inherently unstable. Understanding the risk of WAIS collapse has been identified as one of science's Grand Challenges but requires robust models of the WAIS, fully tested against geological data. A wide variety of such data exists and suggests that the WAIS has probably collapsed in the past, but with substantial uncertainty and disagreement between the proxy records of precisely when. Some records even suggest no collapse has occurred in the last 2 million years.

The only well-dated evidence is largely indirect and from outside Antarctica (e.g. past sea-levels in low latitudes) and is difficult to directly ascribe to WAIS, whilst the only direct evidence from beneath WAIS itself is not well dated. We argue that what is needed is a fresh approach, one that provides evidence of WAIS retreat that is both direct and can be dated.

CosmoDrillWAIS aims to provide this evidence via a new approach that exploits the potential of rapid drilling to the ice sheet bed to retrieve direct records of past collapse and critically assess the published hypotheses of collapse timing.

The objectives of CosmoDrillWAIS are to develop a new subglacial rock drill – for which a design concept is presented – and once built and tested to gain access to the bed of WAIS using hot water drilling technology and sample bedrock cores. We propose a transect drilling approach, whereby bedrock will be sampled at progressively deeper locations, and used to determine past down-draw of the ice surface associated with WAIS collapse. At each drillhole, cosmogenic isotope analysis on the rock core will test collapse scenarios.

General principles for the designing of hot-water ice drilling systems

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Hot-water drilling showed extremely high rate of penetration (30-50 m/h) and daily production (380-600 m/day) and can produce the hole of large diameter suitable for different researches (neutrino detectors, sub-glacial lakes sampling, oceanographic investigation of sub-ice shelf sea, ice stream dynamics, etc.). In order to design surface equipment, theoretical estimations for bottom temperature of borehole, diameter of borehole, drilling speed, required power for ice melting and the total pressure loss were done. Assumed that the water flow with the rate of 100 L/min is heating to 90°C, at the bottom of a 2500 m borehole water temperature would decrease to 25°C, diameter of borehole reduces to only 0.1 m and drilling speed drops to almost zero. If hot water flow rate is 200 L/min, temperature would decrease to 48°C, diameter reduces to about 0.36 m and drilling velocity would be 30 m/h. If water flow rate is 300 L/min, temperature would decrease to 59°C, borehole diameter reduces to 0.52 m and drilling velocity may be as high as 67 m/h. So, if the final depth of borehole is 2500 m, the flow rate should be not less than 200 L/min, and the 1 MW heating power have to be maintained. If the length of hose is 2500 m, the total pressure loss in the system is estimated to be 6.3 MPa. The drilling performance is influenced mainly by sizes of utilized hose and nozzle, as ice temperature has a little influence due to a rather high latent heat of ice fusion. The calculation method will be proved by experiments in the near future.

Roosevelt Island Climate Evolution (RICE) project: ice core quality at an intermediate depth site

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One of the primary challenges of intermediate-depth ice drilling is maintaining high core quality through the brittle ice zone. While at deep drill sites brittle-ice ages span the early- to mid-Holocene, intermediate drill sites may place transitional and glacial ice of high scientific value within the brittle ice zone. Brittle ice core quality, through recovery, transport, storage and sampling is one of the technical challenges identified by the International Partnerships in Ice Core Sciences, with implications for the '40k array' initiative gathering spatially-distributed 40,000 year ice core records.

With regard to this challenge, we share recent experiences of the Roosevelt Island Climate Evolution (RICE) project, which recovered a 763.5 meter-long ice core at Roosevelt Island, Antarctica (79.364°S, 161.706°W, ~550 m) during the 2011–2012 and 2012–2013 Antarctic seasons.

In the field, each ice core was pushed through a fluid extraction vacuum upon removal from the drill barrel, with netting subsequently applied to the core below 375 m. Following this, the ~2 m drill runs were cut into 1 m lengths for shipment using a small bandsaw. Below 475 m, ice cores became too brittle to cut without significant damage; drill runs were netted and 'buffered' for 10–14 days in a refrigerated snow cave (–26°C). Relaxation significantly improved the quality of 1 m cuts for shipment. Despite this brittleness, 86% of core reached the surface as a single piece, on average 1.96 m long. Only 38 runs of the 330 recovered multiple pieces. No additional breakage occurred during transport of the cores back to New Zealand.

RICE core processing was conducted from May to July 2013 at the New Zealand Ice Core Research Facility (GNS Science, Wellington, New Zealand). Horizontal cuts were made using the 'Swiss saw' provided by the University of Copenhagen Centre for Ice and Climate (Denmark). Using a vertical bandsaw, significant fracturing arose below 475 m when preparing 34 mm x 34mm longitudinal samples directly after making initial horizontal cuts on the ice core. A further step of relaxation, after making horizontal cuts on the core, lessens brittleness during processing. Additionally, reducing or slowing temperature changes minimizes fracturing in the ice core samples.

We do not propose definite solutions to processing issues concerning brittle ice, but rather seek to share experiences with the international ice drilling community to identify best practices for maintaining high core quality in brittle ice for both deep- and intermediate-depth ice core sites.

Core handling for the WAIS Divide ice core project

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On December 1, 2011 the National Science Foundation-funded WAIS Divide ice core project reached its final depth of 3,405 meters, completing the longest U.S. ice core to date. The WAIS Divide ice core is not only the longest U.S. ice core to date, but it is also the highest quality deep ice core, including ice from the brittle ice zone, that the U.S. has ever recovered. We present the methods that were used to handle the ice at WAIS Divide, as well as the procedures used to safely retrograde the ice back to the U.S. National Ice Core Laboratory.

Ice core drilling at a high-accumulation temperate-glacier site: Combatant Col, Coast Mountains, British Columbia, Canada

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In July 2010, a 141-meter ice core was retrieved from Combatant Col, Coast Mountains, southwest British Columbia, Canada (51.385°N, 125.258°W, 3000 m) with support from IDDO operating the PICO 4-inch electromechanical drill (firn, 0-50 m) and 3-inch thermal drill (temperate ice, 50-141 m). Mean annual air temperature at the site is -5°C with significant surface melt occurring during summer. Meltwater percolation through annual layers is limited due to very high annual snow accumulation (~7 meters ice equivalent per year, 1973-2010).

Paleo-climate and paleo-environmental information at the site are preserved at seasonal-to-annual resolution. Ice-flow modeling, constrained by the observed depth-age relationship and radar-imaged total ice thickness of 250 meters, suggests ice in excess of 200-500 years old exists near bedrock.

Temperate ice conditions at the site prevented drilling to bedrock. The 2010 borehole was water-filled below the firn-ice transition (40-50 m); efforts to depress the freezing temperature using ethanol showed some success though were limited by poor mixing throughout the borehole and possible englacial circulation of fresh water. Water freezing onto the borehole wall restricted access below 100 meters, freezing at rates up to 20 millimeters per 36 hours. Further drilling progress was achieved with diversions of 2-3° from the original borehole at 118 meters and 124 meters but ultimately stopped at 141 meters.

Solutions under consideration for preventing borehole closure include: pumping systems to remove water from the borehole; improving ethanol delivery and mixing; and reducing drill downtime by adopting an around-the-clock drilling schedule and improving weather resistance of the drill equipment. We welcome suggestions, and look forward to exchanging experiences with others regarding drilling in temperate ice.

Ice coring of polythermal glaciers

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Polythermal glaciers exhibit either a cold-temperate ice or a temperate-cold ice transition with depth. Water content in temperate ice can vary from a small fraction of a percent to a few percent of a specimen. Power released during ice core drill penetration also increases water content in the cuttings. Veins or water channels intercepted by the borehole can introduce a significant volume of water to the borehole. The main problems associated with ice coring of polythermal glaciers include: 1) the ability to cut temperate ice, 2) the transport of cuttings to the filter/storage compartment, and 3) the stability of the fluid level in the borehole. This poster demonstrates the technique and protocols used in ice core drilling operations in polar, sub-polar and high-altitude glaciers using electro-thermal and electro-mechanical portable drills. A new type of staggered cutters (SC) made it possible to penetrate temperate ice in semi-wet and water-filled boreholes to depths of 195 m (bedrock) and 190 m. Penetration at 4-7 mm/revolution pitch generates coarse cuttings that are transported to the chip compartment by spiral flights and a buster propeller. The use of hydrophilic antifreeze-lubricant on the outside of the core barrel is essential during drilling of temperate low-water-content ice. Comparative laboratory tests demonstrate that at a high penetration rate the new SC produce better core quality than conventional, full-kerf-width cutters. The main advantages of the SC are: 1) low drill-bottom pressure; 2) excellent-to-good ice-core quality at coarse cutting; 3) overall high ice-core production rates. These results indicate that the use of SC in deep ice core drilling may prove productive.

New applications of hot point drills

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Electro-thermal open borehole drills or hot point drills (HPD) were developed for fast piercing through temperate glaciers to a depth of about 200 m. Two new HPD melting tips were developed at the Byrd Polar Research Center. One is used for a continuous density profiler ("Speedograph"), another in combination with an electromechanical dry hole drill for penetration of the Ross Ice Shelf at the Windless Bight site (2011). The experimental relationship of borehole freezing rate and ice temperature allows a new method of ice temperature measurements to be suggested. Two new HPD applications will be presented.

1. Continuous density profiling with Speedograph.
The penetration rate of a thermal drill depends on the power applied and the density of the ice. As a first approximation density of snow, firn or ice can be determined as followed:

$$\rho = P / \pi r2 L V ; \quad (1)$$

where ρ is density, V is drill penetration rate, r is borehole radius, L is latent heat of ice melting and P is drill power. Therefore, density can be determined using parameters recorded during HPD penetration. Laboratory measurements of penetration rate in known density sections of ice cores show linear dependence between penetration rate and density. The new method of density measurements permits 10 mm depth and 3–10 kg density resolution at penetration rate of 10–15 m/h. Minimum density measured with the Speedograph is 100 kg m-3. The Speedograph was used to study snow and firn stratigraphy in polar and polythermal glaciers.

2. Continuous borehole temperature profiling during HPD penetration.
In polar glaciers a borehole filled with melt water is freezing and borehole diameter is decreasing. The borehole freezing rate was measured in an artificial ice block as a function of temperature and initial borehole diameter. This relationship permits determination of ice temperature based on the borehole freezing rate. Two calipers installed in the HPD housing at known positions permit borehole diameter measurements. Measured HPD penetration rate makes determination of time between borehole diameter measurements made with caliper 1 and caliper 2 possible. Therefore a continuous ice temperature profile can be determined during HPD penetration.

Both HPD applications are suitable for measurements with apparatus as In situ probes (Philberth or autonomous type probes penetrated via melting) for glacier temperatures and density measurements and to control and optimize of penetration tip power.

We present design and continuous density profiles from Greenland and Elbrus and concept of the continuous temperature profiler and the relationship of borehole freezing rate versus borehole diameter.

Snow and firn density variability in West Central Greenland

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Post-depositional erosion, wind compaction, re-crystallization, vapor transport and melting may modify the physical and chemical properties of the stratigraphic record preserved in glaciers and ice sheets. These properties vary over both short and long temporal and spatial scales. Developing models for accurate interpretation of ice core records and remotely sensed radar signatures of the ice sheet surface requires knowledge of the near-surface physical and chemical properties. Density is a particularly difficult parameter to measure accurately in high resolution and is quite variable on short spatial scales. To quantify these differences multiple shallow and intermediate depth (~150-m) cores, complemented by concurrent pit measurements, are characterized by high-resolution density profiling using an improved Speedograph technique that measures the penetration rate of a hot point drill at high-depth resolution (0.9-13 mm). This poster presents new, high-depth resolution instrumentation for in situ density measurements and compares the results of field observations in southwestern Greenland. Here we present preliminary data that will be interpreted with other data from the ice cores taken in the vicinity of six density profiles.

Modified down-hole drill unit based on the EPICA/NorthGRIP design

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The principle layout of the recently built drilling system at the AWI follows the EPICA/NorthGRIP design and is currently undergoing modifications thus enabling the drill to be broken in 2 shorter sections for easier transport esp. by aircraft and maximum flexibility related to chip removal by connection of different kinds of pumps and booster arrangements in the middle of the drill. The motor section is an entirely new design based on off the shelf direct driven torque motors.

When using the EPICA/NorthGRIP drill design for dry drilling, a reduction of the hole-diameter is necessary to prevent the cuttings from creeping up between outer barrel and hole wall, where they have a high potential for blocking the drill. For the shallow drill application, a joint of outer barrel and chip chamber had to be designed which fits into the small annulus. The direct driven torque motor power supply is controlled in a Labview environment that communicates over the drill cable with the down hole off-the-shelf motor controller.

We will present and discuss the modifications and new designs we introduce to the drill system.

Modeled air loss in firn associated with use of the Rapid Air Movement Drill

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The Rapid Air Movement Drill (RAM Drill) was initially developed for creating shot holes in firn for seismological studies on ice sheets. It utilizes high velocity air to propel a rotating drill head into the firn for drilling boreholes, blowing the cuttings to the surface up through the borehole. At sites in West Antarctica, the maximum routine depth has been to 95 m, limited by the length of the drill hose. Use of the drill at sites in East Antarctic however has been much more problematic, with depths reaching only 40m on average. Factors affecting the drilling through the firn to the firn/ice transition have not been well understood. In this paper, we conduct multi-dimensional axisymmetric modeling of air flow through firn that are induced by borehole pressures. Use of measured permeability profiles is used for simulations of conditions at Megadunes, WAIS Divide, and Summit. Ranges of permeability are estimated for conditions at South Pole, since a full measured permeability profile does not exist, and the results are compared to data taken by the ARA RAM Drill Test-South Pole team during the 2010 year. This work serves as a basis for understanding the RAM drill failure seen during the South Pole field test, and notes possible adjustments to be made for better results during future drilling projects.

Design of a new IDDO hand auger

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The design process for a new lightweight hand auger system to replace the aging PICO system began in October 2009. Design of the IDDO Hand Auger was based on a variety of existing drill systems and the fabrication of two prototypes was finished in October 2011. Continuous testing, improvements, and system modifications led to the production of 4 meters of excellent quality 78 mm diameter core during the Antarctic 2012–13 field season at WAIS Divide. A few key features of the new design, along with the results of system testing are presented on the poster.

Electromechanical drill with air reverse circulation

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The most common ice shallow coring tool is auger electromechanical drill in which cuttings are transported into inner chip chamber by conveyer spirals fixed on the surface of core barrel. In many cases, length of the core obtained with auger shallow drill is in the range of 0.5-0.8 m because of the limitation of cuttings removal system. In order to get longer core (theoretically 2.5 m and even more) in "dry" holes the electromechanical drill with near-bottom air reverse circulation is proposed. The concept of the drill is similar to deep ice electromechanical drills with fluid circulation but instead of fluid pump the air vacuum pump is used to suck ice cuttings to the chip chamber installed above the core barrel. The air from the vacuum pump outlet is ejected into annular space between the drill and borehole walls forming near-bottom air reverse circulation. As contrasted to ice drills with fluid circulation, air reverse circulation can be readily applicable to the upper permeable snow-firn zone avoiding problems with circulation loss and drill site pollution. As the result of theoretical estimations, the minimal speed of air flow would be 7.6 m/s leading to the required flow rate of approximately 70 L/s. In order to prove the feasibility of air reverse circulation, simple tests were carried out using simulation of the core barrel made from 3.5-meter length plastic tube with ID/OD of 100/110 mm and air pump borrowed from the vacuum cleaner (73 L/s; 3000 rpm). Ice cuttings were imitated by millet grains with density and diameter (2 mm) similar to ice chips. As the result, the minimal clearance between lower end of the core barrel and grains to be sucked was found. When the clearance is more than 60 mm, the air flow cannot carry ice chips; when the clearance is less than 60 mm, airflow can quickly suck grains and clean the borehole bottom.

New generation of shallow ice drills

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For recent climate reconstruction, anthropogenic pollution study, analyses of biological species, and other researches, light-weight and simple shallow drills are preferable for core drilling in the range from few meters up to the depths of 300-400 m. In order to get samples from shallow holes three new light-weight drills were designed in Polar Research Center at Jilin University. All of them do not require a drilling fluid. The modified hand-driven portable core auger is a small system generally the same as designed by PICO except joints and material. Quick-release joints have the form of semi-cylinders covered by jacket with bayonet joint. The length of the core barrel is 1.5 m destined for recovery of 0.8 m length core with diameter of 100 mm. Hand-drill is produced from aluminum alloy of 6061 type. Optimal depth of drilling is considered to be 6-8 m with possibility to extend up to 15 m depth. Total weight of 15-m depth set is 28 kg. The use of tripod to assist in the lifting drill string would increase the depth capacity to 40-50 m. To make easier tripping operations as well rotating of drill string, the engine-powered auger drill is designed. The core barrel and drill string are basically the same as used in the hand drill, but the core auger is driven by gasoline engine borrowed from Sanbang 71 cc ice drill. The power of the engine is 3.2 kW and its weight is 14 kg. It is equipped by gear with ratio of 30:1 reducing rotation speed to 330 rpm. Working temperature limit of the engine is as low as -40°C. The engine is installed on the platform moving alone the frame. Lifting of the drill string is carried out using the hand winch. The total weight of the engine-powered auger drill with 50-m length set of drill pipes is 120 kg. To drill deeper, the shallow electromechanical drill is designed. The drill is supposed to be able recover at least 1.2 m core. The total weight of the drilling equipment with 400-m cable is minimized to 250 kg. The 1.5 kW motor with electromagnetic brake through the gog-belt transmission drives the winch. The winch has emergency hand band-brake. The 3.5-m length drill weights near 65 kg. It is assumed that drilling of the 300-m depth hole will take not more than 6-7 working days.

Development of a modular drilling winch system

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Ice core drilling is at all points a challenging task and makes high demands on the technology/engineering and the people who are working with this. Therefore equipment is needed that is manageable even in special environments where the ice cores are drilled. One of the goals in technical developments is to reduce the weight of single parts, which have to be moved by hand. Furthermore the diversity of modules and spare parts has to be decreased. Thus a modular design with moderately heavy individual components to decrease the transportation expenses and the ability to adapt to different drilling systems is needed. At AWI we are now developing a new modular winch system, which is able to fulfill these requirements to prevent the problems introduced above. Our development is based on two different sized basic systems, which consist of the same main components. The difference arises from the drilling depth. A small shallow winch system specially adapted for a drill depth up to 200 m and an intermediate and deep drill winch for depth beyond 200 m. The shallow winch can be separated easily into two moderately weighted parts. It is driven by one of the engine-gearbox systems, which are also used for the drive of the intermediate and deep drilling system. To perform the required rope force and speed which is needed for the intermediate and deep drilling system three engine-gearbox systems are interconnected. We will present first results of our developments and present our ideas to solve the previous problems. Our new design of the modular drilling winch system provides the possibility for easily changing the winch drum. The different sized drums with different rope length offer the excellent possibility to adapt to the chosen drill depth. Due to the possibility to break the system easily into its modules it is no longer necessary to move more load than needed for the appropriate ice core-drilling task.

Chips transport research and testing for the SUBGLACIOR project

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Using significant technological breakthroughs and unconventional approaches, the ANR SubGlacior and ERC Ice&Lasers projects aim to advance ice core research by inventing, constructing and testing an in-situ probe to evaluate if a target site is suitable to recover ice as old as 1.5 million years. The probe will make its own way into the ice and measure, in real time and down to bedrock, the depth profiles of the ice δD and/ or $\delta^{18}O$ water isotopes, as well as the trapped gas CH4 concentration, using embedded innovative laser technology.

The probe, anticipated to have a diameter of around 120mm, will electromechanically drill down the ice sheet to a depth of 4000m and sample continuously using a forward pointing melt-probe. One key aspect of the project is the design and implementation of a successful technology to remove the ice chips from the borehole. Several options are evaluated and we present methodologies and results so far obtained with our research into suitable drill fluid, pumping technologies and the verification of hydraulic calculations. Detailed analysis of the required flow rates and pressures to overcome friction losses and effectively transport the chips to the surface indicate that either a pump integrated into the probe or a pump at the surface is feasible, though both options have advantages and disadvantages. A test-rig has been assembled to simulate, as best as possible, the fluid flow and verify key parameters. The pump most suitable for integration within the probe is of the progressive cavity type and these have been evaluated and tested. Silicone oil has been researched and tested as a possible drill fluid taking into account environmental, technical and operational aspects.

In the near future we will decide on our best overall approach for chips transport and start the detailed design of the probe in close collaboration with the project partners.

The French ice drilling facilities

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A few years ago CNRS created the French National Drilling and Coring Facility (C2FN) including 3 groups: Sediment Drilling, Ocean Drilling and Ice Drilling.

We will present you in this poster a quick overview of the equipment available in our Ice Core drilling facility group.

Fabrication of straight and long pipes — Manufacturing methods

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The straightness and the concentricity of the pipes for chip chamber, core barrel and outer barrel are essential tolerances for a smooth drilling process. A deviation of the parameters of these dimensions from the tolerances field can cause problems as e.g. high friction between the core and the core barrel or drilling interruptions due to bad chip removal, both aspects lead to penetration problems.

Acquiring the pipes in the required quality and length and with inner grooves is a frequent challenge when building drill systems. This leads to high costs and long delivery times.

To save costs and be more flexible in timing, we developed a method to produce long precision pipes out of several smaller parts through a welding process. It is much easier to manufacture shorter pipes, even with complicated inner geometry in the required quality. Thus, there is also a greater choice of suppliers, complicated inner geometries are machined on standard-size machines and the prices are also lower. Here we will present first results of our new method and discuss the range of application.

In-situ water production for the WISSARD hot water drill

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Successful hot water drilling in the Antarctic is predicated on the utilization of the abundant water supply locked up in the Antarctic ice. Past projects have used Rodriguez wells, snow melters, and combinations of these two strategies for obtaining drill water. However, these methods both require the existence of seed water to begin the process of melting ice or snow. In the deep field this requirement poses more of a challenge compared to a drill that is based out of a research station with a pre-existing water supply. Additionally, previous snow melting systems for hot water drilling have occasionally proved inadequate in terms of heat supply, pump capacity, agitation, and ease of loading. For the initial WISSARD field season (2012-13), a snow melting system was employed that used waste heat from 225-kW generators to melt snow for seed water; once the initial water supply was established, hot water from the drill system itself could be redirected back to the melter tank to accelerate snow melting. The melt system components were specified to afford relatively easy loading, generous pumping capacity, and powerful mixing; as a result, the melt system was able to operate as a completely redundant supply of drill water over and above the reservoir in the main (3800-gallon) drill tank; that is, the melter output was sufficient to independently supply the WISSARD drill without having to slow or stop the drill itself.

Near field exploration in glacier ice by means of phased array ultrasound technology

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The worst case scenario for any ice-driller is to encounter an impenetrable obstacle after long term drilling. The maneuverable ice exploration probe IceMole, which is currently developed at FH Aachen University of Applied Sciences, combines conventional melting with drilling and hence allows three-dimensional navigation in ice to pass around such obstacles. Navigation is only of benefit if the early detection of structural changes in the ice is guaranteed. We describe an ultrasound-based recon technology, similar to ultrasound imaging, as used in medical and material science applications, to detect and locate objects and structural anomalies in ice. Being integrated into the head of the IceMole, this technology can simultaneously monitor the approach to a sampling area, e.g. the border between ice and a subglacial lake. The big advantage of this technology in comparison to simple ultrasound distance sensors is the ability to electronically steer the acoustic lobe by phase shifting between the single array elements. This makes lateral scanning of the melting probe's environment possible without any mechanically moving parts. The angle of view is expanded to angles bigger than 50° to each side, giving information on dimension of structures and therefore possible drilling paths. The spatial resolution of ultrasound systems is proportional to the sound frequency hence high frequencies would be preferable. Unfortunately ice is almost nontransparent for higher frequency ultrasound waves and so there are some limitations in this aspect. Simulations showed a good balance between resolution and range at frequencies between 500 kHz and 1 MHz. For our laboratory experiments, 750 kHz ultrasound arrays with 16 active elements have been developed, which can withstand the icy environment and can be operated at low temperatures. These have been used to detect structures at distances of up to 1 m. The first field test on the Morteratsch glacier (Switzerland) with the same setup has been performed in 2013. Although the ice quality on this temperate glacier was not perfect (many inclusions like bubbles, dust and sand) our measurements revealed structural anomalies in up to 2.5 m distance. Signal to noise ratio suggests that this is still significantly below the effective range of our system. Further developments might even enable the determination of liquid water currents by analysis of the Doppler shift.

New hollow torque motor for ice coring applications

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Existing ice core drills are powered with different motor-gear-combinations. All designs have in common that the provision of torque is through a central solid shaft. These power supplies are routinely hosted in pressure sections thus imposing design and performance constraints in terms of e.g. hydraulic resistance, cooling and idle running moment.

Throughout the last decade, for industrial and positioning applications torque motors are to increasing fraction the power system of choice over brushed dc motors. Especially the technology of electrical commutation (EC) allows to pressure seal the stator completely by moulding it in. For high torque motors a class of systems with a hollow inner rotor became available for the industrial market. Inspired by these kind of motors, we designed, built and tested a motor with a hollow rotor of 100 mm inner diameter, 127 mm outer diameter of the stator and a torque rating of 20 Nm up to 100 rpm for moderate ambient temperatures around 18°C. Thus fitting the actual power unit into the annulus of e.g. the existing EPICA/NorthGRIP ice core drill, and facing up to mayor electrical and mechanical design challenges at the feasibility limits.

The realized motor performed to our expectations. Towards the application in ice core drills we expect more than an order of magnitude lower hydraulic resistance, much more power beyond the specified rating in the bore-hole due to efficient cooling and a moderate idle running moment as no pressure seals on the shaft are required.

We will present the layout of the motor and results of the performed tests.

Gear-pump as circulation device of the deep ice electromechanical drill: Design and tests

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The thorough removal of cuttings is one of the key requirements for successful drilling in ice, otherwise cuttings can form packed ice rings near the drill head and can eventually cause a stuck drill. In deep ice electromechanical drilling, the cuttings are removed from the bottom of the hole by the fluid flow from a down-hole pump and collected in a chip chamber. Three main parameters determine the applicability of pump: flow rate, outlet pressure and sizes as the pump should be installed in relatively narrow space inside electromechanical drill. By comparison of several pump kinds, the gear ROTAN® pump of CD33EM-3U332 type was chosen for the new Ice and Bedrock Electromechanical Drill 'IBED'. The capacity of the pump at nominal rotation speed of 1286 rpm is 38-41 L/min with pressure of 0.2 MPa. In order to evaluate chips removal ability of the gear pump with different drilling fluid types, the special testing stand for estimation of the pump flow rate - pressure dependence was built up, in which the circulation flow rate can be changed by rotary valve. Three types of drilling fluid with different viscosities (silicon oil KF96-2.0cs, Exssol D40 and Estisol 160) were tested. The gear pump performance at different conditions was analyzed, and the limit parameters were found.

The IceMole clean access and sampling subsystem for subglacial aquatic environments

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The maneuverable ice exploration probe IceMole (IM) is currently developed at FH Aachen University of Applied Sciences. Using an ice screw at the tip of the melting head, it combines conventional melting with drilling. This allows ice penetration into various directions, even horizontally and upwards. One of the IM subsystems, the Clean Access and Sampling Subsystem (CASS), is designed to access subglacial environments and to take clean samples of subsurface materials. In 2014, it shall be used to sample subglacial brine at a depth of approx. 50m at Blood Falls, a crevasse at Taylor glacier (McMurdo Dry Valleys, Antarctica), for subsequent microbiological analysis. In this contribution, we describe the design and functionality of the IM-CASS and outline its clean access and sampling strategy.
The CASS features a two-step approach to obtain a clean sample: First, the interior and exterior IM parts are decontaminated with a 3% hydrogen peroxide solution in situ (decontamination step). Afterwards, the actual subsurface brine sample is taken (sampling step). Shortly before the IM taps the crevasse, decontamination is initiated. Melt water is pumped out of the channel by a pumping system located within the IM. Next, the hydrogen peroxide is injected into the channel through jets located at the IM head until it is fully surrounded by the decontaminating solution. Injection itself is realized via an Argon pressure vessel located at the surface ground station and connected to the IM by a tube. After an appropriate reaction time, the sampling procedure starts. The IM taps the water filled crevasse by means of a proboscis deployed from the interior of the ice screw and a first water sample is pumped to the surface for cleanliness assurance. Once the decontamination status has been confirmed, the brine samples are collected into two internal sample bags of 0.5 liters each. Regulation of valves, pumps and sample temperatures are controlled by a microcontroller and a customized software solution.

The decontamination system has been tested and validated during a field test on the Swiss Morteratschglacier in June 2013. The sampling system has been set up as an engineering model and was verified in laboratory tests. Next steps include the complete integration and testing of the CASS. The validation of the fully integrated subsystem in a relevant environment will then take place in November 2013 on Canada glacier, Antarctica.

Autonomous sonde RECAS for environmental exploration of Antarctic subglacial lakes

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Sealed from the Earth's atmosphere for millions of years, subglacial aquatic environment may provide unique information about microbial evolution and the Earth's climate in the past, and nowadays they are of great interest to the scientific community. The subglacial water most likely contains life, which must adapt to total darkness, low nutrient levels, high water pressures and isolation from atmosphere. It is obvious that in situ investigations should not contaminate these subglacial aquatic systems. This criterion makes sustainability of subglacial environment of chief importance. The proposed RECoverable Autonomous Sonde 'RECAS' will allow sampling of subglacial water while the subglacial lake would stay isolated from the surface. Generally, idea of the RECAS design is based on the Philberth thermal probe that was used to penetrate the Greenland ice sheet in 1960-s. The outstanding characteristic of this probe was that the wire for the transmission of electric power and signals was coiled inside the probe, and paid out when it was advancing and became fixed in the ice with frozen melt-water above it. Unlike the non-recoverable Philberth thermal probe, the RECAS is designed to be recovered by using the upper heated tip and cable re-coiling mechanism. The current concept of the RECAS used a low power approach. A conventional internal combustion engine electric generator on the glacier surface will provide 9–10 kW power to the RECAS via umbilical cable stored in the probe. The low power and high voltage transition scheme make possible the use small of a diameter power and signal cable. Electric power allows 2.4–2.9 m/h penetration rate and thus in order to reach a depth of 3500 m and return to the surface requires nearly 4.5 months.

Sediment vibrocorer for subglacial sampling

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Vibrocoring is an efficient procedure for obtaining long, well-preserved cores in consolidated water-saturated sediments from wetlands, harbors and lakes to the deep ocean. This technique, however, was hampered to be utilized in the field of subglacial sediment sampling because of the weight and sizes of existing vibrocorers. SUBglacial SEdiment Vibrocorer 'SUBSEV' is an electromechanical cable-suspended device developed to take high quality 3 to 5 m length 120-mm diameter cores from sediments under ice shelves, shore and floating ice, or even from the bottom of subglacial lakes. We had designed three different types of vibrators and also four versions of corers based on these vibrators, and chose one corer for experiment. Descriptions and comparisons of the vibrators and corers are given. The SUBSEV characterizes are as follows: a) maximum radial size of 330 mm makes the corer possible to pass through a hot-water borehole with 400 mm initial diameter, b) placed inside driven electric unit provides an adjustable exciting force of near 30 kN with frequency of 40 Hz; c) corer can be operated at the water depths down to 3000 m; e) the duration of one run (including the round trip) to maximal depth is 2-3 hours capable to fulfill sampling before the borehole refreezes to a limit size. In order to research performance of vibrator, the special test stand was designed, and findings from the first experiments are described and discussed.

Size, lifetime and heat requirements in water drilling of holes for IceCube

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The IceCube project required 86 water-filled holes in the South Pole ice 60 cm in diameter and 2500 m deep. An instrument string was lowered into each hole with instruments 33 cm in diameter. It was important to produce holes that would stay big enough long enough that the instrument string could be installed reliably but that didn't use more fuel than necessary. A means was developed of calculating the size of the hole as a function of time and depth during the process of hot water drilling and reaming and then on through freezeback. The equations used were derived from first principles and proved to give a good estimate of maximum hole size and freezeback time. In a large hole with a long lifetime significant heat conducts into the ice outside the ultimate hole diameter. This heat is "lost" in that it doesn't melt ice, yet it contributes to extending the hole lifetime. The calculations included this heat. The approach used explicit equations in the water and a moving finite difference grid, attached to the hole wall, in the ice surrounding the hole. The changing conditions were time stepped over the course of the hole development. Running the calculations at depth increments of 100m allowed an understanding of the effect of depth and the effect of the depth-varying ice temperature. The results of these calculations were used extensively to set the parameters used during IceCube drilling and reaming. I will show the approach taken and some sample results, as well as correlations with measured data.

Development and application of thermal drill in CAREERI, CAS

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The modern glacial research still uses ablation stakes as a valid method to measure glacial accumulation and surface flow velocity. For the purposes of ablation stakes installation on the surface of glaciers the shallow holes need to be drilled most commonly using mechanical drills, thermal drills or hand-operated drills. The paper presents the history of shallow drills development as well as merits and drawbacks of the different drill designs. We give particular emphasis on the development and application of thermal drill developed in Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences (CAREERI, CAS), especially to the steam operated drill and hot water drill. The new improved steam drill is introduced in details.

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