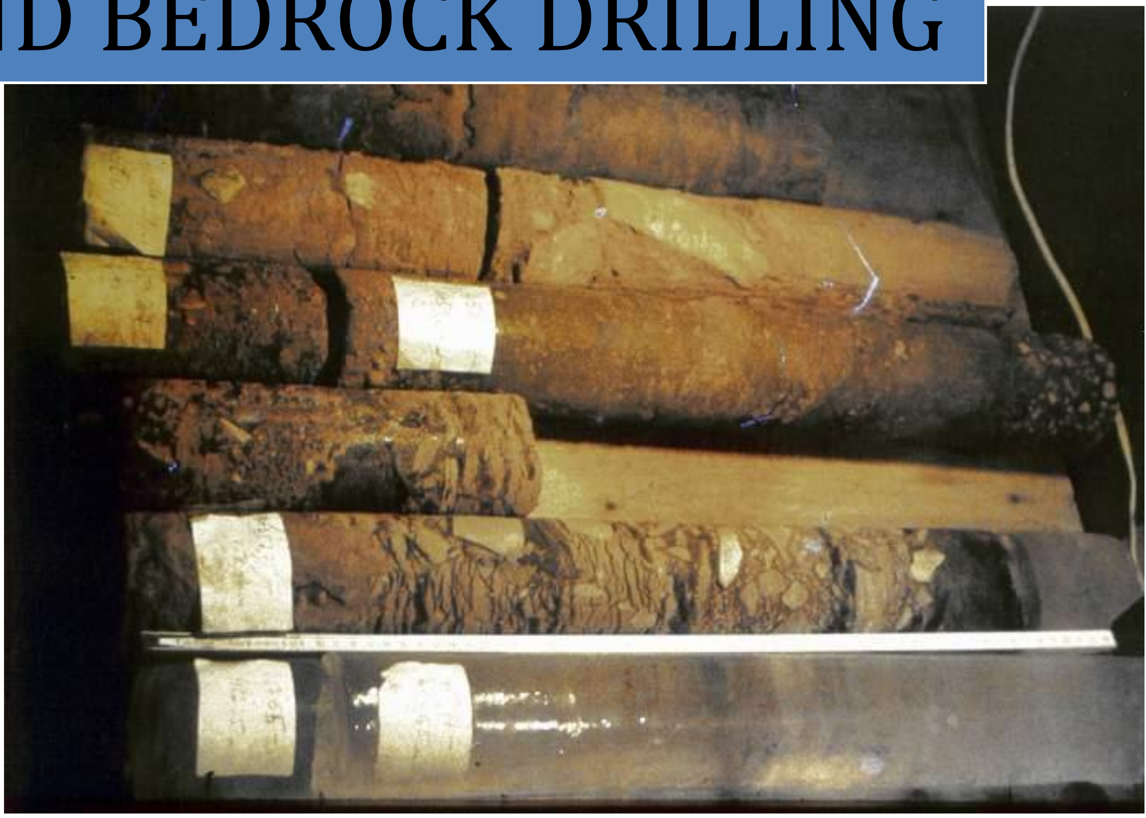
Technical Report
PRC 12-02

REVIEW OF SUBGLACIAL TILL AND BEDROCK DRILLING



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Abstract: Drilling to till and bedrock of ice sheets and glaciers offers unique opportunities for examining processes acting at the bed. Four types of subglacial drilling technologies are considered: (1) non-rotary sampling; (2) non-core penetrating; (3) pipe-string rotary drilling; (4) electromechanical cable-suspended drilling. The different bedrock drilling technologies are reviewed and discussed. The procedure of till and bedrock drilling and the geological description of retrieved debris-containing ice and bedrock cores are given.

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Cover: Subglacial core samples from Vavilov glacier, Severnaya Zemlya archipelago, 1988 (*Vasiliev and Talalay*, 2010)

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1. INTRODUCTION

Glaciers and ice sheets cover 16.3 mn. km^2 or ~11 % of the entire global land area. More than 98 % of Antarctica and most of Greenland are covered by ice. Beneath this ice lies a unique environment, which plays a key role in the dynamics of the overlying ice sheet: debris-containing basal ice layers usually deform more rapidly than clean ice and can contribute significantly to the flow of the ice mass (*Hubbard and Sharp*, 1989; *Cuffey et al*., 2000). Samples of basal and subglacial material contain important paleo-climatic and paleo-environmental records and provide a unique habitat for life (*Willerslev et al*., 2007; *Christner et al*., 2008). In addition, bedrock samples give significant information on sediment deformation beneath glaciers and its coupling to the subglacial hydraulic system (*Boulton et al*., 2001; *Clarke*, 2005), subglacial geology, and tectonics (*Bennett and Glasser*, 2009; *Hansen et al*., 2010).

Nowadays conditions beneath ice are known mainly due to indirect methods of geophysical remote sensing, and there is no single framework for interpreting these data. The glacier bed is very difficult to observe directly. Therefore many studies of subglacial phenomena have been based on observations of former beds exposed by ice retreating (*Knight*, 1999). Direct observation of contacts between ice and substrates remains understandably infrequent. In fact, glacier beds can be accessed and investigated *in situ* (1) through cavities at the margin; (2) via tunnels though the ice or through subglacial rocks, and (3) via boreholes.

There are a few examples of basal sliding and ice-bedrock interaction studies in natural cavities. For example, *Theakstone* (1967) observed the deformation and subsequent incorporation of floor ice layers on to the glacier bed in a cavity beneath Østerdalsisen, Norway. In 1976-1978, a series of caves were observed in Austre Okstindbre, the largest glacier of Okstindan, a mountain range in northern Norway (*Andreasen*, 1983). This type of bedrock accessing could be hazardous (access to the cave may be impeded by a waterfall), and the places for observations are random.

Tunneling technology is well known for different investigations in ice sheets and mountain glaciers. In 1957-1964, several concepts for tunneling in snow and ice were tested at Camp Century (Fig. 1), known as the “town beneath the ice” in northwestern

Greenland (*Clark*, 1965)[1]. After several years of tunneling development work, the project was abandoned because of operational difficulties.

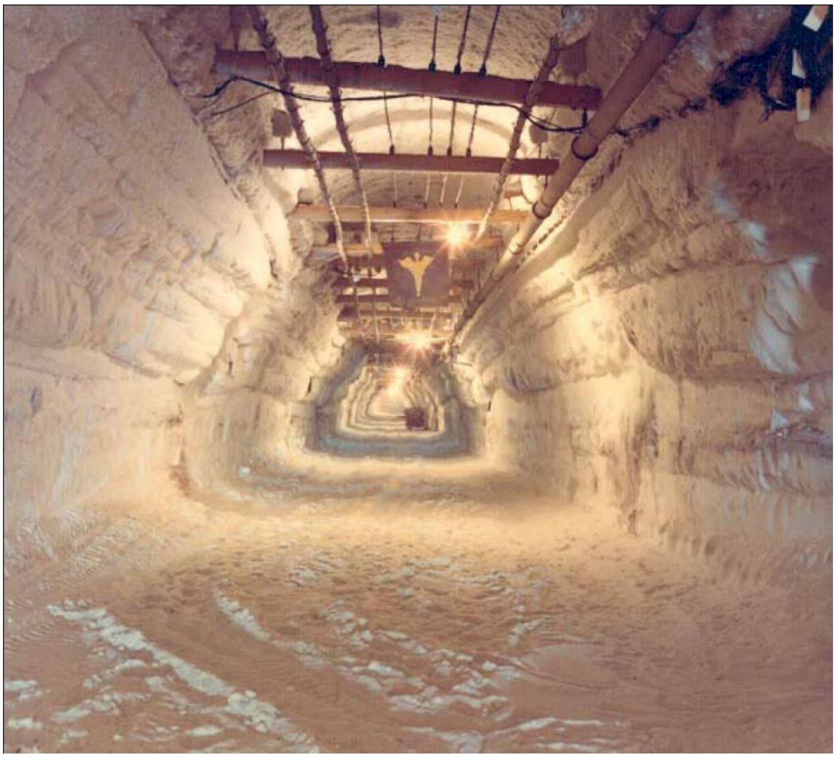

Fig. 1. Main 400-m-long access trench below the surface at Camp Century, 1964; more than a dozen, 150-m-long side trenches radiated out from the main trench (*Langway*, 2008)

Kamb and LaChapelle (1964) were among the first few who made detailed observations at the glacier bed, observing glacier sliding over bedrock by means of a 50m tunnel excavated through the Blue Glacier, a temperate glacier in the Olympic Mountains of northwestern Washington, USA. Later on, several tunnels were dug in Meserve Glacier, a cold-based alpine glacier on the south side of Wright Valley, in Victoria Land, Antarctica (*Holdsworth and Bull*, 1970; *Cuffey et al*., 2000); Urumqi Glacier No. 1, China (*Echelmeyer and Wang*, 1987) and a few others. From 1996 through to 2002, a series of tunnels was driven into firn at South Pole Station, utilizing technology of snow and firn excavation that brought a lot of problems with the tunneler and other equipment (*Walsh*, 2003). Right now, tunneling and mining for observing subglacial conditions at glaciers inland is a very problematic and unpromising task.

[1] The site was built in the frame of "Iceworm", U.S. Army project during the Cold War with the main aim to build a system of tunnels under the Greenland ice sheet and deploy around 600 nuclear missiles, which would be able to reach the USSR in case of a nuclear war. The missile locations were supposed to be changed periodically.

Borehole drilling is much simpler and cheaper than tunneling and mining. Hundreds of boreholes were drilled in the Polar Regions, but only few of them reached the bed and pierced a few meters into tills or rocks (*Bentley and Koci*, 2007). Besides that, there was no successful penetration into bedrock in the interior of Antarctica. Retrieving bedrock samples 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. A particularly difficult-to-surmount barrier is the water layer which is usually situated in between the glacier body and the bed. Nevertheless, borehole drilling might be considered as the optimal method to access beds of the glaciers and to sample subglacial material.

2. SUBGLACIAL ENVIRONMENT AND DRILLING METHODS

The term "subglacial zone" includes everything that lies beneath the glacier, including substrates and anything at the ice/substrate interface (*Knight*, 1999). Sometimes it is used more narrowly, to include only substrate, and sometimes more widely, to include everything in the bottom part of the glacier. The subglacial zone is conventionally taken as a sequential layering of (1) debris-containing (debris-rich, silty) basal ice; (2) subglacial hydrological systems; (3) tilt; (4) bedrock, and (5) sediments on the bottom of the water system (Fig. 2).

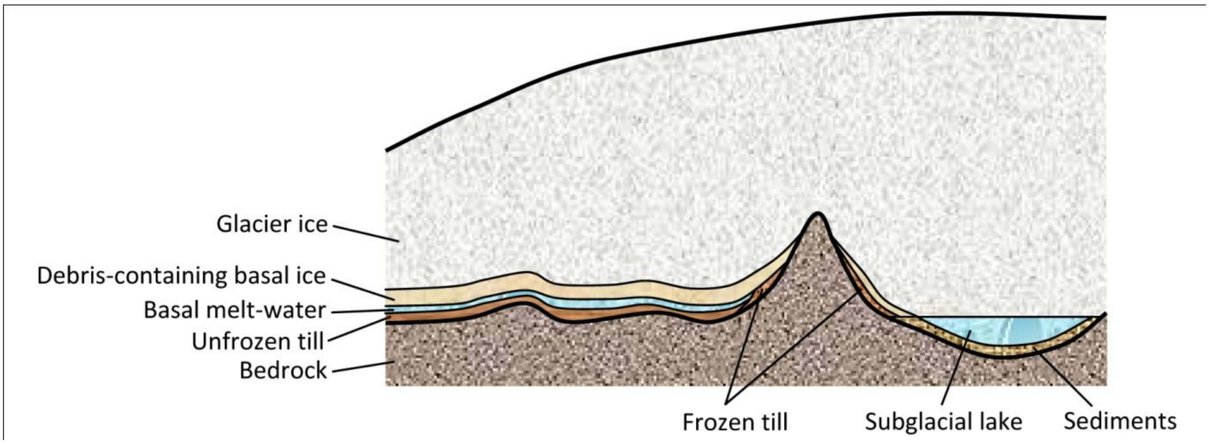

Fig. 2. Schematic layering beneath glacier

A debris-containing basal ice zone may lodge beneath a glacier when the frictional resistance between it and the bed exceeds that of the ice above, which shears over the debris-containing ice mass (*Bennett and Glasser*, 2009). It may have a vertical extent of up to tens of meters. A debris-containing ice zone differs from overlying glacier ice not only by its debris content, but also its structure, properties, and its composition of solutes and gases. In general, debris-containing basal ice sequences have an anisotropic structure, consisting of individual layers, lenses and pods of variable lateral extent. Typically, debris particles have sizes similar to that of silt and sand with occasional particles up to a few cm in diameter. The dirt content is varied from hundredths to several percent by weight.

The deformable subglacial sediments underlying glaciers, irrespective of their origin, are referred to by glaciologists as till; to a geologist, till is a poorly sorted sediment deposited by a glacier (*Cuffey and Paterson*, 2010). A number of recent studies have reported field observations which indicate that strain rates in debris-contained basal ice or frozen till may well be in excess of those expected from theoretical or laboratory-based studies (*Hubbard and Sharp*, 1989). As in debris-containing ice, particles in till range from clay and silt to pebbles, cobbles, and boulders. Till can be frozen (in cold-based glaciers) and unfrozen (in warm-based glaciers). Two processes allow the formation of ice in till: regelation and freeze-on of water and till particles onto the basal ice (*Truffer et al*., 1999).

Types of the true bedrock depend mainly on the geological history before glaciations. The mineral bedrock materials could include sedimentary rocks like siltstone and sandstone (*Bolshiyanov* et al., 1990) or metamorphic rocks that have suffered glacial erosion like gneisses and metamorphosed granites (*Fountain et al.*, 1981), and surficial debris (*Gow and Meese*, 1996). Metamorphic rocks could turn gradually to the igneous rocks of crystalline shield like granite (*Gow and Meese*, 1996).

Beneath warm-based glaciers, free water can exist in the form of lakes, rivers, drainage pathways, and deep groundwater (*Priscu et al*., 2008). Basal melt-water is confined to the pore spaces of glacial sediments immediately underlying the ice base (typically 1–10 m thick, *Alley et al*., 1997). Subglacial lakes beneath the ice are found as: (1) lakes in subglacial basins in the ice-sheet interior; (2) lakes perched on the flanks of subglacial mountains, and (3) lakes close to the onset of enhanced ice flow (*Dowdeswell and Siegert*, 2002). Subglacial lake basins may hold the best geologic archives of paleo-environmental changes that will help determine the timing of past glaciations. The maximal depth of subglacial lakes is at least 1000 m, and there may be several hundred meters of glacial sediments draped over the lake floor (*Siegert et al*., 2001).

The focus of recent studies is on the large subglacial systems lying beneath Antarctic ice sheets where most of the subglacial water on our planet is thought to exist. In the near future core sampling is planned to recover sediments from Antarctic subglacial water basins at Lake Ellsworth and Whillans Ice Stream (*SCAR Annual Reports* 2009, 2010).

To recover subglacial till and bedrock samples, we consider following types of subglacial drilling technologies:

(1) Non-rotary sampling;

(2) Non-core penetrating;

(3) Pipe-string rotary drilling with (i) conventional core barrel, (ii) wire-line core barrel, and (iii) coiled tubing drilling;

(4) Electromechanical cable-suspended drilling with (i) auger conveyer, and (ii) near-bottom fluid circulation.

These drilling technologies have different concepts, limits, performance, and applicable scopes (Table 1). The appropriate type of drilling equipment depends on the borehole depth, thickness of ice, “drillability” of rocks, subglacial geology and hydrology.

Table 1

Limits and applicable scopes of subglacial drilling technologies

Parameters	Non-rotary sampling	Non-core penetrating	Pipe-string rotary drilling			Electromechanical cable-suspended drilling	
			Conventional drilling	Wire-line drilling	Coiled tubing drilling	Near-bottom fluid circulation	Auger conveyer
Max subglacial penetration, m							
reached	3.0	2.5	2.0	2. 0	-	1.5	-
potential	25	25	-*	-*	-*	5.0	2.0
Max thickness of ice, m							
reached	1058	499	86.5	619.5	-	3053.44	415
potential	4000	4000	3000	1200	4000	4000	500
Subglacial environment type	Unfrozen till, subglacial lake sediments	Frozen & unfrozen till	Frozen till, true bedrock				Frozen till, sedimentary bedrock

*Maximal subglacial depth penetration depends on the parameters of the drill rig.

The experience of hot-water and electric thermal drilling technologies showed the possibility of the coring in debris-containing ice as well. For example, in 1997-1998 specialists from California Technological University collected ~100 m ice core in the hole at Siple Dome (West Antarctica) with final depth of 1004 m using a hot-water coring drill (*Gow and Engelhardt*, 2000; *Engelhardt et al*., 2000). A few millimeter sized rock particles were observed in the bottom core.

In principle, it would be possible to collect samples of subglacial material by hot-water drilling. During the 1987-1988 field season, two holes, 370 m and 480 m, were drilled through Crary Ice Rise, southeastern Ross ice Shelf, Antarctica (83°S 170°W) to install thermistor cables. The hot-water drill, designed by the Polar Ice Coring Office melted a hole averaging 26 cm in diameter at an average drilling rate of 0.5 m/min (Bindschadler et al., 1988; Koci and Bindschadler, 1989). The bed was naturally frozen at both sites (temperatures -3.7 C and -5.7 C, respectively). In the second hole (480 m), the hot-water drill was remained left at the bottom for approximately 1 h before being raised to the surface. When the drill was returned to the surface, the drill stem was coated with a thick mud, and a rock 5-cm diameter and a mudclast 4-cm long were lodged in the caliper arms when the drill stem was winched to the surface (Fig. 3). In addition, approximately 1,000 cm3 of sediment material was spread over the drill stem filling most of the ledges and holes.

Fig. 3. Sample of rock recovered from bottom of the 480-m deep hole at Crary Ice Rise, Antarctica (*Bindschadler et al*., 1988)

The rock is strongly faceted, igneous in composition, and appears to be a member of a lodgement till. Striations cannot be seen; the loose sedimentary material contains a large amount of gravel. This material contains a rich but highly fragmented diatom assemblage with common sponge spicules (*Scherer et al*., 1988). The organic carbon in Crary Ice Rise sediments is less than 0.2 %.

Though the penetration into subglacial rocks sediments by hot-water and thermal drilling technologies technically is possible, we do not include them as the options for subglacial bedrock drilling.

This paper does not include experience of rock drilling in ice-free areas or sub-ice-shelf glacimarine sediment like Dry Valleys Drilling Project (DVDP, 1971-1975) in the McMurdo Sound area, Cenozoic Investigations of the Ross Sea (CIROS, 1986), Cape Roberts Project in the Ross Sea (1995-2000), ANtarctic geological DRILLing (ANDRILL, 2006 up to the present) project in the McMurdo Sound area and others.

The drilling technology in debris-covered glaciers (rock glaciers) was also developed and tested *(Barsch et al*., 1979; *Haeberli et al*., 1998*; Green et al*., 2007, and others). These rock glaciers are a special geomorphological form of creeping mountain permafrost, thus drilling through is very important if the history of rock glacier behaviour is to be understood and predictions of future response are to be made. Drilling performance in rock glaciers is quite different from subglacial drilling and deserves a separate review.

Hereinafter the different subglacial till and bedrock drilling technologies are reviewed and discussed.

3. NON-ROTARY SAMPLING

There are a number of non-rotary tools for collecting samples in sediments or other unconsolidated materials (*McGinnis*, 2009). The sampling techniques in unfrozen till and subglacial lakes sediments are generally the same as that used for penetrating seafloor. Subglacial non-rotary sampling tools must be able to function in the harsh and cold subglacial environment several kilometers below the ice surface, where pressures are similar to those in the deep sea, but need to be designed for deployment to the ice bed through pre-drilled (e.g. by hot-water drilling) comparatively narrow ice borehole.

Selection of the most appropriate sampling system is generally driven by project needs and composition of the sediments to be sampled. There have been many accounts, not always published, of fragments of the bed retrieved by methods ranging from accidental (fragments stuck to drills or instruments) or improvised (fragments retrieved with greased brush bristles or even butter). More serious attempts have used gravity corers or hammers operated from the surface to drive samplers into reasonably soft sediments (*Bentley et al.*, 2009).

The gravity corer is a simple core tube, weighted at the top end, which free-falls over an established distance to penetrate the bottom. Gravity is the only driving mechanism, and some designs incorporate tail fins to help stabilize the device during the drop. Some advantages to this system are that it is relatively inexpensive, has essentially no moving parts and is easy to operate. Disadvantages include structural distortion of the strata due to internal frictional compression from the tube itself, the potential for dewatering (which could skew porosity and/or bulk density results) and limited penetration depth of typically not more than 1-1.5 m.

The piston corer is essentially a gravity corer with the addition of an internal piston. The lifting wire is attached to this piston, rather than the tail of the corer. Today piston coring is one of the more common seafloor sampling methods. A typical piston corer uses a "free fall" of the coring rig to achieve a greater initial force on impact than gravity coring, and a sliding piston inside the core barrel to reduce inside wall friction with the sediment and to assist in the evacuation of displaced water from the top of the corer. Some advantages include improved penetration depth (in some substrates it is capable to penetrate up to 25-m in depth), and minimal sediment compression. Disadvantages include some loss of the uppermost surface layer (due to bow wake from the piston-plugged nose during descent) and the corer may be somewhat cumbersome to operate.

Hammer corer and vibrocore use an external driving force to penetrate sediments that are unsuitable for simpler coring devices like gravity and piston corers. In essence, the hammering force allows the core tube to enter the bottom faster and deeper in firm, sandy substrates containing a large amount of small-sized debris. Vibrocore samplers have an electrically powered vibrating head, which vibrates vertically along the axis of the sampler to penetrate the sediment. A vibrocore sampler can penetrate compact sediments and collect core samples up to 10-m long depending on the power of the vibrating head and weight of the sampler.

Ice Streams, West Antarctica. In 1988-1995 sediment coring devices were used for sampling the subglacial sediments beneath ice streams of the West Antarctic Ice Sheet. A typical ice stream has a width of ~50 km and length of ~400 km, and the ice moves here at speeds 10-100 times faster than in the ice sheet as a whole. A total of 27 holes ~10 cm in diameter up to depths of 1026-1058 m were drilled by the hot-water drilling method to the bottom of Whillans Ice Stream (former Ice Stream B) in the vicinity of camp Upstream B (83.5°S 138°W) (*Engelhardt and Kamb*, 1997). As a part of the drilling project focused on investigations of ice stream mechanics, 12 till cores and a number of smaller till samples were acquired beneath Whillans Ice Stream.

Penetration and sampling of the till beneath Whillans Ice Stream were quite difficult (*Engelhardt et al*., 1990). The sampling was carried out not less than four hours after borehole completion using 6-m long piston corer with internal diameter of 5 cm (*Kamb and Engelhardt*, 1991; *Tulaczyk et al*., 1998). The piston coring showed that the material below the bottom of the hole is unfrozen, water-saturated till. The directly measured porosity was 0.40. Borehole measurements showed that the base of the ice stream is at the pressure melting point of -0.8 °C. Presumably, the ice base feeds melt-water into a widespread basal water system.

Lengths of the samples recovered by piston core ranged between ~0.3 and 3.0 m. The sediment cores showed no evidence of disturbance (e.g., grading or sorting) by the jet action of the hot-water drill, although such disturbance undoubtedly occurred during borehole drilling. The lack of disturbed material in the cores is ascribed to the fact that the ice slides at 3–4 cm/hr: during the few hours between completion of a borehole and piston coring, the bottom of each borehole moves away, by sliding, from the disturbed bed area and onto adjacent undisturbed bed, from which the core sample is then obtained.

Sedimentological analyses of these cores showed that the sample subglacial material is fairly homogeneous. On average, the core material was composed of 35 % clay, 23 % silt, 35 % sand, 7% of granules and pebbles. Clasts up to 5 cm in size were present; they are mainly granitic to gabbroic, but metamorphic lithologies (such as slate and gneiss) are also present. Scarce shell fragments are visible macroscopically, and microscopic organic remains (sponge spicules, diatoms, etc.) are present though not abundant.

During the 1997/98 field season a borehole to the bed at 1004.6-m depth was drilled in close proximity to the PICO drilling site (see Section 6.4) at the summit of Siple Dome (81.658°S 148.809°W; 601 m a.s.l.), the largest interstream ridge, located between Kamb Ice Stream (former Ice Stream C) and Bindschadler Ice Stream (former Ice Stream D) (*Engelhardt*, 2004). The borehole was drilled with the Caltech hot-water drilling system in 16 hours. As the ice-sheet bed was reached, the hot-water drill came to a sudden stop, normally indicating a hard rock bed. A subsequent attempt to obtain a soil sample from beneath the bed using a piston corer produced a very small amount of debris but also a smashed cutting head, again showing the hard rock bottom of the borehole. Temperature measurements showed that the ice sheet is solidly frozen to a rock bed, and piston coring is not available in such circumstances.

Columbia Glacier, Alaska. Basal sampling, coring and down-hole water sampling were carried out under the central region of Columbia Glacier, a major valley glacier in Alaska (*Humphrey*, 1993). The fiord-filling lower reach of the glacier is underlain by a thin, ~7 cm, veneer of rock debris. Fluidized debris intruded at least a meter up the borehole. At a higher site, 13 km from the terminus and above the fiord, probing, samples, and the bending of a drill stem, which was stuck in the basal zone for 5 days, showed that the basal till layer was ~65 cm thick.

Bakaninbreen Glacier, Svalbard. The sediment hammer sampler to retrieve bulk samples from the glacier bed was specially developed in the University of Leeds, UK (*Murray and Porter*, 2001). The sampler consists of a hollow cylinder with four windows that can be covered by a sliding sleeve (Fig. 4). The cylinder is hammered into the glacier bed. This pushes up the sleeve, exposing the windows. Sediment is forced through the windows, and as the sampler is withdrawn the sleeve slides down and prevents the sample from being washed out. This type of sampler does not allow sampling of particles larger than the window size (25 mm). Furthermore, the samples may not be representative if the bed is not matrix supported, and the device could adequately sample fine sediments only.

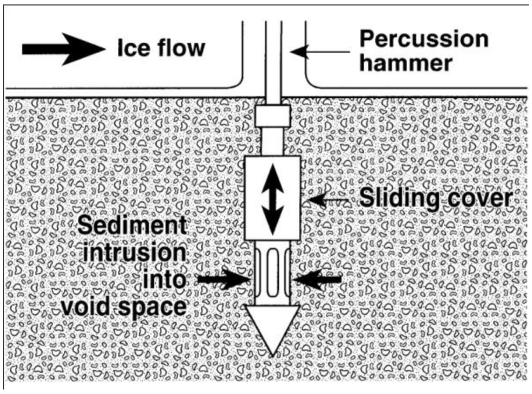

Fig. 4. Sediment hammer sampler (*Murray and Porter*, 2001)

In 1995 five sediment samples were successfully retrieved beneath Bakaninbreen Glacier, Svalbard. The holes were pre-drilled by hot-water drilling system. In most cases the samples were too small and contained insufficient coarse material for sieve analysis to be practical so the results were presented for particles less than 2 mm only, except for one much larger rock sample. Those samples contained rounded and striated clasts typical of material that has been transported basally.

Subglacial Lake Ellsworth, West Antarctica. Subglacial Lake Ellsworth is scheduled for access in 2012/13. In preparation for this, a campaign of ground – based geophysical surveys was completed between 2007 and 2009. Ice flow (~5 m/a) and surface topography were measured using GPS, ice thickness (~3150 m) and internal stratigraphy were mapped by radar, and seismic surveys gave water depth (up to 156 m) and information on the nature of the lake bed.

A hot-water drill is to be developed to produce an initial hole diameter of 36 cm to enable an instrumented probe to enter the lake. The design of the drill will build on previous concepts and developments used by the British Antarctic Survey for hot water drilling in Antarctica (*Blake*, 2011). The probe will be lowered under its own weight into the borehole and subsequently to the subglacial lake (*Siegert et al*., 2007). The diameter limit has the most profound effect on the area available for tip mounted instruments i.e., imaging sonar, conductivity-temperature-depth instrument, water sampler tube, sediment gravity corer (length 0.6 m, outer diameter 60 mm), video camera and light, as shown in Fig. 5.

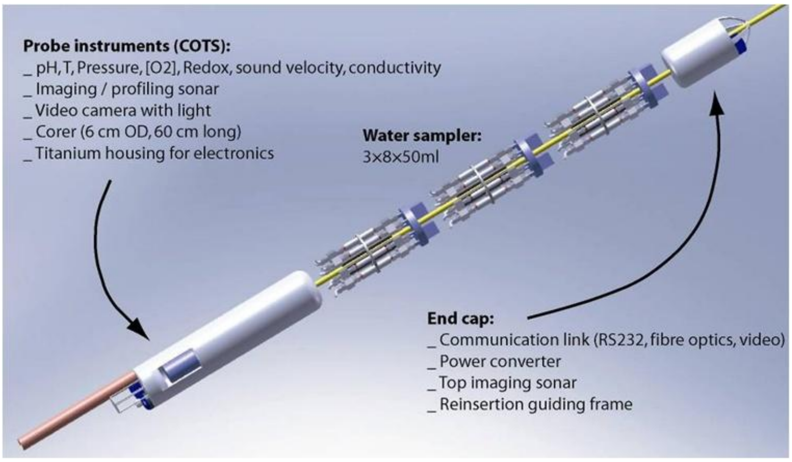

Fig. 5. Probe with gravity corer for subglacial Lake Ellsworth exploration (*K. Makinson,* presentation at the meeting "Ice Drilling Design and Operations Group – Technical Advisory Board", April 20 & 21, 2011, University of Wisconsin – Madison, USA)

WISSARD. To study the subglacial environment of the Whillans Ice Stream in West Antarctica, a 6-year project Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) was funded by NSF, USA. The project plans to test the cleanliness of its drill on the Ross Ice Shelf in 2011-2012, sample Lake Whillans in 2012-2013, and sample the lake's outflow at the grounding zone in 2013-2014 (*Priscu et al*., 2010). Three types of sediment sampling depending on sediment stiffness are considered by WISSARD project: 1) gravity corer; 2) piston corer; 3) percussion corer.

The wide barrel gravity corer consists of a plastic liner inside a steel square barrel with a weight on top that penetrates soft sediment by gravity. Water inside of the tube evacuates through a valve at the top.

Piston corer, designed and built by California Institute of Technology, *H. Engelhardt* has a cutting shoe made of steel protecting the core liner inside a steel barrel. It is able to recover up to 3 m of sediment depending on the stiffness and the number and size of clasts in the sediment.

Percussion corer has been designed and built by DOER-Marine, *S. Vogel* to permit recovery of up to 5-m long cores of stiff sediment (Fig. 6). This corer has an active hammer system driven by a water pump. The percussion corer has a double-wall barrel, which allows water from the top of the sediment corer to flow within the coring tube wall to the coring tip.

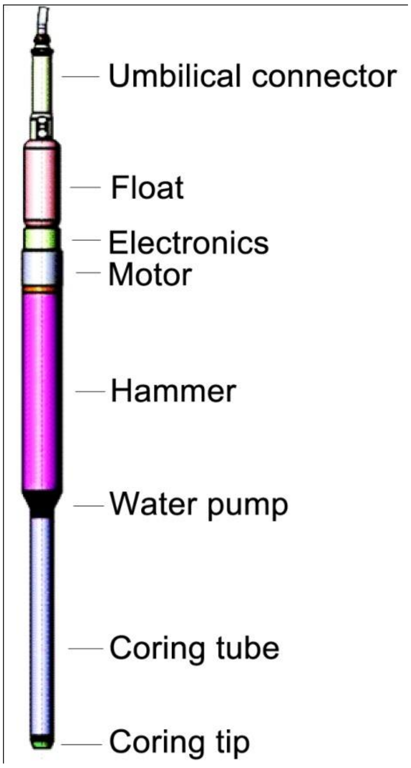

Fig. 6. Percussion corer designed by DOER-Marine and *S. Vogel* for WISSARD project (http://wissard.org)

4. Non-core penetrating

To install different sensors and markers into the soft till beneath glaciers and to measure basal sliding, different types of sediment penetrators were used: "drag spool" system (*Blake et al*., 1994; *Murray and Porter*, 2001), "tethered stake" (*Engelhardt and Kamb*, 1998), hammer penetrators (*Boulton et al*., 2001; *Harrison et al*., 2004). Typically the boreholes are pre-drilled by hot-water systems. Penetrators are driven into the top of the till and afterwards may be pushed in farther by (i) gravity; (ii) mechanical, hydraulic or pneumatic squeezing, or (iii) hammering.

Blue Glacier, USA. One of the first experiments to get a sample of subglacial material were carried out during the summer of 1970 in an area of Blue Glacier near the equilibrium line where the ice thickness is about 120 m (*Harrison and Kamb*, 1976). The holes were pre-drilled with 51-mm diameter electrothermal drills and then maintained at a diameter of 60 mm with a special conically-shaped thermal drill.

Debris-containing ice was penetrated with the help of a cable tool, heavy chisel which is repeatedly raised some tens of centimeters off the bottom with a cable and dropped. The string of tools, consisting of swivel, jars, stem, and bit, was about 3 m long and weighed about 30 kg (Fig. 7). The maximum diameter of the bit was about 50 mm. It was driven off a cathead, which for convenience was not connected directly to the wire cable, but via a rope clamped to it. The cable was continually adjusted so that there was some tension as the bit struck the bottom. A small cable winch, the cathead, and the sheave were all mounted on a wooden tripod.

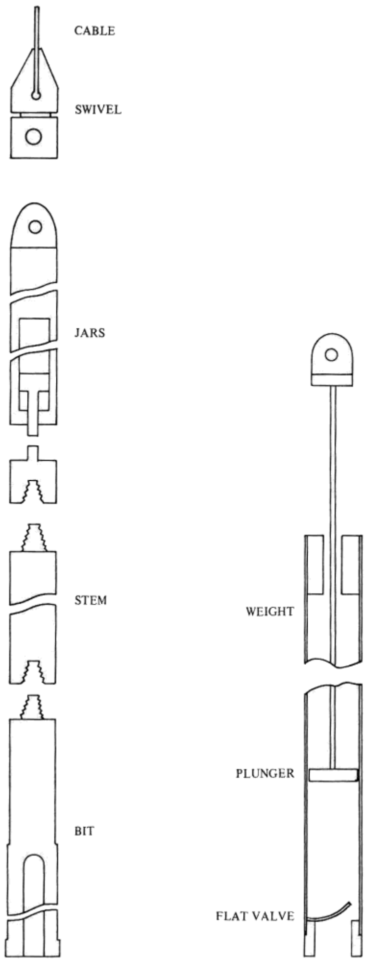

Fig. 7. On the left – cable tool; on the right – sand pump (*Harrison and Kamb*, 1976)

The performance of this cable tool was rather poor, as illustrated by a drilling rate of only 1 m/hr in clean ice. It was difficult to re-enter a hole with a long string of tools after a period of days or weeks, depending on the rate of deformation of the ice. Another difficulty was that the bit was probably striking a fairly large area since no casing was driven to guide it. Despite its inefficiency, layers of heavily debris-laden ice were successfully penetrated with this cable tool.

Water stood in all the holes in which cable-tool drilling was attempted. This permitted debris to be bailed out with a sand pump (Fig. 7). This was a simple device which is operated with a single cable. The body of the sand pump was about 1.5 m long and 51 mm in diameter. The pump was run into the hole with the cable attached to the plunger, which is therefore initially extended. When the pump body reached the bottom and the cable tension was released, the plunger retracted under the influence of gravity. A strong jerk on the cable sucked debris into the bottom of the pump, where it was contained by a flat valve made from a sheet of neoprene. The sand pump worked well, except that it seemed to have difficulty in picking up all the debris in enlarged holes; this complicated the determination of undisturbed subglacial conditions.

Trapridge Glacier, Canada. The Trapridge Glacier is located near the St. Elias Mountains in the Yukon Territory. Sediment strength at this glacier was measured with instruments known as "ploughmeters" installed at the bottom of boreholes (*Fischer and Clarke*, 1994). The ploughmeter consists of a 1.54 m long solid steel rod having a diameter of 19 mm on to which two strain gauge networks are mounted (Fig. 8). The lower end of the rod terminates in a conical tip. The rod is sheathed in an epoxy-resin-filled, protective, vinyl tube having an inside diameter of 25.4 cm and an outside diameter of 31.8 cm.

A metal cap covers the conical tip to protect the sandwich construction during insertion. A 101.6 mm long and 9.5 mm diameter guide hole has been drilled along the axis of symmetry into the upper end of the rod and serves to guide the percussion hammer that is used to insert the instrument. Similar to an ice-entrained clast, the immersed tip is dragged through the sediment as the glacier slides forward. Elastic bending of the ploughmeter is recorded by the strain gauges and is converted into a force on the tip with the use of a laboratory calibration.

To install the plough meter at the glacier bed, the device is lowered down a borehole and hammered into subglacial sediment. The insertion depth must be sufficient to ensure that all strain gauges are immersed in subglacial material. The upper section of the ploughmeter extends into the borehole and becomes pinned by the moving glacier.

In July 1991, two ploughmeters were inserted into sediment beneath Trapridge Glacier near the centre-line flow markers. In the study area, the glacier has a uniform thickness of about 72 m. Both boreholes were unconnected to the subglacial drainage system at the time that ploughmeters were installed. The exact insertion depth of the ploughmeters into subglacial sediment was uncertain.

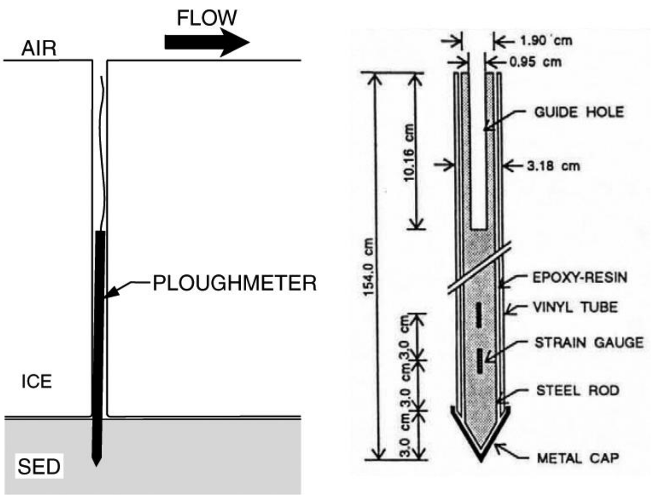

Fig. 8. On the left – installation of ploughmeter at the base of the glacier; on the right – schematic diagram of ploughmeter (*Fischer et al*., 1994, 2001)

Storglaciären, Sweden. A device used here is similar to ploughmeter and referred to as a "dragometer" (Fig. 9). It consists of a steel cylinder with conical ends, dubbed the “fish”, that is dragged through the till by a 1.9 m long steel pipe (*Iverson et al*., 1994).

The fish is 100 mm long and 19 mm in diameter. A flexible, vinyl-covered aircraft cable with a diameter of 1.6 mm runs from the fish up through the bottom of the pipe to a load cell that is housed in a separate module in the pipe's upper end. The module is filled with mineral oil to prevent penetration of water into the load cell. The pipe and fish are lowered down a borehole and driven into the bed with a percussion hammer and insertion tube. After insertion, the hammer and tube are withdrawn leaving the pipe and fish embedded in the till. The dragometer was used to study the residual strength of till beneath 95 m of ice in the ablation area of Storglaciären in the Scandinavian Alps, Sweden.

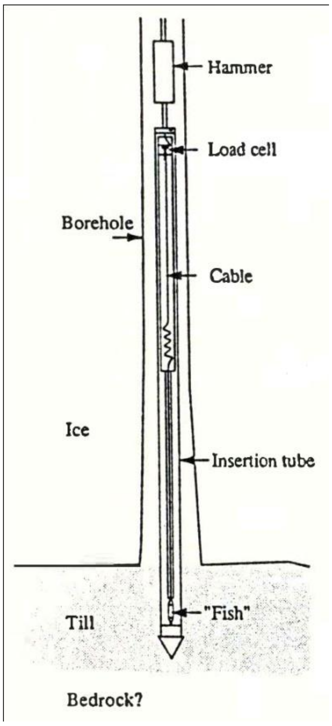

Fig. 9. Light down-hole hammer for dragometer inserting (*Iverson et al*., 1994)

At this site, totally 15 holes were drilled through the glacier during July 1995 (*Fischer et al*., 1998). Two holes were also instrumented with ploughmeters described above to measure the strength of the subglacial till. This ploughmeters were inserted ~0.13 m into the basal till.

Bakaninbreen, Svalbard. Bakaninbreen is a 17 km long surge-type glacier in southern Spitsbergen, Svalbard, which began surging between the springs of 1985 and 1986. An extensive hot-water drilling campaign was undertaken during 1994 and 1995 both up-glacier and down-glacier of the surge front (*Porter et al*., 1997). Drilling has allowed samples of basal sediment to be extracted, and has demonstrated that Bakaninbreen overrides a layer of soft sediments, at least 1 m thick. The basal sediments comprise a mixture of marine muds and glacial till. Several ploughmeters were installed into the deformable sedimentary bed close to the surge front to assess mechanical conditions year-round. The rod of ploughmeter was hammered into basal sediments such that the upper part became trapped within glacier ice.

Breiðamerkurjökull, Iceland. The construction of the penetrator designed in University of Edinburgh, UK is illustrated in Fig. 10 (*Boulton et al*., 2001).

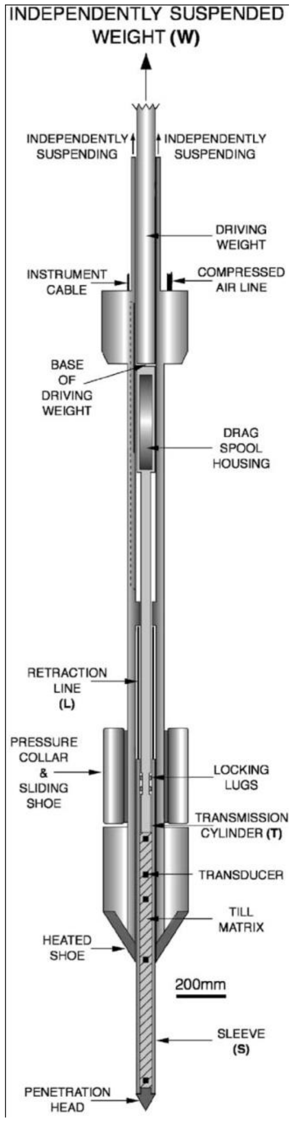

Fig. 10. Penetrator for inserting and measuring transducer strain markers (*Boulton et al*., 2001)

Strain markers attached to drag spools in the drill string were pre-packed in a column of till at 0.1, 0.3, 0.5 and 1 m within the till column. The steel sleeve (S) containing the till column was driven into the till by lowering an independently suspended weight (W), consisting of 300 kg of lead collars, onto the top of the transmission cylinder (T). The weight supported by the transmission cylinder was controlled from surface. The transmission cylinder was locked to the sleeve (S) by lugs. After driving the penetration head as far as it would penetrate into the till, up to a maximum of 1 m, the sleeve was withdrawn by pulling a wire retraction line (L) attached to the sleeve, which also withdrew the locking lugs and permitted the sleeve to slide upwards around the transmission cylinder so that the till column and the transducers it contained could remain in place.

Seven boreholes were drilled in Breiðamerkurjökull, an outlet glacier of the larger glacier of Vatnajökull in southeastern Iceland, using a hot-water system. Holes were drilled to within approximately 1–2 m of the glacier bed up to depths not exceeding 125 m. In four, there was significant penetration into the subglacial bed without apparent breakage of the pressure seal. Penetration depths beneath the apparent glacier bed were 0.27, 0.42, 1.0 and 1.0 m.

Unteraargletscher, Switzerland. Six holes were drilled by hot-water system through the ice to the bed near the central flowline of Unteraargletscher, roughly 3 km up-glacier from the terminus during June 1999 (*Fischer et al*., 2001). At this site, the ice was ~252 m thick. With one exception, all boreholes remained full of water when the drill reached the bed, indicating that the holes were not connected with the subglacial drainage system at that time. Four holes were instrumented with ploughmeters to measure the strength of the subglacial sediment. The ploughmeters were inserted ~0.1 m into the basal sediment.

Black Rapids Glacier, Alaska. In April and May 2002 a heavy hammer system was used to penetrate till under Black Rapids Glacier, Alaska (*Harrison et al*., 2004). A commercially available hammer produced by *Rampp Company*, *Star Iron Works* had a slide of 0.91 m stroke and a diameter of 121 mm. Its mass was 182 kg, but only the upper half is active in the sense that it is raised during hammering. The top of the hammer terminated in a removable 45 kg socket which is connected to the rope. Weights of 114 kg can be placed between the hammer and socket; one or two of these could enlarge the total active masses up to 250 or 364 kg. The drill rod has an outside diameter of 67 mm and a 9.5 mm wall thickness.

The hammer is engaged via a 13mm composition Vectran rope of 130 kN minimum breaking strength. The surface equipment consists of tower, tripod, and 37 kW industrial engine, all mounted on an aluminum frame (Fig. 11). The mass of the entire rig, including the down-hole components, was about 2.3 t, the heaviest piece of which is the engine and drive train of about 0.5 t.

Two holes were drilled. A hot-water drill system was used to drill a 25 cm diameter hole to the ice–till interface. The nominal depth of the Hole 1 from the ice surface to the top of the till was measured with a depth-logging cable to be 497.0 m from the snow surface (snow was 1.5 m deep). Two hammer weights were used. Initial progress was rapid, but progress ceased with the drive point about 1.2 m below the ice-till interface.

Hole 2 was situated 4.1 m toward the center of the glacier from Hole 1. Here the depth from the snow surface to the ice–till interface, measured after hot-water drilling, was 498.9 m, about 2 m deeper than in Hole 1. Two hammer weights were used again. In this case progress ceased when the drive point was about 2.5 m below the ice-till interface.

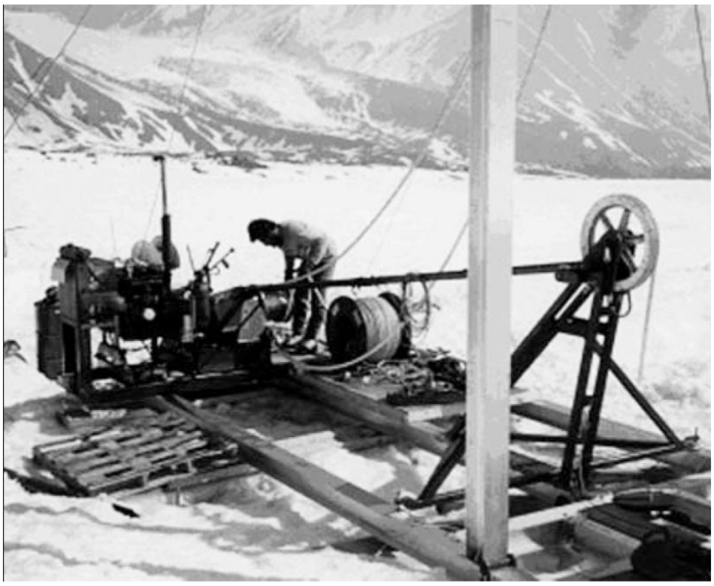

Fig. 11. Surface cable-percussion equipment at Black Rapids Glacier, central Alaska Range (*Harrison et al*., 2004)

One of the main results was that a heavy off-the-shelf down-hole hammer can be operated from the surface on a long, light composition rope. On the other hand the penetration depth into till was rather low (thickness of the till expected to be of ~7 m), although deeper penetration is likely to be possible with more weight on the hammer.

5. PIPE-STRING ROTARY DRILLING

5.1. CONVENTIONAL DRILLING

The concept of conventional drilling with pipe-string is used frequently in mineral exploration where boreholes may be from dozens to few thousand meters in depth. The scheme is simple. The bit is attached to the rod which is rotated from the surface by drilling pipe string with the help of machine-driven rotary rig. In order to remove cuttings, liquid or air circulation is used for cleaning hole and cooling the bit.

Mirny Station, Antarctica. The first subglacial drilling experience was carried out by Soviet 1st Complex Antarctic Expedition just outside Mirny (66°33′ S, 93°01′ E), the first USSR station in Antarctica opened on 13th February 1956. Two holes were drilled in October of 1956 using a conventional GP-1 type drilling rig (*Kapitsa*, 1958). The outer diameter of the drill head was 60 mm (Fig. 12), no cores were retrieved, and the penetration rate was 9.5 m/h. The cuttings were removed by the circulation of air provided by a portable air compressor PKS-6 with a maximum pressure of 0.45 MPa. One of the holes with a depth of 86.5 m penetrated into subglacial rocks.

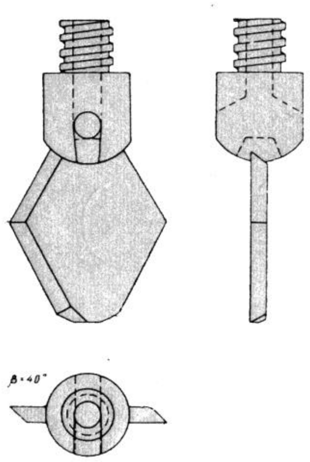

Fig. 12. Drill bit for non-core drilling at Mirny, 1956 (*Kapitsa*, 1958)

During Soviet 2nd Complex Antarctic Expedition a conventional, mechanical drilling rig KAM-500 without any special devices for lifting the cuttings was used for the next soviet drilling project again near Mirny Station in Antarctica (*Treshnikov*, ed., 1960). In July – September 1957 one of the holes with depth of 66.7 m penetrated 2.2 m into subglacial rock using shot drilling. This was a technique used in hard material prior to diamond bit drilling in which steel or cast iron pellets are fed beneath a rotating bit. During rotation the pellets break into small, sharp pieces, which erode the rock.

Churlyenis Glacier, Franz Joseph Land. In the summer seasons of 1958 and 1959 the field drilling operations were carried out by a Glaciological Expedition of the Institute of Geography USSR Academy of Sciences at Churlyenis Glacier in the central section of Franz Joseph Land (*Bazanov*, 1961). The highest altitude of the Churlyenis ice cap is 445 m above sea level. A few holes with depths from 20 to 82 m were drilled using a conventional SBU-150-ZIV type self-propelled drilling rig in the central part and edges of the ice cap (Fig. 13). The drilling reached bedrock beneath the glacier and stopped after penetrating 1.5-2 m into subglacial rocks. The cuttings were removed by the circulation of compressed air produced by a stationary single-stage compressor VK-3-5 with a working pressure of 0.4 MPa at an output of 0.8–1.2 m^3/min.

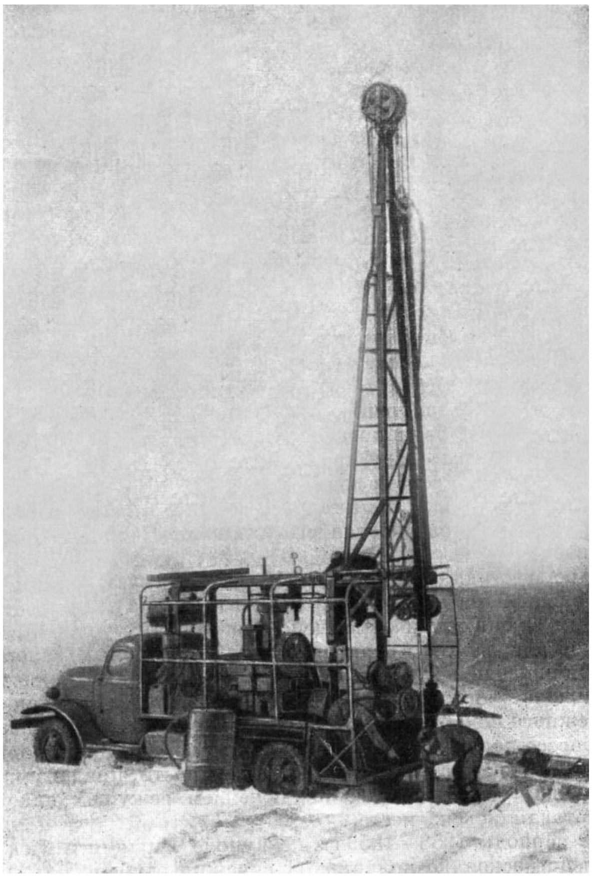

Fig. 13. Drilling operations on Churlyenis Glacier, Franz Joseph Land, 1958–1959 (Photo: *M. Grosvald*, from *Bazanov*, 1961)

Fig. 14. Sandvik Drill Shack for intermediate drilling in Arctic and Antarctica (at the left) redesigned from commercial version for temperate climate (at the right) (www.sandvik.com)

The total power requirements for a conventional drilling rig capable of using jointed pipe for a 3000-m depth rating (e.g. COOPER 550 or Sandvik DE8800), would be not less 250 kW and their weights are in the range of 100-300 t. Considering the power consumption and the weight of conventional rotary drilling rigs, they are not meant for subglacial deep drilling in deep subglacial exploration. A case in point: in 2008, Sandvik engineering group in tooling, mining and construction, designed a special Sandvik Drill Shack for intermediate drilling in Arctic and Antarctica based on the commercial version of the rig for temperate climate (Fig. 14). Taking into account that it was not fully adapted for extremely unfavorable conditions in Polar Regions, this drill rig has never used to date for subglacial drilling.

5.2. WIRE-LINE DRILLING

With wire-line drilling, a core barrel can be removed from the bottom of the hole without removing the drill-string. At the end of the run an overshot is lowered to the borehole bottom at the wire-line end. The overshot attaches to the back of the core barrel inner tube and the wire-line is pulled to the surface with the attached core barrel. The core is then removed from the core barrel and the empty core barrel is lowered back to its position at the bottom of the drill-string.

International Antarctic Glaciological Project, East Antarctica. In the middle of the 1970's a wire-line drilling rig was considered for use within the framework of the International Antarctic Glaciological Project, East Antarctica (*Hansen*, 1976). A major objective of this project was to core through the East Antarctic Ice Sheet and into the bedrock beneath it. A unique drill pipe consisting of lengths of fiberglass-reinforced epoxy pipe cemented to lightweight steel tool joints has been developed which weighs only 2.87 kg/m. Thereby the weight of the drill-string can be reduced by ~50 %. The weight reduction could allow reduction of the mast weight; thus a lighter rig could possibly be used. The project wasn't fulfilled due to organizational and financial reasons.

Black Rapids Glacier, Alaska. In 1998 a commercial wire-line drill rig was used to investigate the subglacial conditions of Black Rapids Glacier in the central Alaska Range (*Truffer et al*., 1999). All holes in the ice were pre-drilled by hot-water drill, which was stopped a few meters above the bed. Then rotary wire-line drilling commenced using a Longyear Super 38 drill rig allowing to drill at least 650 m and obtain a 60 mm diameter core (Fig. 15).

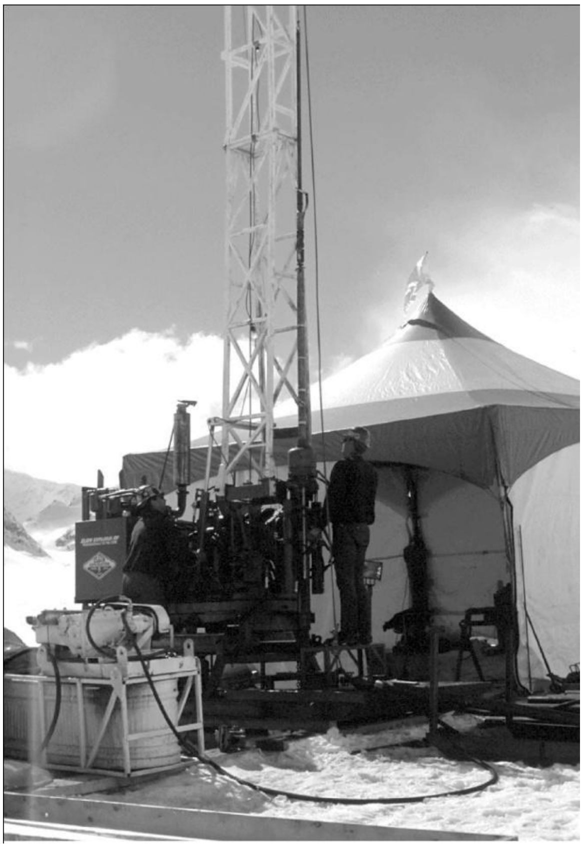

Fig. 15. Longyear Super 38 drill rig at Black Rapids Glacier, central Alaska Range (*Truffer et al*., 1999)

Two drill bits were used: a carbide bit to drill through the ice and soft till, and an impregnated diamond-core bit to drill through till and bedrock. Typical drilling rates were about 2 m/h in till and 1-1.5 m/h in bedrock. The cuttings were removed by circulation of water that was recovered from the hole by submersible pump after hot-water drilling. Till was reached in three of the four holes, bedrock cores were recovered from the bottom of two holes (Table 2). Till contained gabbro and amphibolite inclusions in the form of sand, gravel and pebbles. Subglacial rocks were identified as two-pyroxene gabbro.

The wire-line drilling of bore-hole № 2 was abandoned because of the problems of moving the core barrel up and down the string that resulted from the high inclination (more than 4°) of the hole drilled by hot-water equipment.

The subglacial till and bedrock drilling was very unstable. The penetration itself was difficult because of the clogging of the entrance of the core barrel with fragments of rocks which then prevented entry of any further material. The other problem was caused by water circulation. The stream of water caused the fine sediments, sand and even gravel to be washed away from the core barrel, and chances of core recovery could not exceed 25-30 %.

Table 2

Main results of wire-line drilling at Black Rapids Glacier (central Alaska Range)

Bore-hole №	Interval, m		
	Drilling	Till	Bedrock
№ 1	488.5 – 510.1	502 – 509.5	509.5 – 510.1
№ 1A	498.5 – 504	498.5 – 504	–
№ 2	336 – 348	–	–
Center	602 – 607.5 614.8 – 621.5	614.8 – 619.5	619.5 – 621.5

5.3. Coiled Tubing Drilling

Coiled tubing (metal or composite piping spooling onto a take-up reel) typically has a diameter ranging from 20 to 100 mm and length exceeds of 8000 m. Coiled tubing systems are widely used in oil and gas wells for workover, cleanouts, acid spotting, fishing, drilling, and logging. The usage of coiled tubing drill systems for fast access drilling to the subglacial environment and bedrock coring has recently been proposed by *Clow and Koci*, 2002. A schematic of a proposed coiled tubing drill for polar studies is shown in Fig. 16.

Drilling fluid is pumped downhole through composite tubing using a high-pressure pump located on the surface. An injector provides control for the drill string, maintaining the correct weight on the bit. Fluid passing through the tubing under pressure drives a downhole hydraulic mud motor, which in turn drives the drill head. Standard drill bits, core barrels, or other tools can be attached to the drill head. The chips and fluid return to the surface outside the coiled tubing, using the space between the tubing and the borehole wall as the conduit. The upper part of the hole is sealed by fiberglass casing to prevent drilling fluid from leaking into the surrounding firn, which is permeable. In either case, the chips are separated from the drilling fluid at the surface before the fluid is pumped back down the hole. Coiled tubing drilling system will however require major developments to adapt these systems for exploring subglacial environments. The minimum operating temperature for commercial composite tubing is currently -40 °C. At colder temperatures, the tubing liner becomes too brittle. The long-term performance of other subsurface components (e.g. mud motors, circulation subassemblies, orienting tools) at very low temperatures and repeated drilling cycles should be evaluated, and component modifications likely are required. The coiled tubing itself is subject to fatigue every time it is cycled through any bending. Between 100 and 200 trips is the usual lifetime of a coil, depending upon the axial and pressure loading.

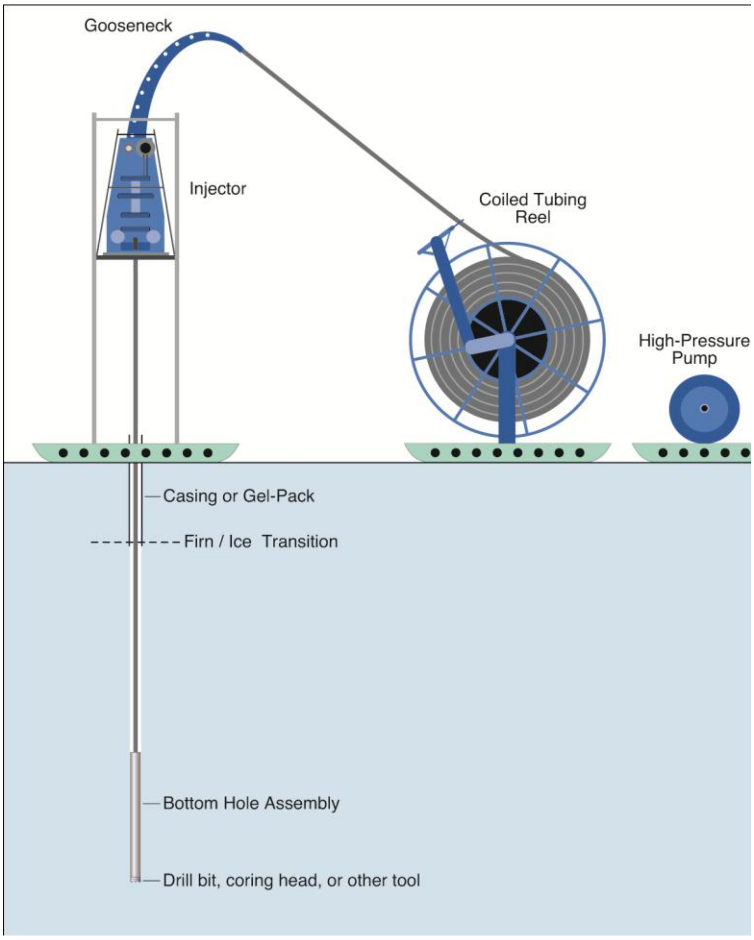

Fig. 16. Primary components of the coiled tubing drilling system (*Clow and Koci*, 2002)

Possibly the most critical area for coiled tubing drilling system development is finding a way to efficiently separate the chips from the drilling fluid once chips reach the surface. This process may ultimately limit how fast the system can penetrate ice. The separation process must be fast enough that the drilling fluid can be pumped back down the hole at the rate required to drive the mud motor and to transport the chips back to the surface. Chip separation for commercial coiled tubing drills is accomplished through the use of a shaker table and high-speed centrifuge. These systems need serious modification to work properly in a cold polar environment.

6. ELECTROMECHANICAL CABLE-SUSPENDED DRILLING

6.1. TYPES OF ELECTROMECHANICAL CABLE-SUSPENDED DRILLS

The main feature of the electromechanical cable-suspended drills is that an armored cable with a winch is used instead of a pipe-string to provide power to the down-hole motor system and to retrieve the down-hole unit. The use of armored cable allows a significant reduction in power and material consumption, a decrease in the time of round-trip operations, and a simplification in the cleaning of the hole from the cuttings (Talalay, 2003, 2005).

Generally, electromechanical cable-suspended drills use the following working procedure. The rotor of the down-hole electric motor produces a rotation that is transmitted through the reducer to the core barrel with the drill head. Usually a drill head with three cutters cuts into the ice and produces ice chips. These are removed to the special chamber by (i) auger conveyer or (ii) near-bottom fluid circulation.

The upper part of the electromechanical drill includes the antitorque system to prevent spinning of the non-rotated section; a hammer to ease core breaking and to retrieve a sticking drill; a pressure instrumentation chamber, containing the sensors and controls; a slip ring unit to prevent cable twisting if the antitorque system fails; and a cable termination to connect the drill with the cable.

The first concept of the electromechanical drill with auger conveyer (so-called shallow drill) was designed in University of Iceland, Reykjavik and used in the summer of 1972 to drill a 415-m deep hole on Vatnajökull glacier, Iceland (*Árnason et al*., 1974). Since that time dozens of electromechanical drills with auger conveyers have been designed, but the first hole on Vatnajökull glacier is still recognized as the deepest hole drilled by auger electromechanical drill. The details of the various internal components give each auger electromechanical drill its own unique operating capacities and weaknesses but all of them were designed especially for drilling of ice.

There were several successful penetrations by auger electromechanical drills through debris- or ash-containing ice (*Suzuki*, 1984; *Mikhalenko*, 2010 and others) but never through bedrock. *Clausen et al*., 1988 reported that UCPH shallow drill was stuck in the debris-containing ice at the depth of 324 m near the bedrock of Renland Ice Cap in East Greenland in 1988. It was caused by very tough ice, and the drill was not able to break the core. In order to free the drill, 20 liters of 30 % water-glycol solution was pumped downward the hole through a 50-m long plastic tube. The next day the drill was freed and used to recover another 90 cm core.

Theoretically, it would be possible to modify the construction of the auger electromechanical drill (drill head, motor, antitorque section, cable, winch) in order to piercing into subglacial sedimentary rocks. This was confirmed by the tests of the Koci drill designed for drilling in rock glaciers (*Green et al*., 2007).

Cable-suspended electromechanical drills with fluid circulation are presently used most for deep ice coring. Fluid is introduced into an open borehole for two purposes. First, circulating fluid in the borehole provides the mechanism for sweeping chips away from the drill head and into the chips chamber, where they are sequestered to be removed later. Second, the presence of a density-balanced fluid in the hole prevents it from closing in on itself through creep. The depth of penetration of the system would be limited only by the length of the cable used. There were four drilling projects recorded with penetration into subglacial rocks (Table 3). A few other boreholes reached the bed of glaciers, and core samples of debris-containing ice were retrieved.

Table 3

List of bore-holes pieced into subglacial bedrock by electromechanical cable-suspended drills

Years	Location	Interval, m		Organization	Drill type
		Till	Bedrock		
1966	Camp Century Greenland	1387.5-1391		U.S. Cold Region Research and Engineering Laboratory	CRREL
1988	Vavilov Glacier, Severnaya Zemlya	457.07-459.33	459.33-461.61	Leningrad Mining Institute, Russia	KEMS-112
1993	Summit – GISP2, Greenland	3040.34-3051.5	3053.44-3055	University of Alaska-Fairbanks, USA	PICO-5,2″
1994	Taylor Dome, Antarctica	~554.9-555.0		University of Alaska-Fairbanks, USA	PICO-5,2″

Challenging tests with an electromechanical drill and near-bottom circulation of an ethanol-water solution were carried out in the laboratory of Byrd Polar Research Center, The Ohio State University, Columbus, USA (*Zagorodnov et al*., 2005). The sampler had two parts: (1) a submersible version of the motor section borrowed from the electromechanical drill and (2) a core barrel from an ethanol thermal electric drill, but, instead of a heating ring, it was fitted with a coring head with cutters (Fig. 17).

To reduce torsional force on the ice core, a swivel was mounted at the lower end of the piston. During the drilling process the ice core pushed the piston up and the ethanol-water solution, which was injected at the lower end of the core barrel, swept the cuttings from the kerf. Drilling of a frozen layer of ice containing crushed limestone particles was conducted with sampler equipped with carbide-tipped cutters. To minimize cutter wear, the rake and relief angles were chosen to be 20° and 5°, respectively. A layer of compacted, crushed limestone particles was filled with water and frozen on top of an ice block, then another layer of pure ice was frozen on top of the limestone layer (Fig. 18). With the given cutter geometry, the maximum penetration rate in pure ice was 1.6 mm/s, while the layer with the limestone particles was penetrated at 2 mm/s and 0.26 kW of power.

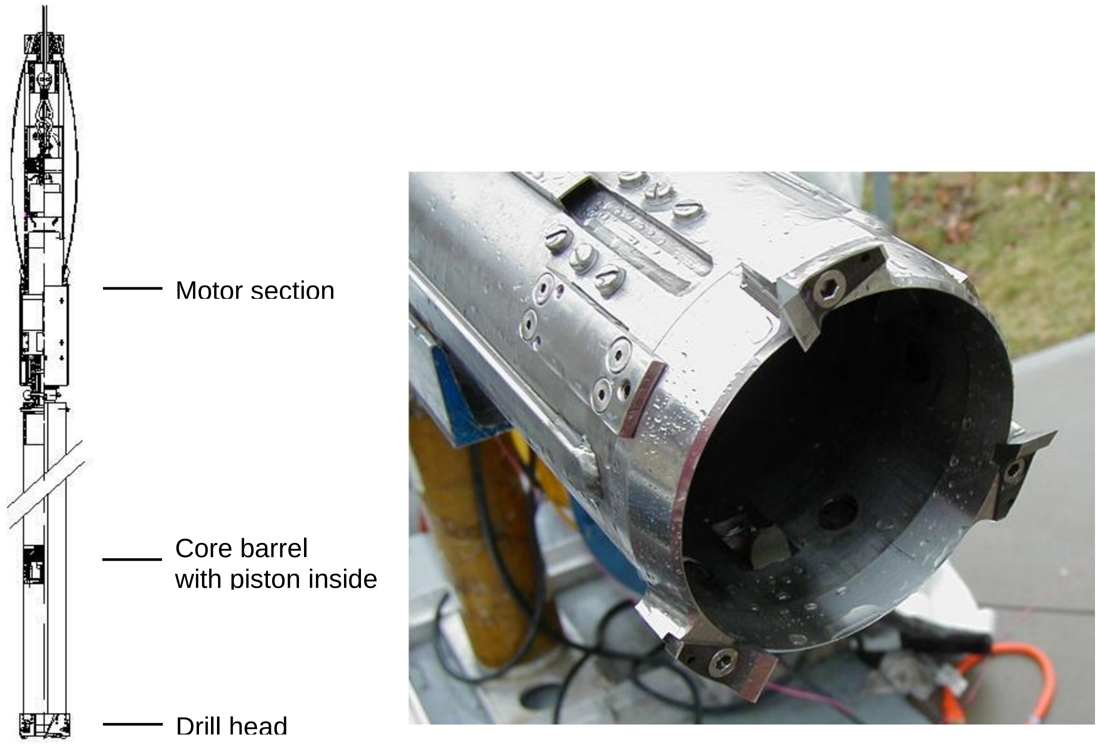

Fig. 17. On the left – schematic of submersible electromechanical sampler; on the right – lower part of the sampler (*Zagorodnov*, 2004)

Fig. 18. Core with limestone particles; details in text (*Zagorodnov*, 2004)

6.2. CRREL ELECTROMECHANICAL DRILL

In 1947, in Oklahoma (USA) an “Electrodrill” suspended on armored cable was used for the first time to be tested on the sedimentary rocks. The depth of the drilling was not more than 400 m. Because of the low power input and small drilling pressure, the speed of penetration did not exceed 2-4 m/h. Repeated accidents with rock fall and down-hole equipment sticking eventually forced the suspension of activities.

In 1964 *A. Arutunoff*, the inventor of the Electrodrill, agreed to sell U.S. Army Cold Regions Research and Engineering Laboratory, USA CRREL, a reconditioned unit (*Hansen*, 1994). This unit was then modified for glacial research, and the method of dissolving the chips in ethylene glycol was used (Fig. 19). This active fluid dissolves ice up to the equilibrium concentration of the aqueous solution. At the bottom, ice chips were picked up by circulation. The glycol dissolves ice chips and dilutes itself up to equilibrium concentration. After the run, when surfaced, a bailer that full of diluted solution was removed and refilled with concentrated glycol.

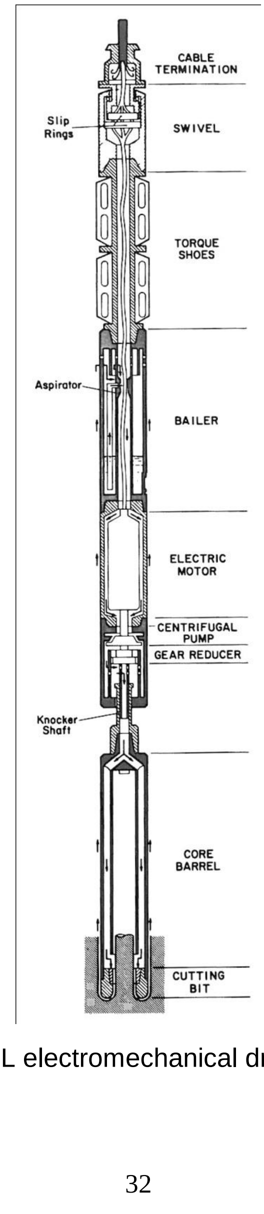

Fig. 19. CRREL electromechanical drill (*Ueda*, 2007)

Camp Century, Greenland. In 1966 the hole at Camp Century, Greenland (77°11′ N 61°08′ W, 1885 m a.s.l.) was advanced by the CRREL electromechanical drill from 535 m, where thermal drilling had been terminated, to the bottom of ice sheet, 1387.5 m from the surface (*Ueda and Garfield*, 1968). The coring continued to 1391 m, until a worn bearing in the gear prevented further penetration. Subglacial material consisted of a conglomerate of frozen till and various sized rocks. In this material, drilling rates decreased to 1.5-2.2 m/h and cutter load increased to 8 kN with power input rising to 16 kW. The diamond bit with eight sintered tungsten carbide teeth was used (Fig. 20). Diamonds were distributed around the outer face of each tungsten carbide tooth with ~0.22-0.28 carats/stone and 8 carats/insert. ID/OD bit dimensions were 114.3/155.6 mm.

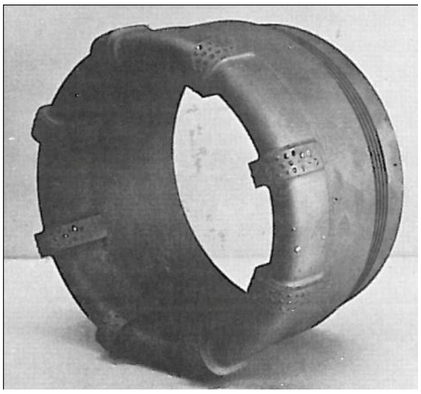

Fig. 20. CRREL diamond bit (*Ueda and Garfield*, 1968)

The subglacial material was a mixture of cobbles, fragments, and dirty ice, and consists of ~50-60 % crystalline ice (*Fountain et al.*, 1981). Based on thin-section petrography, the majority of the sampled rock types could tentatively be ascribed to a single metamorphic complex consisting of gneisses, granites, and metabasalts (Fig. 21). *Herron and Langway* (1979) reported that gas content in the basal ice layer at Camp Century was less than that found in the overlying ice.

Byrd Station, West Antarctica. In 1967 and 1968 the USA CRREL electromechanical drill was used for coring at Byrd Station (80°01′S, 119°32′W, 1530 m a.s.l., mean annual temperature –28 °C), West Antarctica (Fig. 22). On 28th of January, 1968 at a vertical depth of 2158.6 m, the first indication of subglacial debris was recorded (*Ueda and Garfield*, 1969; *Ueda*, 2007). The steel bit replaced with a diamond bit, and the hole was advanced to 2162.2 m. Ice core containing considerable amount of rock and soil was obtained. On the following run at a depth of 2164.4 m a sudden decrease in power and a corresponding increase in cable tension indicated an abrupt change in material had been encountered by the cutting bit. This was later concluded to be a layer of water estimated to be less than 0.3 m thick. After a few minutes the power increased and drilling was continued to the depth of 2165.6 m. A total of 2.3 m of core containing more rocks and soil debris was frozen into the upper part of the core barrel. No subglacial sample was recovered.

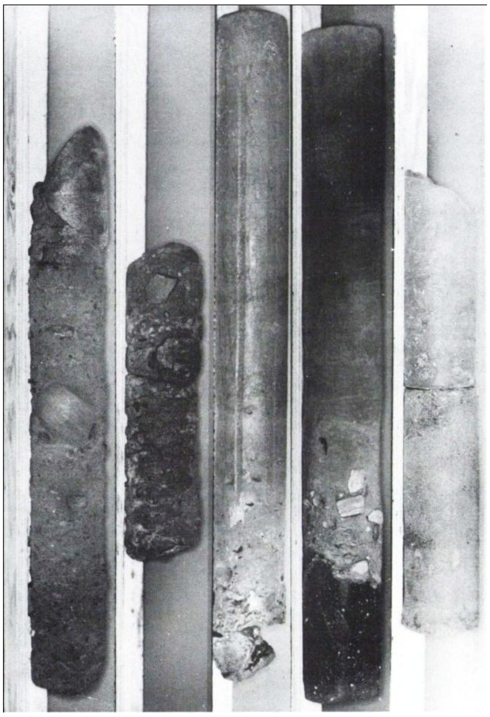

Fig. 21. 3.5 m of sub-ice core and about 25 cm of the "dirty" ice recovered at Camp Century, 1966 (Photo: *D. Atwood*, from *Fountain et al.*, 1981)

By the next run, which was several hours later due to equipment repairs, it was noticed that the fluid level in the hole risen from 192 to 95 m from the surface. Later several unsuccessful attempts were made to recover subglacial samples but in each subsequent run drilling was started from the almost same depth in between 2164.4 and 2164.7 m. The length of each unproductive recovery runs was ~1 m, and the power level was erratic with some high spikes during drilling. The considerable wear of diamond bits indicated the drilling of abrasive materials. An attempt to use a steel bit with cutting surfaces built up with tungsten carbide welding rod was also unsuccessful. After ~1 m of drilling, the carbide surfacing was completely worn off. Various drill surfaces were shown signs of rusting, a phenomenon never noted previously.

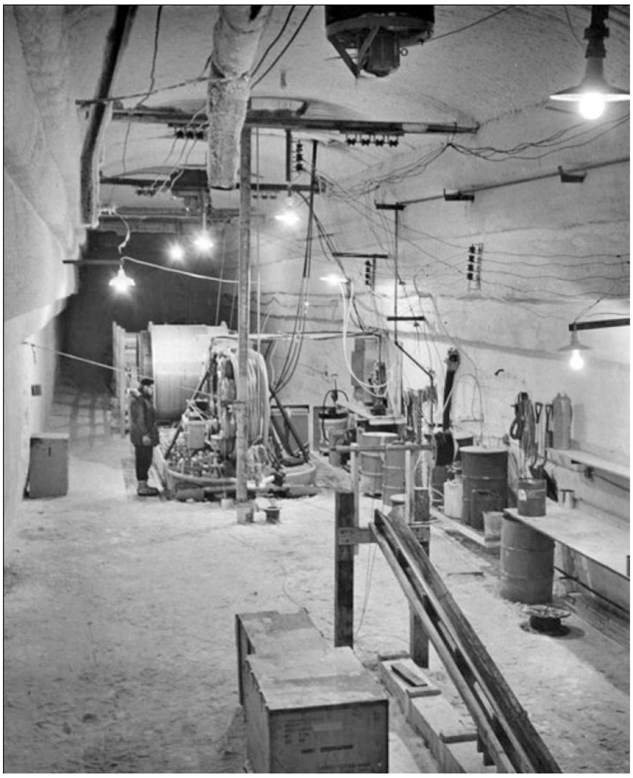

Fig. 22. Winch set-up in main tunnel at Byrd station, 1966 (*Ueda*, 2007)

The only visible evidence of the nature of the subglacial material was thin films of clay on the drill surfaces and clay particles filtered from the melted ice found in the drill sections. It was concluded that the bottom material felt like an unconsolidated material and/or that the glacier was moving very fast. We consider that the first reason for unproductive runs is most likely. In fact, the Byrd station is situated near the source of the Bindschadler Ice Stream (former Ice Stream D) with extensive subglacial water system, and the subglacial material there could be unfrozen, water-saturated till, the same as beneath Whillans Ice Stream (*Tulaczyk et al*., 1998).

During the time spent attempting to obtain a subglacial sample, the water which was welded the hole mixed with the glycol solution in the lower part of the hole. Freezing out of the water created a heavy slush in the bottom 460-meter of the hole. Within a few days, the slush became difficult to penetrate the drill, and on 2nd of February 1968 further attempts to obtain a subglacial sample were terminated because of the possible loss of the drill.

The bottom 4.83 m of the Byrd Station core contained about 14 % by weight rock debris ranging from silt-sized particles to cobbles (*Gow et al.*, 1979). The nature and disposition of the debris, together with measurements of the physical properties of the inclosing ice, indicate that this zone of dirt-laden ice originated by "freezing-on" at the base of the ice sheet (Fig. 23). The transition from air-rich glacial ice to ice practically devoid of air coincided precisely with the first appearance of debris in the ice at 4.83 m above the bed.

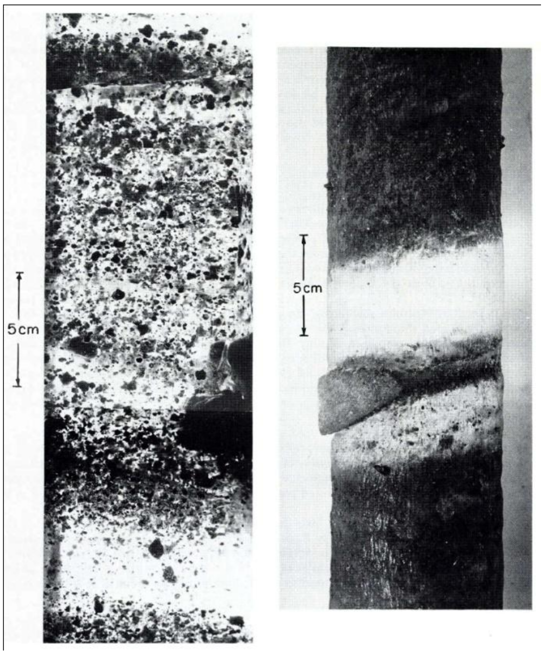

Fig. 23. Core from basal debris zone, Byrd Station, Antarctica: on the left – close-up of particle (mainly mud clot) distribution patterns; on the right – ice-dirt band structure and granite fragment (*Gow et al*., 1979)

In the 1969–1970 field season, the CRREL drill was lost after re-entering the borehole in attempting to recover a subglacial core, when the water unexpectedly gushed up into the borehole and froze in the core barrel. Several attempts to recover the core barrel with special tools were unsuccessful. The cable was severed at 1545 m (*Langway*, 2008).

6.3. ISTUK electromechanical drill

ISTUK electromechanical drill (“IS” means *ice* in Danish, “TUK” means *drill* in Greenlander) was designed in the University of Copenhagen. It was powered by a rechargeable battery pack, and controlled by a microprocessor in the drill (*Gundestrup et al*., 1984). The length and the weight of the drill are 11.5 m and 180 kg, respectively. The drill is clamped to a 6-meter tower and tilted to a horizontal position for easy core removal and drill cleaning (Fig. 24). Even though the ISTUK drill was designed to drill in ice only, it was used to core in debris-containing ice as well. Drilling by ISTUK drill in the true bedrock was not possible, because of the weakly driven motor, pump, drill head, etc.

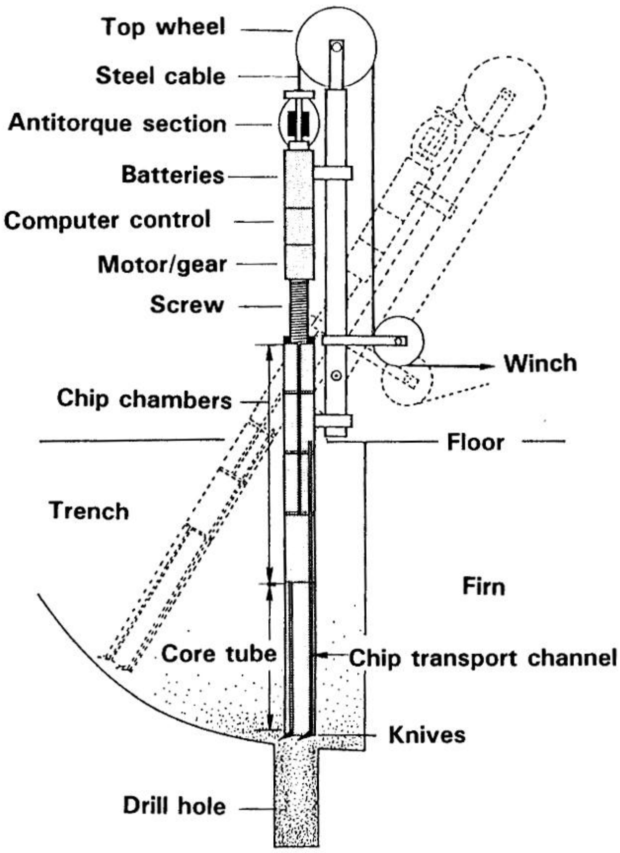

Fig. 24. Danish ice core electromechanical drill ISTUK
(*Johnsen et al*., 1994)

Dye-3, Greenland. In 1979-1981 the ISTUK electromechanical drill was used to core to bedrock near Dye-3 in South Greenland (65°11′ N 43°49′ W, 2490 m a.s.l.). A mixture of fuel Jet A-1 with 10 % of perchloroethylene was used as a drilling fluid. The first indication of the subglacial material at Dye-3 hole was found at the depth of 1949.45 m. Debris-containing ice started at 2012.83 m with an increasing concentration of pebbles downward. At the final depth of 2037.63 m the drill was stuck. The drill was left with tension in the cable and excess pressure in the hole during winter. By the summer of 1982, the drill had become loose, and after being raised to the surface, the last core was removed from it. The bottom 25 m of debris-containing ice had a very high deformation rate, and flow enhancement factor increased to three times the norm (*Dahl-Jensen and Gundestrup*, 1987). The temperature at the bottom was near -12 °C. Debris particles embedded in the basal ice are mainly silt and fine sand-sized with an occasional lithic particle up to 2 cm diameter. The dispersed silty and sandy particles are evenly distributed in the debris-containing ice and diffuse banding is frequent. The dirt content had a mean value of 0.03 % by weight, and it is variable in the range of 0.02-1.2 % by weight (*Souchez et al*., 1998).

Summit – GRIP, Greenland. A new improved version of the ISTUK electromechanical drill was used at the Greenland Ice Core Project (GRIP) at the Summit of the Greenland Ice Sheet (72°34′ N 37°37′ W, 3230 m a.s.l.). The drilling fluid was a mixture of Exxsol™ D60 and Freon 113. After three summer seasons (1990-1992) the final depth of 3028.8 m was reached on 12th of July, 1992, after penetrating 6.3 m of debris-containing ice (*Johnsen et al*., 1994). Drilling was stopped, because the cutting knives were destroyed by hitting gravel and stones close to the bottom. The last core sections were yellow with bedrock material (Fig. 25).

Fig. 25. The leader of the GRIP drilling, Prof. *S. Johnsen*, with final piece of the debris-containing ice, 1992 (*Dansgaard and Gundestrup*, 1993)

The upper 1 m of the debris-containing ice contains interbedded debris-containing and clear ice layers (*Weis et al*., 1997). The lower 5 m exhibit only diffuse banding with dispersed particles of silt, and sand evenly distributed along the boundaries of small ice crystals (0.09-0.4 cm^2). Minor pebbles up to about 1 cm in length are also present. The sediment content is 0.01-0.2 % by weight. The particles are a mixture of quartz, sericite, biotite and plagioclase with minor chlorite. Carbonate minerals, probably of eolian origin, occur in the glacier ice and in clear ice layers interbedded with silty layers, but are notably absent in the lower part of the debris-containing ice sequence. This difference, and the differences in $\delta^{18}O$ and gas composition, indicate a different provenance for the glacier ice and the debris-containing ice.

6.4. PICO–5.2″ ELECTROMECHANICAL DRILL

PICO-5.2″ electromechanical drill was designed and built in the Polar Ice Coring Office, University of Alaska – Fairbanks (*Kelley et al*., 1994). Typical drill head dimensions are 177.5 mm outer diameter and 137 mm inner diameter (*Stanford*, 1992). Total length of the drill was 27.5 m including a 6-meter core barrel. Weight of the PICO-5.2″ electromechanical drill was ~730 kg. The head was driven at a typical rotation speed of 100 rpm. A progressive cavity type pump was used to move the drill fluid in a flow cycle from the drill head, upward between double core barrel, through the pump, into and through the screens and back down to the head. The pumping rate was ~3 liters per min.

Summit – GISP-2, Greenland. In 1989-1993 PICO-5.2″ electromechanical drill was used to acquire continuous ice core through the Greenland Ice Sheet at Summit in support of the GISP-2 project, Greenland Ice Sheet Program. For the first time, *n*-butyl acetate was used as the drilling fluid. On 1st of July 1993, after five seasons of drilling, the drill penetrated several meters of debris-containing ice to reach the bedrock. At GISP2 borehole a sharp transition from clear glacial to brown debris-containing ice occurs at 3040.34 m depth, ~13.1 m above the ice/rock interface (*Gow and Meese*, 1996). The sharpness between the glacial ice and debris-containing ice is similar to that at Byrd Station (Fig. 26). In the debris-containing ice the hardened steel cutters lasted only half as long as usual. Carbide-tipped cutters were an improvement, but only a few were available.

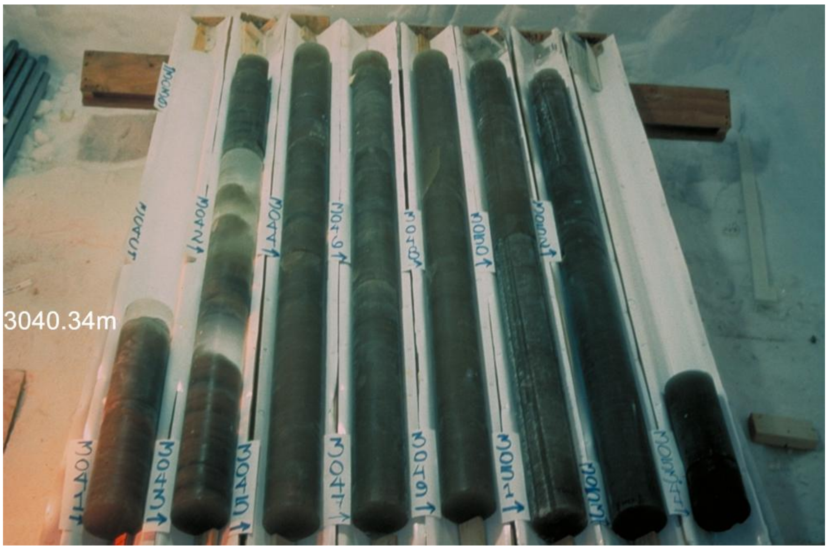

Fig. 26. Ice core from bottom part of GISP2 borehole (core diameter 132 mm): contact between glacial ice and debris-containing ice contact at 3040.34 m depth, located 13.1 m above bedrock
(Photo: *J. S. Putscher*, University of New Hampshire, http://www.ncdc.noaa.gov/paleo/slides/slideset/15/15_282_slide.html)

The top 3 m or so of layers of debris-containing ice were intermixed with clear-ice layers ranging in thickness from a few millimeters to more than 10 cm. Only a few thin ice layers were observed in the deeper parts of the basal ice at GISP2. Entrained debris consisted predominantly of fine-grained amber-to-brown colored sediment, mainly silt, with some sand and occasional lithic particles up to 2 cm in diameter. Numerous rounded particles, ranging in size from 1 to 10 mm, were found to disintegrate on melting. The sediment content was much higher in the GISP2 than in the GRIP debris-containing ice.

The ice/bedrock interface at GISP2 was encountered at 3053.44 m. After several attempts to continue drilling with the ice-coring drill had proved fruitless it was decided to activate a specially designed rock-coring drill. The lower part of PICO-5.2″ electromechanical drill was modified to accept a rock-drilling bit in order to penetrate the rock substrate under the ice (Fig. 27). The well screen sections were removed along with the large diameter core barrel and replaced with a weighted drive section and small diameter, diamond-tipped core barrel. A 1.55-m length of rock core with 33.4-mm in diameter was recovered using a standard rock-coring diamond bit before drilling was terminated. The ice was frozen to the bedrock, and the basal temperature was –9.8 °C.

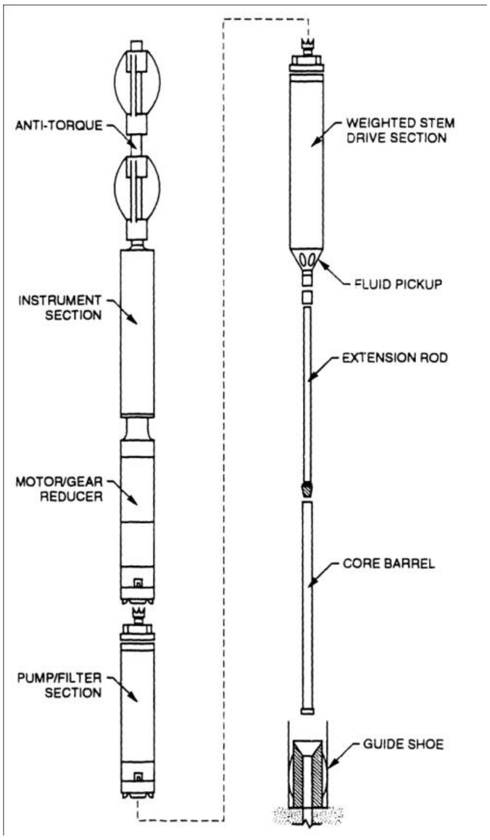

Fig. 27. Schematic of rock-coring drill adapted for use on the PICO-5.2″ electromechanical drill (*Kelley at al*., 1994)

Examination of the bedrock core showed that the top 48 cm consisted of surficial debris overlying the true bedrock (Fig. 28). It was identified schistose rock in the top 20 cm followed by fresh biotite granite to 35 cm. Between 35 and 39 cm a vertical contact separated granite from a "dioritic-looking" rock. This in turn was underlain by 10 cm of unconsolidated (now frozen) soil, consisting of silt and coarse clasts (1-2 cm) of both granitic and mafic rock. The true bedrock consisted of gray, medium-grained biotite granite.

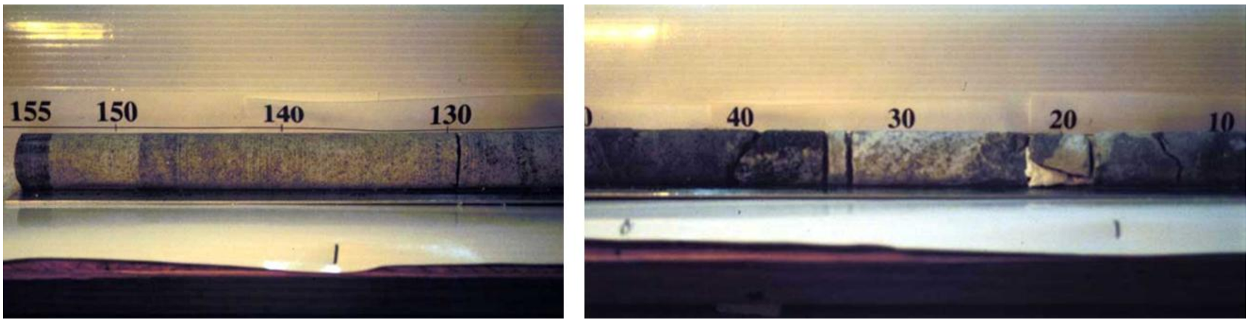

Fig. 28. Bedrock core from GISP2 borehole (core diameter 33.4 mm):
on the right – surficial debris at the upper part of the bedrock core;
on the left – gray, medium-grained biotite granite at the lower part of the core

Taylor Dome. The drilling site (77°47′47″ S 158°43′26″ E, 2365 m a.s.l., mean annual temperature -43 °C) was situated in the central part of Taylor Dome, a local ice dome just inland of the McMurdo Dry Valleys. In January 1994 the borehole reached bedrock at a depth of 554 m using the PICO-5.2″ drill in an n-butyl-acetate-filled hole (*Steig et al*., 2000). Actual drilling took 17 days, working around the clock. A short (10 cm) bedrock core was obtained, containing sandstone and dolerite fragments typical of outcropping rock formations in the Dry Valleys. Borehole temperature measurements show that the basal temperature is -22 °C. The transition between ice and bedrock occurs over a few tens of centimeters; there is no zone of debris-containing ice as was observed at Byrd Station in Antarctica and Camp Century and Summit in Greenland. The ice at the Taylor Dome drilling site is clearly frozen to the bed and the ice stratigraphy is largely undisturbed, even close to the bed.

6.5. KEMS electromechanical drill

KEMS drill was designed in the Leningrad Mining Institute in the early 80s (KEMS is the Russian abbreviation for “core electromechanical drill”). It is interchangeably referred to as KEMS-112, KEMS-132 or KEMS-135 depending on the outer diameter of the utilized drill head (*Ueda and Talalay*, 2007). The main difference of the KEMS drill from other electromechanical drills is that it was equipped by two electric motors: one is three phase AC motor (2.2 kW) for rotation of the core barrel and drill bit, and another is DC motor (220 W) for driving of the rotary type pump (Fig. 29). The independent smoothly regulated eclectic drive of the pump provides continuous circulation of the hole liquid not only during drilling but also during other technological operations (borehole cleaning, for example).

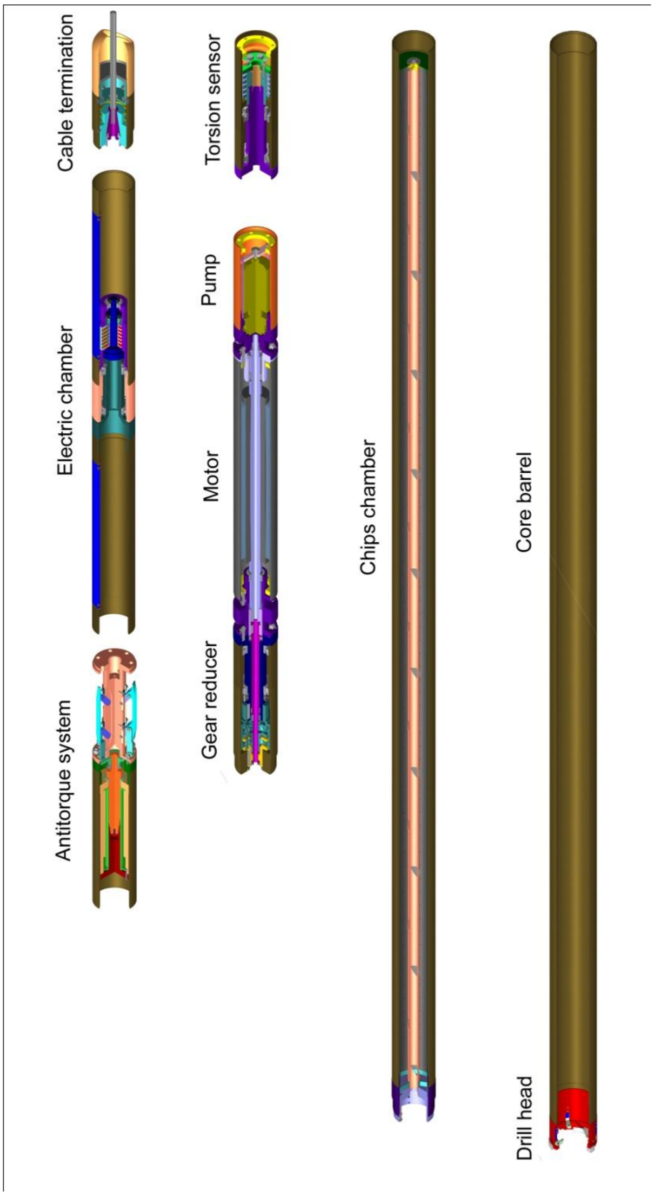

Fig. 29. KEMS Electromechanical ice core drill (*Vasiliev and Talalay*, 2011)

Vavilov Glacier, Severnaya Zemlya. In 1988 a hole with a total depth of 461.6 m was drilled in the northern part of Vavilov Glacier (October Revolution Island, Severnaya Zemlya) using electromechanical drill KEMS-112 (*Kudryashov* et al., 1994; *Vasi-*

liev and Talalay, 2010). Drilling of the glacier ice, till and subglacial rocks was carried out by the same construction of electromechanical drill. The only difference concerned the type of the drilling bit: instead of a toothed coring bit, a conventional carbide faced drill head type SA-1 with ID/OD of 93/112 mm was used. The drill head SA-1 has 16 carbide inserts normally. In order to improve the near-bottom circulation system and to decrease required cutter load, half of the carbide inserts (one after another) were cut off. The rate of penetration in subglacial rocks was 1.6 m/h, and length of run decreased to 0.37 m in average. The cutter load increased to 1.2 kN. The driving electric motor consumed about 1.5 kW.

The boundary between Vavilov glacier and bedrock was placed at the depth of 459.33 m by the content of ice in the core and texture of ice and mineral inclusions (*Bolshiyanov* et al., 1990). The thickness of till was estimated to be 2.15 m, where the content of the ice was more than 70 %, and mineral material was in suspended condition (Fig. 30). The length of the bedrock core was 2.28 m. it was characterized by less than 50 % ice content and by typical structures and textures of permafrost.

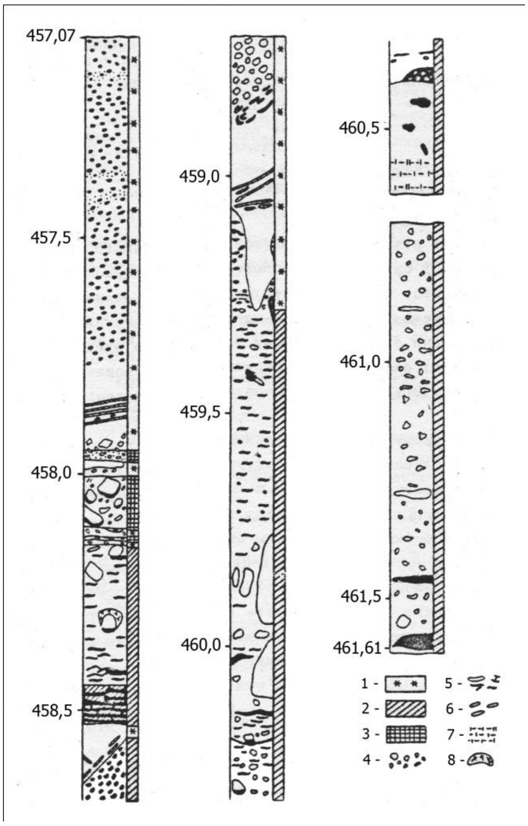

Fig. 30. Graphic description of the bedrock core from a depth of 457.17-461.61 m, Vavilov Glacier, Severnaya Zemlya archipelago, 1988: 1 – ice; 2 – argillaceous/aleurolitic rock; 3 – sandy rock; 4 – coarse fragmentary material with size more than 10 mm; 5 – ice lenses; 6 – ice layers with fine fragmentary material; 7 – reticulated cryogenic permafrost structure; 8 – fine plant detritus (*Bolshiyanov et al*., 1990)

Mineral materials included red-brown siltstones, sandstones and mudstones (Fig. 31). Petrographic studies showed that ice sliding occurs above the ice – bedrock boundary at the depth of 457.85-457.90 m. Shear deformations at the boundary of ice and bedrock are absent. The hole temperature increased uniformly from –11°C at 40 m to –6°C at the hole bottom.

Fig. 31. Subglacial core samples from Vavilov glacier, Severnaya Zemlya archipelago, 1988 (*Vasiliev and Talalay*, 2010)

Akademiya Nauk Glacier, Severnaya Zemlya. In 2001 the second penetration into the till by electromechanical drill KEMS-135 was carried out on Akademiya Nauk Glacier, the largest glacier on the Severnaya Zemlya archipelago (*Fritzsche et al*., 2002). In accordance with an international Russian–German project, a field base (80.52° N and 94.8° E) on Akademiya Nauk Glacier was established during the spring campaign of 1999. In two years the drill reached the moraine at 723.91 m depth, and ~2 meters of debris-containing ice were recovered (Fig. 32).

Fig. 32. Bottom part of ice core from Akademiya Nauk Glacier, Severnaya Zemlya archipelago, 2001 (Photo: *D. Fritzsche*, www.awi.de)

6.6. HANS TAUSEN ELECTROMECHANICAL DRILL

The Hans Tausen electromechanical drill was designed for the European Project for Ice Coring in Antarctica (EPICA) and North Greenland Icecore Project (NorthGRIP). The electronic parts including motor and gear section were imported either from the UCPH shallow drill or the ISTUK drill, and the antitorque section from the ISTUK drill (*Johnsen et al*., 2007).

A drill prototype was built in 1995 and tested in the hole with the final depth of 344 m on Hans Tausen Ice Cap, Peary Land, Greenland. The drill prototype was equipped with a *Suzuki* booster and a simple coupling of the core barrel. The experimental drilling at Hans Tausen cap showed that *Suzuki* booster did not ensure the effective cleaning of the bottom. Later two types of the booster were tested on a special stand, and neither of them can create discharge pressure (*Takahashi et al*., 2002). Therefore the pump for fluid circulation instead of *Suzuki* booster piston pump was installed just above inner auger core barrel (Fig. 33).

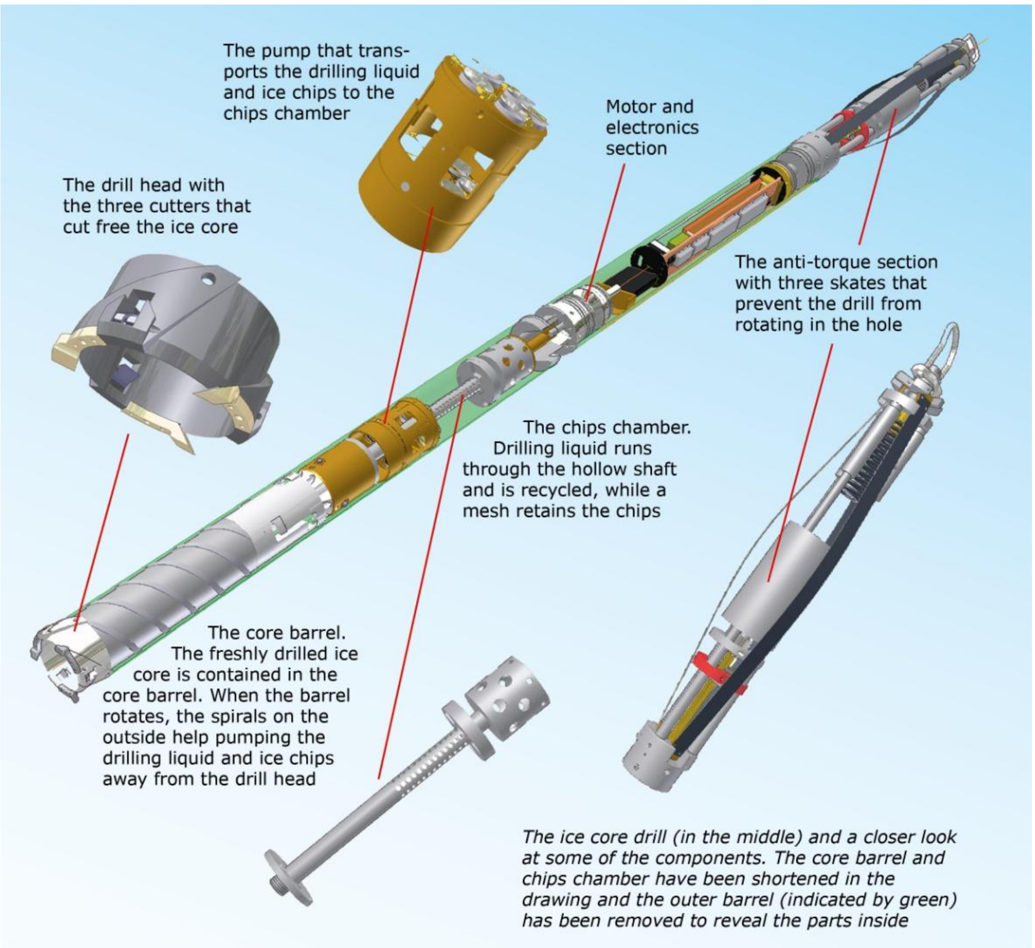

Fig. 33. Major components of Hans Tausen drill (*Johnsen et al*., 2007)

Since 1995 over 12 km of good-quality ice core have been drilled by the different versions of this drill: NorthGRIP, Greenland (3090 m, 1998-2004); Dome C, Antarctica (3270 m, 2000-2005); Berkner Island, Antarctica (998 m, 2002-2005); Kohnen, Antarctica (2774 m, 2001-2006); Talos Dome, Antarctica (1620 m, 2003-2008); NEEM, Greenland (2537 m, 2007-2010). Twice the drill was stuck, once at NorthGRIP (1371 m, 1997), once at Dome C (720 m, 1999). There was no way to recover drills from the hole.

The Hans Tausen drill was unable to core the bedrock, nevertheless the drill twice had tried to penetrate into subglacial rocks.

NorthGRIP, Greenland. In 1996 the NorthGRIP drilling site was built in the central part of Greenland (75.1° N, 42.32° W, 2917 m a.s.l.). On 17th of July, 2003 NGRIP-2 hole reached the depth of 3085 m, where the melt-water flushed the hole, immersed the drill and shorted the electric connections in the antitorque section. The drill was pulled up slightly. When the drill came out from the hole 12 m of the cable and the antitorque section were covered with frozen water and a black spot was noticed where the short had occurred. A 30 cm of light brown frozen water hanged from the drill (Fig. 34). The brown ice has the diameter comparable to the drill, but channels have been formed on the surface of the ice following the angles of the drill head. The inner core barrel was solidly frozen to the outer barrel, and the chip chamber was 60 % full of frozen water. The ice core drilled just before hitting subglacial water was ordinary clear ice. During the next three days the liquid level rose from 132 to 87 m and then stabilized. The end result was that ~45 meters of subglacial water leaked into the hole.

Fig. 34. Refrozen subglacial water hanging underneath Hans Tausen drill, NorthGRIP, 2003 (*NGRIP ice core drilling project*, www.gfy.ku.dk)

The next year, 2004, the frozen subglacial water was re-drilled. Drilling of refrozen pink core was started from 3037.1 m (48 meters above the “old” bottom). Because of the non-centering of the core barrel and the hole axis, the moon of “white” ice has gradually increased as the drill moves further away from the hole from last year. At a depth of 3051.9 m the refrozen water was completely gone from the core. At a depth of 3084.2 m red material was observed in the crystal boundaries.

At a depth of 3090.5 m, 5.5 m below the water channel drilled into the year before, the drill could not penetrate deeper. When surfaced, it was found that the cutters were damaged (Fig. 35). Red mud was noticed at the bottom of the last core and red material was observed in the slush. All attempts with hardened cutters and conical scraper produced big amounts of reddish slush with 1-2 cm mud and ice lumps in (Fig. 36). It was impossible to recover core of subglacial rock. No water has entered the hole.

Fig. 35. Damaged cutters while hitting bedrock, NorthGRIP, 2004
(*NGRIP ice core drilling project*, www.gfy.ku.dk)

Fig. 36. Conical scrapper with icy-muddy slush from the bedrock of NorthGRIP hole, 2004
(*NGRIP ice core drilling project*, www.gfy.ku.dk)

Berkner Island, Antarctica. Lying to the south of the Weddell Sea, embedded between the Ronne and Filchner Ice Shelves, Berkner Island is the largest Antarctic ice rise. The drilling project was financed by the British Antarctic Survey and Natural Environment Research Council of the UK, and the Institut Polaire Français–Paul Emile Victor and Institut National des Sciences de l'Univers of France (*Mulvaney et al*., 2007). The site was situated on the southern dome of the Berkner ice rise (79°32.9′S 45°40.7′W, 890 m a.s.l., 10m temperature –26.5 °C). The drilling operation was started during the 2002-2003 season and took three austral summer seasons. The shorter version of the Hans Tausen drill was used; the drilling fluid was Exssol D60 and HCFC-141b.

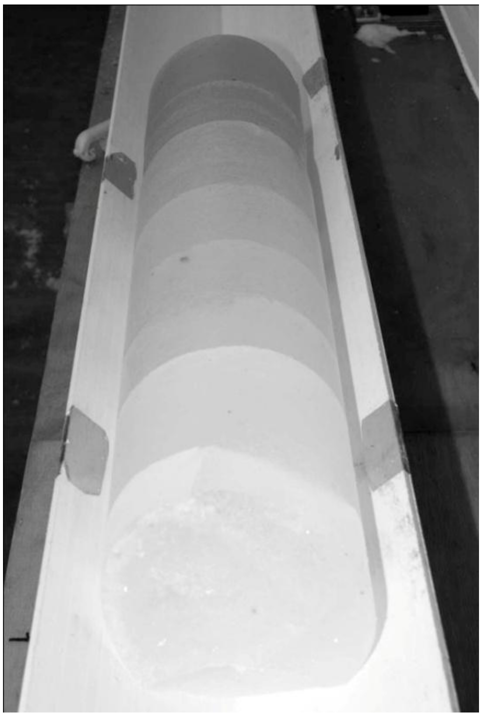

Fig. 37. The final 0.5m of ice core recovered at Berkner Island, Antarctica; the deepest ice is furthest from the camera (*Mulvaney et al*., 2007)

On 14th January 2005 the bed of the ice cap was reached at the depth of 948 m. The final few metres to the bed showed little in the way of visible sediment. However, the final 0.5m of ice recovered showed a rapid change from clear ice to debris-containing ice (Fig. 37). The banding was due to horizontal cracks in the core from the drilling which were not apparent on earlier cores. The transition from ice to sediment was abrupt: once the final ice core had been recovered, all subsequent runs of the drill captured no further ice, but instead large quantities of fine sand were covering the barrel and fluid pump. Several further attempts were made to penetrate the bed, but with no success beyond approximately 5 cm and at a cost of several severely worn and abraded cutters. The drilling was consequently terminated.

In season 2005-2006, the drill site was reoccupied and the winch system set up over the capped borehole. Using a modified Polar Ice Coring Office (PICO) manual drill barrel equipped with tungsten carbide tipped cutters mounted on a standard electromechanical drill motor and antitorque system, penetration a further 50cm into the sediment was obtained. Unfortunately, the drill was unable to capture a sediment core, but did succeed in recovering several kg of the basal material on the barrel spirals, which appeared to be composed of fine unconsolidated quartz sand.

NEEM, Greenland. The North Greenland Eemian Ice Drilling (NEEM) project aimed to drill again through the ice sheet in North-West Greenland (camp position 77.45°N 51.06°W). Drilling started in June 2009, and on 26th of July, 2010 drilling reached bedrock at 2537.36 m. The last 2 m of ice above the bedrock contains rocks and other material (Fig. 38, 39). After a few more runs, no penetration was made, and when the cutters were damaged, the drilling was terminated (*Wang et al*., 2011).

Fig. 38. Prof. D. Dahl-Jensen officially declared termination of the NEEM deep drilling project, 2010 (*Photo: Tim Burton, NEEM ice core drilling project*, www.neem.ku.dk)

In the next season in 2011, several ideas to get subglacial samples were tested in NEEM hole (*Steffen Bo Hansen*, personal communication). The season was started with the special extension with rock polycrystalline diamond (PCD) drill head in combination with the small down-hole rotary pump, the standard motor and gear section with

75 rpm, and the 70-kg dead-weights. This provides a maximum load on the cutter head of ~120 kg in the drilling fluid. A test drilling at the surface into the granite showed the drill was able to penetrate at a rate of ~0.3 m/h. In the drill head used, the triangle PCD cutters are set in the drill crown as cutting elements, and the gauge (i.e. outside of the head) is enhanced by large natural diamond grits. ~80 cm of coarse grained ice of unknown origin was drilled first.

Fig. 39. The last NEEM core contained several cm sized mineral inclusion like granite, 2010 (*Photo: Kenji Kawamura, NEEM ice core drilling project*, www.neem.ku.dk)

The following runs were then made with the new carbide step cutters installed onto the standard drill head on the Hans Tausen drill (Fig. 40). 74 cm of heavily silt loaded ice cores were then retrieved in three runs (Fig. 41). The current was low and the pitch was constant even when cutting through the small stones. A broken carbide insert and ground adapters for the inserts were a sign that a hard rock piece was encountered.

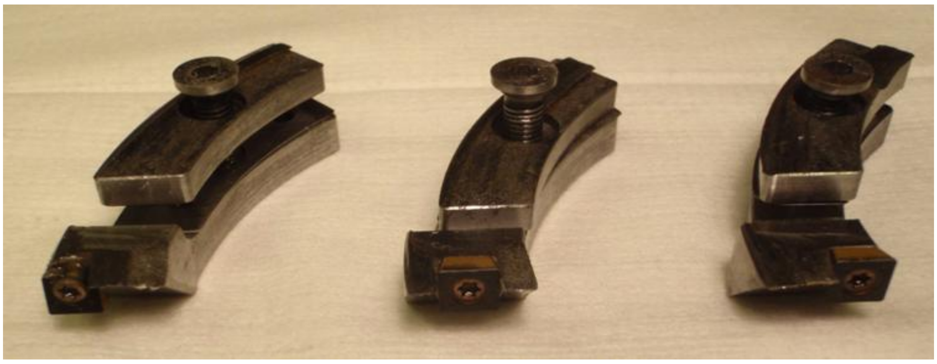

Fig. 40. Step cutters with carbide inserts (Photo: *S. Hansen*)

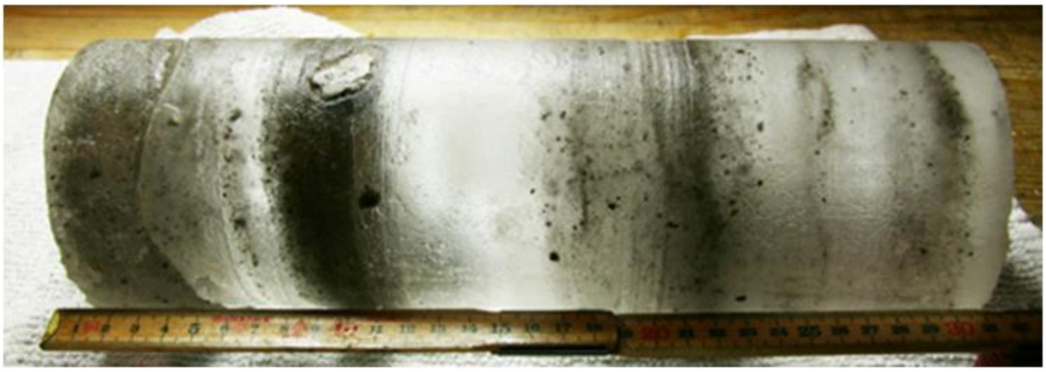

Fig. 41. The bottom section of the NEEM ice core contained mud and gravel (*NEEM ice core drilling project*, www.neem.ku.dk)

Then the extension with PCD drill head was installed again. After a few runs, two additional 70-kg dead-weights were added on top of the motor section, resulting in a maximum load on the drill head of ~240 kg. The fluid flow direction had been chosen to suck the drilling fluid into the core barrels with the intention to collect the rock cuttings and bring them to the surface. However, it turned out that the clearances in the rock drill extension, especially the annulus between outer and inner barrel were too small for the reverse flow direction leading to rapid clogging with ice chips and silt. The drilling was accompanied by very high current, and when surfaced, it was found that the drill was full of refrozen basal water with frost flower of basal water hanging under the rock drill (Fig. 42). The video camera was lowered into the hole, and a layer of almost one meter of basal water was found at the bottom of the hole.

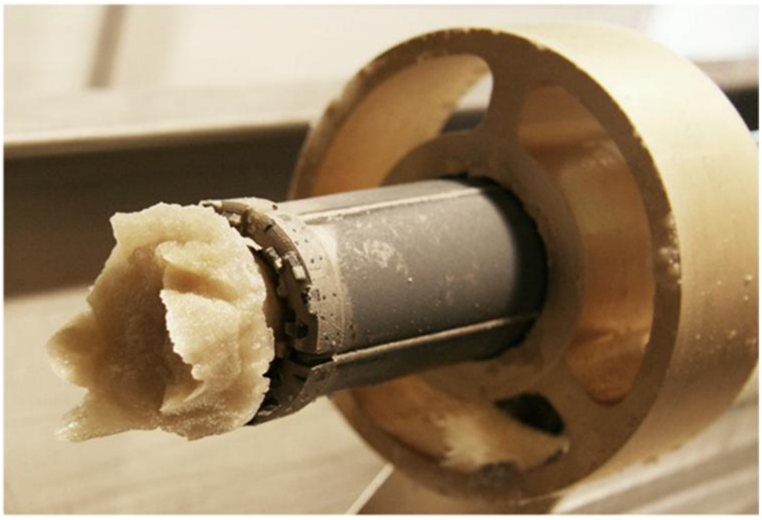

Fig. 42. Refrozen basal water hanging under the 1 inch rock drill head, NEEM, 2011 (*NEEM ice core drilling project*, www.neem.ku.dk)

The fluid flow direction was changed to forward flow mode leading to stable and low drilling current. In the following two runs 50 cm of core consisting of layered ice and sediments was retrieved. The runs each lasted over an hour and were finally stopped when the motor temperature exceeded 60 °C. The core diameter varied between 2 and 3 cm (3.3 cm nominal) pointing to a wobbling head and possibly drilling by partial melting of the ice.

The next run with carbide cutters on the Hans Tausen drill terminated again with broken inserts and damaged insert adapters. Drilling was continued with the PCD drill head, and a total of 63 cm debris-containing ice was retrieved before the NEEM deep drilling project was terminated. Despite measures taken for penetrating into bedrock, the Hans Tausen drill cannot be considered for coring of the true subglacial rocks.

6.7. PLANNED DRILLING AT GAMBURTSEV SUBGLACIAL MOUNTAINS

The Gamburtsev Mountains constitute a subglacial mountain range located near the center of East Antarctica. Buried beneath several kilometers of ice, the mountains are characterized by peak elevations reaching ~3000 m above sea level (*Bo et al*., 2009; *Hansen et al*., 2010). The Gamburtsev Subglacial Mountains are of great interest since they may have served as a nucleation point for the first large-scale ice sheets that formed in Antarctica as the Earth's climate cooled ~34 Ma ago. Yet, with only limited constraints available on the topography, geology, and lithospheric structure, the origin of the Gamburtsev Subglacial Mountains within the framework of Antarctic tectonics has been a matter of considerable speculation. With no rock samples available, geochronologic constraints on the age of the Gamburtsev Subglacial Mountains have not been acquired.

US Committee on Future Science Opportunities in Antarctica and the Southern Ocean concluded (Committee on Future Science Opportunities in Antarctica and the Southern Ocean, 2011): "… much of East Antarctica remains absolutely unknown yet is critical to the understanding of the continent and the ice sheets. Regions to be sampled include the enigmatic Gamburtsev Mountains, subglacial lakes, and other major subglacial provinces." The initiation to drill through the ice and collect the first Gamburtsev rock samples was declared by Lamont–Doherty Earth Observatory, Columbia University but without working out in detail drilling technology and time-line[2].

In order to penetrate through the 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 in the region of Gamburtsev Subglacial Mountains the development activity already has been started in China (*Talalay et al*., 2011). According to plan, drilling operations will be carried out during one or two summer seasons starting in 2014/2015. In order to shorten the time for building and installing the drilling equipment a movable drilling shelter will be constructed (Fig. 43). All necessary equipment (two diesel generators, winch, control desk, fluid dumping station, etc.) is installed inside the shelter and is ready to start drilling immediately upon arrival to the chosen site.

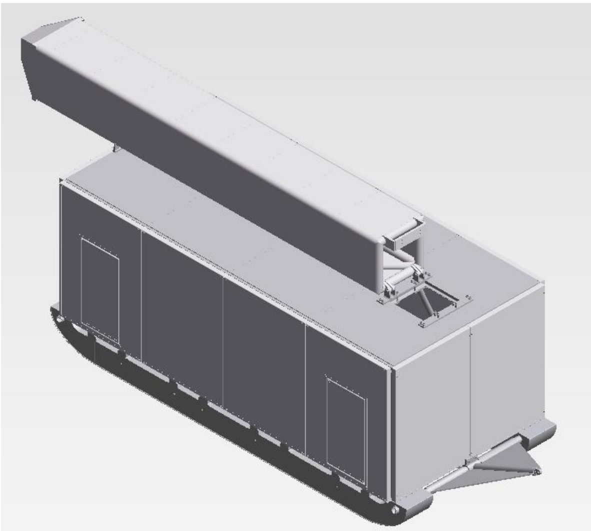

Fig. 43. Movable warm-keeping and wind-protecting drilling shelter for planned drilling at Gamburtsev Subglacial Mountains (3D-modeling by *M. Sysoev*)

The ice layer will be penetrated with a new, modified version of the cable-suspended electromechanical ice core drill. The expected average daily production of ice drilling would be not less than 25 m/day. The lower part of the drill will be adapted for coring bedrock to the depth of at least 2 m. The conception of the drill will be checked by digital simulation, laboratory and field tests.

[2] The Lamont–Doherty Earth Observatory next goal is to drill through the ice and collect the first Gamburtsev rock samples. “Amazingly, we have samples of the moon but none of the Gamburtsevs,” said Robin Bell, Research Professor. “With these rock samples we will be able to constrain when this ancient piece of crust was rejuvenated and grew to a magnificent mountain range.” [http://www.ldeo.columbia.edu/news-events/researchers-unravel-origins-antarcticas-ice-covered-mountains]

CONCLUSIONS

The most simple and effective systems for sampling in subglacial soft sediments or unfrozen till from pre-drilled access holes are the gravity corer and the piston corer. The maximal thickness of ice is determined by the length of wire rope attached to the corer and could possibly be more than 4000 m. Potentially, piston sampling can reach a maximal depth of 25 m in soft subglacial lake sediments. In stiffer sediments a hammer corer or vibrocorer should be used.

The experience of pipe-string rotary drilling in subglacial environment showed that drilling operations were very unstable, and the recovery of subglacial sediment was generally poor. Commercial drilling rigs for drilling up to the depth of 3000 m or more tend to be very heavy and require a large logistical load to move and support. They also require more equipment for the circulation system. This consists of a large pump, with its needed power, pits, and solids separation systems. In addition, rotary drilling rigs tend to be less efficient under conditions requiring many trips of in and out of the bore-hole, as in continuous coring operations. In fact, the tripping issue is one most operators try to avoid as it is labor and time intensive and can be a safety hazard as equipment is moved around.

So today the most effective method to penetrate frozen till and bedrock is cable-suspended electromechanical drilling with near-bottom fluid circulation. This was confirmed by four successful penetrations into the bedrock carried out by U.S. and Russian specialists. Auger conveyer cable-suspended drilling technology has never been used for subglacial drilling. Modification of the recent shallow drills for subglacial drilling seems to be difficult to accomplish, but nevertheless remain a feasible option.

All deep ice coring, however, requires a drilling fluid in the borehole during operation in order to keep the hole open and to compensate the hydrostatic pressures acting to close it. The review of drilling fluid properties indicates that there are no ideal drilling fluids (*Talalay and Gundestrup*, 2002). Members of *International Partnerships in Ice Core Sciences*, 2004 declared: "The identification of a non-toxic, non-flammable, density appropriate, hydrophobic, inexpensive, environmentally friendly and readily available fluid(s) with predictable performance characteristics has become somewhat of a Holy Grail in the ice-drilling community." *Talalay* (2007) proposed to use silicone oils as a borehole fluid, but the final conclusion about their applicability for deep drilling could be made only after field experiments in test borehole.

The main problems of subglacial drilling by cable-suspended electromechanical drills connect with weakness of (i) driven motor; (ii) near-bottom fluid flow; (iii) antitorque system. To intensify bedrock drilling process and to minimize cutter load, rotary-percussion mechanism could be used. A further challenge for subglacial investigations is the adaptation of existing, and the development of new, sampling and drilling systems.

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