

Drilling to the beds of the Greenland and Antarctic ice sheets: a review

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ABSTRACT. We give a review of drilling to the beds of the Greenland and Antarctic ice sheets, with a history of just a century. We use a chronological rather than a geographical ordering to emphasize the way drilling has developed. The review is divided into two parts: core drilling and hole-only drilling for access to the beds or the deep interior of the ice sheets. This is an overview, not a comprehensive report on each project. While we have endeavoured to include all projects that fit our selection criteria, we have not provided all the technical details.

INTRODUCTION

In this paper we give an historical review of drilling to, or nearly to, the beds of the two polar ice sheets, with a history of just half a century. The focus on drilling that reached the beds arose from a paper contributed to a workshop on Subglacial Antarctic Lake Environments in Grenoble, France, in April 2006. We expanded our coverage to Greenland, because the drilling histories in Antarctica and Greenland are intimately intertwined. We set our boundary in the Arctic at the edge of the inland ice of Greenland, thus excluding drillings through all other glaciers and ice caps, including those around the periphery of Greenland.

We use a chronological rather than a geographical ordering because that is the way drilling has developed, and we want to emphasize this development. The review is divided into two parts. The first describes core drilling comprising 18 projects, 5 in Greenland and 13 in Antarctica. The second describes hole-only drilling for access to the beds or the deep interior of the ice sheet, comprising 12 projects, all but one of which, including the only one in Greenland, involved multiple holes. Except for the Cape Folger project, core-drilling projects are set out in order of completion (or near-completion), not starting dates, whereas hole-only projects are in order of starting dates, as many are ongoing and involve a sequence of holes.

This is an overview, not a comprehensive report on each project. While we do hope we have included all projects that fit our selection criteria, we do not claim to have provided all the technical details for each. Many additional details can be found using the References.

HISTORY OF CORE DRILLING TO OR NEAR THE BED

Prologue

This history begins with two drilling projects that did not reach to the beds, one at Site 2, Greenland, and one at Byrd Station, Antarctica. Both employed a Failing rotary well-drilling rig using cold compressed air as the drilling fluid; the ice chips were blown out of the hole by the air stream. This pioneering work in deep ice coring was performed by the US

Army Snow, Ice and Permafrost Research Establishment (USA-SIPRE). In Greenland, two holes were cored, the first reaching a depth of 296 m on 27 August 1956, and the second reaching a depth of 407 m in late boreal summer of 1957.

Meanwhile, in 1956, a duplicate of the Failing rig was shipped to Antarctica, arriving in December at Little America V, from where it was shipped to Byrd Station in October 1957. Coring by SIPRE personnel commenced at Byrd Station on 16 December 1957, and terminated at a depth of 309 m on 26 January 1958. In February, the drill was returned to Little America (Patenaude and others, 1959; Lange, 1973).

Little America, Antarctica, 1958–59

The first drilling into the bed of an ice sheet was at Little America, near the front of the Ross Ice Shelf, Antarctica (Fig. 1), during the International Geophysical Year. Coring at Little America with the Failing rig was dry to 249 m, then the hole was filled with diesel fuel for pressure balance; thereafter circulating fluid removed the chips. Drilling stopped on 5 December 1958 at 255 m, 2 or 3 m above the base of the ice, when sea water entered the hole and rose to 188 m. Core recovery was 98%. The base of the ice was estimated at a depth of 257–258 m from seismic and



Fig. 1. Map of Antarctic deep core drilling sites.

[†]Deceased 13 November 2006.

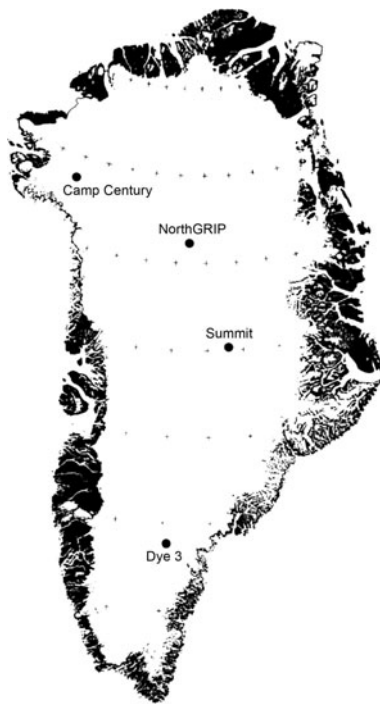


Fig. 2. Map of Greenland deep core drilling sites.

temperature measurements. The drilling was again done by SIPRE (Ragle and others, 1960; Gow, 1963; Lange, 1973).

Camp Century, Greenland, 1961–66

Drilling at Camp Century in northwest Greenland (Fig. 2) started in 1961. The drilling rig was installed on the floor of one of the covered-over, undersnow trenches in which the station was built. Using a thermal coring drill designed and built by the US Army Corps of Engineers Cold Regions Research and Engineering Laboratory (SIPRE had become CRREL in February 1961), holes of 186, 238 and 264 m depth were cored in 1961, 1962 and 1963, respectively. The third hole was extended to 535 m in 1964 after adding fluid. The drilling fluid was 'Diesel Fuel Arctic' (DFA) with trichloroethylene (TCE) as the densifier. In 1965 the hole was deepened to 1002 m using a modified commercial electromechanical drill (the 'Electrodrill'). The ice chips were removed by dissolving them in ethylene glycol, which was carried to the bottom of the hole in the drill with each run and brought back with the dissolved ice on each return trip. The bed at 1387.4 m was reached on 4 July 1966. Continuous core was recovered from all drilling. The bottom 17 m contained silt bands and small pebbles, and 3.55 m of frozen till was recovered from the bed. The basal temperature was -13°C (Hansen and Langway, 1966; Ueda and Garfield, 1970).

Byrd Station, Antarctica, 1966–68

After reaching the bed at Camp Century, CRREL moved its drills immediately to Byrd Station in central West Antarctica. As at Camp Century, the rig was set 12 m below the surface in a station tunnel (Fig. 3). (This was the second Byrd Station, known as New Byrd, which was built in the early 1960s along the lines of Camp Century, i.e. in covered-over trenches.) The drill was set up, a pilot hole drilled with the CRREL Thermodrill, the casing set, and coring to 200 m was carried out in 1966/67. After the winter, on 1 November

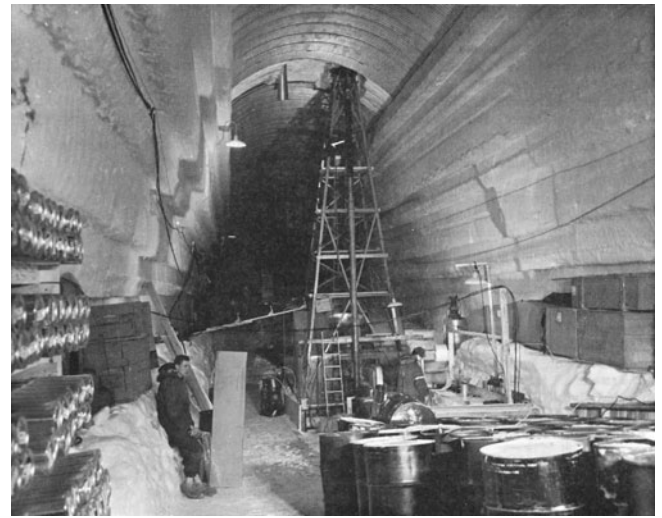


Fig. 3. CRREL electromechanical drill set-up in undersnow trench at Byrd Station, Antarctica.

1967, coring resumed with the Electrodrill. The drilling fluid was again DFA and TCE and ice chips were, as before, dissolved in ethylene glycol for removal. Drilling proceeded in two shifts, 24 hours a day, and reached the wet bed at 2164 m on 29 January 1968. The upper 1250 m were drilled with a diamond bit (eight tungsten carbide inserts serving as matrices for surface-set diamonds); a steel bit worked better below 1250 m, the approximate boundary between randomly oriented and highly vertically oriented *c* axes in the ice. Englacial debris was encountered at 2160 m, leading to a return to a diamond bit. A layer of water approximately 0.1 mm was found at the bed. The bed was penetrated to 1.3 m, but no material was recovered. The drill was frozen in and lost following re-drilling into the bed in 1969 (Ueda and Garfield, 1969, 1970; Gow, 1970; Ueda, 2007).

Cape Folger, Antarctica, 1969–83

In 1969, the Australian National Antarctic Research Expeditions (ANARE) began an intermittent series of ice-core drillings near Cape Folger on Law Dome, East Antarctica, some of which penetrated nearly to the bed. That year, a modified CRREL thermal drill (Bird, 1976) was used to drill to a depth of 320 m at a location (SGA) about 7 km inland, where the surface elevation was about 300 m and the ice thickness about 350 m. In 1974, at a spot 3 km farther upstream (SGP), two further thermal holes (separated by 100 m) were drilled and cores collected. There, the surface elevation was 360 m and the ice thickness, determined by radar sounding, was 385 m. More coring using the same modified CRREL thermal drill was done in the same area near Cape Folger during the 1981/82 austral summer (Morgan and others, 1984): hole BHC1, 301 m deep, was over a bedrock high point where the radar ice thickness was 303 m, and BHC2, 344 m deep, was over a bedrock trough, with an ice thickness of 350 m. These were all open holes, and rapid closure rates, particularly in the warm ice below about 250 m, at times were a threat to trap the drill. All but the SGA hole were filled with fluid after the drilling was completed to keep them open for further measurements. These cores and boreholes have been used primarily for studies of crystal fabrics and ice dynamics (Russell-Head and Budd, 1979); Thwaites and others, 1984).

Novolazarevskaya, Antarctica, 1975/76

In 1975/76, groups of the Soviet Antarctic Expeditions at Novolazarevskaya performed two ice-core drillings, 356 and 412 m, respectively, through the nearby ice shelf, and a third one of 374 m through the local grounded ice. They used an electrothermal drill with alcohol as the drilling fluid, as a Soviet team with the Ross Ice Shelf Project did 3 years later (Morev and others, 1988; Horwath and others, 2006).

Shackleton Ice Shelf, Antarctica, 1978/79

The same Soviet group from the Arctic and Antarctic Research Institute in Leningrad and the Institute of Geography of the Academy of Sciences in Moscow, using the same kind of electrothermal coring drill with ethanol as the drilling fluid, reached the ocean through 202 m of ice on the Shackleton Ice Shelf, not far from Mirnyy station (Morev and others, 1988).

Dye 3, Greenland (GISP), 1979–81

The next deep core drilling, the Greenland Ice Sheet Project (GISP), was at the Dye 3 station in southern Greenland. It began in the summer of 1979, 12 years after the drilling at Byrd Station, following several years of shallow and intermediate drilling at 12 sites across Greenland. This was an international venture, involving groups from Denmark, Switzerland and the United States (Fig. 4). The drilling was done with the new Danish ISTUK electromechanical drill, much lighter than the massive CRREL drill used at Camp Century and Byrd Station, and introduced the tipping drill into deep ice-sheet coring. The tilting action reduced the height of the tower by 5 or 6 m, but then required a slot several meters deep cut down from the ice-sheet surface to accommodate the lower part of the drill. The drilling fluid was kerosene (Jet A1) and perchloroethylene (PCE). Only steel cutters were used, in contrast to the grinding-type bits used by CRREL for the earlier drilling. Drilling reached 225 m in 1979, 901 m in 1980, and the bed at 2037 m in 1981. Silty ice was found at a depth of 2013 m. The drill was stuck in 1981 but recovered in good condition in 1982 (Gundestrup and others, 1984; Gundestrup and Johnsen, 1985; Langway and others, 1985b).

Summit, Greenland (GRIP), 1990–92

Nearly another decade passed as the European GRIP (Greenland Icecore Project) and US GISP2 projects, separate but coordinated efforts 30 km apart, were planned for the Greenland summit. For the first time the site was chosen for scientific rather than logistic reasons. GRIP drilling with an improved ISTUK drill began in June, 1990 and ended in August at a depth of 770 m. This was the first project to use the now-common combination of a low-aromatic solvent (Exxsol D60) with a fluorocarbon densifier (CFC-113), although a fluorocarbon densifier (CFC-11) was used with jet fuel (TS-1) by the Russians at Vostok as early as 1980. The drill was set in a trench 5 m wide and 5 m deep, into the floor of which was cut a 5 m deep slot for the drill to tilt into. Drilling continued to 2321 m in 1991 and reached the bed at 3029 m in July 1992, the first ice drilling to over 3 km. The lowest 6.3 m were silty. There was no attempt to core the bed. The temperature at the bed was -8.5°C (Johnsen and others, 1994, 1995).



Fig. 4. The main players in organizing the GISP project at Dye 3. From the left: Duwayne Anderson, US National Science Foundation/Division of Polar Programs (NSF/DPP); Robert Rutford, NSF/DPP; Willi Dansgaard, University of Copenhagen, Denmark; Chester Langway, State University of New York at Buffalo, USA; Richard Cameron, NSF/DPP; James Zumbege, US National Science Board; Hans Oeschger, University of Bern, Switzerland. From Langway, and others (1985a).

Summit, Greenland (GISP2), 1989–93

The GISP2 project employed the new US Polar Ice Coring Office (PICO) 132 mm (5.2 in) electromechanical drill that took cores up to 6 m long. For the first time, *n*-butyl acetate was used as the drilling fluid. A centrifuge system recovered the drilling fluid from the ice chips because of the high cost of the *n*-butyl acetate. The 31 m drill tower needed to accommodate the 27.5 m drill sonde remained vertical from the surface; full and empty core barrels were exchanged on the drill through a carousel arrangement. On 1 July 1993, after five seasons of drilling, the drill penetrated several meters of silty ice to reach the bed at 3053.4 m depth, 24 m deeper than GRIP, thus allowing the project to take over the claim of the deepest coring ever. In the silty ice the hardened-steel cutters lasted only half as long as usual. Carbide-tipped cutters were an improvement, but only a few were available. A core 1.5 m in length and 50 mm in diameter was taken from the bed using a standard rock-coring diamond bit. The basal temperature was -9°C (Mayewski and others, 1994; Stanford, 1994; Wumkes, 1994).

Law Dome, Antarctica, 1987–93

After a 20 year hiatus, deep core drilling finally returned to Antarctica at Law Dome, a local ice dome on the Budd Coast of Wilkes Land. Fieldwork by ANARE started in 1988 with thermal core drilling to 96 m and casing to 84 m. Electro-mechanical drilling with an ISTUK-type drill reached 553 m in 1991/92 and 1200 m in February 1993. The drilling fluid was kerosene (Jet A1) and PCE. Silty ice was encountered at 1196 m; drilling was terminated by an encounter with a rock fragment at 1200 m. Total ice thickness, as determined by radio-echo sounding, is $\sim 1220 \pm 20$ m; ANARE glaciologists believe that the basal silty layer is probably no more than 20 m thick. The basal temperature was -7°C (Morgan and others, 1994, 1997).

Taylor Dome, Antarctica, 1993/94

At Taylor Dome, a local ice dome just inland of the McMurdo Dry Valleys, a 554 m core into the bed was recovered in 1993/94 using the PICO 132 mm drill in an *n*-butyl-acetate-filled hole. Basal sediment (60 mm) and

rock debris were also recovered. Actual drilling took 17 days, working around the clock. The basal temperature was -26°C (Grootes and others, 1994).

Siple Dome, Antarctica, 1996–99

The 132 mm PICO drill was used again at Siple Dome, starting in 1996. Siple Dome is another local dome, in this case between ice streams bordering the eastern edge of the Ross Ice Shelf. Unfortunately, the drill was not in as good condition as on previous projects, making progress slow. The drilling fluid again was *n*-butyl acetate. Depths attained were 154 m in 1996/97, 351 m in 1997/98, and the bed at 1004 m in 1998/99. The temperature at the bed (where the pressure-melting point is -0.8°C) was -2.54°C . No problems were encountered with drilling in the warm ice, likely because of the large pumping rate used by this drill. No effort was made to drill into the bed (Engelhardt, 2004a,b; personal communication from K. Taylor, 2006). This drill has been retired and replaced in the US program by a new 'Deep Ice Sheet Coring' (DISC) drill (Shturmakov and others, 2007).

NorthGRIP, Greenland, 1996–2003

In Greenland, drilling on the multinational NorthGRIP project also started in 1996, reaching 350 m. The drill was a new one designed and built as a cooperative European effort led by the University of Copenhagen, Denmark (Johnsen and others, 2007). The drilling fluid was Exxsol D60 and HCFC-141b. In 1997, drilling continued to 1371 m, where the drill became stuck. Recovery attempts in 1998 were unsuccessful, so drilling was restarted in 1999, reaching 1750 m. This was extended to 2930 m in 2000, where the drill stuck again. This time it was freed, but there was no further drilling that season. Before drilling could recommence in 2001, 3 weeks were spent recovering the glycol that had been dumped down the hole during the previous season to retrieve the stuck drill. Drilling was then very slow (in warm ice), reaching only 3001 m. The drill was stuck and freed four times during the season, using 2–3 kg of frozen glycol pellets each time. Finally, in July 2003 at 3085 m depth, subglacial water flooded into the hole. In 2004 the lowest 40 m was re-drilled to a several meters greater depth than in 2003, recovering 10 m of refrozen basal water. Pebbles, dirt and microfossils were recovered from the bed (Dahl-Jensen and others, 2002; NorthGRIP members, 2004; Johnsen and others, 2007; personal communication from J. White, 2006).

Dome C, Antarctica, 1996–2005

Drilling started in 1996/97 at the DC1 site in central Wilkes Land, the current Concordia Station site (56 km from the 1977–79 900 m drilling site at the former Dome Charlie station), using the new EPICA (European Project for Ice Coring in Antarctica) drill, essentially the same as the NorthGRIP drill. The drilling fluid was Exxsol D30 and HCFC-141b. Coring continued throughout 1997–99, reaching 781 m, where the drill became stuck. A new hole was begun at DC2, 10 m north from DC1, in 1999/2000. Depths attained in succeeding seasons were 1459 m in 2000/01, 2864 m in 2001/02 and 3200 m in 2002/03. Drilling was very slow in the warm basal ice. At 3120 m (temperature -6.3°C) the drilling production rate dropped abruptly from 35 m d^{-1} to almost zero as refrozen ice began to block the channels above the cutters. The solution was to inject an ethanol/water mixture into the bottom of the hole, at first by

a separate injector device, then carried down in the chip chamber, a technique previously developed and used successfully at NorthGRIP. On 21 December 2004, drilling reached 3270 m, 5 m above the bed. The ice was expected to be melting at the bed, so drilling stopped at this depth to avoid contaminating the basal water. Small reddish-brown inclusions were found in the bottom 10 m of the core (Augustin and Antonelli, 2002; Augustin and others, 2007; Johnsen and others, 2007; personal communication from L. Augustin, 2006).

Berkner Island, Antarctica, 2002–06

Berkner Island is the ice rise that separates the Filchner and Ronne Ice Shelves. After setting casing there in 2002/03, core drilling by the British Antarctic Survey (BAS) and French colleagues began in 2003/04, reaching a depth of 526 m. The drill was a slightly lengthened version of the Danish Hans Tausen drill (transportable in a Twin Otter aircraft); the drilling fluid was Exxsol D60 and HCFC-141b. The next season, drilling continued into the bed at 948 m, attained on 12 January 2005. The last 2 m of core contained some grit particles. Attempts to drill into the bed yielded sand on the drill but no core. In 2005/06 a temperature of -11°C was measured at the bed; additional attempts to core the bed with carbide-tipped steel cutters penetrated 0.5 m into the bed and produced several kilograms of fine sand but again no core (Johnsen and others, 2007; Mulvaney and Alemany, 2007; personal communications from R. Mulvaney, 2006, 2007).

Dronning Maud Land, Antarctica, 2000–06

Kohnen station, in northwestern Dronning Maud Land, was built and the hole casing set in 2000/01. Drilling below the casing, using the NorthGRIP drill, began in 2001/02, reaching 450 m. Drilling fluid was Exxsol D40 and HCFC-141b. Continued drilling reached 1564 m and 2565 m at the end of 2002/03 and 2003/04, respectively. There was no drilling in the 2004/05 season. Drilling continued in 2005/06 to 2774 m, attained on 17 January when water started coming into the hole. Attempts to drill deeper recovered only refrozen meltwater. Upon reducing the level of the drilling fluid, the water rose to 163 m above the base (Johnsen and others, 2007; personal communication from H. Oerter, 2006; personal communication from F. Wilhelms, 2008).

Vostok, Antarctica, 1970–98; 2005–07

Deep coring at Vostok, in central East Antarctica, has a long history. It began in 1970 with completion of 507 m open hole 1G with the TELGA electrothermal drill. Coring continued in 1972, with the hole still open, to 952 m. Attempts at deepening beyond that in 1973, still without fluid, failed because of hole closure. Another dry hole, started by deviation from 1G at 307 m depth, was drilled with TELGA to 905 m in 1974. Drilling efforts continued in succeeding years (1975–79) when a new electrothermal drill (TBZS, a successor to TELGA for drilling in fluid) was tested in a new hole 2G that was finally stopped at a depth of $\sim 500\text{ m}$. Drilling of the first deep fluid-filled hole 3G at Vostok started in 1980 with TELGA and TBZS-152M electrothermal drills; the latter was then changed (at 1501 m) for the high-frequency electrothermal drill TBS-112 HF. The drilling of 3G was complicated by three major drilling accidents and two deviations and finally terminated in 1986, with the

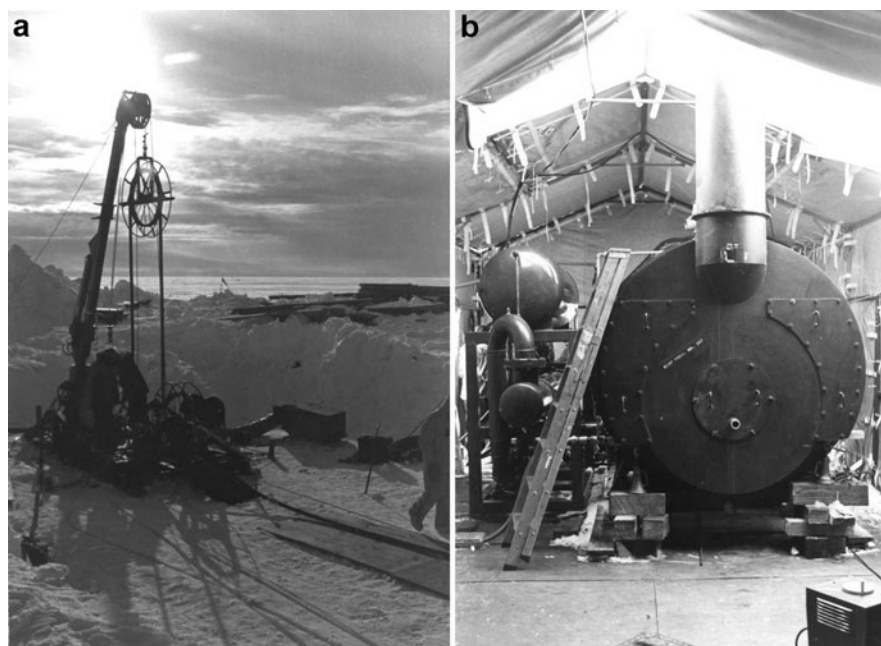


Fig. 5. The 2 MW Browning hot-water drill used at Ross Ice Shelf Project station J9 to penetrate the ice shelf. (a) Scenic view of the drill surface unit in place. (b) The mammoth boiler for the drill; the 2.4 m (8 ft) stepladder gives the scale.

deepest branch-hole reaching a depth of 2002 m. Meanwhile, new hole 4G was started in 1983 with TELGA and finished (after two accidents/deviations) to 2428 m with TBZS-152M. Drilling resumed in June 1989 with the KEMS-112 electromechanical drill. At 2546 m the drill became stuck and was abandoned in November 1990. Also in 1990, hole 5G was started with TELGA and TPZS. In December 1991, when the hole depth reached 2502 m, the drill became stuck and was eventually lost at a depth of 2259 m. In 1992, deviation was made at depths of 2232–2246 m and branch-hole 5G-1 was continued with the same TBZS drill. By 1993 the coring had reached 2755 m. After Vostok was closed for a year, drilling resumed with a KEMS drill in 1995. From 1997 to 2007, drilling was only during (short) summer seasons. A depth of 3623 m, ~ 130 m above Vostok Subglacial Lake, was reached in hole 5G-1 in February 1998. Ice accreted from the lake below was entered at a depth of 3540 m.

After an 8 year hiatus to study whether and how to drill into Vostok Subglacial Lake, drilling resumed in 2005/06, reaching a depth of 3650 m on 22 January 2006. Difficulties with warm ice were encountered for the first time in the 2005/06 season. Drilling resumed in 2006/07 and continued into the austral winter. Progress has been very slow; as of 10 June 2007, the depth was 3661 m. The drill was stuck at the bottom of the hole on 14 January 2007, but recovered on 7 February (Korotkevich and Kudryashov, 1976; Kudryashov and others, 1994, 2002; Vasiliev and Talalay, 2007; personal communication from V. Lipenkov, 2006; J Priscu, unpublished information).

Dome Fuji, Antarctica, 1995–2006

Drilling of the first hole at Dome Fuji, the western high dome of the East Antarctic ice sheet, started in August 1995 and reached 2504 m in December 1996. The drilling fluid was *n*-butyl acetate. The drill was irretrievably stuck at 2332 m by hole closure owing to an insufficient amount of fluid loading in the hole. Drilling started in a new hole in 2003/04, reaching a depth of 362 m, and continued to 1850 m in

2004/05. The depth of 3029 m, several meters above the bed, was reached on 23 January 2006. Drilling was slow below 3000 m because of warm temperatures. Drilling continued in 2006/07 but was extremely slow, reaching only a depth of 3035 m below the surface. Refrozen meltwater and pebbles suggest that the bed is very near (Tanaka and others, 1994; Fujii and others, 2002; Takahashi and others, 2002; Motoyama, 2007).

HISTORY OF CORELESS DRILLING TO OR NEAR THE BED

Ross Ice Shelf, Antarctica, 1976–79

The first hole-only drilling through an ice shelf was part of the Ross Ice Shelf Project (RISP), which also included core drilling. RISP drilling, aiming to penetrate 420 m of ice at station J-9 on the southeastern Ross Ice Shelf, started in 1976/77 with a PICO wireline drill. This was a Longyear rig that drilled a hole 187 mm in diameter to retrieve a 60 mm core. The initial hole was left dry of drilling fluid to keep it clean; as a consequence, a greater than expected closure rate trapped the drill 90 m above the base (420 m) during a drill crew changeover. In 1977/78, attempts to melt out the wireline drill with hot water failed. A second, cobbled-together wireline drill penetrated successfully to 170 m in a hole filled with a mixture of DFA and TCE; at that depth, time ran out at the end of the season. Concurrently, a Browning flame jet, producing 600 kW of thermal power, was used successfully to reach the ocean. Drilling rates for a 500 mm hole were 0.9 m min^{-1} . A hole reached the water on 2 December 1977 after 9 hours drilling time, but it refroze. A second hole was completed on 14 December and kept open for 3 weeks by flame-reaming every 3–4 days. The hole diameter was kept at 300–460 mm (at isolated depths it was up to 750 mm). A Browning 2 MW hot-water drill system (Fig. 5) replaced the flame jet the following year (1978/79) and drilled several holes through the ice shelf that were up to 750 mm in diameter. Drilling time was ~ 15 hours. That

same year a lightweight Russian electrothermal drill, using alcohol as antifreeze, provided continuous core to the ice-shelf bottom and access to the ocean (Clough, 1977, 1978; Rand, 1977; Browning and Somerville, 1978; Clough and Hansen, 1979).

Ekströmsen (Ekström Ice Shelf), Antarctica, 1985–95

In January 1982, Ekströmsen was penetrated at Georg-von-Neumayer station by accident with a coring drill and the drill was lost. In 1985/86, a newly developed hot-water drill, to be used later that season on the central Ronne Ice Shelf, was tested by drilling two holes through 208 m of ice just south of the station. Drilling took 4 days. Three holes were drilled at (newly rebuilt and renamed) Neumayer station by Alfred-Wegener-Institut (AWI) personnel during the 1992/93 season, using a newly modified hot-water drill. The principal modification, to avoid the large hole inclination that occurred with drilling on the Ronne Ice Shelf the previous season, was to add winch electronics that prevented the nozzle from touching the bottom of the hole. The ice was 240 m thick. Holes were at least 350 mm across and no more than a few degrees from vertical. The actual drilling took 12 days. In 2005/06, four holes were drilled north of Neumayer station near the ice front (ice thickness 95–100 m) for installation of oceanographic instruments below the ice (Beck and others, 1987; Nixdorf and others, 1994a; personal communication from H. Oerter, 2006).

Ronne Ice Shelf, Antarctica – Germany, 1985–95

After two unsuccessful attempts, the bottom was reached through the central Ronne Ice Shelf in February 1986. The ice was 465 m thick and the drilling took 12 hours. The drill was an updated version of a type used on Variegated Glacier in Alaska. The speed near the surface was 120 m h^{-1} ; the hole diameter was 70 mm, which was reamed to 100 mm. The ice was increasingly slushy below 430 m and the water level in the hole dropped to sea level. In 1989/90, the shelf was penetrated again five times with a 60 mm nozzle (one was enlarged with a 150 mm nozzle) near the ice front west of Filchner station, where the ice thickness was $239 \pm 2 \text{ m}$. The holes were used for temperature measurements in the ice and water and to measure basal melt rates. One ocean-current meter was deployed, but became stuck in the ice when pulled back for maintenance the same season. In 1991/92 the shelf was penetrated twice through 420 m (at station B15) with the AWI hot-water drill. The holes were strongly inclined: in each drilling it took 580 m of hose to reach the water. The steep slope meant that oceanographic instruments could not be lowered into the ocean. In 1994/95 two holes were bored: HWB2, near B15 (420 m of ice; drilling time 10 hours) and HWB3 (264 m; drilling time 5.5 hours) near the 1989/90 holes. At HWB2 there was a slush layer at the base. Instruments emplaced through the holes soon ceased transmitting data. Holes were reamed with a new 130 mm nozzle that circulated water inside a rounded tip and back up so there was no water jet; this was to eliminate the danger of the reamer going off into a new hole (Engelhardt and Determann, 1987a,b; Miller and Oerter, 1991; Nixdorf and others, 1994b, 1997; personal communication from H. Oerter, 2006).

Crary Ice Rise, Antarctica, 1987/88

Two holes, 370 m and 480 m, were drilled through Crary Ice Rise (near station J9 in the southeastern Ross Ice Shelf) in

1987/88, using a specially designed PICO hot-water drill that melted a 260 mm hole at an average rate of 0.5 m min^{-1} . The drill was instrumented with inclinometers, thermistors and calipers. The bed was naturally frozen at both sites (temperatures -3.7 and -5.7°C , respectively), but was warmed up enough by the hot water to yield some mud and rocks; the drill penetrated $\sim 5 \text{ m}$ of bottom sediments (Bindschadler and others, 1988, 1990; Koci and Bindschadler, 1989).

Jakobshavn Isbræ, Greenland, 1988–89

In 1988 and 1989, a joint group from Eidgenössische Technische Hochschule, Zürich, Switzerland and the University of Alaska Fairbanks, USA, drilled several boreholes at three sites in a line across Jakobshavn Isbræ, $\sim 50 \text{ km}$ upstream from the glacier front. The holes at two flank sites reached the bed at 1540 and 1630 m, respectively, whereas the deepest central hole, at 1560 m, terminated still nearly 1 km above the deep bed of the glacier. The drill developed for this work was relatively lightweight – 1000 kg plus 30 kg $(100 \text{ m})^{-1}$ for the hose – with the heaviest single piece weighing 180 kg. The drill consisted of a 6 m long, 30 mm diameter drill stem with a nozzle diameter of 4.5–5.5 mm, and a 19 mm (inside diameter) hose. The water discharge rate was $60\text{--}80 \text{ L min}^{-1}$; six to eight oil heating units heated the water to $80\text{--}90^\circ\text{C}$. Drilling time to 1550 m was ~ 20 hours. A few cubic centimeters of bed material was retrieved from the bottom of one of the flank holes (Iken and others, 1989, 1993).

Siple and Gould Coasts, Antarctica, 1988–2001

Over a 12 year period (1988–2001) more than 100 holes were melted to the bed at 20 sites across the ice streams and interstream ridges of the Gould and Siple Coasts of West Antarctica, by teams from California Institute of Technology (Caltech), USA, using a hot-water drill of their own design and construction (the ‘Kamb/Engelhardt’ drill). Initially drilling was done with a nozzle flow rate of 40 L min^{-1} at a temperature of 95°C . In subsequent years this was increased to 80 L min^{-1} . The objective was to investigate and understand mechanisms of ice-stream motion, so many measurements were made in the hole and especially at and in the bed. Where the bed was soft it was penetrated several meters and samples recovered. At some locations, video imagery was recorded within the borehole, and ice cores were taken using a hot-water ice corer. Hole depths ranged from 900 to 1200 m and were routinely completed in 16–26 hours of drilling depending upon depth (Engelhardt, 2004a,b; personal communication from R. Bolsey, 2006).

Ronne Ice Shelf, Antarctica – UK, 1990–2003

BAS used a hot-water drill of their design and construction during 1990/91 and 1991/92 to penetrate ice 562 and 541 m thick, respectively, on the Ronne Ice Shelf. The drill had a nozzle flow rate of 80 L min^{-1} . The holes were 200–250 mm in diameter and were drilled in 1–3 days. Repeated reaming kept the holes open for 5 days after drilling. Hole S1 (1990/91) encountered 15 m of slush at the base that was easily drilled but quickly refilled the hole. Repeated drops of a heavy streamlined weight were needed to force passage for the oceanographic instruments through the slush. No slush layer was found at S2 (1991/92). In 1995/96 S3 was drilled

through 825 m of ice. In 1998/99 two sites were drilled (S4 and S5), through ice thicknesses of 941 and 763 m, respectively. In 2002/03 four more holes were drilled (Fox 1–4) in the northern Ronne Ice Shelf. Thicknesses were 300–400 m. There was weak basal melting at three holes and basal freezing at the fourth, near the northern edge of the shelf. At that site the drill entered slush in an apparent bottom crevasse some 70 m above the base of the ice. BAS drillers, according to K. Makinson (personal communication, 2006) ‘found that at sites with a melting base, it is difficult to enlarge the hole near the ice water interface as heat from the nozzle is taken away by the underlying seawater. This narrowing can lead to a slot being cut by the instrument cable (also deflected by the ocean current) and the trapping of the instrument and occasionally its loss. Sites with slush/freezing bases do not suffer this problem’ (see Makinson, 1994; Nicholls and others, 1997, 2001, 2004; personal communication from K. Nicholls and K. Makinson, 2006).

South Pole, AMANDA, 1990–97

Hot-water drilling for the englacial Antarctic Muon and Neutrino Detector Array (AMANDA) at Amundsen–Scott South Pole Station (ice thickness 2800 m) began during the 1990/91 season. In the first season, an 800 kW hot-water system was able to drill a 0.5 m hole to 800 m, so a single string of three photomultiplier tubes could be lowered into the ice to collect preliminary data. In 1992/93 a 1.2 MW drill was used to drill four holes to a depth of 1000 m to make the first array. An instrumented drill assured straightness (the holes had to be plumb within 1 m in 2500 m) and measured hole diameter. A separate cable was used to support the hose and retrieve information from the drill. Drilling time was 70 hours and fuel consumption was 17 000 L per hole. At 1000 m the bubbles in the ice had not formed the clathrates that would make the ice clear. Two years later (1994/95), a 1.8 MW system was used to drill to a depth of 2000 m. Drilling time per hole was ~80 hours and fuel consumption ~30 000 L. A maximum depth of 2500 m was reached in 1995/96 in 100 hours, consuming 38 000 L of fuel. Power was increased to 2.2 MW to accommodate longer deployment times as more detector modules were added to the strings. The final array consisted of 19 holes (author’s information (B. Koci)).

Amery Ice Shelf, Antarctica, 2000–06

In 2000/01 a borehole 300–350 mm in diameter and 373 m deep was drilled through the Amery Ice Shelf at site AM02, the first of a series of holes as part of ANARE’s Amery Ice Shelf Ocean Research (AMISOR) project. Drilling took 24 hours; alternate reaming and sampling then gave a hole nearly 500 mm across and kept it open for a week. No slush was reported – AM02 is believed to be a site of basal melting. One short ocean-bottom mud core was retrieved. In 2001/02 a 479 m deep borehole was melted at site AM01 (where coring to 315 m in 1968 yielded marine ice below 270 m). A hydraulic connection to the ocean was made at a depth of 376 m, still 100 m above the basal boundary. Several ice cores were taken with a Caltech-style hot-water corer. Highly porous ‘honeycomb’ ice was found at 390 m. Attempts to core the ocean floor failed at this site. In 2003/04 a new hole was drilled at the AM01 site and an ocean-bottom core was this time successfully collected. In 2005/06, after increasing

the flow rate of the drill from 45 to 80 L min⁻¹, AM03 and AM04 were drilled, the former through 722 m with no marine ice and an apparently melting base and the latter through 603 m with 203 m of marine ice and a hydraulic connection to the ocean at around 525 m. There was a minor basal ‘necking’ effect at AM03 owing to insufficient heat supply at this large depth, but passage of instruments in and out was not a problem. At AM04 the ice from 550 m to the base at 603 m was very irregular, so instruments were bumping against the walls as they were lowered and raised. Oceanographic instruments deployed below these holes are still yielding data (Craven and others, 2002, 2004, 2005, 2006); personal communication from M. Craven, 2006; personal communication from A. Elcheikh, 2006).

McMurdo Ice Shelf, Antarctica, 2002/03

In January 2003, two holes (70 and 140 m deep) were drilled through the ice as part of the ANDRILL project, to allow ocean bottom cores to be collected. The holes were >0.5 m in diameter (Barrett and others, 2003; personal communication from H. Oerter, 2006).

Rutford Ice Stream, Antarctica, 2004/05

In 2004/05 BAS attempted to drill to the base of Rutford Ice Stream, through 2200 m of ice, with a beefed-up hot-water drill. The hose diameter was increased to 1.25 in (32 mm) (from 0.75 in (19 mm)) and flow rate enhanced to 150 L min⁻¹ (from 80 L min⁻¹). Penetration was successful to 2000 m, but a hose coupling (at the surface) then broke, a back-up system also failed and the entire 2000 m of hose was lost down the hole (personal communication from A. Smith, 2006; personal communication from K. Nicholls, 2006).

South Pole, IceCube, 2004–06

The IceCube drill design was based on the performance numbers obtained in the AMANDA drilling. Three hose reels were replaced by one gigantic winch containing 2700 m of 64 mm inside diameter hose to allow a complete hole to be drilled in a single continuous operation. Overall power was increased to 4.8 MW. To date, nine 650 mm diameter holes have been drilled to a depth of 2500 m and instrumented. Drilling time is ~40 hours (including reaming), permitting drilling of two holes per week. Maximum drilling speed is over 2 m min⁻¹. Fuel consumption for the drilling is ~20 000 L per hole. Hole inclinations are about 0.1–0.2° from vertical. Some 70 more holes will be drilled and instrumented over the next 5 years (author’s information (B. Koci); personal communication from J. Cherwinka, 2006; personal communications from A. Elcheikh, 2006, 2007).

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