Production drilling at WAIS Divide

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ABSTRACT. The deep ice-sheet coring (DISC) drill was used for production ice-core drilling at WAIS Divide in Antarctica for six field seasons between 2007 and 2013. Continuous ice-core samples were obtained between the snow surface and 3405 m depth. During the 2012/13 austral summer, the DISC drill's newly designed replicate ice-coring system was utilized to collect nearly 285 m of additional high-quality core samples at depths of high scientific interest. Annual progress graphs are described, as well as milestones achieved over the course of the project. Drilling operations, challenges encountered, drill fluid usage, drilling results, and the drill crew's experiences with the DISC drill and replicate coring system during production drilling are described and discussed in detail. Core-processing operations are described briefly, as well as the logistical undertaking of the DISC drill's deployment to Antarctica.

KEYWORDS: Antarctic glaciology, ice and climate

INTRODUCTION

The deep ice-sheet coring (DISC) drill (Shturmakov and Sendelbach, 2007), designed by Ice Coring and Drilling Services (ICDS), the predecessor of Ice Drilling Design and Operations (IDDO), was utilized at the West Antarctic Ice Sheet (WAIS) Divide Camp in West Antarctica to enable the study of climate history through ice cores. Supported by the US National Science Foundation (NSF), the drill was designed and built to enable the science of over 40 distinct NSF-funded endeavors by US researchers. From 2005 to 2013, the WAIS Divide Camp served to support drilling operations. The tremendous undertaking of such a large-scale drilling project is described in detail in this paper. The WAIS Divide Camp and associated logistics are discussed and the entire drilling operation, from the project timeline to the drilling structure, experiences with coring and replicate coring and some of the challenges encountered are described. Several factors key to the success of the project, including safety and crew continuity, are also discussed.

WAIS DIVIDE CAMP

WAIS Divide Camp, located just off the ice divide in West Antarctica at 79°28.058′ S, 112°05.189′ W, was identified as the DISC drilling site due to its smooth bed topography and minimal horizontal ice flow. At this site, annual-layer resolution of at least 1 cm thickness is identifiable to ~40 ka. The site's high accumulation rate aids in this layer resolution. Established during the 2005/06 Antarctic field season, the camp was generally operational from early November until the first week of February each year. The camp's primary purpose was to support DISC drilling and borehole-logging operations; however, a number of smaller NSF-funded projects were able to utilize the camp's infrastructure, and the camp served as an equipment depot for several scientific overland traverses. On average, the camp supported approximately 40 people, with the maximum during high-population times being around 65 personnel. A breakdown of personnel consisted of 10 drillers, up to 9 core-processing personnel, 15–20 camp staff and other science groups.

WAIS Divide Camp proper consisted of a 3 km ski-way for Hercules, Basler and Twin Otter aircraft operations, a mechanic's shop, a science office tent, a 'comms' or communications tent, a galley tent with an attached hard-sided kitchen module, a combination bathing, laundry and recreation tent, a medical tent, a berthing tent for aircraft crews and two tents for transient or camp staff berthing. A 'tent city' was established where drilling, core handling and other camp personnel slept in either mountain tents or Arctic Oven tents. Located adjacent to camp proper were a number of cargo lines. The 'arch', the building which housed the drilling and core-handling operations, was located ~0.4 km from the main camp. A generator building housing twin 225 kW Caterpillar generators was also located near the drill arch, supplying power for both drilling and camp operations via power poles and overhead power lines running back to the main camp. Also near the drilling arch was a weather port used for both warm storage and as a personnel break area. A Mobile Expandable Container Configuration (MECC™) container, the DISC drill's on-site machine shop and electronics laboratory, also resided near the arch. An aerial view of WAIS Divide Camp is shown in Figure 1.

Weather at WAIS Divide Camp was quite variable over the course of the eight-season project. Temperatures generally ranged from –25°C to –5°C from late November through the first week of February.

PROJECT TIMELINE

During the initial 2005/06 field season, the DISC drill arch structure was erected by the Raytheon Polar Services Company (RPSC), the Antarctic subcontractor of the NSF. In 2006, the DISC drill was tested at Summit Camp, Greenland, prior to its use in Antarctica (Johnson and others, 2007). During the 2006/07 Antarctic field season, three IDDO personnel and a contract electrician deployed

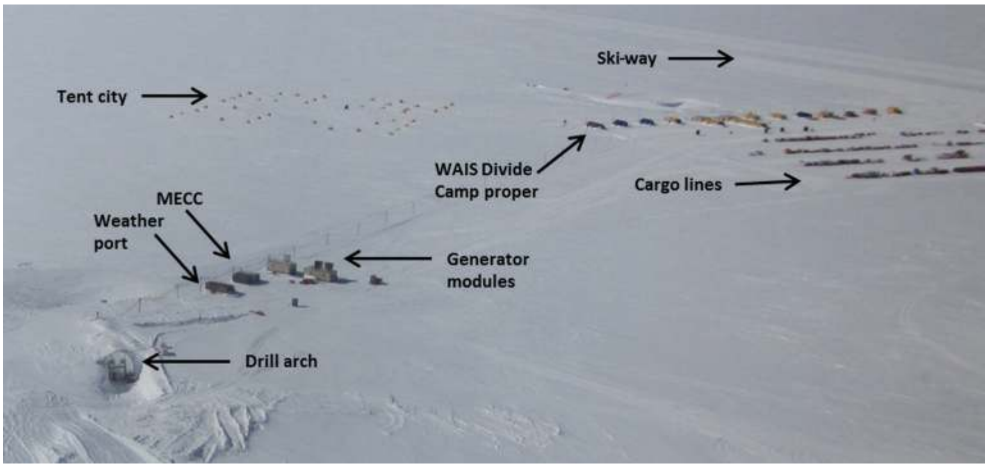

Fig. 1. Aerial view of WAIS Divide Camp, Antarctica.

to WAIS Divide. A 130 m borehole was drilled adjacent to the arch area to ensure that a full core would be recovered from the surface at WAIS Divide, since the area over the future DISC drill borehole had to be excavated for arch and drill installation. Also during this season, IDDO personnel completed the drilling of the DISC drill pilot hole from the arch floor level down to 114 m depth using an IDDO 4-inch drill. The borehole casing was installed and one of the DISC drill's two overhead gantry cranes was erected. This initial work paved the way for the arrival of the entire DISC drill system and a full crew of ten drillers and engineers during 2007/08, the first production coring season at WAIS Divide. Production drilling continued through the 2011/12 field season, when the parent borehole was completed at a depth of 3405 m. Following the completion of the parent hole, the DISC drill's new replicate coring equipment was field-tested in January 2012. Modifications were then made to the replicate coring components, and full-production replicate coring was completed during the 2012/13 field season.

LOGISTICS

Camp infrastructure and personnel support for WAIS Divide Camp were provided by RPSC and the Antarctic Support Contract (ASC), RPSC's successor. Transportation of all field personnel, camp and drilling equipment to and from the camp was provided by support from the 109th New York Air Guard through the use of ski-equipped Hercules LC-130 aircraft, which have a maximum cargo payload of ~9070 kg in polar field conditions. Transport of the entire DISC drill system, weighing ~59 000 kg, as well as drilling fluid and borehole casing, required approximately ten Hercules flights from McMurdo Station to WAIS Divide. It is anticipated that the disassembly of the DISC drill will be completed during the 2014/15 field season and the drill will be returned to McMurdo Station via Hercules aircraft or overland traverse. The drill system will then be returned to the US via vessel transport and back to Madison, WI, where it will be repaired and modified as needed for future use.

Fig. 2. Interior view of the drill side of the arch, looking toward the core-processing side.

DRILL ARCH

The DISC drill arch, purchased, erected and maintained by RPSC and ASC, is a steel structure divided into two separate rooms. The larger of these, measuring 30.5 m × 9.1 m × 7.6 m, housed the entire DISC drill system as well as the main power distribution panels for the building. The smaller part of the structure, measuring 25.6 m × 9.1 m × 4.6 m housed the core-processing equipment, including stations for measuring, cutting and packing the ice cores as well as drying booths where the ice core was dried of any residual drilling fluid through forced air fans. Below the floor of the core-processing side, an 18.3 m × 3.6 m × 3.6 m basement was utilized for storage of the brittle ice cores during the 2009 austral winter. This period of storage allowed the brittle ice time to relax prior to transport back to the US National Ice Core Laboratory (NICL) in Lakewood, Colorado. An interior view of the drill side of the arch is shown in Figure 2, looking toward the core-processing side.

Images of the DISC drill structure over the years at WAIS Divide can be seen in Figure 3. Average annual accumulation at WAIS Divide is 20–20.5 cm w.e. (Banta and others, 2008). This high accumulation combined with drifting snow buried the arch throughout the course of the project. Each year, RPSC and ASC maintained access to the doors on either end of the structure, to enable movement of equipment and ice cores into and out of the arch, and also maintained a side entrance as a third point of entry and egress for personnel. Accumulation around the arch had slow-acting but detrimental effects on the steel arch structure over the life of the project. Across the 9.1 m width of the structure, a ~50 cm rise was seen in the center line of the arch floor, as the outside and underlying snow compressed the side-walls and heaved the floor panels.

2005/06 season **2006/07 season** **2007/08 season** **2008/09 season**

2009/10 season **2010/11 season** **2011/12 season** **2012/13 season**

Fig. 3. DISC drill structure over the course of the WAIS Divide ice-core project.

Operations inside the arch were manageable from year to year, but early-season alterations had to be made to doors and to the alignment of crane rails to allow smooth functioning of all equipment. In addition, slow creep of the drill slot walls inward necessitated the shaving of the slot walls with chainsaws. This exercise was completed annually to ensure smooth tilting of the DISC drill tower. During the 2011/12 season, the drill slot ventilation running alongside the slot was removed, repaired and recessed back into the slot snow wall, as it had begun to interfere with tower travel.

AUXILIARY SYSTEMS

Successful operation of the DISC drill was enhanced and aided by several key auxiliary systems. Layout of the drill system was very similar to that used during the 2006 field test in Greenland (Johnson and others, 2007), with a few improvements made to increase efficiency of operations. A sliding window was implemented in the drill control room next to the operator's desk and allowed for communication with personnel out on the drill floor as well as an improved view of the drill tower, cable and sonde as it entered the borehole. The room was heated to ~15°C using a small electric heater for operator comfort. A secondary manual winch control station located outside the control room could be used to bring the drill back to the surface in the event of a computer system failure. Drilling data were logged automatically by the LabVIEW software (Mortensen and others, 2007), but paper drill-run sheets were also completed by the operators for each run, allowing for comments and additional notes.

Inside the drill arch, two overhead gantry crane systems shared use of a common rail system running the entire length of the drill side. The blue gantry crane, with a maximum capacity of 7260 kg, was used for heavy equipment installation at the start of each season and for packing at the end of each season. A smaller yellow gantry crane with dual 900 kg hoists served as the daily workhorse during drilling operations, transporting the core and screen barrels around the arch.

A two-part drilling fluid was used in order to pressure-compensate the borehole and keep the hole open for drilling and logging operations. The primary drilling fluid, Isopar K, with a density of 0.76 g cm^{-3} was mixed with a densifier, HCFC 141b, with a density of 1.25 g cm^{-3}, at a ratio of 70% to 30%. Drill fluid operations were handled via a closed-loop system for cleanliness, but also to limit loss of the HCFC 141b, which readily evaporates in air. The primarily odorless fluids were not found to have harmful effects on personnel. Initially during the first production season, drill fluid was pumped out of individual drums and into a 1041 L mixing tank located inside the arch. In 2008/09, two bulk fluid tanks were introduced into the system. Handheld barrel pumps were used to fill the bulk tanks at a drill fluid depot located away from the arch. A 3785 L tank was used for Isopar K holding and transport and a smaller 1514 L tank was used for HCFC 141b transport. Both tanks were sled-mounted and parked on the snow surface immediately outside the arch and plumbed down into the arch with Goodyear Plicord Arctic Flexwing hose. Electronic batch controllers mounted to a mixing tank inside the arch were then used to bring fluid into the arch as needed. Utilizing the bulk fluid tanks allowed for drilling operations to continue during inclement weather, as there was no longer a need for accessing individual drums of fluid on poor weather days. The two-part fluid was then mixed to a desired density and pumped directly into the borehole by means of hose plumbed directly into the borehole casing. Chemical-compatible Dailove brand drilling gloves made by Dia Rubber Co. were worn during surface operations involving fluid or fluid-soaked drill parts, but no other personal protective equipment was necessary for handling fluid. Throughout the course of drilling the parent borehole, fluid loss rate averaged ~35%, i.e. the total amount of drilling fluid used for the project was 35% more than the volume of the borehole up to the fill level.

A manual screen-cleaning station, modified from a semi-automated system used during the Greenland test, was used for the processing of ice chips after each drill run. During normal operations, the screen barrel contained ten 10.8 cm

Fig. 4. Cable vacuum used during ascent of the drill.

inside diameter × 76.2 cm long screen tubes in line that would collect ice chips and send fluid back into the borehole. Upon reaching the surface, the screen barrel was transported to the screen-cleaning table and a clean screen was inserted into one end of the barrel. This would force a full screen into a tilting cradle at the other end of the barrel. A foot-operated vibrator system was used to vibrate the screen, shaking the chips into a hopper below. Screens were then dried in a heated, tiered box in order to remove any remaining fines. In the meantime, a fully clean second screen barrel was placed on the drill tower and another drill run immediately initiated. Time spent on the surface readying the drill between runs was generally 15–20 min.

Each drill run produced approximately two hoppers full, or ~70 L, of chips and drill fluid slurry. Each hopper was then lifted with a small chain hoist into an industrial centrifuge made by Barrett Centrifugal. The chips were spun for a 3 min cycle at 1200 rpm, recovering and recycling 90% of the drill fluid back into the fluid-mixing tank. The dried ice chips were then removed from the hoppers with a vacuum system and discharged into a dumpster outside the building. When full, the dumpster was emptied using one of the camp vehicles. Chip disposal sites were flagged and GPS coordinates recorded. The 10% of fluid remaining in the chips was allowed to evaporate in the sun.

Fig. 5. DISC drill portable machine shop (MECC™).

Fig. 6. Cross section of the DISC drill's fiber-optic cable.

In order to reclaim and reuse as much drilling fluid as possible, a cable vacuum device was connected to the drill cable during ascent. The vacuum device, based on a design used at NEEM Camp in Greenland, was then connected via a hose to an explosion-proof vacuum canister. It is estimated that 19 L of fluid were reclaimed during each drill run using this vacuum. A picture of the cable vacuum device is shown in Figure 4.

IDDO's MECC™ machine shop, based on a 6 m ISO shipping container supplied by Weatherhaven, allowed for numerous and critical on-site modifications to drill components. The two side-walls of the container can be folded out and down, essentially tripling the amount of interior workspace. Shipping weight of the MECC™ container, complete with all machines and tools, was ~8680 kg. An exterior view of the MECC™ can be seen in Figure 5. The MECC™ contains a mill, lathe, TIG (tungsten inert gas) welder, grinder, bandsaw and a full complement of hand tools. A working area was also provided to perform maintenance and repairs on the drill electronics. All equipment could be moved to the center of the container and stored during transport.

CABLE SPOOLING AND FIBER-OPTIC CABLE

The electromechanical DISC drill is tethered to the surface by a 15.2 mm diameter cable, which provides the mechanical connection as well as power and communications. The drill cable, manufactured by Rochester Cable Corporation, has two outer layers of steel wires and an inner layer of copper-clad steel wires that provide mechanical strength. Power is sent to the drill over the copper-clad steel wires and a second layer of copper wires. The six fiber-optic channels at the core of the cable are used to send commands to the drill sonde and for receipt of operational data back from the sonde (Shturmakov and others, 2007). A cross section of the cable is shown in Figure 6.

Cable-spooling operations occurred three times during the project, when borehole depth or cable damage necessitated use of a longer cable. New cable was spooled onto the DISC drill winch drum through use of a Pengo

Table 1. Drilling parameters for main borehole across production drilling seasons

Drilling data	2007/08	2008/09	2009/10	2010/11	2011/12
Number of days on-site	51	53	65	70	73
Number of drilling days	17	37	45	43	7
Number of drill runs	180	401	328	257	33
Start depth (m)	114.6	580.4	1514.2	2564.4	3331.5
End depth (m)	580.6	1513.9	2564.4	3331.5	3405.1
Average production ($\mathrm{m\,d^{-1}}$)	37	32.6	25.8	23.24	10.51

Table 2. DISC drilling and replicate coring parameters

Drilling parameter used	Value
Max winch descent speed	$1.2\,\mathrm{m\,s^{-1}}$
Max winch ascent speed	$2.3\,\mathrm{m\,s^{-1}}$
Pump motor rpm	1800–2300
Cutter motor rpm for coring	80
Cutter motor rpm for broaching/milling (replicate)	60–110
Penetration rates	2.5–$6.7\,\mathrm{mm\,s^{-1}}$; 3–4 mm common
Coring rates per day (common)	20–32 m

cable tensioner, to ensure consistent tension and proper wrapping of each layer. Swapping of cables generally took 1–2 days. Fiber-optic termination was then completed in ~3–5 days. While fiber-optic cable was beneficial overall for data transfer purposes, it is complex and difficult to work with in such conditions due to time constraints, the delicate nature of the fiber and the high cost of the associated slip rings and connectors.

DRILLING OPERATIONS

Each season, initial camp-opening operations consisted of arch repair and the reinstallation of do-not-freeze (DNF) equipment that had been removed at the end of the previous season. All drill staff generally remained on one shift during this period. Two to three days of coring and core-processing 'shakedown' followed, ensuring all drillers and core handlers were ready to receive ice cores. After the initial shakedown, three-shift operations were implemented until pack-up at the conclusion of the season.

Drilling days per season ranged from just 7 days during the 2011/12 season when the parent borehole was completed (Table 1), to just over 50 days during the 2012/13 season when replicate coring operations were completed. A work schedule of 24 hours per day and 6 days per week was implemented, with Sundays off or used for drill repair or preventive maintenance. Three shifts of ~8.5 hours each, with three drillers per shift, proved most advantageous and served to reduce driller 'burnout', as had been experienced during the 2006 test season in Greenland when two 10–12 hour shifts were run. A lead driller was on-site each season to coordinate logistics with camp personnel, complete reporting duties, direct coring operations and fill in as needed due to illness. A ten-person crew was standard across all seasons at WAIS Divide. Drill staff generally rotated positions during operations, alternating between control of the drill and cleaning operations on the surface.

After drilling of the pilot hole to a depth of 114 m in 2006/07 using a 4-inch drill system, ~1770 drill runs were subsequently completed using the DISC drill in the parent borehole between 2007 and 2012. This includes coring runs, minimal cleaning runs and trips with the borehole camera. The DISC drill utilizes a four-cutter, four-core-dogs and four-penetration-shoes set-up. The cutters have a 50° cutting face and a 15° relief angle, providing an excellent smooth surface on the ice cores. These cutters performed well in both ductile and brittle ice. On occasion, a faint spiral pattern matching cutter pitch could be seen on the cores. In general, cutter sets were used for ~200 m of coring before being replaced or resharpened. A variety of pitches of penetration shoes were used, with 4 mm pitch per revolution being used most frequently.

Diameter of core produced throughout the parent borehole was 122 mm. Borehole diameter was 170 mm from 114 to 1530 m, and maximum core lengths were ~2.8 m. Below 1530 m, a new thin kerf core barrel, cutter head and cutters were used, reducing the borehole diameter to 163 mm from 1530 to 3405 m depth. Due to the creation of fewer chips, core length per run increased by nearly 0.5 m, with the longest core drilled being 3.62 m. In both configurations, core length was limited by the ability of the pump to pack the chips in the screens, and penetration was halted by the operators when a pronounced decrease in pump torque was observed. An added benefit to the reduced borehole size was the use of less drilling fluid. Additional DISC drilling parameters for drilling of the parent borehole and replicate deviations are shown in Table 2. It should also be noted that the pump was run during descent operations. This enabled higher tripping speeds, up to $0.2\,\mathrm{m\,s^{-1}}$ faster than without the pump running. Annual drilling progress over the lifetime of the project can be seen in Figure 7. At a final borehole depth of 3405 m, the DISC drill borehole at WAIS Divide is the deepest US ice core drilled to date.

DRILLING THROUGH THE BRITTLE-ICE ZONE

A brittle-ice zone was encountered during the 2008/09 field season between approximately 575 and 1300 m depth. Ice drilled from this section was particularly susceptible to spalling and cracking when brought to the surface. Different methods were utilized to reduce the stress on the cores and maintain their integrity. First, cores were inserted into green plastic netting when being transferred from the core barrels on the drilling side of the arch into the core-processing side. The netting served to both insulate the cores from the aluminum handling tray as well as to hold the core together when spalling or cracking occurred. Second, since the core from this brittle zone would not allow for cutting it into 1 m sections without risking loss of a portion of each sample, a drilling technique was tried whereby a series of shorter cores were drilled and brought to the surface pre-cut to 1 m shipping lengths. Using this method, 1 m of core was drilled, a core break was performed, drill ascent was immediately halted, a second 1 m core was drilled, another core break was performed and the ascent stopped again. A final 0.5 m core was drilled and all three cores were then returned to the surface. During the following run, the process was reversed and one 0.5 m and two 1 m cores were collected. Core quality was excellent throughout the brittle-ice zone. The core dogs performed well using this method and were

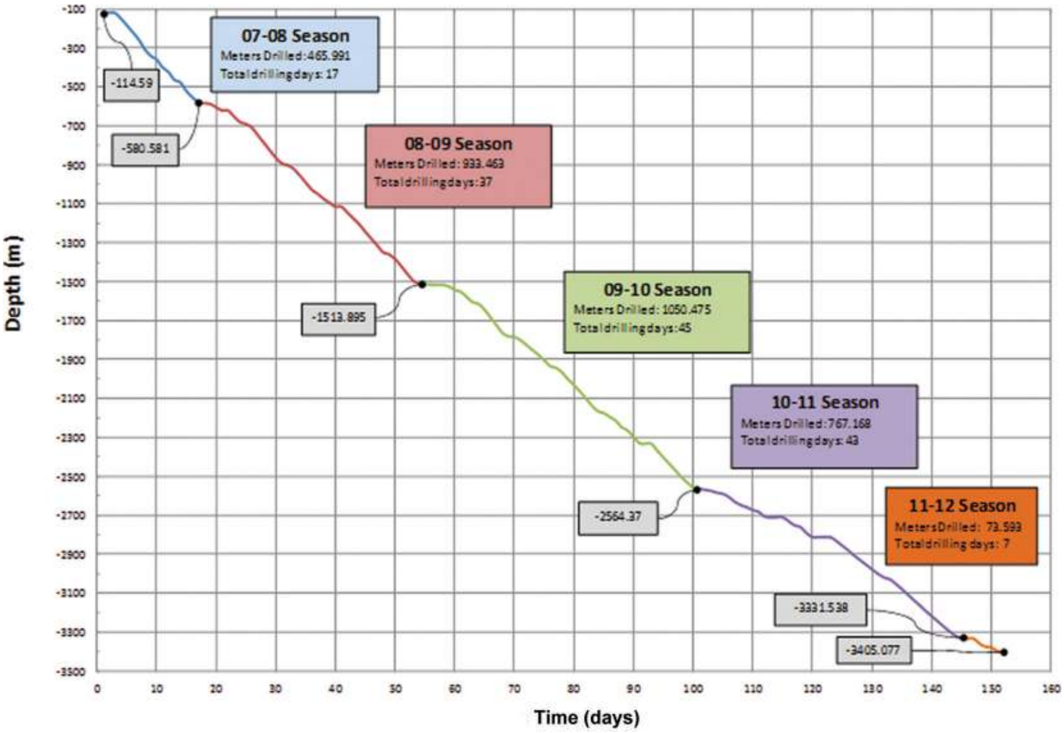

Fig. 7. Annual drilling progress for DISC drill borehole WDC06A, WAIS Divide Camp. Flat portions of the graph indicate Sundays off or downtime for repairs such as replacement of sheave bearings and re-termination of the drill cable.

consistently reliable without being cleaned between cores. Penetration rate varied between 3.5 and 6 mm s^{-1}; however, 4 mm s^{-1} proved to provide the best core quality, as was also the case in ductile ice. In the majority of runs, brittle cores were brought to the surface in one intact piece, though fracturing occasionally occurred during subsequent processing. The brittle ice was then stored in the subsurface basement of the core-processing area for a period of 1 year, allowing the cores time to relax before transport to the US. This 3-for-1, i.e. three cores per drill run, technique was highly successful and >750 m of ice cores were drilled using this method.

DRILLING IN WARM ICE

Drilling operations at WAIS Divide continued to 3405 m depth, at which depth the consensus of several project-affiliated scientists was that the drilling had reached a point within 50 m of the ice/bedrock interface. As experienced in other deep-drilling projects, drilling this ice is often the most time-consuming aspect, as ice at the bottom of the borehole rapidly warms and it becomes difficult to obtain samples of the desired length. A temperature log completed 48 hours after completion of the main borehole showed the temperature to be ~–6°C at the bottom. Communications feedback from the DISC drill showed that drilling operations added ~4°C of heat to the borehole during active coring. This essentially created a situation where the ice at the bottom was –2°C, the pressure-melting point of ice in the WDC06A borehole. Operational tactics were incorporated to ensure the drill did not spend added unnecessary time in the hole at such temperatures. Drilling was initiated immediately upon reaching the bottom, and motor hand-offs were quickly completed after coring was complete and a core break immediately initiated. Overall, the DISC drill performed well in warming conditions, and little effect of the warming ice was witnessed on operator monitors or on the drill upon its return to the surface, except for very small amounts of refrozen water on the drill head itself during the last few runs. It is believed that the flow rate of the DISC drill pump (Mason and others, 2007) aided in continuously flushing the cutter head with cooled drilling fluid and prevented issues with coring normal-length cores, as had been experienced with other deep-drilling endeavors by IDDO's international colleagues (L. Augustin, unpublished information).

REPLICATE CORING

The desire of the science community to collect additional cores at depths of high scientific interest drove the design and development of replicate coring capability for the DISC drill. The original replicate coring concept was first field-tested in January 2012, following completion of the parent borehole. While no replicate core was collected during that field season, valuable data were collected and the drill was modified during the following summer at IDDO. Following modification, full-production replicate coring was successfully completed during the 2012/13 field season. A preliminary goal of 250 m of replicate core was outlined. In the end, five deviations were completed at four depths of high scientific interest, with nearly 285 m of replicate core collected. Replicate coring statistics are shown in Table 3. In contrast to the 122 mm ice cores drilled in the parent borehole, replicate cores were 108 mm in diameter. Also utilized during replicate operations was a variety of new drill heads, including a milling head, a broaching head, a coring head, and a conical tool and a magnet head, both designed to retrieve lost hardware bits in the borehole. Replicate coring progress is shown in Figure 8, and a borehole depiction can be seen in Figure 9.

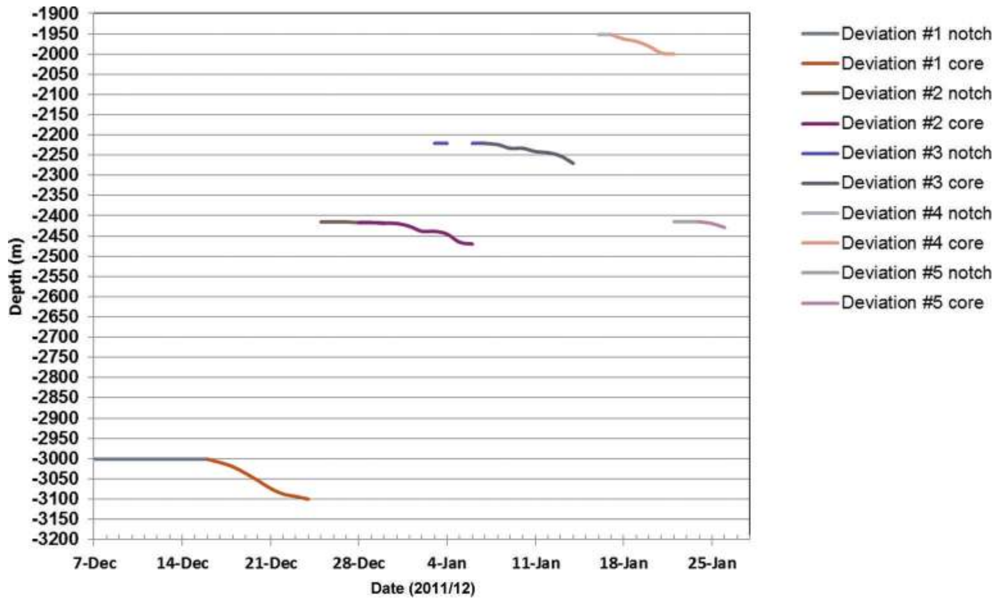

Fig. 8. Replicate coring progress graph. Initial flat lines for each deviation indicate time spent broaching and milling in order to exit the parent hole.

Further detail on the replicate coring system's architecture and testing can be found in related papers (Gibson and others, 2014; Johnson and others, 2014; Mortensen and others, 2014).

CORE PROCESSING

Throughout coring operations at WAIS Divide, core-processing support was directed by the NICL, who worked closely with IDDO in designing and maintaining core-processing equipment and providing feedback on core quality. Core-processing support was provided by the WAIS Divide Science Coordination Office (SCO), who employed many early-career investigators for core-handling duties. Ice cores were inspected on-site, measured for length and diameter, visually analyzed for surface finish, cracks and layers of interest (e.g. cloudy bands or volcanic ash layers) and a portion of the core was further analyzed using dielectric profiling. Hundreds of ash layers or cloudy bands were visible in the WAIS Divide core, with over 31 such layers being found in one 3.3 m core alone. An image of a pronounced ash layer from 2569 m depth is shown in Figure 10.

In order to maintain integrity of the ice core, particularly for gas analysis, the core-processing structure was maintained at a temperature of –26°C using four industrial air-conditioning units. Ice cores were cut into 1 m sections using a circular saw and were bagged and boxed for transport. An image of the core-processing station is shown in Figure 11. The bulkhead wall shown in the picture separates the drilling and core-processing sides of the arch.

Throughout the project, a core-processing line was held each summer at the NICL facility where principal investigators and other researchers cut the cores for sample transport to laboratories across the US.

Table 3. Replicate coring statistics (unit is m)

Deviation No.	Depth of exit from parent hole	Full diameter core	Coring end depth	Total core collected
1	3001.55	3006.16	3100.26	98.71
2	2416.70	2420.02	2469.49	52.79
3	2221.00	2226.16	2290.80	69.8
4	1952.00	1956.90	2000.20	48.2
5	2414.50	2420.02	2428.74	14.24
Total meters of replicate core collected				**283.74**

CHALLENGES

Challenges can be expected with any deep-drilling operation and many were encountered during the project. Early on, it was determined that flexing of the tower crown sheave and too much movement in the assembly was fatiguing the screws mounting the bearing hub to the sheave. This dictated periodic repair and monitoring of the assembly, particularly

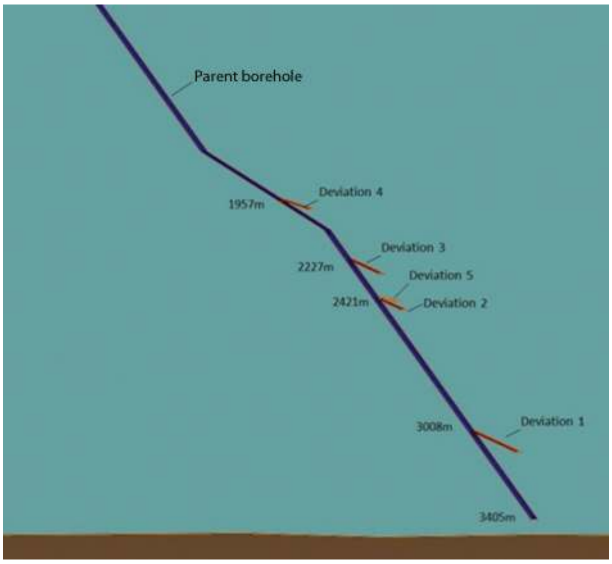

Fig. 9. Replicate coring borehole depiction.

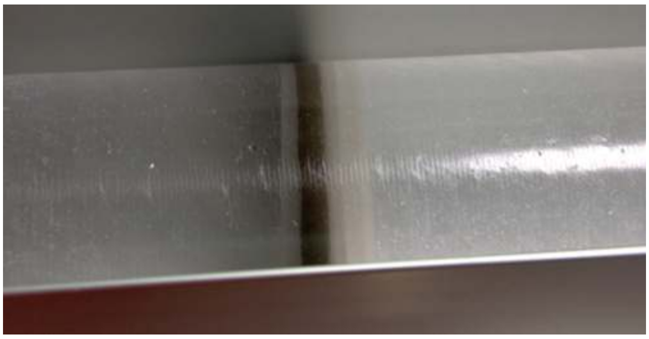

Fig. 10. Volcanic ash layer from 2569 m depth.

Fig. 11. Core-processing side of arch.

during times of high cable tension (e.g. core breaks). Sheave-bearing issues were also experienced with the level wind sheave. Continuous but varied issues with the winch control software also slowed operations. Whenever a new drill cable was put on the winch drum, the rubbery void filler found between the outer layers of the cable would slough off the cable and contaminate the borehole and build up on the sheaves. This prevented penetration on some attempts and required additional cleaning of the cable.

During the 2009/10 field season, the borehole inclination rapidly increased from 3.5° to just over 5°. The cutters were modified for improved side-cutting ability, and the core-dog cages were machined down to allow the drill to hang more freely in the borehole, allowing the side cutters to work. Stabilizers were added at key points on the lower sonde to manage drill flexure. Reaming was performed 6–15 m from the bottom of the borehole during each drill run for a portion of the season. These correction efforts stabilized and decreased inclination down to below 4°. Figure 12 shows a graph of the borehole inclination throughout the duration of the project. During the 2010/11 season, the drill contacted a small chip of ice on descent in the borehole. This resulted in an instant and large change in weight-on-bit (WOB) and a kink in the drill cable. Six hundred meters of cable had to be cut off and the cable re-terminated to proceed. The drill's WOB sensor and auto winch stop would have prevented this occurrence; however, the WOB housing was often plagued by fluid leaks into the chamber. This was later remedied by redesigning the housing and electronics to operate in fluid.

Another electronics issue was encountered early in the project, in which liquid water entered the exposed wiring connections in the top of the motor section, causing shorting of the electronics. The cause is believed to be from excess ethanol, used to clean electrical connectors, melting ice chips that had accumulated in this area. This was remedied by restricting the use of ethanol, by sealing areas where chips could enter this space and by venting the cavity by adding sintered bronze filter disks to prevent pressure from building up.

While each section of the drill sonde was fabricated in triplicate, occasionally all three sections of a certain assembly would fail, necessitating in-field repair. During replicate coring, a cutter head screw came loose while coring in a deviation bore. The drill's rotation on this screw caused substantial damage to the shoes and cutters. To retrieve the broken hardware from the deviation bore and to enable continued coring, a conical tool was used, at which point the hardware fell into the newly created cup and was later removed by coring over this depth.

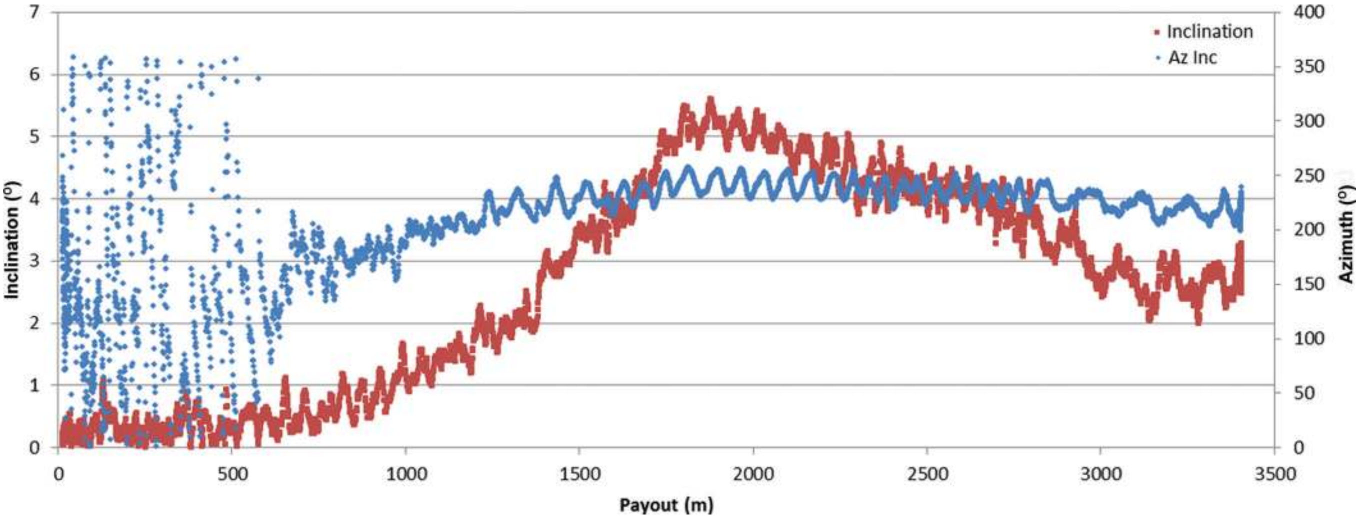

Fig. 12. DISC drill WDC06A inclination and azimuth of parent bore.

CREW CONTINUITY

Throughout the WAIS Divide ice-core project, crew continuity between field seasons was found to contribute greatly to the success of operations and crew morale. Over the course of the 6 drilling seasons, employing 10 drillers per season, only 29 different personnel served as drillers. This decreased the amount of training time needed each season. The crew generally comprised a mix of staff engineers and contract drillers, with a balance of skill sets needed to field an operation of this size.

SAFETY

Safety of operations was of the utmost importance for the WAIS Divide ice-core project. From the initial conceptual design of the DISC drill, personnel and equipment safety was afforded greatest priority. Prior to each season, drill operators completed several safety trainings, including back safety, confined space, DISC drill safety and fall protection trainings. A failure modes and effects analysis was conducted for all subsystems of the DISC drill, and safety mitigations and procedures implemented to ensure safe operation. Season start-up, daily and weekly safety checks of all equipment were performed. DISC drill personnel received basic first-aid, cardiopulmonary resuscitation and automatic external defibrillator training at a minimum, and the DISC drill arch structure was outfitted with extensive first-aid and safety equipment. The drill system was well equipped with signage and personal protective equipment, including eye and ear protection, a variety of gloves, chemical spill kits and sorbent pads, lighting, fire extinguishers and basic first-aid equipment. The drill arch was also equipped with an emergency alarm system, to notify occupants to evacuate in the event of an emergency. A four-channel air-monitoring system continuously monitored fluid vapor levels in the drill arch in the recessed winch pit, the drill slot, the drill control room and near the screen-cleaning system. A supplementary handheld oxygen monitor was also utilized when entering the slot, which was considered a permit-required confined space. Close coordination with the logistics provider also ensured safe operation throughout the life of the project. In the six production drilling seasons, only approximately eight minor injuries or near misses were reported, including bruises, small lacerations and sore muscles.

CONCLUSION

The WAIS Divide ice-core project was a very successful ice-coring effort and resulted in the deepest US ice core drilled to date. Lessons learned during a test of the DISC drill system in Greenland and during each production season were applied to operations in subsequent field seasons at WAIS Divide, and the drill system dialed in to produce excellent core across the life of the project. Newly designed and revolutionary replicate coring techniques implemented during the 2012/13 field season proved successful in capturing additional cores at depths of high scientific interest.

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