Collaborative Research: Climate, Ice Dynamics and Biology Using a Deep Ice Core from the West Antarctic Ice Sheet Ice Divide (I-477)
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Collaborative Research: Replicate Coring at WAIS Divide to Obtain Additional Samples at Events of High Scientific Interest (I-476)
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Field Team:
Don Voigt[1,6], John Fegyveresi[1], Bradley Markle[2], Emily Longano[3], Ross Beaudette[4], Jihong Cole-Dai[5], and Kari Peterson[5]

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Field Season Tasks:
The first task for season was to use the newly-developed DISC Drill Replicate Ice Coring System to collect 252 meters of replicate core from five of the most interesting time periods in the WAIS Divide climate record by deploying into the main 3,405 meter deep borehole and then actively deviating from it at specific depth (e.g. time) intervals of high scientific interest. The goal was to deviate on the uphill side of the main borehole, thereby maintaining the ability of logging tools to make measurements in the entire main borehole. The second task for the season was to remove the chips that accumulated in the main borehole as a result of the replicate coring process.

Task 1: Replicate Coring:
The put-in crew, led by Camp Manager Kaija Webster, made it to WAIS Divide on October 26 after waiting only one day for favorable weather. This is the first time in many seasons there was a deep field put-in before November 1. Don Voigt arrived in McMurdo station on 17-Nov and quickly made it to WAIS Divide on 22-Nov. John Fegyveresi, Brad Markle, Emily Longano and Ross Beaudette arrived to McMurdo on 28-Nov and then to WAIS Divide on 7-Dec. Due to a combination of good weather when we needed it to get people and equipment in to camp and to great camp staff support, the IDDO drilling team was able to start using the replicate drilling equipment down hole about 10 days sooner than expected.

The field team was able to surpass the initial goal of 252 meters of replicate core, collecting a total of 285 meters of excellent ice core from all of the depth intervals of interest. In addition, each deviation was successfully carried-out on the uphill side of the main borehole, thereby maintaining the ability of logging tools to make measurements in the entire main borehole. This is the first time replicate coring has been carried-out while retaining access to the main borehole. At the conclusion of each deviation, a logging tool equipped with a weight-on-bit sensor was lowered past the depth of deviation to demonstrate that logging tools can successfully pass the deviation. Table 1 summarizes the starting and ending depths of each deviation.

Deviation #	Coring Start Depth (m)	Full Diameter By (m)	Coring End Depth (m)
1	3001.55	3006.16	3100.26
2	2416.70	2420.02	2469.49
3	2221.00	2226.16	2290.80
4	1952.00	1956.90	2000.20
5	2414.50	2420.02	2428.74

***Table 1**. Summary of the five replicate coring deviations carried-out during the 2012-2013 field season. Deviation #1 corresponds to AIM8 and the Laschamp Event. Deviation #2 corresponds to the 18 ka event. Deviation #3 corresponds to the Bølling-Allerød event. Deviation #4 corresponds to the Younger Dryas event. Deviation #5 corresponds (again) to the 18 ka event.*

Fugitive Gas Sampling:
Ross Beaudette collected ice samples for fugitive gases (helium, neon, oxygen), within half an hour of the core being brought to the surface, and sealed them in gas-tight bottles. Fugitive gas samples were collected mostly from deviation #1, plus four samples from deviation #2. The samples were 10 cm long and consumed the entire cross section. Table 2 lists the fugitive gas samples collected during the field season.

Deviation #	Bottom Depth (m)
1	3005.008
1	3009.497
1	3011.9
1	3015
1	3020.1
1	3023
1	3029
1	3032
1	3037.1
1	3040
1	3043
1	3046
1	3049
1	3054.28
1	3057.1
1	3061
1	3064
1	3068
1	3072.31
1	3076
1	3079
1	3082
1	3088.36
1	3091.1
1	3095
1	3098
2	2469.42
2	2469.31
2	2469.2
2	2469.09

***Table 2**. Fugitive gas samples taken during the 2012-2013 field season replicate coring. Each sample was 10 cm long and consumed the entire cross section.*

Replicate Coring Process:
The DISC Drill Replicate Ice Coring System collected additional ice at depths of interest by deploying into the existing 3,405 meter borehole and then actively deviated from it. The drill used two steering actuator sections to tilt itself in the main borehole by applying sideward force against the borehole wall. In the first step of the process, the broaching cutter head was deployed to the target depth. Using the actuators, the drill was then tipped to the high ("up hill") side of the borehole to engage the cutters. Ice was then removed in repeated passes of approximately 15 meters in the up-stroke. In the second step of the process, a milling head was deployed to create a landing for the coring head. In the third step of the process, a coring head removed a 20 mm kerf allowing a 108 mm diameter core to enter the core barrel. Two meters of core were removed per trip. The coring was repeated until all of the desired replicate ice from the target depth was obtained.

Task 2: Remove Chips from Main Borehole
The process of replicate coring created chips that fell to the bottom of the main borehole. We had a problem when we tried to clean the chips from the bottom of the main borehole and came very close to sticking the replicate coring drill due to ice refreezing on the drill head. We think the chips behaved like toothpaste when the drill tried to core, and oozed around the drill head rather than cutting like ice would. The chips then refroze on the cold drill. Tension during core break was about 10,000 N, which is within 2,000 N of the highest core break seen, even though there was no core to break, just chips. The drill was then reconfigured with the DISC coring head (which is a larger diameter head than the replicate coring head) used for drilling the main borehole to see if that configuration yielded better success. However, we were only able to get to a depth of 2498 meters before having to ream. This proceeded at a rate of 20 mm/sec. Given the remaining depth to the chip pack, the volume of chips that would be produced by this process, and the time available, it became clear that we would not reach the bottom of the borehole before the end of the season. The difficult decision was then made to call it a season and leave about 12 meters of chips at the bottom of the borehole; touch-off was at 3393 meters depth. While we are disappointed not to be able to leave a pristine hole to 3405 meters, the risks involved (i.e., a stuck drill) outweighed the scientific benefits of a chip-free hole to 3405 meters.

This brings the core collection phase of the WAIS Divide project to a close. It has taken eight field seasons to prepare for drilling, collect the main core, and collect replicate cores from five intervals. It will take another two field seasons to complete the repeat borehole logging and remove the camp and drill arch. It has been a wonderful journey and we thank everyone that contributed in any way to the effort.

Fig 1. *View of the (buried) arch at the end of the 2012-2013 field season. The power poles on the right-hand side of the photo lead back towards camp. The ventilation conduit in the center of the photo marks the start of the drilling arch, which then runs 100-feet to the left. The core handling arch runs to the right of the conduit for 84-feet. Photo: Don Voigt.*

Fig 2. *On Monday, 17 December 2012 at 2:10 PM the first-ever replicate ice core taken from the high-side of the borehole was successfully drilled from 3001 meters depth in the WAIS Divide Ice Core borehole in West Antarctica. The first replicate core was ~80% of a full round core, but as the drilling continued on the new path 100% round cores were obtained. Photo: Jay Johnson/IDDO.*

Fig 3. *Replicate coring system actuator section. Photo: Chris Gibson, UW-Madison/IDDO.*

Fig 4. *Replicate coring system broaching head. Photo: Chris Gibson, UW-Madison/IDDO.*

Fig 5. *Replicate coring system milling head. Photo: Chris Gibson, UW-Madison/IDDO.*

Supplementary Science #1: Recent Temporal and Spatial Climate Variability Around the WAIS Divide Site – Bradley Markle

This season, 2012/13, I led a side project to quantify recent temporal and spatial climate variability around the WAIS Divide site. With the tremendous help of Don Voigt, John Fegyveresi, Emily Longano, Ross Beaudette, Graham Colegrove, and Jeremy Miner, we collected a series of five shallow firn cores in a transect extending 40 km from the WAIS Divide drilling site, up and over the main ice flow divide (~20 km from camp). Cores were drilled every 10 km along the transect to depth of 10 to 12 m, which should allow for the analysis of the last couple decades of accumulation. A 1.5 meter snow pit was also dug at each firn core site to enable high resolution sampling of the upper, loosely consolidated snow. Additionally surface snow samples were taken during and immediately after several precipitation events at the WAIS Divide site. These cores and samples will be analyzed at the University of Washington's Stable Isotope Laboratory, for stable water isotope ratios, a widely used proxy for past temperatures and circulation. This project involved several extended snowmobile traverses away from the main camp, including one overnight trip, all of which went extremely well. A huge debt is owed to the core handlers and camp staff whose efforts and enthusiasm made this possible. The drill used for this project was a prototype hand auger designed and provided by Josh Goetz of IDDO, which worked extremely well thanks to his expertise and that of Jay Johnson.

The aim of this study is to better understand the recent spatial and temporal variability of WAIS Divide, building on previous work. This will have many applications toward better understanding the deep ice core record, such as extending the climate record through the most recent decade, correcting for the possibility of ice flow through local temperature or isotopic gradients, and quantifying the level of spatial and temporal "climate noise" at the site. An important part of this project will also involve understanding the recent atmospheric circulation that lead to the deposition of the snow that constitutes these firn cores. To that end, I conducted atmospheric back-trajectories modeling of the last 30 years while at camp this season, which I aim to combine with isotope models in the near future.

All field aspects of this project went extremely well. I'm very excited to begin analyzing the results!

***Fig 6**. Brad Markle and Emily Longano drill a shallow ice core on the main ice divide of the West Antarctic Ice Sheet. Photo: Graham Colegrave*

***Fig 7.** Jeremy Miner and Ross Beaudette drill a shallow ice core, WAIS Divide, Antarctica. Photo: Bradley Markle*

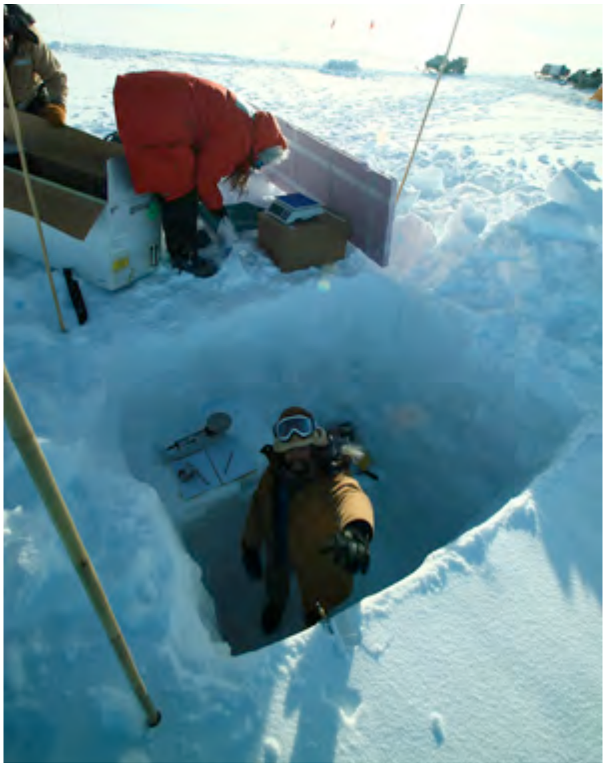


Fig 8*. John Fegyveresi, Emily Longano, and Brad Markle sample a snow pit for stable isotopes and density measurements, WAIS Divide Antarctica. Photo: Graham Colegrave*

Fig 9*. John Fegyveresi drills a shallow ice core near the main WAIS Divide Camp, West Antarctica. Photo: Bradley Markle*

Fig 10*. Brad Markle transports shallow ice cores back to WAIS Divide Camp from a field site. Photo Graham Colegrave*

Supplementary Science #2: Investigation of Physical Properties at the WAIS Divide Site – John Fegyveresi

On-site, I calibrated and installed (with the help of Brad, Emily, and Ross) five platinum thermistor sensor strings in order to obtain a long-term, near-surface temperature profile over a two kilometer survey line. The purpose of this sensor array deployment is to better quantify the temperature fluctuations in the upper 5 meters of firn and determine if there is a correlation to specific surface features and metamorphism that have been noted at WAIS Divide over the past few seasons. It is hypothesized that these noteworthy features are caused under specific meteorological conditions and under varying degrees of solar radiative exposure and penetration at the surface. Varying temperature gradients in the upper few meters of firn may be modulating differing degrees of vapor flux through near-surface. The survey line was laid out in an upwind (grid-west, true-north) direction starting near the on-site Automatic Weather Station (Kominko-Slade), which also houses a solar, net-radiometer sensor that I installed last season (11/12). The thermistor strings were calibrated over a 60 minute period using a constantly-stirred ice-bath method, and were then deployed over a 10 day period starting December 15th. The sensor strings were spaced at 10 meter, 100 meter, 1000 meter, and 2000 meters intervals from the origin string at the AWS, and were taking measurements every 1 minute. Platinum thermistors were used as they allow for higher accuracy measurements, and respond to temperature changes more linearly that standard thermistors. 12V batteries were swapped out periodically to ensure that the sensor strings were constantly recording. During each site visit, photographs were taken and local meteorological conditions were noted (as well as any observed surface observations). Net accumulation was also noted. Lastly, firn density measurements were also taken at two of the five sites. Initial build and design of sensor strings was done at Penn State with the help and guidance of Atsuhiro Muto (post-doc researcher).

***Fig 11**. Surface "glaze" photographed this year on Dec 23rd - 24th (GMT). Photo: John Fegyveresi.*

***Fig 12**. Building a logger housing-box. Photo: John Fegyveresi.*

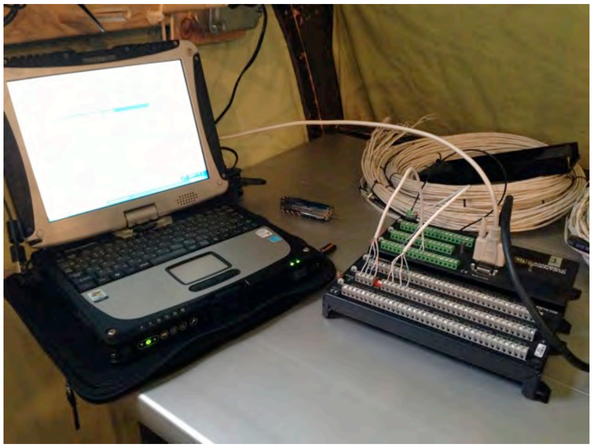


***Fig 13**. Programming and testing a logger. Photo: John Fegyveresi.*

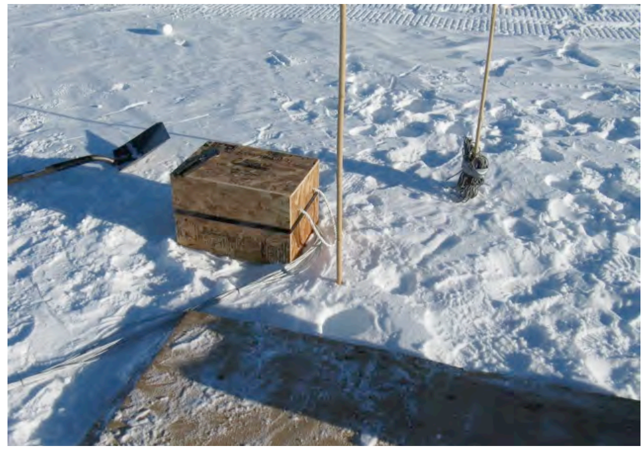


***Fig 14**. Setting up logger station (drilled 5-meter hole can be seen). Photo: John Fegyveresi.*

***Fig 15**. Installing the thermistor string. Photo: John Fegyveresi.*

***Fig 16**. View of the thermistor set-up after installation is finished. Photo: John Fegyveresi.*

Supplementary Science #3: A Snowpit Study of Visible Snow Stratigraphy and Preservation of Volcanic Signals – Kari Peterson and Jihong Cole-Dai

Kari Peterson and Jihong Cole-Dai (South Dakota State University) excavated a 2.50 m snowpit near the WAIS Divide Camp. Snow layers of different appearance and other physical characteristics were recorded to generate a stratigraphic description that will be used to determine the patterns of snow layers useful for identifying chemical indicators of seasonal snow. Three sets of snow samples of vertical sequence in the snowpit were collected. They will be analyzed in the South Dakota State University lab for chemical composition of the snow. The analytical results will be used to determine if two recent (2009 and 2011) small but explosive volcanic eruptions are recorded in the Antarctica ice sheet. In addition to stratigraphy and sampling, snow density was measured in the field with a density sampling tool from the Berg Field Center and another density kit provided by John Fegyveresi of Penn State University.

Acknowledgements:

There was great support from the Antarctic Support Contractor during the season. We were able to start using the replicate drilling equipment down hole about 10 days sooner than we anticipated. This early start occurred because of both good weather when we needed it to get people and equipment in to camp, and also because of the great support we received from the camp staff, led by Camp Manager Kaija Webster. We would also like to thank Terry Jordan, and his assistant Nate Bourassa, for their hard work keeping the generators operating this field season with limited parts and supplies. Michael Davis' cargo support, the NYANG's fixed wing and cold-deck support, and Steve Mikel's SAFECORE reefer support were also critical to the success of the field season. This project would not be possible without the dedication and continual support of Julie Palais, Brian Stone and George Blaisdell.

Ice Drilling Design and Operations (IDDO) Activities at WAIS Divide 2012-2013 (T-350)
PI: Charles Bentley (University of Wisconsin-Madison) NSF-OPP supported

Field Crew:
The IDDO field crew consisted of eleven drillers lead by Jay Johnson, IDDO Drill Operations Engineer and Kristina Dahnert, IDDO Field Support Manager. The field crew and the dates of their stays at WAIS Divide are shown in the following table.

Name	Date In	Date Out
Patrick Cassidy	December 8	February 1
Kristina Dahnert	November 22	February 1
Dave Ferris	December 8	February 1
Chris Gibson	November 30	January 7
Jason Goetz	December 8	February 1
Josh Goetz	November 22	February 1
Mike Jayred	November 30*	February 1
Jay Johnson	November 30	February 1
Tanner Kuhl	December 8	February 1
Nicolai Mortensen	November 30	January 28
Elizabeth Morton	November 22	February 1

*Jayred's arrival at WAIS Divide was delayed by accident at McMurdo

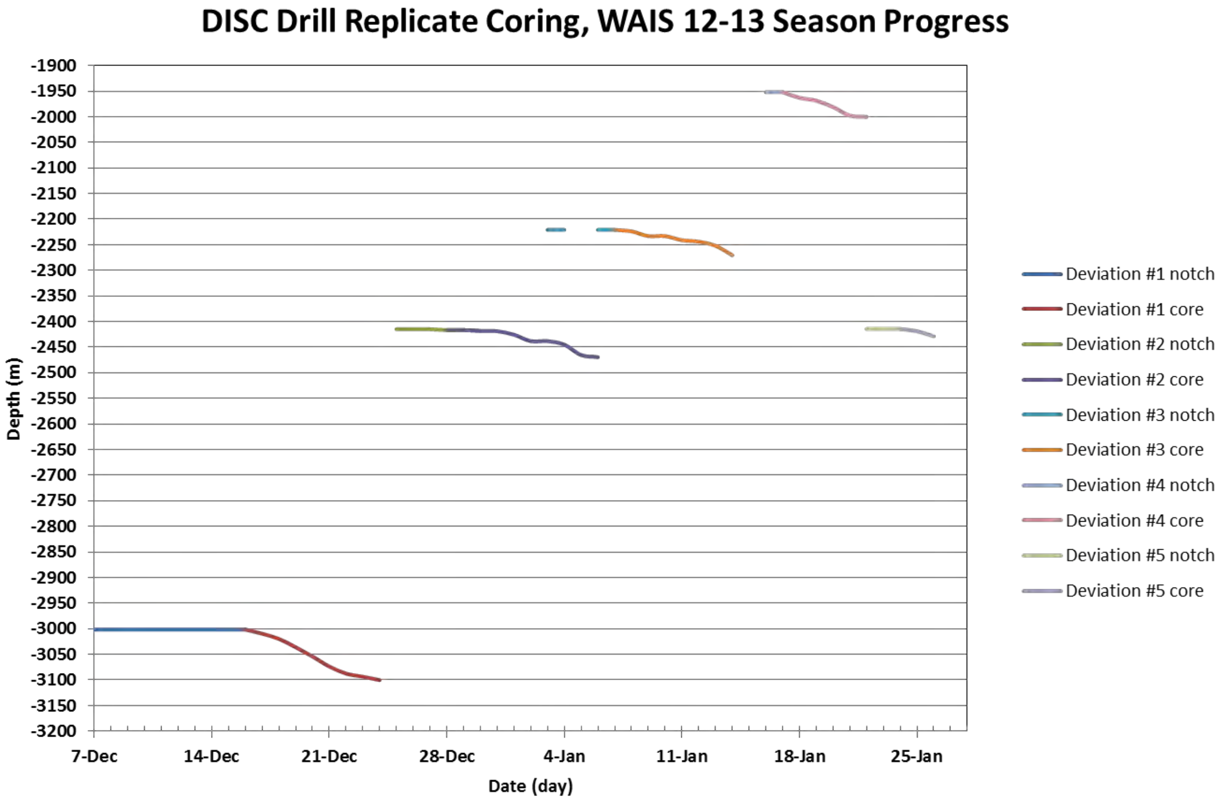
Season Overview:
- Camp opened on schedule.
- Weather was a bit worse than the past few seasons – storms each week with blowing snow and poor visibility.
- Warmest day was January 14 with high of -4C (24F).
- Thanks to excellent winter berm building the previous season, camp structures were quickly erected and heavy equipment fully operational quickly despite the secondary carpentry crew's arrival being delayed.
- No lost days due to weather
- Elizabeth, Josh and Krissy of IDDO along with Don Voigt, the SCO Representative, arrived in camp after the end doors of the Arch had been excavated and repairs on the doors started.
- Drill Arch sustained additional damage over the winter
    - Floor buckling was substantially more than in previous years
    - Floor heaving near slot entrance was severe
        - Floor panels were removed in order to remove some of the insulation below
        - Footers were fully reworked in certain areas
    - Floor near back door had to be recessed so doors would open and cargo could be set inside
    - Slot did not have to be excavated for drill tower clearance and slot drip pans were usable in spite of the severe buckling.
    - Optical table had to be re-leveled.
- Cargo Movement
    - All cargo arrived at WAIS quickly
    - Carrie Schaffner, new WAIS Divide Cargo Coordinator, did a great job.
    - Tony Wendricks and Eric Thompson in Madison quickly got necessary parts ordered and shipped to WAIS Divide.

- Many large pieces of equipment no longer need at WAIS Divide were shipped out on flights of opportunity. Shipments included:
  - Pengo cable tensioner
  - Spare drill cable
  - P05 cable spooler
  - Electrical equipment spares
  - Components that can be used on the Intermediate Depth Drill
- Heavy Equipment Support
  - Excellent support by operators
  - Equipment held up well and needed few repairs
  - Excellent maintenance of Arch doorways during inclement weather
- Generators
  - The power system was reliable and had only a few unscheduled outages including the failure of the main breaker on December 12.
  - The generator that failed last season was not available until December 19 because the repair parts originally ordered were not the right ones. An emergency back-up, however, was in place.
  - Switch gear was not operational and all equipment had to be shut down for the generators to be switched. This was not, however, a big problem.

IDDO Goals for the Season:
- "Dial-in" replicate coring system
- Collect at least 252 meters of high quality replicate core from five requested depths
- Improve methods of broaching, milling, and coring off the parent borehole

Drilling:
REPLICATE CORING A HUGE SUCCESS – first replicate core successfully collected December 17, 2012 and replicate core collected from all intervals of interest. IDDO believes that these are the first ever cores taken from deviations from the high side of the borehole either in ice or rock. The tremendous success of the replicate coring at WAIS Divide is the result of the ingenuity and hard work of the DISC Replicate Coring Development Project team headed by Alex Shturmakov and the WAIS Divide Project drill crew, especially Jay Johnson, Nicolai Mortensen, and Chris Gibson who were members of both teams.

- All five deviations were completed with coring intervals between 1952 and 3100 meters. Drilling progress is shown in the following graph.



- Total core drilled: 285.4 meters
  - Replicate core had good depth-age correlation to the main core, as witnessed by ash layer depth matching.
- Tripping speeds
  - Descended at up to 1 m/s with pump running
  - Ascended at up to 2.3 m/s
- Cutter speed
  - 60 to 110 rpm for broaching and milling
  - 80 rpm for coring
- Coring penetration rates of 3 to 4 mm/s
- Borehole fluid density
  - Density maintained at 0.920 @ -31°C throughout the season
  - Fluid mixed to density of 0.935 @ -31°C to compensate for 141b losses
- 12,398 liters (3,275 gal) of fluid used
  - 7,823 liters (2,067 gal) of Isopar K
  - 4,575 liters (1,209 gal) of 141b
- Total fluid loss for season was 104% compared with
  - 2011-12 season loss of 91%
  - 2010-11 season loss of 43%
  - 2009-10 season loss of 25%
  - 2008-09 season loss of 37%
  - 2007-08 season loss of 35%

    - Losses for this season and the 2012-13 season are estimated because the exact volume of each deviation notch is not known. Estimated loss is higher than in past seasons due the replicate coring.
- Total of 71 days at WAIS
    - 12 days for arch work and set-up
    - 3 days for testing
    - 53 days for replicate coring operations
    - 3 days for packing at end of season

<u>Challenges:</u>

- Winch clutch – bearing in clutch started to make noise indicating start of potential failure
- Small winch motor – motor at times would not stop on command. This problem was first experienced last season. The e-stop had to be used to stop the motor.
- Crown sheave – 3 of 6 screws that mount the hub to the sheave sheared; all screws replaced.
- Frost build-up in the magnetic coupler of pump
    - Caused high running current or prevented the pump from starting
    - Problem mitigated by preventing ice particles from entering the housing
- Preventing the broaching head from cutting while ascending
    - The "bumper" designed to prevent the problem did not work well when hole inclination was more than a few degrees.
    - A new "drop ring" was designed and implemented in the field. Implementation was in stages to reduce impact on drilling.

Spring Loaded Bumper

New Drop Ring in Deployed Position

- Catching the casing with the broaching head. Care had to be taken when raising the broaching head through the casing to prevent head from catching the casing and shaving pieces off the casing.
- Failure of shear pins in the actuator arms – some drilling scenarios require care to prevent failure.
- Icing in the actuator arm ball nut – required that maintenance be performed routinely
- Instability of control software – frequent , random crashing of software
- Level wind encoder failure – had to be replaced with spare
- Axial stick-slip made creating initial ledge with milling head very time consuming – broaching cutters were added between the milling cutters to improve efficiency of cutting process
- Collecting chips from the broaching process
    - Majority of cuttings were left in borehole and were collected later on coring runs
    - Check valve design was changed to improve chip collection
    - Chips from the lower two deviations settled to the bottom. Recovery attempts at the end of the season proved to be very time consuming and dangerous – risk of

getting drill stuck – due to the warm borehole temperature and the chips re-sintering together.

- Broaching chips clogged pump on several occasions.
  - Compressed air used to clean pump before each run
  - Led to failure of motor driver
- Cutter head problems:
  - Screw failure, probably due to screw failure itself and poor cutter fit, caused the loss of two cutters and hardware down hole
  - The conical tool was used to recover all parts after magnet tools fabricated onsite failed to retrieve the parts
  - All cutters were modified to improve fit and accept different screw type

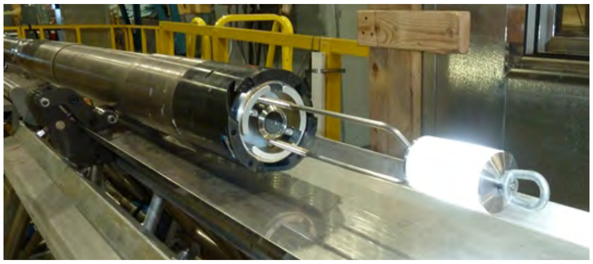
Broken Cutter Hardware Recovered from Deviation

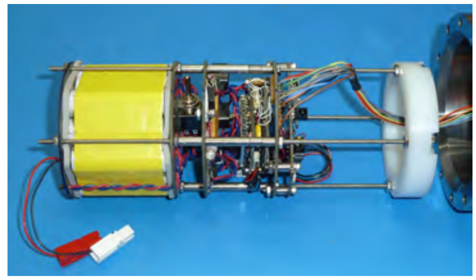
Conical Tool Used for Recovery of hardware, Milling Head, Magnetic Recovery Tool and Broaching Head

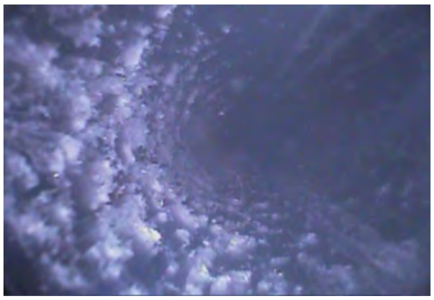
- Instrument section problems were ongoing
  - Motor Drivers failed due to presence of larger-than-usual chips from broaching (Locked rotor)
  - A logic level incompatibility showed itself at low temperatures intermittently on an internal serial bus causing lock-up of the bus
  - Leaks continue to be an issue

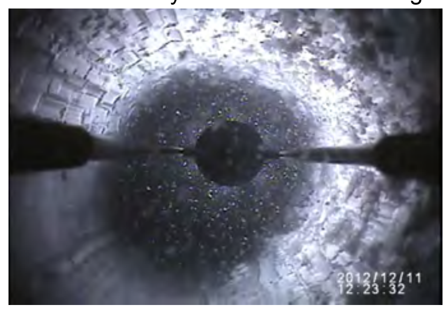
<u>Borehole Camera:</u>

- Excellent downhole videos were obtained this year using a re-designed borehole camera
- New features of the borehole camera include
  - Forward light head that greatly improved image quality over “ring” lighting used in previous design
  - Internal battery pack, which, along with internal data storage greatly simplified the camera
  - Internal data storage; data downloaded via external USB port
  - Mounts in core barrel


Downhole Camera with Forward Light Head


Camera Battery Pack and Data Storage


2011-12 Camera Image Using Light Ring



2012-13 Camera Image Using Forward Light Head

Logging Tool Test:

- The ability to move a logging tool past deviations was an important requirement for the replicate coring system and operation.
- To test the implementation of this requirement, a 30 lb dummy logging tool that mimicked Gary Clow's temperature logger was lowered through each of the deviation zones.
- Tool was suspended below the borehole camera by a 10 m tether.
- Weight on bit was monitored to verify that the tool did not get hung up at the deviations.

Lessons Learned:

- Overall System
    - The testing and upgrades done since last season were a major factor in the success of this season
    - The ability to configure the drill barrels to a desired length was very important and useful
    - The course alignment procedure is needed for the drill to repeatedly reach its desired inclination
    - An entire deviation can be done with the actuators clocked in the opposing configuration
- Control system/electronics
    - The sonde and winch control programs need work; they don't run reliably and must be restarted frequently
    - Auto azimuth works well
    - No matter how much testing is done off season, you will always have new surprises in the field
- Cutter heads
    - The new broaching cutters worked well, especially with rotation
    - The new milling head worked much better
    - Once an initial ledge was formed, milling with shoes worked very well
    - The coring head cutters must have a tight fit with the pocket in the head

  - A conical tool is very effective in aiding the recovery of metal objects at the bottom of a borehole
- Surface operations
  - The new barrel wrenches worked much better
  - Rigidly mounting the transit to the core transfer truss simplified the alignment procedure
- Machine Shop
  - Critical to the success of this season

Safety:
Overall the 2012-13 season was very safe.

- Air Monitoring
  - Ventilation system worked well again this season
    - Approximately 1-2 air monitor alarms per drill run
    - Alarmed mainly during ascent tripping
    - O_2 sensor still will not hold calibration
    - Trouble keeping screen cleaning sample line frost free
  - Tried to get handheld O_2 monitor ordered from McMurdo, but it had not arrived by the end of the season
  - NICL monitor maintained by Don Voigt/SCO
- Only two reported injuries this season
  - One sustained in McMurdo – Shoulder injury led to subsequent NPQ, return to NZ for MRI and re-PQ. IDDO believes that the McMurdo medical personnel overreacted to the person's injury in sending them back to NZ for MRI.
  - One sustained during packing at the end of the season – Cheek injury just below eye when hit by Amphenol connector while coiling stiff cables

End of Season:
- Began packing the drill, January 28-30 – Good headway was made on next season's work
- Debriefing held at WAIS Divide January 27
- Remaining nine drillers left WAIS Divide on February 1