Recommendation of the Ice Core Working Group to the National Science Foundation on Deep Ice Core Drill Options

April 4, 2003

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Summary

The Ice Core Working Group (ICWG) met on March 11-12, 2003 to discuss and recommend a deep drill design to the NSF. The ICWG had earlier presented NSF with a set of Science Requirements for deep ice core drilling, and these requirements were used by a deep drill design team to formulate four options. In brief, these options were:

Option 1. **EPICA drill with minor modifications,** 10.0 cm diameter
Option 2. **EPICA drill with major modifications**, 10.0 cm diameter
Option 3. **DISC drill based on KEMS design**, 10.0 cm diameter
Option 4. **DISC drill based on KEMS design, 12.2 cm (nominal) diameter**

RECOMMENDATION #1. The ICWG recommends Option 4 as our first choice based on our judgment that this option is most likely to meet the Science Requirements. In particular, the goal of recovering sufficient quality *and* quantity of core in warm ice for continuous-melter chemistry and biology studies is most likely to be met under Option 4. The ice core biological record has never been investigated in ice core studies of climate change, and acquiring sufficient ice to include biological studies opens a new area of science in polar ice coring efforts. Critical tests of abrupt climate change mechanisms that require replicate coring technology are most likely to succeed under Option 4.

RECOMMENDATION #2. As a second choice, we recommend Option 3. The Science Requirement of high-quality core in warm ice is likely to be met by this Option. The Science Requirement of replicate coring is more likely to be met by this Option than by Options 1 or 2.

RECOMMENDATION #3. Our third and last choice is Option 1. This Option will probably not meet all the Science Requirements due to difficulty recovering quality core in warm ice and problems with replicate coring.

RECOMMENDATION #4. We recommend that Option 2 be removed from further consideration, because this is essentially a new design lacking the security of a proven design but without the advantages of a totally new design.

RECOMMENDATION #5. Collecting the Inland Site core on the planned schedule is a higher priority than fully developing and testing replicate coring.

RECOMMENDATION #6. Development of short (20 m) replicate coring capability is a higher priority than long (400 m) replicate coring capability. However, note that we recommend that if Options 3 or 4 are chosen they be designed for replicate coring.

Summary of science implications of drill selection

EPICA drill

The EPICA drill requires the use of antifreeze compounds to drill warm ice. This will preclude biology studies in the oldest ice and in the basal environment. This will also preclude determining the minimum age of the ice sheet because the gas measurements from the basal ice, which are used to date the ice, will be compromised. Thermal drilling will probably also compromise gas-based age measurements of the basal ice.

An additional season will be required to recover the warm ice that will be compromised by the antifreeze compounds. It is questionable whether the limited science that can be can be accomplished on antifreeze-drilled ice is sufficient to justify the effort at the Inland site. (Drilling warm ice is justified at NGRIP in an effort to address the Eemian issue, and Dome-C in an effort to get the oldest ice yet recovered.) If the biology and glaciology goals for drilling the basal ice are compromised by antifreeze compounds, it is difficult to make a compelling argument to recover the warm ice at Inland. This is because better climate records from the time interval covered by the warm ice are available from other Antarctic ice cores at depths where basal flow disturbances are not a concern.

Replicate coring with the EPICA drill is likely to require the design of a new smaller-diameter drill or canceling the replicate coring program. Canceling the replicate coring program would greatly reduce the science issues we can address.

The EPICA drill will only provide enough ice for a limited biology program (and only in the cold ice) and will restrict the amount of ice that can be set aside for future projects.

The EPICA drill will produce core more slowly than the DISC drill, slowing the rate of discovery.

Replicating the EPICA drill will advance the abilities of the United States ice coring community but will not significantly advance the abilities of the international community. Replicating the EPICA drill will not make advances in ice coring even though it is widely recognized that such advances are possible and are required to meet future needs.

DISC 10 cm drill

The DISC drill will enable a biology program in the warm ice and basal environment. This will also allow the glaciology objective to be realized of determining the minimum age of the ice sheet.

The 10 cm DISC drill will only provide enough ice for a limited biology program (in the cold ice) and will restrict the amount of ice that can be set aside for future projects.

The DISC drill is more likely to produce replicate core than the EPICA drill.

The DISC drill will produce core faster than the EPICA drill, speeding the rate of discovery.

The DISC drill will be a significant advance in drill design that will benefit future projects and place the United States in leadership role.

DISC 12.2 cm drill

The 12.2 cm DISC drill will provide enough ice for a robust biology program and continuous-chemistry program while still retaining an archive of ice for future analysis. The 12.2 cm DISC drill is more likely to succeed at replicate coring than the 10 cm drill.

Drill design options and ICWG comments and recommendations

This section contains a distillation of the more comprehensive document, "Comparison of Ice Coring Options for the Antarctic Inland Core Project". This document was prepared by a design team (Eustes, Fleckenstein, Gerasimoff, LaBombard, Lebar, Mason, Rhoades Robl, Taylor, and Wumkes) in advance of the March 11-12 ICWG meeting. For greater detail the reader is referred to this report. The ICWG wishes to emphasize that this drill is to be used for future projects in addition to the Antarctic Inland site core, and this fact influences the design choices. Future projects on the horizon include mid-depth drilling (500-1000 m) at a variety of coastal sites in Antarctica (Roosevelt Island, Dyer Plateau), a deep core in North Greenland, and a deep core in East Antarctica to recover million-year-old ice (see report by ICWG, U.S. Ice Core Science: Recommendations for the Future, from the March 2002 meeting at NSF).

The ICWG was presented with the following four options for a new deep ice coring drill:

Option 1. **EPICA drill with minor modifications,** 10.0 cm diameter
- Redesign bottom hole assembly (BHA) electronics
- Make seals n-butyl acetate-compatible
- Redesign drill head to improve chip transport and mechanical reliability
- Make minor improvements to winch and tower.

Option 2. **EPICA drill with major modifications**, 10.0 cm diameter
- Increase pump rate to improve chip transport
- Increase cable size and winch to provide more down hole power and improve communications

Option 3. **DISC drill based on KEMS design**, 10.0 cm diameter
- Rotating outer core barrel to reduce stress on core
- Stationary inner core barrel for sleeve to protect ice in brittle-ice zone
- Rotating outer core barrel makes replicate coring possible
- Fast data communications for better drill control and core quality
- Larger pump with separate motor to better clear chips to allow drilling in warm ice
- Greater clearance with borehole wall and pumped tripping for faster trips
- Longer core barrel to reduce number of trips (saves one season over EPICA)
- Motor power increased for bedrock coring and replicate coring

Option 4. **DISC drill based on KEMS design, 12.2 cm nominal diameter**
- Same as above but with larger diameter core, giving 50% more ice for science
- Greatly enhances continuous-melter-chemistry science opportunities
- Greatly increases ice available for biology studies.
- Larger annulus due to wider diameter makes replicate coring easier
- Easier construction of BHA with more off-the-shelf parts

At the March 11-12 meeting the pros and cons of these options in terms of the science requirements (but not in terms of cost) were discussed in detail. The committee did not have sufficient information to consider the relative costs of the options proposed.

The ICWG voted unanimously (8-0) to recommend elimination of Option 2 from further consideration. The sense of the meeting was that the modifications were sufficiently major that this was in essence a new design and thus lacked the security advantage of the tried-and-true EPICA drill, without the benefits of a truly new design that could solve several additional problems.

The ICWG voted unanimously (8-0) to recommend that Option 4 be pursued as our first choice, with Option 3 as a second choice and Option 1 as a third choice. This ranking reflects our judgment of the likelihood of meeting the science requirements, but does not consider cost or logistics burden explicitly. The consensus was that Option 1 would only partly meet the science objectives due to problems in warm ice and difficulties collecting replicate cores. Option 3 and 4 very likely will solve the problems with warm ice and replicate coring that the EPICA drill has. Option 4 will give more ice for studies of biological material and continuous-melter chemistry as well as making replicate coring more likely to succeed. The ICWG also recommended that the development and testing of replicate coring capability should not result in a delay of the drilling of the main deep core at the Inland Site. In other words, collecting the Inland Site core on the planned schedule is a higher priority than fully developing and testing replicate coring. In addition, short (20-m) replicate coring capability is more important to develop than long (400-m) capability, although the latter would be desirable and feasibility tests should be done. The ICWG recommended that replicate coring be part of the future of US ice core science in any case.

Justification for recommendations

EPICA with minor modifications – Option 1.

The basic problem with the EPICA drill is that it does not do well in warm ice (> -10˚C). Ice melts from the heat generated by the drill head and then refreezes, causing the chips to get stuck and prevent further progress of the drill (Figure 1). As can be seen from Eric Wolfe's email (attached), the EPICA drill at Dome C only drilled 330 m of core this season in the warm ice. Progress is not only painfully slow in warm ice, but major sacrifices to core quality occurred due to the necessary use of an ethanol-water solution as the drilling fluid. Ethanol-water solution causes partial dissolution of the ice. This core will very likely be unusable for scientific gas studies, as the gases tend to leak out of core that has been partially dissolved (see for example, the gas results from the warm-ice part of the Byrd core as described by Bender et al. (1996), which was drilled using a dissolving solution (glycol-water)). Because of the facts that the planned drilling at the Inland Site, future drilling in North Greenland, and future drilling for million-year-old ice in East Antarctica all involve warm ice near the pressure melting point, the capability to drill efficiently and recover science-quality core in warm ice was deemed critical by the ICWG. To sum up, the EPICA drill will not meet all the science requirements as stated by the ICWG.

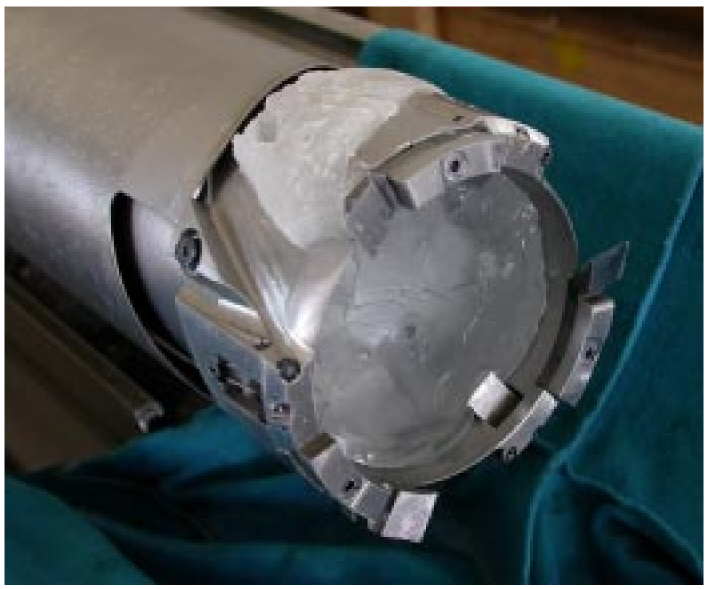

Figure 1. Photo of EPICA drill head showing the buildup of ice that occurs when it is operated in warm ice (> -10˚C). This ice buildup reduces the drilling production rate, reduces core quality, and greatly increases the likelihood of the drill becoming stuck. On the old United States 5.2 inch drill, and the Russian KEMS drill, the ice chips are sucked into the drill closer to the cutters than on the EPICA drill.

It should be noted that there is not unanimous agreement among drillers about the cause of the EPICA drill getting stuck in warm ice. Here is one view from Sigfus Johnsen:

"The EPICA drill has been stuck twice resulting in a lost drill. We attribute this mainly to the negative properties of the Forane 141b densifier that sends the chips lost from the drill to the bottom of the hole. Coping with these chips at bottom was the only serious (and annoying) problem to be dealt with when using the EPICA drill in ice colder than -7 deg C. It is possible that a more efficient pumping system could have alleviated this problem.
The ISTUK drill used at Dye-3, GRIP and Lower Dome was never stuck or lost even though the pumps were only able to suck in 2 liters/minute or about 15 times less than the EPICA drill nominal pump rate. The reason is mainly due to the properties of the freon densifier we used that directed all cuttings toward the hole top and away from bottom. By using n-butyle acetate the EPICA drill with its much higher pumping speed is most unlikely to get stuck since the chips will not want to rest at bottom."

An alternative design that has been proven to work in warm ice is the KEMS drill used successfully at Vostok. This drill has recovered science-quality core from the warm ice near the base of the ice sheet at Vostok, although its progress was slow (see the excellent gas records from warm basal ice in Petit et al. (1999)). The KEMS drill has 4 times the fluid flow of the EPICA system and unlike the EPICA drill the fluid flow is directly over the cutters. This moves chips away from the cutters allowing the KEMS drill to operate in warm ice while the EPICA drill cannot.

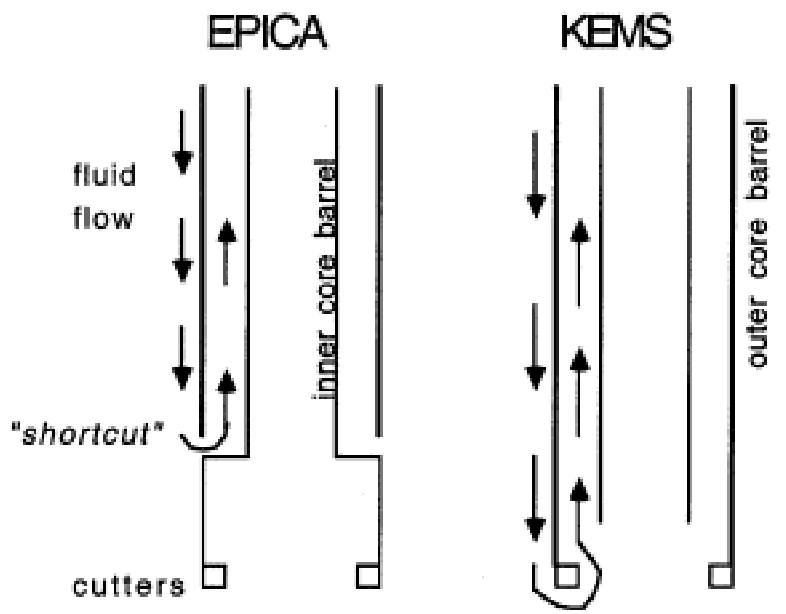

Figure 2. Comparison of the drilling fluid flow paths on the EPICA drill and KEMS (Russian) drill. On the KEMS and the old US 5.2”, fluid flows near the cutters, clearing chips effectively and keeping the cutters cool. Together with the powerful KEMS pump, this prevents melting/refreezing and jamming problems that are inherent to the EPICA drill in warm ice. The DISC drill is modeled after the KEMS.

Other identified problems with the EPICA drill include limited data transmission rate between the bottom hole assembly (BHA) and the surface. This is due to the small cable size and number of conductors. This limits the ability of the operator to know what the BHA is doing in real time, and thus to control the drill for optimum core quality. The motor on the EPICA drill is also small, and it is unlikely that it is powerful enough to meet the science requirements of drilling into bedrock and replicate coring (more torque is required to deviate from the hole than in normal coring). It will be difficult (or impossible by some opinions) to adapt the EPICA drill to replicate coring because of its tight clearance in the borehole and its fixed (non-rotating) outer barrel, both of which make deviation from the hole problematic. The tight clearance makes tripping times long, and the short barrel (3 m) makes trips numerous, both factors making this drill slower such that 3 deep drilling seasons will be required to reach the warm ice at ~3000 m. A fourth deep drilling season is likely to be needed for warm ice. This is 2 more seasons than is anticipated with a new drill design. A final disadvantage of EPICA is that it requires a very precise configuration of its components to operate. This configuration is difficult to maintain even by a highly skilled crew. The design is working so close to its operational limits that there is little margin for error or scope for adaptation to changed circumstances. In a sense, it is a highly optimized drill that is closely tuned for one purpose: drilling a single hole in cold ice (< -10˚C).

Advantages of the EPICA drill include that it has a proven track record of success in cold ice in both Greenland and Antarctica. It has produced generally excellent core quality except in warm ice. It is fairly lightweight compared to other drills (KEMS, US 5.2") and relatively easy to set up and take down. The tipping tower arrangement makes it easy to work on it at the surface. It is mechanically simple and reliable. Other advantages include the potential for sharing of parts with the Europeans, and potential collaboration with the Europeans in developing the drill. Finally, trained drillers from Europe may be available for US projects.

On balance, it was the consensus of the ICWG that the EPICA drill would only partly meet the science requirements. We would get a core, but probably not to the bed, and would possibly only get 90-95% of the way to the bed. The critical science goals of testing theories of abrupt climate change by doing continuous gas measurements with replicate cores would probably not be met by the EPICA drill. Biologists would probably not have enough ice to meet their science goals. The use of antifreeze drilling compounds in warm ice would prevent biological studies in the basal ice. The use of antifreeze compounds would also prevent gas measurements on the basal ice. This would preclude dating the basal ice, and we would not be able to determine the minimum age of the basal ice, which is a key glaciology objective. Similarly, the use of thermal drilling probably would cause gas (O_2 and Ar) to leak out of the cores and fractionate, as seen in the Vostok thermally drilled cores (Bender et al., 1995), which would preclude the dating of the basal ice. There is a significant risk that the drill would get stuck multiple times in the warm ice, as it did at North-GRIP, with implications for core quality and the time required for scientists to get their hands on the ice.

DISC drill based on KEMS design, 10 cm diameter - Option 3

This drill design is essentially the one used at Vostok by the Russians in the warm ice at the base of the ice sheet. It has a rotating outer barrel with cutters mounted on the bottom of the barrel, and a powerful separately controlled motor for the pump. Most importantly, excellent core quality in warm ice has been delivered by this design at Vostok.

Disadvantages with the KEMS design include that there are probably no up-to-date plans available that can be copied (although this should be investigated further by contacting the Russians). The lack of plans implies that this option is effectively a new design, with all the risk that is entailed from venturing into the unknown. However, this risk can be mitigated somewhat by close consultation with Russian colleagues during the detailed design phase and by the planned extensive test season (unencumbered by science goals) in Greenland prior to Antarctic field deployment.

Another drawback of the KEMS design is that it is heavier than the EPICA design. The cable is 16 mm in diameter and the winch is likely to weigh 4 tons with 4000 m of cable. The drilling progress at Vostok was quite slow, although it is not clear why this was the case and if the DISC drill would suffer from this same problem. The KEMS design uses more power than the EPICA design, so more fuel and larger generators are required. However, this increase in fuel is largely offset by the reduction of additional drilling seasons.

The proposed DISC drill would incorporate several improvements into the KEMS design, taking advantage of lessons learned from previous drills. One such improvement is the ability to actively pump the drill in and out of the hole to speed up the tripping time. The friction due to the viscosity of the fluid passing around the drill is the major obstacle to increasing the tripping speed. This friction would be minimized in the DISC design by increasing the clearance with the borehole wall and by pumping fluid through the drill. This would substantially cut down on the total time required to reach bedrock, because tripping time is the major limiting factor in production rate at great depth. Another time-saving feature would be a longer core barrel, up to 5.5 m in length, so that fewer total trips are needed. Estimates of the total time saved are very imprecise, depending greatly on downtime and other contingencies. A conservative estimate is that the DISC design would reach the bed at ~3400 m in one less season than the EPICA drill would require to reach the warm ice at ~3000 m. The EPICA drill would still require a second additional season to recover the warm ice. This estimate does NOT include possible delays due to the higher probability of getting the EPICA drill stuck in the warm ice.

Other advantages of the KEMS and proposed DISC designs are greater motor power to drill into bedrock and to deviate out of the hole for replicate coring. The rotating outer barrel will also greatly facilitate the ability to deviate out of the hole for replicate coring, because cutters on the outside of a special core barrel can ream the sidetrack hole in order to increase its radius of curvature. The rotating outer barrel will permit the inner barrel to contain a stationary plastic sleeve, so that in the brittle ice the sleeve will protect the core and minimize fracturing during retrieval and handling. In non-brittle ice, the inner core barrel may be dispensed with altogether, as the Russians did with the KEMS drill at Vostok. A teflon-coated head also improved the performance of the KEMS in warm ice.

Improved communications with the bottom-hole assembly (BHA) is another advantage to the proposed DISC design. With a multi-conductor cable, dozens of drilling parameters can be monitored by the operator in real time, so that the drill is much better controlled resulting in better core quality (the KEMS cable has 8 conductors). Semi-automation with computer control will also make the drilling sequences much more reproducible and less operator-dependent. For example, cable stretching differs from operator to operator due to small differences in drill speed. This results in imprecise depth measurement, but with automation the stretching is much more reproducible. Semi-automatic control will also reduce the time need for driller training and will result in a safer operation.

The consensus of the ICWG was that Option 3 would probably meet all or almost all of the science requirements including quality core to the bed, bedrock coring, and replicate coring. The main trade-off is a somewhat higher level of risk than Option 1 due to the lack of available plans for the KEMs and the unknowns associated with a new design.

DISC drill based on KEMS design, 12.2 cm diameter - Option 4

This option is nearly identical to Option 3, except that the larger diameter would provide scientists with 50% more ice. The 12.2 cm figure is nominal, being chosen for illustrative purposes, and could change by a few mm. Disadvantages include somewhat heavier bottom-hole assembly and higher logistics burden, making the drill less usable in lightweight mid-depth coring operations that the science community envisions in the next two decades. Estimated extra weight of drilling fluid and core (including containers) is 57,200 kg relative to Option 3 for the Inland Site project. One estimate from a knowledgeable OPP official is that this translates to 10-15 more Herc flights.

Advantages of the larger diameter include the ability to cut three replicate longitudinal samples ("sticks") of 3 cm x 3 cm cross section for continuous-melter chemistry. This promising new technique appears likely to revolutionize ice core science by providing extremely high-resolution major ion, trace metal and isotope data. These data will allow more confident counting of annual layers, improving the chronology. The need for three replicate longitudinal samples, in contrast to the two that would be available under Option 3, comes from the need to repeat measurements at regular intervals for quality assurance. Due to mechanical strength and cleaning requirements, and sample volume considerations, longitudinal samples with at least a 3 x 3 cm cross section are required. Thus there is surprisingly little flexibility in this requirement, and a virtual "step change" in science return is afforded by the increase from a 10 cm to a 12.2 cm diameter core. It is recognized that technology will continue to evolve in the ~5 years before the core is available, so this advantage should be viewed with appropriate caution.

Another advantage of the larger diameter is that more ice will be made available to biologists, whose studies are likely to require an ever greater share of the ice from deep cores. It should be made clear, however, that the larger diameter is not a substitute for replicate coring. In order to accomplish the science goals associated with replicate coring, calculations indicate that a core of 150 mm diameter would be required if it were a single core. This size would require prohibitive amounts of drilling fluid, would fill NICL with unused ice, and is impractical.

The larger diameter hole created by Option 4 would make replicate coring easier, in the opinion of the design team. The replicate core could be a smaller diameter than the main core, and made with a smaller diameter core barrel fitted to the same BHA, so that the annulus between core barrel and borehole wall would be larger, making it easier for the drill go around a bend. Finally, building a larger diameter drill would be easier and less costly, with fewer custom-made components, than building a smaller diameter drill. Many off-the-shelf components would fit into the pressure casing of a 12.2 cm drill, but not a 10 cm drill.

The sense of the meeting was that the extra science that can be accomplished with Option 4 outweighed the relatively modest extra cost and logistical difficulty, although this sense was not unanimous. Even though both Option 3 and Option 4 are likely to meet almost all of the science requirements, Option 4 has a better chance of success with them all (replicate coring in particular). Due to the central position of replicate coring in achieving our science goals, the large improvement in the quality of the chemistry-melter science afforded by the larger diameter, and the needs of the biology community for samples, the ICWG recommends to NSF that Option 4 be pursued as our first choice.

Other recommendations

There was some concern among several members of the ICWG that development of replicate coring capability may turn out to be much more difficult than currently envisioned by the design team, and thus may hamper the overall progress of the Inland Site coring to bedrock. The question was posed to the group, "Would you be willing to wait two more years for the main core in order to get replicate coring to work?" The group clearly answered "no" to this. Therefore, the ICWG recommends to NSF that development of replicate coring capability NOT be allowed to significantly delay the acquisition of a single initial core to bedrock at the Inland Site. Based on current opinion of the design team, replicate coring capability will be developed in parallel with the building of the drill, and will not interfere with progress on the primary goal of quality core to bedrock. However, in the event that it does, the priorities outlined here should hold sway. The "absolute bare minimum definition of success" of the ICWG for the Inland Site is to produce a single 10 cm diameter high-quality core to 95% of ice sheet depth with a drill whose design does not foreclose the option of replicate coring capability in the future.

A second issue concerned the length of replicate cores. As discussed below, the main purpose of replicate cores is to double or triple the volume of ice available for science during rapid events that typically span only a few cm to 10 m in thickness. Hence most replicate cores will be <20 m long. However, a second purpose could be to duplicate the entire bottom 400 m of the Inland Site core. The argument for this view comes from the surprising disagreement between GRIP and GISP2 in the bottom 10% of the ice sheet that demonstrated that the ice was stratigraphically disturbed. If there had not been two cores drilled, we may not have known that the ice was disturbed near the base. This highlights the importance of duplicating a core near the bed. However, a longer replicate core poses greater technical or logistical challenges. It is easier to get a short core barrel around the corner made by a deviation, but short barrels mean more trips. Hence if duplicating the bottom 400 m of the core is to be practical, a way to get the long core barrel (3 m) around the deviation must be developed. In concept, this could be done by reaming to widen the hole. The ICWG recommends to NSF that short (20 m) replicate coring capability be given a higher priority than long (~400 m) duplicate coring capability. If possible, both capabilities should be developed, and the feasibility of long-duplicate coring should be explored.

Finally, the management plan proposed at the meeting was not well developed. A solid plan needs to be developed which will lead not only to development of a capable drill, but also to a qualified team for maintenance and deployment.

General recommendations to NSF and the science community

No temperature control is needed for the cores recovered in the course of the Greenland test (the gas community is not interested in this ice). No science proposals should be considered by NSF for this ice, until after it is drilled. The overriding objective of this test is for the drillers to learn to optimize core quality. To do this they must be able to experiment freely and ruin a lot of core. The core will be set aside in snow-cave storage onsite. Only if the drillers complete their test and have remaining time, will science-driven coring be done (such as a replicate core in the Younger Dryas from the GISP2 borehole).

The ICWG recommends that testing the feasibility of the concept of replicate coring with a mechanical ice-drill should not wait until summer 2005. This should be tested in 2003 or 2004 with an existing drill in a laboratory test bed or an Alaskan glacier, in a dry hole. This way any show-stoppers can be identified early, and this test can inform the design process.

Some reservations were expressed about the loss of mobility implied by the 12.2 DISC design. Perhaps the European drills will serve as the lighter, portable ones, and the US drill will be the one that goes to bedrock.

The sentiment was expressed that we should keep enough young people going out in the field to train the next generation, despite the policy of minimizing the number of researchers in the field.

Background information: Why replicate coring?

While replicate coring is already clearly stated as a Science Requirement by the ICWG, it was felt that some background information on the science behind replicate coring would be helpful. The impetus to develop replicate coring capability comes from the recognition that certain small intervals of the GISP2 core in the NICL archive have been completely consumed. Most other parts of the core, however, still have most of the ice remaining (averaging 70% for the Holocene; Eric Cravens, NICL database). These

intervals of consumed ice are times of rapid climate change, when massive changes in ice core chemistry, gases, and isotopes occur over the space of 5 or 10 m in the core. Work on these intervals has yielded enormous scientific returns, even though they constitute less than one percent of the length of the entire core. In other words, the usage of ice and the science return have been extremely heterogeneous with depth. Therefore, it is argued here that the volume of ice recovered should also be heterogeneous with depth.
Replicate coring is the practice of deviating the drill into the borehole wall to take a second core that is nearly parallel to the main core (Figure 3). This is common practice in the oil industry, but has been little done in ice coring (except for the Russian deviation around stuck drills at Vostok and one experiment by Victor Zagarodnov in a test well, both done with thermal drills). Replicate coring could in principle triple or quadruple the volume of ice available in short key intervals.

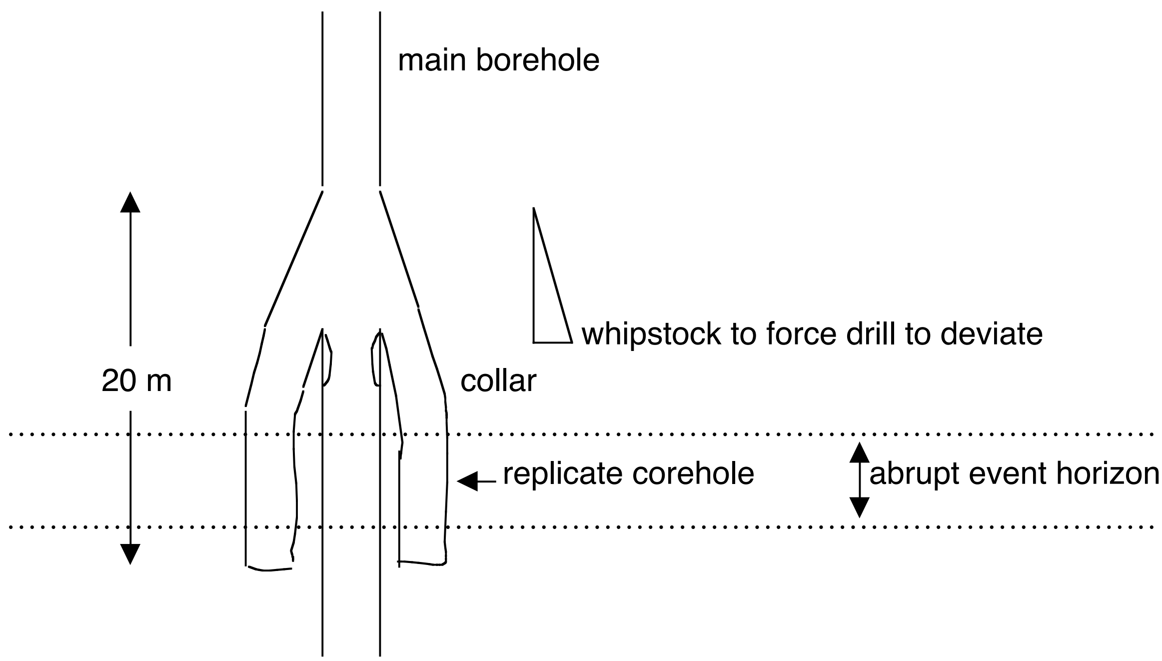

Figure 3. Schematic of replicate coring. A toroidal collar ("donut") is permanently placed in the borehole to support the whipstock, which is removable after completion of replicate coring. The collar permits subsequent logging to be done of the borehole. Replicate coring must be done starting at the bottom of the hole and working upwards.

A major goal of the Inland site core is to test hypothesized mechanisms of abrupt climate change. This can be done by examining at decade-scale precision the relative timing of changes in methane (an indicator of tropical and Northern Hemisphere climate) and local West Antarctic temperature as recorded by inert gas isotopes (^{15}N and ^{40}Ar). Carbon dioxide is likewise expected to respond to abrupt climate change because its atmospheric concentration is set by the partial pressure of this gas in sea surface waters, which in turn is very sensitive to sea surface temperature. Relative timing of carbon dioxide shifts and inert gas isotopes in the ice core can therefore also define the sequence of temperature events in the ocean versus Antarctica. Importantly, these changes are so fast (occurring in ~30 years) that the gas measurements must be made continuously, representing one sample per year. These measurements require large volumes of ice, however, which would consume most of a single 10-cm core. Therefore conventional ice coring would not allow these hypotheses to be tested due to lack of ice. Replicate coring would make possible the dedication of an entire core to gas measurements. Registration of the replicate core to the main core can be accomplished by matching the continuous electrical conductivity and water isotope records.

Additional types of measurements are justified at times of special interest. For example, pollen and leaf wax in the ice may indicate the speed of biotic change across abrupt climate events. Volcanic eruptions leave thin horizons of sulfate, the sulfur isotopes of which would reveal source characteristics. Mass-independent oxygen isotope fractionation in the sulfate would be diagnostic of atmospheric oxidative pathways. Tephra analysis would fingerprint the volcanic source. Magnetic field collapse 41,000 years ago (the Laschamp event) produced a spike of cosmogenic radionuclides (Be-10, Cl-36) that could be analyzed at annual resolution for clues to solar variability, which is more sensitively recorded in the absence of a geomagnetic field. Possible biotic responses to geomagnetic collapse deserve investigation. The possibility of nitrate spikes from nearby supernovas is being explored, and isotopes of nitrate would be diagnostic. Extraterrestrial impacts should leave iridium spikes, for example the 1908 Tunguska event whose imprint was seen in the GISP2 core. All these events share the property that they are abrupt and occupy a very small amount of the ice in a core. Their study involves special measurements that cannot be made all along the core, and these measurements often require much more sample than classical ice core measurements. Replicate coring would make these studies possible.

Finally, a critical need for replicate coring arises from the need to reproduce the data supporting controversial interpretations. For example, the Siple Dome record is missing a meter of core (due to poor core recovery) at a rapid climate change event 15,000 years ago that appears to have led the Bølling warming in Greenland by several hundred years. The inability to replicate this significant and controversial interpretation, and to fill in the gap created by the missing core, has hampered acceptance of this finding. The importance of replication was also dramatically illustrated by the divergence of the GISP2 and GRIP records near the base of the ice sheet.

Recommended schedule for drill design, construction, and Inland Site core

2003	June-July	Engineering meeting with European, US, Russian, and Japanese drillers to brainstorm on a next-generation International Deep Ice Sheet Coring (IDISC) drill
	September	NSF decision on drill option
		ICDS hires project manager
		Formal design commences
2004	April	Finish design, begin fabrication
	June 1	*Submit science proposals for Inland site work ("1st try")*
	October	Finish drill fabrication
		Begin in-house testing
		Make necessary adjustments
2005	March	Pack drill and ship to Greenland
		Select drill site
	April-May	Drill test, focus on core quality in brittle ice
	June 1	*Submit science proposals for Inland site work ("2nd try")*
	July-August	Extended-season drill test, focus on replicate coring
05/06	November-March	Set up camp at Inland Site
		Build skiway
		Transport butyl to site
		Construction: tunnels, core handling rooms
		Drill firn, set casing
		Drill 4" dry hole cores, firn air study
		Complete science investigations that are required in advance of core collection, or which make logistical sense to move to the first field season.
		Back in Wisconsin: Repair/reconfigure drill as needed
		Build 3 copies of optimized BHA
2006	*June 1*	*Submit science proposals for Inland site work ("3rd try")*
	July	Training of core handlers at NICL
06/07	November-March	First deep drilling season (70 day long season)
		Brittle ice cored and set aside to relax
		Shallow ice and ductile ice retro to NICL
2007	July	Training of core handlers at NICL
	May-August	*Core processing line (CPL) at NICL*
07/08	November-March	Second deep drilling season (70 day long season)
		Bed reached.
		Log borehole (caliper, inclination, optical, sonic, grainsize, temperature)
		Subsample all cores for rough $\delta^{18}O$ "roadmap"
		Retro ductile ice
2008	*May-August*	*Plan replicate coring locations*
	May-August	*Core processing line (CPL) at NICL*

08/09	November-	Log borehole for temperature Drill bedrock core Replicate coring Retro all remaining ice including brittle ice
09/10	December	Close camp Move drill to next site

References

Bender, M., T. Sowers, and V. Lipenkov, On the concentration of O_2, N_2, and Ar in trapped gases from ice cores, *J. Geophys. Res.* **100**, 18651-18660 (1995).

Petit., J.R. *et al*.,Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, *Nature* **399**, 429 (1999) .

Date: Wed, 26 Feb 2003 07:54:57 +0000
From: "Eric W Wolff" <ewwo@bas.ac.uk>
To: <mark.twickler@unh.edu>
Subject: Re: ICWG Meeting
X-MailScanner: Found to be clean
Status:

Hi Mark,

I am not sure what information you have received from Europe during the last season - I had the impression that people knew what was appening in EPICA - but just in case, here is a summary of EPICA progress that you may want to convey to the ICWG meeting.

EPICA continued this season with both its ice core sites, at Dome C and Dronning Maud Land (DML).

At Dome C, the idea was to drill as far as possible into the ever-warmwer ice towards the bed, while processing the remaining core that was drilled in the last season. Drilling started this season at 2870 m, and it was possible to continue with essentially the same setup as before to about 3100 (temperature about -6 degreesC). After that, increasing problems with refrozen ice and chips forced other solutions to be tried. Some efforts with new designs of drill head were not as satisfactory as was hoped, and eventually drilling was continued using and ethanol water system. Although this was very slow, and the core quality deteriorated significantly, a depth of 3200 m was achieved by the end of the season. The new estimated total depth is 3300 m, so just 100 m to go. Logging, DEP and ECM has been carried out on all the core drilled. The rest of the processing line (cutting of samples, thin sections, CFA chemistry and packing) processed all the core from 2200 m to 3140 m. It is impossible at this stage to say what age has been achieved. However, a preliminary interpretation of the DEP/ECM signal is consistent with model estimates that the age at 3120 m could be about 820 kyr.

At DML, progress was also very good this season. The drilling now seems to have become well-established and smooth. The final depth of 1551.55m at the end of the season is, according to first estimates, equivalent to an
age of approximately 50,000 years before present. In total 1113 m of
core were drilled this season. All of the core has been logged, DEP-ed and packed for transport to Bremerhaven where processing will take place later in the year.

As an additional piece of information (not part of EPICA), a 6 person UK/French team finally reached Berkner Island this season, after heavy sea ice prevented any access via Halley last season. They have constructed a drill trench, drilled and cased a pilot hole (drilling was continued to 85 m) and started to set up the new 1000 m drill ready for next season. In parallel with this activity, an extensive programme of firn air sampling for the EU-funded CRYOSTAT project was carried out in another hole.

I hope this is helpful. Have a good meeting.

[redacted]

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