Replicate Coring and Borehole Logging Science and Implementation Plan:

WAIS Divide Ice Core and Beyond

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Abstract

Replication of results is fundamental to experimental science, and replication of key findings in ice core science should be no less a requirement. The current practice of taking a single deep ice core from a given region makes replication and verification of the validity and spatial representativeness of key results difficult, and leaves the record vulnerable to missing intervals of ice (due to drilling problems, for example). The GISP2-GRIP experience highlights how important it is to have two cores in validating the stratigraphic integrity of the records. Furthermore, scientific demand for ice samples has been and will continue to be very unevenly distributed, with the ice core archive being completely depleted in depth intervals of high scientific interest (abrupt climate changes, volcanic sulfate horizons, meteor impact horizons, for example). In other intervals, however, nearly 90% of the ice remains, and space for storage at the National Ice Core Laboratory is becoming increasingly scarce. The lack of sample in key horizons hampers development and application of new techniques, and discourages entry of young investigators to the field.

The ability to obtain additional volume of ice sample in selected intervals would address these concerns and add value to the scientific return from ice coring. The US Ice Core Working Group recommended in 2003 that NSF pursue the means to accomplish taking of replicate samples, termed replicate coring. This recommendation was part of an agreement to reduce the diameter of the core to 12.2 cm to lighten logistics burdens, and the science community accepted the reduction in ice sample with the understanding that replicate coring would occur and provide extra sample volume in key intervals. The WAIS Divide effort would particularly benefit from replicate coring, because of the unique quality of the expected gas record and the large samples needed for gases and gas isotopes.

This Science and Implementation Plan discusses the scientific goals that may be attainable using replicate coring, and lays out a plan for achieving them. It does not make recommendations on the technological approach to obtaining extra sample, but does outline the scientific pros and cons of various approaches. In particular, it is of critical importance that the **taking of replicate cores not compromise other scientific activities in a substantial way**. Borehole logging is one such activity that may be impacted to varying degrees by the choice of technology for replicate coring. One technology under discussion is deviating the drill out of the borehole to take extra ice samples, using a device known as a whipstock to force the drill to one side. With input from the borehole logging community, it has become clear that leaving devices such as whipstocks in the hole would fundamentally compromise the science from borehole logging. Therefore we make the recommendation that **1) Replicate coring activities adopt a "leave no trace" ethic to the extent possible; and 2) that any whipstock or other device must be entirely removeable.** We recognize that scarring of the borehole wall is unavoidable with deviation coring, but recommend that NSF study ways to minimize the potential for logging tools to become stuck on such scars. Furthermore, if deviation coring is the chosen method, we recommend that a full 2 year period is made available to logging activity, after reaching the bed, but before deviation coring commences. This will minimize adverse impacts on logging activity. We also recommend that NSF study the costs and benefits of other technological options, such as taking entirely separate second cores a few meters or kilometers away; these options need no such 2 year period.

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Acknowledgements

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Eric Cravens of the National Ice Core Laboratory (NICL) provided us with ice availability data.

I. Motivation: Why pursue replicate coring?

The pattern of depletion of the ice archive in deep ice cores has shown that scientific demand for ice samples has historically been very unevenly distributed with depth (Figure 1). Small intervals of high interest, such as major climate transitions or volcanic ash layers, are completely depleted and little or no archive remains, prohibiting further studies and precluding application of new techniques that arise with time. The entry of young investigators into the field is also hampered by this lack of sample. In contrast, large amounts of ice remain in the archive in most depths, typically comprising more than half of the core cross section. These "less interesting" intervals occupy ever-scarcer space in the National Ice Core Laboratory (NICL) freezer.

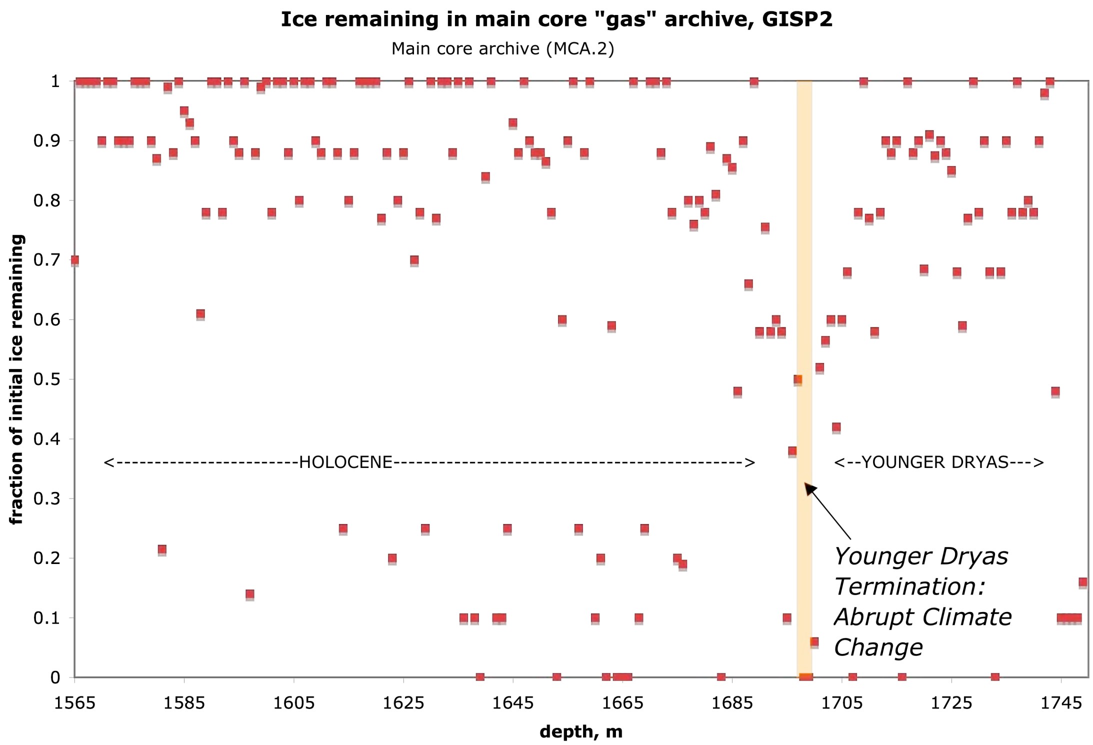

Figure 1. Fraction of main core archive (MCA.2) remaining in GISP2, showing that the end-of-Younger Dryas interval is entirely depleted. Less-demanded ice from the Holocene is still abundant, however. Each point represents approximately a one-meter interval. Source: Eric Cravens, NICL, 2008.

Taking additional (replicate) ice samples in specific depth intervals of high scientific interest would alleviate this problem. In a document written by the US Ice Core Working Group in 2003, it was recommended by the scientific community that the US develop the capability to recover replicate ice samples (US Ice core Science: Recommendations for the Future, 2003; available at http://nicl-smo.unh.edu/icwg/ICWG2003.pdf).

A second motivation for replicate coring is to provide a check on the stratigraphic integrity of an ice core near the base of the ice sheet. The experience of the dual Greenland ice cores GISP2 and GRIP, separated horizontally by just 27 km, showed that the bottom 200 m of the cores were disturbed by ice folding. This stratigraphic disturbance would probably have gone undetected for much longer, with more damaging consequences, if there were only a single core.

More broadly, replication is a fundamental tenet of experimental science. In most scientific fields that involve experiments, no result is generally accepted until it has been independently replicated; the field of ice core science should be no different. The finding of extraordinary past events, such as abrupt climate shifts or meteor impacts, requires an extraordinary level of proof. Replication in such instances is therefore mandatory. Past ice coring has partially met this need in an *ad hoc* way with single cores in widely separated regions, but the real regional differences in climate, ash layer thickness, etc. that exist between these core sites obscures the interpretation and leaves open the question of whether a core taken just 1 meter away would also show these differences.

A third motivation is that core quality is seldom perfect and recovery is almost never 100% complete. For example, in the Siple Dome core a 1-meter section of the core was reduced to rubble during drilling and was recovered in small pieces that did not retain their stratigraphic order (673-674 m depth). After analysis it was discovered that this particular meter comprised part of the most significant abrupt climate warming of the entire 100 kyr record (15 kyr BP). Because of the gap in the record from this critical part of the core, scientific conclusions could not be firmly drawn about the timing and significance of this warming event. To this day, this event remains essentially uninterpreted in the scientific literature (Taylor et al., 2004). Replicate coring would allow the recovery of a second short core in cases such as this, to plug critical gaps in the record.

A fourth motivation stems from a strategic decision made for logistics reasons by the Ice Core Working Group and NSF in the design of the DISC drill (ICWG Recommendation for a Deep Ice Core Drill, 2003; see attached document). A smaller diameter core was accepted, instead of the 5.2 inch diameter used for GISP2, Taylor Dome, and Siple Dome, on the basis that replicate coring capability would be developed to provide the scientifically anticipated volume of ice samples. The smaller diameter core was thought to provide greater logistical flexibility and adaptability, including a lighter weight drill sonde that could be easily adapted to an intermediate-depth coring objective (future drilling under the IPICS agenda includes this). The ability to take additional samples to increase the volume of ice available for science was thus explicitly part of the agreement to pursue a 12.2 cm diameter core in the DISC drill, right from the beginning.

Replicate coring has particular significance to the WAIS Divide effort, because the WAIS Divide core is intended to provide the best and highest-resolution atmospheric gas record through the major climate changes of the past glacial cycle. Because Greenland ice does not preserve CO_2, the GISP2 record lacks this key greenhouse gas. Furthermore, Siple Dome does not have a high enough accumulation rate or cold enough temperature for a world-class CO_2 record, suffering from slight artifacts probably due to melt layers (Ahn et al., 2004). The anticipated WAIS Divide record has been viewed for more than two decades of planning as the likely "gold standard" pre-Holocene gas record of the last 100,000 years (The Law Dome core covers the Holocene). However, high-resolution gas studies become increasingly difficult with depth in the core due to layer thinning, which restricts sample availability. Replicate coring thus has perhaps its most important role to play in providing additional samples at great depth, in order to maintain the high resolution of the gas records as annual layer thinning makes samples scarce. It is this - the extraordinary value to science of having a suite of many different gases and gas isotopes with high resolution from a single core, all co-registered on the same depth scale, that perhaps best justifies the expense and effort of replicate coring.

To more clearly illustrate the added value to science of replicate coring, two specific scientific case studies are described in detail, which are not possible with only a single 12.2 cm core under the current load of funded projects. These are by no means the only such projects that would be enabled by replicate coring capability; but they are illustrative and are provided as examples. Scientific target intervals for the WAIS Divide core are then summarized.

The purpose and scope of this document is to make the case for the scientific need for replicate ice samples, and to articulate the scientific motivation for the US community to develop this capability. The intent of this document is not to specify which technology is best suited to achieve this goal. Various technological approaches have been discussed, including 1) deviating the drill out of the borehole to take short replicate cores, termed "deviation coring", 2) taking an entire second core several meters away from the first borehole, and 3) taking an entire second core several tens of kilometers away as in the case of GISP2 and GRIP. Each of these technologies has benefits and drawbacks, and some discussion of the potential scientific and logistical trade-offs is included here. A complete and detailed cost-benefit analysis of each option is beyond the scope of this document, and is not attempted. However, some supporting information that could enter into such an effort is provided.

Finally, it is important that replicate coring activities not foreclose other major scientific activities, such as borehole logging. This document adopts the principle that the overall science return from the whole project should be maximized. Recent advances in borehole logging techniques have provided major new scientific data that are extremely complementary to ice core data, such as optical logging, and these techniques should not be compromised in any substantial way. Some small trade-offs are inevitable, however, and this document attempts to describe those so that advance planning can be done to minimize their impact. To further this end, an entire document written by several members of the borehole logging science community is included within this Science and Implementation plan (titled "Borehole logging and Replicate Coring"). Overall, the US Ice Core Working Group believes that both replicate coring and borehole logging can coexist with virtually all of their respective goals intact.

II. Case study #1: An ultra-high-resolution gas record of Termination I

Although the ultimate cause of glacial terminations is undeniably Milankovitch-type changes in the distribution of sunlight, the proximate cause and detailed mechanism by which the Earth leaves a glacial period is still not understood (Kawamura et al., 2007; Huybers and Wunsch, 2005). This zero-th order change of environment has far-reaching implications for our understanding of biological, geomorphological, chemical, and even magmatic/volcanic aspects of the Earth system. In some sense, because we do not understand why we are in an interglacial period now, we do not understand why we have the climate that we do. Predicting future climate now lends urgency to the task of improving this situation.

In particular, it is not clear how the retreat of northern ice sheets due to increases in summer sunshine (the Milankovitch theory) leads to warming of Antarctica and rising atmospheric CO_2 (Figure 2). Alternative theories involving southern hemisphere insolation have been proposed (Broecker and Henderson, 1998; Stott et al., 2007). The cause of CO_2 increase remains enigmatic, although much circumstantial evidence hints at a role of the deep ocean (Toggweiler, 1999; Adkins et al., 2002; Marchitto et al., 2007). A basic problem that obscures the situation is that the exact timing and sequence of CO_2 rise and other events at Termination I are still not well resolved (Monnin et al., 2001; Loulergue et al., 2007), partly due to the low accumulation rate of most Antarctic cores used for CO_2 measurements in this time interval and the consequent large uncertainty in the gas age-ice age difference (Blunier et al., 2004; Landais et al., 2006).

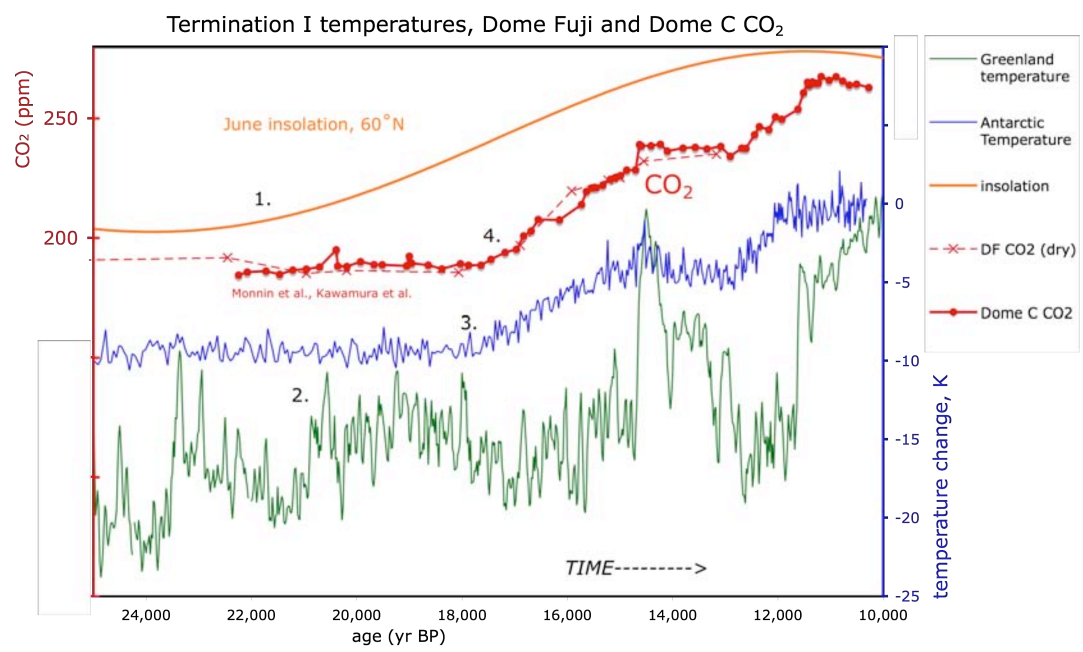

Figure 2. Records of the last deglaciation, with one possible sequence of events (numbered 1-4). However, this sequence is not well known, and motivates an ultra-high resolution study using replicate coring. Temperature data are from Jouzel et al. (2007) and Cuffey and Clow (1997).

For these reasons a major step forward would be to create an ultra-high-resolution CO_2, methane, and gas-based ($\delta^{15}N$ and $\delta^{40}Ar$) local temperature record, all on a layer-counted timescale with better than 1% age accuracy (corresponding to an age uncertainty of 200 yr at 20 ka). Due to the high accumulation rate, the anticipated gas age-ice age difference is only 200-400 yr and so would add minimal uncertainty (40-80 yr) to the chronology. Methane and CO_2 isotopes would also be done at lower resolution (50 yr).

The precise relative timing of different events in such a record will shed light and provide important clues on the mechanism of the Termination. The needed resolution is 5 yr during the rapid changes in CO_2 and methane between 14.8 and 14.4 ka (the Bølling transition), where CO_2 appears to have undergone an abrupt "jump" of about 10 ppm in the low-resolution Dome C record (Monnin et al., 2001). A similar resolution is needed at the beginning of the Younger Dryas interval, 13.0 to 12.6 ka, when CO_2 appears to have resumed its rise after pausing in the Antarctic Cold Reversal (ACR) (Monnin et al., 2001). The same applies to the end of the Younger Dryas, when CO_2 may have increased in another 10 ppm "step" (Monnin et al., 2001). The relative timing of methane versus CO_2 can be determined with virtually no uncertainty due to the fact that both gases are trapped in the same core, and likewise for nitrogen and argon isotopes (indicators of local site temperature change at WAIS Divide). For the rest of the record, between 18 ka and 11 ka, a resolution of ~20 yr is adequate.

Because 5 years amounts to approximately 20 cm at the anticipated layer thicknesses for this interval in WAIS Divide, this level of detail requires far more sample than is available and so is impossible to achieve with the single core currently planned. The cut plan cross section is already essentially spoken for, given existing funded projects. Therefore the recovery of additional ice via replicate coring is essential for this scientific goal to be realized.

III. Case study #2: A test of the Bipolar Seesaw mechanism at Interstadial 8

For more than a decade it has been apparent that during the last glacial period Antarctic temperatures varied in a systematic but asynchronous manner with Greenland temperature (Blunier et al., 1998; Blunier and Brook, 2001). This temporal relationship was first revealed using atmospheric methane and oxygen isotopes of O_2 for precise interhemispheric chronological synchronization (Sowers and Bender, 1995, Blunier et al., 1998). The pattern is this: Antarctica gradually warms while Greenland is cold, in a millennial-scale Stadial event, and then Antarctica begins cooling when Greenland warms abruptly in an Interstadial event. Both hemispheres appear to reach maximum temperatures synchronously, and both cool together (EPICA Community Members, 2006).

This observation led to the so-called thermal Bipolar See-saw hypothesis (Broecker, 1998; Stocker and Johnsen, 2003), which holds that changes are driven from the North by switching between "off" and "on" modes of the Atlantic Meridional Overturning Circulation (AMOC). This hypothesis posits that heat is removed from the southern hemisphere by the AMOC, causing cooling in

Antarctica while warming Greenland (the "heat piracy" idea of Crowley, 1992). The Bipolar Seesaw hypothesis, in its simplest form, makes a clear prediction: the abrupt warming in Greenland should lead the cooling in Antarctica by several decades to centuries (Schmittner et al., 2003). This temporal pattern is observed in model experiments in which the AMOC is "shut down" by freshwater addition to the North Atlantic ocean (Vellinga and Wood, 2002).

However, this idea seems to be inconsistent with the observed timing of several events, notably the onset of the Antarctic Cold Reversal, which in the Law Dome record appears to lead the abrupt Greenland Bølling warming by several hundred years (Morgan et al., 2002). The Siple Dome record may show a similar timing, but the missing piece of core mentioned above precludes a firm conclusion (Brook et al., 2005). Farther back in the record, in MIS 3, the chronological uncertainties remain too large at present to discriminate among the various hypotheses (>200 yr).

The WAIS Divide ice core allows a unique opportunity to critically test the Bipolar Seesaw hypothesis, because its high accumulation rate permits both a small gas-ice age uncertainty and the deployment of the nitrogen-argon gas-based temperature indicator. [At lower accumulation rates, such as at Siple Dome, the gas thermometer fails due to thinner firn, and longer bubble close-off duration, which makes the firn thermal equilibration time shorter than the time needed to clearly record a gas-isotopic signal in the bubbles (Severinghaus et al., 1998; 2003; Severinghaus and Brook, 1999).] The gas thermometer should give direct temperature signals that can be compared with methane from the same core, allowing an estimate of the relative timing of Greenland warming and Antarctic cooling with only decade-scale uncertainty. If it can be shown that Antarctic cooling began 50 years before the Greenland abrupt warming, for example, then the Bipolar Seesaw hypothesis will have to be rethought.

The best event for testing this hypothesis is probably Interstadial 8 (also known as AIM 8 for Antarctic Isotope Maximum 8), because it has a very clear and rapid cooling in the Siple Dome record, which is synchronous with the abrupt Greenland warming within the current ~200-yr uncertainty (Figure 3). Because the lag may only be ~30 years (Vellinga and Wood, 2002), it is essential that 5-year sample resolution be obtained to answer this question. Past experience has shown that even 10-yr resolution provides an unsatisfactory answer, because the entire conclusion typically rests on a single data point when the lag is only 30 yr. At 5 yr spacing, virtually the entire core would be consumed by the needed measurements. For this scientific goal, therefore, replicate coring of a small (~35 m long) interval is needed, that spans the abrupt methane increase at Interstadial 8.

CO_2 is also of interest; recent (unpublished) results from the EPICA Dronning Maud Land (DML) core suggest that CO_2 exhibits ~8 ppm "jumps" at all the abrupt Interstadial Greenland warmings (Lüthi et al., 2008). Ideally, methane, CO_2, and nitrogen/argon isotopes would all be measured in such a replicate core.

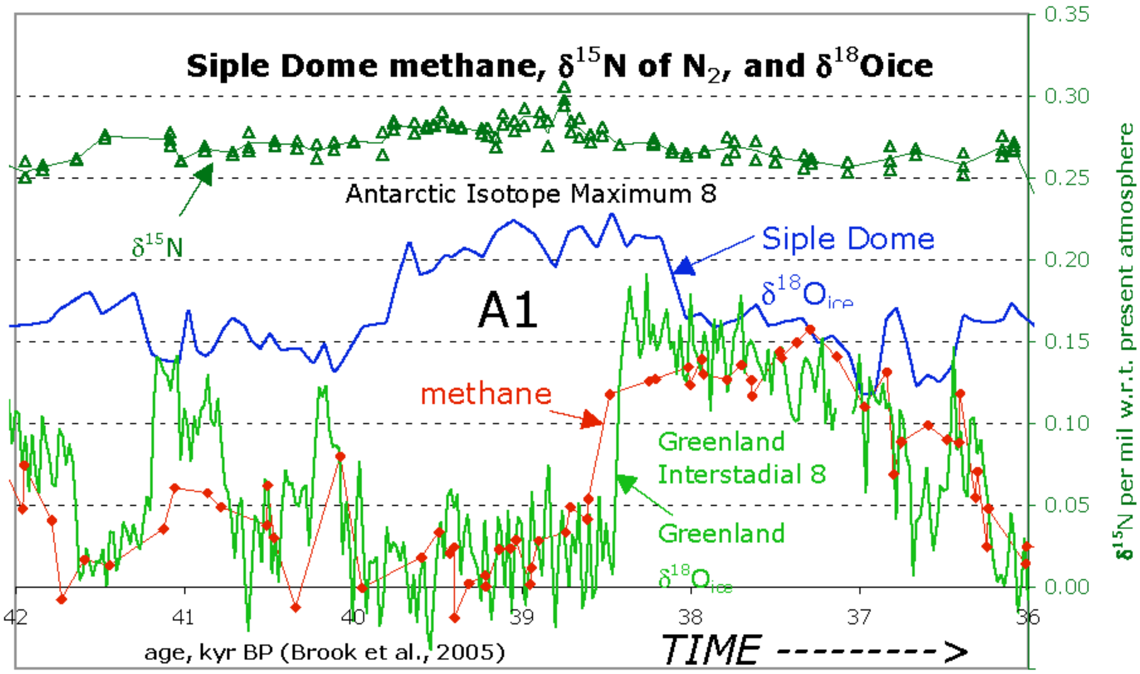

Figure 3. Records of Antarctic Isotope Maximum 8 or Interstadial 8 from Siple Dome and GISP2, synchronized with methane (Brook et al., 2005). Current age uncertainty precludes firm conclusions about the phasing of cooling at Siple Dome with respect to abrupt warming at Greenland. The WAIS Divide core can refine this phasing and provide a critical test of the Bipolar Seesaw hypothesis [which predicts that the GISP2 abrupt warming should lead the Antarctic cooling by several decades], if replicate ice samples are obtained in this interval.

IV. Target intervals for replicate coring in the WAIS Divide core

The case studies discussed above provide some of the leading examples of how we will use replicate coring. When the time comes to select the depth intervals for coring, the WAIS Divide executive committee will take into consideration all relevant issues and select the final depths. However, at this point we envision four intervals where replicate cores will be taken, in order of priority.

1) the bottom 200 m of the core, where the ice will be extremely compressed and replication will permit maintenance of high resolution gas records, in addition to a check on stratigraphic integrity (this interval may contain the last Interglacial, a period of high scientific interest, and is thus the highest priority);

2) AIM 8 (Interstadial 8) with a 35-m long replicate core (spanning ~3 kyr);

3) ACR onset/Bølling event with a 50 m- long core (gas age of 15.0-14.2 ka); and

4) ACR end/Younger Dryas event with a 130 m-long core (gas age of 13.0-11.5 ka).

The depths of these four intervals [in the gas phase, in terms of gas age] correspond approximately to 3200-3400 m, 2985-2950 m, 2260-2210 m, and 2100-1970 m (Figure 4). In total these intervals comprise 415 m, which is slightly more than 12% of the main core length of 3400 m. Because the diameter of the replicate cores will be slightly less than the main core (10 cm or so), the total extra volume of borehole implied by these figures is about 10%.

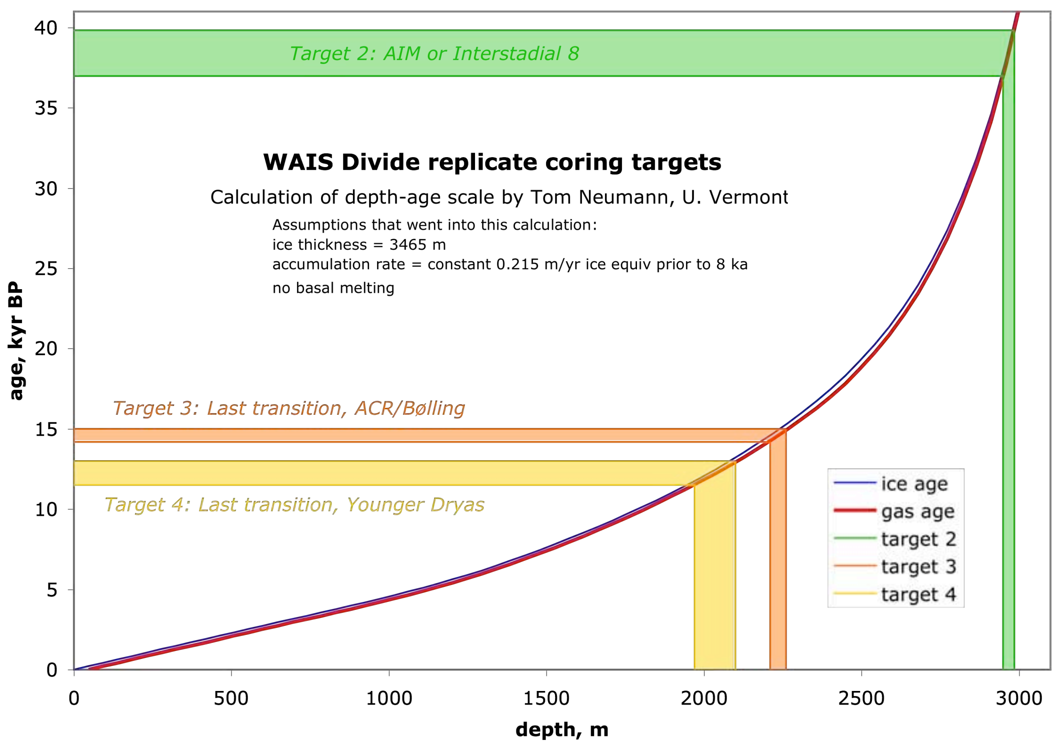

Figure 4. Depths of target intervals for replicate coring in WAIS Divide. Target 1 is the bottom 200 m of the core, and is not shown here. This depth-age calculation does not account for the known reduction of accumulation during the glacial period, and thus is likely to underestimate the duration of age spanned by the target intervals. Actual target depths will be decided after completion of a preliminary stable isotope profile.

Drilling fluid densifier (HCFC-141b) availability is of some concern at the time of this writing; it is not clear at this point that sufficient volume of drilling fluid is in hand to supply this extra 10% of volume. With phase-out of this substance under the Montreal Protocol, it has become difficult to find supplies on the open market. Thus efforts to find a replacement fluid, and in particular a fluid that is "backwards-compatible" with the existing fluid in the borehole and the seals on the DISC drill, are critical and should be given the highest priority by NSF. Another avenue that should be explored is the possibility of recovering 141b-kerosene mixtures from old boreholes that are no longer used for scientific purposes. These fluids would be compatible with the WAIS Divide fluid, and there would also be an environmental dividend from cleanup of old boreholes.

Dielectric Profiling (DEP) and Electrical Conductivity (ECM) will be measured on the replicate cores to precisely register them to the main core. Stable isotopes of water ($\delta^{18}O$ and δD) may also be measured if a PI proposes to do so, because this will afford an opportunity to assess the spatial decorrelation effect of sastrugi and other surface disturbances on the records, and to assess the degree to which cores taken a few meters apart bear the same (regional) climate signal.

The timeline planned for bedrock drilling, borehole logging, and replicate coring takes into account the need for several years of lab analysis for the creation of a first-order timescale on the main core, in order to precisely refine the above depth estimates for targets for replicate coring. Bedrock drilling and some borehole logging will be done in the season following arrival at the bed, although some logging will be disturbed by the bedrock drilling (such as temperature logging). Replicate coring will commence in the season two full years following the arrival at the bed. This delay will permit most logging activities to take place prior to disturbance of the borehole wall by replicate coring, if indeed the chosen technology disturbs the wall. For logging of the deformation of the borehole shape, this delay will permit a minimum of 3 visits (two full years of deformation), if logging can be done at the very beginning of the season that replicate coring begins. Because logging is typically rapid, taking a few days at most, this will not interfere substantially with replicate coring.

In the event that the bottom 200 m (for example) is immediately and obviously stratigraphically disordered upon recovery of the main core, then the replicated interval should shift upwards to recover the deepest 200 m that appears intact. Steeply inclined layering, sudden changes in layering orientation, abrupt inflections in the temperature profile, and/or silty ice layers all constitute clues of stratigraphic disturbance. This strategy maximizes the science return in favor of reconstructing an atmospheric composition history, which is the main purpose of the core, because of the difficulty of deciphering a disordered stratigraphy.

V. Beyond WAIS Divide: 1.5-Million-Year-Old Ice

Replicate coring capability in some form will be needed for the planned IPICS Oldest Ice project, which aims to recover intact records of the 41,000-year oscillations in climate that occurred between 1.3 and 1.5 million years ago, along with greenhouse gas concentrations. Ice of this age is likely to exist in east Antarctica in areas of extremely cold surface temperature and low accumulation rate (for further detail see the Oldest Ice science plan at http://www.pages-igbp.org/ipics/data/ipics_oldest_sip_v4_forapproval.pdf).

At this writing, it appears likely that at least two separate cores may be drilled, one or two in the region of Dome A (>3100 m ice thickness), and one in the Aurora Basin, where the thickest ice in Antarctica occurs (>4700 m). At all of these sites, the interval containing the 41-kyr cycles will likely be very compressed and near the bed, at depths perhaps exceeding 4000 m, and perhaps only spanning a few tens of meters. For this reason, this ice will be extremely precious, and the ability to obtain replicate samples to double or triple the volume of ice available will be of considerable significance to this international effort. The IPICS Steering Committee has endorsed the general plan of replicate sampling, without specifying which technology should be used (see letter of endorsement in supplementary documents).

VI. Some possible technological solutions, and their trade-offs

This section provides ideas as a starting point for discussions, and points out some of the scientific and economic trade-offs, but is not intended to supplant the judgment of the ICDS engineers. Therefore the contents of this section should be taken in a slightly different light than the other parts of this Science and Implementation Plan. Furthermore, this list of technological solutions is by no means a complete one; it is quite possible that the solution that is ultimately adopted does not appear among these four options. Nonetheless we thought it beneficial to outline the current state of our thinking about these trade-offs.

1) *Deviation coring into the borehole wall*

Deviation drilling, or deviation coring, was the first option discussed within the ice coring community and Ice Core Working Group, and arose in the context of the ICWG's decision to build a 12.2 cm drill (Recommendation of the ICWG to the NSF on Deep Ice Core Drill Options, 2003; see supplementary documents). Of all the options, this one has by far the longest history of discussion in the ice coring community. The DISC drill was specifically designed with deviation coring in mind. The instrument section of the sonde was made small enough to fit inside a typical borehole for a 10 cm diameter core, in order to facilitate "getting around the corner" while deviating out of the hole. Deviation drilling is routinely practiced by the oil industry, so much information and experience already exists.

The technique is summarized nicely in the attached report by the late Bruce Koci (see supplementary documents). Typically, a whipstock is set in the hole at the desired location for deviation. The whipstock is a device that forces the drill into the borehole wall much as a shoehorn forces a foot into a shoe. A special type of drill head with cutters on the sides, called a mill, is used to make the initial hole in the wall of the old borehole, and the new hole is widened with these tools to allow the core barrel to pass easily. The replicate coring barrel, somewhat smaller than the regular coring barrel, is attached to the sonde. Replicate cores are then taken.

Advantages of deviation drilling:

- Does not require an entire extra borehole of drilling fluid, in contrast to an entire second core (estimated savings: roughly $1-2 M plus 10 Herc flights)

- No replacement drill fluid has yet been identified for 141b; thus deviation drilling is currently the only definitely feasible option for WAIS Divide (although it seems likely that a replacement will be identified by 2016, the time of drilling the Oldest Ice project, because that core will require a replacement).

•Does not require several extra seasons of drilling, as an entire separate core would (large but difficult-to-quantify cost savings). Probably can be completed in one season.

•Does not clog NICL with unwanted ice (although unwanted ice could be stored on site). Addresses directly the problem of uneven distribution of scientific demand with depth.

•Permits recovery of third and fourth replicates, instead of just a second one as in the case of an entire separate core, for intervals of special interest (e.g., volcanic sulfate layer, in which a large sample is required for mass-independent isotopic analysis to fingerprint stratospheric oxidation).

•Represents an investment that can and will be used beyond WAIS Divide, on future projects, and in old boreholes, where entire new cores are cost-prohibitive. Solves a problem that can be expected to persist.

•Ideal for very thin horizons that record abrupt events such as supernovas, meteor impacts, or biological outbreaks, that may be found in future cores, and which will likely attract high public interest.

•Ideal for extremely deep boreholes, up to 4700 m, that may be drilled in the context of the "Oldest Ice" project, with only a few tens of meters of target material at the bottom (for example, the oldest possible ice).

•ICDS engineers are unanimous in their opinion that it is technically feasible (see letter of feasibility in supplementary documents).

Disadvantages of deviation drilling:

•Requires substantial engineering and technology development (possibly 0.5 – 1 $M?? and several years of effort). Never been done routinely in ice coring before (except for one field test by Victor Zagorodnov. The Russian Vostok deviation drilling is another exception, but these deviations were permanent and clogged the old hole).

•Leaves scars/sideholes in borehole wall that may cause logging tools to hang up (though these tools can be designed to get around this problem, with a heavy weight suspended below, if the deviation is always done on the high side of the hole so that gravity will tend to keep tools in the main hole)

•Leaves scars that mar the optical properties of the ice locally (but most optical logging will be done prior to replicate coring, so this only applies to new optical loggers that were not developed at the time of the main logging). More importantly, the scars would affect measurements of borehole deformation. However, the scars only will exist in a limited number of places (e.g., four places in the WAIS Divide, probably comprising ten meters each). Thus the total scarred borehole would likely be order of 40 m out of 3100 m, or <2% of the total borehole.

•Further disturbs the thermal environment of the borehole, which already will have been disturbed by the initial drilling. Will prolong the thermal recovery time required before paleoclimate reconstructions from borehole thermometry are possible.

2) *Taking an entire second core, a few meters away from the first borehole*

This option would probably involve moving the drill slightly, but need not require moving the arch (C. Bentley, personal communication, 2008). Hence it would likely be the most cost-effective way to obtain a second complete core. It also could be done much more quickly than the first hole, if some non-coring (i.e. destructive) technology were used for the top 1900 m (the Holocene) such as an auger that produces only chips. It is conceivable that a more viscous drill fluid such as the "coconut oil" mix ESTISOL-COASOL (now used in Greenland for the NEEM core) would suffice at the relatively warm temperatures of WAIS Divide. It is not known if the DISC Drill seals are compatible with ESTISOL-COASOL.

Advantages:

•Leaves old borehole in best possible condition for future developments in optical logging, temperature logging, and probes with centralizers that press against the wall.

•Leaves old borehole in best possible condition for repeat logging of deformation of borehole shape.

•No new technology needed. Uses existing DISC drill with 12.2 cm core.

•Wider diameter replicate core produced, with 50% more volume (deviation coring would produce a 10-cm diameter core).

•Can be used for *in situ* scientific radar, optical, seismic or sonic cross-borehole studies, with instruments down both boreholes, measuring fabric properties between the two holes. (high-pressure rheology, high-pressure compressibility, lateral variability in stratigraphy, fabric analysis).

Disadvantages:

•Cost (essentially doubles the drilling fluid volume, plus 10 Herc flights). [20,000 gallons of ISOPAR K and 10,000 gallons of HCFC-141b are presently in hand for the main hole at WAIS Divide – cost was $750,000. Probable cost for a second hole in 2012-2014 would be double or triple that, i.e. 1.5-2.3 M (C. Bentley, personal communication, 2008)]. If the replacement densifier is one of the hydrofluoroethers, the densifier cost could increase tenfold.

•Fluid not available currently in USA. Depends on purchasing fluid on the international market (e.g., China) or identifying a replacement fluid.

•Three to four extra seasons required (with cost implications).

•No capture of economy of scale for future projects (investment in deviation technology could be amortized over many future projects)

•Does not provide third or fourth core in areas of high interest

•Not well suited to extremely deep boreholes (e.g., 4700 m), where target material is a rather short section of ice at the very bottom, because of the high cost of drilling and pressure-compensating a second hole of this length.

•Possible risk of accidentally intersecting old hole. Difficult to control exact drill direction and thus spacing between holes at depth.

•Possible risk of thermal contamination of primary borehole temperature logging signal if boreholes are only a few meters away from each other.

3) ***An entire separate hole, ten ice thicknesses away***

Advantages:

•Best way to test for stratigraphic integrity. Other options involve replicate cores that could look very much like original, because they are so close, even if they are disturbed. Disturbance at GISP2 took the form of smeared-out, isoclinally folded strata that were quite horizontally homogeneous on the several-meter scale. Thus it is doubtful that a core several meters away would have revealed the problem with GISP2, in the way that the GRIP core did.

•Ideal for borehole loggers; zero disturbance to borehole wall and temperature profile.

•More scientific return from the spatial variability information that would be recovered, especially if a second bedrock core were collected (bedrock is unlikely to be very different a few meters away from the primary hole, but is very possibly different ten ice thicknesses away).

•Same advantages as 2) in larger diameter core, existing 12.2 cm DISC Drill technology.

Disadvantages:

- More moving costs; arch at WAIS Divide is snowed in.
- Same problems as 2) with fluid.
- Requires an entirely new camp

In summary, the main trade-offs with deviation coring appear to be that optical and borehole-deformation logging would have to sacrifice having a pristine borehole wall to work with, for repeat logging beyond the initial 2-year (3-season) phase of borehole logging. Also, this sacrifice would apply to applications of new logging technology that might become desired after the initial 2-year logging phase is over.

The main tradeoffs with the other options appear to be related to cost.

For the deviation option, it seems clear that the whipstock must be removeable, so that nothing remains in the hole that could obstruct passage of logging tools. The whipstock must also be orientable, so that deviation can be done on the high side of the hole.

An idea for a fully removeable, orientable whipstock is outlined in concept here. This is intended for discussion purposes only and is not meant to supplant the judgment of the ICDS engineers. The top part of the whipstock would be a complete cylinder only very slightly smaller than the borehole diameter, and would serve as the docking and ice-gripping section. Below the docking section an elongate parabolic opening in one side of the cylinder would permit deviation.

The whipstock would be deployed by a "whipstock tender" rigidly attached during replicate coring activity to the existing drill sonde instrument/motor section, in place of the coring barrel/screen section, with data and power connections. The tender would fit snugly within the top of the whipstock with flared registration slots to insure exact positioning and easy docking, and would have the ability to release and recover the whipstock remotely, using springs and solenoids controlled from the surface.

The whipstock would be secured to the borehole wall with three ice screws driven in and out by motors on the tender, with appropriate mating connectors. Once fully driven in, the ice screw heads would be flush with the inside diameter of the whipstock so that they do not impede replicate coring operations. An on-board video camera would aid in making the needed docking connections downhole. An on-board gyroscope sensitive to both tilt and azimuth would permit orienting the azimuth of the parabolic opening in such a way that the deviation is always done on the "uphill" side of the hole, so that subsequent gravity-driven borehole logging would not be hampered by the tools inadvertently entering the sidetrack hole.

VII. Borehole logging and Replicate Coring

(First draft by Erin Pettit 18 January 2008; revised 2 June 2008)

After recovery of an ice core for paleoclimate studies, the borehole becomes a new access point to the interior and bed of the ice sheet for collecting data that will complement the ice core record by providing further paleoclimate studies, modeling of ice sheet behavior, and structural properties of the continental crust underlying the ice, among other things. Although replicate coring of the ice at important intervals within the record is a valuable addition to an ice coring program, the borehole itself provides access to more volume of ice at each age (depth) in the paleoclimate record – we should take every advantage of the opportunity to non-destructively sample the ice surrounding the borehole using a variety of borehole logging tools. The replicate coring procedure may diminish the usability of the borehole for logging studies. We intend this document, therefore, to outline the goals and needs of the borehole logging activities and considerations that must be taken into account in the decision to move forward with replicate coring. We have received input from a number of people within the borehole logging community. This document is a summary of the ideas of the following scientists:

- Dr. Gary Clow (USGS)
- Dr. Bob Hawley (Dartmouth)
- Dr. Ryan Bay (UC Berkeley, with Dr. Buford Price)
- Dr. Ed Waddington (UWash)
- Dr. Kenichi Matsuoka (UWash)
- Dr. Erin Pettit (Portland State)

The general consensus is that replicate coring would cause many possibly severe challenges for the borehole logging community. Even if done entirely with removable components (such as the whipstock), the deviation drilling technology would leave a borehole with altered surface texture (scarring) and modified borehole diameter in places and a hole, possibly as long as 10 meters in the borehole wall. Although a significant amount of logging can occur before the deviation drilling starts, certain types of repeat logging will doubtless be affected.

We encourage NSF to consider other options for recovering additional ice samples from specific depths. Of the currently planned studies, those that would be most affected by the replicate coring program are those that require repeat logging over a number of years.

The borehole logging community would prefer solutions that do not disturb the integrity of the primary hole. One option is a new hole is drilled adjacent to the original hole. This may preserve the integrity of the original hole sufficiently to use it for repeat logging studies for deformation; however, this solution would not be sufficient for the desired borehole seismic work (PI Matsuoka). Another possible solution that would benefit both the borehole geophysics and the ice core analysis: simply move the drill by a small amount (minimum 1m) and drill a second complete ice core. The reduction in costs for developing new replicate coring technology may offset the increased costs for drilling more core; a cost-benefit analysis should be done to explore this option quantitatively.

Overarching Scientific Goals for Borehole Logging

As the borehole provides access to parts of the ice sheet and bedrock not normally available, there are many questions that can be approached by lowering instruments into the borehole in addition to supplementing the paleoclimate questions that drove the initial ice coring efforts. These questions include:

1. Bedrock Geology of West Antarctica
    a. What is the geothermal flux in West Antarctica?
    b. How does it vary across the West Antarctic Rift Zone?
2. Paleoclimate
    a. What is the history of surface temperature reflected in the present ice temperatures at depth?
    b. What is the stratigraphy of particulates in the ice sheet?
    c. How are abrupt changes in climate recorded in physical properties of the ice near the borehole (as reflected in stratigraphy, crystal fabric, or optical properties).
3. Ice Sheet Properties (for modeling, etc.)
    a. What is the temperature profile in the ice sheet?
    b. What is the depth-age relationship in the ice core?
    c. How much densification is occurring below pore closeoff?
    d. What is the profile of vertical and shear strain with depth at this site? What does this imply about ice rheological properties?
    e. What is the nature of the ice/bedrock interface?
    f. What is the profile of crystal fabric in the ice sheet and how does this affect the regional ice flow pattern?
    g. What are the *in situ* properties of the ice that contribute to the radar signals observed from the surface?

For some of these questions, researchers already have plans for proposal submission as early as June 2008.

Instrumentation

The instrumentation currently being proposed for borehole geophysical studies of the WAIS borehole includes both proven technology from past ice coring efforts, technology adapted from the rock borehole geophysics community, and new technology that will be developed specifically for the WAIS core.

The instrumentation that researchers are currently proposing to use:

1. *USGS Polar Temperature Logging System* (PI Clow). This instrument provides very high quality temperature data using a variety of custom temperature sensors. This instrument has been successfully used in several of the recent ice coring programs (Greenland, Siple Dome, etc.). The diameter of this instrument is about 2.5cm, with a maximum diameter on the order of 5cm. This instrument uses gravity to guide tool down the borehole. *Special needs*: The best temperature data requires allowing the borehole fluid to thermally equilibrate with the surrounding ice. This requires **repeat logging** the hole several times over a 3-year period (assuming minimal disturbance of the hole by other borehole instrumentation during that period).
2. *Borehole Optical Televiewer Probe* (PI Hawley). This instrument was developed for geophysical exploration by Advance Logic Technology (ALT). It uses optical sensors to image the borehole walls at high resolution. The instrument also includes inclinometry measurements. The instrument has a diameter of approximately 7cm, but would require centralizers which would expand to the borehole walls. *Special needs*: One of the questions this instrument aims to answer will require **repeat logging** on a yearly basis for several (probably 3) years. Due to the optical light used by this instrument, any turbidity in the drilling fluid from debris-rich basal layers or bedrock drilling would affect the signal; therefore logging with this instrument would require waiting until particulates have settled to the bottom of borehole.
3. *HRAT High Resolution Acoustic Televiewer* (PI Bay). This instrument is from the same company as the Optical Televiewer and has been used in ice in the GRIP borehole. It uses a high frequency acoustic signal to image the borehole wall, including measuring the shape of the borehole, the inclination of the borehole, and the potential (after processing) grain size. This instrument will also have centralizers. *Special needs*: There are two purposes for this instrument. The first is to extract a grain size for the ice, this does not require repeat logging. The second is to measure the deformation of the borehole shape and tilt over several years for ice deformation and flow modeling studies. This will require **repeat logging**.
4. *Dust Logger* (PI Bay). The dust logger was developed by B. Price and R. Bay and uses a laser emitted horizontally into the borehole wall. It has been used in the Siple Dome, GISP2, GRIP, NGRIP, and the IceCube boreholes. The instrument is approximately 9cm in diameter, but has baffles and centralizers that conform to the borehole wall. *Special needs*: Similar to the optical televiewer, the dust logger uses an optical signal that may be affected by turbidity in the drilling fluid; therefore, a settling time is required between drilling into the bedrock and logging.

5. *Sonic Velocity Logger (*PI Pettit). This instrument was used by Greg Lamorey (of DRI) in the Siple Dome and Greenland boreholes. It measures the in-situ compressional wave velocity with a vertical resolution of 2 m, providing information about the crystal fabric. *Special needs*: This instrument does not have any specific special needs; especially if the hole is logged before any replicate coring occurs.
6. *Seismic Sensors* (PI Matsuoka). Multiple studies using seismic techniques are being developed that will take advantage of hole configuration, including an upgraded higher resolution version of the sonic velocity logger. For example, seismic transducers will be lowered into the hole for active seismic profiling (both with source and receiver in the hole and with the source at the surface and the receiver in the hole). This is a new concept not used before with ice; however, similar techniques have been used in rock. The diameter of the transducers are approximately 10cm. *Special needs*: there are several possible configurations for this experiment, depending on the borehole configuration. The PI is planning to take advantage of holes left by replicate coring or multiple coring, for use with cross borehole seismics.

These instruments are all guided by gravity and most of them use centralizers, which use spring action to contact the borehole wall. These centralizers are the most likely technological challenge after deviation coring is complete; the centralizers might be difficult to pass by the hole in the borehole wall. The current plan is for all of them to use a universal winch (Clow's USGS 4km winch). The winch would have a universal connector on it to provide communication and power as needed to the instruments.

Borehole Logging and Replicate Coring

The two biggest challenges with having borehole logging and replicate coring in the same hole are related to the need for some kind of whipstock in the main hole to divert the drill and the existence and location of the diversion hole in the borehole wall.

With respect to the whipstock, none of these instruments would be able to successfully navigate through a permanent whipstock, even with a hole in it. Many of them require centralizers along the borehole wall and maneuvering through a hole smaller than the borehole would be challenging, if not impossible. For replicate coring to be compatible with borehole logging, therefore, one constraint is that *the whipstock be completely removable*.

The second major issue is the gravity fed system for these instruments. In order to smoothly move past a diversion hole in the borehole wall, the diversion hole must be on the "upslope" side of the wall. Further issues regarding passing the hole successfully may be difficult to predict at this stage and would depend on the instrument and the type of centralizers that it uses and the size and shape of the diversion hole. Instruments using centralizers may tend to "hang" when encountering a hole in the borehole wall. However, it may be possible to design loggers that are resistant to this type of "hanging up", employing a heavy weight hung far below the centralizers, and we recommend that ICDS be tasked to study this problem and make recommendations to NSF and the scientific community.

A number of the borehole logging studies could be completed before the replicate coring is begun. Several key questions, however, require **multiple logs** over several years. These include the paleothermometry, which needs the borehole and fluid to equilibrate to the local ice temperature, and ice deformation studies, which require remeasuring the borehole over a period of time to observe the change in borehole shape, curvature, and observable stratigraphic features in the borehole wall. **These repeat-logging studies would be the most affected by replicate coring needs**.

Despite the mechanical issues of smoothly moving past a hole in the wall or a whipstock, for most instruments, the quality of the data generally will not be affected by the presence of the hole in the wall. Some instruments, such as the televiewers, will be missing data or only get partial data for sections as long as ten meters, depending on how large the diversion hole is. How critical this missing data is depends on the desired resolution of the data set.

The seismic data may also be disturbed where two boreholes are very close together, i.e. with the holes adjacent.

Summary of instrument needs and possible conflicts among borehole instruments:

- Immediately after drilling the sonic velocity logger (roughly 1 week time required) and the first seismic logging of the borehole (2 weeks time required) can be completed. Ideally, the first of the repeat logs with the optical and acoustic televiewer will be done.
- One year later. Temperature log can be completed first in the season to take advantage of equilibration. Then optical televiewer, optical dust loggers, and acoustic televiewer logging devices collect their first data set.
- Ideally, repeat logs of temperature and the optical and acoustic televiewers will occur on a yearly basis for the next 2 years (3 years total). Then the PIs on this study would request that the hole be kept accessible for relogging the hole in future years (5 years later, for example).
- Further seismic studies will utilize the multiple holes created by the duplicate coring. The PIs on this study will request to be able to leave their seismic sensors in the hole for a period of a year or longer, depending on the distance between the main and duplicate boreholes.

VIII. Implementation Plan

Implementation of the development of replicate coring capability must by its nature proceed in a number of separate, somewhat iterative steps, with feedback going both ways between the science community and IDDOG/ICDS, and between NSF and both groups. At some point a workshop may be necessary to bring together all interested science participants in replicate coring activity, in order to insure an open process. A drilling technology workshop may also be needed. The timeline below is proposed for discussion purposes, and will likely require some modification as the plan unfolds. Words in italics indicate concurrent events not directly related to replicate coring (e.g., progress in drilling the main core). For discussion purposes only, the timeline assumes the deviation option. The other options would take several additional years and a different timeline would be implied; importantly, the lack of a timeline for these options should not be taken as an indication that they are less desirable or feasible.

October 3, 2008:	WAIS Divide Executive Committee formally endorsed Replicate Coring and Borehole Logging Science and Implementation Plan. Science and Implementation Plan formally presented to NSF.
November 2008-January 2009	Proposals submitted for external funds for instrument development (e.g., MRI competition).
February 2009:	*Drilling at WAIS Divide reaches bottom of brittle ice (~1500 m).*
April 2009:	*No ice retrograded to NICL.*
June 2009:	Earliest date for potential MRI award for instrument development. If successful, Ice Drilling Program Office (IDPO) and IDDOG/ICDS begin design planning process.
September 2009:	Conceptual design submitted to ICWG and WAIS Divide Executive Committee.
October 2009:	Ice Core Working Group advises NSF on science view of design and any science implications. Detailed science requirements drafted and circulated in science community.
November 2009:	Detailed Science Requirements submitted to IDDOG/ICDS.
December, 2009:	ICWG/WAIS Exec. Comm. formally adopts conceptual approach, and IDDOG/ICDS begins formal design phase.
October 2009:	*WAIS Divide Science meeting, venue Scripps Inst. Oceanography*
February 2010:	*Drilling at WAIS Divide reaches AIM 8 (~2900 m).*
April 2010:	*Retrograde of ice (includes brittle ice) to NICL.*
June-July 2010:	*Core processing line (CPL). Water isotope analysis.*
August 2010:	*USGS winch shipped to Antarctica for logging borehole in 10-11 season (via ship)*

October 2010: IDDOG/ICDS presents design at WAIS Divide Science meeting. Opportunity for feedback from borehole logging community, gas community, and any other affected science group. Preliminary water isotope profile to LGM shown.

November 2010: Ice Core Working Group and WAIS Divide Executive Committee approve design.

December 2010: IDPO and IDDOG/ICDS begin construction phase.

Jan. 2011- June 2012 Construction phase (ICDS).

February 2011: Drilling at WAIS Divide reaches bed (~3465 m). Deformation/temperature borehole logging activities begin (1st borehole logging season). USGS winch is used.
April 2011: Retrograde of last portion of main core.
June-July 2011: Core processing line (CPL). Water isotope analysis.

June 2011: Science proposals submitted to NSF for WAIS replicate coring targets

October 2011: First results of water isotope profile over whole core presented at WAIS Divide Science meeting. Science meeting extended by one day for a workshop on science goals related to replicate coring target depth intervals, open to all participants. Preliminary water isotopes to bed shown.

Nov. 2011-Feb. 2012: Bedrock coring, subglacial water sampling, and borehole optical, sonic velocity, borehole deformation, and other logging at WAIS (2nd borehole logging season).

June -Aug. 2012 Replicate coring tool Testing Phase (ICDS, with input from Exec. committee).

June 2012: Second round of science proposals submitted to NSF for WAIS replicate coring targets. Proposals submitted to NSF for post-WAIS replicate coring activity (e.g., Siple Dome old borehole, to recover "missing" critical intervals).

Sept. 2012 Replicate coring technology shipped to Antarctica.

October 2012: WAIS Divide Science meeting. WAIS Divide executive committee makes final decision on target depths for replicate coring.

Nov. 2012	*Borehole temperature logging at WAIS, prior to thermal disturbance of borehole by replicate coring. Optical and deformation logging, prior to disturbance of borehole wall by replicate coring (3rd borehole logging season).*

Dec. 2012-Feb. 2013: Replicate coring activity at WAIS.

April 2013:	Retrograde of replicate cores (approx. 415 m)
June-July 2013:	Core processing line of replicate cores. ECM done (critical for fine-scale registration of replicates with main core).
October 2013:	First results from replicate cores discussed at WAIS Divide Science meeting. Registration of replicate cores to main core (in depth scale) formalized by Executive committee.
Dec. 2013-Jan. 2014	*Field season for activities related to securing the borehole for long term scientific access. Part of the arch must be removed and the cavity backfilled with snow so that when it settles it does not snap the casing. The borehole casing must be extended to accommodate future snow accumulation.*

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X. Supporting documents

Letter of feasibility from Ice Coring and Drilling Services (ICDS)

Letter of endorsement from International Partnership
in Ice Core Sciences (IPICS)

Excerpts from "Recommendations for a deep drill, Ice Core Working
Group, 2003"

Replicate Coring (feasibility study by Bruce Koci)

ICE CORING AND DRILLING SERVICES
SPACE SCIENCE AND ENGINEERING CENTER
UNIVERSITY OF WISCONSIN – MADISON
1225 West Dayton Street
Madison, Wisconsin 53706-1695

July 14, 2008

Dr. Jeffrey P. Severinghaus
Associate Professor of Geosciences
Scripps Institution of Oceanography
University of California, San Diego 92093-0244

Dear Jeff,

The drill engineers at ICDS are firmly convinced of the feasibility of developing a deviation drilling capability for the DISC drill in the WAIS Divide (and other) ice boreholes for the purpose of obtaining additional cores to replicate particular sections of the main core. The basic technology is mature -- almost a century old -- and has been applied countless times for drilling in rock, using mechanical drills. The technique has also been used repeatedly with electrothermal drills in ice. Although it has not yet been accomplished with an electromechanical drill in ice, there is no fundamental obstacle to that application. The development is not routine and will require a substantial investment of time and money, but we are confident in ultimate success.

Leaving the main hole usable for various logging applications is a further challenge, but also one we believe can be met. The most important part, removal of the whipstock(s), is routinely done in other applications and should be achievable in ice. While the side-wall holes cannot, of course, be made invisible to all logging applications (e.g. visual logs), we are sure that, working with the logging experts, we could prevent diversion of logging tools from the main hole.

In short, ICDS expects that it can accomplish the replicate coring and do it in a fashion that reduces interference with logging operations to an acceptable level.

Sincerely yours,

Charles R. Bentley
Principal Investigator
Ice Coring and Drilling Services

International Partnerships in Ice Core Sciences

Dr. Karl Erb (with copies to Dr. Julie Palais and Dr. Alexandra Isern)
Office of Polar Programs
US National Science Foundation

May 2, 2008

Dear Dr. Erb,

At the recent IPICS Steering Committee meeting in Vienna, a recurring theme was the need to increase the volume of ice sample available to investigators in particularly interesting sections of ice cores, in order to add value to the scientific return from ice coring. We would therefore like to express our enthusiastic support for any method of obtaining additional material in such sections. We therefore strongly welcome the planned development (about which we have heard) of the capability to take additional, replicate cores in areas of high scientific interest in ice-core boreholes.

In particular, replicate coring will be extremely useful in our IPICS Oldest Ice project, in which we aim to recover a 1.5 million year continuous record of atmospheric gases and climate. The key targets of this project are the interval between 1.3 and 1.5 million years ago, when the climate oscillated with a 41,000-year period for reasons that are currently not well understood, and the transition to a 100,000-year period between 1.3 and 0.7 million years ago, which has also resisted explanation. The 1.5 to 1.3 Ma interval will likely be compressed into a short section of ice near the bed, perhaps only a few tens of meters long. Scientific demand for these ice samples will no doubt be very high, and already we have proposed that at least two cores are essential at the international level to ensure replication and integrity of the record obtained. Therefore, the ability to take additional material in this ice will be decisive in insuring that the broadest international participation will be realized in analyzing these unique samples, and that the scientific returns from the project are maximized.

If we can provide assistance to you in any way, please do not hesitate to ask.

Sincerely,

International Partnerships in Ice Core Sciences (IPICS) Steering Committee

Ed Brook (co-chair)	
Eric Wolff (co-chair)	
Tas van Ommen	Australia
Jean-Louis Tison	Belgium
Jefferson Simoes	Brazil
David Fisher	Canada
Li Yuansheng	China
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Thomas Stocker	Switzerland
Robert Mulvaney	United Kingdom
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Jeff Severinghaus	United States
Joe McConnell	United States
Eric Steig	United States
Jim White	United States

EXCERPTS FROM: "Recommendation of the Ice Core Working Group to the National Science Foundation on Deep Ice Core Drill Options"

April 4, 2003

Ice Core Working Group members:

Jeff Severinghaus, Chair
Mary Albert
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Joe McConnell
Buford Price
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With substantial input from Edward Brook and Mark Twickler

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

April 4, 2003

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.

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Replicate Coring

An ICDS white paper

Bruce Koci

Replicate Coring

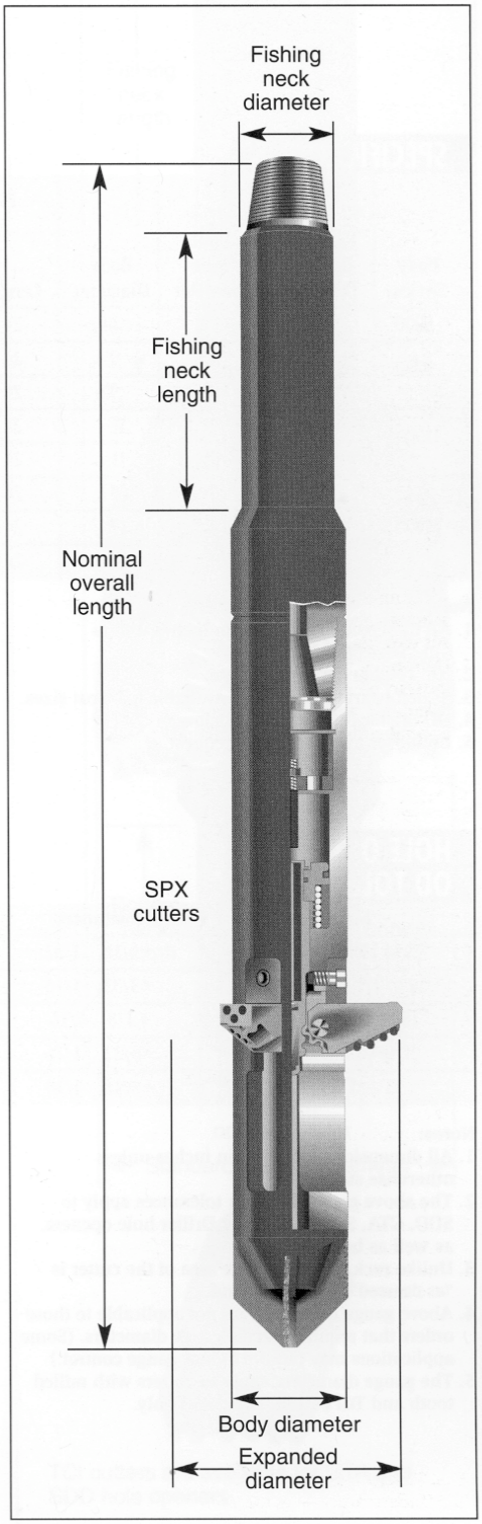
An ICDS white paper

Bruce Koci

Summary

We are proposing a method to increase the volume of ice core available from interesting areas in deep coring operations. Logistics restraints limit the size core that can be drilled and returned from the field. Since a high percentage of the core has limited interest and most of the interesting intervals are in the deep regions of the glacier, it makes sense to develop a method of sidetracking the borehole to provide additional core volume. We can borrow technology developed by the rock coring industry in the early 1900's(1) to accomplish this task. Since ice is relatively easy to drill compared to rock, the normal methods used by the oil and mining industry can be modified to make the tools lighter and easier to use. The purpose of this paper is to present choices to open the discussion on the best way to proceed.

Introduction



• Figure 1

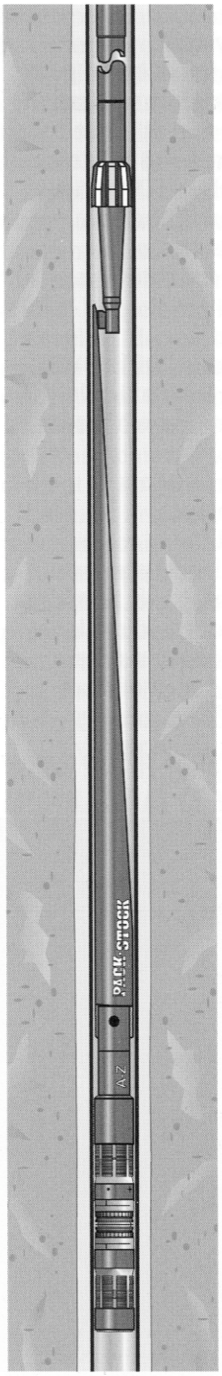
Replicate coring is really a part of a larger drilling technique called directional drilling. The technique was developed in 1912 by the mining industry as wedging off an existing hole to start a new one. The technique has become highly evolved through the use of coiled tubing drilling, which makes further use of drills that can be steered into promising areas remote from the main hole. Fortunately, our task is much easier since it is limited to short excursions from the main borehole that do not require steering the drill. We need only exit the hole and core through a limited vertical distance.

The first task is to enlarge the main hole to help get the drill out of it. A device called an under reamer is used for this operation. The under reamer is smaller than the borehole diameter but has wings that can be extended to increase the borehole diameter. These devices are available off the shelf (but would have to be modified) or are simple enough that one could be designed as part of the drill package (Figure 1).

All directional drilling begins with a whip-stock, which is placed at the point where the drill is to leave the hole. The whip-stock serves three purposes:

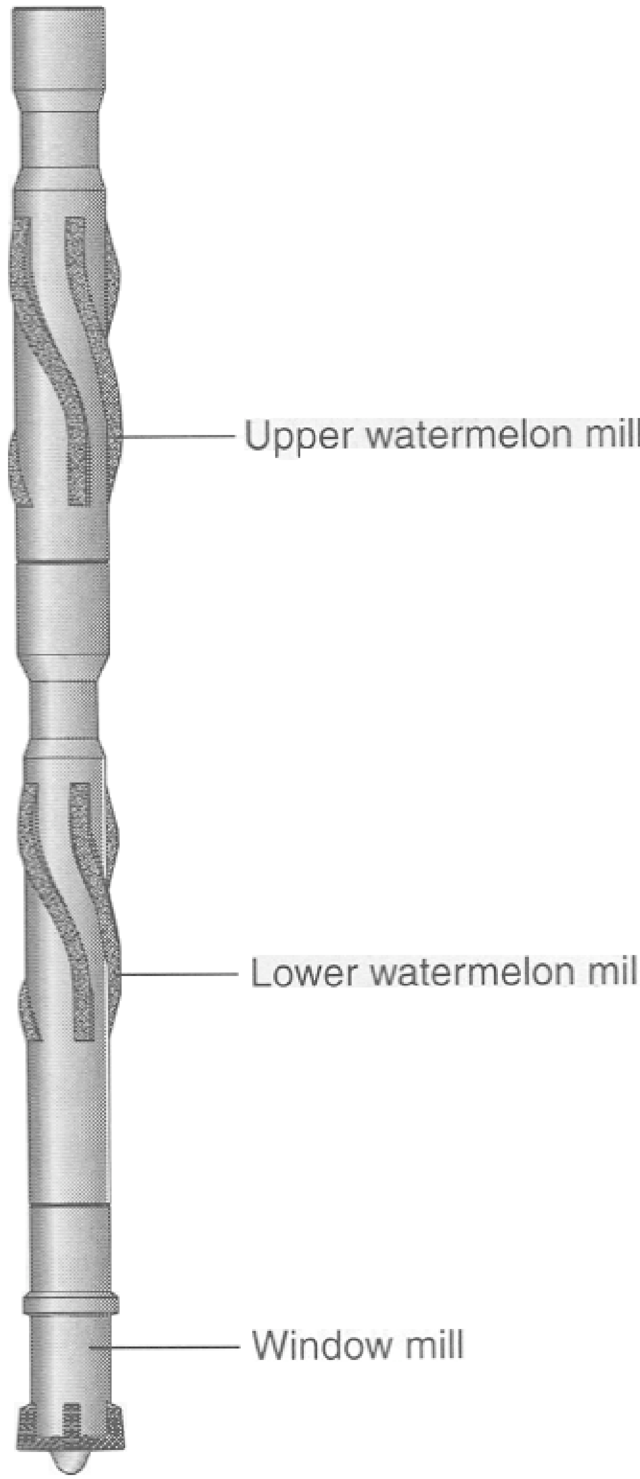
- To provide positive displacement of the drill out of the hole
- To provide proper orientation if needed
- To provide a positive method for re-entering the sidetracked hole

The whip-stock is a long tapered device that forces the drill out of the hole. It is locked in place mechanically by retractable springs or hydraulically with packers. The mechanisms are designed so the whip-stock can always be retrieved. It is designed to resist downward force. Figure 2 illustrates one type of whip-stock placed in a hole. The whip-stock can be actuated electrically, mechanically, or hydraulically. Starting the new hole requires several reamers to initiate side tracking, begin the hole, and create a slot so the drill can clear the corner as it leaves the main hole. An illustrative set of reamers is shown in Figure 3 and Figure 4. A starting mill is used to open the hole over the length of the whip-stock. It is replaced with a window mill to drill through the side of the hole and begin the new hole. Watermelon and string mills are added as needed to mill a slot in the borehole wall for the drill to pass. Once this is done the drilling or coring operation can begin. Keeping track of and removing the cuttings may be challenging.

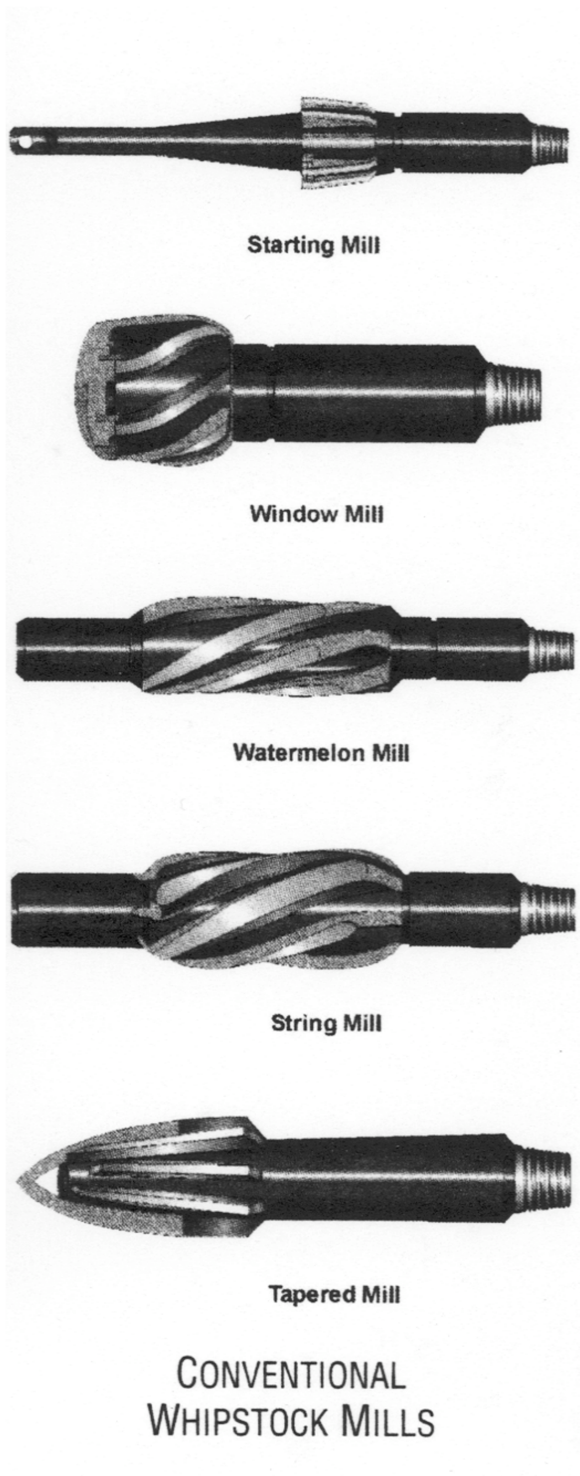


Retrievable
Pack-Stock

• Figure 2



• Figure 3


Starting Mill
Window Mill
Watermelon Mill
String Mill
Tapered Mill
CONVENTIONAL
WHIPSTOCK MILLS

• Figure 4

Specific Applications to Ice

We have four problems associated with replicate coring in ice:

- How to sidetrack the main bore hole
- How to correlate the two cores
- How to remove the whip-stock
- How to isolate the side tracked hole from logging operations

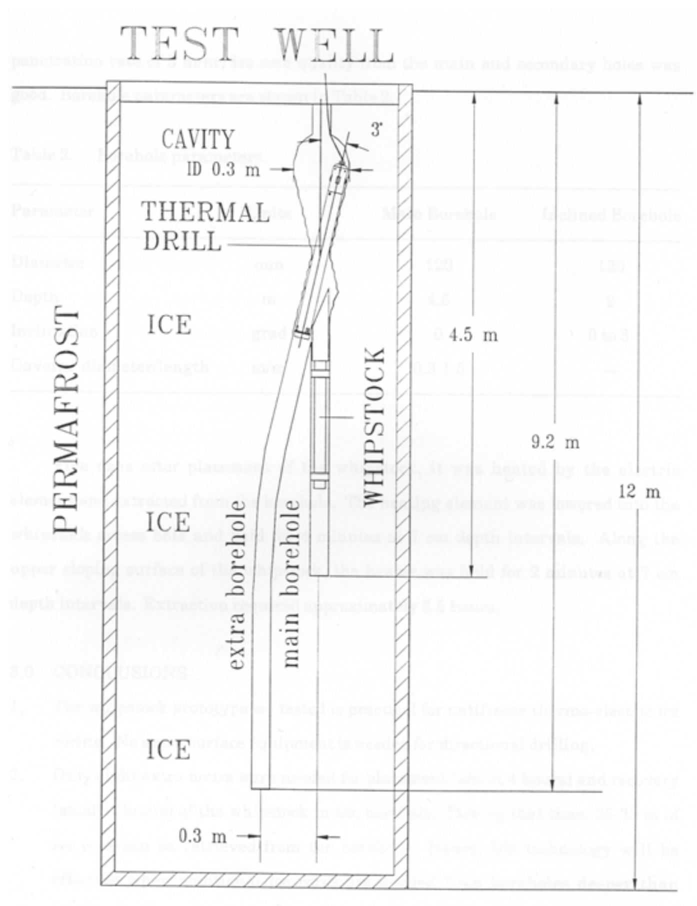
Sidetracking the Borehole

When coring ice there are two sidetracking methods that are used:

- Thermal
- Mechanical

Thermal

The thermal method has been used several times at Vostok to deviate around stuck drills. Victor Zagarodnov (2) demonstrated the successful deviation from a test borehole in Fairbanks as shown in Figure 5. The author also drilled multiple holes off a main hole on the Barnes Ice Cap on Baffin Island, Canada in the early 70's.



• Figure 5

Using a thermal drill to sidetrack is straightforward if the ice is warm and certainly the cheapest method available. However, it may compromise the science since hydrophilic fluids are needed to keep the hole open if it is below freezing and the core is heated to the melting point in the annulus by the drill. If the temperature is warmer than -10 C there is no evidence of thermally induced cracking as long as the heating elements lie in a narrow vertical region. The older model thermal drills used cartridge heaters that caused a wide zone of heating.

Sidetracking a hole using a thermal drill is similar to mechanical side tracking except that borehole enlargement is accomplished by melting rather than mechanically removing material. The melt water has to be dealt with to avoid excessive refreezing. The whip-stock does not have to be isolated from the drill bit since there is no mechanical abrasion and the sidetracking operation becomes much less complex as a result. The thermal process is:

1) Insertion of the whip-stock
2) Thermal enlargement of the hole
3) Immediate start of the coring operations

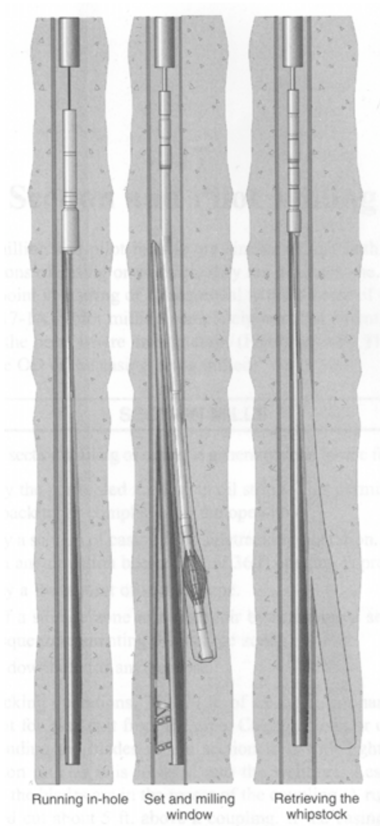
The drill fits the hole so there is no need for multiple operations with several milling devices to start and ream the hole

Water generated in the drilling and reaming operations near the primary hole may freeze onto the borehole wall causing a partial blockage. Any icicles created can be removed by mechanical reaming once the whip-stock is removed. If the whip-stock freezes to the borehole wall, it can be drilled out since it is made of a soft material.

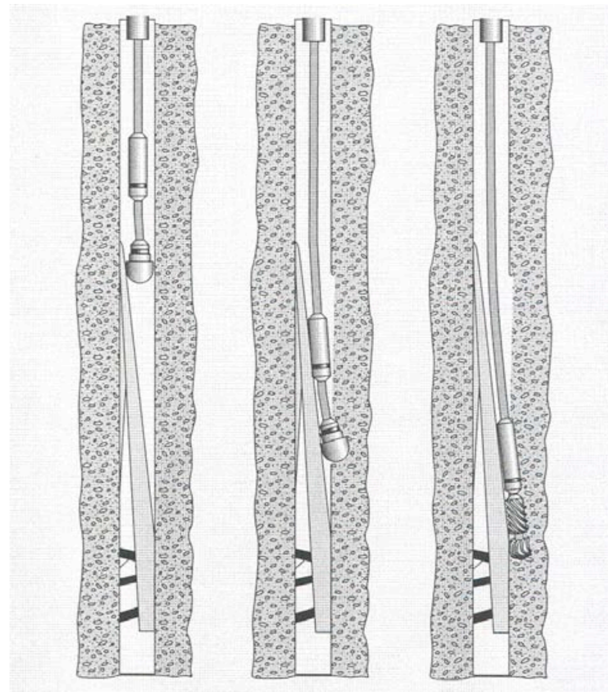
Mechanical

Simple Method

A simplified version of sidetracking is shown in Figures 6 and 7. The 3-step process assumes a single step to sidetrack the hole. Multiple reamers are attached to the drill as shown (1, 3, 4). While it may be possible to sidetrack the hole in one step it is unlikely we will want to do this because of the volume of chips generated. The filters will have to be cleaned at least once during this operation.



• Figure 6



• Figure 7

Complex Method

A more complex procedure for starting a replicate coring hole is as follows:

1) Identify the interval of interest.
2) Locate an interval several meters above to prepare the hole
3) Under ream the hole
4) Place the whip-stock
5) Lower the sonde with starting mill to begin exiting the hole
6) Drill bit starts out of the hole
7) Add watermelon mill to adjust drill path
8) Continue drilling and milling until entire drill is out of the hole
9) Continue drilling with coring barrels.
10) Match core logs of existing hole with replicate hole
11) Drill until interesting area is covered.
12) Remove whip-stock and plug hole

Complex Method Detailed Explanation

Steps 1 & 2

The first two steps require accurate depth correlation, which may be beyond the capability of standard drilling cables. Accurate depth measurement is generally done using special logging wire made of a single strand of Invar. The wire has a negligibly small coefficient of expansion and the single strand eliminates the uncertainties caused by helically wound cables.

Step 3
This step is accomplished using the under reamer to enlarge the hole. The bit is lowered to the bottom of the exit area where the wings are allowed to spring out. The drill is then pulled out of the hole as it is rotated to enlarge the hole. Several reaming operations may be required to open the hole to the desired diameter. The larger the hole, the less reaming is required by the watermelon reamer as the drill goes around the corner. Problems associated with this operation are available torque reaction and storage of large volumes of chips. Once complete, the reamed section provides a platform for the whip-stock to sit on.

Step 4
Placement of the whip-stock requires accurate knowledge of depth. Once the whip-stock is in the right place, wires or other locking devices that prevent the whip-stock from proceeding down hole are released. The whip-stock will be designed to permit retrieval, though it will be made of a drillable material in case it sticks in the hole.

Step 5
The sonde is lowered into the hole with a starting mill (something that rides on the whip-stock plus drilling head), pump, and well screens for chip storage. The drill is started and operated until the drill has begun to exit the hole. This point is determined by drill length and borehole diameter.

Steps 6, 7, & 8
The starting mill is replaced by a watermelon mill and drill head. The watermelon mill cuts sideways to form a slot so the drill can round the corner from the main drill hole to the direction imposed by the whip-stock. This length of cut is also determined by drill length and clearance in the hole. Many runs may be required because of the large volume of chips generated by this process.

Step 9
Finally the core barrel is attached and the replicate coring begun. While the replicate core barrel will have a smaller diameter than the main 12.2 cm core barrel it will have the same diameter as the upper portions of the drill. The replicate drill will be shortened by substituting core barrels and screens designed to take 2-meter cores rather than the normal 4-meter length.

Steps 10 &11
Drilling continues and core logs are matched until the area of interest is covered.

Step 12
The whip-stock is removed and exit hole plugged

Because the drill has a complete navigation package, it should be possible to provide multiple cores from particularly interesting areas by orienting the whip-stock in different directions at slightly different depths. Additional cores could be retrieved in future seasons when borehole logging operations are performed.

Correlation of Cores

The first step of this process is defining the area of interest and its depth. Since we are limited by time, hence depth of replicate coring, knowledge of the exact depth is important. This may require the use of the Invar logging wire to meet the science requirement (0.02 % of depth). Once the depth is known, the whip-stock will be inserted slightly above the area of interest. After the replicate coring drill has left the main hole and the coring operation begun, the core will be logged and compared to the log from the primary hole. If the two logs match coring will continue until the interval of interest is covered. If the logs don't match, drilling will probably continue until they do match.

If the interval is especially interesting, as most transitions are, it will be possible to take several cores from the same interval by orienting the whip-stock in different directions as is done in multilateral drilling. We can again rely on the modular nature of the drill, its complete navigation package and its ability to take oriented core.

Removing the Whip-stock

Since the main borehole provides an important site for logging temperature and other glaciological investigations, removal of the whip-stock or other blockage must be assured. Most whip-stocks are designed to resist downward forces. Mechanisms to lock the tool in the borehole wall can be designed in a way that permits retrieval. As a failsafe alternative the whip-stock will be made of a material that is easily drilled out. A commonly used material is polyethylene.

Blocking the Replicate Borehole

During the process of removing the whip-stock, it is possible to deploy a metal band that will seal the replicate hole and mark it as a point of reference. This method was used on the Antarctic Peninsula in the late 1980's to investigate vertical strain in the borehole. A sheet of metal is released at a known depth where it springs into the borehole wall. Its presence is then detected magnetically.

Discussion of Sidetracking & Coring Options

Here we discuss further the two options to consider for sidetracking and coring in glacier ice with regard to associated problems, relative cost and probability of success.

Thermal Option

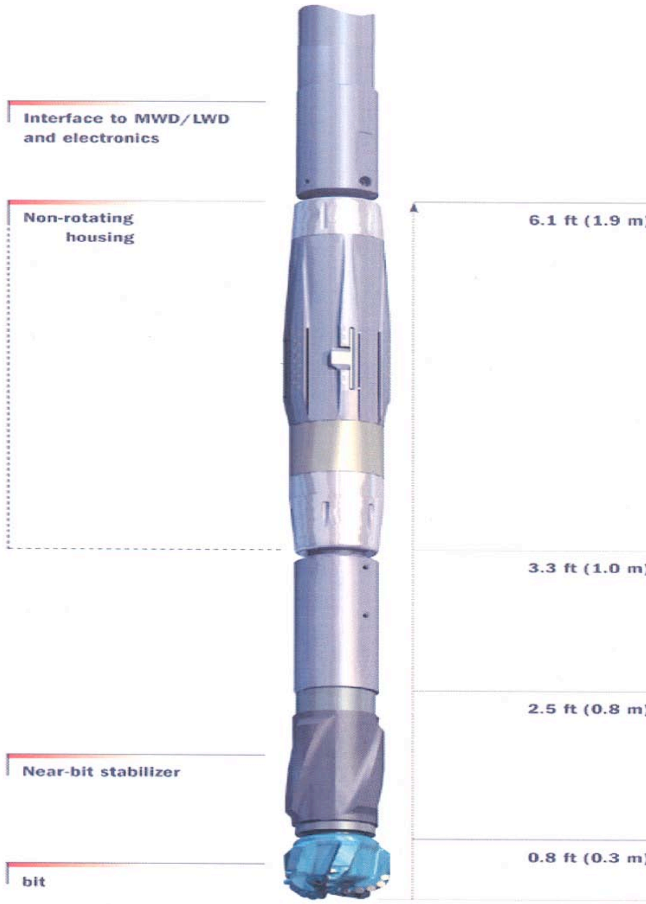
The thermal options are by far the simplest and cheapest. The absence of rotating drill bits makes getting out of the main bore hole relatively easy. We can build the whip-stock. Thermal drills are easy to build and do not represent a large time or money infusion. However, there are potential conflicts with scientific goals. Since they create water, the drill or whip-stock can freeze in. There is also the possibility of having water freeze in the main borehole blocking passage. Success is not guaranteed but the method has been used in glacier ice.

Mechanical Option

Several options for mechanical systems exist. Sidetracking and directional drilling are mature technologies in the rock drilling industry that can be adapted to our needs. The drawback is that these systems are often heavy and consume a lot of power.

One method is to bring in a coiled tubing drill (5) that weighs 50,000 lb. Coiled tubing drills use circulation driven by surface pumps to provide power for drilling and chip removal. The chips move up the borehole between the conduit and the borehole wall. The drill could either be used for directional drilling off the main hole or to drill a completely new hole, taking core at interesting intervals. It would require additional borehole fluid. The complete drilling system with steerable drill costs several million dollars. One possibility is to rent the drill and pay a contractor to operate it, but this would guarantee high cost. The core quality may not be as good as with the electromechanical drill because a Moyno type of mud motor is generally used. This type of motor induces oscillations in the drill string that could fracture ice core. The drill is capable of penetrating ice and rock depending on choice of bits. Success is not guaranteed but probable. The biggest problem with this method is drill chips that are returned to the surface by way of the annulus between the pipe and borehole wall. The transport time is long and the chips present a threat of causing anything in the borehole to stick.

The discussion would not be complete without a mention of steerable drilling technology. Steerable drills flex somewhere between stabilizers that hold the drill in the hole. An illustration of one of the newer technology drills is shown in Figure 8. Further discussion of steerable drills is beyond the scope of this white paper.



• Figure 8

We plan to modify the deep ice coring drill that currently is being designed. Since the most expensive components are the instrumentation, pump, motor, and anti-torque modules, the cost is kept at a moderate level. Generally, the replicating drill is a smaller diameter than the drill used for the main borehole. The reason for this is that reamers must be added to the outside to enlarge the hole so the drill can get around corners created by sidetracking. It is possible to avoid re designing the drill by putting on a smaller diameter barrel to initiate sidetracking. The normal coring barrel would replace the specialized sidetracking barrel once the drill exits the hole. The replicating drill will be used in the short 2-meter coring mode to shorten the task of exiting the borehole. Coring will be limited to less than 100 meters in an interval. The probability of success is high because we will know the characteristics of the drill.

A potential for sticking the drill exists when the sidetracking operation is underway because the chips are outside the drill before being sucked in for filtering. Loose chips in the hole always represent a potential for sticking the drill.

It would be possible to build a new drill specifically designed for replicate coring operations, but the cost of this approach is much higher than the cost of modifying the existing drill. At this time we do not see a need for this approach.

Conclusion

The general method of sidetracking and drilling holes using a single access hole is known. We have to adapt it to ice, which is much easier to drill than rock. It is important to begin with the components that cut the ice: the drill bits and reamers. These are relatively inexpensive items and, more importantly, tests on them can be conducted in a manner similar to the drill head tests currently being conducted. We can test for the ability of exit bits to begin drilling sideways without having to resort to full-scale tests on a glacier. The tests can begin immediately because we can use 300 lb blocks of ice and our 4-inch drill to get preliminary data in a cold room. The watermelon reamers can also be tested in this manner. These tests will help us understand the process and define power requirements for removing the amount of ice necessary to get the drill out of the main hole into the sidetracked hole. This is primarily a geometry problem. Once it is in the sidetracked hole the drill behaves like a normal drill. Funding and time spent on this portion of the development should not compete with the primary mission of developing a working deep drill first.

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