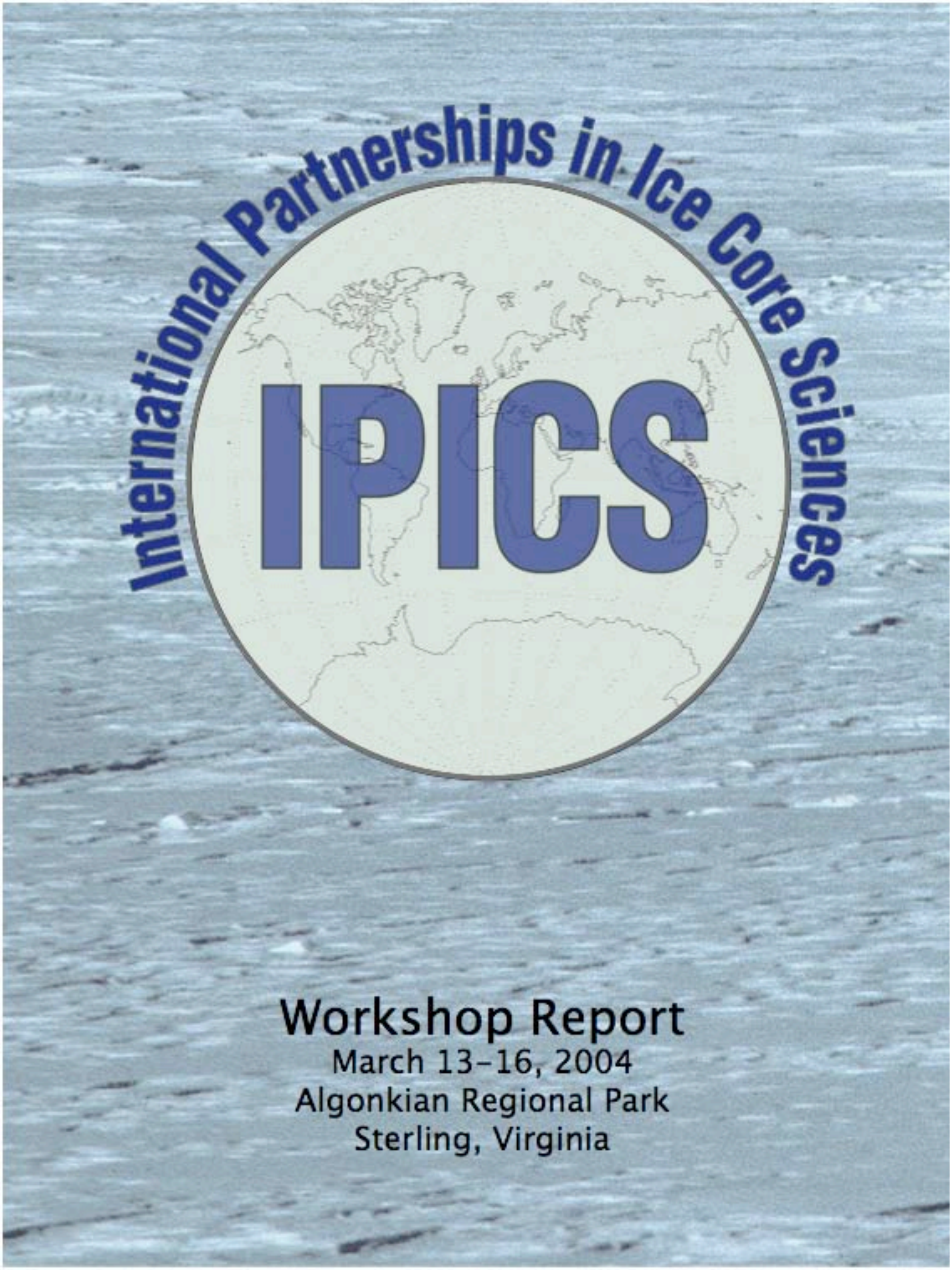

International Partnerships in Ice Core Sciences

IPICS

Workshop Report

March 13-16, 2004
Algonkian Regional Park
Sterling, Virginia

International Partnerships in Ice Core Sciences (IPICS)

Workshop Report
April, 2005

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IPICS Steering Committee

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This document and the IPICS pre-Meeting Report are available on the web at:
http://nicl-smo.unh.edu/IPICS/IPICS.html

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Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Executive Summary

Society would benefit greatly from the ability to efficiently allocate resources to minimize disruptions caused by climate change. This requires the ability to predict the response of future climate to natural and anthropogenic forcing on time scales of months to centuries. To do so we need to understand how the sun, ocean, land, atmosphere, and cryosphere interact to create the climate that controls so many aspects of our daily lives. One of the ways the science community develops this understanding is to study the earth's climate history. By learning how and why the climate changed in the past, we will be able to make better predictions of how the climate will change in the future.

Ice sheets and glaciers contain well-ordered accumulations of ancient ice that fell as snow years to millions of years ago. The dust particles, soluble chemicals, and gases trapped in the ice are routinely used to study how the climate system operated in the past, and how it will operate in the future. To sample this ice, an international community of scientists and engineers drill into ice and collect ice cores. The information from ice core programs helps explain how climate changes occur throughout the world, not just at the site at which the core was drilled. This is possible because most of the material in the core, such as dust and gases, is representative of large regions. Ice coring projects range in size from a single investigator working for a single field season, to multi-national, multi-year efforts. Investigations using ice cores have documented how climate varied naturally before anthropogenic influences, and have shown there is a tight link between temperature and the atmospheric concentrations of greenhouse gases.

Ice core data have become central to our understanding of past climate change, and to assessments of possible future climate change. Ice core investigations are now a major branch of climate research, and the complexity of ice core projects has increased accordingly. To meet the expectations of the climate research community, increasingly complex future ice coring projects will require international collaboration. In March 2004, representatives from the international ice coring research community convened a workshop to develop concepts for the projects that are needed to predict both natural and anthropogenic climate change. The *International Partnerships in Ice Core Sciences* (IPICS) Workshop was supported by the U.S National Science Foundation. Fifty-five scientists, engineers, and funding agency representatives from Australia, Canada, China, Denmark, France, Germany, Italy, Japan, Russia, Switzerland, the United Kingdom and the United States attended the workshop. The major recommendations of the workshop are:

- ***Continue the Dialogue.*** Representatives of the international ice coring community should meet in 2005 to discuss implementation of current plans, and then continue to have regular meetings that include the exchange of information on ice core science and drilling that will be helpful to future and ongoing projects. Heinz Miller, on behalf of the European Polar Board, stated that Europe would like to host a follow-up IPICS meeting during 2005.

- ***Retrieve Longest Possible Antarctic Ice Core Climate Record.*** A program should be initiated to collect an Antarctic ice core climate record longer than 1.2 million years. This program will provide insights into the way future climate will respond to changes in the distribution of solar heating, by examining how natural changes, driven by changes in the earth's orbit, evolved over this long time frame. Initially this will require a multi-year effort to locate the optimal drilling locations for the collection of cores to address this topic. Ice cores should be collected from at least two locations in East Antarctica. The site selection work should be initiated during the International Polar Year. Additional workshops should be held to develop a framework for this program.

- ***Longest Possible Arctic Ice Core Climate Record.*** A program should be initiated to collect the longest possible Arctic ice core climate record, with the specific goal of completely penetrating ice deposited the last time the earth was in a warm (interglacial) state like today. This program will provide critical insights into the natural variability of our current climate and, by elucidating how the last warm period ended, may yield information on how the current warm period will end. The optimal location for this project has been narrowed down to a small area in northwest Greenland. A minor amount of additional site selection work, which could occur early in the International Polar Year, is required before drilling can proceed. Preparations for the drilling could be completed by the end of the International Polar Year. Additional workshops should be held to develop a detailed plan for this program.

- ***Spatial Array of Ice Cores.*** A program should be initiated to collect a spatial array of ice cores on time scales ranging from centuries to millennia. Many climate questions can only be answered if there is a well-designed spatial array to investigate how hemisphere-scale climate phenomena interact to create climate, and a coordinated effort is required to develop such an array. The individual coring projects that make up the array should be facilitated, but not directed, at the international level. This program would include polar sites with records extending into the last glacial period, and a worldwide distribution of sites with higher time resolution records extending through the last millennium. Some of the smaller individual projects that make up this program could be completed during the International Polar Year. The site selection for some of the larger individual projects that make up this program could be initiated during the International Polar Year. Additional workshops should be held to develop a planning document for an international body to facilitate the development of this global array.

- ***Improve Ice Coring Methods.*** An ongoing international effort to improve ice coring methods should be initiated. This effort would focus on improving drilling fluids, core quality, drilling efficiency, and replicate coring methods. This effort could be facilitated with annual workshops and international exchanges of drilling staff.

To reach the objective of being able to predict future climate variations, a new international approach to ice coring is required. Implementing these recommendations is a necessary step towards reaching that objective.

Introduction

Ice core data are the foundation for much of the modern global change research because of the particularly clear linkages between climate and biogeochemistry that the records reveal, and because the data provide an unparalleled picture of the human impact on the atmosphere since the industrial revolution. Relatively small groups working incrementally on one isolated project at a time have made many of the fundamental achievements. Yet answers to pressing global climate issues that face all societies today require larger, coordinated efforts that combine both the intellect and the drilling expertise of nations working together. The aim of the IPICS workshop was to discuss such efforts in the ice coring community, and to determine the next steps needed to proceed. The very positive response of international participants shows that the need for such an initiative is widely recognized.

IPICS brought together representatives from all the nations with ice coring programs to discuss: 1) a potential agenda of new projects addressing critical scientific questions, 2) technical obstacles to these projects, and 3) the benefits, difficulties, and facilitation of international collaboration on these projects.

Ice coring has a long history of international collaboration under various models, including the primarily Danish-Swiss-U.S. effort GISP1 at Dye 3, the paired European and U.S. coring at GISP2/GRIP (Greenland Ice Sheet Project/Greenland Ice Core Project), the first Dome C core with U.S. heavy-aircraft support of a primarily French coring effort, and the strongly coordinated EPICA (European Project for Ice Coring in Antarctica) and NorthGRIP (North Greenland Ice Core Project) efforts in Europe. Recently, U.S. drilling specialists participated in drilling operations at EPICA and NorthGRIP drill sites. Despite this history, coordination of deep ice coring has remained somewhat ad hoc. Many ongoing collaborations can be cited, but to our knowledge, the IPICS gathering was the first international meeting to discuss broad collaboration among countries involved in deep ice coring activities, and the first attempt to develop a consensus on future goals.

IPICS is pursuing more substantial international collaboration in ice core sciences for several reasons. We believe that coordinated international collaboration could dramatically improve our knowledge of earth systems; by working collaboratively we can investigate more complex, universal issues than can one nation working alone. In addition, collaboration may foster breakthroughs in drilling and analytical technology that will significantly enhance ice core science, and more efficiently develop and utilize logistical and personnel resources. A broad collaboration could bring together efficient and effective mixes of different types of analytical, logistical, and drilling expertise, facilitating new knowledge growth toward important scientific goals in ways that are possible for individual nations. We believe that the time is ripe to discuss significant international scientific and logistical collaboration on future ice coring projects. The United States ice coring community is planning a deep ice core project in West Antarctica. The U.S. ICWG has identified several other scientific goals for ice coring, with input from several European colleagues. The European community is currently finishing two deep ice coring projects, and is in the early planning process for future projects. The Australians, Canadians, Chinese and Japanese scientific groups have active and proposed projects. The international community is in a good position to consider how to collaborate for the benefit of future science.

The development of IPICS will have numerous broader impacts. Ice core sciences address questions of human interest related to the earth's climate system, including global warming, abrupt climate change, changes in sea level, biogeochemical cycling, and other aspects of climate. The goal of IPICS is to facilitate the collection and analysis of additional ice cores and, through the dissemination of the resulting information, to advance our understanding of the earth's climate and environmental systems. The data and interpretations derived from these new ice cores will give policymakers the information necessary to make better decisions affecting the future of the earth. Through the media, ice core science provides a magnet for the public's attention to science and the important role that science plays for the benefit of humanity. Every past ice coring endeavor has yielded students who, in the course of their graduate and post-graduate work in ice coring, have blossomed to take their places among the new cadre of young professional scientists and academia scientists. Ice coring has and will continue to develop the next generation of scientists, engineers, and leaders in the field. Society will benefit on many levels by improving ice core sciences through international partnerships.

Significance of Ice Core Science

Ice-core studies have already revolutionized our view of the earth system, documenting the existence of abrupt climate changes, the tight coupling of climate and greenhouse-gas concentrations, the rise of pollution, and in some cases the clean-up of pollution, among many other results. However, much more still needs to be done, especially to meet the challenge of understanding how the earth's combined biogeochemical/climate system works, and how it will respond to the change in atmospheric composition currently taking place. The IPICS workshop identified some of the contributions that can still be made by ice cores.

Abrupt climate changes have been clearly identified in the paleorecord, but so far only in glacial periods and in the early Holocene. There is a major societal need to understand how they work, and to develop climate models that incorporate the underlying mechanisms. This is essential if the models are to successfully predict the likelihood and consequences of future abrupt climate change, as currently suggested by some of them. Ice cores can contribute to questions such as:

- Are abrupt climate changes found in any previous interglacials, including ones that are warmer or longer than the present one? Are they found in all glacial periods?
- What is the detailed phasing between north and south, and within each polar region, for rapid climate changes, and how does this constrain the mechanisms and model responses?
- Is there a pace to Dansgaard-Oeschger (D/O) events? If yes, what is it and what causes it? Is this pacing also relevant to natural but less abrupt climate variability in the Holocene?
- Where are the thresholds in the climate system?

Terminations and inceptions are the most dramatic climate events of the late Quaternary period. To understand current climate, we need to understand why we find ourselves in an interglacial, and when it might end if left to run its natural course. Ice cores can contribute to questions such as:

- What is the detailed sequence of events during climate transitions (forcings and responses, north and south, ocean and atmosphere)?
- Are terminations and inceptions before 400 kyr BP different from the four more recent ones, and if so, why?
- What determines the length of an interglacial? Does the paleorecord hold a good analogue for the present one, and how long should the present one be?
- Why did earth's climate shift from a dominant 40-kyr to 100-kyr cycle? (Why does it have a 100-kyr cycle now?)

Climate sensitivity is key to improving predictions from climate models. Ice cores can help to answer questions such as:

- How did the major forcing agents change over the last 1.2 million years?
- What determines the strength of amplifiers in the system? In particular, what are the concentrations

of greenhouse gases throughout this period, and what determines the upper and lower bounds of their variability, which appear remarkably constant?

- Are the different climate regimes telling us something new about climate sensitivity?

Mechanisms of change. Understanding climate requires that we know about as many of the important parameters and mechanisms as possible. Ice cores can give us previously unobtainable information about, for example:

- whether the bipolar seesaw is a valid concept;
- extra-polar changes derived from proxies such as dust and deuterium excess;
- the role of sea ice, and its link to ocean circulation;
- the past status of the Greenland and West Antarctic ice sheets.

Climate and atmospheric variability in the present climate system form the context for future change, and must be understood and represented in models. Ice core chemical signals have the potential to give well-calibrated recent indicators of

- circulation indices such as NAO, ENSO, SAO (but further work is needed to calibrate the proxies);
- past influence of changes in solar and volcanic activity;
- past changes in atmospheric chemistry.

The issues listed above are just a subset of possible science issues, and do not include more exotic studies such as microbiological studies of ice and the sub-ice environment, or studies of ice on other planets. The issues above immediately suggest a few possible targets, some of which were explored at the workshop:

- reconstruct regional climate change in Antarctica during the last deglaciation;
- recover >1.2-million-year continuous ice record(s);
- obtain a record of the last interglacial in Greenland;
- obtain high-resolution and well-dated recent records from ice cores around the world;
- improve analytical techniques, for example for isotopes in gases;
- develop more high-resolution analysis techniques;
- improve drilling techniques to allow targeted study of the most relevant time periods.

In summary, both new cores and new techniques on old cores will allow ice cores to continue to contribute very significant and essential information, particularly aimed at understanding the earth system, and the processes that determine climate change.

Proposed IPICS Projects

This part of the workshop report focuses on discussions around the topic of deep ice coring. In this context, deep coring implies efforts involving large, static, multi-year drilling efforts, with cores of greater than about 2000 m depth. A brief background section describes the past and present work in this area, summarized from discussions and documents produced before the meeting. Then follow summaries of the two formal presentations of potential deep drilling projects made during the meeting (one for Antarctica, one for Greenland). The section headed "Summary of breakout group discussions" gives the conclusions and open questions determined by the "deep ice cores" breakout group, and also incorporates the discussions held after the two presentations.

Background

Starting with the initial deep ice coring in the 1960s (Camp Century and Byrd), deep ice cores have come to be regarded as a crucial pillar of knowledge about late Quaternary paleoclimate. The size of the logistic, technological and scientific effort required has led to a realization that ice coring must be multi-institutional, and often multinational, from the three-nation Dye-3 drilling to the ten-nation efforts of EPICA (see below).

The current state of the art is represented in Greenland by the three detailed records of GRIP and GISP2 (at Summit) and of NorthGRIP. These are supplemented by the earlier records from Dye 3 and Camp Century, and by the more compressed but valuable Greenland coastal cores (such as Renland). The most compelling message from the Greenland cores has been that of the very abrupt, millennial-scale, climatic flips of the last glacial period, known as Dansgaard-Oeschger events. Understanding the cause(s) of these events, and their implications for future change, has become one of the hottest topics in climate studies, with significant policy implications. The last interglacial (also known as the Eemian) has proved to be a tantalizing target—present but garbled in the Summit cores, and incomplete due to basal melting in the NorthGRIP core. Other than NorthGRIP, there are no other currently funded deep drilling programs in Greenland.

Among Antarctic cores, the 420-kyr record from Vostok in East Antarctica has become iconic. This core, both the longest and, until recently, oldest available, is used frequently in documents such as those of the IPCC, and forms a core of understanding for natural climate change. It highlights in particular the close linkage between climate and greenhouse gas concentrations over the last four glacial-interglacial cycles. It is supplemented by the 340-kyr record from Dome Fuji, which demonstrates the heterogeneity of the basic climate signal over the East Antarctic Plateau and by a number of other cores showing higher detail but over a shorter time period in West Antarctica (Byrd) and in coastal domes (Law Dome, Taylor Dome, Siple Dome). The European Project for Ice Coring in Antarctica (EPICA) is close to recovery of two new deep cores: the one at Dome C has already produced a record of 740 kyr, and may extend beyond 900 kyr; the core at Dronning Maud Land is expected to yield at least 200 kyr. Further deep cores are underway or at a detailed planning stage: a new Japanese effort to reach bedrock at Dome Fuji has started (current depth 362 m of 3030 m total), while the USA intends to drill to the bed (around 3300 m depth) in inland West Antarctica, where a highly detailed record of around 100 kyr at a site with high snow accumulation is eagerly awaited. Other coastal domes are also the subject of current and planned programs (Berkner Island, Talos Dome); such sites will be discussed in the "Shallow Ice Coring and Coastal Arrays of Ice Cores" section below.

In 2004, many of the established ice coring nations and groups are engaged with completion of the analysis, interpretation and drilling associated with current projects (NorthGRIP, EPICA, Dome Fuji) and the initiation of the new Inland WAIS coring efforts. The WAIS Divide core will be drilled during the International Polar Year (IPY) years, and may serve as one springboard for international cooperation. IPY activities, such as collaboration on the WAIS Divide core, ice coring arrays and ice coring traverses, and planning for the Greenland deep core, provide the perfect backdrop for the establishment of long-term international planning for future ice coring science endeavours well beyond 2008, and the establishment of a long-term International Partners in Ice Coring Sciences program.

A project to recover the longest possible ice core paleoclimate record (Jean Jouzel, presenter)
The criteria for getting the longest possible ice core record are relatively easy to define. We need to drill at sites characterized by high ice thickness, low accumulation and low horizontal speed. To minimize the risk of disturbed layers in the bottom part of the core, which even over a few hundred meters covers a long time span (e.g., more than 300 kyr in the last 300 m of the EPICA Dome C core), drilling should be performed in a relatively flat bedrock area. In addition, as illustrated at NorthGRIP and probably EPICA Dome C, a slight melting at the base could be favourable for getting undisturbed sequences in this bottom part.

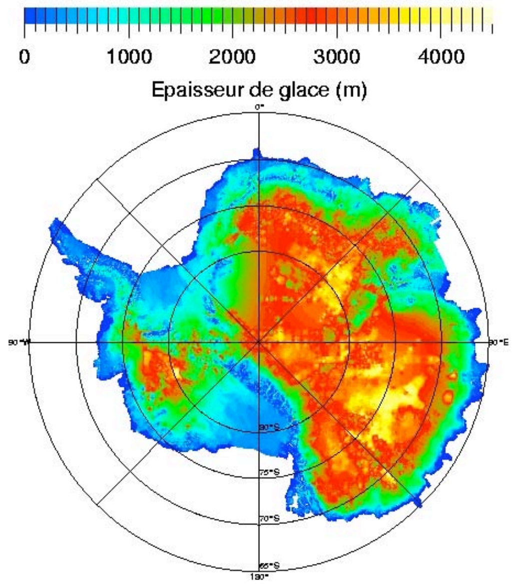
Low accumulation, on the order of a few cm/yr of ice, is encountered only in East Antarctica with ice thickness generally greater than 2.5 km and, for a large part, greater than 3 km. Drillings on the Antarctic Plateau have up to now provided the longest records, with cores at four sites covering more than one, and up to nine, climatic cycles. Key relevant data are given in Table 1.

Table 1: Characteristics of the drilling sites with more than one climatic cycle record.

Site	Thickness (m)	Accumulation (g/cm^2)	Current Depth (m)	Age (kyr)
Vostok	3750	2	3310	420
Dome F	3090	2.7	2503	330
EPICA Dome C	3270	2.7	3260	890
EPICA DML	2760	6.4	2565	200

Only one of these four drillings has up to now reached the bed. Vostok drilling was stopped because of the existence of a subglacial lake, a situation to be avoided for getting very long records, whereas the bed was reached in 2004 at EPICA Dome C, drilling continues at DM. Dome Fuji, a site where records as long or slightly longer than at EPICA Dome C (about 890 kyr) may exist, was interrupted because of drilling difficulties but continued this past field season.

The EPICA Dome C isotopic record has shown very intriguing changes, with a clear change of pacing, when the periods before and after termination V (around 430 kyr) are compared. Extending the record by an additional 400 kyr—i.e., back to 1200 kyr—would allow recovery of ice core records for a period dominated by a 40-kyr periodicity. Some areas of the East Antarctic Plateau have the potential to provide such long records (see Figure 1), but these areas are still largely unexplored, and priority should be given to reconnaissance field work that aims to get precise maps of accumulation and horizontal speed as well as echo radar measurements to make possible the tracing of isolines over large areas.



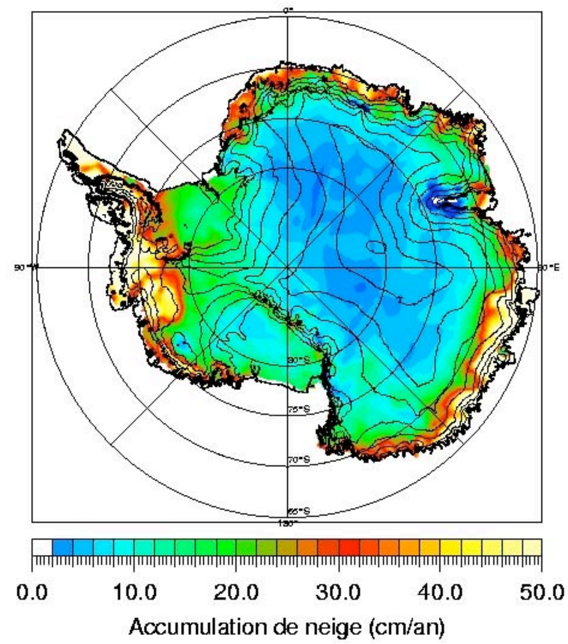


Figure 1: Maps of Antarctica showing thickness of ice sheet in meters (left) and accumulation of snow in centimeters per year (right).

A project to recover Eemian ice from Northwest Greenland (Dorthe Dahl-Jensen, presenter)

The major objective of drilling an Eemian Greenland ice core is to obtain from the Northern Hemisphere a climatic record of the onset of the Eemian period and perhaps even the previous glacial period. This is a climatic period that has not been obtained from other Greenland ice cores because the ice stratigraphy has been disrupted in the Central Greenland ice cores, the ice has melted at the base at NorthGRIP, and this climatic period was too compressed at Camp Century and Dye3. The process of understanding the climate dynamics on the scale of interstadials and interglacials, including the north-south teleconnections, is an area of research that we expect to yield major results in the coming years with the highly resolved records from the NorthGRIP and EPICA ice cores. This makes the need to have a full Northern Hemisphere Eemian record very urgent. In addition it is believed that a site selected further north than NorthGRIP will have a stable isotope curve with a clear interglacial climate signal because the source region for the precipitation is more influenced by the Baffin Bay weather system, with only minor influence from the Icelandic low pressure system.

The RSL Group at the University of Kansas has produced a remarkable number of Radio Echo Sounding (RES) profiles over the Greenland Ice Sheet, and these are very helpful in selecting a good site (see Figures 2 and 3) (http://tornado.rsl.ukans.edu/Greenlanddata.htm).

The RES images from NorthGRIP, GRIP, NEEM1 and NEEM2 are compared in Figure 4 with the stable isotope curve from NorthGRIP. The deepest traceable internal layer is dated to 82 kyr. The predicted positions of the Eemian at the two proposed drill sites were made by Monte Carlo fitting of flow models based on the dated internal layers. At NEEM1 the ice thickness is 2542 m, accumulation rate is 0.23 m ice/yr, and the Eemian thickness is 80 m with annual layers 7 mm thick. At NEEM2 the ice thickness is 2756 m, accumulation is 0.17 m ice/yr, and the Eemian thickness is 100 m with annual layers 8 mm thick. The bedrock at NEEM2 is not as smooth as at NEEM1, and there is a folding "shadow" at the predicted location of the NEEM2 Eemian, indicating a risk of folding layers here. We prefer the NEEM1 site for a coming deep drilling location in north Greenland.

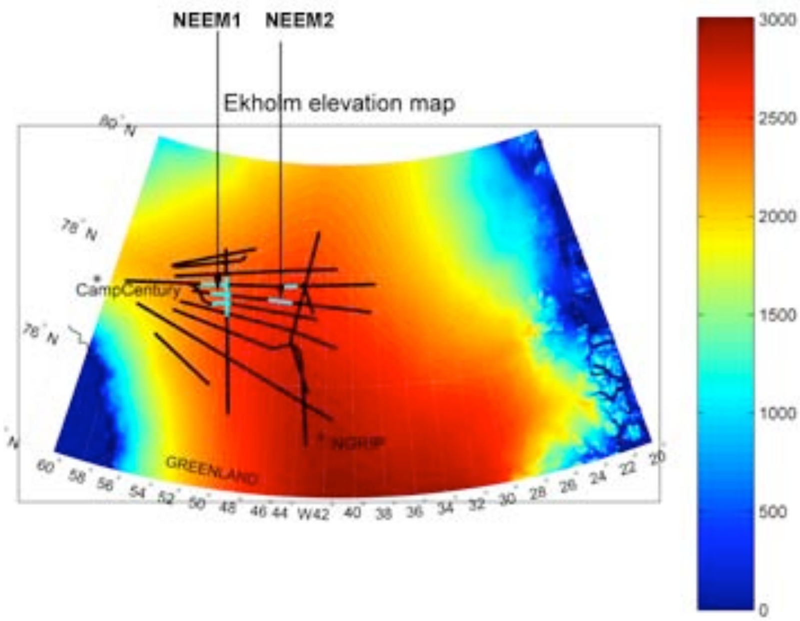


Figure 2: The two suggested drill sites shown on the surface elevation map of the northern Greenland ice sheet. The elevation map is from Bamber et al., 2001. The RES lines are shown on the figure.

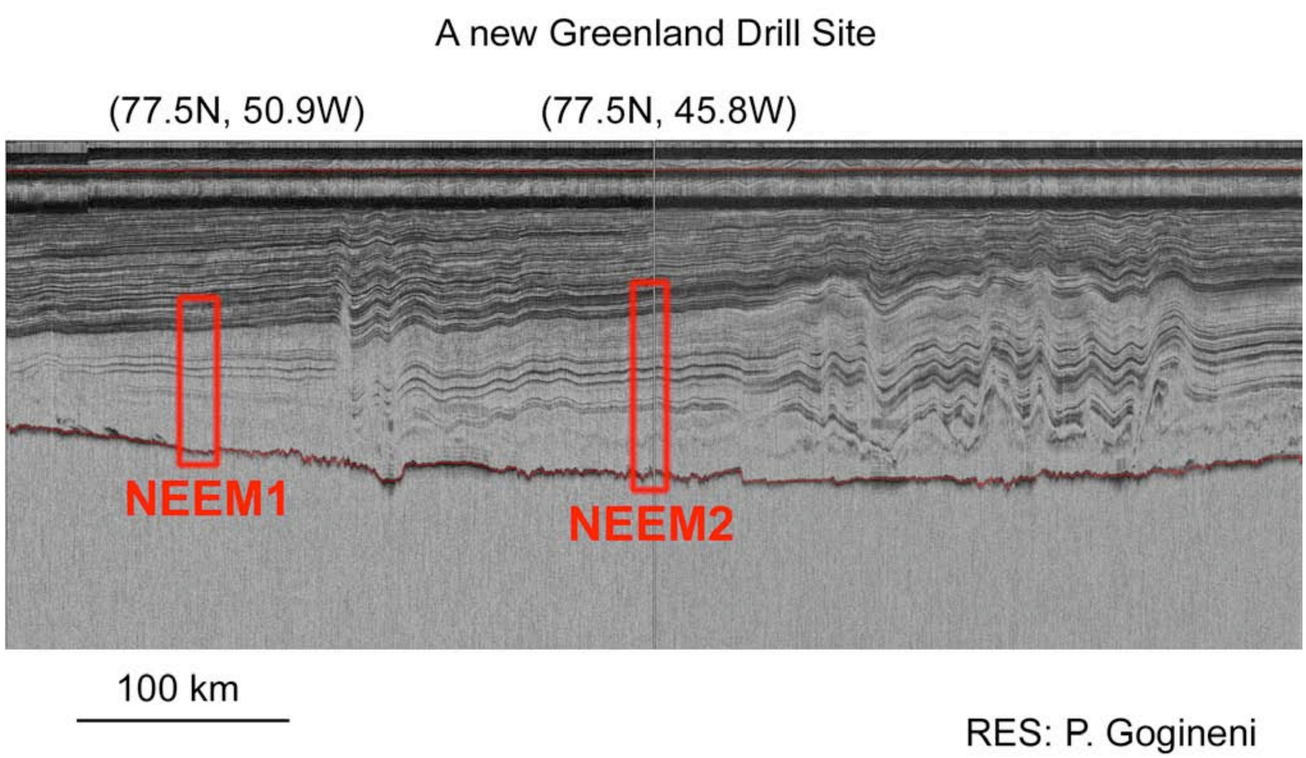


Figure 3: The RES profile with the two drill sites marked.

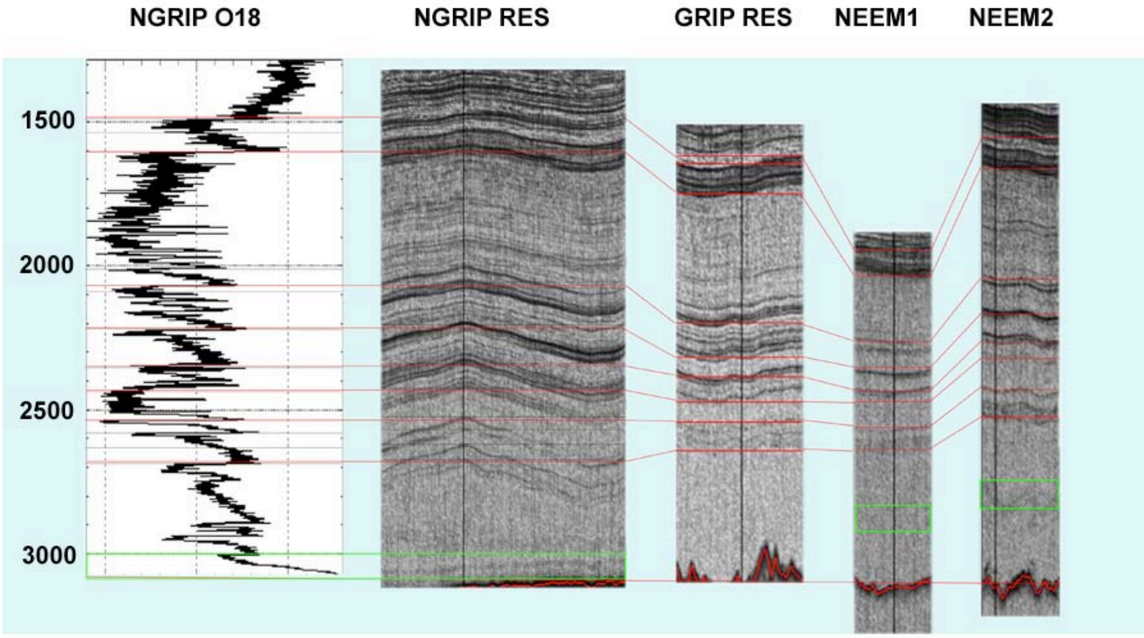


Figure 4: Details of the internal RES layers at NorthGRIP, GRIP, NEEM1 and NEEM2. The modeled depths of the Eemian ice at NEEM1 and NEEM2 are marked with green boxes.

Summary of breakout group discussions – deep ice cores

This breakout group was facilitated by Eric Wolff, and had a varying population of about 10 members. It mainly concentrated on summarizing the key characteristics of the two projects that clearly emerged as the ones to pursue in the deep drilling area. As such, this part of the report will duplicate some of what precedes it in the individual presentations, but the aim is to summarize the consensus of the workshop participants.

The group started by confirming that the two projects:

Longest record(s) – Antarctica, and

Longest record/Eemian ice – Greenland

were indeed the main ones under consideration. While specific Antarctic deep core targets are mentioned in the pre-workshop reports, they are mainly there as possible sites for very old ice, and therefore form part of project 1. Motivations, other than climate, for drilling deep into the ice sheets would include access to small lakes or to bedrock at specific locations, ice dynamics studies, and biological studies. However, none of these had been highlighted at this meeting, and most of them did not call for continuous core recovery. Such studies could indeed be valuable, but would not form a focus for the collaborative IPICS. The group proceeded to look at each project in turn.

Longest record(s) – Antarctica

Motivation: The main motivations for obtaining very old ice were: (1) to obtain data from a 40-kyr (as opposed to 100-kyr) world (including CO_2 level and range), and (2) to replicate and confirm the Dome C and Dome F records (including improved common timescales). These motivations imply that we should look for the oldest possible ice, but aiming for approximately 1.2 Myr.

How? The first task must be site selection, which would involve an iterative process of modeling and survey to find suitable sites. Basic criteria would include a low ratio of accumulation rate to ice thickness, flat bedrock topography, and well-ordered internal layers. Initial modeling can already identify areas of East Antarctica as candidates for survey; measurements should include:

- elevation/surface topography
- ice thickness
- snow accumulation rate (including shallow cores, use of radar internal layers); preferred sites likely to have <2 cm/yr
- internal radar layers
- velocity (e.g., preferably low)
- temperature (including estimates of basal temperature)
- basal topography
- atmospheric context (including deployment of AWS units).

The improved survey data will allow better modeling to pin down more specific areas, eventually leading to the identification of one or more target sites (assuming that suitable areas are found). (We noted that in the pre-meeting documents, some potential targets are already suggested: north of Vostok, deepest ice (inland from Casey), Dome A.)

The group was in favor of planning to drill two cores, because:

- Replication/validation would be needed as in previous efforts.
- Any single core may not find the old ice we expect; even small differences in location might lead to presence or absence of the oldest ice: two cores gives us double the chance of finding old ice.
- Recovery of two cores also allows opportunities for a greater number of experienced international investigators to apply their efforts and intellects to the problem.

Who's interested? Many probable interested parties were not present. However, we know that this project is of interest to Europe and to several US investigators, and we can anticipate interest from Japan, Russia, China, and Australia, among others.

Timing: Given other commitments, a realistic timescale might be to start survey in 2007/08 (IPY), with drilling possibly in the years 2010-11 to 2013-14.

Obstacles/needs: A number of potential issues were identified that need to be addressed before the project could progress:

- coordination of international logistics and science (may require high level agreements between funding agencies);
- agreement on who does what will require the different science teams to be able and willing to work together (the drilling of two cores may be very helpful in this respect, allowing different groups to take a lead on one core and a smaller role on the other for each topic);
- funding;
- missing logistic support (because the likely sites are so difficult to access)–traverse support may be necessary;
- timing of other programs would dictate the scheduling;
- drill fluid: none has been identified so far that is suitable for the low temperatures expected, safe, and still legal in 2010.

Longest record/Eemian ice – Greenland

Motivation: The main objective of this project would be to obtain a continuous Greenland record from the whole of the Eemian (stage 5E) and Transition II. Subsidiary benefits would be to gain a further site for determining the spatial pattern of climate in Greenland, and a Holocene and glacial ice core signal from a site with a single atmospheric source.

How? While site selection work will be required, the search area is already quite narrow, with the main candidate area being in northwest Greenland. However, within this area, the usual survey (see above) would be needed, including for example AWS deployment.

It was felt that a single core would be sufficient initially, although as always a second core might become necessary if there were any question about the integrity of the stratigraphy in the deeper ice.

Who's interested? Again, some of the possible participants were not present in the breakout group. There is certainly European interest (with a special role for Denmark), and there are U.S. investigators eager to participate. Based on their interest in previous Greenland projects, we expect that at least Japan and Australia would also be interested.

Timing: Again taking into account other commitments, but also the much smaller scale of the survey compared to the Antarctic project, a realistic date for the drilling itself seems to be (at the earliest) 2008-2011.

Obstacles: Some of the same issues as for Antarctic drilling would have to be solved, notably, international logistic coordination (but this is more established in the Greenland context), funding, and agreement on who does what scientifically. However, in this case suitable drills and fluids already exist, and the logistic challenge is not unusual.

A number of generic obstacles (common to all future projects) were also mentioned, including those of suitable and sufficient core storage, driller availability and training, and the need for exchanges of scientists as a precursor to further internationalization of projects (the European Marie Curie Fellowships offer one funding route for such actions).

Summary

The breakout group felt that it had a consensus for two exciting, challenging, and already quite well-defined projects that would significantly advance our understanding of the climate system.
The group noted that their notional timetables imply that the coring efforts for the WAIS Divide site and the start of the Antarctic survey and the Greenland drilling will fall within the International Polar Year (IPY) 2007-2008. This is an attractive combination to set the stage for agreements on future international projects and establishment of the International Partners in Ice Coring Sciences program.

To take these projects further, the group agreed to set up a writing team to produce a concept paper on future deep cores. This will flesh out some details of the projects discussed above. The target audience was firstly the ice core community (to ensure wide agreement), secondly the wider science community (especially the paleoclimate community), and finally funding agencies. The writing team will consist of Eric Wolff (UK, co-chair), Ed Brook (USA, co-chair), Dorthe Dahl-Jensen (Denmark), Yoshiyuki Fujii (Japan), Jean Jouzel (France), Volodya Lipenkov (Russia), and Jeff Severinghaus (USA).

Shallow ice coring and coastal arrays of ice cores

This part of the workshop report focuses on discussions around the topic of ice coring along ice sheet margins, as well as shallow drilling in all parts of the major ice sheets as well as in mountain glaciers. The focus here is on shallow ice cores, generally 1000 m or less, but occasionally extending to 2000 m. A brief background section summarizes the past and present work in this area. The "Summary of breakout group discussion" will itemize the conclusions and open questions determined by the breakout group.

Shallow ice coring

Many different efforts and approaches fall under the general heading of "shallow ice coring." Established projects include ITASE (the International Trans Antarctic Scientific Expedition), PARCA (Program for Regional Climate Assessment in Greenland), and ICAPP (Ice-core Circum-Arctic Paleoclimate Programme). Brief details of these programs follow, taken from their web sites, but as these are established programs, many more details can be found at the program web sites given below. We conclude this section with two new initiatives: one, a Coastal Array of Ice Cores (CAIC), designed to focus specifically on the interface between the ice and the ocean; the other recognizing the plight of mountain glaciers, a rich repository of paleo-environmental information that is rapidly melting away.

International Trans Antarctic Scientific Expedition (ITASE)

Nineteen countries participate in ITASE. Details of this highly successful and ongoing international program, including the ITASE Science and Implementation Plan, can be found at http://www.ume.maine.edu/itase/nationals/.

The primary goal for ITASE is the investigation of the last 200+ years of change in climate and atmospheric chemistry over the Antarctic ice sheet. Available Antarctic meteorological data (re-analysis fields, in-situ observations, operational model fields) provide approximate descriptions of spatial and temporal variability of Antarctic accumulation and associated atmospheric circulation from approximately 1980 to date. Progress has been made in describing the impact of the seasonal cycle, the Antarctic Circumpolar Wave, the Antarctic Dipole, and the impact of the ENSO cycle on the Antarctic over this time period. Difficulties still remain in explaining fully the history and forcing of Antarctic climate and the links between the tropics and the high latitudes. These difficulties arise largely because of the relatively short duration and sparse spatial coverage of Antarctic meteorological data. By combining available meteorological data from the Antarctic and Southern Ocean with annually dated, highly resolved, multi-parameter ice core proxies for a variety of climate parameters (e.g., moisture balance, atmospheric circulation and temperature), ITASE is extending the Antarctic climate record. This coverage offers the temporal perspective needed to assess the annual to multi-decadal state of natural variability in Antarctic climate. In the process, ITASE is contributing to understanding the impact of global change (natural and anthropogenic) on the Antarctic continent and the influence of Antarctica on global change. Figure 5 shows the completed and proposed ITASE traverses.

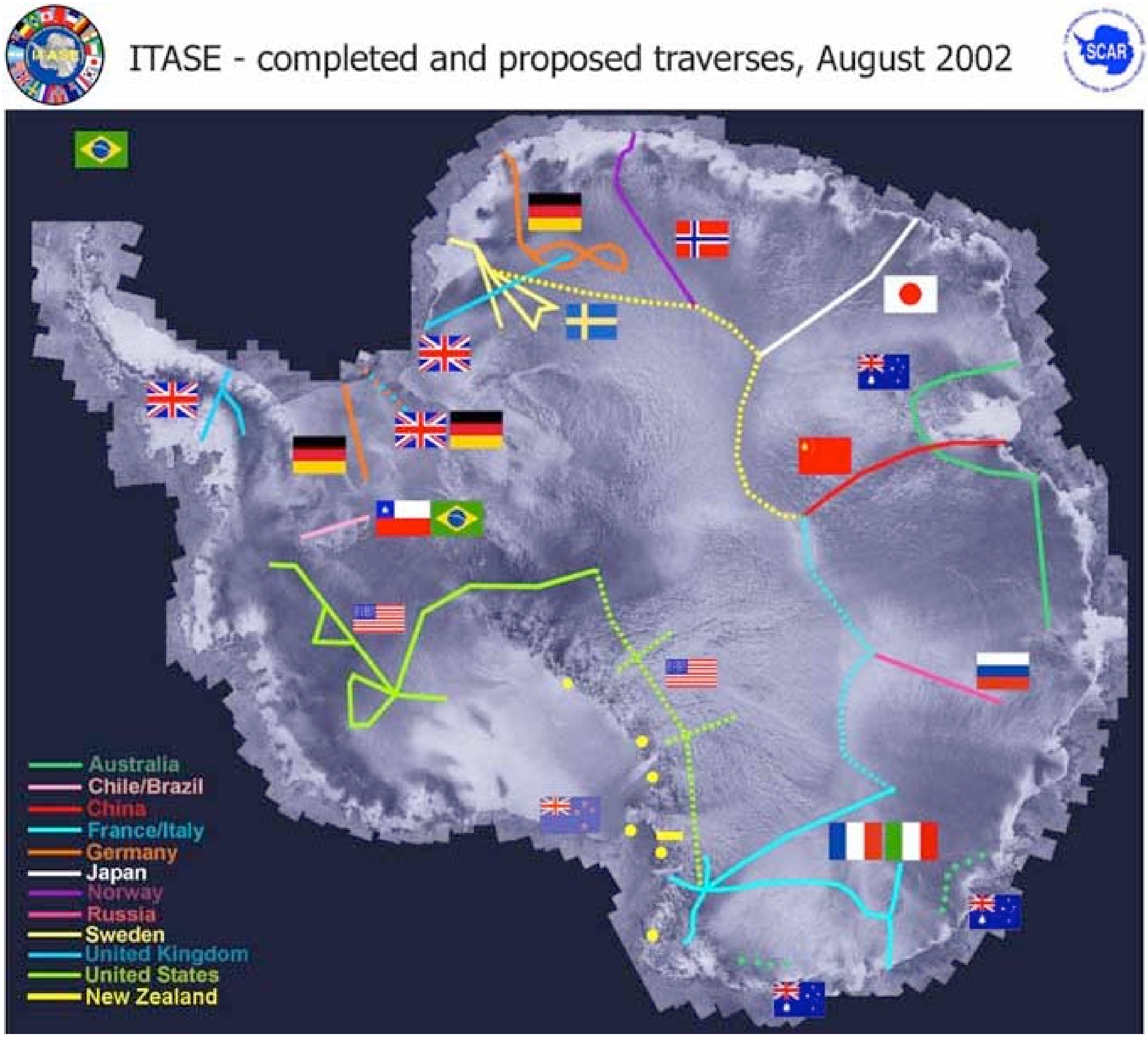


Figure 5: Completed and proposed traverses of ITASE.

Program for Regional Climate Assessment (PARCA)

The focus of PARCA is on assessing whether airborne laser altimetry could be applied to measure ice-sheet thickness changes. Its primary goal is to measure and understand the mass balance of the Greenland ice sheet. A dozen research groups participate in PARCA. The PARCA homepage is http://cires.colorado.edu/steffen/parca.html.

The main components of the program are:

- Periodic airborne laser-altimetry surveys along precise repeat tracks across all major ice drainage basins. The first survey was completed in 1993/1994, with repeat flights along selected routes in 1995 and 1996, when flights were also made over ice caps in Svalbard, Iceland, and eastern Canada.
- Ice thickness measurements along the same flight lines.
- Localized measurements of ice thickness change in shallow drill holes.
- Monitoring of various surface characteristics of the ice sheet using satellite radar altimetry, SAR, passive-microwave, AVHRR, and scatterometer data.
- Surface-based measurements of ice motion at 30-km intervals approximately along the 2000-m contour completely around the ice sheet, with interpolation of local relative ice motion using interferometric SAR.

- Shallow ice cores (10-200 m) at many locations to infer recent climate history, atmospheric chemistry, and interannual variability of snow-accumulation rates, and to measure temperature and vertical ice motion at various depths.
- Investigations of surface energy balance and factors affecting snow accumulation and surface ablation. This program is a collaborative effort with NSF, and includes the installation of automatic weather stations (AWS) at many of the drill-hole sites.
- Estimating snow-accumulation rates by climate-model analysis of column water vapor obtained from radiosondes and TOVS data.
- Detailed investigations of individual glaciers and ice streams responsible for much of the outflow from the ice sheet.
- Development of a thermal probe to measure various ice characteristics at selected depths in the ice sheet.
- Continuous monitoring of crustal motion using Global Positioning System (GPS) receivers at coastal sites.

Ice-core Circum-Arctic Paleoclimate Program (ICAPP)

ICAPP (part of CAPE (Circumpolar Arctic Paleo Environments) is an international project, under IASC and PAGES, aimed at synthesizing old and new ice core records from the northern circum-polar region. The emphasis, not exclusive, is on the Holocene record, and on improving ice core transfer functions by studying the present spatial variation of ice core variables. ICAPP's initial focus is on sea ice (more information at www.ngdc.noaa.gov/paleo/cape/icapp.html). The proposed Arctic Array project is an excellent program that could be coordinated with the ICAPP, which would expand this program to include ice coring sciences.

A Coastal Array of Ice Cores (CAIC)

CAIC is a new initiative first proposed and discussed formally at the IPICS meeting. CAIC combines elements of ITASE, PARCA and ICAPP to focus on coastal ice cores of Greenland and Antarctica, exploiting explicitly the paleo-environmental information available at the interface of the ice sheets and the ocean. CAIC is concerned with all time scales, but in practical terms, the focus is on cores of no more than 1000 to 2000 m, thus on time scales usually less than 100,000 years and most often less than 30,000 years.

CAIC is proposed to be an international project of coring coastal sites along the large ice sheets (Antarctica and Greenland). Coastal ice cores are different from deep inland cores in a number of important ways that make them both complementary to inland cores and valuable paleo-environmental archives in their own right. First, the lower-lying coastal sites are thought to be more sensitive to local oceanic conditions, such as sea ice extents, deep water upwelling, and ocean productivity, to name a few, and to local climate drivers (such as ENSO). Measurements such as MSA, sodium and chlorine concentrations and deuterium excess are all thought to be sensitive to local oceanic conditions. New trace chemical analyses may also be available in the future to focus on specific types of oceanic production. Second, coastal sites on higher domes (e.g., Law Dome, Siple Dome and Renland) have much of the same characteristics as those described before, but can "see" further out into the ocean, allowing for quasi-independent records of Pacific, Atlantic and Indian Ocean conditions, for example, in Antarctica. Third, coastal domes are often restricted in their geometry by their location, and thus they cannot become significantly higher or lower. This makes them valuable calibrators of deep inland cores, in whose paleoclimatic records elevation changes are potentially convolved. They can also tell us when the larger ice sheets have overrun their coastal positions, as well as when ice domes were free from the larger ice sheets. Fourth, coastal cores have a wide range of accumulation rates, from extremely high (Law Dome) to relatively low, depending on local meteorology. High-accumulation-rate cores have proven to be valuable, temporally detailed archives of paleo-environments, with high-resolution gas records and sub-annually resolved climate records. Lower-accumulation-rate cores, such as Siple Dome, contain paleo-environmental records of 100,000 years or more. Finally, coastal domes are generally shallower than inland ice sites, meaning that ice coring proceeds rapidly, often in one season, and many sites, or an array, can be contemplated within the same logistics funds and constraints that are used for a single deep ice site. Arrays of ice cores are particularly attractive, given the significant regional differences that have emerged in ice cores that are relatively close (e.g., Siple Dome, Taylor Dome and Byrd, or NorthGRIP-Summit cores).

Examples of previous work

Renland

The Renland ice cap is located near the Scoresbysund Fjord region in eastern Greenland. The present mean annual temperature is -18 °C, accumulation rate 48 cm ice/year and elevation 2340 m a.s.l. Estimated ice thickness at the drill site from ice radar measurements is 321 ± 5 m. A deep core was drilled in 1988 very close to the local summit (Johnsen et al., 1992). Of the 324 m drilled, only the deepest 18 m contain the last glacial period and a part of the Eemian. The core was drilled with the Danish dry shallow drill, producing some fractures in the core, and the coring did not quite reach bottom.

- There is an amazingly precise presentation of all the Dansgaard-Oeschger events in the core, but the $\partial^{18}O$ amplitudes are only half of those normally found in Greenland and less “saw-tooth-like.”
- The isotope record displays a strong climatic optimum in the Holocene part of the core.
- The deepest part of the core, from the isotopically warm (3 per mil more positive than at present) Eemian period, contains a few meter-thick layers of melt, suggesting that summers during that period were several degrees warmer than at present.
- In spite of the fractured core, the chemistry and dust profiles are of good quality (Hansson, 1994). But gas measurements on the core are problematic. A new core from the summit reaching the bottom would be a cheap and scientifically rewarding project. The ice cap is accessible by helicopter or Twin Otter from the nearby Constable Point Airport.

Law Dome (http://www.antcrc.utas.edu.au/antcrc/)

Law Dome is a medium-sized (200 km dia., 1390 m high), ice dome situated at the edge of the main East Antarctic Ice Sheet. Precipitation on Law Dome is mainly due to easterly winds from the low-pressure systems centered on 65°S, which move around Antarctica. These result in exceptionally large amounts of precipitation on the eastern side, while the western side experiences relatively low precipitation, with net accumulation reaching zero in some areas. The high accumulation, low temperatures and lack of strong winds in the summit area cause records from cores drilled there to have exceptionally fine resolution and high dating accuracy due to the easily resolvable annual accumulation layers.

Recent findings from Law Dome include:

- The relatively high annual accumulation and the low incidence of strong winds allow annual layers of snow to be consolidated so that measurements all show clear annual cycles back 8-10 thousand years. Based on MSA analyses, there has been a 20% decline in sea ice extent since about 1950 (Curran et al., 2003).
- Data from the preliminary analysis of the core confirms that Law Dome existed as an independent ice sheet even at the Glacial Maximum and that only relatively minor changes occurred as sea level rose in response to the melting of the Northern Hemisphere ice sheets.
- The time scale covered by the DSS core gives exceptionally good resolution of the emergence of the earth's climate from the LGM to the present climatic regime. For example, the ACR leads the Bolling warming in Greenland (Morgan et al., 2002).

- Atmospheric chemistry is well recorded in cores from near the Law Dome summit because the high accumulation gives good age resolution of both the ice and the trapped air, and temperatures are sufficiently low to preclude summer melting which affects air composition. Examples include high resolution CO_2, CH_4, halocarbon and other gas records that blend into the modern records (Etheridge et al., 1996, 1998; Francey et al., 1999; Trudinger et al., 2002).

Siple Dome

This ice dome at the base of the ice streams in West Antarctica has yielded a number of records that serve to illustrate the utility of coastal cores.

- Has been a dome for 100,000 years, implying that the ice streams are also at least that old and that WAIS has not overrun Siple Dome in that time.
- Has several records that correlate well with ENSO, including chemistry (Kreutz et al, 1999), accumulation (Bromwich et al., 2000), and stable isotopes.
- Has a very different Holocene climate record from Taylor Dome on the other side of the Ross Ice Shelf, implying that regional climatic differences have evolved over that time, in turn implying that climate processes in this part of the world have evolved over that time.
- Has an abrupt climate change not seen in other cores.
- Has a period of apparent "no accumulation" not seen in other cores.
- Has a fundamentally different deuterium excess record than that seen at Vostok, implying that different regions of Antarctica get their moisture from distinctly different oceanic regions. Coastal cores should help to clarify those differences.

Berkner Island

Berkner Island faces the Weddell Sea, and provides the best opportunity for seeing the pattern of climate change out of the last glacial period and into the Holocene in this sector of Antarctica. A UK/French-led project is currently drilling to bedrock at Thyssenhohe, the south dome of the island. The ice is 950 m thick, and the snow accumulation rate is 12 cm water equivalent per year. As of April 2004, the project had reached a depth of 500 m (with an estimated age of about 6000 years). The team reached bedrock in 2005 and expects at least a 30,000 year record. The core should provide both climatological and glaciological information, answering questions about the extent of the ice sheet in this region during the last glacial maximum.

Desirable characteristics of the drill site(s)

Drilling on domes or divides is generally best, but to test some hypotheses, flank cores may be desirable as well. Also, shallow coring in support of deep (i.e., 1000-m) cores is desirable to constrain spatial and temporal gradients in the region.

Two types of coastal cores are envisioned. One type has the highest snow accumulation available in a region to maximize the temporal resolution and provide annual to near-annual dating of the recent (Holocene +) part of the record. The second type has moderate accumulation to yield maximum age. Regardless, we envision that cores should be drillable in one field season.

Schedule

We envision a program of acquiring coastal ice cores that could begin in the IPY and continue for 10 to 20 years. Periodic evaluation of the program would be based on such measures as numbers of publications from the various projects, impact, and utility for improving the interpretation of deep ice cores.

Current and potential sites

Antarctica

1. Talos Dome (TALDICE)

Talos Dome is an ice dome (72°48'S; 159°06'E, 2316 m) on the edge of the East Antarctic plateau and adjacent to the Victoria Land Mountains in the western Ross Sea area. The firn core temperature is -41°C, and average snow accumulation over the last eight centuries is 80 $kg/m^2/yr$ (Stenni et al., 2002). Airborne radar measurements indicate that the dome summit is situated above a sloping bedrock (ice thickness 1880 ± 25 [m?]), but there is a relatively flat bedrock 5-6 km in the distance along the SE ice divide (ID1 159°11'00"E, 72°49'40"S, 2315 m), where the bedrock is about 770 ± 25 m in elevation and covered by 1545 ± 25 m of ice (Frezzotti et al., 2005). An Italian-French-Swiss-German-UK project is currently drilling to bedrock at the ID1 site, and one glacial/interglacial period of usable record is expected. A drilling at Talos Dome should greatly improve our knowledge about the response of near-coastal sites to climate changes and Holocene history of accumulation rates in the Ross Sea region. In addition, this ice record would strongly contribute to the understanding of the last glacial-interglacial transition when different climatic features and trends are observed between West-East Antarctica (Byrd, Vostok, EPICA-Dome C, Dome Fuji, Law Dome) and two near-coastal sites in the Ross Sea sector (Taylor and Siple Dome). Lastly it would provide a perspective for future variability of accumulation and dynamic changes in this sensitive area.

2. Roosevelt Island (Ross Ice Shelf area) has been proposed as a first site.
3. Many others are possible. A site selection team should be assembled to identify and prioritize these.

Greenland

1. Ingelfield Land: A small local ice cap north of Thule.
2. Disco Island: Some interesting small ice caps.
3. Sukkertoppen: A small ice cap south of Sondre Stromfjord.
4. Milne Land: A small local ice cap, south of Renland in Scoresbysund.
5. Scoresbysund Massive: Small ice caps in the mountains south of Scoresbysund.
6. Others are possible. A site selection team should be assembled to identify and prioritize these.

Mountain glaciers

Alpine glaciers have yielded a wealth of paleo-environmental information, but most are in danger of disappearing in the coming decades as global temperatures increase and these ice masses waste away. Such cores not only form a bridge to the polar cores, but as most of the world's population is concentrated in the tropics and temperate zones, such cores may more directly record environmental conditions in the populated areas of the planet. The focus here is time. We must recover these cores before they are permanently lost, and every year we delay in mounting a global effort to core the available mountain glaciers, we risk losing a potentially important record. A coordinated international effort is needed, and planning for such an effort needs to happen quickly.

Summary of breakout group discussions

An inland Antarctica array of ice cores (Paul Mayewski, discussion leader)

- It was suggested that the ITASE program should be expanded to include the atmospheric community. How best to do that?
- Use the bore holes, for example, to observe temperature changes in the past not currently available using dry firn zones.
- There was consensus that we should keep ITASE going. It has already succeeded, but is poised for expansion of both the geographic coverage of the project and what is measured.

A coastal Antarctica array of ice cores (Jim White, discussion leader)

The minimum core age required was discussed extensively. If possible, capturing the glacial-to-interglacial transition, extending back to 30,000 years, is thought to be essential. Where that is not possible, in very high accumulation zones, then retrieving a detailed section of the late Holocene–for example, the 2000-year "Mann time scale"–has its own considerable merits. There should be an effort to avoid sites with ages in between these ranges. Brittle ice may force us to focus on the older and younger sites.

- It was pointed out that CAIC was ideal for international cooperation as the obstacles to a nation's participation are considerably lesser than those for deep drilling operations.
- This is expected to be a 10- to 20-year project, and funding agencies should plan accordingly.
- A site selection team of experts should be convened to map out the most likely sites in Antarctica and Greenland, and then produce a draft prioritized list that would be revisited frequently as results from cores became available.
- A list of key parameters to be measured in each core needs to be established, and frequently revisited, along with procedures for inter-calibration of labs, particularly, but not limited to, new measurements such as new gas concentrations or isotopic ratios in gases.
- A workshop may be needed prior to site selection or any other activity to provide a more comprehensive scientific rationale and list of key scientific questions than presented here.

An Arctic array of ice cores (Joe McConnell, discussion leader)

- ICAPP needs to be reinvigorated, perhaps by adding human health as an issue–for example, records of mercury or persistent organic pollutants (POPS).
- As with CAIC, a list of key parameters to be measured in each core needs to be established, and frequently revisited, along with procedures for inter-calibration of labs, particularly, but not limited to, new measurements such as new gas concentrations or isotopic ratios in gases.
- The influence of the Arctic Oscillation and ENSO on Arctic climate for the past 2,000 years is a key concern so we should consider what sites need to be sampled to ensure that we capture these key atmospheric oscillations.
- In this region in particular, where human impacts over the last few centuries to millennia are profound, we need to ensure that a full suite of pollutants is analyzed in each core and this could also include DNA, pollen and other biomarkers.
- We need to better understand the "air-snow transfer" problem, this is a long-standing issue, but one that continues to require careful study.

Ice core Climate Archive Recovery Activity (ICARA) – An ice coring program for non-polar regions (Margit Schwikowski, discussion leader)

- Non-polar regions are where the world's fresh water and majority of population are found. We need more paleo-environmental information from these non-polar areas. Non-polar ice cores provide an essential link with polar ice cores that is necessary to understanding the global climate system.
- There needs to be international cooperation on collecting and storing cores from mountain areas. The storage conditions in many parts of the world may not be adequate for safe core storage.
- Ice coring research in high alpine areas requires unique experience and skills that have to be shared among the alpine ice coring community to have proxy records and reliable and adequate interpretation no matter where the ice core has been processed.
- Time is critical for non-polar ice coring. Most, if not all, mountain glaciers and ice caps are rapidly receding. It is critical that a coring program is initiated soon to retrieve these critical environmental records before they melt away.
- There are new technical challenges in mountain glaciers–for example, thick layers of ash that may need to be drilled through.

- Can PAGES help with this? There was general consensus that this needs to be a PAGES initiative as well as an ice core initiative.

Ice Drilling Technology Issues

Session 4 at the IPICS meeting was focused on improving ice core drilling and recovery techniques. The goals of this session were to identify common challenges associated with the drilling and recovery of ice cores from deep drilling sites and to discuss potential solutions based on the field experiences of the group. A pre-meeting poll of the participants identified several areas of common concern. A summary of all issues raised in the pre-meeting questionnaire responses is presented in Appendix 3. Issues of common concern included: difficulties with drilling and recovery of warm ice, difficulties keeping brittle ice intact during drilling and subsequent handling, the development of drilling technology that will allow replicate coring, and the identification and testing of a better drilling fluid than those currently in use.

Warm ice

Difficulties using an electromechanical (EM) drill in warm ice are most frequently encountered toward the end of deep drilling projects as the ice/bedrock interface is approached and the in-situ temperature of the ice approaches or reaches its pressure melting point. As the drill penetrates into warm ice near the bed, refrozen ice begins to build up on the cutters and shoes of the EM drill head, and the performance of the drill rapidly deteriorates to a point where penetration stops. A comparison of the pressure-corrected temperatures at which drilling difficulties were first encountered from four deep EM drilling sites in Antarctica and Greenland indicates that the in-situ ice temperature alone does not predict when drill performance will begin to deteriorate. The design of the drill also plays an important part in dictating how the drill performs in increasingly warming ice.

A variety of procedures have been used to restore EM drill performance once difficulties are encountered. These include (1) introduction of a density/temperature-balanced ethanol/water solution (EWS) at the drill head/ice interface, and/or adjustments to the drill system, including increasing pump flow rate to increase transportation of chips, (2) changing the cutting angle at the cutter/ice interface, (3) changing the drill motor speed, and (4) coating cutters with teflon. Utilization of EWS at the cutting interface has been used with success on several deep drill sites, most recently at NorthGRIP in Greenland and Dome C in Antarctica. Use of EWS generates its own set of difficulties, namely, refreezing of core and chips into the core barrel on the return trip to the surface and the generation of cracks in the core during drilling. These cracks and the subsequent infiltration of drill fluid into them can compromise the core quality for certain types of analyses. While adjustments to the drill system alone can extend the depth of operation without introducing EWS into the hole, recent experiences at Dome C and NorthGRIP show that even the combination of both procedures has a performance limit.

Switching to a thermal drill once the EM drill ceases to be effective may, in the long run, prove to be the only viable alternative. This solution currently has the limitation of requiring two different sets of drill system components; however, ongoing research in this area may yield a more workable solution.

Brittle ice

During deep drilling projects, a zone of extremely fragile ice is typically encountered between 200 and 500 m. This zone persists until the depth is reached at which the hydrostatic load is sufficient to transform the trapped air bubbles into air-hydrate clathrate crystals (typically in excess of 800-1,000 m for complete transformation). In the brittle interval the internal gas pressure in the bubbles creates tensile stresses in the vicinity of the bubbles that exceed the strength of the ice. The phenomenological result of these stresses is a marked tendency for the ice to crack and break, with very little provocation, both during and after drilling. In extreme cases where the drill itself adds additional stresses to the ice, drill runs consisting of severely cracked and broken ice result. In the most benign cases where drill-induced stresses are minimized, a run can be recovered intact only to break spontaneously during handling or storage due to thermal and mechanical stresses.

Additional factors implicated in brittle behavior include crystal anisotropy (leading to differential thermal expansion), stresses induced during breaking the core off the bottom of the hole, drilling (cutting) stresses, stresses induced by hydrostatic pressure change during and after the trip up-hole, thermal stresses due to the temperature difference between downhole and surface conditions, and mechanical shock due to mishandling during core ejection and/or core processing.

Because the characterization of the onset of brittle behavior is based on the subjective observation of the depth at which the ice becomes difficult to handle without inducing breakage, it is difficult to quantify an expected onset depth at a given site based on observed past behaviors at other drilling sites. It has, however, been generally observed that colder in-situ ice temperatures favor shallower onset of brittle behavior and subsequently, shallower depths lessen this phenomenon as gas bubbles are converted to clathrates. This is consistent with the known phase diagram for air hydrate clathrates. Recent experiences at Siple Dome indicate that the flow regime and resultant stress state of the ice are also factors in this behavior.

Field experiences dealing with brittle ice indicate that a variety of approaches can be taken to minimize core breakage in the brittle zone. At Dome Fuji, Antarctica, drillers attribute their success in recovering ice intact through the brittle zone to low penetration rates (2 mm/rev), resulting in a smooth core surface, and to minimization of thermal shock. Other recommendations include keeping the core as cold as possible, avoiding vibration during hoisting, avoiding any mechanical shock or the application of bending stresses (this requires careful leveling of surfaces across which the core will transit in unloading and handling), use of stiff metal core trays, and damping of thermal shock by unloading the core from the barrel into an immersion bath of cold drilling fluid. Other variables, whose effect is unknown at this time, have also been identified. These include the hoisting speed through the thermal gradient in the liquid column in the hole, the transition speed of the drill string from liquid to air in the hole and potential for resulting rapid change in the weight of ice bearing on the core dogs at the fluid/air interface, and the effect of cutter geometry on crack initiation and propagation during drilling.

Replicate coring

Acquiring the ability to retrieve additional volumes of ice from intervals of scientific interest is a desirable goal for two reasons. First, the suite of measurable parameters has grown enormously, increasing sample needs. Second, determining the significance of abrupt climate change in ice core studies now demands records at much higher resolution than previous work. Two concepts have been articulated to accomplish this: rapid access drilling to the depth interval of interest followed by core recovery, and the development of deviation drilling (and coring) capability. In the first instance, multiple closely spaced holes can be used to recover replicate cores. In the second instance, additional core can be recovered from a single main borehole by creating alternate drilling pathways in the main borehole at the depth of interest.

The feasibility of the first method was demonstrated most recently during the early stages of the drilling effort at Siple Dome, Antarctica. In 1997 the Caltech hot water jet drill system was used at Siple Dome to drill to depths of interest and obtain discontinuous core samples at that site in advance of fielding the

EM drill the following season. In this process the hot water jet drill was used to rapidly create an access hole to a desired depth; then a thermal coring device was introduced into the hole to recover core sections at those depths. Once the core through the interval of interest was recovered, the hot water jet drill was reintroduced into the hole to continue down to the next interval of interest. Examination of sections of the ice retrieved with the thermal coring device showed highly disturbed bubble structures, indicating that the heat introduced at the wall of the core by the thermal drill had substantially altered the ice. The hot water jet drill performed exceptionally well. Adjustments to the thermal coring device or the utilization of an EM drill rather than a thermal drill for the actual coring would make this replicate coring system completely successful.

Deviation drilling has been used successfully in the oil and mining industries since the early 1900s. Successfully transferring this technology to ice is the challenge. However, successful deviation drilling in cold ice has been demonstrated in several instances. At Vostok Station, whipstock and a thermal drill were used successfully to deviate the main borehole to bypass stuck drills. In this case, the primary borehole was not re-entered, but drilling continued in the secondary hole. A feasibility demonstration under controlled conditions in warm ice has also been run in a test well at the University of Alaska, Fairbanks. This successful demonstration utilized whipstock and an antifreeze thermal electric drill (ATED) to create a second borehole 9 m deep off a primary borehole 4.5 m deep. No coring experiment was conducted. More recently, utilization of mechanical reamers rather than some type of thermal drill to initiate sidetracking has been proposed but remains untested technology in ice.

Both thermal and mechanical sidetracking methods have challenges when utilized in ice. The disposition of water generated in the process of sidetracking using a thermal drill and the potential for this water to freeze in undesirable places can be problematic. Chips generated during mechanical sidetracking may require additional passes to remove them from either the sidetracked hole or the main hole. Challenges associated with either type of deviation drilling include safe removal of the whipstock and blocking the side hole after the completion of coring if the main borehole is to be re-entered. Necessary accommodations for the downhole drilling fluid in deviation drilling also remain largely unarticulated at this point in time.

In summary, adaptation of deviation drilling techniques for ice is within the capability of current technologies, but significant challenges exist. A program dedicated to design and testing of such a capability will be required before this capability can be successfully fielded.

Drilling fluids

Fluid is introduced into an open borehole for two purposes. First, a circulating fluid in the borehole provides a mechanism for sweeping chips away from the drill head and into the screen sections, where they are sequestered for ultimate removal. Second, the presence of a density-balanced fluid in the hole prevents it from closing in on itself through creep.

During electromechanical drilling, chips are generated at the cutting face of the core barrel. Unless these chips are swept away from the drill head and trapped above the cutters, they quickly pack against the head and sidewalls, making drilling impossible. Fluid circulating in the hole sweeps these chips away from the head and provides a transportation mechanism for capturing chips in the screen sections of the drill string, allowing eventual removal from the borehole.

Because ice is a plastic medium at typical ice-sheet temperatures, open boreholes at depth will eventually close on themselves unless an effort is made to maintain hydrostatic equilibrium in the hole. This equilibrium can be established by introducing a non-freezing fluid of a density close to that of ice into the borehole. Filling the borehole to the appropriate level with a density-balanced fluid will maintain it indefinitely in an open state.

At this time the performance of the drill fluid continues to present major challenges in deep core recovery projects. Despite a variety of approaches utilizing different single- and dual-phase fluids, virtually every fluid or fluid combination utilized to date has had its performance shortcomings – some with exceedingly expensive results. The identification of a non-toxic, non-flammable, density-appropriate, hydrophobic, inexpensive, environmentally friendly and readily available fluid(s) with predictable performance characteristics has become somewhat of a holy grail in the ice-drilling community. In the final analysis, an intelligent compromise between desirable and undesirable qualities in a drilling fluid will likely be necessary in order to identify a suitable fluid(s) that will behave predictably.

Drill fluids used to date fall into two general categories – single- and dual-component fluids. Although early drilling projects utilized combinations of hydrophilic fluid mixtures, these will not be discussed here. The solubility of ice in such fluids is widely recognized as an undesirable characteristic under all but exceptional circumstances where dissolution of the ice is sought. The appeal of a single-component system is simplicity. If a single fluid can be identified that meets all required criteria, no mechanism for mixing two-component fluids is required. This approach has the additional benefit of simplifying the logistical stream. The single-component fluid most recently used by both the U.S. and Japan has been n-Butyl Acetate (n-BA). Due to its toxicity, use of n-BA defeats at least part of the benefit of drilling with a single-component fluid. Although no metering or mixing mechanism is required and logistics are somewhat simplified, an extra effort to provide adequate ventilation at the drillsite is necessary, as is the use of protective clothing and breathing equipment. Even after long periods of ventilation, vapors are still generated from the cores drilled in n-BA, making transportation and long-term storage somewhat problematic as well. n-BA is also a highly aggressive solvent. This has caused failures in drill components during the prolonged exposure of vulnerable drill subsystems during normal drilling operations.

Dual-component drill fluids have typically consisted of a base component, usually an organic solvent, and a second fluid used to adjust the density of the base component. The second fluid (or densifier) has, in the past, frequently been a halogenated chlorofluorocarbon (HCFC). Many of these densifiers consist in whole or in part of compounds that are either toxic or are now subject to environmental law by some countries. This situation presents its own challenges. New densifiers consisting of hydrofluorocarbons (HFC) and hydrofluoroethers (HFE) have been recently examined. These may prove to be workable alternatives and will be field-tested within the next few years.

Presentations and discussions on drilling technology issues

This portion of the meeting consisted of four short presentations–"Brittle ice" (Jakob Schwander), "Warm ice" (Laurent Augustin), "Replicate drilling" (Bill Mason), and "Drilling fluids" (Michael Gerasimoff)–and thereafter of discussions held by a working group made up of Jakob Schwander*, Pavel Talalay*, Mike Gerasimoff*, Laurent Augustin*, Grant Emmel*, Joan Fitzpatrick (facilitator), Bruce Koci, Alex Shturmakov, William Mason, Steffen Bo Hansen, Todd Hinkley, Frank Wilhelms, Geoff Hargreaves, Fabrizio Frascati, John Rhoades, Simon Sheldon, Nobuhiko Azuma, and Brian Stone (*denotes report members).

In the following report the main outcomes of the working group discussions are added at the end of each section.

Brittle ice (Jakob Schwander, presenter)

Ice from cold glaciers contains about 10 percent by volume of air, usually a few hundred bubbles per cubic centimeter. As the ice sinks deeper into the glacier or ice sheet, bubbles are compressed and are finally transformed into air hydrates (clathrates). By the drilling process and the recovery of ice cores, the hydrostatic pressure is released. The pressure difference between the bubbles and the outside causes stress, which is most concentrated at the bubble surface. Numerical calculations show that tangential stress at the bubble surface is on the order of 1.4 times the bubble pressure. If the maximum stress exceeds the breaking strength of ice, fresh cores are very fragile and we are speaking of "brittle ice." Initial cracks at the bubble boundary increase the stress at the site of the cracks by increasing the effective surface (wedging effect), leading to a rapid propagation of the cracks and in the worst case to a complete shattering of the core.

In mechanical drilling we can consider 3 distinct cases:

- drilling in a dry hole
- drilling in a fluid-filled hole at pressure equilibrium
- drilling in a hole with a small amount of liquid at the bottom.

Drilling in a dry hole: Here, the hydrostatic pressure around the core is released at the kerf. In addition to the stress from the bubbles comes the stress from the drill bits and the strong gradient in the ice pressure in the vicinity of the bottom of the kerf. Figure 6 shows the tensile strength of ice as a function of temperature (Butkovitch, 1954). The scale at right shows the approximate corresponding depth where the maximum stress around the bubble equals the pressure given on the scale at the left. From that we expect, for example, at -30 °C severe problems due to brittleness below about 150 m, which corresponds roughly to experience.

Drilling in a fluid-filled hole at pressure equilibrium: Here, the ice is not stressed by a change in hydrostatic pressure while drilling. Therefore, drilling through the brittle zone is unproblematic in a fluid-filled hole. The hydrostatic pressure is slowly and uniformly released during hoisting of the core. It is the shaking during this phase and the handling afterwards that can cause breaks in the core.

Drilling in a hole with a small amount of liquid at the bottom: Various experiences have proved that adding a small amount of drilling fluid has a positive effect on the performance of the drill at the critical depth below 150 m or in ice under other stresses, e.g., fast-flowing glacier ice. The positive effect is likely due to stress reduction at the level of the cutters by the lubricating effect of the liquid.

Measures to reduce breaking of brittle ice:

- A small pitch in a dry hole reduces the extra stress from cutting. Experience has shown that drilling at 250 m depth is possible with an extremely low pitch. However, the transport of the fine chips is inefficient and the chips tend to clog.
- Precise cutting produces a smooth surface, which reduces the initiation of cracks from the surface.
- Careful handling and soft surfaces are essential in the brittle zone.
- As the strength of ice increases at lower temperature (Fig. 6), handling at low and constant temperatures helps to keep the cores in good shape. On the other hand, higher temperatures speed up the relaxation of the cores.

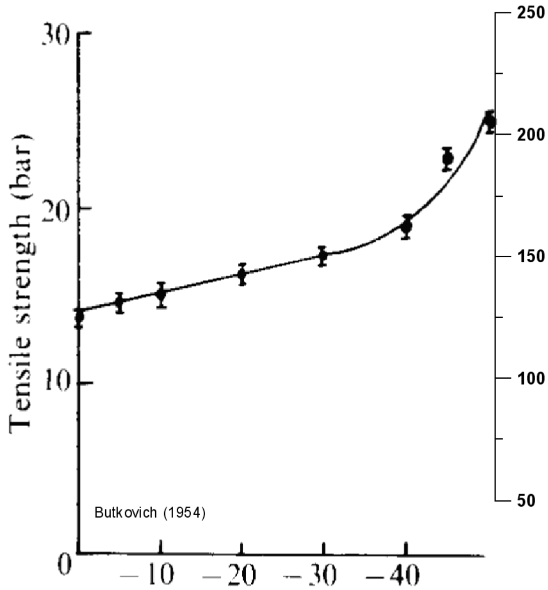


Figure 6: Tensile strength of ice. Scale at right shows approximate depth (in m) where the maximum stress from bubbles would correspond to the scale at the left. Bottom scale is temperature in degrees C.

Discussion group summary and recommendations:

- Adopt a universal, standardized system for core quality indication.
- Minimize thermal stressors: relaxation in core buffer (possibly with ramping temperature).
- Minimize mechanical stressors: use of stiff core troughs.
- Slow core lifting from the bottom to the surface in order to release inner ice tension didn't help to solve core quality problem.

Warm ice (Laurent Augustin, presenter)

The performance of an electromechanical drill can be drastically reduced when the temperature of the ice is approaching the melting point. This is mainly due to ice building on the cutters, under the shoes and on the drill head. The conditions of examples where difficulties were encountered are listed in Table 2.

As we can see, the temperature at which the warm ice difficulties begin is mainly a function of the drill design and its characteristics. By working on the drill design (pump flow, chip transportation, drill motor rpm and cutter angle), the performance of the drill can be improved. One means to improved performance is the use of ethanol-water solution (EWS). EWS is transported to the bottom of the borehole (inside the drill or with a special tank) and decreases sticking of the drilling chips.

This technique has the disadvantage of damaging the core slightly and creating cracks. However, most scientific measurements are still possible. Another disadvantage is the refreezing of the core and the chips into the drill on the way up due to the large temperature gradient of the hole. This requires some defrosting process at surface to retrieve the core and clean up the drill. This defrosting process adds some stress to the core. That technique was used successfully, in July 2003, at NorthGRIP after the preliminary tests at EPICA Dome C in January 2003. To accomplish EPICA Dome C, that technique, further improved at NorthGRIP, will be used again in the 2004-2005 season down to bedrock. Due to the disadvantage of EWS, Laurent Augustin proposes to drill in warm ice with a thermal drill without any EWS as soon as the electro-mechanic drill has lost too much performance.

Table 2. Warm ice problems in deep drilling operations.

Site	Drill	First difficulties: Depth (m), Temp (°C)	Measures for improvement	Start use EWS[1] Depth (m), Temp (°C)	Final depth (B = bedrock) Depth (m), Temp (°C)
GRIP	ISTUK	---	---	---	3028(B), -6.443
Vostok	KEMS 132	3400, -8.181	rpm, pump and cutters.	---	3628, -3.259
NGRIP	NGRIP/ EPICA	2600, -14.666	EWS	2931, -5.091	3085, -2.3 (B, at melting point)
Dome C	EPICA	2550, -16.48 and 2700, -13.30	pump	3119m, -6.2	3200, -4.4

[1] EWS: ethanol-water solution

Discussion group summary and recommendations

According to the theory of N.H. Fletcher (Fletcher, 1970**)**, on the surface of ice at -6 °C the quasi-watery layer with near 10 Å thickness appears instantaneously, and at temperatures near 0 °C the thickness of the layer increases up to several hundred Ångströms. At nearly the same temperature (-5 °C), the transition from brittle to plastic strain takes place even at high strain rates like those that obtain under electromechanical drilling (Epifanov and Faustov, 1984). The shape of ice cuttings is changed from grain-shaped to long shavings. All these phenomena lead to rapid gluing together of ice cuttings, forming ice spots and rings on the surface of the drill equipment (especially on the surface of cutters and near the body of the drill head). The closure of fluid circulation then follows, and the drill sticks.

- The main improvement that really helped to solve the problem of warm ice drilling by electromechanical drill at Vostok was special slots on the edges of cutters.
- Keep the flow rate high enough to keep the ice/water droplets separate till the droplets re-freeze.
- When using EWS, the amount and concentration used are critical for good performance.
- At present, the use of a thermal drill is considered the only method to guarantee good performance in warm ice.

Replicate cores (Bill Mason, presenter)

Logistics restraints limit the size of the core that can be drilled and returned from the field. Since some of the most 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 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.
All directional drilling begins with a whipstock, which is placed at the point where the drill is to leave the hole.

The whipstock 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 whipstock 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 whipstock can always be retrieved.

There are 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 whipstock;
- how to isolate the side-tracked hole from logging operations.

When coring ice, there are two sidetracking methods that are used:
- thermal (simpler and cheaper);
- mechanical (sophisticated design, steering capability).

Discussion group summary and recommendations
- Thermal sidetrack drilling has been used many times at Vostok for bypassing stuck drills.

Drilling fluids (Michael Gerasimoff, presenter)
Boring ice to depths in excess of about 300 m requires a fluid with a density closely matched to that of ice to prevent lithostatic pressure from causing plastic collapse of the borehole; the latter frequently results in loss of the drilling equipment. The fluid, or mixture of fluids, must simultaneously satisfy criteria for density, low viscosity, and frost resistance, as well as workplace safety and environmental compliance over both the short term (e.g., fire hazard and acute toxicity) and long term (chronic toxicity, local and global environmental degradation). The fluid must also satisfy other criteria–for example, those stemming from the analytical methods employed on the ice core.

A number of different fluids and fluid combinations have been tried in the past. Since GISP2 (1990-1993), the U.S. Polar Program has utilized a single-component fluid system, n-butyl acetate, but the toxicology, flammability, aggressive solvent nature, and long-term liabilities of n-butyl acetate raise serious questions about its continued application. The European community, including the Russian program, has concentrated on the use of two-component drilling fluid consisting of a low-density hydrocarbon base boosted to the density of ice by addition of halogenated-hydrocarbon densifier. Many of the proven densifier products are now considered too toxic, or are no longer available due to efforts to enforce the Montreal Protocol on ozone-depleting substances.

A number of compounds suggested as replacements for ozone-depleting substances such as HCFCs were investigated. Most of these are unsuitable for ice-drilling applications and can be dismissed out-of-hand due to toxicity, flammability, unsuitable density, and so forth.

Alternatives categorized as hydrofluorocarbons (HFCs) and hydrofluoroethers (HFEs) may prove to exceed the engineering performance of the now-obsolete densifiers: simultaneously providing high density, low viscosity, materials compatibility, very low toxicity, high safety, convenience in handling, and low environmental liability.

Detailed engineering-related testing tailored to our application would begin by procuring large samples of each compound as soon as is practical. Following a preliminary set of engineering tests to assure ice and drill-materials compatibility, samples of fluid would be supplied to the science community for compliance testing in their analytical streams.

Because both HFCs and HFEs evaporate cleanly, and drawing upon experience with the similar HCFC compounds they replace, interference with scientific analyses is not anticipated with either HFC or HFE densifiers.

(More details can be found in "Drilling Fluid Observations and Recommendations for U.S. Polar Program, WAISCORES Drilling Project" by Michael Gerasimoff http://www.ssec.wisc.edu/icds/reports/Drill_Fluid.pdf.)

Discussion group summary and recommendations

- Test with drilling fluid to continue.
- Suggestions to look into silicone oil.

Other issues and recommendations

- Develop a common set of parameters for drill system control and monitoring interface (working group: Pavel Talalay, Laurent Augustin, Grant Emmel).
- Establish a procedure for regularly scheduled working meetings of this group: informal meetings once or twice per year, larger meetings about every 2 years (working group: Jakob Schwander, Frank Wilhelms, Joan Fitzpatrick, Laurant Augustin, Mike Gerasimoff).

Rationale for International Collaboration

IPICS proposes an ambitious research agenda, understanding that the pressing science questions of our time can best be addressed through international collaboration to gain the considerable intellectual, logistical, and financial resources required for success. Current issues of the impact of human activity on our planet and the prospects of rapid climate change make it imperative that better understanding of the earth's linked systems be established. International efforts for ice coring science are imperative.

Intellectually, the science proposed by IPICS is truly global, addressing fundamental issues of earth's climate history, and pressing, societally relevant issues related to human impacts on global systems. The science of ice coring has become quite international (witness the participation in the IPICS workshop). Formal and informal collaboration among research groups in different countries is fairly common (and productive), though not universal. Expansion of this collaboration in interpreting data, designing field programs, and disseminating results will be required for the success of IPICS, due to the magnitude of the proposed programs. This substantial collaboration will also enhance the quality of IPICS results, as investigators with a variety of backgrounds work together on the IPCIS projects.

IPICS will also require a substantial amount of analytical work, beyond the capability of laboratories in any individual country. Sharing the laboratory work is the best way to insure that IPICS results are produced in a timely fashion. This requires close cooperation in sharing samples and inter-calibrating instruments, but the community has already developed relevant experience on previous projects, and analytical collaboration is not viewed as a major challenge.

From a logistics perspective, many of the IPICS projects can clearly benefit from, and probably require, international cooperation. Deep ice coring in remote Antarctic locations will require substantial transport resources, probably including traverse and aircraft capability. Programs involving multiple coring (spatial arrays) are clearly beyond the logistics capabilities of any one nation. Furthermore, different approaches to drilling technology have been pursued by individual national programs – sharing the best drilling ideas can help to move drilling technology forward.

Financial considerations are also relevant to the IPICS initiative. Though ice coring is not particularly expensive compared to other branches of science, the important discoveries outlined in the IPICS discussion above could not be supported by any one national program. Combining resources will allow larger, more complex questions to be answered than could be answered by any nation working alone.

Combining resources on the scale proposed by IPICS will be an unprecedented effort for the polar science community. Though there are likely to be challenges, the steering committee believes that the synergies promoted by the IPICS collaboration will result in lasting contributions to science.

Moving Forward – IPICS Recommendations

Discussions among the steering committee and participants at the workshop resulted in a series of recommendations to keep moving in the direction of international collaborations on ice core sciences. Heinz Miller, on behalf of the European Polar Board, stated that Europe would like to host a follow-up IPICS meeting during 2005.

1. Support international collaborations between ice core scientists and drilling engineers.
Experience has repeatedly proven that ice coring is most effective when drilling engineers and scientists are working closely together to jointly solve the numerous problems that invariably arise in dealing with different ice types, temperatures, debris concentrations, logistical settings, and scientific requirements. Equally, it is clear that no single nation can generate the pool of experts needed to have an active and successful ice coring activity; ice coring is and should be an international activity. Improved international collaborations between ice core scientists and drilling engineers are required for progress, and should be fostered by meetings, exchanges, and other activities.

2. Support the following projects through international collaborations:

- Locate and collect the oldest ice core climate record in Antarctica;
- Collect a full Eemian record in Greenland;
- Collect an expanded suite of records from smaller glaciers and ice caps, including high-elevation and low-latitude sites;
- Collect an array of ice cores (0-200, 0-10000, 0-30000 yrs) from coastal and inland locations on the large ice sheets.

Discoveries from ice cores are central in understanding of the earth system, are prominent in the documents of the Intergovernmental Panel on Climate Change, and clearly are informing decisions about our future. Each new ice core has added to this legacy, and there is no evidence of diminishing returns. Indeed, the more that is learned and the more reliably these results are established, the more questions are raised. New advances in instrumentation allow additional measurements, and advances in interpretation increase the need for spatially distributed data. The unavoidable trade-off between length of climate record and time resolution in that record, complicated by the nonlinear effects of ice flow, dictates that a range of cores be collected to optimize interpretations across many time scales. Numerous projects are recommended by these considerations. Those listed here have especially high priority.

3. Develop internationally collaborative projects for the International Polar Year.
The International Polar Year, or IPY, will be the fourth great internationally collaborative "expedition" to the earth's polar regions. IPY offers an unparalleled opportunity to galvanize international collaboration, and raise the profile of key scientific efforts with policymakers and the public. As one of the highly visible and important aspects of polar research, ice coring should be prominently represented. Efforts through IPICS (already well begun) will enable ice core participation in IPY.

4. Improve ice coring, with special emphasis on:

- better drill fluids;
- better quality through the "brittle ice" zone;
- better core recovery in warm or silty ice.
- replicate core recovery in key intervals.

The international collaborations between drilling engineers and scientists, promoted in recommendation 1, will face numerous challenges in site selection, camp preparation, core recovery, core analysis, core archival, site cleanup, etc. Of particular importance will be drilling better; most recent projects have been hampered by problems in one or more key areas. Drill fluids must meet numerous challenges--environmentally benign for long times and for all working with the fluid, non-damaging to the ice and to analyses made of the ice, and technically capable to meet all the viscosity, chip-handling and other factors of the drilling. Much progress has been made, but improvements would be beneficial. The strong tendency for ice samples to fracture, often catastrophically, following recovery from regions with highly pressurized bubbles has limited the quality of many paleoclimatic records, and novel solutions may be required. Special difficulties attend core recovery from warm regions or through debris-bearing ice. The great expense of coring, and the inevitable result that some sections of each core are in greater demand for scientific experiments than are other sections, argue that science could be advanced at low cost if replicate coring through deviation drilling or other technologies were easier and more nearly routine. Pursuit of these and other goals will be important in the future.

Acknowledgements

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Appendix 1:

International Partnerships for Ice Core Science

Workshop Agenda
Algonkian Regional Park, Sterling, VA, USA

Saturday (March 13, 2004)

Arrival of participants

Sunday (March 14)

9:30-10:30 Brunch
10:30 Bus to Washington D.C
17:00 Leave Washington D.C and return to Algonkian
18:30 Welcome dinner and lecture
Challenges for the International Ice Core Community
Richard Alley

Monday (March 15)

7:30-8:15 Breakfast

Session 1: Building a Common Framework

Session chair: Ken Taylor

The desired outcome of this session is to develop a common understanding of the goals of this meeting and the long-range goals of the international community of ice core researchers.

8:30 Welcome and purpose of meeting
Ken Taylor
8:40 Remarks from the U.S. National Science Foundation
Karl Erb and Julie Palais
8:55 Remarks from the European Polar Board
Paul Edgerton
9:10 What are the most significant science issues for ice core research?
Presentation and discussion: *Thomas Stocker*

Session 2: Opportunities for International Ice Coring Programs

Session Chairs: *Ken Taylor and Eric Wolff*

The desired outcome for this session is to improve the science plans for projects that have been suggested, to consider other projects that may be proposed as a result of the discussions, and to determine how international collaboration could facilitate the suggested projects.

9:45 A project to recover the longest possible ice core paleoclimate record
Jean Jouzel
10:00 Discussion of a project to recover the longest possible ice core paleoclimate record
10:20 Break
10:40 A project to recover Eemian ice from Northwest Greenland
Dorthe Dahl-Jensen
10:55 Discussion of a project to recover Eemian ice from Northwest Greenland.

11:15 <u>An inland Antarctica array of ice cores</u>
Paul Mayewski
11:30 Discussion of an Antarctic inland array
11:50 <u>A coastal Antarctica array of ice cores</u>
Jim White
12:05 Discussion of an Antarctic coastal array
12:25 Lunch
14:00 <u>An Arctic array of ice cores</u>
Joe McConnell
14:15 Discussion of an Arctic array
14:35 <u>An ice coring program for non polar regions</u>
Margit Schwikowski
14:50 Discussion of an ice coring program for non-polar regions
14:10 Break
14:40 <u>Discussion of collaboration</u>:
Discussion led by *Ed Brook*
What do we mean by collaboration?
Why collaborate?
Examples of collaboration that worked and why did they work?
Examples of collaboration that did not work and why did they not work?
How can we collaborate on the projects we just discussed?

15:20 End of meetings for the day

Session 3: Drilling Technology and Other Topics

The desired outcome of this session is to exchange ideas on drilling technology by physically examining drill components.

17:30 <u>Posters and appetizers</u>. Posters on drilling technology are strongly encouraged.
Posters are other topics are also welcome.
Attendees are encouraged to bring interesting parts of their drills to the meeting to show and discuss with each other.
8:30 Dinner

Tuesday (March 16)

7:30-8:15 Breakfast

Session 4: Improving Ice Core Drilling and Recovery

Session Chairs: *Joan Fitzpatrick and Jakob Schwander*

The desired outcome of this session is to identify ways to improve core quality and the efficiency of drilling operations.

8:30 <u>Introduction and summary of a survey on the technical challenges associated with ice core drilling and recovery.</u>
Joan Fitzpatrick
8:45 <u>Replicate coring:</u>
15 minute talk: *Bill Mason*; 10-minute discussion
Suggestions for a system to collect replicate cores from depths of special interest.

9:10 Options for drilling fluids:

15 minute talk: *Michael Gerasimoff*; 10 minute discussion: *Joan Fitzpatrick*

What fluids have been used? What fluids can be used in future? What do we need to do to evaluate a new fluid?

9:35 Break

10:00 Problems and solutions related to drilling brittle ice:

Jakob Schwander

(15 minute talk, 20 minute discussion)

What is brittle ice? Can we measure brittleness? Why does it occur? How have different groups dealt with brittle ice? What is the best way to drill and handle brittle ice?

10:40 Problems and solutions related to drilling warm ice:

Laurent Augustin

(15 minute talk, 20 minute discussion)

What is warm ice? What problems has it caused? How have different groups dealt with warm ice? What is the best way to drill and handle warm ice?

11:20 Lunch

Session 5: Moving Forward

Session Chairs: *Eric Wolff and Ken Taylor*

Meeting participants are expected to have determined how their nation's interests can be best represented in the discussions in this session. The desired outcome of this session is to identify ways international collaboration can facilitate the suggested projects and technology improvements.

12:40 Break into working groups and discuss the listed topics.

The working groups will be:

Deep ice cores:

Facilitated by: *Eric Wolf*

How can international collaboration facilitate these projects?
How much interest is there in these projects?
How do these projects fit in with the International Polar Year?
What steps need to be taken to move these projects forward?

Spatial arrays of shallow and intermediate ice cores:

Facilitated by: *Ken Taylor*

How can international collaboration facilitate these projects?
How much interest is there in these projects?
How do these projects fit in with the International Polar Year?
What steps need to be taken to move these projects forward?

Ice drilling technology:

Facilitated by*: Joan Fitzpatrick*

What are the advantages and disadvantages of international collaboration on drilling efforts?
What steps need to be taken to develop better collaboration between drilling groups?

14:00 Reports from working groups

14:45 Break

15:00 Discussions led by Ken Taylor and Eric Wolff

How can international collaboration be facilitated to maximize the science we produce?

How does the International Polar Year factor into our plans?

What are specific actions should we take to move these projects forward?

What suggestions or recommendations do we want to make?

Should we plan a follow up meeting?

Who will take the lead, and who will assist, writing specific sections of the workshop report?

16:45 End of meeting

Arrangements will be made for transportation to the Airport. Do not plan on catching flights that leave prior to 21:00. Most people will spend the night at the meeting venue.

18:30 Dinner

Wednesday (March 17)

7-8 Light Breakfast in cabin 7

Arrangements will be made for transportation to the airport for flights leaving at any time.

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Appendix 3

IMPROVING ICE CORE DRILLING AND RECOVERY
Pre-Meeting Survey Results

Drill Systems

#1 Issue: Brittle Ice - drilling without damage, handling without damage
This topic created a great deal of discussion among both scientists and drillers. Both DML and Dome Fuji crews indicate minimal trouble with brittle ice. It is not clear whether it is the ice characteristics at a particular site that dictate how successfully this interval can be recovered, or whether success or failure is specific to drill/ice interactions at any site. (How does the strain of the ice affect the interaction at the cutters?) The U.S. drill was the cause of major damage to the core at SDM (ice was severely damaged coming out of the barrel), but unless side-by-side tests of multiple drill systems at the same site are run, it is difficult to deconvolute the impacts of cutter/ice interactions from the plethora of other drill system issues and ice parameters that are proposed as possible causes for damage during recovery.

Specifics

Drilling issues

- Ice/cutter interactions: Field tests needed to determine the effect of cutter geometry on crack initiation and propagation during cutting.
- Break-off-bottom interactions: Field tests needed to determine the role of core dogs in crack initiation and propagation.
- Straight barrel issues: All parties generally agree that barrel geometry must be completely straight to prevent transverse cracking as core feeds into the barrel from the head.
- Trip time uphole: If there is a strong thermal gradient in the hole, is it better to trip out as quickly as possible in the brittle zone to reduce thermal shock?
- Role of air-fluid interface: Is damage induced as the floating core settles onto the dogs during the transition out of the liquid into air during trip out? We should be able to quantify the sudden change in load at that point. What is it?

Post-recovery issues

- DML operation utilized stiffened core trays to insure zero bending stresses after unloading barrel.
- There was strong support in some quarters for re-immersion of the core into a cold bath immediately after recovery.
- Results from NorthGRIP , DML, and Dome Fuji indicate that keeping the core as cold as possible reduces post-recovery damage from both bubble expansion and non-isotropic differential thermal expansion of single crystals.

Improved drill performance in brittle ice

- Improve core quality.
- Develop techniques for coping with broken cores at surface.
- Develop techniques for reducing breakage, e.g., damping or pressurizing cores after recovery.
- Brittle ice for dry drilling (i.e., poker chips and hockey pucks at >100 m).

Other issues raised under Drill Systems

- Improved system monitoring and control for better performance and increased safety.

- Development of software systems for simulation of down-hole conditions and driller training.
- Incorporation of specific safety technologies.
- Design improvements to increase productivity (faster cutting, shorter trip times, longer one-pass recovery).
- Cutters` for all kinds of ice conditions.
- Improved drill performance in warm ice.
- Improved drilling and coring of sub-glacial till and bedrock.
- Improved drilling to approach sub-glacial lakes.
- Bedrock drilling, sub-glacial hydrology, sub-glacial geology, geothermal flux.
- Recovering debris-laden ice from basal zone.
- Better systems for chip recovery.
- Improved systems for recovering chips and re-injecting drilling fluid.
- Develop a reliable way to retrieve and indicate core azimuth.
- Development of replicate sampling capability:
  - Development of directional and/or deviation drilling.
  - Development of a rapid access drill to reach and resample interesting intervals.
  - Replicate/deviation drilling technology sharing should be accomplished through a *close cooperation* between national operators and funding agencies. Test sites for multiple drillings legs should be considered (e.g., Greenland Summit).
- Development of clean drill systems to sample the environment at the bottom of ice sheets (bed water, lakes, interstitial fluids, etc.).
- Use of new materials (improved drilling fluids, use of plastics or composite materials for different parts of drills, cables, surface equipment, etc.).
- Need safer, well behaved, well characterized drill fluid.
- Develop a lightweight system to drill approx. 1000m cores.
- Light, approx. 100m drill that is easy to put up and take down.
- Better use of the borehole after drilling (i.e., borehole logging).

Core/Sample Handling

- Sampling and stabilization strategies for fugitive species (e.g., He).
- Develop more efficient and effective process for removing drill fluid from core before retro.
- Learn how to successfully handle brittle ice after recovery.

Logistics

- Drill operations in high accumulation areas. Operational challenges due to rapid accumulation of snow around the drill.
- Science people should plan to leave opportunities for drillers to perform tests under real conditions and forget about production and target for a while.
- Scientists should understand the concept of functionality vs. performance. Functionality (must have, must work), performance (nice to have, can work), and develop realistic expectations.

Appendix 4: List of acronyms

ACR:	Antarctic Cold Reversal
ATED:	Antifreeze Thermal Electric Drill
AVHRR:	Advanced Very High Resolution Radiometer
AWS:	Automatic Weather Station
CAIC:	Coastal Array of Ice Cores
CAPE:	Circumpolar Arctic Paleo Environments
DML:	Dronning Maud Land
DSS:	Dome Station – South
D/O:	Dansgaard-Oeschger
EM:	ElectroMechanical
ENSO:	El Nino Southern Oscillation
EPICA:	European Project for Ice Coring in Antarctica
EWS:	Ethanol/Water Solution
GISP1:	Greenland Ice Sheet Project 1
GISP2:	Greenland Ice Sheet Project 2
GPS:	Global Positioning System
GRIP:	Greenland Ice Core Project
HCFC:	Halogenated Chlorofluorocarbon
HFC:	Hydrofluorocarbons
HFE:	Hydroffuoroethers
IASC:	International Arctic Science Committee
ICAPP:	Icecore Circum-Arctic Paleoclimate Programme
ICARA:	Icecore Climate Archive Recovery Activity
ICWG:	Ice Core Working Group
ID1:	Ice Divide 1
IPCC:	Intergovernmental Panel on Climate Change
IPICS:	International Partnerships in Ice Core Sciences
IPY:	International Polar Year
ITASE:	International Trans-Antarctic Scientific Expedition
LGM:	Last Glacial Maximum
MSA:	Methane Sulfonic Acid
NAO:	North Atlantic Oscillation
NEEM1:	North Eemian 1 drill site
NEEM2:	North Eemian 2 drill site
NGRIP:	North Greenland Ice Core Project
NorthGRIP:	North Greenland Ice Core Project
NSF:	National Science Foundation
PAGES:	Past Global Changes
PARCA:	Program for Regional Climate Assessment in Greenland
POPS:	Persistent Organic Pollutants
RES:	Radio Echo Sounding
SAO:	SemiAnnual Oscillation
SAR:	Synthetic Aperture Radar
TALDICE:	Talos Dome Ice Core
TOVS:	TIROS Operational Vertical Sounder
WAIS:	West Antarctic Ice Sheet