COMPILED REPORTS OF THE

U.S. ICE CORE RESEARCH WORKSHOP

held from 13-17 June 1988

at the Glacier Research Group
Institute for the Study of Earth, Oceans and Space
University of New Hampshire
Durham, New Hampshire 03824-3525

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Preface

From 13-17 June 1988 an NSF-Division of Polar Programs sponsored workshop entitled: "The U.S. Ice Core Research Workshop" was held in Durham, New Hampshire. The Workshop brought together a relatively large number (42) of U.S. researchers interested in ice core research and representatives of the European ice core research community.

The purpose of the Workshop was to develop a consensus concerning the direction of U.S. ice core research through the 1990's. Specific emphasis was placed on the newest major proposed U.S. deep drilling effort, GISP II (Greenland Ice Sheet Project II) and the development of a global strategy for U.S. ice core research to include deep drilling efforts in not only Greenland but also in Antarctica plus shallow to intermediate core recovery programs at low, middle and high latitude sites.

The first morning session was devoted to a series of invited lectures designed to set the stage for the remaining days of discussion. Specialty groups representing the major measurements conducted as part of ice core programs then met separately to prepare reports focusing on the primary scientific objectives sought by those researchers and plans for attaining these objectives. The Workshop participants then met as a whole to hear and comment on specialty group reports. Following these reports moderators convened sessions which dealt with specific aspects of GISP II, Antarctic deep drilling and a global array of shallow to intermediate ice cores. Each moderator prepared a session report which was distributed to all participants for their input during the Workshop. Final specialty group and moderator convened session reports were handed in within the next few days following the close of the Workshop in order to allow the inclusion of any additional comments. A brief statement from the Workshop was submitted to EOS, the AGU Newsletter, in order to inform the scientific community. Copies of all reports and the Workshop statement are included in this document.

Participants at the Workshop expressed a concerted desire that the results of the Workshop be viewed by the scientific community, scientific organizations and funding agencies as a firm statement that U.S. ice core researchers intend to develop a global array of ice core records that will make a significant contribution to the understanding of global change. It is clear that such a contribution will require a major commitment from the ice core research community and funding agencies as well as active interaction with several other scientific disciplines including for example, atmospheric chemists, geochemists, geophysicists and modelers. The next few years promise to be an exciting period of scientific discovery.

Paul A. Mayewski
8 July 1988

Acknowledgements

Lyn Preble undertook a major role throughout all phases of the Workshop. Her efforts are greatly appreciated. Several members of the Institute for the Study of Earth, Oceans and Space, notably Bob Lent, Byard Mosher, Laura Hampe provided invaluable assistance and Mary Jo Spencer provided valuable additions to the Workshop as it was in progress. Funds for this Workshop were provided by an NSF-Division of Polar Programs award to the University of New Hampshire.

U. -S. Ice Core Research Workshop Agenda
(Meetings to be held in Howes Auditorium,
Demeritt Hall, Room 152 unless otherwise specified)

13 June

8:00 A	Breakfast with early arrivals (Young's Restaurant, Main St., Durham)
12:00-5:OOP	ICWG Meeting (3rd floor Room 301 Science and Eng. Res. Bldg.)
7:30 P	Ice Breaker, (refreshments, hot and cold hors d'oeuvres) (New England Center) - Windsor Charles Room

14 June

8:30-8:45	Welcoming Remarks - Dean Otis Sproul (College of Engineering and Physical Sciences))
8:45-9:30	Ice Cores and the Global Change Program - Berrien Moore (EOS)
9:30-10:15	The Value of a Deep Ice Core Record - Wally Broecker (Lamont)
10:15-10:30	Break
10:30-11:15	Current International Ice Core Efforts (e.g. Soviet-French Vostok program, EUROCORE and GRIP) - Claude Lorius (LGGE, France)
11:15-12:00	Ice Core Research and NSF - Ted-DeLaca (Division of Polar Programs) GISP II - Herman Zimmerman (Division of Polar Programs) DPP Glaciology - Harold Borns (Division of Polar Programs)
12:00-1:30	Lunch (Durham restaurants)
1:30-1:45	Introduction to the World Data Center-Glaciology-Richard Armstrong
1:30-2:00	Organization of Specialty Groups (e.g., stable isotopes in ice, gases and isotopes of gases, cosmogenic isotopes, trace metals, major anions and cations, organic compounds and other trace constituents, physical and mechanical properties, borehole studies, atmospheric studies, modeling and GISP H Site Selection Panel Meeting). Speciality Group meetings will be assigned to rooms in Science and Engineering Research Building.
2:00-6:00	Speciality Group Meetings (Report preparation to include: state-of-the-art, importance and major problems, etc. due 8:00 AM next day at secretary's desk for typing and distribution. Participants should be familiar with the information included in: 1) V~DC-A Report GD-8 Glaciological Data-Ice Cores (available from WDC-A for Glaciology-Boulder); 2) Scientific Planning for Deep Ice Core Drilling in Central Greenland (GISP II) (available from the BPRC, OSU) and 3) U.S. Ice Core Research Capabilities (available from the EOS/UNH) - a limited number of copies of 1, 2 and 3 are available.
7:30P	Transportation to Portsmouth, New Hampshire for dinner (reservation arrangements to be made during day). A van and cars will be provided for transport.

15 June

8:30A-10:30 Deep Drill Technology, The Core Processing Line and Camp Design
(K Kuivinen - Moderator)

10:30-10:45 Break

10:45-12:00 GISP II Site Selection and Related Activities
(S. Hodge - Moderator)

12:00-1:30 Lunch (Durham restaurants)

1:30-6:00 Specialty Group Reports and Discussion

7:OOP Transportation to Portsmouth for dinner (reservations and transport same as 14 June).

16 June

8:30A-10:00 GISP II Laboratory and Field Analysis (P. Grootes-Moderator)

10:00-10:15 Break

10:15-12:00 GISP 11 Core Sectioning and Distribution (M. Whalen - Moderator)

12:00-1:30 Lunch (Durham restaurants)

1:30-2:30 GISP II Data Handling, Comparison with Other Data Sets and
Preparation of Reports (R. Armstrong- Moderator)

2:30-4:00 Antarctic Deep Ice Core - Site Selection and Related Activities
(C. Bentley - Moderator)

4:00-4:15 Break

4:15-5:30 Antarctic Deep Ice Core - Laboratory and Field Analysis
(C. Laird - Moderator)

7:00 Transportation (bus) to Group Dinner meet at Science Building for departure.

8:00 Group Dinner - Clambake at Bill Foster's, Maine (Cash bar)

17 June

8:30A- 10:00 The Need for a Global Array of Shallow to Intermediate Depth Ice Cores
(L. Thompson - Moderator)

10:00-10:15 Break

10: 15-12:OOP Non-Core Studies Related to a Global Array of Shallow to Intermediate
Depth Ice Cores (R. Borys - Moderator)

12:00-1:30 Lunch (Durham restaurants)

1:30-5:00 General discussion, concluding remarks, the future (P. Mayewski)
Moderator's meeting - discussion of final reports.

Moderator Duties: Moderators are responsible for handling discussion groups and for a rough draft summary report (including recommendations) no later than the morning of the next day Rough draft reports will be distributed to Workshop participants for their comments and then moderators should collect comments for inclusion in their final reports. A typist will be available to assist in report preparation.

Report Schedule:
25 June Submission to L. Preble of any report revision by moderators and participants.

1 July Submission of Workshop Summary to Earthquest and to AGU for use in EOS.

15 July Distribution of Final Workshop Report.

For Assistance:

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SPECIALTY GROUP REPORT: STABLE ISOTOPES

I. Introduction

Stable isotopes in ice, $\delta^{18}0$, δD and deuterium excess (d = δD-8 $\delta^{18}0$), provide a set of tools for monitoring the hydrologic cycle at the time that the snow was deposited. These parameters track the history of water from its evaporation over the ocean to its deposition as snow at the ice core site. Stable isotope information in ice cores can be separated into two categories: (1) stable isotope ratios or delta values, $\delta^{18}0$ and δD, and (2) deuterium excess, which is the combination of both delta values. Delta values are controlled primarily by the temperature difference between the evaporation site and the snow deposition site, and thus can be used to infer paleotemperature changes, changes in the elevation of the ice sheet and changes in the accumulation rate of snow on the ice sheet. It is important when examining time series of $\delta^{18}0$ and δD values in ice cores to remember that conditions at the evaporation site, i. e. air and water temperatures, isotopic composition of the surface ocean and multiplicity of moisture source areas, must always be considered. Deuterium excess values are controlled primarily by conditions at the moisture source region, specifically the air and sea temperatures, the moisture content of the atmosphere and the turbulence of the surface boundary layer. Deuterium excess values can be used to reconstruct changes in meteorological conditions over the ocean as well as to infer shifts in the moisture source regions from one area of the ocean to another. While deuterium excess has only recently been employed in ice core research, our understanding of its response to paleoenvironmental changes is improving rapidly. These stable isotope tools are useful on all of the time scales available in ice cores. 5180, 8D and deuterium excess commonly exhibit seasonal cycles, and can be used to track Holocene climate changes. 8180 has been one of the primary tools in identifying glacial/interglacial transitions as well as shorter term, rapid climatic reversals.

In low and mid-latitude glaciers, the relationship between $\delta^{18}0$ and δD and surface temperature is not as simple as on the high latitude ice sheets. At low latitudes a δ-T relationship may be weak or non-existent. In these areas, isotopic fractionation accompanying weaker vapor loss from air masses during their crossing of broad continental areas where plant transpiration and surface evaporation can add to the atmospheric moisture must be considered. Nonetheless, the same basic reasons for pursuing stable isotopes in deep ice cores on the ice sheets apply to these glaciers/ice caps; namely, the length and temporal detail of the record. The scientific community should be aware that temperature is not the only signal contained in stable isotopes in ice cores, a fact which also applies to the deep ice cores in the ice sheets.

II. Objectives

The overall objective is to obtain the maximum amount of paleoenvironmental information contained in the $\delta^{18}0$, δD and deuterium excess records in ice cores. To do this,, we must deconvolute the isotope signal and focus on whichever of the primary controlling variables is most important or most desired. These primary signals include:

1) changes in climate on the ice sheet
2) changes in climate at the moisture source area
3) changes in elevation of the ice sheet

4) changes in the location of the moisture source area(s) over the ocean

5) ice flow effects, or changes in the site of snow deposition relative to the site of core collection.

Note that specific problems such as the discharge of ice and/or meltwater from the ice sheets into the moisture source areas are included in changes in climate at the moisture source area and/or on the ice sheet.

To accomplish this objective, combinations of parameters must be used. For example, the total gas content of the ice can be used to help constrain suspected elevation changes, and deuterium excess can be used in conjunction with $\delta^{18}0$ or δD to determine if changes at the moisture source area contribute significantly to the $\delta^{18}0$ changes seen in the ice core. Other paleoenvironmental records from outside of the ice sheets should also be employed. Examples include $\delta^{18}0$ and faunal assemblages in ocean sediment cores, geological evidence of glacial advances and retreats and other paleoenvironmental changes on the continents, and the wealth of paleoenvironmental changes recorded in lake cores.

The goal is to fully utilize the information in stable isotopes in ice cores, to sharpen and focus what can be learned. The ice core community realizes the pitfalls in simplistic interpretations of 8 values in ice cores. It is now time to go beyond such interpretations and extract more reliable and meaningful information from these isotopes.

III. Scientific Plan for State of the Art Measurement/lnterpretation

Recently, substantial changes have been made in how stable isotope values in ice cores are interpreted and in what is being measured. Improvements in theories of fractionating processes combined with a concerted effort on surveys of surface snow have led to more definite interpretations by the French of isotopes in the Vostok core, as well as wider use of the data, for example as an indicator of accumulation rates. The combination of isotopes in spatial surveys of surface snow and shallow cores, with isotopes in deep ice cores, has proven to be very successful. Another major change has been an increased focus on hydrogen isotope ratios, δD, as a complement to the traditional $\delta^{18}0$ values and as a part of the measurement of deuterium excess values. At the present time there is no laboratory in the U.S. measuring δD and deuterium excess values in ice cores. This deficiency should be addressed in the near future.

Our recommendations for future research stress the importance of surface surveys and shallow to intermediate depth ice cores, as a necessary complement to deep ice cores. Isotope delta values from these samples can fulfill two important needs: the need for better calibration of delta values and deuterium excess by comparing these values with modem environmental records, and the need for more isotope records on the decade to century time scale. Changes in climate and environment taking place over decades to centuries are of most direct interest to assess man's impact on climate and the impact of climate change on man. The resulting δ changes, however, are not well understood, due to a lack of data and due to the nature of the δ changes: they are usually small, are superimposed on a spectrum of longer term climate changes, and unlike the major glacial-interglacial changes, the short term climate fluctuations may manifest themselves in different ways in different parts of the globe. Nonetheless, improving our understanding of these changes will greatly improve what we can learn from stable isotopes in deep ice cores.

Our longer range ice core research plan consists of the following elements:

A. A deep core to bedrock at/near Summit in Greenland to obtain a long paleoenvironmental record. This would be the first detailed terrestrial record covering several glacial-interglacial cycles and allow study of the three Milankovitch cycles of ~ 2 x 10^4, 4 x 10^4 and 10^5 years. To assure bedrock was reached one needs to penetrate bedrock and recover some bedrock core. It is highly desirable that the results from such a core can be compared with those from a core nearby, analyzed independently, to safeguard against analysis problems and ice flow related artifacts in the deep core record. Comparison of the two deep cores with each other and with existing intermediate and deep Greenland ice cores will indicate whether additional intermediate cores and/or cores penetrating the last glacial are needed. An array of shallow cores and snow pit studies is needed to determine spatial variability.

B. A deep core to bedrock in the Ross Sea drainage of West Antarctica to obtain a long paleoenvironmental record. This deep core will explore whether ice from the previous penulimate interglacial and preceding glacial is present in West Antarctica. This tests the hypothesis that the West Antarctic ice sheet disappeared during the previous interglacial, giving rise to ~ 6 m higher sea level. Interpretation of the results of this core will be facilitated by the high resolution record of the intermediate Siple Station core and the knowledge gained from ice dynamics studies at the Siple Coast. The interpretation of the isotopes in this core requires at least one additional core penetrating ice from the last glacial period and several well situated shallow cores and pits at varying distances to study present day spatial δ variations. This spatial variability study as well as a survey of surface and bedrock topography, ice flow and accumulation should precede the deep drilling and lead to the selection of the most suitable drill site.

We do not address the problem of constructing a time scale for the core δ records. We believe other techniques like continuous acidity and particle measurements, electroconductivity and/or H_20_2 are more suitable than δ analyses for this purpose. Detailed comparison of the Greenland and Antarctic long δ records may separate global from local influences in both cores.

C. Though climate change is often global it may express itself differently in mid and low-latitudes than at the Poles. An array of cores at these latitudes is therefore required to show the changes in climate and environment at these more inhabited latitudes that correlate with recent changes in the polar δ records. This defines spatial variability both zonally and latitudinally. Comparison with local pollen, lake sediment and other paleoenvironmental records will help interpret the observed δ changes. These cores provide transfer functions to translate the long records of polar δ changes into global climate/environmental change. Ice caps and glaciers in Southern Alaska, the high Andes, the Himalaya, China and New Guinea need to be studied. In general shallow to intermediate drilling will be sufficient to reach bedrock.

SPECIALTY GROUP REPORT: TRAPPED GAS COMPOSITION

Justification

Analyses of air bubbles embedded in polar ice reveal the composition of the pre-industrial and ancient atmospheres. So far, extensive measurements of carbon dioxide, methane, nitrous oxide and some chlorocarbons have been made on ice cores from both polar regions. The results provide a remarkable record of the magnitude and timing of human influences on the global cycles of these gases. Except for the chlorocarbons, for which there is no evidence of any substantial pre-industrial concentrations, the other gases (CO_2, CH_4 and N_20) started increasing only during the last 200 years with the growing population and increasing needs for energy and food. The increase of N_20 probably started only a few decades ago. The record shows that $C0_2$ concentrations were about 280 ppmv 200 years ago while methane and nitrous oxide concentrations were about 700 ppbv and 285 ppbv respectively. Today there is 25% more $C0_2$, 8% more N_20, and 100% more CH_4 in the atmosphere.

Measurements on existing ice cores provide longer records for $C0_2$ and CH_4 which show large natural variations during glacial and interglacial periods. The Bern and Grenoble groups have published data that provides a convincing case that the $C0_2$ content of the atmosphere during glacial time (~ 200 ppmv) was substantially lower than that for the interglacial time (~ 280 ppmv).

Recent experiments by the Bern and Grenoble ice core groups show that the concentration of CH_4 dipped to a low of about 350 ppbv during the last ice age. Khalil and Rasmussen's (in press) data spanning the Little Ice Age between 1450 and 1750 show a proportionate decrease in methane (about 40 ± 30 ppbv/°K) and also a decrease of N_20 (about 5 ± 3 ppbv/°K). These decreases are believed to be a measure of the response of emissions from the Earth's soils, oceans, and high northern wetlands to global climatic change. The character and details of the transition of the atmospheric concentrations of $C0_2$, CH_4 and N_20 during the last deglaciation have yet to be well documented. Nevertheless, it is clear that concentrations of the radiatively active gases in air influence climate and are in turn influenced by climate.

The large role which varying levels of radiatively active gases play in climate change emphasizes the importance of understanding the global-scale interactions between climate and the biosphere. Studies of the δ13C of $C0_2$,δ13C and δD of CH_4, $\delta^{15}N$ of N_20, $\delta^{18}0$ Of 0_2, and the 0_2:N_2:Ar ratio in the trapped gas can help in achieving this understanding. The importance of studying these variables lies not in their environmental influence, but in their role as tracers of selected geochemical processes that influence global climate. $\delta^{13}C$ of $C0_2$ serves as a tracer for studying the roles of the ocean and terrestrial biosphere in changing atmospheric pCO_2. $\delta^{13}C$ and δD of CH_4 reflect the relative production rates by the different sources. The same is true for the $\delta^{15}N$ of N_20. $\delta^{18}0$ of 0_2 is governed by isotope fractionation during photosynthesis, respiration, and hydrologic Processes. Hence it reflects global scale interactions between the hydrosphere, biosphere and atmosphere. The atmospheric 0_2 concentration (expressed as the $0_2/N_2$ or 0_2/Ar ratio) indicates changes in the magnitude of the reduced carbon reservoirs, as well as the metabolic $C0_2$ content of the deep sea. N_2/Ar, the $\delta^{15}N$ of N_2, and $^3He/^4He$ must have been constant in the ice age atmosphere, and serve as indicators of the integrity of trapped gas samples.

In summary, studies of the composition of trapped gases in ice cores inform us directly about changes in the atmospheric concentrations of the radiatively active gases. They also reveal the composition of various tracers, which can help us unravel the nature and causes of Pleistocene climate change.

Objectives

In this section we review in more detail what can be learned from studies of trapped gas composition. There are three basic kinds of information which emerges from such studies. The first is the concentration of the radiatively active gases, $C0_2$, CH_4 and N_20, which directly influence Earth's heat balance. The second bears on the causes of changes in radiatively active gas concentrations and other alterations of geochernical cycles. This information comes from the following chemical and isotopic tracers: δ13C of $C0_2$, $\delta^{13}C$ of CH_4, $\delta^{18}0$ of 0_2, and the atmospheric 0_2 concentration. The third type of information is the integrity of trapped gas samples. This is reflected by several conservative parameters, $\delta^{15}N$ of N_2, the ratio of N_2/Ar, the He concentration and isotopic composition and the Ne concentration all of which must have been constant in the Holocene and Pleistocene atmosphere.

C02

The reconstruction of the atmospheric $C0_2$ concentrations during past periods of different climatic conditions is one of the most important and fundamental pieces of information to be obtained from ice cores. A detailed $C0_2$ record reveals the natural disturbances in the carbon cycle and is necessary to ultimately understand the relationship and interaction between $C0_2$ and climate. The modem $C0_2$ increase and the change upon deglaciation are well documented from different cores, Arctic and Antarctic. 'Me rapid variations observed in the Dye 3 core during the later Wisconsin have yet to be confirmed. If confirmed, this would mean that climate changes could occur on short time scales, and it would provide important information on the probable outcome of man's dangerous "experiment" of increasing the atmospheric $C0_2$ by releases from biospheric and fossil carbon. Also large portions of the Holocene have never been analyzed for $C0_2$/air ratios. New cores will extend into the previous interglacial, providing information on the atmospheric conditions at that time, and on what happened during the transition into the last glacial.

CH_4 and N_20

As discussed in the previous section, CH_4 and N_20 concentrations in air have varied over both anthropogenic and glacialfinterglacial time scales. It is important to measure the variability in much more detail, understand its causes, and gauge its effects.

$\delta^{13}C$ of $C0_2$

Atmospheric $C0_2$ exchanges with the biosphere and the oceans. The size of the biosphere may vary as climatic changes, and the uptake or release of $C0_2$ by the oceans is governed by pCO_2 of the ocean surface waters, which depends on a number of factors.

$\delta^{13}C$ and the $^{14}C/^{12}C$ ratio of $C0_2$ can be used to learn whether atmospheric $C0_2$ concentration changes are due to biospheric or oceanic exchange. Atmospheric $\delta^{13}CO_2$ (~ -7°/oo PDB) is closer to that of the oceans (+2 °/oo) than to the more depleted biosphere (~ - 25°/oo); the radiocarbon in the biosphere and atmosphere are about equal, while the surface waters of the ocean are somewhat lower (~95%). Thus if, for example, an atmospheric increase in $C0_2$ were caused by a net flux from the biosphere, the $^{13}C/^{12}C$ ratio would decrease, with almost no change in $^{14}C/^{12}C$. On the other hand, if a $C0_2$ increase is the result of a predominant influx from the oceans, the $^{13}C/^{12}C$ ratio would be minimally affected and the $^{14}C/^{12}C$ ratio would decrease. The expected variations in $\delta^{13}C$ are small and thus extreme care is required in the experimental techniques.

At the proposed drilling site in Central Greenland one expects to encounter the ice conditions most favorable for obtaining a detailed $C0_2$ concentration record during glacial and interglacial. times. High depth resolution measurements can be performed and compared to $\delta^{18}0$ of H_20 (and particulate content, chemical species, and the concentrations of cosmogenic radio-nuclides), in order to determine the relative timing of $C0_2$ and climate variations, and therefore the causal relationship. Ultimately the achievable resolution is determined by the inherent age difference of enclosed air and surrounding ice, which can vary with time.

$\delta^{13}C$ of CH_4

Isotopic measurements are the major constraint to understanding the rapid increase in methane in the atmosphere during the past several hundred years, as well as the change associated with glacial/interglacial cycles. Methane is produced by a variety of sources, including ruminant animals, uses of fossil hydrocarbon fuels, biomass burning and even termites. It is labelled with an isotopic signature that reflects relative fluxes from these sources and the fractionation effect of hydroxyl radical removal. If the sink for methane is relatively constant the sources will produce the greatest impact on the isotopic signature. Evidence from measurements on recent Holocene ice collected at DYE-3 and Site A indicate that isotopic methane concentration changes mirror atmospheric changes. Further study of $\delta^{13}CH_4$ in ice cores throughout the Holocene and into the Pleistocene should reveal the nature and relative importance of methane sources and sinks, as well as causes of concentration changes associated with major climate change in the past.

$\delta^{15}N$ of N_20

The change in $\delta^{15}N$ of atmospheric N_20 accompanies changes of N_20 production in oceans and soil by nitrification and denitrification, and, to a lesser extent by fossil fuel combustion. N_20 in the atmosphere and oceans exhibit similar enrichments of ^{15}N relative to atmospheric N_2. This enrichment coincides with the ^{15}N enrichment of oceanic nitrate and ammonia and implies that soil ammonia and nitrate may be enriched in the same manner. The N_20 record in ice cores may very likely reflect these isotopic changes. An isotopic N_20 record in the Holocene would be particularly important in understanding any recent isotopic source and consumption changes.

$\delta^{18}0$ of 0_2

$\delta^{18}0$ of atmospheric 0_2 is governed by the $\delta^{18}0$ of seawater (which is the ultimate source of all photosynthetic 0_2), as well as isotopic fractionations during photosynthesis, respiration and hydrologic processes (which transport seawater to the sites of terrestrial photosynthesis). The first order control on the $\delta^{18}0$-time record of atmospheric 0_2 is the seawater $\delta^{18}0$, which of course changes with sea level. Respiratory and hydrologic fractionations are very different for terrestrial and marine ecosystems. The second order signal in the record is thus the ratio of terrestrial to marine productivity, and its variation through time. The $^{18}0$ change of atmospheric 0_2 lags the seawater change because of the time required for photosynthesis to replace the 0_2 in the atmosphere (~2000 yrs.). The lag itself is an indicator of the planetary rate of primary production. $\delta^{18}0$ of atmospheric 0_2 is, like other gases, homogeneous throughout the atmosphere. It thus serves as a time stratigraphic marker for the correlation of ice cores, and may also allow correlation of ice cores in the seawater $\delta^{18}0$ record.

0_2 Concentration

The atmospheric 0_2 concentration, expressed as the 0_2/Ar ratio, is affected by the carbon cycle via photosynthesis and respiration. The processes thought to be responsible for changing atmospheric $C0_2$ levels leave different imprints on the atmosphere $C0_2$ content. The burial of organic carbon or production of terrestrial biomass raises the 0_2 concentration in air, erosion or destruction of biomass decreases 0_2. Changes in the transport of organic carbon to the deep sea have the same effect. Reactions between $C0_2$, $CaC0_3$ and oceanic $HC0_3$- can change atmospheric $C0_2$ but have no effect on the 0_2/Ar ratio. The measurement of the variable thus provides an important constraint for unravelling the behavior of the carbon system and understanding the causes of variations in the atmospheric $C0_2$ content.

N_2/Ar and $\delta^{15}N$ of N_2

The N_2/Ar ratio in air must have been constant during the Pleistocene (geochemical fluxes are too small to have changed the concentration of either parameter). The N_2/Ar ratio thus gives a measure of the integrity of ice core samples. For some existing deep ice cores, this ratio can vary by as much as 4% or more. Such a variation must be accompanied by changes in the concentrations of $C0_2$, CH_4, N_20 and 0_2/Ar from the true paleoatmospheric values. It is thus important to measure N_2/Ar as an index of sample integrity.

$\delta^{15}N$ of N_2, which must also have been constant during the Pleistocene, provides an independent and very important control on sample integrity. The N_2 in trapped gases are uniformly enriched in ^{15}N. This enrichment is a primary feature resulting from the more rapid expulsion of light isotopes as bubbles seal under pressure. Mass-dependent fractionation has an important affect on the $\delta^{13}C$ of $C0_2$, $\delta^{13}C$ of CFU, and the $\delta^{18}0$ of 0_2. It is essential to measure $\delta^{15}N$ of N_2 and use the values to correct the isotopic composition of the nonconservative compounds back to their original paleoatmospheric value.

He and Ne

Helium is one of very few substances soluble in ice (10% of the concentration in bubbles) which makes it unique for studying gas diffusivity. Helium in cut cores diffuses out of the ice primarily along the C-axis (five times less perpendicular to the axis) down to the level of unrelaxed equilibrium solubility. Owing to the higher diffusivity of ^3He relative to ^4He the depletion of ^3He is reversed by exchange with atmospheric helium in samples stored for several months accompanying relaxation processes. Similar observations have been made on neon.

A detailed study of helium and neon in situ by sampling in a manner which preserves the in situ concentrations should reveal much about diffusion processes of trapped gases and help unfold fractionation effects which may be diffusion controlled. Depending on the actual diffusive transport it might be possible to observe geomagnetic reversals in the proposed Laschamps and Blake events by large changes in the $^3He/^4He$ isotope ratio. Another effect which may be observed is the modification of helium contents in ice by the gravitational field effect on solubility.

SPECIALTY GROUP REPORT: COSMOGENIC ISOTOPES

Cosmogenic isotopes in ice cores can be used to determine a chronology for the core, to study the history of terrestrial magnetic field and of solar activity and to investigate global atmospheric mixing. The cosmogenic isotopes to be measured in ice include ^{14}C, ^{1O}Be, ^{26}Al, ^{36}Cl and ^{81}Kr. Because the applications are somewhat different, these isotopes are discussed in separate groups.

Current Status

^{14}C

^{14}C is a powerful tool for determining ice core chronology beyond ages which can be reached by $\delta^{18}0$ annual layer counting, i.e., for ages older than about 10 kyr in Greenland. Current analytical techniques utilizing accelerator mass spectrometry (AMS), will, with minor improvements, allow dating of 1-2 kg of ice ± 800 years at 15 kyr and ± 2500 years at 25 kyr. The precision could be improved by taking larger samples. Samples up to 30 kyr can be dated at present. Calibration studies win have to be completed, before 14C dating can be fully implement. The time resolution depends both on the precision with which the 14C measurements can be made and on the time span over which close-off of the firn occurs. 'Me second may be an important factor in Antarctic cores from, low accumulation rates areas.

^{10}Be, ^{26}Al and ^{36}Cl

The concentrations of ^{1O}Be, ^{26}Al and ^{36}Cl in polar ice can be effected by changes in the production rate of these isotopes in the atmosphere, by changes in atmospheric transport processes and by changes in precipitation mechanisms. Studies to date have allowed the following conclusions to be drawn.

81Kr

^{81}Kr ($t_{1/2}$=2.1 x 10^5 y) could be very useful for dating old ice at the bottom of the ice sheet where model-based estimates are very uncertain. At the moment 50 kg of ice are required for a 30% precision. Work now in progress may reduce the sample size and increase the precision significantly.

A. Because ^{1O}Be, ^{26}Al, and ^{36}Cl have short atmospheric residence times, their ratios to their stable isotopes are not uniform in the atmosphere. Therefore a simple radioactive to stable isotope ratio cannot be used to given an age as it can for ^{14}C. In addition to radioactive decay, climate, atmospheric chemistry and atmospheric circulation also effect the concentrations of these isotopes in polar precipitation. It was hoped that ratioing ^{36}Cl to ^{1O}Be might normalize these effects so that dating would be possible. It is now known that the $^{36}C/^{10}Be$ ratio varies by up to a factor of ten in samples of essentially the same age. Because aluminum and beryllium chemistries are more similar than chlorine and beryllium, it may be that $^{26}A1/^{10}Be$ ratio measurements will prove useful for dating ice. This ratio has a half-life of 1.4 x 10^6 y and so would be useful for dating very old ice.

B. Measurements at Milcent in central Greenland have shown that during the Maunder Minimum (1645-1715 A.D.), a period of quiet sun when there were almost no sunspots, the ^{1O}Be concentration was substantially higher than during other periods. Recent measurements at Camp Century have shown a good correlation between the main short-term variations of the ^{1O}Be record in ice and the ^{14}C record in tree rings for the last 5000 years. This data strongly supports the explanation that solar modulation of the galactic cosmic ray flux causes these fluctuations.

C. Detailed studies at Milcent and at Dye 3 have revealed that the 11 year Schwabe sunspot cycle can be observed in the ^{1O}Be data.

D. Holocene ^{14}C dam from tree ring studies suggests there is a correlation between the geomagnetic: field and the atmospheric ^{14}C concentrations. The dam support a picture in which there was a slow variation of the geomagnetic: field over the past 10,000 years, with a peak roughly 2000 years BP. ^{1O}Be studies of Holocene ice, which show a different pattern than ^{14}C, have led to a reexamination of this question. The isotope pattern can also be interpreted as indicating that production rates were higher during glacial time.

E. During the last glaciation and at the transition between the Glacial and Holocene there are large changes in the ^{1O}Be concentration of polar ice that seem to be due mainly to changes of the precipitation rate. The quantitative form of this relation has not yet been worked out.

Future Work in Polar Cores

The major uncertainty in interpreting cosmogenic isotope levels in ice cores is the role of atmospheric transport and chemistry. If these processes can be understood, it will be possible to use cosmogenic isotope concentrations in dated cores to deduce the history of several important geophysical parameters such as solar activity and the strength of the geomagnetic field. One way to understand the effects of transport is to examine cores from several geographic areas. A Summit Core in Greenland and Antarctic cores as they become available will be important in this comparison. It will be important to study cosmogenic isotope concentrations in both Pleistocene and Holocene sections of these polar cores in order to unravel the various influence or to find which is dominant. The object of this work can be grouped into three broad categories.

1. Production rate effects: Studies under this category will require measurements of isotope concentrations during the following critical periods: Schwabe 11 year cycle (recent samples with one to two year time resolution); quiet sun periods (Maunder, Spoerer and Wolff minima and correlations with ^{14}C wiggles in tree rings); geomagnetic field variations (multi-year averages throughout the Holocene). The ultimate goal of this work is to be able to extend studies of changes in cosmic ray flux caused by these effects to periods beyond the reach of ^{14}C.

2. Climate: ^{IO}Be concentrations show an approximate inverse correlation with precipitation rate. Pit and shallow core studies combined with analysis of meteorological records can be used to investigate the current fallout pattern. Changes in isotopic concentration at the Pleistocene-Holocene transition and at periods of rapid climate change in the Pleistocene, as shown by rapid ^{18}0 changes should be examined and correlations of these measurements with those of chemical impurities which would also be affected by climate change looked for.

3. Dating: Work on meteorological effects may give some insight to the causes of the large variations observed in the ^{10}Be/^{36}C1 ratio. In addition, development of ^{26}Al

measurements in ice and studying the utility of ^{26}Al/^{10}Be ($t_{l/2}$= 1.4x 10^6 y) as a dating pair for old ice should be undertaken. It is possible to date cores by matching the ^{1O}Be variations which correspond to the Suess ^{14}C wiggles. Such dating would require continuous measurement of IOBe with 5-10 years time resolution. Since ^{1O}Be measurements require 1 kg samples this technique should be applied only if other dating techniques are not available or if core material becomes available in abundance. A second technique of relative dating relies on finding the large ^{1O}Be spikes which have now been observed in a number of Antarctic cores. The spikes should be looked for in cores from both Greenland and the Antarctic.

Specific Sample Requirements

14C: 2-3 kg of ice required for an AMS dating. Sampling will concentrate on pre-Holocene ice where annual layer counting is not longer reliable.

^{IO}Be, ^{26}Al, ^{36}Cl: The amount of ice required depends on the snow accumulation rate and is on the order 1 kg for ^{1O}Be, 1.5 kg for ^{36}0, and 10 kg for ^{26}Al The high resolution comparison with the tree-ring ^{14}C record requires sampling on a one to two year interval for the last 1000 years. This means that about 1/3 of the core would be required at Summit. It may be necessary to drill more than one core to intermediate depths to provide enough material for the cosmogenic isotope studies. It is important, however, that the cosmogenic: isotope measurements be directly comparable with other chemical and isotopic data in the same core.

For ice older than 1000 years strip samples of total mass 1-2 kg will be required. These samples would be chosen to coincide with regions of the core exhibiting changes in climate parameters in order to provide information about changes in precipitation rate. In addition the ^{IO}Be spikes observed in the Antarctic cores would be searched for. Finding these in Greenland would allow direct correlation between the northern and southern hemisphere records.

If the ^{26}Al/^{1O}Be ratio proves to be useful for dating, 10 to 20 kg of ice would be required. It is probable that only one or two measurements would be required from the bottom of deep ice cores.

81Kr: Currently 50 kg of ice is required for ^{81}Kr dating, which has been used successfully on Canadian aquifer samples in producing an age of 100 kyr. Several samples from the bottom of the ice core could be obtained from the core itself and possibly from side-track drilling. Improvements in enrichment of the isotope will allow for smaller samples and better precision.

SPECIALITY GROUP REPORT: TRACE METAL STUDIES

Objectives for studies of trace metals in ice cores are :

1) Large meteoritic impacts probably modify global climate and ecosystems, but the size and frequency of these events is not well established. Ice cores preserve the record of cosmic dust input and meteorite impact, which can be measured by determining concentration pulses of Ir and changes in the $^{187}0s/^{186}0s$ ratio.

(2) Anthropogenic emissions into the atmosphere have increased dramatically over the last 200 years. Long range transport of anthropogenic emissions of Pb and Cd through the atmosphere and their preservation in ice cores allow us to determine the timing and magnitude of anthropogenic emissions to the global atmosphere by Pb and Cd back to 1750 A.D.. Parallel investigations on ancient ice extending through and beyond the present glacial cycle will enable a better understanding of the natural sources of trace metals, and their bio-geochemical cycles. They will yield a firm perspective for assessing the significance of anthropogenic increases, and a basis for predicting future trends.

(3) Ice cores preserve a record of volcanic eruptions, so they can be used to determine the extent of volcanic emissions of Pb, Bi, T1, and Cd (and evaluate possible Ir and Os emissions) to the troposphere and stratosphere.

(4) Terrestrial atmospheric dusts are linked to global climate change during the last several hundred thousand years. Ice core studies can determine sources and magnitudes of metals contributed by atmospheric dusts and their relation to global climate change. They will enable more thorough tests of the ability of climate models to predict the effect of such perturbations of the earth-ocean-atmosphere system.

(5) The intercorrelation of ice core climate records is difficult because absolute age dating is not possible in most cases. Global trace metal event horizons (e.g. from volcanic or impact events) whose occurrence is globally synchronous could be used as stratigraphic horizons for the intercomparison of different ice cores, and hence provide important chronological information.

Rationale for these objectives are:

(1) Polar ice contains a record of the accretion and variability of materials from outer space. The occurrence of "cosmic spherules" in polar ice is well known. The element iridium, which is highly enriched in extraterrestrial debris relative to crustal materials, has been determined in Antarctic ice as a measure of the steady state cosmic debris influx, and a pulse of cosmic iridium has been observed to coincide with the 1908 Tunguska impact event. This measurement indicates that the Tunguska object was 0.2 Ian in diameter. It has been estimated that less frequent impacts of 0.51an objects (which would produce a 10 km crater on land) occur every 100,OW years. If this estimate is COIT ct, it is likely that many events of Tunguska magnitude would be preserved in a 250,000 year ice core. A complete record of Ir in a long polar ice core would allow us to determine the size-frequency history of previous cosmic impacts. It would also allow us to determine whether the more uniform background influx of small particles is truly constant. To observe these pulses, it is necessary to distinguish them from normal background crustal and cosmic dust Ir deposition.

While it is believed that Ir found in ice cores is dominantly of cosmic origin, there is still room for doubt on this point. Ir is also known to be enriched in volcanic emissions. Since volcanic acids are observed in ice cores, it is possible that volcanic Ir may also be found in ice cores. In order to use Ir as a tracer of extraordinary cosmic impacts, it is necessary to correct the ice core signal for the possible influence of volcanic emissions. A study of Ir in the proximity of known volcanic events recorded in ice cores is needed to provide a basis for this correction.

Similarly, while the concentration of Ir in crustal dusts is low, the total concentration of crustal dusts in ice cores is high relative to the abundance of cosmic dusts. To allow for the possible influence of these high concentrations of crustal dusts on the cosmic Ir signal, it is necessary to examine the Ir concentration in relation to changes in the terrestrial dust record.

Further confirmation of the extraterrestrial nature of Ir can be provided by measurement of the isotopic composition of osmium. Due to fractions of radioactive parent 187Re from radiogenic daughter 1870s during magmatic processes, the ratio of 1870s/1860s is 400 in crustal rocks while it is only 3 in meteorites. Hence variation of the osmium isotope ratio can help to distinguish cosmic (or mantle-derived) Os from meteoritic Os.

(2) Chronological variations in emissions of lead (and its isotopes), cadmium, and thalliurn to the atmosphere from dust, volcanic emissions, and sea salts recorded as concentration variations in ice will be measured with focus on three periods: (A) the most recent two centuries; (B) the "Little Ice Age" from 1300 A.D. to 1700 A.D., and (C) the last 1/3 of the Wisconsin and the first 1/2 of the Holocene.

(A) During the past several centuries global fluxes of industrial lead emissions to the atmosphere increased 100-fold above natural global lead emission fluxes. Profound contamination of the earth's biosphere and oceans has obliterated original, natural levels of lead. In the oceans, the switchover from major natural fluvial input pathways to major industrial eolian input pathways has established a transient equilibrium situation for the chemical oceanographic cycles of lead. This concentration transient combined with the use of isotopic compositions of lead as tracers makes lead useful for defining and imposing contraints on models of oceanographic cycles of other trace metals. Knowledge of temporal changes in eolian fluxes of lead to the oceans provides parameters which allow transient equilibrium models of oceanic lead to be explicitly defined. Measurements of temporal changes in lead isotopic compositions will identify the lead as industrial and indicate the geographic source of the industrial emissions.

In a similar fashion, the waxing and waning of the input flux of industrial cadmium to the atmosphere should be determined from the ice record because eolian inputs of cadmium to the ocean may also be significant. Proper modeling of the chemical oceanography of cadmium requires quantitative knowledge of variations in the fluvial/eolian input ratio.

Present biochemical knowledge of the effects of metal pollution is founded on studies of systems highly contaminated with lead and cannot be referenced to a truly natural system. In terrestrial ecosystems, organisms are contaminated by atmospheric industrial lead aerosols which enter food pathways mainly by dry deposition on leaf surfaces. Corrections for effects from these fluxes of industrial lead can be evaluated from contemporary studies of atmospheric lead/plant and soil interface interactions, combined with historical studies of integrated flux inputs (as established by lead data from ice cores) to selected ecosystems. Natural levels of lead in organisms, inferred from such studies will allow new animal controls containing natural levels of lead to be grown which will serve as the basis for new biochemical studies of non-lead contaminated systems. (B) Measurements of global volcanic emission fluxes of lead, bismuth, thallium and cadmium indicate that this was the origin of major portions of these metals in the atmosphere during the pre-industrial Holocene period. Comparable proportions of these metals in the atmosphere were also contributed from soil dusts during this period. Temporal changes in these proportions have probably occurred during waxing and waning of global volcanic emissions and global wind velocities. Some modelers have proposed that volcanic activity may have triggered the "Little Ice Age". Ice from this period should be examined to see whether there is any evidence for enhance elemental tracers of volcanic emissions.

(C) Changes in lead, dust, and seasalts have recently been shown to be substantial in the Antarctic tropospheric cell during the period of transitions from late Wisconsin to early Holocene. It is desired that studies of these substances be carried out in Greenland ice to see whether comparable temporal changes occurred in the Arctic tropospheric cell. Such studies will contribute to an understanding of natural controls on trace element concentrations in the atmosphere. These objectives can be met by undertaking the following experiments at ice core drill sites from both poles and in suitable mid-latitude high-elevation sites:

(I) Snow pit and hand auger collections, in which principle investigators collect their own large samples with extensive contamination precautions. High elevation sites should be supplemented by such collections from two other sites at elevations of 1 and 2 km above sea level.

(II) A series of ~100 meter deep firn cores (collected with pre-cleaned coring gear and with coring supervised by trace element principle investigators) at the sites of the snow-pit studies.

(III) 100 30-cm whole core sections (018 sampling from periphery OK) covering the period from the entire core. 25 of the core sections will be taken from the Holocene; 25 of the core sections would be taken from 13,000 to 40,000 yrs. bp.; the remainder would be taken from older ice.

(IV) These studies should be integrated with aerosol sampling and meteorological studies to document regional transport processes.

SPECIALTY GROUP REPORT: SOLUBLE AND INSOLUBLE CONSTITUENTS

Ice cores contain a historical record of aerosols and soluble gases relatable to global climate and to biogeochernical cycles of elements such as C, N, S, and Cl. These components affect the Earth's radiation balance directly via absorption and scattering of light, and indirectly by influencing cloud nucleation processes. The aerosol concentrations and composition both contribute to and respond to global climate change.

General Problem Areas

The overall objective for the examination of soluble and insoluble constituent records is to document the Earth's climatic history using a global array of ice cores which span glacial/interglacial transitions, focus upon specific abrupt events (e.g. volcanic activity, Younger Dryas) and document recent anthropogenic influences upon the chemical and physical properties of the atmosphere. These environmental records, when obtained from a variety of analytical approaches, provide a unique opportunity to understand more thoroughly some of the complex processes which control global climate. These processes include the long distance transport and degree of atmosphere loading of continental dust, the production and release of trace gases and aerosols from the oceans, and the injection of volcanically derived material. 'Me source strengths of these components as a function of time and in response to varying environmental conditions needs to be assessed.

Specific Problem Areas

Soluble Constituents:

Nitrate continues to be one of the most difficult ionic species in glacial ice to quantify in terms of discrete sources. The relative importance of biological, tropospheric, solar and stratospheric sources of nitrate and the modulating factors and processes need to be assessed.

Sulfate is a major component of the aerosol in the polar regions. The origin of this sulfate aerosol is of considerable importance because of its role in the formation and transport of acid precipitation and its effects on the optical properties and climate of the atmosphere. There are three major potential sources of this sulfate: anthropogenic emissions, stratospheric sulfate (largely of volcanic origin), and biogenic emissions of reduced sulfur gases.

Methanesulfonic acid (MSA) is an atmospheric oxidation product of DMS which is of interest as a potential tracer for the cycling of organosulfur emissions. The incorporation of MSA into aerosols and subsequent preservation in ice cores provides a unique opportunity to study the history of the input of organo-sulfur compounds into the ancient atmosphere and its relationship to global climate.

In addition the $\delta^{15}N$ of $N0_3$- and the $\delta^{34}S$ of SO_4^{2-} should be determined to help ascertain the sources of these constituents. It is hoped that marine biogenic, terrestrial biogenic as well as volcanic and anthropogenic sources can be distinguished based on differences in their isotopic signatures.

Ice cores should be recognized for their value as a unique tool for the examination of global atmospheric chemistry through time. Investigators should be encouraged to conduct analyses for a wide range of constituents including all of the major anions and cations, as well as trace constituents such as F, Fe, Mn, Al, and silica. Analyses of major constituents yield information concerning basic input sources and their modulating factors and set the stage for the interpretation of other records. F is a tracer for local volcanic eruptions. The other species yield information concerning the concentration and composition of particulate matter which is integrally linked to climate and atmospheric circulation. Organic constituents such as aldehydes which are important for understanding cloud processes as well as other organic constituents with biological sources should also be investigated.

Oceanic emissions play a major role in the atmospheric cycling of the halogens (Cl, Br, I). In particular, there is a large enrichment of iodine in marine aerosols. A historical record of sea surface iodine emissions from the high latitude oceans should be preserved in ice cores. This signal would contain information about the productivity of the oceans and about the state of the atmosphere during various climatic regimes.

Insoluble Particulates:

Variations in the concentration of dust document the major and minor shifts in global temperature. In all ice cores containing glacial/interglacial transitions, increased particulate deposition characterizes the cool periods. The concentration, size distribution, and chemical composition of the material entrained in the atmosphere directly affects the radiation balance by differential absorption and scattering of shortwave and longwave radiation.

The insoluble particulate matter (continental dust, volcanic ash, diatoms, and pollen) preserved in the ice provide an opportunity to examine both long and short term variations in the contribution of various sources to the atmospheric particulate mass. The contributions as a function of time (hence, of varying environmental conditions) when interpreted along with the other ice core parameters (i.e., isotopes, chemistry, accumulation) will allow documentation of climatic and environmental history over the last -150,000 years. The ultimate objective is to better understand the role of particulates in the global environmental system.

Particulates are of specific interest, not only because of the demonstrated close link with temperature and wind strength, but also the particulate loading of the atmosphere responds quickly to changes in surface conditions and circulation intensity. Excluding melting and percolation, particulates are quickly incorporated into the firn and the input signal is not altered substantially by post-depositional processes. Greater emphasis should be placed upon particle identification and size distribution determinations. It should be possible to link many of the major dust events in both glacial and interglacial ice to similar dust events in other ice cores.

Ice Core Dating:

The establishment of an annual time scale is essential for the proper analysis and interpretation of each ice core and should be given highest priority. Since no single constituent is perfectly preserved each year, at least 3 independent properties should be measured simultaneously as a cross-check. This approach will require the ability to make continuous, high-resolution measurements along the entire length of each core. Therefore those techniques that are least destructive, can be performed most rapidly after core procurement (e.g. on site), and are most consistently reliable should be considered. The resulting time scale and interpretations must be made available shortly after core collection for use in core allocation.

To date only DC (surface) conductivity has been proven to generally satisfy all of the above criteria. Therefore, priority should be given to the development and testing of alternate dating methods. Those which show some potential include: 1) AC conductivity (dielectric constant), 2) liquid conductivity, 3) NO_3- ion (using UV spectrophotometry), 4) H_20_2, and 5) laser light scattering. Well-established, but time-consuming measurements such as $\delta^{18}0$, ^{82}H and microparticles should be made intermittently or at a later date to confirm the dating of the core.

At greater depths (e.g. pre-Holocene), resolution becomes the limiting factor. Thus it is essential to identify those techniques that will remain useful for dating annual layers after the others have failed. Ultimately, less precise but longer time scale methods such as radioactive isotope dating should be used on an intermittent basis if sample size requirements can be kept within reason.

Throughout the cores, marker horizons such as volcanic events, ^{10}Be peaks, and the glacial/interglacial transitions should be used for cross correlation of the ice cores and absolute dating where possible. Finally, geophysical ice flow modeling should be used to complement the dating methods at depth.

Analyses to be Performed

Particulates
- Microparticulates
  - total count
  - size distribution
  - elemental analysis
  - particle morphology
- Pollen
- Diatoms

Major Anions and Cations
- Cl, $N0_3$, SO_4, Na, NH_4, K, Ca, Mg, Acidity

Trace Constituents
- F, Methane Sulfonic Acid, Aldehydes
- Fe, Mn, Al, Silica, Sr, Organic Acids, I

Other Constituents
- Hydrogen Peroxide

Detail - Continuous analyses
- Subannual to examine seasonal cycling and natural cycling and variability
- Much detail around episodic phenomena such as volcanic events
- Much detail over interglacial/glacial transition period to examine response of various constituents to this climate change.

Specific Experiments

Greenland Deep Drilling - Summit

Greenland Shallow Core Studies

Antarctic Deep Core Studies

Antarctic Shallow to Intermediate Core Studies

High Elevation Sites and Low Latitude Shallow to Intermediate Core Studies

S. America
China
Himalayas
Indonesia
Alaska

SPECIALTY GROUP REPORT: PHYSICAL AND MECHANICAL PROPERTIES, ICE DYNAMICS AND GEOPHYSICS

I. Justification

A. Understanding the physical and structural properties of ice and the detailed flow and strain-rate patterns of selected regions is crucial to understanding ice-sheet dynamics and assessing future stable or unstable changes in ice sheets.

B. Ice-dynamical modeling is needed to provide the depth-age scale for deep cores. The modem dynamical state and temperature-depth profile contain important paleoclimatic information that can be extracted through modeling studies.

C. Physical and structural properties accurately reflect the deformational history of ice, which we must understand to evaluate the continuity of geochemical records; internal-shearing or folding could seriously distort records used in climatic reconstruction. Physical and structural properties also exert an important control on current rates of deformation and modem ice dynamics.

D. Accurate documentation of bulk physical and structural properties of ice is necessary for rational interpretation of chemical and other properties. Core is subject to rapid changes in most properties in response to decompression and thermal stress during recovery; these changes can include microcracking, fracturing, recrystallization, and potentially incomplete exsolution of gases, all of which could bear critically on interpretation of geochemical data.

II. Scientific Objectives

A. Log and identify stratigraphic discontinuities in core
B. Examine densification processes
C. Characterize pore close-off
D. Understand grain-growth processes
E. Determine deformation history of ice
F. Detemiine rheological properties of ice
G. Examine D.C. conductivity characteristics
H. Investigate internal layering
I. Measure 3-D velocity and strain-rate fields
J. Evaluate gas solution and dissolution mechanics and effect on ice rheology
K. Determine physical environment and boundary conditions
L. Estimate past changes in surface elevation
M. Reconstruct age-depth relationship
N. Reconstruct past climatic forcing from modem temperature - depth profile and dynamic state
0. Measure whether fifth force exists

III. Experiments

Objective A.

- Acquire and examine visually smooth-surfaced core.

Objective B.

- Measure depth-density profile on samples selected with regard to stratification

Objective C.

- Examine crystal/bubble relationships in thin sections.
- Examine closed bubbles in thin sections (complementary to total-gas content measurements).
- Measure air permeabilities.
- Model air-exchange processes and age of enclosed gas.

Objective D.

- Measure grain size in thin sections to determine growth rate as function of depth and time, and identify discontinuities.
- Examine crystal/bubble relations in thin sections
- Investigate relative distributions of grain sizes, bubbles, microparticles, and dissolved impurities (including location of impurities) on closely spaced samples from several depths.

Objective E.

- Measure c-axis fabrics and other fabric and texture elements (bubble elongation, grain shape, limited a-axis studies, etc) on thin sections.
- Measure c-axis fabrics through 3-component sonic/seismic measurements on core, on borehole, and from surface geophysics.
- Use laboratory and model studies to relate fabrics and textures to strain history.

Objective F.

- Deform samples from various depths in pressure chambers to simulate englacial conditions and determine rheological properties; at least some samples should be recovered under pressure and used as soon as possible to minimize relaxation.
- Relate these results to fabric, grain size and shape, impurity levels and states (gas, microparticle, dissolved impurities).
- Compare results to similar experiments conducted at ambient pressures.

Objective G.

- Measure continuous D.C. - conductivity profile on core and on ice in hole walls.
- Compare D.C. conductivity and amount and location of impurities on selected samples, using 4-contact probe.
- Measure resistivity using surface-geophysical techniques.

Objective H.

- Measure permitivities and losses on core at radio-echo frequencies; compare to results of detailed high-frequency ground-based radar survey.
- Use borehole-target radar experiments to constrain interval velocities and study internal reflections.
- Use downhole radar to study internal layering, possibly to include tomographic experiments between boreholes.

Objective I.
- Measure surface strain-rate field in vicinity and upstream of borehole.
- Measure borehole tilting, closure (caliper log), and vertical strain (repeat vertical positioning of markers in borehole).

Objective J.
- Use x-ray techniques to search for clathrates in pressurized ice.
- Measure gas solution and dissolution in a pressure chamber.
- Compare rheologic properties of pressurized samples before and after controlled exsolution or dissolution of gas.

Objective K.
- Use standard glaciological techniques to measure accumulation and 10-m temperatures in borehole vicinity and upstream.
- Measure borehole temperature in ice and about 10 m or more into subglacial materials.
- Measure thermal conductivities of core materials and combine with \ temperature data to determine heat flow.
- Measure sliding velocity (if any). Measure basal water pressure (if any). Conduct geological studies on englacial and subglacial rock material.
- Combine geological and isotopic results to identify basal entrapment mechanisms of rock debris.
- Measure strain rate, surface, bed, and internal-layer topography on a detailed grid encompassing the two boreholes

Objective L.
- Measure total-gas content of core samples and evaluate in terms of past ice sheet
- elevation changes in conjunction with isotope and model studies.

Objective M
- Use all available data as inputs to models to construct ice-core chronology.

Objective N.
- Calculate modem mass balance, and use modeling to infer causes of any imbalances.
- Use borehole-temperature profile to construct past surficial temperature changes.

Objective 0.
- Conduct highly accurate borehole-gravity survey.
- Measure basal topography accurately using imaging radar.
- Measure surface topography accurately using standard surveying techniques.
- Measure borehole length accurately using single-cable logging device.

IV. Issues
- Cooperation (we must measure multiple properties on the same samples)
- Core storage
- Core shipment at *in situ* temperatures and pressures
- Cooling of processing trench to -10°C or below
- Need for two holes in many proposed experiments to cross-correlate data records and determine if serious miscorrelations exist.

V. PICO Drilling/Logging Needs

- Pressurized core barrel
- Side-wall sampling
- Ability to conduct diverted drilling for closely spaced cores through selected depths
- Accurate depth control (single-cable logging tool)
- Ability to core debris-rich ice
- Ability to core bedrock
- Ability to core unconsolidated subglacial materials
- Ability to measure vertical strain

SPECIALTY GROUP REPORT: ATMOSPHERIC TRANSPORT/ POST-DEPOSITION STUDIES

This report contains three sections. First, a brief scientific justification for atmospheric studies of importance to glacial record research is presented. A list of three specific objectives related to the justification is given next. Finally, detailed research methods to achieve the objectives are presented.

I. Justification

The purpose of the atmospheric studies summarized here is to provide a better understanding of how glacial snow, firn, and ice can be used to determine characteristics of the atmosphere during previous times.

II. Objectives

The objectives of the atmospheric work summarized here can be divided into three categories:

A. To determine the source regions and transport pathways for contaminants reaching the atmosphere over Greenland.

B. To determine rates and mechanisms of deposition from the atmosphere onto the Ice Sheet.

C. To develop an understanding of processes which may change the distribution of contaminants in the Ice Sheet after deposition.

Research methods to achieve each of these three objectives will now be discussed.

III. Research Methods to Achieve the Objectives

A. Source Regions and Transport Pathways

1. Sampling at the surface of the Ice Sheet

One of the primary objectives of the atmospheric component of GISP II will be identifying source regions and transport pathways relevant to deposition on to the ice sheet. We will attempt to identify geographical source areas, the relative importance of statospheric and troposheric inputs, and the roles of natural (marine, continental) and anthropogenic sources. We hope to characterize variations in transport processes on seasonal and shorter time scales.

Sources will be characterized using a variety of chemical and meteorological approaches. Regional scale apportionments can be estimated using signatures of pollution tracers from North America and Eurasia. Stable Pb isotopic ratios can also be used to resolve regional and smaller sources. The relative importance of statospheric and tropospheric inputs can be deduced from 7Be/21OPb and ozone measurements. Distributions of various elements can be used to identify marine, crustal and anthropogenic sources. For example, size fractionated aerosol samples can be used to distinguish fine particulate, anthropogenically derived Cd from Cd in volcanic emissions. In addition, it may be possible to use the concentration of Bi and T1 to identify specific volcanic events.

Meteorological analysis will be used to complement the chemical approaches. Synoptic analysis can be used to describe large scale transport pathways. Forward and backward trajectories will be correlated with chemical data. More sophisticated meteorological models may also be compared with the chemical data.

Measurements will be made at a ground station near the GISP II site during each summer season and by aircraft at selected times through the project. Total and size fractionated aerosol samples will be collected daily at the ground station for the determination of trace metals, radionuclides and stable isotopes of Pb. Continuous monitoring of 03 will also be conducted at the sampling site. The aircraft sampling will include as many of these types of samples as the constraints of the platform allow.

2. Aircraft Sampling

The variability of chemical species in ice cores is currently being used to infer both natural (e.g., volcanic) and anthropogenic impacts on regional and global scale atmospheric chemical composition. The transport of aerosol and gas species to Greenland summit occurs at various altitudes ranging from the atmospheric boundary layer (e.g., sea salt) to the stratosphere (e.g., volcanic debris, ^{1O}Be). In other words, the deposition to the Greenland summit surface is influenced, to variable degrees at specific times, by the entire atmospheric column. Ground-based atmospheric sampling during GISP II, while very important, cannot address a number of questions related to sources and transport.

We strongly recommend that the atmospheric chemistry community be encouraged to develop a series of aircraft experiments to define the structure and composition of the atmospheric column over Greenland. Such studies would include remote sensing of aerosol vertical distribution, mixed layer height, tropopause height, and ozone vertical distribution along flight lines designed to characterize the range of meteorological conditions which occur over Greenland and adjacent regions. The aircraft would also include in situ sampling capabilities similar to those planned for the ground-based atmospheric chemistry campaign.

An aircraft sampling program offers the opportunity for seasonal sampling and detailed chemical characterization of air masses from specific source regions (e.g., central Europe, North Atlantic, etc.).

Finally, it should be noted that the aircraft studies proposed above will require funding levels of $1-2M per expedition. However, there are currently several major atmospheric chemistry projects being proposed and developed for the North Atlantic region (e.g., EUROTRAC, NASA/ABLE-3, NSF/AEROCE) which could provide much of the data required for GISP II atmospheric chemical study objectives. It is important to initiate communication and coordination between these efforts as soon as possible.

B. Deposition Processes

1. Wet Deposition

Included in this category are the mechanisms of nucleation scavenging, in-cloud scavenging by existing cloud droplets and ice crystals, and below-cloud scavenging. The first process is believed to be dominant in the polar regions. Developing an understanding of wet deposition rates and mechanisms requires simultaneous measurement of contaminant concentrations in precipitation and in the air passing through clouds. Characteristics of the contaminant particles and gases as well as characteristics of the clouds must also be determined. This is extremely important since the aerosol population to a large degree determine the microphysical characteristics of cloud/precipitation systems and thus what mechanisms are dominant in determining deposition rates and efficiencies, especially in remote regions. For instance, increased concentrations of CCN may shift the snow crystals growth process away from riming dominant (more efficient aerosol scavenging) to diffusional growth dominant (less efficient aerosol scavenging).

The sampling should be conducted on an event basis. An aerosol sampler (H1 VOL + filterpack) should be operated simultaneously with collection of falling precipitation. Cloudwater should also be sampled. The precipitation, cloudwater, and filter samples should be analyzed for the following species: PH, anions (Cl^-, $S0_4^{2-}$, $N0_3^-$ cations (NH_4^+, Na^+, K^+ Ca^{2+}; Mg^{2+}), trace metals (analysis by INAA, AA, XRF, etc.), radionuclides (e.g., ^{7}Be, ^{1O}Be, ^{21O}Pb), elemental and organic carbon, and stable isotopes (e.g.,$\delta^{18}0$, δD). In addition, air monitoring should be conducted for several species which may be incorporated into the Ice Sheet, such as $HN0_3$, H_20_2, $S0_2$, CH_4, $C0_2$, CO, and N_20.

2. Dry Deposition

Although wet deposition is often assumed to dominate in removing atmospheric contaminants, previous work has shown t hat dry deposition may be important in locations where cold weather is frequent and where amounts of precipitation are low. It is likely that dry deposition dominates for at least part of the year in central Greenland.

Two methods of estimating dry deposition should be attempted. First, direct measurements of dry deposition should be possible by sampling aging surface snow at various time intervals after snowfall. Work at Dye 3 suggests that sampling at intervals of at least 4 days are needed to provide measurable accumulation on the surface. Second, characteristics of the atmosphere, the surface, and the depositing species can be used to model dry deposition. Characteristics of the atmosphere include wind speed and temperature profiles, while characteristics of the surface include the geometry of the roughness elements. Characteristics ofthe depositing species include particle size distributions, particle density, and reactivity of gases. It is proposed that measurements be conducted at the GISP-2 site to enable dry deposition modeling.

Data from aircraft sampling and from ground-based sampling at other locations (e.g. Dye 3, coastal Greenland, Canadian Arctic, and Scandinavian Arctic) can be used to estimate airborne concentrations at other times of the year to allow modeling of dry deposition at Summit on a year-round basis.

Direct dry deposition monitoring should be conducted during dry periods in each of the five summer field seasons. Information should also be collected to permit dry deposition modeling for those species where sufficient data from summit exist. In addition, data from aircraft sampling and from ground-level sites at other Arctic locations can be used to estimate airborne concentrations throughout model dry deposition on a year-round basis.

Chemical species of interest would be the same as those of interest in wet deposition.

3. Occult (Fog) Deposition

Occult deposition is defined here in context to ice core related studies as any wet deposition process other than that due to precipitation in the form of snow. This includes deposition of cloud (fog) droplets to the snow surface by direct impaction due to near surface eddy motion. It also includes deposition associated with surface hoar frost formation. Cloud droplet impactions can occur with or without precipitation. Hoar frost deposition occurs primarily during clear sky conditions. In some desert climates (which many high altitude and or high latitude regions are classified) occult deposition may be a significant part of the total annual precipitation.

Occult deposition may be studied in two ways, direct measurements or modeling studies. However, in order for modeling studies of eddy flux deposition of cloud droplets to the surface to be successful it is necessary to know the droplet size distribution. In addition to adequately model chemical wet deposition by cloud droplets it is necessary to know the composition of the cloud droplets as a function of their size. This may be dependent on the aerosol source region, chemical transformations along the transport pathways and the dynamics of the cloud formation process. Therefore it is recommended that at a minimum, measurements of the cloud droplet size distribution and chemical composition versus size be included as a priority measurement at ice core retrieval site in order to make a direct comparison to wet deposition by snow.

Wet deposition due to frost formation (water mass and chemical) can also be measured on site and modeled using knowledge of the vertical gradient of temperature, absolute humidity and wind speed. On site measurements are needed to ascertain the relative magnitude of thedeposition process. Modeling studies can be used to extend the results of the measurements to other locations or at other times if the appropriate micrometeorological measurements are made.

Measurements of cloud droplet size distributions can be made instrumentally and continuously during cloud events while an ice core camp is manned. At the same time, discrete collection of cloud droplets versus droplet size should be made over intervals of about a few hours, to determine what, if any, dependency exists between cloud composition and droplet size. These measurements should be made throughout a precipitation event. The ideal situation would be continuous collections. Such a method does not exist. Discrete collection methods are available.

Hoar frost deposition should be measured on an event basis, intra. storm. Surrogate surfaces may be used or the surface deposit removed from the natural snow surface. The period between frost collection should be tied to changes in the meteorologic conditions (i.e., the lack of suitable frost forming conditions). This is where the distribution between dry depositional process may be made. Measurements of deposition rates and chemical composition of cloud droplets and frost should be conducted as part of any wet chemical deposition program at the GISP and other ice core sites.

Cloud droplet and frost deposition of anions, cations, trace elements, radionuclides, and stable isotopes at a minimum should be characterized at the GISP H core site during all summer seasons that coring activities are being conducted. Additionally, the frequency of potential occult depositions during the winter, unmanned season should be addressed by the installation of suitable remote meteorological station with a cloud occurrence measurement device such as a simple nephelometer.

C. Post-Deposition Processes

A number of investigators have shown that contaminant concentrations in snow may change with time as the snow ages, even in the absence of dry deposition. Examples of process affecting these concentrations include snow sublimation, meltwater percolation, and diffusion of contaminants through the snowpack. Possible research methods to explore post-deposition changes in the Arctic include the following:

1. Measurement of contaminant concentrations in surface snow during dry periods of varying length between storms is needed to assess sublimation. Comparing time-varying concentrations for species with and without appreciable dry deposition may help separate the effects of sublimation.

2. Measurement of contaminant concentrations in shallow snowpits are needed for comparison with previous measurements of concentrations in fresh snow corresponding to the same set of storms. This will provide an indication of changes in concentration between the original fresh snow and the older snow in the pits.

3. Statistical analysis of concentrations in intermediate depth cores is needed for species whose airborne concentrations and deposition rates are believed to have been constant over the period of the cores. This may identify longer term post-deposition changes in concentration.

GISP II: SITE SELECTION PANEL REPORT

Prepared by:

S. Hodge (Chairman), I Bolzan, E. Waddington and 1. Whillans

<u>Introduction</u>

This report outlines the conclusions reached by the Site Selection Panel. These conclusions are based solely on scientific considerations and purposely do not consider logistical, financial or political factors.

Although much numerical modeling work has already been done, considerably more could still be applied. In fact, more computer calculations will be done in the next few weeks to clear up some points raised during our discussions, and the results will be incorporated into the next version. This current report thus represents only our initial recommendations.

We have tried to consider all factors which would influence the choice of drill sites. These factors, however, are all based on the fundamental assumption that detailed knowledge of the ice flow is necessary to date the deep ice. Direct dating techniques would probably cause us to change some conclusions and rearrange priorities, but this would not change the basic fact that an ice sheet is a dynamic, deforming medium, and so even with ideal independent dating techniques, it would still be necessary to understand how, and from where, the ice has flowed throughout the history covered by the ice cores.

We assumed that two holes are to be drilled. Although not entirely independent, we have attempted to distinguish between the criteria used to select the general location of the pair of holes ("site" criteria) and the criteria used to determine the separation of the two holes ("separation" criteria).

Issues considered:

- surface topography
- bed topography

- ice thickness
- bed roughness
- accumulation rate
- horizontal gradients in accumulation rate
- length of flowline special flow effects near the ice divide
- ice divide migration
- basal melting departures from two-dimensional "flowline" flow
- age of 20 mm and 5 mm thick layers (thinnest layers for continuous and intermittent counting, respectively, at Camp Century)

<u>Area considered:</u>

Our analysis concerns a 180 x 180 Ian square centered on the 1987 Summit Camp. Ice radar soundings were made over this entire area, along lines spaced 12.5 Ian apart in both eastwest and north-south directions, and accumulation data were obtained throughout the same region. The actual summit of the ice sheet turned out to be about 30 km north, and 10 krn east, of this camp.

<u>Divide versus flank flow:</u>

Throughout this report we refer to divide flow and flank flow. Using finite element modeling, Raymond (1983) showed that the ice flow within several ice thicknesses of an ice divide is distinctly different from that at greater distances. Flow within this band, which is very narrow relative to the entire width of the ice sheet, is predominantly vertical, whereas,-flow outside this region is simple laminar flow, which is predominantly horizontal. Figure 1, produced as part of our calculations, illustrates these two types of flow.

In the past, it was difficult to model the flow of ice in the vicinity of an ice divide and this was one reason that there was reluctance to drill at such a site. Numerical modeling of ice flow, however, has now advanced to the point where this is no longer a valid objection. In principle, either region can be modeled equally effectively and so "more complicated" flow should not be considered as a disadvantage of an ice divide drill site, relative to a flank site. Numerical models:

Two distinctly different numerical models were used in our calculations. The models complement each other well and are in good agreement where results could be compared. Figure 2 shows the predicted age-depth relationship for both divide flow and flank flow. Note that the two models give identical results for flank flow (one model cannot be used for divide flow), and that outside the divide flow region the relationship is essentially independent of distance from the divide.

<u>Site criteria:</u>

- oldest ice
- best resolution (thick annual layers)
- most reliable dating

<u>Site choice:</u>

Based on the modeling calculations and examination of the ice radar records, we conclude that:

- For the oldest ice, the entire region is suitable, and that basal melting was probably unimportant at any time throughout the last glacial cycle. No particular area stands out as clearly older than the rest.

-For the best resolution, the southwest quadrant gives the thickest layers in young ice (less than 10 kyr), but the entire region is equally suitable for older ice. The southwest quadrant is best for young ice because of the higher accumulation rates there, but since deeper ice comes from closer to the divide the original layer thicknesses all approach the same value, and so there is less variation in the results the older ice.

- For the most reliable dating, the entire region is more or less equally suitable. Assuming a constant accumulation rate with time, 20 mm thick layers are about 30 kyr old and 5 mm thick layers are about 60 kyr old. These values do not vary significantly over the entire grid. Disturbances due to basal hills and bumps should affect only ice older than about 100 kyr in most places. Migration of the ice divide is not important for flank sites (as long as they remain a flank site).

Except for the northeast comer (which is a poor choice anyway because of very mountainous bed topography), the accumulation rate satisfies the minimum requirement (20 cm/yr) for ice coring everywhere throughout the region. This, combined with the fact that divide and flank sites probably have more or less equal advantages and disadvantages (see next section), means that the choice of site probably boils down to simply choosing an area where the bed topography is as smooth as possible. Fortuitously, a reasonably flat, smooth, wide it plateau," or "bench," extends west from the current summit dome, along the ice flow direction. Thus we recommend drilling the two holes somewhere on this bench, with the exact location within this area being determined by the hole separation criteria.

<u>Reasons for two holes:</u>

We feel that there are strong justifications for drilling two holes, and that the scientific results obtained from either core will be enormously enhanced by the results from the other core. T"he increase in our understanding of the ice flow and the age-depth relationship that win result from two carefully positioned coreholes, will, apart from any other advantages, warrant drilling of both holes, by the same party if necessary. The following reasons are not in any particular order by priority.

(1) To assess the reproducibility of core measurements and discriminate non-climatic signals.
(2) To determine and correct for, the effects of migration of the ice divide.
(3) To greatly improve the reliability of the calculated time scale.
(4) To compensate for the fact that divide/flank sites have complementary advantages/disadvantages

The last point is important to keep in mind. Neither location is ideal. For example, divide sites give potentially longer records and low shear strain, but have the disadvantages of possibly undecipherable complex flow changes with time due to ice divide migration effects and lower resolution in young ice (back to the Holocene-Wisconsin transition). On the other hand, flank sites give better resolution in young ice (Figure 6) and do not suffer from divide complexities, but the old ice could be subject to disturbances from flow over or around basal bumps. The best ice flow dating of the old ice in the divide core will depend strongly on the time scale derived for the flank core, where presumably direct dating methods can be carried back further into the past. Deformation measurements in both holes will greatly aid the dating of both ice cores.

From an ice dynamics point of view, the two holes should clearly be located along the same flow line. Although our modeling ability has improved considerably, all existing ice flow models which could be applied to the detailed small-scale flow analysis required here are nevertheless still just two-dimensional "flow line" models. This condition, that the two holes be on the same ice flow line, is implicit in the following discussions.

Separation criteria:

We recommend a separation of about 30 km. Although partly a compromise, it is nevertheless a reasonable compromise, one which is clearly superior, overall, than larger or smaller separations. The points we considered are:

(a) If two holes are to be used to determine the effects of divide migration, then they must be at least 20 ice thicknesses (20*h*) apart to ensure that they were always in *different* flow regimes (divide versus flank) at *any* time in the past. This result comes from finite element modeling of the flow at an ice divide by Raymond (1983), which shows that one must go at least 10*h* away from the ice divide before all traces of divide flow vanish and the flow becomes simple laminar flow characteristic of flank flow. This distance must then be doubled to allow for the situations where the divide could have been between the two holes. For an average ice thickness of $h = 3$ km, this translates into a minimum hole separation of 60 km.

(b) If one requires that *only* the vertical component of velocity must become characteristic of flank flow, instead of both components, then this minimum separation can be reduced to 4*h*, or about 12 km. If divide migration were the only consideration, this separation might be acceptable; it would be a matter of deciding how much of the disadvantage pointed out in (c) could be tolerated. However, since criteria (d), (e) and (f) would not be met as well, such a separation would not be a satisfactory compromise scientifically.

(c) We estimate maximum divide migration (Holocene to Wisconsin) to be of the order of 100 km (see Appendix). Even though the suggested separation of 30 km is less than this, and thus both holes may still be subject to both types of flow at some time in their history, this distance is probably large enough to ensure that stratigraphy characteristic of ice divide regimes will occur at distinctly different depths in the two cores. However, if very small separations, of the order of 1-3*h* (3-10 km), are used, then it will be difficult, if not impossible, to distinguish one hole as divide flow and the other as flank flow at any time in the past. On this distance scale, the divide is likely to be migrating back and forth through both hole sites so frequently that, for all practical purposes, they are in the same flow regime. Under such conditions, it would be very difficult to use the two holes to determine the effects of divide migration.

(d) If two holes are to be used to improve the reliability of the calculated time scale they must have a separation of at least 3 cycles of the characteristic wavelength of the ice flow pattern. This result comes from an analysis of surface strain measurements around the Dye 3 and Byrd coreholes (Whillans and Jezek, 1984; Whillans and Johnsen, 198?), where the characteristic wavelengths are 8 and 10 km, respectively. This wavelength is also typical of the internal layering and bed topography in central Greenland, based on the ice radar data. Hence the hole separation should be 25-30 km.

(e) Two holes can also be used to greatly improve our ability to test and fine-tune ice flow models, by allowing one hole to be used as "control" and the other to provide known data to be "predicted" by the model. The hole separation must encompass several cycles of topographic relief in order for the bed topography to affect realistically and correctly the calculated ice flow. For reasons similar to those referenced in (c), three cycles are the minimum number required for an adequate test, so once again this points to a separation of 25-30 km. Even on a flat bed, the flow at any given point is affected by conditions up to several ice thicknesses upstream or downstream, so the separation should be of the order of 10*h* to optimize the benefits of information from two holes. Again, 25-30 km is ideal.

(f) In order to distinguish non-climatic signals in the core records, the two cores must be separated by a distance greater than the scale length typical of microclimate processes in central Greenland. This scale length is of the order of 10 km (Reeh, 198?) and these zones may be transient and may move with the divide crest. Depending on the "noise" source, one core or the other can be treated as "control" to make corrections in the second core, but in order for this to be possible, ice in at most one of the cores can have originated in the affected zone. Assuming that one site is the divide, the second site must be sufficiently far away that all ice of interest for these comparison originates more than 10 km from the divide. Preliminary flow models suggest that at a distance of 30 km from the divide, ice which originates at 10 km from the divide will be about 14 kyr old, which should be just enough to reach the Wisconsin period. Smaller separations will open up the possibility that some Holocene ice in both holes will have originated from the same microclimate source area.

(g) Because the regional climatic signal, as distinct from the local, transient microclimate, is the primary target of GISP II, the two holes should be close enough together that they both experience the same regional climate at all times. This regional climate should be coherent over large distances, but the coherence drops as separation increases, and thus we would lose the ability to test signal reproducibility by using the two cores. This is the counter argument to (f) and is one of the reasons for not using too large a separation.

(h) As the separation of the two holes is increased there is an ever-increasing accumulation of flow complexities in the deeper, older ice, due simply to the ice having flowed over more and more bed topography. There is also an increasing chance of an especially complex perturbation occurring at some point, which could destroy any chance of cross-correlation of data between the two cores. If one hole is placed at the current summit of the ice sheet, and the other one down the ice flow line to the west, as suggested earlier, then a separation of significantly more than 30 km starts to run into this problem: the bed topography has a saddle, a small bump, and then, at 50-60 km from the summit, starts a steady decent of over 200 m into a "canyon" whose bottom is below sea level.

(i) In a similar vein, as the separation of the two holes increases, there is an ever-increasing chance that the actual ice flow line will deviate, either now or in the past, from the one which is estimated based on the current topography. Errors in the measurement of this topography, as well as the uncertainties inherent in any interpolation and contouring technique, progressively degrade our ability to define the flow line, and therefore the relative orientation of the two holes with respect to the ice flow, as the holes become further and further apart. Like the two previous points, this is another reason for making the separation too large. Beyond 30 km or so, in fact, the proposed plateau narrows considerably, and changes direction slightly, so this problem could be significantly more important for separations greater than 30 km.

Ideally, the effects of divide migration would be best determined by a large hole separation, 60 km or more. However, given the constraints imposed by the actual topography, the increasing loss of coherence in the regional climate as separation increases, and the fact that the other criteria are either completely, or at least reasonably closely, satisfied by a separation of 30 km., we have selected the latter figure instead. All of the vertical velocity and most of the horizontal velocity would still be characteristic of different flow regimes at this spacing. However, if the separation is less than this value, then the two holes will not be glaciologically distinct, and it will be difficult to use ice flow to help interpret the ice core records. Advantages lost by having two holes clo5e together:

If the holes are situated close together, less than a few ice thicknesses apart, then reasons (2) and (3) are lost for either a flank or divide location, and reason (4) reduces to just the advantages and disadvantages of the flank or divide site chosen. In addition, it will be much more difficult to determine which flow regime the chosen location actually had throughout most of its history, regardless of where it happens to lie at the present time.

Recommended sites:

Figures 3, 4 and 5 show our recommended drill site locations. They are at either end of the bench referred to earlier.

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Reeh, N., 198?..

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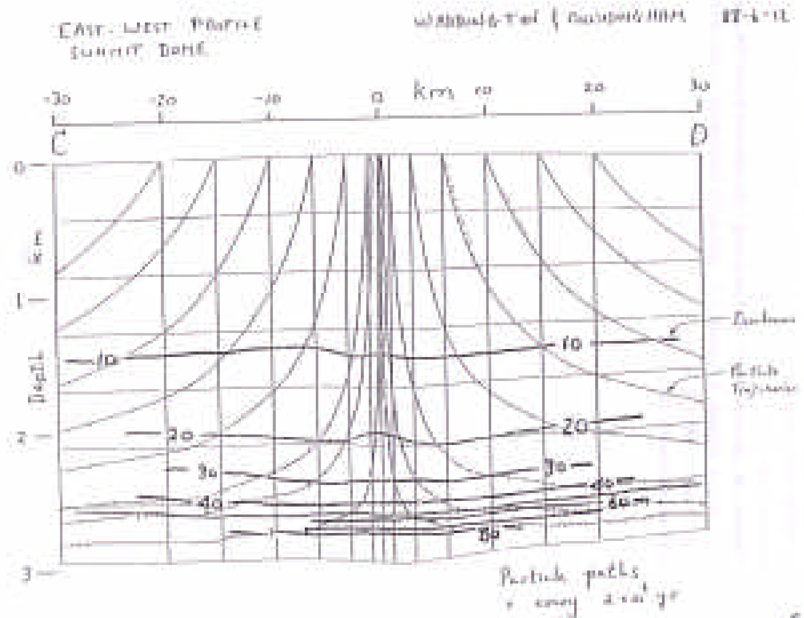
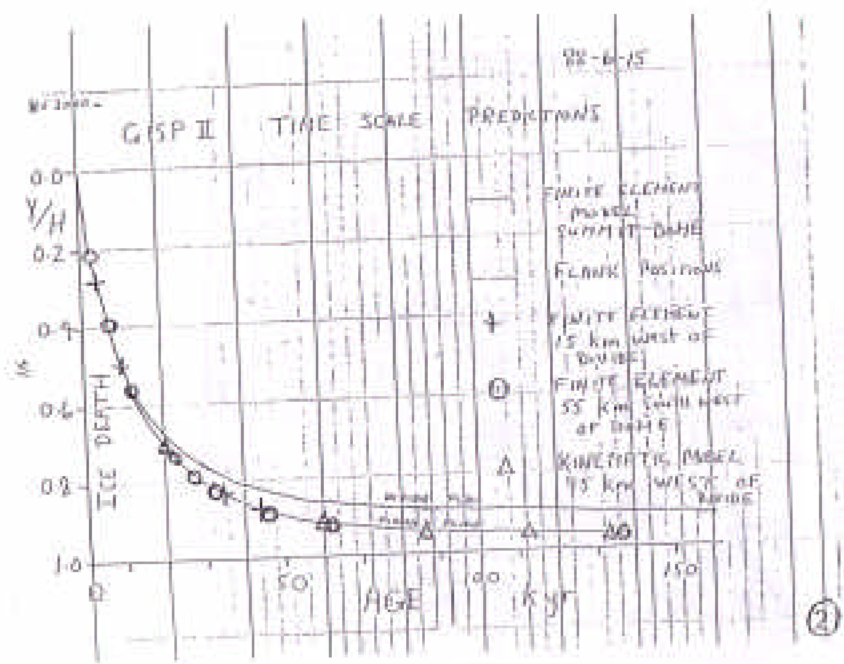
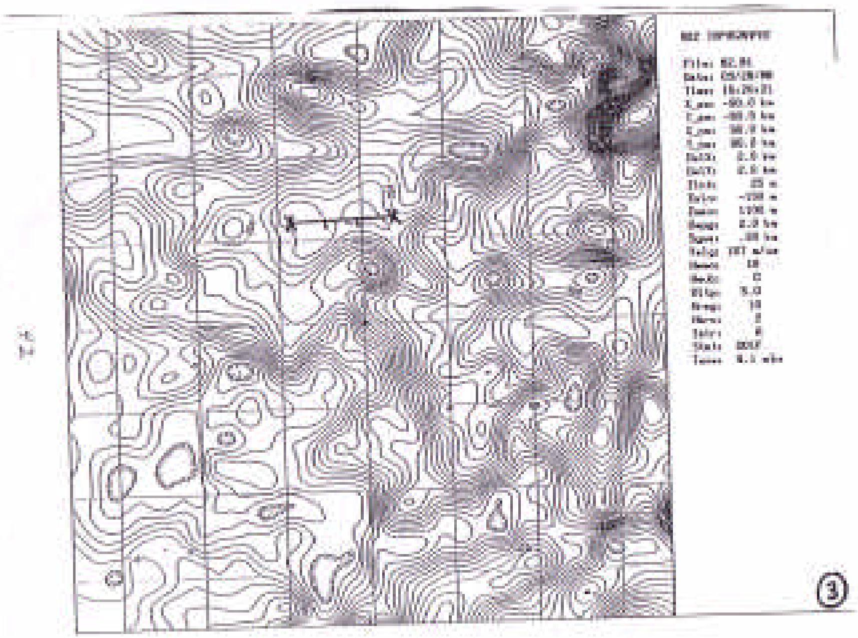
Whillans and Johnsen, 198?.


EAST-WEST PROFILE
SUMMIT DOME
-30
-20
-10
0
Km
10
20
30
C
D
0
1
2
3
Depth
Km
10
20
30
40
Particle paths

6


88-6-15
GISP II TIME SCALE PREDICTIONS
0.0
y/H
0.2
0.4
0.6
0.8
1.0
ICE DEPTH
FINITE ELEMENT MODEL SUMMIT DOME
FLANK POSITIONS
FINITE ELEMENT 15 km west of DOME
FINITE ELEMENT 55 km South West of DOME
KINEMATIC MODEL 75 km WEST OF DOME
0
50
100
150
AGE
Kyr

②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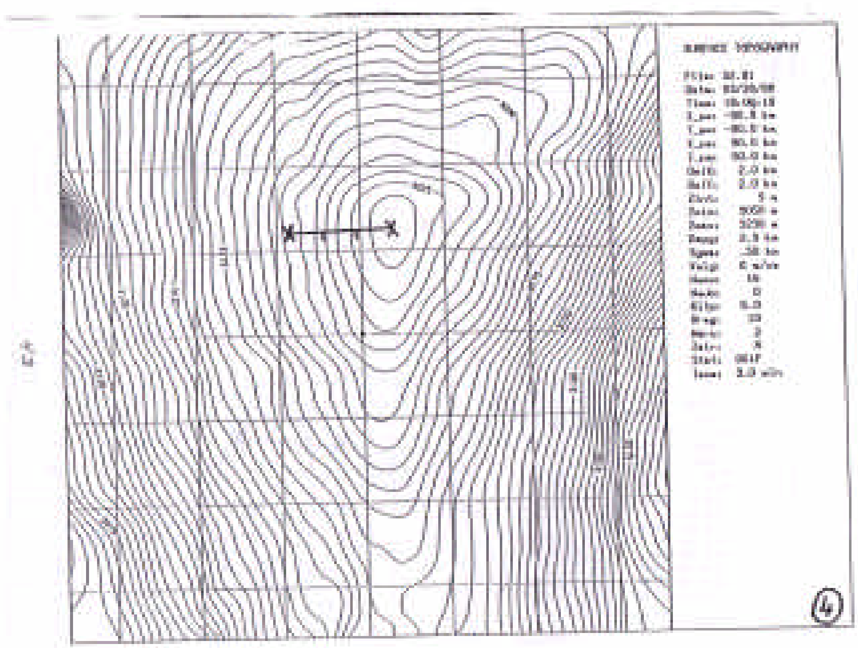
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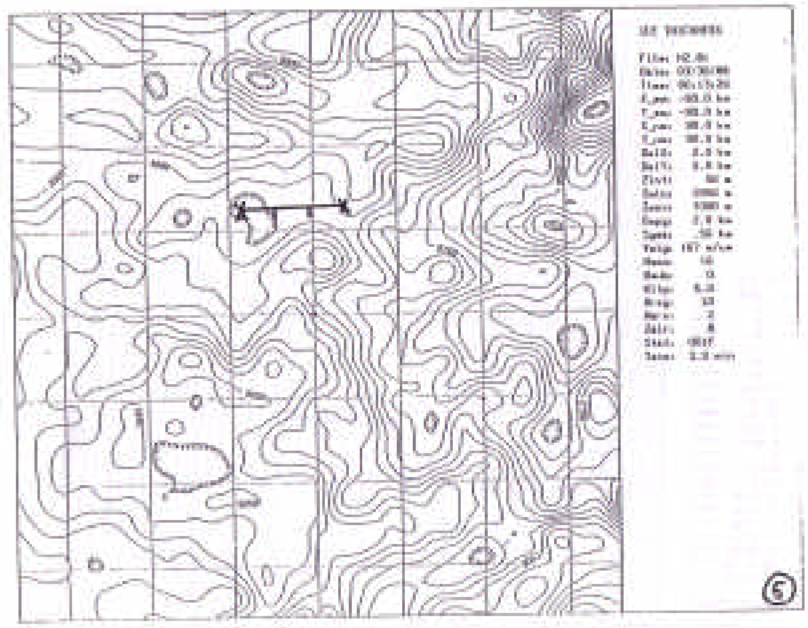
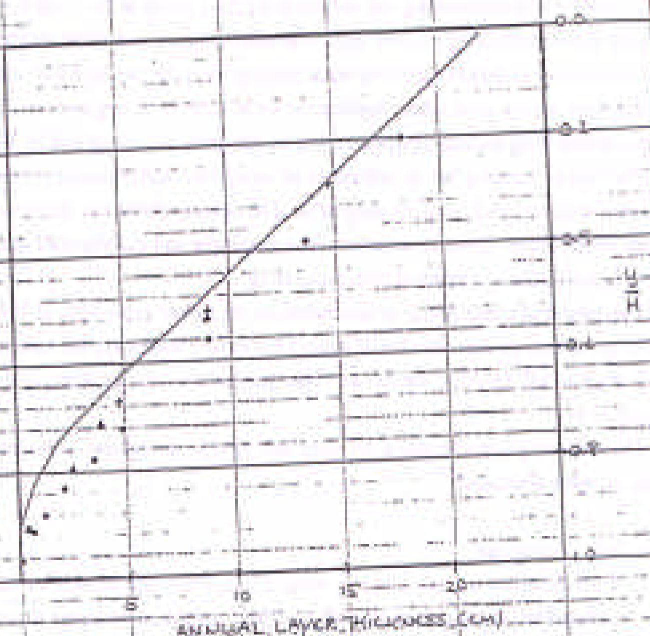


SUMMIT GREENLAND 98-6-15

PREDICTED LAYER THICKNESS VS REDUCED DEPTH



ANNUAL THICKNESS AT SUMMIT DOME (finite-element)

\+ 15 KM WEST OF DIVIDE (finite-element)

• 55 KM WEST OF DIVIDE (finite-element)

▲ 75 KM WEST OF DIVIDE (kinematic)

⑥

GISP II: DEEP DRILL TECHNOLOGY,
THE CORE PROCESSING LINE AND CAMP DESIGN
(Moderator: K Kuivinen)

The role of the engineering and technical services group at the Polar Ice Coring Office (PICO) is to provide the deep ice core drill, sidewall sampling, borehole instrumentation, bedrock and sub-ice sediment sampling equipment to meet the needs of the scientists. Off-the shelf technology will be used where applicable; some new ice coring and ancillary shallow coring and access hold drilling equipment will be designed and fabricated by PICO.

The core processing line is defined as an equipment and procedures needed to handle the ice core once it is removed from the deep drill. The design criteria for this processing line are dependent on the extent to which scientists plan to sample and analyze core in the field, and the rate of core production and optimal core processing.

The deep drill camp design is dependent on the extent and length of site occupation, the number of personnel on site, the size of equipment to be transported, the extent to which auxiliary projects will be using the site as a base for traverse and satellite projects, the airport facilities required.

The following considerations for deep drill design parameters, core processing line and camp design were discussed:

A. Deep Drill Technology

1. Core diameter will be 5.2-inch (<20 kg/m). Five-inch diameter core could be considered as maximum size for handling purposes; the larger the better for sampling.
2. Core productivity is planned at 2-3m per run for the prototype and 1000m drilling. For greater depths core barrels would be extended to 6-m length. This reduces transit time up and down hole. The core processing line must be scaled up to handle increased length.
3. Drill materials (stainless steel, polyethylene, viton, composites, scintered tungsten heads, diamond bits) will be provided to geochemists for testing.
4. Toluene appears to be a good candidate for a deep drilling fluid. Samples will be provided for testing.
5. Sidewall sampling (coring and notch sawing) capabilities exist and directional drilling will be investigated further to meet science needs at critical depth/age targets. Good depth control in the borehole is critical. Samples could be pressurized upon retrieval.
6. Pressurized cores could be collected on an intermittent basis to control microcracking.
7. Borehole logging capabilities should include temperature, diameter azimuth
and inclination. If hole wall could be polished, conductivity could be measured continuously. 'Me capability of inserting vertical strain rings on markers in the hole wall should be investigated. Good depth control is critical.
8. Sub-ice sampling and sampling of basal ice is important.

9. Hot water drilling could provide rapid access to great depths in ice (estimate 3000m. in one week of drilling; 0.5m/minute penetration rate). Core could be taken on air intermittent basis.
10. Existing radar resolution can detect ice/bedrock to ± 5m.

B. Deep Core Processing

1. High pressure fluid (e.g., toluene if used as drilling fluid) could be used to cut core. Advantages over a bandsaw are: no vibration, small kerf (.25mm). Tests should be done on sample ice prior to decision to use fluid over a bandsaw.
2. The rate at which core can be processed depends on the number of investigators that must handle/sample the core in the field. Fifty meters of core per day (average) should be manageable.
3. Core should be allowed to relax after drilling and before cutting/processing. Several days worth of core storage capability should be provided.
4. Core produced in this brittle ice zone (700-1400m est.) could be fractured but intact after elastic relaxation. A pressure equilibration chamber should be considered.
5. The issue of -core archiving has not been resolved. The concept of minimal core processing in the field, with core being retrograded to a centralized ice core processing facility in the U.S. was discussed. This could enable investigators to conduct their field session in a controlled laboratory environment at a more convenient and possibly cost-effective location than a remote field camp. A subcommittee will provide an outline of facility specifications so that PICO can do a cost evaluation. The ocean core curation system might be considered as a model.
6. Core packaging materials should be defined to reduce contamination. New insulating foams blown with C02 should be used instead of polyurethane.

C. Deep Drill Camp

1. Drilling will be done on the snow surface inside a windbreak structure.
2. Core processing will be done in a subsurface trench.
3. Core will be stored in a subsurface trench.
4. The key to logistical cost savings is to reduce heavy-lift air support (LC- 130) flight hours by minimi7ing fuel consumption, permanent camp structures, heavy surface vehicles, and rotation of personnel. Core samples would be retrograded on the return leg of re-supply flights at projected one-month intervals.

GISP II: FIELD AND LABORATORY ANALYSIS
(Moderator: P. M. Grootes)

The logical order of various property analyses and whether sampling and analysis should occur in the field or in the laboratory were discussed. The choice depends on:

(i) How sensitive the property is to core relaxation and microfracturing which starts immediately when a core segment is brought up.

(ii) The need for controlled and clean sampling conditions. These are not usually found in a core processing trench.

(iii) The possibility that a paleoenvironmental record can be derived in the field that can focus sampling for other core properties.

It is technically feasible to measure δD and $\delta^{18}0$ in the field. For $\delta^{18}0$ existing mass spectrometer technology can be used-, a system for real time measurements of δD in the field is under development. However, stable isotope measurements in the field are expensive. Their stratigraphic task is better fulfilled by other analyses. Limited $C0_2$ content measurements can be made in the field.

Core stratigraphy can be obtained in Holocene ice by continuous sampling and analysis of:

Electrical conductivity (ECM)
Particulates by laser light scattering
$N0_3$-
H_20_2
Liquid conductivity

It was felt that a combination of at least three of these techniques will provide a reliable record of environmental change that can be used to guide further sampling. Below the Holocene, only the particulates may still be useful. Isotope verification through direct $\delta^{18}0/\delta D$ measurements becomes desirable.

Analyses requiring immediate field sampling were identified as:

Physical properties
Density
Thin sections
Gases (He, Ne, $CC1_4$)

Field processing must not alter the integrity of the core and it was decided that sampling for the above properties and for stable isotopes can be done in such a way.

Concern arose that a full sampling program by P.I.'s in the field may slow drilling progress, create logistical problems, and be expensive. A preference was expressed for minimal core processing, as listed above, by a mostly technical staff. The bulk of the core would then be shipped to a central U.S. core processing and storage location. A U.S. "field season" would be declared later to sample the core for the various properties. Cost estimates for the two options (processing in the field with possible storage of remaining core at an accessible site in the Greenland ice versus processing and storage of such core at a central U.S. site, maybe a new PICO) will be developed.

GISP II: CORE SECIONNING AND DISTRIBUTION
(Moderator. M. Wahlen)

In order to assess the demand versus availability for core samples, a revised estimate for sample requests should be obtained immediately. Proposers should later specify very detailed sample requests (size, age, special requirements) which, together with the best depth-age estimates from flow models, will provide the basis for a preliminary sectioning scheme. No difficulties are expected for ice from the Holocene; only in critical time periods at the transition and in glacial times demand might exceed the available material. In this case a mechanism has to be found to resolve possible conflicts. Investigators are strongly encouraged to closely cooperate so the maximum information can be extracted from any one sample.

Discussions were held about the possibility of archiving a fraction of the core, This is important for spike features or variations which might be missed at a first glance. Recommendations were postponed until after a detailed sample request survey is obtained. PICO was asked to evaluate the possibility of side wall sampling, which would provide additional material for critical time periods and eliminate archiving.

Possible options where to section the core were explored. The recommendations are: minimal sectioning should be performed in the field (removal of a continuous slab for $\delta^{18}0$ and δD and intermittent samples for thin sections and gas analysis). The bulk of the core should be brought to a facility in the U.S. where the final core sectioning will be performed as a group effort under clean conditions. NSF DPP is asked to explore the realization of such a facility.

DATA MANAGEMENT

(Moderator. R. Armstrong)

In order to assure timely and efficient access to data as they become available, it is important to address the task of data management at an early stage in a large research project such as GISP II. The objectives of the data management plan would include the provision of a central storage location to assure short-term access to data as well as long-term data storage. Services will assure standard formats, safe archival, comprehensive cataloging, and ready access. Recommended specifications for digital data format will be provided. All data accession and archival procedures will be compatible with those of the National Geophysics Data Center.

In order to provide pertinent data to project scientists on a timely basis, certain information will be designated as basic data sets. In general these are data which have been obtained by well known and proven methods and procedures and which serve as supporting information for other studies. Examples of these basic data which should be available to project participants as soon as possible include: Physical Glaciology

Borehole Temperature
Borehole Closure
Ice Density
Strain Rates
Surface Velocity Field

First Order Stratigraphic Markers

Laser Particulates
$\delta^{18}0$, δD
H202
Acidity
Continuous Nitrates

In some cases the initial release of these types of data will represent a more coarse resolution. For example $\delta^{18}0$ might be at one meter intervals, while later releases, would provide finer resolutions. All basic data would be sent to a centralized data center as soon as possible and the current holdings, or data catalog, would be provided to the participants through an electronic mail bulletin board system. This listing would be updated as each new data set arrived. The actual basic data could be distributed to the participants on a generally accepted electronic medium such as PC floppy disks.

A more comprehensive data reporting mechanism would take the form of workshops scheduled approximately six months after the field studies were completed. The workshops would provide the opportunity for broad data set comparison among scientists while still allowing the initial data releases and reports to appear under the name of the principal investigators. Workshop proceedings should be published in appropriate, reviewed, journals to avoid the loss of this information in the "grey literature". However, it should be stressed that the medium chosen for publication should allow the timely release of these basic data.

Following the workshop phase, results of the ice core studies would be published through the conventional journals. At this stage dam would be available to the scientific community at large and authors should describe how others could obtain the data by a footnote in the published paper.

ANTARCTIC DEEP CORE: OBJECTIVES AND SITES

(Moderator: C. Bentley)

1. Introduction

There are two primary interrelated purposes for deep core drilling in Antarctica: to examine the record of global paleo-environmental changes as viewed from the Antarctic, and to study changes in the Antarctic ice sheet itself, together with its more immediate surroundings. It is important to emphasize that changes in the volume of the Antarctic ice sheet have direct global consequences through changes in sea level. In particular, the potential exists for sea level rise as rapid as a meter per century if the flow of the inland West Antarctic ice sheet into the surrounding ocean should accelerate, as it theoretically is capable of doing.

In citing two primary purposes, we should make it clear that they are strongly intertwined-ice sheet changes are both a consequence of, and a contributor to, global environmental change. Furthermore any deep core drilling should, and inevitably will, contribute to both aspects; nevertheless, different primary objectives for different deep coring projects will result in different criteria for site selection and thus in different drilling sites.

2. Objectives

It was the consensus of the Workshop that the primary emphasis for the U.S. deep ice core program should be on West Antarctica. The dynamics of this ice sheet are presently poorly understood but are important to understand. Because of its responsiveness, the West Antarctic ice sheet is particularly important in climatic and, especially seal level changes. The record in West Antarctica is probably complicated because of elevation variations caused by changes in the thickness of the ice sheet through time, perhaps including disappearance altogether. East Antarctica records provide a necessary base for comparison in decoding the elevational influences since the East Antarctic ice sheet has been significantly more stable through time and should have been subject to much smaller elevation influences. Thus, studies should continue in East Antarctica. Additionally, longer time records can be obtained from East Antarctica, certain paleoatmospheric/paleometeorology problems are better solved there, and records from East Antarctic cores from sites close to West Antarctica may show perturbations due to changes in the West Antarctic ice sheet.

Specific objectives of the U.S. program may be listed as follows. Of course, any drilling plan that would address more than one objective at one site would be particularly valuable.

A. Determine the history of the West Antarctic ice sheet over the last 20,000 years. Understanding the past history of the ice sheet, together with understanding its dynamics, is crucial to being able to predict its future, and thus to predicting sea level change. This objective complements the ongoing Siple Coast Project, which currently is a major focus of the U.S. program.

B. Obtain a high-resolution paleo-environmental record over the last 20,000 years. This is needed to correlate events in Antarctica with those in Greenland and at lower latitudes in order to determine what signals are truly global, and to search for north-south differences in the timing of events. This work has a time priority in that it is necessary to modeling and interpreting global climatic changes.

C. Determine the history of the West Antarctic ice sheet on the 200,000 year time scale to integrate with geological evidence on changes in glacial extent, particularly in the Ross Embayment. Of particular interest is the period of the last interglacial, 100,000 to 125,000 years ago, when the West Antarctic ice sheet may have been mostly or entirely absent.

D. Determine the third dimension of glacier dynamics. Studies of West Antarctic ice dynamics are essential to predicting the future of the ice sheet, but are hampered by the unavailability of any information about processes in, and characteristics of, the ice throughout its thickness. Core holes are needed to study bottom processes, to examine deformation through the ice sheet, and to determine the mechanical and other physical characteristics of the ice, particularly near the bed.

E. Examine the paleo-environmental record over the last 200,000 years or so. T'his is essentially the same objective as for GISP III. The reasons for moving it below other objectives for the U.S. Antarctic program is that it is being addressed elsewhere, both in Greenland and Antarctica, and that there may be no appropriate site in West Antarctica, where we propose the main U.S. activity should be concentrated. Nevertheless, this objective remains highly important and should be addressed to the extent possible in any deep core hole.

F. Study atmospheric processes that address the relationship between the physical and chemical properties of the atmosphere and the ice core. This research should be coordinated with complementary investigation of stratosphere/troposphere exchange, the sources and pathways of contaminants reaching Antarctica, and the processes by which contaminants in the atmosphere are deposited to the ice surface. These complementary studies can be accomplished by measuring airborne contaminants, cloud and precipitation microphysical and chemical characteristics, and changes in contaminant distributions in the aging snowpack via snowpit sampling.

<u>3. Criteria for Site Selection</u>

A. History of West Antarctic ice sheet, last 20,000 years:

1. A region of simple flow, past as well as present, and so preferably with a local source of ice (i.e., an ice dome, ice rise, or ice divide).
2. A region sensitive to changes in extent of the West Antarctic ice sheet.

B. High-resolution, 20,000 year core:

1. A region with a high snow accumulation rate at the surface so that the record will be expanded and counting of annual layers can be carried back in time as far as possible.
2. Partly counter to criterion 1 -- a combination of deep enough ice and low enough surface accumulation rate that the 20,000 year level win be reached well above the bottom of the ice sheet.
3. Expectation of high-quality core over critical time periods.
4. Reasonable stability of ice flow over the last 20,000 years, i.e., no major changes in ice thickness or flow direction.

C. History of the West Antarctic ice sheet over the last 200,000 years:

1. A continuous stratigraphic record over the entire time range. This may mean actually drilling in East Antarctica, since there may be no place in West Antarctica where we can be sure to find ice any older than Wisconsinan. On the other hand, if drilling for this purpose is to be carried out in West Antarctica, then an alternate criterion is a site that would maximize the likelihood of finding marine sediments of last interglacial age, if ice that age is missing, so that paleontological dating might be possible.
2. A location likely to show large changes in response to changes in the West Antarctic ice sheet.
3. An expected flow pattern history simple enough that the record is likely to be interpretable.

D. Glacier dynamics:

1. A region where more than one hole can be placed along one flow line of interest.
2. A region that will address a specific ice-dynamic problem, such as an ice stream, or a transition zone between a "catchment area" and an ice stream, or between an ice stream and an ice shelf.

E. The 200,000 year paleo-environmental record (cf. site-selection criteria for GISP II):

1. Oldest possible ice.
2. Best resolution (thick annual layers).
3. Most reliable dating.

F. Atmospheric processes:

1. High resolution capability (snowpits and cores)
2. Regions that will address specific atmospheric problems (e.g., troposphere/ stratosphere exchange, marine influence)
3. Area should not be dominated by strong local emissions if a global record desired.
4. Regions that have remained geographically stable (e.g., no elevation changes)

4. Specific Site Suggestions, by objective

A. 20,000 year West Antarctic history:

1. Siple Ice Dome or Ridge BC (ice thickness H = 1000 m, snow accumulation rate a° = 80 mm/yr).
2. McMurdo Ice Dome (H = 800 m, a°=?).

3. Roosevelt Island (H = 800 m, a° = 100 mm/yr).
4. Berimer Island (H = 1000 m, a° = 200 mm/yr).

B. High-resolution paleo-environment:

1. Ellsworth Land (H = 200 m, a° = 2\500 mm/yr).
2. South Pole (H = 2800 m, a° = 70 mm/yr).

C. 200,000 year West Antarctic history:

1. Vicinity of "Hercules Dome" (86S, 105'W) in East Antarctica. (H = 2500 . a° = 150 mm/yr).
2. Central West Antarctic divide between Whitmore Mountains and ML Woollard. (H = 2500 m, a° = 250 mnx/yr, bed 1000 m below sea level).
3. Deepest West Antarctic ice (Bentley Subglacial Trench 80-1/2'S, 1100, H = 4500 m, a° = 200 mm/yr, bed 2500 m below sea level).
4. Byrd Basin 77-1/2°S, 97°W, H = 35000 m, a° = 300 mm/yr, bed 200 m below sea level).

D. Glacier dynamics:

1. Catchment - ice stream B - ice plain flow line (H = 800-2500 m, a° = 50-200 mm/yr).

E. 200,000 year paleo-environment:

1. East Antarctic site cooperative with other SCAR country or countries.
2. South polar plateau (H = 3000 m, a° = 50 mm/yr).
3. Same as C2.
4. Same as C3.
5. Same as C4.

F. Atmospheric processes:

1. Interior of East Antarctica (S. Pole) since near an atmospheric record).
2. Traverses inland from the coast (W. and E. Antarctica)
3. Circumnavigation of Antarctica to assess differences in coastal regions.

ANTARCTIC DEEP CORE: FIELD AND LABORATORY ANALYSIS
(Moderator: C.M. Laird)

The requirements for analysis of a deep Antarctic ice core are similar to those outlined in the GISP II Lab and Field Analysis section (Grootes) and will not be repeated here. However, there are some unique differences between Antarctica and Greenland that require special consideration.

Dating

Unlike Greenland, there are many areas in Antarctica where low accumulation and strong winds obscure the annual cycles. Thus absolute dating of the upper portion of each ice core with conventional methods is not always feasible and other techniques must be used. Ice cores obtained from these areas of the continent can be dated be identifying marker horizons such as volcanic eruptions and ^{1O}Be spikes for the era in which historical records exist and by cross-correlation with cores taken from high accumulation areas that have been dated accurately. For prehistoric periods, less precise methods such as radioactive isotope dating, and ice flow modeling will have to suffice.

One possibility for establishing a continuous climate/time curve which would not require large samples is δD measurements using a portable mass spectrometer. Such a system could be developed with off-the-shelf hardware to make these measurements on site or at some central location where ice cores from different parts of the continent could be brought for analysis.

Comparative Studies

The Antarctic environment is quite different from Greenland and these should be exploited more fully. Due to its location, Antarctica is more subject both to marine (as opposed to continental) influences and to stratospheric conditions. This makes it an ideal place to study ocean/air and air/ice transfer, and troposphere/stratosphere exchange of soluble and insoluble species. In order to establish a baseline for proper interpretation of the paleoatmosphere, short-term environmental and meteorological records at various sites in Antarctica should be compared with the analytical results from ice cores and surface studies from the same regions and time intervals. Finally, in order to do these studies properly, greater interactions with meteorologists and atmospheric scientists are urgently needed and should be established.

Potential Facilities

The new science building in McMardo could be utilized by major drilling projects for initial and time-priority ice core processing and analysis. Therefore, a priority list of equipment required at the facility together with a brief justification for each item should be developed for consideration. In addition, the Christchurch airport in New Zealand is being remodeled and U.S. operation procedures are being modified. Space may be available for a modest ice core facility. Any thoughts or comments on this possibility should be brought to the attention of Hal Bornes at DPP.

A GLOBAL ARRAY OF SHALLOW AND UNTERMEDIATE ICE CORES AND SITE SELECTION

(Moderator L. T'hompson)

Climatic and environmental variability over the last 2000 years is poorly documented and yet this period will represent the conditions prevailing over the next 200 years.

It is widely recognized that ice core information can be used to address problems which are of concern to a wide sector of the scientific community. The problems include:

-Large scale climatic events such as El Nino-Southern Oscillation and Monsoonal variability

-The long term variations in greenhouse gases (e.g., C02, Methane, etc.)

-The timing and abruptness of climatic events

-A calibration of the deep polar ice core records with high resolution ice core records on a global scale.

The paleoclimatic information extracted from the polar ice sheets is insufficient to provide a completely global perspective. Much of the important climatic activity in the world does not affect the polar ice caps and thus, is lost if the polar regions are the only places where ice cores are recovered.

The successful execution of ice core recovery programs on a global scale requires detailed planning and coordination with institutions within the countries where the field site is located. Field site selection requires snow pit and shallow core studies, ice temperature measurements and radar depth determinations for location of the drilling site. Once a site is selected, a detailed strain network for ice deformation and accumulation measurements is essential. Even though the basic components of ice core drills remain the same, they must be modified for the conditions of the site. Emphasis must be placed on logistical considerations for getting personnel, drilling equipment and supplies in and out of the field. Transportation of frozen ice core samples out of these remote field sites must receive special attention.

Issues which must be considered include percolation and the need to insure that the particular property being studies is properly preserved in the ice. The processing/handling must be more sophisticated, especially when gas studies are planned. For chemistry there are two choices: (a) a more sophisticated transport system for samples or (b) analyses conducted in the field which requires a long lead time for equipment development.

A global array of ice core studies is essential to establish the linkages between hemispheres in order to study the synchroneity of specific events and the regional, hemispheric and/or global extent of climatic and environmental perturbations. These types of ice core studies which focus on problems affecting man on present time scales e.g., monsoons and El Nino-Southern Oscillation events) open up new areas of research for which ice cores are a unique tool. Understanding the global climate system requires a multidisciplinary approach through the study of high resolution records not only from ice cores, but also from tree rings, corals, marine and lake sediments, and historical documentation. On the longer time scales, comparisons can be made with glacial geologic and palynology studies. Sites for future study include Alaska, Arctic Canada, the Soviet Union, Africa and high resolution records from Greenland and Antarctica. Reconstruction of past environments and the global network role of ice cores have been recognized as priority items for the U.S. Global Change Program. Similarly, these objectives are entirely consistent with the goals of the NSF Global Geosciences Initiative. A sufficient number of such programs have been conducted to indicate that the goals of the global array of ice cores can be reached within the existing capability of drilling and laboratory analyses.

Recommendations are that the research projects aimed at recovery of a global array of shallow and intermediate cores should continue simultaneously with polar drilling activities.

NON-CORE STUDIES RELATED TO A GLOBAL ARRAY OF SHALLOW TO INTERMEDIATE DEPTH ICE CORE

Moderator: R. Borys)

I. Justification

Proper interpretation of ice cores requires an understanding of processes by which contaminants are transported from source regions to their ultimate sink in the glacial ice.

Previous work has shown that a number of complex factors influence each step. As a result, using ice core dam to interpret past atmospheric levels of trace constituents is not likely to be straightforward. Research by the atmospheric science community is needed to identify these factors to assist in interpreting the ice cores. Listed below are several scientific objectives which may serve as a guide to what areas of research would be useful in the eventual interpretation of the information obtained from ice core research.

II. On-Site Scientific Objectives

A. Surface

1. Measure the chemical composition and physical characteristics of the aerosol for use in long-range and atmosphere-to-ice sheet transport and deposition studies.
2. Measure the chemical composition and physical characteristics of the clouds and precipitation for use in cloud-to-ice sheet deposition studies.
3. Conduct post-depositional studies of snow/firn/ice transportation processes.
4. Determine site representativeness from wet/dry atmospheric deposition studies.
5. Determine site representativeness from an array of snowpits.
6. Monitor year round the basic atmospheric state parameters including accumulation rate.

B. Airborne

1. Determine vertical structure of parameters measured at the surface (A.1, A.2, A.5) concurrently and when surface measurements are not available whenever possible (ground truth studies).
2. Track material through the atmosphere to the ice core site both vertically (stratosphere/troposphere exchange) and horizontally (long range transport).
3. Compare changes in stratosphere/troposphere chemistry with changes in snow pit/ice core chemistry.
4. Radar studies of ice volume, depth, layering.

III. Off-Site Scientific Objectives

Many studies related to the selection of ice coring sites as well as core interpretation can be conducted off-site. These studies could utilize data collected specifically for a given ice core research site as well as the wealth of historical atmospheric data available. These include but are not limited to the following topics:

A. Satellite Remote Sensing

1. Laser altimetry of the ice surface.
2. Vertical aerosol/gas profiling over the core site.
3. Ice movement from successive visual images.
4. Accumulation rates from accurate laser altimetry.
5. SAR data.
6. Transport and circulation patterns from consecutive image analysis and eventual wind profiles.

B. Historical Atmospheric/Biological/Marine/GeologicaI Records

1. Records of atmospheric turbidity derived from aircraft and ground observing stations.
2. Records of atmospheric events such as volcanic eruptions, nuclear accidents, supernovas, ozone anomalies, etc.
3. Known changes in plant pollen sources with time.
4. Use of temperate and tropical tree ring patterns.
5. Use of coral growth patterns in the tropics for glaciers in high altitude/low altitude locations.
6. Use of annual varves in marine sediments.
7. Use of annual varves in lake sediments, in particular, glacier outflow lakes.

C. Modeling

1. Atmospheric/Dynamics models - Global Circulation Models (GCM's) could be used to estimate changes in atmospheric stability, turbulence and predominant airborne transport pathways over the period of time recorded in the ice core.
2. Biogeochemical models - May be applied to describe changes in the composition of the atmosphere and resultant expected changes in ice core chemistry.
3. Chemical/Transport Models - Ongoing studies of the chemistry of the aerosol and the meteorology of transport may be applied to ice core studies (e.g., EUROTRAK, AEROS). Additionally chemical mass balance models, source apportionment models and source receptor models currently in existence could be applied to the interpretation of snowpit and ice core data.
4. Wet Scavenging Models - Microscale models of the physical and chemical scavenging processes that occur within mix phase clouds could be applied to different core sites where the processes of precipitation formation may be significantly different, i.e., between tropical glaciers and the Greenland Ice Sheet.
5. Dry Deposition Models - Given sufficient information about the composition of the atmosphere over a core site, dry deposition rate estimates can be made and compared to the wet process.
6. Trajectory Models - Atmospheric trajectory models could be applied both backward, using historical meteorological data to derive a transport statistic, and forward, from "events", to assist in the description of the causes of observed variability in the composition of ice cores or snow pits with depth.

IV. Special On-Site Facilities Requirements for Non-Core Related Studies

A separate camp would be required to conduct any on-site special studies of atmospheric chemistry and deposition studies. The basic requirements of such a camp would be:

A. Remote (1 km+) and upwind from the main drilling activities.
B. Self sufficient in accommodations, provisions and power.

C. Living space, clean laboratory, outside working platform and a cold working space needed for personnel, instrumentation, sample collection and sample handling.

U.S. ICE CORE RESEARCH AND GLOBAL CHANGE

(Moderator- P. A. Mayewski)

For scientists interested in global change problems, ice core records provide a unique and invaluable medium for studying the past. These records yield both direct and proxy links to the paleoenvironment over periods potentially as long as hundreds of thousands of years with resolution down to seasonal scale for time-series on the order of hundreds to thousands of years. In addition, the fact that most ice core records are retrieved from locations rarely, if every, occupied by observers adds to the value of these data sets.

In response to the growing importance of such records, the NSF's Division of Polar Programs recently sponsored the U.S. Ice Core Research Workshop in Durham, New Hampshire. At the workshop, 45 U.S. scientists actively involved in ice core research together formulated a globally-based strategy planned through the 1990s, that would result in -the development of an ice core program integrally tied to global change issues. Representatives from the European ice core research community also attended, to aid in discussions of anticipated joint international efforts.

A prime stimulus for the workshop was the newest planned major U.S. ice core effort, GISP II (Greenland Ice Sheet Project II). A proposal solicitation for this project appeared in EOS (24 May 1988).

GISP II and a corresponding European effort GRIP (Greenland Icecore Program), plan to retrieve a ~3200 meter deep core which would extend to the base of the central Greenland ice sheet. Both programs are expected to run from 1989-1994. Conditions at the proposed drill site are such that seasonal resolution will be possible back to ~ 10,000 years and the total record could include the last ~ 200,000 years. A section of the workshop dealt with detailed discussions of the properties to be measured on the core, drill technology, core processing and data management.

At the workshop plans were also drafted for drilling efforts in both West and East Antarctica. Emphasis was given to sites in West Antarctica in light of the extensive programs already undertaken by U.S. glaciologists interested in the dynamics and potential stability of this ice mass. Participants proposed a 1991 start for drilling to the base of the Antarctic ice sheet.

Data comparisons between GISP II and Antarctic deep drilling programs as well as deep sea sediment, lake sediment and glacial geologic records will be necessary to answer questions dealing with the hemisphere to hemisphere synchroneity of global change events.

Considerable enthusiasm was also expressed for immediately expanding the current array of low- to middle-latitude, high elevation coring sites. The suitability of sites in Asia, South America, Europe, and North America for the recovery of ice core records has been well documented, but they remain a virtually untapped paleoenvironmental. resource. These sites can provide documentation of the remote atmosphere and of major atmospheric circulation phenomena, such as ENSO events, while also completing the global linkage between Antarctic and Arctic ice core records.

Workshop participants detailed the analyses (Table 1) that can be conducted on ice cores, noting the considerable potential for new types of measurements and additional new technologies. The repertoire of measurements has been expanded in the last few years as more geochemists, atmospheric chemists, geophysicists, climatologists, and modelers have become involved in the analysis and interpretation of ice cores. As a result of these new interactions, ice core programs now integrally relate a range of measurements on not only ice cores, but also on the atmosphere, surface snow and snowpit samples.

The documentation of global change is a major key to understanding the history of and the current changes in the global system. As ice core programs such as GISP II come on-line, they will provide an exciting new look at the past; the global array of ice core retrieval sites proposed at the workshop has the potential to add important details (Table 2) concerning the changes in and characterization of major components in the global system.

Table 1
Ice Core Measurements

Stable Isotopes:	$^{18}0/^{16}0$, D/H, S, Clv C. N, ….
Gases:	total gas, $C0_2$, CH_4, N_20, $\delta^{18}C$ of CO_2, $\delta^{13}C$ of CH_4, $\delta^{18}0$ of 0_2, 0_2, $\delta^{15}N$ of N_2, N_2, Ar, He, Ne, H_2, ….
Cosmogenic Isotopes:	^{1O}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{81}Kr, ….
Major Chemistry:	$S0_4$ =, Cl^-, $N0_3^-$, F, Na^+, NH_4^+, K^+, Ca^{++}, Mg^{++}, H^+, H_20_2, ….
Trace Metals:	Ir, Au, Se, Os, K, Rb, Cs, Ca, Sr, Ag, Bi, Cu, In, Pb, T1, Cd
Organics:	MSA, formate, acetate,…….
Particulates:	concentration, morphology, composition (e.g., major, minor, trace elements, organics),….
Physical and Mechanical Properties:	stratigraphy, texture, fabric, density, bubble characteristics, viscosity, clathrates, surface conductivity,….
Borehole Studies:	temperature, creep, seismic wave velocity,…….

Table 2

Global Change Components That Can be Documented Using Ice Core Records

-Global Climate

e.g., greenhouse gases
aerosols
atmospheric temperature
stratosphere/troposphere exchange
air mass sources
precipitation patterns

-Global Ice

e.g., distribution of glaciers, snow, and sea ice
ice volume and sea level
glacier dynamics and ice properties

-Biogeochemical Cycles (C, N, S, etc.)

e.g., biogenic gases
marine aerosols
continental aerosols
atmospheric interconversions

-Anthropogenically Derived Material

e.g., radiatively active gases and aerosols
inorganic and organic pollutants

-Geologic and Extraterrestrial Activity

e.g., volcanic activity
geomagnetic field
solar activity
extraterrestrial fluxes

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(Please note: many of the addresses of participants have changed since the meeting in 1988)

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