GISP2 Notebook

Institute for the Study of
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The Greenland Ice Sheet Project Two (GISP2)

On 1 July 1993, after five years of drilling, the Greenland Ice Sheet Project Two (GISP2, Figure 1) penetrated several meters of silty ice and reached bedrock at a depth of 3053.44 meters (Figure 2), and then shortly thereafter penetrated 1.55 meters into the bedrock (Figure 6 and 7) producing the deepest ice core thus far recovered in the world. A companion European ice coring effort, the Greenland Ice Core Project (GRIP), located 28 km east of GISP2 reached an ice depth of 3028.8 meters (> 250,000 years of record) in July 1992 (Dansgaard et al., 1993). Ongoing and planned comparisons between the ice core records at these two sites will add substantially to our understanding and verification of this unparalleled view of climatic and environmental change, the longest ice core record available from the Northern Hemisphere.

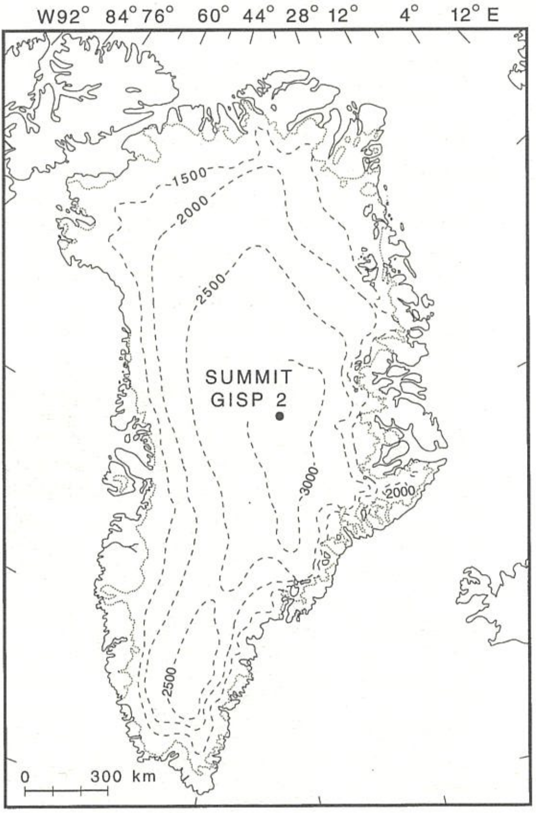
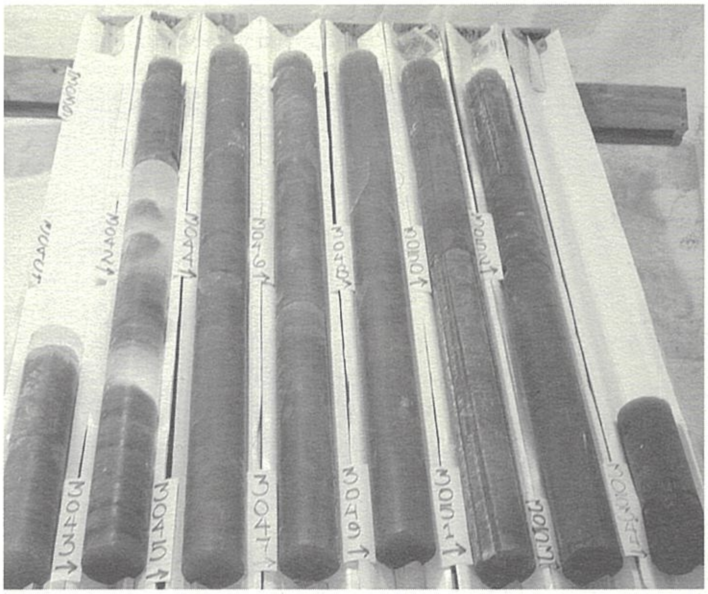


Figure 1. Location map of GISP2 and GRIP. GISP2 is located at 72.58º North latitude, 38.48° West longitude and at an elevation of 3207 meters. Mean annual temperature at GISP2 is -31ºC and modern accumulation rate is 0.23 m H_2O equivalent per year.



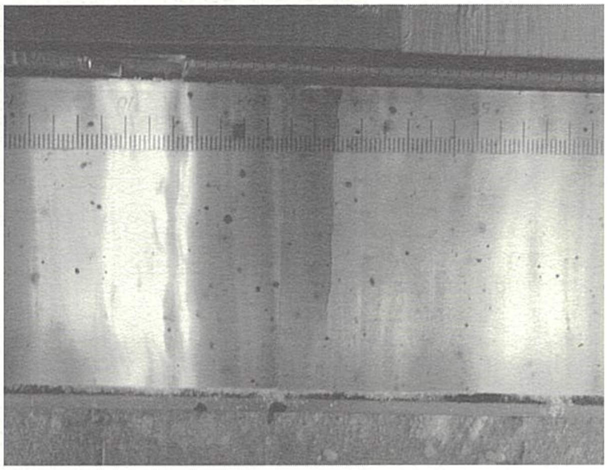


Figure 2. At a depth of 3040.33 meters there is a sharp transition from clear to silty ice, followed at depth by alternating bands of silty and clear ice followed by progressively siltier ice until the contact with bedrock. Preliminary observations indicate that the silty ice formed by regelation involving incorporation of basal debris at the ice rock interface during a period when the base was at the pressure melting point (estimated at -2.8°C for current conditions). The current bed temperature is ~ -9ºC. The transition from clear to silty ice and all of the silty ice appears above, left. A closer view of a section of the silty core appears above right.

GISP2

GISP2 General Background

In late 1988 the Office of Polar Programs (OPP, formerly the Division of Polar Programs), of the US National Science Foundation (NSF) officially initiated GISP2. GISP2 was developed as the first in a series of integrated studies, administered by OPP under its Arctic System Science (ARCSS) program, focusing on environmental change in the Arctic.

The primary goals developed for GISP2 included:

1. Recovery of a high resolution record of Holocene and pre-Holocene climate.
2. Characterization and interpretation of the electrical and physical properties of the core and of its gaseous, soluble, and insoluble components in terms of the partitioning, reservoir exchange, and production rates for the various sources contributing to the atmosphere and the snow deposition over central Greenland (anthropogenic, biogenic, oceanic, terrestrial, cosmogenic).
3. Investigation of the timing and forcing of climate change and of the atmospheric and biospheric response to climate change as revealed by correlated core parameters measured at high resolution (stable isotopes, visual stratigraphy, major anion and cation chemistry, dust concentrations, Electrical conductivity (ECM), volcanic particles, gases, e.g. CO_2, CH_4).
4. Development of accurate dating techniques and flow modeling for Holocene and pre-Holocene ice.

The drill-site selection at the Greenland summit for the US GISP and the European EUROCORE/GRIP cores was based on airborne radar studies of surface and bedrock topography (Hodge et al., 1990) and on data from a 1987 surface survey of a 150x150 km grid (Bolzan and Strobel, in press; Mayewski et al., 1990a). The EUROCORE/GRIP site was located at the present ice divide, and the GISP2 site was chosen over a bedrock plateau about 10 ice thicknesses (28 km) downstream to the west of the divide to obtain a flank-flow regime compared with the GRIP divide flow.

In May of 1989, a ski-equipped LC-130 aircraft operated by the 109th Air National Guard touched down on the surface of the Greenland ice sheet near Summit, and dropped off an advance party of 5 people with 9,000 pounds of equipment and supplies. GISP2 had begun. Within weeks the GISP2 site became the focus for several integrated science experiments.

Once complete, the GISP2 camp was comprised of several surface structures including: a 26 foot by 52 foot prefab building situated on top of 12 foot pilings that acted as a meeting place, administrative office and cafeteria; a 55 foot geodesic dome to house drilling activities; several temporary buildings and tent for berthing. The camp was equipped to accommodate ~ 55 people for up to 5 months per field season.

Each year between 1989 and 1993, from early May until September, the GISP2 camp provided a base for the personnel working on the core drilling and the eighteen programs and forty-two types of measurements that comprise the current GISP2 deep drilling program. Nine non-core studies provide direct information necessary to the interpretation of the core record (e.g. atmospheric sampling, automatic weather stations, surface glaciology, modeling).

The GISP2 Notebook is published by the GISP2 Science Management Office (SMO) at the University of New Hampshire. Layout and design for Volume 3 by Jennifer Putscher.

The GISP2 Science Management Office is the coordinating office for the GISP2 project. It is responsible for coordinating scientific and logistical activities for GISP2. Paul Mayewski is the Director of the SMO, Michael Morrison is the Associate Director.

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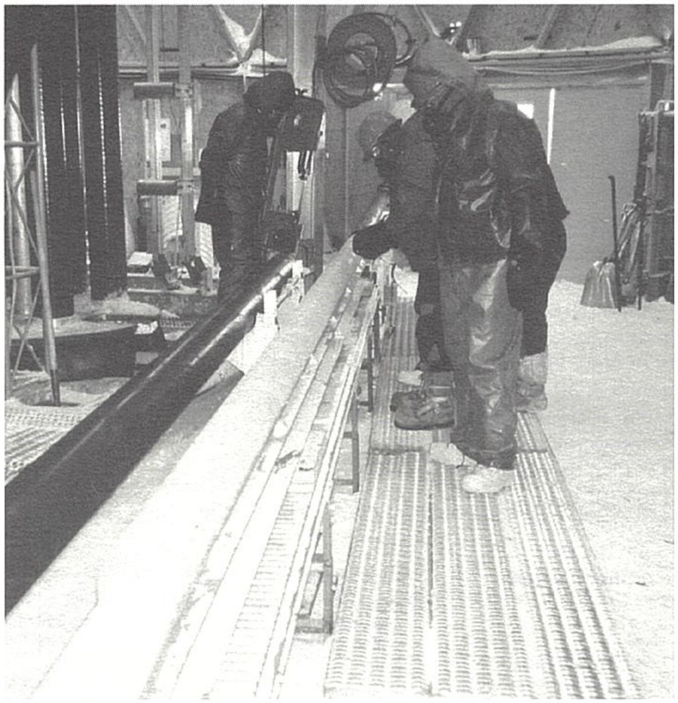
Transport to GISP2

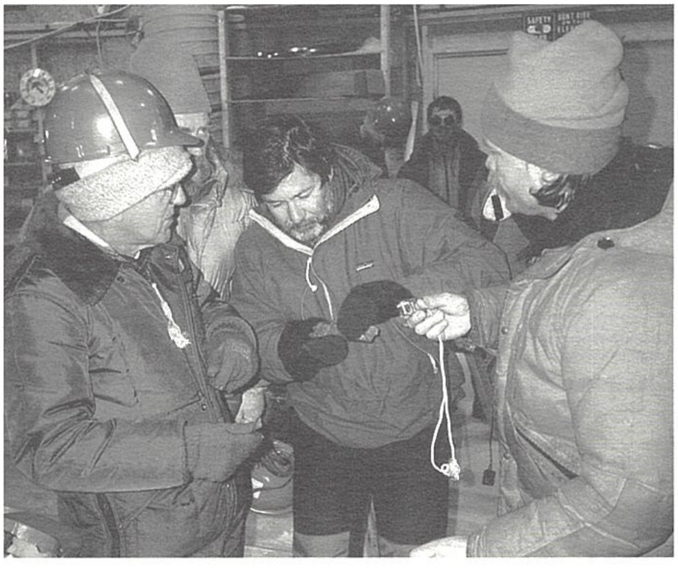
Aircraft support to the project was provided by the 109th Airlift Group based in Scotia, New York. Ski-equipped LC-130 Hercules aircraft landed on a flagged 15,000 ft by 200 ft prepared snow surface, the highest and longest snow landing strip in the world. Over the total duration of the program ~1,000 passengers were transported to GISP2 and more than 3 million pounds of science equipment, construction supplies, fuel and food. (Photo: Jen Putscher)

The GISP2 PICO Deep Drill

The drill used to recover the GISP2 ice core is the product of a five year developmental project undertaken by the Polar Ice Coring Office (PICO), University of Alaska-Fairbanks. The drill was housed in a 52 foot diameter dome (interior, Figure 4) . This drill retrieves an ice core 13.2 cm (5.2 in) in diameter with a volume nearly twice that of previous deep coring drills. It is capable of drilling cores 6 meters (19.7 foot) long in one unbroken piece. A carousel type handling system was developed to reduce time spent on the surface. It contains two complete sets of drill string components. Six meter long screen sections retain ice chips produced during cutting. These are brought to the surface with each run and cleaned. The deep coring drill has been designed to work in a new borehole liquid, n-butyl acetate, which has minimal health and environmental risks. In April 1989, Dr. Ken Anderson of UNH researched drilling fluids for SMO and recommended ethyl acetate and butyl acetate as candidates. Following this lead, PICO chose butyl acetate for the deep core drilling fluid in 1990 (Gosink et al., 1991). A drilling fluid recovery system was designed to recycle the drilling fluid from the chips and return it to the bore hole, thereby minimizing the amount of n-butyl acetate needed to retrieve a core of this depth and reducing the environmental impact on the site.

The control panel and instrument package (Figure 5) for the PICO deep drill were developed at the University of Nebraska-Lincoln. The instrument package in the drill monitors sixteen different parameters (e.g., weight, pressure, temperature, inclination, azimuth, rpm, current). It transmits this data to the control panel which provides a digital readout of any of the measured parameters and depth as well as providing control of the speed and direction of the drill motor. The control panel also transmits data to a desktop computer which displays all of the parameters simultaneously as well as logging the data on a hard drive.





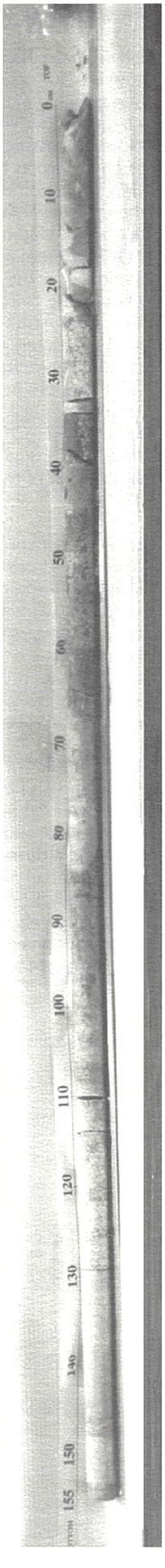
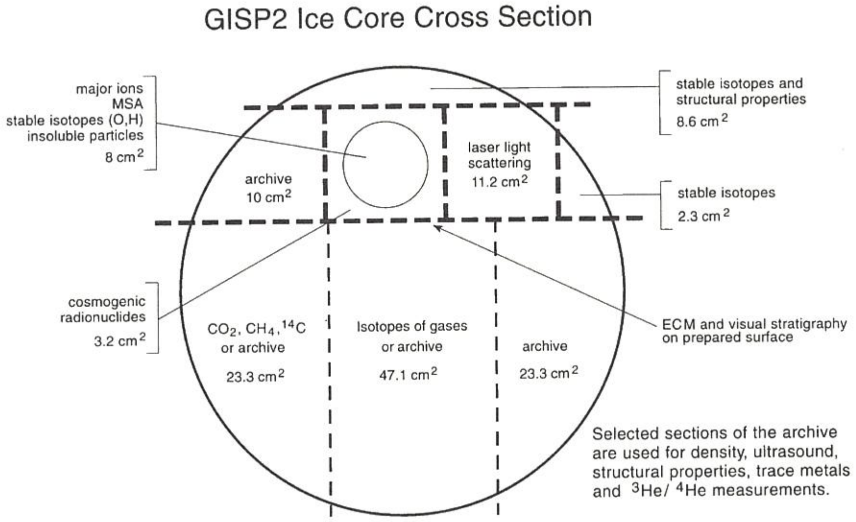


Figure 4 (above right)*, shows the interior of the drill dome and a piece of newly drilled core. Figure 5* (center right)*, Walt Hancock, (Univ. Nebraska-Lincoln) examining the instrument package for the drill. (Photos: Mark Twickler, UNH) Figure 6* (right) *shows (from left to right) Tony Gow (CRREL), Paul Mayewski (UNH) and Mark Wumkes (PICO) examining the first piece of rock core retrieved. (Photo: Suzanne O'Brien, UNH) Figure 7* (far right)*, shows the entire length of the 1.55 meter rock core. (Photo: Dave Giles, PICO)*

Core Processing Line

Several meters below the surface of the snow is a 50 meter long, 3 to 4 meter wide trench that connects the drill dome to a large room where core is stored before processing, a main processing trench known as the core processing line (CPL), and another large storage room where processed core and samples are kept before shipment back to the US. The CPL system and protocol were developed by the Science Management Office of the University of New Hampshire. The main CPL trench is 30 meters long by 4 meters wide with 6 alcoves off the side (Figure 8). The temperature in the CPL ranges from -35° C in the early part of the field season to -20° C near the end. Up to 50 meters/day were processed through the CPL by an average staff of twelve to fifteen scientists.

Processing of core was performed as soon as practicable after cores were brought to the surface. The only exception was with ice from the brittle zone, located between 700 and 1300 meters. This ice contained highly pressurized bubbles which required several months to depressurize (relax) before it could be processed.



Selected sections of the archive are used for density, ultrasound, structural properties, trace metals and $^3He/^4He$ measurements.

Full Core Cross Section Area = 137 cm^2 Diameter = 13.2 cm

Heavy dashed lines indicate saw cuts made on each piece of core.
Light dashed lines indicate saw cuts made only at depths selected for sample.
Labels indicate the area of the core used for each of the primary GISP2 analyses.

Figure 9

Certain studies of a time-priority nature were made on freshly drilled core. These included measurements of density, ultrasonic velocity and pressurized bubble dimensions. These properties of ice all change with time after core recovery, thus had to be measured at regular intervals to document the relaxation behavior of ice recovering from moderate to high confining pressures. Such studies are important to the understanding of: (1) the mechanical properties of deeply buried ice undergoing relaxation and (2) the mechanisms by which gas originally dissolved under pressure in the ice exsolves with release of the overburden pressure. This elimination of bubbles is attributed to diffusion of gas molecules into the ice to form a gas hydrate (clathrate) (Miller, 1971; Gow and Williamson, 1976). In addition to these time-sensitive studies, samples for helium isotope studies were taken immediately upon arrival of the newly drilled core at the surface.

Samples obtained from the deep core were divided on the basis of volume and analytical requirements (Figure 9). Sample frequency varied from: one sample per millimeter (for electrical conductivity and laser light scattering); to continuous sampling at biyearly intervals (plus selected sections of ten samples/year) through the Holocene and multi-annual to multi-decadal intervals in the pre-Holocene (for chemical species, stable isotopes and particles); to discontinuous sampling at several meter intervals for properties such as gases.

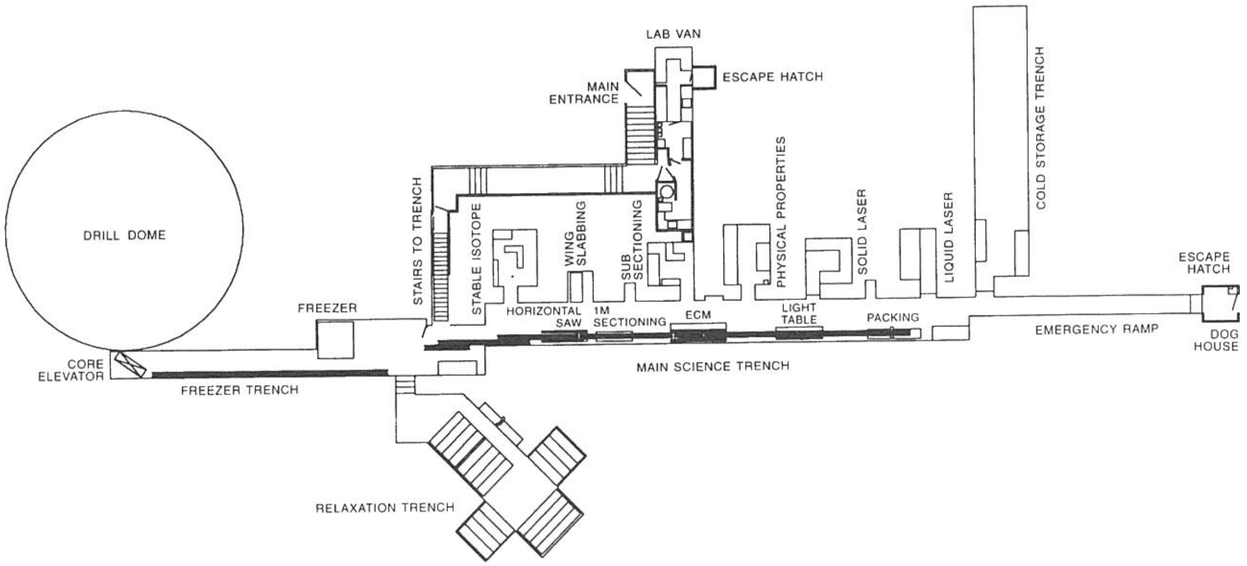


Figure 8. Core processing line layout

Data Management

A data manager on site each season collected all data regarding core recovery, handling, use, and storage. Data management in the field and throughout the interpretative phase of GISP2 has been the responsibility of the SMO. Eighty percent of the sampling and some analyses were performed directly on site.

Sampling from common sections of the core (e.g., shaded section, Figure 9) for several parameters (calcium, magnesium, potassium, ammonium, sodium, chloride, nitrate and sulfate), methanesulfonic acid (MSA), oxygen isotopes, deuterium, deuterium excess, insoluble particles, ^{10}Be, ^{36}Cl and ^{26}Al) assures that detailed multi-parameter time-series can be developed.

Between 20-67% of the core has been maintained as an archive for future investigations (Figure 9). This portion of the core is stored in the National Ice Core Laboratory (operated by the United States Geological Survey, Denver, Colorado).

Communication and cooperation between GISP2 investigators is facilitated by a file server located and maintained at the SMO which holds all data sets recovered during the program. All information will eventually reside at the World Data Center for Glaciology (NOAA, Boulder, Colorado).

A Summary of GISP2 Results

Although deep drilling has only recently been completed, several important scientific observations have already been reported from GISP2. Summaries of these observations follow.

Surface and bottom topography of a 180 km by 180 km grid that includes the GISP2 and GRIP sites was determined by airborne ice-radar soundings (Hodge et al., 1990). Calculated surface topography is accurate to +/- 6m and ice thickness and bottom topography to +/- 50 m. This survey provided information necessary for choosing the Summit core sites.

Surface maps of accumulation rate, stable isotopes and chemistry in the region of the core site were developed from a 150 km by 150 km survey grid sampled in 1987. This survey established the basic pattern of accumulation for the region for the period 1959-86 (Bolzan and Strobel, in press) as well as the chemical composition and spatial distribution of the snow in the region and chemical species input timing, (Mayewski et al., 1990a). Chemical species input timing and loading data provided by this survey has been used to investigate bipolar relationships (Whitlow et al., 1992). Measurements of current surface snow accumulation at several sites within the vicinity of GISP2 (Gow, pers. comm.; Dibb, pers. comm.) indicate an average annual accumulation of 70-75 cm of snow.

Six automatic weather stations (AWS) have been installed in the Summit region by the University of Wisconsin-Madison (UW-M). The earliest was placed in May 1987 and the most recent in August 1991. Each AWS is equipped to monitor a variety of meteorological parameters (e.g., temperature, barometric pressure, wind speed, wind direction, global short wave incoming radiation, humidity, snow depth) and relay output to the ARGOS system. AWS data are supplied to GISP2 researchers for their use in surface, near-surface and atmospheric experiments. In addition, UW-M has also supplied weather forecasts for the GISP2 camp.

Snowpit studies have been maintained on a regular basis throughout all field seasons. These studies have documented the formation of hoar layers (near surface mass loss and grain growth features produced by summertime solar heating) which serve as seasonal markers in the ice core (Alley et., 1990) and have provided a basis for correlating the formation of these features with changes in Special Sensor Microwave/Imager (SSMI) brightness temperature data (Shuman et al., in press).

An increasing range of atmospheric and surface- and near-surface snow sampling campaigns have been undertaken since 1989 in order to examine the transfer of chemical atmospheric signals into the firn near Summit. The bulk of these efforts have taken place at the remote, solar powered, clean sampling site (ATM) 29 km southwest of the GISP2 drill camp. Early emphasis was placed on the relationships between the concentrations of aerosol-associated species in surface snow and surface-level air (Dibb, 1990). These investigations continue, with increasing integration of meteorological information (local boundary layer dynamics and synoptic data) to establish the relationship between air sampled at the surface and that aloft at snow formation elevation (e.g., Dibb et al., 1992). Limited results are so far available for reactive gaseous species (e.g., HCl, HNO_3, H_2O_2), (Silvente, 1992), but the 1993 season has yielded continuous records of H_2O_2 concentrations and high resolution, short-duration (3-hour intervals for several 3 day periods) snapshots of the concentrations of gaseous acids in surface-level air. The importance of ice-fog and dry deposition in the delivery of atmospheric constituents to the snow surface has been suggested by pilot studies (e.g., Borys et al., 1992). Quantification of fluxes of soluble ionic species attributable to these processes has been one objective of 1993 sampling.

Several studies are attempting to relate modern instrumental records to the ice core record. For example, Mayewski et al. (1990b) found a reasonable similarity between emission records of anthropogenically derived sulfate and nitrate versus signals for these species in Greenland ice cores including GISP2. In addition, correlation's between yearly winter temperatures in Jacobshavn, Greenland and deuterium excess may provide useful information related to atmospheric circulation (e.g., Figure 10).

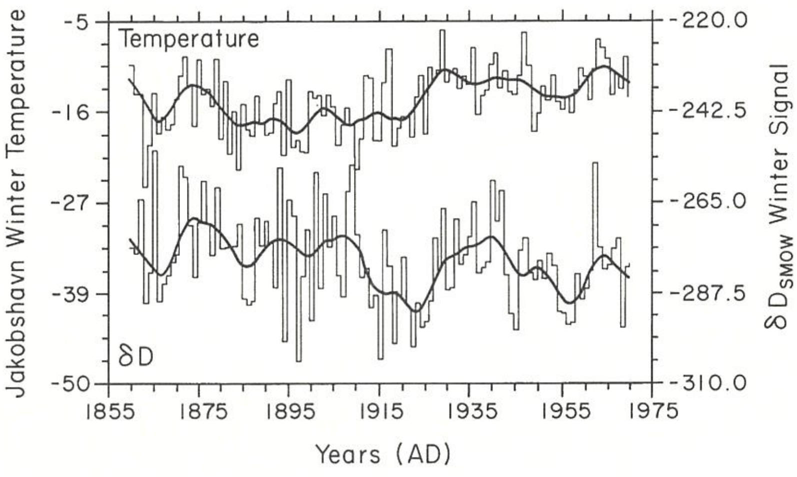


Figure 10. Comparison of yearly winter temperatures from Jacobshavn, Greenland (upper curve) with deuterium excess winter signal from the GISP2 core (Barlow and White, unpub.). Smooth lines are smoothed curves with 10% weighting (original sampling 10 per year).

Several new and/or modified ice core measurement techniques for ^{14}C dating of ice (Wilson and Donahue, 1989, 1990; 1992), CO_2 in occluded air (Wahlen et al., 1991); electrical conductivity (Taylor et al., 1992) and solid ice laser light scattering (Ram and Illing, in press) were developed for GISP2.

Depth/age relationships for the GISP2 core have been developed from a variety of core parameters including: annual layer counting of visual stratigraphy, electrical conductivity, laser light scattering of dust (Figure 11), stable isotopes, major anions and cations, insoluble particles, ^{210}Pb, total beta activity and ^{14}C from occluded CO_2 (e.g.. Wilson and Donahue, 1990, Dibb, 1992; Taylor et al., 1992; Alley et al., 1993; Meese et al., in press) plus ice dynamics modeling (Schøtt et al., 1992). Current estimated age error is 2% for 0-11,640 years ago, 5% for 11,640-17,380 years ago and 10% for 17,380-40,500 years ago (Alley et al., 1993). Current work plus intercalibration of the GISP2 and GRIP depth/age scales is expected to reduce these error estimates substantially (Hammer and Meese, 1993). Annual layer counting (based on visual stratigraphy, electrical conductivity and laser light scattering) appears to provide a viable dating tool to depths of at least 2600m (~65,000 years ago) as suggested by observations during the 1993 field season (A.J. Gow and K. C. Taylor, pers. comm.).

Where the time scale cannot be derived from core data, models can be used to estimate the depth-age relationship (Schøtt et al, 1992). Deviations between model time scales and the observed time scales can reflect transient ice flow patterns which also indicate climate change.

Thin section studies of GISP2 ice have revealed a structurally stratified ice sheet entailing major changes in the dimensions and orientations of the crystals comprising the ice (Gow, pers. comm.). Particularly significant is the attainment, by 1600 meters, of fine-grained ice with a vertical c-axis fabric resulting from horizontal stress. This condition persists to about 2990 meters before giving way entirely to very coarse-grained ice that exhibits a weaker multiple fabric in place of the single pole vertical c-axis fabric. The transformation is attributed to annealing at temperatures warmer than about -14°C. These changes in the polycrystalline character of the GISP2 ice closely mimic those observed in the Antarctic ice sheet at Byrd Station (Gow and Williamson, 1976). Ultrasonic measurements of the vertical and horizontal p-wave velocities, conducted on samples taken at 10 meter intervals along the entire length of the GISP2 core, fully confirm the thin section crystal structure observations.

The interpretation of the paleoclimate record from the GISP2 ice core will be further enhanced by ice dynamics analysis and associated geophysical data. Computer models incorporated into formal inverse analyses allow ice core and geophysical data to be interpreted in terms of climate. Ice motion and strain has been surveyed between GRIP and GISP2 (Technische Universitat Braunschweig) and the network is currently being extended 30 km downstream from GISP2 (Waddington, pers. comm.) so that the GISP2 site can be embedded in the central region of data-verified models, rather than at the boundary.

Examination of a 217 meter temperature profile developed from a site at the GISP2 camp reveals a recent warming in near-surface firn which is within the range of natural variability, providing no definitive evidence of anthropogenically-induced greenhouse gas warming (Alley and Koci, 1990). Independent calibrations of the oxygen isotope-temperature relationship have been developed through the analysis of borehole temperature, allowing conversion of isotope-derived surface-temperature histories to temperature-depth profiles (Cuffey et al., 1992). In addition, temperature models (e.g. MacAyeal et al, 1992) and borehole temperature data provide a paleotemperature history to compare to the stable isotope temperature proxy record. Finite element models (Waddington, pers. comm.) and spectral models (Bolzan, pers. comm.) are now under development and modification in order to further investigate paleotemperature and depth/age relationships.

The temperature distribution in the hole was also measured at high resolution (mK level) to 1510 meters in 1992 (G. Clow, pers. comm.) and at the completion of drilling in 1993 borehole temperature, inclination and hole diameter were measured (W. Hancock and M. Wumkes, pers. comm.; Gundestrup and Hansen, pers. comm.).

Anthropogenic influences on climate and atmospheric chemistry have been investigated in the GISP2 record. Previously identified increases in sulfate and nitrate seen in south Greenland ice cores and attributed to anthropogenic activity (Neftel et al., 1985; Mayewski et al., 1986) have been identified in the GISP2 record and contrasted to the pre-anthropogenic atmosphere (Mayewski et al., 1990b). Increases in excess chloride associated with anthropogenically increased sulfate and nitrate have also been suggested from the GISP2 core (Mayewski et al., 1993a). Additional confirmation of the role that anthropogenic sulfate may have on the depression of North Atlantic temperatures (Wigley, 1989,1990; Charlson et al., 1990) has also been provided by a comparison of GISP2, south Greenland and Yukon Territory ice cores with temperature change records (Mayewski et al., 1993b).

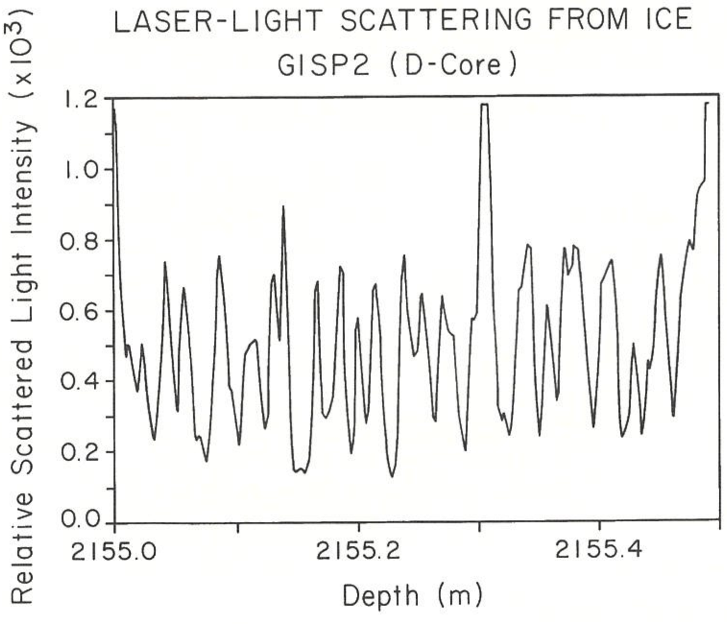


Figure 11. Measurement of 90^{o} light scattering from a section of glacial ice from the GISP2 core (Ram et al., unpub.).

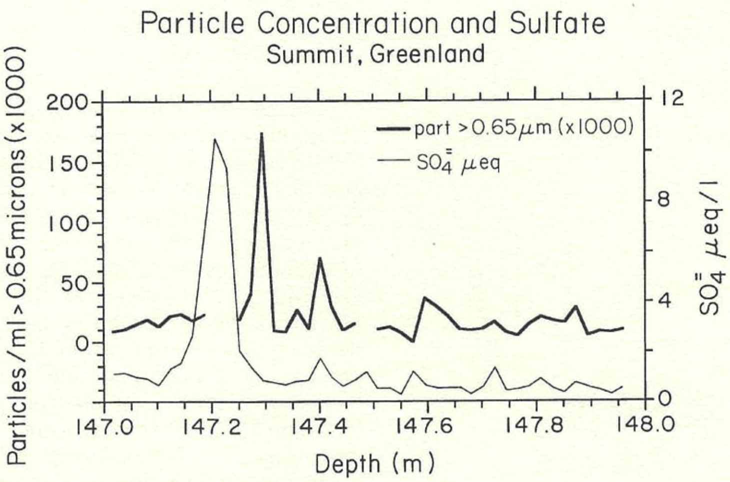


Figure 12. Peaks in the concentrations of sulfate aerosols and insoluble particles Figure 12. Peaks in the concentrations of sulfate aerosols and insoluble particles (modified from Fiacco et al., in press) (due to the presence of volcanic glass) from the AD 1479 eruption of Mt. St. Helens. Sulfate levels recorded in the ice core are used to postulate how the atmospheric loading of climate-forcing aerosols has varied in the past. Many of these eruptions are of greater magnitude than the 1991 eruption of Pinatubo (Philippines). The identification of volcanic glass in the ice core provides valuable information on former circulation patterns and verifies the location of the source volcano.

Initial measurements of CO_2 in air bubbles of the GISP2 core (Wahlen et al., 1991) indicate that between 1530-1810 AD atmospheric CO_2 levels remained constant at 280 +/- 5 ppmv . After this period concentrations rise rather abruptly and smoothly connect to the atmospheric observations at Mauna Loa.

Volcanic event signatures have been identified in the GISP2 core by the measurement of electrical conductivity, chemistry and insoluble particles providing evidence of local eruptions (e.g.., the 1362 AD. Oraefajokull (Iceland) eruption, Palais et al., 1991), intrahemispheric eruptions (e.g., the 1479 AD. Mt. St. Helen's (Washington) eruption, Figure 12, Fiacco et al., in press) and interhemispherically distributed eruptions (e.g.., the 1259 AD. eruption possibly produced by El Chichon (Mexico), Palais et al., 1992). The GISP2 volcanic record for the last 300 years has also been contrasted to volcanic records developed from cores in south Greenland and the Yukon Territory in order to investigate transport of volcanic aerosols (Mayewski et al., 1993b).

Several selected climatic events have already been investigated in detail. As an example, the Little Ice Age (LIA) and Medieval Warm Period (MWP) environments (the most recent analogs for conditions cooler and warmer, respectively, than the present century) can be characterized by interpreting the multi-parameter GISP2 series. The LIA appears to span the period AD 1350 or 1450 to ~AD 1900 depending upon measurement type (since each may respond to climate change differently). GISP2 temperature modeled from oxygen isotopes reveals a relatively subdued temperature effect at this site for the LIA period. Accumulation rate is generally lower during the LIA than the MWP. Carbon dioxide values may dip slightly during the LIA. Non seasalt sulfate (reflecting primarily volcanic source sulfur) as plotted here (50 year smoothing) does not appear to be a major forcing agent on multi-decadal scale climate. Dust (via particles, calcium, magnesium and potassium) and marine (via sodium, chloride and MSA) sources and/or transport to the site increased during the LIA. Nitrate sources (e.g., lightning, soil exhalation) decreased during the LIA. Finally ammonium, primarily reflecting biomass destruction, has peaks that parallel the onset and end of the LIA. Biannual and finer sampling of the major ions in the GISP2 record coupled with newly developed signal analysis techniques have provided insight into the state of the environment (e.g., changes in

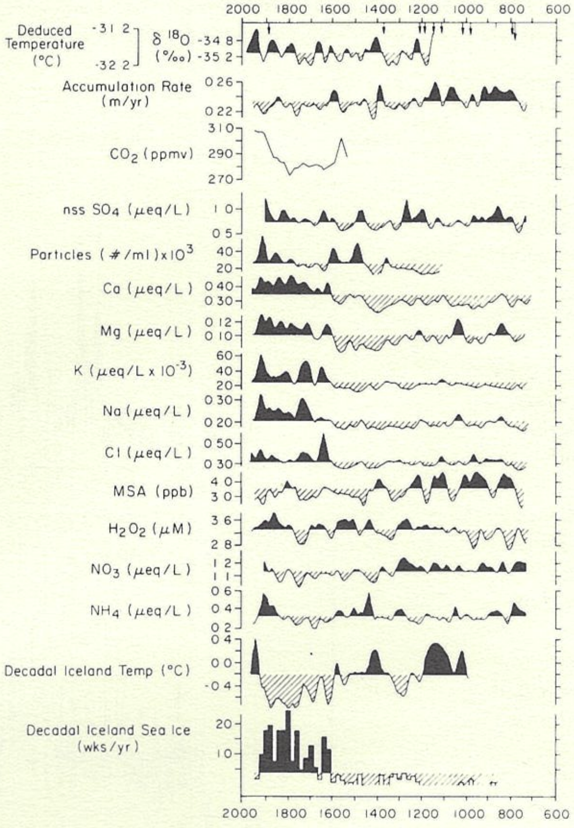


Figure 13. Examples of some of the properties measured using the GISP2 core (50 year smoothing of biannual or finer scale resolution sampling). Oxygen isotopes (Grootes et al., unpub.), accumulation rate (modified from Meese et al., in press and Alley et al., unpub.)), CO_2 (modified from Wahlen et al., 1991); ions (modified from Mayewski et al., in press b), particles (Zielinski et al., unpub.) and Icelandic temperatures (modified from Bergthorsson, 1969).

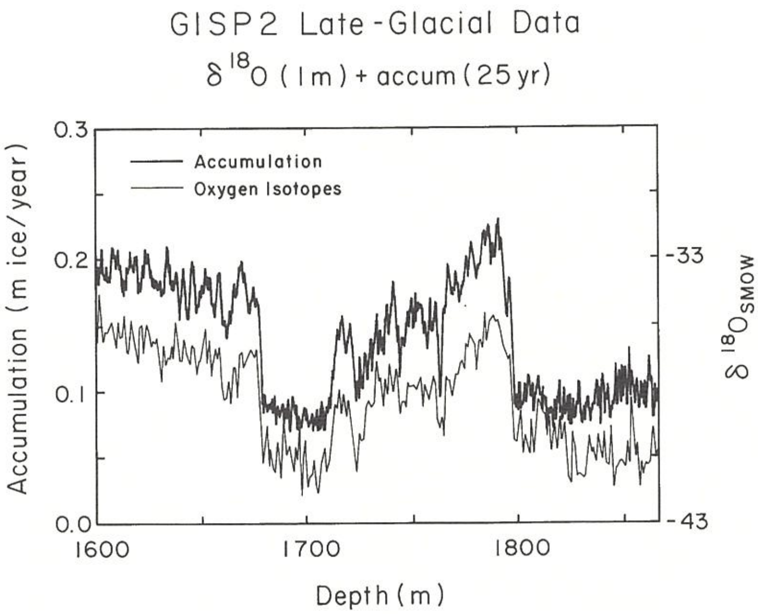


Figure 14. Annual accumulation rate (modified from Alley et al., 1993) and one meter average values for oxygen isotopes (Grootes et al., unpub.) plotted against depth. The cold periods (the Oldest Dryas below 1800 m, the Younger Dryas near 1700m and certain events during the Bolling/Allerod near 1750m) have low accumulation and the warm periods (most of the Bolling/Allerod and the Preboreal above 1670m) some of the changes such as the terminations of the Oldest Dryas and the Younger Dryas are very large and abrupt, indicating important reorganizations of the ocean-atmosphere system.

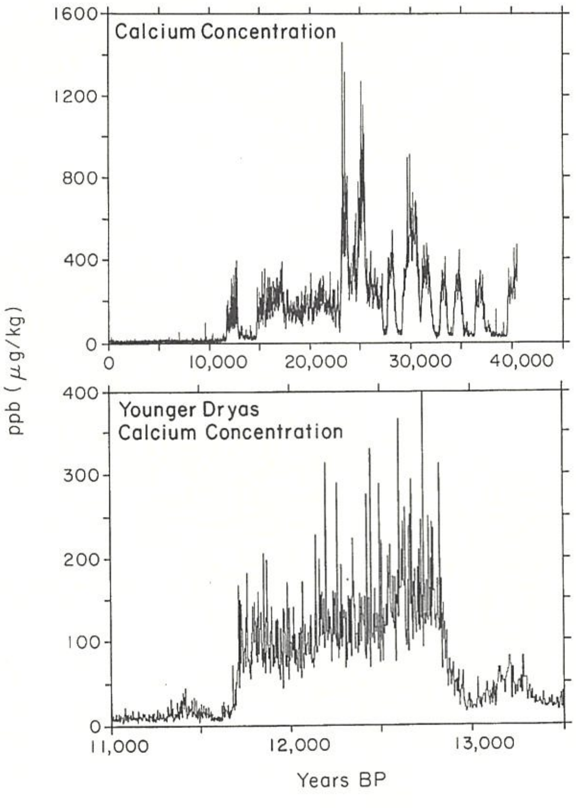


Figure 15. The GISP2 calcium (ppb) record provides a detailed and continuous view of continental source dust levels in the atmosphere. Sample length is ~ 2 years for 0-12,000 years, ~3.5 years for the Younger Dryas and 2-13 years for the remainder of the record. Stadial (high calcium) and interstadial (low calcium) events stand out prominently in the record. A blow-up covering the period of the Younger Dryas demonstrates the rapid onset and termination of this major event during the deglaciation. Dramatic decadal scale variability during this event is believed to be related to marked expansions and contractions of the polar atmospheric cell. By contrast with the glacial and deglacial portions of the record the Holocene appears to be an extremely quiescent period. After Mayewski et al., in press).

nitrogen and sulfur cycling, marine and terrestrial source influences) during the LIA and MWP (Mayewski et al., 1993a).

One of the most dramatic climate events observed in marine and ice core records is the Younger Dryas (YD), a return to near glacial conditions that punctuated the last glaciation (Figure 14). Multiparameter annual layer counting of the GISP2 core has provided a high resolution view of this event (Alley et al., 1993). The end of the YD is characterized by a doubling of accumulation at GISP2 in perhaps one to three years and the onset of this event is also characterized by a large and abrupt change in accumulation rate (Alley et al., 1993). Further, dramatic and rapid changes (10-20 years) in the soluble composition of the atmosphere over central Greenland (Figure 15), attributed to changes in the size of the polar atmospheric cell and in source regions (e.g., growth and decay of continental biogenic and terrestrial source regions) mark the Younger Dryas onset and termination (Mayewski et al., 1993c). Massive and frequent, decadal or less scale changes in atmospheric composition also exist throughout the YD (Mayewski et al., in 1993c). These high resolution views of environmental change coincident with the YD provide new fuel for investigating the cause of this major and abrupt reversal in climate.

A comparison of the Holocene and glacial portions of the GISP2 record indicates that sulfate concentrations were low during the Holocene and markedly higher during cold periods reflecting increased input of terrigenous dust to the glacial atmosphere (Figures 15 and 16). In contrast marine biogenic source sulfur (in the form of MSA) is higher in concentration during warm periods and lower during glacial conditions (Figure 16). This suggests a reduced contribution of oceanic sulfur to the Arctic atmosphere during glacial climates. This trend is dramatically different from that observed in the Vostok ice core in East Antarctica where high latitude oceanic sulfur emissions apparently increased during glacial periods.

Fluctuations in the electrical conductivity of GISP2 ice on the scale of <5-20 years have been used to reveal rapid changes in the dust content of the atmosphere during the last glacial (Figure 17) which have been only been hinted at in previous records (Taylor et al., 1992). These rapid changes appear to reflect a type of "flickering" between preferred states of the atmosphere (Taylor et al., 1993) which provides a new view of climate change.

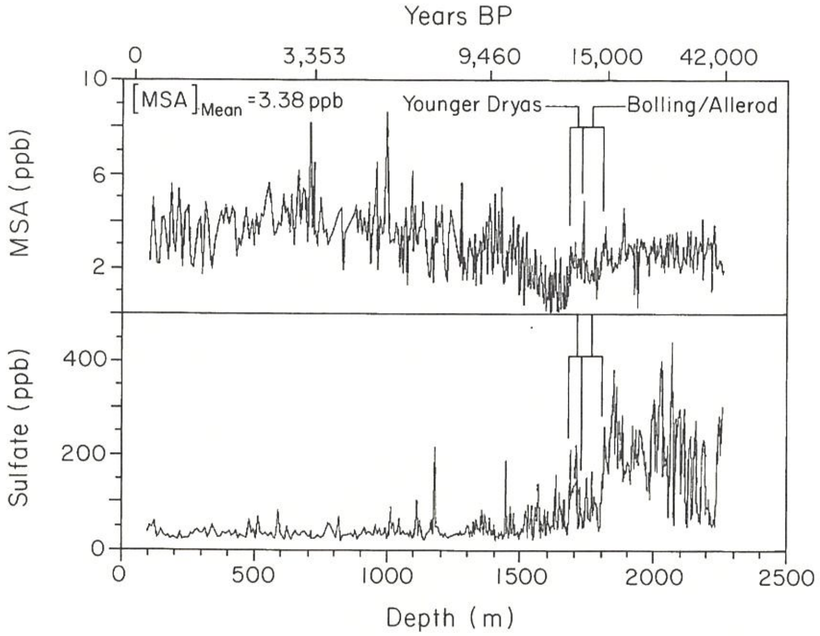


Figure 16. Depth profiles of MSA (Saltzman and Whung, unpub.,) and sulfate (Mayewski et al., unpub.) in the GISP2 ice core.

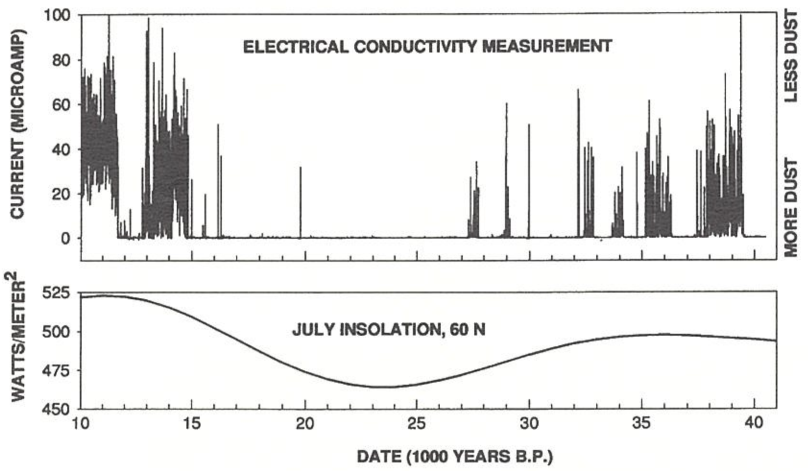


Figure 17. The electrical conductivity measurement on the GISP2 cores shows periods of high and low dust concentrations. Low current values indicate times when the alkaline dust has neutralized the acids in the core. High current values indicate times that are less dusty. Notice that the absence of dusty times, associated with cold conditions, that occurs during the period of decreased summer insolation between 20 and 25 KYR BP.

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Two committees provide oversight of GISP2: the Executive Committee; Pieter Grootes, Paul Mayewski (Chairman), Martin Wahlen, and the Advisory Committee; Charles Bentley, Wallace Broecker (Chairman), George Denton, John Imbrie.

Concluding Remarks

With the completion of the two ice coring programs (GISP2 and GRIP) at Summit, Greenland, a new era in paleoenvironmental investigation has been opened. These records are of extreme significance to our understanding of environmental change because they provide the highest resolution, continuous, multi-parameter view produced thus far. As importantly, the two records can be used to validate each other, the only such experiment of this magnitude in ice core research.

In addition to providing a remarkable paleoenvironmental record, the GISP2 ice core also provides our first view of the basal conditions (clear ice into silty ice into bedrock) beneath the central (spreading) region of a polar ice sheet. The Summit drilling programs, future deep drilling in polar glaciers and our understanding of glacial dynamics (e.g., basal ice processes, flow modeling) will benefit greatly from the examination of the GISP2 and GRIP basal records.

Now that the longest ice core record from the northern hemisphere is a reality, it is time to develop new ice core records for the southern hemisphere. Future deep drilling in the Antarctic promises new approaches to our understanding of environmental change. For example, the recovery of ice cores from Antarctic sites with accumulation rates similar to those at GISP2 (e.g., interior West Antarctica) will provide equivalent (continuous, high resolution and multi-parameter) and comparable records from which bipolar aspects of climate change (response and forcing) can be investigated. In addition, the recovery of ice cores from Antarctic sites with lower accumulation rates and thicker ice than that at GISP2 (e.g., interior East Antarctica) will eventually provide the longest ice core records (spanning several glacial/interglacial cycles) available on Earth.

Within the coming months and years ice core records may provide the perspective needed to dramatically advance our understanding of climate change (response and forcing) and perhaps the perspective needed to understand the consequences of our involvement in this dynamic environment. In addition they may also provide the framework needed to incorporate and further interpret the wealth of other proxy environmental records that are already available (e.g., tree rings, marine and lake sediments) leading toward even better regional paleoenvironmental reconstructions.

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Camp logistics support was provided by the Polar Ice Coring Office of the University of Alaska-Fairbanks. The drill was developed and operated by PICO and the instrumentation package for the drill was developed by the University of Nebraska-Lincoln. The core processing line and sampling and data protocols were developed and are maintained by the Science Management Office of the University of New Hampshire.

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GISP2 Programs

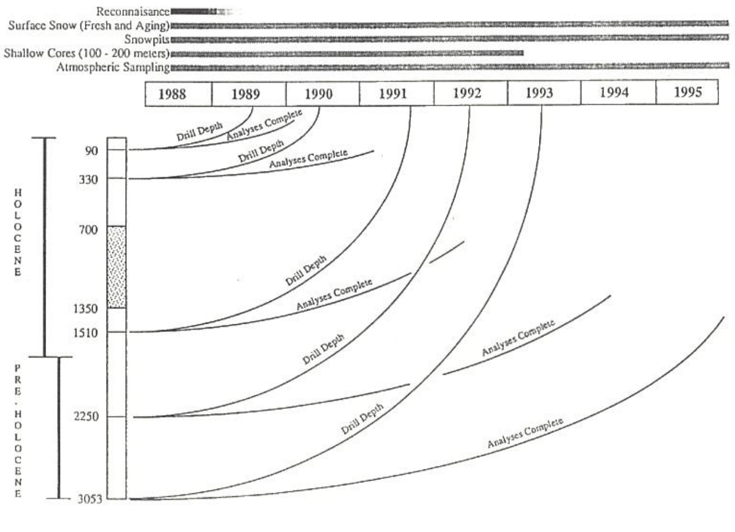
Eighteen programs and a total of forty-two types of measurements comprise the GISP2 deep drilling effort and a total of nine provide direct information necessary to the interpretation of this record (e.g., atmospheric sampling, automatic weather stations, surface glaciology, modeling). A complete list of all measurements and investigators related to GISP2 follows:

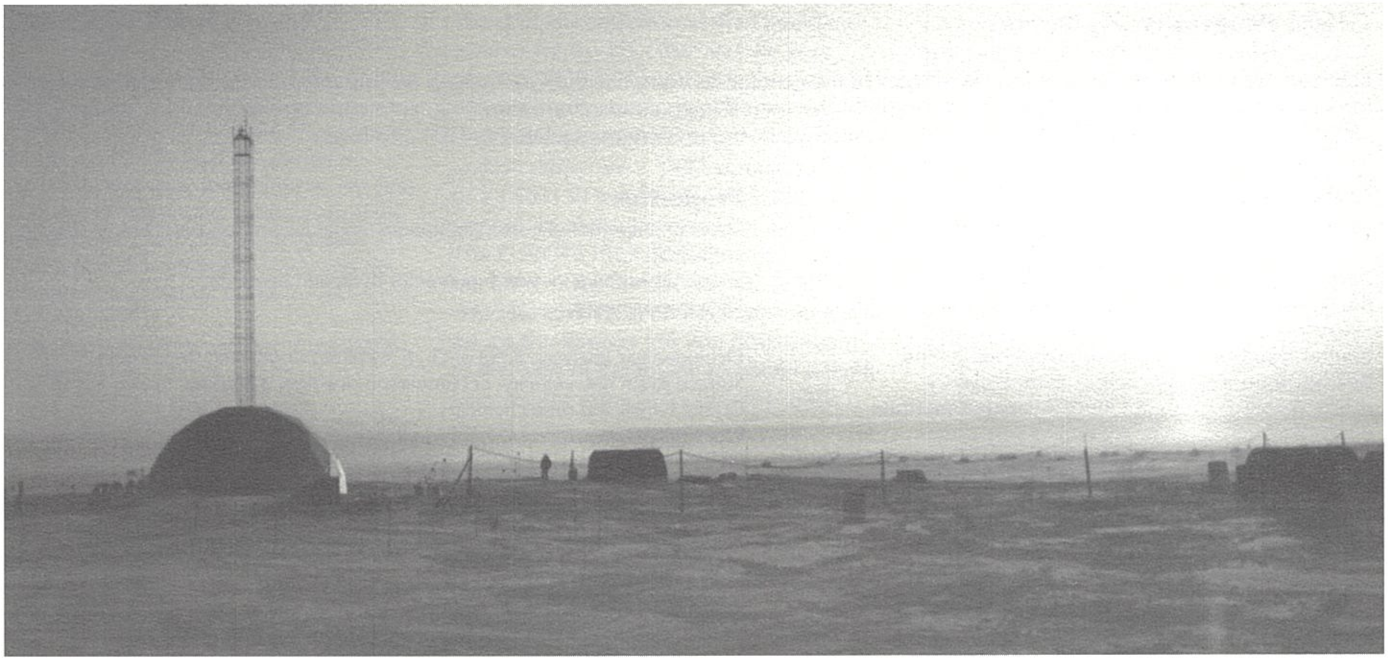
Investigator	Institution	Properties
Alley, Richard*	Penn State Univ.	Physical properties of core. Continuous visual logging of core, density, texture, and fabric.
Bales, Roger	Univ. of Arizona	Snow-Atmosphere transfer function for hydrogen peroxide
Barry, Roger Armstrong, Richard	Univ. of Colorado	Data management.
Bender, Michael	Univ. of Rhode Island	Occluded gas analyses. $\delta^{18}O$ of O_2, $\delta^{15}N$ of N_2, O_2/Ar ratio, N_2/Ar ratio.
Bolzan, John	Ohio State Univ.	Surface strain net, velocity, accumulation, ice flow modeling.
Borys, Randy	Desert Research Institute	Crystal habits and rime chemistry.
Boyle, Ed*	MIT	Trace metal Chemistry.
Craig, Harmon*	Scripps Inst. of Oceanography	Helium isotopes
Davidson, Cliff	Carnegie Mellon Univ.	Major ions and trace metals of aerosols and snow.
Dibb, Jack	Univ. of New Hampshire	Radionuclides in aerosol and snow.
Gow, Tony* Meese, Debra*	Cold Regions Research and Engineering Laboratory	Physical properties of core. Annual layering, core relaxation mechanisms, and precision density measurements.
Grootes, Pieter* Stuiver, Minze*	Univ. of Washington	$\delta^{18}O$ record of ice.
Hodge, Steve	U.S. Geological Survey, St. Olaf College.	Airborne ice radar determination of the Surface and Bed Topography.
Mayewski, Paul*	Univ. of New Hampshire	GISP2 Science Management Office.
Mayewski, Paul*	Univ. of New Hampshire	Major anions and cations, total acidity, and ionic balance.
Mosher, Byard	Univ. of New Hampshire	INAA analysis of aerosols and snow.
Nishiizumi, Kunihiko* Arnold, James* Finkel, Robert*	Univ. of California - Berkeley, Lawrence Livermore Laboratory	Cosmogenic Radionuclides, ^{10}Be, ^{26}Al, ^{36}Cl
Ram, Michael*	SUNY Buffalo	Continuous particulate concentrations.
Saltzman, Eric*	Univ. of Miami	Methanesulfonic acid (MSA) and Iodine (Iodide and Iodate) in ice.
Stearns, Charles	Univ. of Wisconsin	Automatic Weather Stations.
Taylor, Ken*	Desert Research Institute	Continuous electroconductivity of core.
Waddington, Edwin	Univ. of Washington	Temperature history inference from bore-hole temperature measurements.
Wahlen, Martin* Broecker, Wallace*	Scripps Inst. of Oceanography, Lamont-Doherty Earth Observatory	CO_2/Air ratios, $\delta^{13}CO_2$ in occluded gas, total gas content, CH_4 and N_2O concentrations, bubble volume.
White, James*	Univ. of Colorado	δD ($^2H/^1H$ ratio) of ice.
Wilson, Alex* Donahue, D. J.*	Univ. of Arizona	^{14}C dating of core from occluded CO_2 .
Wilson, Alex*	Univ. of Arizona	Concentration and $\delta^{13}C$ of CO_2 in occluded gas.
Zielinski, Greg*	Univ. of New Hampshire	Insoluble particles. Mass concentration, size distribution, chemical composition, and morphology.

** GISP2 deep drilling investigator*

Summary of GISP2 Science and Drilling Activities to Date

This figure shows the progress of drilling and analysis of samples for GISP2. The core, and depths reached each year are shown on the left. The speckled zone between 700 and 1350 meters represents the location of the brittle ice. 3053.44 meters of ice and 1.55 meters of rock were ultimately recovered.





GISP2 Midnight, Summer Solstice
Photo: Jen Putscher

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