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Record Drilling Depth Struck in Greenland

Paul Andrew Mayewski
University of Maine, paul.mayewski@maine.edu

M. S. Twickler

J. E. Dibb

M. Wumkes

J. Klinck

See next page for additional authors

Authors
Paul Andrew Mayewski, M. S. Twickler, J. E. Dibb, M. Wumkes, J. Klinck, J. S. Putscher, K. C. Taylor, D. A. Meese, E. D. Waddington, R. B. Alley, P. M. Grootes, M. Ram, M. Wahlen, and A. T. Wilson

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P. A. Mayewski, M. Wumkes, J. Klinck, M. S. Twickler, J. S. Putscher, K. C. Taylor, A. J. Gow, E. D. Waddington, R. B. Alley, J. E. Gibb, P. M. Grootes, D. A. Meese, M. Ram, M. Whalen, and A. T. Wilson

On July 1, 1993, after 5 years of drilling, the Greenland Ice Sheet Project (GISP2) penetrated several meters of silty ice and reached bedrock at a depth of 3053.4 m. It then penetrated 1.5 m into the bedrock, producing the deepest ice core ever recovered (Figure 1).

In July 1992, a nearby European ice coring effort, the Greenland Ice Core Project (GRIP), reached an ice depth of 3028.8 m, providing more than 250,000 years of record. Comparisons between these ice core records have already demonstrated the remarkable reproducibility of the upper ~90% of the records unparalleled view of climatic and environmental change.

The completion of GISP2 and GRIP in Summit, Greenland, has heralded a new era in paleoenvironmental investigation. These ice core records not only provide the highest resolution, continuous, multi-parameter view yet produced but can be used to validate each other in the only experiment of this magnitude in ice core research.

Besides providing a remarkable paleoenvironmental record, the GISP2 ice core also gives a first view of the basal conditions—clear ice into silty ice into bedrock—beneath the central region of a polar ice sheet. The Summit drilling programs, future deep drilling in polar glaciers, and dynamical glaciology will benefit from the examination of the GISP2 and GRIP basal records.

The Program's History

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

GISP2 began in May 1989, and within weeks the project's site (Figure 2), on top of a bedrock plateau about 10 ice-thicknesses (28 km) west of GRIP, became the focus for several integrated science experiments. The camp was comprised of several surface structures including a prefab building that was situated on top of pilings and used as a meeting place, administration office, and cafeteria; a geodesic dome to house drilling activities (Figure 3); several temporary buildings; and tents for berthing. The camp was equipped to accommodate 55 people for up to 5 months per field season.

The Drill

The drill used to recover the GISP2 ice core allows the retrieval of an ice core 13.2 cm in diameter and up to 6 m in length in one unbroken piece with a volume nearly twice that of previous deep coring drills. The instrument package in the drill monitors sixteen different parameters including weight, pressure, temperature, inclination, azimuth, rotations per minute, and current. The deep coring drill was designed to work in a new borehole liquid, n-butyl acetate, which has minimal health and environmental risks.

Several meters below the drill dome was a trench that connected a large room where core was stored before processing to the main processing trench where GISP-2 scientists occupied several stations dedicated to analyzing the core (CPL, Figure 4). In another large storage room processed core and samples were kept before shipment to the United States. Eighty percent of the sampling and a variety of analyses were performed on site.

GISP2 ice core sampling (Figure 5) has provided a remarkably high-resolution record. Measurements range from one sample per millimeter for electrical conductivity and laser light scattering to continuous sampling at biyearly intervals through the Holocene and multi-annual to multi-decadal intervals in the pre-Holocene for chemical species, stable isotopes, and particles. Between 20–67% of the core has been maintained as an archive for future investigations.

GISP2 Results

Several important scientific observations have already been reported from GISP2.

Surface and bottom topography of a 180-km×180-km grid that includes the GISP2 and GRIP sites was determined by airborne ice-radar soundings. Surface maps of accumulation rate, stable isotopes, and chemistry in the region of the core site were developed from a 150-km×150-km survey grid. This survey established the pattern of accumulation for the region for 1959–1986 as well as the chemical composition, chemical species input timing, and distribution of the snow in the region. Measurements of current surface snow accumulation at several sites near GISP2 indicate an annual average of 70–75 cm.

Six automatic weather stations (AWS) monitor the Summit region. The earliest was placed in 1987 and the most recent in 1991. Each AWS can monitor a variety of meteorological parameters—for example, temperature, barometric pressure, wind speed, wind direction, global short wave incoming radiation, humidity, and snow depth.

Atmospheric and surface and near-surface snow sampling campaigns have been undertaken since 1989 to examine the transfer of chemical atmospheric signals into the

P. A. Mayewski, M. S. Twickler, and J. E. Dibb, Glacier Research Group, Institute for the Study of Earth, Ocean and Space, University of New Hampshire, Durham NH 03824-3525; M. Wumkes, Polar Ice Coring Office, University of Alaska at Fairbanks, Fairbanks, AK 99775-1710; J. Klinck, Polar Ice Coring Office, University of Alaska at Fairbanks, Fairbanks, AK 99775-1710; J. S. Putscher, GISP2 Science Management Office, Institute for the Study of Earth, Ocean and Space, Morse Hall, University of New Hampshire, Durham, NH 03824-3525; K. C. Taylor, Desert Research Institute, Reno, NV 89506-0220; A. J. Gow and D. A. Meese, Cold Regions Research and Engineering Laboratory, Hanover, NH 03755-1290; E. D. Waddington, University of Washington, Seattle, WA 98195; R. B. Alley, Earth System Science Center and Dept. of Geosciences, Pennsylvania State University, University Park, PA 16802; P. M. Grootes, Quaternary Isotope Laboratory, University of Washington, Seattle, WA 98195; M. Ram, Dept. of Physics, Univ. at Buffalo, Amherst, NY 14260; M. Wahlen, Scripps Institution of Oceanography, Geological Research Division, La Jolla, CA 92093-0220; A. T. Wilson, Geoscience Dept., University of Arizona, Tucson, AZ 85745

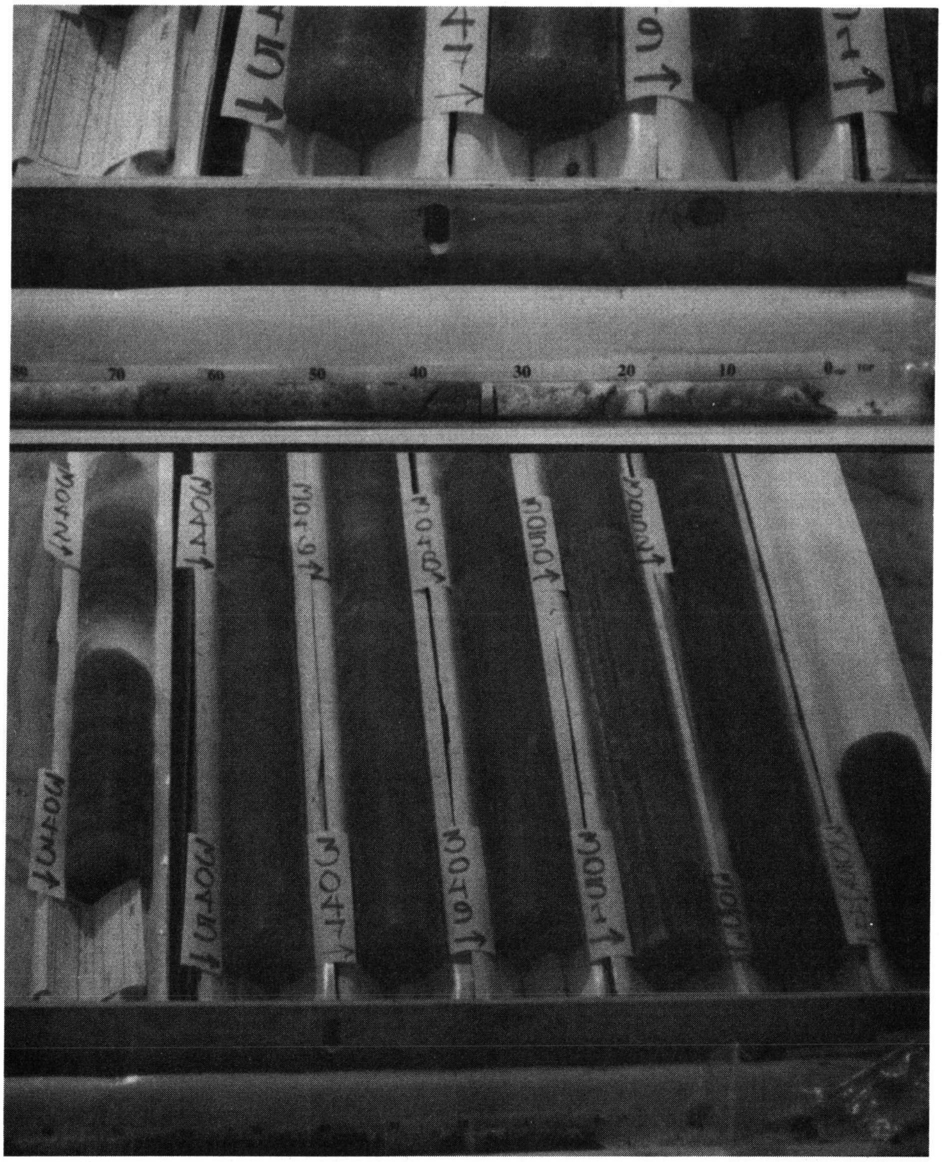

Fig. 1. (Below) At a depth of 3040.33 m, there is a sharp transition from clear to silty ice. This is followed by alternating bands of silty and clear ice and progressively siltier ice until contact with bedrock. Silty ice formed by regelation involving incorporation of basal debris at the ice rock interface 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 ~-9°C. Preliminary observation of the core in the field indicates that the upper 10–15 cm are a weathered "schist-like" rock that grades into a fresh "granite gneiss" below. (Above) The 0–70 cm section of the rock core. Courtesy of David Giles, University of Alaska, Fairbanks. Original color image appears in the back of this volume.

firn near Summit. Many of these efforts have taken place at the remote, solar powered, clean sampling site (ATM) 29 km southwest of the GISP2 drill camp. These investigations continue, with increasing integration of meteorological information, to establish the relationship between air sampled at the surface and that aloft at snow formation elevation. Limited results are available for reactive gaseous species, but the 1993 season has yielded continuous records of H_2O_2 concentrations and high-resolution, short-duration 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. Other studies document the formation of hoar layers—near surface mass loss and grain growth features produced by summertime solar heating—that serve as seasonal markers in the ice core. These features have been correlated with changes in Special Sensor Microwave/Imager (SSMI) brightness temperature data.

Several studies relate modern instrumental records to the ice core record. For example, in 1990, P. Mayewski and others found a similarity between emission records of anthropogenically derived sulfate and nitrate versus signals for these species in Greenland ice cores such as GISP2. Also, correlations between yearly winter temperatures in Jacobshavn, Greenland, and deuterium excess may provide information related to atmospheric circulation.

Several ice core measurement techniques for ^{14}C dating of ice, CO_2 in occluded air, electrical conductivity, and laser light scattering were developed for GISP2. Initial measurements of CO_2 in air bubbles of the GISP2 core indicate that between 1530–1810 AD, atmospheric CO_2 levels remained constant at 280+/− ppmv. After 1810 AD, concentrations rise abruptly and smoothly connect to the atmospheric observations at Mauna Loa.

Depth/Age Relationships

The major parameters used to develop depth/age relationships for the GISP2 core are annual layer counting of visual stratigraphy, electrical conductivity, and laser light scattering of dust. Other parameters used include stable isotopes, major chemical species and insoluble particles plus ^{210}Pb, total beta activity, ^{14}C from occluded CO_2, and ice dynamics modeling.

The 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, but ongoing work plus intercalibration of the GISP2 and GRIP depth/age scales is expected to reduce these error estimates and result in validated depth/age scales for the length of these cores. Annual layer counting based on visual stratigraphy, electrical conductivity, and laser light scattering provides a viable dating tool to depths of at least 2600 m (about 65,000 years ago) as suggested by observations during the 1993 field season.

Thin section studies of GISP2 ice reveal a structurally stratified ice sheet. The dimensions and orientations of the crystals comprising the ice vary. At a depth of 1600 m, fine-grained ice with a vertical c-axis fabric signals the effects of horizontal stress. This type of ice persists to about 2990 m before giving way to coarse-grained ice that exhibits a weaker multiple fabric in place of the single pole vertical c-axis fabric.

The transformation between ice types is attributed to annealing at temperatures warmer than about -14°C. These changes in the polycrystalline character of ice mimic those observed in the Antarctic ice sheet at Byrd Station. Ultrasonic measurements of the vertical and horizontal p-wave velocities, conducted on samples taken at 10-m intervals along the entire length of the GISP2 core, confirm these observations.

The interpretation of the paleoclimate record from the GISP2 ice core will be further enhanced by on-going ice dynamics analysis and associated geophysical investigations.

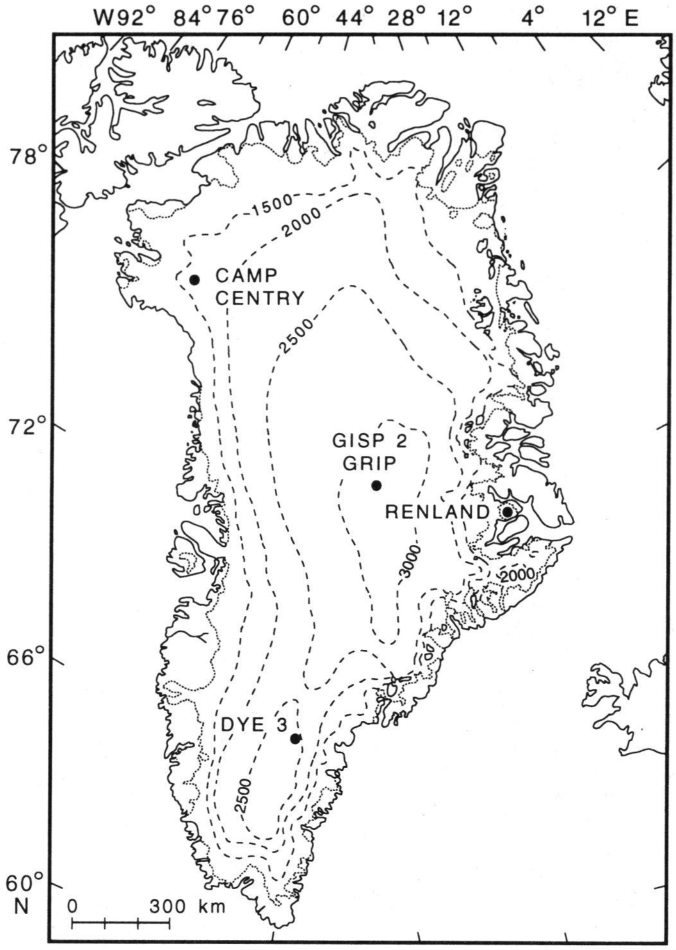

Fig. 2. Location map. GISP2 is located at 72.58° N, 38.48° W at an elevation of 3207 m. Mean annual temperature at GISP2 is -31°C and modern accumulation rate is 0.23 m H_2O equivalent per year.

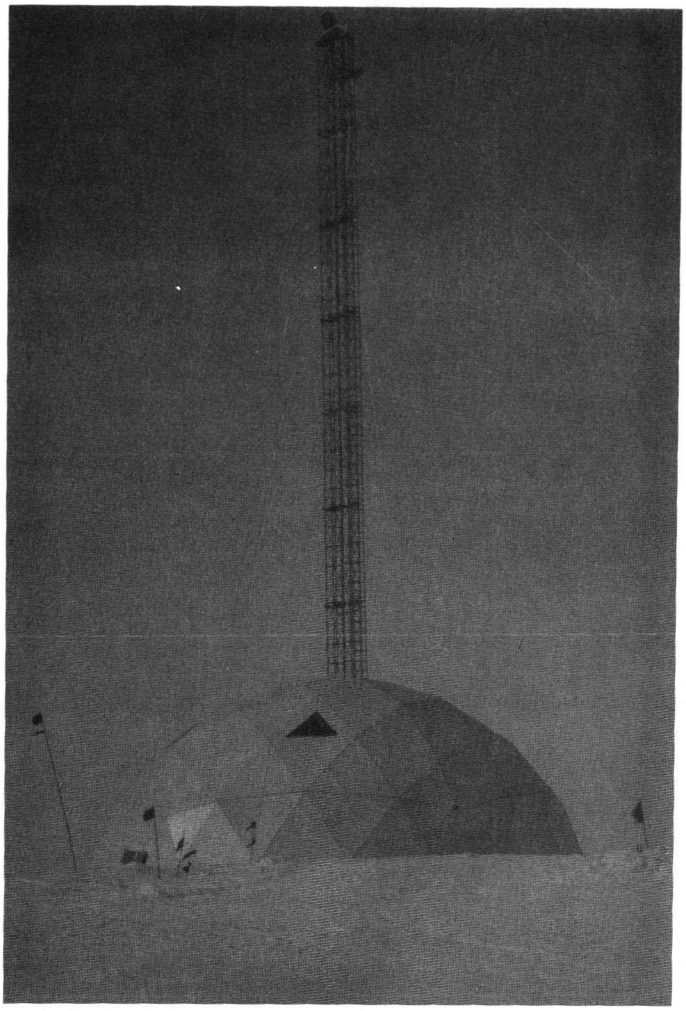

Fig. 3. A 52-foot geodesic dome housed the deep drill. Courtesy of Jen Putscher, University of New Hampshire. Original color image appears in the back of this volume.

Recent Temperature Trends

A 217-m temperature profile developed from a site near the GISP2 borehole reveals a recent warming in near-surface firn that is within the range of natural variability, providing no definitive evidence for or against anthropogenically induced greenhouse gas warming. Independent calibrations of the oxygen isotope-temperature relationship have been developed through analysis of borehole temperature, allowing conversion of isotope-derived surface-temperature histories to temperature-depth profiles.

Anthropogenic Influences on Climate and Atmospheric Chemistry

Previously identified increases in sulfate and nitrate seen in south Greenland ice cores attributed to anthropogenic activity have been identified in the GISP2 record and contrasted to the pre-anthropogenic atmosphere. Increases in excess chloride associated with anthropogenically increased sulfate and nitrate are also suggested from the GISP2 core. A comparison of GISP2, south Greenland, and Yukon Territory ice cores with temperature change records confirms the role that anthropogenic sulfate may have on the depression of North Atlantic temperatures via shielding of incoming radiation by sulfate aerosols.

Volcanic event signatures have been identified in the GISP2 core by measuring electrical conductivity, chemistry, and insoluble particles. These provide evidence of local eruptions such as the 1362 AD Oraefajokull, Iceland, eruption; intrahemispheric eruptions, for example, the 1479 AD Mt. St. Helen's, Wash., event; and interhemispherically distributed eruptions, such as the 1259 AD eruption possibly produced by El Chichon, Mexico.

Little Ice Age and Medieval Warm Period

Selected climatic events have been investigated using the GISP2 record. The Little Ice Age (LIA) and Medieval Warm Period (MWP) environments, which represent the most recent analogs for conditions cooler and warmer than the present century, can be characterized by interpreting the multi-parameter GISP2 series. Based on the GISP2 record, the LIA spans AD 1350 or 1450 to ~AD 1900. This depends on measurement type, since each parameter may respond to climate change—response and forcing—differently.

GISP2 temperature modeled from oxygen isotopes reveals a subdued temperature effect at this site for the LIA. Accumulation rate was generally lower during the LIA than the MWP. CO_2 values decreased slightly during the LIA, and dust from particles such as calcium, magnesium, and potassium and from marine sources such as sodium, chloride, and MSA, increased in source or transport to the site. Nitrate sources, including lightning and soil exhalation, decreased. And 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 and newly developed signal analysis techniques have provided insight into the state of the environment, such as changes in nitrogen and sulfur cycling, marine, and terres-

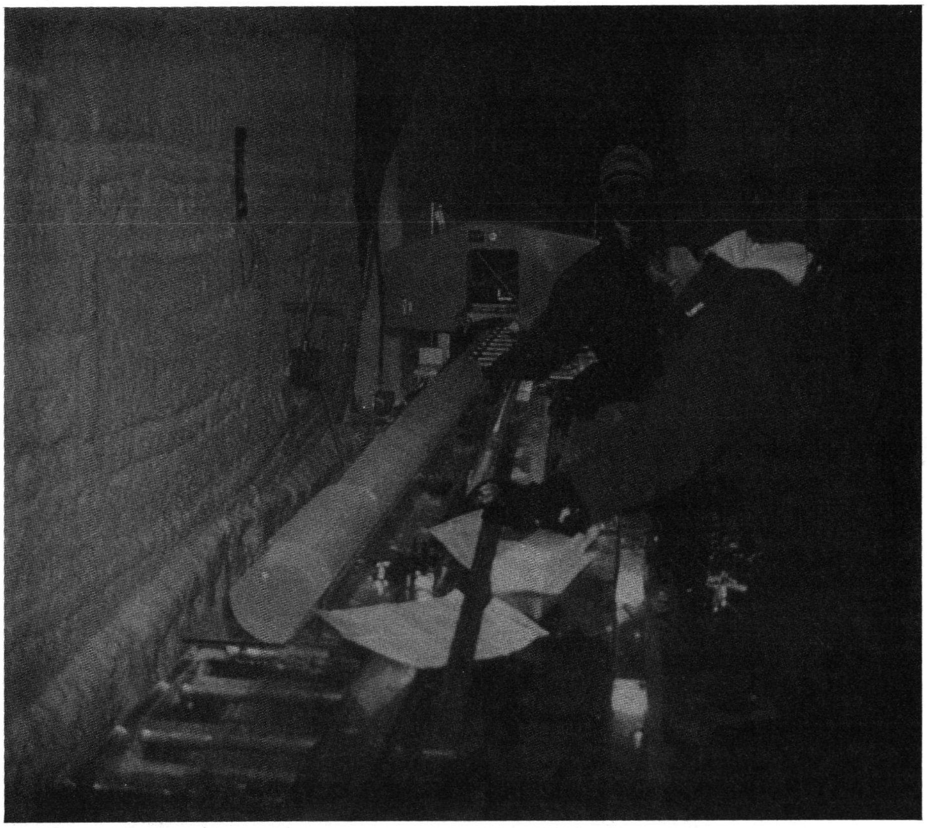

Fig. 4. The horizontal coring station in the core processing line. Courtesy of Michael Morrison, University of New Hampshire. Original color image appears in the back of this volume.

trial source influences during the LIA and MWP.

Younger Dryas, a Return to Near-Glacial Conditions

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. The end of the YD is characterized by a doubling of accumulation at GISP2 in perhaps 1–3 years and the onset of the event is characterized by a large and abrupt change in accumulation rate.

Dramatic and rapid changes over 10–20 years in the soluble composition of the atmosphere over central Greenland are attributed to changes in the size of the polar atmospheric cell and in source regions. These changes include growth and decay of continental biogenic and terrestrial source regions. Massive, frequent, decadal or less scale changes in atmospheric composition also exist throughout the YD. These high-resolution views of environmental change coinciding 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 higher during cold periods as a consequence of increased input of terrigenous dust to the glacial atmosphere. In contrast, concentrations of marine biogenic source sulfur are higher during warm periods and lower during glacial conditions. This suggests a reduced contribution of oceanic sulfur to the Arctic atmosphere during glacial climates, which is dramatically different from that observed in the Vostok ice core in east Antarctica where a high-latitude oceanic sulfur source 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. These rapid changes reflect a type of "flickering" between preferred states of the atmosphere not previously observed. The presence of such events in the record reveals the importance of high-resolution paleoclimate records.

Future Study

Now that the longest ice core record from the Northern Hemisphere has been recovered, it is time to develop new ice core records for the Southern Hemisphere. Future deep drilling in the Antarctic promises new approaches to understanding environmental change.

The recovery of ice cores from Antarctic sites with accumulation rates similar to those at GISP2 will provide equivalent and comparable records for bipolar studies of climate response and forcing. Also, the recovery of ice cores from Antarctic sites with lower accumulation rates and thicker ice than GISP2's will eventually provide the longest ice core records available on Earth, spanning several glacial/interglacial cycles.

In the future, ice core records may provide the perspective needed to dramatically advance our understanding of climate response and forcing and perhaps the perspective needed to understand the consequences of our involvement in this dynamic environment. They may also provide the framework

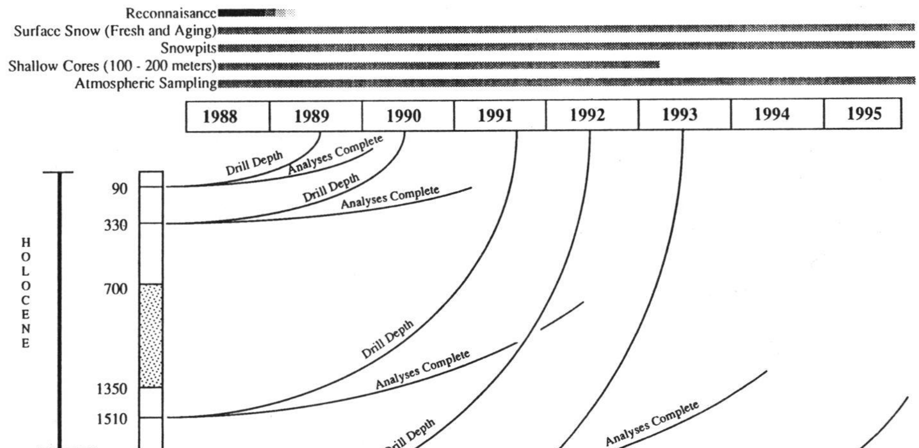

Fig. 5. Summary of GISP2 science and drilling activities to date. The core and depths reached each year are shown on the left. The specked zone between 700 and 1350 m represents the location of the brittle ice. 3053.4 m of ice and 1.5 m of rock were finally recovered.

for incorporating and further interpreting the wealth of available proxy environmental records, for example, tree rings, marine and lake sediments, leading toward even better developed regional paleoenvironmental reconstructions.

Rock core samples 1.55-m-long are available from Julie Palais or Scott Borg, Office of Polar Programs, NSF, 4201 Wilson Blvd., Rm. 755, Arlington, VA 22203 (see *Eos*, Feb. 22, p. 84). Also, a list of references from the GISP2 project is available from the GISP2 Science Management Office, Institute for the Study of Earth, Ocean and Space, Morse Hall, University of New Hampshire, Durham, NH 03824-3525.

Acknowledgments

GISP2's science and support staff thanks OPP/NSF for support and encouragement; the 109th Air National Guard at Scotia, N.Y., for many years of close cooperation, support, and enthusiasm; and our GRIP colleagues for the seasons we shared as neighbors in central Greenland. The Greenlandic and Danish governments granted permission for GISP2 to work in Greenland.

Participants in the GISP2 Field Program

Camp logistic support was provided by the Polar Ice Coring Office (PICO) 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 maintained by the Science Management Office of the University of New Hampshire.

Research institutions involved in GISP2: Carnegie Mellon University Cold Regions Research Laboratory, Desert Research Institute, Lawrence Livermore National Laboratory, Massachusetts Institute of Technology, Ohio State University, Polar Ice Coring Office, Pennsylvania State University, Scripps Institute of Oceanography, State University of New York at Buffalo, United States Military Academy at West Point, University of Arizona, University of California, Berkeley, University of Colorado, Boulder, University of California, San Diego, University of Miami, University of New Hampshire, University of Rhode Island, U.S. Geologic Survey, University of Washington, and University of Wisconsin.

Eaton to Be Sworn in as USGS Director

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On the eve of the U.S. Geological Survey's 115th anniversary, Gordon P. Eaton was confirmed as the survey's 12th director by unanimous consent of the U.S. Senate. His swearing-in ceremony is tentatively scheduled for March 14.

Eaton, 64, is a distinguished Earth scientist, administrator, and former employee of USGS. His most recent post was director of the Lamont-Doherty Earth Observatory of Columbia University. He has been an AGU member since 1963. Eaton follows in the footsteps of Dallas Peck, who held the post from 1981 to 1993, and interim director Robert M. Hirsch, who followed Peck.

The first USGS director was Clarence King, who served from 1881 until 1897.

On March 3, USGS celebrated 115 years of serving as the nation's largest Earth and water science and civilian mapping agency. Its mission is to provide Earth science to the public service. The survey employs 10,000 in 200 regional and field offices in the United States and abroad.

NSF to Fund Special Northridge Earthquake Study

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The Northridge earthquake of January 17, 1994, had a serious impact on southern California and the nation. H.R. 3759 makes available a $15 million emergency supplemental appropriation to the Federal Emergency Management Agency (FEMA) to study the earthquake.

The appropriation is intended to increase the scientific understanding of earthquakes and to assess and make recommendations for improving seismic safety throughout the nation based on lessons learned from this disaster.

The National Earthquake Hazard Reduction Program (NEHRP) agencies, consisting of FEMA, the U.S. Geological Survey, the National Institute of Standards and Technology, and the National Science Foundation are organizing this investigation. The NEHRP agencies will direct much of the funding to non-government research grants supporting the goals of the appropriation. NSF has agreed to distribute a special announcement of opportunity, conduct a competitive review of proposals, and manage the successful grants.

For inclusion in the mailing list regarding this research, contact Jim Whitcomb (Geosciences, tel. 703-306-1556; fax 703-306-0382; e-mail jwhitcom@nsf.gov) or Bill Anderson (Engineering, tel. 703-306-1362; fax 703-306-0319; e-mail wanderso@nsf.gov).

Exploring the Eastern Arctic Ocean Margins

PAGES 113–115

A joint German-Russian oceanographic expedition was made in August and September 1993 to the Eurasian continental margin of the Barents and Laptev seas, a region of high scientific interest that until recently was inaccessible to western oceanographers. The expedition addressed a range of scientific problems spanning geology, oceanography, biology, and sea-ice research, and it marks a major breakthrough in Arctic Ocean research cooperation among Russian and western scientists.

The program grew out of discussions between ocean researchers from the Alfred Wegener Institute for Polar and Marine Research (AWI) in Bremerhaven, Germany, the GEOMAR Research Center for Marine Geosciences and the Institute for Polar Ecology (IPÖ) in Kiel, Germany, the Arctic and Antarctic Institute (AARI) in St. Petersburg, Russia, and several institutes involved in ecological research within the Russian Academy of Sciences (RAS). It was coordinated by the AWI and AARI.

The expedition was carried out by 70 researchers aboard the German icebreaking research vessel RV *Polarstern* (Figure 1) of AWI and the Russian research vessel RV *Ivan Kireyev* of the Hydrographic Department in Arkhangel'sk. From Murmansk, the *Polarstern* departed for the Svalbard region (Figure 2), where four current moorings were deployed and two transects incorporating geological, oceanographic, biological, and sea-ice research were occupied extending from the continental shelf out into the deep Arctic Ocean basin. Steaming eastward, the *Polarstern* met with the *Kireyev* in the Laptev Sea, where the remainder of the program was carried out. The *Polarstern* used its icebreaking abilities to occupy four transects from the shelf out into the deep ocean, much of this in heavy pack ice, while the smaller and non-icebreaking *Kireyev* occupied a dense set of stations over the ice-free, shallow shelf. In late September, a final meeting and exchange of data was held and both vessels departed the region for their home ports.

Oceanography

The oceanographic program collected temperature, salinity, dissolved oxygen, and nutrient data, and a variety of tracer data that will be used to examine water mass distribution and modification on and near the shallow Barents and Laptev shelf seas. These regions, which are sites of ice and brine formation, are believed to play a major role in the formation of the Arctic Ocean halocline and of saline Arctic Ocean Deep Water and also help, because of a large summer river

Fig. 1. (Below) At a depth of 3040.33 m, there is a sharp transition from clear to silty ice. This is followed by alternating bands of silty and clear ice and progressively siltier ice until contact with bedrock. 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 ~-9°C. Preliminary observation of the core in the field indicates that the upper 10–15 cm are a weathered "schist-like" rock that grades into a fresh "granite gneiss" below. (Above) The 0–70 cm section of the rock core. Courtesy of David Giles, University of Alaska, Fairbanks.

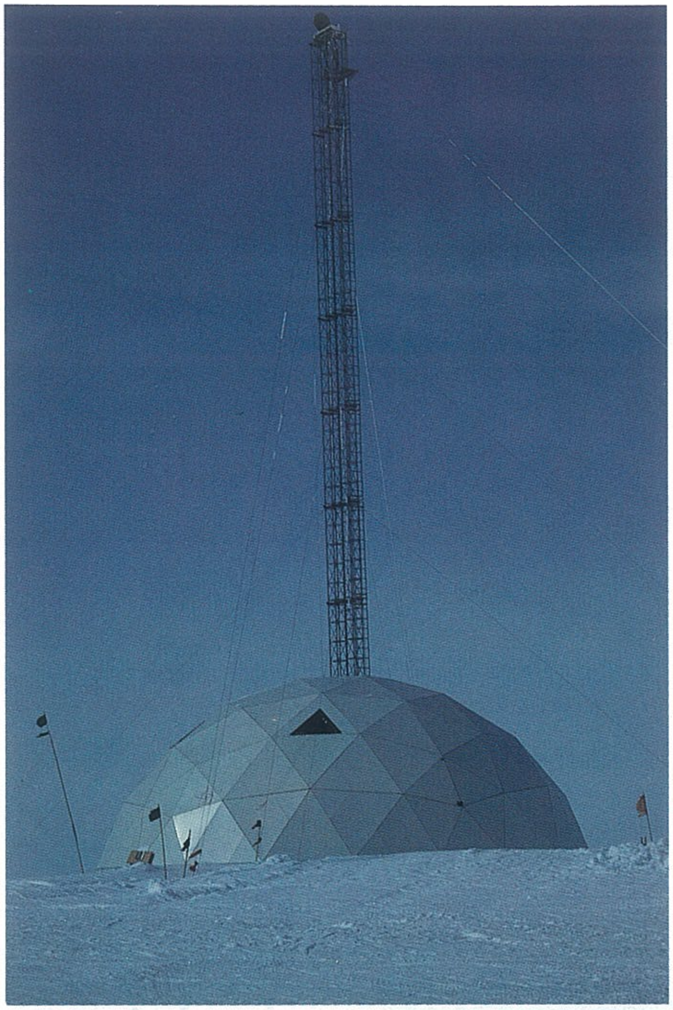

Fig. 3. A 52-foot geodesic dome housed the deep drill. Courtesy of Jen Putscher, University of New Hampshire.

Fig. 4. The horizontal coring station in the core processing line. Courtesy of Michael Morrison, University of New Hampshire.

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