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Preface

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This special issue of the *Journal of Geophysical Research* presents 47 papers developed from research on the two deep ice cores drilled in central Greenland during the years 1989–1993 by the U.S. Greenland Ice Sheet Project 2 (GISP2) and the European Greenland Ice Core Program (GRIP). In this "grand experiment," two large ice-core-drilling programs were combined. A major reason was to validate the presence of fast climate oscillations that could not be verified by a single deep ice core.

The drilling programs were based on several seasons of field work and years of negotiations between U.S. and European glaciological groups. As a consequence, top-ranking scientists within the field of ice-core research were provided the opportunity to access samples and information needed to demonstrate to the scientific community the implications of climate change, especially those associated with human activities. Both projects had as their overall objective the extraction of as many data as possible from these deep ice cores so that the scientific community would receive the highest quality and most detailed and well dated information concerning our planet's past few hundred thousand years of climatic, atmospheric, and environmental change.

The advantage of the polar ice cores as archives of past global climatic and environmental conditions relates to the special character of this sediment. Unlike other paleoclimate media, it is a sediment that captures within it the atmosphere itself. Further, the high-resolution measurements available from ice cores reveal a wealth of information on the past state of the atmosphere, i.e., temperature, chemical composition, atmospheric circulation, and gas composition.

Previous deep ice core records from Greenland (Site 2, Camp Century, and Dye 3) and Antarctica (Byrd Station, Vostok, and Dome C) have from the early 1960s to the 1980s added greatly to the understanding of past climate and revealed aspects of the global climate and environment that today are well known in the scientific community. Some of the highlights of the GRIP and GISP2 drillings were not totally unexpected, since preceding deep drilling programs (e.g., Dye 3 and Camp Century) had already suggested the possibility of rapid climatic change events during the glacial period. These events were, however, only suggested rather than proven, and the dating and rapidity of these climatic change events lacked definitive evidence. Improved techniques utilized by GISP2 and GRIP have unequivocally demonstrated the presence and significance of the rapid climate-change events.

The GISP2 and GRIP ice cores each extended more than 3 km deep and approximately 250,000 years back in time. Investigators developed and exploited the ability to count annual layers in the cores well into the glacial period and probably through 110,000 years (to ~90% of the depth of the cores), with differences between dates of these cores and independent age indicators of roughly 1% in the Holocene and 5% through most of the ice age. This advance is unparalleled in paleoclimate studies. The almost perfect match back to 110,000 years ago between records from the two cores 30 km apart should dispel any lingering doubt about the climatic origin of the events. Use of volcanic markers and atmospheric oxygen isotopic ratios allowed matches between these and other ice core records and correlation with ocean sediment records, greatly extending our ability to map climate changes and understand their causes.

From the central Greenland ice cores we now know that the Earth has experienced large, rapid, regional to global climate oscillations through most of the last 110,000 years on a scale that human agricultural and industrial activities have not yet faced. These millennial-scale events represent quite large climate deviations: probably up to 20°C in central Greenland, twofold changes in snow accumulation, order-of-magnitude changes in wind-blown dust and sea-salt loading, roughly 100 ppbv in methane concentration, etc., with cold, dry, dusty, and low-methane conditions being correlated. The events often begin or end rapidly: changes equal to most of the glacial-interglacial differences commonly occur over decades, and some indicators, more sensitive to shifts in the pattern of atmospheric circulation, change in as little as 1–3 years.

The rapid climate change events are regional to global. They are observed in local climatic indicators such as snow accumulation rate and isotopic composition linked to temperature; in regional climatic indicators such as wind-blown sea salt and continental dust; and in regional to global indicators such as atmospheric concentrations of methane, nitrate, and ammonium. (The latter two, nitrate and ammonium, probably reflect more regional aspects.) Some events are readily identified in the ocean sediment record, and a few are recorded in the isotopic temperature record of the Vostok core from central East Antarctica.

Initial interpretation of the GRIP ice core data indicates that the large, rapid climate oscillations that dominate the record of the last 110,000 years also persisted through the previous warm period (the Eemian, Sangamonian, or Marine Isotope Stage 5e). The GISP2 core also shows rapid oscillations

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during that time period, but with different timing and character. Careful physical examination shows that significant structural disturbances from ice flow begin in both cores at or slightly above the depth when differences appear between their climate records (roughly 2800 m, or approximately 110,000 years ago). Globally mixed gases in both cores differ from similar records in the Vostok (Antarctica) core, where Eemian ice is far above the bed and therefore undisturbed by ice flow. Details of the gas records and the chemistry indicate that some Eemian ice is probably present but that the stratigraphic sequence older than 110,000 years is probably disturbed in both Greenland cores. The probability remains that much will be learned about the Eemian climate from these cores. Ultimately, just as these cores were needed to validate the rapid oscillations observed in older cores, a new core or cores from a site or sites where the Eemian is farther above the bed and thus less subject to flow disturbance will provide the best answer.

This volume details a wide variety of other important contributions to climate and environmental research. These contributions include (1) the origin of the ice sheet and its basal conditions, (2) borehole thermometry calibrations that allow stable isotopic series to be converted to temperature, (3) reconstruction of atmospheric circulation patterns and their changes over time from chemical indicators and dust sources, (4) documentation of changes in atmospheric acids, (5) evidence of extraterrestrial impacts, (6) influence of anthropogenic activity on the chemistry of the atmosphere, (7) reconstruction of forest fire frequencies upwind of the site, (8) details of Holocene climate variability and biospheric response seen in soluble chemistry series and methane series, (9) work on the air-snow transfer function for chemicals and particulates that will lead to more robust environmental interpretations in the future, (10) glacier geophysics and flow modeling, which, coupled with ice-core physical and electrical studies, improve understanding of ice cores and of ice sheet behavior, stability, and possible contributions to sea-level change, (11) examination of solar influences on climate, derived from historical records and $\delta^{14}C$ series in tree rings or ice-core ^{10}Be:oxygen isotopic ratios (temperature) and chemical series (atmospheric circulation) that reveal clear solar-modulated climatic response, (11) examination of the ice-core volcanic eruption record leading to estimates of both eruptive size and atmospheric response, and (12) time series analyses of chemical and other data that reveal significant periodicities, some related to cyclic changes in Earth's orbit.

The ice-core records tell a clear story: humans have come of age agriculturally and industrially in the most stable climatic regime of the last 110,000 years. However, even this relatively stable period is marked by change. Change—large, rapid, and global—is more characteristic of the Earth's climate than is stasis. Until we understand the operative mechanisms, it will not be possible to understand current change or predict future change. Further analyses of the central Greenland ice cores will help us develop that understanding.

The GISP2/GRIP legacy has resulted in new deep drilling that is now taking place in Greenland in order to investigate the "Eemian problem" and new drillings in Antarctica that will investigate teleconnections between the climate changes in the northern and southern hemispheres.

Much of the data presented in this special issue will be available, along with GISP2/GRIP descriptions and information, on a CD-ROM entitled "The Greenland Summit Ice Cores" as well as on the World Wide Web, from the National Snow and Ice Data Center, University of Colorado, Boulder (http://www-nsidc.colorado.edu/) and from the World Data Center–A for Paleoclimatology, National Geophysical Data Center, Boulder, Colorado (http://www.ngdc.noaa.gov/paleo/paleo.html).

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