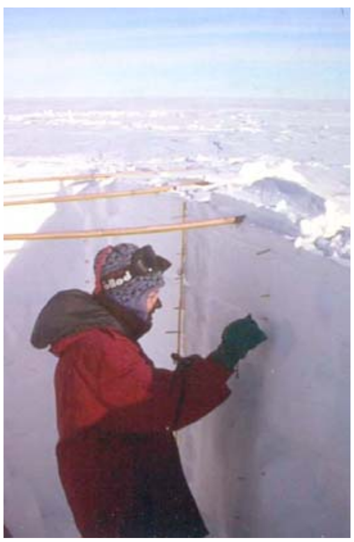
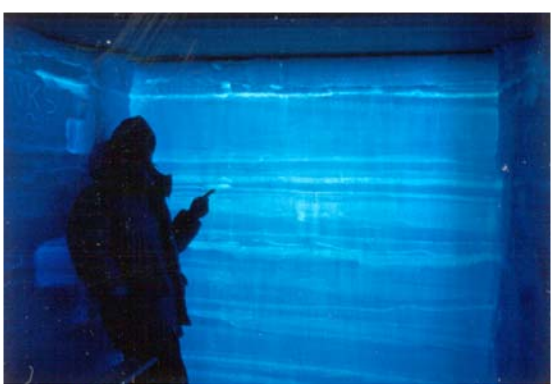
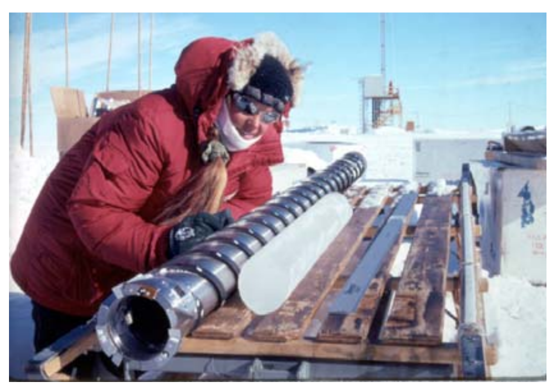
WAISCORES

A Science and Implementation Plan for Climate, Cryobiology and Ice Dynamics Studies in West Antarctica

United States Ice Core Working Group: June, 2000



This document was prepared by Kendrick Taylor of the Desert Research Institute. Richard Alley and Ed Waddington played a major role by helping to define the main themes of the program and reviewing many drafts. David Morse contributed the site-selection section and Tom Neumann performed the timescale and temperature calculations. Contributors include: Pierre Biscaye, Roger Bales, Lloyd Burckle, Ed Brook, John Castello, Gary Clow, Chris Fritsen, Karl Kreutz, Gregg Lamorey, Debra Messe, Joe McConnell, John Priscu, Scott Rogers, Todd Sowers, Michael Ram and Greg Zielinski.

The U.S. Ice Core Working Group unanimously endorsed this plan in June, 2000. Comments or questions about this plan should be sent to Kendrick Taylor (Kendrick@dri.edu).

This document is available on line at http:www.dri.edu/Projects/waiscores

Cover Photographs (clockwise from left)

Mary Albert samples a snow pit to determine how air movement in the firn influences the preservation of the climate record stored in the ice.

The deep ice coring drill as set up at Siple Dome, Antarctica. The same drill will be used in this program. The support wires on the 35-meter-tall tower are visible because of frost.

Lou Albershard removes a core from the drill.

Rhonda Ecker examines a core barrel and core. This drill is used for recovering shallow cores.

Kendrick Taylor stands in front of the wall of a snow pit at Siple Dome, Antarctica. Light shining through the wall highlights the snow stratigraphy. He is pointing to a 30-cm-thick sequence of light and dark bands that are formed during the summer. The thick darker band by his head was formed during winter.

SUMMARY

Abrupt changes in climate and sea level, and emerging issues in biocomplexity and life in extreme environments, offer great opportunities and challenges for humanity. A more complete understanding of these topics is needed to make sound policy decisions. Although these topics are of global significance, ice cores from Antarctica are among the best ways to advance our knowledge about these socitally relevant topics.

Large, abrupt climate changes have dominated the earth's history, but have not occurred during the few millennia when humans invented agriculture and industry. If similar large and rapid climate changes occurred now there would be major societal impacts. Current hypotheses suggest that human activities could cause the return of abrupt climate changes.

Investigation of biological process in extreme environments provides insights on the adaptability of life, evolutionary processes, astrobiology, and might lead to useful products for humanity. The bottom of ice sheets is one of the few remaining terrestrial environments that has not been studied by biologists. Antarctic ice also contains continuos and well preserved samples of biological material from previous times.

The West Antarctic ice sheet has the potential to change rapidly, affecting global sea levels and coastal populations. Ice sheets and sea level are known to have experienced large and rapid changes in the past. The West Antarctic ice sheet is still responding to past climate changes, in ways that we do not fully understand. Recent reductions in the size of ice shelves in the Antarctic Peninsula raise our concern.

A deep ice-coring program in West Antarctica is an excellent way to explore these climate, biology and ice dynamics topics. The investigation of these topics is synegistic and can not be completed individually.

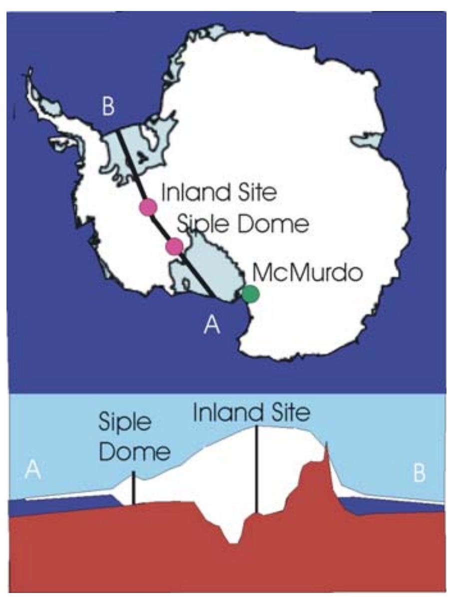
Some of the specific topics that will be address are listed below.

•What are the characteristics of natural climate change during the last 60,000 years?
•Is recent climate change abnormal?
•What is the influence of solar activity on climate?
•How did the Southern Hemisphere respond to the well-documented abrupt climate changes in the Northern Hemisphere?
•What was the relationship between climate and atmospheric carbon dioxide during pre-industrial times?
•What biological activity occurs at the contact between the bottom of the ice sheet ice and the bed?
•What biological activity occurs within the ice sheet?

•What does a continuous collection of biological material spanning the last 100,000 years tell us about ecological and evolutionary process?
•How is the West Antarctic Ice sheet changing and what is the influence of this change on sea level?

These topics are of global significance, yet the United States Antarctic Program is uniquely qualified to support the field component of this program. International science planning documents assume the completion of this program by the United States. The proven United States ability to drill and analyze deep ice cores is the backbone of this project. For the first time the biology community is involved in the initial planning of a deep ice-coring program, assuring biology will be fully integrated into the program. Associated atmospheric and glaciology investigations will improve interpretation of the biologic and climatic records in the ice core, and determine the implications for ice-sheet influences on sea level.

The program will require significant resources. The ice core drilling equipment will require refurbishment. A sterile drilling system needs to be developed for the basal biology portion of the program. One large field camp, and possibly a smaller refueling camp, will be required. About 30 individually proposed science projects would be involved in the program. Preliminary work has been funded to assist in the selection of the drilling site. If resources were available drilling could start in 2003/2004 and take about 5 field seasons.



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SCIENCE PLAN

INTRODUCTION

The United States Antarctic Program has been active in West Antarctica for over 40 years. During the last ten years, this activity has been part of the WAIS (West Antarctic Ice Sheet) program, which strives to better understand the interaction of the West Antarctic ice sheet, sea level and climate. Answers to the societally important questions of how sea level and climate will change in the next few decades to centuries can be answered only if we improve our understanding of the ice dynamics of West Antarctica and the climate records that are stored in its ice. The WAIS program utilizes methods from geology, geophysics, geochemistry, glaciology, oceanography and climatology. One aspect of the program involves the recovery of ice cores. The original plan for the ice core work was established at a workshop in 1992 and was incorporated into a planning document (Alley, 1992b). The planning document called for the recovery of two ice cores from West Antarctica: one at Siple Dome, and one in the vicinity of the flow divide upstream of Byrd Station (Figure 1.) This second site is referred to as the Western Divide site. The Siple Dome core has been recovered and the analysis of the ice is underway. This document is a Science and Implementation Plan for the next phase of United States-funded deep ice core-related investigations in West Antarctica, a deep ice core near the ice divide in West Antarctica.

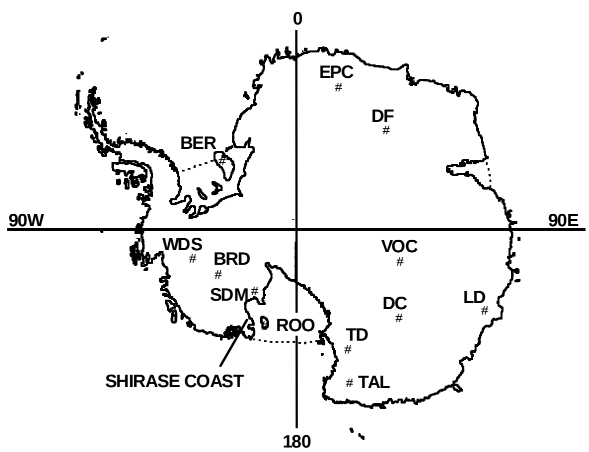

Figure 1. Map of places discussed in text.

WDS= Proposed Western Divide site
EPC = Proposed EPICA drilling site
BER= Proposed Berkner Island drilling site
SDM = Siple Dome Core
ROO = Suggested Roosevelt Island drilling site
DF= Dome Fuji Core
VOC= Vostok Core
DC= Dome C Core
TD= Taylor Dome Core
LD= Law Dome Core
TAL= Suggested Talas Dome drilling site.
BRD = Byrd Station

GENERAL OBJECTIVES AND SIGNIFICANCE

The main objectives of the proposed work fall into three broad categories: climate, biology, and ice dynamics. These studies are tightly linked; most of the objectives in this program can only be obtained if all three categories of studies are undertaken simultaneously.

The climate studies will utilize a deep ice core to develop paleoclimate records that span the last ~60,000+ years. The records will have annual resolution for the last ~20,000 years. These records will be used to address broad topics such as:

1) What are the causes of climate changes that have occurred in the past?

2) How likely is a recurrence during the next century of the major rapid climate changes that occurred in the past?

3) Is human activity likely to initiate a major and rapid change in climate?

4) How do the climate transitions that occurred in West Antarctica compare to climate transitions in other parts of the world?

5) What is the natural variability of the climate system during the Holocene?

6) Has the climate in West Antarctica changed in an unprecedented way during the industrial era?

7) Is there evidence that solar cycles influence climate on time scales of less than 10,000 years?

The biological studies will utilize ice and basal material samples to investigate the biological process in these environments and to determine the biological response to climate change. This will be used to address questions such as:

1) What types of microbes occur in glacial ice and the basal material?

2) Do the microbes in glacial ice provide the biological seed for the basal environment?

3) What types of metabolism do microbes in the ice and basal material have?

4) How does biological activity influence the preservation of the climate record?

5) How are life forms that have been separated from the main part of the biosphere for at least ~100,000 years different than the life forms that are part of the main biosphere?

6) How does climate influence the biodiversity of life forms at the drilling site?

The ice dynamics studies will utilize the same ice core and borehole to develop a history of how the surface elevation of the ice sheet and ice flow has changed over the last ~100,000 years. This will be used to address questions such as:

1) To what extent have changes in the distribution of ice in Antarctica contributed to changes in sea level in the past?

2) To what extent will changes in the distribution of ice in Antarctica contribute to changes in sea level during the next century?

The work proposed here will not be sufficient to unambiguously answer these questions; however, when combined with other ongoing and future programs, it will take a large step in that direction. The climate, biology and ice dynamic studies are intertwined. We cannot interpret the climate records and life forms obtained from an ice core without understanding how the movement of the ice has influenced the recording of the climate record. Likewise, we cannot understand the ice dynamics of West Antarctica unless we understand how climate has built and driven the ice sheets. There is a strong synergistic benefit from combining both climate and ice dynamics studies.

BACKGROUND

Climatology

Paleoclimate records have played a key role in improving our understanding of how the climate system works, how it is changing, and how it might change in the future. Recent noteworthy and widely accepted paleoclimate findings include:

- The ability of climate to change rapidly and on hemisphere-wide scales in a manner that would be extremely disruptive to our society (Alley *et al.*, 1993, Taylor *et al.*, 1997a).
- The global identification of climate oscillations with an approximately 1,500-year cycle during the last glacial period (the Dansgaard-Oeschger events) (Johnsen *et al.*, 1992, Mayewski *et al.*, 1997), and the possible continuation of this oscillation during the Holocene (Denton and Karlen, 1973, Bond *et al.* 1992; Keigwin and Jones, 1989).
- The grouping of the Dansgaard-Oeschger events into longer cycles (Bond cycles), which are closely associated with the discharge of massive amounts of icebergs into the North Atlantic (Heinrich events) (Bond *et al.*, 1992; Alley and Clark, 1999.
- The link between the thermo-haline circulation and rapidly changing climate, and the sensitivity of the thermo-haline circulation to freshwater influx in the North Atlantic (Manabe and Stouffer, 1988; Rahmstorf, 1995; Stocker and Schmittner, 1997).
- The unprecedented rapid increase in greenhouse gases that is occurring due to human activity and a tight association of atmospheric greenhouse gases and surface temperature (Raynaund *et al.*, 1993; Petit *et al.*, 1999; Mann *et al.*, 1999).
- The large changes in non-greenhouse gases during the industrial era (Staffelbach *et al.*, 1991; Butler *et al.*, 1999).

All of these findings relied heavily on the paleoclimate records developed from ice cores. The Greenland GISP2 and GRIP cores have set the northern hemisphere standard, against which much of this work takes place. The annual layers in these cores are well preserved to 40,000 years before present (Meese *et al*., 1997). Records from these cores extend to about 110,000 years before present (Meese *et al*., 1997; Alley *et al*., 1997b, Taylor *et al*., 1993; Ram and Koenig, 1997). Other arctic cores allow investigation of the spatial variability of climate changes during the Holocene and late Wisconsin and confirm the main features observed in the GISP2 and GRIP cores during the time period the records overlap (Koerner and Fisher, 1990). Low-latitude, high-elevation cores provide records extending into the last glacial and provide insights into the changes in temperature and moisture (Thompson *et al*., 1998). The Vostok and Byrd cores have become the standard for Antarctic studies. The Byrd core has annual resolution to an age of 31,000 years before present (Hammer *et al*., 1994), but records from this core were developed before modern analysis methods were available, and the ice from the most interesting sections has been consumed. The Vostok core lacks annual resolution and extends back 420,000 years before present (Petit *et al*., 1999a). The Vostok and Byrd cores are best known for their records of surface temperature and atmospheric CO_2 (Barnola *et al*., 1991; Petit *et al*., 1999; Neftel *et al*., 1988). The Taylor Dome core has raised intriguing questions about the phase relationship between climate transitions in the northern and southern hemispheres and within Antarctica (Steig *et al*., 1998b). Yet questions remain regarding the interpretation of this record (Wolf, personal communication, 1999). The preliminary work on the Dome Fuji core has provided a record similar to the Vostok core and the more detailed studies that are underway hold considerable promise (Watanabe *et al*., 1999). When the analysis of the Law Dome core is complete, it will provide an excellent Holocene record in Wilkes Land. The Siple Dome core is still being analyzed.

Biology

Recent advances have made it possible to study the DNA of small quantities of biological material in ice, and there has been an increased interest in investigating life in extreme environments. Recent noteworthy biological findings related to this program include:

- The discovery of liquid water oases that support microbial assemblages in Antarctic lake ice (Priscu *et al.* 1998, Fritsen and Priscu 1998, Adams *et al*. 1998, Fritsen *et al.* 1998).

- The discovery of viable microbes in Vostok accretion ice (Karl *et al*. 1999, Priscu *et al*. 1999).

- Implications that the biological seed for deep subglacial Antarctic lakes is derived from atmospheric deposition, particularly during glacial periods (Priscu *et al.* 1999, Abyzov *et al*. 1998).

•The contention that microbes metabolize and move in crystal veins (triple junctions) within deep ice (Price, 2000).

•The detection of viable viruses in glacial age ice (Castello *et al.*, 1999, Rogers and Castello, 2000, unpublished data).

Ice Dynamics

Recently, there have been unprecedented advances in our understanding of the dynamics and history of the large ice sheets. Recent noteworthy findings include:

- Indications that during the Holocene, the surface elevation of Siple Dome has not changed significantly, while the ice along the Shirase Coast has thinned considerably (Waddington and Conway, personal communication, 1999).
- The role of subglacial geology in controlling the rapid movement of ice from the interior of an ice sheet to the ocean (Bell *et al.*, 1998, Anandakrishnan *et al.*, 1998).
- The dynamic nature of ice shelves, which are more susceptible to warming and can change faster than previously thought (Vaughan and Doake, 1996; Doake *et al.*, 1998).

These climate and ice dynamics findings have important implications for the behavior of ice streams, ice shelves and ice sheets. These findings are the bases for understanding the changes that are occurring today, as well as for predicting future changes. The biology findings increase our knowledge about one of the few earth environments where biology has not been investigated. Ice coring programs have played a key role developing these findings and will continue to contribute in the future.

TOPICS RIPE FOR FURTHER RESEARCH

Despite the progress in recent years there are many topics of great interest that will be advanced by this program.

The variability of climate around Summit, Greenland, is well documented by the annually resolved GISP2 and GRIP records that extend to at 100,000 years before present (Meese *et al*., 1993, Ram and Koenig, 1997; Hammer *et al*., 1997). Some ocean cores have comparable resolution and provide an insight into ocean processes (Hughen *et al*., 1996, Sachs and Lehman, 1999). These records permit development of annual resolved records of climate variability that are used to study topics such as the North Atlantic oscillation, the Dansgaard-Oeschger oscillations, the characteristics of rapid climate change, the significance of athropogenic-related environmental changes and solar influences on climate. Unfortunately, there is no Antarctic equivalent to the high time resolution Northern Hemisphere ice cores. Law Dome provides an excellent Holocene record but it does not extend back far enough into the last glacial period for many applications. The Vostok, Taylor Dome and Dome C cores extend further back in time but do not have the time resolution to address many of the topics mentioned above. The most interesting sections of the Byrd Core were consumed by earlier studies before the development of many new analytical techniques. To make headway in our understanding of climate oscillations, teleconnections, and rapid climate change, and to put the climate changes we are observing today into perspective, we need to obtain an Antarctic equivalent to the long and high time resolution GISP2 and GRIP Greenland records.

The phase relationship between millennial time scale climate changes in the Arctic, mid latitudes, and the Antarctic is of considerable interest (Sowers and Bender, 1995; Blunier *et al.*, 1998, Broecker, 1998). Understanding if major climate changes originate in single location, or oscillate between different climate states in different regions, will help us define the mechanisms that cause climate transitions. Results from the Taylor Dome core indicate that the climate of the area around Taylor Dome was in-phase with Summit, Greenland, during the last climate transition (Steig *et al.*, 1998b). The Byrd core is out of phase with Summit, Greenland (Blunier *et al.*, 1998), and gas age-ice age uncertainties prevent determining the phase relationship at Vostok (Petit *et al.*, 1999). Ocean sediment cores from the southern ocean suggest the climate transition from the glacial to the deglacial started in the Southern Hemisphere (Vidal *et al.*, 1999, Charles *et al.*, 1996, Burckle, personal communication, 2000). There are also modeling results that suggest that Antarctica would not have responded uniformly to the last glacial transition (Stocker *et al.*, 1996; Stocker and Wright 1996,). More work needs to be done to confirm these results and to expand our understanding of the spatial characteristics of climate change in Antarctica.

Ice cores have identified anthropogenic induced changes in atmospheric chemistry on decade-to-century time scales (Mayewski *et al.*, 1990; Anklin and Bales, 1997). The development and application of sensitive, high-resolution analytical techniques to ice cores during the past one to two decades offers the possibility to enhance our understanding of natural changes in atmospheric photochemistry, global nutrient cycling and related biogeochemical issues. The drilling of a deep Antarctic core at a cold, high-accumulation site offers unprecedented opportunities for studying these questions. The earlier West Antarctic core from Byrd Station showed that important reactive species such as hydrogen peroxide were well preserved in older ice (Neftel and Klockow, 1986) but because of sample availability, the Byrd core is not suitable for development of a meaningful hydrogen peroxide record.

Our understanding of anthropogenic impacts on greenhouse gases also relies on measurements of gas samples from ice cores. It is important to know if high levels of atmospheric CO_2 will force an increase in global temperatures. Greenland cores cannot be used to develop records of atmospheric CO_2 because of *in situ* CO_2 production associated with the high dust content of Greenland ice. The Vostok and Byrd cores show the tight relationship between elevated temperatures and atmospheric CO_2 on millennial time scales (Stauffer *et al*., 1998; Fischer *et al*., 1999). Unfortunately, the Vostok and Taylor Dome cores have a low accumulation rate that makes it difficult to determine the phase relationship of CO_2 and temperature. The low accumulation rate also makes it impossible to develop records of changes in atmospheric CO_2 on decadal time scales. The Byrd core has a higher accumulation rate than the Vostok or Taylor Dome cores, but the storage history of the core is uncertain and most of the interesting ice has been consumed. Initial studies at Vostok suggest that changes in atmospheric CO_2 occur 600 years after the change in local surface temperature (Fischer *et al*., 1999), but there is a 400-year uncertainty in this result that relies on calculation of the ice age-gas age difference. A preferable way to determine the phase relationship between atmospheric CO_2 and temperature would be to use the thermal fractionation of nitrogen and argon to identify when the local temperature changes (Severinghaus *et al*., 1998a) and use a core with higher time resolution. This avoids the uncertainty associated with calculating the gas age-ice age difference. It is also desirable to develop a record of atmospheric CO_2 with greater time resolution than is possible from current cores. A CO_2 record with greater time resolution would allow us to investigate changes in deepwater production associated with abrupt changes in ocean circulation during rapid climate changes (Indermuhle *et al*., 2000).

West Antarctica contains a large and potentially unstable mass of ice. Estimates of the current rate of grounding-line retreat indicate that the ice mass of West Antarctica has been decreasing for at least the last several thousands of years (Bindschadler, 1998; Ackert *et al*., 1999; Conway *et al*., 1999). More ice core records from multiple locations in West Antarctica are necessary to help us resolve the history and current dynamics of the West Antarctic ice sheet.

Ice flow is controlled by its response to a force. The stress-strain relationship for large ice sheets is not well known and is dependent on site-specific conditions such as strain history and ice impurities (Alley, 1992a). To determine how ice flow has affected the climate record and how an ice sheet will respond to changes in the future, we need to improve our understanding of the physics of ice flow. The space and time scales of ice sheets cannot be duplicated in a laboratory, so these investigations must take place in the field.

The movement of ice is also controlled by the conditions at the contact between the ice and the bedrock. Softer sedimentary rocks provide material for a deformable till that lubricates the ice-rock contact and enhances flow. Harder metamorphic, intrusive and volcanic rocks are believed to inhibit the development of rapid ice movement by ice streams (Blankenship *et al*., 1986). Obtaining even a single bedrock sample from the central portion of West Antarctica would improve our understanding of the geology of this region. This knowledge of the geology would improve our ability to predict how far inland the Siple Coast ice streams can advance and how rapidly the size of the West Antarctic ice sheet can change.

Recent studies of McMurdo Dry Valley lake ice (Priscu *et al*. 1998) and Vostok accretion ice from 3590 m (Priscu *et al.* 1999) and 3603 m (Karl et al. 1999) have shown the presence of microbes at densities of 10^2 to 10^4 cells ml^{-1}, and the development of metabolic activity in the presence of liquid water. Bacterial 16S rDNA of the Vostok accretion ice revealed low diversity in the gene population (Priscu *et al.* 1999). The phylotypes were closely related to extant members of the alpha- and beta-Proteobacteria and the Actinomycetes. Actinomycetes were also observed in overlying glacial ice (Abyzov *et al.* 1998) implying that the biological seed for the accretion ice (and presumably for Lake Vostok) may have arisen from airborne particles (e.g. Marshall 1996) deposited on the surface of the ice sheet ~500,000 years before present. The microbes would then have been released into the lake and subsequently refrozen to the overlying glacial ice following downward migration and melt at the glacial grounding point. Microbial densities observed in Vostok glacial ice by Abyzov *et al*. 1998, were positively correlated with dust particles deposited during interglacial periods.

Phylogenetic identification of microbes in ice from the WAISCORES project would allow us to determine the type of microbial assemblages associated with specific atmospheric deposition events. Such data would also provide information on the source of the deposition (e.g., aquatic, terrestrial), that would support concurrent sulfur and gas measurements. Microbial characterization will also yield a biodiversity index for the period recorded within the core. The extreme environment posed by glacial and subglacial ice system provides an important Earthly analogue for studies of other ice worlds.

ONGOING PROGRAMS

The first part of the WAISCORES program was the recovery and interpretation of an ice core from Siple Dome. The bottom half of this core became available for analysis in June 2000. Initial modeling results (Waddington, personal communication, 2000), tuned with crystal fabric data (Fitzpatrick and Lamorey, personal communication 1999), and total gas measurements (Brooke, personal communication, 2000), suggest that the surface elevation of Siple Dome has not changed much during the Holocene. Results from hot water coring at Siple Dome (Engelhart, personal communication 1998) and ice-penetrating radar investigations at Roosevelt Island (Conway *et al.*, 1999) suggest that a ridge of ice extending from the Shirase Coast to Roosevelt Island restricted the transport of sea salt to Siple Dome until the start of the Holocene when this ice ridge diminished (Waddington and Mayewski, personal communication, 1999).

The WAISCORES program must integrate with other ongoing and planned programs. The International TransAntarctic Expedition (ITASE) is an international program to investigate climate phenomena throughout Antarctica during the last 200 years. The heart of the program is a network of surface transverses conducted by the partner nations along which shallow cores and glaciological information are collected. The United States ITASE program, led by Paul Mayewski, will operate in West

Antarctica between 1999 and 2004. The US-ITASE program will provide an excellent, and unprecedented, view of the spatial variability of climate in West Antarctica during the last 200 years. The ITASE program will greatly improve our understanding of the significance of paleoclimate records collected from West Antarctica.

A pilot project to evaluate the possibility of collecting a 500,000-year paleoclimate record from Mt. Moulton, Marie Byrd Land, West Antarctica, is underway. On the crest of Mt. Moulton, there is ~600-m-long stratigraphic section of upwelled blue ice. Tephra layers in the ice allow the stratigraphy to be visually observed in the field. Initial Ar/Ar dating places the youngest tephra layer about 15,000 years before present and the oldest about 482,000 years before present (Dunbar and Zielinski, personal communication). During the 1999/2000 field season, Zielinski, Mayewski, Dunbar, and McIntosh collected continuous samples along most of the ~600-m-long blue ice section exposed on the crest of Mt. Moulton. A series of ice pits was also used to investigate the possibility that near surface weathering of the ice compromised the record. If the initial work shows that a paleoclimate record can be recovered from these samples, a science and implementation plan for this "horizontal ice core" will be circulated to the ice-core and glaciological communities. Mt. Moulton has the potential to provide the longest paleoclimate record from West Antarctica. The surface exposure of the record also makes it practical to collect large volume samples at selected time horizons. Unfortunately, the relatively low time resolution (500,000 years over 600 m) makes the Mt. Moutlon record unsuitable for addressing many of the science issues discussed here. In particular, it cannot be used to investigate the detailed structure of the phenomena related to the Dansgaard-Oeschger cycles. It may be possible to use tephra layers as stratigraphic markers between the Mt. Moulton record and Western Divide core that is proposed here.

The three United States programs related to ice cores complement each other perfectly. ITASE focuses on the last 200 years with extensive spatial coverage and sub annual time resolution. The Western Divide site record proposed here will have a duration of >60,000 years and annual time resolution. The Mt. Moulton record would have a duration of >500,000 years, decade to century time resolution, and the potential to provide large volume samples. The three different programs will be well integrated because about a third of the investigators are involved with more than one program.

Other Antarctic ice core programs focus on different time scales than the project proposed here. The very high-resolution Australian work at Law Dome and the planned British investigations on Berkner Island focus on the current warm period and the transition to the industrial era. The low-resolution EPICA efforts at Dome Concordia and Dronning Maud Land, the Japanese program at Dome Fuji, the Italian Program at Talos Dome, and the Russian Program at Vostok Station focus on long records of glacial-interglacial cycles.

The large, abrupt, widespread climate changes observed in the Arctic ice cores through the last glacial cycle, and as recently as 8,200 years ago, pose fundamental questions that are best answered by an intermediate resolution core such as the one proposed here for West Antarctica. The international Paleoclimates from Ice Cores (PICE) activity of PAGES includes the WAISCORES deep coring in central West Antarctica as an essential element (http://www.unibe.ch). To improve our understanding of the mechanisms of rapid climate change, we need a record that contains many high-resolution examples of rapid climate change. This requires a record that is at least 50,000 years long. At least some of these changes need to be studied with annual resolution and the remaining changes should be studied with near-annual resolution.

WAISCORES STRATEGY

Some Options

The broad science issues and programs discussed above set the stage for development of a strategy for the next phase of WAISCORES. A program focusing on the analysis of long, annually resolved paleoclimate records from West Antarctica is an effective way to address the broad science issues discussed above. Even though the international community is conducting and planning many ice coring programs, none of these programs will provide a long and annually resolved record like the one we are proposing.

The record we are searching for should have the following characteristics:

- Extend to at least 50,000 years before present with near-annual resolution.
- Have countable annual layers to at least 20,000 years before present.
- Have minimal disturbances due to ice flow.
- Enhance our understanding of the history of West Antarctica ice dynamics.
- Has good preservation of chemical species.

This leads us to look for a site that:

- Has thick enough ice, without too much basal melting, so that an undisturbed 50,000-year record can be collected.
- Has a modern accumulation rate of at least 25 cm/year.
- Is located on or close to an ice divide in West Antarctica that is over relatively uniform bedrock terrain.
- Is located where it is logistically feasible to conduct a deep drilling program.
- Has an average annual temperature of less than –20°C.

Similar criteria led the participants of a 1992 workshop (Alley, 1992b) to conclude that a favorable drilling location would be near the West Antarctic ice divide upstream of

Byrd Station. Participants of the EPICA program have also been interested in this site but have focused their attention elsewhere because of the interest the United States program has expressed in this area (Wolff, personal communication, 1998). Three alternate sites are discussed below.

Roosevelt Island will provide an excellent 3,000-year climate record. The Southern Oscillation Index and retreat of the Ross Ice Shelf should be well recorded in the chemistry at this site (Mayewski *et al.*, 1996; Cullather and Bromwich, 1996; Kreutz *et al.*, 2000). Ice dynamics will complicate the interpretation of the climate record stored in ice older than about 3,000 years. However, the ice older than 3,000 years will improve our understanding of the drawdown history of the Siple Coast region (Conway *et al.*, 1999). This site would address our ice dynamics goals for the Eastern Ross Sea sector of the West Antarctic Ice Sheet during the Holocene, but it would not meet the climate goals of the WAISCORES program. We feel it would be best to dry-drill the top portion of Roosevelt Island to recover a ~2,000-year climate record. The deeper portion of the ice that is most relevant to ice dynamics would require drilling 500 to 700 meters with a logistically intensive fluid-based drilling system. We anticipate the bottom portion of a Roosevelt Island core will contain ice similar to the exceptionally brittle ice encountered at Siple Dome. This brittle ice would make it difficult to sample the core for continuous records. It may be possible to recover this core in conjunction with the Australians who have a deep drill that is less logistically intensive than the United States' deep drill. The Australians have informally expressed interest in this idea. (Morgan, 1999, personal communication). We are not prepared to do deep drilling at Roosevelt Island; however, this is a promising site that should be drilled.

Another second candidate program is returning to Taylor Dome to recover a second core 5-10 km from where the existing core was collected. The interest in returning to Taylor Dome arises because the existing Taylor Dome record shows a different phase relationship for the last climate transition than other cores in Antarctica (Steig *et al.*, 1998b). The ice thickness of the late glacial maximum and deglacial transition portion of the record is twice as thick in the area where a second core might be drilled than at the original core site (Morse *et al.*, 1998). This site would not enhance our understanding of climate or of the ice dynamics of the West Antarctic ice sheet as much as other sites under consideration. Although we endorse an additional core near Taylor Dome, we feel this activity should be postponed to a later date.

A third candidate program is the South Pole. Unfortunately the low annual ice accumulation rate at the South Pole will result in a record that does not have the time resolution required for many of the studies proposed here. Because the South Pole is not near an ice divide, ice flow and upstream surface features will greatly complicate the interpretation of the climate record. Also, the South Pole site will not be as useful for investigating the ice dynamics of West Antarctica.

Consideration has also been give to using ice that has already been collected. In particular the suitability of the Byrd core has been considered. We note that there have been major analytical advances since the Byrd core was measured and the ice from the most interesting sections of the Byrd core have been consumed by previous studies. The Byrd core has some irregularities that are believed to be due to temperature fluctuations during storage. For example the isotopic concentration of atmospheric oxygen is not correct in the lower portion of the core (Brook, 2000 personal communication). The Bryd core is also not near an ice divide so interpretation of the climate record is more difficult than at a divide site.

After considering the alternatives, the Ice Core Working Group advises that the next phase of the WAISCORES program be a deep ice coring program in the vicinity of the ice divide in West Antarctica.

The Western Divide Site

In recognition that a site near the ice divide upstream of Byrd would be an interesting location for an ice core, the glaciology program of NSF has been funding glaciology studies that will permit selecting a favorable deep drilling site. Initial modeling (Nereson *et al.*, 1996) suggested that an ice core record close to 60,000 years long, with annual resolution for at least the last 10,000 years, should be obtainable from this locale. During the 1994/95 and 1995/96 Antarctic field seasons, the University of Texas conducted an aerogeophysical survey over the central portion of the Ross Sea/ Amundsen Sea ice flow divide in West Antarctica shown in Figure 1. Laser altimetry and ice penetrating radar from these surveys provide ice surface and bed elevation data that are the basis of a joint University of Texas and University of Washington study to identify candidate sites favorable for ice coring in the western ice divide region. A preliminary result of this study is the identification of two sites that span the likely ranges of ice thickness and accumulation rates that would be encountered in this region. These candidate sites are shown in Figures 2, 3 and 4; Table 1 summarizes some of the relevant information about these sites.

The principal parameters to consider for ice core site selection are ice thickness (Figure 3) and accumulation rate (Figure 4). For other parameters held constant, a high accumulation rate results in high time resolution records in the upper part of the ice column, but at the expense of a more compressed record at depth. For West Antarctica, the combination of thick ice and warm surface temperatures raise the concern of possible melting at the bed and consequent loss of the oldest part of the environmental record. This is emphasized by the occurrence of basal water at Byrd and the identification of possible volcanic structures underlying the Western Divide. We focus on the North and South candidate areas as ice thickness end members of sites within approximately 10 km of the modern flow divide. The South site exhibits flat-lying radar stratigraphy over smooth basal topography and is likely the thickest ice in the region without basal melting being a near certainty. (Thermal modeling suggests that melting would occur for geothermal flux in excess of 65 mW/m^2.) The North site is proximal to the highest bedrock topography encountered along the flow divide in the survey region, hence the thinnest ice and the least likelihood of basal melting.

Data in Table 1 and Figures 2 through 5 are from Morse (personal communication, 2000).

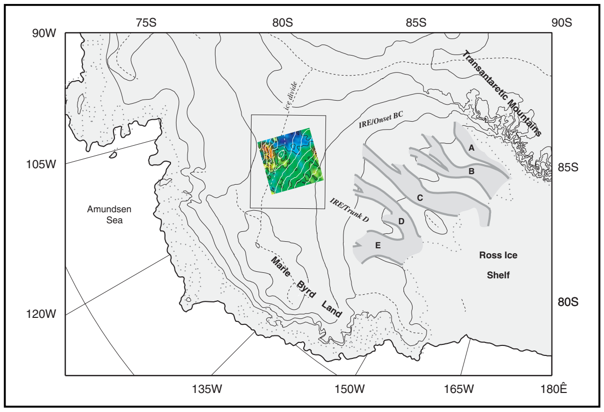

Figure 2: A close-up view of West Antarctica centered on the Western Divide region considered for ice coring as part of WAISCORES. The colored inset shows ice thickness (interpreted as colors) and surface elevation contours over a 222 by 222 km region that was surveyed at 5.3 km line spacing by the University of Texas. The inset box shows the region of Figures 3 and 4. (Morse, personal communication, 2000.)

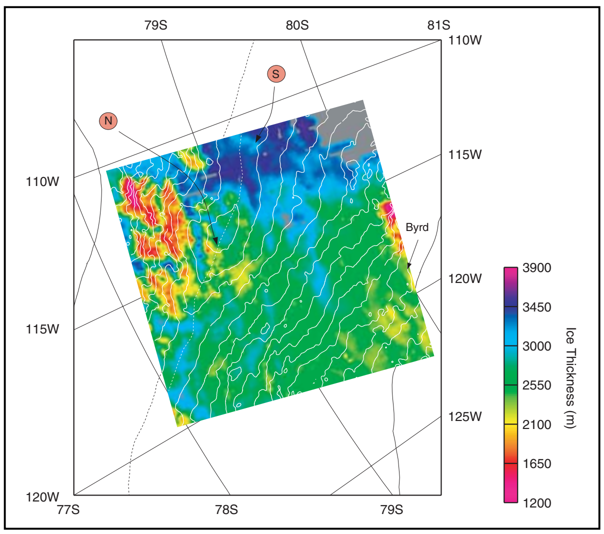

Figure 3: Ice thickness (colors) and 25 m surface elevations contours of the Western Divide region of central West Antarctica. The locations of the North (N) and South (S) candidate sites discussed are indicated. These sites correspond with sites G and E described on the site selection web site maintained at the University of Texas (http://www.ig.utexas.edu/research/projects/wais/inland/inland.html.) (Morse, personal communication, 2000.)

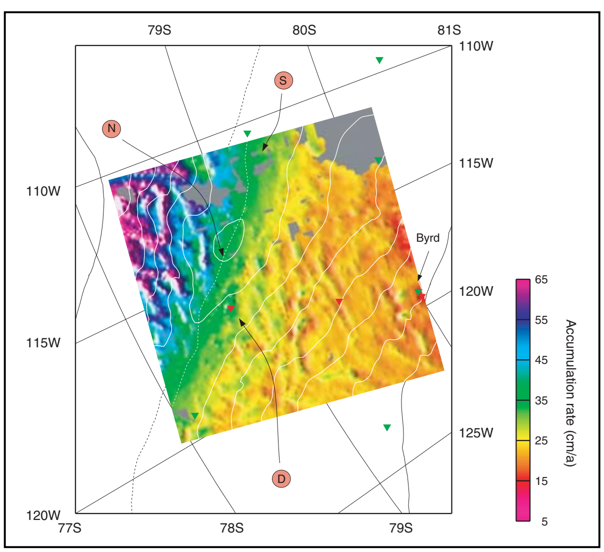

Figure 4: Snow accumulation rates (ice equivalent) for the Western Divide airborne survey region from mapping of spatially continuous radar layers. The values are an average over the last 2,700 years normalized by the ~200 year value measured at site "D" by the University of New Hampshire in 1995/96 (Mayewski, personal communication, 1999; Morse, personal communication, 2000).

Table 1. Characteristics of North and South candidate Western Divide core sites.

Site Characteristic	North Site	South Site
Longitude	114° 22' 19" W	111° 31' 40" W
Latitude	78° 46' 47" S	79° 28' 5" S
Ice Thickness	1,950 m	3,330 m
Surface Elevation	1,800 m	1,770 m
Mean annual temperature	~ -30 ^{o} C	~ -30 ^{o} C
Annual accumulation rate	~ 28 cm	~ 30 cm
Age of ice at 90% depth	56 kyr	76 kyr
Age (depth) that annual layer thickness is less than 1 cm	28 kyr (1,000 m)	51 kyr (2,800 m)
Estimate age of oldest ice (96% depth)	67 kyr	113 kyr
Basal melting in last 100 kyr	Unlikely	Likely
Estimated age range of brittle ice zone (predicted to occur between 400 and 1,600 m)	2 - 25 kyr	1 - 8 kyr

(Morse and Neumann, personal communication, 2000.)

The results of time-scale calculations are shown in Figure 5. Despite the assumed basal melting of 3 mm/a, the thicker South site promises a more detailed record could be recovered for the early part of the last glacial. The enhanced vertical strain rate for the thinner North site causes it to be a poor candidate for old ice recovery. At the South site, or at some other intermediate ice thickness site, there is a small possibility of collecting ice from MIS-5e that is useable for climate investigations. Although a final site has not been selected, the greater time resolution, longer record, and restriction of brittle ice to the Holocene, makes the deeper south site preferable to the northern site. Ongoing and future site selection studies are required though before this decision can be made.

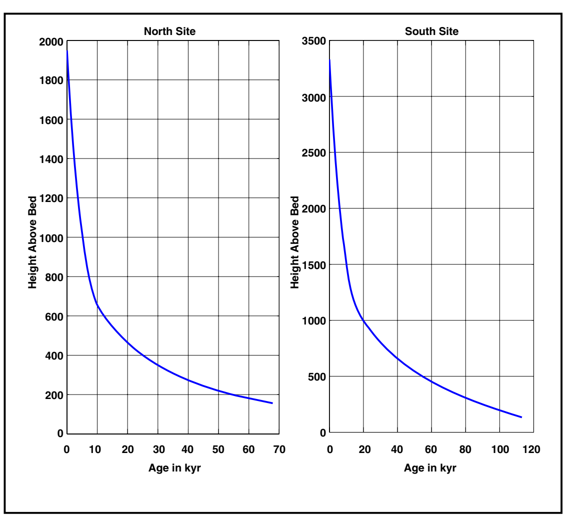

Figure 5: Predicted time scales for the North and South candidate sites. These curves were calculated assuming the glacial accumulation rate decreased steadily to 40% of its modern value at the last glacial maximum (LGM) consistent with prior modeling by Nereson *et al.* (1996). For the South site, a basal melting rate of 3 mm/a was assumed. (Morse and Neumann, personal communication, 2000.)

The current work is based on airborne measurements conducted on a 5 x 5 km grid. During January 2000, new airborne radar data were collected along flow lines intersecting some of these candidate areas[1]. Flow modeling along these new profiles will give further indication of the suitability of these sites for coring as well as guide further ground-based studies. In 2000/2001, the ITASE program is planning to obtain a ~100 m core from one of these areas and will also conduct a limited shallow and intermediate radar program over both sites. The University of Wisconsin installed an automatic weather station in early 2000 at the South site. To select the final drilling site will require more detailed information than these projects will provide. Proposals were submitted in June 2000 for a two-season glaciology project that would include strain nets, detailed surface radar, remote sensing image analysis, and ice flow modeling. One proposal has been submitted to address air mass trajectories in West Antarctica, but more proposals investigating the proposed areas are encouraged.

One idea that is sometimes discussed is using a hot water coring system to rapidly acquire several meters of core from multiple widely spaced depths. For example Engelhardt used the CalTech hot water drill at Siple Dome to acquire about 4 m of core every 100-m of depth. Once the drill had been set up it only required a few days to complete this coring. The current CalTech drill is limited to a depth of 1,000 m. The depth limit could be increased with additional equipment. These cores gave us a preview of what we would see in the main core but this information did not alter the planned activities. If the site selection has been done properly, it is difficult to imagine what new information hot water coring would provide that would require altering the science plan. Hot water coring does not provide a continuous record, and the thermal history of the cores is not compatible with many analysis methods.

We do not recommend using the hot water coring system to acquire cores at the Western Divide site unless the system is going to also be used for other purposes such as drilling holes for vertical strain experiments. We feel that the resources required to extend the operating depth of the hot water system and to put the drill in the field would be better spent on preparing the deep drill coring system, supporting other science activities, or being held in reserve for unanticipated situations.

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[1] Further information on this project is available at: http://www.ig.utexas.edu/research/projects/wais/divide/divide.html.

Another rapid drilling technology that has been proposed is a hose-mounted mechanical drill. The approach uses the hydraulic force of the downward-moving drilling fluid in the hose to turn a drill bit that pulverizes the ice in front of the drill. The ice chips are carried to the surface by the upward flow of the drilling fluid in the hole. This technology has been used in commercial drilling applications and has been proposed for ice drilling (Clow, personal communication, 1996 to 2000). This method can also be used to collect cores, however, the large amount of hose required to operate the system makes it impractical to do large amounts of coring. This system is a perfect complement to the traditional core drilling approach because it allows rapid collection of cores in areas of special interest. After the main core has been drilled, this system should be used to collect additional replicate cores from depth intervals of special interest. Use of this drill to measure geothermal heat flux in the region around the drilling site would improve the ice flow models that assist the interpretation of the ice core. This drill could also be used to test design concepts for coring drill heads (a.k.a. drill bits) before they are used on the deep coring drill.

DETAILED OBJECTIVES

The broad objectives discussed above led to defining the desirable characteristics of the drilling site. Now that the characteristics of the site have been defined, it is possible to discuss specific objectives in greater detail. This section explains the specific objectives for this program.

Holocene Variability

The earth's climate is always changing. The socially relevant question is to determine if the current changes that are taking place are abnormal by comparison to the changes during the last several thousand years. To answer this question, we need climate records that extend back several thousands of years. Records that are several hundred years long are too short to determine if the current changes are abnormal. Time scales longer than a few thousand years are influenced by orbital factors and are not relevant to the question of athropogenic-related climate change. We propose to develop annually dated records of accumulation rate, atmospheric circulation, atmospheric chemistry, biomass indices, surface temperature, and sea ice extent. The methods that will be used are listed in Table 2. Borehole paleothermometry will be used to develop a low temporal resolution record of the surface temperature that does not depend on proxy relationships between the measured property and the interpreted climate record (Clow, 1999). The records will be used to address issues such as changes in the Southern Oscillation Index, the strength of the Antarctic vortex, sea ice extent, and biogeochemical cycling. We will search for changes that are coincident with the anthropogenic era, and we will use the length of the records to place any recent changes into perspective. We will also search for Holocene evidence of the ~1,500 year oscillation that is associated with the Dansgaard-Oeschger events in the North Atlantic. There is some evidence that these oscillations continue into the Holocene (Bond *et al*., 1997; Denton and Karlen, 1973; Keigwin and Jones, 1998).

Solar Influences on Climate

The influence of solar activity on climate has been the subject of much research but has led to inconclusive results (Beer *et al*., 2000). Numerous ice core studies have shown a correlation between solar activity and climate (Ram *et al*., 1997; Ram and Stolz, 1999; Ram *et al*., (in press); Taylor *et al*., 1992; Mayewski *et al*., 1994). The high resolution of this record will make it possible to investigate the influence of the 11-year sun spot cycle, and longer time period solar activity, on climate. The numerous climate proxy records will allow many aspects of the climate system to be compared to solar activity. Annual cosmogenic isotope measurements may also be used in selected intervals to provide proxy records for solar activity.

Table 2. Methods used to develop climate proxy records.

Climate Proxy Record	Methods That Will Be Used To Develop Record
Annual accumulation and dating of shallow-to-intermediate ice where annual layers can be counted	Visual stratigraphy Electrical measurements of acids and salts Optical measurements of dust Optical measurements of bubble size and concentration Continuous flow chemistry High frequency radar Beta horizons Volcanic markers ^{10}Be and ^{14}C Ice dynamics
Dating of deep ice where annual layers cannot be counted	Correlation of methane and atmospheric oxygen isotopes to other records
Paleo-surface temperature	Deuterium, $\delta^{18}O$ Borehole temperatures Gas isotopes Surface melt layers
Paleo-sea-surface temperature in tropical regions	Deuterium excess
Atmospheric circulation and chemistry	Major ions and other soluble species Trace element analysis of insoluble dust Mineralogy of insoluble dust Radiogenic isotope analysis of insoluble dust Carbon Monoxide
Strength of Antarctic vortex	Major ions

Biomass and biogeochemical process	Biological material in the core Atmospheric carbon isotopes Atmospheric Oxygen Isotopes Major ions Atmospheric methane Nitrous oxide MSA
Non-polar surface temperature and atmospheric transport	Changes in biodiversity of biological material in the core
Age of ice sheet	Diatoms from basal sample

Nature of the Last Climate Transition in Antarctica

Numerous Antarctic ice cores document the climate transitions from the last glacial maximum to current conditions. Unfortunately, all of these cores are at sites that have low annual ice accumulation rates. This reduces the resolution of the records and increases the uncertainty in the difference between the age of the ice and the age of the gas in the ice. The sites we propose have a high accumulation rate (>25 cm/year). This will assure us annual time resolution at the Holocene/Wisconsin transition. The annual time resolution will make it possible to investigate the phase relationship of the measured climate parameters and permit a good comparison of the phase relationship between the Western Divide site and other areas. This will help us to determine where the climate transition started and what aspect of the climate system changed first.

Expression of Dansgaard-Oeschger Events in West Antarctica

The Dansgaard-Oeschger events are well documented in the Greenland ice cores and numerous ocean cores from around the world (Johnsen *et al.*, 1992; Taylor *et al.*, 1993; Bond *et al.*,1997; Alley and Clark, 1999). Climate events related to the Dansgaard-Oeschger events also show up in the Taylor Dome, Vostok and Byrd cores; however the expression of the smaller Dansgaard-Oeschger events is not clear in Antarctica (Blunier *et al.*, 1998). To understand the role of the southern oceans in the Dansgaard-Oeschger cycles, it is important to understand how climate features associated with the Dansgaard-Oeschger events are reflected across Antarctica and correlate with climate changes in the Northern Hemisphere. Measurements of paleo-atmospheric methane and oxygen provides a stratigraphic tool for correlating climate records from different sites.

Phase Relationship between Surface Temperature and Atmospheric CO_2

The Western Divide core will provide an excellent opportunity to determine the phase relationship between atmospheric CO_2 and surface temperature. The accumulation rate is high enough that there will be near-annual resolution, yet not so high that the relevant portions of the record will be excessively thinned by ice flow. Measurements of the thermal fractionation of nitrogen and argon will be used to identify when the surface temperature changed (Severinghaus *et al.*, 1998b) and will be compared to measurements of atmospheric CO_2 and methane. Timing uncertainties associated with the gas age/ice age relationship will be avoided by using gas measurements to determine when the temperature change occurred. It is anticipated that leads and lags of greater than 50 years will be detectable. It should also be possible to develop a record of atmospheric $CO_{2,}$ NH_4 and N_2O with decadal time resolution during periods of special interest. On this time scale, atmospheric CO_2 may be influenced by changes in the sequestering of carbon by deep-water formation, so the record might give us an indication of the changes in the global production of deep water during rapid climate transitions. N_2O will tell us about the response and phasing of changes in the global nitrogen cycle (Sowers and Jubenville, in review; Fluckiger *et al*., 1999).

Biology of the Basal Environment

The contact between the ice and the bed is likely to contain liquid water. The presence of liquid water has been shown to be the key to life on our planet, where there is liquid water there is biological activity (Kennedy 1999, Priscu *et a*l. 1998, 1999, Karl *et al*. 1999, Price, 2000). The basal ice environment is likely to have started as a marine environment that was covered by ice, and has been effectively isolated from the rest of earth's biosphere for more than 100,000 years. Investigation of the biological populations and activities in this type of ice/bedrock environment has never been accomplished and would will yield new information on the structure and function of these novel systems. Studies in the ice and basal water layer may allow us to extent the limits of the biosphere and further our understanding of carbon biogeochemistry on Earth. Sub-ice biology programs are also being discussed for Lake Vostok and a sub-ice lake near South Pole. These sites are not paleomarine environments and hence complement the paleomarine environment at the Western Divide Site.

Microbial Biology of the Ice

Ice sheets potentially harbor a range of microbial life forms (Abyzov *et al.* 1998, Priscu et al. 1999). Some of these life forms may be in resting stages but still viable, while others may be minimally active within the ice (Fritsen and Priscu 1998, Karl *et al.* 1999, Price 2000). Phylogenetic identification of microbes in ice from the WAISCORES project would allow us to determine the type of microbial assemblages associated with specific atmospheric deposition events. Such data would also provide information on the source of the deposition (e.g., aquatic, terrestrial), that would support concurrent sulfur and gas measurements. Microbial characterization through the cores will also yield a biodiversity index for the period recorded within the cores. It will be possible to develop paleoclimate records of changes in the microbial assemblage, much like that developed from pollen records, which occur in response to specific environmental stresses.

Recent work (Price 2000) has shown that triple junctions between ice crystals can contain adequate carbon and energy sources to support an active microbial assemblage in "solid" ice. If this turns out to be true, then this metabolism may alter gas and chemical signatures within the ice core, affecting the interpretation of climate variation. It is important that the nature and magnitude of biological activity be know for an accurate depiction of climate record to be made.

History of West Antarctic Ice Dynamics

The volume of the West Antarctic Ice Sheet is decreasing on millennia time scales. There is uncertainty regarding how the current rate of decrease compares to the rate of change over the last several millenniums (Squeak and Diddlesworth, 1987, Conway *et al.*, 1999). There is also uncertainty regarding how large and consistent future changes will be. To address this issue, we need to know how the West Antarctic Ice Sheet has changed during the last ~60,000 years. To do this, it is necessary to know how much the surface elevation of the ice divide in West Antarctica has changed. The best way to do this is to compare the age-depth relationship observed in a core with ice dynamics models that hypothesize a range of different possible histories for the ice sheet geometry. The model that best fits the observed age-depth relationship is considered to be the leading candidate for a description of the history of the ice sheet geometry. Further confidence in this interpretation can be gained by incorporating measurements of the total gas content of ice from different ages. Although the interpretation of the total gas content is not always straightforward, it does give an indication of paleo-surface elevations (Raynaud *et al.*, 1997; Martinerie *et al.*, 1992). Changes of greater than 300 m should be detectable (Brook, personal communication, 2000). Low accumulation rates in the past and rapid thinning of the ice sheet both produce thin layers. These two processes can be differentiated by measuring an accumulation proxy such as ^{10}Be that does not depend on ice dynamics.

Age of the Ice Sheet

An important question is how old is the West Antarctica ice sheet? If it persisted through the warm MIS-5e period, then we will have greater confidence that it will continue to persist through the current warm period. If there was no ice in West Antarctica during the warm MIS-5e, then we will have a greater concern regarding the current stability of the West Antarctic ice sheet and the possibility of large and rapid increases in sea level. It is difficult to determine the age of the oldest ice because the stratigraphic sequence of the ice is likely to be disturbed near the bed and the time scale is compressed by ice flow. Exposure age dating methods on bedrock samples will not be effective at the south site because in the absence of ice the site would have been below sea level. Diatoms may be useful for determining the last time the site was ice-free. Recent advances in thermal luminescence dating methods provide a small possibility of determining the age of the oldest ice by dating the last time the dust in the ice was exposed to sunlight. Paleomagnetics might be useful if an intact marine section is recovered from below the ice. Isotopic decay of ^{230}Th and ^{10}Be may also provide a way to determine when basal marine sediments were last deposited from ocean water.

Determination of Geothermal Heat Flow

An understanding of the geothermal heat flow would improve our understanding of the rift system upon which the West Antarctic ice sheet is draped. The geothermal heat flow in the rift system may be high if the rift system is still active as is suggested by the presence of active volcanoes in Marie Byrd Land and the TransAntarctic Mountains. The geothermal heat flux and its spatial variations have an impact on the dynamics of the overlying ice sheet (Payne, 1995) by influencing where the bed is frozen or melting. Geothermal heat flux also influences the temperature distribution in the ice sheet, which in turn influences the rate of shear strain in the ice. If the geothermal flux is sufficiently high, widespread basal melting allows unstable behavior. If the geothermal flux is low, basal freezing may suppress instabilities (MacAyeal, 1993). Despite the importance of the geothermal heat flux to understanding the dynamics of the ice sheet, there are no geothermal heat flux measurements in West Antarctica. Constraints on the geothermal heat flux at Siple Dome will be available soon. Once the Western Divide core is recovered, it will be relatively simple to measure the geothermal heat flux at the base of the resulting borehole.

Flow Law of Ice Deformation

Ice-sheet models are used to predict future ice volumes and sea-level change, and to help interpret paleoclimate records. The models rely on an understanding of how the ice moves in response to a force. The strain rate is typically assumed to increase with some power of the stress, to increase exponentially with temperature, and to depend on c-axis fabric, impurities and perhaps other factors (Thorsteinsson *et al.*, 1999; Alley, 1992b). Laboratory studies cannot reach the deformation conditions that dominate much of ice-sheet ice, and theoretical understanding is not sufficient to calculate the flow law from first principles. Field observations are used to calibrate the flow law for use across broad regions. A deep core is a key element in flow-law studies because it provides data on ice fabric and impurities, and provides access to the ice for sonic logging, thermometry, and repeat inclinometry.

Process-Level Atmospheric Chemistry Studies

The composition of air over an ice-core site is the result of air masses from multiple sources and is altered by changes en route. Post-depositional modification of the chemical record greatly complicates quantitative interpretation of the ice-core record. Process-level transfer studies and atmospheric chemistry measurements over multiple years are necessary to understand the temporal and spatial variability recorded in ice cores. Sampling and measurements could be taken during the field season. Ideally, automatic systems would also make measurements during the winter. Such studies at the deep drilling site, which are not possible on the highly mobile ITASE program, would enhance both programs.

METHODS

Site Selection

Initial site selection is underway using a combination of airborne geophysics, satellite imagery, and ice dynamics modeling (Morse, personal communication, 2000). These results were summarized above. This work is based on a 5 x 5 km grid spacing of the flight lines and is sufficient to define a few candidate areas where the core might be drilled, but it is not sufficient to select the exact location of the drilling site. A surface program is required to choose the exact location of the drilling site. Key elements of this surface program include glaciological field studies to determine the history of divide migration, spatial patterns of accumulation, and the current horizontal strain field. These glaciological studies can be done with a combination of shallow and deep sounding surface radar traverses and surface strain nets. Interferometric Synthetic Aperture Radar should also be part of the site selection program to determine strain rates and ice velocities. The field observations then have to be incorporated into ice flow models of the potential sites. Key questions to address include the following:

- Estimation of the age/depth scale.
- Estimation of the depth at which stratigraphic continuity might be lost.
- Estimation of the impact divide migration might have on the climate record.

These questions must be answered for several locations within each of the candidate areas. Proposals for these activities were submitted in June 2000.

In addition to the glaciology program, it is important to characterize the preservation of annual layering at the candidate sites. This can be done with a series of snow pits that will allow visual observation and documentation of the annual layers. A two-dimensional array of closely spaced shallow cores should be recovered to determine how well the annual signal correlates between the cores. We envision an array of five cores in a cross pattern, each core being about 10 m deep and about 5 m away from the adjacent core. In addition to the spatial continuity issue, we need to confirm that we can accurately count the annual layers. To do this, we should also recover a core that contains a 200-year-long record. This core will be used to check our dating methods against events of known time (e.g., atmospheric nuclear tests and known volcanic events). This combination of a shallow array and a 200-year record will allow us to determine which of the candidate areas will be best for the preservation of annually resolved layers. These shallow site selection cores would be measured with a variety of chemical, isotopic, electrical and visual stratigraphic methods. The ITASE program may accomplish some or all of these coring and snow pit activities.

Meteorological modeling should be done to determine if there are significant differences in the climatology of the proposed drilling sites. The accumulation rate is different in the different areas, so it is possible that there may be significant climate differences on short spatial scales. For example, one area may be a better recorder of ENSO events than the other. To our knowledge, as of June 2000, only one proposal has been submitted for this activity and we encourage more proposals related to this topic.

The final site selection will be made after these studies have been completed. Members of the ice core community will select a site that balances the inevitable tradeoffs between these different issues. Interested PIs include: Richard Alley, Roger Bales, Howard Conway, Joe McConnell, Dave Morse, Kendrick Taylor, and Ed Waddington.

Ice Dynamics

Deep polar ice is deformed as it travels from where it is deposited on the surface to where it is collected by ice coring. The climate where the ice was deposited also depends on the elevation and shape of the ice sheet when the ice was deposited. An ice dynamics program is required to understand how the shape and elevation of the ice sheet influenced the climate, and how the paleoclimate record in the ice has been altered by ice flow. An ice dynamics program can determine the original locations and elevations of ice deposition. This allows spatial gradients of climate to be separated from temporal changes in climate. An ice dynamics program also determines how much the ice flow decreased the thickness of the annual layers, allowing the observed thickness of annual layers to be converted into annual accumulation rates. Interested PIs include: Dave Morse, Howard Conway, Nadine Nereson, Charlie Raymond and Ed Waddington.

Meteorological Modeling

To develop a climate interpretation, we need a quantitative understanding of how climate influences the ice core properties we measure. To do this, we need to know the paths air masses have taken over the site, and how those paths have influenced the chemical and isotopic properties of the air mass. We also need to know what the modern variability of these influences is and how this variability might have changed in the past. In particular, we need regional back trajectory analysis coupled to local orographic and transport models. Existing data provide a means to relate ice core records to larger features of the atmosphere such as the Southern Oscillation (Kreutz *et al*., 2000). Back trajectory analysis from reanalysis data sets helps to identify the source area for the water and associated chemistry in the core (Noone and Simmonds, 1998). Recent developments in climate downscaling in temperate latitudes (Cavazos, 1999; Crane and Hewitson, 1998; Hewitson and Crane, 1996) suggest it may be possible to acquire subgrid-scale climate data for the Antarctic without the cost of mesoscale climate modeling (van Lipzig, 1999, Reusch and Alley, 2000). Chemical and isotopic tracers should be included into the models so that the ice core measurements can be quantitatively interpreted. Interested PIs include: Richard Alley, Pierre Biscaye, Dave Bromwich, Joe McConnell, and Dave Reusch.

Atmospheric Chemistry

The composition of air over an ice-core site is the result of air masses from multiple source regions and the changes that occur en route. For most species, ice cores record monthly to seasonal values at best, even in high-accumulation regions. Atmospheric chemistry measurements over multiple years are necessary to understand the temporal and spatial variability recorded in ice cores. The nearest continuous measurement site is South Pole, with Halley and von Neumeyer on the coast next. Sampling and measurements are needed during the summer when the camp is occupied, to link this site to the continuous records at permanent stations. Measurements that should be made include hydrogen peroxide, formaldehyde, aerosols, hydrocarbons, and balloon/kite soundings and energy balance. Ideally, winterover measurements would be made as well, possibly by automatic systems. Measurements of particulate organic carbon and nitrogen will provide information on the proportion of particulate matter within the ice that is organic. This information will also be important to understand the carbon and nitrogen sources; and thermodynamics, of microbes that may exist within and beneath the ice. Interested PIs include: Roger Bales, Joe McConnell, and John Priscu.

Ice Core Dating

As much of the core as possible will be dated by counting annual layers. We will attempt to identify annual layers with the methods listed in Table 3. In areas of special interest and as a check of our methodology, we will employ ^{10}Be to identify the 11-year solar cycle that is preserved even when some individual years cannot be identified (Steig *et al*., 1988b) and comparison to century scale features in the ^{14}C record (Nishiizumu and Finkel, 1997). To check our counting accuracy, we use horizons of known age such as beta peaks from nuclear tests and volcanic eruptions of known age. Based on flow modeling, we believe we can count annual layers to ~28,000 years before present (Morse, 2000 personal communication). Correlation of the atmospheric methane and oxygen isotope records to other dated records will be used to date sections of the core that do not have annual layers. Interested PIs include: Richard Alley, Roger Bales, Michael Bender, Ed Brook, Tony Gow, Paul Mayewski, Joe McConnell, Deb Meese, Todd Sowers, Michael Ram, Kendrick Taylor, Jim White and Greg Zielinski.

Table 3. Methods used to identify annual layers.

Method
Major ion analysis
Visual stratigraphy
Direct current electrical conductivity (acids)
Alternating current electrical conductivity (all ions)
Ice albedo
^{10}Be (to count 11-year solar cycles)
Bubble concentration
Dust concentration

Hydrogen peroxide (for top 100 m only)	
Stable isotopes (for top 100 m only)	

Annual Ice Accumulation Rate

The annual accumulation rate of ice is an important characteristic of climate that tells us the net flux of moisture to the site. The annual accumulation rate is also used to determine chemical and biological fluxes and as one of the forcing functions for ice flow models. Annual accumulation is calculated by adjusting the thickness of the annual layers for ice flow (Alley *et al.*, 1993; Cutler *et al.*, 1995; Cuffey and Clow, 1997). To check our understanding of the interaction of accumulation on ice flow, ^{10}Be and ^{14}C should also be used to determine accumulation rate in selected intervals. Interested PIs include: Richard Alley, Ed Brook, Bob Finkel, Tony Gow, D. Lal, Paul Mayewski, Deb Meese, Michael Ram, Eric Steig, Kendrick Taylor, Ed Waddington, Jim White and Greg Zielinski.

Stable Isotopes of Oxygen and Hydrogen in Ice

The isotopic signature of the oxygen and hydrogen in the water of the ice depends on the environmental conditions when the snow fell. Major environmental influences are the storm track, moisture source area, and humidity and temperature of the moisture source area. Deuterium and $\delta^{18}O$ are the benchmark records of an ice core that are used for climate interpretations and comparison to most other paleoclimate records. A simplistic interpretation of the records is that they are primarily a reflection of surface temperature when the snow fell. Deuterium excess, which is a function of the difference between deuterium and $\delta^{18}O$, is frequently considered to reflect the temperature of the source area. Interested PIs include: Eric Steig and Jim White.

Gas Measurements

Ice cores contain samples of the atmosphere from previous times. The methane concentration of the paleo-atmosphere can be measured and methods for methane isotopic measurements are being developed. This core would provide the longest continuous layer counting time scale for a Southern Hemisphere record. By comparing the methane record from this core to the GISP2 methane record it will be possible to determine the interpolar methane gradient with considerably more precision than is currently possible. The methane gradient is useful for determining the location of methane source regions. Isotopic measurements on methane also help characterize methane sources. Understanding how the sources of methane change is critical for understanding the climate phenomena associated with the Dansgaard-Oeschger events. The high time resolution available from this record will also allow us to examine rapid fluctuations in the existing methane records that do not coincide with variations in Greenland surface temperature (Brook *et al.*, in press), but that do appear similar to rapid oscillation in subtropical sea surface temperature (Sachs and Lehman, 1999). Interested PIs include: Ed Brook, Susan Harder, Jeff Severinghaus and Todd Sowers.

The carbon dioxide concentration in the paleo-atmosphere can also be measured (Petit *et al.*, 1999b). Greenland ice cores are not suitable for this work because of *in situ* production of CO_2 from the reaction of calcium carbonate dust and acids. Antarctic cores have about 100 times less dust than Greenland cores and can be used to produce good atmospheric CO_2 records. Currently, we have CO_2 records from Vostok (Petit *et al.*, 1999a), Byrd (Neftel *et al.*, 1988) and Taylor Dome (Indermuhle *et al.*, 2000). In every core, the age of the ice at a given depth is different than the age of the gas at the same depth. In the Taylor Dome and Vostok core, the uncertainty in the gas age-ice age difference is many hundreds to a few thousand years, which makes it difficult to compare the phase relationship of CO_2 to other parameters. The Byrd core has a gas age-ice age uncertainty of a few hundreds of years, which makes it more suitable for investigating the phase relationship of atmospheric CO_2 and climate changes. The Byrd measurements were made on ice that had been stored for a long time. Although the Byrd record is widely accepted, the role of atmospheric CO_2 in climate change is so significant that this record should be replicated at the Western Divide site with higher temporal resolution and modern methods. Interested PIs include: Todd Sowers, Martin Wahlen.

Carbon monoxide plays an important role in the oxidation processes that control the atmospheric concentration of $C0_2$, CH_4 and O_3. In order to understand the atmospheric process that operated in the past we need to know the paleo-concentration of atmospheric CO. Interested PIs include: Ed Brook, Susan Harder.

When gas is deep enough in the firn that it is not mixed by wind, some isotopes will fractionate in response to gravity and temperature gradients. Measurements of the isotopic concentration of argon and nitrogen can be used to determine how much of this fractionation was caused by an abrupt change in surface temperature that altered the temperature gradient. This effect can be modeled to determine the magnitude of the temperature change and to determine the gas age-ice age difference (Severinghaus *et al.*, 1998). This is a powerful tool for investigating the phase relationship between changes in the concentration of atmospheric gasses and climate. Interested PIs include: Jeff Severinghaus.

Major Soluble Species

Analysis of a selected suite of major ions (Na^+, Ca^{2+}, Mg^{2+}, K^+, NH_4^+, Cl^-, NO_3^-, and SO_4^{2-}) via ion chromatography provides information on water-soluble aerosols and certain gas-phase species deposited onto the ice sheet. In West Antarctica, sea-salt and biogenic aerosols transported onto the polar plateau from coastal regions dominate the ionic balance of precipitation (Kreutz and Mayewski, 1999; Reusch *et al.*, 1999). When correlated with modern atmospheric data and model fields on annual and interannual time scales (Kreutz *et al.*, 2000), major ion records of aerosol transport developed from the Western Divide core have the potential to provide estimates of synoptic-scale atmospheric circulation conditions in West Antarctica as well as teleconnections with subtropical regions (i.e., ENSO) throughout the Holocene (e.g., Kreutz *et al.*, 1997). In addition, total SO_4^{2-} concentrations represent a combination of sea-salt, biogenic, and volcanic emissions, and thus can be used to investigate marine productivity, volcanic activity (see MSA and volcanic sections), and potentially sea-ice extent (Welch *et al.*, 1993). Interested PIs include: Paul Mayewski and Karl Kreutz.

Analysis of other major species, including hydrogen peroxide and formaldehyde, provides indications of past atmospheric chemistry. Partial records previously developed for the Byrd Station and Siple Station cores in West Antarctica show potentially large changes in these species during the Holocene (Staffelbach *et al.*, 1991; Neftel and Klockow, 1986). Formaldehyde analyses would need to be done on site. Interested PIs include: Roger Bales, Joe McConnell.

We note that advances in analysis systems make it possible to measure a wide suite of soluble chemical species with high spatial resolution, high precision, low detection limits and reasonable economics. These systems are based on the continuous analysis of melt water from a melting subsection of core. European investigators started to develop this technology during the GRIP program and have refined it further. Regretfully, the nature of funding in the U.S. has made it difficult for us to incorporate the major advances in soluble chemistry analysis into our programs. We hope that at the start of this project the U.S. capabilities in this area can be made comparable with our European colleagues.

Electrical Methods

Electrical methods provide information on the major chemical characteristics of the ice. These methods have the best spatial resolution of any of the continuous methods and hence are well suited for the identification of short-duration features such as annual layering, volcanic eruptions and biomass burning (Taylor *et al.*, 1993, 1997, 1998). Methods that measure the acidity and total ion content of the ice will be employed. A new method that provides a two-dimensional map of the acidity of the ice along a vertical plane will be used to investigate flow disturbances and inclined layering. Interested PIs include: Kendrick Taylor

Atmosphere-Snow Transfer Issues

To quantitatively interpret the ice-core chemical and isotopic record requires detailed understanding of the physical processes that control atmosphere-to-snow transfer of chemical species and water. Studies demonstrate the importance of post-depositional modification of hydrogen peroxide (McConnell *et al.*, 1998, 1999), formaldehyde (Hutterli *et al.*, 1999), nitrate (Honrath *et al.*, 1999; Jones *et al.*, 2000) and water

(Whillans and Grootes, 1985). Coupled atmosphere and snow chemistry studies are ongoing at Summit, Greenland, at South Pole (McConnell *et al.*, 1998; Davis *et al.*, 1999) and at the European stations at Halley Bay and von Neumeyer. Atmosphere-snow transfer studies of sufficient duration are not possible on the ITASE traverse. A modest program was implemented at the Siple Dome deep drilling site but warm temperatures and low accumulation rates prevented long-term preservation of many volatile species. Preservation of volatile species will be better at the Western Divide site because of colder temperatures and a higher accumulation rate (McConnell *et al.*, 1999). The multiyear occupation of the drilling site provides an ideal opportunity to conduct a coupled atmosphere and snow chemistry program. Such a program would ideally include gas-phase measurements of photochemically active species such as hydrogen peroxide and formaldehyde, nitrate, NO_x, and O_3 along with snow, firn and ice measurements of related chemical species. Surface energy balance and meteorological conditions will also need to be measured. The physical characteristics that control the movement of air through the firn will need to be incorporated into these studies. Ideally, some of these measurements and samples can be collected by automatic systems during the winter. Interested PIs include: Mary Albert, Roger Bales, Gayle Dana, Jack Dibb, Joe McConnell, and Chris Shuman.

Physical Properties

Physical properties research involves the physical characterization of the core. When favorable conditions exist, visual examination of the core can identify the location of annual layers, volcanic layers, melt layers, and flow disturbances. Grain size, bubble-size, and c-axis fabric record the deformational history integrated over some time, and affect the softness of the ice in deformation. Physical properties researchers provide real-time advice to the drilling operation and the subsequent core processing. This activity would require a field component to observe changes that occur shortly after the core is recovered. Interested PIs include: Richard Alley, Tony Gow, Deb Meese, Joan Fitzpatrick, and Larry Wilen.

Insoluble Particles

Insoluble particles can be counted and sized with Coulter counter or optical methods on melted samples. In ice where the bubbles have gone into clathrates, a proxy for the dust concentration can be developed using optical measurements on the core (Ram *et al.*, 1997; Ram and Koenig, 1997). These measurements can identify the major climate cycles and in favorable conditions can detect annual layers. Interested PIs include: Michael Ram and Michael Stolz.

Bubble Evolution

The transition of gas bubbles to clathrates may have implications on the preservation of gas records. Bubble shape provides information on ice deformation. Bubble size may provide an indication of accumulation rate. Several methods exist for measuring bubble characteristics including optical measurements on intact cores (Ram and Stolz, 1999) and thick and thin sections (Fitzpatrick, personal communication, 1999). This activity would require a field component to observe changes in bubble characteristics that occur shortly after the core is recovered. Interested PIs include: Richard Alley, Joan Fitzpatrick, Michael Ram and Michael Stolz.

Volcanics

Volcanic eruptions produce gases that eventually oxidize to acids as well as mineral matter including the volcanic glass component (tephra). Both of these products are preserved in ice cores, thereby providing a detailed chronology of past volcanism including the climatic-forcing potential of past eruptions as well as distinct timelines useful for developing the depth-age scale of the core (Zielinski, 2000). H_2SO_4 is the dominant climate-forcing component of an eruption and will be transported over much greater distances than the HCl and HF components. However, all three acids can be detected in ice cores through electrical methods that are sensitive to total acids (Hammer *et al.*, 1980), total ions (Taylor, personal communication, 1998), and through ion chemistry (Lyons *et al.*, 1990). Tephra may be detected by optical microscope scans with composition of the glass determined by scanning electron microscope and microprobe techniques (Zielinski *et al.*, 1997). Matching glass composition in the core with that from glass known to have been derived from a particular eruption can verify the source of the acidic signal (Palais *et al.*, 1990). Interested PIs include: Richard Alley, Pierre Biscaye, Tony Gow, Paul Mayewski, Deb Meese, Michael Ram, Kendrick Taylor, Jim White, and Greg Zielinski.

Continental Provenance of Insoluble Particles

The atmosphere transports insoluble dust to Antarctica. Using chemical tracers it is possible to determine the continent the dust originated from, and infer paleo-atmospheric circulation patterns. The tracers used to match ice-core dusts to their possible source areas have been fine-fraction (clay) mineralogy, and the radiogenic isotopic composition of the elements Sr, Nd and Pb. Clay mineralogy reflects the weathering regime in the source area, and the three radiogenic isotopes reflect the lithology and geologic age of the rocks from which the sediments in the source region were derived. These four independent tracers vary in the sediments derived from rocks over the continental surface of the earth on spatial scales comparable to those of eroding and transporting winds. The combined use of these tracers makes it possible to determine the sources of ice-core dust in both Antarctica (Grousset *et al.*, 1992; Basile *et al.*, 1997) and in Greenland (Biscaye *et al.*, 1997; Svensson *et al.*, 2000). Interested PIs include: Pierre Biscaye and Francis Grousset.

Rare Earth Elements

New analytical methods make it practical to determine the concentration of rare earth elements in an ice core with more samples and greater time resolution than in previous studies. This raises the possibility of measuring the temporal changes in the composition of crustal material in an ice core on yearly to decadal time scales. One such application has been the measurement of the rare earth elements, which forms a chemically cohesive series of 14 lanthanide elements (La through Lu) and which fractionate under various petrogenic processes (Henderson, 1984). The compositions of these elements have the potential to identify source-specific dust inputs to remote ice core sites, assuming that the source material is geochemically distinct and does not undergo significant alteration in transport. Such measurements have been made in polar ice core samples from the Last Glacial Maximum (Grousset *et al.*, 1992; Basile *et al.*, 1997; Svensson *et al.*, 2000), modern Antarctic snow (Ikegawa *et al.*, 1999), and a Central Asian firn core (Kreutz and Sholkovitz, 2000); these data have proven very useful for identifying volcanic and lithogenic dust inputs. A continuous record of rare earth elements with annual to decadal resolution from the Western Divide core, when combined with mineralogy and isotopic studies, would offer the potential to examine temporal changes in large-scale atmospheric transport pathways in the Southern Hemisphere. Interested PIs include: Karl Kreutz and Kendrick Taylor.

Exterrestrial Particles

Orbital dynamics may result in the earth periodically passing through dust bands in the solar system, which may have an influence on climate. Polar ice is an archive of exterrestrial dust. Measurements on the ice core of elements and isotopes that are enriched in exterrestrial particles can be used to constrain the flux of ex terrestrial particles to the earth surface (Brook *et al.,* in review). This may improve our understanding of orbital influences on climate. Interested PIs include: Ed Brook and Mark Kurz

Microfossils

Diatoms and radiolarians occurring in basal sediments may provide an indication of the last time the drill site was ice-free. Collection of as much basal material as possible is encouraged to facilitate these studies. Interested PIs include: Lloyd Burckle and Reed Scherer.

Borehole Methods

Borehole paleothermometry is expected to yield the surface-temperature history for the last 40,000 years. We should be able to establish the magnitude of the temperature difference between the Last Glacial Maximum and the Holocene (e.g., Cuffey *et al.* 1995; Cuffey and Clow, 1997; Dahl-Jensen *et al.*, 1998) and the magnitude of temperature trends during the Holocene, especially for the last 4 kyr (Clow, 1999). This will provide important information quantifying the magnitude of long-term temperature changes in Antarctica. The regional geothermal heat flux (e.g., Dahl-Jensen *et al.*, 1998) will also be determined if the bed is frozen. Despite the influence the geothermal heat flux has on the dynamics of the ice sheet there are no geothermal heat flux measurements in West Antarctica. The temperature profile also provides important information for understanding the local ice dynamics because the strain rates are exponentially dependent on temperature. Interested PI: Gary Clow.

A borehole method to measure the general characteristics of the ice fabric is well-developed (Bentley, 1972**;** Taylor, 1982). The method depends on the influence of the velocity of a vertically traveling compression wave on the orientation of the ice crystals. When combined with thin section studies, this method allows the influence of ice fabric to be incorporated into ice flow models (Thorsteinsson *et al.*, 1999). Interested PIs include: Gregg Lamorey and Kendrick Taylor.

Biological Methods

Biological analysis will allow us to determine the types and metabolic patterns of microorganisms deposited on the ice over time. Cryo-SEM (with energy dispersive spectrometry) and TEM will identify particulate organic matter (viral, cellular and detrital) and determine mineral composition and size of sediment particles. Phylogenetic characterization of viruses, prokaryotes and eukaryotes throughout the core can use molecular DNA-based methods, which are suitable to samples of low biomass. Phospholipid fatty acid analysis can also be used to identify the diversity of prokaryotic microbes. Oligonucleotide DNA probes developed from microbes in the ice can be used to define the source of microbes within the ice and in subglacial liquid water. Molecular and electron microscope methods can be combined with epifluorescence microscopy to enumerate DNA stained bacterial and viral particles.

DNA fingerprinting by the methods described above provides the best means for describing the microbial community genetic structure. However, the relative activity of the community members is best assessed by rRNA analysis (Teske et al.1996, Miskin et al. 1999). RT-PCR of ribosomal genes and direct probing of total RNA extracted from environmental samples are two common and straightforward techniques. Theoretically these techniques should be as sensitive as the DNA techniques, though their limits have not been fully tested. Molecular identification and characterization of viruses can be accomplished by sequence analysis. A DNA library (and/or cDNA library if RNA viruses are detected) can be constructed in E. coli using both cosmid and plasmid based vectors. Clones from the library will then serve as both templates for DNA sequence analysis and as hybridization probes for linking a specific virus morphology with a specific DNA clone.

The physiological responses of melted ice samples and cultures to temperature, pressure, pH, ionic strength, and oxygen regime provides a direct way of assessing conditions associated with distinct ice layers. These data together with the results from the molecular work will allow us to define physiologically distinct regions in the ice core and to assess the origin of the microbes.

Interested PIs include: John Castello, Chris Fritsen, Alison Murray, John Priscu, and Scott Rogers.

Closing Remarks on Science Plan

The program presented above is a logical extension of 30-years of United States ice Core drilling programs. It addresses socially relevant questions related to the magnitude and speed of future climate and sea level changes. It investigates how organic carbon is transformed in deep ice and how life adapts to an extreme environment, the biology of which has never been studied. This program may allow us to extend the bounds of the Earth's biosphere to include deep ice systems. The program includes the disciplines of climatology, glaciology, biology, geology, geophysics, and geochemistry. It builds on our existing infrastructure and analysis methods, yet contains many advances from previous programs. We expect analytical advances during the course of the program.

We encourage international partners to participate in the program. We believe that international collaboration is a way to increase the knowledge base available to the program and a way to provide access to instrumentation without incurring the cost of replicating existing instruments.

We are familiar with the inventory of ice cores, both domestically and internationally, and have determined that the studies proposed here can not be done with existing ice cores. Limiting factors include the location, annual ice accumulation rate, or time span of existing cores. There are no samples of the basal environment suitable for biological analysis. The Byrd core deserves special consideration because of its close proximity to the Western Divide Site. The Bryd core is not on an ice divide so the interpretation of the record is complicated by upstream spatial variability. The Bryd core has been heavily sampled so that the most interesting sections are gone. The storage temperature history of the Bryd core is not well known and some aspects of the record have been compromised.

There is a strong synergism between the climate, biology and ice dynamics aspects of the program. The ice dynamics program requires the age-depth relationship and ice sheet surface elevation history that will be developed by the climate program. The climate program requires the ice dynamics program to select the drill site and remove the influence of ice flow from the climate records. The climate community also requires the biology program to investigate the influence of climate changes on ecosystems and to assure that biological activity in the ice has not influenced the climate record preserved in the ice. The biology program requires the climate program to determine the age and climate context of the biological material in the ice. Most of the objectives of this program can not be accomplished with out an interdisciplinary approach.

We anticipate publications in leading journals that will have a major influence on our understanding of the earth's future climate and sea level. We are confident that this will occur because all previous major ice-coring projects have led to such advances and this project can be expected to do the same. This is the first time the biology community has been fully integrated into a deep ice core program. The biology program will develop results from environments that have not been previously investigated, and hence will expand our knowledge about how life adapts to challenging conditions.

IMPLEMENTATION PLAN

OVERVIEW

The National Science Foundation has conducted three deep ice coring projects in the last 10 years including the GISP2, Taylor Dome, and Siple Dome projects. The ice and rock coring technology required for most of this program is well developed and familiar to the many of the investigators. An exception to this the need to develop sterile drilling technologies to support the basal biology program. The level of field support required is comparable to other major Antarctic field programs. The National Ice Core Laboratory can store the ice cores if some modifications are made to the storage rack system. We propose the program consist of about 25 individual science projects focusing on the issues discussed in the science plan. Two projects should be devoted to outreach activities. A Science Coordination Office would coordinate the activities of the science projects, outreach activities, and the support organizations. The community of ice core researchers is well organized and has a history of collaborative work on multi-institution projects leading to significant scientific results. The proposed program is within the capabilities of the United States Antarctic Program, but will require a major commitment of resources.

SCHEDULE

We propose the following schedule.

June 2000 (Completed)

-Endorsement of Science and Implementation Plan by Ice Core Working Group
-Submit site-selection proposals for surface studies

November 2001

-NSF/OPP makes commitment to program
-Start preparation of deep coring drill

June 2001

-Submit lead proposal including formation of a Science Coordination Office
-Submit science proposals for work that does not require the main core
-Submit outreach proposals

Field Season 2001/2002

-First site-selection field season (glaciology studies)

June 2002

-Submit science proposals for work on cores

Field Season 2002/2003

-Second site-selection season (glaciological and atmospheric studies)

May 2003

-Select the exact location for the drill site

June 2003

-Submit additional science proposals for work on cores

Field Season 2003/2004

-Build the drilling camp
-Set up the drill
-Drill to 100 m and set surface casing

2004-2008

-It will take about three to five more field seasons to complete the drilling
-Design, test and build drill for sterile basal drilling

-Basal material would be available sometime around 2006 to 2008

PROJECT COORDINATION

We propose to follow the successful project management model established by Paul Mayewski on the GISP2 Project. Proposals for a Science Coordination Office would be submitted to NSF for peer review. The Science Coordination Office would have the following responsibilities:

- Oversight of drilling preparations prior to deployment
- Selection and training of core handlers
- Planing of field activities
- Oversight of drilling, and other field activities
- Sample handling in the field
- Development of sampling plan
- Sample distribution, including assuring the integrity of the samples
- Coordination with the National Ice Core Lab
- Management of information related to core sample allocation
- Facilitation of data exchange and archiving of data from science projects

- Facilitate interactions between science projects within WAISCORES program
- Facilitate interactions between the WAISCORES program and other programs
- Facilitate interactions between NSF, science projects and support organizations
- Interact with the media, public and agencies about the science associated with the project
- Facilitate outreach efforts
- Establishment of an outside advisory and review panel.

The Science Coordination Office would consist of a Chief Scientist and several assistants. The Chief Scientist would seek advice from the principal investigators when making major decisions. There would also be an Executive Committee consisting of the Chief Scientist and at least three of the principal investigators, who would assist the Chief Scientist in making decisions when it is impractical or unwarranted to seek advice from all principal investigators.

OUTREACH

The program proposed here is exceptionally well suited for outreach activities because it covers a wide range of topics and has a “big picture” view of socially relevant issues. We anticipate at least two projects that are exclusively devoted to outreach activities. Examples of this model are the WAIS-related “Glacier” program run by Stephanie Shipp, and the ITASE-related collaboration between Paul Mayewski and the Boston Museum of Science. In both cases, there are people whose primary effort is outreach, thus assuring a serious commitment to outreach activities.

The outreach programs will develop curriculum for grades K-12. Through the use of moderate bandwidth communications we can provide opportunities for students to interact with field personnel. We would like to involve some of the teachers in the field for short periods of time and be the interface between scientists in the field and the students in the classroom.

To develop a useful curriculum the Science Coordination Office would have a teacher in residence program. Each year one or more K-12 teachers would take a year off from teaching and spend a year at one of the institution involved with the WAISCORES program. During this year the teacher would learn about the science in the program and develop web distribute curriculum. We would like the program’s web site to be known as a source of educational material for both teachers and students.

Undergraduate students have been the mainstays of our core processing efforts at the National Ice Core Lab. We would like to expand this into an undergraduate program that includes both a classroom component, where students can learn about the science behind this program, and a simultaneous lab component, where students assist in processing ice cores. This program could be conducted during the summer at the National

Ice Core Lab and could include students from all over the nation. We envision the students rotating every few hours between working in the cold lab and warming up during lectures. The students could stay in the same college dorms as the scientists currently do when we process ice cores in the summer. This would provide the students an opportunity to interact with the scientists both professionally and socially, thus furthering the mentoring opportunities. Following the summer session, some of these students could be employed at their home institutions during the school year in research labs involved with this program. This would extend the length of time that the students are exposed to the science of this program beyond the three to four week summer program. This program would target students associated with groups that are traditionally underrepresented in science professions and would be a good site for a Research Experience for Undergraduates program.

The program will also provide an opportunity to train graduate students. In addition to the normal training associated with most NSF projects, we want opportunities for graduate students to participate in the fieldwork. A full-length drilling field season interferes with two semesters of classes and is unattractive to most students. To overcome this drawback of field work, some field positions would be time-shared sequentially between two students so that students can get the benefit of the field experience without a major impact on their progress toward graduation.

We will also take advantage of media opportunities to educate the public. For example, the Siple Dome Project was featured in four international television programs and dozens of times in the national print media. This program should provide even more opportunities to educate the public.

DRILLING ISSUES

A critical aspect of this program is our ability to efficiently obtain a high quality core. The U.S. Program has a drill that was designed to recover a continuous core to a depth of 4,000 m specifically so that it could be used in the deep ice of West Antarctica. Although we have been successful in the past, our drilling operations have not gone smoothly. Many of these problems occur because of the large variability in the year-to-year work load of the drilling organization caused by the starting and stopping of other drilling programs, and a tendency for organizations to use internal staff even when more experienced personnel exist in another organization. Although one of the most important responsibilities of the Chief Scientist is to recover the core in the best condition possible, the Chief Scientist has a very limited role in preparations for drilling.

In previous projects the drilling was done by the Polar Ice Coring Office, which was a university-based organization that supported all U.S. ice drilling. This contract will be awarded to a new organization based on a competition that includes consideration of a range of drilling activities including hot water drilling, shallow coring in polar and high alpine environments, and deep ice coring. This model of an organization that does it all is good for projects that only last for a few years. But, experience shows when an organization combines a project the size and duration of a deep coring program with a highly variable work load associated with the shorter life cycle of other projects, the larger program suffers because the availability of personnel and resources is dependent on the boom and bust of other projects. This organizational approach also isolates the scientists from the drillers and leads to poor communication between the groups.

We have not evaluated the current structure of the ice drilling support contract and cannot comment on if it is the best approach for this program. If we believe there is a better way to meet our science goals, we will propose that a separate drilling organization be established to support this project.

The deep ice coring equipment needs a large amount of work before it is used. The overall design of the drill is sound, however, there are many issues associated with the current implementation of the system. The system should be reviewed by several independent drilling engineers to identify where improvements can be made. To allow new ideas to surface, this review should be made by people who were not part of the original design team and should be done as early in the project as possible. The major improvements needed are listed below.

- The core heads need to be checked and most likely replaced.
- There needs to be alternatives to the current core dog design.
- The core barrels need to be replaced with a more rigid design.
- The couplings between sections need to be replaced.
- The drill needs to be dynamically balanced to reduce vibration.
- The drill electronics and control software need to be upgraded.
- The cable needs to be replaced and a second cable acquired.
- The winch and cable path need refurbishment to operate at speeds of >30 m/min.
- The handling of brittle ice needs to be improved.
- Numerous safety and efficiency issues need to be addressed.

Unfortunately there is no practical way to test the complete drill system except on a polar ice sheet. In order to do so would require 1) a 40 m tall ice column so the harmonic dynamics of the drill are realistic; 2) air temperatures below 0ºC to avoid explosion and fire hazards associated with the drilling fluid; and 3) manufactured ice with brittle characteristics. We have considered proposing a field season just for testing and improving the drill. We feel that a serious drill preparation program without a field test prior to deployment can address most of our concerns at a greatly reduced cost and logistics effort compared to testing the drill in the field. However, the drill preparation program must be more involved and more responsive to the scientists than previous efforts. Preparation efforts will require small-scale tests of the drill heads and core dogs that could be done at NICL or a similar freezer facility. It will also be necessary to erect the complete drill tower to test the coupling and winch systems. Drill preparation efforts should be started immediately and the scientists should be involved from the beginning. Scientists should also have a strong voice in the selection of drilling personnel.

The number of field seasons required to complete the drilling is mostly determined by the depth to bedrock, the number of days per season that are available for drilling, the speed the drill is raised and lowered, and length of core recovered on each drill run. The length of core that is collected on each run is limited by the equipment to less than 5.5 m. The mechanical properties of the ice in some depth intervals limit the amount of ice that can be collected on each drill run to less than a few meters. The length of core that is collected on each run can vary by a factor of 5 and has the largest, and most difficult to predict, influence on the core recovery rate. A model of the core recovery rate was developed during the Siple Dome project that allows estimation of the time required to recover a core. Table 4 shows estimates of the required drilling time for different assumptions of the most influential drilling parameters. We anticipate that during the first season, the camp will be built, the drill will be set up, and the surface casing will be set. The most likely estimate is that it will take four to five normal-length field seasons to collect a 2,000-m core at the North site or, five to seven normal-length field seasons to collect a 3,400-m core at the South site. It would take one season less if field seasons were two weeks longer, or two seasons less if the field seasons were four weeks longer than normal. The deeper southern site is the site that is most likely to be selected. If the drilling were done during the winter, one winter and two or three summers would be required. However, it may not be possible to find suitable personnel for the winterover, not to mention large logistics issues associated with a winterover. More seasons are required to collect a deep core in Antarctica then in Greenland because Antarctic drilling seasons are shorter. These estimates are based on the assumption of only minor increases in drill performance. Significant improvements to the drilling system would decrease the time required to recover the core, however, it is not clear if improvements can be made that would significantly increase the drilling speed without compromising core quality.

Table 4. Estimated time required to recover core.

Depth of Core (m)	Site	Depth interval where 2.5 m long cores are recovered # (m)	Depth interval where 1 m long cores are recovered # (m)	Speed drill is lowered and raised (m/min)	Number of drilling days required	Number of field seasons to complete project ψ (30 drilling days per seasons)	Number of field seasons to complete project ψ (45 drilling days per seasons)
2,000	N	300-1,800	400-800	20	103	4.4	3.3
2,000	N	300-1,800	500-800	25	87 **	3.9**	2.9
2,000	N	400-1,700	500-700	30	70	3.3	2.5
3,400	S	300-1,800	400-800	20	168	6.6	4.7

3,400	S	300-1,800	500-800	25	145 **	5.8 **	4.2
3,400	S	400-1,700	500-700	30	121	5.1	3.6

** Indicates most likely values for each depth.
\# Five-meter-long cores are recovered except for these intervals.
ψ Includes one season to set up drill and install surface casing.

It is possible that the bed will not be frozen where the hole is drilled. If the bed is not frozen, there will be a water layer at the bed, and this has two major implications. The first implication is that there can be an exchange of fluids between the bed and the borehole. If the fluid level in the hole is high, the drilling fluid will enter the basal fluid system. This is undesirable from an environmental stand point and will comprise the proposed biological research.

If the fluid level in the hole is low, water will enter the borehole and refreeze. There is a risk of freezing in the drill depending on how far the water penetrates up the hole and what drilling procedures are used. At Byrd Station, the hole connected to a basal water system. Initially, glycol in the hole prevented freezing, and drilling was able to continue. After several days, the glycol was diluted by the basal water and melting ice. The slowly freezing drilling fluid became slushy and caught the drill, freezing it in place, where it remains today.

The second implication of a basal water system is that it provides an environment favorable for biological activity. There has been some work on the biological characteristics of basal sediments and this is a rapidly developing field. It is important to sample the basal material for biological material. Sampling procedures should be developed that preserve the biological integrity of the sample. There should be an open discussion about the risk of transferring undesirable biological agents from the basal material to our biosphere. There is a small concern that living organisms that have been isolated from our biosphere for ~100,000 years, and which have adapted to the low-energy and nutrient-poor basal environment, would be invasive species in the high-energy, nutrient-rich environments that are common in our biosphere. The basal samples must be considered biologically hazardous until proven otherwise. Informal discussions with investigators planning the handling of the Mars samples indicate that it may be possible to use NASA facilities for the initial handling of basal samples until they are considered safe for transfer to other facilities (Wharton, personal communication, 2000). We note that the biological material in the core and basal environment is exchanging with the rest of the terrestrial biosphere through the process of iceberg calving and basal water systems. Our concern is related to the small possibility of invasive species, not pathogens. The earliest the basal samples would be available is 2006, so there is time to address these issues. If issues related to a basal water system cannot be resolved, the drilling could stop a few tens of meters above the bed and potential problems would be avoided.

The technology and methods for ice and sub-ice rock coring are well developed for non-biological studies. The existing coring equipment needs improvements but the over all concept is sound. Standard ice core drilling and handling techniques require only minor modifications to support biological investigations of the ice core. However the technology for biological sampling of the basal environment has not been developed. The use of glycol at the bed would cause large problems for the biology investigations. The biological studies of the basal environment contain a much larger logistics risk and uncertainty than the rest of the program. It is difficult to estimate the equipment development costs and field time that will be required for drilling support for the basal biological studies, however they are likely to be significant. The same issue exists for the sub-ice lake programs that are being discussed for the South Pole and Vostok. The sterile drilling technologies would likely be similar for all the sub-ice biology programs.

All deep ice coring projects encounter a zone of ice that is brittle and difficult to recover without fracturing the core. The proposed drill sites have similar characteristics to the GISP2 site in Greenland and we anticipate similar brittle ice conditions. Although brittle ice did cause complications for the GISP2 program, it did not greatly limit the scientific return of the project. At the deeper southern drilling site discussed above, the brittle ice would be limited to ice from the Holocene time period.

LOGISTICS ISSUES

The logistics requirements will be similar to those during the Siple Dome Project. The major elements are:

- A field camp with a science and drilling population of 22-28.
- Shared use with the camp of a forklift (Cat 941), bull dozer (D-4), tucker or sprit, and snow blower.
- A separate drilling site with electrical and shelter requirements (60Kw, two 12 section Jamesways).
- Preparation and operation of the deep coring drill to collect a 2,000- to 3,400-m-deep core. A 3,400 m deep core is most likely.
- Collection of several hundred meters of shallow cores within 10 km of the drilling camp.
- A core storage and science lab trench. This is a major effort. The trench would be about 7 m deep with an area of 5 m x 50 m. The roof must be able to support 7 years of drifted and accumulated snow, which might be up to 5 m. The trench can be excavated with a D-4 or snow blower. Steel arches would be the best way to construct the roof. An alternative might be to use a tunneling machine that would avoid the need for a roof structure.
- At least one investigator is discussing making continuous chemical measurements on the core in the field. This would require a larger and more complex trench structure and additional housing for about four to six people.

- A refrigerated structure to evaporate the drilling fluid. (The need for refrigeration will depend on the maximum surface air temperature during the summer. Data from the recently deployed automatic weather station will be used to determine if refrigeration is required at the drilling site. The structure and refrigeration equipment used at Siple Dome would be acceptable.)
- A remote atmospheric science site. Depending on the funding of proposals this site could be a three-section Jamesway a few kilometers from the drilling site with a 5 kW generator, or two six-section Jamesways 20 Km from the drill site with a 5 kW solar power system.
- An Internet connection with a bandwidth of >56kb/s for >8 hours/day. (For outreach activities, communication with PIs who are not in the field, and troubleshooting equipment.)
- Ice core storage space in McMurdo (at less than -20^{o}C).
- Vessel transport of ice cores to CONUS (at less than -20^{o}C).
- It is likely that either Siple Dome or Byrd Station will need to be used as an aircraft refueling site.

The Siple Dome project required about 30 C-130 missions per year to support the drilling and related camp activities. The Allowable Cabin Load of the C-130 missions to the Western Divide site will be about 60% of the Allowable Cabin Load at Siple Dome because of the greater distance and higher elevation. The lower Allowable Cabin Load at the Western Divide site means it will take about 60 C-130 missions per year to support this program. A large field camp at the Western Divide Site would also provide a forward logistics base for Twin Otter support of field programs that are being discussed for the Pine Island Bay area.

To minimize the logistics requirements, the majority of the measurements on the cores will be conducted in the United States. Only activities that require immediate access to the core or surrounding environment will be done in the field. At least one investigator is suggesting making continuous chemical measurements on the core in the field.

The annual requirements for core storage and transport in McMurdo are similar to the Siple Dome Project. We do not foresee any significant difficulties in McMurdo. However, there may be complications if another project, is also shipping large quantities of ice in the same season. Fortunately the ITASE program is collecting 6-cm diameter cores which do not take much space and will be winding down as this program starts. This project would ship a maximum of 300 core boxes/year. If a suitable trench was available at the drill site this peak load could be spread out, but that would delay the science results.

ESTIMATED BUDGET

To estimate the science budget we have estimated the number of projects per year by discipline (Table 5). The estimated costs in year 2000 dollars, assuming an annual project cost per year of $150K, are also shown.

Table 5 Estimated Science Budget

Project Year	1	2	3,4,5	6,7,8	9	10
Fiscal Year	2001	2002	2003-2005	2004-2008	2009	2010
Main Activity	Site Selection	Site Selection	Drill 1,2,3	Drill 4,5,6	Interp.	Interp.
Ice Dynamics	1 project	1 project	3 projects	3 projects	3 projects	2 projects
Climate	0 project	4 projects	14 proj.	16 proj.	15 proj.	12 proj.
Biology	0 project	1 project	4 projects	5 projects	5 projects	4 projects
Outreach	0 project	1 project	2 projects	2 projects	2 projects	2 projects
Science Coordination	0 project	1 project	1 project	1 project	1 project	1 project
Total	1 project $150K	8 projects $1,300K	24 proj. $3,700K	27 proj. $4,150K	26 proj. $4,000K	21 proj. $3,250K

Funding these projects out of traditional NSF programs would distort funding allocations by concentrating resources in the WAISCORES program and greatly reducing other efforts. Efforts to set aside additional funding for the WAISCORES program are encouraged.

To estimate the drilling cost we have contacted the University of Wisconsin, which is the lead institution for ice drilling services for NSF. Information related to the drilling costs was not received in time for this document.

NATIONAL ICE CORE LABORATORY SUPPORT

The core will be stored at the National Ice Core Laboratory (NICL) in Denver. During the summer, groups of investigators will sample the core at NICL. NICL does not have enough room to store the cores that are proposed here and is working towards obtaining funding for a movable rack system that will almost double the storage capacity. It is important to integrate the staff at NICL with the field program. The sampling of the core that occurs during the summer is an excellent opportunity to train new personnel who will handle the core in the field. Likewise, it is important to have some of the people who handled the core in the field assisting in the sampling that occurs during the summer. Some of these core handling positions could be made permanent for the duration of the project. This would increase continuity between the field and NICL, and would provide needed stability for the personnel in these important positions. The Science Coordination

Office will work closely with NICL to assure that all the data related to the core collection and sampling are provided to NICL in an acceptable format.

CLOSING REMARKS ON IMPLEMENTATION PLAN

People supporting our drilling efforts have been Antarctic field support staff, drillers, or staff at the NICL. The seasonal nature of these tasks leads to short-term employment opportunities for many of the key people associated with collecting and sampling the core. It also creates an adverse high turnover rate and a lack of commitment to the program by many of our support staff. In this program, we would like to share staff among the drilling group, the Science Coordination Office and the NICL. This would create several fulltime positions for the duration of the project instead of parade of seasonal positions, and would lessen the transient nature of many of the support positions. The details of the personnel sharing are unclear and would be worked out in the lead proposal.

We are nearing the end of the Siple Dome project and have built up a contingent of science and support staff that is familiar with deep ice coring programs. In order to utilize this hard won knowledge it is important to make a commitment to this program before 2001. One issue is if NSF is willing to commit the logistics resources required to support this program. A second issue is science funding. It is not clear how the science and science coordination proposals will be funded because a program of this size would distort funding in existing programs such as Earth System History, Glaciology, and Biology. A cross program funding mechanism is required but it is not clear what that mechanism might be. The science community is looking to NSF for guidance on this issue.

Although the logistics requirements associated with the program are large, the majority of the program only requires technology and logistics support that we are familiar with. Only the basal biology component will require new technology that is currently unavailable. We are familiar with the need to balance our logistics requests with other major programs and will work toward minimizing our needs while still maintaining enough redundancy to minimize unexpected problems.

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