WAISCORES 1991

EXECUTIVE SUMMARY.

We must understand the climate system if we are to predict climate changes. The causes and mechanisms of past climate changes can be learned from careful paleoclimatic study. Ice cores are especially valuable, because they sampled the paleoatmosphere directly, and because they can provide exceptionally high time resolution over the critical period from the most recent ice age to today.

Key questions that must be answered about the climate system include: How rapidly has climate changed? Have changes been global or local? Have all climate variables changed at the same time, or were there leads and lags? In particular, have changes in temperature begun before or after changes in greenhouse-gas concentrations? Are large climate changes primarily linked to the smooth, periodic variation of Earth's orbital parameters, or are sudden `mode flips' more important?

These and many other questions cannot be answered fully without analysis of carefully selected ice cores. These cores must sample ice-sheet regions near both poles where melting has not occurred, must have annual resolution from the most recent ice age to today, and should sample regions with simple ice flow to allow easy corrections for dynamical effects. More than one core is needed near each pole, to separate local from regional effects and to document these effects at key scales of space and time.

U.S. and European teams are drilling such ice cores in Greenland. However, no long, high-resolution records have been collected in the southern hemisphere. Records based on studies of existing Antarctic ice cores are insufficient in scope, and ice in archives will not suffice to answer fundamental questions. Here, the U.S. Ice Core Working Group presents a science plan for WAISCORES (West Antarctic Ice Sheet Cores), a project to collect two critical southern-hemisphere cores.

A high-resolution, long record from a southern-hemisphere region with simple ice flow is only possible in restricted areas of inland West Antarctica (Figure 1). We identify the most favorable area and outline a site-selection program to choose a drill site for deep coring inland. We discuss necessary investigations and outline field and analysis plans, with a timetable.

A core through an ice sheet necessarily samples a flowing ice mass, so we must understand ice-sheet changes to allow confident core interpretation. We recommend that a second West Antarctic core, which is needed to assess the regional significance of the first, inland core, be located to provide information on ice-sheet changes as well. We also recommend that paleoclimatic investigations be integrated with ice-dynamical studies to increase the scientific return from the project. As an added benefit, this will contribute important results to the question of West Antarctic ice-sheet stability and its effect on global sea level.

The WAISCORES Project proposed here is of global importance. The scientific and logistical capabilities of the U.S. community are adequate to complete this project. If sufficient funds are secured, execution of this science plan should lead to major advances in understanding and ultimately predicting climate change.

SCIENCE PLAN FOR WAISCORES.

We believe we have clear motivation and an important goal and objectives for deep coring in West Antarctica. We now seek to outline how the coring project should proceed, as an aid to scientists proposing the research and to the Division of Polar Programs of the National Science Foundation and its contractors.

Site-Selection Activities.

Inland Core.

The major requirements for the proposed inland core are that it have a high accumulation rate and simple ice flow, and that it be logistically accessible within West Antarctica.

The logistical constraint is obvious--if we cannot get there, we cannot drill there. This argues against sites along the Amundsen Sea Coast, which are far from the U.S. base at McMurdo and which have exceptionally bad weather. It also argues against sites near the Filchner-Ronne Ice Shelf, because of distance (Figure 1).

Simple ice flow is needed to improve interpretation of the climatic record--we wish to interpret changes in parameters as climate changes without introducing uncertainty by having to correct for large ice-flow effects. This rules out marginal regions, such as the Siple Coast or the Ross Ice Shelf, where considerable flow complexity is almost guaranteed. In fact, it restricts consideration to a relatively narrow zone near the ice divides closest to McMurdo Station (Figure 1).

The question of whether drilling should occur on a divide or nearby at a flank site is more difficult. This question was solved in Greenland by putting one hole on the divide and one on the flank. In West Antarctica, we do not anticipate European collaboration on the second hole. Also, we believe that rugged bedrock topography beneath the flank sites near the divides under consideration (Drewry, 1983) would complicate interpretation, and we focus on divide sites. However, we believe that ice-flow modeling should be conducted to address whether this complexity is serious, and to predict likely depth-age scales and layer thicknesses at preferred divide and nearby flank sites, following acquisition of better radar data (see below).

Accumulation rates are known moderately well in West Antarctica (e.g. Giovinetto and Bentley, 1985). As noted above, accurate interpretation of annual layers using isotopes or hydrogen peroxide normally requires accumulation >20 cm water/yr; this much accumulation also makes the interpretation of annual layering in electrical conductivity (ECM), dust, visible strata, and chemistry easier than for lower accumulation rates. Most regions with accumulation rates higher than this in West Antarctica also are far from McMurdo Station, have very bad weather, and occur near the ice margin where flow would be complicated.

As can be seen in Figures 1, 3, and 5, the only region that is near McMurdo Station, near an ice divide, and has high accumulation is in the vicinity of 79S, 115W. There, the ice divide overlies a prominent sinuous bedrock ridge. It thus is unlikely to have moved much over time, insuring simple ice flow (a statement that should be tested by further ice-flow modeling). We thus propose to focus site-selection activities on and near this area.

The major site-selection activities needed (Table II) are airborne-radar flying on a dense grid, and ice-flow modeling. The radar is needed to map ice thickness, surface elevation, and internal layering. These in turn will allow the ice divide to be located with precision, flow lines to be estimated, and regions of simple bedrock topography (and thus likely to have simple ice flow) to be identified. The shape of internal layers will indicate how simple the ice flow has been. Imagery and altimetry collected with the radar data or separately will allow better constraint on divide positions, surface slopes, and local regions of surface relief that may indicate large bedrock roughness and complicated ice flow.

These are necessary inputs to ice-flow models to address the following questions:

Within a wide range of possible ice-sheet configurations and accumulation rates, is the ice divide likely to have remained near its present position?

How simple is the ice flow at the best flank sites; that is, can it be modeled numerically?

What are the likely depth-age scales and layer thicknesses at the divide and flank sites?

These data can then be submitted to the ICWG or (preferably) a committee of funded PIs to determine the optimum coring site. Additional data needed will be how thin annual layers can be and still allow accurate dating by layer counting. The experience now being gained in Greenland will be invaluable here.

Preliminary indications are that a divide site will allow identification of annual layers from at least the LGM to the present. Hammer et al. (1985) report annual signals in electrical conductivity for at least the last 40,000 years in the Byrd core, with some indications of annual layering even older (and, according to the authors, limited primarily by near-bed heating of the core rather than by layer thickness per se). The ice at the proposed divide site has similar thickness to Byrd, and the accumulation rate at the proposed divide site is about 50% higher, so it seems likely that annual layering should be interpretable for at least the last 15,000 years, as desired.

Again, it is worth emphasizing here that the proposed inland site is not simply a redrilling of the Byrd core. Compared to Byrd, the proposed site will have:

1) higher accumulation, and thus less uncertainty in the ice-air age difference;

2) less-complicated ice flow, and thus easier separation of ice-dynamical from climatic effects;

3) two generations of improvement in analytical techniques, allowing more and better data to be retrieved than was possible with the Byrd core; and

4) more-accurate dating by layer counting in at least the younger ice.

This fourth point deserves further clarification. Ice flow causes a trade-off in annual resolution: for a steady ice sheet of specified thickness with zero vertical velocity at the bed and with laminar flow, simple models show that a core with higher accumulation will have young annual layers that are thicker and old annual layers that are thinner than a core with lower accumulation. In essence, the ice sheet must pack an infinite number of annual layers, or at least a layer for each year since it formed, into its thickness. If the young, near-surface layers are thick because of high accumulation, then the old, deep layers must be thin. This has no effect on the difference between ice and gas ages. It can be avoided to some extent by drilling in thicker ice; for given accumulation rate and ice flow, thicker ice has thicker annual layers at all ages.

At a site with similar ice thickness to Byrd but with twice the accumulation rate, such as the divide sites under consideration for the proposed inland core: annual layers would be thicker than at Byrd for about the last 10,000 years; annual layers would be thinner than at Byrd in older ice; and annual layers 25,000 years old would have about the same thickness as 40,000-year-old layers at Byrd (which are recognizable; Hammer et al., 1985). (Calculated using simple Nye and Dansgaard-Johnsen models; see Paterson, 1981, p. 328-329. A proper ice-divide solution, perhaps following Schott et al. (in press) would alter these numbers somewhat, but not the basic conclusions.) Clearly, flow modeling should be conducted to estimate the thickness of annual layers of various ages for possible divide and flank sites, and this information should be used in the final site selection.

A number of other site-selection activities would be valuable. These include (but are not limited to): installation of an automatic weather station in the vicinity; surface, pit, and shallow-core sampling to confirm reported accumulation rates, to assess the prominence of annual layering and the suitability of geochemical records, and to assess spatial variability; initiation of ice-motion surveys for modeling purposes; initiation of studies of the air-snow transfer function to improve core interpretation; and atmospheric modeling to learn how accumulation is likely to have changed in the past, as a constraint on modeling of divide stability. Most of these are not prerequisites to site-selection, but can be conducted concurrently with drilling if necessary. However, motion surveys (horizontal and vertical strain rates) must be started as soon as practicable to allow measurable motion to occur within the life of the project.

Siple Coast Core.

Site-selection for the Siple Coast core is somewhat easier than for the inland core. Only two features sit as clear `dipsticks' capable of measuring elevation change of the Siple Coast ice streams, which appear to be the best-developed ice streams (in terms of having the lowest driving stresses for the greatest length) in the modern ice sheet. These are Ridge BC, between ice streams B and C, and Siple Dome, between ice streams C and D (Figure 1).

Some arguments can be advanced in favor of Ridge BC. Previous research as part of the Siple Coast Project (SCP) has provided a reasonably good base of radar coverage, pit observations, and shallow coring on Ridge BC (e.g. Shabtaie et al., 1987; Whillans and Bindschadler, 1988; Alley and Bentley, 1988), and it is known to overlie sediments (Munson et al., 1990) that would be of interest to paleontologists. In comparison, the radar coverage of Siple Dome is sparse, detailed surface studies have not been conducted, and seismic studies to detect subglacial sediments have not been conducted.

We nonetheless favor Siple Dome over Ridge BC, based on available data, for three reasons. First, the surface topographic closure of Siple Dome is about 320 m, compared to 120 m for Ridge BC (Shabtaie and Bentley, 1988). Even slightly thicker inland ice in the past would have overrun Ridge BC, but only a large change would have allowed past ice flow across Siple Dome. We are interested in major changes of the ice sheet, and so favor Siple Dome.

Second, this experiment would be confused if an ice stream had migrated across the drilling site. There is evidence that ice streams do move over time (e.g. Whillans et al., 1987). If this had happened, then the occurrence of inland ice in the bottom of a Siple Coast ice core might simply record ice-stream migration rather than more-general thickness changes. It is probable that we could distinguish these cases based on radar mapping of internal layers, on ice fabrics, or on other careful analyses, but it would be better to avoid the possibility. In this regard, the large closure of Siple Dome, its symmetric shape, and the large bedrock high beneath it (>300 m relief, based on Shabtaie and Bentley, 1988) argue that Siple Dome is unlikely to have been the site of an ice stream. Ridge BC, with its irregular shape, smaller surface relief, and slightly smaller bedrock relief (measured from its highest point on the surface perpendicular to the ice-stream margin into ice stream C), is a less-favorable target.

Third, hot-water drilling by Dr. B. Kamb and co-workers from the California Institute of Technology is planned to retrieve limited samples and study the bed of Ridge BC. By conducting coring on Siple Dome, a larger sampling of basal conditions is possible.

Site-selection activities for a Siple Dome core should be similar to those for the inland core. Radar surveys are essential to locate the top of the dome, measure the ice thickness, and map bedrock topography. This will detect whether internal layers show the contortions indicative of ice streaming, or whether they are more smooth, indicative of local flow or inland flow. (If contorted layers are observed, the wisdom of drilling on Siple Dome must be reassessed.) Ice-flow modeling should be conducted based on the radar data to assess steady-state layer thicknesses and depth-age relations, as a first guide to sampling the core. In addition, surface surveys should be conducted before or during coring, to assess ice motion and deformation, atmospheric processes and transfer functions, and other interesting processes.

Site-Selection Summary.

The U.S. clearly has the workers to conduct all necessary site-selection activities. Radar flying is the most difficult task, but the CASERTZ team (Corridor Aerogeophysics of the Southeastern Ross Transect Zone) has indicated that the favored inland drill site falls within their planned radar survey, and that the data are scheduled to be collected during the 1992-93 field season. CASERTZ plans to fly a few radar lines over Siple Dome during the 1991-92 season, which should reveal whether the internal layers are regular or highly distorted. In addition, the ICWG, CASERTZ, and NSF are pursuing plans to have a survey grid flown over Siple Dome.

Proposals should be solicited from ice-flow modelers for site selection activities. Automatic weather stations should be placed at the likely drill sites as soon as practicable. Proposals for surface surveys, shallow coring, and other site-selection activities also should be solicited as soon as possible and funded as practicable (see Tables III, IV).

Necessary Core and Related Analyses.

Long lists of potential investigations are given in Ice Core Working Group (1989; 1990) and Table III. We would like to see all of these, plus others, conducted on the proposed cores, following peer review of proposals. We recognize, however, that at least initially funding may not be available to do this. Here, we highlight those investigations that are absolutely essential to achieve the Primary Objectives as listed above.

Inland Core.

The primary purpose for the inland core is similar to that for GISP2 and GRIP, and comparison to those cores is central to the interpretation of the West Antarctic inland core. Thus, the analyses conducted should mirror GISP2 and GRIP in many ways.

Clearly, to reconstruct paleoclimates, we must measure paleoclimatically important variables. A variety of chemical, particulate and gaseous species, stable and radioactive isotopes, physical properties, and borehole parameters should be measured. Peer review is the appropriate means to select among these valuable and exciting studies (Table III), and we attempt no further prioritization here.

It is essential to have good absolute and relative dating. We envision a hierarchical approach to dating, with each level more difficult to achieve, but providing more information, than the last (Table IV).

At the first level, the search for leads and lags in the southern-hemisphere climate system (Primary Objective 1) requires that the age difference between ice and trapped air be known accurately. This difference can be estimated from a consideration of the physical processes of firn densification and air trapping, together with the history of temperature and accumulation rate for ice in the core (e.g.

Barnola et al., 1991). By drilling a core in a high-accumulation region where the age difference is centuries rather than millenia, this should allow identification of leads or lags within decades.

Even the crudest dating scheme should allow the identification of the most recent deglaciation, and knowing the ice-air age difference will allow us to learn the leads and lags in the climate system before, during, and after the deglaciation. Thus, the histories of temperature and accumulation rate (perhaps from isotopes and 10Be or from other indicators), basic physical modeling, and a crude time scale (perhaps from simple ice-flow modeling) should provide the ability to assess leads and lags accurately among any climate parameters measured on an appropriately located deep core.

At the next level, we wish to know how long given climate events lasted, and how rapidly changes occurred (Primary Objective 2). The key here is counting of annual layers. Notice that an accurate absolute chronology tied to the surface is not yet needed--only an accurate chronology near events of interest.

Counting of annual layers has proven quite successful at GISP2. Annual oscillations are present in most properties of the core, including oxygen and deuterium isotopic ratios, hydrogen-peroxide concentrations, and concentrations of a variety of major ions (e.g. calcium, ammonium, nitrate). The longest records thus far, and those that are being used primarily for dating, are electrical conductivity (ECM), dust, and visual appearance. These also show annual cycles in the Old and deep Byrd cores (Gow, 1968; Thompson, 1977; Hammer and others, 1985. The visible cycles are as prominent or more so at Old Byrd as at GISP2; A.J. Gow, personal communication, 1990), so we anticipate no problems in counting annual layers for perhaps 25,000 years or more (see above).

An intercomparison experiment reported by Taylor et al. (in review) found that three independent indicators of annual stratification are needed to provide great confidence in the dating and in the estimation of errors. Two indicators are needed to allow estimation of errors. Depending on the strength of the annual signal and on other factors, a single annual indicator may give errors less than 1% in counting years, or may give errors as large as 10%. Accuracy better than 1% is possible with multiple indicators, and we recommend that such accuracy be sought on the proposed inland core.

At the highest level, we wish to correlate events in the Antarctic inland core to the GISP2 and GRIP cores and to other ice and sediment cores from various locations and environments. This can be done by absolute dating of the new inland core, or by correlation through reference horizons which record well-characterized chronostratigraphic events.

A variety of absolute-dating techniques is available, including ice-flow modeling, radiometric dating of impurities in ice, of trapped air, and of volcanic ash in ice, and counting of annual layers. Realistically, the best accuracy that we can count on from these is 100-200 years at the LGM. If achieved in the new inland core and in other records such as the GISP2 and GRIP cores, this would place rather restrictive limits on synchroneity or diachroneity of important events of the global climate system. Radiometric dates of old ice (10Be/26Al?) would provide information on whether the West Antarctic ice sheet collapsed during the previous interglacial, for Primary Objective 4.

We can, however, aspire to even greater resolution through the use of global time lines to calibrate annual-layer dating. This would allow us to begin to address Primary Objective 3--Do we see the same events at both poles? Where do they start? How rapidly do they propagate? (Recognizing, of course, that a wiggle in a local variable such as temperature may occur in different cores at the same time for different reasons, so that variations in global variables such as atmospheric composition must be sought as well.) The techniques required for dating at this level are not standard today, so we cannot say with confidence that we can achieve this. However, the possible scientific gains are large enough that we believe we should pursue such high-precision dating through the study of marker horizons.

Possible global marker horizons include events in atmospheric composition, such as methane concentration, which we do not discuss in detail here but which might prove quite useful. Of special interest is the possibility of using the global deposits from large volcanoes as time lines.

Large volcanoes, especially equatorial ones, produce fallout at both poles. Volcanic deposits produce large signals in electrical conductivity (ECM) of the ice, allowing precise sampling for volcanic ash. Ash, in turn, has the chemical composition of the volcano that erupted it, so chemical analyses can demonstrate that ash in two different cores came from the same volcano (Palais \fIet al.\fR, 1987). If the approximate ages of the two cores are known (so that different eruptions of the same volcano are not correlated), then tephrachronology should allow time horizons to be determined precisely (typically better than one year, depending on differences in atmospheric transport time to the two ice caps).

Thus far, use of this technique in ice cores is in its infancy. Volcanic horizons are identified by ECM, sampled in detail, filtered, and analyzed by microprobe for major-element chemistry (e.g. Palais et al., 1990). A clear, interhemispheric marker is known from C.E. 1259 (Langway et al., 1988), and some other tentative correlations are known, but a full chronology of interhemispheric markers to the LGM is not available.

It should be possible to solve this difficulty through three steps.

1) Increased effort. Numerous interhemispheric markers almost certainly exist; the search for them has not been sufficiently vigorous to find them. Table V contains a listing of some volcanoes that are likely to appear in cores at both poles, and others probably exist (a few years ago, the C.E. 1259 eruption would not have appeared on such a list). If more effort were expended in the search, more markers would be found.

2) Counting of annual layers in cores from both poles. Identification of marker horizons must be iterative. That is, an approximate date from layer counting restricts an ECM peak to a few possible eruptions, and then chemical analyses of ash determine which it is. Without an approximate date, an ash might be assigned to more than one eruption of a given volcano, or to one of multiple volcanoes with similar compositions; with an approximate date, this ambiguity can be eliminated. At present, long records with good approximate dates are not available from both poles, which has hampered correlation efforts. (The known marker and several suspected ones fall within the time range for which annual-resolution records are available from both poles.)

3) Improved analytical techniques. Correlations now are being made based on major-element chemistry as measured by electron microprobe. This is the first successful technique for correlating volcanic ash in ice cores, but it is not an especially sensitive technique--many volcanoes have similar major-element chemistry, and a single volcano may have variable major-element chemistry. Trace-element compositions can be measured in many ways, including the ion microprobe, and if added to major elements would provide a more sensitive fingerprint of volcanoes.

We propose that the deep drilling in West Antarctica include a major effort to implement these three steps, or other steps that might be better, and to establish intercomparisons with the GISP2 and GRIP cores. Suppose, for example, that a marker horizon were established approximately every 1000 years. Then no event would occur more than about 500 years from a marker horizon. If annual-resolution dating were available with an accuracy of 1%, then the timing of any climatic event in West Antarctica relative to the timing in Greenland could be determined to better than 10 years, with the timing of events near the marker horizons known to the nearest year. Such accurate dating would allow determination of asynchronous behavior between the hemispheres with unprecedented accuracy, and would be of great value in understanding the climate system.

This technique is unlikely to work in ice from West Antarctica near the LGM, because the Byrd core records huge numbers of local events that would make identification of any global signal difficult or impossible (Kyle et al., 1981). The local source was primarily confined to the most recent ice age, however, so this technique should work in younger ice and possibly also in older ice.

We thus believe that the necessary investigations to date a deep inland core include flow modeling, layer counting by a number of techniques, radiometric dating, plus careful search for interhemispheric markers, primarily in gas compositions and in volcanic fallout. ECM, which is needed to identify volcanic layers as well as to count years, is clearly essential. Laser detection of particulates shows a strong annual signal in Greenland, and the particles are not subject to significant diffusion and so promise to retain the annual signal to thinner layers and greater depth than other indicators; however, increase in the speed on processing should be sought. Visual stratigraphy is a fast and low-cost technique that has proven quite successful at GISP2, Byrd, and elsewhere, but that requires a skilled PI at all times for maximum reliability. Improvements in the technique, including possibly automating it, should be considered. Isotopic and chemical methods have been too slow and expensive to allow continuous sampling, although clear annual signals exist in many indicators. Continuous isotopic sampling using a hot-point melter is being investigated at GISP2; if this proves successful, it should be considered for the West Antarctic deep cores. Continuous chemical sampling has been implemented successfully at GRIP, and also should be considered.

We wish to emphasize that the success of this project does not rest on success in finding hypothesized interhemispheric horizons. As outlined in Table IV, we will obtain important paleoclimatic information simply by drilling a deep core in the right spot, and we will achieve almost everything we seek through the application of standard techniques. We emphasize the search for interhemispheric markers because it offers the potential for unprecedented resolution and because, as a new technique, it deserves to be considered in designing the program.

Once the time scale is established, the climatic record can be read from a variety of indicators to reconstruct the local and global records. Isotopic, chemical, particulate, gas, and physical analyses all can contribute important information. More-complete listings of potential analyses and their benefits are given in Committee for Science Planning in Greenland (1985), ICWG (1989, 1990), and Table III. We believe that analyses funded should be chosen by peer review in some form, with attention to duplicating GISP2 analyses whenever possible to improve intercomparison of the records. Consideration especially should be given to 10Be studies for correlation of old ice (if present) through the known peaks in production (Raisbeck et al., 1987), as well as for solar-activity and magnetic-field histories. A variety of other studies that are not directly paleoclimatic and part of GISP2 also should be considered. In particular, total-gas content is important in determining ice-sheet history, reconstructing the contribution of surface-elevation changes through the lapse rate to reconstructed temperature changes, and constraining time-dependent ice-flow modeling.

The borehole opened for coring is of considerable value as well. The temperature profile in it records paleoclimatic information, and can be used to calibrate the isotopic thermometer for paleotemperature reconstructions. For WAIS purposes, borehole and surface ice-deformation studies should be undertaken. The bed should be studied and cored, and the temperature gradient and thermal conductivity of the bed should be measured for determination of geothermal flux. Of these, the geothermal flux is especially critical because it is needed to calculate basal melting and determine the significance of any absence of old ice as a possible indicator of former ice-sheet collapse.

Siple Coast Core.

For optimal comparison to the inland core, the Siple Coast core should be analyzed for the same suite of paleoclimatic indicators in the same way as the inland core. This will allow us to determine whether events recorded in the inland core are regional in nature, and what variations occur on the regional scale. The resolution of a Siple Coast core (~10 cm water/year and a gas-ice age difference of ~400 years; Alley and Bentley, 1988) will not be as good as the inland core (estimated as ~25 cm water/year and a gas-ice age difference of ~200 years) but the Siple Coast resolution will be better than in East Antarctic cores and almost as good as at Byrd.

The accumulation rate on the Siple Coast is well below the optimum for counting of annual layers. However, annual-layer counting has been achieved at even lower accumulation rates with very careful work (Mosley-Thompson and Thompson, 1982; A.J. Gow, personal communication, 1990), and annual layers are clearly evident in pit stratigraphy from Ridge BC and ice stream B on the Siple Coast (Alley and Bentley, 1988), so it is worth the effort to look for annual layers in a Siple Coast core. Even without annual layers, dating should be possible through correlation to the inland core using marker horizons, as well as through radiometric techniques.

The other major result from a Siple Coast core will be determining whether the deep ice formed inland or locally. This can be done most directly through the measurement of total-gas content (e.g. Raynaud and Whillans, 1982). It also can be done through isotopic measurements (Grootes and Stuiver, 1987) or measurements of the concentration of sea-salt. Analysis of radar records and ice-core fabrics and textures should be done to insure that an ice stream did not migrate across the drilling site. The U.S. lacks an active total-gas-content research program at present, but the analytical capability is certainly available--a proposal or proposals to do this work should be solicited.

Summary of Necessary Analyses.

The ice-core community in the U.S. has the capacity to conduct the needed analyses (Table II), but some further development is needed. The major needs are:

a total-gas-content program;

improved ability to identify annual layers rapidly;

improved ability to identify marker horizons, especially volcanic horizons; and

the ability to recover cores from the bed of the ice sheet, measure their thermal conductivity, and measure temperature gradients in the bed to allow calculation of geothermal flux.

Beyond these, we recommend that the inland and Siple Coast cores proposed here be analyzed for a full suite of paleoclimatic indicators and dating tools, and that ice-dynamical studies be conducted in and around the holes. We also recommend that atmospheric studies be conducted to learn how contaminants are incorporated in the snow and ice.

Coring.

The Polar Ice Coring Office (PICO) has developed a deep-coring capacity for the National Science Foundation, and is developing an `intermediate' (1,000 m) coring capacity. The proposed Siple Coast core would be about 1000 m, within the `intermediate' range, and the proposed inland core would be about 2000 m if on the ice divide and deeper if at a flank site, requiring the deep-coring capacity. Pending successful completion of the GISP2 hole and development of the 1000-m drill, we believe that PICO should be tasked to drill the cores proposed here. We strongly urge that PICO strive for the ability to conduct drilling to 1000 m within a single season, using an apparatus as small and portable as practicable. It appears that many new opportunities in ice-core paleoclimatology relate to `intermediate' cores--1,000-meter cores drilled in fluid-filled holes--such as the Siple Dome core proposed here as a West Antarctic `dipstick', or the planned McMurdo Dome core (Figure 1) to link ice-core and nearby glacial-geological records in the Antarctic. Any number of such cores could be suggested and justified easily, to address specific questions while contributing to the regional and global climatic database. To fully utilize such cores, we must be able to recover many of them as quickly and inexpensively as possible.

Successful completion of the plan here requires the ability to core into the bed, recover rock cores, and measure temperatures for calculation of geothermal flux. It is our understanding that PICO is developing this capability, and believes that the drills now available or being developed will be able to do this. We strongly urge that PICO design and test this capability, use it in Greenland, and then use it in West Antarctica.

We anticipate that any deep-drilling program will involve one or more shallow cores (<200 m, drilled without hole fluid) to study local and regional variability and for special purposes. Such cores have been a PICO staple for many years, but core quality has been variable. We suggest that PICO should make those adjustments to their shallow-coring machinery and procedures needed to improve shallow-core quality.

Previous ice-coring projects have revealed that some ice (such as that from the Younger Dryas or spanning the end of the last ice age) is in greater demand than other ice. The ice-core community would be happiest if extra ice could be retrieved from selected depths. PICO representatives have indicated that this is technologically straightforward (B. Koci, oral communication, U.S. Ice Core Workshop, Durham, NH, 1988). If this is still the opinion at PICO, we suggest that they be tasked to develop this capability. We recognize the finite abilities of any organization, however, and suggest that this should come after the rock-drilling capability, the capability to recover 1,000-meter cores rapidly, and an improvement in dry-core quality.

Core Processing.

Core-processing strategies in the U.S. have run the gamut from the Byrd model (physical-properties studies done in the field, all others in the laboratory) to the GISP2 model (ECM, visual stratigraphy, laser particulates, chemical sampling, isotope sampling, dust sampling, gas sampling, chemical blanks, some chemical analyses, physical-properties studies, and more done in the field). Each has significant advantages and disadvantages.

The GISP2 model was adopted to gain maximum ice-core experience for an often-inexperienced corps of Principal Investigators (PIs), and because there was no suitable analysis laboratory available in the U.S. The GISP2 model produces science very rapidly. However, because the total cost of maintaining a scientist in the field is higher than at home, and because of the need for laboratory construction and equipment shipping, the GISP2 model is quite expensive. Also, core drilling and processing rarely progress at the same speeds, so the GISP2 model virtually guarantees wasted time.

The Byrd model avoids the costs of field laboratories and the inefficiency of waiting for core. It runs the slight risk of core melting during transport, does not get field experience for the analysis team, and slows down production of scientific results.

The U.S. National Ice Core Curatorial Facility (NICCF) now being developed in Denver appears to have the capacity to allow a core-processing line to be established there. (This question is being examined by the NICCF staff, but the answer is likely to be positive.) Thus, the Byrd, GISP2, and intermediate models should be available for core processing.

The ICWG surveyed the community during 1991 on the topic of processing schemes. Three options were offered: Byrd, GISP2, and an intermediate plan in which visual stratigraphy and physical properties, ECM, and isotopic sampling (from the cut taken off for ECM and visual stratigraphy) are conducted in the field, with all others in the laboratory. A total of 23 scientists responded (from a total mailing list of about 300, including international colleagues), with 13 respondents claiming experience with ice-core analyses. The survey asked for a ranking of best (1) to worst (3) for the

GISP2, intermediate, and Byrd models. Averaging the rankings yielded: GISP2: 2.52; Intermediate, 1.50; BYRD: 1.98. Those with field experience provided almost exactly the same rankings as those without.

Some comments added to the surveys indicate that the GISP2 model is viewed as having been successful in gaining experience for a new generation of ice-core researchers and in avoiding the lack of an ice-core laboratory. However, now that experience has been obtained and an ice-core lab is becoming available, the overhead associated with the GISP2 model is viewed as being too large to merit repeating.

The voting favored the intermediate model for core processing. Despite this, we propose that the Byrd model should be preferred. (The ultimate decision should be made by the PIs for the project, as discussed in section 4.5, below, in consultation with NSF and PICO.) The intermediate model still has significant overhead: it requires a horizontal band saw to take off an isotope sample and expose a surface, an isotope-sampling area or side lab, an ECM bench, and a light table, plus personnel (probably 2 isotope, 2 ECM, and 3 physical properties/light table) to run the analyses. This constitutes a large fraction of the existing core-processing line at GISP2. Also, making a continuous cut along the core in the field might cause contamination for later analyses in the laboratory, but without a chemical laboratory to run blanks, problems with contamination cannot be identified and corrected.

We thus suggest that, to the extent possible, time-priority analyses should be conducted in the field (physical properties, sampling for helium) and that other analyses be conducted during a U.S. ``field'' season at the NICCF. We qualify this by noting that, if practicable, individual investigators should be able to go to the field if they so desire. However, any continuous cutting of the core should be coordinated to minimize risks of contamination. We also believe that at least one experienced scientist should be at the drill site at all times for consultation with drillers as needed.

A major disadvantage of this plan is that the time-priority physical-properties measurements and the visual stratigraphy now are conducted by the same researchers, and they do not seem to have the ability or desire to conduct a true field season followed immediately by a second `field' season in Denver. There are several possible ways around this problem, which should be explored within the community.

Governance.

The ICWG is coordinating planning activities for the proposed deep cores. Governance of such a project is not within the advisory scope of the ICWG, however. We believe that PIs should be chosen for the project by NSF-mediated peer review as soon as possible. The chosen PIs then should meet, form an executive committee for the project, and insure that chief scientists are chosen to function in the field and the Denver `field' seasons. The project may `ramp up' gradually, so the ICWG may need to continue to play a role until a large group of PIs is selected. This should be negotiated among the initial PIs, the ICWG, and NSF.

The proposed deep coring is an integral part of WAIS. The chair of the WAIS steering committee should be an ex officio member of any executive committee chosen, and a representative from the executive committee should attend all WAIS steering committee meetings.

Data Management.

The GISP2 program has adopted a protocol to insure rapid sharing of data within the project, deposit of data with the World Data Center, and release of data to other scientists after an appropriate period for internal analysis. The executive committee of the West Antarctic drilling program is urged to adopt a similar protocol.

Science Management.

For the GISP2 project, the University of New Hampshire Science Management Office (SMO) has assumed responsibility for building and running the core processing line, much of the cargo shipment to Greenland, advice on field equipment, general communications among scientists, summary of scientific needs for communication to PICO and NSF, publicity, and other functions almost too numerous to mention. Many of these functions will be absent from a West Antarctic project--shipping and field equipment are handled by the U.S. Antarctic Program, for example. Nonetheless, coordinating core processing at the NICCF, communications, organizing meetings, publicity, interface with PICO, and other activities will remain. A scaled-down SMO should be considered for the West Antarctic project. The GISP2 SMO was funded through a peer-reviewed proposal, which is an appropriate way to proceed. Consideration might be given to a combined GISP2/WAIS SMO, although we believe that separate SMOs would be better. Consideration also might be given to utilizing some of the expertise of the GISP2 SMO.

The GISP2 project has invested considerable effort in coordinating the complementary data sets collected by the participating laboratories. One possible solution for the West Antarctic core would be for one of the participating groups to gain endorsements from other collaborators and include in their proposal the responsibility and resources for coordinating the intercomparison and interpretation of data such as annual-layer picks. Alternatively, such activities might be taken on by the SMO and included under a SMO proposal. If competing proposals are received, peer review can choose between them. In the absence of any proposal, we urge NSF to reserve a small sum of money (enough for one post-doctoral fellow and some travel and communications) for this purpose, and for the executive committee to make arrangements for someone to assume responsibility.

Timetable.

We suggest the following timetable for the proposed cores:

Austral summer, 1991-92--Siple Dome radar reconnaissance; modeling for site selection

June, 1992--Proposals for site selection

Boreal summer, 1992--Completion of GISP2 core

Austral summer, 1992-93--Siple Dome and inland core airborne radar surveys; modeling for inland-core site selection

June, 1993--Proposals for analysis of Siple Dome and inland cores

Austral summer, 1993-94--Site-selection activities for Siple Dome and inland cores

June, 1994--Further proposals for analysis of Siple Dome and inland cores

Austral summer, 1994-95--Camp put-in, 100-m drilling and borehole casing for Siple Dome core; Siple Dome and inland-core surface surveys

Boreal summer, 1995--Core processing line for first 100 m of Siple Dome core; modeling; early data analysis

Austral summer, 1995-96--Siple Dome coring; continuing surface work

Boreal summer, 1996--Core-processing line for Siple Dome core

Austral summer, 1996-97--Camp put-in, 100-m drilling and borehole casing for inland core; continuing surface work

Boreal summer, 1997--Core-processing line for first 100 m of inland core; data analysis; modeling

Austral summer, 1997-98--Inland drilling

Boreal summer, 1998--Core-processing line for inland core

Austral summer, 1998-99--Finish inland drilling

Boreal summer, 1999--Finish core-processing line for inland core

2000-2001--Data analysis and publication

Proposal Guidelines.

Best results will be obtained if both the Siple Dome and inland cores are analyzed for the same suite of parameters using the same techniques. We thus suggest that proposals should be submitted to cover the entire span of this project, including both cores. Proposals by investigators who are interested in continuous dating of the cores or recent records should be submitted by June, 1993; those who are only interested in the deep record may wait until June, 1994 to submit proposals. Even if no field work is involved, NSF advises that a participant in a summer core-processing line submit a proposal two years before the line actually runs (so June, 1993 proposal for the boreal summer, 1995 processing line or June, 1994 proposal for the boreal summer, 1996 processing line).

Estimated core recovery during the main drilling years is about 1000 meters per year. Based on experience at GISP2, it is reasonable to expect the Denver core-processing line to handle this in 6 to 7 weeks of core processing per year. Each project should budget for personnel costs for that period. Inexpensive berthing, food, and transport will be arranged by the NICCF, probably at a local college dormitory. NICCF is preparing an estimate of cost/day for a participant, which will be distributed by the ICWG prior to the June, 1993 proposal target. Workers lacking cold-weather gear should budget for appropriate clothing. Core handlers (taking core out of the bag, making the horizontal cuts, putting core back in the bag) will be supplied by SMO or NICCF, so no separate funding is required for the individual PIs. (This should be worked out between NICCF, SMO, and the executive committee of the project. Approximately 4 core handlers will be needed for each `field' season, and NSF should plan on retaining enough funds to pay for them, through NICCF or SMO as decided.)

Those who anticipate making time-priority measurements in the field should budget for Antarctic field seasons. Otherwise, do not budget for Antarctic work. If it becomes necessary for a member of the executive committee to be on-site as a chief scientist, and that member has not budgeted for such an activity, supplemental funds should be provided by NSF for travel. For the upper tens of meters, there is concern about changes in the core between collection and analysis in Denver. We anticipate that a separate 100 m core will be collected at each drill site and sectioned in the field for isotopic or other analyses. Those investigators who anticipate needing to conduct sectioning and sampling of firn cores in the field should budget for field work during the firn-coring years (austral summers 1994-95 and 1996-97).

Many GISP2 investigators have found that they budgeted for sufficient time to collect their data but not for analysis and publication (or that requested funds were eliminated by NSF owing to budgetary constraints). Proposers and NSF should bear this in mind when preparing budgets.

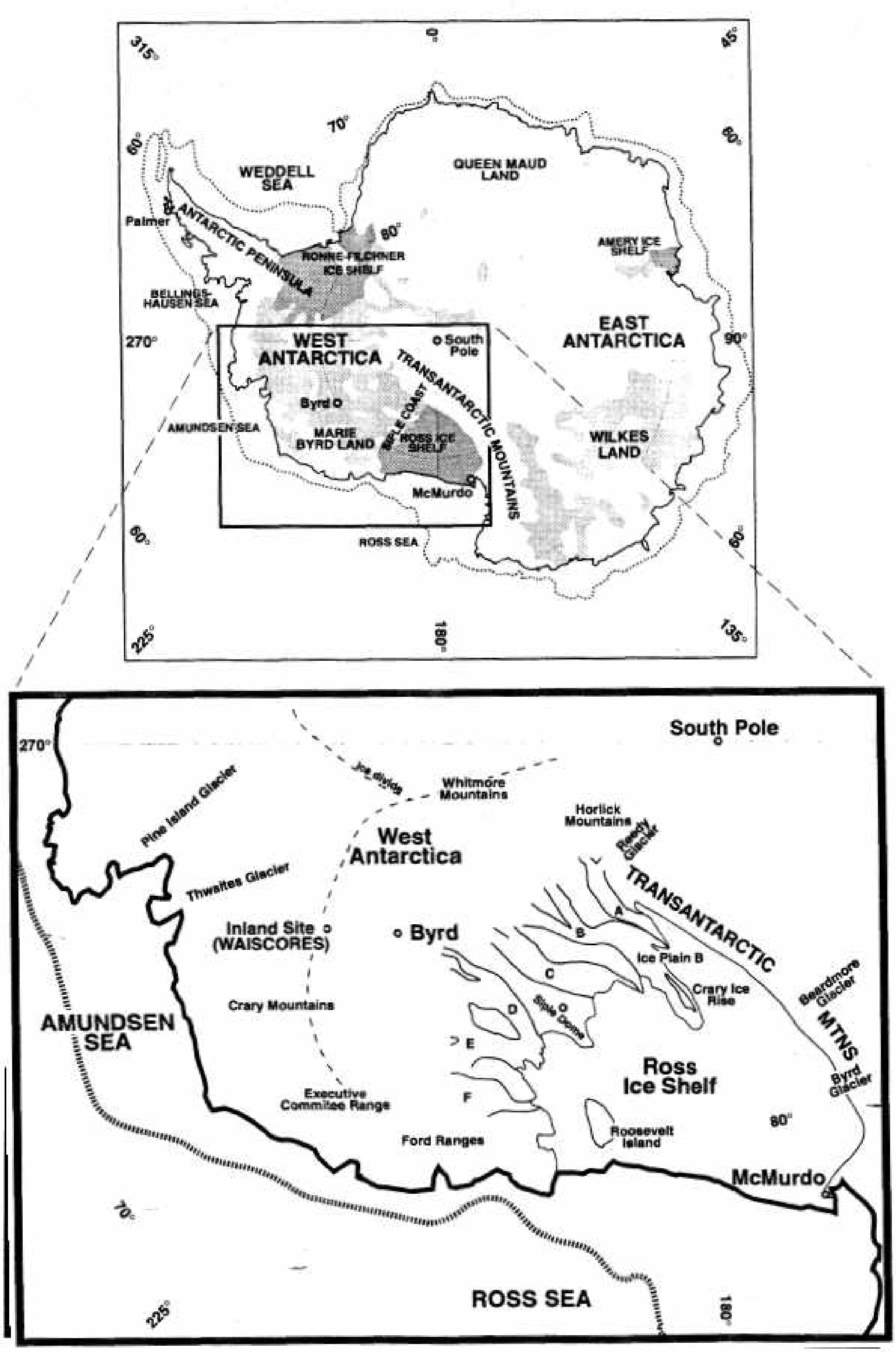

Figure 1. Location Map. The most-likely coring sites are on the sinuous bedrock ridge shown under one of the West Antarctic ice divides, and on Siple Dome, as discussed below.