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First Annual West Antarctic Ice Sheet (WAIS) Science Workshop

Proceedings of a workshop held at
the Sheraton National Hotel
Arlington, Virginia
September 13–14, 1992

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First Annual West Antarctic Ice Sheet (WAIS) Science Workshop

Edited by
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Proceedings of a workshop sponsored by the
NASA Goddard Space Flight Center
and the National Science Foundation
and held at the
Sheraton National Hotel
Arlington, Virginia
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Preface

The West Antarctic Ice Sheet (WAIS) initiative was first formulated under the name SeaRISE at a workshop held in January 1990, where a distinguished group of Antarctic earth scientists recommended to the National Science Foundation (NSF) that a multidisciplinary study be initiated to assess the potential for rapid changes occurring in the marine-based West Antarctic ice sheet (NASA Conference Publication 3075). In answer to the response from NSF's Division of Polar Programs (DPP) that a more detailed implementation plan was needed, a second workshop was held in October 1990, at which an even greater community representation drafted the WAIS Science and Implementation Plan (NASA Conference Publication 3115).

The plan was well received by DPP. To adequately fund the program, DPP proposed an initiative to NSF. Although this initiative proved very competitive within NSF, it ultimately failed to secure additional funding. Nevertheless, DPP committed approximately two million dollars of its core budget in FY92 to scientific activities contained within the WAIS plan. Thus, the WAIS project began, albeit at a more modest level than recommended by the WAIS Science and Implementation Plan.

In September 1992, the first WAIS Science Workshop was convened in Arlington, Virginia. This document records the events of that meeting. Sixty scientists attended the two-day workshop and many expressed their delight at the quality and breadth of the research discussed. DPP's Polar Operations Section graciously supported the meeting by permitting it to be held under its auspices at the facilities used for its annual Antarctic Orientation Meeting. This greatly eased the travel and financial burdens of many of the workshop participants. Even though this required that the two-day workshop begin on a Sunday, attendance at both day's sessions was excellent. It is hoped that future workshops will be held in a similar fashion on an annual basis.

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Session 2: Current State of the West Antarctic Ice Sheet (cont.)

Session 3: Internal Dynamics of the West Antarctic Ice Sheet

Session 4: Interactions of the Environment and the West Antarctic Ice Sheet

Executive Summary

This workshop represents a milestone in interdisciplinary Antarctic research. Never before have Antarctic scientists from so many disciplines met to discuss their current research, exchange their ideas and concerns, and attempt to collectively answer the same question. To answer this question is the goal of the WAIS project: *What is the future behavior and potential for rapid collapse of the West Antarctic ice sheet?* This question must be answered. It is central to the importance of Antarctica in future global climate change, particularly future change in sea level.

The workshop was organized into sessions corresponding to the four objectives identified as necessary to reach the WAIS goal. These objectives are focused on the *history, current behavior, internal dynamics and environmental interactions* of the West Antarctic ice sheet. Presentations were organized by their relevance to each objective rather than by discipline and were aimed at the multi-disciplinary audience. Liberal amounts of time were allowed for questions and discussion. Thus, the workshop provided a forum for Antarctic researchers to broaden their knowledge of the physical environment and its history by listening to the research of others and discussing the ramifications of that unfamiliar research for their own work. At the end of each objective session, a discussion was held to assess the current state of knowledge aimed at achieving that objective, to identify the questions remaining to be answered, and to describe the approaches best taken to answer those questions. These summary discussions are reported in this document, along with an abstract of each presentation. In addition, each session is briefly summarized below.

History

The research presented left no doubt that the West Antarctic ice sheet has had a very dynamic history. Although the studies discussed at the workshop varied widely in temporal resolution and record length, this viewpoint is held by almost every discipline within WAIS. Intercomparison of records will be beneficial to understanding the various time-scales of ice-sheet behavior. Answering the question of what forces the changes can be best served by obtaining more complete and more detailed records of these changes.

Current Behavior

There also was ample evidence presented of changes taking place today. The textbook equilibrium (or steady-state) condition is nowhere to be found. In some places the changes are modest, but in many areas dramatic changes are underway. Most of the ice sheet remains unmeasured, however, and the obvious need is to extend our measurements to those areas to obtain a more comprehensive picture of the current state of the ice sheet. New techniques are making this task more practicable.

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Internal Dynamics

The complexity of the internal dynamics of the ice streams became apparent from a number of papers. While most of the competing mechanical and thermal processes involved in ice flow are known, their relative importance is an area of increasing debate. In places where the subglacial till is very weak, the sides of the ice stream offer significant resistance to flow. The positions of the sides depend on a sensitive balance of heat generation and advection, leading to the possibility of migration of ice–stream margins. It was warned that detailed, but isolated, field studies can inadvertently narrow our perspective of what is a large range of rapid ice–flow conditions. Sticky spots are expected to exist but their characteristics are still vague.

Environmental Interactions

The debate on ice–flow mechanics spilled over into discussions of how the environment immediately adjacent to the ice sheet might be influencing strongly the nature of ice flow. Substantial heat input from subglacial sources was mooted as having a significant impact on the character of the ice sheet and possibly on the initiation of ice streams. In addition, the importance of interactions with the oceans and the atmosphere cannot be dismissed before more studies are carried out. Models are the essential tools in understanding these interactions, but they only crudely account for the necessary interactions.

In a break from the presentation of scientific results, the workshop included an open discussion between staff of NSF/DPP and the attending scientists. DPP still strongly supports WAIS, and scientists urged DPP to reconsider proposing an initiative in anticipation of increased funding requirements by ice–coring activities in West Antarctica recommended by the U.S. Ice Core Working Group.

Finally, the WAIS Working Group was reconstituted into a combination of disciplinary representatives and at–large members. Positions were filled by acclamation from the audience and are included in this report. The Working Group chose Hal Borns as the new chairperson.

FIRST ANNUAL WEST ANTARCTIC ICE SHEET (WAIS) SCIENCE WORKSHOP

Final Agenda

Sunday, September 13, 1992

9:00	Bindschadler	Welcome and Introductions

History of the West Antarctic Ice Sheet

9:10	Anderson	Reconstruction of Late Wisconsinan Ice Sheet and Sea-level Implications
9:30	Jennings	Chronology and Lithologic Record of Ice-sheet Fluctuations
9:50	Prentice	Macrofossil Records of WAIS Retreat During the Holocene (for Berkman)
10:10	Harwood	Paleoclimatological Record Derived From Subglacial Diatoms (for Scherer)
10:30	Nishiizumi	In-situ Produced Cosmogenic Nuclides in Terrestrial Surface Rocks
10:50	White	Isotopes, Ice Cores and Temperature Reconstructions
11:10	Grootes	Reconnaissance and Deep-drill Site Selection on Taylor Dome
11:30	MacAyeal	Climatic Response of the West Antarctic Ice Sheet to the Glacial Cycle
11:50		Summary Discussion

Current State of the West Antarctic Ice Sheet

Poster	Lucchitta	Glacier Velocities on the Bakutis Coast
1:30	Casassa	Flow Stripes on the Ross Ice Shelf
1:50	Merry	SPOT Satellite Mapping of Ice Stream B
2:10	Bindschadler	Mass Balance of the Ice Plain of Ice Stream B and Crary Ice Rise
2:30	Shabtaie	Changes on the Ice Plain of Ice Stream B and Ross Ice Shelf
2:50	Scambos	Velocity and Strain-Rate Fields of Ice Streams D and E Derived From Repeat Satellite Imagery
3:10	Jacobel	Radar Studies of the West Antarctic Ice Streams
3:30	Hulbe	Use of Precision GPS in Antarctica

3:50	Ferrigno	Recent Acceleration of Thwaites Glacier
4:10	Bell	Airborne Gravity and Other Geophysical Techniques for Understanding the Lithosphere Beneath the West Antarctic Ice Sheet
4:30	Blankenship	Aerogeophysical Evidence for Active Volcanism Beneath the West Antarctic Ice Sheet
4:50		Summary Discussion

Monday, September 14, 1992

Internal Dynamics of the West Antarctic Ice Sheet

9:00	Echelmeyer	Ice Stream B Margin: Stress, Strain and Temperature
9:20	Raymond	Ice Stream Margin
9:40	van der Veen	The Role of Lateral Drag in Ice Stream B Dynamics
10:00	Novick	Character of the Deformable Layer Beneath WAIS Ice Streams
10:20	Englehardt	Basal Water Pressure and Water Flow of Ice Stream B
10:40	Alley	Basal Restraint of Ice Flow/Deforming Beds
11:00		Summary Discussion

Interactions of the Environment and the West Antarctic Ice Sheet

12:50	Anandakrishnan	Geologic Controls on WAIS
1:10	Behemdt	Speculation on the Effect of Subglacial Volcanism on Changes in the West Antarctic Ice Sheet
1:30	Jacobs	Oceanographic Interactions
1:50	Steams	Sublimation on the Ross Ice Shelf
2:10	Bromwich	Surface Winds over West Antarctica
2:30	Fastook	Modeling Ice Streams: Derived Quantities
2:50		Summary Discussion
3:20		International Programs
3:40		Dialogue with NSF/DPP Science Section Managers
4:20		Dialogue with NSF/DPP Polar Operations Staff
5:00		Election of New Working Group Members and Chair

Session 1: History of the West Antarctic Ice Sheet

N93-31879

Reconstruction of Late Wisconsinan Ice Sheet and Sea-Level Implications

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The Ross Sea exhibits north–south oriented troughs associated with modern ice streams and outlet glaciers. Seismic reflection profiles across the troughs show evidence that they were glacially eroded. Seismic records show morphologic features interpreted as till tongues, morainal banks, and possibly glacial deltas formed near the grounding line of the former marine ice sheet.

Piston cores from the continental shelf penetrated diamictons whose origin and age is problematic. Detailed petrographic analyses of the minerals and rocks comprising these diamictons were conducted to determine subglacial versus glacial marine origin, and to reconstruct the glacial setting of the Ross Sea during the most recent glacial maximum. The most detailed work, conducted in the western Ross Sea, shows that diamictons do occur in distinct petrologic provinces. This is consistent with deposition from the basal debris zone of either an ice sheet or an ice shelf. Overcompaction, in conjunction with the widespread nature of these deposits, favors deposition from marine ice sheets; ice shelves are believed to deposit their basal debris close to their grounding lines.

The data demonstrate that the East Antarctic Ice Sheet and West Antarctic Ice Sheet grounded on the continental shelf during the last glacial maximum. In the western Ross Sea, the grounding line existed near the shelf break. Diamictons from the central and eastern portion of the continental shelf contain stable mineral and rock fragments, indicating considerable recycling of these particles. Because of this, the grounding-line positions and paleodrainage divides within the eastern Ross Sea cannot be constrained as confidently as those in the western Ross Sea.

In the western Ross Sea, glacial marine sediments of the outer shelf are correlated with subglacial tills on the inner shelf. The glacial marine sediments yield radiocarbon ages of >35,510 yrs. B.P. to 17,390 yrs. B.P. The majority of piston cores from the continental shelf penetrated diatomaceous muds resting in sharp contact on glacial marine sediments and subglacial tills. This implies rapid retreat of the ice sheet from the shelf.

Future research will involve collection of high-resolution seismic data and piston cores to define the grounding-line positions and establish the chronology of the retreat history of the ice sheets. Additional work will concentrate on establishing a more detailed paleodrainage map using geochemical methods.

N93-31880

Lithology and Chronology of Ice-Sheet Fluctuations (Magnetic Susceptibility of Cores from the western Ross Sea)

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The goals of the marine geology part of WAIS include reconstructing the chronology and areal extent of ice-sheet fluctuations and understanding the climatic and oceanographic influences on ice-sheet history. As an initial step toward attaining these goals, down-core volume magnetic susceptibility (MS) logs of piston cores from three N-S transects in the western Ross Sea are compared. The core transects are within separate petrographic provinces based on analyses of till composition. The provinces are thought to reflect the previous locations of ice streams on the shelf during the last glaciation.

Magnetic susceptibility is a function of magnetic mineral composition, sediment texture, and sediment density. It is applied in the western Ross Sea for two purposes: 1) to determine whether MS data differentiates the three transects (i.e., flow lines), and thus can be used to make paleodrainage reconstructions of the late Wisconsinan ice sheet; and 2) to determine whether the MS data can aid in distinguishing basal till diamictons from diamictons of glacial-marine origin and thus aid paleoenvironmental interpretations.

Comparison of the combined data of cores in each transect shows an overlap in the MS distributions. However, the median MS of transect 1 (the westernmost transect) is ca. 100 x 10^{-5} SI units, whereas the median values of transects 2 and 3 are 30 x 10^{-5} and 50 x 10^{-5} SI units, respectively. To refine the MS signal, data points from "till" and "glacial-marine sediment" were analyzed separately. The MS distribution of the basal till from each transect should be narrower than the total MS distribution, reflecting a limited provenance. In contrast, the MS distribution of glacial marine sediment from the three transects should be broad and overlapping, reflecting heterogeneous sediment sources from iceberg rafting. The MS distribution of till in transect 2 (median = 90 x 10^{-5} SI units)does not overlap with that of either transect 1 (median = 20 x 10^{-5} SI units) or transect 3 (median = 20 x 10^{-5} SI units). The MS distributions of till in tran-sects 1 and 3 barely overlap.

MS is a promising technique for distinguishing provenance and reconstructing paleodrainages in the Ross Sea. The MS distributions of the glacial marine sediments of the three transects overlap considerably. However, as in the "total" and "till" comparisons, the median MS of transect 1 is higher than the median MS in the other two transects. The reason is that the same pattern is maintained relates to the east to west direction of surface currents in the region. Surface currents bring icebergs and sediment with low MS toward the high MS region. The low-MS sediments have very little effect on the overall high MS signal in the west.

N93-31881

Macrofossil Records of West Antarctic Ice Sheet Retreat During the Holocene

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(presented by R. Bindschadler)

Marine macrofossils in emerged beaches around Antarctica represent a geochemical framework for interpreting meltwater signatures associated with variations in the adjacent ice sheet margins during the last 10,000 years. In particular, mollusc species provide ideal experimental templates for assessing hydrochemical variations in Antarctic coastal marine environments because of their excellent preservation, high abundances, circumpolar distributions, and carbonate shells, which incorporate trace elements and stable isotopes. Modern samples of the bivalve *Adamussium colbecki*, which were collected across a depth gradient in the vicinity of a glacial meltwater stream in West McMurdo Sound, revealed shell trace element concentrations that were significantly higher above 10 meters because of their exposure to meltwater runoff. This meltwater signature also was reflected by the shell oxygen isotopic composition, which was in equilibrium with the ambient seawater, as demonstrated by the overlap between the predicted and actual $\delta^{18}O_w$ values. These modern samples provide analogs for interpreting the geochemical records in their fossils, which based on preliminary oxygen isotopic values, indicate that fossil *Adamussium* shells were exposed to warmer and/or fresher water along the Victoria Land Coast during the mid-Holocene. Beach emergence profiles from around Antarctica, which were based solely on molluscan fossils, complement the above geochemical data by suggesting that the rate of beach emergence fluctuated around Antarctica during the mid-Holocene. Paleoenvironmental analysis of macrofossils from emerged beaches represents a new direction in Antarctic research that can be used to assess changes in the margins of the ice sheets since the Last Glacial Maximum. The resolution of these analyses will be enhanced by collaborations that are developing with scientists who are conducting comparable studies in other coastal regions around the continent.

N93-31882

The Diatom Record from Beneath the West Antarctic Ice Sheet and the Global Proxy Perspective

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(presented by D. Harwood)

Recent glaciological evaluation and modeling of the marine-based West Antarctic Ice Sheet (WAIS) support the possibility that the WAIS disintegrated during one or more Pleistocene interglacial period(s). The magnitude of sea level and oxygen isotope variation during certain late-Pleistocene interglacial periods is also consistent with the possibility of major retreat of the WAIS. Although oxygen isotopes from deep-sea sediments provide the best available proxy record for global ice volume (despite the ambiguities inherent in that record), the source of ice volume changes must be hypothesized. Based on the intensity of interglacial isotopic shifts recorded in Southern Ocean marine sedimentary records, Stage 11 (400,000 years ago) is the strongest candidate for WAIS collapse, but the records for stages 9, 7 and 5.5 are all consistent with the possibility of multiple late-Pleistocene collapses.

Seismic reflection studies through the WAIS have revealed thick successions of strata with seismic characteristics comparable to upper Tertiary marine sediments. Small samples of glacial diamictons from beneath the ice sheet have been collected via hot-water drilled access holes. These sediments include mixed diatom assemblages of varying ages. Late-Miocene diatoms dominate many samples, probably reflecting marine deposition in West Antarctic basins prior to development of a dominantly glacial phase in West Antarctica. In addition to late-Miocene diatoms, samples from Upstream B (1988/89) contain rare post-Miocene diatoms, many of which imply deposition in the West Antarctic interior during one or more Pleistocene deglaciation periods.

Age-diagnostic fossils in glacial sediments beneath ice sheets provide relatively coarse chronostratigraphic control, but they do contain direct evidence of regional deglaciation. Thus, sub-glacial till samples provide the evidence regarding the source of ice sheet variability seen in well-dated proxy records. Combined, these independent data sets can provide a more comprehensive and less speculative interpretation of the history of past glacial minima in currently glaciated polar regions.

N93-31888

Reconnaissance and Deep-Drill Site Selection on Taylor Dome, Antarctica

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Taylor Dome (about 77°40' to 77°50'S, 158°10' to 159°20'E) is a small ice dome near the head of Taylor Valley, Southern Victoria Land. The location of the dome, just west of the Transantarctic Mountains, is expected to make the composition of the accumulating snow sensitive to changes in the extent of the Ross Ice Shelf. Thus, it is linked to the discharge of the West Antarctic ice sheet but protected against direct influences of glacial–interglacial sea–level rise. The record of past climatic and environmental changes in the ice provides a valuable complement to the radiocarbon–dated proxy record of climate derived from perched deltas, strandlines, and moraines that has been obtained in the nearby Dry Valleys.

We carried out a reconnaissance of the Taylor Dome area over the past two field seasons to determine the most favorable location to obtain a deep core to bedrock. A stake network has been established with an 80–km line roughly along the crest of Taylor Dome, and two 40–km lines parallel to it and offset by 10 km. These lines have been surveyed in 1990/91, and the positions of 9 grid points have been determined with geoceivers. A higher density stake network was placed and surveyed around the most likely drill area in the second year. Ground–based radar soundings in both years provided details on bedrock topography and internal layering of the ice in the drill area. An airborne radar survey by Blankenship and Hodge in January 1992, completed the radar coverage of the Taylor Dome field area.

The spatial and temporal variability in the accumulation of snow and in the trace constituents of the snow have been determined in an array of 11 snowpits spread over the survey network. The layering observed in the pits is predominantly horizontal. Wind–packed hard layers (buried sastrugi) are evident, and increase in size and frequency from southwest to northeast across the dome, roughly along the direction of katabatic winds from the center of East Antarctica to the Taylor Valley. The character of the firn and of the oxygen–isotope record change along the same line; from a detailed stratigraphy with grain size varying by layer and large isotope fluctuations along the southwest gridline, to strongly metamorphosed, coarse–crystalline firn (depth hoar) with little stratigraphy or isotope fluctuations preserved in the northeast. Particles showed a seasonal pattern, with about 9 layers in the upper 2 meters (E. Mosley–Thompson). Major ion chemistry (Na, K, Mg, Ca, Cl, NO_3, SO_4, MSA, and H_2O_2) showed a similar layering. Concentrations in the drill area near the center of the dome are similar to, or lower than, those observed at South Pole (P.A. Mayewski), indicating little direct influence from the Dry Valleys, immediately to the east. The requirements for an ice–core drill site—simple ice flow over fairly flat bedrock, regular snow deposition without surface melting, and preservation of the deposited signal in the firn—all can be met in the summit area of Taylor Dome. Observations on an array of snow accumulation boards and stakes indicate, however, that the layering observed in the snowpits may represent episodic accumulation interspersed with no accumulation or erosion.

The change in accumulation and firnification observed over Taylor Dome demonstrates the necessity of surface studies to determine suitable drill sites for the deep core planned in the Ross Sea/Amundsen Sea divide area of West Antarctica, and for the Siple Dome core (WAISCORES). The data recently available from the deep core at the summit of the Greenland ice sheet (GISP2, unpublished data) show that the deep core may provide a detailed climate history with a time–scale constructed from seasonal cycles. The deep core will provide a detailed history of the West Antarctic ice sheet for use in flow modelling (WAIS), as well as a comparison of climate change in the Southern Hemisphere with that in the Northern Hemisphere derived from the GISP core.

N93-31884

Irregular Oscillations of the West Antarctic Ice Sheet

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Model simulations of the West Antarctic ice sheet suggest that sporadic, perhaps chaotic, collapse (complete mobilization) of the ice sheet occurred throughout the past one million years. The irregular behavior is due to the slow equilibration time of the distribution of basal till, which lubricates ice-sheet motion. This nonlinear response means that predictions of future collapse of the ice sheet in response to global warming must take into account its past history, and in particular, whether the present basal till distribution predisposes the ice sheet towards rapid change.

Session 1 Summary Discussion: History of the West Antarctic Ice Sheet

Rapporteur: Richard Alley

Chair Bindschadler summarized the presentations as providing important new data on past ice-sheet fluctuations (Anderson and Jennings on ice-marginal retreat at the end of the Wisconsinan; Harwood for Scherer on recent collapse of the ice sheet; White suggesting recent changes in the WAIS based on the Byrd core) and on techniques to study those fluctuations (Nishiizumi and Finkel on cosmogenic exposure ages; MacAyeal on modeled changes in ice sheet; Grootes relating coring planned at McMurdo Dome; Bindschadler for Berkman on isotopic composition of Antarctic shells).

The time-scale of ice-sheet changes was discussed in much detail (primarily MacAyeal, Raymond, Anderson, and Alley). One of the striking results to emerge is that ice-sheet response to a climatic forcing may be rapid but long-delayed. For example, the ice sheet may collapse when basal lubrication linked to meltwater production responds to surface warming that occurred thousands of years before. This may be preconditioned by processes with longer time constants, such as uplift of the Transantarctic mountains (Behrendt).

White observed that the WAIS may dictate climate as well as react to it, and MacAyeal noted that the North Atlantic Heinrich or Dansgaard/Oeschger events may represent climate response to analogous behavior of the Laurentide ice sheet, for which the WAIS analog may prove critical. Bromwich cautioned that the climate forcing on the ice sheet still remains important, and Anderson added that oceanic as well as atmospheric interactions must matter.

Experiments still to be done include developing a coherent history of ice extent from marine studies, and of ice thickness from glacial-geological (with exposure-age dating) and ice-core studies; the data available now are more tantalizing than conclusive (Bindschadler, Borns). The ability to interpolate between ice cores using radar might extend the ice-core records (Raymond). And ultimately, the focus of ongoing studies within the Ross drainage basin must be expanded to the Weddell and Pine Island drainages (Harwood, Bromwich, and Mullins, speaking for Lucchita).

Session 2: Current State of the West Antarctic Ice Sheet

N93-31885

Velocities of Thwaites and Land Glaciers

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Changes in the area of volume of polar ice sheets are intricately linked to changes in global climate and may severely impact the densely populated coastal regions on Earth.

An ice sheet's velocity is a critical parameter, which, together with ice thickness, allows the determination of discharge rates. Using moderate-resolution satellite images such as Landsat, the velocity of floating ice can be measured quickly and relatively inexpensively by tracing crevasse patterns on shelves and ice tongues. Errors in measured velocities are as little as 0.02 km per year, if 1) the time interval is longer than 10 years, 2) the velocity is higher than 0.5 km per year, 3) the coregistration points are well dispersed and enclose the area to be measured, and 4) the image pair includes a Landsat 4 or 5 image. The fewer of these conditions that are met, the less accurate the results become; but even for poor conditions, the velocities are generally reliable to near 0.1 km per year.

We are in the process of obtaining velocities of all ice shelves and ice tongues along the Bakutis and Ruppert coasts, wherever suitable crevasse patterns exist. So far, we have obtained velocities for the Thwaites and Land glacier tongues.

The velocity measurements on the Thwaites Glacier Tongue were made by using five Landsat images acquired at three different times—a Multispectral Scanner (MSS) scene from 1972, two consecutive MSS scenes from 1984, and two consecutive Thematic Mapper (TM) scenes from 1990 (Ferrigno *et al.*, in press). The consecutive scenes were mosaicked together and all scenes were coregistered to the 1984 image set. The measurements covering the time span from 1972 to 1984 gave an average annual velocity of about 2.58 km per year, and those from 1984 to 1990 gave an average annual velocity of about 2.71 km per year (Figures 1A and B). As the early measurements involve a Landsat 1 MSS image, whose internal geometric distortions may be substantial, these measurements are less reliable than the later ones. Future measurements are needed to verify our observations and determine if the change in average velocity is real.

The Land Glacier, with its associated ice tongue, also drains into the West Antarctic ice sheet. Two image pairs cover this glacier—an early MSS set dating from 1973 and 1975, and a later TM set dating from 1986 and 1988. Each pair spans a period of only a few years, but the two pairs are separated by an 11-year hiatus). Unfortunately, the long time gap between pairs, coupled with the rapid disintegration of the glacier tongue, precludes tracking crevasse patterns between the two pairs (Lucchitta *et al.*, in press).

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The average annual velocity of the earlier pair is about 1.83 km per year, result that agrees reasonably well with the average annual velocity of the later image pair—about 1.68 km per year (Figures 2A and B). The discrepancy may be real, reflecting a reduction in glacier velocity; but the difference is small enough to warrant additional testing. Unfortunately, the velocity change is opposite to that of the Thwaites measurements relative to time. Again, we regard the second set of measurements to be more reliable because it involves TM images, whose internal geometry and scale distortions are minimal and provide a three–fold increase in resolution.

Overall, both the Thwaites and Land glaciers are exceptionally fast for Antarctic glaciers. It remains to be seen whether other glacier tongues draining into the West Antarctic ice sheet through Marie Byrd Land are moving rapidly as well.

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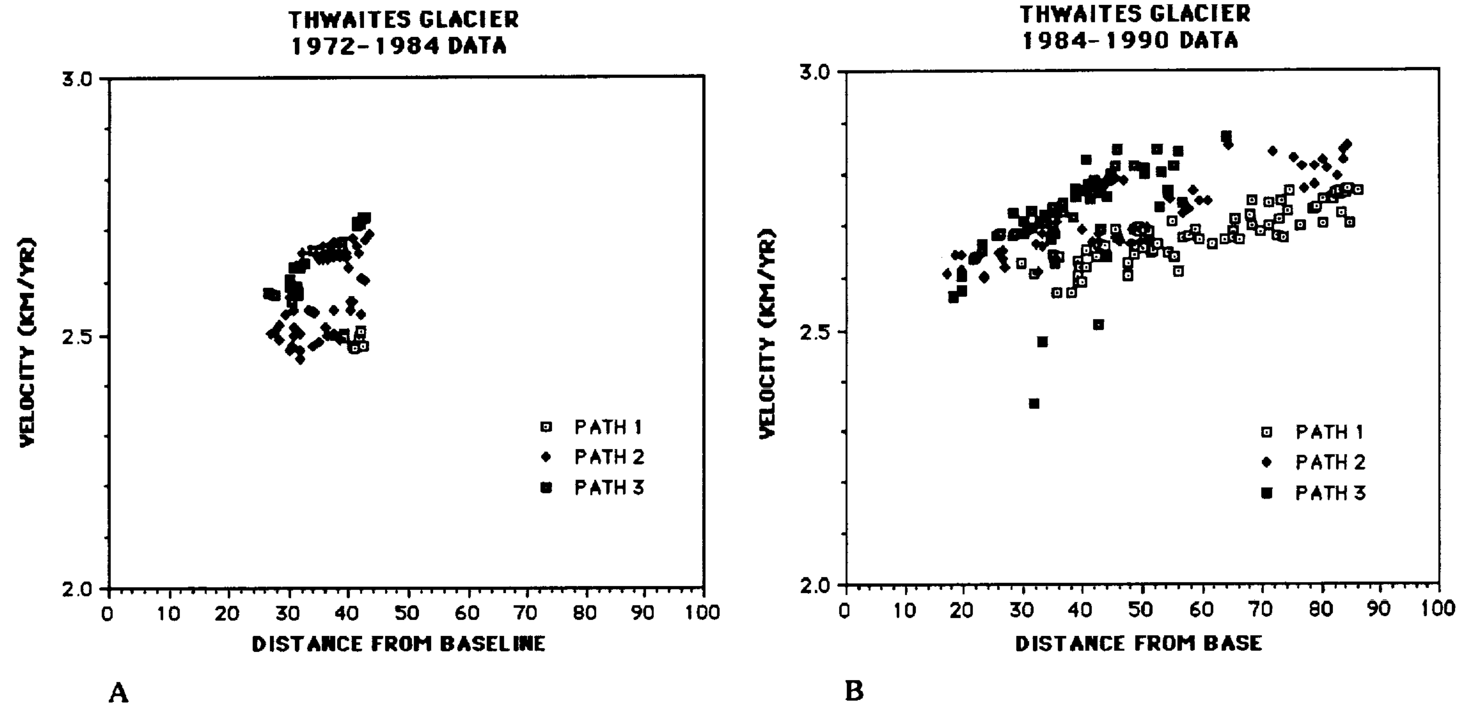

Figure 1. Thwaites Glacier Tongue. Average annual velocity plotted against distance to baseline(arbitrary line on tongue,but identical for both image pairs). Paths denote different longitudinal fields on glacier tongue. A) 11.9-year interval. B) 5.1-year interval.

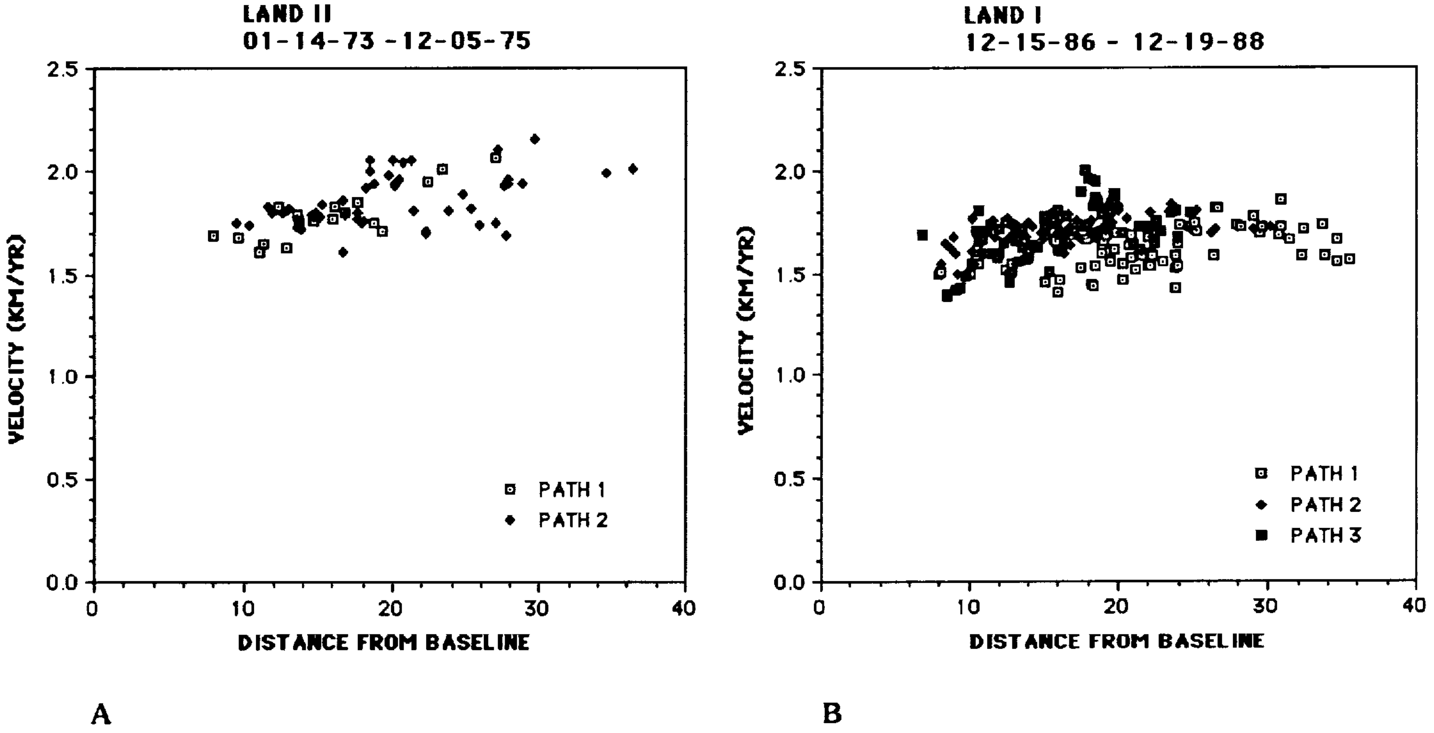

Figure 2. Land Glacier and its tongue. Average annual velocity plotted against distance to baseline (located near grounding line). Paths denote different longitudinal fields on glacier tongue. A) 2.9-year interval. B) 2.0-year interval.

N93-31886

Condition of the Ross Ice Shelf Derived from AVHRR Imagery

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Advanced Very High Resolution Radiometer (AVHRR) satellite imagery is combined with the Ross Ice Shelf Geophysical and Glaciological Survey (RIGGS) data to study recent changes on the Ross Ice Shelf. Flow stripes that appear on the AVHRR imagery agree with significant changes in ice flow that have occurred over the past 1,100 years on the ice shelf sector fed by East Antarctica. A large looping pattern of flow stripes that disagrees with RIGGS flowlines appears west of Crary Ice Rise, on the eastern part of the ice shelf. This looped pattern is interpreted as relict flow stripes related to past activity of a major ice stream of West Antarctica, which occurred about 800 years ago (Casassa and Turner, 1991; Casassa *et al.*, 1991).

AVHRR imagery of the 1987 and 1990 calving margin is compared to the 1971 position of the margin from a historical map to derive an ice-margin advance rate of 1.1 km a^{-1} in the center of the ice shelf. This advance rate is similar to the advance rate reported by Jacobs *et al.* (1986). The advance rate derived from AVHRR imagery is 10 to 30 percent larger than the value of RIGGS velocity data, which suggests a recent increase in ice velocity. The ice margin advance rates and ice velocity data are used for calculating calving rate—which is slightly negative—except near the lateral boundaries of the ice shelf margin, where important calving has occurred. Negative calving rates can be explained by a recent increase in ice velocities. The above evidence indicates that the ice margin advance over the past 20 years is a consequence of minimal calving rate (Casassa, in preparation). Higher resolution satellite data will be analyzed to test if ice velocities have in fact, increased on the Ross Ice Shelf in recent years.

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N93-31887

SPOT Satellite Mapping of Ice Stream B

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Numerous features of glaciological significance appear on two adjoining SPOT High Resolution Visible (HRV) images that cover the onset region of ice stream B. Many small-scale features, such as crevasses and drift plumes, have been previously observed in aerial photography. Subtle features, such as long flow traces that have not been mapped previously, are also clear in the satellite imagery. Newly discovered features include ladder-like runners and rungs within certain shear margins, flow traces that are parallel to ice flow, unusual crevasse patterns, and flow traces originating within shear margins.

An objective of our work is to contribute to an understanding of the genesis of the features observed in satellite imagery. The genetic possibilities for flow traces, other lineations, bands of transverse crevasses, shear margins, mottles, and lumps and warps are described. In particular:

—Shear margins are readily identified on the imagery. Elements of the shear margin follow a pattern described by the Vornberger and Whillans (1990) model.

—Two large warps were identified on the imagery near the upglacier end of the Snake. The two warps are interpreted to be compressional buckles. In the same region, trains of lumps seem to follow the direction of ice flow. Each lump is a piece of inland ice or a fold in the ice. Each warp and the trains of lumps are aligned at approximately right angles to the inferred direction of principal horizontal compressive stress. Crevasses with a large radius of curvature are associated with shear margins. This indicates slower shearing than farther downglacier in the stream margin. The region is interpreted to be the onset of a shear margin.

—Evidence from the satellite imagery favors the view that flow traces are formed in shear margins.

—Other lineations are observed on the imagery that bear no obvious association with present ice flow. They may be old flow traces or shear margins that were stranded due to a change in flow. Another possibility is that these features are compressional folds formed where faster ice impacts against slower ice.

—Most of the crevasses on the ice streams are transverse and occur in bands. The evidence favors the view that ice structure or temperature is responsible for crevasse location.

—Mottles are observed on ice moving at relatively fast speeds, indicating that the processes generating mottles in slowly moving ice also act in fast ice.

The SPOT 10-m panchromatic imagery has worked well in mapping large-scale glacial features and has provided new insights for describing the flow of ice streams.

N93-31888

The Mass Balance of the Ice Plain of Ice Stream B and Crary Ice Rise

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The region in the mouth of Ice Stream B (the ice plain) and that in the vicinity of Crary Ice Rise are experiencing large and rapid changes. Based on velocity, ice thickness and accumulation rate data, the patterns of net mass balance in these regions have been calculated. Net mass balance, or the rate of ice thickness change, was calculated as the residual of all mass fluxes into and out of subregions (or boxes). Net mass balance provides a measure of the state of health of the ice sheet and clues to the current dynamcis.

In work published by Bindschadler and others (*J. Glac.*, **35**, (121), 1989) the region around Crary Ice Rise shows a pattern of thickening upstream of the ice rise (0.76 m/a ice equivalent) and thinning downstream (-1.02 m/a). This pattern corresponds to an upstream migration of the ice rise with time.

On the ice plain of Ice Stream B, field data of ice thickness, velocity, and accumulation rate were organized into a Geographical Information System (GIS) and were used to calculate the spatial pattern of net mass balance. This organizational scheme greatly facilitated the calculations, simplified the spatial averaging, and will assist in the use of these data by other investigators. Overall, the ice plain is thickening at a rate of 0.13 ± 0.05 m/a. Large uncertainties of the 1-kilometer grid calculations were reduced by spatial averaging, which revealed a number of areas significantly out of balance. Ice in the broad diverging flow field of tributary B2 is mostly thinning. Ice discharging tributary B1 is thickening upstream of a subglacial rise and thinning downstream of this rise. The position of the rise corresponds roughly to ice raft "a," a relict ice rise, that appears to be moving now with nearly the same velocity as the surrounding ice. The asymmetric patterns of net mass balance for the two major tributaries of Ice Stream B demonstrate a real difference in the current dynamics of these two tributaries.

N93-31889

Changes on the Ice Plain of Ice Stream B and Ross Ice Shelf

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During the 1970s and 1980s, nearly 200 stations from which accurate, three-dimensional position fixes have been obtained from TRANSIT satellites were occupied throughout the Ross Ice Shelf. We have transformed the elevations obtained by satellite altimetry to the same geodetic datum, and then applied a second transformation to reduce the geodetic heights to elevations above mean sea level using the GEM-10C geoidal height. On the IGY Ross Ice Shelf traverse between October 1957 and February 1958, an accurate method of barometric altimetry was used on a loop around the ice shelf that was directly tied to the sea at both ends of the travel route, thus providing absolute elevations. Comparisons of the two sets of data at 32 station pairs on floating ice show a mean difference of 0 ± 1 m. The elevation data have also been compared with theoretical values of elevations for a hydrostatically floating ice shelf. The mean difference between theoretical and measured values of elevations is –2 ± 1 m.

The southern legs of the IGY traverse several times crossed the grounding lines of what we now know to be the Ice Stream B ice plain upstream of Crary Ice Rise (Shabtaie and Bentley, 1987; Shabtaie *et al.*, 1989). Since 1983, three-dimensional positions from the TRANSIT satellites have been obtained at several stations near the IGY traverse in this area. A few of these stations are tied together by airborne radar sounding and optical leveling. There are 14 locations in five different zones where the IGY and SCP profiles cross; all show a lowering of the surface since 1958. We conclude that there has been a regional thinning of the ice on the order of –0.40 ± 0.07 m yr^{-1} over the last three decades, accompanied by a retreat in the position of the grounding line.

N93-31890

Surface Velocity Fields of Ice Streams D and E Derived from Repeat Satellite Imagery

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Sequential Landsat TM images were used to map in detail the surface velocity of Ice Streams D and E by tracking small ice features in coregistered images. The majority of both ice streams have now been mapped for velocity, and in most areas, approximate strain-rates are also determined. Tracking was accomplished semi-automatically using an image-to-image cross-correlation technique. Measurement density is roughly four per km^2 in regions with distinct surface features (crevasses, snow dunes, etc.), and with cloud-free image coverage.

Measurements extend from the most upstream crevassed areas near the onset of fast ice motion to the grounding-line area. The velocity and strain-rate fields show the expected broad pattern of longitudinal stretching, but include several deviations from this general flow. Three areas of particular interest are discussed in detail: several "sticky spots" where ice flow slows and deviates around regions of apparently greater flow resistance; upstream onset areas where several small, more slowly flowing tributaries converge to form the main trunk of Ice Stream E; and side-entrant areas where ice from the nearly stagnant inter-ice-stream ridges appears to merge with the fast-flowing trunk. Strain-rate values within the ice stream are highest near the shear margins, but other areas—notably near the "sticky spots"—show increased shear, transverse, and longitudinal strain. Velocity and strain-rate determinations over entire ice streams, now possible using satellite imagery coupled with the semi-automated cross-correlation technique, has great potential for investigating the dynamics of ice streams and for contributing to theories on the mechanism of ice-stream flow.

N93-31891

Radar Studies of the West Antarctic Ice Streams

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A collaboration has carried out measurments of ice thickness at the mouth of Ice Streams D and E, West Antarctica, using a surface-based impulse radar. These studies have been undertaken as a part of the continuing effort to understand the state of the West Antarctic Ice Sheet and its response to climate change. Thickness measurements will be used in the mass balance calculation currently in progress and to better understand features in the surface topography seen at low-angle Sun illumination in the satellite imagery. Results show that the discharge areas of Ice Streams D and E are thickening by approximately 1 meter per year, and thus that these ice streams are likely losing mass. Aperiodic wavelike features in the surface topography are described, which pose interesting questions about migration of the grounding line and ice-stream dynamics.

N93-31892

Mass Balance Assessment Using GPS

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Mass balance is an integral part of any comprehensive glaciological investigation. Unfortunately, it is hard to determine at remote locations where there is no fixed reference. The Global Positioning System (GPS) offers a solution.

Simultaneous GPS observations at a known location and the remote field site, processed differentially, will accurately position the camp site. From there, a monument planted in the firn atop the ice can also be accurately positioned. Change in the monument's vertical position is a direct indicator of ice thickness change. Because the monument is not connected to the ice, its motion is due to both mass balance change and to the settling of firn as it densifies into ice. Observations of relative position change between the monument and anchors at various depths within the firn are used to remove the settling effect.

An experiment to test this method has begun at Byrd Station on the West Antarctic Ice Sheet and the first epoch of observations has been made. Analysis indicates that positioning errors will be very small. It appears likely that the largest errors involved with this technique will arise from ancillary data needed to determine firn settling.

N93-31893

Recent Acceleration of Thwaites Glacier

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The first velocity measurements for Thwaites Glacier were made by R. J. Allen in 1977. He compared features of Thwaites Glacier and Iceberg Tongue on aerial photography from 1947 and 1967 with 1972 Landsat images, and measured average annual displacements of 3.7 and 2.3 km/a. Using his photogrammetric experience and taking into consideration the lack of definable features and the poor control in the area, he estimated an average velocity of 2.0 to 2.9 km/a to be more accurate.

In 1985, Lindstrom and Tyler (*Ant. Jour. of the U. S.*, **19** (5), 53–55) also made velocity estimates for Thwaites Glacier. Using Landsat imagery from 1972 and 1983, their estimates of the velocities of 33 points ranged from 2.99 to 4.02 km/a, with an average of 3.6 km/a. The accuracy of their estimates is uncertain, however, because in the absence of fixed control points, they assumed that the velocities of icebergs in the fast ice were uniform.

Using additional Landsat imagery in 1984 and 1990, accurate coregistration with the 1972 image was achieved based on fixed rock points. For the period 1972 to 1984, 25 points on the glacier surface ranged in average velocity from 2.47 to 2.76 km/a, with an overall average velocity of 2.62 ± 0.02 km/a. For the period 1984 to 1990, 101 points ranged in velocity from 2.54 to 3.15 km/a, with an overall average of 2.84 km/a. During both time periods, the velocity pattern showed the same spatial relationship for three longitudinal paths. The 8-percent acceleration in a decade is significant.

This recent acceleration may be associated with changes observed in this region since 1986. Fast ice melted and several icebergs calved from the base of the Iceberg Tongue and the terminus of Thwaites Glacier. However, as early as 1972, the Iceberg Tongue had very little contact with the glacier.

(Taken from "Velocity measurement and changes in position of Thwaites Glacier/Iceberg Tongue from aerial photography, Landsat images and NOAA AVHRR data," J. G. Ferrigno, B. K. Lucchitta, K. F. Mullins, A. L. Allison, R. J. Allen, and W. G. Gould, *Annals of Glaciology*, Vol. 13, in press.)

N93-31894

Airborne Gravity and Other Geophysical Techniques for Understanding the Lithosphere Beneath the West Antarctic Ice Sheet

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As part of a program entitled Corridor Aerogeophysics of the Southeastern Ross Transect Zone (CASERTZ), we have developed an aerogeophysical platform to study the interaction of geological and glaciological processes in West Antarctica. A de Havilland Twin Otter has been equipped with an ice–penetrating radar, a proton–precession magnetometer, an airborne gravity system and a laser altimeter. The 60–MHz ice–penetrating radar can recover sub–ice topography with an accuracy of about 10 m through 3 km of comparatively warm West Antarctic ice, while the laser altimeter profiling of the ice surface is accurate to approximately 1 m. The magnetic field observations are accurate to several nT, and the gravity measurements are accurate to better than 3 mGal. The aircraft is navigated by a local radio–transponder network, while differential positioning techniques based on the Global Positioning System (GPS) satellites are used for recovering high–resolution horizontal and vertical positions. Attitude information from an inertial navigation system is used to correct the laser altimetry and a digital pressure transducer is used to recover vertical positions and accelerations in the absence of satellite positioning. Continuous base–station observations are made for the differential GPS positioning and the removal of ionospheric noise from the airborne magnetometer measurements.

N93-31895

Aerogeophysical Evidence for Active Volcanism Beneath the West Antarctic Ice Sheet

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Although it is widely understood that the collapse of the West Antarctic Ice Sheet (WAIS) would cause a global sea-level rise of 6 m, there continues to be considerable debate about the response of this ice sheet to climate change. The stability of the WAIS, which is characterized by a bed grounded well below sea level, may depend on geologically controlled conditions at the base, which are independent of climate. Ice streams moving up to 750 m yr^1 disperse material from the interior through to the oceans. As these ice streams tend to buffer the reservoir of slow-moving inland ice from exposure to oceanic degradation, understanding the ice-streaming process is important for evaluating WAIS stability. There is strong evidence that ice streams slide on a lubricating layer of water-saturated till. Development of this basal layer requires both water and easily eroded sediments. Active lithospheric extension may elevate regional heat flux, increase basal melting, and trigger ice streaming. If a geologically defined boundary with a sharp contrast in geothermal flux exists beneath the WAIS, ice streams may only be capable of operating as a buffer over a restricted region. Should ocean waters penetrate beyond this boundary, the ice-stream buffer would disappear, possibly triggering a collapse of the inland ice reservoir. Here, we present aerogeophysical evidence for active volcanism and elevated heat flux beneath the WAIS, near the critical region where ice streaming begins.

Session 2 Summary Discussion: Current State of the Ice Sheet

Rapporteur: Richard Alley

Chair Bindschadler observed that the striking thing about the WAIS is that everywhere we look, there is evidence of rapid changes occurring. Casassa found looped structures on the Ross Ice Shelf, possibly indicating surging; Merry found intricate and complex patterns of crevassing that are hard to explain in steady-state models; Bindschadler found large changes near the mouth of Ice Stream B; Shabtaie found changes occurring just farther downglacier; Bindschadler presented data for Ferrigno that probably indicate recent acceleration of Thwaites Glacier (although Bindschadler was not able to answer fully some questions on methods used by Ferrigno); and Blankenship and Bell showed a newly discovered, active volcano under the inland ice of West Antarctica.

These results were obtained using powerful new techniques such as repeat satellite imagery and GPS surveying, which have greatly expanded our ability to study the ice sheet. Especially notable are the techniques reported by Scambos for extracting dense fields of velocities from repeat images, improved imagery coverage (Mullins for Lucchitta), improved airborne (Bell and Blankenship) and ground (Jacobel) geophysical techniques, and GPS for changes in surface elevations and in ice column thickness (Hulbe).

The changes in the Ross drainage, though not presently understood or predicted, are likely to be addressed by the next few field seasons. The quality of the data on these changes was so good that the discussion had little to complain about, and so drifted off into an exchange on what should come next. The changes in Thwaites Glacier generated comment because the path to understanding them is not as clear as for the Ross drainage, and because Thwaites may differ in dynamics from the Siple Coast ice streams (Echelmeyer, Raymond). Anderson pointed out that Thwaites Glacier is associated with offshore sediments indicative of subglacial water discharge but with little cumulative sediment over crystalline basement—unlike the Ross Sea—and Alley observed that this made Echelmeyer's suggestion of a hard-bed glacier more likely. MacAyeal also pointed out that the higher rate of snow accumulation there than in the Ross Embayment might dictate different behavior. It is clear that field workers will not lack for problems to address in the near future.

Session 3: Internal Dynamics of the West Antarctic Ice Sheet

N93-31896

The Role of the Margins in Ice Stream Dynamics

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At first glance, it would appear that the bed of the active ice stream plays a much more important role in the overall force balance than do the margins, especially because the ratio of the half-width to depth for a typical ice stream is large (15:1 to 50:1). On the other hand, recent observations indicate that at least part of the ice stream is underlain by a layer of very weak till (shear strength about 2 kPa; Kamb, 1990), and this weak basal layer would then imply that some or all of the resistive drag is transferred to the margins.

In order to address this question, we have measured a detailed velocity profile near Upstream B Camp, which extends from the center of the ice stream, across the chaotic shear margin, and onto the Unicorn, which is part of the slow-moving ice sheet. Comparison of this observed velocity profile with finite-element models of flow shows several interesting features. First, the shear stress at the margin is on the order of 130 kPa, while the mean value along the bed is about 15 kPa. Integration of these stresses along the boundaries indicates that the margins provide 40 to 50 percent, and the bed, 60 to 40 percent of the total resistive drag needed to balance the gravitational driving stress in this region. (The range of values represents calculations for different values of surface slope.) Second, the mean basal stress predicted by the models shows that the entire bed cannot be blanketed by the weak till observed beneath upstream B—instead there must be a distribution of weak till and "sticky spots" (e.g., 85 percent till and 15 percent sticky spots of resistive stress equal to 100 kPa). If more of the bed were composed of weak till, then the modeled velocity would not match that observed. Third, the ice must exhibit an increasing enhancement factor as the margins are approached (E=10 in the chaotic zone), in keeping with laboratory measurements on ice under prolonged shear strain. Also, there is either a narrow zone of somewhat stiffer ice (E=5) outward of the shear margin, or the bed is frozen there. And last, the high shear stress and strain rate found at the margin are likely to cause significant viscous heating (q) in the marginal ice. The increase in temperature is proportional to qX/u, where X is the width of the shear zone and u is the transverse velocity component bringing cold ice in from the ice sheet outside the shear zone. Near upstream B, this heating is likely to cause an increase in temperature of 4 to 10 K.We are planning to measure this temperature increase in a series of boreholes near the margin during the 1992–93 field season, as well as to provide a more detailed description of the velocity field there.

N93-31897

Thermal Control of Ice-Stream Margins

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I and graduate student Paul Jacobson are investigating theoretically the thermal balance at the base of an ice sheet near an ice-stream margin. We investigate specifically conditions such that the base of the ice sheet would be frozen in the absense of heat generated by the ice motion. The base of the ice stream is maintained at melting as a result of high dissipation of heat at the base associated with its fast motion over the bed. Heat dissipation in the inter-ice-stream ridge ice is presumed to be too small to maintain melting conditions on the bed there. Two opposing effects can be identified near the shear margin separating the fast and slow motions.

Because the velocity of an ice stream falls off toward its margin, there is a near-margin heat deficit zone where the heat generated at the bed is not, by itself, sufficient to maintain melting conditions. Without some counteracting process, the base could freeze inward toward the ice stream and cause it to narrow.

The marginal shearing generates heat within the ice above the bed. This heat produces a thermal shielding effect that tends to warm the bed on both sides of the boundary between the fast and slow motion. This shielding effect, if strong enough, could produce a thawed zone beyond the fast/slow boundary. If melting at the bed by itself allows fast motion, then the ice stream would be free to widen.

A coupled mass and heat flow model is being developed to examine these competing processes. Preliminary calculations using available information for boundary conditions appropriate for Ice Stream B predict that the shielding effect is most important. This tentative result suggests that thermal conditions are such that the ice stream could widen unstably. Other constraints would be required to stabilize the width. Possible factors could be bed morphology beneath ridges that does not allow fast motion even in thawed conditions, or inward advection of cold ice from the ridges across the margin and into the ice stream, which suppresses the shielding effect. The unknown geothermal heat flow beneath ice streams and inter-ice-stream ridges is a major uncertainty in doing these calculations.

N93-31898

Basal Hydraulic Conditions of Ice Stream B

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Fifteen boreholes have been drilled to the base of Ice Stream B in the vicinity of UpB Camp.The boreholes are spread over an area of about 500 x 1000 m. Several till cores were retrieved from the bottom of the 1000-m-deep holes. Laboratory tests using a simple shear box revealed a yield strength of basal till of 2 kPa.This agrees well with in-situ measurements using a shear vane. Since the average basal shear stress of Ice Stream B with a surface slope of 0.1 degree is about 20 kPa, the ice stream cannot be supported by till that weak. Additional support for this conclusion comes from the basal water pressure that has been measured in all boreholes as soon as the hotwater drill reached bottom. In several boreholes, the water pressure has been continuously monitored; in two of them, over several years. The water pressure varies but stays within 1 bar of flotation where ice overburden pressure and water pressure are equal. The ratio of water and overburden pressure lies between 0.986 and 1.002. This is an extremely high value as compared to other fast-moving ice masses; e.g., Variegated Glacier in surge has a ratio of 0.8, and Columbia Glacier—a fast-moving tidewater glacier—has a ratio of 0.9. It implies that water flow under the glacier occurs in a thin film and not in conduits that would drain away water too rapidly. It also implies that basal sliding must be very effective.

Water flow under the glacier was measured in a salt-injection experiment where a salt pulse was released at the bottom of a borehole while 60 m down-glacier, the electrical resistance was measured between two other boreholes. A flow velocity of 7 mm/s was obtained. The thickness of the water film can be obtained through a unique water-injection experiment that occurs in every borehole: during hot-water drilling, the water level in the borehole stands high near the permeable firn about 20 m below the surface; when the bottom is reached, the water level rapidly drops to about 100 m below the surface, a value close to the flotation. The water film is less than 1 mm thick. More information about the hydraulic condition at the base of the ice stream can be deduced from the water-pressure pulse propagation and attenuation data recorded in boreholes neighboring the injection borehole. The results from the borehole drilling program require a rethinking of the mechanisms for fast ice-stream flow. Basal drag will contribute less and marginal shear will be more important than previously thought.

N93-31899

In Search of Ice-Stream Sticky Spots

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The form drag of large bedrock bumps sticking into the base of an ice stream can produce effective "sticky spots" supporting large basal shear stress. Bedrock regions surrounded by lubricating till at the same topographic level can cause sticky spots, but tend to collect lubricating water and thus are unlikely to support a shear stress of more than a few tenths of a bar unless they contain abundant large bumps. Raised regions on the ice–air surface also can cause moderate increases in the shear stress supported on the bed beneath. Surveys of large-scale bedrock roughness, strain grids across the margins of ice-surface highs, and possibly, water-pressure measurements in regions of thin or zero till would help identify and characterize sticky spots.

Session 3 Summary Discussion: Internal Dynamics

Rapporteur: Richard Alley

The internal–dynamics session was short on speakers but long on results. Echelmeyer showed data and calculations indicating that both the sides and the bed of Ice Stream B near the Upstream B camp restrain the flow, and Raymond showed that the side dynamics can be very complicated and might be incapable of reaching a steady configuration. Engelhardt showed that the soft bed of Ice Stream B near the Upstream B camp is separated from the ice by a thin, high–pressure water layer that conducts water only inefficiently, but that has significant pressure variability over time. Alley used simple basal models to place constraints on how the basal shear stress may be partitioned between sticky and slippery spots.

The lively discussion that followed addressed several important topics. Bindschadler and Echelmeyer noted the importance of considering both the sides and the beds of ice streams (mirroring Alley's slide "What fun. Everyone gets to play.").

Engelhardt emphasized that Upstream B is a special case—it is one of the few sites on the Siple Coast ice streams where crevasses are absent and LC–130 planes can land. Alley observed that study of other places will require greater use of airborne geophysics and satellite remote sensing; Bindschadler pointed out that Upstream B cannot be studied with Landsat, and that Ice Streams D and E are favorable for remote studies.

Raymond noted that his model studies of the ice streams are sensitive to the geothermal flux. This led to a long discussion of geological controls on ice streaming. Blankenship, Bell, Behrendt and Anderson all pointed to evidence for ice streams occurring in recently rifted regions that should have high heat flow (available data indicate high heat flow but are not unambiguous). The ice streams seem to follow rift valleys that contain young, soft sediments that would be needed to produce a lubricating till. Whether the onset of streaming is related to the sediment distribution is an important question (Borns) that could be studied seismically (Anandakrishnan). Anderson said that the Ross Sea shelf is sediment–covered, but on other shelf regions, the inner shelf is largely sediment–free, and deep, glacially carved troughs run along the sediment–crystalline boundary; the Filchner–Ronne and Prydz Bay regions may fall between the Ross Sea model and the stripped–inner–shelf model.

Borns commented further on the sediment–ice stream correlation, and noted that some former ice streams of the Laurentide seem to cross crystalline bedrock. Alley pointed out that there are different flavors of ice streams, with the Siple Coast ice streams and the former Lake Michigan ice stream on one end (very low basal shear stress but with high velocity, underlain by soft sediments) and Jakobshavns or Byrd Glaciers on the other end (very high shear stress, able to cause the entire high ice velocity by internal deformation). Echelmeyer and others have thrown much light on the Jakobshavns end member, and WAIS is working on the soft–bed end member. MacAyeal pointed out that the Hudson Bay ice stream ran on carbonates, not crystalline rocks.

Grootes and Raymond commented on the importance of mapping internal reflectors with radar. This will allow interpolation between ice cores, and should reveal much about dynamics of ice–stream heads and margins if it can be done successfully. Blankenship reported that some of the CASERTZ radar records show beautiful layering, but that the layering is broken up in others.

Anderson asked about the scale of sticky spots, and how they might be identified. Raymond said that big ones would affect the ice surface. Alley said that Raymond had already solved that problem, and sticky spots, by definition, were things that weren't solved yet, so the sticky spots must be fairly small (<1 to 10 ice thicknesses in extent?).

Lunch intervened, or things would have rumbled merrily along.

Session 4: Interactions of the Environment and the West Antarctic Ice Sheet

Geologic Controls on the West Antarctic Ice Sheet

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The stability of the West Antarctic Ice Sheet is intertwined with its geologic history. The sub-ice geology and the possibility of active rifting and associated elevated heat-flux and volcanism might be determining factors in ice-sheet behavior.

Seismic monitoring of natural events at the base of Ice Stream C reveals the presence of a young sedimentary basin beneath the ice stream. The sediments are presumed to be of glacio-marine origin, similar to those beneath Ice Stream B and in the Ross Sea. The young sediments are approximately 1/2 km thick at UpC camp, but thin abruptly southward to 100 m or less. We hypothesize the presence of a fault with a throw of 400 m to account for this (though we have not directly detected the fault), rather than invoking unrealistic basement dips.

To extend these studies to critical inland regions, we suggest an expanded explosive-source seismic survey of the Byrd Subglacial Basin to determine the extent and character of the hypothesized rift basin. High-resolution seismic monitoring will detect layering in the sedimentary column, as well as possibly imaging faults directly.

N93-31901

Effect of Subglacial Volcanism on Changes in the West Antarctic Ice Sheet

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Rapid changes in the West Antarctic Ice Sheet (WAIS) may affect future global sea-level changes. Alley and Whillans (*Science*, 11/15/91, pp. 959–963) note that "the water responsible for separating the glacier from its bed is produced by frictional dissipation and geothermal heat," but assume that changes in geothermal flux would ordinarily be expected to have slower effects than glaciological parameters. I suggest that episodic subglacial volcanism and geothermal heating may have significantly greater effects on the WAIS than is generally appreciated. The WAIS flows through the active, largely aseismic West Antarctic rift system (WS), which defines the sub-sea-level bed (Byrd Subglacial Basin) of the glacier (LeMasurier, *Ant. Res. Ser.*, **48**, pp. 1-17,1990; Behrendt *et al.*, Geological Evolution of Antarctica, 1991). Various lines of evidence summarized in Behrendt *et al.* (1991) indicate high heat flow and shallow asthenosphere beneath the extended, weak lithosphere underlying the WS and the WAIS. Behrendt and Cooper (*Geology*, **19**, pp. 315–319, 1991) suggest a possible synergistic relation between Cenozoic tectonism, episodic mountain uplift and volcanism in the West Antarctic rift system, and the waxing and waning of the Antarctic ice sheet beginning about earliest Oligocene time. A few active volcanoes and late-Cenozoic volcanic rocks (Fig. 2) are exposed throughout the WS along both flanks, and geophysical data suggest their presence beneath the WAIS. No part of the rift system can be considered inactive (LeMasurier, 1990; Behrendt *et al.*, 1991).

I propose that subglacial volcanic eruptions and ice flow across areas of locally (episodically?) high heat flow—including volcanically active areas—should be considered possibly to have a forcing effect on the thermal regime resulting in increased melting at the base of the ice streams. The modest eruption of Mount St. Helens (in a different type of tectonic setting) on May 18, 1980, released about 1.7 x 10^{18} joules (Decker and Decker, 1981). An equivalent volcanic eruption beneath the WAIS could result in melting a 1-cm-thick layer part of their catchment area). If an eruption of this magnitude occurred once every 1 to 10 years in an area this size, it probably would have a significant effect on the glacial regime; if once every 1,000 to 10,000, years the results would be negligible. Of course, energy released by volcanic eruptions varies by orders of magnitude, particularly when duration of particular eruptions is considered (only one day of the Mount St. Helens eruption was considered above). The only point of this overly simplistic calculation is that active volcanism in the West Antarctic rift system, which might be reasonably expected (LeMasurier, 1990; Behrendt *et al.*, 1991), must be considered when studying changes in the WAIS. Geophysical surveys such as the Southeast Ross Transect Zone (CASERTZ) program (Blankenship *et al.*, 1991) presently surveying a 330-km-wide swath of aeromagnetic, gravity and radar ice surrounding data across the West Antarctic rift system might provide evidence of subglacial volcanism and concentrations of meltwater beneath the WAIS.

N93-31902

Sensible and Latent Heat Flux Estimates in Antarctica

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The assumption has been made that the net annual contribution of water by the processes of deposition and sublimation to the Antarctic Ice Sheet is zero. The U. S. Antarctic Program started installing reliable automatic weather stations on the Antarctic Continent in 1980. The initial units were equipped to measure wind speed, wind direction, air pressure, and air temperature. During the 1983–1984 field season in Antarctica, three units were installed that measured a vertical air temperature difference between the nominal heights of 0.5 m and 3.0 m and relative humidity at a nominal height of 3 m. The measurements of the vertical air temperature difference and the relative humidity are the minimum required to estimate the sensible and latent heat fluxes to the air, while not exceeding the available energy requirements for the weather stations. The estimates of the net annual sublimation and deposition on the Ross Ice Shelf amount to 20 to 80 percent of the annual accumulation. We conclude that the assumption that annual sublimation and deposition are zero is not valid under Antarctic conditions.

N93-31903

Surface Winds Over West Antarctica

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Five winter months (April–August 1988) of thermal infrared satellite images were examined to investigate the occurrence of dark (warm) signatures across the Ross Ice Shelf in the Antarctic continent. These features are inferred to be generated by katabatic winds that descend from southern Marie Byrd Land and then blow horizontally across the ice shelf. Significant mass is added to this airstream by katabatic winds blowing from the major glaciers that flow through the Transantarctic Mountains from East Antarctica. These negatively buoyant katabatic winds can reach the northwestern edge of the shelf—a horizontal propagation distance of up to 1,000 km—14 percent of the time. Where the airstream crosses from the ice shelf to the ice-covered Ross Sea, a prominent coastal polynya is formed. Because the downslope buoyancy force is near zero over the Ross Ice Shelf, the northwestward propagation of the katabatic air mass requires pressure gradient support. The study shows that the extended horizontal propagation of this atmospheric density current occurred in conjunction with the passage of synoptic cyclones over the southern Amundsen Sea. These cyclones can strengthen the pressure gradient in the interior of West Antarctica and make the pressure field favorable for northwestward movement of the katabatic winds from West Antarctica across the ice shelf in a geostrophic direction. The glacier winds from East Antarctica are further accelerated by the synoptic pressure gradient, usually undergo abrupt adjustment beyond the exit to the glacier valley, and merge into the mountain-parallel katabatic air mass.

N93-31904

Modeling Ice Streams: Derived Quantities

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(presented by H. Borns)

The model is a finite-element, map-plane, time-dependent, column-averaged continuity equation solver that is described in detail elsewhere (Fastook, *J. Glac.*, **35**, pp. 48–52, 1989; Fastook, Computer Assisted Analysis and Modeling on the IBM 3090, 1990; Fastook and Prentice, *J. Glac.*, in press, 1992). The key to the fitting process involves the balance between ice motion dominated by flow in internal layers, and ice motion dominated by sliding at the bed.

The fitting process involves an iterative process carried out in the time domain. Beginning with the portion of the ice sheet being modeled identical to the present ice sheet (Drewry, *Ant: Glac. and Geop. Folio*, 1983) with uniform flow, sliding, and fraction specified at nominal values, the model monitors each nodal point surface elevation. As the calculated surface elevation deviates from the present surface, a correction proportional to the difference is applied to selected parameter sets. This correction is in a sense that would tend to improve the fit at the particular nodal point. A calculated surface elevation that was higher than the present surface would result in an increased fraction, which would tend to lower the calculated surface (if the flow or sliding constant were being used as the fitting parameter, they would be lowered to improve the fit). This process is allowed to proceed as long as is necessary for the situation to stabilize. Typically, this takes tens of thousands of model years, but the rate is dependent on other external forcings such as the accumulation rate.

The primary result is that while a typical sample of ice streams from around Antarctica can be fitted quite reasonably using only the fraction of the velocity due to sliding, a different mechanism seems to be in play along the Siple Coast, where reduced sliding constants are required to attain a reasonable fit. Flow is more strongly channelized in this region, and velocities are, in general, higher than are observed in other regions. It is unlikely that the mechanism that controls the ice movement along the Siple Coast is exactly similar to the mechanisms in the other ice streams. The concept of deformable sediments and their contribution to the fast flow along the Siple Coast may have limited applicability to other Antarctic ice streams.

Session 4 Summary Discussion: Interactions With the Environment

Rapporteur: Richard Alley

Anandakrishnan showed how geology could control ice streaming, and what experiments might place constraints on this. Behrendt placed this in a larger geologic context. Speaking for Jacobs, MacAyeal posed a detective story, and solved it by showing that dissipation of tidal energy in shallow water near grounding lines produces the meltwater that emerges from under the Ross Ice Shelf. Stearns showed that sublimation may be important in the ice–sheet mass balance. Bromwich reviewed his extensive studies on katabatic winds and their interaction with synoptic systems, and how this may affect accumulation on the continent. Borns finished by presenting results from Fastook on tuning models to fit modern ice–stream profiles.

No summary discussion occurred. It appears to this correspondent that important progress is occurring on interactions. The geologic–control problems are well–posed, and the experiments to elucidate them are known, though not always in progress. Interesting atmospheric problems occur both at the WAIS scale and at the continental scale, and experiments to solve them are moving ahead slowly but steadily, in step with funding. Little new work is being done on oceanographic interactions in WAIS because of a lack of funding. Further work on geologic, atmospheric, and oceanic interactions would be valuable.

Discussion with NSF

The summary discussion of the fourth objective (interactions of the ice sheet with its environment) was preempted by a rare, open exchange of views on WAIS by staff of NSF/DPP and the attending scientists. Dr. Wilkniss began with a stimulating statement of unabashed support for WAIS. Following this, Dr. Wilkniss was joined by the managers and head of the Science Section to answer questions and concerns of the audience. Foremost among these was the concern for future availability of funds at the levels recommended by the WAIS Science and Implementation Plan without funding augmentation from NSF. DPP (Peacock) argued that WAIS was being funded at an acceptable level to make substantial progress and pointed to the results of the meeting to justify that claim. It was pointed out (Alley ? Grootes ?) that DPP's core budget would not be sufficient shortly when the GISP coring community turned their attention to West Antarctica, as has been called for by the recent WAISCORES document of the Ice Core Working Group.

A brief description of the life and death of the SeaRISE (cum WAIS) initiative was given. The initiative was proposed by the then-Polar Glaciology Program Manager (Borns) and was put forth by DPP as their only initiative proposal in 1990. It competed very well against a wide variety of other scientific initiatives, nearly succeeded, but ultimately failed. No details could be given on what initiatives did succeed. Lettau suggested that often, success or failure depends far more on timing than the absolute or relative importance of competing initiative proposals.

The sense of the scientific community seemed to be that DPP should try again to get a WAIS initiative funded. There was some disagreement as to whether such an initiative should be all of WAIS or a more limited program like WAISCORES. Elliott argued that WAISCORES was more clearly defined and relevant to global climate; a position Bindschadler took strong exception to, stating that WAIS also was clearly defined and relevant.

DPP appeared to pick up on the notion that WAIS was still vague and needed a fleshing out of its science and implementation plan. The opposite view was expressed by some scientists (Alley, Bindschadler, ?) that, if anything, the already-published Science and Implementation Plan was too detailed and had not been assimilated by DPP.

Unable to agree on whether the existing plan had too much or too little detail, it was agreed that the WAIS Working Group would review the document, in light of current research activities and available facilities, and deliver a revised plan to DPP. Peacock indicated that the middle of December 1992, was when budget requests for the fiscal year 20 months hence (FY94) were expected to be finalized. On behalf of the Working Group, Bindschadler promised to meet that deadline.

Following the discussion with the DPP Science Section, Simon Stephenson gave a brief description of the facilities the Polar Operations Section maintains for the support of scientific research in Antarctica. Scientists were encouraged to utilize these facilities whenever possible. Stephenson said that the Polar Operations Section is sensitive to the charge that Antarctic logistics is now driving Antarctic science. He expressed the view that it is up to the scientists working through the Science Section to make sure that such is never the case. Bindschadler made the point that WAIS investigations are wide-ranging and would benefit from coordinated logistics support. Stephenson repeated his view that he felt such coordination was an issue to be addressed by the Science Section in their decisions of what investigations were funded and when.

WAIS Working Group
(elected September 14, 1992)

Ice Dynamics	Robert Bindschadler
Ice Cores	Pieter Grootes
Marine Geophysics	John Anderson
Terrestrial Geophysics	Harold Borns (Chair)
Meteorology	Charles Stearns
Oceanography	Douglas MacAyeal
At-Large	Richard Alley
At-Large	Donald Blankenship
At-Large	Alan Cooper
At-Large	Barclay Kamb

Epilogue

In the few days following the workshop, a new strategy was adopted in the formulation of a suggested initiative to DPP. This strategy eventually led to a new project as a subset of WAIS called WAIS–2000. WAIS–2000 encompasses the most expensive components of WAIS and focuses on adressing the WAIS goal for a single ice stream—Ice Stream D. This ice stream was chosen because it lies downstream of the proposed primary site for the West Antarctic deep core, it lies downstream of Byrd Station, it is well–covered by existing Landsat imagery for which a detailed velocity map already exists, and it traverses a relatively short stretch of ice shelf, before ending in the Ross Sea, where an existing submarine ridge and trough pattern define its history.

WAIS–2000 is not intended as either a replacement or a substitute for WAIS. Rather, it extracts the most expensive components and identifies them as needing non–core funding by DPP, thus relieving their burden from the core budget of DPP. The remaining WAIS investigations will then be able to be supported by the core budget.

WAIS–2000 has been described in a document available from the Institute for Geophysics, The University of Texas, Austin, Texas. DPP has received copies of this report, but the formal presentation of the plan is awaiting the installation of the new Director of Polar Programs.

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13. ABSTRACT *(Maximum 200 words)*

This document is a compilation of abstracts presented at a 2–day workshop focused on interdisciplinary Antarctic research. The goal of the West Antarctic Ice Sheet (WAIS) Science Workshop was to answer the question, "What is the future behavior and potential for rapid collapse of the West Antarctic Ice Sheet?" The question is central to the importance of Antarctica in future global climate change, particularly future change in sea level. The workshop was organized into four sessions corresponding to the four objectives identified as necessary to reach the WAIS goal: history, current behavior, internal dynamics, and environmental interactions. Presentations were organized by their relevance to each objective, rather than by discipline. The workshop concluded with an open discussion between the NSF/DPP staff and the attending scientists.

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