REPORT GD-13

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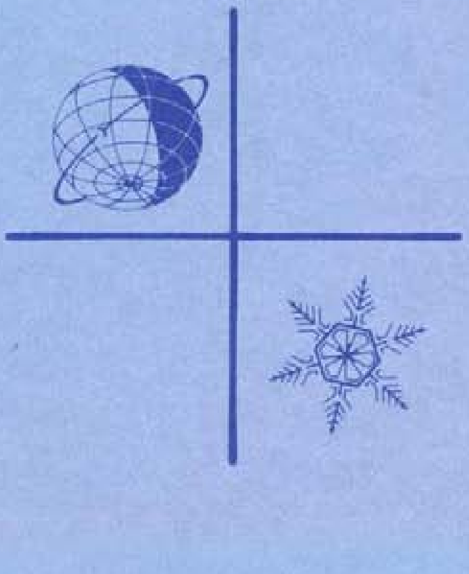
GLACIOLOGICAL DATA

WORKSHOP PROCEEDINGS:
RADIO GLACIOLOGY
ICE SHEET MODELING

World Data Center A
for
Glaciology
[Snow and Ice]



August 1982

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World Data Center A consists of the Coordination Office and the following eight subcenters:

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World Data Centers conduct international exchange of geophysical observations in accordance with the principles set forth by the International Council of Scientific Unions. WDC-A is established in the United States under the auspices of the National Academy of Sciences. Communications regarding data interchange matters in general and World Data Center A as a whole should be addressed to the World Data Center A, Coordination Office (see address above). Inquiries and communications concerning data in specific disciplines should be addressed to the appropriate sub-center listed above.

GLACIOLOGICAL DATA

REPORT GD-13

WORKSHOP PROCEEDINGS: RADIO GLACIOLOGY ICE SHEET MODELING

August 1982

Published by:
WORLD DATA CENTER A FOR GLACIOLOGY
[SNOW AND ICE]

Cooperative Institute for Research in Environmental Sciences
University of Colorado
Boulder, Colorado 80309 U.S.A.

Operated for

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
Environmental Data and Information Service
Boulder, Colorado 80303 U.S.A.

DESCRIPTION OF WORLD DATA CENTERS[1]

WDC-A: Glaciology (Snow and Ice) is one of three international data centers serving the field of glaciology under the guidance of the International Council of Scientific Unions Panel of World Data Centers. It is part of the World Data Center System created by the scientific community in order to promote worldwide exchange and dissemination of geophysical information and data. WDC-A endeavors to be promptly responsive to inquiries from the scientific community, and to provide data and bibliographic services in exchange for copies of publications or data by the participating scientists.

1. The addresses of the the three WDCs for Glaciology and of a related Permanent Service are:

World Data Center A
University of Colorado
Campus Box 449
Boulder, Colorado, 80309 U.S.A.

World Data Center B
Molodezhnaya 3
Moscow 117 296, USSR

World Data Centre C
Scott Polar Research Institute
Lensfield Road
Cambridge, CB2 1ER, England

Permanent Service on the Fluctuations
of Glaciers
Swiss Federal Institute of Technology
CH-8092 Zurich, Switzerland

2. Subject Matter

WDCs will collect, store, and disseminate information and data on Glaciology as follows:

Studies of snow and ice, including seasonal snow; glaciers; sea, river, or lake ice; seasonal or perennial ice in the ground; extraterrestrial ice and frost.

Material dealing with the occurrence, properties, processes, and effects of snow and ice, and techniques of observing and analyzing these occurrences, processes, properties, and effects, and ice physics.

Material concerning the effects of present day and snow and ice should be limited to those in which the information on ice itself, or the effect of snow and ice on the physical environment, make up an appreciable portion of the material.

Treatment of snow and ice masses of the historic or geologic past, or paleoclimatic chronologies will be limited to those containing data or techniques which are applicable to existing snow and ice.

3. Description and Form of Data Presentation

3.1 General. WDCs collect, store and are prepared to disseminate raw[+], analyzed, and published data, including photographs. WDCs can advise researchers and institutions on preferred formats for such data submissions. Data dealing with any subject matter listed in (2) above will be accepted. Researchers should be aware that the WDCs are prepared to organize and store data which may be too detailed or bulky for inclusion in published works. It is understood that such data which are submitted to the WDCs will be made available according to guidelines set down by the ICSU Panel on WDCs in this Guide to International Data Exchange. Such material will be available to researchers as copies from the WDC at cost, or if it is not practicable to copy the material, it can be consulted at the WDC. In all cases the person receiving the data will be expected to respect the usual rights, including acknowledgement, of the original investigator.

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[1] International Council of Scientific Unions. Panel on World Data Centers. (1979) Guide to International Data Exchange Through the World Data Centres. 4th ed. Washington, D.C. 113 p.

[+] The lowest level of data useful to other prospective users.

This Guide for Glaciology was prepared by the International Commission on Snow and Ice (ICSI) and was approved by the International Association of Hydrological Sciences (IAHS) in 1978.

3.2 Fluctuations of Glaciers. The Permanent Service is responsible for receiving data on the fluctuations of glaciers. The types of data which should be sent to the Permanent Service are detailed in UNESCO/IASH (1969)*. These data should be sent through National Correspondents in time to be included in the regular reports of the Permanent Service every four years (1964-68, 1968-72, etc.). Publications of the Permanent Service are also available through the WDCs.

3.3. Inventory of Perennial Snow and Ice Masses. A Temporary Technical Secretariat (TTS) was recently established for the completion of this IHD project at the Swiss Federal Institute of Technology in Zurich. Relevant data, preferably in the desired format**, can be sent directly to the TTS or to the World Data Centers for forwarding to the TTS.

3.4. Other International Programs. The World Data Centers are equipped to expedite the exchange of data for ongoing projects such as those of the International Hydrological Project (especially the studies of combined heat, ice and water balances at selected glacier basins***), the International Antarctic Glaciological Project (IAGP), and Greenland Ice Sheet Project (GISP), etc., and for other developing projects in the field of snow and ice.

4. Transmission of Data to the Centers

In order that the WDCs may serve as data and information centers, researchers and institutions are encouraged:

4.1. To send WDCs raw+ or analyzed data in the form of tables, computer tapes, photographs, etc., and reprints of all published papers and public reports which contain glaciological data or data analysis as described under heading (2); one copy should be sent to each WDC or, alternatively, three copies to one WDC for distribution to the other WDCs.

4.2 To notify WDCs of changes in operations involving international glaciological projects, including termination of previously existing stations or major experiments, commencement of new experiments, and important changes in mode of operation.

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*UNESCO/IASH (1969) Variations of Existing Glaciers. A Guide to International Practices for their Measurement.

**UNESCO/IASH (1970a) Perennial Ice and Snow Masses. A Guide for Compilation and Assemblage of Data for a World Inventory; and

Temporary Technical Secretariat for World Glacier Inventory. Instructions for Compilation and Assemblage of Data for a World Glacier Inventory.

***UNESCO/IASH (1970b) Combined Heat, Ice and Water Balances at Selected Glacier Basins. A Guide for Compilation and Assemblage of Data for Glacier Mass Balance Measurements; and

UNESCO/IASH (1973) Combined Heat, Ice and Water Balances at Selected Glacier Basins. Part II, Specifications, Standards and Data Exchange.

+The lowest level of data useful to other prospective users.

FOREWORD

This issue contains reports on two workshops that focused on aspects of glacier and ice sheet studies. The first was a workshop on radio glaciology organized by WDC-A for Glaciology and held in September 1981 at Columbus, Ohio, immediately preceding the Third International Symposium on Antarctic Glaciology (TISAG). The second was an informal meeting on ice sheet modeling held in August 1981 at the Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, and arranged by Dr. U. Radok. The latter was principally a scientific meeting, but it dealt with general modeling tasks and problems. The wider dissemination of these discussions can serve to enhance the communications between the various glaciological modeling groups, including those that could not be represented at the workshop. Moreover, the modeling of ice sheet behavior requires input data (ice surface elevation, thickness, and net accumulation rates) and validation data such as observed velocities and changes in surface elevation or mass balance. The provision of these data sets is now becoming possible through remote sensing techniques, including radio-echo sounding; and the Data Center hopes to continue and expand its data services to the scientific community in this area.

The workshop on radio glaciology was intended to provide a forum for assessing the status of research and, through working group discussions, for documenting scientific needs, hardware developments, data processing, and data products and services. Through its linkage with the TISAG meeting, a wide range of international participation was achieved. This issue contains summaries of many of the papers presented at the workshop and the reports and reommendations of the working groups.

The WDC is now planning an issue of Glaciological Data on permafrost and frozen ground as a contribution to the Fourth International Conference on Permafrost to be held at Fairbanks, Alaska, in July 1983. We should like to encourage our readers to forward copies of their recent publications in this, and other subject areas, to the Data Center. This increases our efficiency and helps to reduce our costs.

R. G. Barry
Director
National Snow and Ice Data Center and
World Data Center-A for Glaciology [Snow and Ice]

CONTENTS

RADIO GLACIOLOGY WORKSHOP
COLUMBUS, OHIO, 4-5 SEPTEMBER 1981

International Workshop on Radio Glaciology

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Radio glaciology, the study of the internal properties of terrestrial ice masses by means of radar, has evolved to become a significant tool for probing glaciers and ice sheets. The advent of new data acquisition and processing techniques, coupled with a growing interest in the use of radio glaciological data by earth scientists, prompted the World Data Center-A for Glaciology (Snow and Ice) to organize an international workshop to address questions relating to data acquisition and processing, and data archiving and distribution. This activity was also planned in recognition of the potential magnitude of the future "data explosion" in this field, paralleling the already existing pattern in other geophysical sciences. The Workshop was held in Columbus, Ohio, on September 4 and 5, 1981, prior to the Third International Symposium on Antarctic Glaciology (TISAG). We are grateful to the local arrangements committee of TISAG and staff of the Institute of Polar Studies, Ohio State University, for their assistance and support. Thirty-two representatives from eight countries assembled to present status papers and participate in working group discussions. This issue of Glaciological Data reports the results of this Workshop. A wide range of radio glaciological research was covered in the 16 papers presented; 8 of these papers are reproduced in this report. An earlier NSF-sponsored workshop on U.S. efforts in radio-echo sounding of ice was held in 1978 at Durham, New Hampshire (Sivaprasad, 1978).

The primary objective of the Columbus meeting was to provide a forum through which radio glaciologists and those interested in radio glaciological data could assemble to discuss current issues with Data Center representatives. It was fortunate that Dr. V. Kotlyakov from Moscow and Dr. G. Robin from Cambridge were able to attend the workshop, providing the first opportunity for a joint informal discussion on the overall roles and scope of WDCs A, B, and C for Glaciology.

Participants were divided into four Working Groups in an effort to provide a balanced point of view within the theme of each group. The groups focused on scientific needs, hardware, data processing, and data products and distribution. Of particular concern to the Data Center is the role the Data Center system can play in promoting the widest possible use of data derived from radio glaciological studies. The degree of analysis, data integrity, format, and ownership responsibilities are among the issues where the Data Centers require guidance from the scientific community. Current Data Center holdings in Boulder include raw and semi-processed data in analog and digital form from airborne surveys of the Greenland and Antarctic ice sheets (see p. 00). Selected data from alpine regions are also available. Results from various published studies are available through the Data Center's snow and ice library. Some 13 requests for digital or other radio-glaciological data have been handled by WDC-A since April 1979. Apart from the principal scientific users, there is a potential demand for such information from hydro-power agencies, for example, in Greenland.

The identification of scientific needs within the field of radio glaciology was a central theme of the workshop. From this vantage, the application of appropriate hardware, the types of desired data, data processing requirements and data products could be identified. Of some sixteen research problems discussed in the papers session, the Working Group on Scientific Needs identified the three primary issues as (1) ice thickness studies, (2) determining the physiography of the sub-ice interface, and (3) understanding the causes of internal reflections in both polar ice sheets and temperate glaciers.

Recommendations in support of these scientific objectives came from the Hardware Working Group which proposed the development of systems for digital recording of data. Further support for this trend came from the Working Group on Data Processing. That group formulated a series of recommendations based on the anticipated dominance of digital over analog and optical data. Furthermore, it recommended that conversion facilities be made available in order that digital processing may be applied to data recorded in any format. The Working Group on Data Products and Distribution nevertheless recommended that hardcopy of all data types (analog and digital) should be available.

The trend toward digital data acquisition, the ability to process data digitally, and the subsequent facility to make digital data products will generate large volumes of machine-readable data. It also provides a means by which data sets can be easily duplicated

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* Current address: Quasar Systems Limited, Ottawa, Ontario, Canada.

by conventional technology. However, the mechanisms whereby these data can be exchanged, the question of priority access and data ownership, the necessary minimal levels of processing, software support, and numerous related issues, still need to be resolved in order to provide the international geoscience community with a general set of guidelines which will permit convenient interdisciplinary use of radio glaciological data.

There was wide agreement on the importance of documenting and reporting on data collected and processed and on the role of Data Centers in providing information services, via inventories and data catalogs. The Working Group on Data Processing also recommended that data duplication services be provided. The Data Products group, however, proposed the continued primary distribution of digital data through the original researchers, with the Data Centers handling such data when they become 'orphaned' (e.g. by the termination of a project) or when the Centers are designated to receive such information.

Specific recommendations from the Working Groups that relate to the role of the World Data Centers are given as follows:

1. a questionnaire should be developed and circulated to the radio glaciology community to confirm and update information on hardware systems, their usage, and anticipated future developments;

2. a catalog of raw and processed data be developed and maintained;

3. analog to digital conversion facilities and duplication facilities for raw analog, optical, and digital records should be provided;

4. notification should be sent to a Data Center as data are generated, processed, and archived;

5. centers should act as clearing houses for information;

6. centers should act as repositories for orphaned data and data which they are requested to store by research workers or agencies;

7. suppliers of data should be informed of data exchanges and intended usage.

A synthesis of these recommendations suggests that there remains a need for a preliminary analysis of the state of radio glaciological studies world-wide. Specifically, information is needed concerning workers, hardware systems, usage, and anticiapted developments. Furthermore, there is a need to inventory what studies have been undertaken, what data have been generated and the degree of processing performed on them, and their manner of archiving. In order to be effective in an operational mode, means must also be developed whereby these services can be operated on a continuing basis. There is also a perceived need for the establishment of at least one world center which can provide an analog to digital conversion facility along with duplication capability to handle analog, optical, and digital records.

The World Data Center-A for Glaciology (Snow and Ice), dependent upon its level of funding support, is prepared to implement some of these recommendations. The first effort must be to organize a global picture of the state of radio glaciology. The Center is willing to develop a survey questionnaire, in an effort to expand the prelimianry inventories of users, hardware systems, and data products identified in the Hardware, and Data Products and Distribution Working Groups. From this survey and additional follow-ups, an inventory of primary data sources could be developed. This information could then be exchanged with the WDCs for Glaciology in the Soviet Union and Great Britain. The Data Center System could thereby become a key source of radio glaciological information. Once operational, this would meet the request for the Centers to act as clearing houses.

Notification to principal investigators of the subsequent use of their data is a standard procedure already in place at WDC-A. However, notification to the WDC on the generation, processing, and archiving of data by the radio glaciological community is not standard practice. This will require a conscientious effort on the part of individual scientists to provide the Data Center System with up-to-date information. From a practical point of view, it would be more efficient to supply all information to one of the Data Centers where it could then be collated and distributed.

Lack of adequate facilities for duplication of analog and digital data and for digital conversion presents a serious problem. Currently, none of the Data Centers is capable of meeting these recommendations. The financial impacts are significant; the logistics possibly even more complex.

Overall financial and logistical impacts are noted elsewhere in the recommendations. These relate particularly to the conduct of large scale reconnaissance surveys of unmapped regions of Antarctica and the development of satellite survey systems. In the case of Antarctica, unmapped areas are remote and it is logistically difficult to gain access to these regions. What is needed is a cooperative arrangement whereby national or international efforts can develop a complete map of the continent. Currently, the surface bedrock beneath the ice sheet of Antarctica is less well known than the surface or seabed of the rest of the planet.

In the case of satellite radar systems, the capability, limitations, and feasibility of such systems should be carefully examined in the light of current trends in conventional radar-sounding techniques before embarking on an operational system. The costs and data volumes of such systems are large. A well planned processing and dissemination facility must be in place to handle the vast array of satellite data that will become available in the next few years.

The Workshop made it clear that there is a need to know more about radio glaciological studies on a world-wide basis. Furthermore, there is a concern among radio glaciologists as to how to manage effectively the large volumes of data expected as output from digital recording systems. Discussion of these issues at the Workshop has provided a useful first step towards identifying the problems and proposing means for their solution. We hope that the communication of the results of the Workshop to a wide audience, through this publication, will facilitate this endeavor.

Reference

Sivaprasad, K. (1978) Report of the Radio Echo Sounding of Ice Workshop, Durham, New Hampshire. University of New Hampshire, Department of Electrical and Computer Engineering, 18 p.

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RECOMMENDATIONS

WORKING GROUP ON SCIENTIFIC NEEDS

Chairman: Gordon Robin
Scott Polar Research Institute
University of Cambridge, England

In order to focus the discussion, Dr. Bentley's list of scientific problems that can be studied using radio glaciology was considered by the group. These research problems are:

1. absorption
2. velocity
3. ice thickness
4. physiography of the sub-ice interface
5. internal reflections
6. brine infiltration
7. crevassing
8. scattering by inclusions
9. fading patterns and movement
10. layering deformation
11. debris tracks
12. polarization studies
13. basal interface
14. wave propagation
15. total water content
16. temperature studies

As it would not be possible to discuss each item in the time available, the Chairman asked that each member of the Working Group review the list and select the three topics he considered most important. This exercise showed a clear consensus that the three most important scientific areas of study by means of radio glaciology are:

1. ice thickness
2. physiography of the sub-ice interface
3. internal reflections in both polar ice sheets and temperate glaciers.

In emphasizing the scientific importance of ice depth measurements provided by radio glaciology, the Working Group appreciated that many scientific investigations of glaciers and ice sheets were severely hampered or made impracticable by lack of such information. On a global scale, the surface bedrock beneath the ice sheet of Antarctica is less well known than the solid surface beneath any part of the oceans or continents.

Radio sounding techniques are available to complete sounding of the ice sheets at a reconnaisance level. The problems of completing this work are primarily ones of logistics and finances.

The Working Group recommends that nations with Antarctic bases giving access to unmapped areas of the continent should make special efforts to complete a 100 km grid of radio echo sounding lines over those parts of the ice sheet not yet mapped. These are mainly areas that are farthest from the base of United States airborne operations at McMurdo Sound.

Bottom roughness and the internal structure of ice sheets and glaciers were considered extremely important research problems requiring further development of special equipment to provide a better view of the bottom surface and internal characteristics. A suggestion was made that devices developed by different laboratories could be tested at one site on an ice sheet. Such equipment might include a multi-frequency ionosonde-type sounder, holographic techniques, or pulsed radars.

WORKING GROUP ON HARDWARE

Chairman: K. Sivaprasad
Department of Electrical and Computer Engineering
University of New Hampshire

At present there is considerable expertise in radio echo sounding technology which has not been fully exploited by the community. This is primarily due to funding problems, inadequate logistics support, and lack of time. The Working Group recommends the further development and/or initiation of programs by laboratories and national and international groups to optimize the availability of these techniques in order to increase data coverage. This recommendation is in concurrence with the Working Group on Scientific Needs.

The Working Group recommends that computer-accessible recording of data should be undertaken immediately and encouraged in future projects.

The Working Group also recommends that more ground-based surveys should be undertaken to obtain greater detail than can be obtained from airborne surveys. This is particularly important for borehole surveys and studies of internal structure and small-scale basal morphology.

The group recommends that the WDC-A for Glaciology circulate a questionnaire to the radio glaciology community to confirm and update information on hardware systems, their usage, and anticipated future developments.

It is recommended that future research should be directed towards increasing sensitivity and resolution in order to aid in understanding internal structure and polarization changes.

Sensing systems which are in use in related disciplines such as ionosonde and sonar should be assessed for possible applications to radio glaciology, especially for obtaining better resolution of internal layering.

The potential of wider coverage using satellite sounding should be examined. However, the capability, limitations, and feasibility of such a system should be examined in the light of current radio echo sounding expertise before recommending an operational program.

WORKING GROUP ON DATA PROCESSING

Chairman: Ray Watts
United State Geological Survey
Denver, Colorado

Investigators record radio glaciological data in many different formats (viz on photographic film, analog magnetic tape, and digital magnetic tape). Each recording medium has its unique processing requirements. As a trend, however, data are likely to be recorded in digital form. The Working Group has formulated recommendations, therefore, based on the anticipated dominance of digital over analog or optical data, but recommends that conversion facilities be made available to the radio glaciological community in order that flexible, digital processing may be applied to data recorded in any format.

The Working Group identified four broad areas of data processing effort that are addressed in the following paragraphs.

1. Algorithms for processing of radio glaciological data

The Working Group recommends publication of data processing algorithms and procedures in appropriate scholarly journals. When processed data are exchanged and the processing algorithm has not been described in the literature, the supplier of the data should provide a description of the algorithm to the data recipient.

2. Programs or code for data processing

The Working Group sees an immediate requirement for documentation and sharing of computer programs (i.e. implementations of algorithms) for accomplishing the following functions:

a. Coordinate transformations between commonly used coordinate systems and decimal latitude and longitude (see Standards, 4., below);

b. Migration of bottom echoes to true, rather than apparent, echo position;

c. Pulse compression and background removal (including filter design and applications programs);

d. Echo picking for the determination of echo time, especially in the presence of scatters or noise;

e. Data processing to select or average data in order to reduce the data set size or its density for synoptic studies;

f. 'Cleaning' data to allow for interpolation, smoothing, etc., and to allow for greater continuity as may be required for input to other processing steps or for graphic output.

The recommended language for the coding of computer programs is FORTRAN 77. It is recommended that all programs be exchanged in the form of subroutines that communicate data through argument lists. This procedure avoids the problem of incompatible data structure, storage, and communication, while offering the user complete flexibility in coding his own input and output programs.

3. Services and products

The following list of products and services was derived from the viewpoint of processing equipment and standardized services, rather than from the viewpoint of scientific needs.

a. Digitization of photographic or analog recorded data

The Working Group recommends that a Data Center be designated to make this function available to the glaciological community; without it, a great deal of existing data cannot be processed in the most flexible and powerful way, e.g. digitally.

b. Echo picking

As a means of compressing two-dimensional data sets nearly to one-dimensional functional form, radio echo records can be presented as echo delay times as a function of position. The recommended information for each data point includes, at a minimum:

1. latitude
2. longitude
3. sounder altitude
4. arrival time for first echoes.

c. Migrated data

Migrated data should be in the same format as echo picking above, except that interpreted bottom elevation in meters replaces echo time. A description of the assumed velocity model should accompany the data set.

d. Catalog of processed and raw data

Records should be kept of raw and processed data. This is particularly important for tracking processed components of large data sets. Updates to and maintenance of a master catalog should be undertaken by a Data Center.

e. Raw data duplication service

Duplication of photographic, analog, and digital records should be provided through a Data Center.

f. Digital products

Production of graphic products and images from digital data should be made available. These are an important product format for many investigators.

4. Standards

The Working Group recommends adoption of the following standards insofar as they are consistent with the various investigators' capabilities.

a. Recording

Standard digital formats already exist, as specified in the WDC-A Data Announcement for airborne polar ice sounding data [Data Announcement 1980(GL-A)]. Analog recording should be done in IRIG standard tape formats. Time-base calibration signals should be recorded with the data for accurate delay-time recovery.

b. Programming

Subroutines should be coded in FORTRAN 77 with data communicated to and from subroutines through argument lists.

c. Data quality indicators

In data sets where data quality varies, an indicator should specify relative quality or error for each datum, especially if some data are derived from others (e.g. interpolated).

d. Coordinate reference

Data set distributions should include references to maps or other sources of geographic coordinate data. Coordinates should be specified in 0 to 360 degrees (+ west) longitude and -90 to +90 (+ north) latitude. The values should be expressed in degrees and fractions and not minutes and seconds.

e. Inventory

As data are generated, processed, and archived, notice should be made to the Data Center.

WORKING GROUP ON DATA PRODUCTS AND DISTRIBUTION

Chairman: Paul Cooper
Scott Polar Research Institute
University of Cambridge, England

The Working Group compared areas of interest and types and volumes of data produced. It emerged that there were three main levels at which data were produced. They are:

1. Mountain glacier sounding results. These are comparatively small scale. Researchers involved in this work felt that the system operated by the Temporary Technical Secretariat (TTS) of UNESCO at Zurich was adequate for their purposes. However, the provision of maps with flight or traverse tracks would be a useful addition to the TTS service.

2. Large scale surveys. Examples include those surveys carried out on the Greenland ice sheet by the Technical University of Denmark and on the Antarctic ice sheet by the Scott Polar Research Institute-Technical University of Denmark-U.S. National Science Foundation. The Technical University of Denmark presentation of horizontal compression data from Greenland was felt to be generally useful, but that the inclusion of some quality indication would be a valuable addition.

3. Satellite surveys, such as the radar altimetry data from SEASAT and GEOS. The volume of data produced by these systems is so large that the tabulation of every data point is considered to be impracticable for large-scale dissemination. The Working Group felt that the production of contour maps, with associated data-density maps, would be a useful primary reference. A condensed data set could serve as a secondary reference. The exact method used to condense the data should be documented.

The Working Group reached the following conclusions:

1. Hard copy should be available for all data held. This provides a readily useable reference for those working on a small-scale. The minimum data provided for each data point should be latitude, longitude, surface elevation, and bedrock elevation (if available). Also, some indication of the quality of the measurements should be given. Any interpolated values should be noted. It is also recommended that latitude and longitude should be given in degrees and fractions, and that the sign convention should be defined in accompanying documentation, which should also include track charts.

2. The data producing groups should be required by funding agencies to produce data reports.

3. The World Data Centers should act primarily as clearing houses for information, referring researchers who require machine-readable data to the group producing the data. Exceptions to this will arise when data are 'orphaned', or data storage is requested by research workers or agencies. In these situations the Centers may act as repositories.

4. Suppliers of data should be informed of subsequent usage by other groups.

Finally, the Working Group compiled a preliminary list of institutes and researchers with radio glaciology data (table 1).

Table 1. Institutes and Researchers Holding Radio Glaciological Data.

Organization	Contact	Region Covered	Type of Data
NASA	J. Zwally R. Bindschadler	Polar Regions	Radar altimetry on SEASAT ± 72° GEOS ± 65°
Arctic and Antarctic Research Institute, Leningrad	V. Bogorodski	Antarctica Severnaya Zemlya	Z-scope films, etc.
Institute of Geography Department of Glaciology (USSR)	IU.IA. Macheret	Svalbard USSR mountain glaciers	Z-scope altimetry
Technical University of Denmark	P. Gudmandsen	Greenland	Z-scope films
Geological Society of Greenland	A. Weidick	Greenland mountain glaciers	
U.S.G.S.	R. Watts	Columbia Glacier, Alaska	
Scott Polar Research Institute	G. deQ. Robin D.J. Drewry	Antarctica Svalbard Devon Island Ellesmere Island	
British Antarctic Survey	C.S.M Doake R. Crabtree	Antarctic Peninsula	
U. of Melbourne (ANARE)	W. Budd	Traverse: Casey - Vostok Law Dome Lamberg Basin Amery Ice Shelf Enderby Land	RES film, maps (some plotted)
National Institute of Polar Research (Japan)	M. Wada	Yamato Mts. - Shirase Glacier Syowa - Mizuho Station Yamato - Mizuho Station	Airborne; Z-scope and A-scope Oversnow
Norsk Polarinstitutt	O. Orheim	RES on icebergs Svalbard Norway Antarctica	Z scope - not digitized, not precise on navigation
Norges Vassdrags-og Elektrisitetvesen	B. Wold	Norwegian glaciers	
Polar Continental Shelf Project (Canada)	R. Koerner	Arctic Islands, Canada	A-scope
Environment Canada	S. Ommanney	Rocky Mountain glaciers, Alberta	A-scope
University of British Columbia	B. Narod	Yukon Territory glaciers	

Partial List of Radio Echo Equipment

Country	Organization	Equipment	Contact
Australia	Australian National Antarctic Expedition (ANARE)	3 - 100 MHz systems. BW about 10 MHz.	W. Budd
Canada	C-Core	Impulse radar	T. Keliher
	Environment Canada	620 MHz BW 10 MHz	G. Holdsworth
	MPB Tech, Montreal	Synthetic impulse Impulse radar	(L. Davis, Xadar)
	University of British Columbia	840 MHz analog magnetic recording STR4 - recorder (IRIG)	B. Narod
		Monopulse system 5-20 MHz, up to 600 m temperate ice developing digital recording	B. Narod
		Mark II (N/S)	B. Narod
Denmark	Technical University	60 MHz, airborne A and Z scope BW 14 MHz	P. Gudmandsen
		300 MHz, airborne A and Z scope BW 14 MHz	P. Gudmandsen
Iceland	University of Iceland	2-5 MHz Z scope	M. Sverrisson
		2-10 MHz Z scope	M. Sverrisson
Japan	National Institute of Polar Research	SPRI MK-II 35 MHz	M. Wada
		NIPR-V 60 MHz A and Z scope	M. Wada
		NIPR-A 179 MHz A and Z scope	M. Wada
Norway	Norsk Polarinstitutt Norges Vassdrags-og Elektrisitetvesen (joint ownership of equipment)	Icelandic impulse sounder	O. Orheim B. Wold
United Kingdom	Bristol University	Phase sensitivity radar	M. Walford
	British Antarctic Survey	SPRI MK-II 35 MHz	C. Doake
		SPRI MK-IV 35 MHz	C. Doake
		BAS MK-I 60 MHz	C. Doake
	Cambridge University	3 SPRI MK-IV, 60 MHz BW 5-6 MHz	D. Drewry
		440 MHz borehole system	D. Drewry
		1 GHz impulse sounder	D. Drewry

Contact	Organization	Equipment	Contact
United States	Stanford Research Institute	Various	R. Vickers
	U.S. Geological Survey	5 MHz mono-pulse	R. Watts
	University of Wisconsin		C. Bentley
	Ohio State University		K. Jezek
	California Institute of Technology		M. Brugman
	Xadar	Impulse radar	L. Davis
	U.S. Army. Cold Regions Research and Engineering Laboratory	Short-pulse radar	A. Kovacs
	U.S. National Aeronautics and Space Administration		
	Jet Propulsion Laboratory		
Soviet Union	Institute of Geography	620 MHz airborne	V. Kotlyakov
	Arctic and Antarctic Institute	60 MHz	V. Bogorodskii
		440 MHz	V. Bogorodskii
		700 MHz	V. Bogorodskii

Englacial Stratigraphy

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Unlike polywater, a new and more stable form of H_2O, and Kurt Vonnegut's ice-nine, the alternate and more stable form of water that has a melting point of 114.4 degrees Fahrenheit, internal layering of ice sheets is a scientific fact, not science fiction. The internal layering recorded in both the Greenland and Antarctic ice sheets is not yet a fully utilized source of information on the internal character and flow dynamics of ice sheets. I envision the study of these layers as a subfield of glaciology which I shall call englacial stratigrphy. If, as has been supposed, these layers are time lines, they would be unique in the geological sciences for their consistency and areal extent. Mapping of prominent layers as key horizons in the ice sheets would need to be undertaken first to establish the rationale for further detailed mapping.

Data are now available for an ice thickness map of Greenland and of course, the ice thickness measurements in Antarctica should be continued to complete the map of that ice cover. However, englacial stratigraphy as such holds the promise of a quantum leap in understanding large ice sheets. I consider data gathering on surface topography, ice thickness, and internal layering of ice sheets more important than ice sheet modeling at this time.

Not a great distance from Columbus, Ohio, is Pittsburgh, Pennsylvania, the site of the first radio station in the United States, KDKA. Radio has been used for the dissemination of information by such radio networks as Australian Broadcasting Commission, British Broadcasting Corporation, Canadian Broadcasting Corporation, and Radio Moscow. I consider this meeting as a broadcast of Radio Glaciology. This station is telling the glaciolgical community and those that support it of the importance and future possibilities of radio echo sounding. I plan to utilize this broadcast of Radio Glaciology to encourage and find ways to fund more equipment, flights, and data analysis. I'll be listening intently to the rest of the broadcast.

A Digital Recording System for Deep Polar Ice Sheets

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Introduction

Radar data collected on the polar ice sheets have been conventionally recorded on film, most commonly as continuous, intensity-modulated profiles, and occasionally, as amplitude displays of returning wave forms. These techniques suffer from a number of disadvantages, including limited dynamic range of the film, no amplitude data on continuous profiles, and the requirement that the film records be digitized for any sophisticated processing. Because of these drawbacks of photographic recording, we have initiated the development of a digital recording system used with the Scott Polar Research Institute (SPRI) Mark II transmitter and receiver.

The design philosophy behind our approach is different from several recently developed recording systems (as reported at the Radio Glaciology Workshop). Along with modifying the receiver to enable us to preserve phase data, we use a transient recorder to digitize the data and thus eliminate the need for a sample and hold scheme. Consequently, relative phase information is preserved along the wave train even while the system is moving. Additionally, the high data rate from the transient recorder should allow us to do real-time averaging and still maintain a short horizontal displacement over which the averaging takes place.

Specification

The recording system we developed was designed to be used primarily on the ice sheet surface. With this in mind, we specified the following criteria that the system had to meet:

1. dynamic range of about 50 db;
2. sampling rates of at least 20 MHz with total record lengths of at least 60 μs;
3. record acquisition rates of at least 1 Hz;
4. a data recording format that would produce manageable amounts of physical data;
5. 160 db system response; and
6. phase sensitivity.

The remainder of this section describes the first attempt at achieving these goals.

The digital recording system is built around the SPRI Mark II radio echo sounder. The transmitter emits a 0.2 μs burst on a 50 MHz carrier. The peak radio frequency is about 10 Mhz. Peak power is 500 watts into 50 ohms.

The first stage of the receiving equipment is a time varying attenuator (TVA). This is shown in the block diagram of figure 1. This device compensates for the inverse square spreading loss, effectively increasing the dynamic range of the system by causing return echoes to be recorded at more nearly equal levels. The receiver is kept at minimum sensitivity until it is hit by the surface wave where upon the sensitivity is increased up a variable ramp about 5 μs long.

The 50 MHz receiver is a radio frequency amplifier with a half wave rectifier and a bandwidth of 10 MHz. The position of the receiver in the radar system is illustrated in figure 2. By modifying the transmitter to fire at constant phase and heterodyning the receiver (a 55 Mhz oscillator is used), it is possible to capture the phase of the reflected pulse. From the receiver, the signal is sent down parallel lines terminating in a Honeywell Visicorder Oscillograph and the digital recording system. The oscillograph is used as a real-time monitor and produces hard-copy profiles.

The heart of the digital system is the Biomation 8100 transient recorder. It is an 8-bit device (7 bits plus sign) that can sample at rates up to 100 MHz. It has a 2048-word memory. The 8 bits yield a dynamic range of 48 db; coupled with the TVA, this range should be about 30 db better than that of amplitude displays recorded on film. The transient

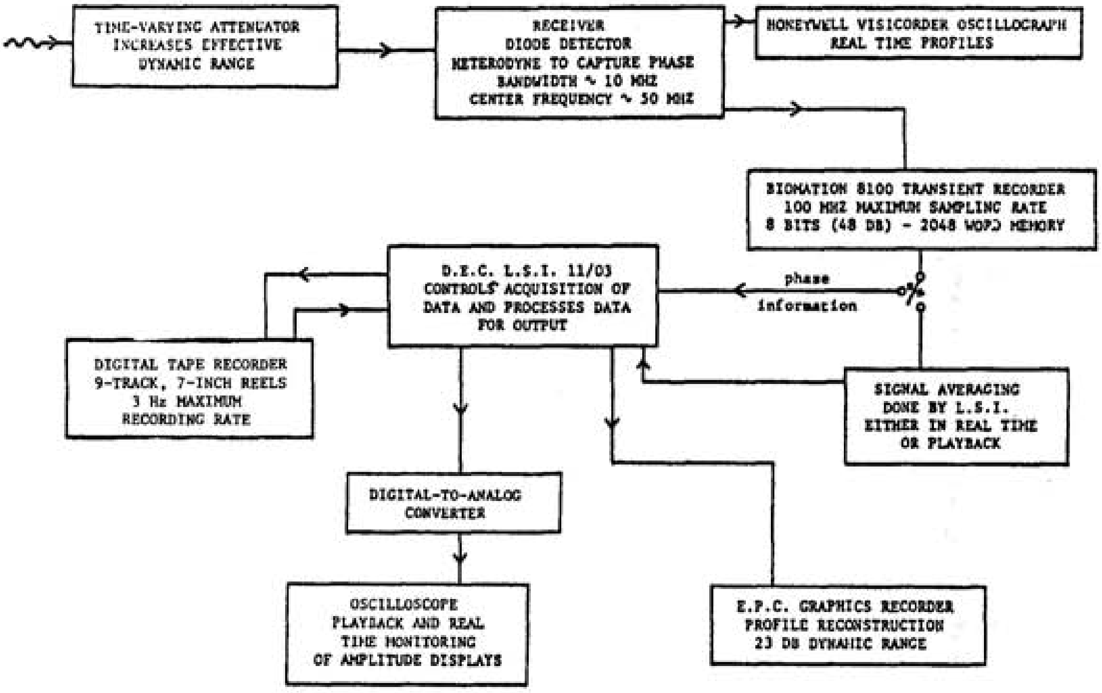

Figure 1. The role of the time varying attenuator (TVA) in the receiving equipment of the digital recording system.

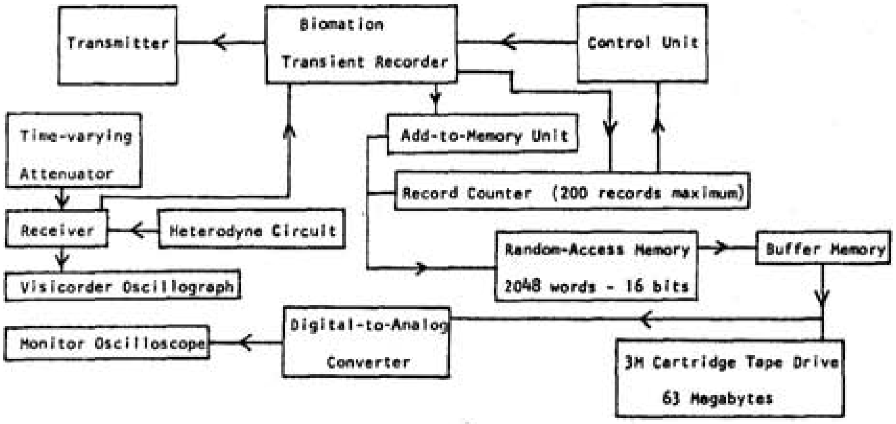

Figure 2. Illustration of the position of the receiver in the radar system.

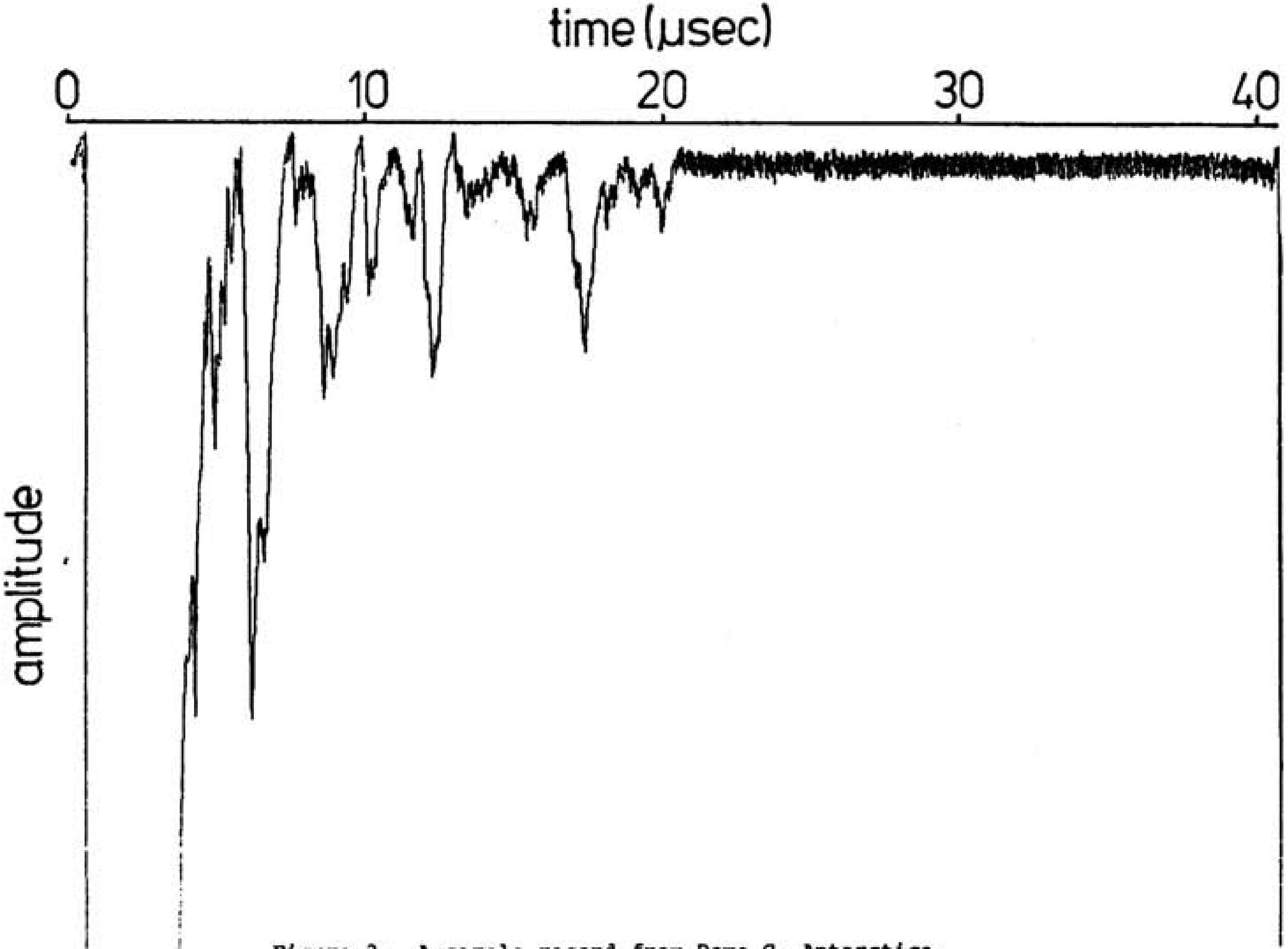

Figure 3. A sample record from Dome C, Antarctica.

recorder has none of the signal continuity problems associated with sample and hold techniques. This means that changes in velocity of the vehicle carrying the recording system will only effect the horizontal sampling of scans, not signal reconstruction.

A Digital Equipment Corporation LSI 11/03 computer controls the entire system. It also processes data for visual output on an oscilloscope and on a graphic recorder (dynamic range 23 db) for profile reconstruction. When studying the deepest layers, noise levels can be reduced by signal averaging in the 11/03. The system can record at a maximum rate of 3 Hz. A single 7-inch diameter tape holds better than 2000 records. The 3 Hz recording rate should insure that the density of sample points along a traverse line is easily controllable using typical surface vehicles.

The concept of this system offers many advantages over past techniques. Since all information detected by the receiver is stored, profiles can be constructed with much greater control. Rather than spending large amounts of field time obtaining profiles over the same line with varying intensities, horizontal sweep rates, and attenuations, the same type of reconstruction can be made in the laboratory. It should also be possible to enhance profiles constructed from digital signals by filtering, migration, and magnification of the profile. Data used to pick travel times can be used to correlate reflectors. Finally, the increased dynamic range should allow us to study much deeper and fainter features in the ice.

The above discussion represents an outline of the driving ideas behind the radar we designed and built during the summer and fall of 1978. The radar had its first season in the field that winter and it did not work as well as we had hoped. An unexpected problem of radio frequency noise generated in the computer forced us to modify or abandon many parts of the equipment. It also limited us to stationary recording at a single site. In the end we were able to successfully sound down to a depth of 2000 meters, accurately recording internal layers. We were unable to detect the ice-rock interface with the computerized system. A sample record near the Dome C borehole, Antarctica, is shown in figure 3. The abrupt change in the amplitude of internal layers at about 1700 m depth may indicate a real boundary in the electrical properties of the ice.

As a result of our experience at Dome C in 1978, we have redesigned the system as shown in figure 2. A microprocessor now controls the operation of the system making the entire unit much smaller and more easily shielded. Also we have included additional memory circuits and two 2048-word random access memories (RAM) for real-time signal averging. We estimate that about 200 signals can be studied every 0.5 seconds. Finally, we are trying a new cartridge tape recorder built by the 3M Company. The unit has about 63 megabyte storage capacity. It is planned to test this system at Dome C during the 1981/82 field season in Antarctica.

Summary

We are confident that the concept of our recording system is sound and, assuming we can overcome our noise problem, will prove to be a valuable glaciological tool. The methodology behind this system can be summarized as follows: 1. the use of transient recorder; 2. heterodyning for phase recovery; 3. the use of field computing power to verify data tapes and to provide in-field data processing; and 4. real-time recording as a back-up record.

Radar Studies of Glacier Ice

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INTRODUCTION

The frequency spectrum used in radar studies lies in the dielectric region between the polarization relaxation band and the optical absorption band (figure 1). In this region the wave speed, determined by ϵ_∞ is very nearly, if not entirely, independent of temperature; on the other hand, the absorption, determined by the relaxation time, is strongly temperature dependent (figure 2).

The following outline is a list, not in order of importance, giving a summary of the different kinds of measurements which have been included in radio glaciological work.

I. Absorption measurements have been used as a way of determining englacial temperatures, although accuracies thus far have not proven to be very great.

II. Wave propagation speed. Several techniques have been used to measure the wave speed. A summary of measurements in solid ice is given in figure 3. Techniques include:

A. Direct logging in drill holes;

B. Reflection sounding right next to drill holes where the thickness of the ice is accurately known;

C. Measurement by oblique reflection sounding, a standard geophysical technique:

1. Reflections from the base of the ice (figure 4),

2. Reflections from internal layers (figures 5, 6);

D. Comparisons between radar reflection time and seismic sounding time (figure 7). In some cases the scatter of the observed comparisons is clearly greater than the experimental error (figure 8);

E. Direct propagation between drill holes. This technique appears to have been attempted only by the Soviet Antarctic Expedition.

III. Ice thickness. Most radar measurements are made in order to determine ice thickness. Two examples of subglacial topographic maps from Antarctica are shown in figures 9 and 10.

IV. Studies of subglacial physiography. Classification of subglacial terrain units on the basis of subglacial topographic maps has been carried out by Drewry in Wilkes Land, Antarctica (figure 11).

V. Reflections from internal reflectors.

A. Internal layering. By far the most extensive application of internal reflections is to the study of flat internal layering, probably representing constant time horizons;

B. Brine infiltration zones, particularly applied to the McMurdo Ice Shelf (figure 12);

C. Bottom crevasses (figure 13);

D. Buried surface crevasses (figure 14);

E. Scattering by air bubbles, water-filled cavities, and ice lenses:

1. Resulting in loss of signal (figure 15),

2. Showing a change in time (figure 16).

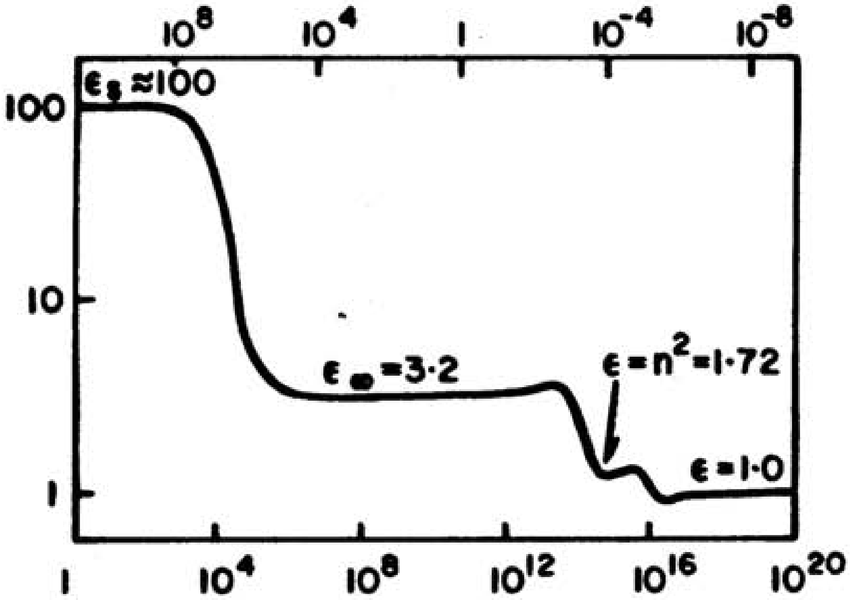


Figure 1. Schematic representation of the behavior of the dielectric constant of ice, , as a function of frequency at a temperature near -10°C. (From Fletcher, 1970)

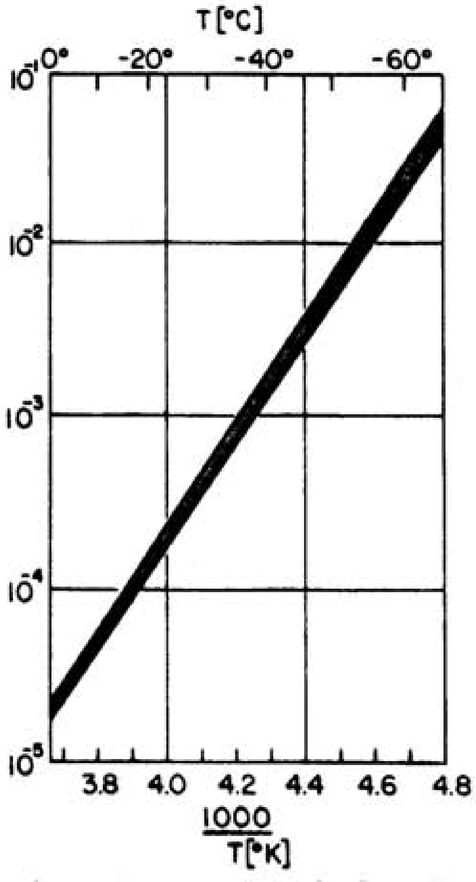


Figure 2. Characteristic relaxation time as a function of absolute temperature for pure monocrystalline ice.

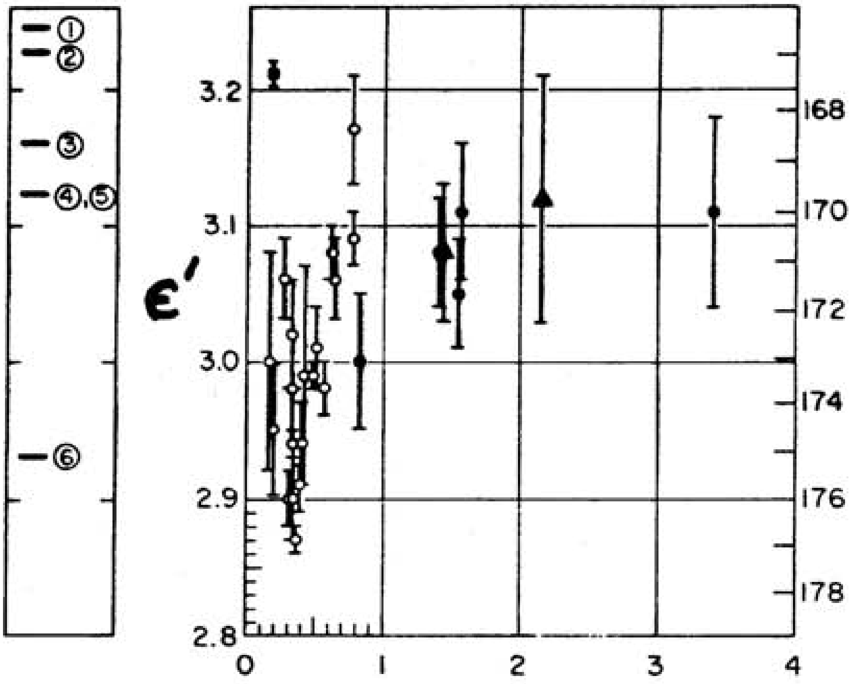


Figure 3. Plot of determinations of ε' in glacial ice, as calculated from field velocity measurements. Solid circles: oblique reflections on on grounded ice; open circles: oblique reflections on floating ice; solid square: interferometry; solid triangles: reflection times at deep drill holes, corrected to T = -15°C. Also shown for reference are laboratory measurements on polar ice samples, correct to T = -15°C, from Westphal (Jiracek, 1967): 1 - 4; Fitzgerald and Paren (1975): 5; Paren and Glen (1978): 6.

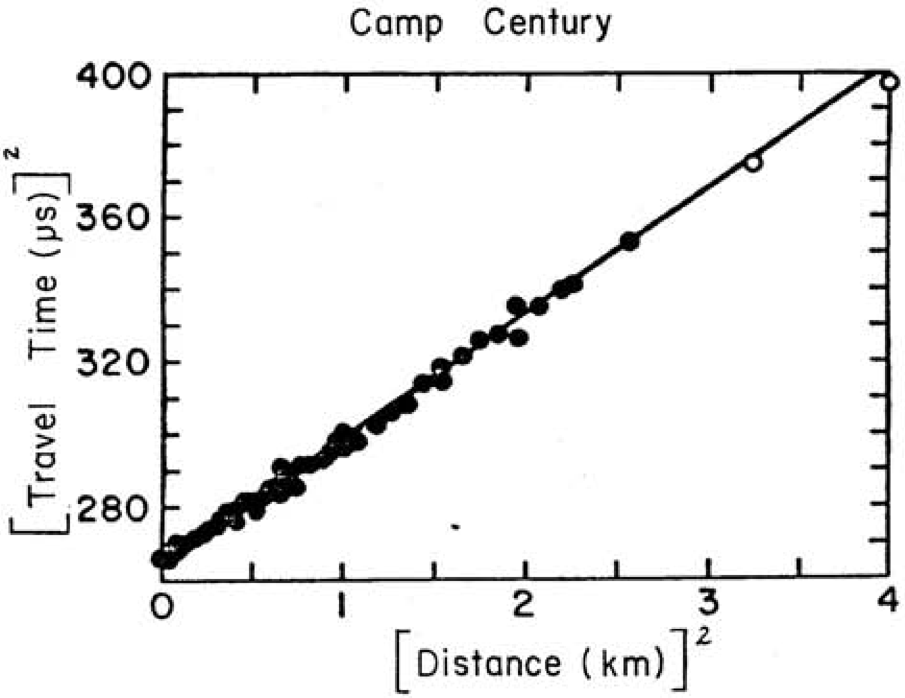


Figure 4. Plot of (travel time)^2 vs. (distance)^2 (t^2 vs. x^2) for oblique ice-bottom reflections at Camp Century, Greenland. Open circles were not used in the least-squares fit to the slope.

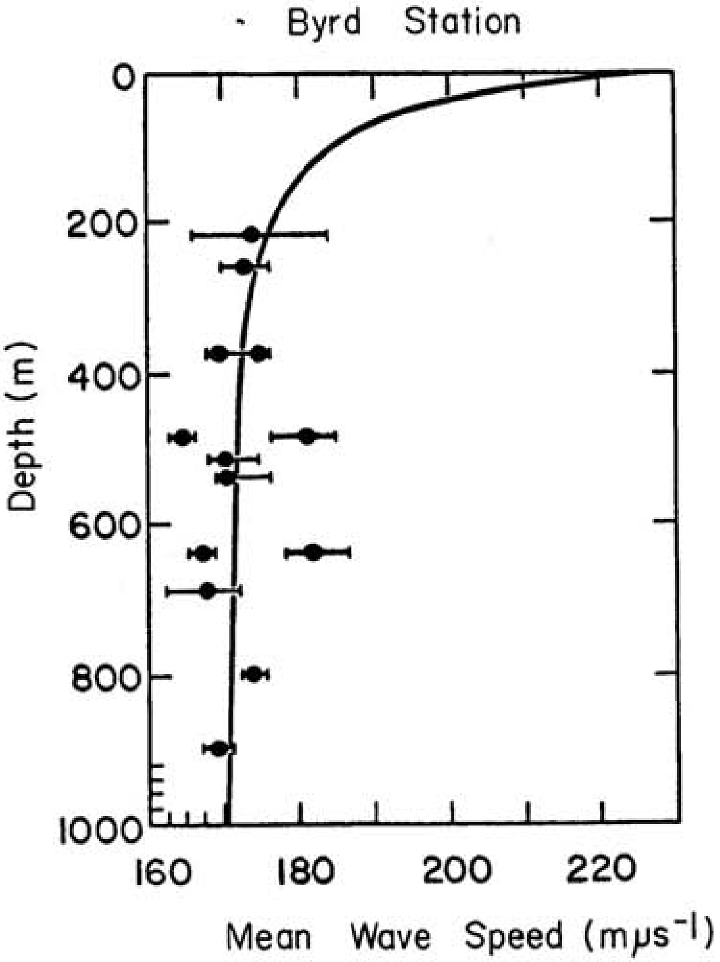


Figure 5. Average wave speed from the surface to various internal layers in the ice sheet at Byrd Station, Antarctica, as a function of the depth to the layer. The solid line is a calculated curve of average velocity vs. depth from measured densities and the v(ρ) equation. (From Clough, 1974)

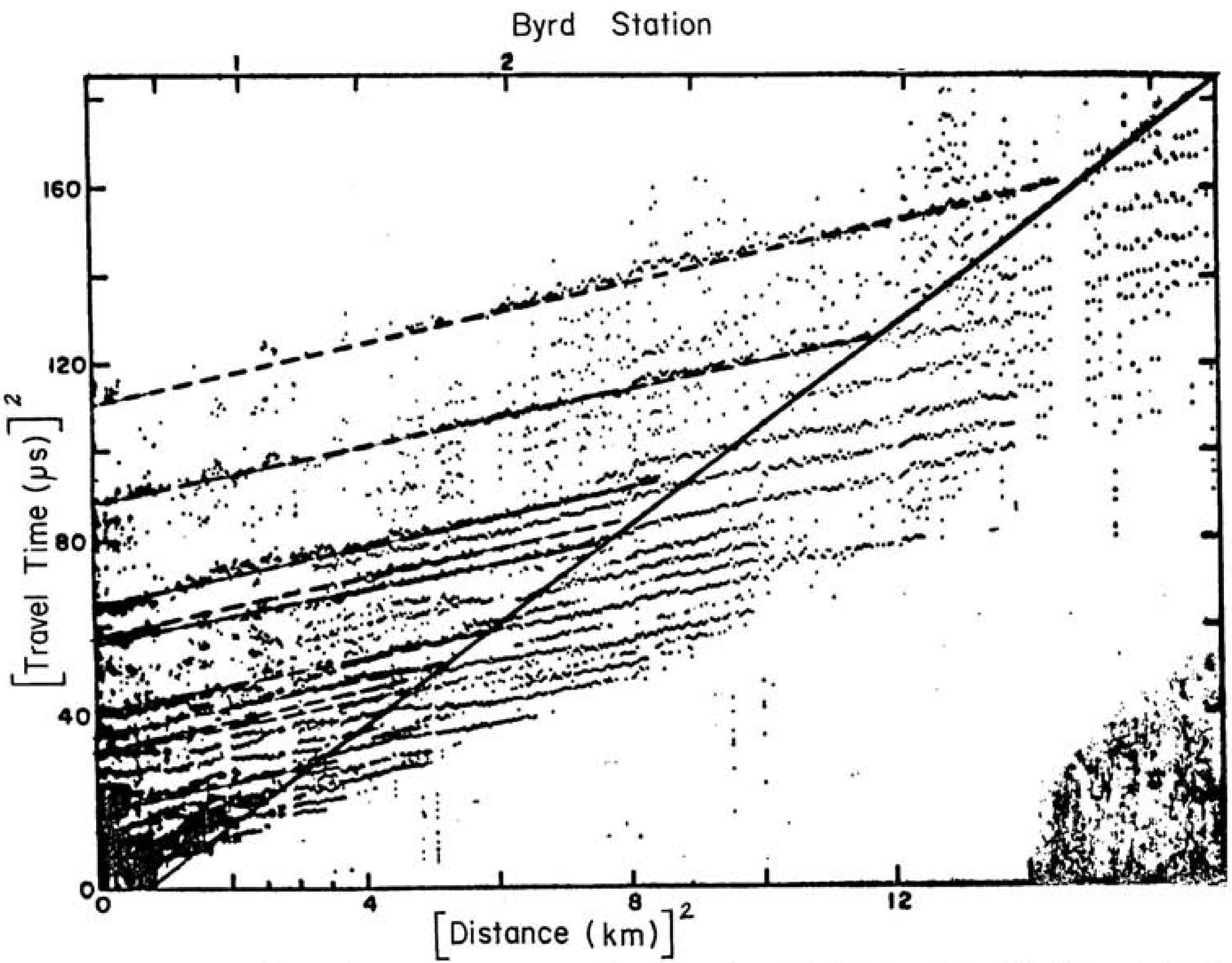


Figure 6. Plot of t^2 vs. x^2 for oblique reflections from internal layers at Byrd Station, Antarctica. Dashed lines were used to calculate the average wave speeds in figure 5. (From Clough, 1974)

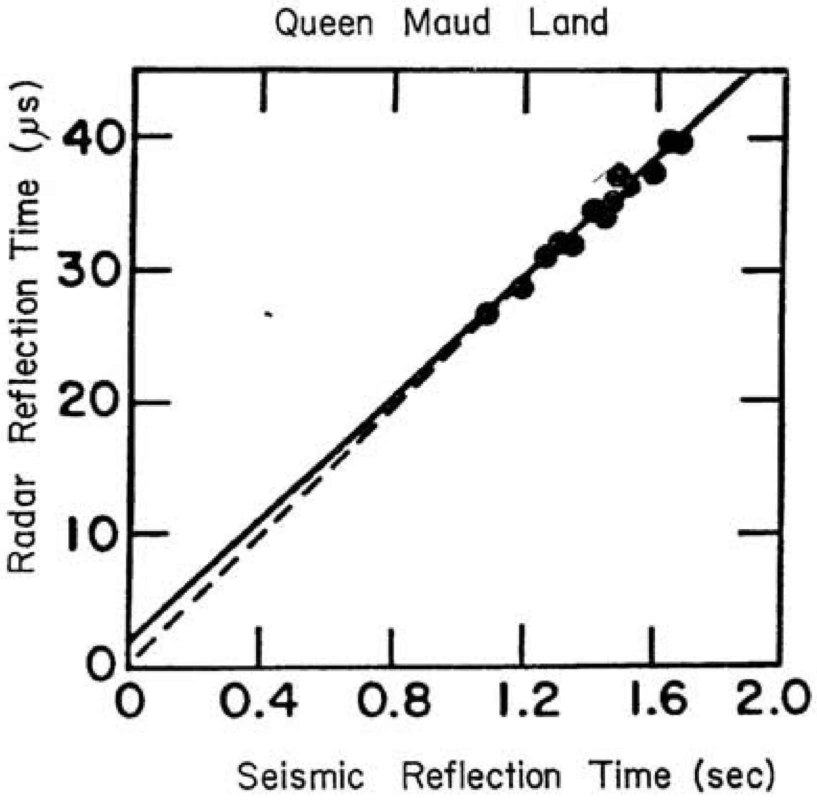


Figure 7. Radar reflection time vs. seismic reflection time in Queen Maud Land, Antarctica. (From Clough and Bentley, 1970)

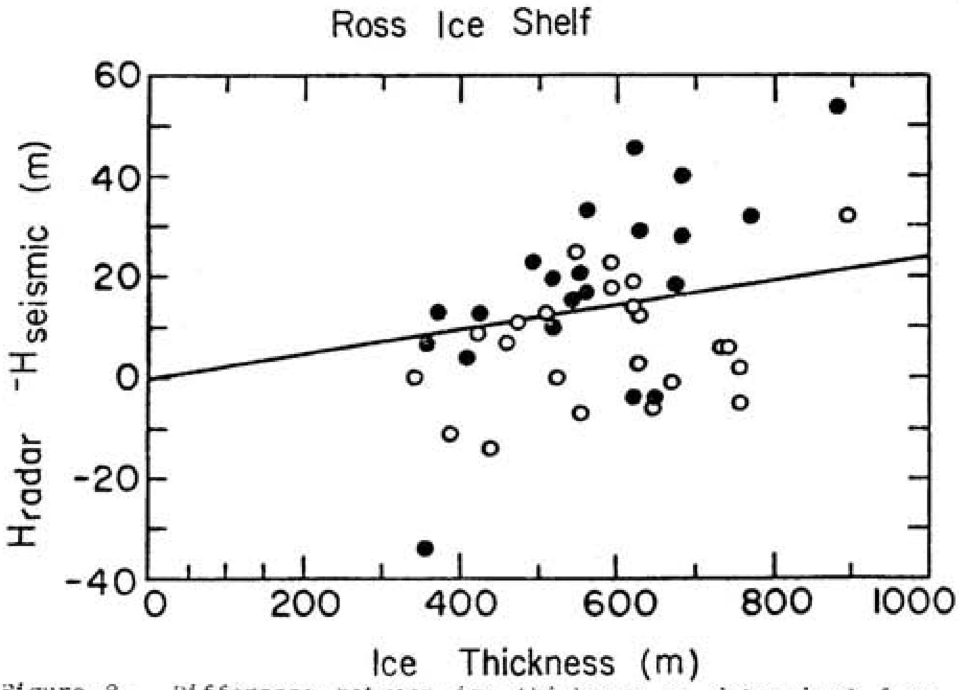


Figure 8. Difference between ice thickness as determined from radar reflections, H_{radar} and from seismic reflections, $H_{seismic}$, as a function of ice thickness for the Ross Ice Shelf. Solid and open circles are from the 1974-75 and 1975-76 seasons and represent primarily the grid northwestern and grid southwestern portions of the ice shelf, respectively. The line is a least-squares fit to all the data, forced through the origin (From Robertson, 1975)

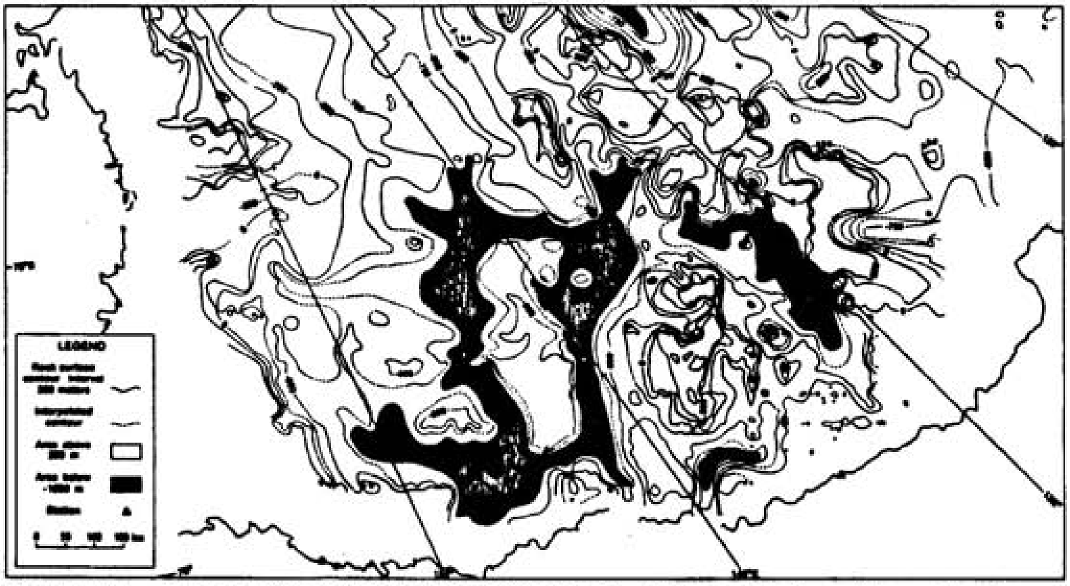


Figure 9. Map of the subglacial topography, Wilkes Land. (From Steed and Drewry, 1982)

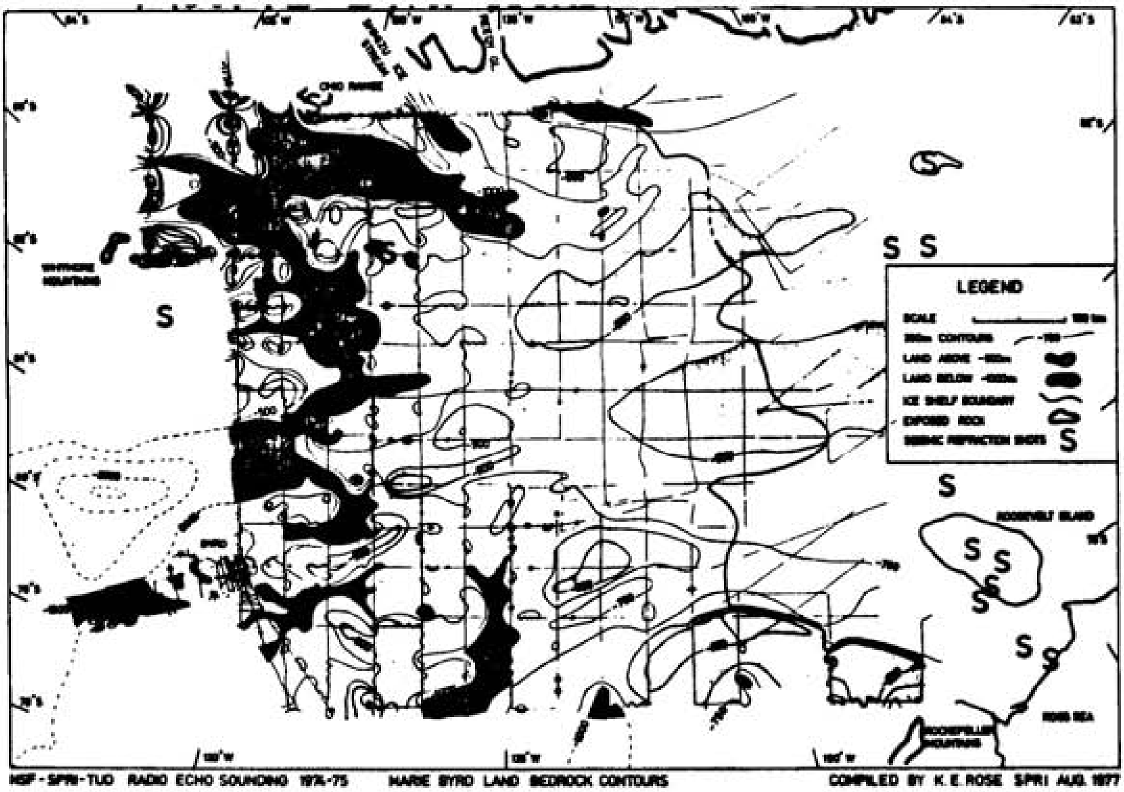
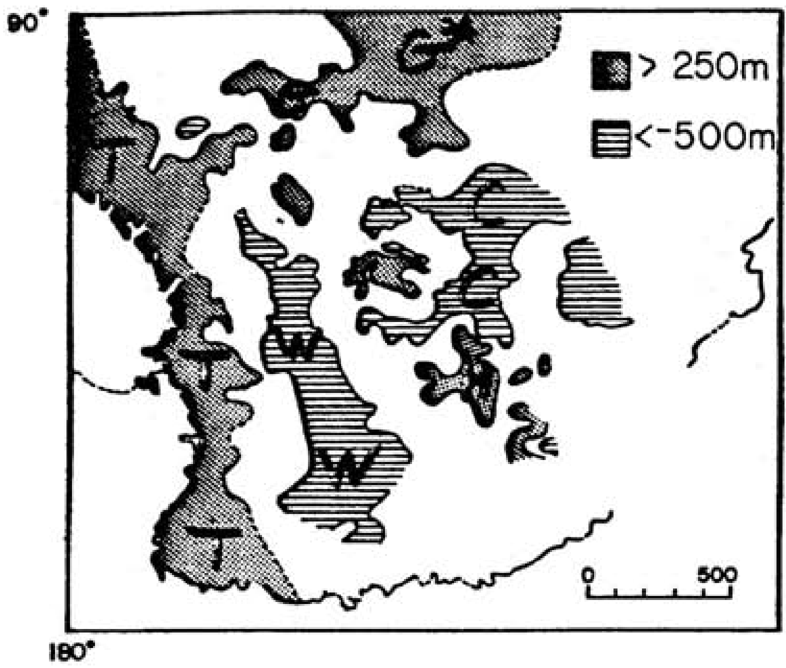


Figure 10. Map of the subglacial topography beneath the Rockefeller Plateau (western West Antarctica. (From Rose, 1982)

Wilkes Land Terrain Units (Drewry)



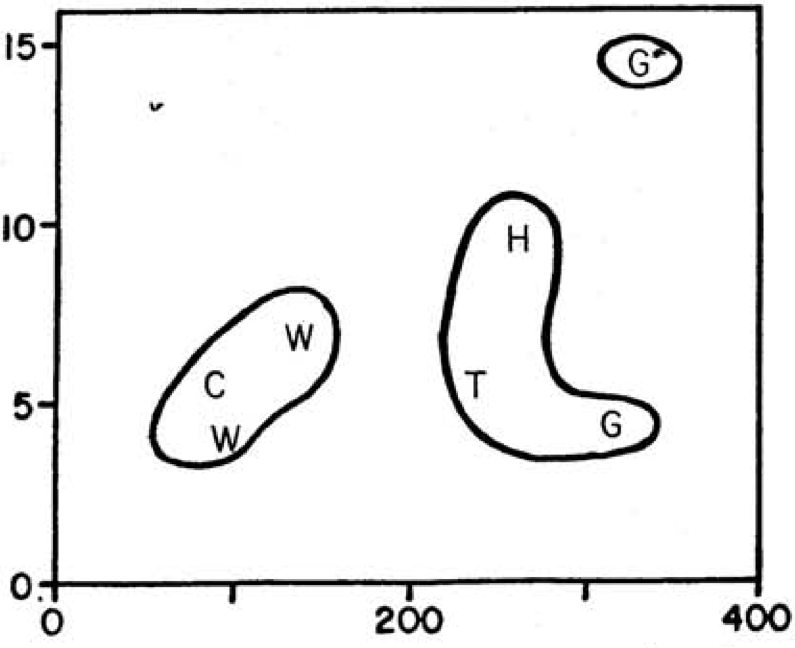
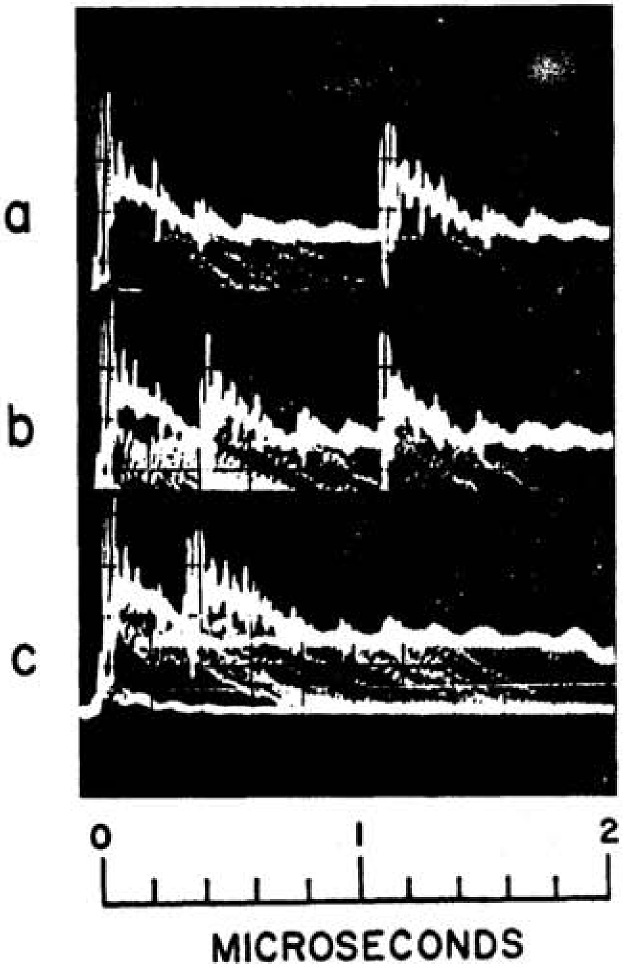


Figure 11a (top). Major large-scale terrains of eastern East Antarctica. T: Transantarctic Mountains; W: Wilkes subglacial basin; H: unnamed highland massifs; Aurora subglacial basin; G: Gumburtsev Mountains. Stippled areas (a) subglacial elevation >250m; lined areas (b) subglacial elevation >-500m. (From Drewry, 1975)

Figure 11b (bottom). Average terrain roughness characteristics of terrain regions in eastern East Antarctica. A: Lowland regions - Wilkes and Aurora Basins. B: Dissected highland regions, Transantarctic Mtns., Gamburtsev Mtns., central east Antarctic highland; C: Rugged mountain region - Gamburtsev Mtns. (From Drewry, 1975)



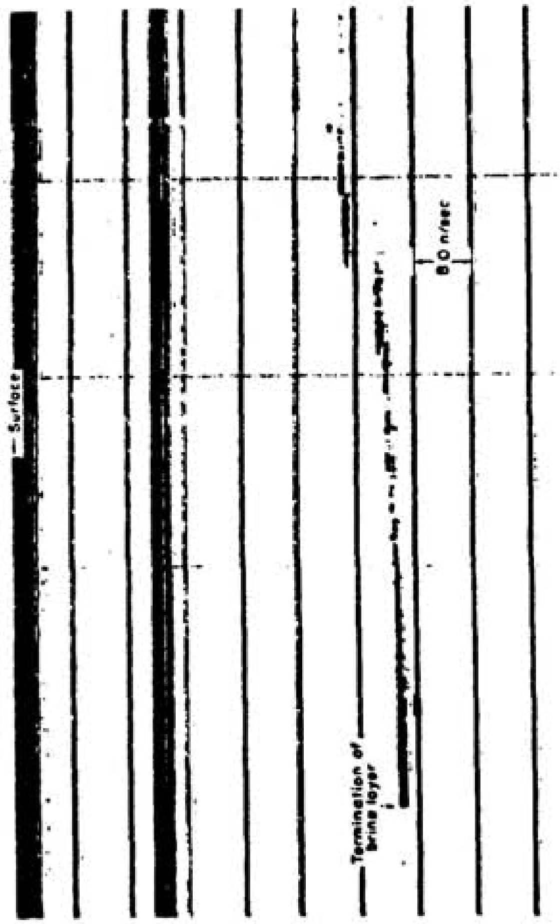


Figure 12a (left). Reflection records across the brine layer boundary. (a) Reflection from the bottom of the ice shelf is seen at approximately 1.1 μs. (b) Reflection from both the bottom of the ice shelf and the top of the brine layer (∿0.4μs). (c) Reflection from the top of the brine layer. The reflection from the bottom of the ice shelf is still visible but small. (From Clough, 1973)

Figure 12b (right). Impulse radar profile across the termination of the brine infiltration zone. An apparently discontinuous step in the reflecting surface also can be seen. (From Kovacs and Gow, 1975)

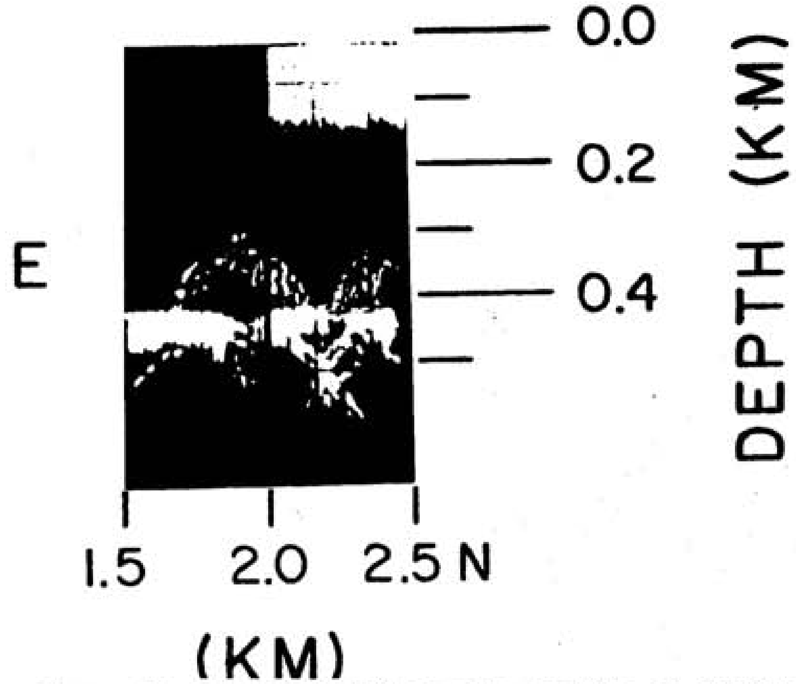


Figure 13. Detailed radar profile at station J9 showing two hyperbolas generated at the base of a bottom crevasse. (From Jezek, 1980)

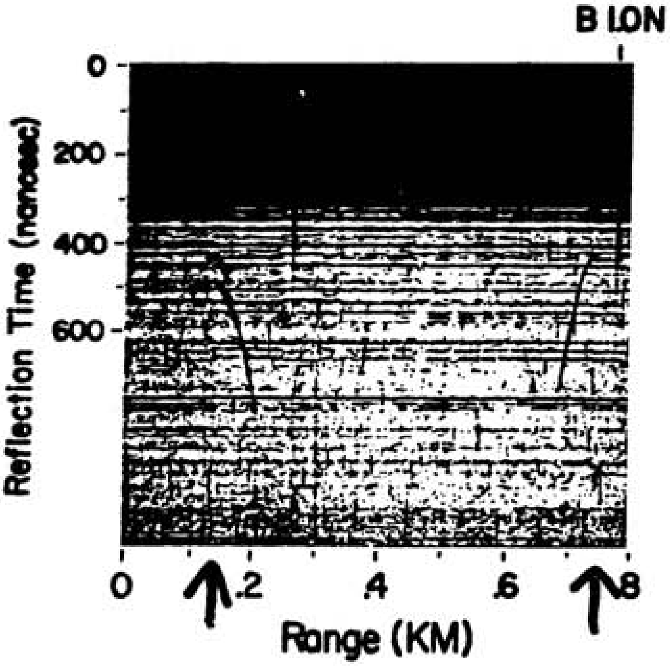


Figure 14. Impulse radar profile at station J9 showing hyperbolas believed to be diffractions from relict surface crevasses. (From Jezek, 1980)

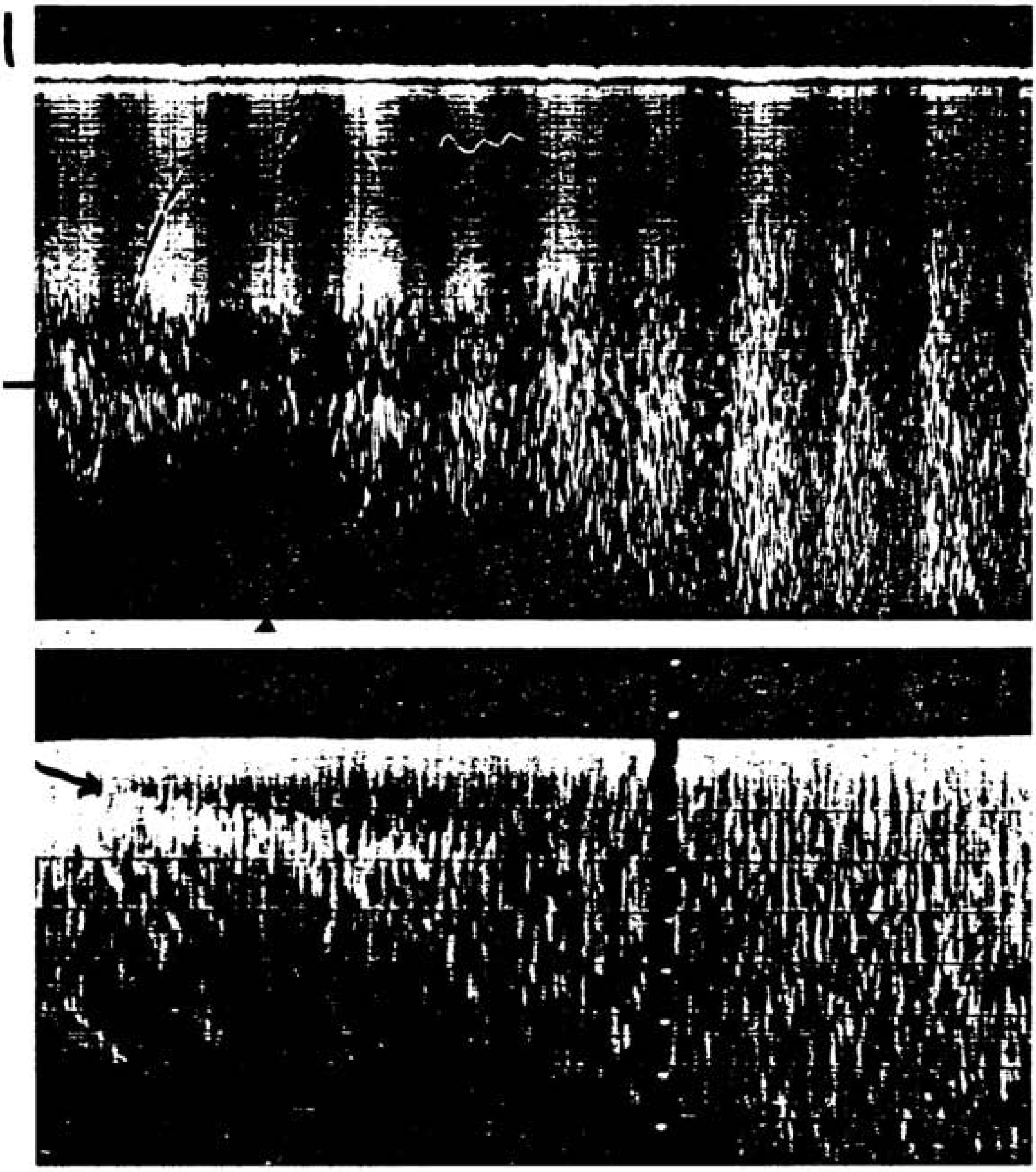


Figure 15a and b. Radar records showing the bottom echo disappearing into scatter echoes. The upper record (a), courtesy of Randall Electronics Ltd., was obtained on Hardangerjokulen, Norway, using a 480 MHz sounder on the surface. The bottom echo, to the left, is at a depth of 100 m and it disappears into the scatter echoes to the right. The lower record (b) was obtained on the Fuchs Ice Piedmont, Adelaide Island, Antarctica, using a 35 MHz sounder in an aircraft. The bottom echo is 40 dB above the receiver input noise level but it is nevertheless lost in the center of the picture at 150 m depth. (From Smith and Evans, 1972)

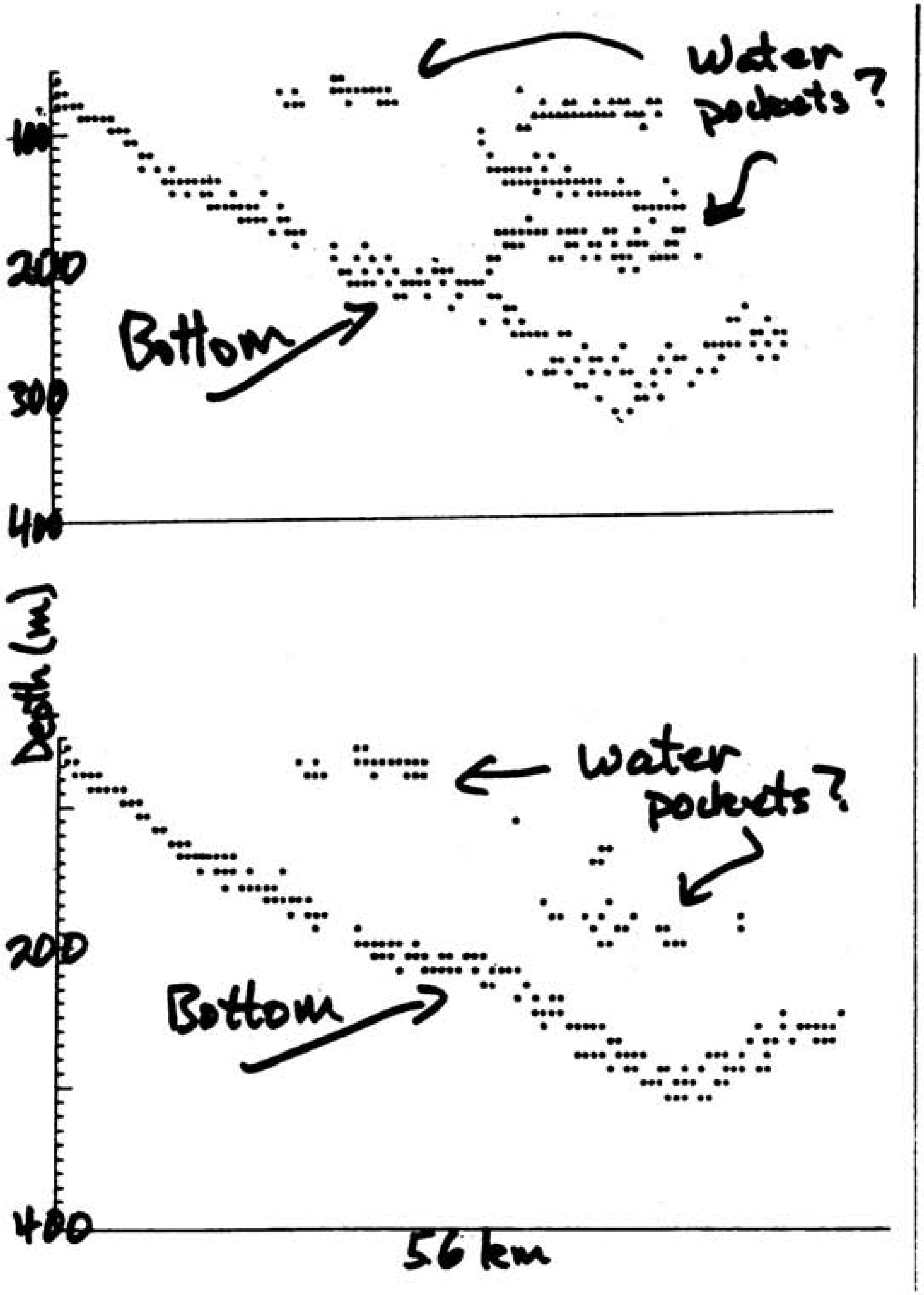


Figure 16. Computer print-outs of radar soundings made on Athabasca Glacier at two different times one month apart. The bottom echo is unchanged, but a marked change in the internal reflections can be seen. (From Goodman, 1973)

VI. Movement of glaciers.

  A. From repeated ice thickness mapping (Soviet Antarctic Expeditions);

  B. From relationship between ice thickness and surface slope;

  C. Measurement of horizontal movement from displacement of echo fading patterns relative to the surface (figure 17);

  D. Vertical movement from change in echo fading patterns. This has not yet been successfully completed, although first measurements have been made on Devon and Ellesmere Islands;

  E. Determination of past velocities from a comparison between observed and calculated internal echoes (figure 18);

  F. Determination of past glacial flow lines by tracing identifiable radar reflectors downstream (figure 19).

VII. Radio wave polarization studies (figure 20).

VIII. Nature of the basal interface.

  A. Subglacial lakes (figure 21);

  B. Location of ice streams (figure 22):

  C. Determination of bottom echo strength:

    1. On grounded ice (figure 23),

    2. On ice shelves (figure 24).

IX. Crevasse detection (figure 25).

X. Study of wave propagation phenomena.

  A. Lateral wave (figure 26);

  B. Critical angle internal reflections (figure 27);

  C. Head wave traveling just below the upper surface.

XI. Determination of total water content in temperate glaciers. Undertaken by Soviet investigators only.

XII. Depth sounding of the water in lakes beneath the ice. Carried out only by Soviet investigators.

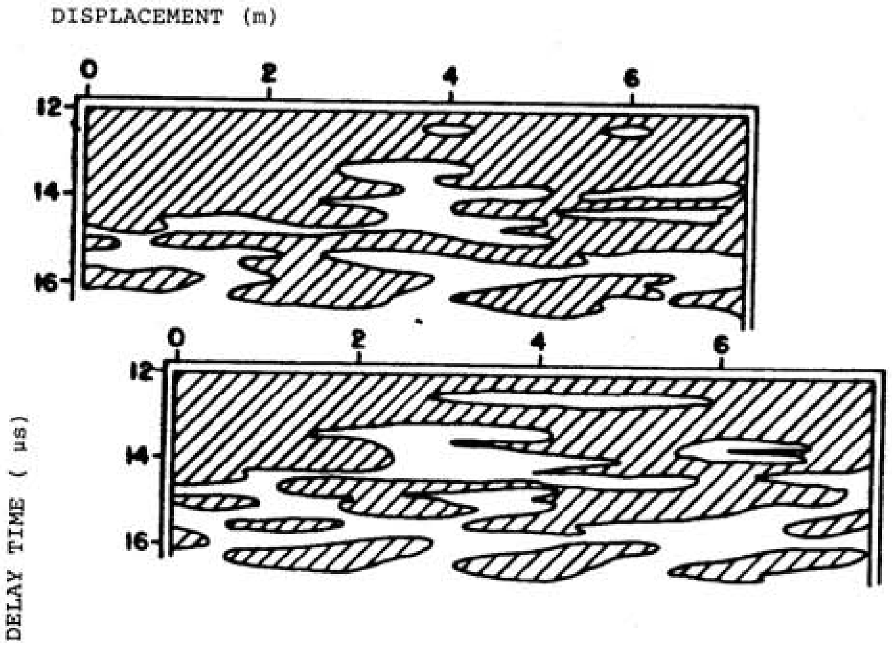


Figure 17. Radar fading patterns obtained on Fleming Glacier, Antarctica, at 1106 G.m.t. on January 28, 1972 (upper figure), and at 1242 G.m.t. on January 31, 1972 (lower figure) along a line bearing 267° from a marker fixed in the snow. The data were derived from records photographed at 25 cm intervals along the line. Hatched areas show where the echo strength is high. The site was displaced by approximately 1 m in 3 days. (From Walford, 1972)

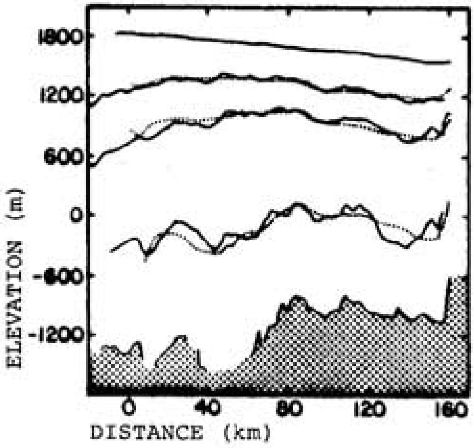


Figure 18. Profile along the axis of the strain net from Byrd Station to the ice divide. The radar reflectors are shown by the solid lines and the calculated isochrons by the dotted lines. Approximate ages of the isochrons are 2500, 5500, and 30,000 years, respectively. Stippled area represents bedrock. (From Whillans, 1976)

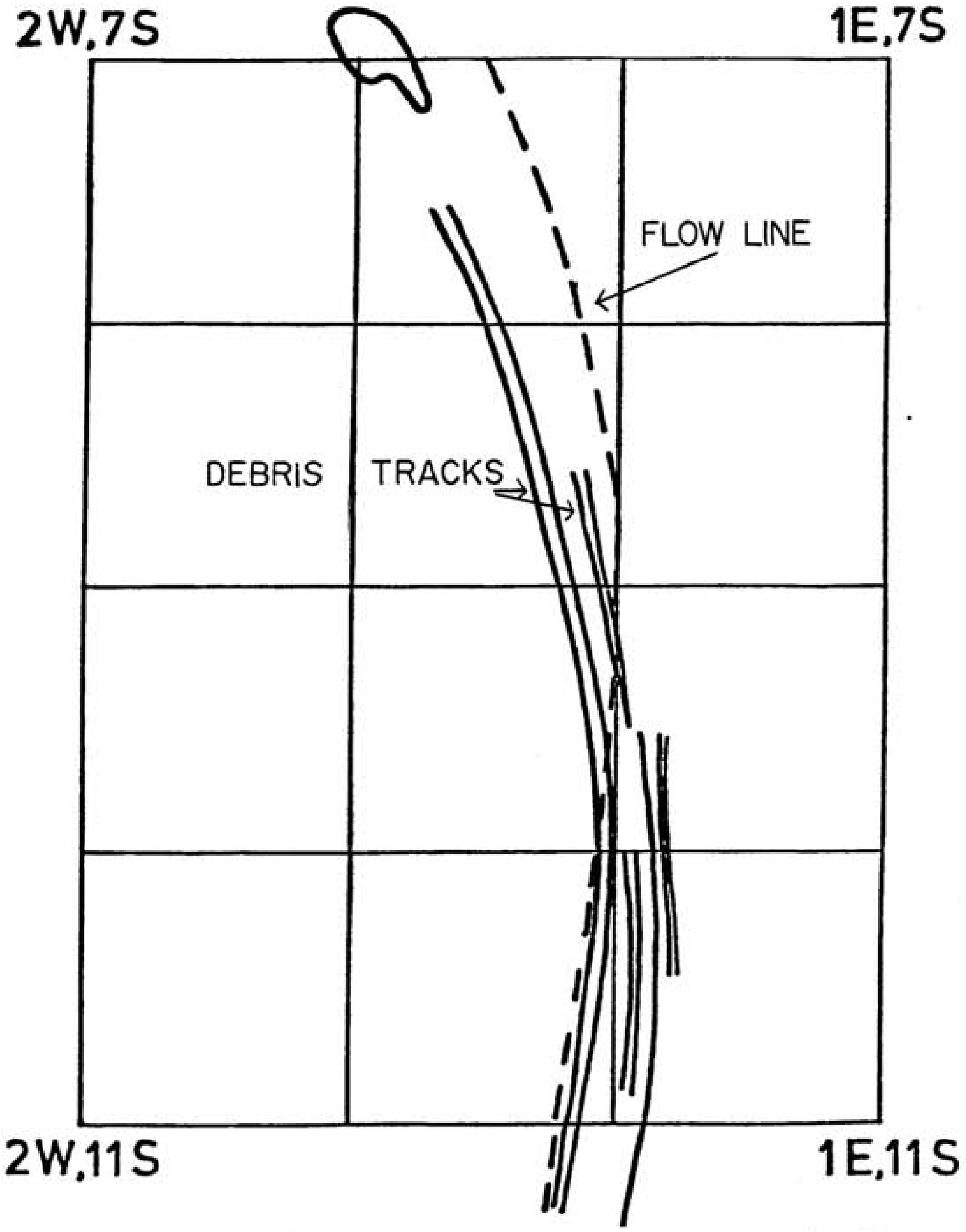


Figure 19. "Debris" tracks (heavy lines) and a present-day flow line based on the velocity vectors (dashed line) downstream of Crary Ice Rise, showing the striking divergence between them. (From Jezek, 1980)

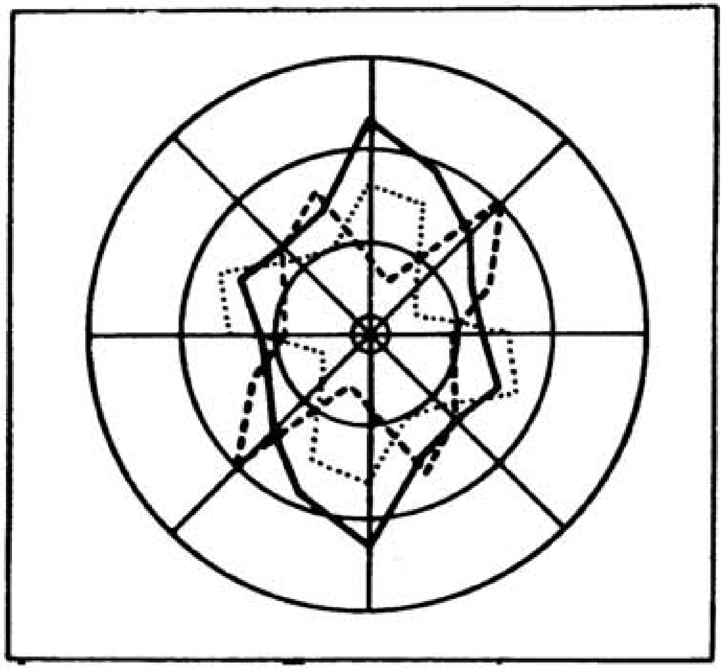


Figure 20a. Reflection amplitudes as a function of azimuth for different orientations of the transmitting and receiving antennas. Antenna orientations: parallel , perpendicular----, colinear.... . The site is on Skelton Glacier. (From Clough, 1974, unpublished)

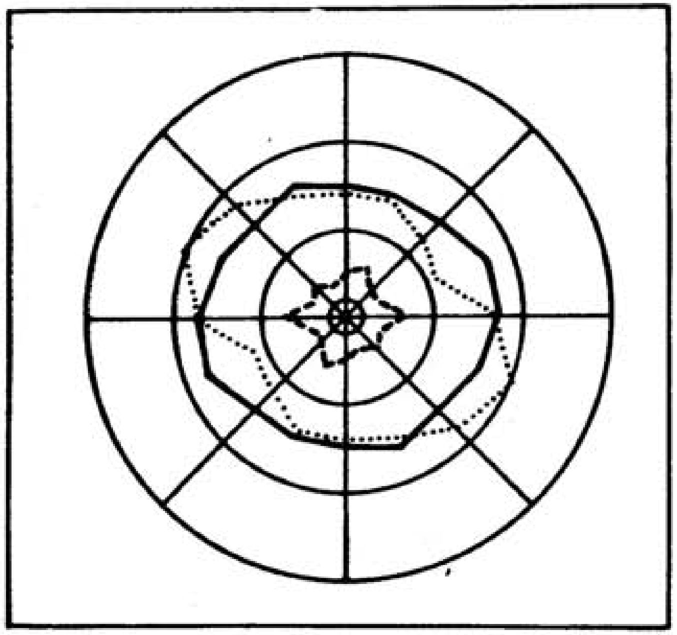


Figure 20b. Reflection amplitudes as a function of azimuth for different orientations of the transmitting and receiving antennas. Antenna orientations: parallel ——— , perpendicular ----, colinear ..... The site is on Skelton Inlet, a few kilometers downstream from the site of figure 20a. (From Clough, 1974, unpublished)

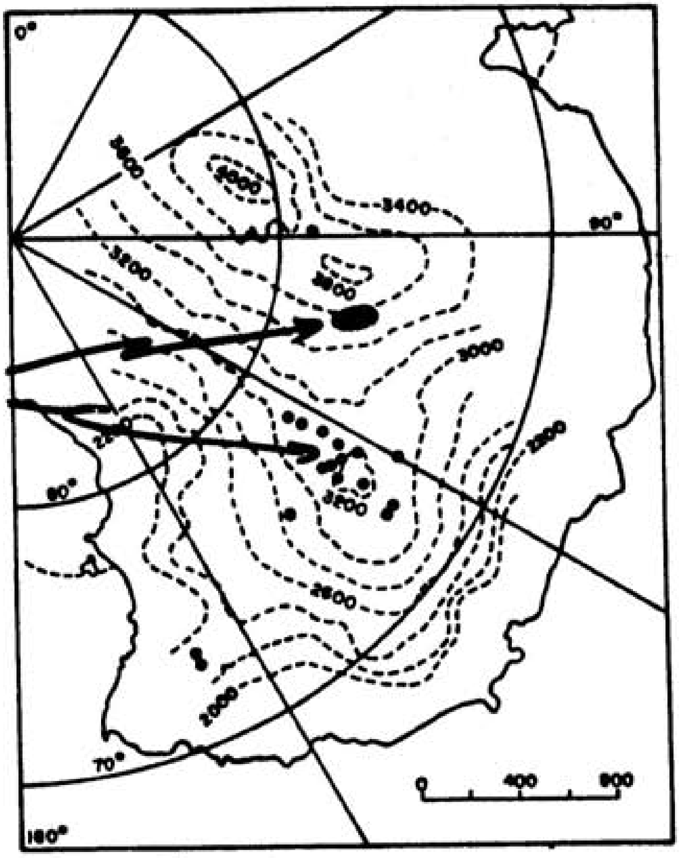


Figure 21a. Map of eastern East Antarctica, showing the locations of subglacial lakes identified by radar sounding. Small areas are shown as black dots; one large lake is also indicated in black. Contour lines show surface elevations. Lakes tend to occur beneath low surface slopes. (From Oswald and Robin, 1973)

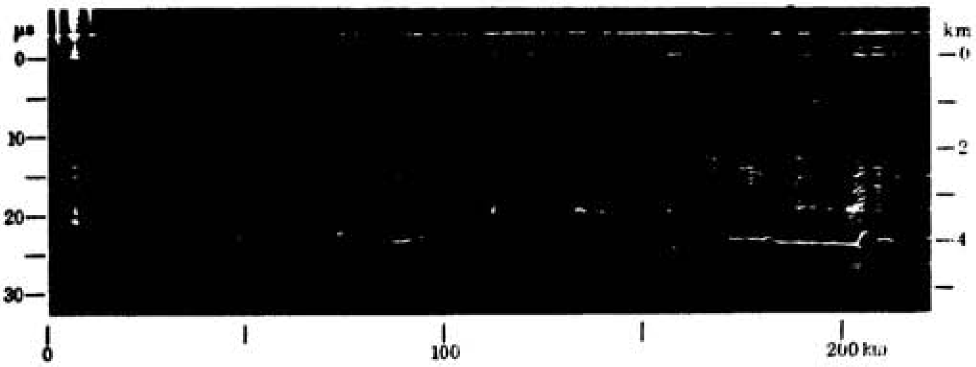


Figure 21b (bottom): Intensity-modulated profile of the large subglacial lake shown in the top figure. The zig-zag flight track crossed the lake twice, between 20 and 70 km, and between 170 and 200 km. (From Robin et al., 1977)

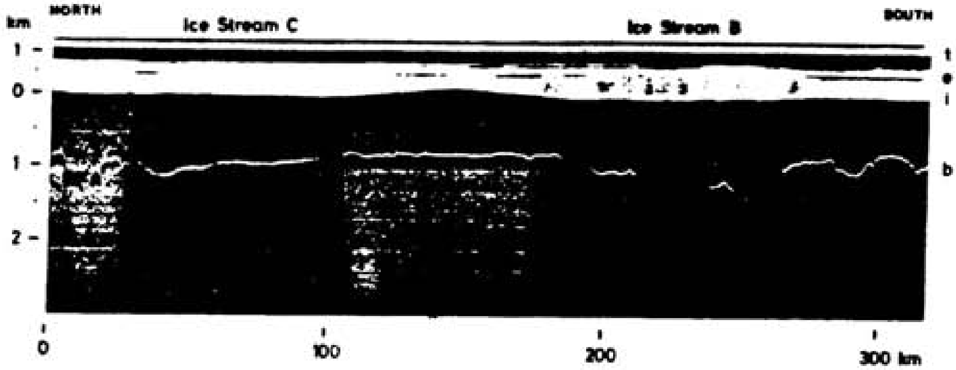


Figure 22. Intensity-modulated profile across two West Antarctic ice streams, a short distance east of the junction with the Ross Ice Shelf. (The actual flight line was from 81.7°S, 139°W to 84.5°S, 141°W) (From Rose, 1979)

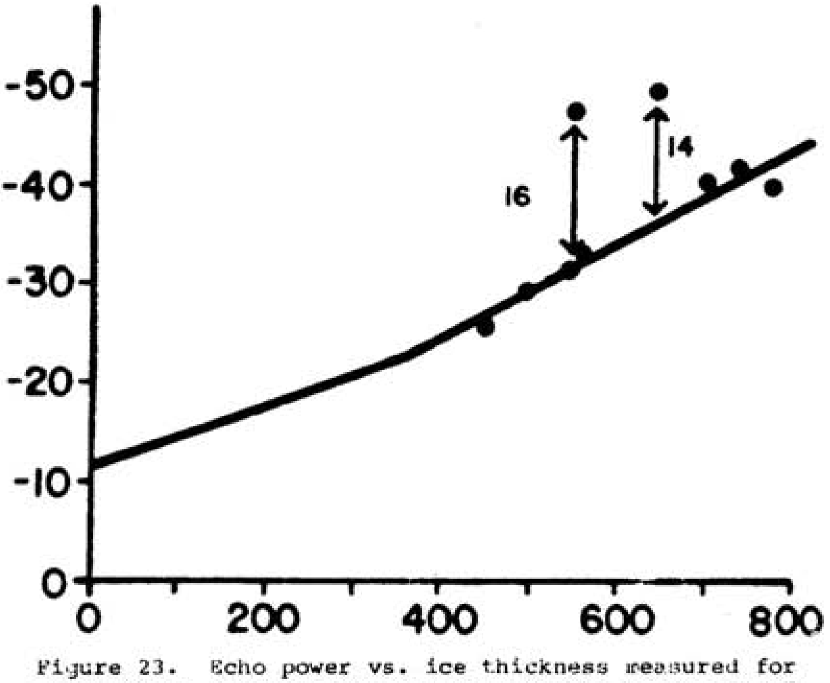


Figure 23. Echo power vs. ice thickness measured for reflections from the bedrock beneath the Devon Island ice cap (Canada). The echo power shown is the total attenuation relative to that in the case of no absorption or reflection losses. The two straight lines represent the expected absorption according to a model ice cap with a mean temperature of -20°C from the surface to a depth of 400 m, and a mean of -12°C from 400 m to the base at about 800 m. The intercept thus yields the measured reflection loss. (From Oswald, 1975)

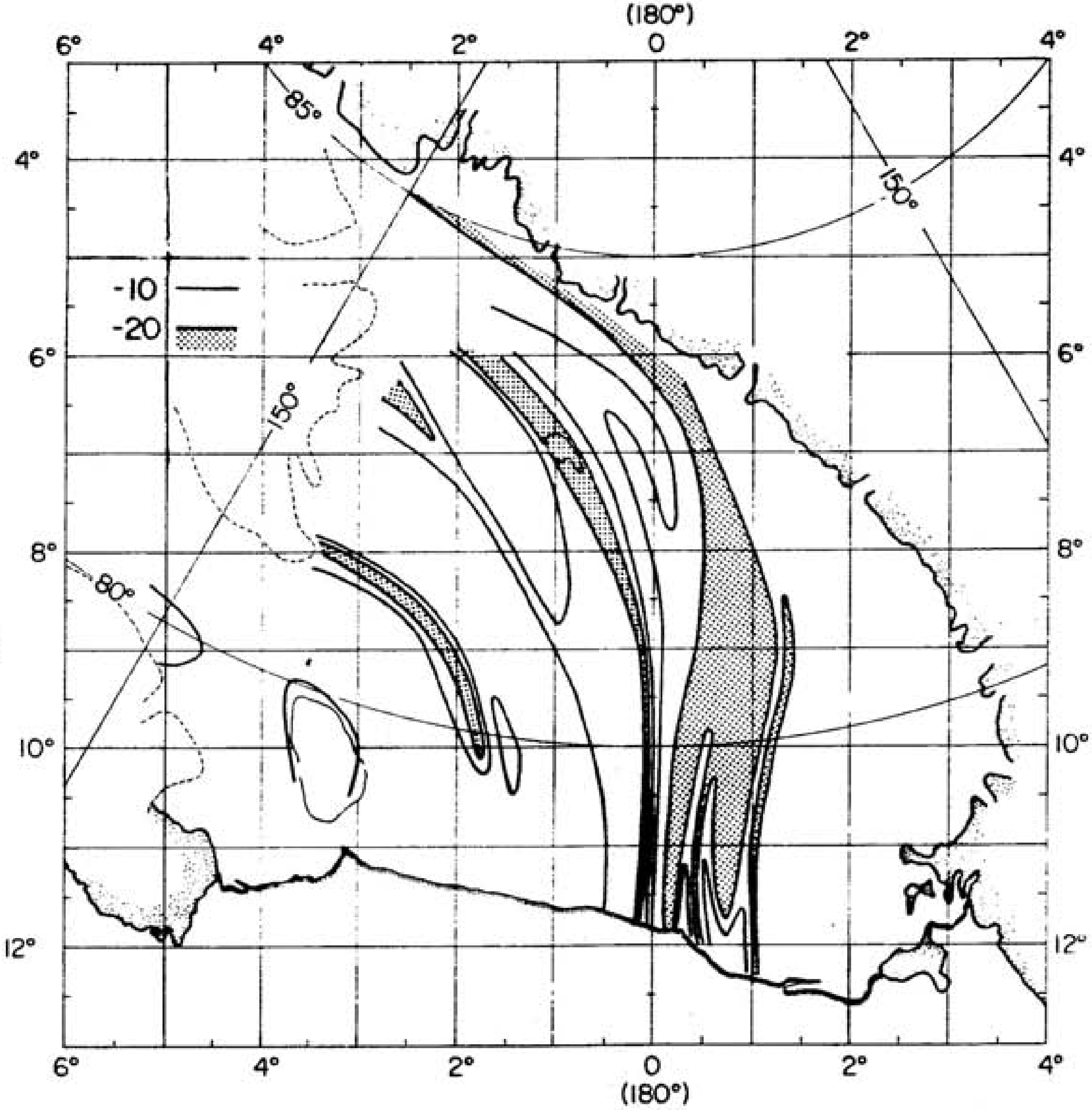


Figure 24. Map of the Ross Ice Shelf, showing contours of the reflection coefficient at the ice-water boundary. Shaded regions exhibit a reflection loss of >20 dB. The contour interval is 10 dB. (From Neal, 1979)

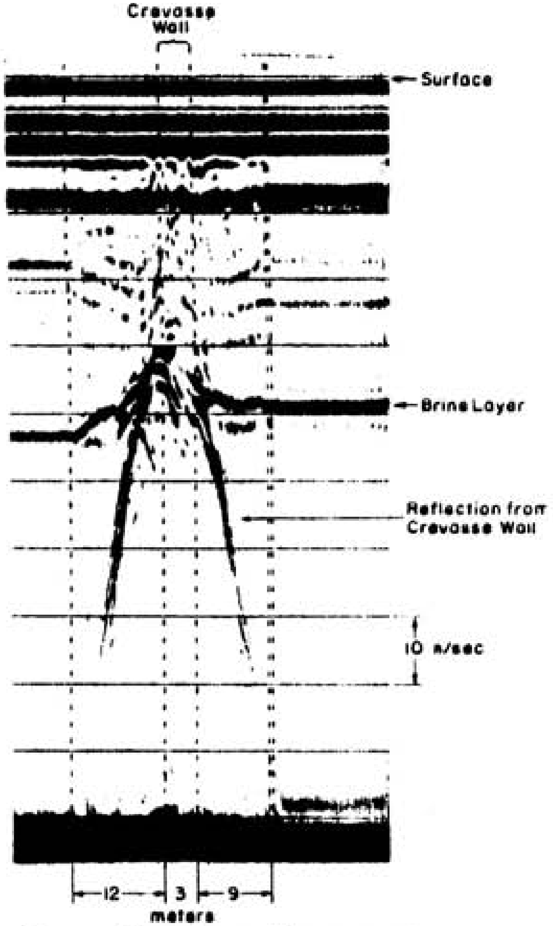


Figure 25. A graphic record of the reflected radar signal obtained with an impulse radar system when the antenna approached, passed over, and moved beyond a 3 meter-wide snow-bridged crevasse. The record also shows the echo from the well-known brine layer in the McMurdo Ice Shelf. (From Kovacs and Abele, 1974)

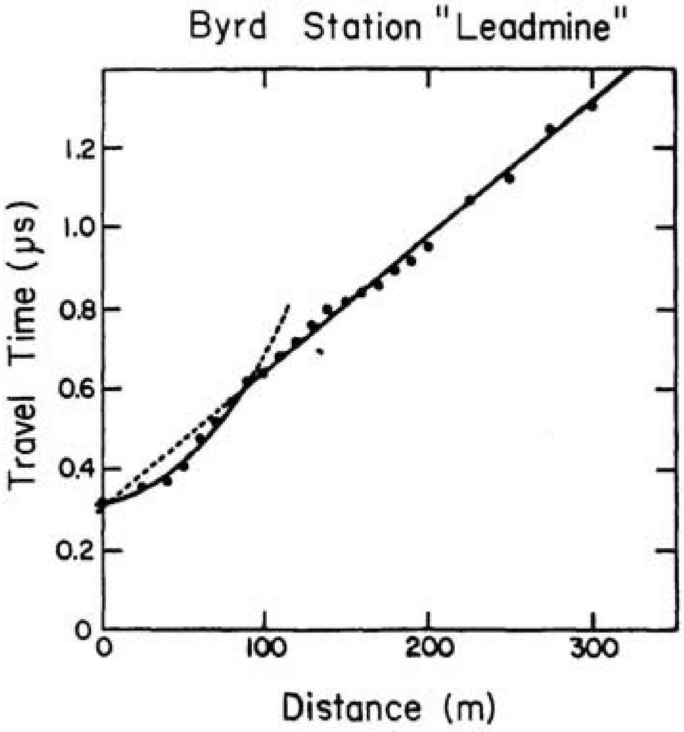


Figure 26. Travel-time plot for oblique propagation between the surface and a receiving antenna 42 m below the surface. (From Clough and Bentley, 1970)

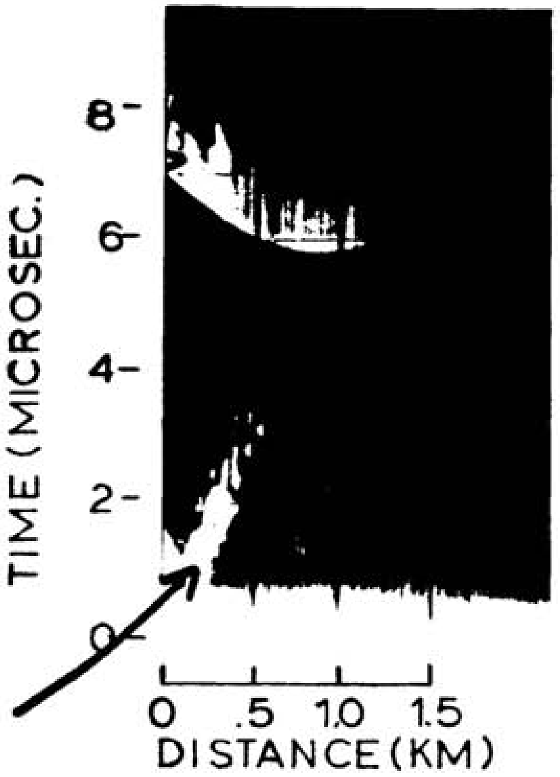


Figure 27. Reduced travel-time curve of oblique reflection profile, Ross Ice Shelf, Antarctica. Visible are the direct wave (bright line across the bottom of the figure), reflected wave, lateral wave (1.2 - 1.5 km, just below 6 μ s), and line formed from critical-angle internal reflections. (From Clough, 1976)

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Satellite Radar Altimetry

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The Ice Section of the Goddard Laboratory for Atmospheric Sciences (NASA/Goddard Space Flight Center) has been analyzing radar altimeter data over the polar ice sheets from Geos-3 and Seasat satellites. Extensive treatment of the raw data has been required to correct for a number of errors in the instrument measurements. The most important correction was to adjust the instrument's indicated range to the ice sheet surface to the true range by retiming the first return for each received waveform (10 per second). This range corresponds to the closest distance between the satellite and a 20 km diameter "beam-limited" footprint on the surface beneath the satellite. With an apparent groundspeed of 6.7 km/sec, the approximate distance between range measurements was 670 meters. Figure 1 illustrates the footprint of a satellite over an ice sheet environment. Over the three-year lifespan of Geos-3, (1975 to 1978), more than 83,000 elevation measurements were taken over the southern third of Greenland (up to 65°N). Seasat, at a higher inclined orbit, covered latitudes within ±72° and, although lasting only 100 days, made more than 90,000 measurements of Greenland and approximately 600,000 measurements of Antarctica. Figure 2 represents Seasat passes over southern Greenland. From these tracks, data were gathered which permitted the construction of surface contours as illustrated in figures 3 and 4.

After correcting for the errors mentioned above, the resulting elevations were accurate to ±1-2 meters (the larger errors applying to the regions of larger local slopes). These elevations were interpolated to a rectangular grid and contoured at a 50-meter interval for Greenland and a 100-meter interval for Antarctica. These data represent the most accurate maps of elevation for these regions. These data will become available as a NASA data base to be described in forthcoming NASA documents and will be distributed to the World Data Centers for Glaciology.

Extensive design analysis was conducted by NASA to achieve improved altimeter performance over ice sheets on future satellites, but no current plans exist within NASA for future space-borne radar altimeters in polar orbit. (The Geos and Seasat altimeters were designed for measuring ocean elevations and therefore frequently lost "track" over the undulating ice sheets causing gaps in the data.) Investigation of a satellite laser altimeter (Zwally, et al., 1981) also has been discussed because of the considerable advantages to be gained over the conventional radar altimeter for measuring ice-sheet topographies.

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Zwally, H.J.; Thomas, R.H.; Bindschadler, R.A. (1981) Ice sheet dynamics by satellite laser altimetry. U.S. National Aeronautics and Space Administration. NASA Technical Memorandum 82128.

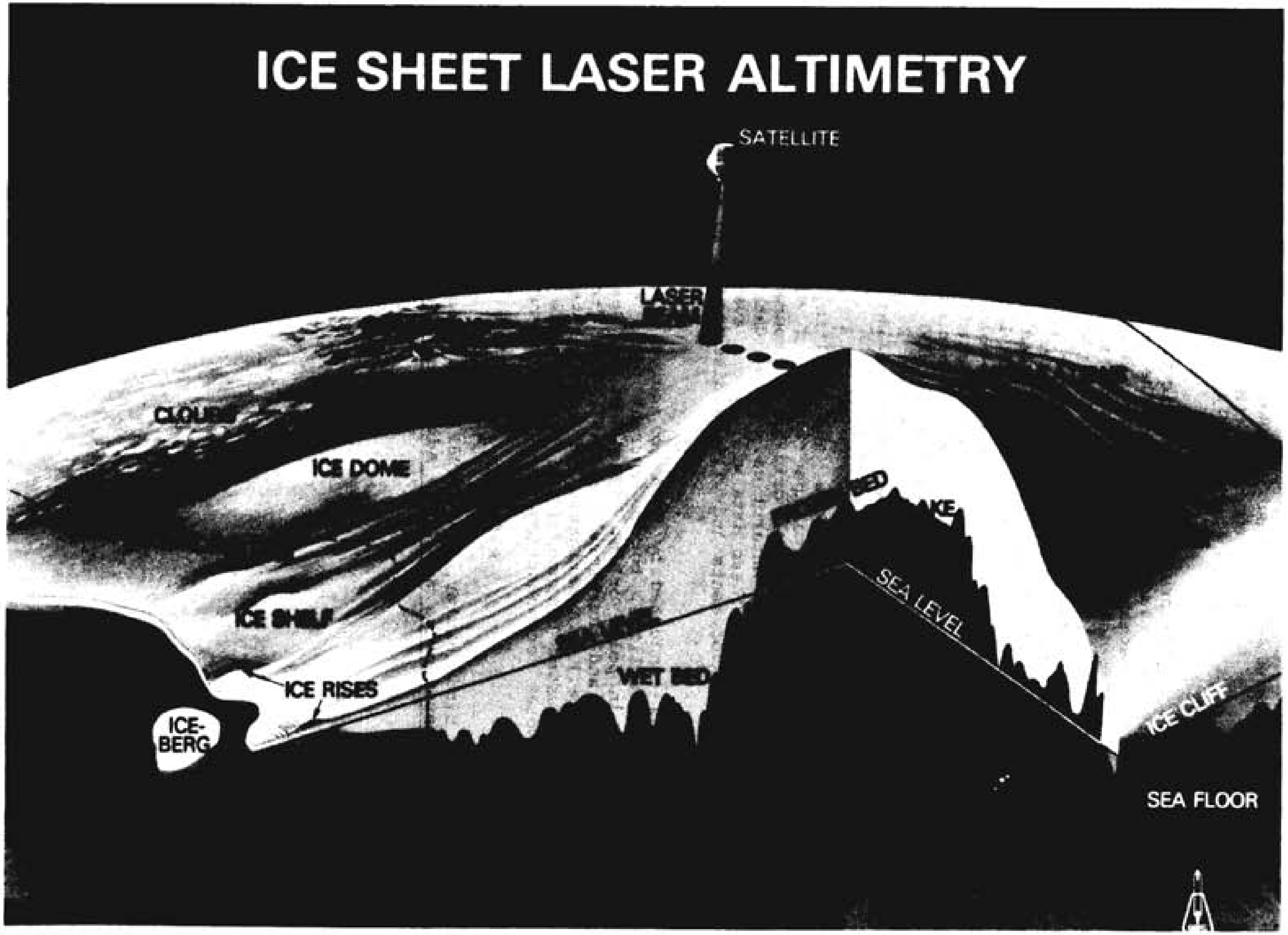

Figure 1. Specific features of ice sheets which could be measured by a laser altimeter.

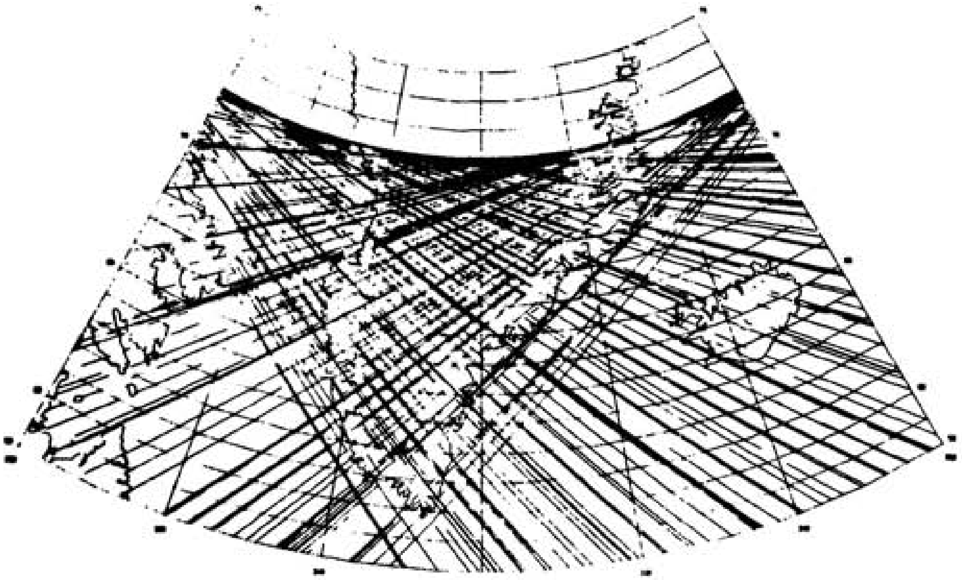

Figure 2. Seasat altimetry data over Greenland.

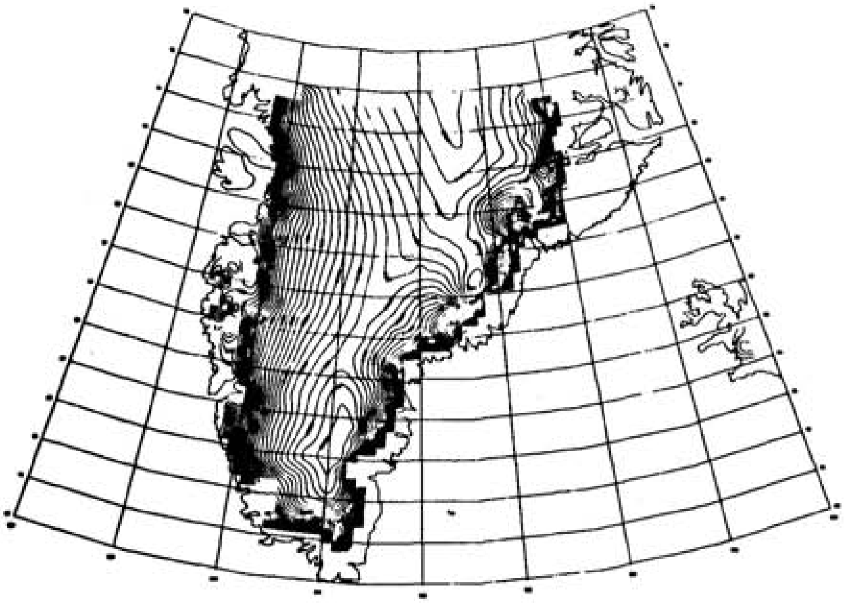

Figure 3. Greenland topographic map from retracked Seasat data.

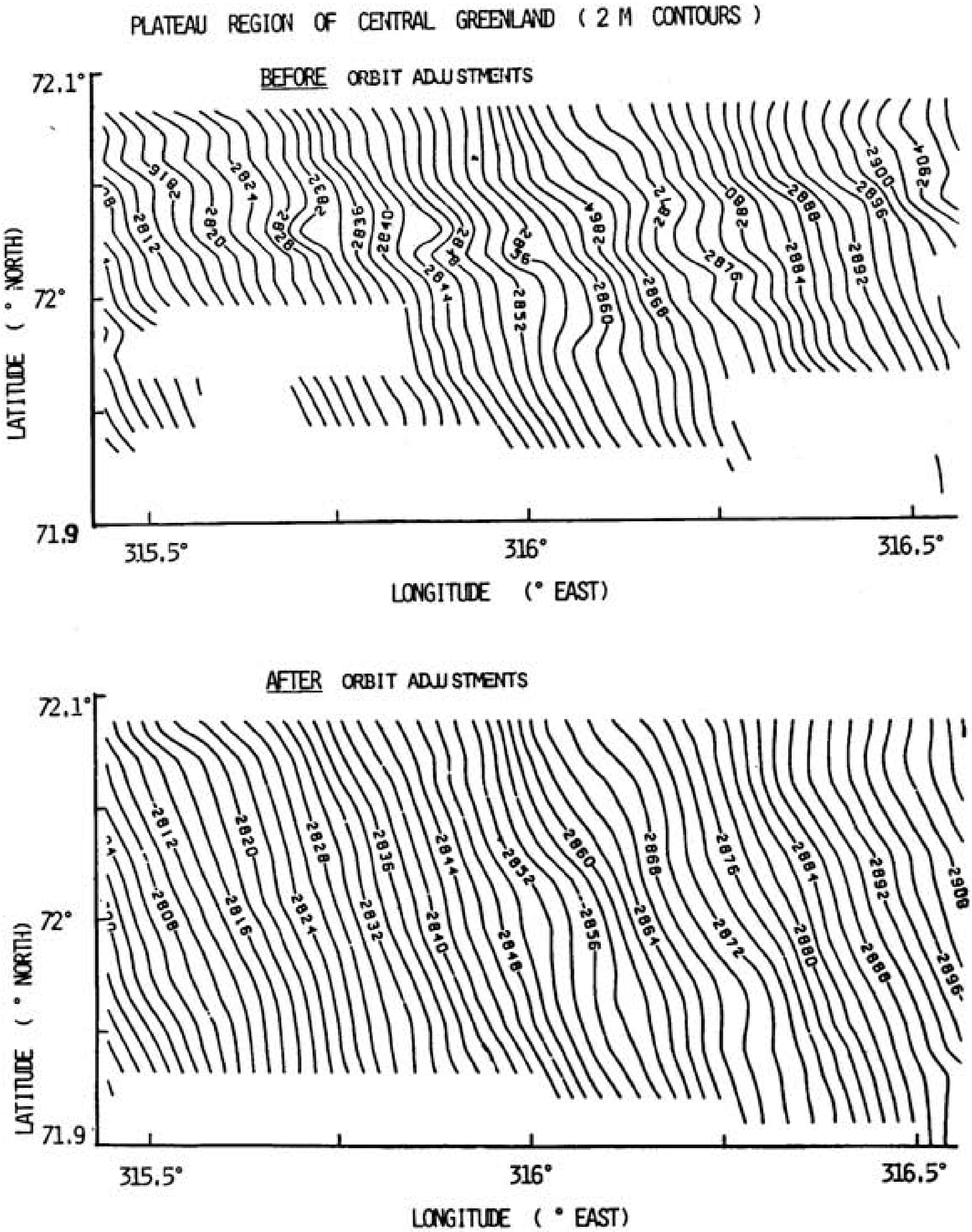

Figure 4. Contours of the plateau region of Greenland from Seasat data.

Radio Echo Sounding by the British Antarctic Survey

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Summary

The British Antarctic Survey has been engaged in airborne radio-echo sounding of the Antarctic Peninsula area since 1966 (Swithinbank, 1968, 1977, 1978; Evans et al., 1969; Smith, 1972; Swithinbank et al., 1976; Crabtree, 1981; Crabtree and Doake, in press). Throughout this period the principal objectives have been to outline the main features of the sub-glacial landscape over an area of about one million km^2, to identify problems of special glaciological interest, and to measure ice thicknesses wherever they were needed in support of experiments being made on the ground. Aircraft used have been ski-equipped DHC-3 Otter, Pilatus Turbo-Porter, and since 1970, DHC-7 Twin Otter.

Instruments used have been Scott Polar Research Institute Mark II (35 MHz), SPRI Mark IV (35 MHz), and currently a BAS-designed and BAS-built system (60 MHz) developed from the earlier models. Peak pulse power is about 500 W and overall system performance about 160 dB. Significant improvements in performance are limited chiefly by antenna size, which itself is constrained by the size and strength of the airframe. Navigation systems used have been magnetic compass and airspeed indicator, Litton 51 inertial, and Decca Doppler 71. A total of 467 flying hours have been devoted to the project.

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Soviet Studies of Mountain Glaciers by Airborne Radio Echo Sounding

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During the last ten years great progress in the study of the cold ice sheets of Antarctica and Greenland was achieved due to radar technology. However, the problem of radio echo sounding (RES) of mountain glaciers from aircraft has remained unsolved until now. The main causes of the problem are the more complicated structure and the higher mean temperature of the ice sequence of these glaciers, engendering greater absorption and scattering of electromagnetic energy, as well as the absence of effective equipment.

Since 1966, a number of institutions in the Soviet Union have been involved in searching for solutions to the equipment problem. The Department of Glaciology of the Institute of Geography, the USSR Academy of Sciences, is among them. Research is also being conducted in Great Britain, Canada, and the U.S.A. Standard 440 MHz equipment was applied in the USSR for RES of mountain glaciers at the beginning of these investigations. They were airborne radar altimeters of the RV-10 and RV-17 type with carrier frequency of 440 MHz and system performance of 130 dB. Similar equipment yielded good results in the coastal areas of the Antarctic and Greenland ice sheets, including valley glaciers with ice thickness up to 300-900 m (Bogorodskiy, 1968; Davis et al., 1973). However, ground and airborne studies on cold and especially, temperate glaciers of the Caucasus, Polar Urals, and Spitsbergen, with typical mean temperatures of the ice sequence ranging from -5°C up to melting point, demonstrated a number of essential drawbacks of this equipment (Macheret and Zhuravlev, 1980, 1981). The main defects are low spatial resolution and insufficient total system performance. They cause difficulties and ambiguity in the interpretation of obtained data and smaller sounding depth (usually not more than 150-250 m). Difficulties of interpretation are mainly connected with essential obscuring returns from internal inhomogeneities, abutting mountains, and the surface roughness which hamper and sometimes completely exclude the possibility of distinguishing useful returns from the bed and long internal boundaries. Interpretation becomes still more complicated if internal reflections and returns from surrounding mountains are registered over considerable areas, while reflections from the bedrock are recorded with large gaps.

Analysis of the obtained results has shown that in order to sound these glaciers to depths of 500-600 m and to diminish probability of the ambiguous interpretation, the total system performance of radar should be increased, to 185-195 dB and the beam width of antennas considerably narrowed, i.e. special equipment is required (Macheret and Zhuravlev, 1980).

This modified equipment was developed and constructed in 1976-1977 at the Polytechnical Insitute of Yoshkar-Ola on the Volga (Vasilenko et al., 1980; Macheret et al., 1980). The selection of the carrier frequency of the radar presents the main difficulty. In order to overcome this, experimental studies in the broad range of frequencies (150-930 MHz) with use of different types of antennas were undertaken on the glaciers of the Polar Urals and Spitsbergen.

Figure 1 shows the experimental relationship of the total attenuation of signals returned from the bed obtained on one of the Spitsbergen glaciers in the 430-740 MHz frequency range. Averaged values of the total attenuation (curve 3 in figure 1) grow considerably at frequencies of more than 620 MHz. A similar dependence was also obtained in the ablation area of the two temperate glaciers on the Polar Urals; however, the losses are higher.

These data enabled us to conclude that frequencies ≤620 MHz are preferable for RES of similar glaciers. Higher frequencies may be also used, but especially for the sounding of thinner glaciers, as well as for studies of the internal structure and regime of the upper sequence of glaciers. The latter conclusion was confirmed by our measurements on the same Spitsbergen glacier at frequencies of 786 and 865 MHz (Macheret et al., 1980). The maximum ice depth sounding at these frequencies with the system performance of the radar of about 120 dB made up 178 m and 163 m respectively. The possibility of using relatively high frequencies is supported by the recent report about the successful use of more powerful 840 MHz radar "UBC" for the sounding of small and middle-sized cold mountain glaciers in the Yukon Territory, Canada (Narod and Clarke, 1980). However, we also have information about the successful application of "Antarctic" SPRI MK-IV equipment with lower carrier frequency of 60 MHz for airborne RES of Spitsbergen glaciers (Drewry et al., 1980).

Various types of simple antennas were also tested on the Polar Ural glaciers. It was established that narrowing of the beam width in both planes considerably improves the quality of obtained results; while narrowing of the beam width in one of the planes proves inefficient if permanent observations with constantly orientated antennas are conducted near the steep slopes of a glacier.

One of the suitable kinds of antennas with a narrow axial-symmetric beam width and high forward gain is a multicomponent antenna grid. Calculations have shown that the grid, consisting of 16 elements of the "triple square" type, at 600 MHz frequency will have a beam width of 18°, coefficient of forward gain of about 18 dB, and the dimensions of 1.5x5x0.3m, which makes it possible to mount it under the fuselage of a helicopter.

Field tests of the working model of the 620 MHz-airborne equipment with 16-element antenna grid were undertaken on the Spitsbergen glaciers in 1977 (Macheret et al., 1980). The tests showed that similar equipment is quite efficient for airborne RES of mountain glaciers.

In 1978-1979, the improved airborne equipment RLS-620 with carrier frequency of 620 MHz (figure 2) was worked out and applied to airborne RES of Spitsbergen glaciers. The basic parameters of this equipment are presented in table 1. The parameters of the 440-MHz standard equipment and Canadian 840 MHz-equipment "UBC" are also given.

The use of RLS-620 equipment made it possible to increase the depth of Spitsbergen glaciers' sounding up to two to three times as compared to the standard 440 MHz equipment, and to receive good records of returned signals (Kotlyakov et al., 1980). Figure 3 presents an example of a record obtained on the Veteranen glacier when the returns were registered on the evenly moving film from the screen of the oscilloscope (Z-record). As can be seen from the figure, reflections from the bed were obtained nearly continuously along the whole glacier when the flight altitude was 300 m. Reflections from the bottom were also obtained on the majority of the other studied glaciers of the mountain, "reticulated"[1] (Spitsbergen) and ice-sheet types[2] with different sizes and temperature conditions. On 75 of the 87 glaciers studied, i.e. 85 percent of them, observations were made over 40 to 100 percent of glaciers' length. Returns from the bottom were not obtained mainly in the accumulation areas of large glaciers of the "reticulated" type situated in the western, central, and southern parts of Spitsbergen, where the existence of areas with wet firn layers and "warm" glacier ice, as well as with considerable ice thickness, are assumed. Internal reflections were registered on a number of glaciers. Flight routes over the glaciers and some results of the airborne RES of Spitsbergen glaciers of various types are shown in figures 4, 5, 6, 7, and 8. Maximum ice thicknesses of 500-540 m were measured on the Veteranen and Mittag-Leffler glaciers. Very close coincidence of airborne RES results with data of borehole and seismic measurements and considerable differences with data of gravity measurements are also shown in figures 5, 6, and 8.

As the glaciers of mountain and "reticulated" types are similar in structure and temperate conditions to glaciers typical of the majority of the glacierized areas of the temperate belt, the available results show that the majority of cold mountain glaciers in these areas can be sounded successfully with the help of similar equipment. It is noteworthy that good results were also obtained on the cold mountain glaciers of Alaska, 200 to 400 m thick, with the help of the 840 MHz Canadian instruments. However, these flights were undertaken at lower altitudes, below 50 m. In some cases, these measurements are impossible on other glaciers. The problem of airborne RES of temperate glaciers, especially of their accumulation areas, still remains unsolved, though efficient special equipment, working at 620 MHz and 2-10 MHz frequencies has been already developed in a number of countries (Goodman, 1975; Sverrisson et al., 1980). However, their antennas are large and this makes it difficult to apply this equipment to RES from helicopters. Nevertheless, it was recently reported about successful applications of similar low frequency equipment, mounted on light aircraft for RES of glaciers in Alaska (Watts and Wright, 1981).

We consider our next task to conduct RES on many mountain glaciers of the USSR. This is necessary for the calculation of ice storage, in addition to the already accomplished Glacier Inventory of the USSR. These studies were begun in 1981 in Zailiysky Alatau and Dzungarsky Alatau where more than 100 glaciers were successfully sounded from helicopter using the RLS-620 equipment.

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[1] Ice fields with many nunataks: the transitional form between mountain glaciers and ice sheets.

[2] We use the morphological classification of Spitsbergen glaciers assigned Troitskiy et al. (1975).

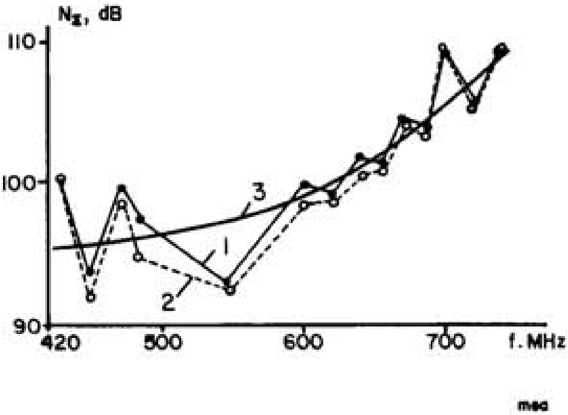

Figure 1. Dependence of the total attenuation N_Σ of signals reflected from the bed upon frequency f. Measurements on the ice divide of glaciers Austre Gronfjordbreen and Fridtjovbreen, Spitsbergen, 1977. 1 and 2 - data of measurements of the maximum amplitudes of reflected signals observed at every fixed frequency by small shifting of the measuring installation and by rotating the receiving antenna in the horizontal plane; 3 - the curve obtained by the averaging of experimental data.

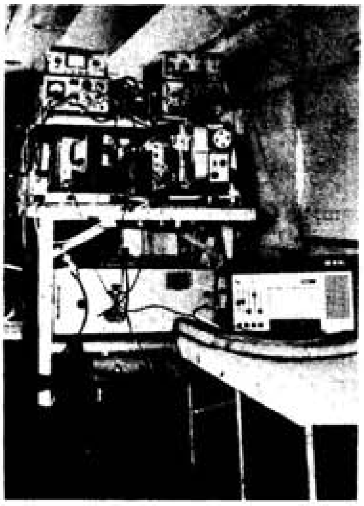

Figure 2. The airborne equipment RLC-620 on board helicopter Mi-8.

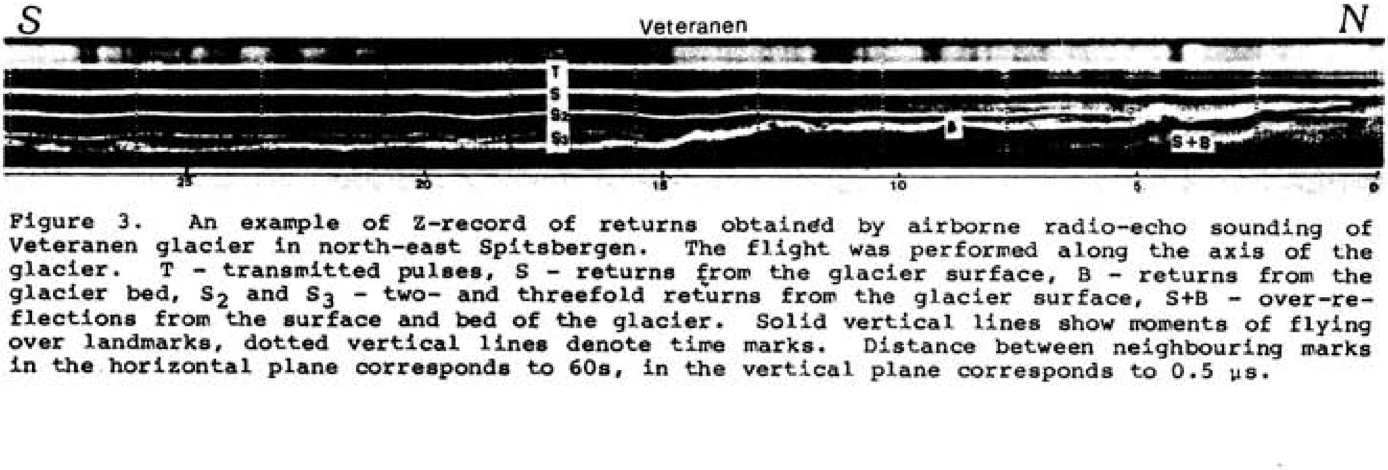

Figure 3. An example of Z-record of returns obtained by airborne radio-echo sounding of Veteranen glacier in north-east Spitsbergen. The flight was performed along the axis of the glacier. T - transmitted pulses, S - returns from the glacier surface, B - returns from the glacier bed, S_2 and S_3 - two- and threefold returns from the glacier surface, S+B - over-reflections from the surface and bed of the glacier. Solid vertical lines show moments of flying over landmarks, dotted vertical lines denote time marks. Distance between neighbouring marks in the horizontal plane corresponds to 60s, in the vertical plane corresponds to 0.5 μs.

Table 1. Basic parameters of the equipment for airborne radio echo soundings of mountain glaciers.

Parameter	Equipment		
	RV-10, RV-17	RLS-620	UBC
<u>Transmitter</u>			
Carrier frequency/MHz	440	620	840
Pulse length/micro sec	0.5	0.1-1.0	0.05
Power/watt	7	820	4100
<u>Receiver</u>			
Bandwidth/MHz	6	15	40
<u>Receiver-Transmitter</u>			
System performance/dB	130	146	124
<u>Antennas</u>			
Construction	Two half-wave vibrators with flat reflector	Antenna-grid of 16 elements (of the "triple square" type) with flat reflector	Two dipole collinear collinear array with a third parasitic element and 90° corner reflector
Beamwidth (at half power)			
in E-plane	100°	18°	18°
in H-plane			44°
Forward gain (in one direction), dB	2	19.5	15.5
<u>Radar</u>			
Total system performance/dB	134	185	155

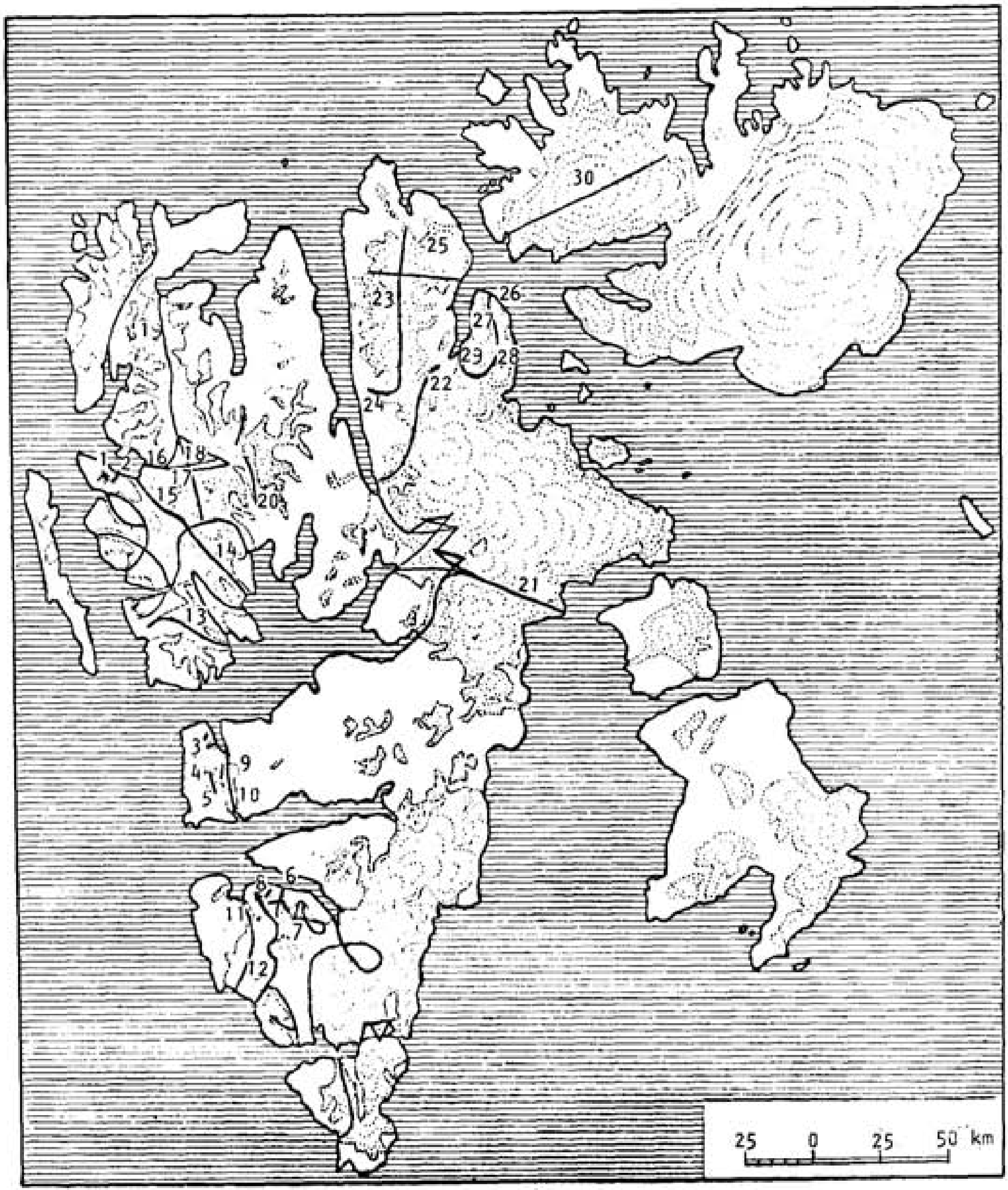

Figure 4. Radio-echo sounding of Svalbard glaciers during 1974-1975 and 1977-1979 field seasons. Lines show the routes of the airborne radio-echo soundings. The figures denote the glaciers whose profiles are shown in figures 5, 6, 7 and 8.

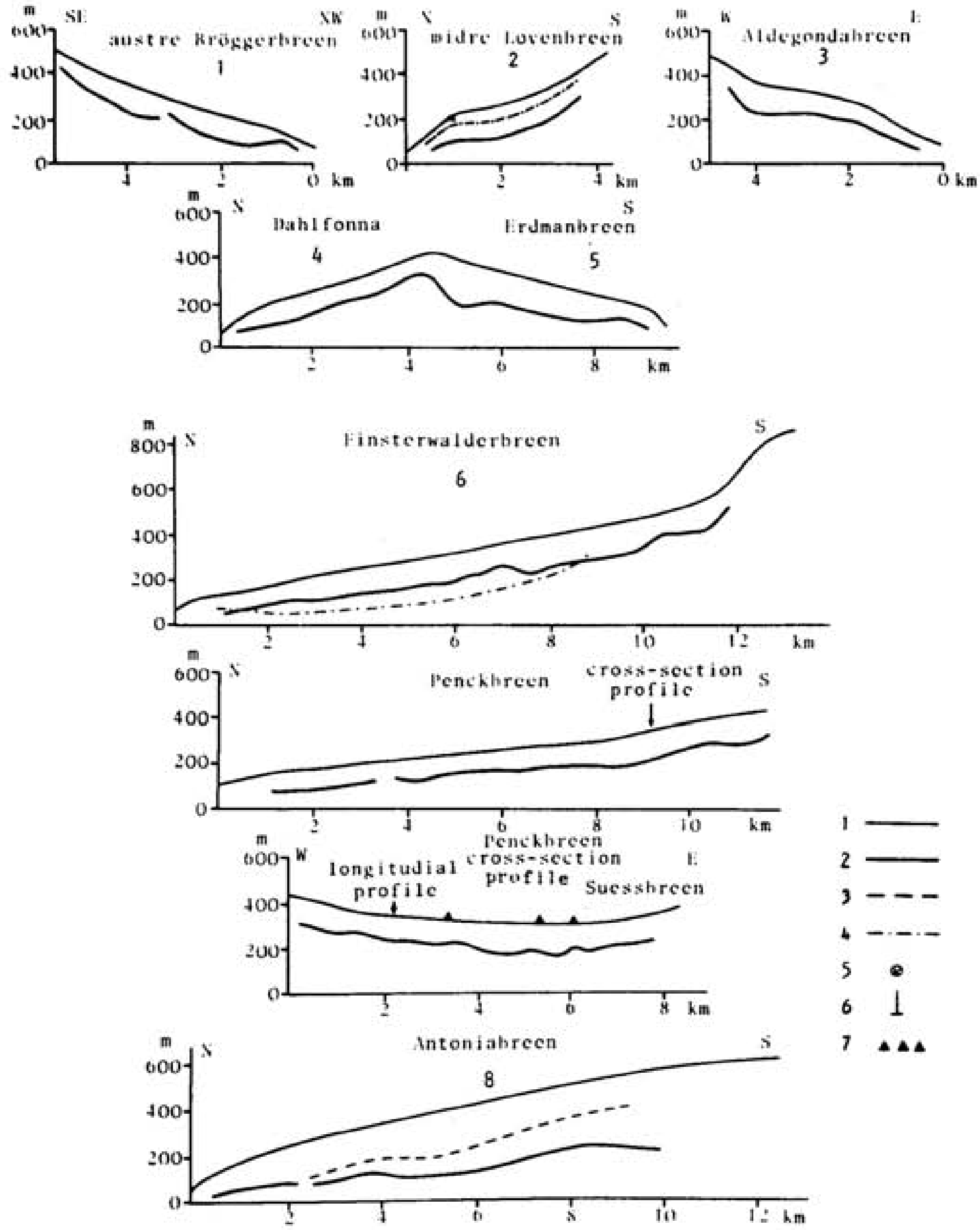

Figure 5. Profiles of typical mountain glaciers on Spitsbergen by airborne radio-echo sounding data. 1 - the glacier surface, 2 and 3 - the glacier bed and internal reflecting boundary by the airborne radio echo sounding, 4 - the glacier bed by gravity measurements on the glaciers Midre Lovenbreen and Kongsvegen in 1964 and Finsberwalderbreen in 1961, 5 - the glacier bed from seismic shooting by the Swedish expedition in 1958, 6 - the thermoboring bore holes, 7 - the medial moraines.

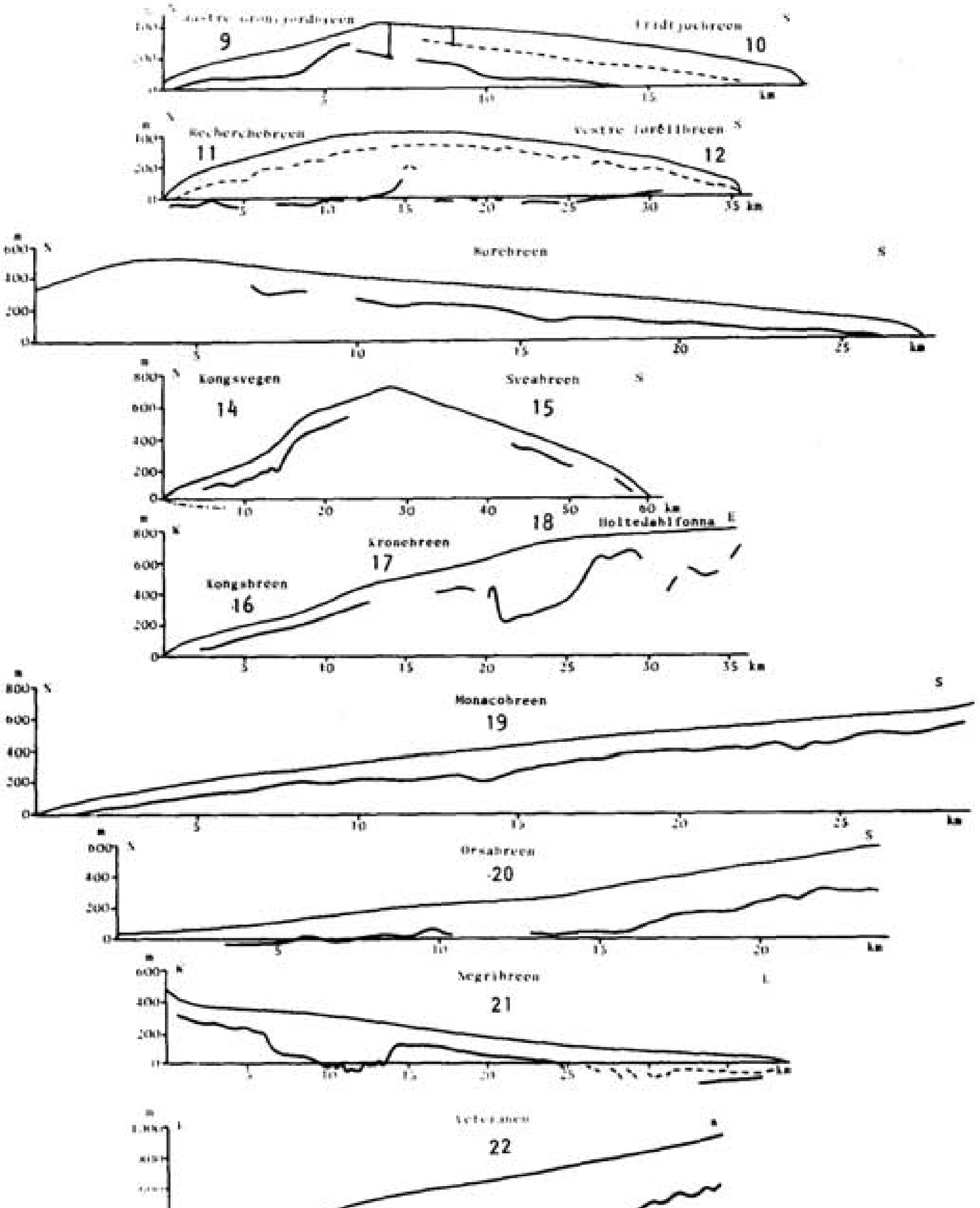

Figure 6. Profiles of typical "reticulated" glaciers on Spitsbergen occupying negative land forms by the airborne radio-echo sounding data. Key as in figure 5.

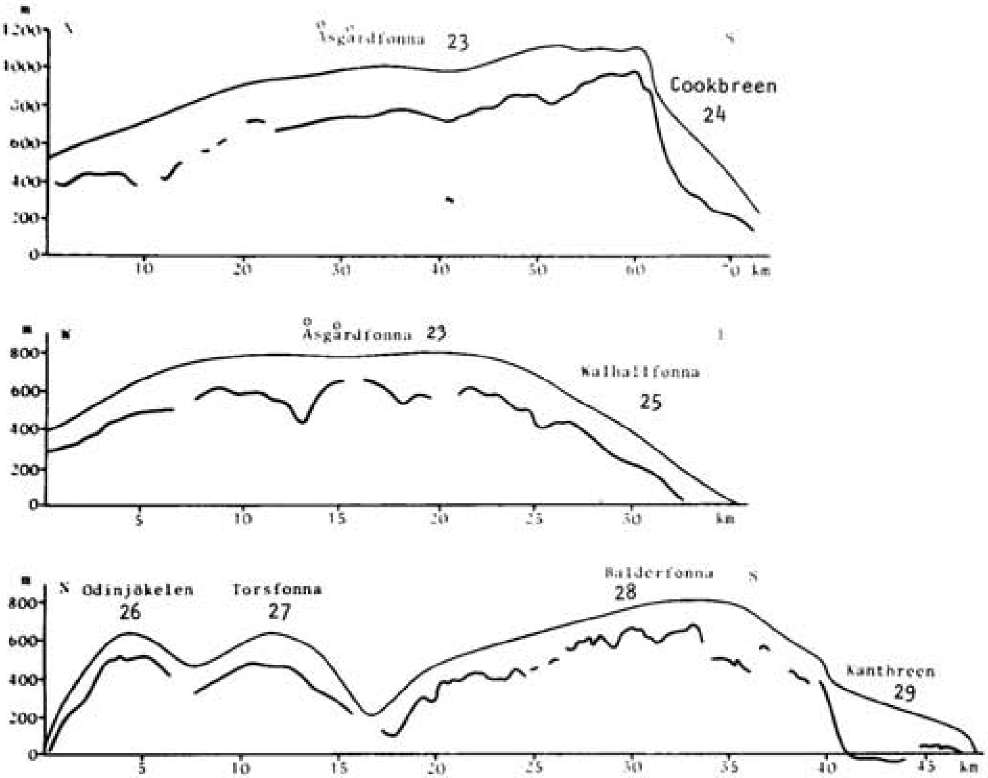

Figure 7. Profiles of typical "reticulated" glaciers on Spitsbergen occupying positive land forms by the airborne radio-echo sounding. Key as in figure 5.

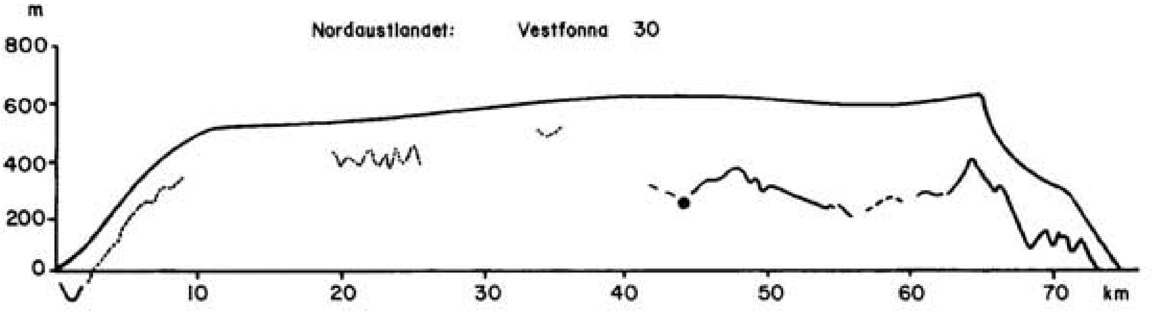

Figure 8. Profile of the Vestfonna on Nordaustlandet ice cap by the airborne radio-echo sounding. Key as in figure 5.

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A Data Base Structure for Radio Echo Sounding Results

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Since 1971, Scott Polar Research Institute has participated with the U.S. National Science Foundation and since 1974 in collaboration with the Technical University of Denmark, in four Antarctic field seasons. Digitization and data reduction processing have produced approximately 250,000 points at which some measurement has been made. To handle these data efficiently, a data base structure was evolved for use on an IBM 370/165 computer. The data base is a large direct-access file, with the size of each block chosen for efficient I/O operation, and to maximize the density of data in the file. In this type of file, the basic unit for I/O operations is the block, rather than the record. Data are written in binary to further increase efficiency and packing density. The first block in the file consists of a directory (figure 1), which holds a list of flight numbers, and indicates the blocks which hold data for that flight, thus enabling the information for any flight to be readily accessed. Within each flight, data are organized in increasing time/distance order, which allows specified points within a flight to be rapidly accessed using simple search techniques.

The use of this structure has greatly increased the efficiency of certain common procedures. For example, CPU time required to plot a profile along a given flight has been reduced from minutes to seconds. Other operations, which could not be considered previously because of CPU time contraints are now practicable.

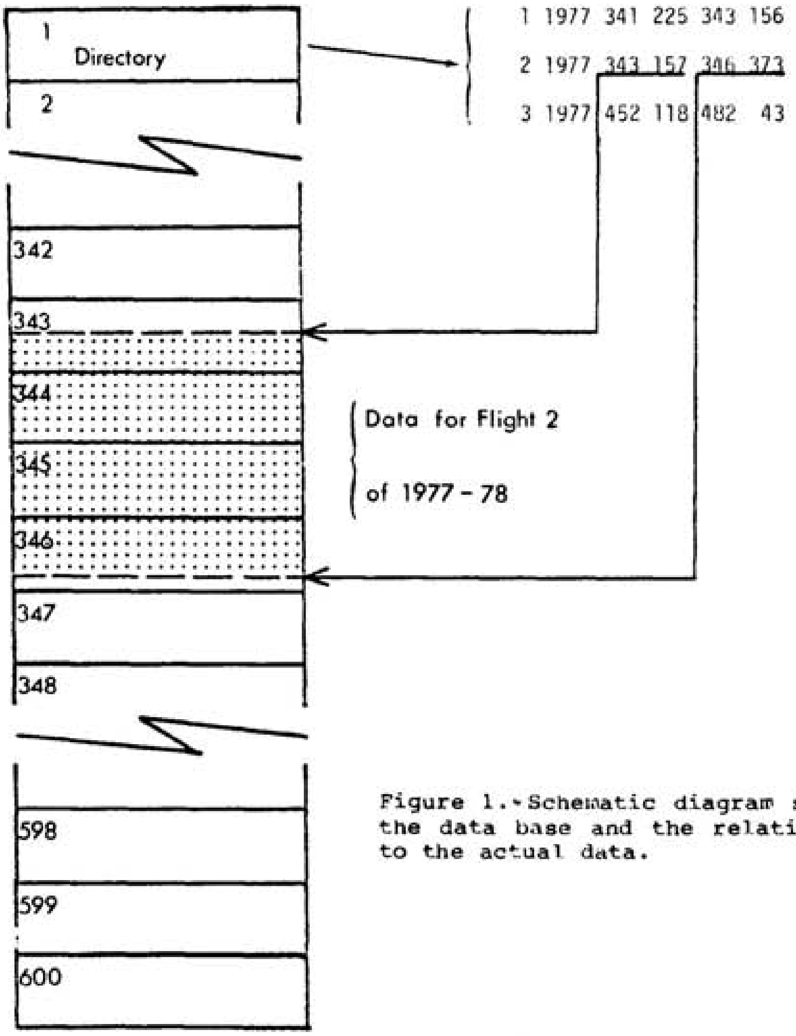

Figure 1.- Schematic diagram showing the structure of the data base and the relationship of the directory to the actual data.

Radio Echo Sounding by the Japanese Antarctic Research Expedition

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The Japanese Antarctic Research Expeditions (JARE) began to survey ice thickness by means of radio echo sounding in the Mizuho Plateau area of East Antarctica in 1969. The instrument used for these measurements was a SPRI MK-II radio echo sounder. Basically, the instrument was a standard ranging system with a 35 MHz transmitter and receiver equipped with an oscilloscope for reading echo times. The transmitter produced 500 W peak power. Separate antennas for transmitting and receiving were properly selected from a folded-dipole of 0.7 wavelength, a 4-wire half-wave dipole, or 3-element Yagi, depending upon the conditions of the ice sheet during the 1969/70 season. A 3-element Yagi was used during the 1973/74 field season as a common antenna for transmitting and receiving.

From 1969 to 1974 radio echo soundings were carried out along traverse routes totalling a distance of 1,500 km. Throughout this period, the soundings were made from an oversnow vehicle during stops on glaciological traverses. The collection of continuous ice thickness data over a wide area was difficult logistically and only limited data resulted.

In 1978 a new radio echo sounder (NIPR-V) was developed by the National Institute of Polar Research. This sounder was used on the traverse route between Syowa and Mizuho Stations in 1979. Also in 1979, another new radio echo sounder (NIPR-A) was developed. This sounder, built for airborne use, was installed in a Pilatus Porter PC-6 aircraft. The carrier frequency of NIPR-A is 179 MHz and that of NIPR-V is 60 MHz. The other specifications of these sounders are the same. The peak power is about 1 kW, and pulse width is 0.3 μs. Both 35-mm z-mode and A-scope recording systems are used. The A-scope system uses a steel Polaroid camera.

In 1980, airborne surveys were carried out along the previous survey routes, between Syowa and Mizuho Stations, in the Yamato Mountains area, and on the Shirase Glacier and its drainage basin. In the Yamato Mountains area, several glaciological and geological surveys have been carried out since 1969. The discovery of meteorites in the blue-ice area near the Yamato Mountains has prompted numerous studies to attempt to understand the concentration mechanism of meteorites. The survey of the area was carried out in support of these studies. Up to the 1979/80 season, some 4000 pieces of meteorites have been studied. The Shirase Glacier has a drainage area of 200,000 km^2. This is the main outlet of the Mizuho Plateau. The average thickness of the ice in the drainage basin is 1840 m, with a total estimated volume of 370,000 km^3.

Along the traverse route between Syowa and Mizuho Stations, the airborne sounding compared well with the more detailed bedrock topography identified by the surface traverse data. An A-scope ground-based record obtained with the 60 MHz sounder showed the deepest echo along this traverse. However, the continuous records along the traverse did not show echoes from more than 2000 m depth. On the other hand, results from the 179 MHz airborne sounder did not show echoes from more than 1500 m depth. No bedrock echoes were received on any of the equipment in an area near the Mizuho Station. It might also be pointed out that experiments with differences in transmit and receive antenna alignments at Mizuho Station indicate a polarization effect in the intensity of returned echoes.

In the Yamato Mountains area, two 80 km long North-South flights and three East-West flights, totaling 400 km, were surveyed. The presence of many nunataks below the surface of the ice sheet near the Yamato Mountains area was revealed. The surface of the eastern side of the Yamato Mountains is about 500 m higher than that of the western side. Furthermore, the elevation of the western sub-ice mountains near the 35°20'E longitude line is less than 1000 m, whereas the elevation of the eastern sub-ice mountains is more than 1500 m.

The position of the aircraft was determined by terrestrial navigation. The flights were planned to pass over as many known sites on nunataks or exposed rocks while keeping a constant altitude and speed. The errors in position are estimated to be less than 3 km in the direction of flight and less than 1 km perpendicular to the flight line.

Airborne surveys of the Shirase glacier were cluttered by echoes from crevasses and cracks on the surface. It was noted that there was a slow decrease in the echo intensity with travel time throughout the basin. This was typical of the region. Some 500 km of flight lines were flown.

Based on results to date, JARE plans to continue radio echo sounding as follows:

1. airborne surveys in a wider area near the Yamato Mountains and the Shirase Glacier drainage basin;

2. more detailed surface traverses in special interest areas, such as the Motoi Nunatak where many meteorites have been found; and

3. experiments in echo intensity from depolarized waves along traverse routes.

Investigation of Sub-Glacial Bedrock from Radio Echo Sounding and Allied Geophysical Techniques

(Extended Abstract)

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Interpretation of the gross geological composition of sub-glacial bedrock can be based upon four principal factors:

1. Bedrock topographic maps and profiles compiled from reduced radio echo sounding (RES) surveys define the major relief regions. An example of such results is given from East Antarctica in figures 1 and 2.

2. Numerical description of terrain roughness taken from RES profiling (deconvoluted where appropriate). The scale of this analysis is such as to lie between the region Berry terms "geography" (i.e. the bedrock surface smoothed at scales equivalent to the height of the radar above the bed) and "roughness" (departures from the geographic surface down to about a tenth of the radio wavelength). Such statistical parameterization allows differentiation of "terrain roughness." Techniques include the use of simple bulk statistical descriptors (four moments of frequency distribution), autocorrelation and spectral analysis, and filter processing. An example of terrain differentiation from East Antarctica is given in figure 3. "Terrain fabrics" can be calculated by considering surface derivatives in two or more different directions, which yield information on lineation or structural grain of the sub-glacial surface as shown in figure 4.

Figure 1. Contour map of subglacial bedrock relief in East Antarctica. (From Steed and Drewry, 1982)

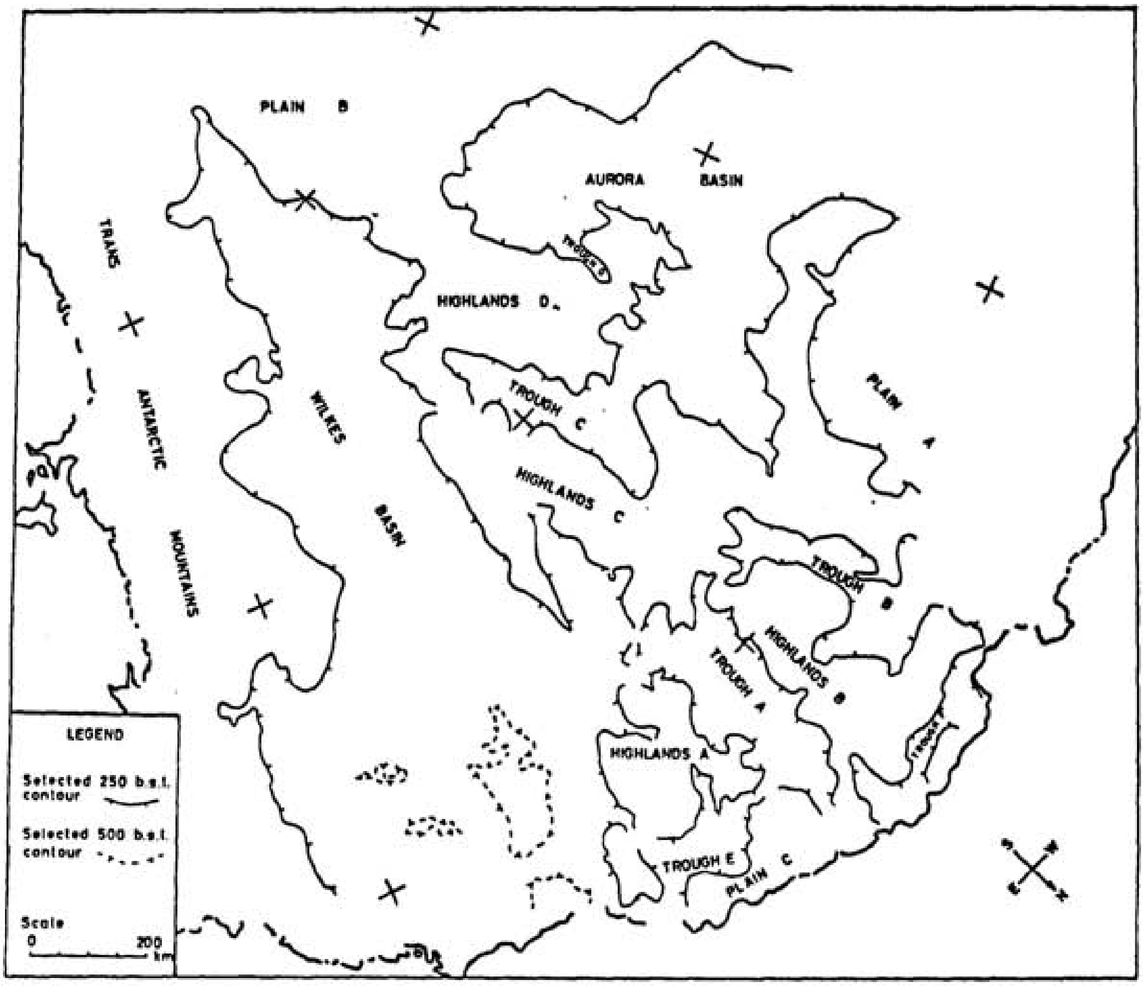

Figure 2. Major relief regions in East Antarctica. (From Steed, 1981; Steed and Drewry, 1982)

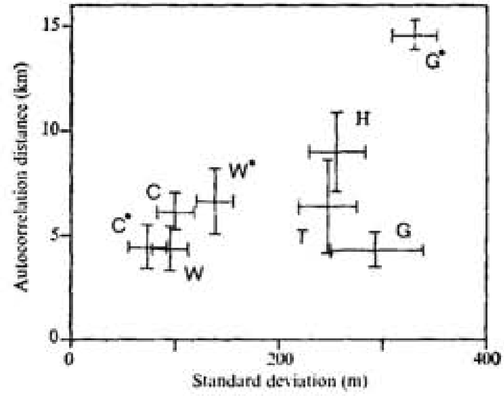

Fig. 3. Average terrain roughness characteristics of topographic units of eastern Antarctica. Bars indicate root mean squares of measurements. G and G*, Gamburtsev Mountains; H, central massif in eastern Antarctica; T, Transantarctic Mountains; W, central portion of Wilkes Basin; W*, marginal zones of Wilkes Basin; C*, northerly portion of central eastern Antarctic Basin; C, southerly portion of central eastern Antarctic Basin.

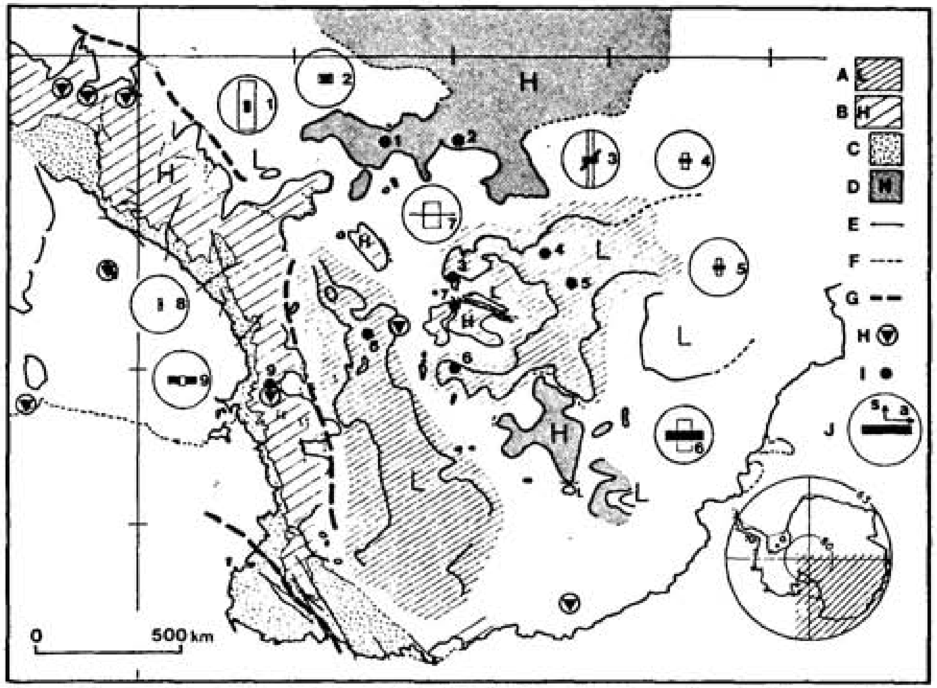

Figure 4. Geological elements of East Antarctica, principally from radio echo sounding. A, sedimentary basins (the included contour is − 500 m a.s.l.; L, low); B, areas of Beacon Supergroup strata, exposed or inferred from radio echo sounding (the bounding contour is + 250 m a.s.l.; H, high); C, exposures of granitic and metamorphic basement of the Transantarctic Mountains; D, undifferentiated highland (areas above + 250 m a.s.l.; H, high); E, faults detected from surface investigations; F, faults inferred from radio echo soundings; G, inferred boundaries of orogens; H, location of significant seismic refraction profiles; I, location of terrain fabric studies (numbers correspond to fabric diagrams given under J); J, fabric diagrams at numbered localities (I). Autocorrelation distance (a) and standard deviation (s) of elevations were determined in two orthogonal directions (or more), open lines, grid north-south direction; solid lines, grid east-west direction. The length of lines corresponds to the autocorrelation distance (a = 20 km). The thickness corresponds to value of standard deviation (s = 300 m).

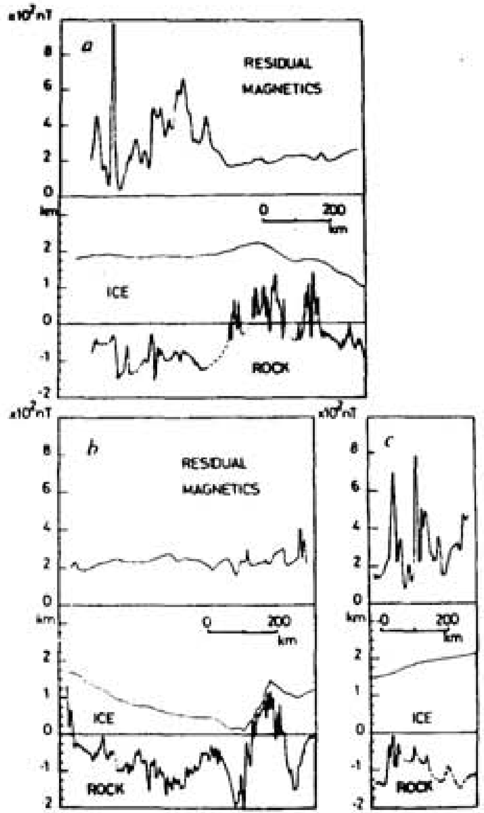

Fig. 5. RES and magnetic profiles in West Antarctica. *a*, Boundary between Byrd Subglacial Basin and Ellsworth Mountains block. *b*, Bedrock low at head of Ronne–Filchner Ice Shelf. *c*, Sinuous ridge cutting across Byrd Subglacial Basin.

3. Radio reflexion characteristics. Analyses of the returned radio signal power allow estimates of reflexion strengths to be made from the sub-glacial surface. Reflexion strength is related to both micro-scale bed roughness and its dielectrical properties. Variations in reflection coefficients when calculated at closely spaced intervals (i.e. approximately 0.5-1.0 km) should relate to changes in bedrock composition rather than uncertainties in dielectric absorption in ice and loss due to geometrical factors. Table 1 shows differences between the mean value of the power reflexion coefficient between adjacent terrain regions in East Antarctica, principally between the Wilkes and Aurora Basins and their margins.

Table 1. Difference in mean radio power reflection coefficients between basins and adjacent areas in East Antarctica.

		Difference in dB
1	Eastern margin of Wilkes Basin and central Wilkes Basin	9
2	Western margin of Wilkes Basin and central Wilkes Basin	5
3	Eastern margin of Aurora Basin and central Aurora Basin	13
4	Northern margin of Aurora Basin and central Aurora Basin	5*

*Mean value for northern margin derived from only a small sample (>50 measurements).

4. Combination of RES with other geophysical techniques can provide a powerful means of interpreting sub-glacial bedrock geology. The principal additional methods are simultaneous airborne magnetic sounding, ground-based seismic refraction shooting, and gravity observations. An example of the combination of RES and magnetics is provided in figure 5 while figure 4 includes information from seismic profiles.

To the above four criteria can be added a second group of factors which constrain any inferences regarding sub-glacial geophysical characteristics. They are:

a. the known geology as revealed in nearby outcrops;

b. the petrography, mineralogy, and palynological content of offshore ice-rafted and terrestrially-derived sediments which may suggest provenance of certain suites of rocks on-shore beneath the ice;

c. the notion of a common geological history with adjacent continents. Antarctica, for instance, shared a common "Gondwana" evolution with neighbouring southern hemisphere land masses during much of the Phanerozoic. This allows certain conjugate parts of adjacent land to be considered as possible and partial geological/geophysical analogues.

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*Cambridge. University. Scott Polar Research Institute. Radio Echo Sounding: Bibliography 1961-1980.

DATA ANNOUNCEMENT

1980(GL-A)

AIRBORNE POLAR ICE SOUNDING AND GEOMAGNETIC DATA SETS

The World Data Center-A for Glaciology (Snow and Ice), through an agreement with the U.S. National Science Foundation (NSF), has acquired ice thickness profiles and related geomagnetic data sets generated during NSF-funded remote sensing flights over Antarctica and Greenland.

Data are available in a combination of digital and/or analog forms. Cross references in time and geographical position exist for all digital and analog records. Radar soundings of ice thickness have been recorded as analog Z-mode oscillographic traces. A scalar and a vector magnetometer provided digital geomagnetic data.

At present, Antarctic data are archived for 1977-78 (25,000 km) and 1978-79 (26,000 km) austral summers; and Greenland data for 1978 (18,000 km) and 1979 (19,000 km) boreal summers. These files will be updated as new data become available. Current geographic coverage is illustrated in Figure 1. Data may be selected for either complete flights or user-selected geographic "windows."

Data sets from these NSF-funded projects are normally available to users 1 year after the data have been received by the principal research groups.

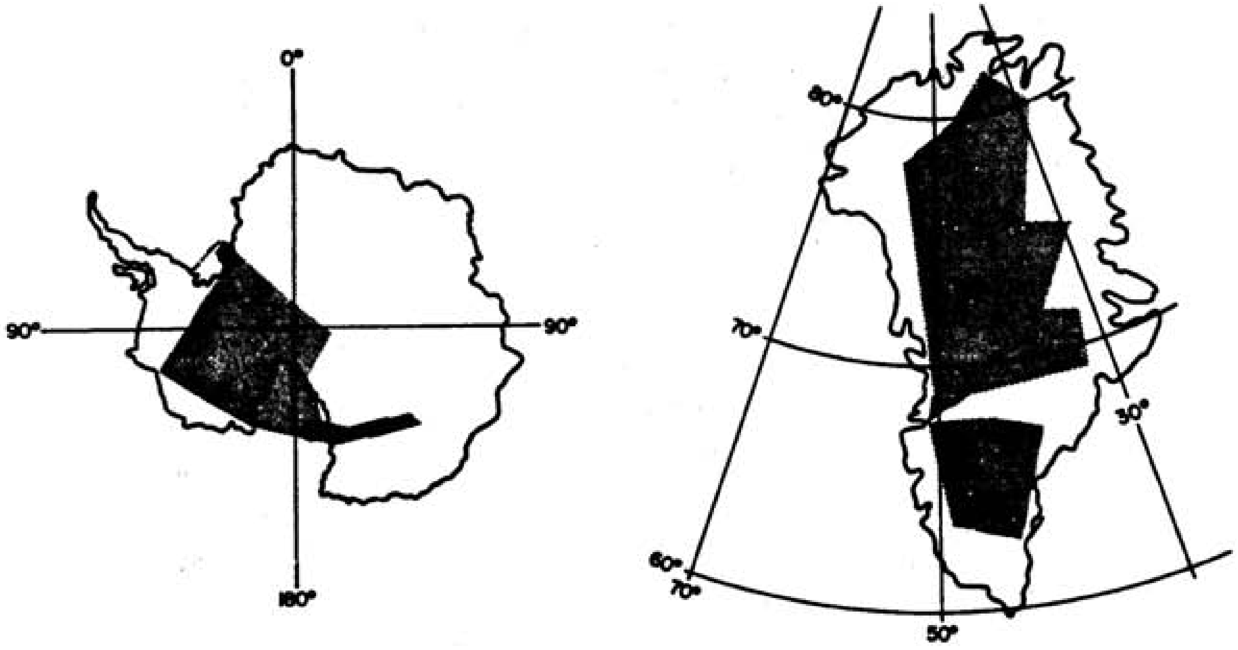

Figure 1. Shaded areas indicate current geographic coverage, polar ice sounding and geomagnetic data.

World Data Center-A for Glaciology [Snow and Ice]
National Geophysical and Solar-Terrestrial Data Center, NOAA
Boulder, Colorado

DATA DESCRIPTION

Digital Data:

Digital data are acquired via the Airborne Research Data System (ARDS), which records up to 38 channels of data from onboard instruments. Table 1 lists these data channels with signal source, units, and range of data values. Any combination of channels may be selected by the data requester, but not all channels are operative on every flight.

Table 1. Data channels, signal source, units, and range of data values for 1977 through 1979 ARDS digital data.

CHANNEL NO.	PARAMETER	SIGNAL SOURCE	UNITS	RANGE
0	FRAME SYNC	MASTER CONTROL		
1	IDENTIFICATION	MASTER CONTROL		
2	MO/DAY/YEAR (DATE)	MASTER CONTROL		0-123199
3	HR/MIN/SEC (TIME)	MASTER CONTROL		0-235959
4	QUADRANT (MSD)/LATITUDE	LTN-51 INS	0.1 MIN	1-7/0-90
5	LONGITUDE	LTN-51 INS	0.1 MIN	0-180
6	RELATIVE TERRAIN ALTITUDE	APN-194 RADAR	1 FOOT	0-5000
7	SPARE (MANUAL)	MANUAL DATA UNIT		
8	PRESSURE ALTITUDE	GARRETT PRESSURE TRANSDUCER	1 FOOT	0-80000
9	SPARE (MANUAL)	MANUAL DATA UNIT		
10	ANGLE OF ATTACK PRESSURE FORCE	ROSEMONT PRESSURE TRANSDUCER	0.01 MB	-92.00 TO +92.00
11	ANGLE OF SIDESLIP PRESSURE FORCE	ROSEMONT PRESSURE TRANSDUCER	0.01 MB	-92.00 TO +92.00
12	DRIFT ANGLE/TRUE HEADING	LTN-51 INS	1 DEG/1 DEG	-39 TO +39/0-359
13	HEADING/TRUE AIRSPEED	C12 COMPASS #1/TAS CMPTR A/A 24G-9	1 DEG/1 KNOT	0-359/70-450
14	HEADING/TRUE AIRSPEED	C12 COMPASS #2/TAS CMPTR A/A 24G-9	1 DEG/1 KNOT	0-359/70-450
15	TRACK ANGLE/GROUND SPEED	LTN-51 INS	1 DEG/1 KNOT	0-359/0-999
16	DRIFT ANGLE/GROUND SPEED	APN-147 DOPPLER RADAR	1 DEG/1 KNOT	0-359/0-999
17	SPARE (MANUAL)	MANUAL DATA UNIT		
18	STATIC PRESSURE	GARRETT PRESSURE TRANSDUCER	0.001 IN HG	3.000-31.000
19	WIND DIRECTION/WIND SPEED	LTN-51 INS	1 DEG/1 KNOT	0-359/0-379
20	STATIC PRESSURE	GARRETT PRESSURE TRANSDUCER	0.01 MB	100.00-1050.00
21	DIFFERENTIAL PRESSURE	ROSEMONT PRESSURE TRANSDUCER	0.01 MB	0-204.00
22	TOTAL TEMPERATURE	ROSEMONT TRANSDUCER	0.01 DEG C	-99.00 TO +64.00
23	DEW POINT TEMPERATURE	GENERAL EASTERN HYGROMETER 1011	0.1 DEG C	-75.0 TO +50.0
24	FREE-AIR TEMPERATURE	HP QUARTZ THERMOMETER 2801	0.01 DEG C	-80.00 TO +99.99
25	SPARE			
26	SPARE			
27	SPARE			
28	ECHO SOUNDING EVENT COUNTER	MANUAL DATA UNIT		
29	WATER VAPOR	303 MOISTURE MONITOR	0.01 PCT. FS	0.00-100.00
30	CABIN PRESSURE ALTITUDE	ROSEMONT PRESSURE TRANSDUCER	1 FOOT	0-20000
31	ICE SOUNDING CLOCK	ICE SOUNDING SYSTEM	1 SEC	0-235959
32	ICE SOUNDING FRAME NUMBER	ICE SOUNDING SYSTEM	UNIT COUNT	0-999999
33	ICE SOUNDING SIDE PICTURE NUMBER	CAMERA CONTROL UNIT	UNIT COUNT	0-999999
34	SCALAR MAGNETOMETER	PROTON MAGNETOMETER	1 GAMMA	0-099999
35	X VECTOR	VECTOR MAGNETOMETER	100 GAMMAS	-999 TO +999
36	Y VECTOR	VECTOR MAGNETOMETER	100 GAMMAS	-999 TO +999
37	Z VECTOR	VECTOR MAGNETOMETER	100 GAMMAS	-999 TO +999

Analog Data:

Z-mode analog strip charts and 35-mm Z-mode pictures are generated during radar sounding flights. The analog records are linked with the system's clock and include identification channels on ARDS tapes. Microfilm of the Z-mode analog strip charts exists for the 1978-79 Antarctic season.

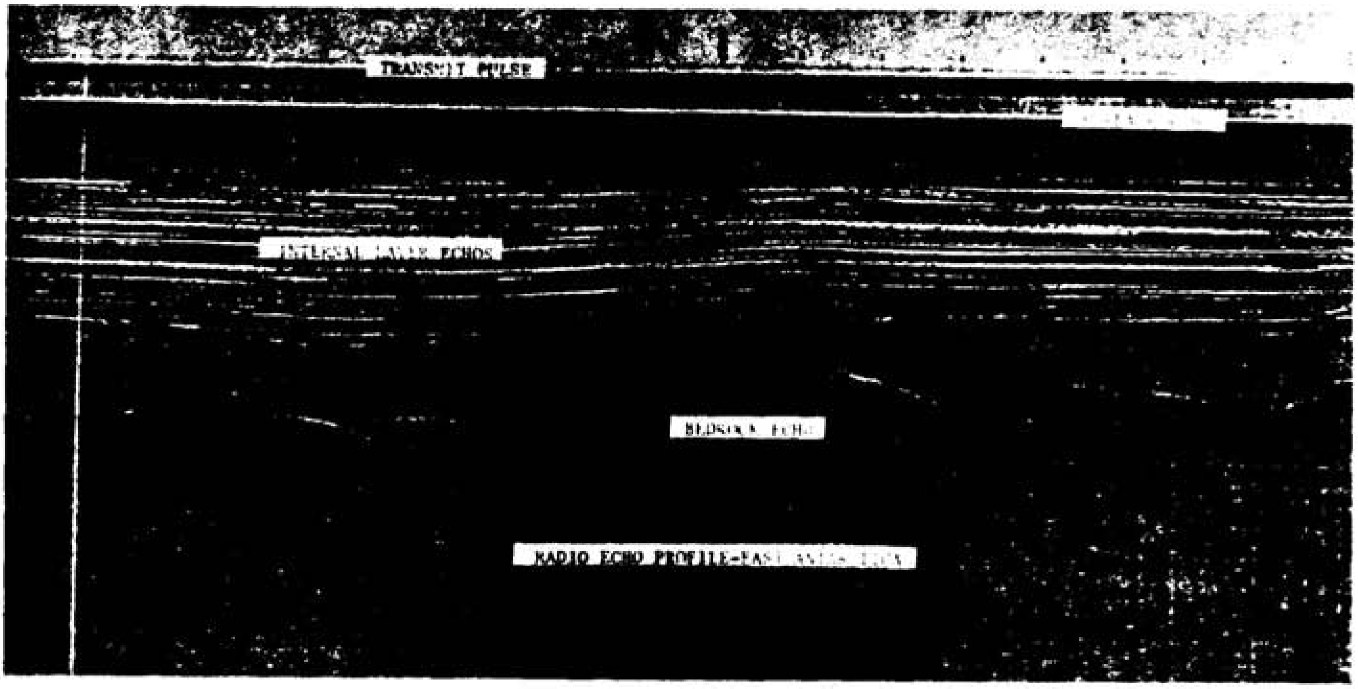

Figure 2. Sample of Z-mode analog strip chart.

DISTRIBUTION MEDIA AND FORMATS

The original ARDS data require specialized software for decoding. Processed ARDS data are available as a computer listing or on magnetic tape. Magnetic tapes are available in the following formats:

9-track 800 or 1600 BPI in ASCII or EBCDIC
7-track 556 or 800 BPI in BCD
Logical record length = 80 characters
Blocking factor = 50 (4,000-character blocks).

Z-mode analog data are available as strip charts and 35-mm film.

Costs are dependent on the amount of digital and analog data requested and computer processing required. Specific cost estimates will be provided on request.

April 1982

SUPPLEMENT TO DATA ANNOUNCEMENT 1980 (GL-A)

AIRBORNE POLAR ICE SOUNDING AND GEOMAGNETIC DATA SETS

Analog Data

Antarctic ice thickness profiles from the 1977/78 and 1978/79 field seasons are now available on 16mm microfilm. These data comprise Z-mode radar echoes originally recorded on paper strip charts from the Airborne Research Data System (ARDS) oscilloscope; they include timing marks from the ARDS clock and the ice sounding identification channels (CBD numbers) on the ARDS digital tapes. Schoenhals and Hutchins (1979) describe the Airborne Research Data System, and Gudmandsen (1976) provides details necessary to interpret the analog records.
16mm microfilm is available at a cost of $20 per reel. Ice sounding flights 1-13 for 1977/78 are contained on 2 reels; ice sounding flights 30-39 for 1978/79 are contained on 1 reel.

35mm film of Z-mode and A-mode oscilloscope traces is also archived for these two field seasons. Because of their large volume these records are available only by special arrangement. Please contact the WDC for further information about this format.

Digital Data

Digital vector magnetometer data in channels 35-37 are not intended as survey data. These channels were included in the ARDS package to aid in calculation of aircraft compensation coefficients.

For further information about the ARDS digital or analog data sets, including cost estimates for digital data, please contact WDC-A: Glaciology.

References: (copies available from the authors or as photocopies from the WDC)

Schoenhals, S.; Hutchins, R. (1979) Airborne Research Data System operations manual. Applied Physics Laboratory, The Johns Hopkins University.

Gudmandsen, P. (1976) Studies of ice by means of radio echo sounding. Technical University of Denmark. Electromagnetics Institute. Report 162, 22 p.

National Snow and Ice Data Center/WDC-A for Glaciology
CIRES, Box 449
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Boulder, Colorado 80309

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WORKSHOP ON ICE SHEET MODELING
COOPERATIVE INSTITUTE FOR RESEARCH IN ENVIRONMENTAL SCIENCES
UNIVERSITY OF COLORADO, BOULDER
24-28 AUGUST 1981

Summary

The presentations and discussions aimed to define current problems and tasks of modeling the polar ice sheets as transient dynamic and thermodynamic components of the global climate system. A consensus was reached on the most appropriate form and parameters of the ice flow law at present available for ice masses with different temperatures and crystal fabrics. However, opinions remained divided on the best way of calculating the sliding velocity of glaciers, the key ingredient in the modeling of surges. The main modeling tasks identified concern the effects of climatic changes on ice shelves, and the precise degree of restraint they exert on a marine ice sheet. These questions need to be settled both by flowline models representing surface and basal heat and mass exchanges which lead to interactions between ice temperatures and ice flow, and by three-dimensional models representing the interaction of the ice shelf with its lateral boundaries (rock or slow-moving ice) and basal pinning points.

A second group of modeling tasks arises from the geological evidence of glaciations and from the growing number of intermediate-depth and deep ice cores. The aim must be to create an ice sheet history which is consistent with that combined information and at the same time makes proper allowance for the associated changes in sea level and in the earth's crust. A reconstruction of the North American glaciations during the last 120ka was described which is now being extended to an assessment of the likely effects produced (largely through the medium of sea level changes) on the Antarctic ice sheet.

The workshop finally explored ways in which these modeling tasks might be systematically tackled by the scattered groups at present engaged in the modeling of glaciers and ice sheets. Recent surveys organized by the Department of Energy through the American Association for the Advancement of Science have established that the most urgent requirements are further measurements in key locations of Antarctica. In this context modeling has an important role to play through identifying the best locations for measurements and predicting the range of effects likely to be encountered there. A tentative consensus was reached on sharing this work. As a first step in that direction it was decided that the workshop report should be made available to a wide circle of modelers of the different components of the global climate system.

Support for the workshop was provided by a grant for ice sheet modeling from NOAA to the University of Colorado. Several scientists were able to participate by being involved in a Greenland modeling project supported by grant #DPP7906789 from the National Science Foundation.

Informal Workshop on Ice Sheet Modeling
Boulder, Colorado, 24-28 August 1981

1. Participants

Speakers:

Prof. John Andrews, Institute of Arctic and Alpine Research (INSTAAR), University of Colorado at Boulder

Dr. R. Bindschadler, Goddard Space Flight Center, NASA

Prof. W. Budd, Meteorology Department, University of Melbourne, Australia

Dr. J. Hollin, INSTAAR

Dr. D. Jenssen, University of Melbourne

Dr. R. Keen, Cooperative Institute for Research in Environmental Sciences (CIRES)

Tamara Ledley, Department of Meteorology, MIT

B. McInnes, CIRES

Dr. S. Paterson, Paterson Geophysics, Inc., Canada

Dr. U. Radok, CIRES (Convenor)

Contributors to discussions

Prof. R. Barry, CIRES/WDC-A - Glaciology

P. MacKinnon, WDC-A

Dr. S. Schneider, NCAR

Dr. S. Warren, CIRES

1.a. Program

Monday 24 August		
8:30	Welcome to participants	Uwe Radok
	Adjustments to program	
9:00	Zero net balance modeling	
	MkII modeling	Uwe Radok
	Antarctic results	Dick Jenssen
	Greenland results	Barry McInnes
1:30	Climatic effects	
	Meltwater percolation and re-freezing	San Paterson
	Ice core gas-content/isotope interpretation	Dick Jenssen
	A synoptic net balance model	Richard Keen
Tuesday 25 August		
8:30	Ice sheet and climate in models	
	A model history of Antarctica	Bill Budd
	Problems of interactive ice-sheet/climate models	Tamara Ledley
1:30	Ice sheets and climate in reality	John Andrews
Wednesday 26 August	Workshop field trip	Unprogrammed discussions at Tyndall Glacier
Thursday 27 August		
8:30	The flow law of ice	Stan Paterson
1.:30	Sliding and surging	Bill Budd
Friday 28 August		
8:30	Ice shelves	
	Dynamics of the Amery Shelf	Bill Budd
	Boundary conditions for ice shelf modeling	Stan Paterson
1:30	Transient models	Bob Bindschadler Dick Jenssen

2. Purpose

In welcoming the participants to the workshop Dr. Radok explained that it had been made possible by a grant from NOAA Climate Office and Environmental Research Laboratories to CIRES for two specific modeling tasks. The first of these concerns potential reactions of the polar ice sheets in general, and the West Antarctic in particular, to climatic and environmental changes with time scales of decades to a century or two; this is generally called the CO_2 problem but includes the whole range of natural and man-made effects to receive priority attention in the World Climate Research Program. (Bentley, 1982) The second modeling task is the construction of ice sheet climate histories to match the properties of ice cores extracted from various parts of Antarctica and Greenland.

The first topic has received considerable exposure, often in somewhat sensational terms, and requires a detailed quantitative analysis leading to answers that will convince the majority of glaciologists of their validity. The second topic is steadily gaining relevance with the growing number of cores being extracted from the ice sheets and with the increasing sophistication of measurements that can be made on the cores themselves, in the bore holes, and in their surroundings. A common purpose in both tasks of the modeling program is to draw together, synthesize, and help to coordinate the ice sheet modeling work going on at several places in the United States with that elsewhere (notably in the framework of the International Antarctic Glaciological Project, the IAGP).

The proposed Workshop program was adopted with minor changes and is reproduced on page 73 . It proceeds from a review of the basic and climate-related modeling results already obtained to controversial modeling "ingredients," such as parameterizations to be used for ice deformation and sliding, and to the ongoing development of ice shelf and ice sheet models that hopefully will prove adequate for the two tasks outlined above.

3. Zero Net Balance Modeling

3.1 Mk II modeling (Uwe Radok)

The assumption of a steady state mass balance for an ice sheet was first proposed by W. Budd as a means of constructing, from input fields of ice surface elevation, thickness, and net accumulation rate, the three-dimensional flow and deformation fields of the ice sheet and various other "derived physical characteristics", such as age and residence time of the ice, within the limits of uncertainty set by the input data. When coupled to the surface temperature field and solutions of the relevant (convective) heat transfer problem, the internal ice temperatures can also be specified everywhere. The combined balance mass and heat flow fields provide both a reference framework and the starting point for more advanced ice sheet models embodying the laws of ice deformation and sliding.

The first ("Mk I") survey of Antarctica (Budd, et al. 1970, 1971) involved the combination and arithmetic manipulation of sets of contours. To reduce the implied risk of inconsistencies, and to facilitate updating of the results with new data, an "Mk II" procedure has been developed in which the input data are specified for a fine-mesh grid covering the ice sheet. All results can be put into the form of numerical values for the grid points as well as be displayed as computer-drawn contours for the whole ice sheet or for individual drainage basins and flowline cross sections. The complete software is available on request as print-out or magnetic tape for independent checks of results and for the incorporation of additional observations. It can provide the definitive "Mk III" ice sheet description that might be based on more comprehensive data compilations, such as that now being constructed for Antarctica at the Scott Polar Research Institute in Cambridge, England.

3.2 Results

The creators of the Mk II procedure then presented some of their results. Those for Antarctica (Dick Jenssen) are based on exactly the same detailed assumptions (time invariance, large-scale slopes, no firn layer, basal heating by geothermal flux, and frictional dissipation), and the same data set as the Mk I results; as a consequence Mk II-Mk I differences arise directly from the new automated techniques. It was suggested that reports on this type of modeling should also list relevant processes that have been disregarded as too expensive computationally. These relate mainly to the "dynamics" velocity field created by ice deformation and sliding at the computed ice stresses and temperatures, taken up later in the workshop (cf. 8. and 9. below).

The Greenland Mk II results (Barry McInnes) include sensitivity tests derived from alternative ice flowlines or balance fields. As an example of the scope offered by the Mk II procedure, equilibrium shapes were shown of a cross section along the Jacobshavn Basin of central Greenland, constructed in a preliminary assessment of it's surging potential.

4. Climatic effects

4.1 Meltwater percolation and refreezing (Stan Paterson)

It is known that meltwater percolation and re-freezing in the firn of at least parts of the accumulation zone of glaciers and ice sheets leads to the creation of "warm bands" in which the temperature can exceed the annual mean temperature by several degrees. Particular interest attaches to the possibility that this process could occur over the entire Ross Ice Shelf as a result of a CO_2-induced rise in atmospheric temperatures. A survey of ice shelves in different latitudes suggests that substantial summer melt will occur for annual mean temperatures above about -20°C. Direct observations on the Devon ice cap confirm that meltwater can freely percolate through cold firn to depths of 1-2m. The Ross Ice Shelf at present has annual mean temperatures ranging from -23° to -28°C. An increase in atmospheric CO_2 concentration to four times its pre-industrial value has been shown to increase modeled summer temperature at 80°S by 4°C (Manabe and Stouffer, 1980). Some projected patterns of future fossil fuel consumption lead to CO_2 concentrations seven or eight times the pre-industrial (Keeling and Bacastow, 1977). Such concentrations could then turn at least part of the Ross Ice Shelf into a melt zone.

After considering different models for the thermodynamic consequences, it has been decided to use again the arguments which enabled Paterson and Clarke (1978) to account for the temperature-depth profiles in two boreholes on the Devon ice cap; the dimensions of ice lenses were used as meltwater input. Expected values of this necessary Meteorological quantity will be estimated from the temperatue observations made at different points on the ice shelf since the IGY. The meltwater amounts can be expected to be related to the number of positive degree-days produced by shifts of the present frequency distribution of summer air temperatures towards a higher mean value, but the possibility of increased cloudiness in conditions of surface melt must also be evaluated.Data from ice shelves already subject to melt will be helpful for this.

Once the surface melt and its effects on the subsurface ice temperatures are known, they will be used to study the reaction of the ice shelf through a dynamic-thermodynamic model of an ice-shelf flow line (cf. 10 below).

4.2 Ice-core gas content/isotope interpretation (Dick Jenssen)

A new approach, reported later at a poster seminar at the Third International Symposium on Antarctic Glaciology (TISAG), to the separation of climatic isotope (≈ deposition temperature) changes from those caused by changes in deposition height uses the fact that the temperature change along an ice sheet surface (the "topographical lapse rate") is controlled by its slope and by the surface energy balance. These two factors create a series of zones with distinctive lapse rates. The full interpretation of the core section then needs to identify the zone or zones in which the ice originated, in other words, the upstream shape of the ice sheet at the time that particular ice was laid down. It follows that an adequate interpretation of climate-related core properties needs to go hand in hand with the modeling of the ice sheet topography as function of time.

Bill Budd reported on an atmospheric GCM experiment by Simmonds and Lin (1981) in which the temperatures to be expected for different vertical extents of a smoothed Antarctic ice sheet were estimated. The results suggest a nearly consistent decrease in surface temperatures at a given point of around 6°C per km surface elevation increase. This is similar to the existing atmospheric lapse rate above the surface inversion which was well simulated by the model and remains approximately constant for the different surface elevations used in the experiment.

4.3 A synoptic net-balance model (Richard Keen)

The accumulation on the Greenland ice sheet comes from storms moving over or past the ice sheet. Their tracks and precipitation have been represented by a "Vertical Flow Index" (VFI) readily computed from gridded values of the 500 mb height. The VFI has the alternative interpretation of "vorticity flux intensity", since the key quantity computed is the absolute value of $V \cdot \nabla \zeta$ where V is the wind velocity and ζ the relative vorticity. Its correlation with the net accumulation rate is of the order of 0.6 and is increased by adding an orographic factor such as $V \cdot \nabla E$ where E is the ice sheet surface elevation at the gridpoint considered. The analysis of individual years is showing how the accumulation rate has changed with meridional shifts in the main storm tracks; but more complex processes such as blocking or cyclogenesis over the North Atlantic also play a substantial role. The same type of analysis will be used to clarify the precipitation processes of the Ross Sea sector. It is hoped that the observations for anomalous years and atmospheric modeling results will provide an indication of the conditions that prevailed during previous climatic epochs, and those that may develop with increasing CO_2.

5. Ice Sheets And Climate in Models

5.1 A model history of the Wisconsin ice sheet and its implications for Antarctica (Bill Budd).

A three-dimensional ice sheet model of the type first described by Mahaffy (1976) and parameterizations of present ice sheet regime parameters as functions of ice sheet size and elevation have been used to reconstruct the repeated growth and decay of the Wisconsin ice sheet in response to orbital changes in solar radiation during the last 130ka years. A detailed account of the work has been published (Budd, 1981; Budd and Smith, 1981) and demonstrates that a number of processes (including lagged isostatic depression) must be allowed to interact to bring about the appearance and disappearance of the ice in accordance with the geological evidence. The prime factor for associated changes of the Antarctic ice sheet are relatively small changes in sea level which determine whether the ice sheet can build up to the edge of the continental shelf or develops instead extensive floating ice shelves. The equilibrium ice sheet shapes resulting from different regime assumptions were described; as discussed in a TISAG paper, they provide guidance for the construction of a detailed history of the most recent global Pleistocene glaciations.

5.2 Problems of coupling ice sheet and climate models (Tamara Ledley)

Spectral data from deep-sea cores published by Hays, Imbrie, and Shackleton in 1976 indicated that present climate theories were not adequate to explain long term glacial/interglacial cycles. Since then many studies have tried to include various forms of ice (continental snow, sea ice, ice sheets) in models of global climate in attempts to explain those cycles. These studies have evolved into two schools of thought concerning the nature of these glacial/interglacial transitions. The first holds that long term cycles result from nonlinear interactions internal to the system and do not need external influences. The second holds that the long term cycles are caused by external forcings; however, the physical mechanisms translating these forcings into climatic changes are as yet unknown.

The work of Sergin (1979), and Kallen, Crafoord, and Ghil (1979) belongs to the first school. They built internal oscillator models of the climate system which produce the long term glacial/interglacial cycles. However, by adjusting the many prescribed constants and tunable parameters within these models, various climates and climate cycles can be obtained. These range from cycles with periods and amplitudes similar to those found in the geologic record to non-cyclic behavior in a variety of regimes.

The work of Suarez and Held (1979), Pollard (1978), Pollard, Ingersoll, and Lockwood (1980), and Schneider and Thompson (1979) belongs to the second school. They built deterministic models which attempt to include the interaction of the cryosphere and atmosphere (i.e. coupling). However, while these models produce the higher frequency cycles found in the geologic record, they do not produce the longer term glacial/interglacial cycles.

All of the studies mentioned above met with varying degrees of success; however, each showed sensitivity to the choice of modeling parameters. Since the enormous complexity of both the cryospheric and atmospheric systems and computer time restrictions make it necessary to use these simple models in the study of long term climate, it is also necessary to understand how they respond to various choices of parameters and forcings. This requires extensive sensitivity studies of both the cryospheric and atmospheric climate models before they can be coupled, and before any meaningful conclusions can be drawn from the results they may produce.

Preliminary experiments along these lines were described. They involve a zonally averaged dynamic continental ice sheet model, which encompasses energy-balanced net accumulation at the surface and vertically-averaged horizontal velocity within the ice, and a theromodynamic sea ice model. The strategy is to investigate in detail the sensitivities of these models and comparable climate models to choices of parameters and, forcings, so the ice and climate models can be coupled to produce interpretable and hopefully, realistic results within the confines of a zonally averaged model. This strategy can also be applied to the various hierarchies of ice sheet, sea ice, and climate models now available in order to gain a better understanding of the models, and a broader view of the workings of the whole climate system.

6. Ice Sheets And Climate In Reality

6.1 Reconciliation of ice flow indicators, ice margin chronology, and isostasy data (John Andrews)

From the geological point of view, ice sheet models must account for three separate types of geological evidence: 1) glacial flow indicators; 2) location (chronology of the margins); 3) glacial isostasy. Striations indicate the direction of flow at some specific interval; the problem is to attach an age to the sense of ice motion. A better indicator(s) can be obtained by an analysis of the mineralogy of stacked tills. We must also distinguish between the location of ice divides R on the one hand, and the location of the thickest ice, as deduced from past-glacial rates of isostatic adjustments, on the other.

As an example, the view of the Weichselian ice sheet as centered over the southern Baltic must now be modified in the light of new evidence of separate centers over Swedish Lapland, giving rise to eastward outflow over the Gulf of Bothnia, and another center on the Harvanger Plateau of South Norway, also draining towards the east. In a corresponding change in perception, a major center of outflow is now regarded as having existed east of Hudson Bay, and the Wisconsin ice sheet as made up of a number of separate domes.

It would be interesting if models on a grid scale finer than so far used could confirm this. There is geological evidence from the Hudson Bay Lowlands for successive deglaciations of Hudson Bay during the Wisconsin Glaciation. The evidence is based on stratigraphy and the rate of amino acid racemization. Figure 1 (Andrews, 1982) shows the frequence of specific D allo: L iso ratios and calculated ages. These fit quite well with the Budd and Smith (1981) model of the Laurentide Ice Sheet over the last 125 ka.

The question was raised by Bill Budd whether a central dome over Hudson Bay, formed by the coalescence of other domes and lasting about 15 ka, would have produced as much evidence of basal transport, as compared to the effects of an advancing ice sheet front. The results from the Melbourne model could be examined for guidance on these problems.

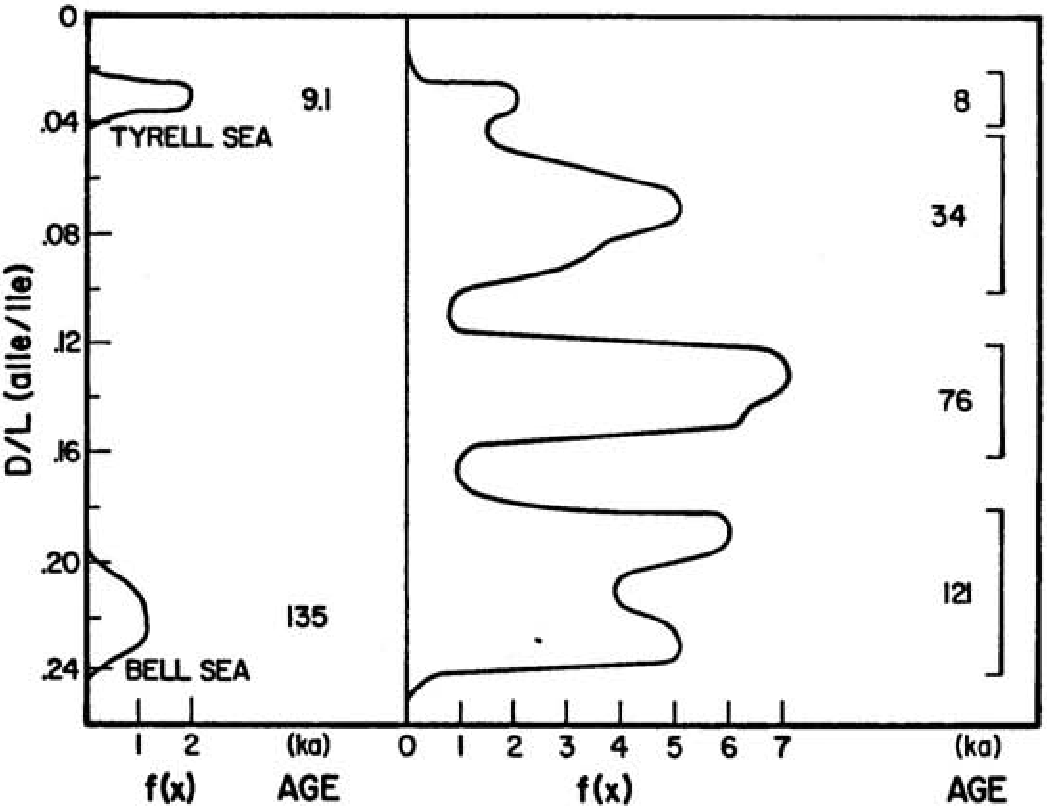


Figure 1. Frequencies of age-related amino acid ratios found in glacial deposits of the southern Hudson Bay region. Left: Deposits of known age, used for calibration; Right: Shell-bearing tills showing the dates of the main transgressions.

6.2 The interpretation of State V isotope changes (John Hollin)

The Northern Hemisphere ice sheet model of Birchfield et al. (1981) and the combined North American and Antarctic model reviewed by Budd (1981) both simulate the marine isotopic record of glaciation very well. Two possible discrepancies are:

a) Budd's (1981) figure 7c does not show the ice minimum at 105kaBP that is suggested by the benthic isotopic record (Shackleton, 1977, figure 2);

b) Both the Birchfield et al. (figure 2) and Budd (figure 7c) papers show relative ice minima at 80 and 40 kaBP, but still enough ice to lower sea level by tens of meters. It is difficult to reconcile this with amino acid shell dates suggesting that Hudson's Bay was ice free at these times (Shilts et al., 1981). However, following Budd, perhaps the extra ice was in Antarctica.

Factors to be considered in reconciling the modeling, marine isotopic, and coastal records are many, and include:

i. ice isotopic ratios varying with locality (Budd, 1981, figure 9a) and time (Mix and Ruddiman, 1981);

ii. marine isotopic changes due to temperature or other changes not necessarily in phase with ice volume changes. Broecker (1978) draws attention to a benthic isotope change of more than +0.2 per mil in the Holocene. Obviously this has not been caused by ice build-up, and may be best explained by a Holocene benthic cooling;

iii. bioturbation (Chappell, 1981);

iv the delayed rheological response of the Earth to ice loading;

v. the importance of different latitudes in the radiation input to the models.

7. Field Evidence For Glacial-interglacial Changes In The Climate And Glaciers Of The Colorado Rockies

This was provided by a field trip to the Tyndall Glacier in the Rocky Mountain National Park, and by the route from there to the University of Colorado's Mountain Research Station across a number of large valleys that had carried glaciers during the Wisconsin. The extent of these glaciers has been determined in an unpublished Institute of Arctic and Alpine Research (INSTAAR) study which could serve for refining and testing the North American modeling results discussed under 5.1 above.

8. Ice Flow Relationships And Parameters

This topic and that of section 9. (sliding and surging) had been covered by Stan Paterson and Bill Budd in a written exchange prior to the Workshop. This had clarified a number of contentious points and permitted the discussions to concentrate on the crucial question of the flow relationship and parameter ranges that should be used in ice sheet modeling. These details have not always been stated clearly in published work, and the issue has been further confused by reference to data compilations that have undergone unpublished additions and changes.

A review of current knowledge, presented in more detail in chapter 3 of the second edition of his book, The Physics of Glaciers, was given by Stan Paterson, with emphasis on field results. The most generally accepted rheological equation for polycrystalline ice has the form

$$\varepsilon = A(\chi_1 . \chi_2 \ldots)\exp(-QRT) = f = (P)\tau^n$$

where n = 3 and Q = 60 kJ/mole for temperatures below -10°C. The value Q = 139 kJ/mole may be taken as an average value for temperatures above that threshold, although in fact the exponential relation no longer applies above -10°C. These are mean values; the Australians have used the equivalent of 75kJ/mole for the lower temperature range. From a comprehensive review of field results, supplemented by laboratory results, the parameter A was found on reduction to -10°C to have a mean value of

$$A = 5.2\times10^{-16}s^{-1}(kPA)^{-3}$$

for n = 3 (Paterson, 1981, p.37).

Temperate ice has different properties so that the behavior of Q at temperatures above -10°C, and especially near the melting point, remains in need of further investigation. Even so there is now reasonably close agreement (within a factor of 2, increasing for high temperatures) on flow law parameters for temperatures down to -20°C. Paterson's values of A are within a factor of 2 of the latest Australian values (Russell-Head and Budd, 1979; Budd, unpublished) for temperatures down to -20°C. The factor increases with decrease of temperature, reaching a value of 5.7 at -50°C.

The parameter A has been written as a function to emphasize its dependence on a number of other factors. These include the form of the crystal fabric, the concentrations of soluble and insoluble impurities, and perhaps the grain size. As an example, the Wisconsin ice from a core from the Mer de Glace Agassiz on Ellesmere Island is very fine-grained (probably due to depositional effects, rather than to shear as suggested by A. Gow) and deforms five times more readily than the ice immediately above it. Wisconsin ice in a borehole through the Devon Island ice cap behaved similarly (Paterson, 1977). A similar phenomenon has been observed with enhanced horizontal shear rates in a hole on the Law Dome, Antarctica, and has been attributed to the strong vertical orientation of crystal c-axes at the level in question; but this explanation cannot apply to Paterson's data.

Australian studies of ice fabrics and flow (Bill Budd) suggest systematic changes with depth and stress system. Thus the ice in the Law Dome summit hole has a girdle fabric (corresponding to unconfined compression) which persists right through the 500m core; a single near-vertical maximum develops at depth, due to horizontal shear as the ice flows toward the coast where the high longitudinal strain rates give rise at the surface to the two-maxima patterns typical of confined compression.

The typical strain rate-time curve shows a minimum around 1 percent strain, followed by increasing strain rates as recrystallization takes place (most rapidly around the 2.5 percent strain stage). If the test is restarted with the new crystal structure, a new higher minimum occurs.

The minimum strain rate can be used as a standard of comparison to judge how far the recrystallization has proceeded. Conditions are shown most clearly by plotting log against log time. It is then seen that in the early stages of primary creep, prior to reaching the minimum strain rate, ε depends linearly on stress. The exponent n = 3 for minimum strain rate arises from the relatively earlier occurrence of minimum ε for greater stresses, for a given temperature.

Laboratory work by Lile and Jacka has suggested that the effects of crystal size for statistically isotropic polycrystalline ice are small and non-systematic. Those of stress and temperature appear to be replaceable by one another; this helps to fill in blank regions of the strain rate-stress-temperature diagram.

Altogether, the laboratory results are coming to match the field results quite well, and the remaining uncertainties relate to the precise stress state and the fabrics of any particular field observation or laboratory test.

9. Sliding and Surging

An overview by Bill Budd of the physical concepts incorporated in the Budd-McInnes surging model started from laboratory experiments (described by Budd et al., 1979) designed to quantify the relationship between sliding velocity, normal load, and base stress. These experiments and their reconciliation with glacier observations showed the role of the regelation process to be insignificant compared with that of ice flow enhancement by englacial water, which develops throughout the ice when a quasi-constant value of the frictional dissipation is reached. The surging model therefore has been designed around a basal stress relationship of the form

$$\tau_b^* = \frac{\tau_c}{1 + \varphi\tau_c V}$$

and the condition that the integrated basal stress of the entire glacier must balance the total driving force,

$$\int_0^L \tau_b \, d\,x = \int_0^L \tau_c \, d\,x$$

It was emphasized that the model makes no assumption about the basal water balance. This is in accord with the observed fact that the increased meltwater production in summer or abnormal rains are neither sufficient nor necessary to start a glacier surge. Instead it is the passage through a critical velocity and stress threshold which appears to initiate a process of rapid sliding, or perhaps intensive shear deformation above a thin basal layer.

Two doubts were raised by Stan Paterson about the validity of the model. The first will be discussed at length in a forthcoming thesis by E. Waddington and questions whether the model conserves mass; but Barry McInnes protested that it is designed to do so and subsequently provided a detailed check and confirmation of mass conservation, reported in appendix 1. Paterson's second objection concerns the predicted existence of an effective thickness (corresponding to the overburden pressure reduced by the basal water pressure) of 170 m dividing the thin-ice regime of predominant sliding from that of the thicker ice moving predominantly by deformation. Budd responded that the existence of such a threshold thickness is more firmly established than its precise value, which may well vary with other factors such as stress state and the vertical distribution of crystal fabrics.

An alternative sliding theory which includes the effect of pressurized subglacial water on sliding was presented by Bob Bindschadler. Its key concept is that the water pressure reduces the normal load of the ice against the bedrock and enhances areas of ice-rock separation and higher sliding rates. The process is quantified by a "bed separation index" which is the ratio of base shear stress (Z) to the difference (N_{eff}) between the ice overburden and pressure and water pressure in a Rothlisberger channel at the bed. A paper with the detailed results has been submitted to the Journal of Glaciology.

10. Ice Shelves

A modeling study of the Ross Ice Shelf is being planned by Stan Paterson and Garry Clarke to establish its reaction to the predicted CO_2 warming. Using existing data, the work will address in the first place the flow-temperature interaction; it is assumed that the ice sheet - ice shelf interaction will be tackled by the NASA-Goddard group. The ice shelf model will consider a flowline in the freely floating ice shelf (the most vulnerable state) and will assume the present grounding line and influx value as given. Of different calving criteria considered, that proposed by Sanderson (1980) appears to be most suitable; this specifies a maximum value for the divergence half-angle ψ, defined by

$$\dot{\varepsilon}_\psi = \frac{\bar{u}}{W} \tan\psi$$

$$\tan\psi_{max} = C(\bar{\rho}, A)\, W h^3 / \bar{u}$$

where A is the flow law parameter, ε_ψ is the strain rate parallel to the ice front, u is the mean horizontal velocity at the ice front, W is the half-width of the shelf, ρ is the mean density of the shelf, and h is the ice thickness. The general validity of such a formulation is questionable however, since strain conditions differ from ice shelf to ice shelf: at the Ross shelf front ε_ψ is larger than ε_χ whereas the reverse is true (with a factor of three) for the Amery Ice Shelf.

In accordance with the estimates of Keeling and Bacastow (1977) and those of Manabe and Stauffer (1980), the surface air temperature will be assumed to rise by 7.5°K over the next 150 years, and then remain constant. This will fix the melted fraction (cf. section 4.1) of the total precipitation which will itself be assumed in a range from present values to twice as much. Initially, the melt factor will be assumed to increase with time from its present value of zero up to various maxima. Improved estimates will be possible when existing meteorological data have been analyzed.

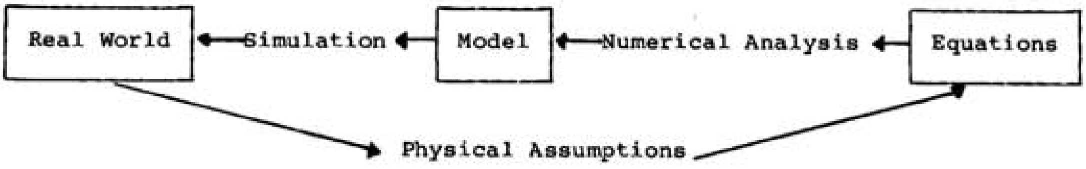
The conditions at the base of the ice will be assumed, following Zotikov et al. (1980), to decrease linearly from about 60 cm/year at the ice front to zero 200 km from the ice front, with accretion at rates between 15 and 30 mm/year elsewhere. The thesis work of Doug MacAyeal on the ocean circulation below the ice shelf should make it possible in due course to refine these assumptions.

A finite-element study of the ice shelf reported by MacAyeal and Thomas to TISAG was reviewed by Bob Bindschadler. The validity of the model has been checked by applying it simulations of the Ross Ice Shelf have predicted velocity and strain rate fields which agree with field measurements to within a factor of 2.

The dynamics of the Amery Ice Shelf, subject of another TISAG paper, was described by Bill Budd. The most important results are that, for this ice shelf, thickness changes due to strain thinning and advection are of roughly equal magnitude near the front (4 m/a) whereas net accumulation amounts to about 0.4 m/a only. Just after leaving the grounding line the ice thickens at a rate that produces a surface rise extending over 40 km down stream. Radar echoes seem to be disturbed by the boundary between the glacial ice and the accreted sea ice, first discovered in the ice core from the 1967 borehole.

11. Development Of Advanced Models For Glaciers And Ice Sheets

Bob Bindschadler defined the modeling problem in the following schematic form:



He then described a model later reported to TISAG. This model divides the driving stress along a flowline into the basal shear stress (friction) and longitudinal stress gradient (stretching) components, in a manner consistent with the ice flow law and a sliding relationship. Experiments have been performed on a steady state ice stream configuration to study the effects of variations in various model parameters and inputs. As examples, the insertion of an isolated (one gridpoint) "ice rise" or a higher sea level produced significant thickening of the ice upstream. Plans for future work include:

a) irregular bedrock;

b) lateral convergence and divergence;

c) non-isothermal, time-dependent temperature field calculation of from the current geometry and ration of basal meltwater production; positive feedback into sliding velocity might result in surging behavior;

d) inclusion of ice shelf with grounding line;

e) appropriate estimate of model parameters from available measurements of ice-stream geometry and dynamics;

f) tests of model behavior sensitivity to all input parameters;

g) predictions of future behavior for specific ice-sheet drainage basins for various climatic scenarios.

Dick Jenssen discussed computational problems of a 4-D model of ice sheet dynamics and thermodynamics. These have been simplified by the introduction of a relative (σ) coordinate system in which the ice always extends vertically from $\sigma = 1$ to $\sigma = 0$. The continuity equation has a finite-difference form which should theoretically make it computationally unstable for arbitrarily small time steps; but in reality the movement of the ice seems to prevent the instability from developing. This suggests that explicit schemes may be used; however for full rigor and safety, implicit schemes should be employed. The thermodynamic stability condition requires increasing smaller time steps as the ice becomes thinner; these can be achieved by suspending the calculations of temperature in regions of thicker ice while permitting those from the thin ice regions to catch up. The most important need is for reducing the grid size which even for Greenland has remained too large, at 20 km, to resolve important details such as the initiation of ice streams.

12. Conclusion

The Workshop was focused on the two concrete tasks described in section 2., and its participants constituted only a sample of the glaciological modeling community. Any conclusions reached in the discussions therefore remain tentative until this report has been reviewed by a wider circle of glaciologists. The discussions showed that, after a period of ad-hoc glaciological modeling in the service of geological reconstructions, the problems of the ice sheets and their reactions to climatic and environmental changes are now being tackled in terms of physical processes by several groups, each concentrating on a somewhat different aspect and using a somewhat different approach. It seems very desirable to establish adequate communication between these groups so that the work and results of each group can be taken into consideration by any other in planning and developing its own ice sheet modeling program.

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Appendix 1

Mass Conservation by the Budd/McInnes Surging Glacier Model

B.J. McInnes

The doubts raised by Ed Waddington relate to figure 4.3[1] in my M.S. thesis (McInnes, 1976). This figure occurred in a discussion of computational stability and served solely to illustrate the growth of instability associated with a 2-point finite difference scheme. The ice thickness profiles in the figure show that the instability sets in from the first point and progresses down the profiles, giving gross errors in ice thickness, velocity and, of course, mass.

This method of finite difference scheme along with a large time step is therefore obviously full of pitfalls. It was not used in later calculation schemes which yielded the results reported in the thesis. Instead I used 5-point differences and as a check, an alternative scheme devised by Dr. Jenssen for the calculation of mass-conserving steady-state profiles (see p.86).

One set of results relates to the Fedchenko Glacier. The figures in question (6.10 and 6.15) were copied from projected movie film images, suffered some distortion in the process, and evidently were intended for displaying basic features, not for numerical checks. Even so the digitized area of the surging profiles shows no substantial changes (see table 1). Numerical checks were carried out, as described in the thesis, and balance depths and velocities were compared, using the following relationships:

$$\frac{\partial VZ}{\partial x} = A \; ; \qquad VZ = \int_0^x A\,dx$$

both A and VZ are specified functions of x.

This test was performed for every run, with tabulation of the numerical values. In a more recent surging calculation for the Jacobshavn Glacier, mass was found in this way to be conserved to an accuracy of better than .25 percent (a maximum difference of 150 in 65,000 between expected and model results).

Table 1. Area enclosed by surging profiles in McInnes thesis.

Fedchenko Figure 5.1

Profile	Area
1	580
2	600
3	585
	area units

Bruarjokull Figure 6.23

Profile	Area
1	524
2	523
3	520
	area units

Medvezhi Figure 6.36

Profile	Area
Decrease in area	56
Increase in area	66
	area units

The profiles checked were hand-drawn from numeric output. The Medvezhi figure has a vertical thickness exaggeration of three, and the lowering of the ice surface in the accumulation region was not shown as it was small relative to the diagram scale. This explains the apparent mass "change" in that diagram.

Reference

McInnes, B.J. (1976) Numerical modelling of self-surging glaciers. M.S. thesis, Meteorology Department, University of Melbourne.

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[1] Figures mentioned in the text refer to McInnes, 1976. They are not included in this appendix.

Attachement to Appendix 1

D. Jenssen's Steady-State Algorithm

$$V = kZ\ \tau_b^n = kZ(pg\,\alpha Z)^n$$

$$VZ = \int_0^x A dx$$

Thus

$$k\left[pg\ \alpha Z^{\frac{n+2}{n}}\right]^n = \int A dx$$

$$Z^{(n+2)/n}\ \frac{d(Z+B)}{dx} = \frac{1}{pg}\left[\frac{1}{k}\int A dx\right]^{1/n}$$

The RHS is known for all x, especially if A is a known, analytic, function of x. Call the RHS Q.

$$Z^{\frac{n+2}{n}}\left[\frac{dz}{dx} + \frac{dB}{dx}\right] = Q$$

Let $\frac{dB}{dx} = \beta$ and use centered differences:

$$Z_i^{\frac{n+2}{n}}\left[\frac{Z_{i+1} - Z_i}{2\Delta x} + \beta_i\right] = Q_i \quad :i = 0,1,2,3 \cdots$$

or

$$Z_{i+1} = Z_{i-1} + \left[\frac{Q_i}{Z_i^{(n+2)/n}} - \beta_i\right]2\Delta x \quad \text{for } i = 1,2,3,\cdots \tag{1}$$

for $i = 0$, Z_0 is prescribed, or can be found assuming symmetry about i = 0. At $i = 0$ for this case, dZ/dx = 0, and

$$Z_0 = \left[Q_c/\beta_c\right]^{n/n+2} \tag{2}$$

(Note β is known *exactly* if B is a known, analytic, function of x). To get Z_1, use a forward difference at i = 0:

$$Z_1 = Z_0 + \left[\frac{Q_0}{Z_0^{(n+2)/2}} - \beta_0 \right] \Delta x \tag{3}$$

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