COASTAL-CHANGE AND GLACIOLOGICAL MAP OF THE RONNE ICE SHELF AREA, ANTARCTICA: 1974–2002

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2005

INTRODUCTION

Background

Changes in the area and volume of polar ice sheets are intricately linked to changes in global climate, and the resulting changes in sea level may severely impact the densely populated coastal regions on Earth. Melting of the West Antarctic part alone of the Antarctic ice sheet could cause a sea-level rise of approximately 6 meters (m). The potential sea-level rise after melting of the entire Antarctic ice sheet is estimated to be 65 m (Lythe and others, 2001) to 73 m (Williams and Hall, 1993). In spite of its importance, the mass balance (the net volumetric gain or loss) of the Antarctic ice sheet is poorly known; it is not known for certain whether the ice sheet is growing or shrinking. In a review paper, Rignot and Thomas (2002) concluded that the West Antarctic part of the Antarctic ice sheet is probably becoming thinner overall; although it is thickening in the west, it is thinning in the north. Joughin and Tulaczyk (2002), on the basis of analysis of ice-flow velocities derived from synthetic aperture radar, concluded that most of the Ross ice streams (ice streams on the east side of the Ross Ice Shelf) have a positive mass balance, whereas Rignot and others (in press) infer even larger negative mass balance for glaciers flowing northward into the Amundsen Sea, a trend suggested by Swithinbank and others (2003a,b, 2004). The mass balance of the East Antarctic part of the Antarctic ice sheet is unknown, but thought to be in near equilibrium.

Measurement of changes in area and mass balance of the Antarctic ice sheet was given a very high priority in recommendations by the Polar Research Board of the National Research Council (1986), in subsequent recommendations by the Scientific Committee on Antarctic Research (SCAR) (1989, 1993), and by the National Science Foundation's (1990) Division of Polar Programs. On the basis of these recommendations, the U.S. Geological Survey (USGS) decided that the archive of early 1970s Landsat 1, 2, and 3 Multispectral Scanner (MSS) images of Antarctica and the subsequent repeat coverage made possible with Landsat and other satellite images provided an excellent means of documenting changes in the coastline of Antarctica (Ferrigno and Gould, 1987). The availability of this information provided the impetus for carrying out a comprehensive analysis of the glaciological features of the coastal regions and changes in ice fronts of Antarctica (Swithinbank, 1988; Williams and Ferrigno, 1988). The project was later modified to include Landsat 4 and 5 MSS and Thematic Mapper (TM) (and in some areas Landsat 7 Enhanced Thematic Mapper Plus (ETM+)), RADARSAT images, and other data where available, to compare changes during a 20- to 25- or 30-year time interval (or longer where data were available, as in the Antarctic Peninsula). The results of the analysis are being used to produce a digital database and a series of USGS Geologic Investigations Series Maps (I–2600) consisting of 23 maps at 1:1,000,000 scale and 1 map at 1:5,000,000 scale, in both paper and digital format (Williams and others, 1995; Williams and Ferrigno, 1998; Ferrigno and others, 2002) (available online at http://www.glaciers.er.usgs.gov).

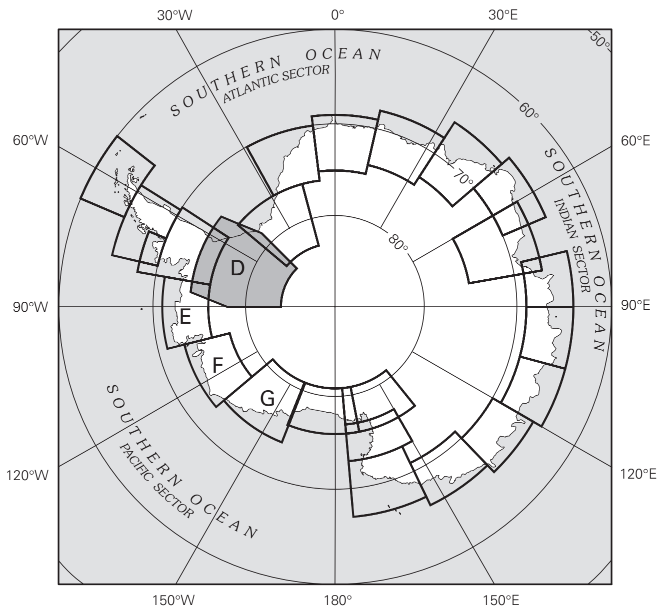

Figure 1.—Index map of the planned 23 coastal-change and glaciological maps of Antarctica at 1:1,000,000 scale. Ronne Ice Shelf area map is shaded. Maps published to date are indicated by letter and are described in table 2.

Objectives

The coastal-change and glaciological mapping project has five primary objectives, listed as follows:

(1) to determine coastline changes that have occurred during the past three decades, or longer where additional information exists;

(2) to establish an accurate baseline series of 1:1,000,000-scale maps (fig. 1) that defines, from the analysis of Landsat and RADARSAT images, the glaciological characteristics (for exam-

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ple, floating ice, grounded ice, etc.) of the coastline of Antarctica during three time intervals: (1) early 1970s (Landsat), (2) middle 1980s to early 1990s (Landsat), and (3) 1997 (RADARSAT);

(3) to determine velocities of outlet glaciers, ice streams, and ice shelves, and the position of the grounding line, from analysis of Landsat images and other sources;

(4) to compile a comprehensive inventory of named (from published maps) and unnamed (from analysis of Landsat images) outlet glaciers and ice streams in Antarctica that are mappable from Landsat and other satellite images or from ancillary sources (for example, maps, gazetteers, digital databases, and so forth) (Swithinbank, 1980, 1985; Alberts, 1981, 1995; National Science Foundation, 1989; British Antarctic Survey and others, 1993);

(5) to compile a 1:5,000,000-scale map of Antarctica derived from the 23 1:1,000,000-scale maps. Each 1:1,000,000-scale map extends to the southernmost nunatak within each map area or to the southernmost extent of Landsat images (about lat 81.5° S.). The coverage area of some maps was extended farther south to encompass an entire ice shelf.

Sources

Landsat images used in the compilation of the Ronne Ice Shelf area map were obtained from either the EROS Data Center[4] or the former Earth Observation Satellite (EOSAT) Corporation, now Space Imaging LLC[5]. The coverage areas of the Landsat 1 and 2 MSS images, Landsat 4 and 5 MSS and TM images, and Landsat 7 ETM+ images used in the compilation are shown in the index maps on the accompanying map. Below the index maps, information about each image is listed. The 1:500,000-scale photographic prints of Landsat images used in the analytical phase were derived from three types of source material: (1) 1:1,000,000-scale film transparencies from the EROS Data Center, (2) 1:1,000,000-scale black-and-white or false-color-infrared prints from EOSAT, and (3) 1:500,000-scale black-and-white digitally enhanced prints from the USGS, Flagstaff, Ariz. Early Landsat scenes cover the years 1973 to 1975; later Landsat images date from 1984 to 2002.

The 125-m picture-element (pixel)-resolution 1997 RADARSAT image mosaic of Antarctica, compiled by The Ohio State University's Byrd Polar Research Center (BPRC), was used both as a base for correct geographic position and geometric rectification of digitized Landsat imagery and as an additional source of coastal-change data. The RADARSAT image mosaic is composed of data recorded from September 9 to October 20, 1997 (Jezek, 1998).

Methodology

The primary steps in the compilation of the Ronne Ice Shelf area map are listed and discussed below:

(1) Identification of optimum Landsat MSS or TM images for two time intervals used for the map series (early 1970s; middle 1980s to early 1990s) and enlargement to a nominal scale of 1:500,000; addition of more recent imagery in some areas;

(2) Manual annotation of glaciological features by SCAR Code (Scientific Committee on Antarctic Research, 1980) or Antarctic Digital Database (ADD) Geocode (British Antarctic Survey and others, 1993) on 1:500,000-scale transparent overlays of Landsat images for both time intervals and directly on the computer workstation monitor for the 1997 RADARSAT image mosaic;

(3) Positional control of mapped features. Because our goal is to produce the most accurate, high-resolution printed maps and digital databases of the coastal regions of Antarctica, we expended considerable thought and research on choosing the optimum method of geolocating mapped features. The initial process of geolocating the Landsat scenes and annotations involved the use of geodetic ground-control points surveyed by the USGS in the 1960s. The control points came from a network of geodetic control that used a single well-fixed point as reference. The internal consistency of the network was known to be quite reliable, but the location of the ground reference point determined by astronomical measurement was subject to error in longitude that could be as large as 1 to 1.5 kilometers (km). Use of these geodetic ground-control points proved problematic in attempts to geolocate the images and annotated overlays for manually mapping the coast. Attempts to use these control points for digital processing in a world coordinate system also proved problematic and generated an unacceptably high positional error. The use of these geodetic ground-control points was rejected in favor of georegistering the imagery and annotations to the 1997 RADARSAT image mosaic of Antarctica produced by the BPRC to give the most geometrically accurate base, as discussed elsewhere in this report. An added benefit was that the RADARSAT mosaic was compiled in polar stereographic projection having a standard parallel at lat 71° S.—the map projection selected for the 24 maps—with due consideration given to scale distortion on map coverage north and south of lat 71° S. (Sievers and Bennat, 1989). The primary benefit of the polar stereographic projection is cartographic continuity between adjacent maps in the coverage provided of the coastal regions of Antarctica.

The RADARSAT image mosaic of Antarctica was generated from Synthetic Aperture Radar (SAR) data collected by the Canadian Space Agency's RADARSAT-1 satellite. Geodetic ground-control points (GCPs) supplied by the National Imag-ery and Mapping Agency (NIMA), now the National Geospatial-Intelligence Agency (NGA), and the Environmen-tal Research Institute of Michigan (ERIM) were used in conjunction with a calibration transponder located at the South Pole in the processing of data to improve the accuracy of geolocation from what is possible from use of satellite ephemeris data alone (Jezek, 1998, p. 15). Most of the 231 GCPs chosen (clustered at 91 locations) were located on nunataks in coastal regions; others were distributed along the Transantarctic Mountains. The geodetic accuracy of the RADARSAT image mosaic is cited as ±150 m (Noltimier and others, 1999). Orthorectification of the mosaic was accomplished using a Digital Elevation Model (DEM) generated by the BPRC specifically for the production of the mosaic. Data used in construction of the DEM were obtained from multiple sources. Types of data include ground-leveling and Global Positioning System (GPS) surveys, radar and laser altimeter data, optical and SAR stereographic image pairs and spot-elevation points, and contours and form lines digitized from map sheets (Liu, 1999, p. 15);

[4]EROS Data Center, U.S. Geological Survey, 47914 252d Street, Sioux Falls, SD 57198-0001.

[5]Space Imaging LLC, 12076 Grant Street, Thornton, CO 80241.

(4) Scanning hard-copy images to produce 400-dots-per-inch (dpi), 256-shade, gray-scale digitized satellite images. The digitized satellite images were coregistered and geometrically corrected to the RADARSAT image mosaic using ERDAS Imagine software. Pass points were used for coregistration to geometrically fit the scenes to the RADARSAT base. Because the RADARSAT mosaic was derived from data collected with an off-nadir, non-orthographic sidescan imaging device, horizontal displacement of local slopes and mountain peaks is evident. Therefore, peaks and features located on slopes were not selected as pass points. Low-elevation features were selected preferentially and used wherever possible. Selection of low-elevation points does not produce an even distribution of control across the image, but strongly clusters the geodetic ground control around image-identifiable features in the coastal regions of Antarctica. Application of second-degree or higher polynomial correction to an image with uneven distribution of control provides unsatisfactory results in image areas distant from the coast. For this reason, a first-degree polynomial function was used in coregistration and geometric correction. Features from corrected image data were digitized to ARC/INFO vector coverages using the digital overlay images as guides;

(5) Addition of geographic place-names (see table 1) and velocity contours; and addition of topographic contours at selected intervals, generated from the BPRC DEM data and modified where necessary to be congruent with surface features;

(6) Description of glaciological features (including the position of the grounding line) and analysis of ice-surface velocities of selected outlet glaciers, ice streams, and the Ronne Ice Shelf.

Geodetic Accuracy of the RADARSAT Image Mosaic[6]

Introduction

The RADARSAT image mosaic of Antarctica was selected as the most accurate base available for geolocating the Landsat imagery; therefore, it was considered essential to confirm the published geodetic accuracy of the mosaic (±150 m, Noltimier and others, 1999).

BPRC's Procedure

With the assistance of BPRC personnel, the procedure for constructing the RADARSAT image mosaic was comprehensively reviewed. BPRC used custom software from Vexcel, a contractor on the project (Norikane and others, 1998). Described simply, long radar data strips were digitally mosaicked into 24 blocks. These blocks were then rectified, using a generated digital terrain model to remove relief distortion, and mosaicked together to form the RADARSAT mosaic. Of the original 164 proposed sites for GCPs, 91 sites containing 231 high-quality GCPs were supplied by NIMA and identified on the RADARSAT imagery by ERIM. These were used in the block construction and the mosaic construction in conjunction with a calibration transponder located at the South Pole (K.F. Noltimier, BPRC, written commun., Oct. 9, 2001). The GCPs used were not evenly distributed over the continent, however, but tended to be in the flat coastal areas, with few in the mountainous regions. Some GCPs were withheld as a check of the overall accuracy. Unfortunately, the BPRC overall-accuracy check of the mosaic construction was not available for analysis. Large amounts of intermediate data were reviewed, basically the residuals for each tie point and control point used in each of the 24 blocks, but the overall results of the final block adjustments were not available. On the basis of a study of the data, the following analysis was made and conclusions reached.

USGS Analysis

Each block had three sets of errors called Block Overall, GCPs Overall, and Tie Points Overall. Each error set had both an average and a root mean square (RMS). Both the average and the RMS had separate values for x, y, and z, but no vector sum. In the sense used, it appears that "average" is really a measure of bias (shift); the RMS is essentially the residual. The RMS of the GCPs for each block was analyzed by the USGS, and a composite residual (the vector sum of the residuals in x, y, and z) for each block was calculated. The largest residual calculated was 113.5 m for block 2; the smallest residual calculated was 28.0 m for block 14. The overall residual for the 24 blocks was determined to be 74.0 m. However, the lack of control in mountainous areas would adversely affect the accuracy of the digital terrain models used to rectify the mosaic blocks and therefore the accuracy of the blocks.

Conclusions

From what is presently known, the published figure of ±150-m geolocation accuracy seems reasonable, at least in coastal areas where adequate control was utilized. This degree of accuracy assumes several considerations:

(1) that Vexcel's software was correctly written. No documentation has been made available that could be evaluated or peer-reviewed by non-Vexcel geodesists;

(2) that NIMA and ERIM technical personnel correctly identified the geodetic ground-control points in the radar data;

(3) that BPRC scientists and engineers made correct decisions in the selection of the 231 optimum GCPs and deletion of suspect GCPs.

Therefore, the only way to be absolutely certain of the geometric accuracy of the RADARSAT image mosaic would be to have the mosaic measured against well-distributed control, including mountainous areas not used in the mosaic construction. This could be done but would require using more GCPs and (or) evaluating the GCPs that BPRC used in the overall accuracy analysis.

Glaciological Features

The Ronne Ice Shelf area map covers that part of Antarctica that includes the ice shelf, Zumberge and Orville Coasts, part of Lassiter Coast, a small section of Palmer Land, and the eastern part of Ellsworth Land. It extends east to Berkner Island and south to the grounding line of the ice shelf. The map area lies approximately between long 45° and 90° W. and lat 74° and 84° S. The Ronne Ice Shelf is named for an American, Edith Ronne, who made important contributions to the planning, organization, and operation of the Ronne Antarctic Research Expedition, 1947–48, led by her husband, then Commander Finn Ronne, U.S. Naval Reserve. She accompanied her husband on the expe-

[6]Geodetic accuracy was determined by J. William Schoonmaker, research geodesist, USGS (retired).

dition, and served as a research scientist and journalist. She also is one of the first two women to winter over in Antarctica.

The Ronne Ice Shelf area map is dominated by the ice shelf containing two large named ice rises (Korff and Henry Ice Rises), one small ice rise (Hemmen Ice Rise), and five other named ice rises (Dott, Fletcher, Fowler, Kealey, and Skytrain Ice Rises) that are not ice rises in the glaciological sense. In addition, Berkner Island to the east is an ice rise. Ice rises are defined as ice masses, commonly dome-shaped, resting on rock and surrounded by ice shelf or ice shelf and sea. Airborne radio-echo sounding flights conducted by the British Antarctic Survey (BAS) (Swithinbank and others, 1976) showed that Fletcher and Fowler Ice Rises are not true ice rises. As a result, they were renamed Fletcher Promontory and Fowler Peninsula by the United King-dom. The remaining ice rises (Dott, Kealey, and Skytrain) would probably more accurately be named domes or promontories. The Ronne Ice Shelf also has several large areas of ice rumples (grounded areas overridden by the ice shelf), of which the Doake Ice Rumples are the most prominent and the largest in Antarctica, having a total area of about 2,300 km^2 (Smith, 1986). In the western side of the map area, the Ronne Ice Shelf is fed by two major ice streams (Evans and Rutford Ice Streams), and, to a much lesser degree, by the ice flowing in Carlson Inlet and through the Ellsworth Mountains. The Ellsworth Mountains are notable because they include Vinson Massif, the highest elevation in Antarctica (4,897 m). The mountains partly dam the flow of the ice sheet to the Ronne Ice Shelf, creating several outlet glaciers that flow through the mountains. Many named and unnamed valley glaciers also are found here. In fact, the number of unnamed glaciers is so numerous that we have not attempted to inventory them for this map. The southern part of the Ronne Ice Shelf is fed by Institute, Möller, and Foundation Ice Streams. There are 80 named glaciers and glaciological features within the map area (table 1), 39 of which are found in the Ellsworth Mountains. Although the large Support Force Glacier and some of its tributary glaciers can be seen in the southeast corner of the map, they are not discussed here, because they feed into the Filchner Ice Shelf, the topic of another map. The total area of the Ronne Ice Shelf, as measured digitally on the RADARSAT mosaic, is 365,441 km^2, including ice rises.

ANALYSIS

Coastal Change

In contrast to previously published maps in this series, the floating ice front of the Ronne Ice Shelf has not fluctuated very much, but recently has undergone substantial calving. From the time of the International Geophysical Year (IGY) (1957–58) until 1998, the ice front moved slowly seaward as the ice flowed from the south and west. The only noted calving event during that time occurred in 1992 and 1993, when an iceberg approximately 34 km by 12 km (~408 km^2 and 82 km^3) broke off the shelf (Oerter and others, 1998). However, on October 13, 1998, a NOAA (National Oceanic and Atmospheric Administra-tion) weather satellite image showed that a very large iceberg, about 140 km long and 40 km wide (~5600 km^2 in area) had calved from the ice front just northwest of Berkner Island. The iceberg, identified as A-38 by the U.S. National Ice Center, drifted north, and on October 22 broke into two large icebergs (A-38A and A-38B) and several smaller icebergs. On October 27, A-38B collided with the front of the ice shelf and caused iceberg A-39 to calve. The October calving events were of more than scientific interest, because iceberg A-38B was the site of the German Filchner summer scientific station and automatic weather station. The stations were later dismantled and recovered (Jung-Rothenhäusler and Oerter, 2000).

From May 4 through May 6, 2000, three more large icebergs (A-43A, A-43B, and A-44) broke off from the Ronne Ice Shelf front northwest of the 1998 calving and westward along the ice front all the way to the Lassiter Coast at the base of the Antarctic Peninsula, essentially straightening the front margin of the ice shelf. The 1998 and 2000 calving events removed between 40 and 50 years' ice advance and returned the ice front to the location mapped in the late 1940s and early 1950s (C.S.M. Doake and Ted Scambos, written communs., 1998).

The 1998 and 2000 calving of the Ronne Ice Shelf is not thought to be associated with climate change (C.S.M. Doake, BAS press release, Oct. 13, 1998), but rather is considered to be the result of accumulated strain. In fact, Doake (1996) had used a finite element model to generate a strain-rate field and predicted that the ice front was likely to calve during the next decade.

Glaciological Studies

The Ronne Ice Shelf area has been studied scientifically since at least the IGY (1957–58). Between that time and 1983, a few nations made independent and somewhat sporadic studies in the area. In 1983, the SCAR Working Group on Glaciology established the Filchner-Ronne Ice Shelf Programme (FRISP) to investigate thoroughly the glaciological regime of both the Filchner and Ronne Ice Shelves. Representatives of six nations (Argen-tina, Germany, Norway, the United Kingdom, the United States, and the U.S.S.R.) agreed to cooperate and to coordinate scientific plans to comprehensively study the area, as reported in Filchner-Ronne Ice Shelf Programme Report No. 1 (Kohnen, 1985). Since that time, annual meetings have been held, and reports of the cooperative work have been published in scientific journals and in FRISP Reports Nos. 1–15. The acronym FRISP originally stood for Filchner-Ronne Ice Shelf Programme. In about 2001, the program was renamed the Forum for Research into Ice Shelf Processes (still FRISP) to recognize the expanded nature of the research that included other related ice-shelf areas and oceanographic processes. The FRISP research has covered all aspects of the glaciological system, using new techniques and tools that have become available. The most valuable new techniques have been the various applications of remotely sensed data, including data from Landsat, the European Remote-Sensing Satellites (ERS), and RADARSAT. Within FRISP, the fieldwork on the western part of the Ronne Ice Shelf has been done primarily by the United Kingdom, and on the eastern and southern parts primarily by Germany.

Rutford Ice Stream

The most studied ice stream in the map area is Rutford Ice Stream. Extensive fieldwork was carried out in 1978–80 and 1984–86 and more recently, and reviews of the status of knowledge have been published (Doake and others, 1987, 2001). Rutford Ice Stream is unlike Siple Coast ice streams, which occupy subtle or subdued depressions in subglacial bed topography. In contrast, Rutford Ice Stream may occupy a major tectonic graben that has existed for millions of years (Doake and others, 1983). Ice thickness in the trough adjacent to the Ellsworth Mountains can be more than 2,300 m, and the subglacial bed about 2,000 m below sea level. The ice in the upper end of the ice stream is as much as 3,100 m thick (Frolich and Doake, 1988). Ice-velocity calculations using SAR interferometry were made by Stenoien (1998) in the drainage basin to the north and west of the Ellsworth Mountains. A maximum of 150 m a^{-1} (meters per year) was found close to the onset region of Rutford Ice Stream. The velocity increases to 200 m a^{-1} a short distance beyond the onset and 300 m a^{-1} where the ice stream flows past the junction with Carlson Inlet (about lat 77°30′ S., long 84° W.), and reaches a maximum of 400 m a^{-1} about 40 km upstream of the grounding line (Doake and others, 2001). Delineation of the drainage basin area, earlier estimated to be about 40,500 km^2 by Crabtree and Doake (1982) and about 36,000±4,000 km^2 by Doake and others (1987), has been somewhat modified with the use of various DEMs generated from radar data, and is now considered to be 62,500±1,000 km^2 (Rignot, 1998a, 2001) or 49,000 km^2 (Doake and others, 2001). Accumulation measurements are sparse, but using the database compiled by Vaughan and others (1999) for accumulation, and using the delineation of the drainage basin from satellite radar altimetry, a balance flux for Rutford Ice Stream is calculated to be 18.7±1 billion (10^9) metric tons per year. An estimate of the discharge at the grounding line amounting to 18.5±2 billion metric tons per year (Crabtree and Doake, 1982) suggests that the ice stream is in overall equilibrium (Doake and others, 2001). Field measurements of mass balance of the ice sheet in the vicinity of the Patriot Hills, made in 1995 by Casassa and others (1998), indicated that the ice was at near equilibrium in that location also during the period of measurement.

Carlson Inlet

The drainage basin of the ice flowing into Carlson Inlet is very small compared with the drainage basins of the adjacent Rutford and Evans Ice Streams (Rignot, 1998a, 2001). According to Rignot (1998a), the area is 9,200±100 km^2, less than 20 percent of the Rutford Ice Stream drainage. The velocity of the ice in Carlson Inlet has been reported by many researchers to range from <5 m a^{-1} to 10 m a^{-1}, a tiny fraction of Rutford Ice Stream velocity. Corr and others (2003) confirmed that the ice in Carlson Inlet is virtually stagnant, but noted that the current dominance by Rutford Ice Stream may not have been true in the past.

Evans Ice Stream

Evans Ice Stream flows in a tectonic trough, the floor of which is as much as 1,800 m below sea level (King and Bell, 1999). It has a large drainage basin, even larger than that of Rutford Ice Stream (Rignot, 1998a, 2001), and also a wider discharge area. The Evans Ice Stream region is noted for poor weather conditions, and it has been difficult to acquire data through either fieldwork or remote-sensing studies. However, observations based on Landsat images and on ERS SAR (European Remote-Sensing Satellite Synthetic-Aperture Radar) images described a complex pattern of flow composed of five tributaries in the interior ice sheet (Jonas and Vaughan, 1996) (as reported by Bamber and others, 2000). Ice-velocity determinations were made in two locations, roughly 10 and 25 km downstream from the grounding line, during an approximately one-year period between the 1994–95 and 1995–96 field seasons. The measurements were 624 m a^{-1} (upstream) and 615 m a^{-1} (downstream) (Adrian Jenkins, BAS, written commun., Nov. 5, 2003). Considering the size of the drainage basin, a velocity probably equal to or greater than that of Rutford Ice Stream, and the larger discharge area, this ice stream provides a substantial, but as yet unquantified, contribution to the mass balance of the ice shelf.

Institute Ice Stream

Institute Ice Stream enters the Ronne Ice Shelf southeast of Skytrain Ice Rise. Its remote location, midway between the main field operations of BAS and the German Alfred Wegener Institute for Polar and Marine Research (AWI), makes it a difficult location for conducting field studies, so much of the information on the area has been derived from remotely sensed data. The AWI made a brief radio-echo sounding survey of the area (Lambrecht, 1998). According to Raup and Scambos (2000), the ice stream is similar in flow and flow variability to the Siple Coast ice streams and has an ice plain similar to that of Whillans Ice Stream, formerly named Ice Steam B. From the position of Institute Ice Stream, it appears that the normal flow of the ice would be northeastward, directly seaward toward the Doake Ice Rumples. However, flow vectors derived by the National Snow and Ice Data Center (NSIDC) from analysis of Landsat imagery indicate that a good part of the flow is west of Korff Ice Rise, probably diverted by the presence of the Doake Ice Rumples. Ice thickness maps of Sandhäger and others (2004) confirm that the majority of the flow is toward the northwest, but work by Scambos and others (2004) indicates that there has been a recent change in outflow, with more flow toward the northeast. The NSIDC compilation of Antarctic ice-velocity data (VELMAP) derived from Landsat 4 and 5 TM data from 1986 and 1989 shows that the velocity of the ice stream ranges from 40 to 80 m a^{-1} on the eastern margin to almost 400 m a^{-1} in the center (http://nsidc.org/data/velmap/fris/institute/institute.html). Scambos and others (2004) used a combination of remotely sensed and geophysical data to comprehensively analyze the velocity, mass balance, and morphology of the ice stream. They determined the catchment area to be 141,700 km^2, the mean ice thickness across the grounding line to be 1,177 m, and the mass flux to the Ronne Ice Shelf to be 22.7±2 billion (10^9) metric tons per year.

Möller and Foundation Ice Streams

Extensive glaciological work has been carried out on the eastern and southeastern Ronne Ice Shelf by AWI since at least 1979–1980 (Kohnen, 1985). Reports of the work have been published in FRISP Reports Nos. 1–15 and in other scientific publications. The glacier flow in this area is entirely supplied by Möller and Foundation Ice Streams, although some of the flow of Foundation Ice Stream also contributes to the Filchner Ice Shelf. The FILCHNER V Campaign in 1995 carried out geophysical and glaciological fieldwork on the Ronne Ice Shelf from the ice edge to the grounding line of Foundation Ice Stream. Analysis of the data yielded information on the mass balance, ice velocity, ice thickness, and other parameters of the ice shelf/ice stream system as reported by Lambrecht and others (1998), as follows. At the grounding zone, the ice in Foundation Ice Stream is more than 2,000 m thick, but it thins rapidly to the north. In comparison, the ice in Möller Ice Stream is only 1,100 to 1,200 m thick, implying that Foundation Ice Stream contributes a much greater quantity of ice to the ice shelf. The ice in most of the southeastern part of the Ronne Ice Shelf is more than 1,000 m thick. The ice-flow velocity of Foundation Ice Stream is 586.5 m a^{-1} just north of the grounding line. The velocity decreases to 208 m a^{-1} south of Berkner Island, then increases toward the coast. Combining accumulation and ice-flow rates with ice thickness yielded a mass flux at the grounding line of 51 km^3 a^{-1} for Foundation Ice Stream and 23 km^3 a^{-1}, or less than half as much, for Möller Ice Stream. Comparing these data with ice-melt rates led to the conclusion that more than 70 percent of the ice volume from the ice sheet melts before it reaches the ice front (Lambrecht and others, 1999).

Remote-Sensing Studies

Remote-sensing studies have contributed greatly to the advance of knowledge of the Ronne Ice Shelf area. During the last 30 years, the data from Landsat, ERS, RADARSAT, and other satellites have been used extensively. One of the earliest uses of Landsat imagery was to make image mosaics in order to visually study the glaciological features and map the Ronne Ice Shelf, an area that could not be examined previously with regional coverage (Swithinbank and others, 1988; Sievers, 1994). Goldstein and others (1993) were among the first to use satellite

radar interferometry to monitor ice-sheet motion. They applied the technique in the Rutford Ice Stream area because of the availability of field studies for confirmation of their results. Complete coverage of the Ronne Ice Shelf with radar images from ERS-1 made it possible to produce an image mosaic (Jonas and Vaughan, 1996). This mosaic was used to create a new and updated analysis of the glaciological features and to calculate new ice-velocity data (Vaughan and Jonas, 1996). Frolich and Doake (1998) gave an extensive discussion of the use of synthetic aperture radar interferometry over Rutford Ice Stream and Carlson Inlet, and Rignot (1998b) confirmed the near equilibrium of Rutford Ice Stream, because he did not observe any hinge-line (grounding-line) migration when comparing radar interferometry of 1992 and 1996, in contrast to Pine Island Glacier (Rignot, 1998a). Most dramatically, the acquisition of RADARSAT data for the entire continent has revealed complex flow features that were not previously recognized, and radar interferometry is making it possible to calculate ice velocities in widespread areas (Jezek, 1999; Bamber and others, 2000).

Glacial History

A few studies have provided evidence about the glacial history of the Ronne-Filchner Ice Shelf area. Among them, Denton and others (1992), from work in the Ellsworth Mountains, determined that in late Wisconsinan time (~20,000 years before present), the West Antarctic Ice Sheet was about 400 to 650 m thicker than it is today, although the ice-flow direction was similar. More extensive work discussed by Kerr and Hermichen (1999) contained the conclusion by Höfle and Buggisch (1993) that the ice level at the end of the Miocene Epoch (~5.3 million years before present) had been high enough to overrun the entire Shackleton Range, east of the map area, implying a much thicker ice sheet in the area. The British (BAS)–German (AWI) Berk-ner Island Project has analyzed ice cores from the island that yield information on the environmental conditions in the entire Weddell Sea area for the last 1,200 years. The environmental conditions of the sites have changed very little in the last 600 years (Mulvaney and others, 2002).

Outlet-Glacier, Ice-Stream, and Ice-Shelf Velocities

Ice-velocity information is important for determining mass balance of the ice and for testing ice-shelf models, but there are too few velocity measurements in the Ronne Ice Shelf area to accurately resolve the basic features of flow (Vaughan and Jonas, 1996). On the map, the fastest flowing glaciers are Rutford Ice Stream and Evans Ice Stream. Velocity measurements made on Rutford Ice Stream, using both field and remote-sensing methods, yielded velocities ranging from 200 m a^{-1} downstream of the onset area, to 300 m a^{-1} where the ice stream flows past the junction with Carlson Inlet (about lat 77°30′ S., long 84° W.), to a maximum of 400 m a^{-1} about 40 km upstream of the grounding line (Doake and others, 2001). Frolich and Doake (1998) reported no significant change in ice motion between 1978 and 1992. Evans Ice Stream has had only two measurements made (624 m a^{-1} and 615 m a^{-1}, 10 km and 25 km downstream of the grounding line, respectively) which indicate that this ice stream is moving as fast as, or faster than, Rutford Ice Stream.

Vaughan and Jonas (1996) presented a digest of published and new velocities of the Ronne Ice Shelf. The published data were of surface measurements made with both celestial Doppler geoceiver and GPS observations. The new velocity measurements were made by calculating displacement of ice features between a Landsat mosaic of the area and an ERS-1 SAR mosaic. The velocity values range from 5 m a^{-1} to 1,736 m a^{-1}, gradually increasing from the grounded areas to the ice front. We have incorporated the velocity data from Vaughan and Jonas (1996) into our map because, although not comprehensive, they do give a very good general idea of ice flow. However, when comparing the distance traveled by the large rifts northeast of Korff Ice Rise (seen on the RADARSAT image as light traces) between March 1986 and September/October 1997, it appears that the ice velocity in that area is more than 1 km a^{-1} rather than the 700 to 800 m a^{-1} shown by the velocity contours.

Ice Thickness

Knowing ice thickness is crucial to studies of ice dynamics, mass balance, and ice-ocean-atmosphere interaction. Different research organizations in several countries have carried out ice-thickness measurements of the Ronne Ice Shelf using radio-echo sounding and seismic-reflection surveys since at least 1974 (Sandhäger and others, 2004). The information has been incorporated in BEDMAP, the digital database of ice thickness and seabed and bedrock topography for the entire continent coordinated by D.G. Vaughan, BAS (see http://www.antarc-tica.ac.uk/aedc/bedmap/). Sandhäger and others (2004) combined all available data sets to derive a comprehensive ice-thickness model for the entire Filchner-Ronne Ice Shelf, including meteoric (from snow accumulation) basal marine ice and total ice thickness. The results clearly show that the thickest ice (>2,000 m) occurs where the major ice streams enter the ice shelf, as would be expected.

Map Improvements

Prior to the advent of remotely sensed data, the Ronne Ice Shelf area as a whole had not been well mapped. In 1984, the USGS released a map of the Ronne Ice Shelf that was based on a mosaic of Landsat 1 images from 1973 and 1974 (U.S. Geological Survey, 1984). However, this map was not well georegistered because of the scarcity of geodetic ground control and the irregular orbit of the satellite.

During the development of the FRISP international cooperation, the German Institut für Angewandte Geodäsie (IfAG) made plans to intensively map the Ronne-Filchner Ice Shelf area using Landsat image data and newly acquired ground control where possible. The result was the publication by IfAG of five excellent maps at 1:2,000,000 scale portraying glaciology, topography, and seabed and bedrock topography (see references cited). However, the geodetic accuracy of these maps was still somewhat limited by the scarcity of ground control. Other larger scale, local-area maps have been produced by individual FRISP cooperating nations.

As discussed in the Sources and Methodology sections, this Ronne Ice Shelf area map was compiled from annotations of geographic and glaciological features on Landsat 1, 2, 4, 5, and 7 images that have been georegistered to the RADARSAT image mosaic, and therefore it is the most geodetically accurate map of the area currently available.

GLACIER INVENTORY

Producing a sophisticated and comprehensive glacier inventory of Antarctica according to the requirements of the World

Glacier Monitoring Service (WGMS), as part of its ongoing "World Glacier Inventory" program, is not possible with the present state of glaciological knowledge about Antarctica (Swithin-bank, 1980). Rignot and Thomas (2002) showed catchment-basin boundaries for 33 outlet glaciers and ice streams on their map of calculated ice-sheet-balance velocity. Their published map (approximate scale of 1:46,700,000) provides a continent-wide delineation of major ice-discharge basins, but in areas of steep slopes does not delineate smaller basins accurately. Future studies and additional remotely sensed data will permit higher precision in geographic positioning of divides and much greater detail (for example, subdivisions) of ice-discharge basins, thereby permitting application of WGMS guidelines to glacier inventories, especially in local areas, as has been done for more than 900 individual glaciers and glaciological features in the northern Antarctic Peninsula by Rau and others (in press).

Landsat images and available maps were used to produce a reasonably complete preliminary inventory of named valley glaciers, outlet glaciers, and ice streams, and also to identify related glaciological features more accurately, such as ice shelves, ice rises, ice rumples, and so forth, as defined in various scientific glossaries (Armstrong and others, 1973, 1977; Jackson, 1997) (see table 1). However, the large number of unnamed valley glaciers in the Ellsworth Mountains precluded the attempt to inventory all of the unnamed glaciers in this map area. The analysis of Landsat imagery for this map, coupled with aero-geophysical fieldwork in the ice-shelf area, has shown that in some cases geographic place-names do not accurately describe geographic and glaciological features. Table 1 lists geographic place-names shown on the Ronne Ice Shelf area map with the corresponding glaciological term or geographic feature that more accurately describes them. Ice rises, islands, peninsulas, and inlets in Antarctica were often incorrectly identified on earlier maps because of the lack of sufficient information.

SUMMARY

The analysis of Landsat 1 and 2 MSS images (1973–75), Landsat 4 and 5 MSS and TM images (1984–1991), the RADARSAT image mosaic (1997), and the Landsat 7 ETM+ image (2000), in addition to the extensive glaciological studies carried out by FRISP scientists, made it possible to identify and describe glaciological features of the Ronne Ice Shelf area. This map covers that part of Antarctica that includes the ice shelf, Zumberge and Orville Coasts, part of Lassiter Coast, a small section of Palmer Land, and the eastern part of Ellsworth Land. The map area is dominated by the Ronne Ice Shelf, which has two large named ice rises (Korff and Henry Ice Rises), one small ice rise (Hemmen Ice Rise), and five other named ice rises (Dott, Fletcher, Fowler, Kealey, and Skytrain Ice Rises) that are not ice rises in the glaciological sense. In addition, Berkner Island to the east is an ice rise. In the western part of the map area, the Ronne Ice Shelf is fed by two major ice streams (Evans and Rutford Ice Streams), and, to a much lesser degree, by the ice flowing in Carlson Inlet and through the Ellsworth Mountains. The southern part of the ice shelf is fed by Institute, Möller, and Foundation Ice Streams. The total area of the Ronne Ice Shelf, as digitally measured on the RADARSAT mosaic, is 365,441 km^2, including ice rises. In the map area, there are 80 named glaciers and glaciological features (table 1), 39 of which are found in the Ellsworth Mountains.

The most studied ice stream in the map area is Rutford Ice Stream. The ice thickness adjacent to the Ellsworth Mountains is more than 2,300 m, and at the upper end of the ice stream the thickness is as much as 3,100 m. Velocity calculations range from 150 m a^{-1} to a maximum of 400 m a^{-1}. Delineation of the drainage basin area from DEMs yields results ranging from 62,500±1,000 km^2 to 49,000 km^2. The ice stream is thought to be in near equilibrium. Evans Ice Stream has a larger drainage basin than Rutford Ice Stream. However, little work has been done on Evans Ice Stream. Considering the size of its drainage basin, the probable equal or greater velocity, and the wider discharge area, this ice stream provides a substantial, but as yet unquantified, contribution to the mass balance of the area.

Institute Ice Stream enters the Ronne Ice Shelf southeast of Skytrain Ice Rise, and is similar in flow and flow variability to the Siple Coast ice streams. The NSIDC compilation of Antarctic ice-velocity data shows that the velocity of the ice stream ranges from 40 to 80 m a^{-1} on the eastern margin to almost 400 m a^{-1} in the center.

The glacier flow in the eastern and southeastern parts of the Ronne Ice Shelf is entirely supplied by Möller and Foundation Ice Streams. At the grounding zone, the ice in Foundation Ice Stream is more than 2,000 m thick. In comparison, the ice in Möller Ice Stream is only 1,100 to 1,200 m thick at the grounding zone, implying that Foundation Ice Stream contributes a much greater quantity of ice to the ice shelf. Combining accumulation and ice-flow rates with ice thickness and ice-melt rates led to the conclusion that more than 70 percent of the ice volume from the ice sheet melts before it reaches the ice front.

Prior to the advent of remotely sensed data, the Ronne Ice Shelf area as a whole had not been well mapped. During the late 1980s and the 1990s, IfAG made plans to intensively map the Ronne-Filchner Ice Shelf area using Landsat image data and newly acquired ground control where possible. The result was the publication of five excellent maps at 1:2,000,000 scale. This Ronne Ice Shelf area map, compiled from annotations of geographic and glaciological features on Landsat 1, 2, 4, 5, and 7 images and georegistered to the RADARSAT image mosaic, is the most geodetically accurate map of the area available.

ACKNOWLEDGMENTS

We would like to acknowledge the outstanding support provided for the preparation of this map by numerous individuals. Ken C. Jezek and Katy F. Noltimier of the BPRC were extremely helpful by providing the RADARSAT image mosaic in several formats and by supplying data on digital construction and geometric accuracy of the mosaic. Our thanks go to C.S.M. Doake and D.G. Vaughan, BAS, and John Splettstoesser for thoughtful reviews that improved the map and text. Charles Swithinbank's participation in the project was made possible by the much-appreciated support of Jerry C. Comati, Chief, Environmental Sciences Branch, U.S. Army Research, Development, and Standardization Group (London, United Kingdom) of the U.S. Army Materiel Command. We are indebted to Dann S. Black-wood, USGS (Woods Hole, Mass.) and Lewis V. Thompson, USGS (Reston, Va.) for custom photographic processing of Landsat images. Funding for the project was provided by the USGS commitment to the multi-Federal agency U.S. Global Change Research Program (now the U.S. Climate Change Science Program), the U.S. part of the International Geosphere-Biosphere Programme.

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Table 1.—Inventory of Named Glaciers or Glaciological Features.

Geographic place-name[1]	Glaciological term or geographic feature[2]
Ahrnsbrak Glacier	valley glacier
Balish Glacier	valley glacier
Barcus Glacier	valley glacier
Barnes Icefalls	outlet glacier
Berkner Island	ice rise
Bowie Crevasse Field	crevasse field
Branscomb Glacier	valley glacier
Brown Glacier	outlet glacier
Carey Glacier	valley glacier
Chambers Glacier	valley glacier
Childs Glacier	outlet glacier
Crosswell Glacier	valley glacier
Dater Glacier	valley glacier
Doake Ice Rumples	ice rumples
Dobbratz Glacier	valley glacier
Dott Ice Rise	ice dome
Drake Icefall	outlet glacier
Drewry Ice Stream	ice stream
Driscoll Glacier	valley glacier
Edge Glacier	valley glacier
Ellen Glacier	valley glacier
Embree Glacier	valley glacier
Evans Ice Stream	ice stream
Fendorf Glacier	valley glacier
Flanagan Glacier	valley glacier
Fletcher Ice Rise	peninsula
Ford Ice Piedmont	ice piedmont
Foundation Ice Stream	ice stream
Fowler Ice Rise	peninsula
Gowan Glacier	valley glacier
Grimes Glacier	valley glacier
Guerrero Glacier	valley glacier
Hansen Glacier	valley glacier
Hemmen Ice Rise	ice rise
Henderson Glacier	valley glacier
Henry Ice Rise	ice rise
Hough Glacier	valley glacier
Hudman Glacier	valley glacier
Hyde Glacier	valley glacier
Institute Ice Stream	ice stream
Irvine Glacier	outlet glacier
Jaburg Glacier	outlet glacier
Johnston Glacier	outlet glacier
Kealey Ice Rise	ice dome
Kershaw Ice Rumples	ice rumples
Ketchum Glacier	outlet glacier
Korff Ice Rise	ice rise
Kovacs Glacier	valley glacier
Matthews Glacier	outlet glacier
Median Snowfield	icefield
Minnesota Glacier	outlet glacier
Möller Ice Stream	ice stream
Newcomer Glacier	outlet glacier
Nimitz Glacier	outlet glacier
Patton Glacier	valley glacier
Plummer Glacier	valley glacier
Remington Glacier	valley glacier
Rennell Glacier	valley glacier
Ronne Ice Shelf	ice shelf
Rutford Ice Stream	ice stream/outlet glacier
Sallee Snowfield	icefield
Schanz Glacier	valley glacier
Schmidt Glacier	valley glacier
Schneider Glacier	valley glacier
Seal Glacier	valley glacier
Skytrain Ice Rise	ice dome
Spear Glacier	outlet glacier
Splettstoesser Glacier	outlet glacier
Srite Glacier	outlet glacier
Strange Glacier	outlet glacier
Support Force Glacier[3]	ice stream/outlet glacier
Thomas Glacier	valley glacier
Thompo Icefall	outlet glacier
Ueda Glacier	outlet glacier
Union Glacier	outlet glacier
Waverly Glacier	valley glacier
Webster Glacier	valley glacier
Wessbecher Glacier	valley glacier
Wetmore Glacier	outlet glacier
Young Glacier	valley glacier

[1]The comprehensive listing of 80 named glaciers and other glaciological features was derived from published maps of the area encompassed by the Ronne Ice Shelf area map and gazetteers. The geographic place-names are included in Alberts (1981, 1995), in National Science Foundation (1989), and on the USGS Geographic Names Information System (GNIS) web page.

[2]The descriptive terms used to characterize the glaciological or geographic features were derived from analysis of the Landsat images and geophysical work described in the text. For definitions of glaciological terms, see Armstrong and others (1973, 1977) [primary references] and Jackson (1997) [secondary reference].

[3]This glacier is not discussed in the text because it feeds into the Filchner Ice Shelf, which is the topic of another map in this series.

Table 2.—Coastal-change and glaciological maps of Antarctica at 1:1,000,000 scale, published to date.

[Information on ordering published maps can be obtained by calling the U.S. Geological Survey at 1-888-ASK-USGS or by visiting the USGS online at http://www.usgs.gov/]

As shown on index map	Map number	Map name	Reference (see References Cited)
D	I–2600–D	Ronne Ice Shelf	This report
E	I–2600–E	Eights Coast	Swithinbank and others (2004)
F	I–2600–F (2d ed.)	Bakutis Coast	Swithinbank and others (2003b)
G	I–2600–G	Saunders Coast	Swithinbank and others (2003a)