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Coastal-change and glaciological map of the Bakutis Coast area, Antarctica: 1972–2002

By Charles Swithinbank, Richard S. Williams, Jr., Jane G. Ferrigno,
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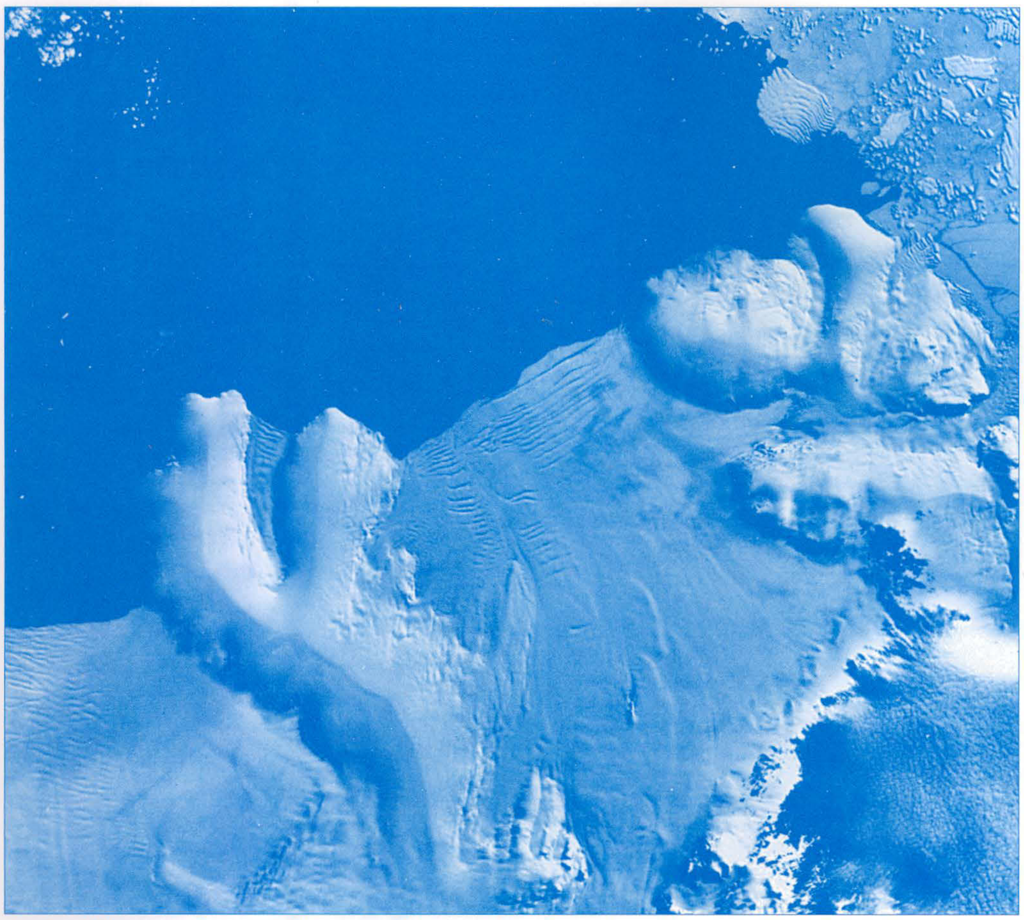
Geologic Investigations Series Map I–2600–F (2d ed.)



Landsat Multispectral Scanner (MSS) image of Martin and Bear Peninsulas and Dotson Ice Shelf, Bakutis Coast, Antarctica. Path 6, Row 113, acquired 30 December 1972.

Swithinbank and others—Coastal-change and glaciological map of the Bakutis Coast area, Antarctica: 1972–2002 1:1,000,000 I–2600–F (2d ed.)

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COASTAL-CHANGE AND GLACIOLOGICAL MAP OF THE BAKUTIS COAST AREA, ANTARCTICA: 1972–2002

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Kevin M. Foley,[3] and Christine E. Rosanova[4]

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 the western part is thickening, the northern part is thinning. Joughin and Tulaczyk (2002), based on 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. The mass balance of the East Antarctic 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 over 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 consisting of 24 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; and Ferrigno and others, 2002).

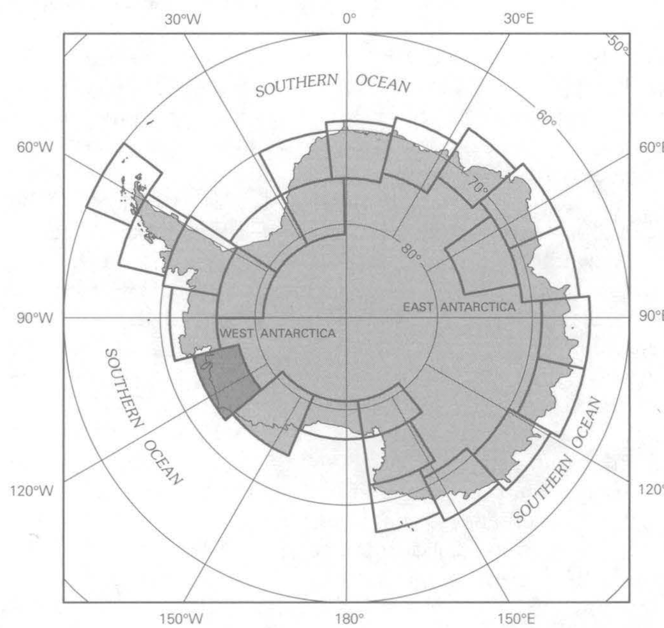

Figure 1.—Index map of the planned 24 coastal-change and glaciological maps of Antarctica at 1:1,000,000 scale. Bakutis Coast area map is shaded.

Objectives

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

(1) to determine coastline changes that have occurred during the past three decades, or longer where 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 example, floating ice, grounded ice, etc.) of the coastline of Antarctica during three time intervals: (1) early 1970s

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(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 images or from ancillary sources (for example, maps, gazetteers, digital databases, etc.) (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 24 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 81.5° S. lat).

Sources

Landsat images used in the compilation of the Bakutis Coast area map were obtained from either the USGS EROS Data Center, Sioux Falls, SD 57198, or the former Earth Observation Satellite (EOSAT) Corporation, now Space Imaging LLC, 12076 Grant St., Thornton, CO 80241. The coverage areas of the Landsat 1 MSS and Landsat 4 and 5 MSS and TM 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 specific images that were used to measure ice velocities are listed in table 1 in this pamphlet. 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. The early Landsat scenes cover the years 1972 and 1973. The later Landsat images are from 1984 to 1990. The 125-m picture-element (pixel)-resolution RADARSAT image mosaic of Antarctica 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 9 September to 20 October 1997 (Jezek, 1998). The 1997 RADARSAT image mosaic was obtained from The Ohio State University's Byrd Polar Research Center (BPRC). An Advanced Very High Resolution Radiometer (AVHRR) image dated 11 March 2002 was downloaded from the National Ice Center website to document recent coastal change in the Thwaites Glacier area.

Methodology

The primary steps in the compilation of the Bakutis Coast area map[5] are listed and discussed below:

(1) Identification of optimum Landsat MSS or TM images for two time intervals (early 1970s; middle 1980s to early 1990s) and enlargement to a nominal scale of 1:500,000;

(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. Having a goal of producing the most accurate, high-resolution printed maps and digital databases of the coastal regions of Antarctica, considerable thought and research was expended 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 again 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. 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 25 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 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 Imagery and Mapping Agency (NIMA) and the Environmental 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 mosaic is cited as ±150 m (Noltimier and others, 1999). Orthorectification of the mosaic was done using a Digital Elevation Model (DEM) generated by the BPRC specifically for the production of the mosaic. Data used in construction

[5]This 2003 edition is the second edition of Map I–2600–F; the first edition, a prototype map using only annotated Landsat images for two time intervals and conventional ground-control points, was published in 1997 (Swithinbank and others, 1997). The second edition is intended to supersede, not supplement, the first edition. It is recommended that the second edition be cited as follows:

Swithinbank, Charles, Williams, R.S., Jr., Ferrigno, J.G., Foley, K.M., and Rosanova, C.E., 2003, Coastal-change and glaciological map of the Bakutis Coast area, Antarctica: 1972–2002: U.S. Geological Survey Geologic Investigations Series Map I–2600–F (2d ed.), 1 sheet, scale 1:1,000,000, with 10-p. pamphlet.

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) 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 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 passpoints. 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 velocity vectors, geographic place-names, and codes for unnamed outlet glaciers and ice streams identified on Landsat images (see tables 1 and 2); and addition of topographic contours at selected intervals, generated from BPRC DEM data and modified where necessary to be congruent with surface features;

(6) Analysis of coastal changes, glaciological features (including the position of the grounding line), and ice-surface velocities of selected outlet glaciers, ice streams, and ice shelves.

Geodetic Accuracy of the RADARSAT Image Mosaic of Antarctica[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 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., 9 Oct. 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. Based on 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 Bakutis Coast area map covers the part of Marie Byrd Land that extends from the western part of Pine Island Bay (long 104° W.) to the western part of Getz Ice Shelf (long 130° W.) and includes parts of the Hobbs and Walgreen Coasts. The map shows two main types of glaciological features: the constantly moving, floating ice front of the ice shelves (Getz, Dotson, and Crosson Ice Shelves) interspersed with relatively stable ice walls

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

of islands and peninsulas, and the Thwaites Glacier system (Thwaites Glacier, Thwaites Glacier Tongue, and Thwaites Iceberg Tongue). The digitally measured length of the ice front is 1,120 km, of which 510 km or 45 percent is ice walls and 610 km or 55 percent is floating ice front. The part of Getz Ice Shelf in the western three-fifths of the map area is by far the largest ice shelf shown. It is about 450 km long and ranges from 25 to 110 km wide. The area of Getz Ice Shelf on this map, including ice rises, was measured to be 26,922 km^2 using the 1997 ice front. The ice shelf continues for another 140 km to the west of the map area. Getz Ice Shelf is divided into five ice-front segments by four islands (Dean, Siple, Carney, and Wright) from the western edge of the map area to Martin Peninsula. The next ice shelf to the east is Dotson Ice Shelf, between Martin and Bear Peninsulas. It is about 50 km long and 70 km wide, and its area in 1997 was 3,872 km^2. Dotson Ice Shelf is fed by the large Kohler Glacier and several smaller named and unnamed glaciers. Crosson Ice Shelf, south and east of Bear Peninsula, is slightly smaller than Dotson Ice Shelf and is nourished mainly by Smith, Pope, Vane, and Haynes Glaciers. Its size was not measured because it blends into the Thwaites Glacier system on the east. Siple Island, Carney Island, Martin Peninsula, and Bear Peninsula also contain small ice shelves. Twenty-seven named and 11 unnamed glaciers and ice streams flow into the ice shelves or directly into the Amundsen Sea; three other named glaciers are located in interior mountain ranges.

The Thwaites Glacier system, on the eastern edge of the map, is the most dynamic and shows the most change in the map area. As is sometimes the case with large glaciers, the Thwaites Glacier had a relatively coherent iceberg tongue as a detached part of the glacier tongue. The location of the iceberg tongue as of December 1972 is plotted on the map from Landsat data. All three glaciological features in the Thwaites Glacier system were prominent enough to carry separate place-names. Subsequent satellite data show that the Thwaites Iceberg Tongue has disappeared and the Thwaites Glacier Tongue has experienced major calving. The changes in the Thwaites Glacier system are discussed further in the section on coastal change.

ANALYSIS

Overview

As would be expected, ice fronts, iceberg tongues, and glacier tongues are the most dynamic and changeable features in the coastal regions of Antarctica. Seaward of the grounding line of outlet glaciers, ice streams, and ice shelves, the floating ice margin is subject to frequent calving and rapid flow. Both of these situations lead to annual and decadal changes in the position of ice fronts on the order of several kilometers, even tens of kilometers in extreme cases of major, infrequent calving. On this map, the positions of the dynamic ice fronts as observed on the two sets of Landsat imagery and the 1997 RADARSAT image mosaic have been mapped and annotated with the exact date for each position (the exact date is given for Landsat imagery, but only the year is given for the RADARSAT image mosaic because all the imagery was acquired between 9 September and 20 October 1997). This makes it possible to accurately analyze changes that have occurred. Where lines representing ice fronts on the map end abruptly, it is due to the absence or margin of a Landsat image or to cloud cover. Although calving does occur along ice walls, the magnitude of the change on an annual to decadal basis is generally not discernible on either the Landsat images or the RADARSAT image mosaic; therefore, ice walls can be used as relatively stable reference features against which to measure other changes along the coast. Only a single observation date is given for the position of ice walls.

Outlet Glacier, Ice Stream, and Ice Shelf Velocities

Larger glacier tongues and ice shelves have well-developed crevasse patterns. These patterns can be tracked over time and used for velocity calculations. Surface velocities of selected glaciers were determined by two methods: an interactive one in which crevasse patterns were tracked visually on images (Lucchitta and others, 1993) and an auto-correlation program developed by Bindschadler and Scambos (1991) and Scambos and others (1992). Under optimum conditions, errors can be as small as ±0.02 km a^{-1} (kilometers per year), but for most Landsat image pairs, where registration of features is accurate to one or two pixels, the accuracy of velocity vectors is ±0.1 km a^{-1}. The measurement errors improve when there are longer time intervals between the images and faster velocities, both increasing ice displacement. Ten to one hundred measurement points were made for each glacier tongue or ice shelf (table 1). Thwaites Glacier is the fastest moving ice stream in West Antarctica. It had an average velocity of 2.8 km a^{-1}, ranging from 2.6 km a^{-1} about 20 km downstream of the grounding line to 3 km a^{-1} at the front of the tongue, on the basis of visual feature tracking on images acquired in December 1984 (50276–14524) and January 1990 (42734–14552) (Ferrigno and others, 1993, 1998). These velocity figures reflect the usual trend of glacier velocities gradually increasing from the grounding line to the ice front. Rosanova and others (1998, 2000) reported on new velocity measurements made with Landsat TM images of 1988 and 1990 and ERS SAR (European Remote Sensing Satellite Synthetic Aperture Radar) data of 1993 and 1994 using the cross-correlation technique. The cross-correlation velocities of 1988 to 1990 ranged from 2.5 km a^{-1} just downstream of the grounding line to 3.2 km a^{-1} at the northwest front of the tongue. The apparently lower velocities of the 1984 to 1990 time interval may reflect averaging over a longer time interval, if earlier lower velocities were included. On ERS SAR images, the velocities ranged from 3 km a^{-1} downstream of the grounding line to 3.4 km a^{-1} at the front of the ice tongue. All these data support an increase in velocity on the tongue. In contrast, a velocity of about 2.2 km a^{-1} was obtained for the ice at the grounding line both on the Landsat TM images of 1988 and 1990 and on the ERS SAR images of 1993 and 1994, indicating no increase in velocity in the grounded part of the ice stream. Measurements by Rignot (2001) have indicated that the grounding line of Thwaites Glacier is retreating, which suggests thinning.

On the basis of Landsat images acquired in January 1973 (1174–14325) and January 1988 (42016–14343), the floating tongue of Smith Glacier moved across Crosson Ice Shelf at an average rate of 0.6 km a^{-1}, although the velocity was 0.5 km a^{-1} near the grounding line. The Smith Glacier tongue increased in velocity to an average of 0.7 km a^{-1} between January 1988 and January 1990 at the ice front. Dotson Ice Shelf, into which numerous named glaciers (Singer, McClinton, Dorchuk, Keys, Horrall, Kohler, Boschert, True, Zuniga, Brush, and Sorenson) and two unnamed glaciers flow, has an average velocity of 0.4 km a^{-1}, with a range from about 0.2 to 0.5 km a^{-1} measured at the ice front using ERS SAR data (Lucchitta and others, 1993, 1994; Rosanova and others, 1998). The eastern end of Getz Ice Shelf has measured velocities that range from 0.2 to almost 0.6 km a^{-1}. From Siple Island to Dean Island, the velocities at the ice front range from about 0.5 to 0.7 km a^{-1}. At the western edge of the map area, where part of the Getz Ice Shelf flow is contributed by DeVicq Glacier, the velocities range from 0.7 to almost 1.2 km a^{-1}.

Coastal Change

An analysis of Landsat images and the RADARSAT image mosaic of the coast between Wrigley Gulf and the western part of Pine Island Bay (long 130°–104° W.) indicates the following changes. Along Getz Ice Shelf west of Dean Island, the ice front receded 6 km on the eastern part of the tongue of DeVicq Glacier between January 1973 and February 1988. During the same time period, the ice front advanced 3 to 12 km between the DeVicq Glacier tongue and Dean Island. Because the ice-shelf velocity is more than 1 km a^{-1} near the front of the tongue of DeVicq Glacier, the ice front would have advanced more than 15 km in this area during the 15-year interval between the two Landsat images if no calving had occurred. The 6-km recession actually indicates a net loss of more than 21 km. Between February 1988 and September 1997, the ice front receded about 12 km, a more than 21-km additional loss, yielding a net loss in width in this area between 1973 and 1997 of more than 42 km. It is not possible to give a quantitative evaluation of ice-area or ice-volume loss because so little of DeVicq Glacier is visible on this map sheet. East of the DeVicq Glacier tongue to Dean Island, between 1973 and 1988 the advance of the ice front is close to what would be expected if there had been no calving, with the greater advance occurring closer to the faster-moving glacier and the smaller advance occurring closer to Dean Island, where the ice velocity would be slower. However, between 1988 and 1997, the entire ice front receded between 5 and 18 km, with the greatest amount occurring near DeVicq Glacier.

Between Dean Island and Siple Island, a small advance of the ice front and a slightly larger retreat occurred between 1973 and 1988. Between 1988 and 1997 there was a general retreat of up to 3 km. However, this section of the ice shelf has a velocity at the ice front of about 700 m a^{-1}, which would have produced an ice-front advance of more than 10 km during the 15 years between 1973 and 1988 and more than 6 km between 1988 and 1997. As there was a small net loss along the 70-km-long ice front between Dean and Siple Islands between 1973 and 1988, and a larger loss between 1988 and 1997, this is actually a total net loss of more than 19 km of ice front width, or more than 1,330 km^2 of ice in this area.

West of Carney Island, a small part of Getz Ice Shelf receded 1 to 5 km between December 1972 and February 1988. Between February 1988 and September 1997, a small area advanced 1 km; the rest receded from 0.6 to 1 km. There are no velocity measurements on the ice shelf in this area between Siple Island and Carney Island, and therefore this area cannot be analyzed further. East of Carney Island to Wright Island, the ice velocity near the coast averages 500 m a^{-1}, and the ice front is either in the same position or receded an average of about 1 km on the Landsat images from 1973 and 1990. Between January 1990 and September 1997, the ice front remained stable for about one-third of the distance, and retreated as much as 2 km in the remaining part. The ice front would have advanced more than 8 km in the time interval between the early and later Landsat imagery and more than 3.5 km from 1990 to 1997, a total of 11.5 km. Along this almost 55-km-long, semi-stable ice front, a net ice loss of more than 690 km^2 is indicated. The eastern part of Getz Ice Shelf, between Wright Island and Martin Peninsula, receded between November 1973 and December 1986 an average of about 1 km, and, from December 1986 to September 1997, about 2 km. This ice front would have advanced more than 7 km during the 24 years if no calving had occurred, because of the ice-front velocity of 300 m a^{-1}. This loss of about 10 km of ice through the almost 40-km-wide mouth of the ice shelf indicates a net ice loss of more than 400 km^2.

The 46-km-wide ice front of Dotson Ice Shelf also receded 1 to 6 km, averaging more than 3 km, between January 1973 and January 1990. With a velocity of about 500 m a^{-1} at the front, the ice shelf would have advanced almost 8.5 km during this 17-year interval if there had been no calving activity. Between January 1990 and September 1997, the ice front receded between 1 and 2 km in some areas and advanced as much as 3 km, with an average advance of about 1 km instead of the 3 km that would have occurred with no calving. Therefore, the net loss measures about 13.5 km or more than 600 km^2.

The largest changes have occurred in the Thwaites Glacier Tongue and in the adjacent Crosson Ice Shelf, and along the coast of Pine Island Bay to the eastern edge of the map area. From the southeastern end of the ice wall of the Hamilton Ice Piedmont (at about long 110° W.) to the ice wall west of Pine Island Glacier (just beyond the eastern edge of the map area, at about long 104° W.) is a distance of 186 km. Along the 62-km-wide front of Crosson Ice Shelf that includes the confluence of Smith, Pope, and Vane Glaciers, the ice front receded 5 to 13 km, roughly averaging about 10 km, between December 1972 and January 1988. The ice velocity averages about 700 m a^{-1} at the front of the ice shelf, which would have produced a 10.5-km ice-front advance in the 15 years between images. The recession represented a net loss of 20.5 km or almost 1,300 km^2 of ice. Between January 1990 and September 1997, most of the ice front of Crosson Ice Shelf advanced an average of more than 5 km, an amount to be expected from the measured ice-front velocity, indicating little calving. The exception to this was a 25-km-wide area between the main part of Crosson Ice Shelf and Thwaites Glacier where the ice front had an average net retreat of about 10 km from 1988 to 1997; this ice front is nourished primarily by Haynes Glacier. The calculation of ice loss in this region is complicated by the substantial changes that took place in the Thwaites Glacier system between 1972 and 1995. In 1972, the Thwaites Iceberg Tongue was located just north of and adjacent to the Thwaites Glacier Tongue. Its presence may have slowed the velocity of the glacier and also trapped much of the ice that would have calved from the glacier tongue. In 1986, the ice at the southern end of the Thwaites Iceberg Tongue began to break up (Ferrigno and Gould, 1987). Over the next several years, the iceberg tongue moved northward into the Amundsen Sea, rotated until parallel with the coastline, and moved slowly westward. It grounded briefly north of the Bakutis Coast, but by 1995 had drifted northwestward across the continental shelf (T.A. Scambos, National Snow and Ice Data Center, Boulder, Colo., written commun., 1995), and, by 1996, had moved out of the area and broken into three or more smaller icebergs (S. Jacobs, Lamont-Doherty Earth Observatory, Palisades, N.Y., oral commun., 1996).

The irregular 60-km-wide terminus of the Thwaites Glacier Tongue advanced about 8 km between December 1972 and January 1988; between January 1988 and January 1990, it advanced another 4 km. The velocity at the front of the Thwaites Glacier Tongue averaged more than 2.8 km a^{-1} during these time periods. This would have caused the glacier tongue to advance more than 45 km between 1972 and 1990 and would indicate a 33-km net loss in the length of the ice tongue, or about 2,000 km^2. More recent measurements of ice-front velocity with

Landsat TM images of 1988 and 1990 and ERS SAR images of 1993 and 1994 (Rosanova and others, 2000) indicate the ice front to be moving at 3.2 km a^{-1} or 3.4 km a^{-1}, respectively. The ice front advanced about 26 km between January 1990 and September 1997, an amount that would be expected with little or no calving. Additional remotely sensed data, MODIS (Moderate Resolution Imaging Spectroradiometer) and AVHRR images from February and March 2002, indicated the ice front had advanced another 15 km before calving a massive, 5,500-km^2 iceberg from the glacier tongue. This iceberg represented about 65 percent of the Thwaites Glacier Tongue area before calving.

Eastward of the Thwaites Glacier Tongue, the approximately 60 km of ice front to the eastern edge of the map area advanced as much as 10 km and receded as much as 15 km between the dates of the Landsat images used to map this area. Between the Landsat data and the RADARSAT data, advance of about 3 km and recession of about 15 km occurred. However, there are no velocity measurements to allow more quantitative analysis.

Combining the rough estimates of ice discharge calculated for the ice fronts shown on this map (and considering the several small areas of ice front that were not analyzed) yields a total of more than 12,000 km^2—or a rough average of more than 400 km^2 a^{-1}—of net loss of ice-shelf area from this sector of the Antarctic coastline during the approximately 30-year interval between the Landsat images of the early 1970s and the AVHRR image of 2002. Assuming an average thickness of 200 m at the front of the ice shelf, this represents a net loss of about 2,400 km^3 during the 30 years, or approximately 80 km^3 a^{-1} for the segment of the coastline of West Antarctica shown on the Bakutis area map. The Thwaites Iceberg Tongue had an approximate area in late December 1972 of 7,000 km^2; assuming a thickness of 200 m, the approximate ice volume was 1,400 km^3. This volume is not included in the above calculation of net ice loss.

Map Revisions

As discussed in the Sources and Methodology sections, the Bakutis Coast area map was compiled from annotations of geographic features on Landsat 1, 4, and 5 images that were georegistered to the RADARSAT image mosaic. The area had been previously mapped by the USGS based on trimetrogon aerial photography and geodetic ground surveys on three 1:500,000-scale Antarctica Sketch Maps (Bakutis Coast–Marie Byrd Land, Hobbs Coast–Marie Byrd Land, and Thurston Island–Jones Mountains, all published in 1968), with shaded relief but generally without contours; and on 11 Antarctica 1:250,000-scale Topographic Reconnaissance Series maps (Bear Peninsula, 1978; Crary Mountains, 1976; Dean Island, 1976; Martin Peninsula, 1978; McCuddin Mountains, 1976; Mount Galla, 1960; Mount Hampton, 1960; Mount Murphy, 1977; Mount Sidley, 1960; Mount Takahe, 1988; and Toney Mountain, 1977). Comparison of those earlier maps with the Bakutis Coast area map reveals the following improvements in cartographic representation of the geographic features.

The three sketch maps cover the entire coastal area covered by this Bakutis Coast area map and most of the inland geographic features, with the exception of the Executive Committee Range. Comparing the representation of the coastal features on the sketch maps with this map, the sketch maps do represent the location of the major geographic features along most of the coastline, with several significant exceptions. Some prominent coastal features were mislocated on the reconnaissance and sketch maps. Siple Island lies 20 km west and 25 km south of its mapped position on the Hobbs Coast–Marie Byrd Land Sketch Map; corresponding features on Siple Island were misplaced by as much as 33 km. The coastline from Siple Island east to Bear Peninsula was misplaced 10 to 15 km to the west of its true position. Landsat 4 and 5 imagery also showed that the Thwaites Iceberg Tongue moved from its original mapped position, as would be expected of a dynamic feature. The shape of the iceberg tongue is somewhat different from its 1966 outline, which was based on rectification of (oblique) trimetrogon aerial photographs.

Comparing the Bakutis Coast area map, which is based on analysis of Landsat and RADARSAT images, with the 1:250,000-scale Topographic Reconnaissance Series maps, it is clear that the Reconnaissance Series maps are better at portraying bedrock outcrops and some other small features. However, this map is better at defining many of the glaciological features, especially the grounding lines.

The analysis of Landsat imagery has also shown that in some cases geographic place-names do not accurately describe geographic features. Table 2 lists geographic place-names shown on the Bakutis Coast area map with the corresponding glaciological term or geographic feature that accurately describes them. Islands, peninsulas, and inlets in Antarctica were often incorrectly identified on earlier maps because of the lack of sufficient information. On this map, two inlets are actually ice shelves; Nunn Island has been glaciologically reclassified as an ice rise; and two peninsulas, Bear Peninsula and Duncan Peninsula, are probably islands.

GLACIER INVENTORY

Producing a sophisticated glacier inventory of Antarctica according to the requirements of the World Glacier Monitoring Service, as part of its ongoing "World Glacier Inventory" program, is impossible with the present state of glaciological knowledge about Antarctica (Swithinbank, 1980). Landsat images and available maps were used to produce a reasonably complete preliminary inventory of named and unnamed outlet glaciers and ice streams (those that are unnamed were given a latitude/longitude identifier) and also to identify related glaciological features more accurately, such as ice domes, ice piedmonts, ice shelves, ice rises, ice rumples, glacier tongues, iceberg tongues, and so forth, as defined in various scientific glossaries (Armstrong and others, 1973, 1977; Jackson, 1997) (see table 2).

SUMMARY

The analysis of Landsat 1 MSS images (1972 and 1973), Landsat 4 and 5 MSS and TM images (1984 to 1990), the RADARSAT image mosaic (1997), and AVHRR imagery (2002), all used in the preparation of this map of the Bakutis Coast area, made it possible to identify and describe glaciological features, document coastal change, and look for trends in the changing coastline. The Bakutis Coast area map shows two main types of glaciological features. Most of the coastal area is composed of the constantly moving, floating ice front of the ice shelves interspersed with relatively stable ice walls on islands and peninsulas. The digitally measured length of the ice front is 1,120 km, of which 610 km or 55 percent is floating ice front. At the eastern edge of the map area is the dynamic Thwaites Glacier system (Thwaites Glacier, Thwaites Glacier Tongue, and Thwaites Iceberg Tongue). Twenty-seven named and 11 unnamed glaciers and ice streams flow into the ice shelves or directly into the Amundsen Sea; three other named glaciers are located in interior mountain ranges.

There are three large, named ice shelves along the coast (Getz, Dotson, and Crosson Ice Shelves) and a few small, unnamed ice shelves in inlets of Siple and Carney Islands and Martin and Bear Peninsulas. Getz Ice Shelf is by far the largest, having a length of about 450 km on this map, and an area, including ice rises, of 26,922 km^2. Measured velocities along the front of Getz Ice Shelf range from almost 1.2 km a^{-1} at the western edge of the map area, where the DeVicq Glacier tongue flows through the ice shelf, to 300 m a^{-1} on the eastern part of the ice shelf; the velocities gradually decrease from west to east. Dotson Ice Shelf is smaller than Getz Ice Shelf and has an area of 3,872 km^2. Its ice-front velocities were measured at 500 m a^1. Crosson Ice Shelf is smaller than Dotson Ice Shelf. Its size was not measured because it blends into the Thwaites Glacier system to the east. Velocities along its ice front were determined to be about 700 m a^{-1}.

The Thwaites Glacier system (glacier, glacier tongue, and iceberg tongue) is the most dynamic feature in the Bakutis Coast map area and has shown the most change. Thwaites Glacier is the fastest moving ice stream in West Antarctica, having velocities that range from 2.5 km a^{-1} just below the grounding line to 3.4 km a^{-1} at the front of the glacier tongue. Between 1986 and 1995, the Thwaites Iceberg Tongue, which had been adjacent to and just north of Thwaites Glacier Tongue, moved away from the glacier tongue and slowly drifted out of the map area. In March 2002, a massive, 5,500-km^2 iceberg calved from Thwaites Glacier Tongue; the iceberg represented about 65 percent of the tongue area.

Observing the changes in the Bakutis area coastline for the four time periods represented on this map reveals the following trends. Along the front of Getz Ice Shelf, there has been alternating advance and recession ranging from 1 km to almost 20 km, but the most recent coastline (1997) shows the most recession. Dotson and Crosson Ice Shelves have shown first recession (as much as 13 km) and then advance (as much as 10 km). In the Thwaites Glacier system, the Thwaites Iceberg Tongue has disappeared, and a 5,500-km^2 part of Thwaites Glacier Tongue has calved, leaving the tongue the shortest since first documented by aerial photography in 1947. The overall trend during the time period of the map is recession.

Combining the rough estimates of ice discharge from the ice fronts shown on this map yields a minimum discharge of 12,000 km^2, or a rough average of more than 400 km^2 a^{-1} of net loss of ice-shelf area from this sector of the Antarctic coastline during the 30-year interval between the Landsat images of the early 1970s and the AVHRR data of 2002.

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Table 1.—Landsat MSS and TM images used in the measurement of velocities of outlet glaciers, ice streams, and ice shelves

Glaciological feature	Landsat image	Path/Row	Image No.	Date
Thwaites Glacier Tongue	Base images (MSS)	006/112	50276-14521	2 Dec 84
		006/113	50276-14524	2 Dec 84
	Coregistered images (TM)	004/113	42016-14341	22 Jan 88
		006/113	42734-14552	9 Jan 90
Smith Glacier	Base image (TM)	008/113	41996-14580	2 Jan 88
	Coregistered images (MSS)	008/113	42748-15073	23 Jan 90
		004/114	1177-14500	16 Jan 73
Dotson Ice Shelf	Base image (TM)	008/113	41996-14580	2 Jan 88
	Coregistered image (MSS)	004/114	1177-14500	16 Jan 73
Getz Ice Shelf (between Wright Island and Martin Peninsula)	Base images (TM)	013/112	51029-15244	25 Dec 86
		013/113	51029-15250	25 Dec 86
	Coregistered images (MSS)	010/113	1488-15160	23 Nov 73
		010/114	1488-15163	23 Nov 73
Getz Ice Shelf (between Duncan Peninsula and Wright Island)	Base images (TM)	013/112	51029-15244	25 Dec 86
		013/113	51029-15250	25 Dec 86
	Coregistered images (MSS)	010/113	1488-15160	23 Nov 73
		010/114	1488-15163	23 Nov 73
Beakley Glacier	Base images (TM)	013/112	51029-15244	25 Dec 86
		013/113	51029-15250	25 Dec 86
	Coregistered image (TM)	015/112	42749-15502	24 Jan 90
Armour Inlet (east side)	Base images (TM)	018/112	42050-16013	25 Feb 88
		018/113	42050-16015	25 Feb 88
	Coregistered images (MSS)	014/113	1492-15390	27 Nov 73
		014/114	1492-15392	27 Nov 73
Armour Inlet (west side)	Base images (TM)	018/112	42050-16013	25 Feb 88
		018/113	42050-16015	25 Feb 88
	Coregistered images (MSS)	018/112	1172-16035	11 Jan 73
		018/113	1172-16042	11 Jan 73
Getz Ice Shelf (between Siple Island and Dean Island)	Base images (TM)	018/112	42050-16013	25 Feb 88
		018/113	42050-16015	25 Feb 88
	Coregistered images (MSS)	018/112	1172-16035	11 Jan 73
		018/113	1172-16042	11 Jan 73
Getz Ice Shelf (west of Dean Island)	Base images (TM)	018/112	42050-16013	25 Feb 88
		018/113	42050-16015	25 Feb 88
	Coregistered images (MSS)	018/112	1172-16035	11 Jan 73
		018/113	1172-16042	11 Jan 73

Table 2.—Glacier inventory

Geographic place-name[1]	Glaciological term or geographic feature[2]
Named	
Beakley Glacier	ice stream
Boschert Glacier	outlet glacier
Brush Glacier	outlet glacier
Bunner Glacier	outlet glacier
Clausen Glacier	outlet glacier
Dorchuk Glacier	outlet glacier
Hamilton Ice Piedmont	not a true ice piedmont[3]
Haynes Glacier	ice stream
Holt Glacier	outlet glacier
Horrall Glacier	outlet glacier
Hulbe Glacier	outlet glacier
Keys Glacier	outlet glacier
Kohler Glacier	ice stream/outlet glacier
McClinton Glacier	outlet glacier
Nereson Glacier	outlet glacier
Park Glacier	outlet glacier
Parks Glacier	outlet glacier
Pope Glacier	ice stream/outlet glacier
Roos Glacier	outlet glacier
Simmons Glacier	outlet glacier
Singer Glacier	outlet glacier
Smith Glacier	ice stream/outlet glacier
Sorenson Glacier	outlet glacier
Steuri Glacier	outlet glacier
Thurston Glacier	outlet glacier
Thwaites Glacier	ice stream
Thwaites Glacier Tongue	ice shelf/glacier tongue
Thwaites Iceberg Tongue	iceberg tongue
True Glacier	outlet glacier
Vane Glacier	outlet glacier
Vornberger Glacier	outlet glacier
Yoder Glacier	outlet glacier
Zuniga Glacier	outlet glacier
Unnamed[4]	
AN77427S11344W	outlet glacier
AN77423S11351W	outlet glacier
AN77423S11637W	ice stream
AN77420S11950W	ice stream
AN77353S12032W	outlet glacier
AN77349S12431W	outlet glacier
AN77334S12543W	outlet glacier
AN77322S12608W	outlet glacier
AN77444S12542W	ice stream
AN77452S12919W	ice stream
AN77455S12957W	ice stream

Table 2.—Glacier inventory—Continued

Geographic place-name[1]	Glaciological term or geographic feature[2]
Other features	
Armour Inlet	ice shelf
Bear Peninsula	island (?)
Burke Island	island
Carney Island	island
Clark Island	island
Crosson Ice Shelf	ice shelf
Dean Island	ice rise
Dotson Ice Shelf	ice shelf
Duncan Peninsula	island (?)
Getz Ice Shelf	ice shelf
Gurnon Peninsula	peninsula
Martin Peninsula	peninsula
Moore Dome	ice dome
Nunn Island	ice rise
Philbin Inlet	ice shelf
Rydelek Icefalls	icefall
Scott Peninsula	peninsula
Siple Island	island
Wright Island	island

[1]The comprehensive listing of named glaciers and selected other named glaciological and physical features was derived from published maps of the area encompassed by the Bakutis Coast area map. The geographic place-names are included in Alberts (1981, 1995) and National Science Foundation (1989). The 11 unnamed glaciers were identified from analysis of the Landsat images.

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

[3]The Hamilton Ice Piedmont does not meet the currently accepted definition of ice piedmont (Armstrong and others, 1973).

[4]Unnamed outlet glaciers and ice streams that have been identified on Landsat images were each given a geographic location code. For example, the code AN77427S11344W represents Antarctica (AN7), location at lat 74°27′ S. (7427S), long 113°44′ W. (11344W). AN7 is the continent code assigned for Antarctica by the World Glacier Monitoring Service. A latitude and longitude designator (degrees and minutes) is used in place of a drainage basin/glacier number code, because the latter is yet to be defined for Antarctica.

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