Glaciers of North America–

GLACIERS OF CANADA

GLACIERS OF THE ARCTIC ISLANDS

GLACIERS OF BAFFIN ISLAND

By JOHN T. ANDREWS

With sections on BARNES ICE CAP: GEOMORPHOLOGY AND THERMODYNAMICS
By GERALD HOLDSWORTH

LATE 20TH CENTURY CHANGE AT THE BARNES ICE CAP MARGIN
By JOHN D. JACOBS

SATELLITE IMAGE ATLAS OF GLACIERS OF THE WORLD

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The glaciers on Baffin Island are primarily ice caps or ice fields and associated valley outlet glaciers and include numerous small glaciers as well. The two largest ice caps, the Barnes Ice Cap (5,935 km^2*) and the Penny Ice Cap (5,960 km*^{2}*) are thought to be the last remnants of the Laurentide Ice Sheet. Approximately 8 percent of Baffin Island is covered by glaciers (36,839 km*^{2}*). Nearby Bylot Island is heavily glacierized; it has 4,859 km*^{2} *of its area covered by glaciers, about 45 percent of the island. The Barnes Ice Cap has been slowly shrinking; the recession could accelerate if significant regional warming were to take place*

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GLACIERS OF NORTH AMERICA–

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By JOHN T. ANDREWS[1]

With sections on

BARNES ICE CAP: GEOMORPHOLOGY AND THERMODYNAMICS

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LATE 20TH CENTURY CHANGE AT THE BARNES ICE CAP MARGIN

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Abstract

Glaciers on Baffin Island are strongly influenced by topography and climate. The major glaciers are either ice caps that occupy inland highland areas or ice fields and associated valley outlet glaciers, or they are combinations of both. Other significant glaciers are found on Cumberland Peninsula, on Hall Peninsula, and along the east fjord coast of the island. Baffin Island glaciers are covered by 1:1,000,000-scale, 1:250,000-scale, and some 1:500,000-scale and 1:50,000-scale maps, aerial photographs at 1:50,000 scale, Landsat imagery, and other satellite imagery (e.g., RADARSAT). Landsat images are used to describe individually the separate glacierized areas of the island, especially the areas of Barnes and Penny Ice Caps, which are thought to be the last remnants of the Laurentide Ice Sheet.

Introduction

Baffin Island, Nunavut, Canada[4], extends between lat 62° and 74°N. and long 62° and 90°W. (fig. 1). The island has an area of about 500,000 km^2, which makes it one of the five largest islands in the world. Most of the island is composed of Precambrian granites, granite gneisses, and other metamorphic rocks; therefore, most of the glaciers on the island overlie these hard and resistant lithologies. However, younger sedimentary rocks of Paleozoic to Cenozoic age (Kerr, 1980) crop out at the surface along the west coast of the

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[4] The geographic place-names used in this section follow the usage approved by the Geographic Names Board of Canada. Names in common usage that are not recognized by the Board are shown in italics.

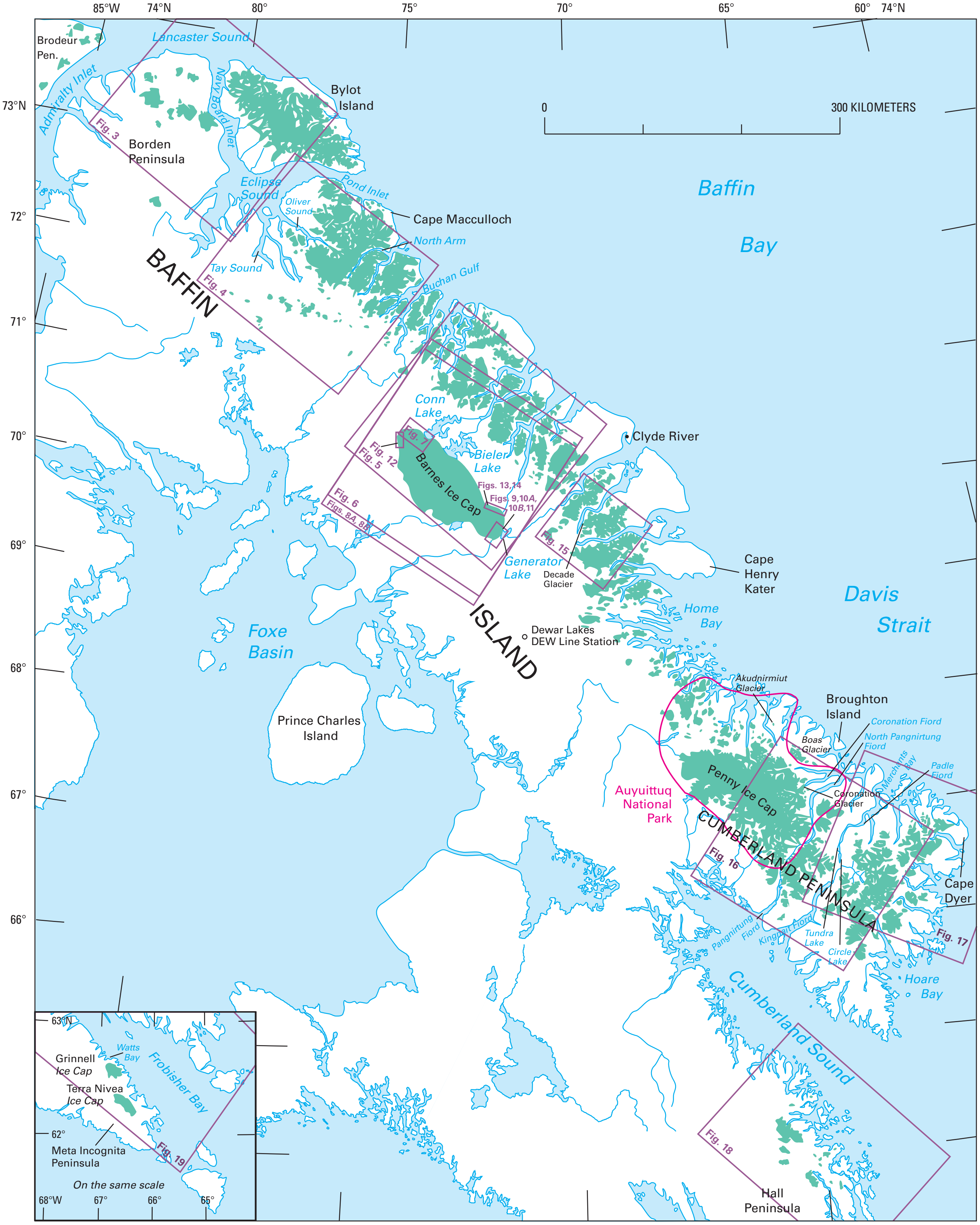

Figure 1.*—Baffin Island and adjacent regions, Nunavut, Canada, showing the location of major glaciers and other features. Also shown are the outlines for figures 3–19, including the approximate outlines of Landsat images discussed in the text and used for figures 3–6, 8, and 15–19 (see also table 3). Abbreviation: Pen., Peninsula.*

island (Paleozoic formations) and extend northward to form major uplands in the northern part of Baffin Island. Mesozoic and Cenozoic (Tertiary) rocks are found on Bylot Island, one of the most heavily glacierized tracts in the region.

The pattern of the present glacierization on Baffin Island is influenced strongly by topography and climate. Baffin Island can be represented simply in cross section (east to west) as a wedged-shaped prism that has the highest land lying within 10 to 100 km of the outer fault-bounded east coast (Ives and Andrews, 1963; Kerr, 1970). Fjords of various sizes cut through the uplifted rim (Dowdeswell and Andrews, 1985) and head toward the broad, rolling interior plateau of the island, where elevations range between 600 and 700 m and decline gradually westward toward the shores of Foxe Basin (see Bird, 1967). The maximum elevations shown on the U.S. Defense Mapping Agency's Operational Navigational Charts (ONC C–12 and B–8) are 2,057 m near the center of the Penny Ice Cap and 1,905 m on Bylot Island (fig. 1). Elevations in excess of 800 m are restricted to the areas between the heads of the fjords and the outer east coast and along the fault-bounded south side of Frobisher Bay (inset map in fig. 1).

Climatic data from Baffin Island are sparse and are biased toward meteorological data recorded at coastal stations. Selected data are shown in table 1. At the Dewar Lakes Distant Early Warning (DEW) Line Station in central Baffin Island (fig. 1), the mean annual temperature is –13°C, with a July mean temperature of 6.0°C (Maxwell, 1980, 1982). Precipitation is notoriously difficult to measure in Arctic areas and is most probably underestimated (Hare and Hay, 1971). Nevertheless, the snowfall records from the stations, combined with snowpit work on the glaciers (for example, Baird, 1951; Ward and Baird, 1954; Sagar, 1966; Weaver, 1975; Hooke and others, 1987), indicate that winter accumulation on most glaciers probably varies between 30 and 60 cm water equivalent.

Distribution of Glaciers

The interaction between topographic and climatic gradients results in a particular geographic distribution of glaciers (see Andrews and others, 1970; Andrews and Barry, 1972). A regional picture of the interaction can be obtained by mapping the glaciation level (also called glaciation limit or glaciation threshold) by the "summit method" of Østrem (1966). The glaciation level for the region of Baffin Bay is drawn from maps in Andrews and Miller (1972) and Weidick (1975) and is shown in figure 2. The glaciation level is the elevation at which, in a regional sense, the long-term net mass balance equals zero (b_n=0). Areas above this level will generally support an ice mass, whereas mountains or hills whose summits lie below this limit will be ice free under the present climate. The glaciation level on Baffin Island dips toward Baffin Bay at about 4 m km^{-1} from a maximum elevation of about 1,200 m to a minimum of 600 m (fig. 2). The proximity of the glaciation level to the broad plateau of the interior of Baffin Island and the evidence there for

TABLE 1.—*Selected climatic data showing temperature in degrees Celsius for climatic regions on Baffin Island and environs*

[Modified from Maxwell, 1982. The averages noted here are from available sources; the length of record is not uniform. For a more complete description of the climatic regions of Baffin Island, see Maxwell (1982).]

Climatic region	January	July	Total precipitation (mm)
Northern Baffin Island	–20 to –33	+3 to +5	150 to 300
Western interior	–28 to –32	+5 to +8	175 to 250
Mountains	–28 to –32	+4 to +5	300 to 600
Southeastern Baffin Island	–25	+5 to +8	400 to 500

extensive neoglacial snow cover (Ives, 1962; Andrews and others, 1976; Locke and Locke, 1977; Williams, 1978) are reasons why Baffin Island is frequently considered to be a major area for the initial growth of the Laurentide Ice Sheet (Ives and others, 1975; Andrews and others, 1972).

On Baffin Island, the major glaciers, such as the Barnes Ice Cap, either occupy inland highland areas or are ice fields and associated valley outlet glaciers (Bylot Island) (Sugden and John, 1976), or they are combinations of both (Penny Ice Cap) (fig. 1, table 2). In the southern part of the island, two significant ice caps located along the south rim of Frobisher Bay are called the Grinnell and Terra Nivea *Ice Caps* (Mercer, 1956). Other significant glaciers are found on Hall Peninsula in the south, Cumberland Peninsula to the north, and as a broad band of glacierized terrain extending along the east coast (fjord) part of the island between the northern Cumberland Peninsula and Bylot Island (fig. 1). Small, largely decaying ice caps and ice patches are present on the upland surfaces in northern Baffin Island and to some extent north and west of the Barnes Ice Cap (Falconer, 1962, 1966; Andrews and others, 1976). The major glaciers were discussed by Mercer (1975), and his work is still a basic reference on Baffin Island glaciers.

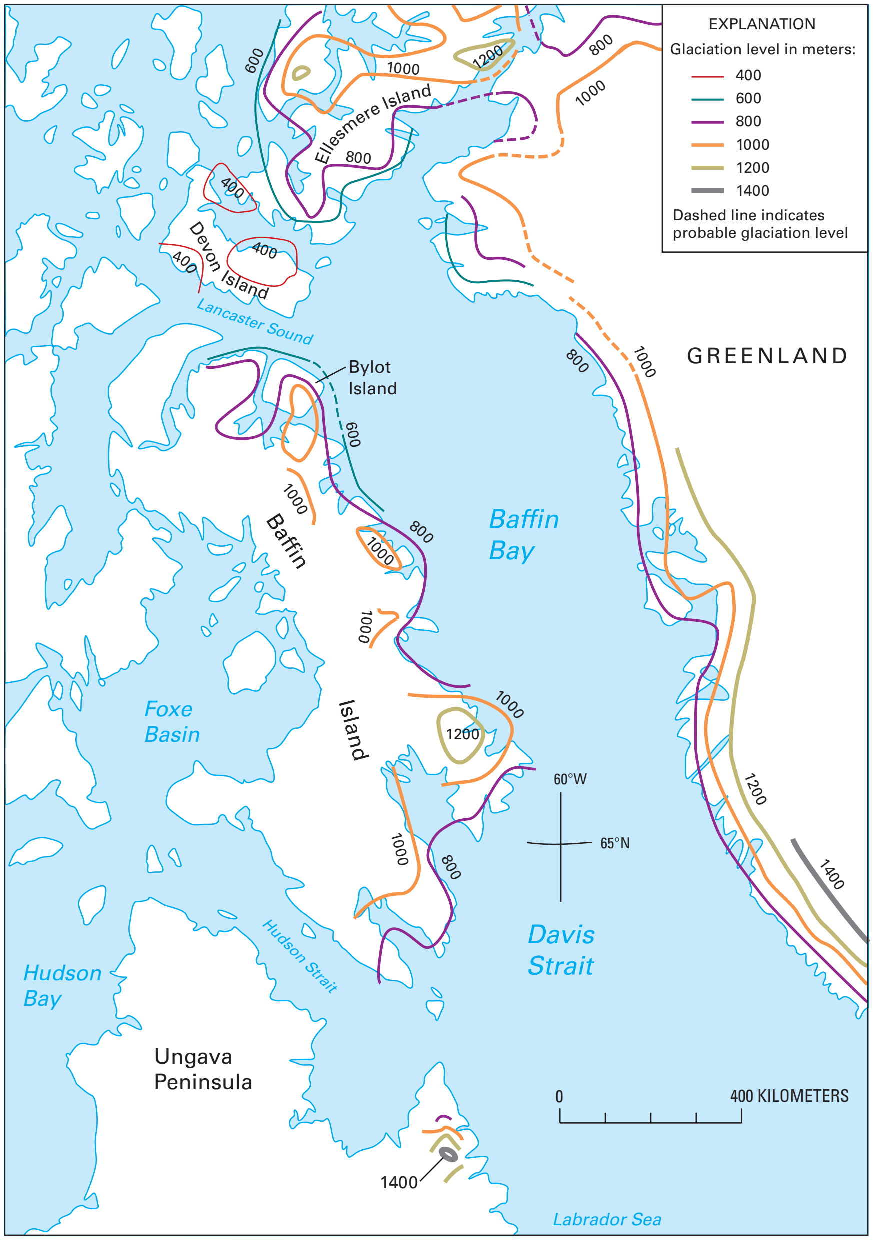

Figure 2.*—Glaciation level (limit or threshold) on Baffin Island and West Greenland (modified from Andrews and Miller, 1972, and Weidick, 1975).*

TABLE 2.—*Areas of glaciers on Baffin Island and Bylot Island*

[Modified from Mercer, 1975; Bird, 1967]

Name	Area (square kilometers)	Figure number (this section)
Baffin Island		
Penny Ice Cap	5,960	1, 16
Barnes Ice Cap	5,935	1, 5, 6, 7, 8*A*, 8*B*, 9, 10*A*, 10*B*, 11, 12, 13, and 14
"Hall" Ice Cap	490	1, 18
Terra Nivea *Ice Cap*	165	1, 19
Grinnell *Ice Cap*	139	1, 19
Other glaciers	24,150	1, 3, 4, 15, and 17
Total	36,839	
Bylot Island	4,859	1, 3

The ice caps, ice fields, outlet glaciers, and smaller glaciers of Baffin Island have been mapped and included in the Canadian National Inventory of Glaciers (Ommanney, 1980); each has a unique glacier inventory code. The area is covered by National Topographic Series (NTS) map sheets 16/26, 25, 27/37, and 48/58, all at a scale of 1:1,000,000. Specific glacier identification is available on a series of 1:500,000-scale maps (for example, the Grinnell and Terra Nivea *Ice Caps* on the Meta Incognita Peninsula, Glacier Inventory, area 46205; Glacier Atlas of Canada, plate no. 5–24; Canada Department of Energy, Mines and Resources, Inland Waters Branch, IWB 1124, 1969). The entire area is covered by 1:250,000-scale topographic maps. For Bylot Island, the glacierized parts of the northern Brodeur Peninsula, Borden Peninsula, and the nearby area southwest of Pond Inlet are covered by 1;50,000-scale topographic maps. Topographic maps at a scale of 1:50,000 cover a number of small decaying glaciers south of Eclipse Sound between lat 71° and lat 72°N.

Glaciological Studies

Falconer (1962) initiated an inventory of glaciers of Baffin and Bylot Islands from aerial photographs. Following this work, done for the former Geographical Branch of the Canadian Department of Mines and Technical Surveys (later Energy, Mines and Resources, presently Natural Resources Canada), the task of collecting historical records on glacier positions was inherited by the Glaciology Subdivision of Environment Canada. To my knowledge, a systematic survey of historical accounts has not been done. The earliest observations known are the observations of John Ross (1819) on glaciers of the Erik Harbour area, the description of glaciers of Bylot Island by P.G. Sutherland (1852), the work of Leopold M'Clintock (1860) on glaciers of the Bylot Island area, and observations of C.F. Hall, an American explorer. Hall sailed along the south coast of Frobisher Bay in 1860–62 (Hall, 1865) and noted (p. 520), "...From the information I had previously gained, and the data furnished by my Innuit companion, I estimated the Grinnell Glacier to be fully 100 miles long." This account may suggest that heavy snows mantled the high ground on Meta Incognita Peninsula, where Grinnell *Ice Cap* is located (fig. 1), to a greater extent than they do today. Another possible source of information is the logs of whalers who sailed into Baffin Bay from the 17th century onward. It would seem likely that some observations of glacier extent would appear in the ship logs.

The scientific observation of glaciers on Baffin Island was initiated in 1950, when the Arctic Institute of North America (AINA) sponsored an experienced expedition to study the Barnes Ice Cap (Baird, 1951). This was followed in 1953 by a smaller venture that focused on glaciological and glacioclimatic measurements of the Penny Ice Cap (Baird, 1953; Baird and others, 1953; Orvig, 1954; Ward and Baird, 1954). Some earlier photographic records and sketches of glaciers in Pangnirtung Pass, Cumberland Peninsula, were obtained by the naturalist Dr. J. Dewey Soper in the course of his sledge travels from 1924 to 1926 (Soper, 1981).

The next major glaciological research program on Baffin Island was promoted by the former Geographical Branch of the Canadian Department of Mines and Technical Surveys. Studies were undertaken on the Barnes Ice Cap (Sagar, 1966; Løken and Andrews, 1966; Anonymous, 1967; Church, 1972) and on the Decade Glacier to the east (Østrem and others, 1967). The Barnes Ice Cap program was continued by the Glaciology Subdivision of Environment Canada (Holdsworth, 1973b, 1977) and by R. LeB. Hooke and colleagues from the University of Minnesota (Hooke, 1973, 1976; Hooke and others, 1980, 1982, 1987; Hudleston, 1976).

In 1969, a small research program in glaciology, specifically on mass and energy balance, was started by the University of Colorado. The focus of the research was the *Boas Glacier*, a small glacier northeast of Penny Ice Cap (fig. 1) (Andrews and Barry, 1972; Jacobs and others, 1974; Weaver, 1975). This work was discontinued in 1976. Plans to extract an ice core from the Penny Ice Cap commenced in the 1980's with a survey of recent snow accumulation (Holdsworth, 1984; Short and Holdsworth, 1985). A combined Canadian, Japanese, and U.S.A. research effort extracted cores to bedrock during the middle 1990's; these cores have been examined in detail for paleoenvironmental data (Fisher and others, 1998).

Other glaciological papers dealing with Baffin Island are listed in an annotated bibliography prepared by Andrews and Andrews (1980). Given the large area covered by various glaciers (36,839 km^2), approximately 8 percent of the island, (Bird, 1967; Mercer, 1975) (table 2), glaciological research on Baffin Island is generally lacking. Virtually nothing is known of the mass balance or dynamics, for example, of the two southern ice caps situated on Meta Incognita Peninsula (Blake, 1953; Mercer, 1956), although research on neoglacial events and on glacial processes has been reported and is part of a program supported from the University of Colorado (Muller, 1980; Dowdeswell, 1982, 1984). Jacobs and others (1997) used Landsat images to evaluate the recent history of the south margin of the Barnes Ice Cap.

Maps, Aerial Photographs, and Satellite Images of Glaciers

Glacier Maps

The Canadian government flew a special series of survey flights in 1961 over north-central Baffin Island in order to provide 1:50,000-scale vertical aerial photographic coverage of Barnes Ice Cap. The photographs were subsequently used to compile, along with aerial photogrammetric methods, a special 1:50,000-scale map series of Barnes Ice Cap and environs. The area is covered by seven map sheets (37E/1W, 37E/2W, 37E/2E, 37E/3W, 37E/6W, 37E/7E, and 37E/7W). A digital elevation model of the Barnes Ice Cap, based on Landsat MSS data was prepared by Lodwick and Paine (1985). Elsewhere on the island, some good quality orthophotomaps exist of the glacierized terrain in the vicinity of Pangnirtung Pass, Cumberland Peninsula (fig.1). These maps were produced at a scale of 1:50,000 for a project associated with the establishment of a new national park (Auyuittuq National Park) that includes most of Penny Ice Cap and large areas of glacierized alpine terrain (fig. 1).

Baffin and Bylot Islands are covered by specially prepared maps produced by the former Glaciology Division, Environment Canada. These maps are at a scale of 1:1,000,000 and show the major and minor glaciers. The map identification numbers for the series are 1WB 1005 (northern Baffin Island) and 1WB 1006 (southern Baffin Island). Information about maps can be obtained by contacting Geomatics Canada, Natural Resources Canada, 130 Bentley Avenue, Ottawa, Ontario K1A 0E9, Canada (tel: 613–952–7000 [1–800–465–6277]; fax: 1–800–661–6277; World Wide Web site: [http://www.geocan.nrcan.gc.ca]).

In addition, the glaciers of the area have been inventoried by the Glaciology Division. Each ice mass has a unique identification code. The individual glaciers that have been inventoried are mapped and identified on a series of color maps at a scale of 1:500,000. Baffin Island and Bylot Island are covered by plate numbers 5–0 to 5–24. Part of Grinnell Glacier, Baffin Island, Northwest Territories [now Nunavut], was mapped by the Norwegian Water Resources and Energy Administration, and a map was published in 1991; the scale of the map is 1:20,000.

Aerial Photographic Coverage of Glacierized Areas

The National Air Photo Library (NAPL) is located in Ottawa, Ontario, and is part of the Department of Natural Resources. All government-sponsored aerial photography is kept in the library, together with index sheets showing flightlines and center points of each photograph. The index maps are normally at a scale of 1:250,000 or 1:500,000.

Much of the glacierized part of Baffin Island was flown in 1948 by using trimetrogon aerial photography. The central image (vertical aerial photograph) of the trio is at a scale of about 1:20,000. Conventional vertical aerial photographs were taken during the 1950's and into the 1970's. The flying height for these photographs appears to have been normally about 9,146 m, and a 15-cm lens was used, which gives a nominal ground scale of about 1:50,000 (assuming a terrain elevation of 1,524 m). Virtually all the glacierized terrain on Baffin and Bylot Islands is covered by this vertical aerial photography. The quality of coverage varies but is most often excellent to good. Many areas have coverage in two or more years.

Color aerial photography is rare; however, some of this coverage exists for parts of Barnes Ice Cap and the mountains between there and Clyde River on the coast (fig.1). In addition, color aerial photography at small scale was taken for part of the Auyuittuq National Park.

Information on coverage can be obtained by contacting the NAPL, Geomatics Canada, Natural Resources Canada, 615 Booth St., Ottawa, Ontario K1A 0E9, Canada (tel: 613–995–4560 [1–800–230–6275]; fax: 613–995–4568; World Wide Web site: [http://airphotos.nrcan.gc.ca]).

Landsat Coverage

Landsat images are available for Baffin Island either through the U.S. Geological Survey's EROS Data Center or through the Canada Centre for Remote Sensing[5] (see table 3 and figure 1). One particularly important product is a series of black-and-white Landsat mosaics that can be bought directly from the NAPL, Geomatics Canada (see above).

The mosaics are at a scale of 1:1,000,000, and coverage is as follows:

NTS 25	Coverage of Terra Nivea and Grinnell *Ice Caps* and parts of Hall Peninsula

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[5] U.S. Geological Survey, EROS Data Center, Sioux Falls, S. Dak. 57198 (tel: 605–594–6151 [1–800–252–4547]; fax: 605–594–6589; World Wide Web: http://edc.usgs.gov/). Canada Centre for Remote Sensing, Geomatics Canada, Natural Resources Canada, 588 Booth Street, Ottawa, Ontario K1A 0Y7, Canada (tel: 613–995–4057; fax: 613–992–0285; World Wide Web: [http://www.ccrs.nrcan.gc.ca]).

NTS 16–26	Coverage of the Cumberland Peninsula (Penny Ice Cap) and northern Hall Peninsula
NTS 26–36	Koukdjuak River, includes Penny Ice Cap
NTS 27–37	Coverage of north-central Baffin Island including the Barnes Ice Cap and mountain glaciers
NTS 48–58	Coverage of most of Bylot Island, all of Devon Island, and the small ice caps on Borden Peninsula and Brodeur Peninsula (figs. 1 and 2)

The quality of the mosaics is normally excellent, and they are at the same scale and cover the same areas as the 1:1,000,000-scale topographic map series produced by the Government of Canada. The Landsat mosaics and topographic maps are an excellent combination for laboratory exercises in aspects of both glacial geology and glaciology.

Glaciological Phenomena Observed on Landsat Images

Several Landsat images have been selected for inclusion in this section. They are mostly high quality false-color composite images that reveal several important glaciological features. Their coverage area is shown in figure 1, and details of each Landsat image are tabulated in table 3. For ease of reference, they will be discussed in a north-to-south sequence.

TABLE 3.—*Landsat images used in figures 3–6, 8, and 15–19 and National Topographic Series (NTS) map sheets*

[Code symbols: ●, Excellent image (0 to ≤5 percent cloud cover), ◕, Good image (>5 to ≤10 percent cloud cover), ◐, Fair to poor image (>10 to ≤100 percent cloud cover)]

Path-Row	Scene center (lat-long)	Landsat identification number	Date	Solar elevation angle (degrees)	Code	Cloud cover (percent)	Figure	Glacier area (NTS map sheet)
017–013	66°29'N. 62°07'W.	20185–15051	26 Jul 75	42	●	0	17	(16L)
017–015	64°08'N. 64°56'W.	1747–15083	9 Aug 74	40	◐	15	18	“Hall” Ice Cap
017–016	62°46'N. 66°10'W.	1747–15090	9 Aug 74	41	◐	15	19	Terra Nivea and Grinnell *Ice Caps*
019–013	66°35'N. 64°37'W.	21663–15103	12 Aug 79	35	●	0	16	Penny Ice Cap (26I)
026–011B	69°31'N. 69°58'W.	30721–15514 subscene B	24 Feb 80	10	●	0	15	(27C)
028–010	70°25'N. 72°55'W.	10380–16182	7 Aug 73	36	●	0	5	Barnes Ice Cap (37E)
028–010	70°25'N. 72°31'W.	22050–16064	2 Sep 80	25	●	0	8*B*	Barnes Ice Cap (37E)
028–010	70°33'N. 72°23'W.	30525–16065	12 Aug 79	32	●	0	8*A*	Barnes Ice Cap (37E)
028–010	70°16'N. 73°13'W.	10740–16100	2 Aug 74	37	◕	10	6	Barnes Ice Cap (37E)
033–009	71°51'N. 77°08'W.	1403–16461	30 Aug 73	27	●	0	4	--
037–008	73°01'N. 80°47'W.	20943–16335	22 Aug 77	--	●	5	3	Bylot Island (48D)

Figure 3.—*Annotated Landsat 2 MSS false-color composite image of the Navy Board Inlet and Bylot Island glaciers. Landsat image (20943–16335, bands 4, 5, and 7; 22 August 1977; Path 37, Row 8) is from the Canada Centre for Remote Sensing, Ottawa, Ontario.*

Navy Board Inlet and Bylot Island

Figure 3 shows a false-color composite Landsat image of northern Baffin Island acquired on 22 August 1977. Variations in bedrock geology are clearly apparent. On the west side of Navy Board Inlet, several small plateau glaciers (ice caps) are visible. The general elevation of the upland surface is about 700 m, and the ice caps rise to more than 1,000 m, which suggests a possible thickness of ice of 100–200 m. The ice caps are located on high ground close to the coast, and this indicates that local orographic effects may be important in their mass balance. Although some "blue" ice can be seen, the high reflectivity of the snow strongly implies that a late summer snowstorm had come through prior to the orbital overpass. The margins of the ice caps are generally smooth on the south side, but small outlet glaciers can be seen pushing downvalley, particularly on the north margin of the ice cap that lies closest to Navy Board Inlet. The decrease in glacierization to the south, even though the topography remains relatively constant, indicates a steep gradient of the glaciation level (fig. 2; Andrews and Miller, 1972).

Bylot Island is heavily glacierized (fig. 3, cover), as it has 4,859 km^2 of its area covered by glaciers, about 45 percent of the island. The image shows that this highland ice field has a "spine" of cirque basins from which ice flows. The ice merges into a series of spectacular outlet glaciers. Sixteen major outlet glaciers can be identified on the image. The lower parts of these glaciers are clearly within the ablation zone, and the transient snowline appears to lie about 1,000 m above sea level (asl). Poorly defined medial moraines can be traced on most outlet glaciers, but no indications exist of contorted medial moraines; hence, the evidence indicates that none of these outlet glaciers exhibit surge behavior.

Small sediment plumes can be seen in the ocean waters adjacent to streams draining from these glaciers, but they are not very distinct. This may reflect the lateness of the season, because meltwater volumes dwindle rapidly after the main melting period in late June to middle July on Baffin Island (Church, 1972). The glacial geology and chronology of Bylot Island is discussed by Klassen (1981, 1982, 1985).

Pond Inlet, Oliver Sound, and North Arm

The area southeast of Bylot Island can be seen on the Landsat 1 multispectral scanner (MSS) false-color composite image taken 30 August 1973 and used for figure 4. The settlement of Pond Inlet is located in this image but is not easily visible. The bedrock geology varies from Precambrian granites and gneisses around Pond Inlet to Paleozoic limestones in the lower half of the image. Figure 4 shows an inland transition from a heavily glacierized coastal zone to scattered small ice masses on the higher ground to the southwest. The style of glacierization is different from that on Bylot Island even near the coast (compare with fig. 3). Particularly in the heavily ice-covered areas on either side of Oliver Sound and North Arm, the lack of surface relief indicates that the ice covers a broad, undissected (interfjord) upland (Ives and Andrews, 1963). Elevations are between 1,000 and 1,500 m asl. Only east of Pond Inlet is the style of glacierization reminiscent of alpine glacierization. From the upland ice caps, large outlet glaciers are channeled in major valleys and, in places, extend at right angles across major fjords—such as in Erik Harbour and toward the head of North Arm. East of Erik Harbour and west of Cape Macculloch (fig. 1), a large (20-km by 15-km) piedmont lobe covers much of a coastal foreland at only 200 m asl.

The large outlet glaciers on Bylot Island (fig. 3) are distinctive; many on this image are remarkable in that no large terminal moraines are associated with them. However, in figure 4, several outlet glaciers do have visible terminal moraines. Examples are the large outlet glaciers that flow eastward to Buchan Gulf. A large lake is dammed between one of the large neoglacial moraines and the coast. Radiocarbon dates from Pond Inlet and near outer Buchan Gulf (Hodgson and Haselton, 1974) indicate that the outer coast of this section of Baffin Island has not been glacierized for at least 30 kiloannum (ka, 10^3 years). In a similar manner, the evidence of Klassen (1981, 1982, 1985) indicates that regional glaciation of Bylot Island took place prior to 30 ka.

Figure 4 shows good separation between "blue" ice on the lower parts of the smaller glaciers and ice caps and the "white" snow and firn of the accumulation zones. The transient snowline lies at about 700 m, and even the small ice patches on the southern part of the image show only small areas of ice. It is possible that some of the effects of the summer melt season are masked by a late summer or early fall snowstorm.

Notable features in the lower left corner of figure 4, which will be described more fully when figures 5 and 6 are discussed, are the light-toned areas that are found south of Tay Sound. A detailed examination of the margins of these areas indicates that they cannot be explained by changes in the bedrock geology; rather these are the "lichen-free" areas of eastern and northern Baffin Island that have been documented, mapped, and studied as possible analogs for the development of the Laurentide Ice Sheet (see Ives, 1962; Andrews and others, 1976; Locke and Locke, 1977). Williams (1978) used these areas to suggest changes in climate during the last several hundred years, the time of the "Little Ice Age" (Grove, 1988).

Barnes Ice Cap and Environs

Barnes Ice Cap (5,935 km^2) is the most studied glacier on Baffin Island (see bibliography in Andrews and Andrews, 1980). For this reason, and because of the information content of different images on different dates,

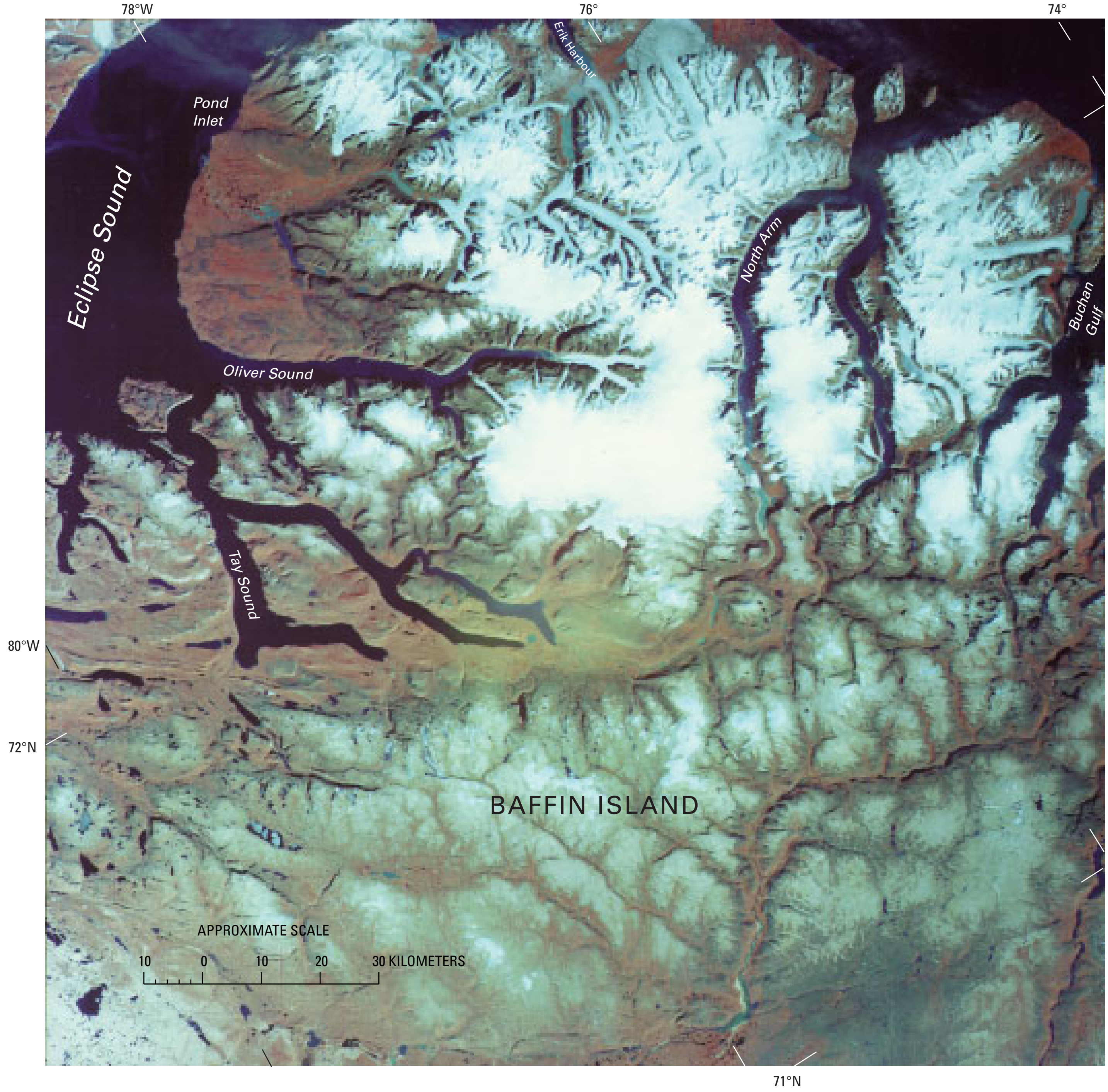


Figure 4.—*Annotated Landsat 1 MSS false-color composite image of the area around Pond Inlet, Oliver Sound, and North Arm. Landsat image (1403–16461, bands 4, 5, and 7; 30 August 1973; Path 33, Row 9) is from the Canada Centre for Remote Sensing, Ottawa, Ontario.*

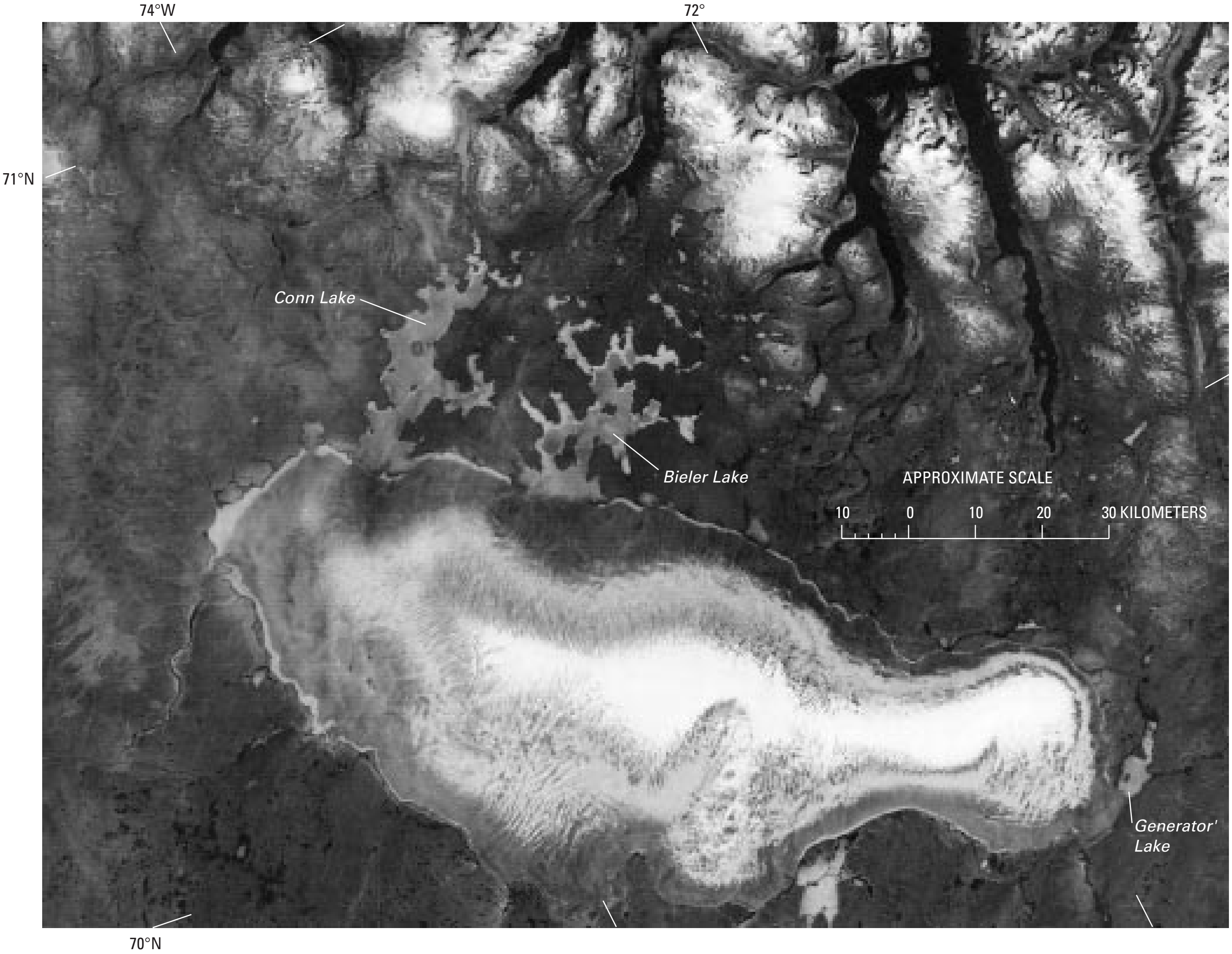


Figure 5.—*Landsat 1 MSS black-and-white image of the Barnes Ice Cap and environs. Landsat image (10380–16182, band 7; 7 August 1973; Path 28, Row 10) is from the Canada Centre for Remote Sensing, Ottawa, Ontario.*

several Landsat images and terrestrial (ground) and aerial photographs have been chosen for presentation in this section. Figure 5 is a Landsat 1 image that shows interesting glaciological and glacial geologic features on the Barnes Ice Cap and in the surrounding area. The crest of the ice cap appears as an intense white area from which surface and subsurface drainage lines diverge. The image also strikingly illustrates a series of snow-and-ice facies (see further discussion in the following section by Gerald Holdsworth on the geomorphology and thermodynamics of the Barnes Ice Cap; and in Williams and others, 1991).

Large calving bays having steep ice cliffs are present on the northeast side of the Barnes Ice Cap, where it flows into Conn and Bieler Lakes, and in the southeast, where it flows into Generator Lake (fig. 6). Icebergs are found in these lakes, but none are visible in figure 5.

North and northeast of the Barnes Ice Cap are light-toned areas that are "type-locations" for lichen-free areas (Ives, 1962; see also fig. 6). Rimrock Lake is in this area (fig. 6), and it is around that lake that Ives (1962) first studied and speculated on the significance of the lichen-free phenomenon. This area was first noted on 1:50,000-scale aerial photographs and was then studied in the field (Ives, 1962; Andrews and others, 1976).

Sugden (1978) and Andrews and others (1985) used black-and-white Landsat images to map areas of heavy, moderate, and light glacial scour. An area of heavy glacial scour is shown in the bottom left of figure 5 and is indicated by a high percentage of small lakes and obvious evidence for

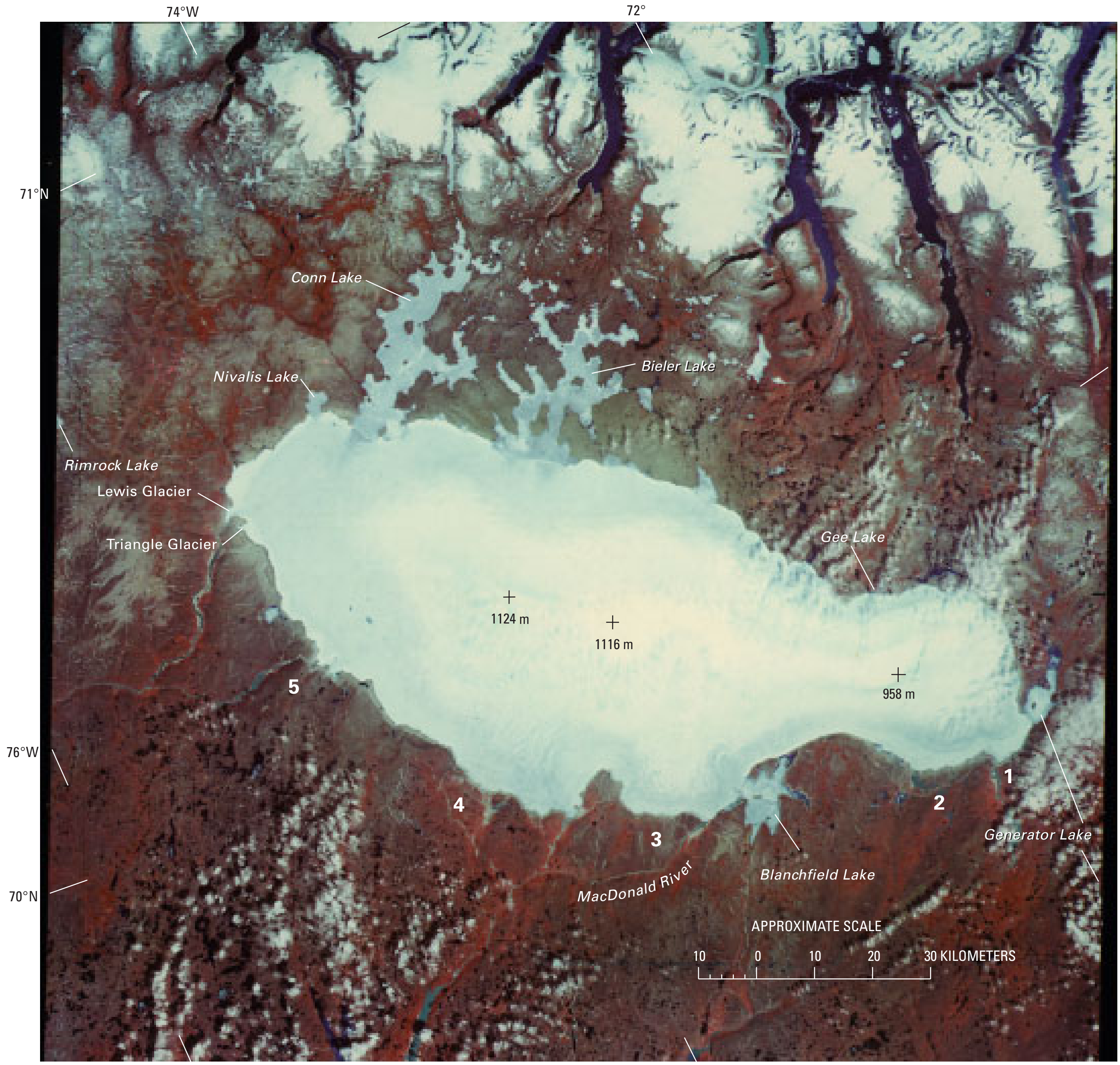


Figure 6.—*Landsat 1 MSS false-color composite image of Barnes Ice Cap. The numbers 1 to 5 locate regions on the adjacent ice cap that have undergone anomalous advances and slumping. Landsat image (10740–16100, bands 4, 5, and 7; 2 August 1974; Path 28, Row 10) is from the Canada Centre for Remote Sensing, Ottawa, Ontario.*

structure in the Precambrian bedrock. This zone contrasts with the area northwest of the Barnes Ice Cap, where lakes are scarce and little structural detail is evident.

Not as obvious, but also present in figure 5, are moraines around the southwest margin of the Barnes Ice Cap and other major neoglacial moraines along the west margin (Davis, 1985). On the east, areas of glacial scour can be seen to occupy lowlands, whereas the major interfluves show little evidence of glacial erosion. A series of moraines can also be observed near the fjord heads that are part of the moraine system deposited during Cockburn time (Falconer and others, 1965; Andrews and Ives, 1978) between 9 and 8 ka B.P.

The southern lobe of the Barnes Ice Cap was the location of intensive research by Holdsworth (1973a, b, 1977) [see following section] and Hooke (1973, 1976). The southern lobe exhibits two major features of interest:

(1) a zone of neoglacial moraines that have been dated by lichenometry as having formed between 1.5 ka and 60 years ago (Løken and Andrews, 1966; Andrews and Webber, 1969; Andrews and Barnett, 1979); and (2) a series of moraines that are crosscut by a distinctive rectangular lobe of the Barnes Ice Cap (southwest margin), which is interpreted as being associated with a recent rapid advance (Løken and Andrews, 1966; Løken, 1969; Holdsworth, 1973b; Jacobs and others, 1997).

Barnes Ice Cap: Geomorphology and Thermodynamics

By Gerald Holdsworth

Introduction

Barnes Ice Cap (lat 70ºN., long 73ºW.) (fig. 1) is situated in the center of Baffin Island. Both the Barnes Ice Cap and the Penny Ice Cap (300 km to the southeast) are probably the last remnants of the Laurentide Ice Sheet, the northeastern part of which covered most of the island as recently as at 10 ka (Dyke and Prest, 1987; Prest, 1969). Prior to that time and up to about the beginning of the Holocene Epoch, mountains along the northeastern coastal strip were more heavily glacierized than now, and outlet glaciers from the ice sheet and from highland glaciers would have filled the deep fjords that run in a northeasterly direction into Baffin Bay.

Having maximum (orthogonal) dimensions of about 150 km by 60 km, the Barnes Ice Cap covers an area of about 5,935 km^2. It has three main “domes” that have a maximum elevation on the northwestern one of about 1,124 m asl (fig. 6). The thickest ice, measured in 1967 (Clough and Løken, 1968), is about 550 m near the central dome (surface elevation 1,116 m). The south dome (surface elevation 958 m) was more than 460 m thick in 1970 (Jones, 1972). The ice cap is known to be shrinking in areal extent from glacial geologic evidence seen around the margin and from direct observations made since 1950.

On the basis of its thermal regime (Holdsworth, 1977; Classen, 1977; Hooke and others, 1980), the glacier is classified as subpolar or polythermal, as parts of the base in the region of the south dome are at the pressure melting point. Except where they are in contact with large proglacial lakes (for example, Conn, Bieler, and Generator Lakes; figs. 1, 5, 6), the margins of the ice cap are frozen to the base, where the temperature is typically about –7ºC. The higher interior ice is several degrees (Celsius) warmer than the marginal ice (Holdsworth, 1977; Hooke and others, 1983). Near the top of the south dome, the mean annual air temperature is estimated to be about –15ºC, whereas the mean annual ice temperature is about –8°C. This is a result of the release of latent heat associated with the formation of superimposed ice under the insulating snow cover in the upper parts of the ice cap each spring. This thermal structure is indirectly responsible for certain features seen on the satellite images.

A net accumulation of iced firn and superimposed ice (refrozen meltwater) is found on the higher parts of the glacier (Hooke and others, 1987). Elsewhere, blue, white, intermediate, or debris-laden ice is exposed in the outer parts of the ice cap later in the ablation season. In many parts of the ablation zone, meltwater lakes form in depressions on the ice surface. The depressions are believed to be troughs in a series of waves or irregular undulations that formed after a section of the ice cap underwent what was described previously as a surge (Holdsworth, 1977). The sections are usually well defined by an anomalously advanced margin and by a typically “slumped” and low-gradient vertical profile extending from the divide to the margin. In at least two cases, local divides show displacement, evidently as a result of the nonsteady ice flow that involves rapid mass transfer. Such profiles are easily obtained from the special series of 1:50,000-scale topographic maps that cover the ice cap.

Although the term “surge” has been applied to specific sections of the ice cap (Løken, 1969; Holdsworth, 1973b, 1977), a more appropriate term would be “local creep slump” (Shoemaker, 1981). The latter process involves enhanced ice creep and basal sliding induced by a bottom layer of meltwater that has slowly accumulated in the warmer central parts of the ice cap.

The main features that distinguish these sections from other parts of the ice cap can be seen on satellite images. These features, which all are located on the southwest side of the ice cap, are (1) the existence of more dendritic (higher-order) meltwater stream channels compared with channels elsewhere (in particular, sections on the northeast side of the ice cap do not divide close to proglacial lakes); (2) irregular folds or offset foliation defined by light- and dark-blue colored, banded ice; (3) the existence of moraine fields that indicate that only a discrete section of the ice margin was involved in an advance or a series of advances (Løken and Andrews, 1966).

Other information that is relevant to interpreting satellite images is as follows:

(1) A marginal or nearly marginal strip of whitish, bubbly, basal ice crops out along the edge of the ice cap. This ice has a density of 0.87 Mg m^{-3}. This is much less dense than most of the ice above, which has a density approaching 0.91 Mg m^{-3} (Hooke, 1976). In addition, the whitish ice has an oxygen isotope $\delta^{18}O$) value that indicates a Wisconsinan (late Pleistocene) age (Hooke and Clausen, 1982). That such a layer can have persisted since the Pleistocene is supported by simple two-dimensional steady-state dynamic modeling of the ice mass along flow lines through the south dome (Gerald Holdsworth and G.E. Glynn, unpub. data, 1975; Hooke, 1976).

Hooke (1976) found that the whitish Pleistocene ice layer was 13-m thick in one marginal section of the south dome region. Its surface exposure on a slope averaging about 10° to 15° is on the order of 40–70 m, so on satellite images, the exposure is at least 1–2 pixels wide. Also, it normally does not crop out exactly at the margin but is commonly underlain by younger ice that it has overridden. Elsewhere, the whitish ice could be much thicker than it is at the south dome location. Sometimes wind-drift wedges of snow may form in the depression between the ice cap proper and a marginal ice-cored moraine. When looking for the Pleistocene ice in photographs and images, these considerations have to be taken into account. Thus, not all the marginal “whitish” ice seen in the following images is necessarily Pleistocene ice.

(2) Proglacial lakes affect the flow of ice in their vicinity. Two large ice-marginal lakes are located on the north side of the ice cap, Conn and Bieler Lakes (fig. 6). Both these lakes are deep where they are dammed against the ice because the slope of the land is toward the ice cap. As a consequence, ice flow is locally focused toward the lakes, and “draw-down” of the ice has produced some of the effects also seen in the “slumped” areas. In contrast, the smaller Generator Lake on the east end of the ice cap has evidently been dammed by the local advance that resulted from “creep slump” in part of the south dome within the last century (Holdsworth, 1973b).

Analysis of Landsat Imagery

Figure 6 is a Landsat 1 MSS false-color composite image of the Barnes Ice Cap acquired 2 August 1974 and processed for standard earth-science analysis. Part of the southeast end of the glacier is obscured by clouds. However, snow, ice, and some structural detail can be seen over most of the rest of the ice cap. The sections that show evidence for local advance are the lobes numbered 1 through 5, all situated on the southwest side of the ice cap. The main observations that define the slump areas are

(1) The irregular or lobate form of the margins.
(2) The arcuate moraine loop associated with slump margin 2. Although most of the advanced lobes have enhanced moraine forms associated with them, the most obvious is this one, which is about 20 km long. These moraines can be easily seen on the NTS map sheet 37D/9 (scale 1:50,000). A detailed structural map and cross section of this moraine system is also shown in Løken and Andrews (1966). They show that, in this system of moraines, the outer one represents a major advance of a section of the ice cap about 700 years ago. Other readvances took place 400 to 500 years ago and about 300 years ago. On the other hand, slump margin 1 is probably the youngest, and its prominent ice-cored moraine ridges are still very close to the edge of the ice cap.
(3) Large supraglacial lakes can still be seen in the slump area marked 5, even in early winter images. The largest lake is about a kilometer long.

Also seen in figure 6 are the ice drawdowns associated with Conn and Bieler Lakes. Note the zone of darker blue ice entering Conn Lake. Figure 7 is part of an aerial photograph that shows this darker ice. The ice here appears darker because it is crevassed and also probably because the banded foliation seen elsewhere is destroyed by compression transverse to the extending flow direction, which is toward the lake.

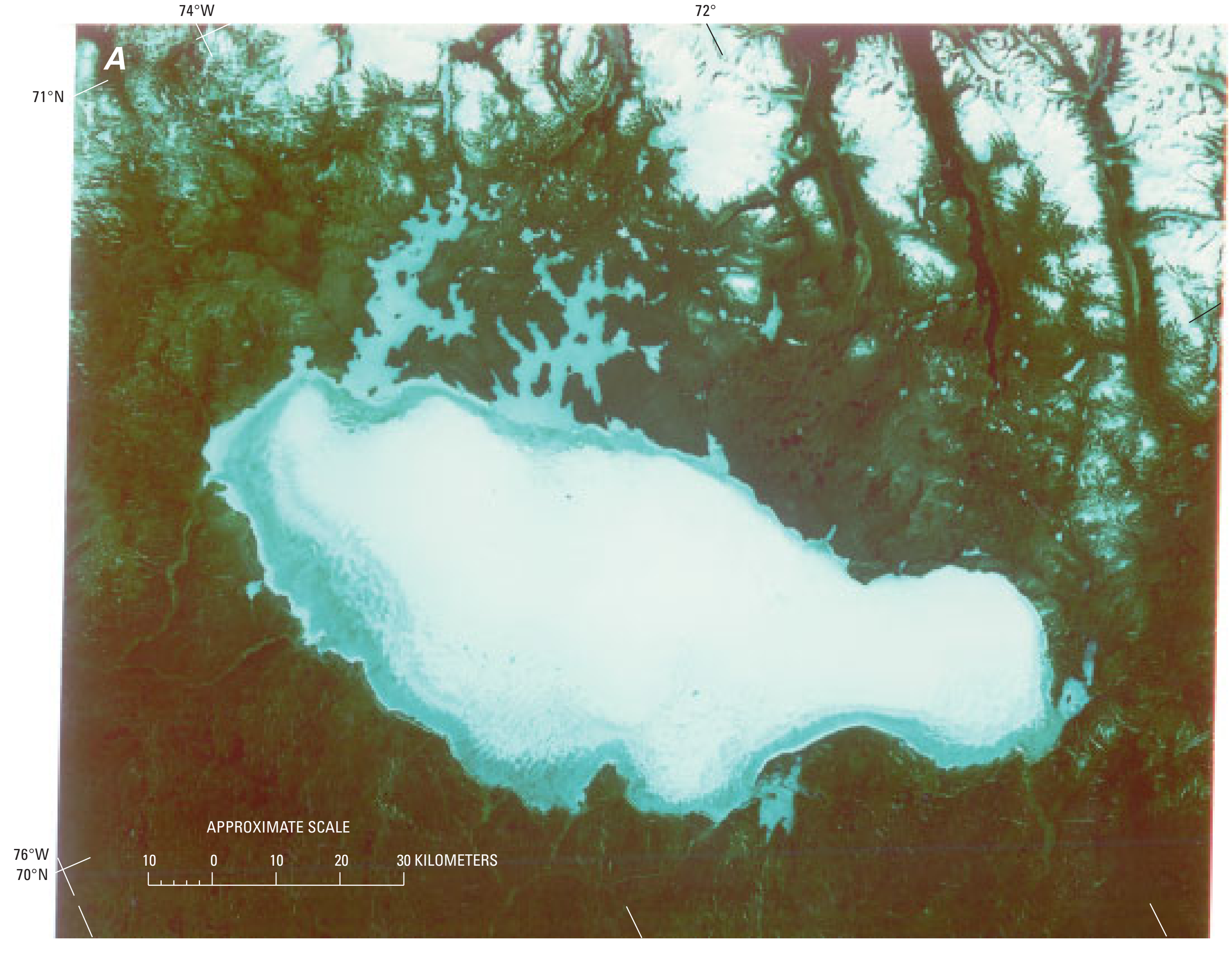
Finally, notice a discontinuous strip of marginal "whitish" ice that appears much lighter than the blue ice higher on the ice cap. This is proba-

Figure 7.—*Vertical aerial photograph of the north margin of the Barnes Ice Cap showing darker ice entering Conn Lake (see fig. 6). Note crevasse traces in the ice. The Pleistocene ice is probably the 50- to 200-m-wide white band that is truncated by Conn Lake and the smaller Nivalis Lake to the northwest. See Hooke (1976) for an explanation of why this ice is often underlain by younger ice. Photograph NAPL No. A–17047–108 courtesy of the National Air Photo Library, Ottawa, Ontario, Canada. Used with permission.*

bly a combination of the Pleistocene ice and marginal wind-drift and wedges of snow, as mentioned earlier. The white strip is particularly visible in the black-and-white satellite image of figure 5. Note that it is continuous between slump margins 2 and 3, but it is absent along the slump margins where it has probably been overridden by younger (Holocene) ice. A short white strip is visible between margins 3 and 4. Also clearly seen in figure 6 are the ice-surface outlines of slump margins 1, 2, and 3. Outlines of slump margins 4 and 5 are less pronounced but are still evident. Slump margin 5 may not have experienced much advance but may be instead a mass transfer from the reservoir regions to the margin in the form of a persistent bulge, such as has been observed on the Trapridge Glacier in Yukon Territory (Clarke and others, 1984). On the other hand, drainage patterns in the moraine fields suggest that the margin may have previously advanced several kilometers more than the adjacent margin. The strip of white ice at the margin of lobe 5 is thought be (or at least to contain) the Pleistocene ice. Even with marginal ice slopes in the northwest sector at under 3°, a 10–20 m thick Pleistocene ice layer would only cover a horizontal distance of 200–400 m.

To see more of the features mentioned above, it is necessary to examine two more satellite images. Figure 8*A* is a Landsat 3 MSS false-color composite image acquired 12 August 1979 showing a considerably greater central area of snow cover than that found in figure 5. Of particular interest are

Figure 8.*—Landsat MSS false-color composite images of Barnes Ice Cap.* **A***, Landsat 3 image showing development of meltwater streams, lakes, and exposed underlying ice (darker blue). See text for further description. Landsat image (30525–16065, bands 4, 5, and 7; 12 August 1979; Path 28, Row 10) is from Canada Centre for Remote Sensing, Ottawa, Ontario.* **B***, See following page.*



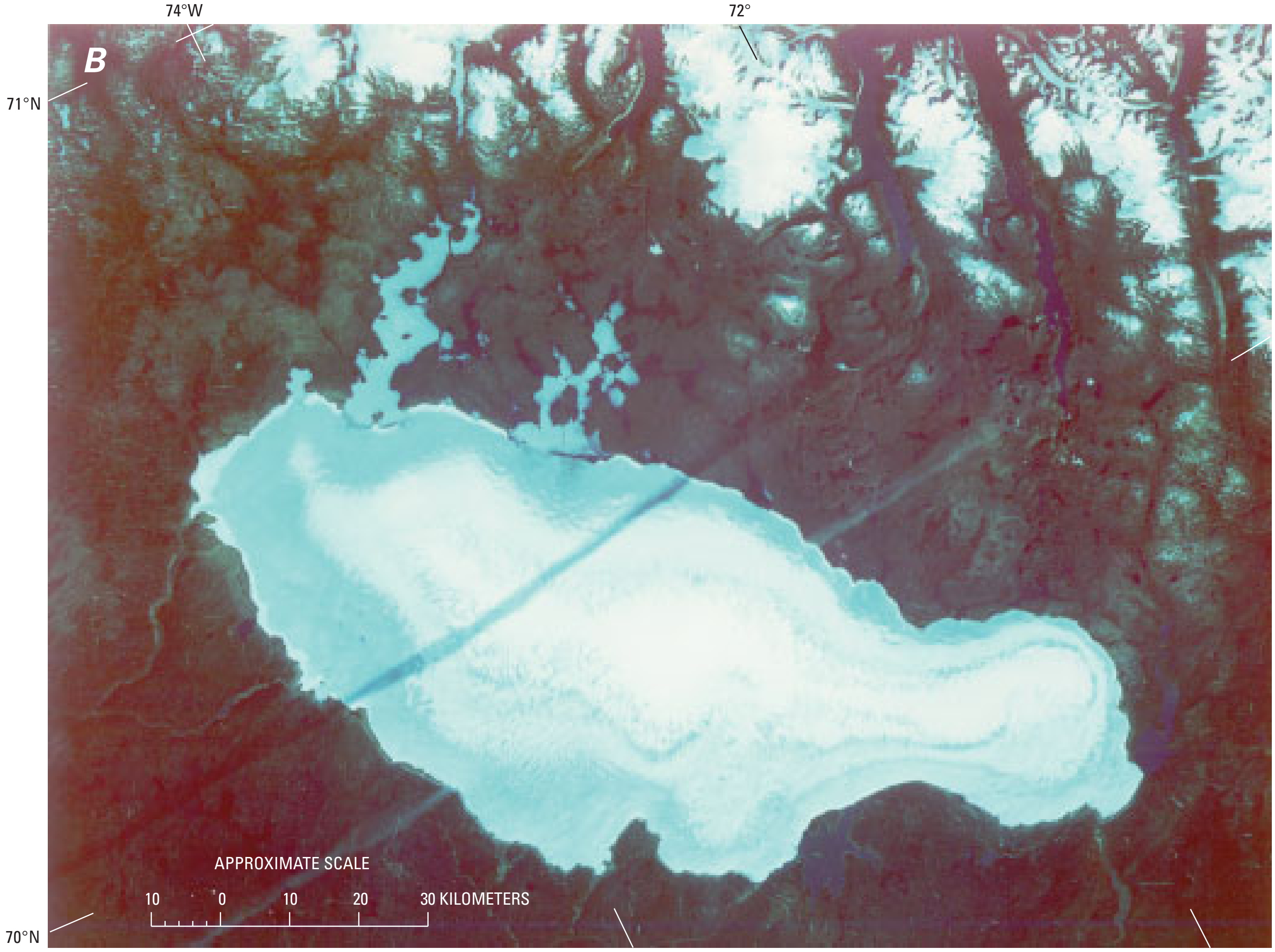


Figure 8B, *Landsat 2 image showing glacier-surface details near the end of the ablation season. Landsat image (22050–16064, bands 4, 5, and 7; 2 September 1980; Path 28, Row 10) is from Canada Centre for Remote Sensing, Ottawa, Ontario.*

(1) the presence of meltwater lakes appearing as dark-blue marks in the zone of sporadic, saturated snow between the central snow cover and the blue ice; (2) the development of meltwater streams appearing as linear blue streaks in areas of smooth contours (seen in the 1:50,000-scale topographic map sheets) or as dendritic networks in areas of irregular contours (typical of the slumped areas); and (3) the existence of the discontinuous narrow strip of white ice close to the edge of the ice cap.

Figure 8*B* is a Landsat 2 MSS false-color composite image taken 2 September 1980 that shows the glacier near the end of the ablation season. The prominent streak running diagonally across the image is a shadow cast by an aircraft "contrail," which is barely visible just below and to the right of it. The central divide area is still covered by residual snow; this area is the 1980–81 firn accumulation zone (Hooke and others, 1987). The shorter blue streaks at the edge of the snow mark the slush zone. Where local topography is favorable, slush avalanches are common in late summer. They drain the saturated snow facies. The prominent, arcuate indentations and converging meltwater streams help define the upper limit of the slump regions. The light-blue zone fringed by the upper and lower dark-blue (ice) probably represents areas of thin slush covering underlying blue ice. The dark-blue zone surrounding it is the outcrop of dense, bubble-poor Holocene ice. Again, the marginal strips of white ice are provisionally interpreted to be Pleistocene ice. The strip is widest in the northwestern part of the ice cap. Elsewhere, the marginal ice is commonly very complex and contains flow folds that have nearly horizontal axial planes.

Features seen in the image in figure 8*A* but not in figure 8*B* are darker areas (>1 km^2) in the blue-ice zone where a slight green hue is also apparent. The origin of these features has not been verified, but they could represent temporary or residual areas of superimposed ice associated with dirt. Such dirt, in the form of scattered small cones, is often visible to an observer traveling over lower parts of slump margin 1 (fig. 6). The dirt would have become concentrated in the bottom of supraglacier lakes. At a later time, a stream may reroute and wash the sediment away. The transient nature of these features is demonstrated by their absence from the image in figure 8*B*.

Figure 9 is a vertical aerial photograph showing slump margin 1. The banded foliation patterns are particularly striking. At Generator Lake (east edge of photograph), the margin shows finer scale foliation in a 10-m-high ice cliff, above which is a heavy moraine cover (upper right part of image). Note the supraglacial channel on the ice cap in figure 10*A*. This channel separates slump margin 1 ice on the left from essentially unslumped ice on the right. A recumbent flow fold is visible in a closer view of this exposure (fig. 10*B*). Hudleston (1976) analyzed the flow field required to produce such folds. He suggested that they can result from changes in the flow field as the shape or profile of the ice cap changes due to climatic factors. Details of the debris content in this ice may be found in Holdsworth (1973a). A 12–15-m-high ice cliff in 30-m deep water is seen in figure 11. These cliffs all show up as sharp edges on the vertical aerial photographs and satellite images.

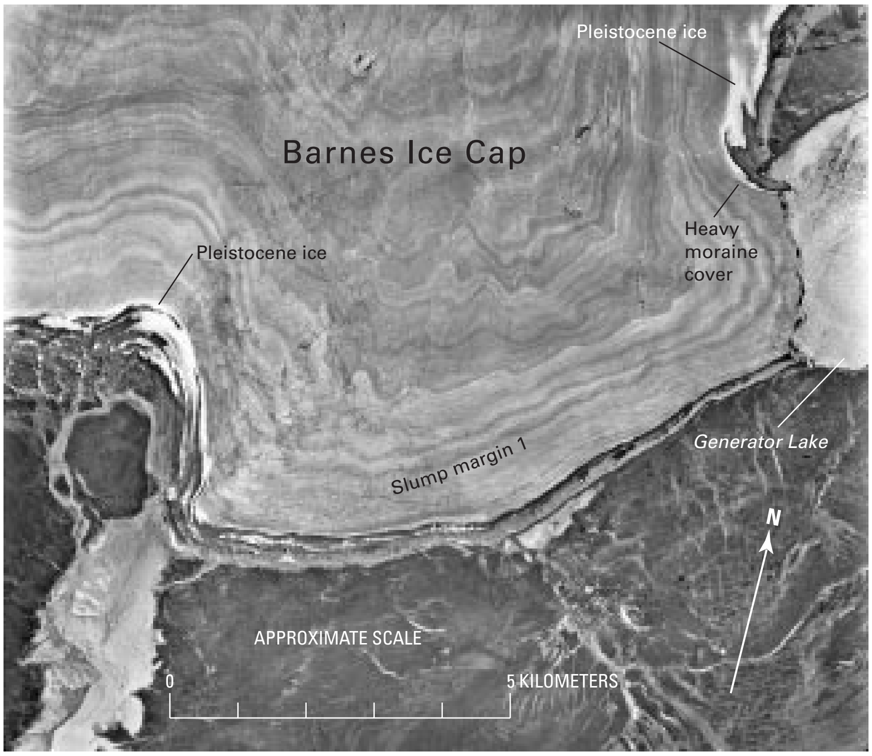


Figure 9.*—Vertical aerial photograph of Barnes Ice Cap showing part of slump margin 1 (see fig. 6 for location). Note the extremely crenulated foliation, which is typical of slumped margins. Generator Lake is on the right. At the contact between the lake and the ice cap margin is an area of heavy moraine cover (see fig. 10*A*). Some of the bright (white) areas seen in this location are possibly the remains of late season snow drifts. The Pleistocene ice layer is present in the bight on the northeast margin, north of the heavy moraine cover, and possibly on the southwest margin on the west edge of the photograph, according to R.L. Hooke (written commun., 22 July 1999). Elsewhere in the image, the layer would be unrecognizable because of the slump. Photograph NAPL No. A–17042–127 courtesy of the National Air Photo Library, Ottawa, Ontario, Canada. Used with permission.*

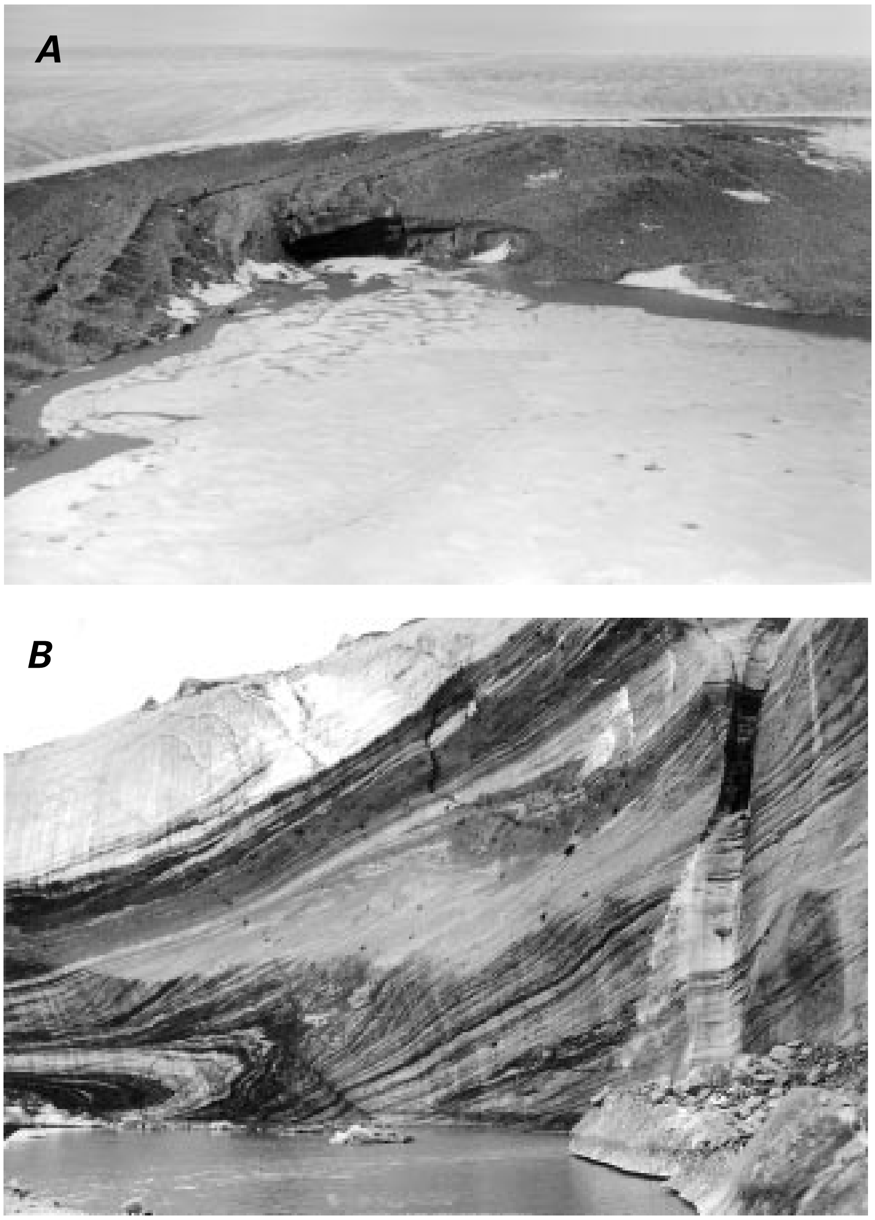


Figure 10.**—Margin of Barnes Ice Cap at Generator Lake.* **A, Oblique aerial photograph showing the heavy moraine cover on the ice seen in the previous air photograph. Also visible are remnant snow patches and an ice cliff, which has a flow fold (fig. 10B). Photograph by Gerald Holdsworth taken in July 1970.* **B***, Ten-meter-high ice cliff in which can be seen a recumbent flow fold defined by submeter-scale layering in the ice. This is about two orders of magnitude smaller than the smallest banded foliation seen in the satellite images. Photograph by Gerald Holdsworth.*

***Figure 11.**—Ice cliffs 12–15-m high at the edge of the Barnes Ice Cap where it calves into Generator Lake in 30 m of water. Photograph by Gerald Holdsworth taken in August 1971.*

Late 20th Century Change at the Barnes Ice Cap Margin

By John D. Jacobs

Introduction

As described in the preceding text, glaciological studies have been carried out on the Barnes Ice Cap since 1950, including several periods of intense investigation in the 1960's and 1970's. Early work recognized that recession had been taking place along the ice-cap margin for centuries, particularly in the south and west, but that the recession had not been uniform along the entire margin. Holdsworth (preceding section) interpreted forms along the west and south margins as advancing lobes associated with slump areas. In these areas and elsewhere, the ice front had receded from well-defined moraine ridges. Along the northeast and east margins, much less change was noted. Løken and Andrews (1966) concluded from lichenometric studies of moraines around the south dome of the ice cap that its northeast margin was either stationary or advancing northeastward as the ice divide migrated in that direction.

Between 1970 and 1984, repeated surveys were conducted by Holdsworth and Hooke along a 10-km-long stakeline running northeast from the summit of the south dome (Holdsworth, 1975; Hooke and others, 1987) (958-m dome in fig. 6). Although large interannual differences were found in mass balance, the net balance averaged over the transect was negative for the 14-year period. It was estimated that the ice cap in this sector had thinned by about 2 m in that time (Hooke and others, 1987). In the absence of continued surveys, subsequent changes there and over the ice cap as a whole remain unknown.

Studies of the Margin Using Landsat Imagery

From 1989 to 1991, an area of the northwest margin of the Barnes Ice Cap including the Lewis Glacier (figs. 6 and 12) was investigated by Jacobs and others (1993), with reference to surveys done in the 1960's (Andrews and Webber, 1964; Andrews and Barnett, 1979). The position of the glacier terminus was surveyed, and a section of the ice cap margin south of the Lewis Glacier was staked for monitoring. Control points were established for registration and classification of satellite imagery.

A Landsat MSS image dated 19 August 1988 was obtained that covered 40 km of the ice cap margin centered on the Lewis Glacier. The 1961 position of the glacier margin was digitized from the 1:50,000-scale map sheet for the area (NTS map sheet 37E/6W, which is based on 1961 aerial photogrammetry) and then was superimposed on the georeferenced Landsat image. The right (south) margin and central terminus of the Lewis Glacier

Figure 12.*—Lewis Glacier, an outlet glacier at the northwest margin of the Barnes Ice Cap (fig. 6). Low-angle oblique aerial photograph taken in July 1993 from the south. The width of the glacier front is approximately 500 m. Recession of the Lewis Glacier terminus averaged 25 m a^{-1} between 1961 and 1991. Photograph by J.D. Jacobs.*

were found to be well defined, but it was not possible to differentiate between debris-covered ice and the surrounding terrain in other sectors. Estimates of retreat were, therefore, most accurate in the former areas. The Lewis Glacier terminus had retreated 680 m between 1961 and 1988, or about 25 m a^{-1}, compared with an estimate of 20 m a^{-1} obtained by earlier workers from detailed surveys of the terminus in 1963 and 1965 (Anonymous, 1967). Recession along the ice cap margin south of the Lewis Glacier was 9 m a^{-1} for the same period. Recession in varying amounts was determined over the entire 40-km segment of the northwest margin contained in the 1988 Landsat MSS subscene (Jacobs and others, 1993).

Additional mapping of the Barnes Ice Cap margin in its southern sector was undertaken by using a Landsat 5 Thematic Mapper (TM) scene (3 August 1993) covering the southern one-third of the ice cap (Jacobs and others, 1997). Low-angle oblique aerial photography was obtained in August 1994 along parts of the margin as a basis for controlling the classification of the TM image. Classification of the glacier facies was based on the TM band 4 to band 5 image ratio, which is effective at identifying ice, open water, and exposed bedrock (Williams and others, 1991). The existing (1961 aerial photogrammetry) 1:50,000-scale NTS map sheet for the ice cap was digitized for digital elevation model (DEM) construction, and the georeferenced, classified image was registered to the DEM by using 47 ground-control points. The combined root-mean square (rms) error of the georeferenced image and the digitized base map was estimated to be 33 m. It was difficult to determine the position of the ice margin in the presence of debris-covered ice and where perennial snowbanks lay on the distal side of ice-cored moraines. Taking this uncertainty into account, the average recession over the 183-km length of the south and east margins between 1961 and 1993 was estimated to be at least 137 m, or about 4 m a^{-1} (Jacobs and others, 1997).

Change Detection Using RADARSAT SAR

Synthetic aperture radar (SAR) offers the advantage for glaciological investigations of coverage in any season or in any cloud conditions, although challenges arise in the interpretation (Bindschadler and Vornberger, 1992). Short (1998; Short and others, 2000) studied the feasibility of ice-margin mapping on the Barnes Ice Cap using SAR imagery from RADARSAT. The field area was the north margin of the south dome, an area of debris-covered ice, massive ice-cored moraines, and distal snowbank features (fig. 13). It was in this sector that Løken and Andrews (1966) suggested the ice cap was stationary or possibly advancing. Ambiguities in

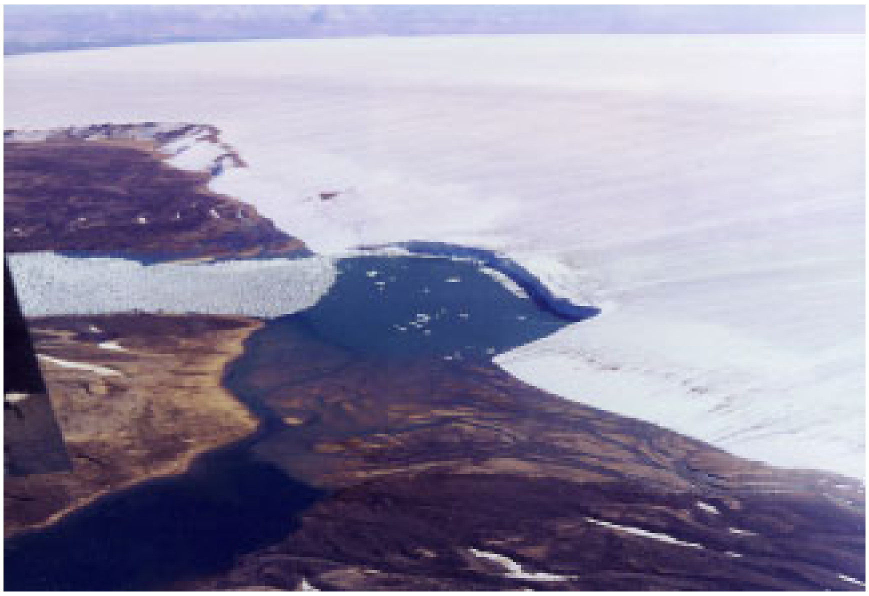


Figure 13.—*North side of the south dome of the Barnes Ice Cap at Gee Lake, view looking southward. Low-angle oblique aerial photograph by J.D. Jacobs taken in July 1997.*

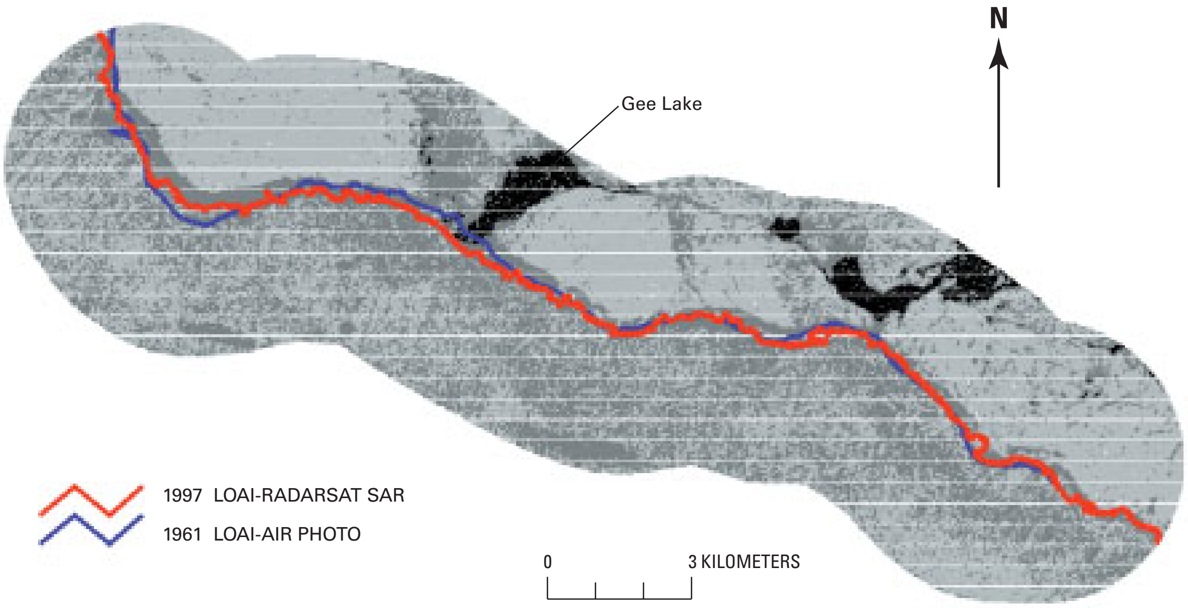


Figure 14.—*Part of a RADARSAT SAR image centered on Gee Lake (lat 60°57'N., long 72°29'W.), Barnes Ice Cap, showing mapped 1997 limit of active ice (LOAI) and 1961 LOAI from air-photograph interpretation. RADARSAT image (S4 ASC, ID M0122606, 26 July 1997) from RADARSAT International, Richmond, British Columbia.*

what was meant by the glacier "edge" or "margin" in such a complex terrain led Short (1998) to focus on the concept *limit of active ice*, defined as the extent of ice that is still fed from the accumulation zone of the glacier.

Three RADARSAT SAR images were obtained for the summers of 1996 and 1997, including descending (view up-glacier) and ascending (view down-glacier) standard modes (picture element (pixel) resolution of 25 m) and an ascending fine-mode image (pixel resolution of 8 m). Field studies were carried out during the summer of 1997 along the 27-km stretch of the moraine selected as a test area (figs. 13 and 14). Image analysis involved image speckle filtering, texture analysis, supervised classification, image segmentation, and edge detection, in that order, and the ascending standard mode provided the best results. The approach was successful in mapping the limit of active ice with an accuracy of 49 m (Short and others, 2000). The resulting map has been used to assess the amount of change along this section of the margin (Jacobs and others, 1999). Interpretation of 1961 aerial photography and the corresponding topographic map permitted delineation of the limit of active ice in this area for 1961, which was transferred to the 1997 SAR image (fig. 14). Recession is evident in some areas, such as the ice front calving into Gee Lake, and slight advance in others; overall, however, the average change in the position of the margin during the 36 years between observations has been slight.

Conclusion

Multispectral satellite imagery has been demonstrated to provide a basis for first estimates of changes in the position of the Barnes Ice Cap margin. Sustained overall recession is evident around the margin. Recession was clearly documented at the two study sites (Lewis Glacier and Gee Lake, fig. 6). RADARSAT SAR was found to be a more sensitive tool for detecting change in the areas of complex morphology in the north part of the south dome. Results from that analysis support the conclusion that the Barnes Ice Cap is experiencing overall attrition. It should be noted that for most of the latter half of the 20th century, ablation-season temperatures in the Baffin Island region did not change significantly, in contrast to the pronounced summer warming that was recorded in the western Arctic (Chapman and Walsh, 1993). Should a regional warming take place, it is to be expected that shrinking of the Barnes Ice Cap will accelerate.

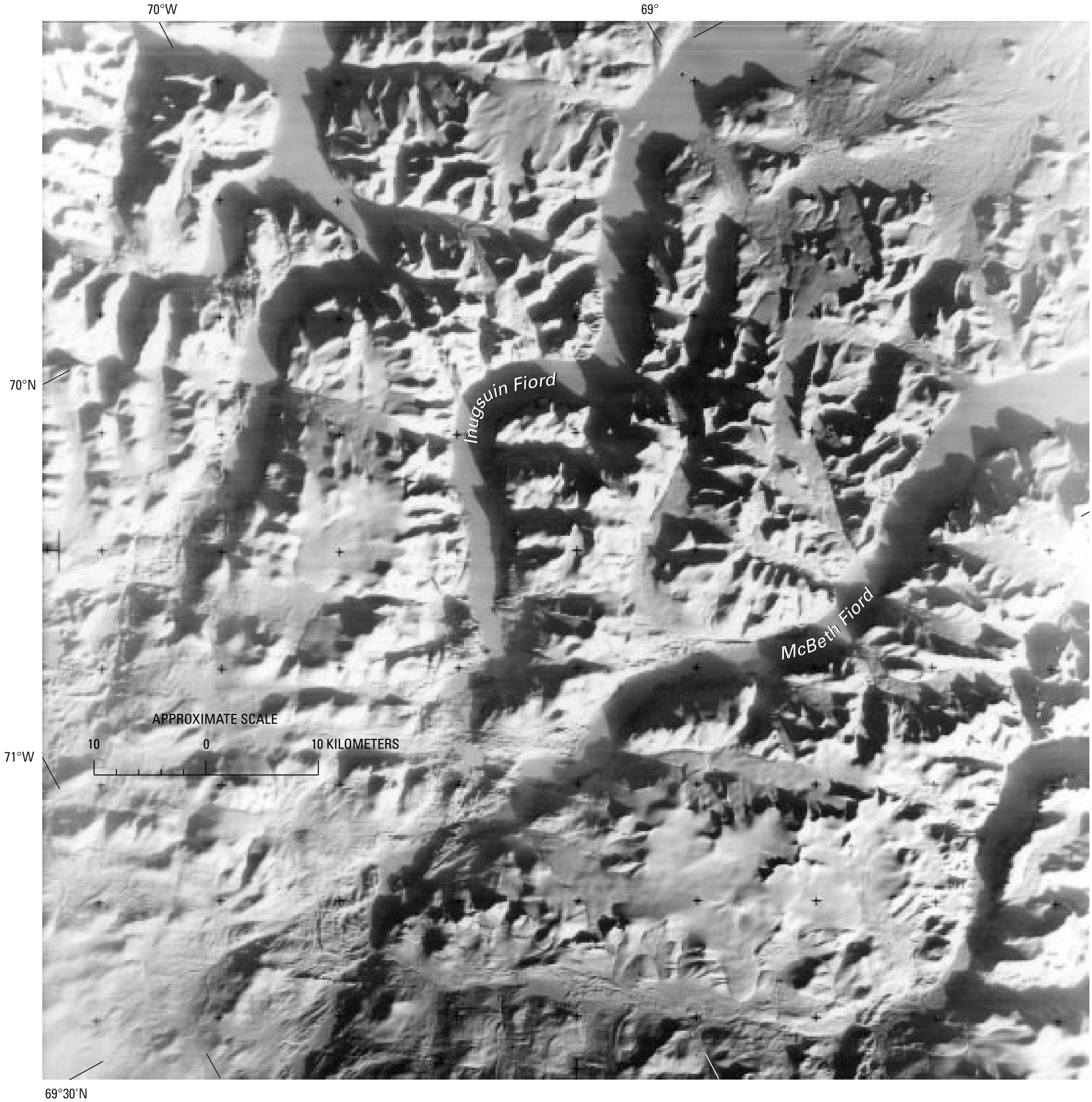


Figure 15.*—Landsat 3 RBV image with low Sun angle (elevation 10°) highlighting the alpine terrain northwest of Home Bay (see fig. 1 for location and text for more details). Landsat image (30721–15514 B; 24 February 1980; Path 26, Row 11) is from the Canada Centre for Remote Sensing, Ottawa, Ontario.*

Alpine Area (Lat 69ºN., Long 69ºW.): Home Bay

Farther to the southeast of the Barnes Ice Cap, the transition between the alpine-sculptured area of the fjord and the more massive, rolling terrain of the interior can be seen on a Landsat 3 return beam vidicon (RBV) image taken 24 February 1980 (figs. 1 and 15). The low solar-elevation angle accentuates the position of individual cirque basins, many of which merge into mountain ice fields and are drained by large outlet glaciers. Large neoglacial moraines can be distinguished in the center bottom of the scene. To the east, the alpine terrain gives way abruptly to the low foreland of the

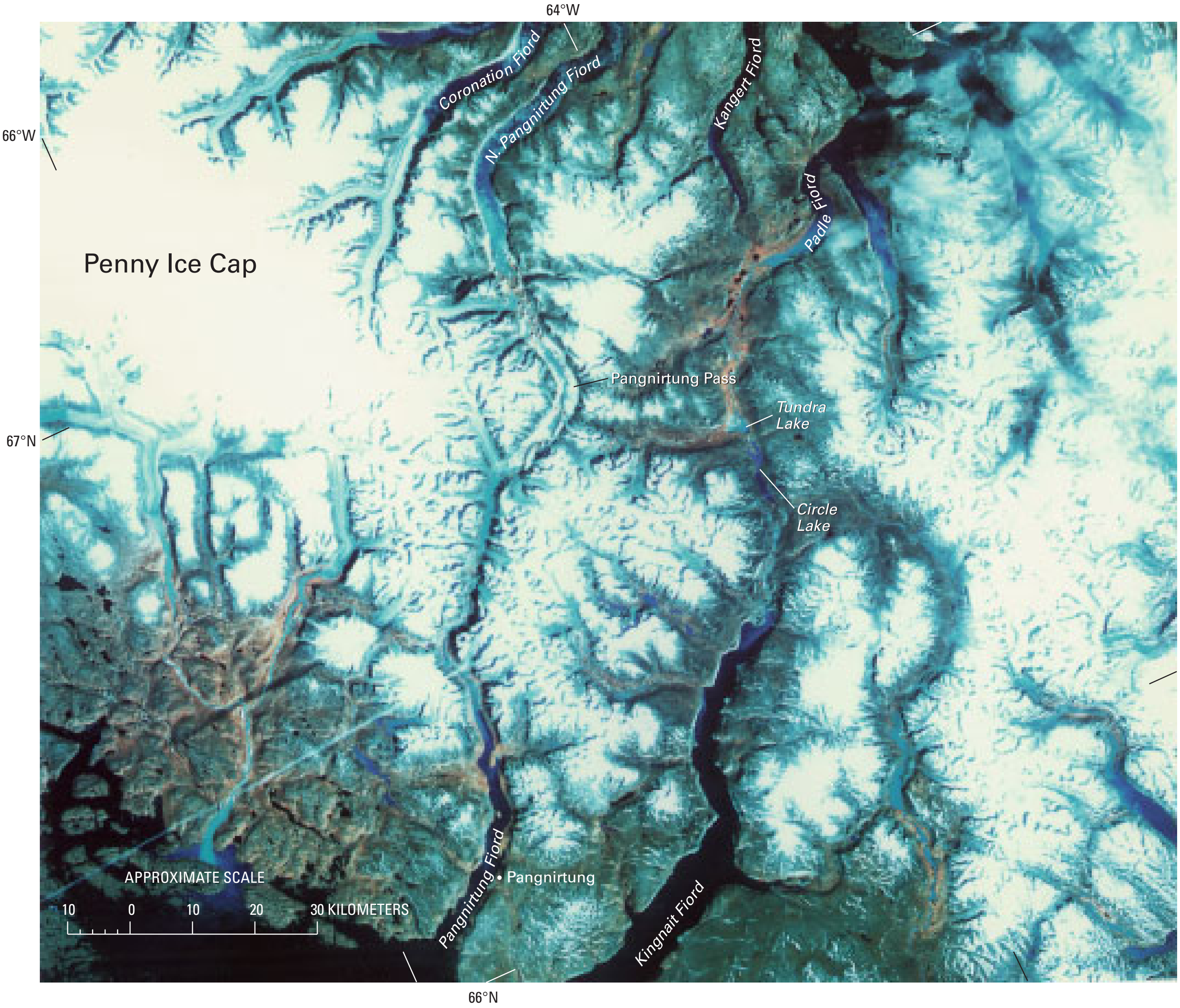


Figure 16.*—Landsat 2 MSS false-color composite image of part of the Penny Ice Cap and the glacierized alpine terrain of the central Cumberland Peninsula (see fig. 1). Abbreviation: N., North. Landsat image (21663–15103, bands 4, 5, and 7; 12 August 1979, Path 19, Row 13) is from the Canada Centre for Remote Sensing, Ottawa, Ontario.*

Cape Henry Kater area (fig. 1) (King, 1969a and b), which contains a long and complex Quaternary glacial and marine record (King, 1969b; Miller, 1985a, b). Controls on the glacierization of this area are discussed in Andrews and others (1970), and mass-balance estimates are contained in Weaver (1975).

Penny Ice Cap and the Cumberland Peninsula

One of the most spectacular regions in Baffin Island is illustrated in figure 16, a Landsat 2 MSS false-color composite image taken 12 August 1979. Most of the area in the right one-half of the image lies within the Auyuittuq National Park (fig. 1). The settlement of Pangnirtung lies within the center bottom of the image but cannot be detected.

The pattern of glacierization readily enhances major rectilinear structural details in the bedrock. Cumberland Peninsula is crossed by two major fjord-valley systems (fig. 1). To the east, Kingnait Fiord leads northward through Circle and Tundra Lakes toward Padle Fiord; farther west, Pangnirtung Fiord heads northward to Pangnirtung Pass and hence into North

Pangnirtung Fiord. Elevations along Pangnirtung Pass vary between 1,500 and 2,000 m asl. Penny Ice Cap lies northwest of Pangnirtung Pass. Near Pangnirtung Pass, the ice cap consists of interlocking cirque glaciers and outlet glaciers forming a highland ice field, but farther west, the relative relief decreases, and an ice cap covers most of the terrain. Large outlet glaciers descend from the ice cap to the north, east, and south. Coronation Glacier ends in a calving margin in Coronation Fiord (Gilbert, 1982) (figs. 1, 16). Figure 16 does not show the extent of the ablation zone, although careful examination indicates that many of the large outlet glaciers are snow-free. The snowline at this time is estimated to lie at about 750 m asl.

In the southwest corner of the image (fig. 16) is a good illustration of the character of what Sugden (1978) called "ice-scoured terrain." Little evidence exists for a thick till cover, and instead, the details of the bedrock structure are visible and are enhanced by small lakes. This area contrasts with the terrain along the north edge of Penny Ice Cap, (5,960 km^2) where outlet glaciers have been topographically steered, and complete glacial inundation, if it were present, may have happened at 1 Mega-annum (Ma, 10^6 years) to 100 ka B.P. (Boyer and Pheasant, 1974).

Cape Dyer, Cumberland Peninsula

Figure 17, a Landsat 2 MSS false-color composite image, partly overlaps figure 16, which lies to the west. However, this Landsat image was acquired on 26 July 1975 during one of the warmest summers on record. The area is heavily glacierized by individual cirque glaciers, valley glaciers, and highland ice caps. Large outlet glaciers flow from the latter and descend to 0 to 200 m asl in most localities. The glaciation level rises steeply from the outer coast (fig. 2). Because of extensive open water off Cape Dyer during a good part of the year, the snowfall around Cape Dyer is the heaviest on record for the eastern Canadian Arctic (Andrews and others, 1970). The average annual snowfall at Cape Dyer, about 5.0 m, declines rapidly to the north and west, so that at Broughton Island (just off the top left corner of figure 17 (see fig. 1)) the average recorded annual snowfall is only about 2.5 m. The transient snowline seen on the image is quite high and is estimated to lie at about 1,000 m asl.

The glacial history of the Cape Dyer area and that of Merchants Bay to the northwest (fig. 17) were studied by Locke (1980) and Hawkins (1980). They showed that neoglaciation affected both areas, but near Cape Dyer, the neoglacial moraines of the large outlet glaciers overran weathered tills that date from the earlier Sunneshine stade, dated at approximately 100 ka B.P. In contrast, Hawkins (1980) and Miller (1975), working in the fjords of Merchants Bay, were able to map extensive late Foxe (=late Wisconsinan) moraines that terminated at sea level and were associated with large deltas, the tops of which are now about 35 m below sea level. Amino-acid age estimates and uranium-series radiometric dating indicate that the outer coast in this area was deglaciated at more than 75 ka B.P. (Szabo and others, 1981). More recent research has used a combination of cosmogenic dating (=exposure age dating) of boulders and radiocarbon dating of lake sediments to provide a more detailed account of the glacial history of this region (Steig and others, 1998).

The heaviest area of sea-ice cover around Baffin Island is located between Cape Dyer and Home Bay to the northwest (fig. 1). In most years, sea ice is very close to the coast until well into late August or even early September, but in 1975, the sea ice broke up early, and most sea ice cleared the coast by the first week in August.

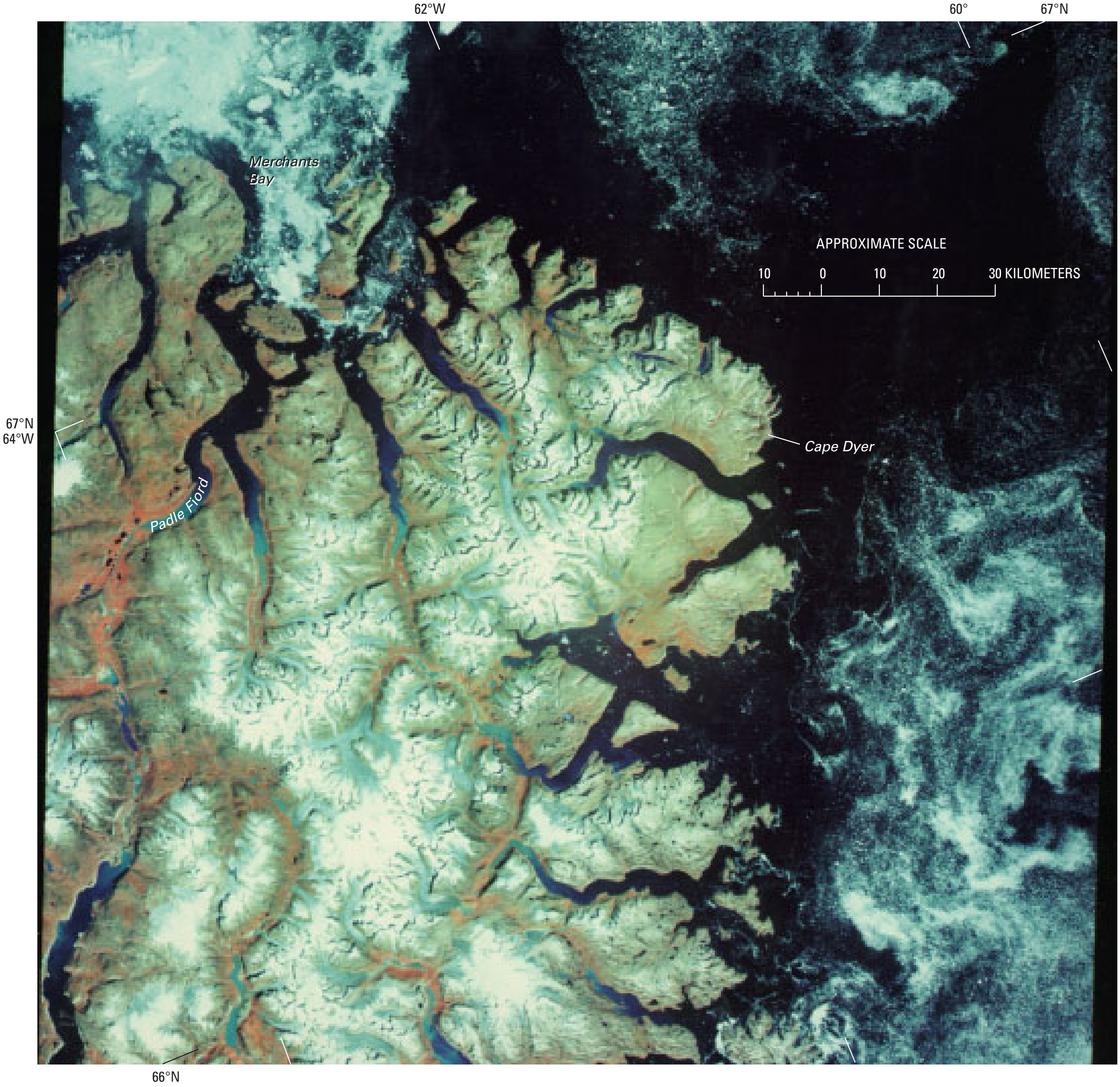


Figure 17.—Annotated Landsat 2 MSS false-color composite image of local alpine glaciers on the eastern part of the Cumberland Peninsula (see fig. 1). Landsat image (20185–15051, bands 4, 5, and 7; 26 July 1975; Path 17, Row 13) is from the Canada Centre for Remote Sensing, Ottawa, Ontario.

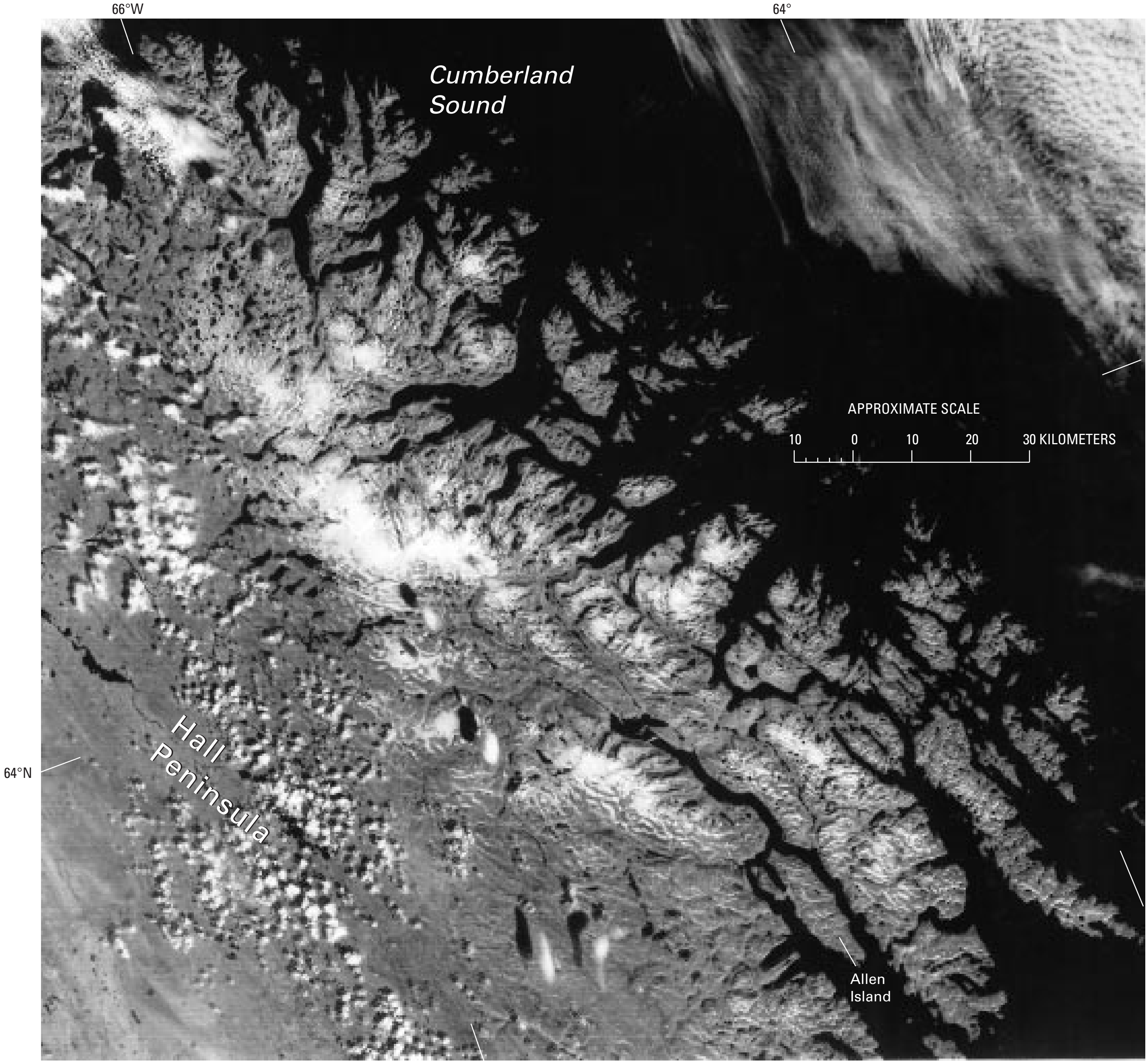


Figure 18.—*Annotated Landsat 1 MSS black-and-white image of an ice cap on the northeast coast of Hall Peninsula (fig. 1). Landsat image (1747–15083, band 7; 9 August 1974; Path 17, Row 15) is from the EROS Data Center, Sioux Falls, S. Dak.*

Hall Peninsula

Small ice caps and small glaciers lie in a restricted zone along the northeast and east flank of the Hall Peninsula (fig. 1). The Landsat image taken 9 August 1974 (fig. 18) illustrates the major geographic features of the glacierization. The margins of the ice caps are simple along the southwest where they terminate on uplands of Hall Peninsula, but on the seaward side, small outlet glaciers are topographically channeled, although none descend to sea level. The glaciation level for the region is shown in figure 2. No glaciological research has been undertaken on any of the glaciers on the Hall Peninsula, and few glacial geological investigations have been carried out (Miller, 1985b). Data on late Foxe deglaciation have come from marine shells in glacial marine deltas, and ages fall between 9.5 and 8.5 ka B.P. (Miller, 1979, 1980). However, amino-acid studies suggest that parts of Allen Island were deglaciated at more than 80 ka years ago. (Andrews and others, 1981).

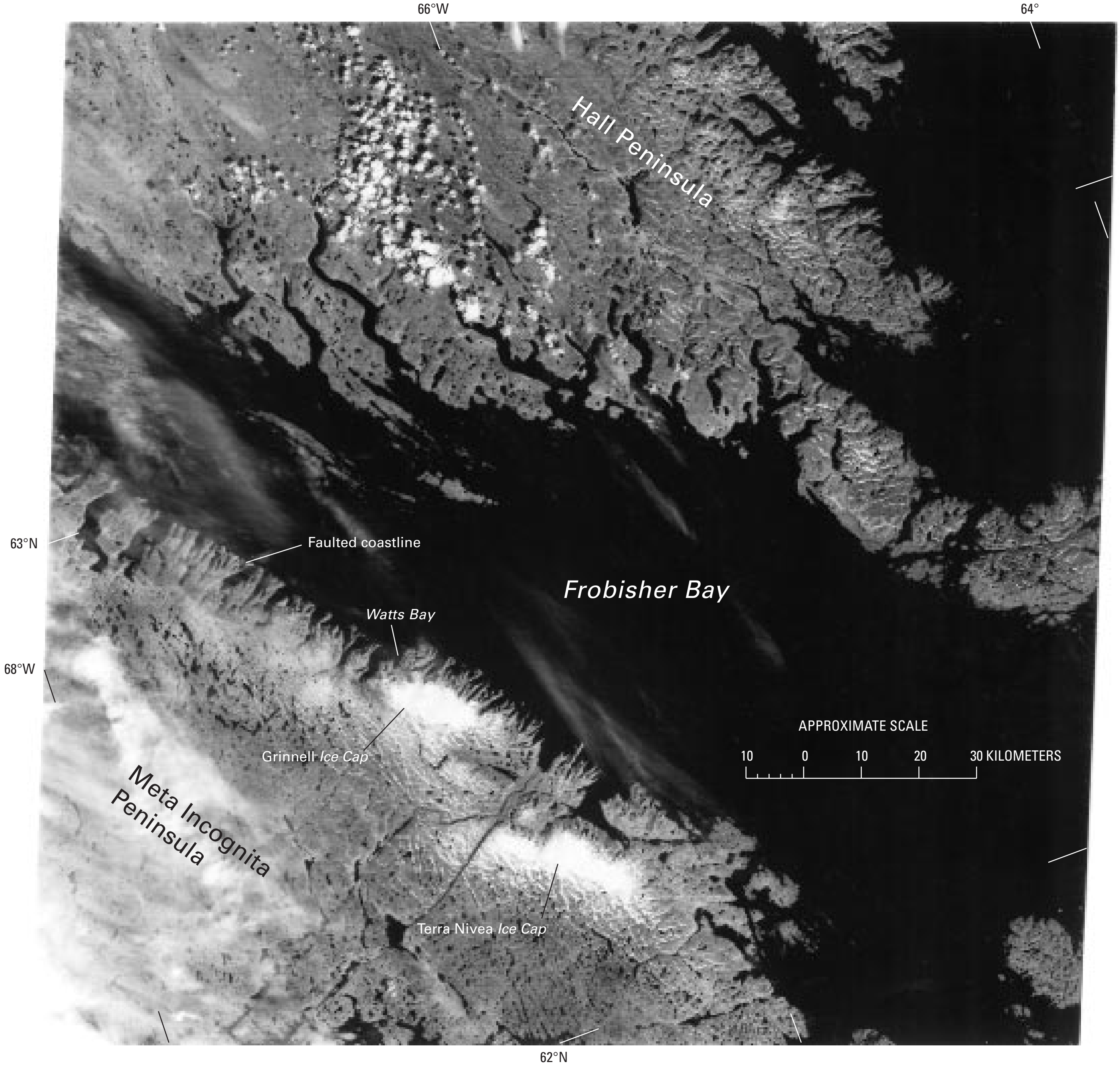


***Figure 19.**—Annotated Landsat 1 MSS black-and-white image of Terra Nivea and Grinnell* Ice Caps *on the Meta Incognita Peninsula, southern Baffin Island (fig. 1). Landsat image (1747–15090, band 7; 9 August 1974; Path 17, Row 16) is from the EROS Data Center, Sioux Falls, S. Dak.*

Meta Incognita Peninsula

Figure 19 is a Landsat 1 MSS image taken 9 August 1974 that covers the small Terra Nivea and Grinnell *Ice Caps* on the uplifted rim of the Frobisher Bay half-graben. The image does not reveal much detail because of extensive snow cover on the ice caps. These two small ice caps have been studied relatively little (Dowdeswell, 1982, 1984), and no reports exist on the amount of winter accumulation, although studies have been made of the neoglacial and Holocene glacial histories (Blake, 1953; Mercer, 1956; Muller, 1980; Lind, 1983; Stravers, 1986; Duvall, 1993).

Dowdeswell (1982) studied the tidal outlet glacier from the Grinnell *Ice Cap* that ends in Watts Bay (fig. 19). This glacier is moving at about 20 m a^{-1} at its terminus, and 100 to 200 years ago, it extended much farther out into Watts Bay. The description of the two ice caps by Hall (1865) during the middle of the 19th century suggests that a significantly thicker snow (if not ice) cover may have been present, so that the appearance from Frobisher Bay was of a continuous ice body. Studies of moraines fronting glaciers around the Terra Nivea and Grinnell *Ice Caps* (Muller, 1980; Dowdeswell, 1982, 1984) indicate that the major glacier recession dates from the last 100 years. In addition to the two small ice caps, a number of small cirque glaciers face Frobisher Bay. These are not well shown on this Landsat image, although the image does indicate the presence of cirques, many of which are drowned or partly drowned, along the steep fault-bound escarpment. The escarpment is strikingly illustrated in the coastline of Frobisher Bay immediately northwest of the Grinnell *Ice Cap*.

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