Glaciers of North America–

GLACIERS OF CANADA

GLACIERS OF THE ARCTIC ISLANDS

ELLESMERE ISLAND ICE SHELVES AND ICE ISLANDS

By MARTIN O. JEFFRIES

SATELLITE IMAGE ATLAS OF GLACIERS OF THE WORLD

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*Ellesmere Island, Nunavut, has ice shelves in several fjords along its northwest coast. They can be classified into three types: sea ice (Ward Hunt Ice Shelf), glacier (Milne Ice Shelf), and composite (*Alfred Ernest Ice Shelf*). Some ice shelves and ice plugs (multiyear landfast sea ice) calve and are the source of ice islands such as* Hobson's Choice ice island *that drift around the Arctic Ocean*

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Abstract

Within fjords along the northwest coast of Ellesmere Island, Nunavut, are several types of ice shelves. Three types have been recognized: sea ice, such as the Ward Hunt Ice Shelf; glacier, such as the Milne Ice Shelf; and composite, such as the *Alfred Ernest Ice Shelf*. Ice plugs, such as the *Nansen Ice Plug*, which are composed of multiyear landfast sea ice, and ice shelves are the source of ice islands, such as *Hobson's Choice ice island*, that drift around the Arctic Ocean. Satellite images are used to characterize the types of ice shelves, ice plugs, and ice islands. Because of winter darkness and persistent summer cloud cover, satellite synthetic aperture radar is the preferred source of image data to identify the changes in, map the areal extent of, and establish a baseline for ice shelves. Ellesmere Island ice shelves have existed since the middle Holocene Epoch and were more extensive in the past. The warming interval during the 20th century has caused a marked reduction in their areal extent. Ice islands are another element of the cryosphere that can be monitored by the use of satellite imagery and can serve as an indicator of climatic amelioration.

Introduction

Ice shelf: "A sheet of very thick ice, with a level or gently undulating surface, which is attached to the land along one side but most of which is afloat and is bounded on the seaward side by a steep cliff **ice front** rising 2–50 m or more above sea level" (Jackson, 1997, p. 317).

Ice island: "A form of large **tabular iceberg** broken away from an ice shelf and found in the Arctic Ocean, having a thickness of 15–20 m and an area between a few thousand square meters and 500 sq km or even more. The surface of an ice island is usually marked by broad, shallow, regular undulations that give it a ribbed appearance from the air" (Jackson, 1997, p. 316).

The first ice island, named *T–1*[2], was seen in 1946, when a U.S. Army Air Force (USAAF) reconnaissance mission over the Arctic Ocean reported a heart-shaped ice mass that had dimensions of 24x29 km and an area of about 500 km^2 surrounded by sea ice (Koenig and others, 1952). Subsequently, ice islands *T–2, T–3, T–4*, and *T–5* were observed from the air or identified on aerial photographs between 1946 and 1950 in the Arctic Ocean, and 59 unnamed ice islands were found in aerial photographs of the Canadian Arctic Archipelago taken in 1950 (Koenig and others, 1952).

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[2] The names in this section conform to the usage authorized by the Secretariat of the Canadian Permanent Committee on Geographic Names (CPCGN); URL address: [http://GeoNames.NRCan.gc.ca/]. The Website is maintained by the Secretariat through Geomatics Canada, Natural Resources Canada, and combines the CPCGN server with the Canadian Geographical Names Data Base (CGNDB). Variant names and names not listed in the CPCGN/CGNDB are shown in italics.

The undulating surface topography of ice islands is accentuated in summer when meltwater lakes form in the troughs (fig. 1). An ice shelf having a similar topography of ridges and water-filled troughs (fig. 2) was observed in 1951 during U.S. Air Force (USAF) reconnaissance missions between Nansen Sound and Ward Hunt Island on the north coast of Ellesmere Island, Nunavut (fig. 3). Little doubt existed that the *Ellesmere Ice Shelf*, as it was initially called (Hattersley-Smith and others, 1955; Crary, 1958, 1960), was the source of the ice islands.

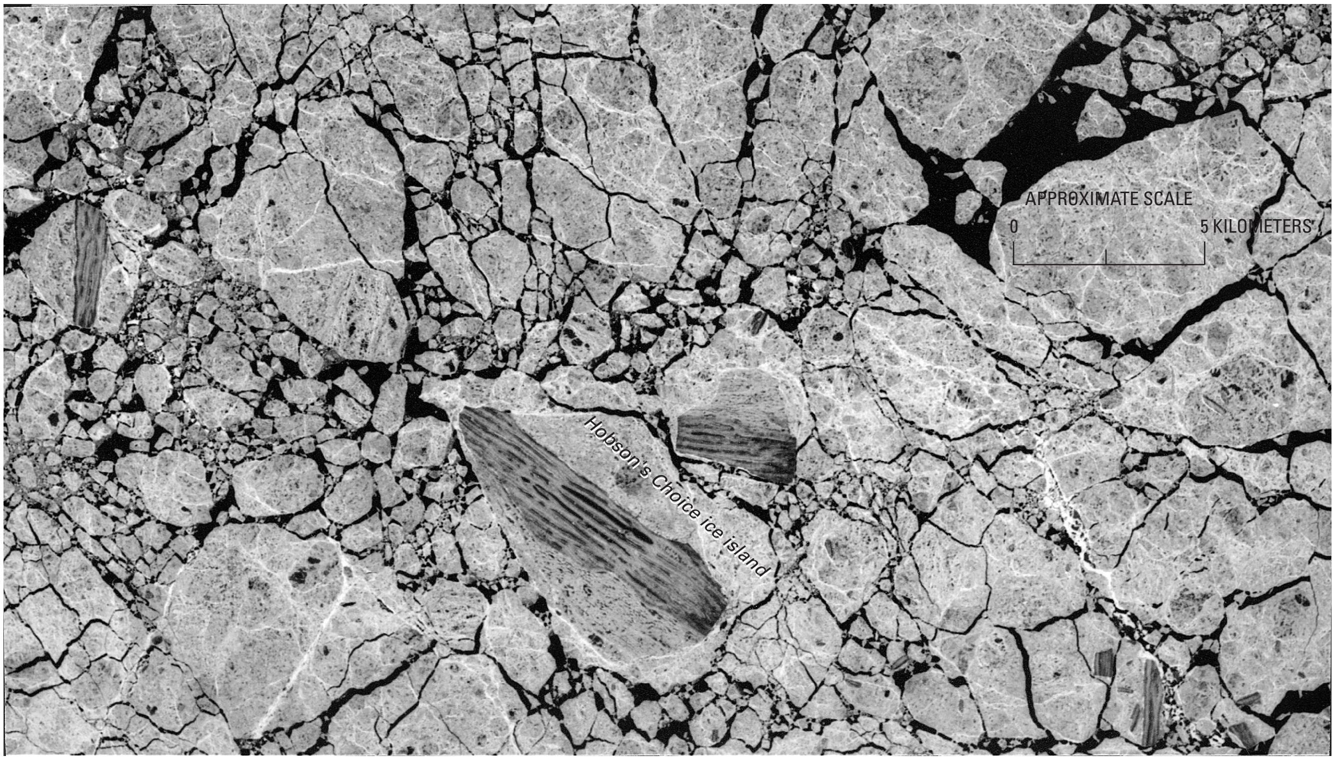


***Figure 1.**—Subscene of a SPOT–1 image of* Hobson's Choice ice island *and 19 smaller ice islands on 25 July 1988.* Hobson's Choice ice island *calved from the east side of Ward Hunt Ice Shelf in 1982–83 (see fig. 4). Image number HRV2 061–108 250788 is from SPOT Image Corporation.*

***Figure 2.**—Left-looking (high-angle oblique) trimetrogon aerial photograph of the Ward Hunt Ice Shelf acquired by the Royal Canadian Air Force in August 1950 from 6,096 m. The ice shelf north (to the left) of the ice rise and Ward Hunt Island ceased to exist in 1961–62, when almost 600 km^2 of ice calved. Photograph number T404L–3 from the National Air Photo Library, Ottawa, Canada.*

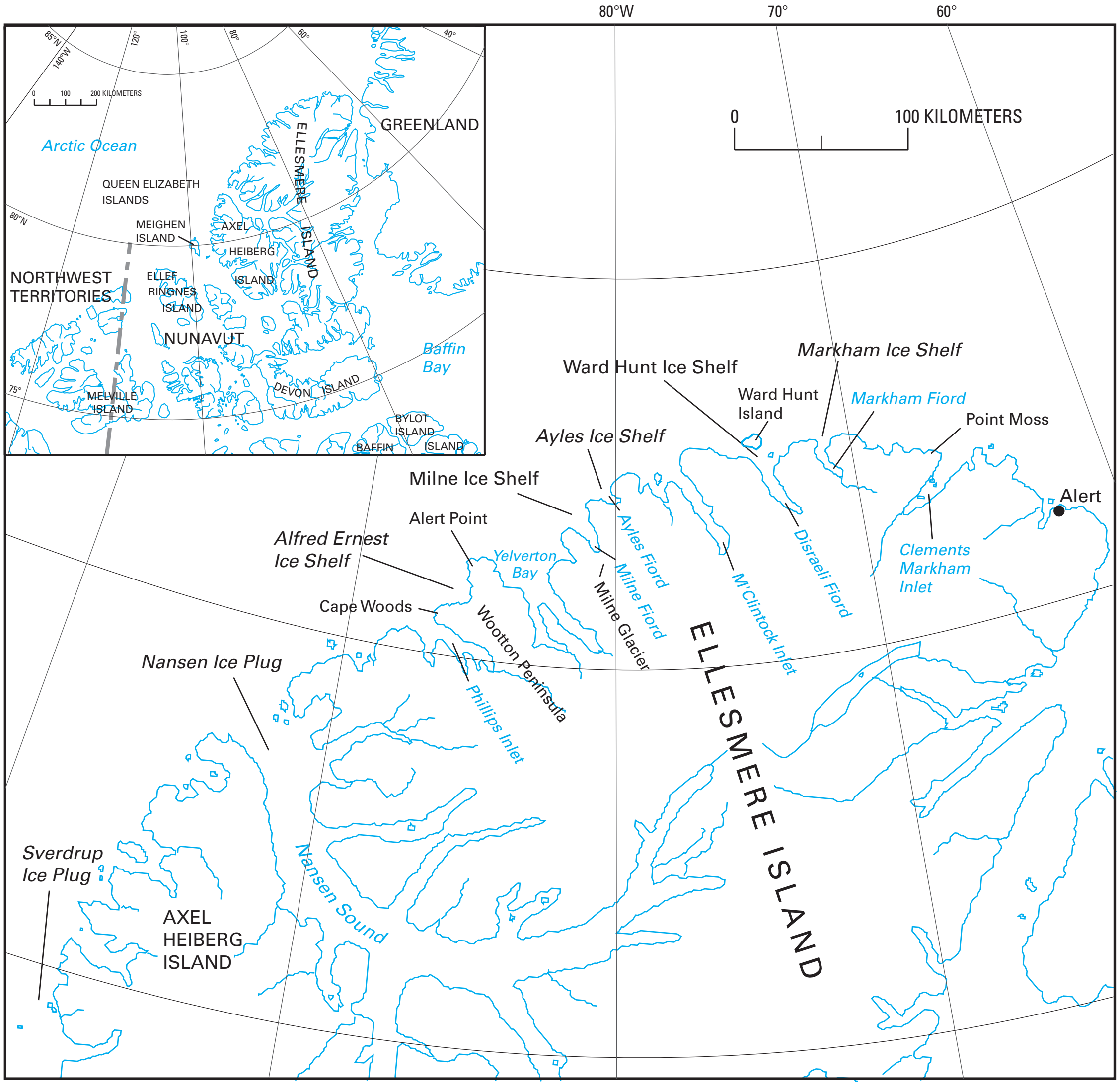


Figure 3.—*Northern part of Ellesmere Island, Queen Elizabeth Islands, Nunavut, Canada, showing the location of the largest remaining ice shelves (*Markham Ice Shelf, *Ward Hunt Ice Shelf,* Ayles Ice Shelf, *Milne Ice Shelf, and* Alfred Ernest Ice Shelf*), as well as other locations mentioned in the text.*

The first to describe the undulating surface of the ice along the north coast of Ellesmere Island was Lt. Pelham Aldrich (Royal Navy) in 1876. Man-hauling a sledge on what is now known as the Ward Hunt Ice Shelf and looking west across the mouth of Disraeli Fiord, Aldrich wrote: "Several low ridges from 30 to 40 feet high, and varying from a few hundred yards to about a mile in length, show up in front of the cliffs. Their general direction being SE to NW, hence on the east coast of the bay to the south-westward they are nearly parallel with it. I imagine these ridges are composed of hard ice under the snow..." (Parliamentary Paper, 1877, p. 201–202). As the party passed between Ward Hunt Island and the mainland (fig. 2), he wrote: "...we crossed a ridge about 30 feet high, and a half mile in width, which runs quite a mile from about the middle of the south shore...Similar looking ridges extended to the eastward and westward of the island" (Parliamentary Paper, 1877, p. 201–202).

Thirty years later, on what is now known as the Ward Hunt Ice Shelf, Peary (1907, p. 185) noted the difficulty of dog-sled travel, which "was accentuated in the series of rolling swells which are a feature of this ice-foot? (sic) along here. These swells are on a large scale...if they are not huge drifts I do not know how to account for them. Off Ward Hunt Island and especially the western end, they are particularly marked, and here they blend into drifts formed in the lee of the island."

Elsewhere along the coast, Peary described the ice topography thus: "...what later became a constant and striking feature of the glacial fringe, the long, prairie-like swells of its surface…” (Peary, 1907, p. 181) and “…a gigantic potato field with a long blue lake or rushing stream in every furrow” (Peary, 1907, p. 220). Although Peary considered the ice surface to be a “watery hell” (Peary, 1907, p. 225), he also predicted that “the glacial fringe” “will form one of the most unique and interesting features of this region to the glacialist…” (Peary, 1907, p. 240).

The historical record suggests that the “glacial fringe” was a single ice shelf that extended from Point Moss to Nansen Sound (fig. 3), hence, the so-called *Ellesmere Ice Shelf*. At the beginning of the 20th century, it had an estimated area of 7,500 km^2 (Jeffries, 1987). A single, continuous *Ellesmere Ice Shelf* no longer exists; its disintegration, which produced the ice islands, has left a number of smaller ice shelves isolated in fjords, inlets, and bays (fig. 3). These are the Ellesmere Island ice shelves, and they are unique in North America.

Peary showed remarkable foresight with respect to the interest of “the glacialist” in the “glacial fringe.” In 1953 and 1954, the Defence Research Board of Canada and the Geological Survey of Canada conducted the first glaciological, geophysical, geological, and oceanographic surveys of the Ellesmere Ice Shelf (Hattersley-Smith and others, 1955; Crary, 1958, 1960). Since then, numerous glaciological and related investigations have been made of the Ellesmere Island ice shelves, and a number of ice islands have been used as platforms for drifting scientific research stations in the Arctic Basin, for example, *T–3*, *ARLIS–II,* and *Hobson's Choice ice island* (fig. 1). Most scientific investigations have been on-site programs. Remote sensing has not been widely used, although imagery has been available since the first aerial photography missions of the late 1940’s. Available remote sensing data now include oblique and vertical aerial photographs, Satellite pour l’Observation de la Terre (SPOT) and Landsat imagery, airborne real aperture radar (RAR), airborne and spaceborne synthetic aperture radar (SAR), and the like.

This paper describes the origin and age of the ice shelves, the different types of ice shelves (sea-ice, glacier-ice, and composite-ice shelves), the origin of the undulating surface topography, the impact of ice shelves on coastal oceanography, ice-shelf regrowth, ice islands, and ice plugs. European Remote Sensing Satellite (ERS–1) and RADARSAT SAR, Landsat, and SPOT images are used to illustrate a variety of physical characteristics and processes of the Ellesmere Island ice shelves and ice islands.

Origin and Age of the Ellesmere Ice Shelves

Most of the Earth’s ice shelves are located in Antarctica, where they are almost all seaward extensions of the grounded Antarctic ice sheet. The glaciers and ice streams that flow into the large embayments of the Antarctic continent are further nourished at the surface by accumulating snow and, in places, by basal accretion of sea ice. Massive tabular icebergs calve from the Antarctic ice shelves. The largest ice shelf on Earth is the Ross Ice Shelf, West Antarctica (525,840 km^2: Swithinbank, 1988, p. B12). The calving of iceberg B–15 (37x295 km, 10,900 km^2) and a number of smaller icebergs from the Ross Ice Shelf in March 2000 reduced its area by 3 percent or less (S.S. Jacobs, oral commun., August 2000).

The Ellesmere Island ice shelves and ice islands are dwarfed by comparison with their Antarctic counterparts. *T–2* (700 km^2) was the largest reported ice island in this area (Koenig and others, 1952). The calving of almost 600 km^2 of ice from the Ward Hunt Ice Shelf in 1961–62 reduced its area by more than 50 percent (Hattersley-Smith, 1963). In 1998, Ward Hunt Ice Shelf had an area of 490 km^2 (Vincent and others, 2001). The

Ellesmere Island ice shelves have a total area of approximately 1,350 km^2 (Jeffries, 1987). Though they are much smaller, the Ellesmere Island ice shelves are no less scientifically significant than the Antarctic ice shelves.

Koenig and others (1952) recognized that some parts of the *Ellesmere Ice Shelf* were receiving inflow from grounded glaciers and other parts were not. Lemmen and others (1988a, 1988b) considered the Ellesmere Island ice shelves to be composed of genetically, dynamically, and geomorphologically distinct systems, and they proposed a simple genetic classification to differentiate among a *sea-ice ice shelf*, a *glacial- [sic, glacier-] ice shelf*, and a *composite-ice shelf*. *Sea-ice ice shelf* refers to an ice shelf that is primarily composed of multiyear landfast sea ice and has a freeboard of more than 2 m. Glacier input is either absent or negligible, although ice rises (where the ice shelf is grounded on the sea floor) may be found in and adjacent to sea-ice shelves. *Glacial- [sic, Glacier-] ice shelf* refers to an ice shelf that is, or has been, nourished directly from grounded (glacier) ice. *Composite-ice shelf* refers to an ice shelf that is composed of significant amounts of both glacier ice and sea ice. Surface accumulation and bottom freezing, as well as surface ablation and bottom melting, are known to take place or have taken place at the Ward Hunt Ice Shelf, a *sea-ice ice shelf* (see next section). It is reasonable to presume that the same processes are present at the other types of ice shelves.

Glaciological and geomorphological studies, along with radiocarbon dating of driftwood, marine mammals, and shells, indicate that the Ellesmere Island ice shelves are Holocene in age (Bradley, 1990; Evans and England, 1992). The *sea-ice ice shelves* began to form at about 4.5 kilo-annum (ka, 10^3 years) (before the present, present defined by geochronologists as A.D. 1950) during a middle Holocene climatic deterioration. Prior to that, the Pleistocene glaciers had retreated to behind their present positions, the summer sea-ice cover was much less severe with predominantly open water compared with modern conditions, and no ice shelves were present (Evans and England, 1992). The timing of glacier readvance and formation of the *glacial [sic, glacier] ice shelves* and the glacier component of the *composite ice shelves* is more difficult to ascertain. Some large glaciers are still advancing in response to the middle Holocene climatic deterioration, and some glaciers display evidence of dual advances, which may reflect both the middle Holocene and "Little Ice Age" (400–100 years before present) accumulations (Evans and England, 1992).

Ice-Shelf Types

Sea Ice: Ward Hunt Ice Shelf

The Ward Hunt Ice Shelf lies across the mouth of Disraeli Fiord (figs. 2,3, and 4) and is the most studied of the Ellesmere Island ice shelves. The undulating surface topography is manifested as a faintly ribbed texture in the SAR image (fig. 4). The undulations are commonly called "rolls" (Hattersley-Smith, 1957). On the western part of the ice shelf (the area to the west of Ward Hunt Island), the rolls have a mean (±1 standard deviation) wavelength of 267±60 m, whereas those on the eastern ice shelf (the area to the east of Ward Hunt Island) have a mean wavelength of 212±42 m (Jeffries and others, 1990). Interest in the rolls has centered primarily on their origin (see "Surface Topography" section). More recently, it has been found that the meltwater lakes on the Ward Hunt Ice Shelf harbor complex and productive microbial ecosystems that offer the opportunity to understand the Proterozoic fossil record and life on "snowball Earth" (Vincent and others, 2001).

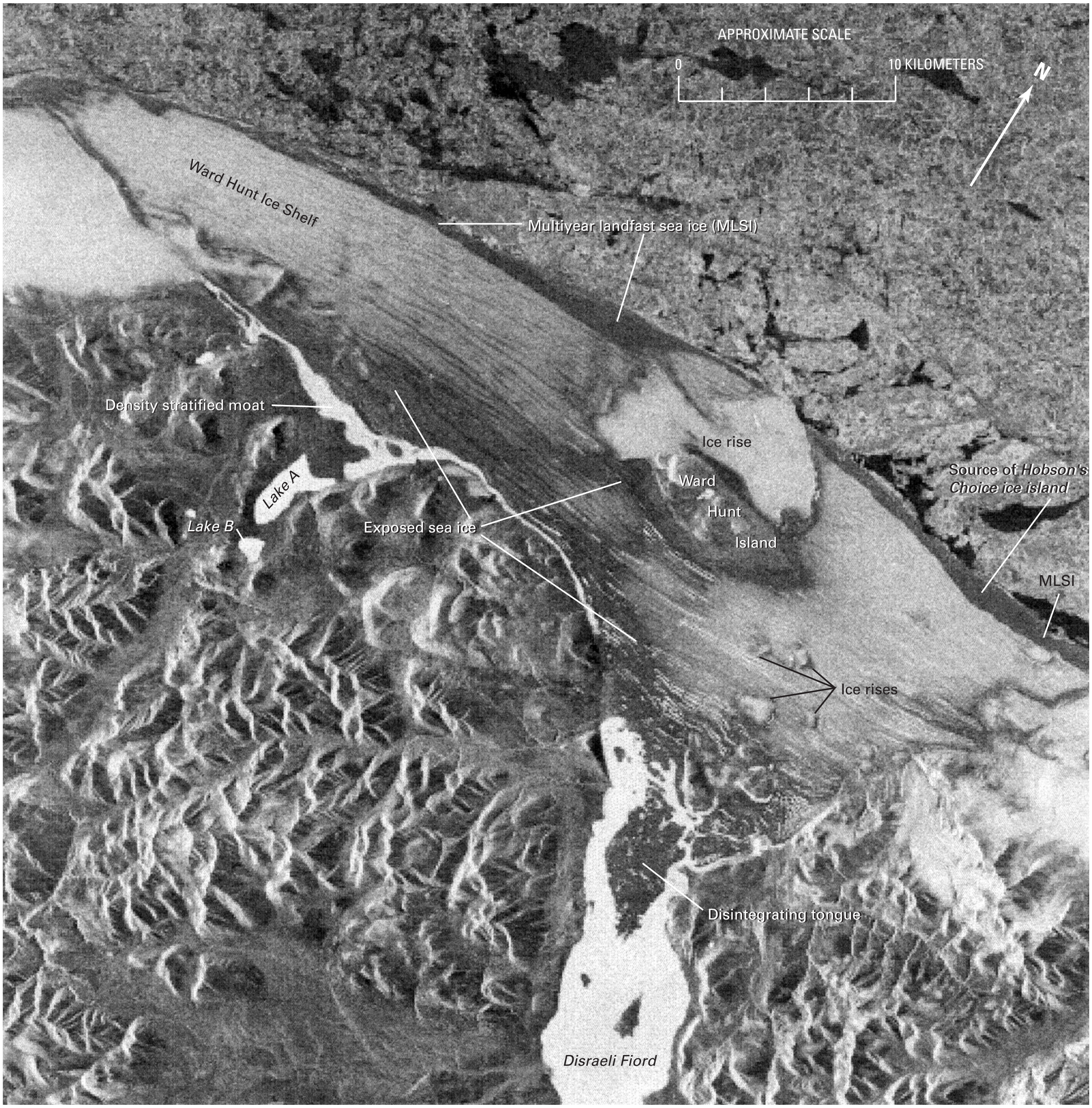


Figure 4.*—Subscene of a radiometrically calibrated RADARSAT Standard Beam 5 (ST5) SAR image of the Ward Hunt Ice Shelf on 26 May 1998 that has a spatial resolution of 150 m and a pixel spacing of 100 m. Image number R113353209 from the Alaska SAR Facility. Original image is © CSA (Canadian Space Agency).*

Radiocarbon dates for basally accreted marine organic compounds collected at the ice-shelf surface range between 4.5 and 3.3 ka (Lyons and Mielke, 1973). The former is the best estimate for the onset of ice-shelf formation in the middle Holocene (Evans and England, 1992). The youngest driftwood (3±0.2 ka) found along the shores of Disraeli Fiord (Crary, 1960) provides a maximum date for the complete blockage of the coast by the ice shelf (Evans and England, 1992). The only known ice rises in all the Ellesmere ice shelves are those in the Ward Hunt Ice Shelf (fig. 4). Heat-flow calculations indicate that they began to ground on the sea floor beginning at about 1.6 ka, the greatest growth taking place in the interval 1,000 to 150 years ago (Lyons and others, 1972).

Sea ice and brackish ice in ice cores reflect water salinity variability below the ice shelf (Lyons and others, 1971; Jeffries and Sackinger, 1989;

Jeffries, 1991a). This saline ice, which still has a high liquid-brine content (Jeffries, 1991a), is exposed at the surface of the ice shelf, particularly to the south and west of Ward Hunt Island (fig. 4). The dark SAR signature can be attributed to attenuation of the radar signal by the brine. The brighter SAR signatures of other parts of the ice shelf are probably due to volume scattering and strong returns from bubble-rich iced firn ("A mixture of ice and firn; firn permeated with meltwater and then refrozen," Jackson, 1997, p. 316) that overlies the sea ice.

Airborne radio-echosounding indicates that the entire area of ice shelf to the west and south of Ward Hunt Island contains sea ice and brackish ice, which has frustrated efforts to make ice-thickness measurements by electromagnetic means in these areas because of signal attenuation (Hattersley-Smith and others, 1969; Narod and others, 1988). However, seismic sounding and ice-temperature profiles in the western ice shelf indicate that it is up to 50 m thick (Crary, 1958; Lyons and others, 1972; Jeffries, 1991a).

Bottom reflections have been obtained by radio-echosounding over a large part of the eastern ice shelf. In 1966, the ice thickness was primarily in the range of 35–40 m, but some values were as high as 80 m (Hattersley-Smith and others, 1969). In 1981, the ice thickness was consistently 45–50 m (Narod and others, 1988). The acquisition of bottom reflections implied that no saline ice was present in much of the eastern ice shelf. This was confirmed by the nonsaline composition of a 42-m ice core (Jeffries and others, 1988, 1991) through *Hobson's Choice ice island* (fig. 1), which calved from the eastern ice shelf (fig. 4) in 1982–83 (Jeffries and Serson, 1983). The absence of sea ice in the eastern ice shelf has been attributed to bottom melting prior to 1952 (Jeffries and others, 1991).

The 42-m *Hobson's Choice* ice core was composed of 37 m of iced firn overlying a tritium-rich, 5-m-thick basal ice layer that had accreted since 1952 from freshwater flowing out of Disraeli Fiord (Jeffries and others, 1988, 1991). It has been estimated that the freshwater ice accreted at 1.3–1.9 times the rate of surface ablation (Jeffries, 1991b; Jeffries and others, 1991). Although the eastern ice shelf might have thickened slightly between the 1950's and the 1980's, evidence exists that significant thinning has taken place since the 1980's (Vincent and others, in 2001). This is discussed in the "Ice-Shelf Dams and Coastal Oceanography" section.

Glacier: Milne Ice Shelf

Milne Ice Shelf is the second largest of the Ellesmere ice shelves. It is 42-km long and extends from the mouth of Milne Fiord to the grounding line of Milne Glacier (figs. 5 and 6). The surface topography of the ice shelf is quite variable, as it has rolls that become shorter in wavelength as the distance from the ice-shelf front increases (fig. 5). The topographic variations are the basis for the division of the ice shelf into three units (outer, central, and inner) plus the floating part of the Milne Glacier (Jeffries, 1986).

Milne Glacier is 10–40 m thick seaward of the grounding line (Narod and others, 1988). In addition to an undulating surface, the floating ice is characterized by a number of moderately contorted medial moraines (fig. 5) that might be evidence that Milne Glacier is a surge-type glacier (Jeffries, 1984). Between 1950 and 1959, the glacier advanced at about 10 m a^{-1}; no advance took place between 1959 and 1966 (Hattersley-Smith and others, 1969). A comparison of the 1959 aerial photography and the SPOT image (fig. 5) indicates that the glacier advanced 2.5 km between 1966 and 1988. A comparison of the SPOT image and the RADARSAT image (fig. 6) indicates that the glacier advanced 2 km at 165 m a^{-1} between 1988 and 2000. These speeds are not as high as those associated with true surge-type glaciers, but they are high for a polar glacier.

Figure 5.*— SPOT–1 haute (high) resolution visible (HRV) [high-resolution visible spectrum] image of the Milne Ice Shelf on 8 August 1988. The ice shelf is composed of the floating part of Milne Glacier north of the glacier grounding line, and the inner, central, and outer units. Abbreviation: MLSI, multiyear landfast sea ice. Image number HRV1 086–122080888 is from the SPOT Image Corporation.*

No radio-echosounding bottom echoes were obtained from the inner unit (Narod and others, 1988), but ice-core drilling has shown the ice to be as little as 3 m thick (M.O. Jeffries, unpub. data, 1983). Short-wavelength (60–100 m, Jeffries, 1986), curvilinear rolls are evident in the SPOT image (fig. 5) but not in the SAR image (fig. 6). Also, the textureless SAR signature of the inner unit is brighter than that of the central and outer units (fig. 6). The bright signature might be due to surface scattering from rough ice deformed by the advance of Milne Glacier. This signature is also similar to that of Disraeli Fiord (fig. 4) where evidence exists that the cause is the same. This is discussed in the "Ice-Shelf Dams and Coastal Oceanography" section.

The central unit is 10–100 m thick (Narod and others, 1988) and is derived from tributary glaciers (figs. 5 and 6: numbers 1, 2, 3, and 6) flowing in from the east and west sides of Milne Fiord (Jeffries, 1986). The thickest ice is found in a tongue extending seaward of glacier 2 (Narod and others, 1988). The rolls (150–180 m wavelength, Jeffries, 1986) on the

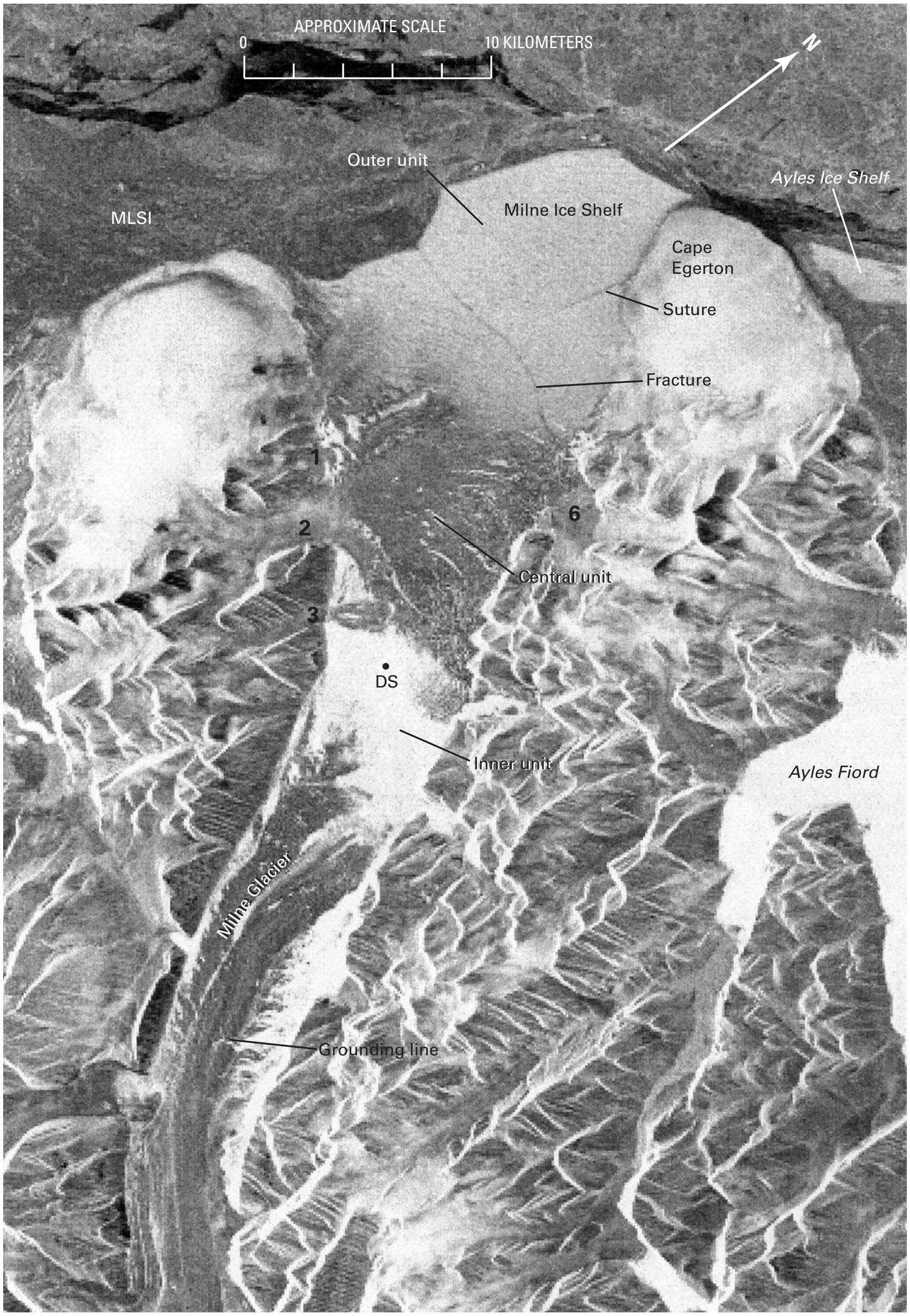


***Figure 6.**—Subscene of a radiometrically calibrated RADARSAT Standard Beam 1 (ST1) SAR image of the Milne Ice Shelf on 13 April 2000 that has a spatial resolution of 150 m and a pixel spacing of 100 m. Tributary glaciers flowing into the central unit are identified by 1, 2, 3, and 6 (after Jeffries, 1986). DS identifies the location where density stratification was observed below the ice in 1983 and 1984. Note multiyear landfast sea ice (MLSI). Image number R123185213 is from the Alaska SAR Facility. Original image is © CSA.*

central unit might be aligned with former crevasses (Hattersley-Smith, 1957), or they might reflect the flow lines of the glacier tongues derived from glaciers 1, 2, 3, and 6 (Jeffries, 1986). Extensive moraines composed of individual boulders many meters across and conical mounds of debris up to 10 m high attest to the glacial origin of the central unit (Jeffries, 1986). The debris-laden ice surface accounts for the dark tone in the SPOT image (fig. 5) and probably the dark signature of the SAR image (fig. 6).

The outer unit is 10–90 m thick, and the thickest ice is found in a tongue that extends west across the mouth of Milne Fiord from the ice field at Cape Egerton (Narod and others, 1988: fig. 6). If this thick tongue of ice is a glacier tongue, then it is likely a relict feature, as I have seen no evidence on the ground or from the air for glacier flow off the ice field today. The rolls on the outer unit have a mean wavelength of 330±62 m (Jeffries, 1986), and those adjacent to Cape Egerton are the most linear of the entire ice shelf (fig. 5). Rather than precluding a glacier origin for the outer unit, the linearity of the rolls might be due to prolonged and intense modification of the surface topography since the glacier advance from Cape Egerton.

Other features on the outer unit include a fracture and a suture (rehealed fracture) (fig. 6) that are also evident in 1959 aerial photographs (Jeffries, 1986). The precise origin of these features is unknown, although airborne radio-echosounding suggests that they might be associated with bottom crevasses where brackish or sea ice is accreting (Narod and others, 1988). Unlike the central unit, the outer unit is not debris-laden, and it has a bright SAR signature (fig. 6) probably due to volume scattering from the iced firn. Note the strong resemblance between the topography of the outer unit (fig. 5) and that of *Hobson's Choice ice island* (fig. 1).

Composite: *Alfred Ernest Ice Shelf*

The *Alfred Ernest Ice Shelf* occupies the bay between Alert Point and Cape Woods on Wootton Peninsula (figs. 3 and 7). Lemmen and others (1988b) described it as a composite-ice shelf that comprises an inner unit known to be glacial in origin, as it is derived from a valley glacier (A in fig. 7) and a trunk glacier (B), and an outer unit believed to have originated as sea ice. A radiocarbon date of 6.83±0.05 ka for a narwhal tusk at site N (fig. 7) suggests regionally abundant open water and locally no ice shelf at that time (Evans, 1989). A radiocarbon date of 4.31±0.07 ka for driftwood at site X (fig. 7) gives a maximum age for the sea-ice component (Lemmen and others, 1988b) that is consistent with the onset of formation of the Ward Hunt Ice Shelf. A radiocarbon date of 1.85±0.05 ka for marine shells from

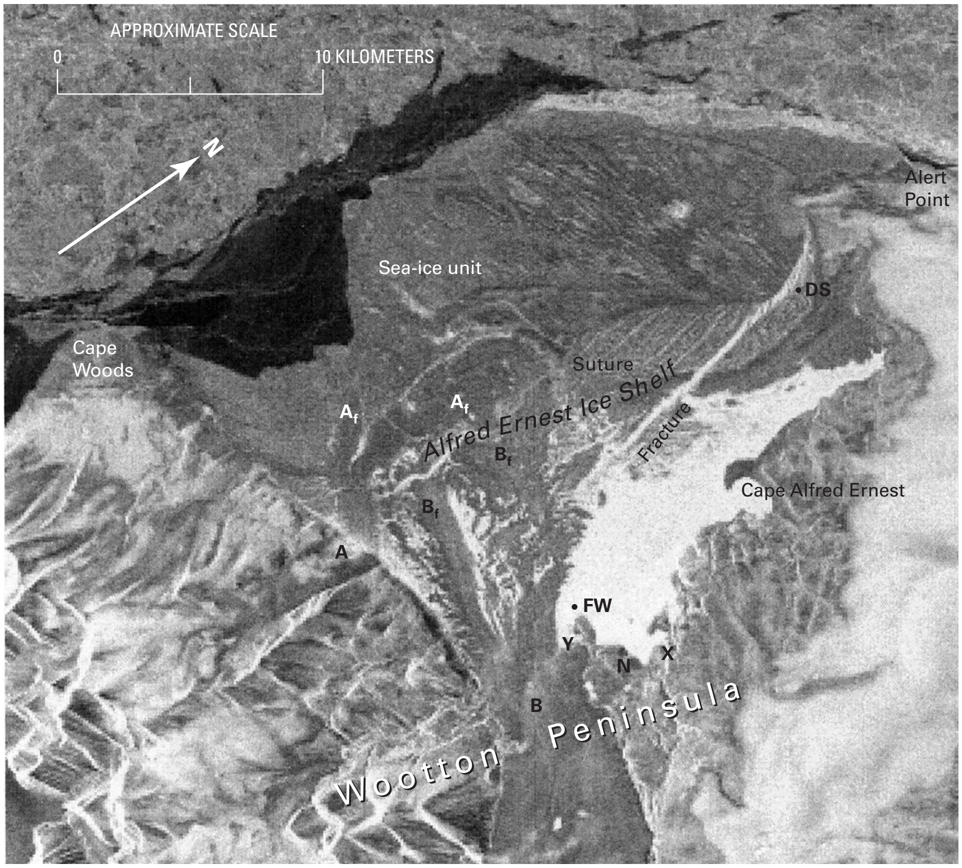


***Figure 7.**—Subscene of a radiometrically calibrated RADARSAT SAR image of the* Alfred Ernest Ice Shelf *on 5 April 2000 that has a spatial resolution of 150 m and a pixel spacing of 100 m. A and B identify a valley glacier and trunk glacier, respectively, and A_f and B_f are the floating tongues of those glaciers. DS is the location where density stratification was observed below the ice, and FW is the location where freshwater was found in a crack in the ice in May 1986. X and Y identify the locations of radiocarbon-dated driftwood and marine shells, respectively (Lemmen and others, 1988b). N identifies the location of a radiocarbon-dated narwhal tusk (Evans, 1989). Image number R123071212 is from the Alaska SAR Facility. Original image is © CSA.*

glacially thrust sediment at site Y (fig. 7) indicates that the glacier component of the ice shelf is quite young and postdates the sea-ice component.

Lemmen and others (1988b) note that the floating tongues of glaciers A and B have "surface patterns that are clearly related to transverse crevasse systems within the grounded ice." On these glacier tongues are also extensive moraines that have boulders and conical debris mounds similar to those on the Milne Ice Shelf (M.O. Jeffries, unpub. data, 1984, 1986). The sea-ice unit has some particularly dark SAR signatures that might denote sea ice exposed at the surface (fig. 7). The ribbed texture of the sea-ice unit is more pronounced than at Ward Hunt and Milne Ice Shelves (figs. 4 and 6), perhaps because of differences in the SAR incidence angle or illumination direction. The rolls on the sea-ice unit have a mean wavelength of 291±69 m (M.O. Jeffries, unpub. data, 1986).

Lemmen and others (1988b) describe a suture (fig. 7) along the east margin of the sea-ice unit and propose that it is a fracture caused by the advance of glacier B. They suggest that the suture has developed rolls since it opened. This might account for the ribbed texture of the suture (fig. 7), but given the present understanding of the processes governing the ice-surface topography (see next section), one would expect these rolls to be aligned parallel with rather than perpendicular to the rolls on the sea-ice unit.

In May 1986, I traveled on the surface of the suture and observed a number of open fractures oriented parallel with the ribbed texture. The fractures contained freshwater, and freeboard values of 0.1–0.2 m indicated relatively thin ice. The bright linear feature running through the suture and oriented parallel with the ribbed texture (fig. 7) is probably a particularly large and recent fracture. A comparison of airborne 1988 SAR data (fig. 4 in Jeffries, 1992) and 1993 ERS–1 data indicates that it opened after 1988. I suggest that the ribbed texture of the suture is due to scattering from old, rehealed fractures that record a history of glacier advances. These advances have progressively widened the suture since its initial opening at approximately 1.85 ka and have displaced the sea-ice unit seaward. The new fracture suggests the presence of some recent glacier activity.

The area adjacent to Cape Alfred Ernest and along the shore of Wootton Peninsula has a bright, textureless SAR signature (fig. 7). It is quite unlike the suture and the glacier- and sea-ice units, but it is similar to Disraeli Fiord (fig. 4) and the inner unit of the Milne Ice Shelf (fig. 6). The cause and implications of these bright signatures are discussed in the "Ice-Shelf Dams and Coastal Oceanography" section.

Surface Topography

The ice shelves and ice islands have a rolling topography of strongly aligned, bifurcating ridges and troughs, that is, the rolls (figs. 1, 2, and 5). Details of the numerous explanations for the origin of the rolls can be found elsewhere (Hattersley-Smith, 1957; Lister, 1962; Holdsworth, 1987). They are either genetic features that began to form at the time of ice-shelf formation or are superimposed features that developed after initial ice-shelf formation, or they are a combination of the two. On any given ice shelf or part of an ice shelf, the wavelength of the rolls is quite uniform and apparently increases as ice thickness increases (Hattersley-Smith, 1957). Jeffries and others (1990) found ice thickness (y) and roll wavelength (x) to be related by a polynomial expression,

$$y=0.1392x+0.0002826x^2–2.085\ m.$$

Of all the explanations for the rolls, the following meltwater-lake hypothesis has been given the most credence. In developing this hypothesis, Crary

(1960) observed that the orientation of the rolls is, in many places, parallel with the direction of prevailing winds and the shore. He suggested that winds blowing parallel to the coastline over an initially randomly distributed array of melt pools would cause them to become elongated as a result of solar heating of the water and wind-accelerated convection currents. The greater the number of summers that this happens, the more developed the rolls become.

The rolls are superimposed features according to the meltwater-lake-alignment hypothesis, but the hypothesis offers no explanation for the uniformity of their wavelength, the relationship between wavelength and ice thickness, and the bifurcations (Holdsworth, 1987). To account for these, Holdsworth hypothesized that the rolls form dynamically as an ice shelf is deformed. He showed analytically that (1) extreme pack-ice pressure against the edge of an ice shelf creates compressive strains that cause ice-shelf creep buckling at a critical stress level; (2) the undulations bifurcate because the compressive strains are nonhomogeneous as the extreme pack-ice pressure events take place over limited sections of the ice-shelf edge for limited periods of time; and (3) as the ice thickens, buckling due to further extreme events creates longer wavelength undulations. The genetic waveforms caused by the creep-buckling instabilities are perpetuated by the meltwater lakes (Holdsworth, 1987).

The creep-buckling-instability hypothesis was developed to explain the rolls on the Ward Hunt Ice Shelf but would apply to the other ice shelves, except where it can be shown that other processes are acting that are capable of compressing and buckling floating ice (Holdsworth, 1987). This would include those parts of the Milne Ice Shelf and *Alfred Ernest Ice Shelf* that are derived from the seaward advance of grounded glaciers. Although the outer unit of the Milne Ice Shelf may be glacier ice in origin, any rolls that were originally oriented parallel to ice flow lines or crevasses may have been modified due to exposure to the prevailing winds' blowing along the coast.

Ice-Shelf Dams and Coastal Oceanography

The ice cover on Disraeli Fiord, which lies to the south of the Ward Hunt Ice Shelf, has a bright, textureless SAR signature that contrasts with the darker, more textured signature of the ice shelf (fig. 4). No ice shelf is present in Disraeli Fiord, but the water there is strongly density stratified and has a layer of freshwater at the surface overlying seawater at greater depth (Keys, 1978; Jeffries, 1991b; Jeffries and Krouse, 1984; Vincent and others, 2001). It is stratified because meltwater that flows in from its catchment area is impounded behind the Ward Hunt Ice Shelf, and the perennial ice cover prevents wind-mixing.

Disraeli Fiord is covered with perennial lake ice that grows from the freshwater layer (Keys, 1978; Jeffries, 1985). The ice surface forms candles [disintegrates into ice prisms oriented perpendicular to the ice surface (Jackson, 1997, p. 94)] because of melting along grain boundaries in summer (Keys, 1978), and also many internal melt features are present (Jeffries, 1985). Consequently, the bright SAR signature is probably due to a combination of surface and volume scattering, plus any reflections from the ice-water interface. An equally bright SAR signature is observed at *Lakes A* and *B* (fig. 4), which are both density stratified and have perennial ice covers (Hattersley-Smith and others, 1970; Jeffries and others, 1984; Jeffries and Krouse, 1985). The bright signature of the moat along the south shore of the western ice shelf near ***Lakes** A* and *B* (fig. 4) suggests that it too is density stratified and covered with lake ice.

The freshwater ice found at the base of *Hobson's Choice ice island* was cited as evidence that some freshwater flows out of Disraeli Fiord below the ice-shelf dam, specifically below the eastern Ward Hunt Ice Shelf (Jeffries and others, 1988, 1991). In 1967, when the density stratification was discovered (Keys, 1978), the freshwater layer was 44.5 m thick; in 1983, it was 41 m thick (Jeffries, 1991b), and in 1999, it was 32 m thick (Vincent and others, 2001). It has always been assumed that the freshwater-layer thickness is equivalent to the mean draft of the ice shelf; hence, a 32-m draft was equivalent to a thickness of 35 m in 1999, which was 22 percent thinner than in 1983 and 27 percent thinner than in 1967 (Vincent and others, 2001). An increase in mean annual air temperature and melting degree days since 1967 suggests that the thinning of the freshwater layer is a genuine loss due to outflow beneath the ice shelf rather than a consequence of decreasing meltwater flow into Disraeli Fiord (Vincent and others, 2001).

Density stratification has also been observed at the Milne Ice Shelf and *Alfred Ernest Ice Shelf*. In May 1983 and 1984, a 17.5-m-thick freshwater layer was found below 3-m-thick lake ice in the inner unit of Milne Ice Shelf (M.O. Jeffries, unpub. data, 1983, 1984). With a bright SAR signature (fig. 6) similar to that on Disraeli Fiord (fig. 4), the inner unit is probably lake ice that has grown from freshwater impounded behind the central and outer units of Milne Ice Shelf. The inner unit of the Milne Ice Shelf, then, is not entirely glacier ice in origin, although it owes its unusual composition to the glacier-ice dam of the central and outer units. It is a hybrid that probably varies in composition according to the advance and retreat of Milne Glacier, as well as the hydrography of the fjord, as determined by the effectiveness of the ice-shelf dam.

In May 1986, a 7-m-thick layer of freshwater was found below 2-m-thick lake ice at the northern end of the *Alfred Ernest Ice Shelf* suture, and freshwater was observed in a seal hole in 2-m-thick ice at location FW (fig. 7) (M.O. Jeffries, unpub. data, 1986). The bright, textureless SAR signature of the ice adjacent to Cape Alfred Ernest and along the shore of Wootton Peninsula (fig. 7) suggests an extensive lake-ice cover that is growing from freshwater impounded behind the glacier- and sea-ice units of *Alfred Ernest Ice Shelf*.

Bright SAR signatures are found in other fjords and inlets of the north coast of Ellesmere Island: West Arm Yelverton Inlet, Ayles Fiord, Taconite Inlet, and M'Clintock Inlet (fig. 8). It is unlikely that the SAR signatures at these locations are due to surface and volume scattering from desalinated, near-surface layers of multiyear sea ice because the backscatter is significantly stronger than that from the multiyear ice on the nearby Arctic Ocean (fig.8). It is more likely that the bright SAR signatures denote lake ice and that these fjords and inlets are also density stratified because of ice dams that impound freshwater. Density stratification is widespread at the moment, but significant hydrographic changes at these locations might be detected by changes in the backscatter from the ice. For example, if an ice dam failed and the stratification broke down—or if the perennial ice melted, and the fjords and inlets were open each summer and subject to wind mixing—the SAR signature of the ice would become darker as the ice began to grow from seawater or brackish water.

Ice Islands, Ice-Shelf Regrowth, and Ice Plugs

Koenig and others (1952) suggested that winds, tides, and pack-ice pressure cause cracks to develop in ice shelves and hasten ice-island calving. Cracks might also develop because of thermal stress (Legen'kov, 1974). Holdsworth (1971) suggested that the massive calving from the Ward Hunt Ice

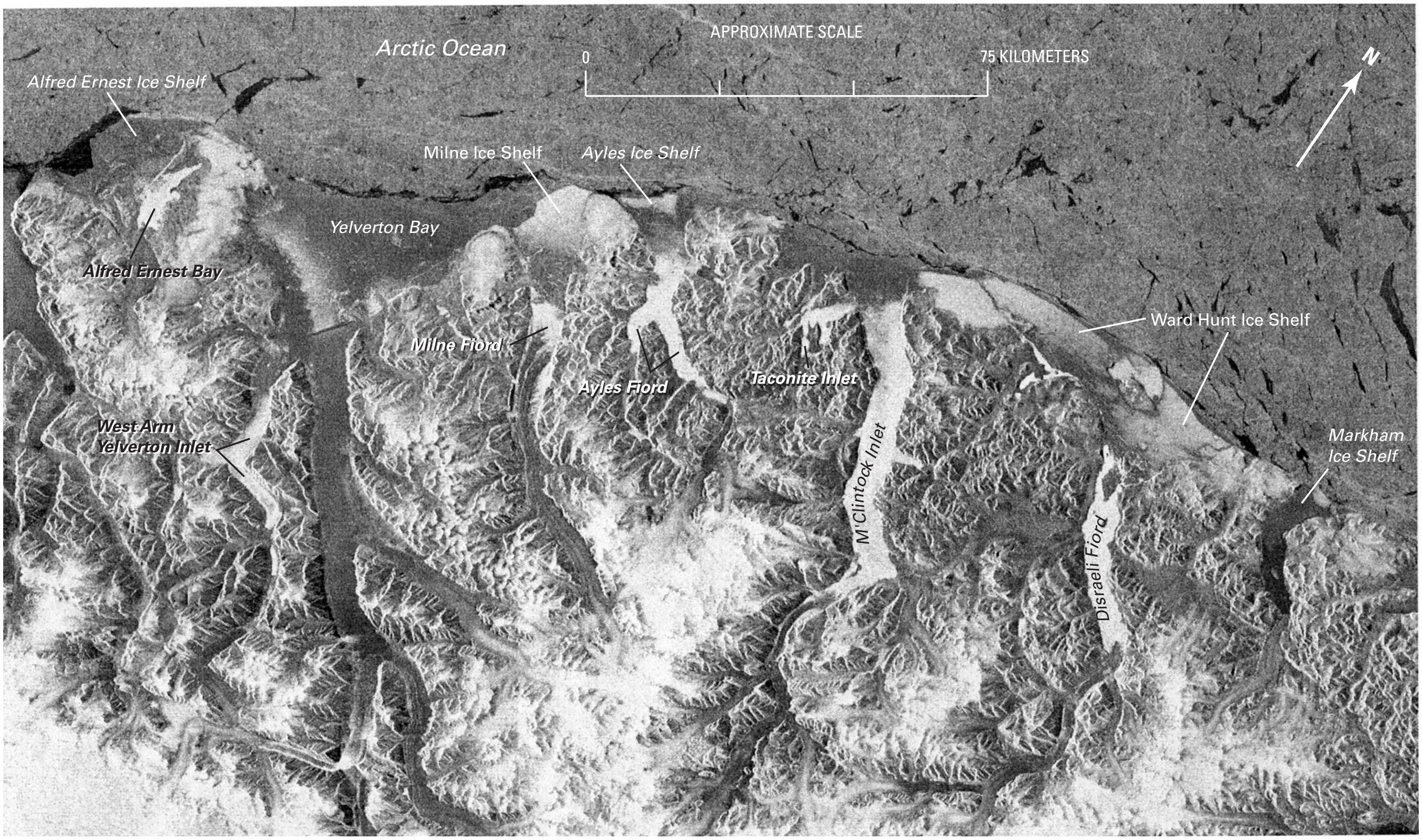


__Figure 8.__—Subscene of a radiometrically calibrated RADARSAT Wide Beam B ScanSAR image of northernmost Ellesmere Island on 8 April 2000 that has a spatial resolution of 150 m and a pixel spacing of 100 m. The five largest remaining ice shelves are marked; the bright SAR signature indicates an area where density stratification probably occurs from an ice dam that impounds freshwater. Image number R123114210 is from the Alaska SAR Facility. Original image is © CSA.

Shelf in 1961–62 might have been due to the coincidence of above-average tides and a seismic shock. Holdsworth and Glyn (1981) invoked a vibration mechanism, where ocean-wave energy intercepted by an ice shelf causes a resonant motion that raises stresses in the ice to the point that fracture results.

Ahlnäs and Sackinger (1988) proposed that calvings are triggered by persistent offshore winds. Frequently, after a major calving event, the lost shelf ice is replaced by multiyear landfast sea ice (MLSI). In February 1988, only 7–10 days after an episode of offshore winds, a piece of MLSI was observed by airborne SAR as it calved from the Milne Ice Shelf (Jeffries and Sackinger, 1990). The SPOT image (fig. 5) shows that that particular piece of MLSI did not move far in the 6 months after calving. ERS–1 SAR data show that the MLSI subsequently broke away completely (M.O. Jeffries, unpub. data, 1991), and the RADARSAT SAR image (fig. 6) shows that it has since been replaced by more MLSI.

Extensive areas of MLSI are observed along the north coast of Ellesmere Island, and in many cases, MLSI is found in areas that are known to have once been occupied by an ice shelf. Yelverton Bay (figs. 3, 5, and 8), the likely source of ice island *T–3* (Crary, 1960), is now covered with MLSI. Since the *M'Clintock Ice Shelf* disintegrated in the middle-1960's (Hattersley-Smith, 1967), MLSI containing ice-shelf fragments has covered the mouth of M'Clintock Inlet (fig. 8). The MLSI is a means by which the ice shelves regenerate after ice-island calvings, although the narrow strip of MLSI along the front of the Ward Hunt Ice Shelf (fig. 4), which has grown since the 1961–62 and 1982–83 calvings, is evidence that the replacement of lost ice shelf is often far from complete. The MLSI can be considered as incipient ice shelf and as analogous to the original sea-ice ice shelves.

The *Nansen Ice Plug* (fig. 9) is MLSI at the mouth of Nansen Sound (fig. 3) (Serson, 1972). The historical record (Peary, 1907, p. 203) suggests

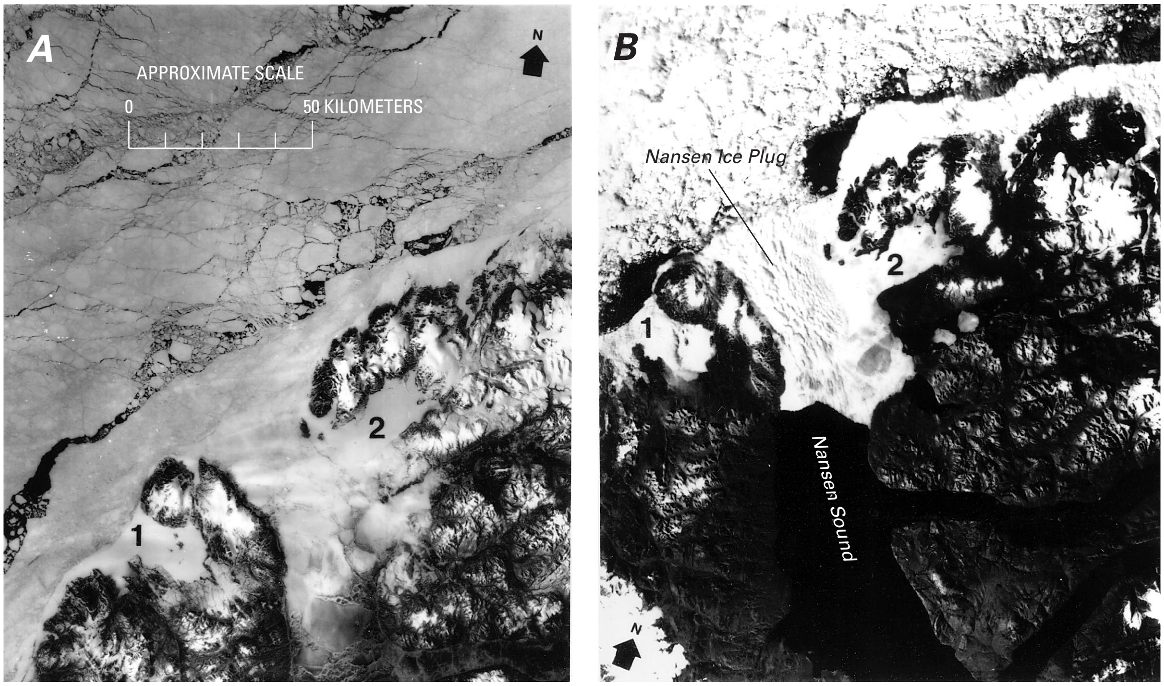


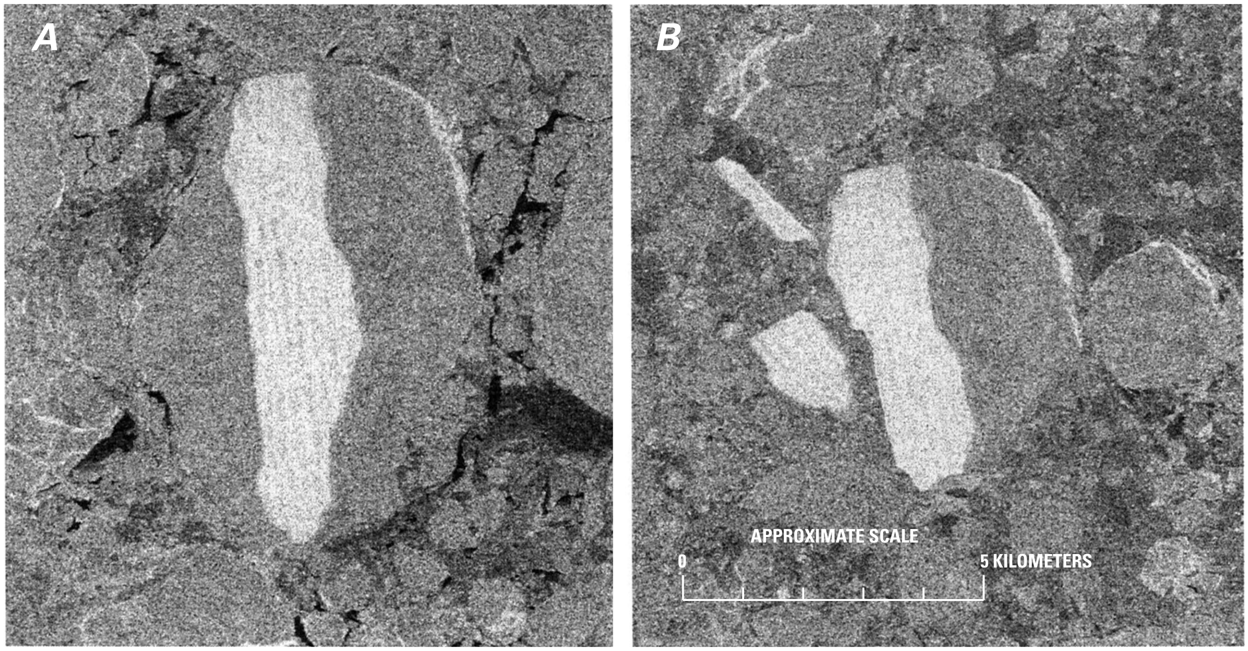
Figure 9.*—Landsat multispectral scanner (MSS) images of the* Nansen Ice Plug *on* **A***, 22 June 1990 and* **B***, 24 August 1990. Landsat image 52304–20574, band 4; 22 June 1990; Path 58, Row 247; and Landsat image 52367–20143, band 4; 24 August 1990; Path 51, Row 248, respectively, were acquired by the now-defunct Quick-Look Project satellite receiver at the Geophysical Institute, University of Alaska Fairbanks, Alaska. Numbers 1 and 2 are reference points that identify the same locations in each image.*

that an ice shelf was present in Nansen Sound at the beginning of the 20th century. The disintegration of that ice shelf or of a subsequent ice plug might have been the source of ice island *NP–6* (Serson, 1972). Figure 9 illustrates the effectiveness of the ice plug as a barrier to the movement of ice from the Arctic Ocean into Nansen Sound (fig. 3) and the Queen Elizabeth Islands (fig. 3 inset). A similar MLSI plug, the *Sverdrup Ice Plug*, is found in Sverdrup Channel between Axel Heiberg and Meighen Islands (fig. 3) (Serson, 1974). In Summer 1998, the warmest summer in the region since 1962, both the *Nansen* and *Sverdrup Ice Plugs* disintegrated for the first time since 1962 (Jeffers and others, 2001). The disintegration of these incipient ice shelves was not an isolated incident. Summer 1998 was a globally warm summer that saw a record reduction in the sea-ice cover of the Beaufort and Chukchi Seas (Maslanik and others, 1999) and the Queen Elizabeth Islands (Jeffers and others, 2001).

An abnormal reduction of the sea ice cover in the Queen Elizabeth Islands also took place in late summer and early autumn 1991 (Jeffries and Shaw, 1993). This allowed *Hobson's Choice ice island* (fig. 1) to drift rapidly south through the interisland channels, where it disintegrated between 13 October and 12 November 1991 (fig. 10) (Jeffries and Shaw, 1993). The demise of *Hobson's Choice ice island* was unfortunate as it forced the closure of the Canadian ice-island research station there. This station had promised to add significantly to geological, geophysical, meteorological, and oceanographic understanding of the Canadian Polar Margin (Hobson, 1989).

Conclusion

Ice shelves have existed along the north coast of Ellesmere Island since the middle Holocene when sea-ice ice shelves began to form in response to a climatic deterioration. The ice shelves were once much more extensive than they are today, and their current extent reflects a 20th century disintegration. The 20th century was a period of exceptionally high temperatures and climatic amelioration in the Canadian High Arctic (Bradley, 1990;



Evans and England, 1992), and it is reasonable to suppose that the disintegration of the *Ellesmere Ice Shelf* was a response to the pronounced warming during the last century (Jeffries, 1992). The apparent thinning of the Ward Hunt Ice Shelf in the 1980's–90's and the disintegration of the ice plugs in the late 1990's came about as significant changes were detected in the sea ice and hydrography of the Arctic Ocean (Dickson, 1999). It is difficult to ignore the connection between the state of the Ellesmere Island ice shelves, the state of the climate, and changes taking place elsewhere in the Arctic Basin. The ice shelves are bellwethers of climate change, which has the potential to cause further glaciological, hydrographic, and cryohabitat changes at these small but environmentally significant ice features (Vincent and others, 2000, 2001). Available ERS–1, ERS–2 and RADARSAT SAR data offer the opportunity to identify changes that may have taken place since 1991, as well as (1) to map the current areal extent of the ice shelves and (2) to establish a baseline for future monitoring. SAR instruments such as RADARSAT–2, ENVISAT, PALSAR, Ice, Cloud, and Land Elevation Satellite (ICESat), and current Earth Observing System (EOS) (*Terra*) instruments, such as the Moderate-Resolution Imaging Spectrometer (MODIS) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), offer unprecedented opportunities for the foreseeable future for change detection and impact assessment. These should increase the understanding of the Ellesmere Island ice shelves and ice islands and their relationship to climate variability.

Figure 10.*—Radiometrically calibrated ERS–1 SAR subscenes of* Hobson's Choice ice island *on* **A***, 13 October 1991 and* **B***, 12 November 1991 as it drifted south through the channels of the Queen Elizabeth Islands and disintegrated into three large pieces and numerous smaller fragments. The spatial resolution is 30 m, and the pixel size is 12.5 m. Image numbers E101262195 (*A*) and E101692193 (*B*) are from the Alaska SAR Facility. Original images are © CSA.*

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