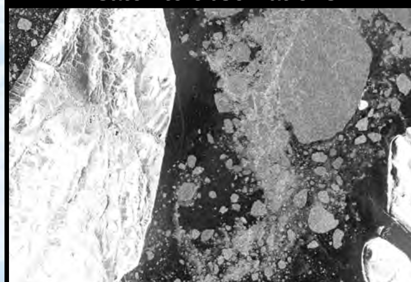
e-Guide to Understanding and Identifying Old Ice in Summer


on-ice thickness measurements


ship-based observations


aerial observations


satellite observations

M.E. Johnston and G.W. Timco

March 2023

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This e-Guide was published in March 2023 as part of the NRC Arctic Program. The Guide remains essentially unchanged from the initial version, aside from newly introduced material to reflect our improved understanding of ice thickness and strength. The updated material is the contribution of the first author, the second having since retired from NRC. Questions or requests for the e-Guide may be directed to Dr. M. Johnston (michelle.johnston@nrc-cnrc.gc.ca) or NRC.OCREAdmin-AdminGOCF.CNRC@nrc-cnrc.gc.ca.

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e-Guide to

Understanding and Identifying Old Ice in Summer

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Preface

Operating ships and structures in ice-covered waters requires reliably recognizing and avoiding, when possible, the most dangerous forms of sea ice. The best means of characterizing ice is still visual observation, however the task is not straightforward in summer – and even less so in winter. *Understanding and Identifying Old Ice in Summer* was first published in 2008 to help personnel better distinguish old ice from first-year ice, and multi-year ice from second-year ice. Those distinctions are crucial to operating safely in ice-covered waters. Hundreds of copies of the Guide have been mailed upon request over the years, proving what a unique and important resource this publication has been to the marine community. When this Guide was first published, it was hoped that it would become a useful tool for the marine community, and indeed it has. That is ample reward for the many people who graciously participated in this work over the years.

Understanding and Identifying Old Ice in Summer was developed as a reference tool to help mariners distinguish first-year ice from old ice (second-year and multi-year ice) because mariners had very few resources to help them characterize sea ice at the time. That is still the case today. This Guide is now being issued as an electronic document in efforts to make the publication easier to access, and hopefully, easier to use. Issuing an e-Guide also provided the opportunity to update the section *Growth and Ageing of Sea Ice*, to reflect our improved understanding of second-year ice and multi-year ice strength, and multi-year ice thickness. The other sections of the e-Guide remain essentially unchanged.

At the outset, it should be stated that the main reason for issuing the initial publication only in hardcopy format was to preserve the colour of the photographs, given that colour is key to recognizing old ice. With the publication of this electronic version, it will no longer be possible to preserve the original colour of the photographs. Colours will vary, depending upon the particular display and/or printing device. Hence, electronic publication makes the Guide more widely available, but at the expense of degrading its overall quality.

Understanding and Identifying Old Ice in Summer first explains what makes old ice more hazardous than first-year ice, and then illustrates the Key Identifiers experienced personnel use to distinguish ice types from the vantage points described below.

On-ice thickness measurements: Detailed thickness measurements provide readers with an appreciation for just how thick old ice can be. Since the thickness is often what sets old ice apart from the more benign first-year ice, detailed thickness distributions are given for ten old ice floes.

Ship-based observations: More than 70 ship-based observations of old ice are used to illustrate the Key Identifiers for distinguishing (1) old ice from first-year ice and (2) multi-year ice from second-year ice. Each ship-based observation includes a large format photograph of the ice feature and a brief discussion of what made the feature easy (or difficult) to identify as old ice.

Aerial observations: Aerial observations can be the deciding factor for classifying a feature as first-year, second-year or multi-year ice. That is largely because ice surface features such as ponding and drainage may not be very evident from a ship or structure, but are readily visible from the air.

Satellite observations: Satellite imagery provides the mariner with information about the ice conditions he/she will encounter over a fairly large area, in near real-time. The imagery is essential for producing operational ice charts and it is important for anticipating ice conditions.

Cautionary Note

Understanding and Identifying Old Ice in Summer is meant to help interpret observations made from the ship's bridge, from a platform or from the air, not replace them. **There is no substitute for real-time observations:** they provide the only means of closely examining ice features, looking at them from many different angles and observing nuances that the photographs reproduced in this Guide simply cannot capture.

The observations described here were made by highly trained, experienced personnel. Every ship-based observation was reviewed by one of the most senior ice observers of the Canadian Ice Service, with more than 30 years experience viewing ice from ships and aircraft. This Guide illustrates that even highly experienced personnel sometimes have little confidence deciding whether an ice feature qualifies as first-year, second-year or multi-year ice. Every operator in the Arctic will encounter situations where they cannot identify an ice feature with reasonable confidence. **Therefore, it is imperative that mariners always use due care and diligence when transiting ice-covered waters.**

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1. Introduction

Rationale for the Guide

Dramatic changes in the ice conditions and increased interannual variability in sea ice extent in the Arctic have been observed over the past decades. These changes have made the Arctic more accessible and, for some, more attractive. The shipping season extends earlier in the summer and later in the fall. Tourism in the Arctic is steadily increasing. Recovering natural resources in the Arctic is becoming more economically viable.

Persistent onshore winds and the presence of multi-year ice made for extremely severe ice conditions off the northeast coast of Newfoundland in the spring of 2007. Here, a Canadian Coast Guard icebreaker escorts fishing vessels through the treacherous ice *(photo courtesy of Canadian Ice Service).*

Ice conditions in the Arctic change from year-to-year, but the Arctic is unlikely to become ice-free in summer or winter in the near future. The decreased extent of first-year ice could make old ice more menacing because thicker, stronger old ice will be able to move through the Arctic more freely (Falkingham, 2000; Falkingham et al., 2002). On the other hand, warming ocean temperatures and an extended open water season may mean that mariners encounter thinner forms of old ice more frequently. This Guide is designed to inform mariners about the properties of a range of old ice, and how best to identify second-year and multi-year ice.

Ships and structures operating in ice-covered waters require personnel to reliably recognize and, when possible, avoid the most dangerous forms of sea ice. Old ice represents a significant hazard in the Arctic and sub-Arctic. Experienced mariners know that identifying the varied shapes and forms of old ice is not straightforward. In fact, a scoping study in which 15 Captains were asked about key concerns facing year-round shipping in the Arctic identified the detection of multi-year ice as the most pressing problem (Timco et al., 2005; 2008).

Visual observation is still the best means of detecting hazardous ice. Operators have very little information at their disposal to help distinguish old ice from first-year ice, or multi-year ice from second-year ice. *Understanding and Identifying Old Ice in Summer* will help operators make useful, real-time observations of old ice by providing more than 200 pages of information about ice from the following four perspectives:

- on-ice thickness measurements
- ship-based observations
- aerial observations
- satellite observations

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Background Information

Background Information provides a 'primer on old ice' that is meant to help the reader understand the four types of observations in the Guide. Background Information contains two parts: *Growth and Ageing of Sea Ice* and *Hazards Posed by Migrating Old Ice*. The first part describes the growth/decay cycle of sea ice, followed by a description of the process by which first-year ice becomes second-year ice, and then multi-year ice. As the ice 'ages', changes occurring at the ice surface are visible from a ship, from the air or from satellite. Changes occurring throughout the full ice thickness must be measured directly, however, and those changes are fundamental to understanding the difference between first-year, second-year and multi-year ice.

The second part of Background Information is called *Hazards Posed by Migrating Old Ice*. Buoy trajectories are used to show how old ice migrates through the Arctic Basin, Canadian Arctic Archipelago and the Eastern Canadian Arctic. Several pages are also devoted to describing the extreme hazards that old ice poses for ships and offshore structures. Detailed information about the thickness of multi-year ice in different geographic regions is also included.

Some ice features appear in several sections, depending upon the number of perspectives from which they were viewed. For instance, several multi-year ice floes were (1) the source of on-ice thickness measurements, (2) captured in aerial photography and (3) appear in satellite imagery. In that case, the same floe appears in three different sections (*On-ice Thickness Measurements*, *Aerial Observations* and *Satellite Observations*). As a result, some cross-referencing will be needed when reading through the Guide.

Key Identifiers for Old Ice

Experienced observers look for certain features, or Key Identifiers, to differentiate first-year, second-year and multi-year ice. This section describes the most commonly used Key Identifiers of old ice. Sketches of an "ideal" second-year floe and an "ideal" multi-year floe show some of the most commonly used Key Identifiers.

On-ice Thickness Measurements

This section includes the thicknesses of old ice floes in the Eastern Arctic and Central Arctic (Canadian Arctic Archipelago). Drill-hole measurements are supplemented by large format photographs of the feature (from the air and from the ice) and ice salinity profiles (when available). Salinity profiles are one of the few means of quantitatively distinguishing first-year, second-year and multi-year ice.

Measuring the strength of multi-year ice, as discussed in the section *Growth and Ageing of Sea Ice*.

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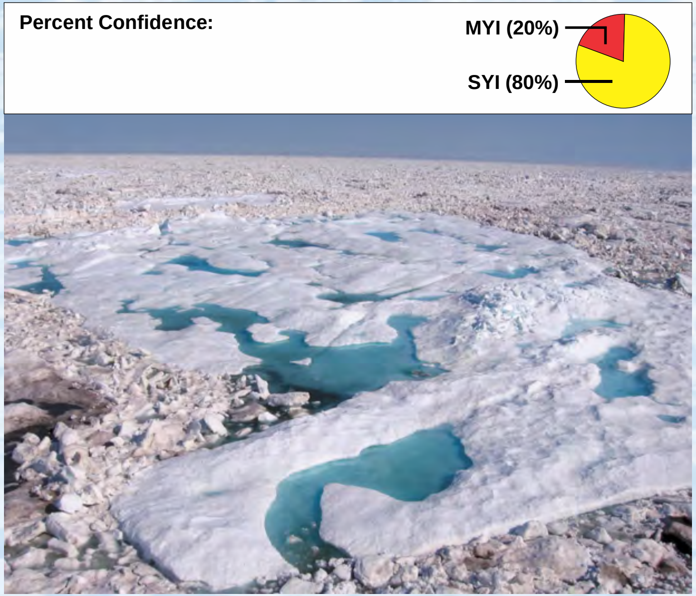
Ship-based Observations

More than 70 ship-based observations are used to show the types of old ice that operators will encounter in the Arctic and sub-Arctic during summer. The ship-based observations were made by experienced Ice Service Specialists (ISS) on the Canadian Coast Guard icebreakers and by Commanding Officers acting in capacity of ice observers on foreign ships. Most of the observations were made along the Northwest Passage or other major shipping routes in the Arctic and sub-Arctic.

Every ship-based observation includes information about the observer's **level of confidence** in deciding whether the feature classified as first-year, second-year or multi-year ice. Experienced personnel had confidence levels ranging from less than 10% (extremely uncertain) to 100% (very sure). The photograph (*right*) shows a floe the observer believed to be second-year ice (SYI, 80% confidence), but it may have been multi-year ice (MYI, 20% confidence). More details on this floe are included in *Ship-based Observations, Western Arctic*.

Differentiating first-year, second-year and multi-year ice is challenging in good weather but snow, fog and poor lighting make the task even more difficult. The ship-based observations in this Guide provide ample evidence of how complex the task of identifying ice types can be, given the range of conditions under which mariners must operate.



Ship-based observation of second-year ice surrounded by dirty, rubbled first-year ice. Observation made off the coast of Alaska in July *(photo courtesy of Canadian Ice Service)*.

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Aerial Observations

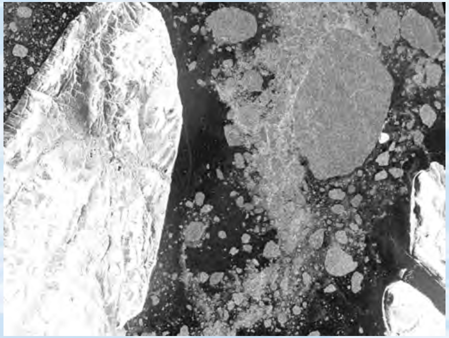
Aerial reconnaissance allows the ice observer to gather detailed information about the ice over fairly large areas. Most Canadian Coast Guard icebreakers use a helicopter to "look ahead" because anticipating ice conditions is essential for them to fulfill their mandate of marine safety, environmental response, facilitating maritime commerce and supporting scientific research. Many of the Key Identifiers for characterizing ice from a ship or structure also apply to observations made during an aerial reconnaissance.

Drainage or ponding is one of the most widely used Key Identifiers for discriminating first-year, second-year and multi-year ice. Aircraft often provide a better perspective (than a ship's bridge or an offshore structure) for determining whether drainage features on a floe are well established. Areal reconnaissance can be the deciding factor in determining whether a feature qualifies as first-year, second-year or multi-year ice.

Aerial photograph of rotten first-year ice sandwiched between two large, decayed multi-year ice floes.

Satellite Observations

Aerial reconnaissance permits greater coverage than ship-based observations, and satellites provide more coverage still. When the Guide was first published in 2008, RADARSAT-1 was the primary dataset used by the Canadian Ice Service (CIS) to produce operational ice charts and provide tactical ice information to Canadian Coast Guard icebreakers. Today, CIS is transitioning from RADARSAT-2 to the RADARSAT Constellation Mission (RCM), RADARSAT-1 having since been decommissioned. This section of the e-Guide has not been updated since its concepts are still appropriate. Satellite imagery is used to demonstrate when ice features can (or cannot) be identified from space, and some of the factors that influence their detection. CIS generously provided imagery for that purpose.



Satellite image of multi-year floes rounding the top of Ellesmere Island and entering Kennedy Channel, August.

Conclusions

A few closing remarks about old ice are provided. Since space does not permit a full discussion of the myriad aspects of sea ice, readers are referred to the list of references for additional information. The terminology in this Guide, for the most part, uses descriptors from the World Meteorological Organization (WMO) as summarized in the back of the Guide under *Sea Ice Nomenclature.* A map of the Arctic and sub-Arctic is also provided to familiarize readers with the names and places commonly used in the Guide.

2. Growth and Ageing of Sea Ice

Growth and Ageing of Sea Ice

The three major classifications of sea ice include first-year, second-year and multi-year ice. The three classes of ice are set apart by a process that we will call the 'growth and ageing' of sea ice. This includes the process by which sea ice grows in the Arctic during the freeze cycle (fall, winter, spring) and decays during the thaw cycle (summer). The changes that the different types of ice undergo during summer is described at length. The rate at which those changes occur determines whether first-year ice survives to become second-year ice, and second-year ice survives to become multi-year ice. The reader is referred to Untersteiner (1986) for a comprehensive discussion of the properties of sea ice and other ice-related topics.

The World Meteorological Organization (WMO, 1970; 1985) describes the melt stages visible from the top ice surface as puddle formation, thaw holes, dried ice and rotten ice. Fifteen years of on-ice measurements showed that the interior of the ice starts to change long before the top ice surface shows any signs of change, as summarized in Johnston (2014; 2017). The on-ice measurements described in this Guide were labour intensive and required about 200 kg of specialized equipment. The process entails first, measuring the drill-hole thickness by drilling through the full thickness of ice – a process that can easily consume more than 23 m of drill rods. A mechanical coring device is used to extract 10 to 15 cm diameter cores from the ice, one metre at a time. Since coring through the ice is extremely labour intensive, cores are not usually obtained below a depth of about 12 m. Cores are used to measure the temperature and salinity of the ice at regular depth intervals. When possible, portions of the core are transported to a laboratory where thin sections of ice are prepared to examine the ice microstructure (ice fabric).

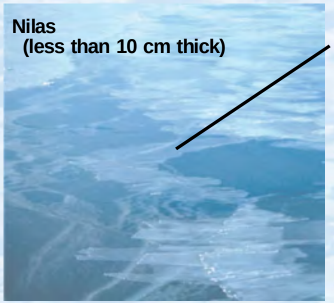
After the cores have been processed, strength tests are conducted in each borehole at a depth interval of 30 cm, until either reaching the bottom of the ice sheet or the bottom of the borehole, if the ice thickness was not fully penetrated. A hydraulically activated borehole indentor (Sinha, 1986; Masterson, 1996) is used to measure the confined compressive strength of the ice (defined here as the *borehole strength)* as its two opposing indentors penetrate the walls of the borehole. Generally, tests are conducted until (a) the total indentor stroke of 50 mm is approached or (b) the pressure levels off, or decreases following the procedure described in Johnston (2014; 2017). Strength tests in cold multi-year ice sometimes result in the pressure increasing until the full capacity of the 10,000 psi electro-hydraulic pump has been reached. In those cases, the pressure must be extrapolated to obtain the borehole strength. The following pages present depth profiles of the borehole strength (showing strengths at every depth interval) and the 'depth-averaged' borehole strength (where strengths are averaged over the full ice thickness). Both strength representations are needed to fully characterize first-year, second-year and multi-year ice.

The three stages of property measurements: ice coring *(right),* processing the cores for temperature and salinity *(centre)* and measuring the confined compressive strength of the ice with a borehole indentor *(far right).*

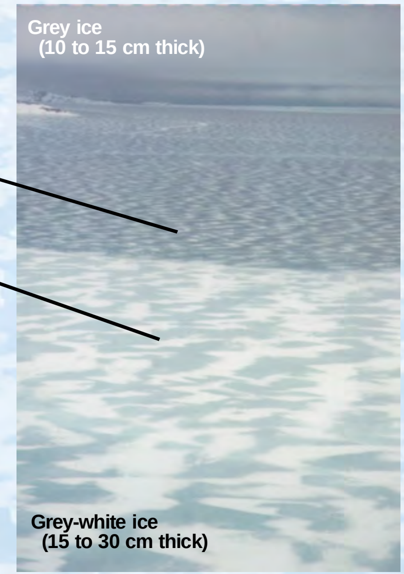
The Beginning: Growth of First-year Ice

We begin the discussion with first-year ice since that is where old ice begins. As sea ice grows, it rejects most of the salt in the seawater from which it forms. Consider this: seawater is about 3.5% salt, but first-year ice has an average salinity of only about 0.5%. A growing sheet of ice cannot eliminate all of the salt, which is why some salt becomes entrained between the grains and sub-grains of a mostly pure ice lattice (see *First-year Ice: Up Close*). The WMO (1970) developed the well-established nomenclature for classifying first-year sea ice described below.

New ice (not shown): Sea ice in its early stages of formation. New ice forms small platelets or lumps of ice, less than 10 cm thick and is usually subdivided into frazil, grease ice, slush or shuga.

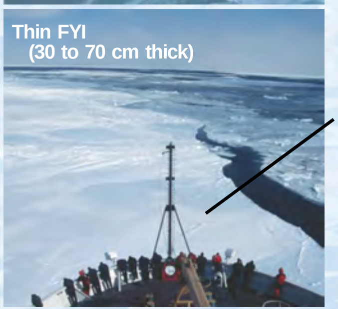


Nilas: A thin elastic crust of floating ice, less than 10 cm thick, that forms in relatively calm conditions and has a matte-like surface appearance. The ice cover that develops in turbulent conditions is quite different than nilas, since it results from the pancake-frazil cycle, as described in Wadhams (2000).



Grey ice: Young sea ice that is 10 to 15 cm thick is less elastic than nilas. It often breaks from swells and usually rafts under pressure.

Grey-white ice: Young sea ice that is 15 to 30 cm thick. It is more likely to ridge under pressure, than raft. Level, uniform types of landfast ice, such as the ice in this picture, form in sheltered bays and fjords.



Thin first-year ice: Sea ice that is 30 to 70 cm thick. Thin first-year ice may be sub-divided into Stage 1 (30 to 50 cm thick) and Stage 2 (50 to 70 cm thick). The photo shows that ice formed on the open ocean is comprised of various sized floes, frozen together at their boundaries. It is also rougher than the undisturbed ice that develops in sheltered areas.

The Beginning: Growth of First-year Ice

Medium first-year ice: Undeformed medium first-year ice has a thickness of 70 to 120 cm.

The photo (*right*) shows a ship transiting medium first-year ice interspersed with nilas in April.

Photo (*far right*) shows a piece of medium first-year ice upturned against a ship. The upturned fragment of ice shows the different colour and texture of the densely packed snow cover (**A**) and the medium first-year ice (**B**) below it.

Thick first-year ice: Undeformed thick first-year ice is greater than 120 cm thick but does not exceed 220 cm.

The photo *(far left)* shows the bow print made in thick first-year ice after an icebreaker rammed this giant floe in April.

The photo *(near left)* shows the blue colour of an overturned fragment of thick first-year ice in September. This first-year ice floe, having survived a melt season already, is bluer than it would be in spring (compare it to the overturned fragment of medium first-year ice above). This first-year ice is destined to become second-year ice later in the fall (see *Old Ice Originates as First-year Ice*).

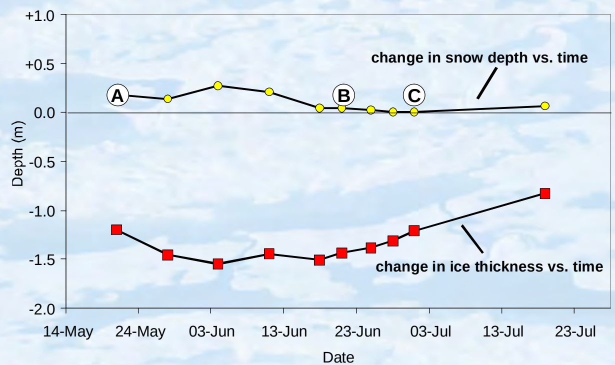
Decay Process for Landfast First-year Ice

Summer, with its above-freezing air temperatures and extended daylight, has a dramatic effect on sea ice. Much of what we know about how first-year ice ages, or decays, comes from years of on-ice measurements in the Arctic and sub-Arctic (Johnston et al., 2001; 2003-a; Johnston, 2006). The active participation of the University of Manitoba and Canadian Ice Service was instrumental to some of those field programs.

Our first measurements of decaying sea ice focussed upon landfast first-year ice in McDougall Sound, 80 km west of Cornwallis Island. The ice site was 5 km east of the University of Manitoba's base camp on Truro Island (75°14'N, 97°09'W). During the summer of 2000, measurements were made on a weekly basis from 21 May to 18 June. Measurements were increased to twice a week after mid-June because the ice surface changed more quickly.

On 21 May, the ice was 1.20 m thick and had an 18 cm deep snow cover (*photo A*). The snow cover persisted until about 4 June, after which it decreased from a maximum of 27 cm to just 4 cm, two weeks later. By 21 June, most of the remaining snow had melted, pools of standing water covered the ice surface (*photo B*) and the ice thickness was 1.43 m. On 1 July, much of the standing water had drained from the ice, exposing raised areas of white, dry ice and the ice thickness had decreased to 1.21 m (*photo C*). Between 18 June and 1 July, the ice thinned at a relatively constant rate of about 2.3 cm per day.

On 19 July, two weeks after the University of Manitoba's field camp on Truro Island was decommissioned, first-year ice in approximately the same area was again visited – this time with the assistance of the CCGS *Louis S. St-Laurent*. By mid-July, the ice thickness had decreased to 0.83 m and the ice surface was covered with 7 mm of dry, crumbled grains of drained sea ice, rather than snow. Photographs of the ice conditions are not available for this period.



Graph *(right)* shows the decrease in snow and ice thickness during the summer compared to photographs of the ice surface *(far right)*. Photos courtesy of University of Manitoba's Centre for Earth Observation Science (CEOS).

A 21 May, 1.20 m

B 21 June, 1.43 m

C 1 July, 1.21 m

Properties of Landfast First-year Ice in Spring and Summer

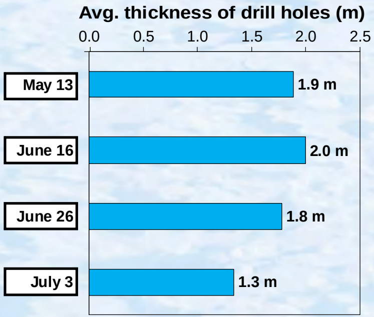
Three years of measurements were made on first-year ice at Truro Island and at a number of sites in Parry Channel. A series of measurements were also made on the first-year ice in Allen Bay, 80 km east of Truro Island, during the summer of 2007, as discussed below. All of the first-year ice sites underwent similar changes, allowing for differences due to site location and sampling years.

May 13: Drill holes spaced 10 m apart, along a 300 m long transect yielded ice thicknesses from 1.70 to 1.90 m and snow depths from 10 to 40 cm *(photo A)*. The snow cover was becoming water saturated, although the ice surface was still quite cold (-8.4°C).

June 16: The snow cover had melted completely, leaving pools of standing water on the ice surface *(photo B)*. The light blue colour of the first-year ice on 16 June resulted from the melting snow – an effect that was temporary, as photographs later in the summer show. Ice thicknesses along the 300 m transect ranged from 1.85 to 2.20 m.

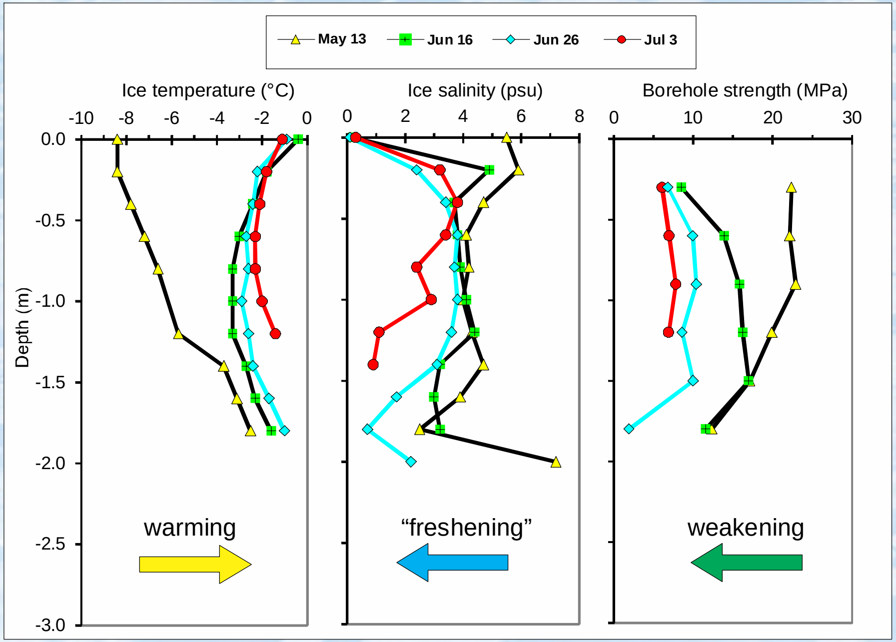
June 26: Most of the standing water had drained from the ice (*photo C*) through rivulets or drainage features on the ice surface, cracks in the ice, thaw holes and through interconnected pore spaces inside the ice (as discussed in *First-year Ice, Up Close*). Ice thicknesses ranged from 1.63 to 1.95 m. Typically, the raised areas of snow-free ice were thicker than ice under the drainage features.

July 3: By early July, the ice surface was beginning to develop the gentle undulations of ice that had survived a melt season *(photo D)*. Temperatures throughout the full thickness of ice were near melting (-2.3°C, or higher). Ice thicknesses ranged from 1.20 to 1.49 m.



Properties of Landfast First-year Ice in Spring and Summer

Cores from the full thickness of ice in Allen Bay were extracted to measure temperatures and salinities, at 20 cm depth intervals. Then, a borehole indentor was used to measure the *in situ* confined compressive strength - or *borehole strength* - of first-year ice in the 15 cm diameter core hole (borehole) using the methodology described in Johnston (2014; 2017).



Temperature, salinity and strength profiles of decaying first-year ice in Allen Bay, from May to July. Profiles have not been adjusted to account for the amount of melt at the top and bottom ice surfaces.

Temperature *(far left):*

Temperatures throughout the full thickness of ice increased from May to July. The ice temperature profile in May was typical of "winter" sea ice: the snow-covered surface of the ice was coldest (-8.4°C) and the bottom ice was warmest. From 16 June to 3 July, the top and bottom ice surfaces were warmer than the interior of the ice, producing the "C-shaped" temperature profile of warming first-year ice.

Salinity *(centre):*

The salinity of the ice can be given in either practical salinity units (psu) or parts per thousand (ppt), the difference between the two measures being very small.

The salinity of the ice was between 4 and 6 psu in May, except for the higher salinity bottom ice. Desalination, or "freshening", first occurred at the top and bottom ice surfaces. As summer advanced, the ice freshened throughout its full thickness. Channels inside the ice acted as a catalyst for desalination by facilitating the percolation of meltwater through the ice (Eicken et al., 2002).

Strength *(near left):*

As summer advanced, first-year ice warmed, became porous and lost strength. This borehole in Allen Bay had a depth-averaged strength of 19.5 MPa in May. By July the depth-averaged borehole strength of the ice had decreased to 6.9 MPa.

First-year Ice, Up Close

The radical transformation that first-year ice undergoes in summer is due, in large part, to the pockets of highly concentrated salt solution, or brine, it contains. Brine is an important component of first-year sea ice. It gives thinner forms of first-year ice, such as nilas, the ability to flex under passing waves but more importantly, the presence or absence of brine is one of the factors that sets first-year, second-year and multi-year ice apart. As sea ice grows, it rejects most of the salt in the seawater from which it forms. A growing ice sheet cannot eliminate all of the salt, which is why some salt becomes entrained in the ice as inclusions. The amount of salt trapped in the ice depends upon factors such as (but not limited to) the salinity of the seawater, the rate at which the ice grows, water turbidity and grain structure. The reader is referred to the chapter by W. Weeks and S. Ackley (in Untersteiner, 1986) for a thorough discussion of sea ice growth.

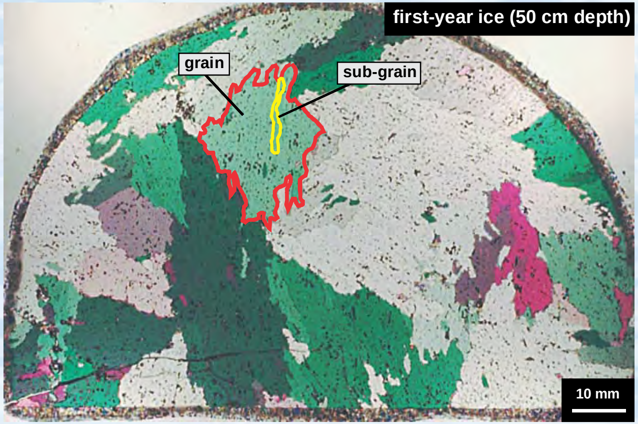
Grains

Thin sections of ice, typically less than 1 mm thick, reveal important information about the ice microstructure, or ice fabric. The vertical section *(next page)* shows that the uppermost layers of first-year ice can be comprised of slender, 'needle-like' grains of frazil ice, below which columnar-shaped grains become established. Columnar grains are narrow at the top and widen towards the bottom. The horizontal thin section (*below*) shows a cross-section of the large, columnar-shaped grains that often develop in sea ice. The different colours in the thin section occur naturally when the sections are examined with an instrument called a polariscope. The colours represent individual grains of sea ice. Light transmits differently through the grains, depending upon their orientation. Grains can either be randomly distributed (in which case the section would have a wide range of colours/orientations) or they can be preferentially aligned (grains would have similar colours/orientations). The horizontal and vertical sections are shown under transmitted light to better illuminate the rows of brine inclusions. Crossed polarized light is preferred for determining grain size and orientation.

Sub-grains

Grains of sea ice are comprised of smaller sub-grains. Neighbouring sub-grains have only a slight difference in orientation (colour), compared to the larger mismatch between neighbouring grains of ice (hence their greater colour variation). Sub-grains give the grains of first-year ice a ragged-edged appearance, as the horizontal thin section shows (*right*).

As ice grows, impurities (brine and air) are trapped at mismatches between the grains and sub-grains, allowing the ice lattice structure to remain pure. The result? Pure ice sub-grains surrounded by inclusions. The degree of mismatch between sub-grains is so slight, they really can't be distinguished by differences in colour. However, sub-grains can be identified by the pattern of inclusions surrounding them, the so-called brine layer spacing (Nakawo and Sinha, 1984). Sub-grains appear as long, narrow "fingers" of uniform colour within each grain.



Horizontal thin section of first-year ice in winter, viewed with a polariscope under transmitted light. Inclusions are less than 0.5 mm long and appear as dark flecks. Grain outlined in red, sub-grain outlined in yellow. Note the ragged-edged appearance of the grains of first-year ice.

First-year Ice, Up Close

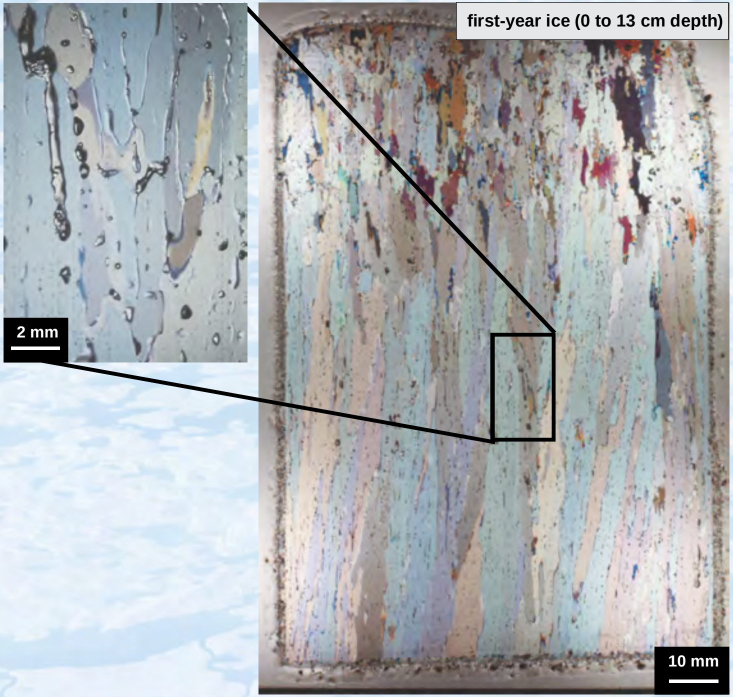
Inclusions

Inclusions in first-year ice usually contain a mixture of brine, air and, depending upon the temperature of the ice, solid salts. These inclusions become apparent when a thin section of ice is viewed with a polariscope. The vertical thin section (*far right*) contains hundreds of inclusions. These thread-like structures appear as dotted lines, parallelling one another from the top of the thin section, to the bottom.

The various shapes and sizes of the inclusions become evident in the vertical thin section when it is examined under a microscope *(near right).* Inclusions range from perfect spheres to long, thread-like structures extending vertically within the ice. Are salt crystals visible inside the inclusions? Not in these images. Solid salts are best viewed using special sample preparation techniques and a scanning electron microscope, as Sinha (1977) shows so eloquently.

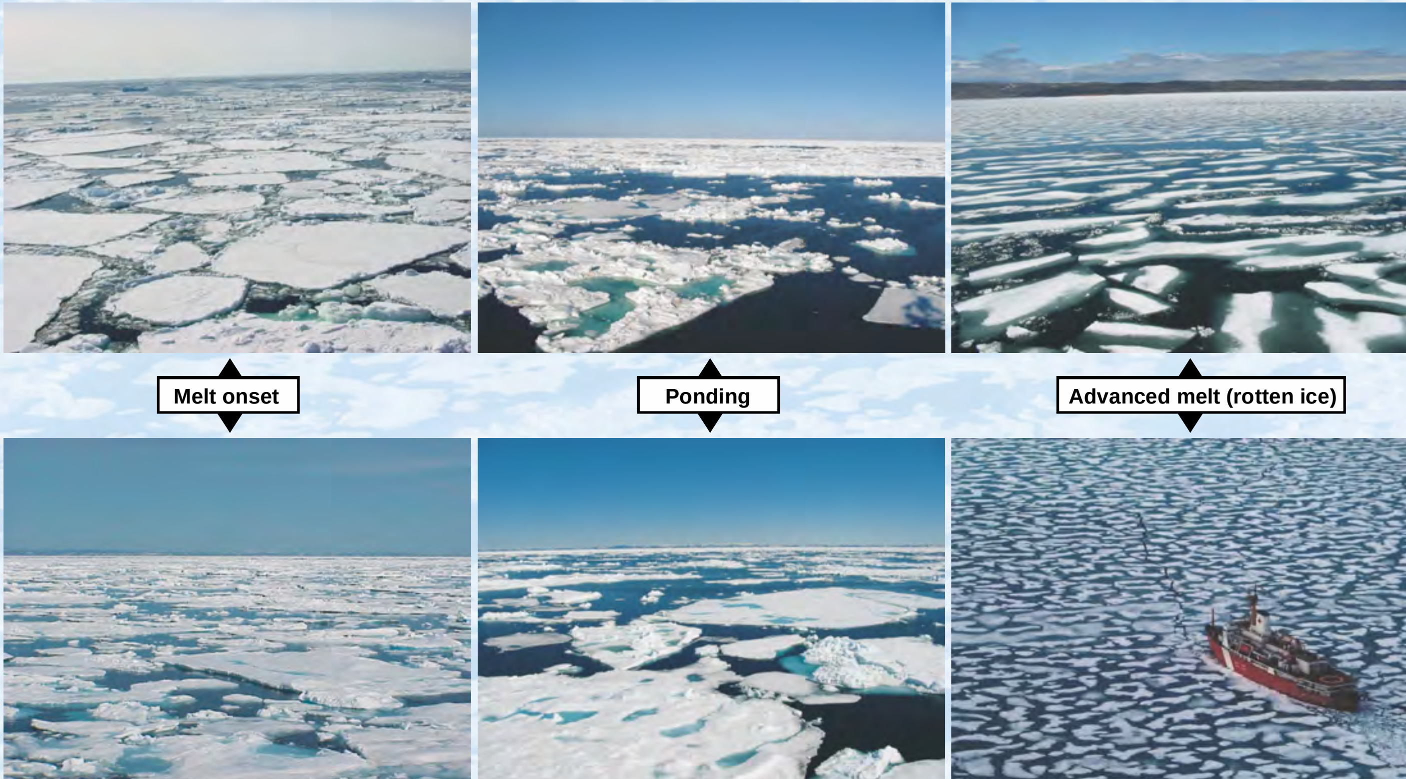
Inclusions in first-year ice are smallest in winter, when the ice is coldest. Winter is also when the brine is most concentrated, and when it contains the most solid salt. As the ice warms in spring and summer, brine inclusions become larger as their solid salts dissolve the ice around them. By late summer, inclusions that had once been isolated from their neighbours merge, forming well-established channels that can extend through the full thickness of first-year ice, from top to bottom. Once these channels have formed, meltwater on top of the ice is able to flush through the ice into the sea, taking brine with it.

In summary, brine absorbs solar radiation more effectively than air, warms the ice more quickly and makes it easier for the ice to melt in summer. The melt process continues until late summer, by which time the first-year ice has become quite porous and most of its salt has flushed from the ice. The borehole strength of first-year ice decreases as the ice porosity increases (Johnston, 2006), since there is less 'solid' ice to resist penetration of the indentors.



Thin section of first-year ice viewed with a polariscope *(right)* and a microscope *(left)* under transmitted light. The mostly brine-filled inclusions appear threadlike to the naked eye (*right*), but the microscope reveals inclusions actually have a variety of shapes and sizes (*top left*).

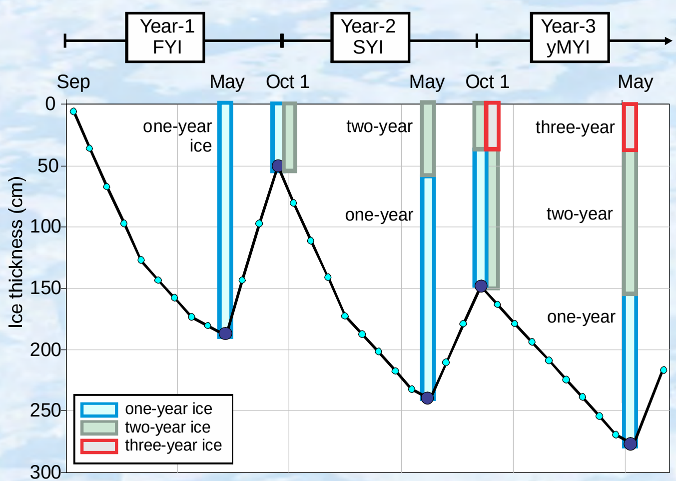
Other Examples of Decaying First-year Ice
(and Stages of Melt)



Old Ice Originates as First-year Ice

First-year ice is the basis of second-year ice, and second-year ice is basis of multi-year ice. First-year ice and second-year ice can survive summer if the ice is sufficiently thick, its snow cover is late melting, and the summer melt season is relatively cool and short. October 1st is the date that the Canadian Ice Service (CIS) uses to graduate first-year ice to **second-year ice** and second-year ice to **multi-year ice**. The WMO defines **second-year ice as having survived one summers' melt and being up to 2.5 m thick, sometimes more.** The WMO defines **multi-year ice as** having **survived at least two summers' melt and typically being more than 3 m thick.**

The diagram below is an idealized depiction of the ageing process that leads to old ice. Ice that survives summer forms the basis of the subsequent year's growth, beginning in the fall. The diagram is idealized because it only shows ice thinning at the bottom ice surface when, in fact, sea ice melts non-uniformly from its top and bottom surfaces in summer. The amount of thinning that occurs at either surface depends upon many factors, including solar radiation, the length of the melt season, the depth of snow cover and when it melts, air and water temperatures, cloud cover and the percentage of ponding. In this sketch, multi-year ice that has survived two summers' melt is comprised of three layers: one-year ice (at the bottom), two-year ice (in the middle) and three-year ice (at the top). In the following pages, the term **young multi-year ice** is introduced to distinguish undeformed multi-year ice of known history and origin from thicker, relatively level multi-year ice and mechanically deformed hummocked multi-year ice.



The sea ice ageing process is important for understanding the differences between first-year, second-year and multi-year ice. Old ice begins with first-year ice, but some (or all) of the first-year's growth may melt during one or more summers. The thickness of the aged, desalinated layer is key to understanding the properties of the different ice types.

Sometimes, first-year ice and second-year ice that develops in sheltered bays of the Canadian Arctic Archipelago (at a latitude of 74°N) survives summer. To illustrate that, the following pages include several examples of first-year ice that did not (and did) survive to become second-year ice, and where second-year ice survived to become young multi-year ice.

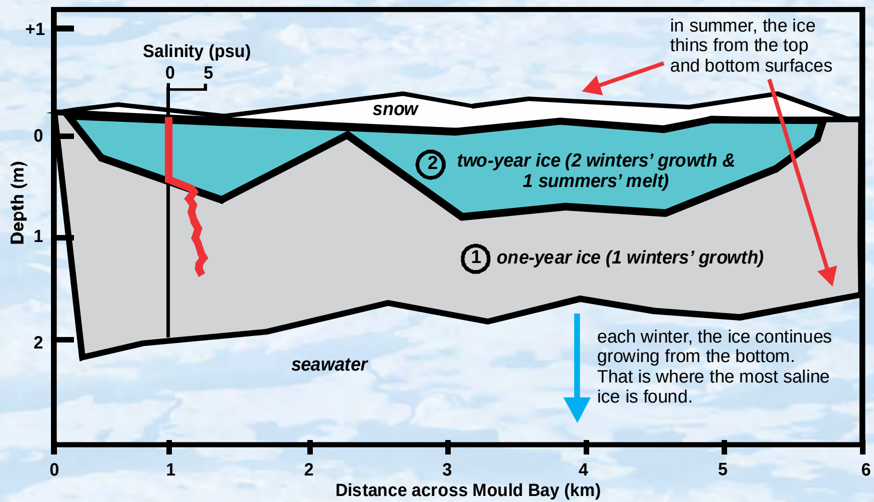
Idealized diagram illustrates the process by which first-year ice (FYI) survives summer to become second-year ice (SYI) that survives summer to become three-year old multi-year ice. The term *young multi-year ice* (yMYI) is used in the following pages to describe landfast, three-year old multi-year ice of known history and origin.

Second-year Ice Consists of Two Ice Layers

As temperatures and solar radiation decrease in the fall, ice thinning stops and new ice begins to form on the underside of the surviving ice. The ice sheet becomes a composite of ice that survived one summer (two-year ice) and the recently formed ice beneath it (one-year ice). Bjerkelund et al. (1985) demonstrated this for the second-year ice in Mould Bay (76°N, 119°W), in the western Canadian Arctic. Their sketch is reproduced below to show the composition of second-year ice in Mould Bay at ten stations across the width of the bay, in spring. The authors extracted cores from each of the stations to obtain ice salinity profiles, and to examine the ice microstructure. Based upon that information, the authors could determine the thickness of ice that survived the previous summer (two-year ice) and the thickness of ice that had grown over the recent winter (one-year ice).

Most of the ice in Mould Bay was a composite of two-year ice plus one-year ice, with a few exceptions. The near-shore ice on both sides of the bay (0 and 6 km stations) had melted entirely during the previous summer, producing pure first-year ice the following year. Ice at the 2 km station was 100% first-year ice because a lead had opened at that location during the previous summer.

Only 17 to 90 cm of the ice thickness in Mould Bay was two-year ice, compared to the 1.35 to 2.06 m thickness of one-year ice below it. The salinity profile for the 1 km station clearly shows the transition (or interface) between the completely desalinated two-year ice and the more saline one-year ice (*right*). The interface at the 1 km station occurred at a depth of about 50 cm. Bjerkelund et al. (1985) noted that the same columnar grains extended across the two-year/one-year ice interface – the difference being that the higher salt content of the one-year ice highlighted its sub-grain structure, compared to the less saline, two-year ice. The reader is referred to the more recent publication of Shokr and Sinha (2015) for additional details.

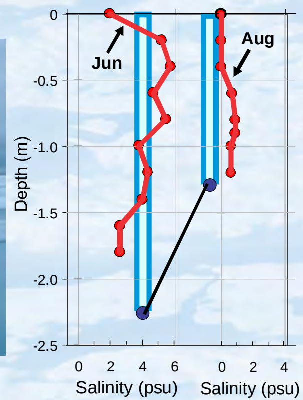


Thickness profile of second-year ice in Mould Bay in spring *(after Bjerkelund et al., 1985, with adaptations).* The second-year ice sheet consisted of two-year ice and one-year ice. Waterline shown at depth zero.

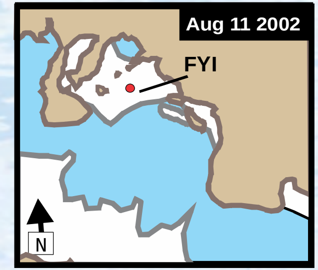
First-year Ice that did not become Second-year Ice

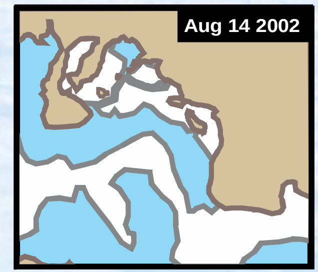
Here, a case is presented where thick, relatively competent first-year ice in late summer did not lead to second-year ice. When the first-year ice in Allen Bay, Cornwallis Island was visited on 11 August 2002, the ice in four sampled boreholes ranged from 1.0 to 1.5 m thick. Depth-averaged borehole strengths were 4.8, 4.7 and 5.0 MPa in three boreholes on dry, white ice and 3.3 MPa at the edge of a melt pond. To put those strengths in perspective, they represent 28% to 36% of the depth-averaged borehole strength of first-year ice in winter (32 MPa), as discussed in Johnston (2017). The satellite imagery-derived sketch shows where the ice was sampled on 11 August (*red marker, top right sketch*). On 14 August, just three days later, the sampling site fragmented into several large pieces, likely due to the mechanical action of winds and/or tidal currents (*middle sketch*). By 25 August, Allen Bay was virtually ice-free (*bottom sketch*).

This example illustrates four points. First, it shows that first-year ice in sheltered bays can be thick and relatively competent in late summer. Second, it shows that wind and/or tidal currents can cause the ice to fracture and drift into more open areas, where ships may encounter it. Third, it shows that late-summer first-year ice may not survive to become second-year ice, even when it is relatively thick, depending upon the environmental conditions. Lastly, it provides an example where the undulating and ponded ice surface (*photograph below*) is similar to second-year ice (*next page*). This site was indeed first-year ice, as confirmed by profiles of ice salinity (*below)* and strength (see *Strengths of Landfast First-year, Second-year and Young Multi-year Ice*) combined with using satellite imagery and ice charts to document its history of development.



The ice that was sampled in Allen Bay on 11 August 2002 was first-year ice *(far left)*, as confirmed by ice salinities measured when the site was visited in June and August *(left).* Satellite-derived sketches of the late summer ice conditions in Allen Bay in 2002 show that the sampling site (red marker, *top right figure*) broke-up on 14 August, three days after it was visited. The bay was virtually ice-free on 25 August.



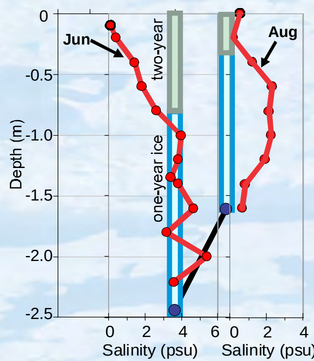


First-year Ice that became Second-year Ice

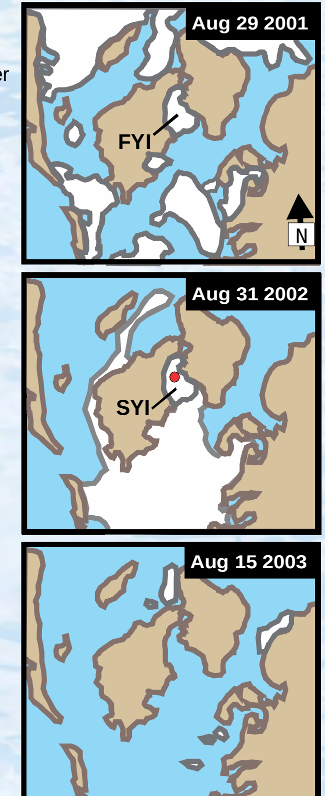
Second-year ice was encountered in Templeton Bay, Little Cornwallis Island on 11 August 2002. For reference, Templeton Bay is ~100 km northwest of Allen Bay, Cornwallis Island. Conditions in Templeton Bay and Allen Bay are different enough that ice at one location may survive, but not the other (*see previous page*). The satellite-derived sketches (*right)* show that first-year ice in Templeton Bay survived the summer of 2001 (*top right*) to become second-year ice that survived the summer of 2002 (*middle right*), and then became young multi-year ice in autumn 2002 (Johnston, 2004). The young multi-year ice did not survive its third summer because Templeton Bay became ice-free on 14 August 2003 (*bottom right*). Here too, winds/tidal currents may have played a role in driving the ice from the bay once decreased ice concentrations in the adjacent channel permitted its mobility.

The June 2002 salinity profile for the second-year ice in Templeton Bay indicates that the 2.5 m thick ice was comprised of ~0.80 m of two-year ice and ~1.70 m of one-year ice grown over the previous winter. When the 1.60 m thick ice was revisited on August 11, only ~0.30 m of two-year ice and ~1.30 m of one-year ice remained. It is estimated that between visits, ~50 cm of thinning had occurred at the top ice surface and 40 cm of thinning from the bottom surface. In this case, the second-year ice consisted predominantly of one-year ice by mid-August. This particular site is important because it is the only second-year ice site for which we have repeat property measurements *(see following pages*). As such, it features predominantly when comparing ice strengths in later pages.

The photograph below shows that the raised areas of the second-year ice in Templeton Bay were higher, and its ponds a lighter shade blue and likely deeper, than first-year ice in Allen Bay sampled on the same date (*previous page*).

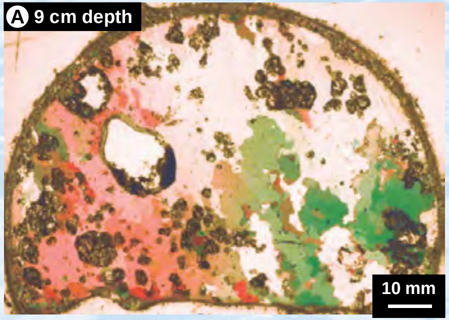


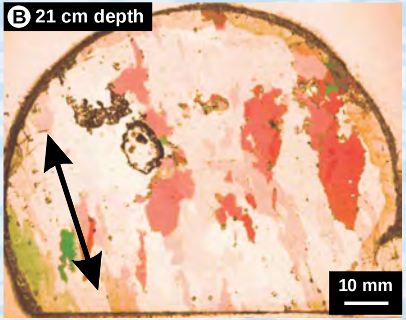
The second-year ice in Templeton Bay on 11 August 2002 *(far left*). The layer of two-year ice was ~80cm thick in June and ~30cm thick in August *(left*). Ice conditions in Bay at three points in time show that the sampling site (red marker, *middle right*) did not survive the summer of 2003, its third summer.

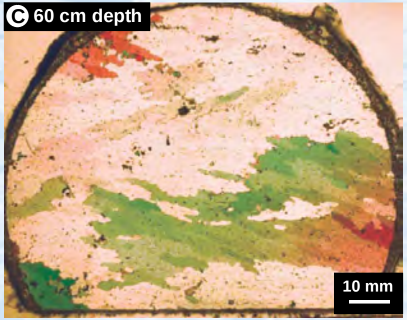


Second-year Ice, Up Close

The landfast second-year ice in Templeton Bay consisted of two ice layers, as noted on the previous page. The thin sections of ice below were prepared from cores extracted during the visit to Templeton Bay in June 2002. They characterize the ~80 cm thick layer of two-year ice as it was at that time. Ice below the 80 cm depth classified as one-year ice *(not shown).*







Horizontal thin sections of second-year ice in Templeton Bay, June 2002. Sections 'A' and 'B' came from the same core piece, Section 'C' from another. The corresponding salinity profile for this ice is discussed in *Properties of Landfast Second-year Ice in Summer (next page).*

9 cm depth (two-year ice)

The absence of dark, thread-like brine inclusions from this two-year ice suggests that the ice is virtually devoid of salt, as confirmed by the 0 psu salinity (*see following pages*). Air inclusions dominate the section, some of which are several centimetres across. Individual grains are apparent, but their edges are considerably smoother than the ragged-edged grains of first-year ice. Sub-grain boundaries are not evident at this depth.

21 cm depth (two-year ice)

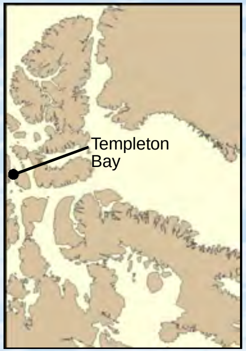
Brine is not visible in the two-year ice at this depth. Air inclusions are smaller overall than in the section at a depth of 9 cm *(left)*, but some large air inclusions are still present. Grains and sub-grains are more ragged-edged than at the 9 cm depth, but not as distinct as at the 60 cm depth *(right)*. Clearly, the grains are preferentially aligned (see arrow in photograph).

60 cm depth (two-year ice)

The ice fabric and 2 psu salinity at a depth of 60 cm indicate it is also two-year ice. However, the ice has characteristics resembling one-year ice: thread-like brine inclusions, ragged-edged grains, well-defined sub-grain boundaries and small air inclusions. Evidently, the ice at this depth depth did not experience melt-induced changes to the same extent as ice at the 9 cm and 21 cm depths.

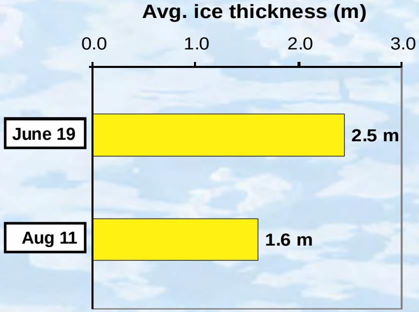
Properties of Landfast Second-year Ice in Summer

Documenting the changes in second-year ice is valuable for the simple reason that so few data on this type of ice exist, apart from the work of Bjerkelund et al. (1985), Johnston et al. (2003-b,c) and Johnston (2015). That is partly because *bona fide* second-year ice is difficult to find, unless one has information about its history of development, as was the case in each of those studies. Two visits were made to Templeton Bay in the summer of 2002, as summarized below.



June 19: The ice was 2.5 m thick when it was sampled on 19 June. The raised areas, or hillocks, had a 15 cm deep snow cover (*photo A*) and ice freeboards from 12 to 15 cm. The saturated snow in the low lying areas provided evidence of where ponds had developed the previous summer (darker areas of ice). The undulating topography produced by the hillocks and melt ponds was apparent, even at this stage of summer. By comparison, first-year ice doesn't develop surface topography until much later in summer (see *Properties of Decaying First-year Ice)*.

August 11: The ice was again visited on 11 August, by which time its thickness had decreased to 1.6 m. About one metre of ice had melted from the top/bottom surfaces between June and August. In August, the ice surface was devoid of snow, melt ponds appeared deeper and hillocks were higher (*photo B*). The freeboard of the hillocks ranged from 20 to 30 cm, compared to 12 to 15 cm in June. By August, the ponds were a deep blue colour.



Properties of Landfast Second-year Ice in Summer

Temperature *(near right)*:

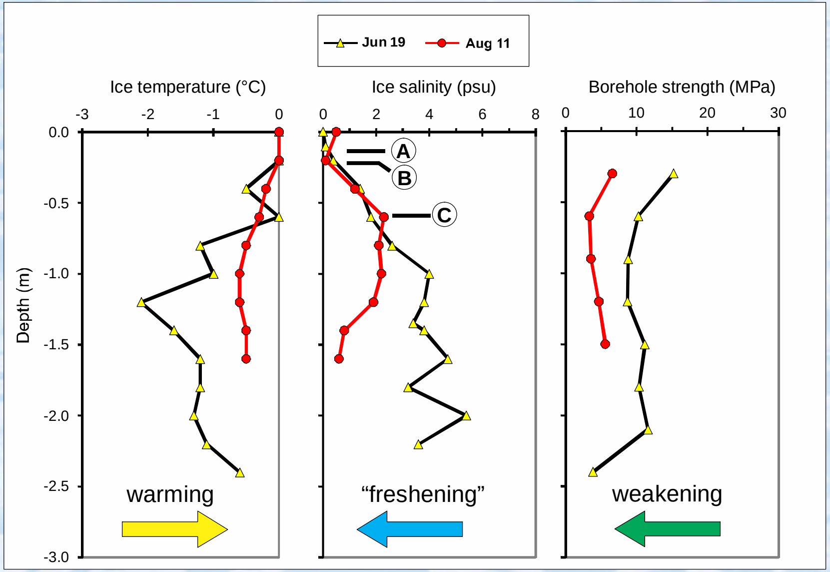
By June, the second-year ice in Templeton Bay had warmed considerably, compared to the typical mid-winter temperature of sea ice. The ice temperature profile had changed from a linear one (typical of winter ice) to a "C-shaped" profile (characteristic of warming sea ice). When the ice was visited again in August, the full thickness of ice was closer to being isothermal, at near-melting temperatures.

Salinity *(centre)***:**

The ~80 cm thick layer of two-year ice had salinities of less than ~3 psu in June (*middle figure*). Below that depth, salinities increased to 4.0 to 5.4 psu, making it comparable to first-year ice (see *Properties of Decaying First-year Ice*). By August, the second-year ice had thinned by ~1 m and salinities had decreased throughout its full ice thickness. At that point, desalination was nearly complete in the top and bottom ice (less than 1 psu), whereas the ice interior had salinities of 2 psu, or less. Given that it was already late summer when the ice was visited, it is unlikely that the ice desalinated completely throughout its full thickness by summer's end.

Strength *(far right):*

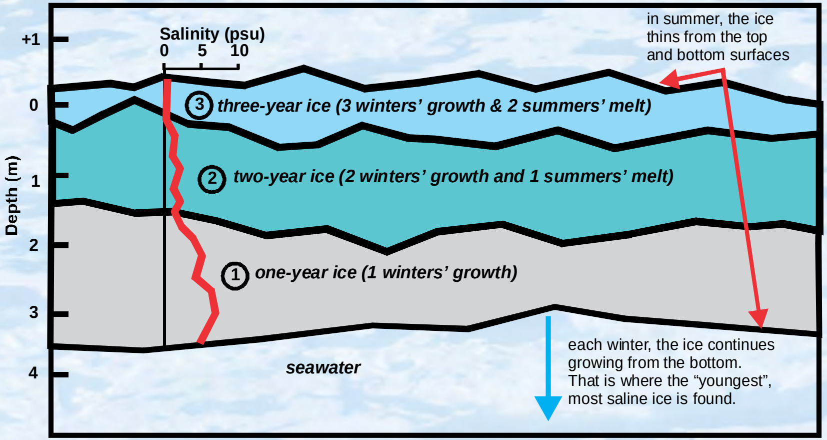
The borehole strength profiles (*far right*) show a marked decrease in strength throughout the full thickness of ice, from June to August. The depth-averaged borehole strength decreased from 10.0 MPa in mid-June to 4.7 MPa in August. In the two boreholes shown here, the uppermost 30 cm of two-year ice was stronger than the one-year ice below it, in both June and August. In comparison, the other two boreholes sampled in August (*not shown*) had lower top surface strengths (4.2, 4.8 MPa), but higher bottom surface strengths (10.2, 10.7 MPa). The difference may have been a result of meltwater draining and freezing on underside of the ice, creating a high-strength lens of freshwater ice on the ice bottom So-called 'false bottoms' have been reported in the literature (Eicken, 1994; Eicken et al., 2002) and are believed to slow thinning of the bottom ice (Perovich et al., 2014).



Temperature, salinity and strength profiles of second-year ice in June and August. Profiles have not been adjusted to reflect the amount of melt at the top and bottom ice surfaces. 'A', 'B' and 'C' refer to the depth at which thin sections were prepared (see *Ageing Second-year Ice, Up Close*).

Young Multi-year Ice can have Three Ice Layers

Depending upon the extent of melt in summer, the youngest form of multi-year ice may consist of ice that survived two summers (three-year ice), ice that survived one summer (two-year ice) and the most recent winter's growth (one-year ice). The oldest, lowest salinity ice occurs at the top surface. The sketch below is an idealized depiction of young multi-year ice, based upon the assumption that a portion of each years' growth survived the summer melt period. In reality, some (or all) of each layer melts during the summer. Surface melting in multi-year ice can be two to three times higher than bottom melt (Untersteiner, 1961; Perovich and Elder, 2001) or, in some cases, bottom melt can exceed surface melt (Maykut and McPhee, 1995; Perovich and Elder, 2001). The amount of melt that occurs at the top and bottom ice surfaces depends upon factors such as (but not limited to) ice thickness, snow depth, pond fraction, surface reflectivity (albedo), atmospheric conditions and oceanography, as discussed in Perovich et al. (2003).

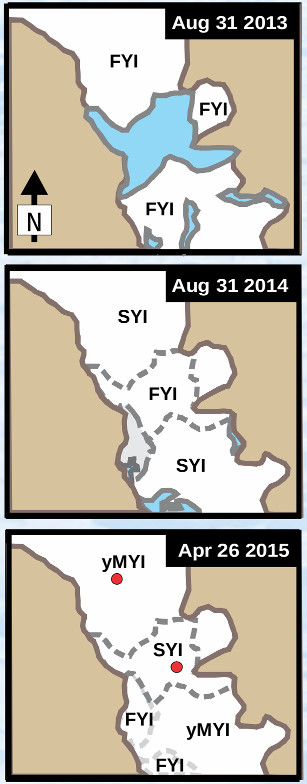


Schematic of multi-year ice (three-year ice) in early summer, once snow has melted and the bottom ice begins to desalinate. Waterline shown at depth zero.

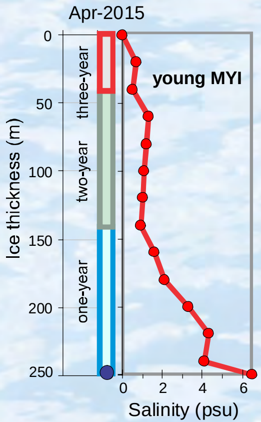
Currently there is no reliable, systematic method for determining the age of multi-year ice. Annual layering is sometimes recognizable in the lower part of multi-year ice (Cherapanov, 1957; Schwarzacher, 1959) and isotopes have been used with some success (Jeffries, 1991; Eicken, 1992, 1998). In this Guide, the growth layers in only second-year ice and young multi-year ice could be identified with any certainty. This was done by examining the salinity profile and/or the ice microstructure from cores extracted in spring or early summer, before the ice had been disrupted by the current year's summer melt process. The overall ice thickness and borehole strength profiles were used to confirm the presence of layers, when possible.

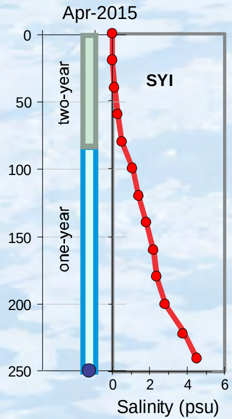
Second-year Ice that Survived to become Young Multi-year Ice

This example involves first-year ice that survived to become second-year ice, which went on to become young multi-year ice. The location is Bathurst Inlet, about 200 km northwest of Allen Bay, Cornwallis Island. The satellite-derived sketch (*right*) shows where first-year ice survived at the end of August 2013 to become second-year ice in the fall. The blue area separating the two main ice sheets is an area of open water that formed when first-year ice melted entirely that summer (*top right sketch*). By the end of the next summer, August 2014, the two areas of second-year ice survived, as did most of the intervening area of first-year ice (*middle sketch*). The young multi-year ice and second-year ice were both sampled in spring 2015, during the only visit that was able to be made to Bathurst Inlet (red markers, *bottom right sketch*).



The young multi-year ice and the second-year ice were both 2.5 m thick. A photograph of the sites is not included because the snow cover masked all surface features at that time of year. The salinity profile of the young multi-year ice (*bottom left*) indicates three ice layers: ~40 cm thick layer of three-year ice, ~1.0 m thick layer of two-year ice, and ~1.0 m thick layer of one-year ice. The salinity profile for second-year ice (*bottom right*) suggests two ice layers: an ~80 cm thick layer of two-year ice and ~1.70 m thick layer of one-year ice. The top surface layer of young multi-year ice had not fully desalinated *(bottom left figure*), whereas the surface layer of second-year ice had *(bottom right figure*). This merely demonstrates the non-uniform summer melt process, which the salinity profiles in *On-ice Thickness Measurements* also demonstrate.





The temperature and borehole strength profiles of the young multi-year ice and second-year ice were virtually identical in spring (Johnston, 2015). Temperatures ranged from -12°C at the top ice surface to -1.8°C at the bottom. Borehole strengths for both ice types ranged from 37 MPa near the top surface to 12 MPa towards the bottom surface (*next page*).

It is important to note that the strengths of young multi-year and second-year ice can be similar in spring, but that does not mean that their strengths will be the same in summer. That is because the thickness of the aged, desalinated layer slows the ice decay process, and therefore the decrease in ice strength.

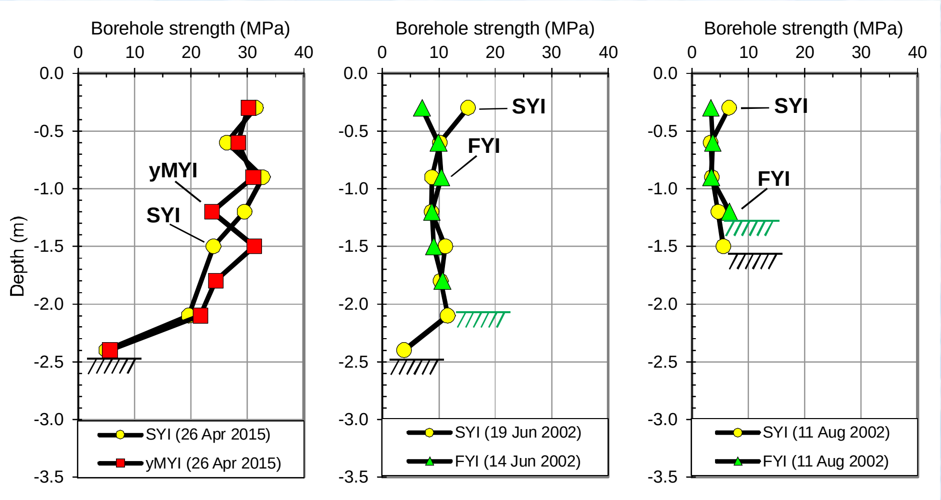
Satellite-derived sketches *(right)* show the development of second-year/young multi-year ice matrix in Bathurst Inlet at three snapshots in time. Both types of ice were sampled in April 2015 (red markers, *bottom right sketch*) when the ice salinity profiles indicated three layers in the young multi-year ice (*far left*) and two layers in the second-year ice (*near left*).

Strengths of Landfast First-year, Second-year and Young Multi-year Ice

Borehole strength profiles for first-year, second-year and young multi-year ice are given below at different points in time. In spring, strengths throughout the full ice thickness were similiar for second-year ice (SYI) and young multi-year ice (yMYI) in Bathurst Inlet (*bottom left*). That is to be expected because the sites had similar thicknesses and temperatures, and because differences in salinity (*previous page*) are less influential in winter and spring than in summer. Brine inclusions are smallest when the ice is cold, and they enlarge as the ice warms in summer (see *First-year Ice Up Close*). In summer, the effect that brine has on (decreasing) the ice strength compounds the effect that warming ice temperatures have on (decreasing) the strength of the pure ice lattice itself. In the fall, that process is reversed: ice temperatures decrease, brine inclusions shrink, and the ice strengthens.

The borehole strength profiles for first-year ice in Allen Bay and second-year ice in Templeton Bay in June (*middle figure*) and August (*far right figure*) were comparable, except in the surface layer. Second-year ice typically has higher strengths at its top surface than first-year ice. If the layer of two-year ice is less than 30 cm thick, it will not be captured in our strength profiles because our first strength test performed at the 30 cm depth. Conversely, the two other SYI boreholes sampled in August (*not shown*) did not have a higher strength top surface; both of those boreholes had a high-strength bottom layer (10MPa). The borehole shown here did not (*far right*).

The key difference between second-year ice and first-year ice in summer is that second-year ice will likely have high-strength layers at the top and/or bottom surfaces. First-year ice will not. None of the hundreds of borehole strength tests that were performed on deteriorating first-year ice contained a high-strength layer, whereas boreholes in old ice often did (Johnston, 2016-a, b).

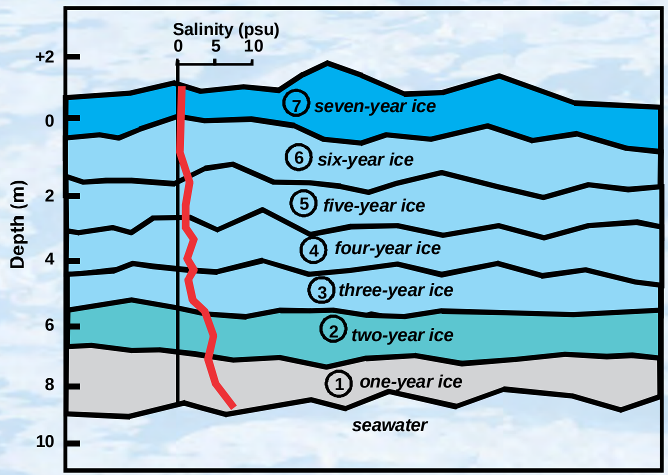


Borehole strength profiles for 2.5 m thick second-year ice (SYI) and 2.5 m thick young multi-year ice (yMYI) in Bathurst Inlet, April 2015 (*left*). Profiles also shown for first-year ice (FYI) in Allen Bay and second-year ice (SYI) in Templeton Bay in June 2002 (*middle*) and August 2002 (*right*). The first-year ice was 2.1 m thick in June and 1.3 m thick in August. Second-year ice was 2.5 m thick in June and 1.6 m thick in August. Cross hatching shows borehole thickness.

Hummocked Multi-year Ice has Many Layers

Typically, multi-year ice is **at least 3 m thick, but it can be upwards of 15 m thick**. Extremely thick multi-year ice can be produced by mechanical forces (ridging, hummock fields) or it can grow thermodynamically. Walker and Wadhams (1979) use model results to show that ice at least 12 m thick ice can grow thermodynamically over tens of years, under certain conditions. The extremely thick multi-year ice reported in Johnston (2019) was believed to have included both thermodynamically grown ice and mechanically deformed ice, but that cannot be confirmed at present. Determining the proportion of thermodynamically grown ice vs. mechanically deformed ice requires documenting the ice microstructure, as done in Richter-Menge et al. (1987) and Richter-Menge and Perron (1988).

The age of sea ice is often gauged by its thickness, although that is not necessarily the case. Rigor and Wallace (2004) used drifting buoys and manned stations to estimate that ice in the Arctic Ocean was, on average, 10 years old in 1981 and that the average age of ice in the Arctic Basin has since declined, as greater amounts of younger, thinner ice replace thicker, older ice. That said, it is true that extremely thick, old multi-year ice will contain more layers than thinner, younger multi-year ice. The schematic (*below*) shows the layers that could comprise 9 m thick multi-year ice, if a portion of each winter's growth survives the summer melt period. Clear boundaries are shown between the layers of ice, but in reality it is very difficult to distinguish the age of very thick multi-year ice based upon its layers. That makes older multi-year ice unlike the two-layer second-year and three-layer young multi-year ice discussed previously.

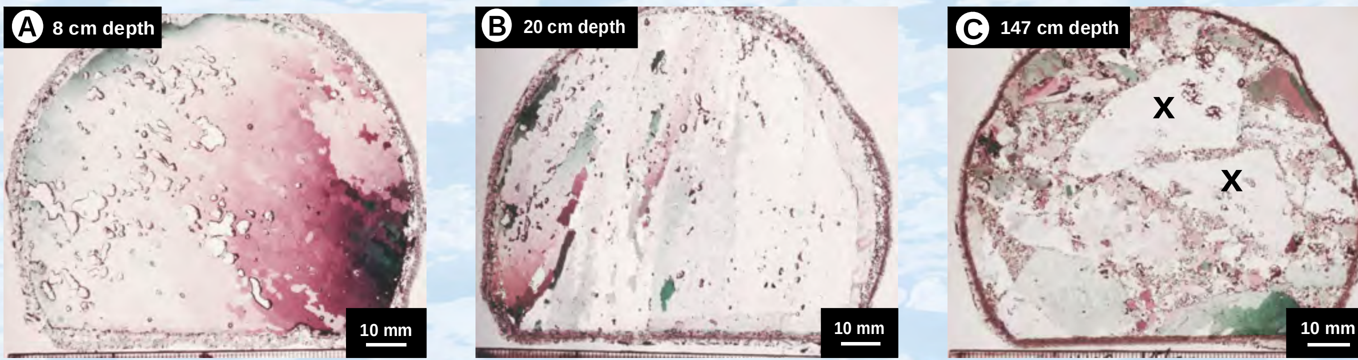


Schematic of the different layers comprising thick multi-year ice. The age of the ice, the thickness of the individual layers and the salinity profile are hypothetical.

Multi-year Ice, Up Close

The thin sections below were prepared from a multi-year ice hummock that was visited in June 2007. The hummock was over 6 m thick, whereas the surrounding ice was remarkably level at about 5.5 m thick (*next page*). The thin sections from depths 8 and 20 cm (*photos A and B*) have many of the same characteristics as the top surface of second-year ice: an absence of brine, large air inclusions that decrease in size with increasing depth, smooth grain boundaries and nearly indistinguishable sub-grains.

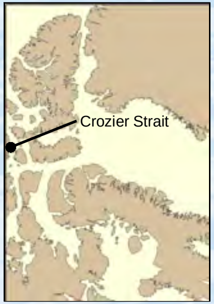
The ice at a depth of 147 cm shows signs of mechanical damage. The two 'grains' marked by an 'x' were part of the same grain before being divided. Other areas of the thin section also show damage, likely caused when parts of the same floe (or two different floes) were thrust together into this pressure hummock. Some of the granular ice in the section likely resulted from water penetrating void spaces in the hummock and freezing, rather than pulverization due to mechanical forces. The reader is referred to the sentinel publication by Richter-Menge and Perron (1988) for a thorough discussion of the microstructure of multi-year ice pressure ridges.



Horizontal thin sections from multi-year hummock sampled near Cornwallis Island in June 2007.

Properties of a Multi-year Hummock

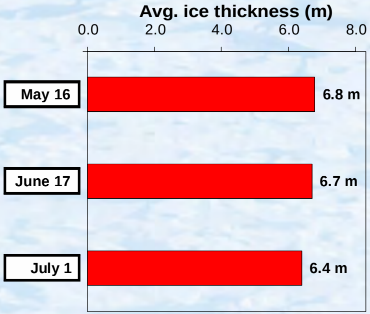
Thick multi-year ice changes dramatically during summer, but not to the same extent as first-year ice, as shown subsequently in *Seasonal Trends in the Strength of Landfast and Drifting Floes*. The 200 m diameter floe shown below was one of two, multi-year floes sampled in Crozier Strait (75°N, 97°W). Visits to the floe were made in May, June and July of 2007, while the floe was landfast. Measurements here focus upon the ice hummock, since that is where the ice was thickest. Profiles of temperature, salinity and strength (*next page*) extend to a maximum depth of 5 m and, as such, did not penetrate the full ice thickness.

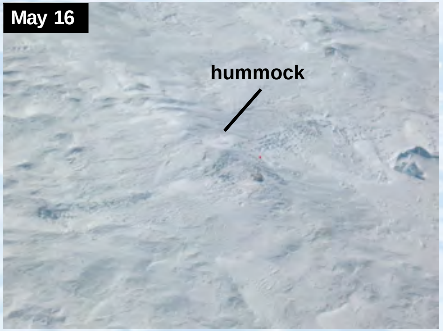


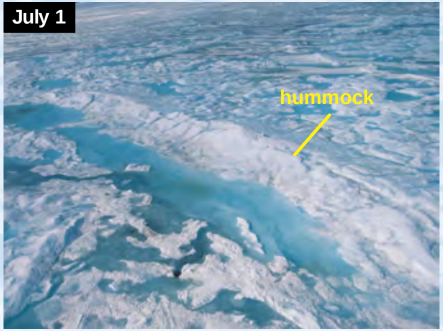
May 16: In May, the snow cover masked all surface features, except for the linear hummock that spanned the floe. The hummock was about 2 m high and 6.8 m thick. Its crest was devoid of snow but its sides (faces) and base were covered by up to 30 cm of snow. The diameter of the floe could not be determined in May, due to the snow cover.

June 17: Most of the snow had melted by mid-June, contributing to melt ponds peppering the floe. The largest ponds formed at the base of the hummock. Drill-hole measurements in the same area as sampled in May indicated that the hummock was 6.7 m thick.

July 1: By this point, ponds at the base of the hummock had merged. A few areas of ponded ice had melted through their full ice thickness. Drill-hole measurements showed the hummock to be 6.4 m thick. This last visit to the floe was timed well because one week later, ice in the area broke up and the floe began to drift.







Properties of a Multi-year Hummock

Temperature *(near right):*

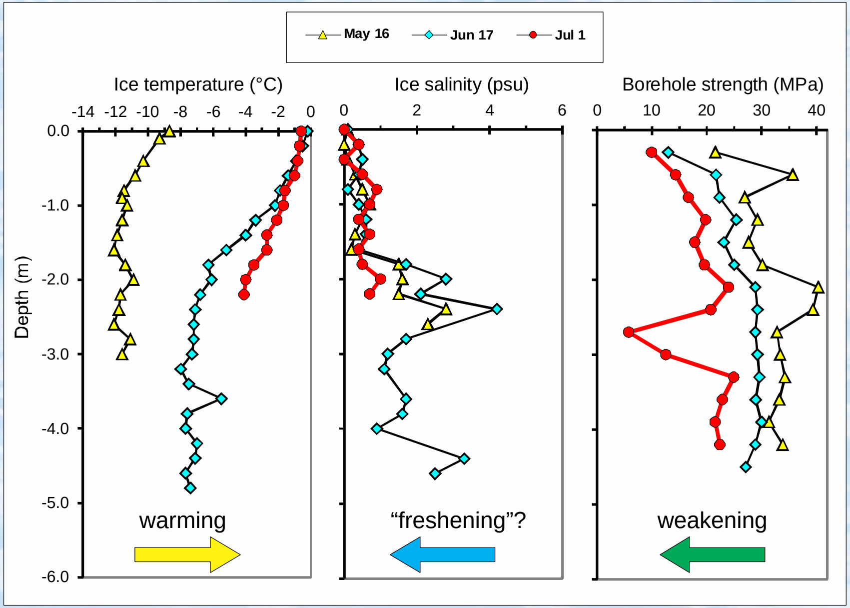
In May, temperatures in the uppermost 3 m of the hummock were cold, ranging from -8.7°C at the surface to -12°C at a depth of 3 m. Temperatures below that depth are not available due to difficulties encountered coring through the ice. By June, temperatures throughout the hummock had increased, with the most notable changes occurring in the uppermost 2 m of ice. Warming slowed in the top metre of ice from June to July, but ice temperatures below that depth continued to increase.

Salinity *(centre):*

Salinities ranged from 0 to 4.2 psu in this ice hummock. Salinities in the 2 m sail (above water portion) of the hummock changed little from May to July, likely because the sail had almost completely desalinated already. Salinities below the sail were higher, and more variable. That is to be expected, given the non-uniform nature of mechanically deformed sea ice. The highest salinities in the hummock occurred at depths of 2.4 m (4.2 psu) and 4.4 m (3.3 psu) in both May and June, and were likely caused by seawater infiltrating voids in the hummocked ice and freezing.

Strength *(far right):*

Strengths in the hummock were highest in May and steadily decreased (at all depths) as summer advanced and the ice warmed. The depth-averaged borehole strength of the hummock was 32.1 MPa in May, 26.1 MPa in June and 19.0 MPa in July. In July, the lower-strength ice between the 2.7 and 3.0 m depths (*red data markers*, *far right figure*) is attributed to the presence of one or more large voids (or cavities). Voids and/or weak layers like the one shown here were encountered in some of the deformed old ice floes that were sampled over the years (Johnston, 2014).



Temperature, salinity and strength profiles of a multi-year hummock in May, June and July. Depths in the profiles have not been adjusted to show the proportion of melt at the top ice surface.

Comparison of First-year, Second-year and Hummocked Multi-year Ice

Ice thickness and strength are the two parameters most of interest to mariners, the operators of offshore structures, and designers of ships and structures. Thickness and strength are interrelated. Ice thickness influences the temperature of the ice which, in turn, affects the strength of the ice. Thick multi-year ice remains cold longer than first-year ice, and cold ice is stronger than warm ice, all else being equal. The salinity of the ice also affects ice strength. First-year ice is not as strong as multi-year ice, not just because it is thinner but because it has higher salinity.

The profiles on the next page compare the temperature ('A'), salinity ('B') and borehole strengths ('C') of first-year ice, second-year ice and a multi-year ice hummock in mid-June. The comparison is limited to some extent because the sites were not sampled in the same year: the first-year ice (Allen Bay) and the multi-year ice hummock (Crozier Strait) were sampled June 2007, but the second-year ice (Templeton Bay) was sampled in June 2002.

Temperature:

The 6.7 m thick multi-year hummock was, by far, the coldest of the three types of ice in June. Temperatures in the 2 m sail of the multi-year hummock (the above water portion) were warmer than the -7 and -8°C temperatures below the waterline. The profile shows that multi-year ice, because of its thickness, remains colder than first-year ice and second-year ice at the same geographic location and time of year.

In June, the 2.0 m thick first-year ice in Allen Bay was several degrees colder than the 2.5 m thick second-year ice in Templeton Bay, which is unusual. Recall that the two sites were sampled in different years, with different environmental conditions. The first-year ice in Allen Bay maintained its cold temperatures longer than normal during the summer of 2007, whereas typically first-year ice at that latitude is near-isothermal around -2.0°C by mid-June (Johnston, 2017). Generally, the temperature of first-year ice should be approximately the same as, or warmer than second-year ice for the same date and geographic location.

Salinity:

Ice salinity is one means of determining whether a feature is first-year, second-year or multi-year ice. The salinity profiles in 'B' show that, overall, first-year ice is more saline than second-year ice, which is more saline than multi-year ice. This was confirmed by the ice thin sections presented earlier: first-year ice has an abundance of thread-like brine inclusions (before it desalinates in summer), whereas the uppermost layers of second-year ice and multi-year ice usually contain very little brine, having experienced one or more melt seasons.

Salinities of **first-year ice** in Allen Bay ranged from 0 to 4.9 psu in mid-June.

Salinities of **second-year ice** were lowest in the uppermost metre of ice, but were comparable to first-year ice below that depth. That is to be expected given that second-year ice is a composite of desalinated, two-year ice from the previous summer overlying saline, one-year ice from the most recent winter (see *Second-year Ice Consists of Two Ice Layers*).

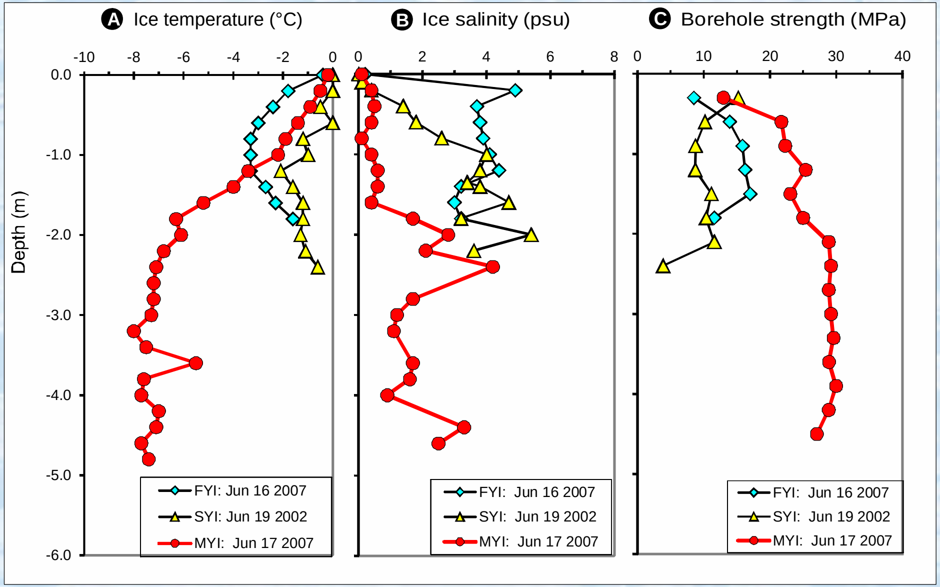
In June, salinities in the **multi-year hummock** ranged from 0 to 3 psu to a depth of 5 m, with two exceptions: higher salinities were measured at depths 2.4 m and 4.4 m (4.2 psu and 3.3 psu, respectively). The higher salinities at those depths indicate that seawater had infiltrated voids in the ice and subsequently froze.

Comparison of First-year, Second-year and Hummocked Multi-year Ice

Strength:

The profiles in 'C' (*bottom right*) show the borehole strengths at various ice depths in June. Strengths in the multi-year hummock were higher than first-year ice at all depths. The multi-year ice hummock was also stronger than second-year ice, except towards its uppermost surface (30 cm test depth) where the second-year ice was stronger. Strengths in the surface layer of the hummock were lower because that is where the ice is most porous and confinement is lowest, allowing test-induced cracks to propagate to the nearest free surface (Johnston, 2014). Below the 2 m sail, borehole strengths in the 6.7 m thick hummock were remarkably consistent until decreasing somewhat towards the ice bottom.

The strength profiles show that second-year was weaker than first-year ice everywhere but in the top surface layer. The same trend was evident in the other second-year ice borehole sampled in June (not shown), which is unusual. To explain the difference in strength, we must refer to the ice temperature profiles (*near right*). Recall that the first-year and second-year ice sites were sampled at the same time of year, but different years (2002 vs. 2007). Because of that, the second-year ice was up to 3°C *warmer* than first-year ice when it was sampled in June. Had the temperatures of the first-year and second-year ice been more similar, their strengths would have been comparable. This was demonstrated earlier in *Strengths of Landfast First-year, Second-year and Multi-year Ice*. Colder ice is stronger ice, all else being equal.



Temperature, salinity and strength profiles of first-year ice (FYI), second-year ice (SYI) and multi-year ice (MYI) in June. Note that SYI was sampled in a different year (2002) than FYI and MYI (2007).

Second-year Ice: Landfast vs. Drifting Floes

Landfast second-year ice (*below left*) can be considerably more uniform than second-year ice floes encountered in more open areas (*below right*). The thickness of the two ice features is not substantially different: the landfast second-year ice sheet was 2.5 m, whereas the isolated second-year floe was 3 to 4 m thick.

The isolated floe does not have the regular pattern of raised areas and melt ponds that are typical of second-year ice grown in calm, sheltered environs. The different appearances of the ice in the photos result from the mechanical deformation that drifting floes undergo as they interact with one other, and with coastlines. As a result, floes consisting of more than one ice type commonly occur in open areas. When seen in those terms, questions may arise about the utility of measurements made on landfast, undeformed ice. Our reply: the properties of landfast ice provide a basis for understanding more complex ice features. This is shown subsequently, where strengths measured on landfast ice and drifting floes are combined to establish seasonal trends in ice strength.

Landfast second-year ice formed in a sheltered bay of the Canadian Arctic Archipelago. Note the regular pattern and preferred orientation of melt ponds.

This is an isolated second-year floe. The colour of the ponds in different areas of the floe ranges from green (where the ice is thinnest) to blue (where the ice is thicker).

Multi-year Ice Floes: Relatively Level vs. Deformed

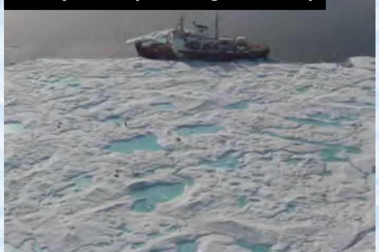
Usually, multi-year ice is not subdivided into different categories - and no recognized terminology for doing so exists at this time. Nevertheless, for the purposes of the following discussion of seasonal trends in ice strength, a distinction will be made between multi-year ice floes that look relatively level (*top row, below*) and those that have clearly undergone mechanical deformation (*bottom row, below*). A similar approach has been used in Johnston (2017; 2021). The term ‘relatively level multi-year ice’ is a misnomer however, since in reality, few drifting multi-year ice floes escape deformation. Also, it must be considered that the top ice surface may suggest undeformed ice, but the floe may have a rough underside (see *Detailed Thickness Measurements of Old Ice*). Our newly proposed terminology is also constrained by the number, and types of floes that were sampled from years 2000 to 2015. For instance, only seven second-year and multi-year ice floes were sampled with thicknesses from 2.5 to 4.0 m, making it difficult to establish trends for old ice in that thickness range. That said, our knowledge has improved considerably since the Guide was published in 2008, as shown on the following pages.

multi-year ice (4.0 m avg. thickness)

multi-year ice (3.6 m avg. thickness)

multi-year ice (5.2 m avg. thickness)

multi-year ice (8.0 m avg. thickness)



multi-year ice (11.3 m+ avg. thickness)

multi-year ice (10.2 m+ avg. thickness)

Multi-year ice floes on which strength measurements were made include ‘relatively level’ multi-year ice (*top row*) and clearly deformed, hummocked multi-year ice (*bottom row*).

Seasonal Trends in the Strength of Landfast and Drifting Floes

Attention now turns to using the depth-averaged strengths to establish seasonal trends for different ice types. The newly proposed terminology 'level multi-year ice' and 'hummocked multi-year ice' (*previous page)* has been used in the figure on the next page, where strengths are plotted in terms of the overall floe, or "floe strength". The "floe strength" is the average borehole strength of all tests conducted on that floe. The reader is referred to Johnston (2017) for additional information about the figure, and the methodology behind it. The figure demonstrates that every ice type displays a seasonal decrease in strength, with some important differences:

First-year ice vs. Second-year Ice:

First-year ice (FYI) and second-year ice (SYI) exhibit the most predictable changes in strength in winter, spring and summer. FYI and SYI strengths are similar in spring, but diverge as summer advances. This is to be expected because brine has a lesser influence on sea ice strength in spring (cold ice) than in summer (warm ice) and because the thickness of the desalinated layer of old ice retards ice deterioration. That makes SYI roughly 10 to 15% stronger than FYI throughout summer. FYI is weakest in mid-July, having just 9% of its winter strength. SYI reaches its lowest strength in mid-August (equivalent strength of 16% of winter FYI). The strength of any FYI and SYI that survives into September will increase, beginning at the top ice surface.

Second-year Ice vs. Multi-year Ice:

The strength of level multi-year ice (MYI) and hummocked multi-year ice (hMYI) also decreases in summer, but less predictably than FYI or SYI. Level multi-year ice and hummocked multi-year ice reach their lowest strengths in mid-September (equivalent strengths of 40% and 51% of winter FYI, respectively).

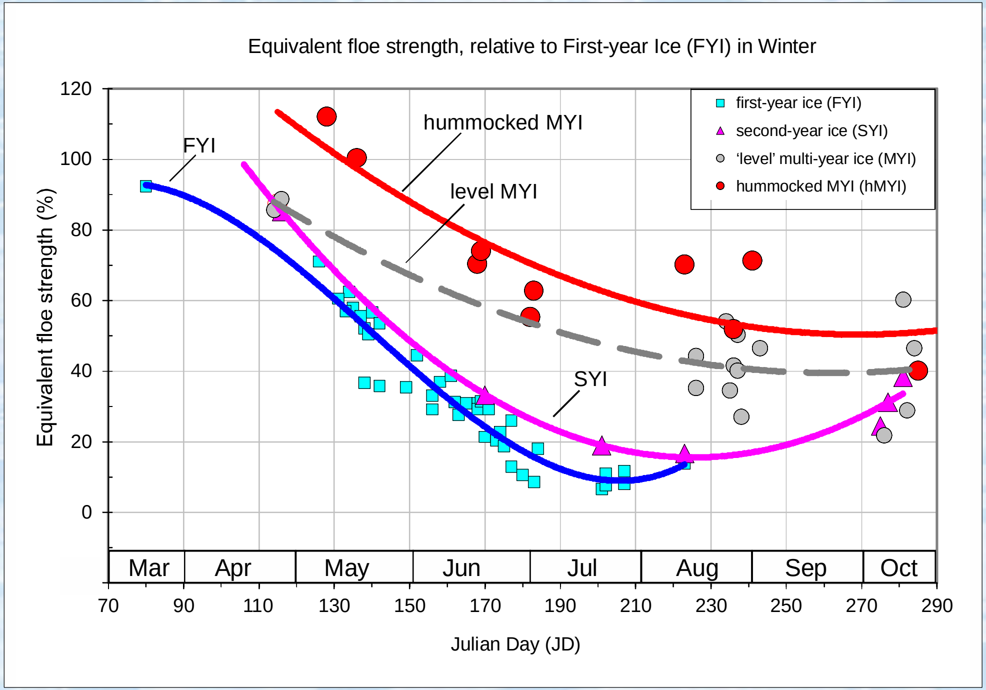
Results from the general literature (Johnston, 2014; Johnston and Frederking, 2014) indicate that the borehole strength of level MYI should be higher than SYI in spring because it is thicker, colder and less saline. Our overlapping strengths of SYI and MYI result from our sampling SYI and young MYI with similar thicknesses, temperatures and borehole strengths in spring (see *Second-year ice that Survived to become Young Multi-year Ice*).

Key points about the methodology behind the figure:

- *"floe strength" is a depth-average of all borehole strengths measured on that floe, from multiple boreholes*
- *"floe strength" is representative of the overall floe but, since it is an average, it will smooth-out the strength variations in individual borehole profiles*
- *all "floe strengths" have been normalized by the maximum strength of undeformed FYI in winter (32 MPa)*
- *equivalent strengths for old ice are based upon the maximum strength of FYI (32 MPa); FYI is the basis of the other types of sea ice, and operators are most familiar with it*
- *trendlines represent polynomial regressions of the measured floe strengths for each ice type*

To summarize, the main reason that MYI loses its strength more slowly than FYI or SYI is because of its thickness: thick ice will maintain colder temperatures longer than thinner ice. The second reason that MYI maintains its strength longer than FYI or SYI is because it has less brine. In general, (i) FYI and SYI are most similar in late summer, (ii) SYI and MYI are dissimilar at most times of year and (iii) hummocked MYI is the thickest and strongest form of sea ice. It should be reiterated that the ice properties reported in this Guide are based on floes sampled from years 2000 to 2015. All of the floes were sampled in the Canadian Arctic, most during summer but some in the spring and fall. Results will need to be adjusted if applied to other geographic regions, and years. One method of relating results from the Canadian Arctic to other geographic regions would be to adjust the borehole strengths for different ice types based on ice temperature using the equations in Johnston (2021).

Seasonal Trends in the Strength of Landfast and Drifting Floes



First-year ice (FYI)

- thinner than MYI and SYI
- highest salinity, overall
- inclusions mostly brine-filled
- weakest strength in July: ~9% of winter FYI strength

Second-year ice (SYI)

- thinner than MYI, but thicker than FYI
- desalinated layer thins as summer advances
- stronger top and/or bottom surface in summer
- weakest strength in August: ~16% of winter FYI strength

Relatively Level Multi-year ice (MYI)

- very thick
- maintains cold temperature late into summer
- mostly desalinated
- air inclusions in surface layer
- weakest strength in September: ~40% of winter FYI strength

Hummocked Multi-year ice (hMYI)

- extremely thick
- maintains its cold temperature
- mostly desalinated
- air inclusions in surface layer
- weakest strength in September: ~51% of winter FYI strength

3. Hazards Posed by Migrating Old Ice

Origins of Old Ice

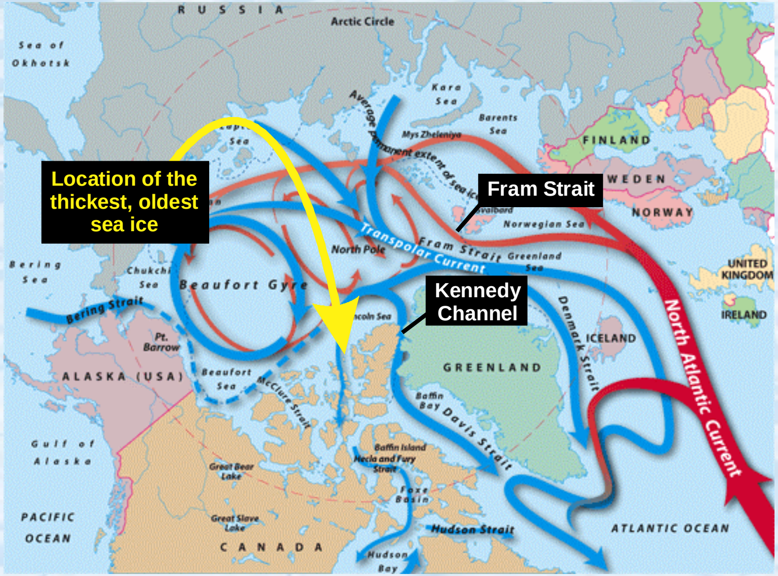
The WMO characterizes second-year and multi-year ice by its undeformed thickness: “second-year ice is generally less than 2.5 m thick” and “the thickness of multi-year ice usually exceeds 3 m”. Undeformed old ice can develop (and persist) on the open ocean, but it is more likely to be found in the sheltered bays of the Canadian Arctic Archipelago, as discussed earlier in *Growth and Ageing of Sea Ice*. Landfast multi-year ice also grows along the northern coast of Ellesmere Island and the Queen Elizabeth Islands, which is where some of the thickest, oldest sea ice in the world still can be found (Johnston, 2019).

Much of the old ice in the Arctic originates from the polar pack, where the summer is short enough to allow ice to survive many years. Often this ice is severely deformed, as floes are forced against each other, and against coastlines. The resulting ice is fractured, ridged and develops into massive pressure hummocks. Kovacs (1975) describes the largest multi-year pressure ridge ever observed: its sail was 10.5 m high and its keel was 31.4 m deep. That massive multi-year hummock was sampled in the southern Beaufort Sea, grounded along the coast of Banks Island.

Winds and ocean currents are the main forces controlling ice movement in the Arctic. Old ice floes in the Arctic Basin can circulate for up to 7 to 10 years as they are carried along the Beaufort Gyre (Wadhams, 2000) or they can break free from the polar pack and drift closer to shore. Since ice in the Arctic Basin is mobile all year round, it is not surprising that multi-year ice incursions regularly occur off the coast of Canada and Alaska, in summer and winter.

Old ice from the polar pack can also be transported across the Arctic Basin into Fram Strait or Kennedy Channel, where it is carried south. It also regularly migrates through the Canadian Arctic Archipelago, congesting narrow passages and blocking potential shipping routes.

In the following pages, the trajectories of a number of instrumented multi-year floes are used to show how old ice drifts through the Arctic. The drift patterns of these old ice floes explain why it is that hazardous ice is commonly encountered all over the Arctic and in the sub-Arctic, far from its point of origin.



Dominant circulation patterns of surface water in the Arctic. Surface currents and winds are the driving forces controlling movement of sea ice (*after Woods Hole Oceanographic Institution, https://www.whoi.edu/know-your-ocean/ocean-topics/polar-research/arctic-ocean-circulation/*)

Migration of Old Ice in the Arctic Basin

Where do old ice floes migrate? Is their movement consistent from year to year? How long do old ice floes survive? Those are some of the questions researchers have been trying to answer by tracking the drift of sea ice and documenting how the ice changes along the way. Much of what we know about ice circulation patterns in the Arctic comes from data obtained by the International Arctic Buoy Program (IABP) and their collaborators. Since 1978, the IABP has maintained a network of drifting buoys in the central Arctic Ocean and its marginal seas. The buoys provide automated meteorological and oceanographic data for real-time operational requirements and research purposes. Data are processed at the University of Washington's Polar Science Centre and are available at **https://iabp.apl.uw.edu.**

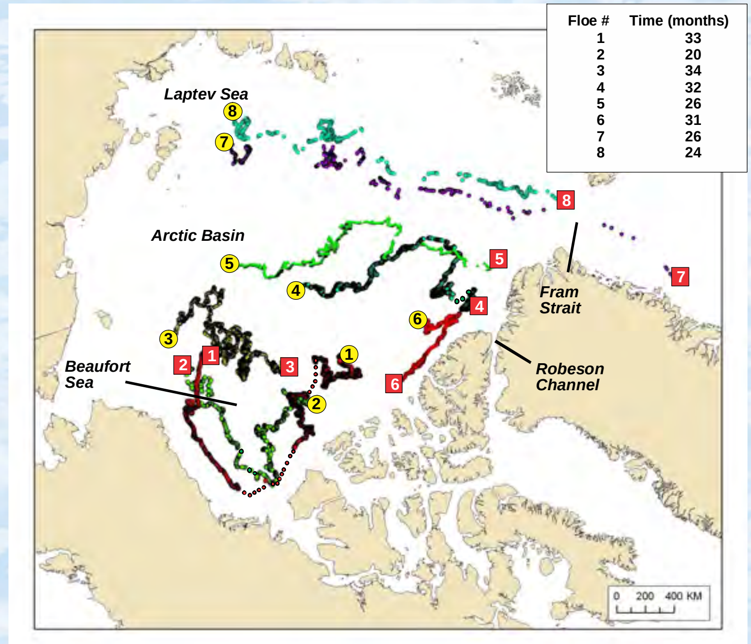
The map (*right*) shows the trajectories of 8 old ice floes, tracked from 2003 to 2005 as part of the IABP network. The yellow circle shows the position of the floes when the buoy was installed and the red square shows their position when the buoy stopped transmitting data. The map illustrates how old ice migrates in the short term – the few years of data are not meant to capture long term variability in circulation patterns.

Floes 1, 2 and 3 travelled in a circular pattern for 20 to 34 months under the influence of the Beaufort Gyre. Floe 1 followed a linear trajectory from April to August 2005, as it drifted about 200 km from the coast, in the southern Beaufort Sea.

Floes 4 and 5 transmitted data for a period of 26 to 32 months as they migrated out of the Arctic Basin towards Robeson Channel and Fram Strait.

Floe 6 traveled east and then reversed direction to follow the Ellesmere coast, where some of the thickest and most deformed multi-year ice in the world exists.

Floes 7 and 8 followed similar routes as they migrated from the Laptev Sea into Fram Strait over a period of 24 to 26 months. Both floes followed a near linear trajectory during much of their transit.



Floe #	Time (months)
1	33
2	20
3	34
4	32
5	26
6	31
7	26
8	24

Trajectories of old ice floes instrumented as part of the IABP (https://iabp.apl.uw.edu). Yellow circle indicates position of floe when it was first instrumented; red square shows position of floe when it stopped transmitting data.

Migration of Old Ice in the Canadian Archipelago

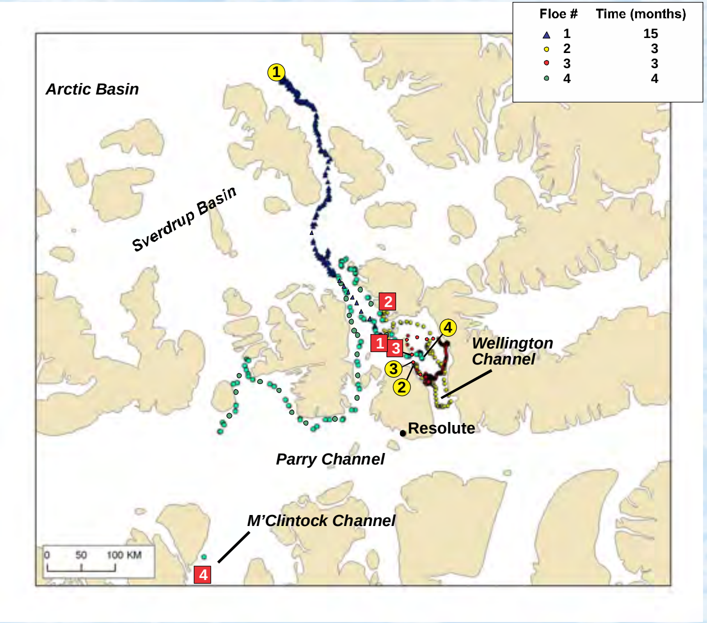
Old ice can meander around the Arctic Basin for up to 7 to 10 years (Wadhams, 2000), but that is not necessarily the case for old ice floes in the Canadian Arctic Archipelago. Only a few buoy deployments have been made in this region (see map below), three of them by the authors in collaboration with the Canadian Ice Service and Transport Canada. Instrumenting floes in the Canadian Arctic Archipelago is extremely challenging because of the many obstructions met as floes drift along coastlines or are crushed in the highly confined channels of the Archipelago. These obstructions do not bode well for a floe's survival and, when combined with logistical difficulties and the natural curiosity of polar bears, make recovering instrumentation nearly impossible.

Floe 1 was instrumented in 1991 but nothing is known about the ice feature itself. The drift record extends for 15 months (January 1991 to April 1992), which tells us that the feature was at least two years old. The trajectory of this floe suggests that migration through the Canadian Archipelago can take at least two years, depending upon the conditions.

Multi-year **Floe 2** was more than 6 m thick when it was instrumented in Wellington Channel in June 2002, while landfast. In mid-July the floe began drifting south, continuing for about two weeks until crossing to the eastern side of Wellington Channel. From there, the floe drifted north and was last heard from on 31 August 2002. The floe was almost 100 km further north than when it was visited three months earlier.

Floe 3 was a multi-year floe with an average thickness of 9.3 m. This landfast floe was instrumented at the north end of Wellington Channel in June 2008. The floe began drifting in late July, as the pack ice around it began to loosen. It transmitted data for about 3 months, during which time the floe made a complete circle in Wellington Channel. It reported its last position on 16 August, when it was less than 50 km north of where it was first visited. Other instruments on the floe continued to function for about another week. Then, on 23 August, all instrumentation went quiet.

Multi-year **Floe 4** had an average thickness of 8.6 m (see *On-ice measurements* observation #3). Floe 4 was at the edge of the multi-year pack ice in Wellington Channel when it was first visited in May. This floe transmitted its position regularly from 30 May to 7 September, as it followed coastlines north, and then south into Parry Channel. The next successful data transmission occurred on 20 September, by which time the floe had entered M'Clintock Channel, 200 km south of its position on 7 September. The floe was not heard from after 20 September.



Map shows trajectories of multi-year ice floes in the Central Canadian Archipelago, as they drift circuitously through the islands.

Migration of Old Ice in the Eastern Canadian Arctic

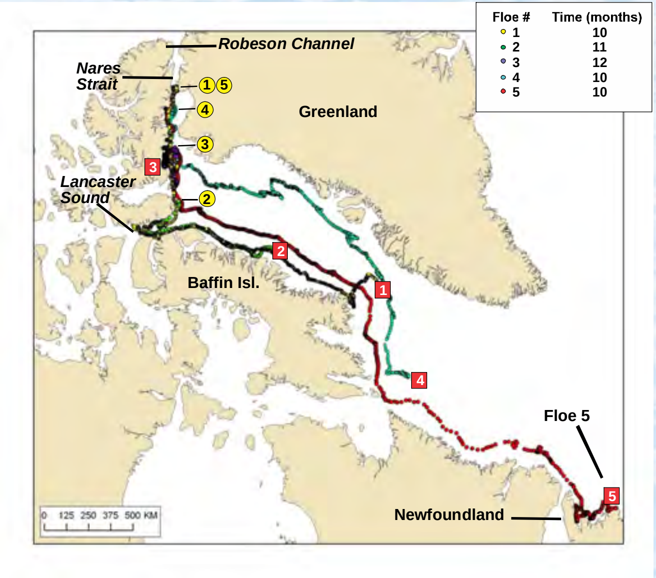
Floes that are swept into Robeson Channel or Fram Strait follow a “fast track” south, generally being exported out of the Arctic in less than one year. The multi-year floes instrumented in 2005, 2006 and 2007 show how quickly old ice floes drift south. These floes were instrumented by the authors as part of collaborative work with Transport Canada and the Canadian Ice Service.

Floes 1 and 2 were swept into (and out of) Lancaster Sound before drifting south along the Baffin coast. Floe 1 stopped transmitting as it headed towards the coast of Greenland, 10 months after it was instrumented. Details of this floe are presented in *On-ice Thickness Measurements* observation #8. The last positional fix on Floe 2 was obtained in August, as the floe drifted along the coast of Baffin Island.

Floe 3 grounded near Ellesmere Island, just two weeks after it was instrumented in August 2006. The floe finally started to move again one year later, but traveled for less than a month before it stopped transmitting data.

Floe 4 was transported east across Baffin Bay to the Greenland coast. From there, it drifted south before returning towards the Baffin Coast, where its last positional fix was obtained in May, 10 months later.

Floe 5 travelled a distance of more than 3000 km in 10 months, from August 2006 to May 2007. The trip took a heavy toll on this floe, however. The floe was about 1.0 km across and was estimated to be more than 10 m thick when it was visited in Nares Strait *(bottom left)*. By the time it reached Newfoundland in the spring, it was not more than 100 m across *(bottom right)*.



Multi-year floes in the Eastern Arctic change dramatically as they drift south. The floe that was instrumented in Nares Strait *(far left)* fragmented and deteriorated into the 100 m diameter feature shown off the coast of Newfoundland in the spring of 2007 *(left)*.

What Old Ice Means for Ships in the Sub-Arctic

The multi-year ice floe that traveled from Nares Strait to Newfoundland was not the only old ice floe to do so that year. An unusual amount of old ice occurred off the coast of Newfoundland in the spring of 2007. The presence of old ice and strong onshore winds made ice conditions that spring the worst seen in 10 to 15 years. The ice presented special challenges for shipping to Labrador (B. Gorman, personal communication) and it was a nightmare for hundreds of small vessels operating off the Northeast Coast of Newfoundland.

The Canadian Coast Guard dedicated three heavy icebreakers and three light icebreakers to the area for several weeks, to assist the more than 100 vessels beset in the ice. Two of the lighter icebreakers required assistance when they became beset in the ice and several small fishing boats were severely damaged or lost. Finally, after two weeks of strong onshore winds, the wind direction changed and the pressured ice dissipated.

Ice conditions off the Northeast Coast of Newfoundland that spring provide a flavour of the kinds of hazards old ice can pose for ships in the sub-Arctic. These fragments of old ice are often difficult to detect because they are simply too small to recognize and/or they are embedded in a jumbled mixture of first-year ice. These fragments of hazardous ice seldom have the colour and thickness of ‘typical’ old ice (discussed in *Key Identifiers of Old Ice*).

Ship-based Observations: Sub-Arctic provides examples of the types of old ice commonly encountered in the sub-Arctic. The observations demonstrate that even experienced, highly-trained personnel sometimes have little confidence classifying features in the sub-Arctic as first-year, second-year or multi-year ice.

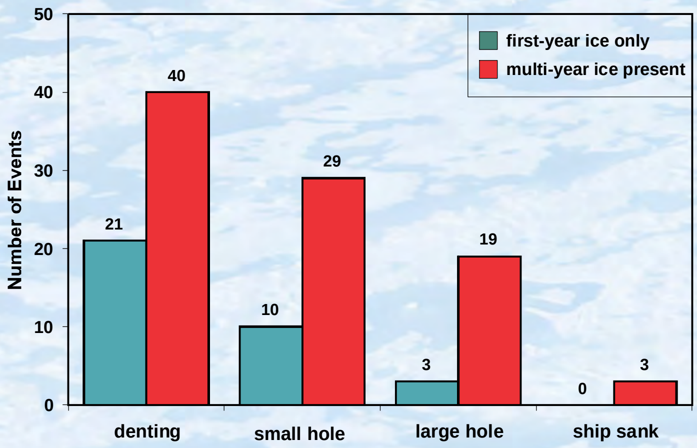
Newfoundland Region, May 2007

Old ice like the floe that drifted south from Nares Strait *(far right)* made for treacherous ice conditions off the Newfoundland coast in the spring of 2007. A Canadian Coast Guard ship escorts small craft through ice *(top right).* Many small vessels were stranded in the ice *(bottom right)*. *Photos courtesy of Canadian Ice Service*.

What Old Ice Means for Ships in the Arctic

Ship damage statistics provide quantitative information about the hazardous nature of old ice. Statistics show that 75% of the reported ship damage incidents in the Canadian Arctic result from ice conditions that had some concentration of multi-year ice (Kubat and Timco, 2003). The graph below shows that multi-year ice accounts for the highest number of ship damage events, and the most severe types of damage (large holes and sinking). Multi-year ice is very capable of damaging ships, as the photographs show.

If multi-year ice is present in an area, due diligence and caution is absolutely essential because multi-year ice has the potential to cause severe damage – for ships not designed for impacts with multi-year ice, and even those that are.



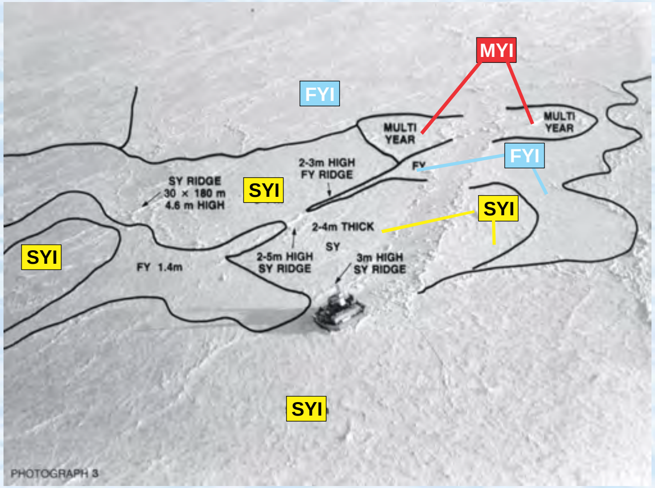
Percentage of ship damage due to first-year ice and multi-year ice (*after Kubat and Timco, 2003)*. Multi-year ice is either directly (or indirectly) responsible for 75% of ship damage events in the Canadian Arctic. Photographs show large holes in two ship hulls resulting from what is believed to have been impacts with multi-year ice *(right)*.

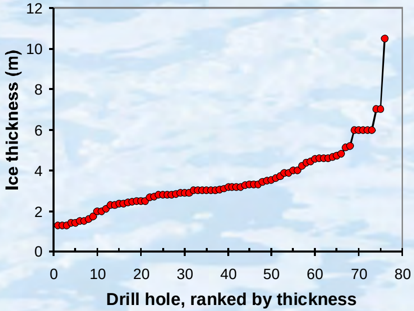
What Old Ice Means for Stationary Structures

Ships have a distinct advantage over bottom-founded structures because they can avoid hazardous ice, when possible. Tethered platforms have the option of disconnecting and moving off-site, although that requires time and is very expensive. Bottom-founded structures, such as the Molikpaq, must remain in place to withstand impacts with ice.

The Molikpaq, which was used to explore for oil and gas in the Beaufort Sea in the 1980s, provides a wealth of information about the challenges of operating in multi-year ice. The aerial photograph *(right)* shows the Molikpaq in the spring of 1986, when it operated at the Amauligak I-65 site, 70 km offshore in the Canadian Beaufort Sea. The old ice floes in the photograph are the exact features that caused the highest loads measured on the Molikpaq that season *(see next page)*. In fact, evacuation alerts were declared several times that season.

There was intense interest in exploring resources in the Beaufort Sea in the 1970s and 80s, and there may be again. Future oil and gas exploration may take place in the deeper waters of the Arctic Basin, where structures would be exposed to more hazardous ice from the polar pack. Should that happen, personnel must be able to recognize the most hazardous forms of old ice, and understand the dangers they pose.





(top right) **Aerial photograph of Molikpaq showing features that caused the highest ice loads measured on the structure. Note the 100 m wide swath that the Molikpaq ploughed through the first-year, second-year and multi-year floes as the ice moved past the structure.**

(right) **Pieces of old ice failed against the near-vertical face of the Molikpaq and either passed around the structure or built-up in front of it and remained stationary, like the 10 m high pile-up shown here.**

(left) **Ranked ice thickness distribution from drill hole measurements on first-year, second-year and multi-year ice around the Molikpaq in the spring of 1986.**

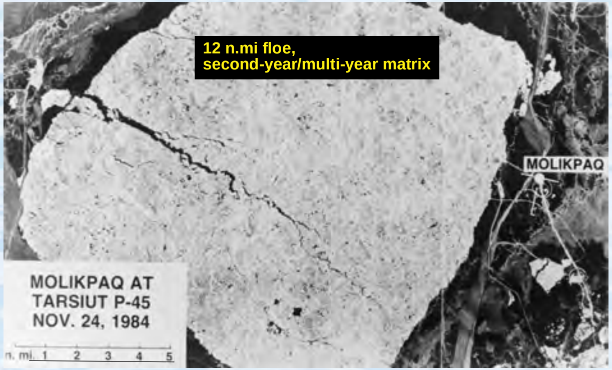
What Old Ice Means for Stationary Structures

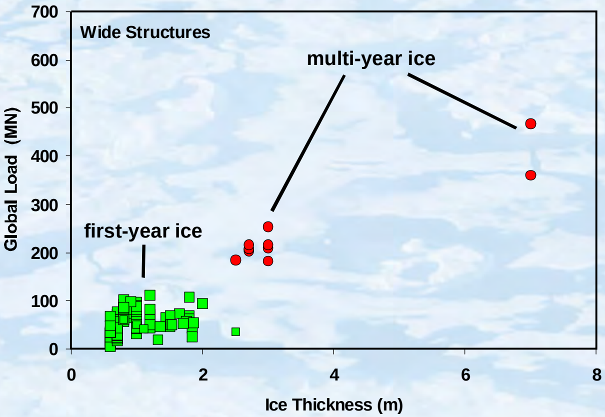
The Molikpaq was also deployed at the Tarsiut P-45 site in the Canadian Beaufort Sea, in 1984. The side-looking airborne radar (SLAR) image *(top right)* shows an old ice floe that drifted towards the Molikpaq in November 1984, when it was at the Tarsiut site. The floe in the SLAR image was about 12 n.mi (22 km) across and was an aggregate of second-year and multi-year ice floes. In this particular case, the giant old ice floe approached the Molikpaq to within several kilometres, but moved away before contacting the structure.

The graph below shows full-scale load measurements on offshore structures such as the Molikpaq, Tarsiut Caissons, and the Steel Drilling Caisson. These offshore structures operated less than about 70 km from shore, which put them within, or at the edge, of the landfast first-year ice. As such, the first-year ice acted as a buffer, protecting the structures (in winter) from old ice floes in the polar pack.

Multi-year ice can generate loads four times higher than first-year ice (Timco and Johnston, 2003; 2004). To date, our knowledge of the forces that multi-year ice can generate on a structure is based upon the roughly two dozen loading events included in the graph *(right).* Most of these data points come from the Molikpaq while operating at the Amauligak I-65 site (*previous page*). Our understanding of the loads that multi-year ice can impose on a structure is quite rudimentary – our understanding of first-year ice loads is much more advanced, primarily because there are many more loading events to draw from.

The limited understanding of multi-year ice loads on structures makes having detailed information about the properties of multi-year ice (thickness, floe size, drift speed, etc.) extremely important for designing and operating offshore structures (Johnston et al., 2009). This Guide provides a wealth of information about the kinds of old ice floes that offshore structures will be exposed to in the Arctic.





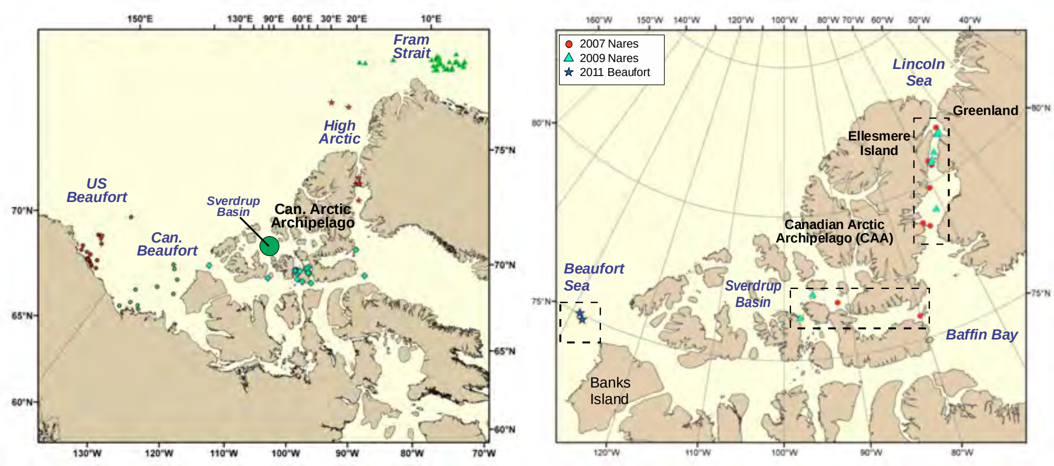
SLAR image of a giant second-year/multi-year aggregate floe approaching Molikpaq, November 1984 (*top right*). Global loads on wide structures resulting from impacts with first-year and multi-year ice (*bottom right*).

Thicknesses of Old Ice, by Region

Thickness distributions of old ice are plotted for different geographic regions (*next page*) based upon the data compiled in Johnston et al. (2009), and compared with more recently acquired data presented in Johnston (2019). Only thicknesses from direct drilling (augering or coring) or a combination of drilling/sonar ranging were included in the compilation. Direct drilling is the gold-standard for measuring ice thicknesses and it provides important information about thickness variations for determining how and where the ice is most likely to fail (see *On-Ice Thickness Measurements*). Drill-hole thicknesses from other researchers date back to the 1970s and 80s, and were conducted in support of Oil and Gas operations. The most intensive field programs to measure multi-year ice thicknesses since the 1980s were conducted as part of our on-going study of old ice, in years 2007, 2009, and 2011. Some of those recent thicknesses are discussed in more detail in *Detailed Thickness Measurements of Old Ice*. Here, data from the 1970s and 80s are compared to more recently acquired data to evaluate whether the thickness of multi-year ice has changed over the years.

The two maps below show where old ice was sampled in the past (*bottom left*) and more recently (*bottom right*). In this thickness comparison, Sverdrup Basin is treated as a subset of the Canadian Arctic Archipelago (CAA) despite the huge number of thicknesses from that region. More than 5000 ice thicknesses were measured in Sverdrup Basin during the spring 1978 Arctic Petroleum Operators Association (APOA) seismic study. The reader is referred to the sentinel paper by Melling (2002) for a discussion of the more than 120,000 thicknesses measured during the entire APOA program, of which the 1978 data are taken here as being representative.

Second-year and multi-year ice usually were not distinguished during past field programs, likely because many of them took place in spring, when the snow cover masks differences between the two ice types. Even the very thorough field program of Tucker et al. (1987) did not distinguish between second-year and multi-year ice in Fram Strait, instead referring to both as “multi-year ice”. In the following discussion, floes sampled by other researchers are considered ‘old ice’.

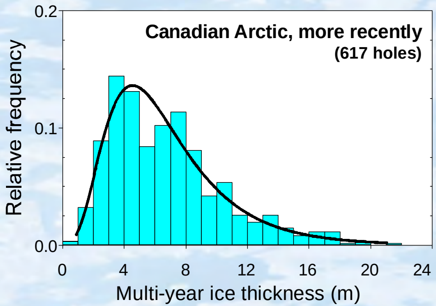


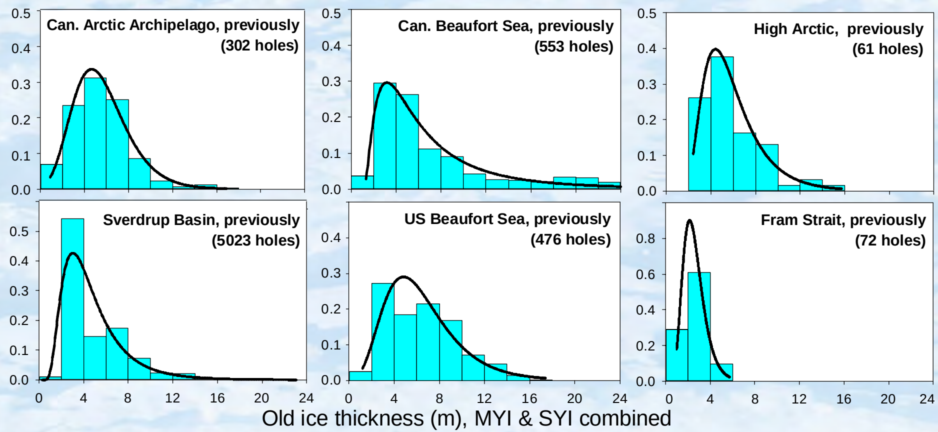
Map showing locations where drill-hole thicknesses on old ice were measured in the distant past (*near right*) and more recently on multi-year ice (*far right*).

Thicknesses of Old Ice, by Region

Histograms of the measured thickness of old ice in the different regions are plotted using 1 or 2 m thickness bins (*below*). Each bin shows the number of measurements in that thickness range in terms of its relative frequency. The solid line in the figures shows the lognormal distribution that was used to model thicknesses in the different regions (see Johnston, 2019). The figures give a general idea of old ice thicknesses for the different regions, but direct comparison is limited for two reasons. First, the thicknesses from other researchers are plentiful enough to be plotted for individual regions (*smaller histograms at right*), but our more recent thickness measurements must be grouped and plotted as 'Canadian Arctic' (*bottom left*) since they are relatively few in number. Second, many (but not all) of the field programs targeted very thick ice and/or avoided thinner types of old ice, so the data from each program will contain some degree of bias. Sverdrup Basin (*bottom left row*) is the exception because thicknesses were measured at regular intervals over large distances, regardless of ice type. In the figure below, ice less than 1.8 m thick has been removed from the Sverdrup Basin data set, as it is taken to represent first-year ice.

In the past, old ice with a thickness of 2 to 4 m was most commonly found in the Sverdrup Basin (*left bottom row*), Canadian Beaufort (*middle top*), US Beaufort (*middle bottom*), and Fram Strait (*right bottom*). The same is true of more recent measurements from the Canadian Arctic (*far left figure*). All of those regions contain an abundance of thermodynamically grown second-year (~2.5 m thick) and multi-year (up to 4 m thick) ice. Conditions may be different today, given the challenges that first-year, second-year and young multi-year ice have surviving summer (see *Old Ice Originates as First-year Ice*). Recent analyses of Canadian digital ice charts for the 1983 to 2009 period found significant changes in the duration of landfast ice in the Beaufort Sea and Eastern Canadian Arctic but no significant trend in the duration of landfast ice for the interior navigable channels of the Canadian Arctic Archipelago (Galley et al., 2012), suggesting that ice in the CAA may take longer to manifest changes.





Thickness distributions for multi-year ice sampled recently (*top*) and old ice in the past (*right*). Locations of geographic regions shown in maps on previous page.

Thicknesses of Old Ice, by Region

Melling (2002) notes that ice in the Arctic Basin that is thicker than 4 m has likely been imported from other regions. Consider also that multi-year ice thicker than 4 m can be thermodynamically grown, but more likely results from mechanical deformation. Whether thermodynamically-grown or mechanically-formed, multi-year ice in the High Arctic (*top right, previous page*) and Canadian Arctic Archipelago (*top left, previous page*) was most commonly 4 to 6 m thick in the past. Today, multi-year ice thickness in the Canadian Arctic is most commonly in the range of 3 to 5 m (*far left, previous page*). The three regions where recent thicknesses can be best compared to past studies are the High Arctic, Canadian Arctic Archipelago (CAA) and the Canadian Beaufort. The table below shows that our recent measurements increased the number of thicknesses on multi-year ice in the High Arctic (450 vs. 61 previously), nudging the average thickness for that region higher (6.1 m vs. 5.6 m). Our 78 thicknesses in the Canadian Arctic Archipelago also increased the average thickness, compared to previous measurements (9.8 m vs. 5.6 m). The 89 drill holes that we made in 2011 on two floes in the Canadian Beaufort Sea produced an average thickness of 7.6 m, which is comparable to the 7.5 m average thickness obtained from previous field campaigns in the same region.

Most geographic regions can have ice features up to 24 m thick or more, although that is not evident from our histograms (*previous page*). These 'extreme' features reside in what is referred to as the 'tail' of the distribution, and they are best shown by plotting thicknesses in terms of their probability of exceedances. Plots of the exceedance probabilities for the different regions were not included here, but can be found in Johnston et al. (2009) and Johnston (2019).

In summary, our measurements indicate that old ice has not become appreciably thinner or less hazardous than in the 1970s and 80s. As for whether old ice is less consolidated (i.e. contains more voids, deteriorates faster) today than in the past, evidence suggests otherwise: hundreds of drill-hole and strength measurements revealed fully consolidated multi-year ice, even in late summer. Although one of the floes that we sampled in August in the Beaufort Sea had a deteriorated bottom, the second floe that was sampled in the same area did not (Johnston, 2011-a). More importantly, the uppermost several metres of the floe with the deteriorated bottom had not appreciably decreased in strength. We found that most multi-year ice floes were not as deteriorated as they looked (see *Detailed Thickness Measurements of Old Ice*).

Having concluded our discussion of the *Growth and Ageing of Sea Ice*, we next itemize the key criteria that can be used to distinguish second-year ice from multi-year ice, and give hundreds of observations to illustrate the technique.

Old Ice Thickness for Different Geographic Regions

Region	Number of measurements	Avg. thickness ± standard deviation (m)	Maximum [minimum] thickness (m)
High Arctic, recent	450	6.1 ± 3.3	19.9 [0.9]
High Arctic, past	61	5.6 ± 2.7	15.7 [2.4]
Canadian Arctic Archipelago, recent	78	9.8 ± 5.5	21.1 [2.4]
Canadian Arctic Archipelago, past	302	5.6 ± 2.6	16.9 [0.9]
Canadian Beaufort, recent	89	7.6 ± 1.9	15.7 [3.6]
Canadian Beaufort, past	553	7.5 ± 6.0	40.2 [1.3]

4. Key Identifiers for Old Ice

Surface Features of Second-year Ice

The WMO defines **second-year ice as being up to 2.5 m thick, and sometimes more** and having **survived one summers' melt.** The photographs below illustrate that second-year ice that forms and remains in sheltered areas is typically more uniform than second-year ice floes drifting in open water areas.

Surface features of second-year ice include:

- regular pattern of numerous small puddles
- drainage patterns that are more extensive than first-year ice, but less extensive than multi-year ice
- bare patches and puddles/ponds are blue, but can have a green hue
- the edges of a second-year floe are less angular than first-year floes, but not as rounded as multi-year floes
- second-year ice usually floats higher in the water than first-year ice, but lower than multi-year ice

Landfast second-year ice formed in a sheltered bay of the Canadian Arctic Archipelago. Note the regular pattern and preferred orientation of melt ponds.

This is an isolated second-year floe. The colour of the ponds in different areas of the floe ranges from green (where the ice is thinnest) to blue (where the ice is thicker).

Surface Features of Multi-year Ice

Typically, multi-year ice is **at least 3 m thick, but it can be upwards of 15 m thick**. Extremely thick multi-year ice can be produced by mechanical forces (ridging, hummock fields) or it can grow thermodynamically. Walker and Wadhams (1979) use model results to show that ice at least 12 m thick can grow thermodynamically over tens of years, under certain conditions. The extremely thick ice floes discussed in *On-ice Thickness Measurements* provide evidence of the mechanical and thermodynamic thickening processes.

Surface features of multi-year ice include:

- hill-and-dale appearance
- naturally-formed hillocks are higher and can be more numerous than hillocks on second-year floes
- pressure hummocks and multi-year ridges are more weathered and have shallower sides than second-year hummocks and ridges
- drainage patterns consist of large, interconnecting, irregular puddles/ponds and a well-developed network of channels
- the colour of the ice, where bare, is often turquoise blue
- freeboard is usually higher and less uniform than second-year ice, and especially first-year ice
- multi-year floes are usually more rounded than first-year and second-year floes

Two extremes of multi-year ice: level ice and hummocked ice. Multi-year ice floe with large areas of level ice and relatively little drainage *(near right).* Very hummocked multi-year ice floe *(far right)*.

The average thickness of the level multi-year floe was 5.0 m *(near right)*, whereas the hummocked floe was, on average, more than 10 m thick *(far right)*. Both floes were visited in August, when the ice was devoid of snow.

Key Identifiers for Old Ice

Differentiating second-year ice from multi-year ice is challenging because the two ice types can look very similar. Old ice can also be confused with first-year ice, especially in the sub-Arctic. Since the three types of ice present different risks to a ship or structure – multi-year ice being the most hazardous – distinguishing them is very important, as any experienced mariner knows.

A number of Key Identifiers can be used to help differentiate (1) old ice from first-year ice and (2) multi-year ice from second-year ice. Usually, a combination of Key Identifiers is used, rather than any one characteristic. Most of the Key Identifiers shown here were obtained from the WMO sea-ice nomenclature (WMO, 1970) or from the Manual of Standard Procedures for Observing and Reporting Ice Conditions (MANICE, 2005). Supplementary information was obtained from written and verbal communications with the Ice Service Specialists and Commanding Officers, and from the authors' own personal experience.

The most commonly used Key Identifiers are illustrated in the subsequent sections *Ideal Second-year Floe* and *Ideal Multi-year Floe*.

Key Identifiers:

☑ **freeboard**

Freeboard is defined as how high the ice floats above the water. Multi-year floes generally have higher freeboard than second-year floes, which, in turn, have more freeboard than first-year floes. Freeboard can be used to estimate ice thickness in the spring and early summer but the relation is less reliable in late summer, when ice floes may float low in the water. Caution is warranted: the ice can be quite thick, but may not appear so.

☑ **floe shape and size**

Second-year and multi-year floes have a rounded shape, compared to the sharper edged, angular appearance of first-year floes. Old ice floes often consist of an aggregate of different floes (second-year and multi-year) welded together by ridges and hummocks. Individual multi-year ice floes are often much smaller and less uniform than first-year floes.

☑ **ponding/drainage**

Ponding describes the accumulation of meltwater on the ice, initially due to melting snow, but in the more advanced stages also to the melting of ice. Summer melting on second-year ice produces a regular pattern of numerous small puddles and ponds, with minimal connectivity. By comparison, melt ponds on multi-year ice are larger, irregular in shape and are usually interconnected. These features give the surface of multi-year floes a much more well defined drainage network, compared to second-year floes.

☑ **colour**

Although the WMO states that 'puddles on second-year ice are usually greenish-blue, whereas ponds on multi-year ice are usually turquoise blue', the colour of the ponds (and ice) can be very similar. Colour is very subjective. Ponds on the same floe can also have a range of colours. 'Colour' also refers to debris on the ice surface, since it can give multi-year floes a characteristic 'dirty appearance'. However, all types of coastal ice can have sediment blown on to them, as can grounded ice features such as stamhuki. In the authors' opinion, colour is a poor Key Identifier because it is so subjective.

Key Identifiers for Old Ice

✔ ice thickness

Second-year ice can be up to 2.5 m thick, and sometimes more. Multi-year ice is typically more than 3 m thick. In summer, second-year and multi-year ice can be thinner. In many cases, multi-year ice is considerably thicker than it appears from ships, structures, or from the air. That is especially true in late summer, when thick multi-year ice can float low in the water (see description of freeboard, *previous page*).

✔ hummocked

A hummock is an uneven surface formed from broken ice, forced upwards by pressure. It can be fresh or weathered. Weathered hummocks appear similar to hillocks (see below). It is not usually possible to distinguish hillocks and hummocks, which is why the 'hill-and-dale' surface of old ice is usually referred to as 'hummocked'. Second-year hummocks are 'peakier' and more steeply sloped than the more weathered, gradually sloping multi-year hummocks.

✔ hillocked

Hillocks are raised areas of ice formed from the natural weathering process. As the floe ages, the melt ponds deepen, accentuating the raised areas (hillocks). Multi-year floes may have greater surface topography than second-year floes, since they have survived more melt seasons.

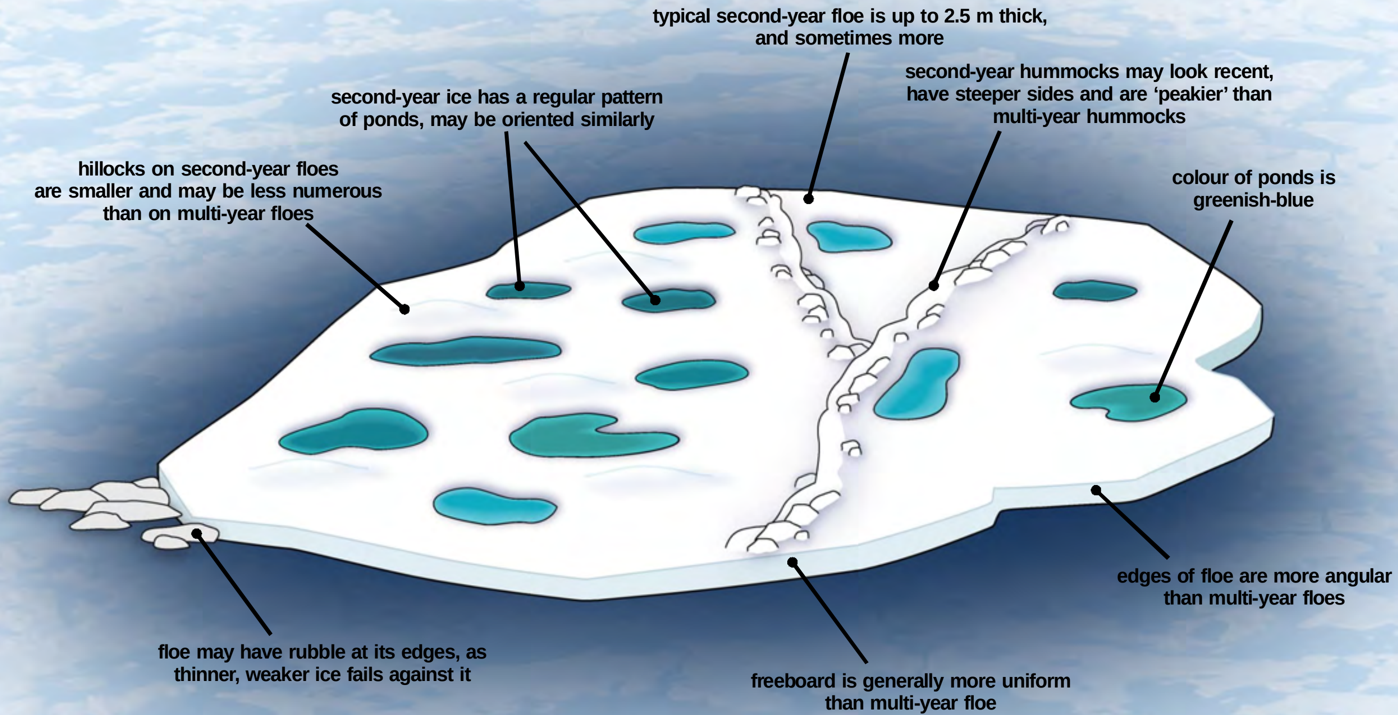
✔ snow cover

Multi-year ice usually has a thicker, less uniform snow cover than first-year ice. As a result, snow can be present on some areas of a multi-year floe long after the snow on first-year ice has melted.

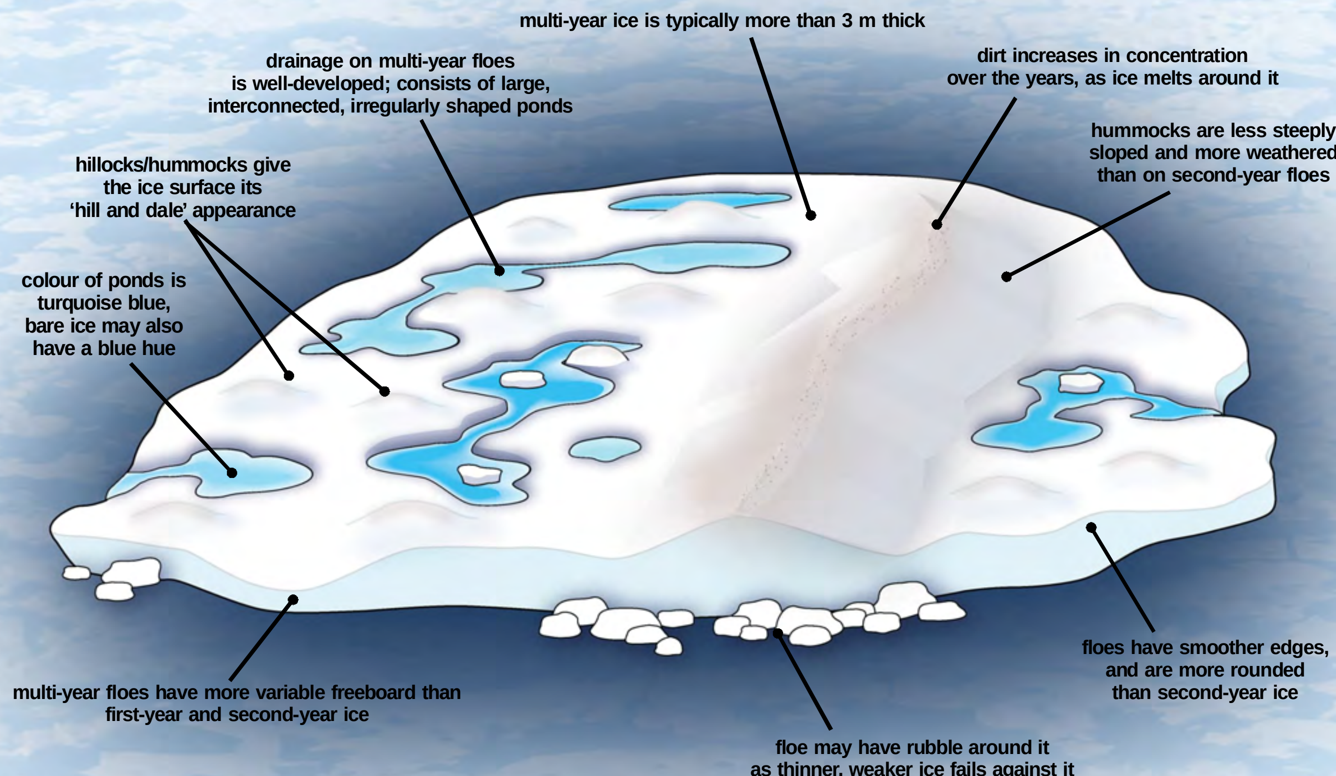
✔ other

- Knowledge of migration patterns, in terms of whether second-year or multi-year ice is likely to be imported into an area
- information about the floe's history, if scientific instruments have been used to track the floe for more than one year
- old ice is often compared to the surrounding ice; if first-year ice in an area is extremely thin and rotten, the thicker floes are very likely old ice
- satellite imagery can be used to document the floe's history. It also helps distinguish old ice from first-year ice at certain times of year (see *Satellite Observations*)
- on-ice measurements such as thickness, temperature, salinity, strength and ice microstructure can be used to differentiate first-year, second-year and multi-year ice

Ideal Second-year Floe



Ideal Multi-year Floe



Key Identifiers from Impacts with Old Ice

When a ship impacts old ice, or an old ice floe impacts a structure, several more Key Identifiers can be used to determine whether the feature is first-year, second-year or multi-year ice. **That said, impacting an old ice floe should not be undertaken to aid floe identification.**

Key Identifiers for old ice when it impacts a ship or structure

- ☑ **sound when hit**

  When multi-year ice is impacted, it produces deep reverberations that can be felt throughout the ship; impacts with first-year and second-year ice do not. The sound of the impact itself is also different for multi-year ice, compared to second-year and first-year ice. The ship's response to a multi-year ice impact is 'snappy'.

- ☑ **backing and ramming**

  Often, a ship will need to back-and-ram to progress through an old ice floe. That is especially true for multi-year ice, but less so for second-year ice. An icebreaker may be able to transit level or moderately ridged first-year ice without backing and ramming. That said, the ship may have difficulty penetrating any type of floe, depending upon the ice conditions and the ship's capability.

- ☑ **floe splitting**

  Progress through an old ice floe becomes much easier if the floe splits as the ship penetrates it. Splitting most often occurs with isolated floes (surrounded by open water) and when there is a free edge in the ship's vicinity (such as an open lead). Since first-year, second-year and multi-year ice floes can all split when floe confinement is low, splitting is not necessarily indicative of the ice type. However, it is reported in *Ship-based Observations* because it provides important information about the ship's ease of transit.

- ☑ **fracture patterns**

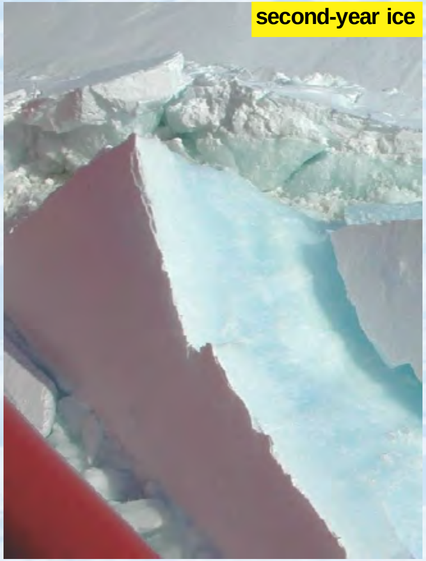
  The pieces of ice (or cusps of ice) overturned by a ship as it penetrates a floe can be used to estimate the ice thickness. The photos on the opposite page show that first-year, second-year and multi-year ice each fracture differently. The upturned pieces also provide an excellent indication of the colour of the ice, which is a better indicator (than pond colour) for classifying ice type.

Fracture Patterns: First-year Ice versus Old Ice

First-year ice fractures into many small pieces, easily turned on their side against the ship. The colour of a cusp of first-year ice is dark blue/grey.

Second-year ice cleaves into larger pieces than first-year ice, and the fragments have cleaner lines. The colour of a cusp of second-year ice is light blue.

Multi-year ice is not nearly as well-behaved as the other two types of ice. Fragments of extremely thick multi-year ice are simply too large to completely turn over against the ship, which makes estimating the thickness of multi-year ice difficult using this approach. The colour of multi-year ice is turquoise blue.



5. On-ice Thickness Measurements

Detailed Thickness Measurements of Old Ice

Hundreds of thickness measurements were made in the Beaufort Sea in the 1980s, in support of oil and gas exploration (FENCO, 1973; Kovacs, 1975; Dickins, 1983; Wright et al., 1984). Some of the data were eventually made public (Kovacs, 1983; Dickins, 1989), however most of the reports are either subject to confidentiality agreements or have been lost. The most massive feature ever observed from these measurements was a 240 m long multi-year ridge, with a 10.4 m sail height and a 31.4 m keel depth (Kovacs, 1975). Does extremely thick ice still exist and, if so, how commonly is it encountered? Johnston (2019) compares multi-year ice thickness obtained recently to those compiled from some of the above-mentioned studies (see *Thicknesses of Old Ice by Region*). The on-ice measurements in this section document some of these recent multi-year ice thicknesses for the central and eastern Canadian Arctic. The floes were sampled in spring (when blanketed by snow) and late summer (when covered by melt ponds). Thicknesses were measured using the drill hole technique, whereby 5 cm diameter holes were drilled through the full-thickness of ice, at regular 10 m intervals (see flags in photo below) along a number of transects. Drilling is not the only means of measuring ice thickness, but it is the most accurate and detailed method to date, especially for thick multi-year ice. The tendency for airborne/ice-borne electromagnetic induction (EMI) sensors to underestimate the thickness of relatively level and deformed multi-year ice (Johnston and Haas, 2011) and visibly deformed first-year ice (Haas et al., 2006) is problematic. Remarkable results have been obtained mapping the underside of multi-year ice floes with multi-beam sonar mounted on autonomous underwater vehicles (Wadhams et al. 2006; 2008, Wadhams and Doble, 2008). The technique provides detailed information about the draft of the ice (distance to the waterline), which then needs to be related to the ice freeboard to obtain the total ice thickness. There are issues relating ice draft (and ice freeboard) to the total ice thickness, as noted by Johnston (2019) and others.

Measuring the thickness of multi-year ice every 10 m along a flagged transect (*left*) using the drill-hole technique (*middle).* The multi-year floe that looked relatively level from the surface actually had a rough underside, with the maximum thickness in the middle of the floe where one least expected it (*right*). This is noteworthy because it shows that the top surface of a multi-year ice floe does not necessarily belie the extreme ice thicknesses beneath it. 3D transect representation courtesy of D. Sudom, as appears in Johnston (2011-b).

Detailed Thickness Measurements of Old Ice

The top surface of a multi-year floe often does not reveal its extreme thickness, especially in summer. The top and bottom ice surfaces can look totally different in terms of their roughness, as shown on the previous page. Drill-hole measurements on that floe showed the thickest ice not at the floe's ridged edges, as one might expect, but under 'level' ice at the centre of the floe. The photograph below shows a multi-year ice floe that looks deteriorated, but its thickness was greater than expected: three transects revealed total ice thicknesses (sail plus keel depths) of up to 8 m. The 40 drill holes on this floe produced an average thickness and standard deviation of 4.7 m ± 1.5 m.

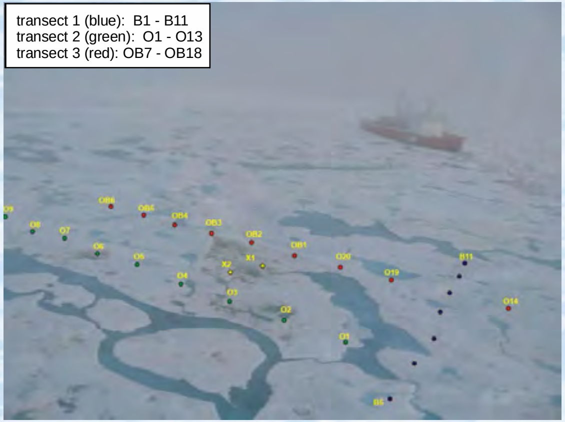
Transect data for two other multi-year ice floes are shown on the next page. The first floe was in Sverdrup Basin, where two transects were mapped in a highly deformed area but, due to the extreme ice thickness, only one transect was drilled. That transect crossed what appeared to be a relatively level area of ice before extending along the crest of the smaller of two, large hummocks. The level-looking ice was 8.3 to 14.5 m thick (between holes B2 and B8); a maximum thickness of 17.9 m was measured along the hummock (hole B15). The average ice thickness along this transect was 12.7 m ± 3.3 m. Additional details about this floe and others are given in Johnston (2011-b).

The second floe (*next page*) was sampled in the Beaufort Sea. A total of 40 drill holes along three transects produced an average ice thickness of 8.0 ± 2.3 m and a maximum ice thickness of 15.7 m. The reader is referred to Johnston (2011-a) for more information about this floe.

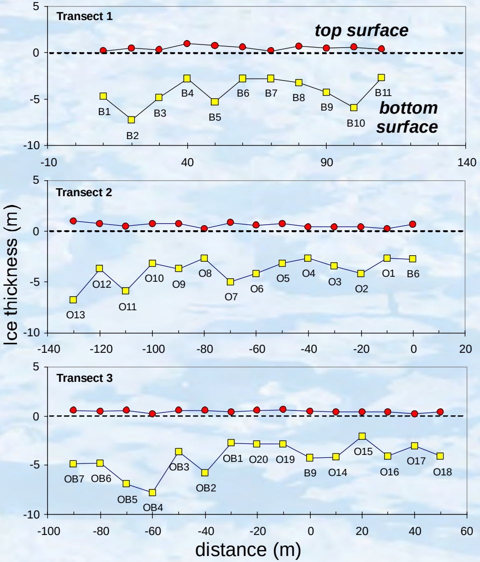
These are just a few of the floes that have been sampled over the years. They are used here to illustrate two important points:

(1) very thick multi-year ice continues to be generated in the Arctic, largely due to mechanical action

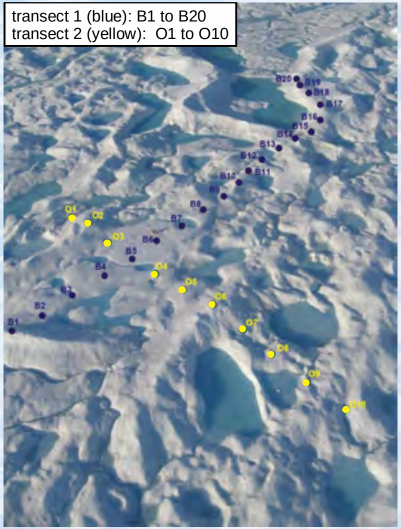
(2) the top ice surface does not necessarily reflect the ice thickness, ice quality or the roughness of the floe's underside.

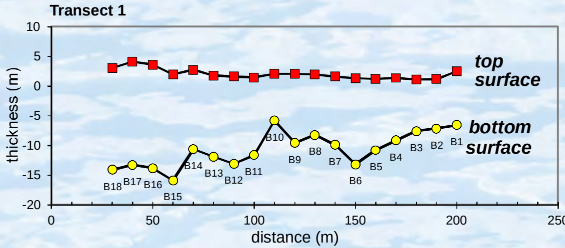


Multi-year ice floe sampled in August. Given the deteriorated looking surface of this floe, it was surprising to find thicknesses of up to 8 m (*far right*).

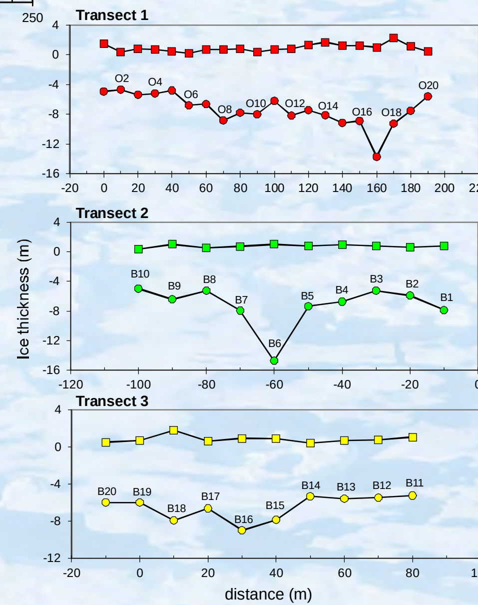


Detailed Thickness Measurements of Old Ice





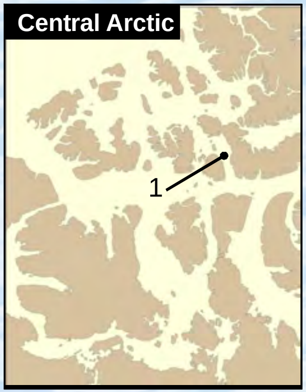
Highly deformed multi-year ice floe sampled in August (*left*), where the maximum thickness along a single transect was 23 m (*top*), combining sail height and keel depth. Even the level-looking portions of this floe had a rough underside.



Multi-year ice floe sampled in the Beaufort Sea in August (*near right*) was up to 15.7 m thick along three transects (*far right*). The top surface of the of the floe did not reflect its rough underside. Borehole strength profiles were conducted at holes H1 and H2, and were included in *Seasonal Trends in the Strength of Landfast and Drifting Floes*.

Multi-year ice

24 May
75°17'N, 93°13'W



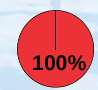
Key identifiers:

- ☐ freeboard
- ☐ floe size
- ☑ floe shape
- ☐ colour
- ☐ ponding/drainage
- ☑ ice thickness
- ☐ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☑ other (see comments)

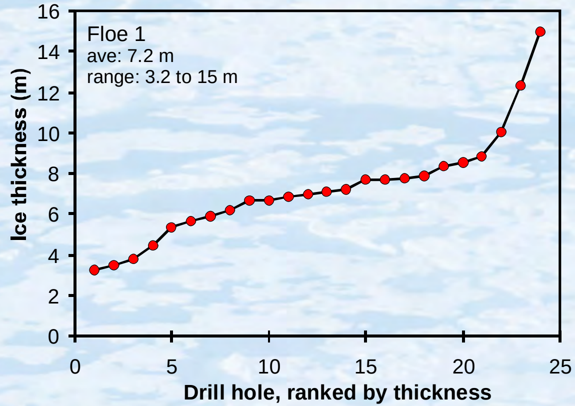
Confidence that it's multi-year ice: 100%

Floe size: 200 m

Average drill hole thickness: 7.2 m

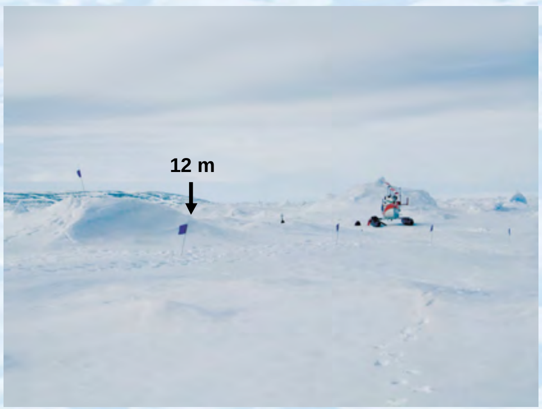


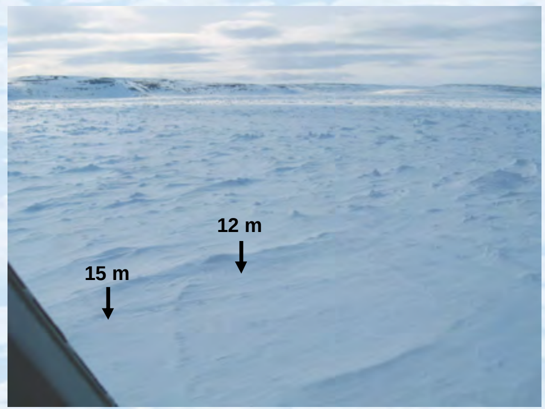
Floe 1 was an aggregate floe selected from RADARSAT imagery before arriving in the field (see section on *Satellite Observations,* observation #1). When viewed from the air, the upturned edges of this 200 m diameter floe confirmed that it was very likely a multi-year floe. In fact, the floe's outline could be easily seen from the air, despite the up to 72 cm of snow that covered it. A relatively flat region of ice was selected for sampling. Drill hole measurements made along three transects indicated an average thickness of 7.2 m *(following page)*, confirming it was indeed multi-year ice.



Multi-year ice

24 May
75°17'N, 93°13'W





A total of 24 holes were drilled along three transects, at a spacing of 10 m. The average thickness of the floe was 7.2 m.

Thicknesses ranged from 3.2 to 15 m. The thickest ice (15 m) occurred in what appeared to be a level area of ice, but actually may have been near the floe's upturned perimeter *(near left)*.

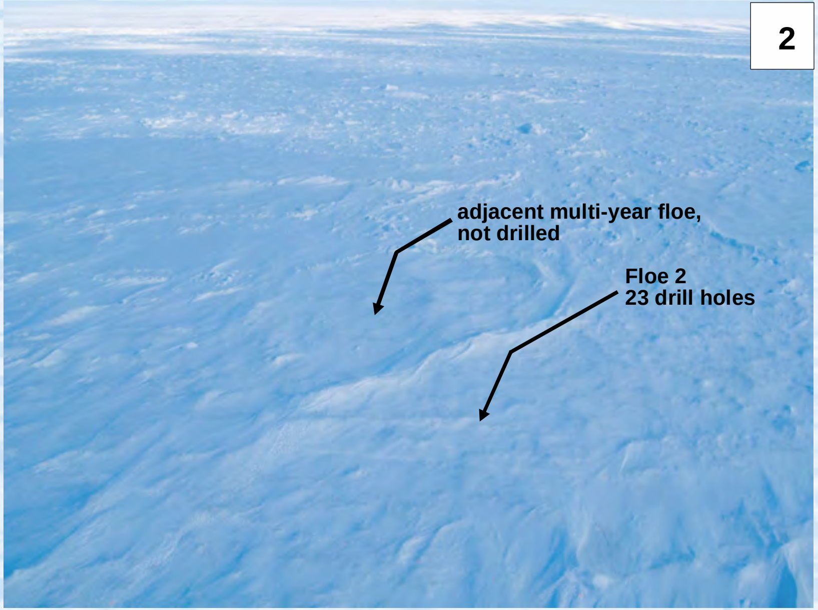
The second thickest ice (12 m) was measured near the 1.5 m high hummock shown in the photo (*far left*). The hummock in that photo was not drilled, due to time constraints.

Multi-year ice

27 May
75°32'N, 95°50'W

Key identifiers:

- ☐ freeboard
- ☐ floe size
- ☑ floe shape
- ☐ colour
- ☐ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☑ other (see comments)



Confidence that it's multi-year ice: 100%

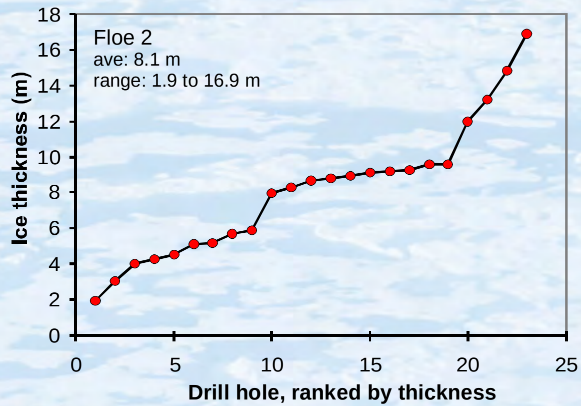
Floe size: 50 m x 250 m

Average drill hole thickness: 8.1 m

100%

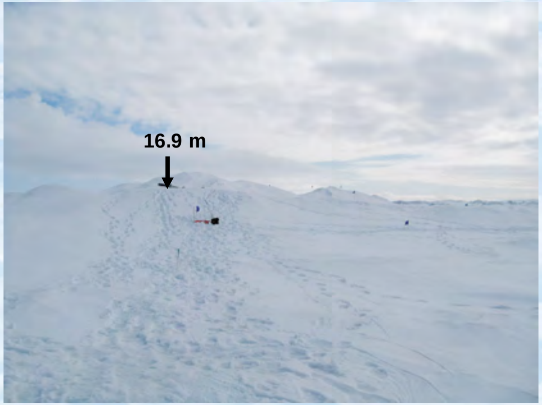
Floe 2 was located in an area of multi-year ice that satellite imagery showed existed between Cornwallis Island and Little Cornwallis Island (see *Satellite Observations*, observation #2). This floe appeared quite thick, had rounded edges and was estimated to be about 250 m across. A prominent 3.5 m high hummock separated Floe 2 from another multi-year floe (other side of hummock). A total of 23 drill holes were made along three transects. The snow was up to 1.15 m deep at some of those drill holes.

2



Multi-year ice

27 May
75°32'N, 95°50'W



Drill hole measurements were made in areas ranging from small hillocks *(top left)* to the face of a 3.5 m high hummock *(bottom left)*. Although the crest of the hummock was not drilled, it would have been thicker than the 16.9 m thick ice that was measured 10 m away *(arrow in bottom left photo)*.

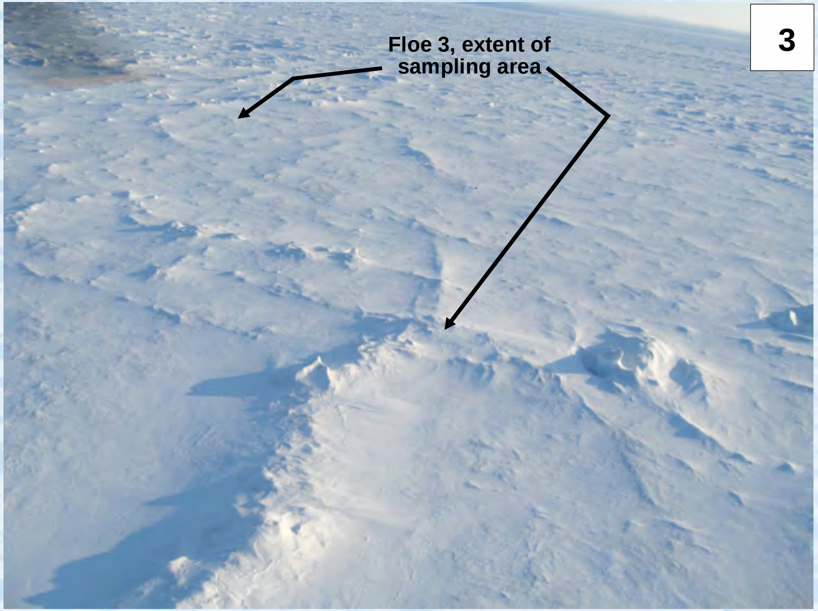
The photo *(near left)* shows the surface of the 150 m diameter multi-year floe adjacent to Floe 2 (other side of hummock). No drill holes were made on this floe, but its surface topography suggested it was also very thick.

Multi-year ice

30 May
75°41'N, 93°41'W

Key identifiers:

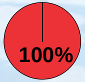
- ☐ freeboard
- ☐ floe size
- ☑ floe shape
- ☐ colour
- ☐ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☑ other (see comments)



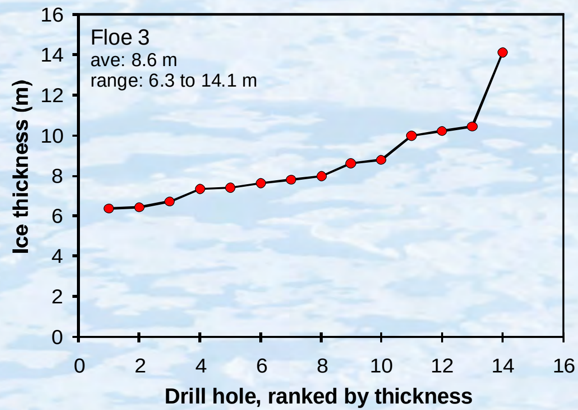
Confidence that it's multi-year ice: 100%

Floe size: 300 m

Average drill hole thickness: 8.6 m

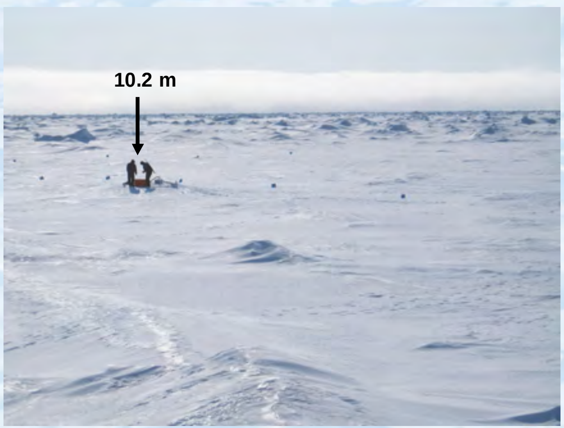


Floe 3 was positioned at the edge of the multi-year pack that extended into Wellington Channel, along northern Cornwallis Island (see *Satellite Observations,* observation #3). The photograph above shows the hummocked area where Floe 3 joined another multi-year floe of similar shape and appearance. Both floes were estimated to be about 300 m in diameter. A total of 14 drill holes were made in the sampling area shown above. The snow cover on Floe 3 exceeded one metre, in places.



Multi-year ice

30 May
75°41'N, 93°41'W



The 14 drill holes on Floe 3 resulted in thicknesses from 6.3 to 14.1 m. The thickest ice was measured about 25 m from the crest of a 2.5 m high hummock *(top left)*. Ice along the hummock's crest was not drilled.

Floe 3 was equipped with a 10 m long temperature chain to monitor changes in temperature as it drifted throughout the summer of 2008 (Johnston, 2009). The temperature chain was installed in a raised area of ice that was 10.2 m thick *(bottom left)*. The fast ice broke-up in early July, releasing the floe to drift through the Archipelago until late September. The last data were received on 20 September, from M'Clintock Channel (see *Migration of Old Ice in Canadian Archipelago,* Floe 4).

Multi-year ice

12 August
78°38’N, 73°33’W

Key identifiers:

- [x] freeboard
- [x] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

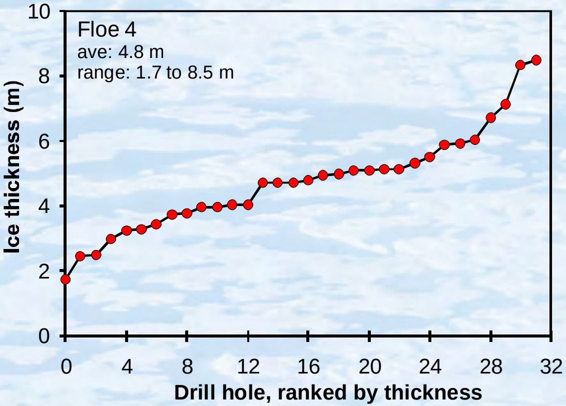
Confidence that it’s multi-year ice: 100%

Floe size: 4 km

Average thickness of relatively level ice: 4.8 m

Floe 4 was sampled in Smith Sound on 12 August. The floe was about 4 km across. A maze of melt ponds covered its surface, providing an excellent example of what is termed “well-established drainage patterns”. This floe was identified as multi-year ice from the air using the Key Identifiers listed above. Portions of the floe were extremely level, but it also had very rough, hummocked areas of ice, as shown by the photos on the following page. Drill hole measurements *(following page)* confirmed that this was a multi-year floe.

4



Multi-year ice

12 August
78°38'N, 73°33'W

Detailed thickness measurements were made at 30 drill holes along 3 transects in a relatively level area of ice. The sampling area was about 100 m across by 100 m wide. Individual holes along a transect were marked by flags *(above left),* separated by 10 m.

The ice ranged from 1.7 m thick (near a pond) to 8.5 m thick (near a ridge). The average thickness of the 30 drill holes was 4.8 m. The maximum measured ice freeboard was 0.90 m. Several of the shallow melt ponds in which drill holes were made had completely drained by the end of the day.

Measurements were not made in the rough areas of ice *(bottom left).* The ice in those areas would have been much thicker than the 8.5 m maximum thickness from the drill holes.

Multi-year ice

13 August
79°50'N, 70°38'W

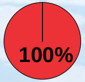
Key identifiers:

- ☑ freeboard
- ☑ floe size
- ☐ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☑ other (see comments)

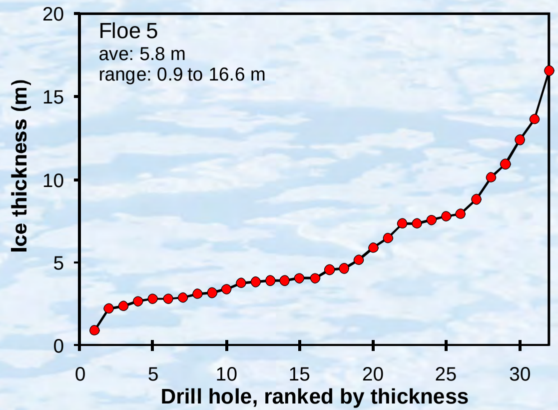
Confidence that it's multi-year ice: 100%

Floe size: 5 km

Average thickness of relatively level ice: 5.8 m



Floe 5 was sampled in the north part of Kane Basin on 13 August. The floe was about 5 km across. The area of the floe selected for sampling had a relatively young looking ridge dividing two areas of level ice. When standing on the ridge, it became apparent that the ice to the west of the ridge had considerably more freeboard than the ice to the east, suggesting that the ridge formed *(see following page)* when two floes of different thickness were driven against one another.



Multi-year ice

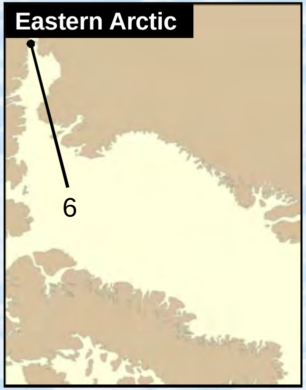
13 August
79°50'N, 70°38'W

The maximum thickness on this floe (16.6 m) was measured along the crest of the ridge that separated two areas of relatively level ice. Ice thicknesses at four drill holes along the ridge crest ranged from 7.9 to 13.7 m.

The floe on one side of the ridge had thicknesses from 0.90 to 5.85 m, and an average freeboard of 0.50 m. The floe on the other side of the ridge had thicknesses from 6.4 to 8.8 m, and an average freeboard of about 1.0 m. Thickness measurements were combined in the graph above.

Multi-year ice

20 August
80°37’N, 68°07’W



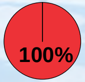
Key identifiers:

- [x] freeboard
- [x] floe size
- [x] floe shape
- [ ] colour
- [ ] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

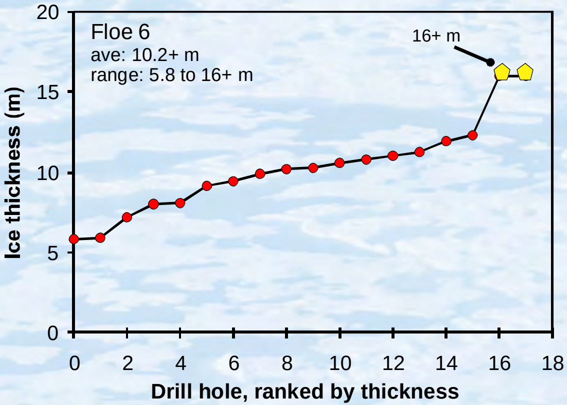
Confidence that it’s multi-year ice: 100%

Floe size: 500 m

Average thickness of relatively level ice: 10.2 m+

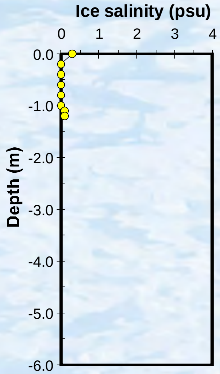


Floe 6 was sampled in Nares Strait on 20 August. The floe was only about 500 m in diameter, but its prominent ridge promised very thick ice. This multi-year ice floe was not blue and its drainage was not well established. The average thickness of this floe was more than 10.4 m *(see following page)*. Ice salinity measurements confirmed that it was multi-year ice.



Multi-year ice

20 August
80°37'N, 68°07'W



A total of 19 holes were drilled on this floe along two transects. The crest of the 4 m high hummock was not drilled because it would have easily consumed the 16 m of drill rod available.

Eighteen holes were drilled in a relatively 'level' area on one side of the hummock, where the ice was 5.8 to more than 16 m thick. One hole was drilled on the opposite side of the hummock, where the ice was 9.9 m thick. The thickest ice was measured about 40 to 50 m from the hummock's crest, where 16 m of drill rod could not penetrate the full thickness of ice. The average thickness of Floe 6 was more than 10.2 m (19 holes).

The salinity profile of the uppermost metre of ice confirmed that the floe was multi-year ice. Only the uppermost metre was able to be retrieved from the ice because the core barrel became stuck soon after coring began. Many hours and much ingenuity were needed to extract the core barrel from the ice.

Multi-year ice

22 August
80°40’N, 68°23’W

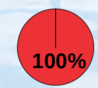
Key identifiers:

- [ ] freeboard
- [ ] floe size
- [ ] floe shape
- [ ] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

Confidence that it’s multi-year ice: 100%

Floe size: 500 m x 200 m

Average thickness of relatively level ice: 5.2 m

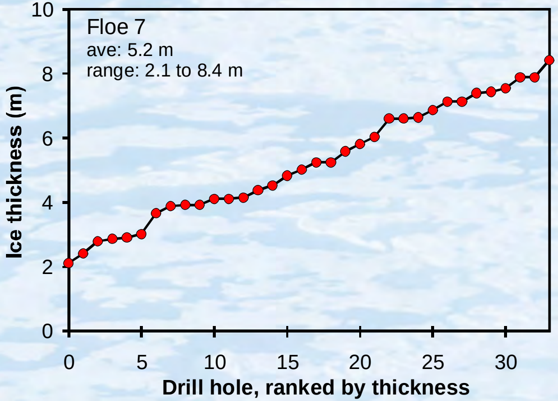


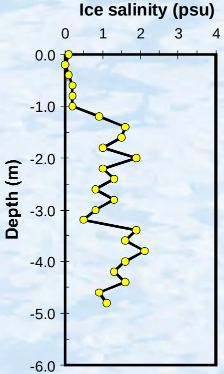
Floe 7 was visited on 22 August, drifting south along the east coast of Ellesmere Island. The floe was only 500 m long and 200 m wide, but it was the largest floe in this area of drifting pack ice. The floe’s surface had the characteristic undulations of multi-year ice and a well-established drainage network. Salinity, temperature and strength measurements confirmed that it was multi-year ice.

7

Multi-year ice

22 August
80°40’N, 68°23’W



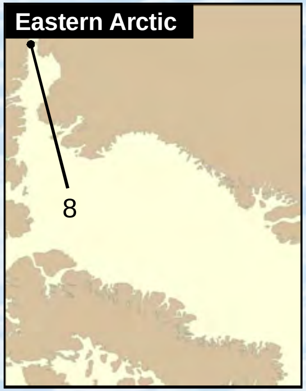


A total of 30 holes were drilled on Floe 7 along five transects. Thicknesses ranged from 2.12 to 8.40 m. The freeboard of the ice varied from 0.15 to 1.86 m.

Temperatures (not shown) and salinities *(above right)* were obtained from a 5.0 m long core near one of the drill holes. The top metre of ice was the warmest (-1.1°C), although temperatures throughout most of the ice ranged from -3.0 to -3.5°C. Salinities varied from 0 to 2.1 psu, with the lowest salinities being measured in the uppermost metre of ice.

Multi-year ice

24 August
80°36’N, 68°04’W



Key identifiers:

- [x] freeboard
- [x] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

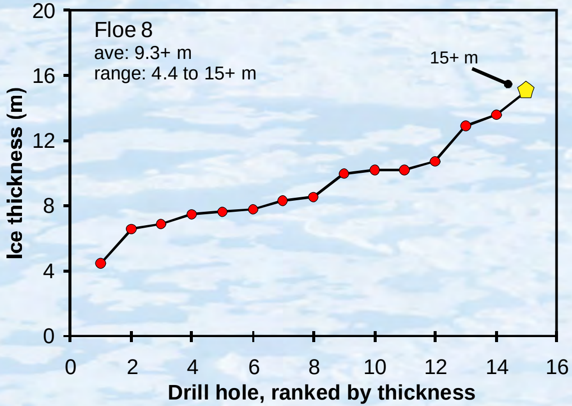
Confidence that it’s multi-year ice: 100%

Floe size: 3 km

Average thickness of relatively level ice: 9.3 m+

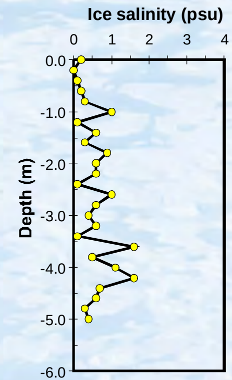
Floe 8 was extensively hummocked, had a dirty, dimpled looking surface and extensive drainage patterns. The floe appeared substantial from the helicopter, but it was even more massive once on the ice surface. Property measurements were made in a 3.5 m high hummock near the centre of the floe. Hummocks on the other side of the floe were considerably larger than that.   This floe was instrumented with a satellite tracking beacon, as discussed in *Migration of Old Ice in the Eastern Canadian Arctic,* Floe 1. Salinity, temperature and strength measurements confirmed this was multi-year ice.

8



Multi-year ice

24 August
80°36'N, 68°04'W

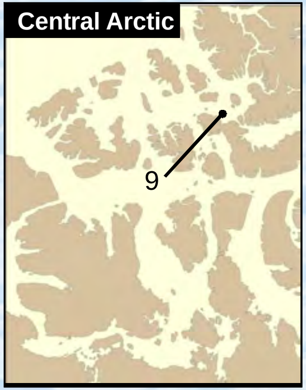


Twenty flags were laid along three transects but, due to the difficulty of drilling and time constraints, measurements were made at only 14 drill holes along two transects. Both transects crossed over the 3.5 m high hummock. Thicknesses of the drill holes ranged from 4.4 m to more than 15 m. The average thickness of the 14 drill holes was more than 9.3 m. The freeboard varied from -0.20 (melt pond) to 3.45 m (ridge crest).

A 5.0 m core was removed for temperature and salinity measurements. The temperature of the hummocked ice was -0.9°C at the top ice surface and steadily decreased to -5.3°C at a depth of 5.0 m (not shown). The salinity of the hummock ranged from 0 to 1.6 psu, as shown above.

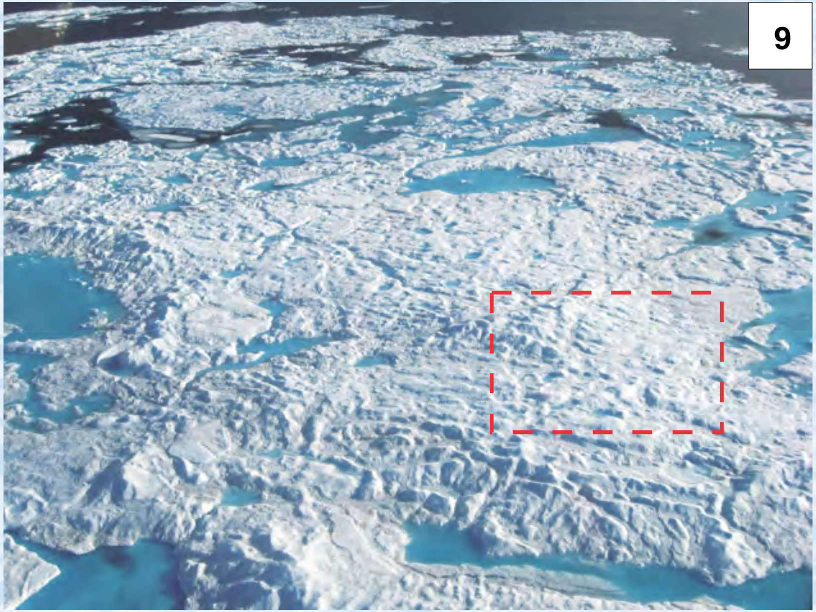
Multi-year ice

29 August
76°56'N, 91°41'W



Key identifiers:

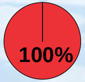
- ☑ freeboard
- ☑ floe size
- ☐ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☑ other (see comments)



Confidence that it's multi-year ice: 100%

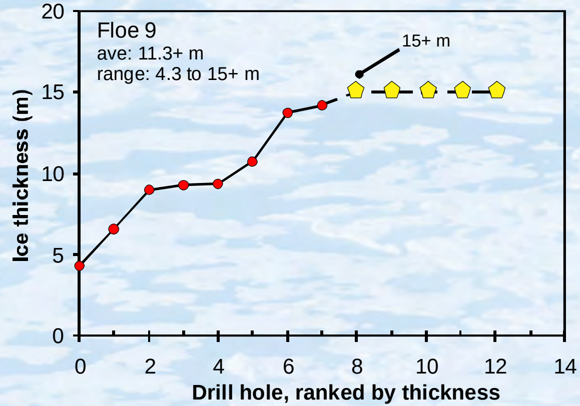
Floe size: 5 km

Average thickness of relatively level ice: 11.3 m+



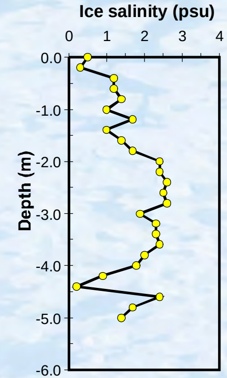
Floe 9 was sampled in Norwegian Bay on 29 August. This floe had the classic signs of multi-year ice: it appeared very thick, its surface was dirty and hummocked, and it had extensive drainage patterns. Two ice thickness transects were made on this floe in the area shown above (dotted line). The first transect extended between two hummocked areas, and the second transect was made where the ice sloped down towards a melt pond.

9



Multi-year ice

29 August
76°56'N, 91°41'W

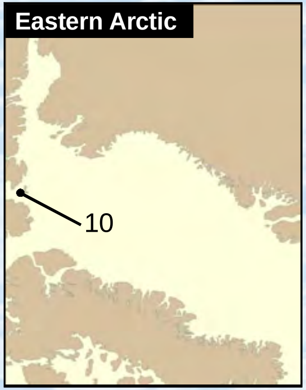


A total of 12 holes were drilled on this floe. Ice thicknesses ranged from 4.3 m (near a melt pond) to more than 15 m, which was the limit of our drill rods. Four of the drill holes were thicker than 15 m. The freeboard of this floe ranged from -0.05 m (melt pond) to 2.97 m. The average thickness of the 12 drill holes was more than 11.3 m.

Temperature and salinity measurements were obtained to a depth of 5.40 m. The temperature was -1.3°C in the top ice and decreased to -6.9°C at a depth of 5.40 m (not shown). The salinity of the ice ranged from 0.2 to 2.6 psu, as shown above.

Multi-year ice

31 August
75°50'N, 80°05'W



Key identifiers:

- ☐ freeboard
- ☑ floe size
- ☐ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☐ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☑ other (see comments)

Confidence that it's multi-year ice: 100%

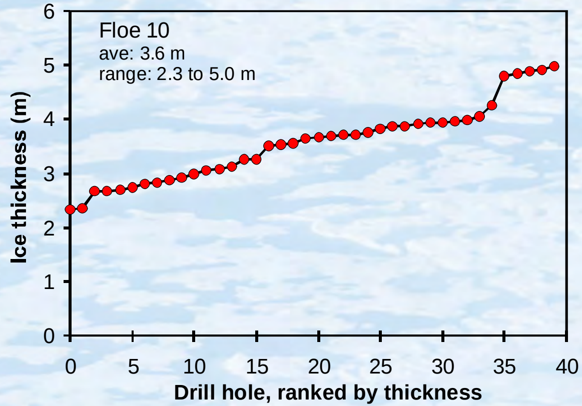
Floe size: 150 x 200 m

Average thickness of relatively level ice: 3.6 m

100%

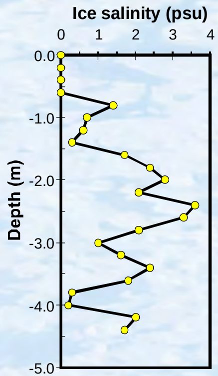
Floe 10 was one of the few floes in this area of Lady Anne Strait that was large enough to sample. The floe was only about 200 m across and drifted at an average rate of 2.1 km/hr during the sampling period. Other floes jostled against this floe as it drifted east in Lady Anne Strait. This floe was classified as multi-year ice because it was hummocked, its melt ponds were blue and it had extensive drainage patterns. Property measurements confirmed the floe was multi-year ice *(see following page)*. People on the floe are circled in red (*above*).

10



Multi-year ice

31 August
75°50'N, 80°05'W



A total of 38 holes were drilled on this floe along four transects. The thickness of the floe ranged from 2.34 to 4.97 m. The freeboard of the ice varied from -0.37 m (melt pond) to 1.15 m. Ice thicknesses at the edge of the melt pond (*top left*) ranged from 2.34 to 4.25 m and pond depths from 25 to 37 cm. The average thickness of the ice was 3.6 m (38 drill holes).

A core from the full-thickness of ice was obtained. The ice was warmest at its top surface (-0.9°C) and bottom surface (-2.9°C), and was coldest at a depth of 2.60 m (-3.3°C, not shown). The salinity of the ice ranged from 0 to 3.3 psu, as shown above.

Ship-based Observations of Old Ice

Participating Ships

The 217 ship-based observations collected during this three year program provide the basis for much of this Guide. These observations provide first-hand information about the types of old ice that ships and structures will encounter in the Arctic and sub-Arctic. The observations were made by highly trained Ice Service Specialists (ISS) and Commanding Officers acting in the capacity of ice observers on the ten ships listed below.

Most of the observations were made along the Northwest Passage or other shipping routes, from mid-July to October, as ships transited ice-covered waters delivering cargo to communities, assisting vessels in distress, supporting scientific research or touring the Arctic.

To keep the Guide to a reasonable number of pages, only a portion of the 217 observations have been included here. These observations were carefully selected to cover the broad spectrum of old ice in the Arctic and sub-Arctic, and the adverse conditions under which it must be reliably identified.

	Vessel type	Length (m)	Observations made over 3 years
CCGS *Louis S. St. Laurent*	**Heavy Arctic**	**111.5**	**35**
CCGS *Terry Fox*	**Heavy Arctic**	**88**	**20**
CCGC *Amundsen*	**Medium Arctic**	**98.2**	**40**
CCGS *Des Groseilliers*	**Medium Arctic**	**98.2**	**9**
CCGS *Henry Larsen*	**Medium Arctic**	**99.8**	**19**
CCGS *Pierre Radisson*	**Medium Arctic**	**99.8**	**18**
CCGS *Sir Wilfrid Laurier*	**Program/Light**	**83**	**42**
USCGC *Healy*	**Heavy Arctic**	**128**	**5**
I.B. Oden	**Heavy Arctic**	**108**	**20**
M.V. Bremen	**Cruise ship (ice strengthened)**	**111**	**9**
	Total observations:		**217**

CCGS *Louis S. St-Laurent*

CCGS *Henry Larsen*

USCGC *Healy*

Observation Booklet: Documenting Ice Features

Each year, participants were given a booklet in which to record their observations. They were asked to complete a two-page questionnaire about each ice feature. The questionnaire attempted to capture the thought process that experienced personnel use to determine whether an ice feature classifies as first-year, second-year or multi-year ice. Questions were divided into the following four sections:

General information: The observer was asked to record the date and time that the feature was encountered, the latitude and longitude of the ice feature and whether the feature was observed from the ship's bridge or from a helicopter (see *Aerial Observations*). A digital camera was used to photograph the old ice feature described in each observation.

Detailed information: What were the most useful Key Identifiers for deciding whether the feature classified as first-year, second-year or multi-year ice? Was the feature easy to identify and what sort of confidence did the observer have in his/her decision? Participants answered these questions and estimated the floe size, freeboard and ice thickness. A comment box was included for elaborating about why the feature was (or was not) remarkable.

Ground-truth information: Was a satellite image available for the observation and, if so, could the ice feature be identified in the imagery? If satellite imagery was available, the participants were asked to display the image on the computer monitor, mark the position of the ice feature on the image (if the floe was identifiable) and note the ship's location. Then, the observer took a picture of the monitor. That picture was used to locate the feature in the satellite image, after the fact. Having a photograph of the computer monitor was essential for determining which floe corresponded to which observation because satellite overpasses and observations seldom coincided.

Ship response: The observer was asked to comment on whether the ship impacted the floe, at what speed and whether the ship slowed as it penetrated the floe. They also noted if backing and ramming was required to penetrate the old ice floe, and whether the floe split.

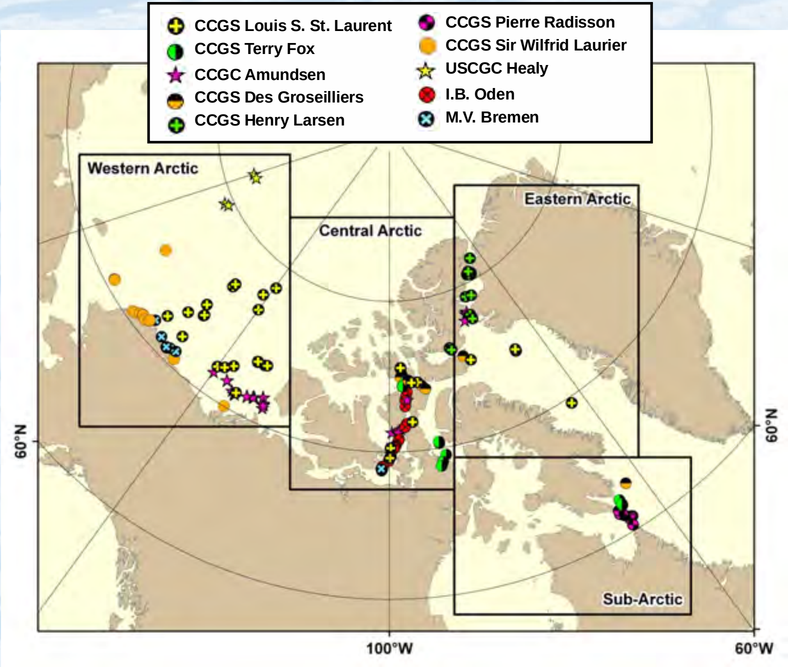
The information in the following pages was reproduced from the observation booklets. All ship-based observations in this Guide were reviewed by the authors, and by one of the most experienced Ice Service Specialists (ISS). The review process ensured that observations were consistent, which is important because they were made by many different people. For the most part, the review process confirmed the original observations. In some cases however, adjustments were made to the confidence level(s) in deciding whether the feature classified as first-year, second-year or multi-year ice. The information in subsequent observations was derived from the comments of the initial observer, the reviewer and sometimes the authors.

Subdividing Observations into Four Regions

The 217 ship-based observations were arbitrarily divided into four regions: Western Arctic, Central Canadian Arctic, Eastern Canadian Arctic and sub-Arctic, as shown in the map below. The number of observations made in each region depended upon the ice conditions, the amount of time that the ship spent in that region and the time available for the observer to answer the two-page questionnaire.

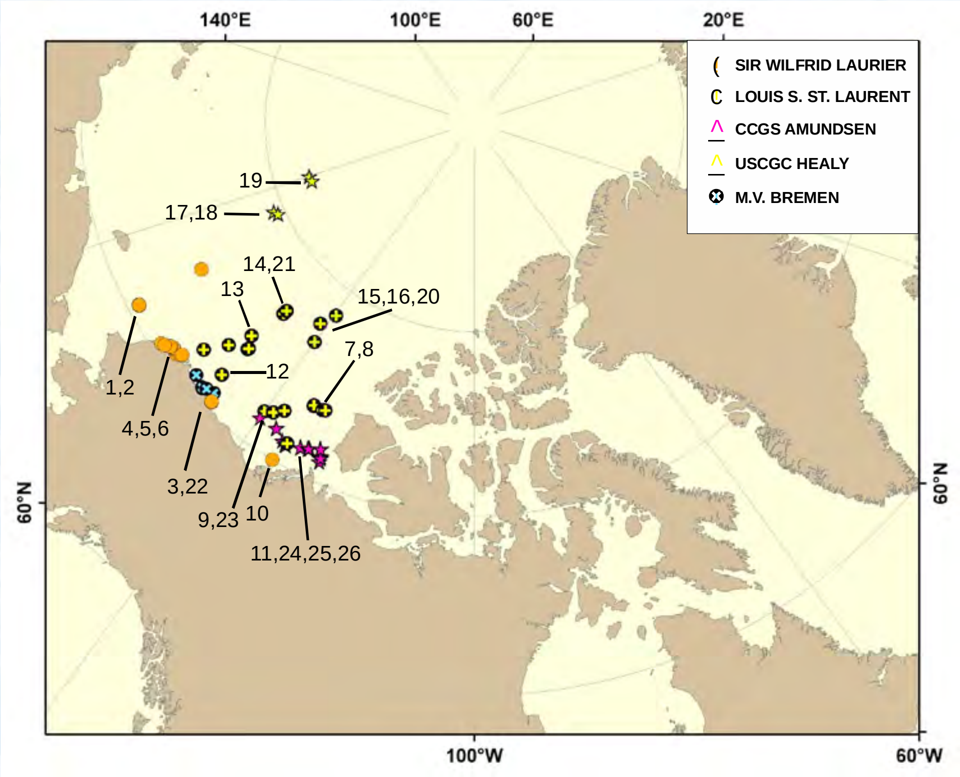
Many observations were made in the western Arctic, where the ship supported scientific research. A considerable number of observations of old ice were also made in the Central Arctic, as ships travelled east-to-west through the Northwest Passage in mid-summer. More than 70 of the 217 observations are included in following pages.

When perusing subsequent pages, the reader is asked to keep in mind that ships follow the path of least resistance when transiting ice-covered waters. **Ships avoid very thick multi-year ice, whenever possible**. Because of that, the ship-based observations in this Guide may be biased towards the thinner types of multi-year ice that are close to the ship, rather than the more extreme ice old ice features (that may be more distant). *On-ice Thickness Measurements* discuss some of the more extreme types of multi-year ice populating the Arctic.



Map showing the 217 ship-based observations collected during the three year study (*right*). Observations were divided into four arbitrarily selected regions: Western Arctic, Central (Canadian) Arctic, Eastern (Canadian) Arctic and Sub-Arctic.

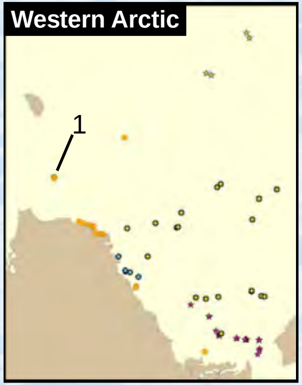
Western Arctic



Multi-year ice

19 July

70°38’N, 168°12’W



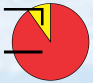
Key identifiers:

- [x] freeboard
- [ ] floe size
- [x] floe shape
- [x] colour
- [ ] ponding/drainage
- [ ] ice thickness
- [ ] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

1



Confidence that it’s multi-year ice: 90%

Floe size: 90 m

Est. average thickness: 2 to 3 m

We came upon this floe floating by itself. It is different than the surrounding ice. First of all, the floe is very intact, compared to the extensively decayed first-year ice around it. It has very blue melt ponds and the years of bumping against other floes has rounded its edges. This feature floats higher, has greater surface topography and is more weathered looking than the surrounding ice. All of these things made it possible for us to identify this feature as multi-year ice. This observation was made from the ship’s bridge, in foggy conditions, while we were about 5 m from the floe.

2

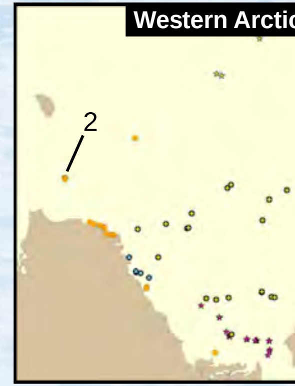
Multi-year ice

19 July

70°37’N, 168°08’W

Key identifiers:

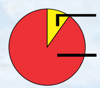
- [x] freeboard
- [ ] floe size
- [x] floe shape
- [x] colour
- [x] ponding/drainage
- [ ] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)



Confidence that it’s multi-year ice: 90%

Floe size: 120 m

Est. average thickness: 2 to 3 m



SYI (10%)

MYI (90%)

Ship response:

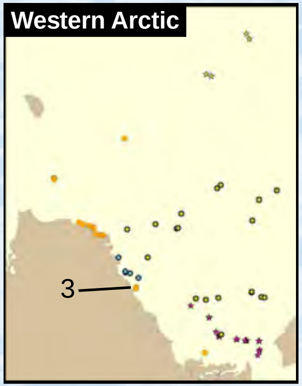
- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

This multi-year ice floe is rougher than the surrounding ice and its surface is weathered. Its ponds are very blue and some drainage pattern is evident. The ice floats higher than the surrounding ice and its edges are rounder than first-year ice. This multi-year ice floe was observed from the ship's bridge at a distance of about 10 m, in foggy conditions.

Second-year ice

23 July

70°33’N, 148°05’W

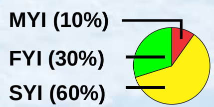


Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [ ] colour
- [ ] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

Ship response:

- [x] Ship impacted ice feature
- [ ] Backing and ramming was required
- [x] Floe splitting occurred



Confidence that it’s second-year ice: 60%

Floe size: 50 x 100 m

Est. average thickness: ?

The floe isn’t blue anywhere, but I want to say that it is old ice because it has a hummocked surface, extreme freeboard and it fractured in a straight line. However, I can't be sure. It is probably second-year ice because its colour is not quite right for multi-year ice. This could also be a remnant of a first-year ice hummock field, which often occur here, right along the Alaskan coast.

4

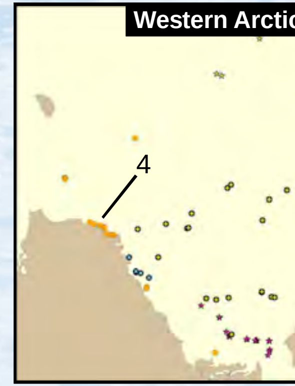
Second-year ice

25 July

70°57'N, 159°01'W

Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [ ] colour
- [x] ponding/drainage
- [ ] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)



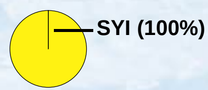
Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

Confidence that it's second-year ice: 100%

Floe size: 100 m

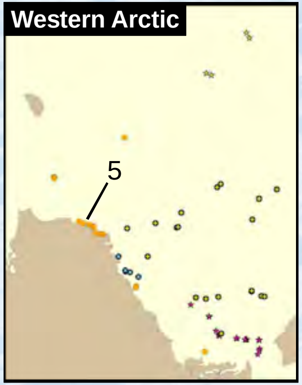
Est. average thickness: 3 m



This floe is definitely second-year ice. It is less decayed than the first-year ice around it. It has a more advanced stage of decay than the surrounding multi-year floes in the area. Its hummocks are also less eroded than the surface features on multi-year ice.

Second-year ice

25 July
70°57’N, 158°51’W



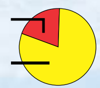
Key identifiers:

- [x] freeboard
- [ ] floe size
- [x] floe shape
- [x] colour
- [x] ponding/drainage
- [ ] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)

Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

MYI (20%)
SYI (80%)



Confidence that it’s second-year ice: 80%
Floe size: 75 m
Est. average thickness: 3 m

This floe is most likely second-year ice because its ponds are not as interconnected as ponds on multi-year ice. Also, the floe is in a more advanced stage of decay than the surrounding multi-year ice floes, but less decayed than the first-year ice in this area. The angular ridge is fresh - which is another sign that this floe is probably second-year ice. That said, it may be a multi-year floe, but I don’t really think so.

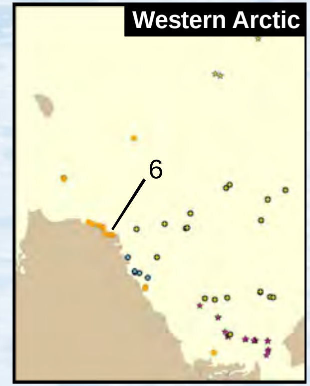
Second-year ice

26 July

71°01'N, 157°23'W

Key identifiers:

- ☑ freeboard
- ☐ floe size
- ☐ floe shape
- ☐ colour
- ☑ ponding/drainage
- ☐ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☑ other (see comments)



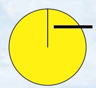
Ship response:

- ☑ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☑ Floe splitting occurred

Confidence that it's second-year ice: 100%

Floe size: 75 m

Est. average thickness: 2.5 m

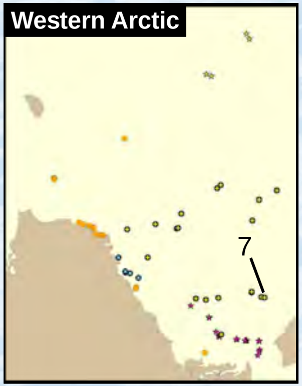


Foggy conditions made classifying this feature from the bridge difficult. The problem was deciding whether it was thick first-year ice or second-year ice. From the bridge, its white colour and separate ponds made me think first-year ice. But it can't be first-year ice because its freeboard (estimated as 15 cm) is too high for this time of year and it has weathered ridges. When the helicopter flew over the area the following day in clear conditions, the floe's drainage patterns, interconnected ponds and surface topography told us it was definitely second-year ice.

Multi-year ice

29 July

73°48’N, 130°24’W



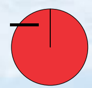
Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [ ] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

MYI (100%)



Confidence that it’s multi-year ice: 100%

Floe size: 125 m

Est. average thickness: 2.5 m

Only old ice is present in the area at this time of year (mid-summer). This is an isolated multi-year ice floe surrounded by open water. The floe is easily identified as multi-year ice because it has significant freeboard (estimated as 50 cm), the colour of the ice and ponds is very blue, it has weathered ridges, and it has well-established drainage patterns.

Multi-year ice

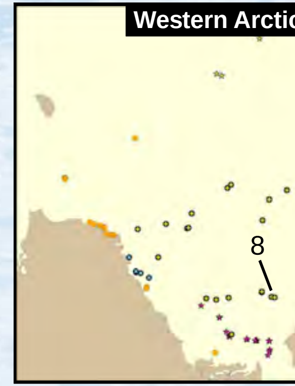
30 July

73°45’N, 130°56’W

8

Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [ ] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)



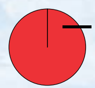
Ship response:

- [x] Ship impacted ice feature (see comments)
- [ ] Backing and ramming was required
- [x] Floe splitting occurred

Confidence that it’s multi-year ice: 100%

Floe size: several kilometres

Est. average thickness: 5 m

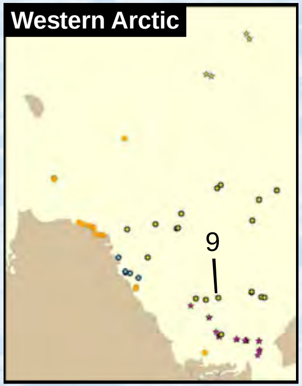


This giant multi-year floe is several kilometres in diameter, although foggy conditions make it difficult to tell exactly how far it extends. The ice freeboard is higher than the surrounding ice, the ice and ponds are bluer in colour, the ridges are weathered and it has some drainage pattern. The floe split when the ship tried to hold fast in it and the crack propagated in a straight line, which also tells me that it is multi-year ice.

Second-year ice

31 July

72°39’N, 137°05’W

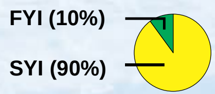


Key identifiers:

- [ ] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred



Confidence that it’s second-year ice: 90%

Floe size: 100 m

Est. average thickness: 1 m

The colour, weathered ridges and the lack of a fully developed drainage pattern tell me this is very likely a second-year floe. It is an aggregate of several loosely connected floes that are barely holding together. The thickness of the floe (estimated as 1 m) at this particular time and location also make me think of second-year ice. The rubbled region of ice in the picture is the only thing that might indicate this is a first-year floe: rubbled second-year ice would be more difficult to create than rubbled first-year ice. But, then it is difficult to tell.

10

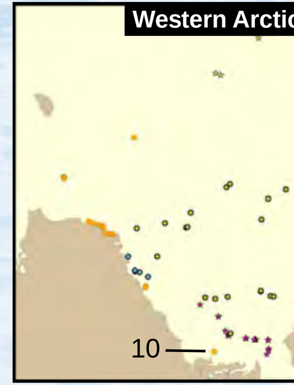
Multi-year ice

31 July

70°01’N, 134°22’W

Key identifiers:

- ☑ freeboard
- ☐ floe size
- ☐ floe shape
- ☑ colour
- ☐ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☑ other (see comments)



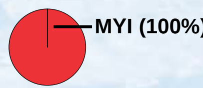
Ship response:

- ☐ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☐ Floe splitting occurred

Confidence that it’s multi-year ice: 100%

Floe size: 250 x 800 m

Est. average thickness: 10 m+

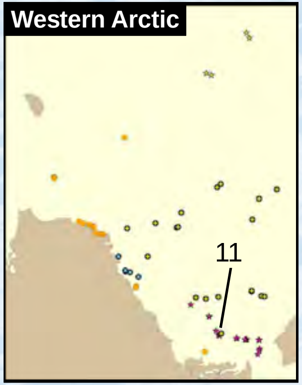


This floe is easily identified as multi-year ice because of its extremely high freeboard (5 to 6 m in places). Its thickness easily exceeds 10 m. The colour of the ice and its hummocked surface topography are two other factors that positively identify this as multi-year ice. From experience, the location and time of year are also good indicators that it is multi-year ice. The ship nudged this ice floe for the purposes of engineering tests. Several of the ship’s crew walked onto the floe, as pictured above, providing a scale for its sizeable hummocks.

Multi-year ice

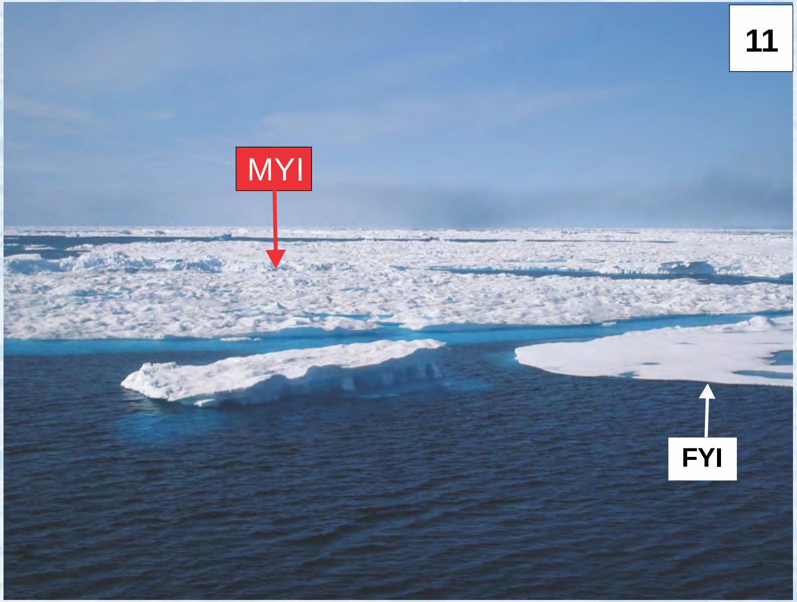
4 August

71°12'N, 133°38'W



Key identifiers:

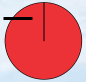
- ☑ freeboard
- ☑ floe size
- ☐ floe shape
- ☐ colour
- ☐ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☐ other (see comments)



Ship response:

- ☐ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☐ Floe splitting occurred

MYI (100%)



Confidence that it's multi-year ice: 100%

Floe size: 300 m

Est. average thickness: 2 m

The weathered ridges and hummocks on this floe told me it was definitely multi-year ice. The floe was positively identified as multi-year ice from a distance of 200 m. Notice the dramatically different appearance of the multi-year ice (centre of photo) and the first-year ice (foreground, right). The freeboard of the first-year ice was used to estimate the freeboard of the multi-year ice floe (30 to 50 cm).

12

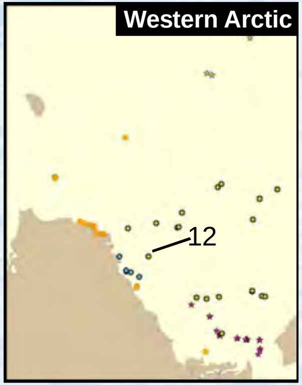
Second-year ice

7 August

72°00'N, 150°00'W

Key identifiers:

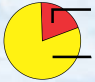
- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [ ] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)



Confidence that it's second-year ice: 80%

Floe size: 50 m

Est. average thickness: 4 m



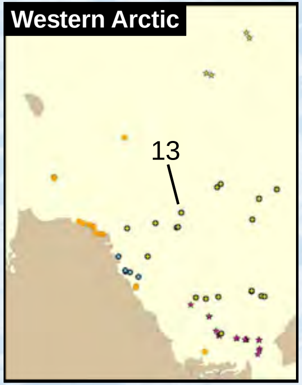
Ship response:

- [x] Ship impacted ice feature
- [ ] Backing and ramming was required
- [x] Floe splitting occurred

This second-year ice floe is distinct from first-year ice because it is much thicker. Even though the bare ice is very blue (like multi-year ice), it is probably second-year ice because its hummocks have relatively steep sides. The not-too-weathered hummocks and the ponds/puddles also indicate second-year ice. This floe looks thick, but the ship barely decreased in speed as it penetrated the floe. The ship's easy passage though the floe, even though it was only 50 m across, is what most convinced me that it is second-year ice.

Multi-year ice

8 August
74°40'N, 151°22'W

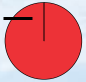


Key identifiers:

- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☐ colour
- ☐ ponding/drainage
- ☐ ice thickness
- ☐ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☑ other (see comments)

Ship response:

- ☑ Ship impacted ice feature (see comments)
- ☐ Backing and ramming was required
- ☑ Floe splitting occurred



Confidence that it's multi-year ice: 100%

Floe size: 150 m

Est. average thickness: 2 m

This floe is definitely multi-year ice because we installed equipment on this same floe two years ago (2005), when it was about 4 m thick. When we visited this floe again in 2007, its thickness was estimated to be about 2 m (as seen above). That said, the floe is deceptive because it looks like second-year ice, and it is only about 0.50 m thick in some places. But we know this is multi-year ice because we have been tracking this floe for two years. The ship split the ice when it "parked" in the floe in order to retrieve the mooring equipment.

14

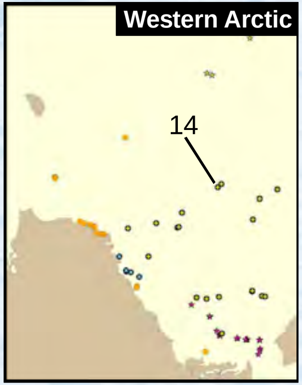
Multi-year ice

13 August

76°44’N, 149°56’W

Key identifiers:

- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☐ colour
- ☐ ponding/drainage
- ☐ ice thickness
- ☐ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☑ other (see comments)



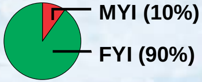
Ship response:

- ☑ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☑ Floe splitting occurred

Confidence that it’s multi-year ice: 10%

Floe size: 100 to 500 m

Est. average thickness: less than 1 m

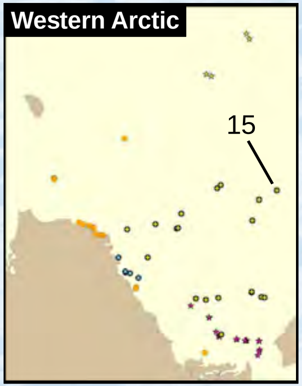


The ice conditions here are similar to the extensively decayed pack ice that characterized this area in 2003. I am not at all confident in classifying this floe as multi-year ice because it looks like rotten thin to medium first-year ice. But it can’t be first-year ice, because it wouldn’t have survived this late in the summer, at this location. The ponds on this floe look grey, rather than blue, but that is probably because of the foggy conditions. Experience tells me that we are operating in an area of multi-year pack ice, so I will call it that, but I am not comfortable doing so. This rotten multi-year ice floe poses no resistance to the ship.

Multi-year ice

17 August

78°30'N, 139°32'W



Key identifiers:

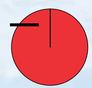
- ☐ freeboard
- ☐ floe size
- ☑ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☐ ice thickness
- ☐ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☑ other (see comments)

Ship response:

- ☑ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☑ Floe splitting occurred

15

MYI (100%)



Confidence that it's multi-year ice: 100%

Floe size: 100 m

Est. average thickness: 2.3 m

We know this is a multi-year ice floe because we installed equipment on it in 2005. The picture shows the floe during our visit in August 2007, when the ice was about 2.3 m thick. Part of the floe split when the ship "parked" in it so that the scientists could retrieve their equipment. The floe's shape, colour and ponding also indicate that it is multi-year ice.

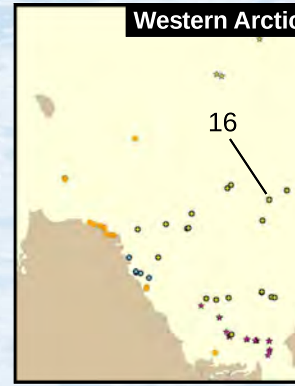
Multi-year ice

19 August

77°39'N, 141°34'W

Key identifiers:

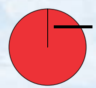
- [x] freeboard
- [x] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [x] snow cover
- [x] sound when hit
- [x] other (see comments)



Confidence that it's multi-year ice: 100%

Floe size: 1000 m

Est. average thickness: 2.6 to 3.3 m



Ship response:

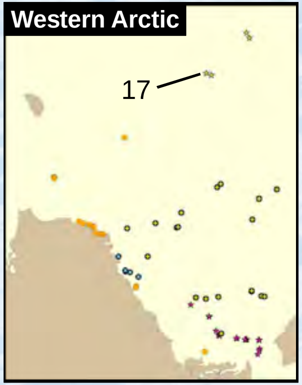
- [x] Ship impacted ice feature
- [x] Backing and ramming was required
- [x] Floe splitting occurred

I know we are in the middle of multi-year pack ice because my experience in this region of the Arctic tells me that it must be, given the location and time of year. The floe's freeboard, size, colour and ponding indicate that it is definitely multi-year ice. The ice is quite solid, as we found out when the ship had to back and ram to get through it. On-ice measurements show that the ice thickness varies from 2.6 to 3.3 m. This photograph was obtained from a digital movie taken from the ship's crows nest, about 35 m above the ice surface.

Second-year ice

20 August

79°27’N, 173°17’W

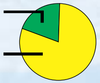


Key identifiers:

- ☑ freeboard
- ☐ floe size
- ☐ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☐ ice thickness
- ☐ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☐ other (see comments)

Ship response:

- ☑ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☑ Floe splitting occurred



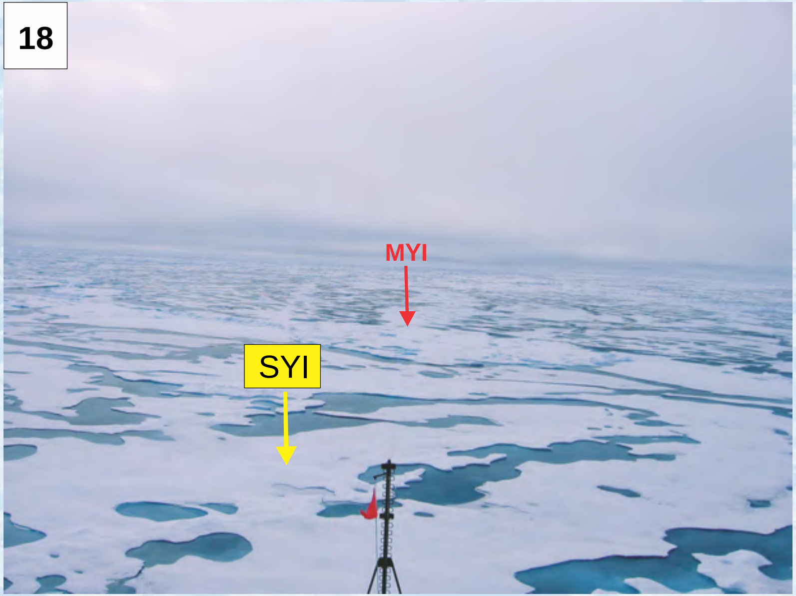
Confidence that it’s second-year ice: 80%

Floe size: ?

Est. average thickness: ?

The colour, freeboard and pattern of ponds/drainage features tell me that this is second-year ice. It was easy for the ship to maintain a constant speed of 4 kn transiting through this floe. There is some chance that it might be first-year ice but usually first-year ice does not survive this late in summer at this location. If first-year ice did survive this late in summer, by chance, it would probably be much more decayed than the ice in this picture.

18



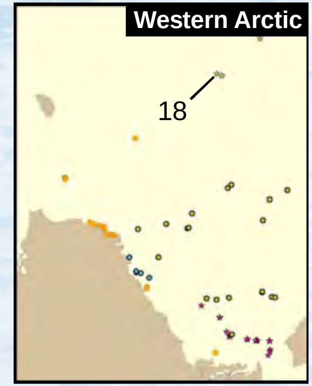
Second-year ice

20 August

79°37’N, 172°15’W

Key identifiers:

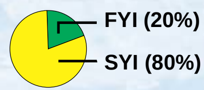
- [x] freeboard
- [ ] floe size
- [x] floe shape
- [x] colour
- [x] ponding/drainage
- [ ] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)



Confidence that it’s second-year ice: 80%

Floe size: 200 m

Est. average thickness: 2 m



Ship response:

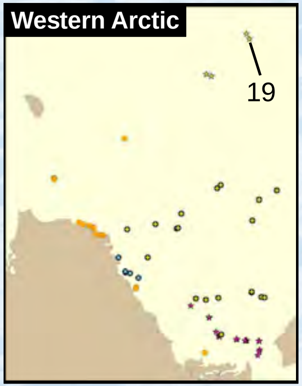
- [x] Ship impacted ice feature
- [ ] Backing and ramming was required
- [x] Floe splitting occurred

This floe is most likely second-year ice because it has a different shape and it is less decayed than first-year ice in the area. Its freeboard, colour, drainage features and ridges/hummocks also tell me that it is probably second-year ice, especially when it is compared to the multi-year ice floe in the distance. There is some chance that it could be first-year ice that has not decayed very much, rather than second-year ice, however.

Multi-year ice

23 August

81°55’N, 178°05’W

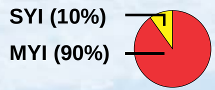


Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)

Ship response:

- [x] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred



Confidence that it’s multi-year ice: 90%

Floe size: 100 x 300 m

Est. average thickness: 2 m

The poor visibility due to falling snow made this feature difficult to identify from a distance. A closer view of its thickness and blue ponds told me that it was very likely multi-year ice. The floe’s fairly smooth surface topography is the only thing that makes me wonder if it might be second-year ice, but the lack of relief is probably because the snow cover masks its surface features.

20

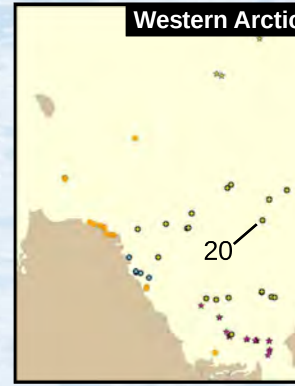
Multi-year ice

27 August

76°40'N, 140°04'W

Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [ ] hummocked
- [ ] snow cover
- [x] sound when hit
- [x] other (see comments)



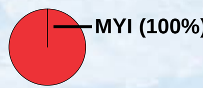
Ship response:

- [x] Ship impacted ice feature
- [x] Backing and ramming was required
- [x] Floe splitting occurred

Confidence that it's multi-year ice: 100%

Floe size: 1000 m

Est. average thickness: 1 to 4 m

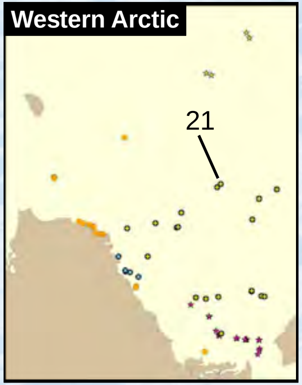


The ship is operating in heavy pack ice. I am sure that this particular feature is multi-year ice because of its freeboard, colour, ponding, its weathered surface topography and the sound when hit. It has less extensive drainage patterns than we usually see on multi-year ice, but it must be multi-year ice given the region in which we are operating and the time of year. The multi-year ice floes in this area all look about the same, and have similar thicknesses, but some of them are more difficult to transit than others. This particular floe required backing and ramming for the ship to get through.

Second-year ice

29 August

76°58’N, 149°53’W

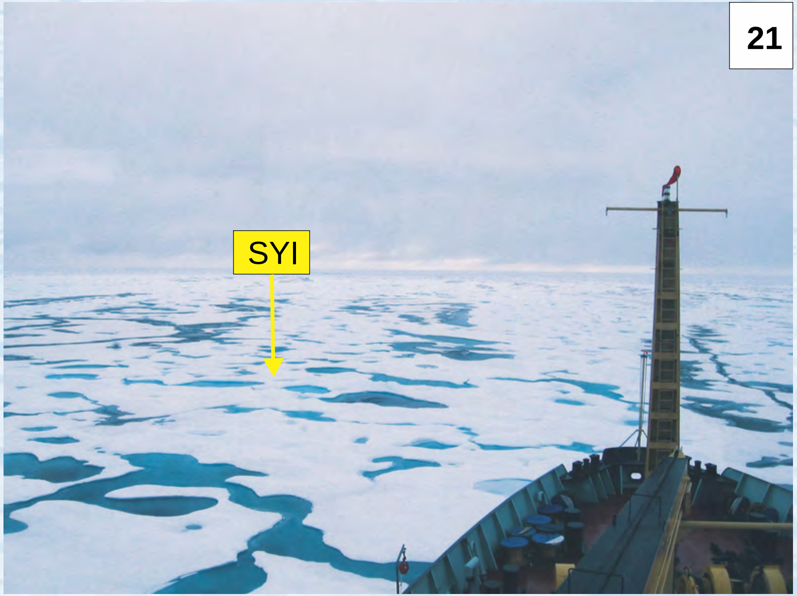


Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [ ] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred



Confidence that it’s second-year ice: 80%

Floe size: 200 to 400 m

Est. average thickness: 1 to 2 m

The second-year ice in this photograph falls somewhere between rotten first-year ice and multi-year ice in the area, both of which are easier to identify. This floe is thicker and more deformed than the surrounding first-year ice. Its freeboard, colour and drainage features all suggest second-year ice. There is some chance that it could be multi-year ice, however. It is the heaviest type of ice that we have encountered while operating over large areas in this region.

22

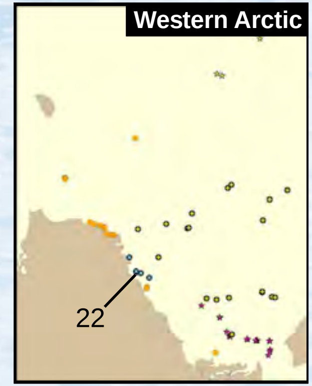
Multi-year ice

29 August

70°50’N, 150°11’W

Key identifiers:

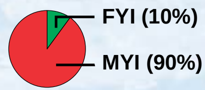
- [x] freeboard
- [x] floe size
- [ ] floe shape
- [x] colour
- [ ] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)



Confidence that it’s multi-year ice: 90%

Floe size: 15 m

Est. average thickness: 12 m (maximum)



Ship response:

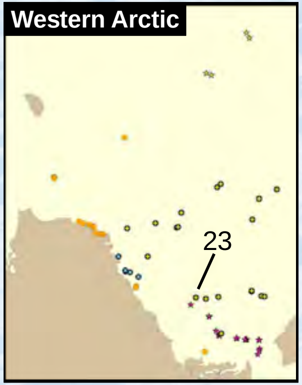
- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

This floe classifies as multi-year ice because of its freeboard, size and thickness. It also has the characteristic colour of multi-year ice. Its hummocked surface isn’t as weathered as one would normally see on multi-year ice, but I am quite confident that it is a multi-year ice floe. However, there is some chance that it could be very deformed first-year ice, given the region in which we are operating.

Multi-year ice

30 August

72°00’N, 139°59’W

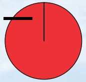


Key identifiers:

- ☑ freeboard
- ☐ floe size
- ☐ floe shape
- ☑ colour
- ☐ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☑ other (see comments)

Ship response:

- ☐ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☐ Floe splitting occurred



Confidence that it’s multi-year ice: 100%

Floe size: 500 m

Est. average thickness: 1 to 5 m

We are in an area of multi-year pack ice. There is about 5 tenths concentration of multi-year ice in the area, and all of the floes look alike. They have extreme freeboard and a weathered surface topography. This particular floe is definitely multi-year ice. Its thickness ranges from 1 to 5 m, or more. We haven't had a chance to break one to find out the thickness of these kinds of floes.

24

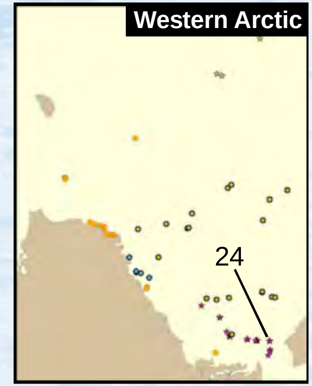
Multi-year ice

3 September

71°47'N, 127°59'W

Key identifiers:

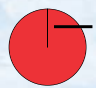
- [ ] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [ ] ice thickness
- [x] hummocked
- [ ] snow cover
- [x] sound when hit
- [x] other (see comments)



Confidence that it's multi-year ice: 100%

Floe size: 1000 m

Est. average thickness: ?



Ship response:

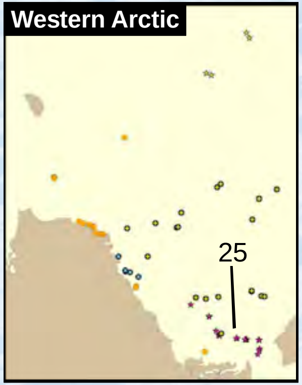
- [x] Ship impacted ice feature
- [x] Backing and ramming was required
- [ ] Floe splitting occurred

The blue colour, surface topography and the look of the ponds tell me this is definitely multi-year ice. The location and time of year, and the sound of the impact are also very clear indicators that it is multi-year ice. The ship had to back and ram to get through this floe.

Multi-year ice

4 September

71°22’N, 131°11’W



Key identifiers:

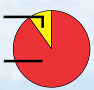
- [ ] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [ ] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)

Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

SYI (10%)

MYI (90%)



Confidence that it’s multi-year ice: 90%

Floe size: 300 m

Est. average thickness: ?

The weathered hummocks and blue melt ponds suggest this floe is very likely multi-year ice. The melt ponds have a recently frozen layer of ice covering them (‘glimmer ice’). Portions of this multi-year ice floe are rotten, with melt holes penetrating through the full thickness of ice. Some of the ridges look quite fresh, which makes me wonder if it could be second-year ice.

26

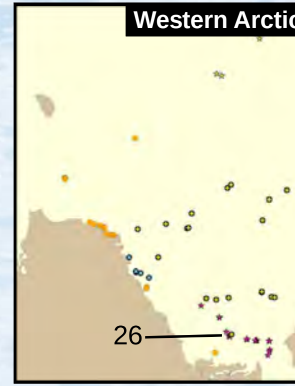
Multi-year ice

6 September

71°06’N, 133°54’W

Key identifiers:

- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☐ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☐ other (see comments)



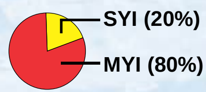
Ship response:

- ☐ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☐ Floe splitting occurred

Confidence that it’s multi-year ice: 80%

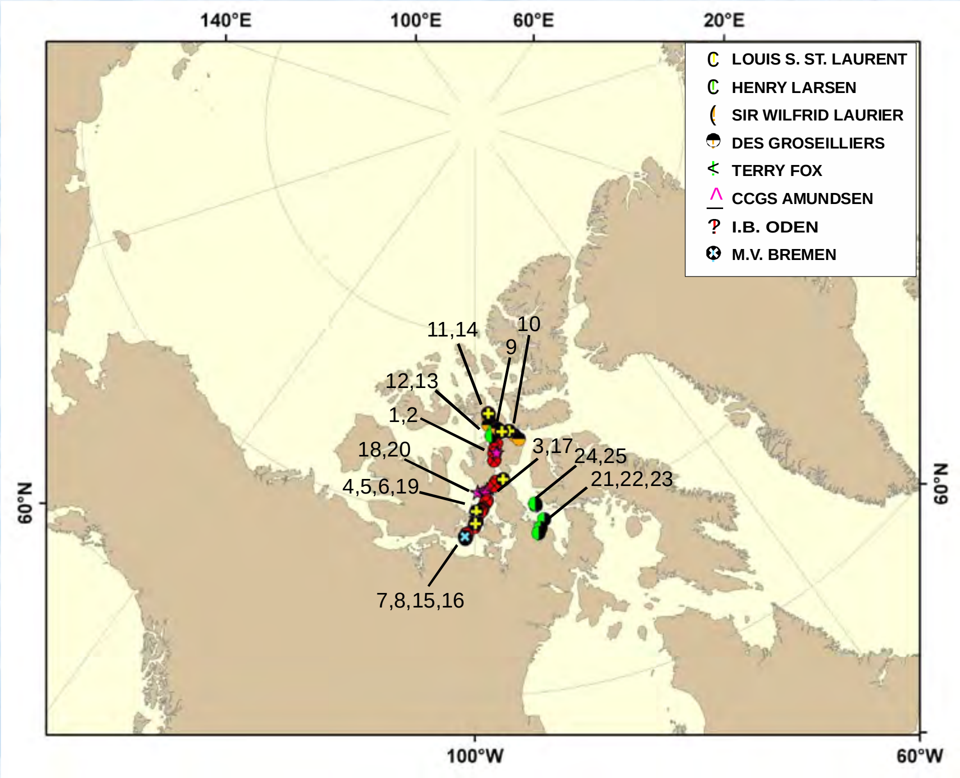
Floe size: 200 x 1000 m

Est. average thickness: ?



I would classify this feature as multi-year ice because of its colour, melt ponds and eroded surface features. There is a 20% chance that it could be second-year ice though, because it floats much lower in the water than multi-year ice.

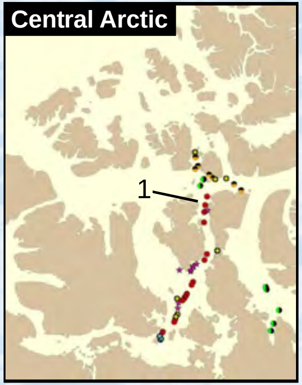
Central Arctic



Second-year ice

19 July

73°26’N, 96°09’W

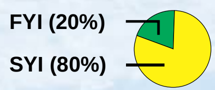


Key identifiers:

- ☑ freeboard
- ☑ floe size
- ☐ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☑ sound when hit
- ☐ other (see comments)

Ship response:

- ☑ Ship impacted ice feature
- ☑ Backing and ramming was required
- ☐ Floe splitting occurred



Confidence that it’s second-year ice: 80%

Floe size: 10 km+

Est. average thickness: ?

This floe is most likely second-year ice because it has a weathered surface and eroded hummocks. There is some chance that it is first-year ice, but it floats higher in the water, is thicker and is bluer than first-year ice (but not as blue as multi-year ice). Its drainage features are also more connected than first-year ice for this time of year. Initially, the ship approached the floe to within 10 m, to get a better look, and then proceeded through it. I estimate this floe to be more than 10 km across, but it is difficult to tell where the floe ends.

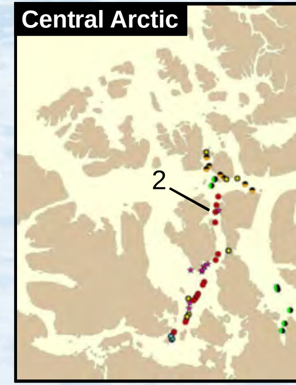
Second-year ice

19 July

73°25'N, 96°15'W

Key identifiers:

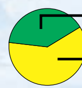
- ☐ freeboard
- ☑ floe size
- ☐ floe shape
- ☑ colour
- ☐ ponding/drainage
- ☑ ice thickness
- ☐ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☑ other (see comments)



Confidence that it's second-year ice: 60%

Floe size: 5 km

Est. average thickness: 1 m



Ship response:

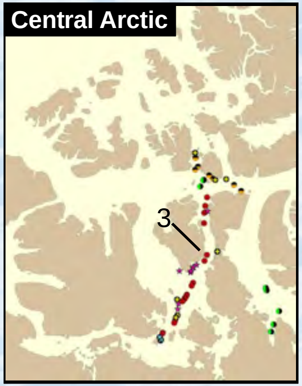
- ☑ Ship impacted ice feature
- ☑ Backing and ramming was required
- ☐ Floe splitting occurred

From a distance of 500 m this second-year ice floe was very deceptive. The low level hummocks (almost flat) and the high percentage of ponding gave the impression of rotting first-year ice, rather than old ice. But, at closer range, the floe's size and colour indicated that it was probably second-year ice. However, this floe could be first-year ice in the early stages of decay (snow melt). Snow melt also gives the ice surface a blue appearance initially, and then the colour changes to grey as the season advances. The estimated thickness of this floe was only 1 m, which also might lead one to believe that it was first-year ice.

Multi-year ice

20 July

71°52'N, 96°13'W

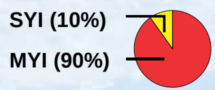


Key identifiers:

- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☑ colour
- ☐ ponding/drainage
- ☐ ice thickness
- ☑ hummocked
- ☑ snow cover
- ☐ sound when hit
- ☐ other (see comments)

Ship response:

- ☑ Ship impacted ice feature
- ☑ Backing and ramming was required
- ☑ Floe splitting occurred



Confidence that it's multi-year ice: 90%

Floe size: 150 to 200 m

Est. average thickness: 7 m

The height of the hummocks is the most obvious feature for classifying this as multi-year ice. The dirty snow and the characteristic blue hue also tell me that it is multi-year ice. There is some chance that it could be hummocked second-year ice, but I don't really think so. The average thickness of the floe (7 m) was estimated from a distance of about 25 to 30 m above sea level.

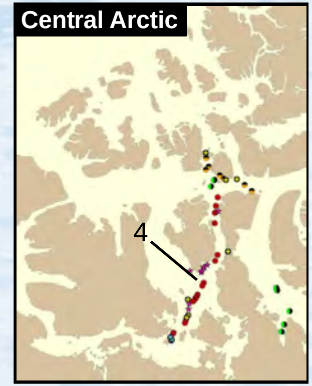
Multi-year ice

22 July

70°46'N, 98°09'W

Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [ ] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)



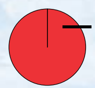
Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

Confidence that it's multi-year ice: 100%

Floe size: 120 m

Est. average thickness: ?

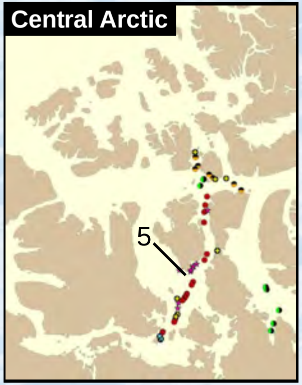


This floe is identifiable as multi-year ice because it floats higher than the surrounding first-year ice, its hummocks are discoloured and eroded, and its ponds are well connected. Hummocks cover about 30% of the floe.

Multi-year ice

22 July

70°25'N, 98°43'W



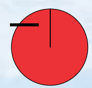
Key identifiers:

- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☐ colour
- ☐ ponding/drainage
- ☐ ice thickness
- ☐ hummocked
- ☐ snow cover
- ☑ sound when hit
- ☐ other (see comments)

Ship response:

- ☑ Ship impacted ice feature
- ☑ Backing and ramming was required
- ☐ Floe splitting occurred

MYI (100%)



Confidence that it's multi-year ice: 100%

Floe size: 150 m

Est. average thickness: 3 to 4 m

We knew this was multi-year ice right after we hit it, because the impact produced that characteristic sound of multi-year ice when hit! The surface of this floe deceptively suggests second-year ice because the hummocks are not very high, compared to other multi-year ice floes in the area, and the snow cover is relatively clean.

6

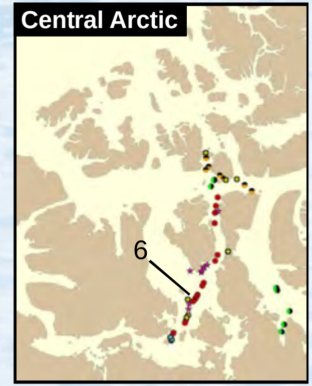
Multi-year ice

22 July

70°17’N, 98°56’W

Key identifiers:

- [x] freeboard
- [x] floe size
- [ ] floe shape
- [ ] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [x] sound when hit
- [ ] other (see comments)



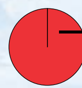
Ship response:

- [x] Ship impacted ice feature
- [x] Backing and ramming was required
- [ ] Floe splitting occurred

Confidence that it’s multi-year ice: 100%

Floe size: 4 km+

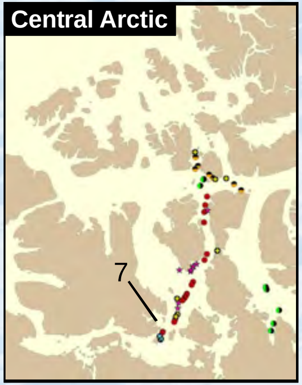
Est. average thickness: 5 m



This is a multi-year floe because it floats higher, has well-rounded hummocks, is thicker than the surrounding ice and it produced the sound of a multi-year ice impact. Since the floe is more than 4 km in diameter, it is probably an aggregate floe of many smaller floes, some of which could be second-year ice. The top of the melt ponds have a skim of ice covering them, which changes their colour somewhat. The average thickness of the floe (5 m) was estimated from a distance of about 25 to 30 m above sea level.

Multi-year ice

24 July
69°02’N, 101°15’W



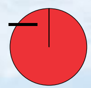
Key identifiers:

- [ ] freeboard
- [x] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [ ] ice thickness
- [x] hummocked
- [ ] snow cover
- [x] sound when hit
- [ ] other (see comments)

Ship response:

- [x] Ship impacted ice feature
- [x] Backing and ramming was required
- [x] Floe splitting occurred

MYI (100%)



Confidence that it’s multi-year ice: 100%

Floe size: 200 to 400 m

Est. average thickness: ?

Fog somewhat hampered the detection of this multi-year floe (foreground of photo). Despite the fog, the floe’s discoloured hummocks and its weathered surface told me that it was multi-year ice. The floe size, ponding, drainage features and the sound when hit also told me it was multi-year ice.

8

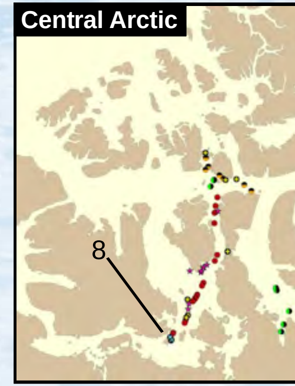
Multi-year ice

24 July

69°00’N, 101°19’W

Key identifiers:

- ☑ freeboard
- ☑ floe size
- ☐ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☑ sound when hit
- ☐ other (see comments)



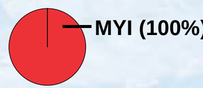
Ship response:

- ☑ Ship impacted ice feature
- ☑ Backing and ramming was required
- ☑ Floe splitting occurred

Confidence that it’s multi-year ice: 100%

Floe size: 500 m

Est. average thickness: 5 to 7 m

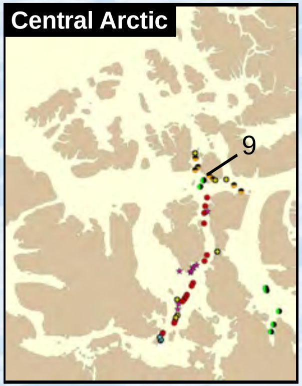


This floe is definitely multi-year ice because its freeboard, size, colour (of the ice and ponds), thickness, and its dirty looking hummocked surface tell me so. The well-established drainage pattern also indicates multi-year ice. The sound of the impact confirmed this floe was multi-year ice.

Multi-year ice

28 July

74°39'N, 94°50'W



Key identifiers:

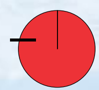
- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [ ] ponding/drainage
- [ ] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

Ship response:

- [x] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

Confidence that it's multi-year ice: 100%

MYI (100%)



Floe size: 45 m

Est. average thickness: ?

All of the old ice floes in this area are less than 100 m in diameter. Most are recognizable by their colour; there is no mistaking the blue, low floating floes as anything but old ice. This floe floats low in the water, but its hummocks are very eroded and its extensive drainage features suggest it is multi-year ice. Also, the ice impact was much 'livelier' than transiting through the rotten, first-year ice in the area – it tossed the ship around more.

10

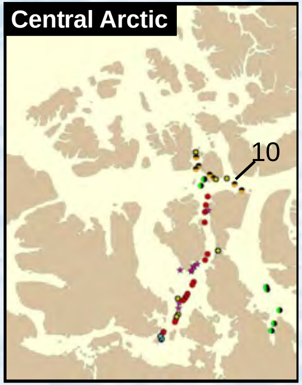
Multi-year ice

4 August

74°21'N, 92°02'W

Key identifiers:

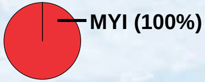
- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☐ other (see comments)



Confidence that it's multi-year ice: 100%

Floe size: 500 to 1000 m

Est. average thickness: 2 to 4 m



Ship response:

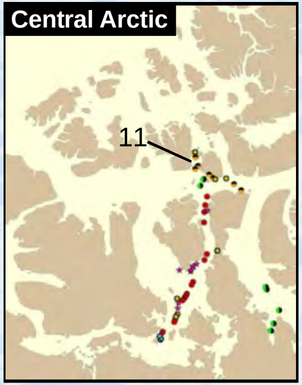
- ☑ Ship impacted ice feature
- ☑ Backing and ramming was required
- ☑ Floe splitting occurred

The multi-year ice floe in this photo is part of a giant drifting floe. Some portions of the giant floe consist of decayed first-year ice. The portion of the floe in this picture is definitely multi-year ice because it has well-weathered hummocks, is very blue and its drainage patterns are well established. The ship caused the floe to split (in some places) during the impact. The floe is estimated to be about 2 to 4 m thick.

Multi-year ice

22 August

75°07'N, 96°47'W



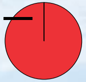
Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

Ship response:

- [x] Ship impacted ice feature
- [ ] Backing and ramming was required
- [x] Floe splitting occurred

MYI (100%)



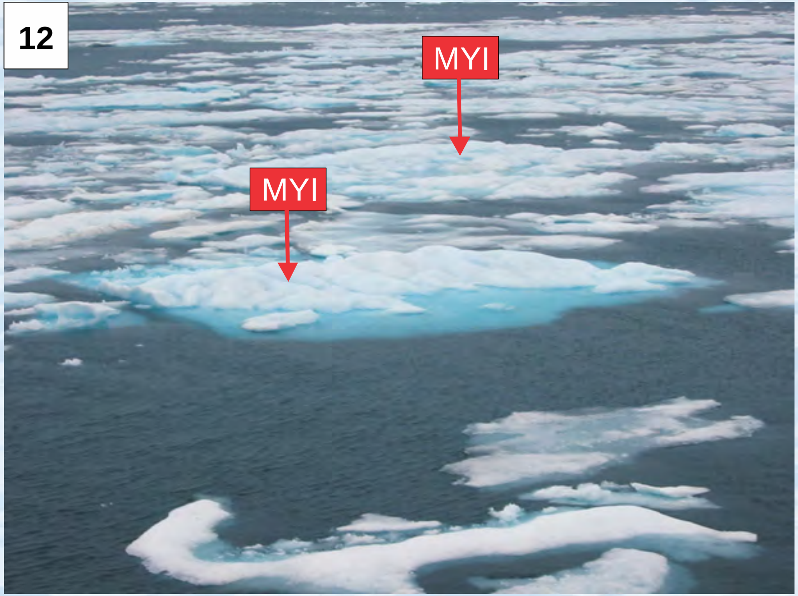
Confidence that it's multi-year ice: 100%

Floe size: 3.5 km

Est. average thickness: 2 to 4 m

This is multi-year ice because it is very blue, its surface features are weathered and it has extensive drainage patterns. About 20% of this giant floe is covered by eroded hummocks. Some areas of the floe have melted through the full thickness of ice. The ship impact caused the ice to fracture in a near-straight line.

12



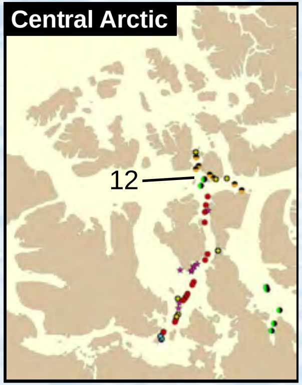
Multi-year ice

22 August

74°37'N, 96°08'W

Key identifiers:

- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☐ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☐ other (see comments)



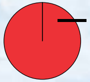
Ship response:

- ☐ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☐ Floe splitting occurred

Confidence that it's multi-year ice: 100%

Floe size: 20 to 40 m

Est. average thickness: ?

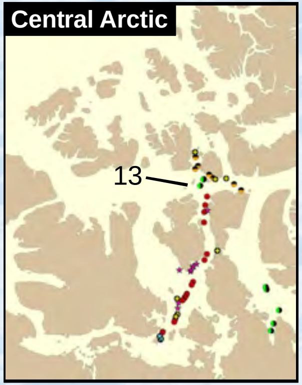


Even though the multi-year ice fragments in this area are small, about 20 to 40 m across, they stand out as multi-year ice because of their weathered hummocks, their blue colour and their well-established drainage network.

Second-year ice

22 August

74°24'N, 96°36'W



Key identifiers:

- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☐ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☐ other (see comments)

Ship response:

- ☑ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☑ Floe splitting occurred

13

Confidence that it's second-year ice: 80%

Floe size: 300 m

Est. average thickness: ?

This feature classifies as second-year ice because it is blue in colour, has some surface topography and its drainage patterns are not very well established. This second-year floe is more difficult to transit than the neighbouring floes of rotten first-year ice. There is some chance that the floe could be multi-year ice, but its freeboard and surface appearance indicate otherwise.

14

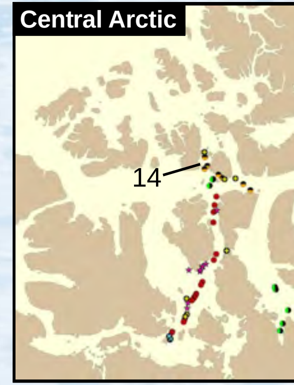
Multi-year ice

23 August

75°01’N, 97°12’W

Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [ ] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)



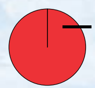
Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

Confidence that it’s multi-year ice: 100%

Floe size: 200 to 250 m

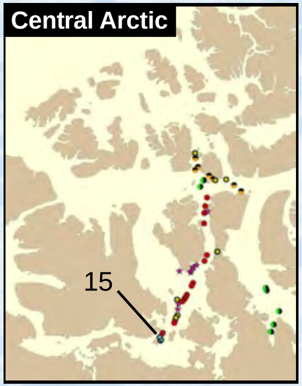
Est. average thickness: ?



This multi-year ice floe is very blue, so it really stands out from the surrounding rotten first-year ice. The freeboard, thickness, dirty appearance and surface topography definitely characterize it as multi-year ice.

Multi-year ice

23 August
68°47'N, 101°26'W



Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [ ] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)

Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

SYI (30%)
MYI (70%)

Confidence that it's multi-year ice: 70%

Floe size: 10 m

Est. average thickness: 2.5 to 3 m

The colour and weathered surface topography of this floe suggest multi-year ice. Its freeboard and thickness also tell me that it is multi-year ice, given the location and time of year. Because the ice fragment is so small, it is hard to tell (with complete certainty) whether this floe is multi-year ice or second-year ice.

16

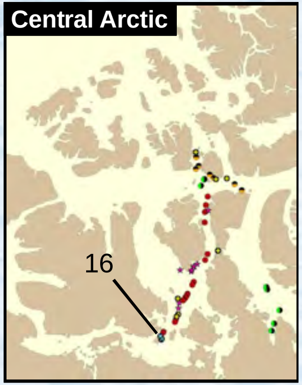
Multi-year ice

23 August

68°52'N, 101°35'W

Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)



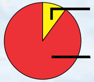
Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

Confidence that it's multi-year ice: 90%

Floe size: 200 x 80 m

Est. average thickness: 9 m

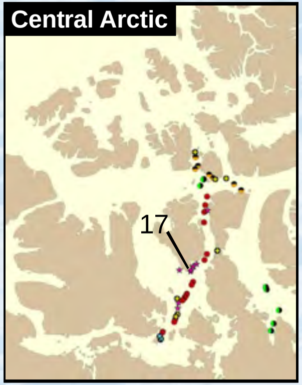


This floe was classified as multi-year ice using the process of elimination. Its weathered surface topography and thickness tell me that it can't be first-year ice, especially at this time of year. It has the blue colour of old ice. Its freeboard, thickness, ponding and drainage features all indicate multi-year ice, but there is a small chance that it could be second-year ice.

Second-year ice

26 August

71°32'N, 97°30'W

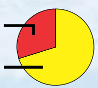


Key identifiers:

- [ ] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [ ] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)

Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred



Confidence that it's second-year ice: 70%

Floe size: 10 km

Est. average thickness: ?

This is definitely old ice. Most likely it is second-year ice because its ponds are not very well established, its surface is not that eroded and it is extensively decayed. Its blue colour suggests that it might be multi-year ice, but it floats lower in the water than would multi-year ice. Some areas of the floe have broken into fragments that are barely attached.

18

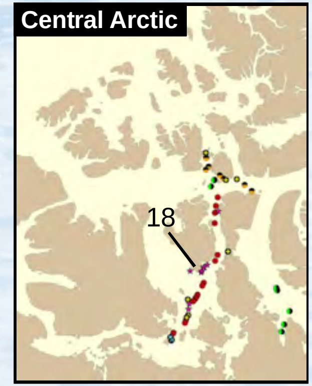
Multi-year ice

26 August

71°20’N, 98°90’W

Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [ ] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)



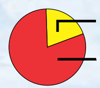
Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

Confidence that it’s multi-year ice: 80%

Floe size: 1000 m

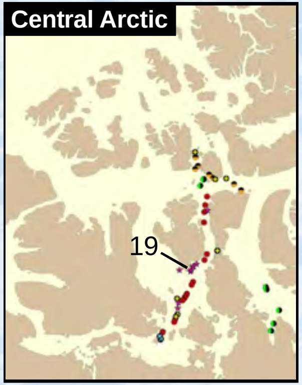
Est. average thickness: ?



This multi-year ice floe has more surface topography than the surrounding floes. The melt ponds, which cover about 40% of the floe, are very blue. It also has a hummocked topography and a well-established drainage network. All of those things suggest multi-year ice, but the floe’s low freeboard makes me wonder whether it is second-year ice.

Multi-year ice

27 August
71°19'N, 98°10'W

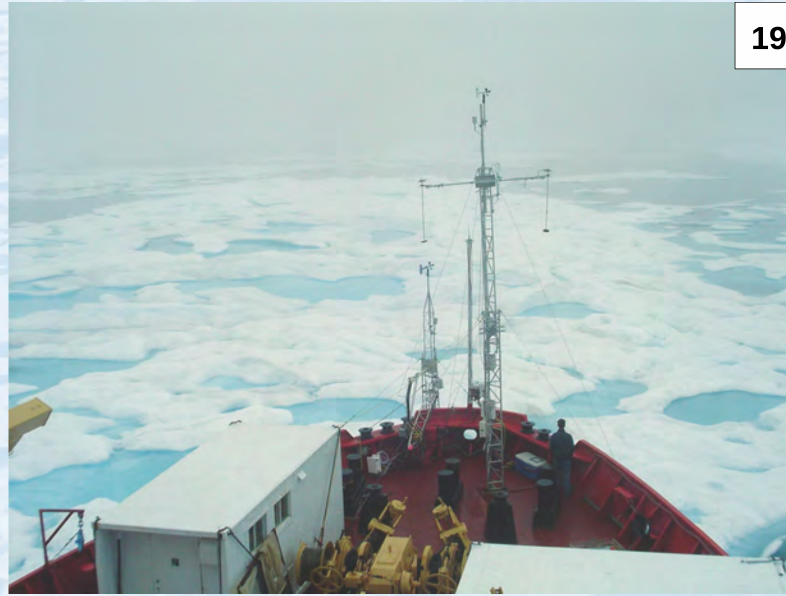


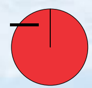
Key identifiers:

- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☐ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☑ sound when hit
- ☐ other (see comments)

Ship response:

- ☑ Ship impacted ice feature (see below)
- ☐ Backing and ramming was required
- ☑ Floe splitting occurred





Confidence that it's multi-year ice: 100%

Floe size: 200 m

Est. average thickness: ?

The large hummocked areas, blue melt ponds and extensive drainage network indicate that this is multi-year ice. The ship impact was the deciding factor: it had the characteristic sound of a multi-year ice impact, even though the floe was only about 200 m across.

20

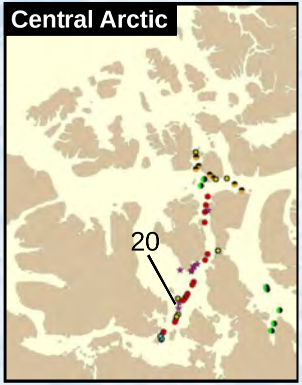
Multi-year ice

27 August

70°07'N, 99°38'W

Key identifiers:

- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☑ sound when hit
- ☐ other (see comments)



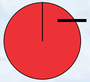
Ship response:

- ☑ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☐ Floe splitting occurred

Confidence that it's multi-year ice: 100%

Floe size: ?

Est. average thickness: ?

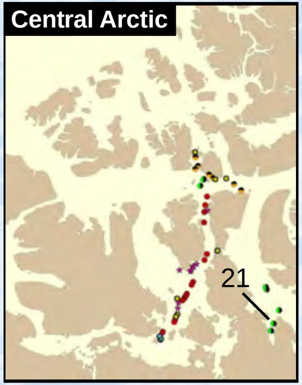


The extensively weathered surface of this floe, and the sound of the ship impact characterize this as multi-year ice. Other indicators include the colour (of the ice and ponds) and the ice thickness. We definitely knew that it was multi-year ice after we hit it. Rather than back and ram to get through it, we decided to find a way around it. Floe size could not be estimated in these foggy conditions.

Multi-year ice

29 August

69°03’N, 89°48’W

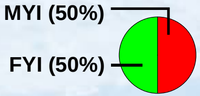


Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [ ] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)

Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred



Confidence that it’s multi-year ice: 50%

Floe size: 10 m

Est. average thickness: 3 m

The dirty colour and rough surface of this feature suggest that it might be a fragment of multi-year ice, but it could be first-year ice from a ridge or hummock field. First-year ice hummock fields are common in this area because onshore winds push the ice against the coast, producing large areas of deformed ice. As for the fragment’s dirty colour, that resulted from dirt from the coast blowing onto the ice.

22

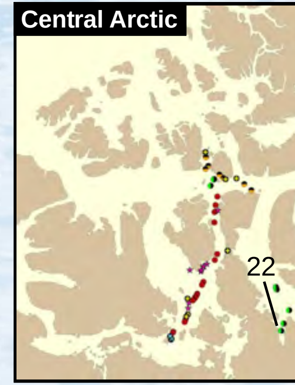
Multi-year ice

4 September

68°48’N, 90°10’W

Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [ ] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)



Confidence that it’s multi-year ice: 70%

Floe size: 20 to 70 m

Est. average thickness: 2 to 4 m

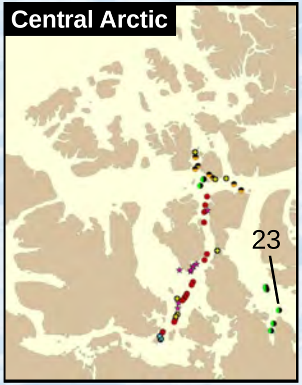
Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

The eroded surface features, dirty surface and very blue colour of most of the floes in this photo indicate they are multi-year ice. Second-year ice, by comparison, has more of a greenish hue. The uncertainty in classifying these floes as multi-year ice arises because some of the floes (the dirty ones) could be remnants of a first-year ice rubble field, given the area in which we are working (see previous observation).

Multi-year ice

7 September
69°30'N, 89°00'W



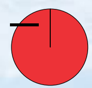
Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [x] sound when hit
- [ ] other (see comments)

Ship response:

- [x] Ship impacted ice feature
- [x] Backing and ramming was required
- [x] Floe splitting occurred

MYI (100%)



Confidence that it's multi-year ice: 100%

Floe size: 100 m

Est. average thickness: up to 10 m

This is definitely a multi-year ice floe. Key identifiers include its freeboard, colour of the ice and ponds, thickness and weathered surface topography. The floe has an estimated freeboard of 1 to 2 m and a thickness of up to 10 m. The ship impact confirmed this is a multi-year floe.

24

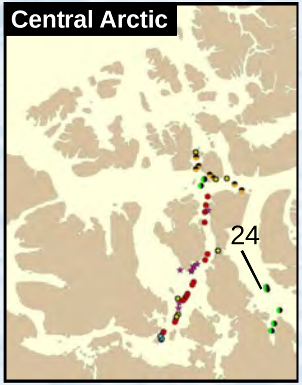
Multi-year ice

16 September

70°24'N, 89°59'W

Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [ ] ice thickness
- [ ] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)



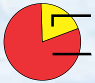
Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

Confidence that it's multi-year ice: 80%

Floe size: 50 m

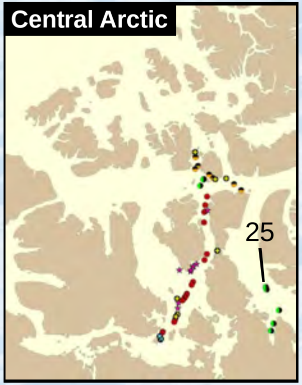
Est. average thickness: 5 m



The freeboard, colour and drainage features of this old ice fragment (50 m across) suggest this is multi-year ice but the keel doesn't really look like multi-year ice, considering how decayed it is. In fact, the ice keel makes me suspect that it is second-year ice but the ice fragment doesn't really have enough surface features to tell one way or the other. Experience tells me that it is multi-year ice, given the time of year and the location in which we are operating.

Multi-year ice

16 September
70°26’N, 90°00’W

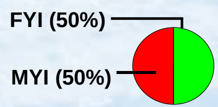


Key identifiers:

- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☐ colour
- ☐ ponding/drainage
- ☑ ice thickness
- ☐ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☐ other (see comments)

Ship response:

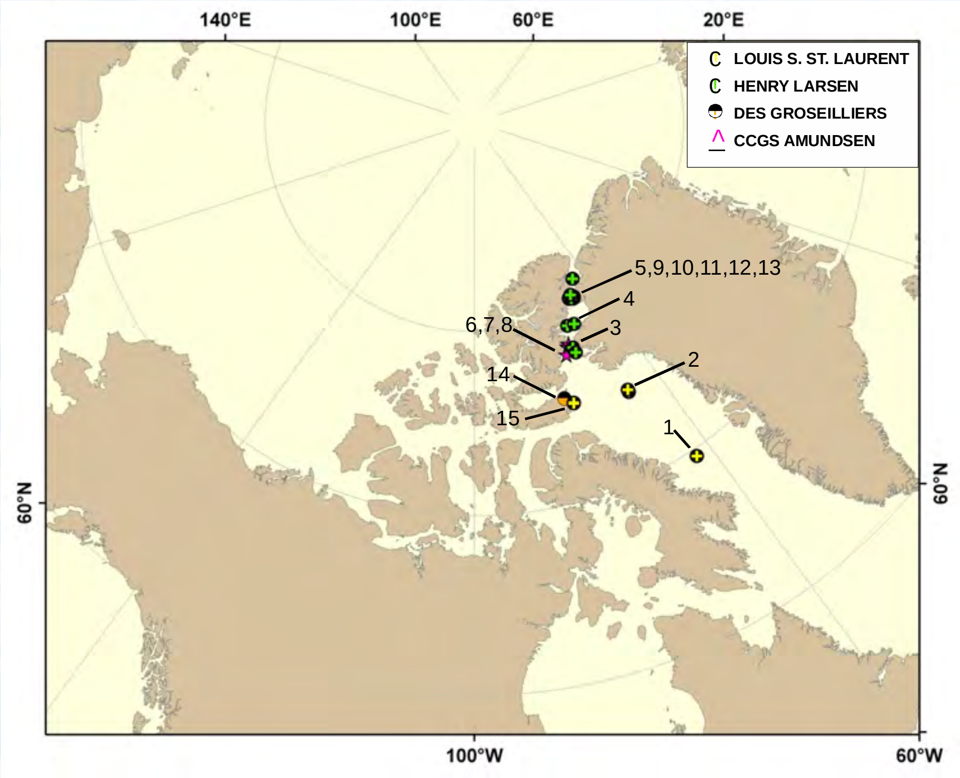
- ☐ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☐ Floe splitting occurred



Confidence that it’s multi-year ice: 50%
Floe size: 20 m
Est. average thickness: 8 m

This floe is thick, but ice thickness alone is not enough to qualify a feature like this as multi-year ice, especially in this area. That is because first-year ice hummock fields can also be very thick in this area. The white colour and surface topography of this floe look more like first-year ice, but there shouldn’t be any first-year ice left at this time of year. Maybe it is multi-year ice – but I am not really comfortable calling it that. This is an excellent example of why detecting hazardous ice is extremely difficult in this area. In many cases, even an aerial reconnaissance is of little use in trying to classify ice types in this region.

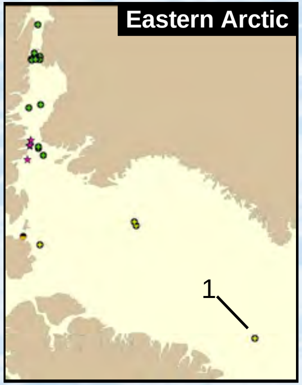
Eastern Arctic



Second-year ice

26 July

69°36’N, 62°35’W



Key identifiers:

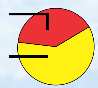
- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [ ] colour
- [x] ponding/drainage
- [ ] ice thickness
- [ ] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

MYI (40%)

SYI (60%)



Confidence that it’s second-year ice: 60%

Floe size: 30 x 40 m

Est. average thickness: ?

Old ice floes in this area are easy to distinguish from first-year ice because they have much higher freeboard. Differentiating second-year ice from multi-year ice is much more difficult however. I would classify this feature as second-year ice because it has a relatively level surface and a limited drainage network (compared to multi-year ice). However, it could be a level piece of multi-year ice, given the area in which we are operating.

2

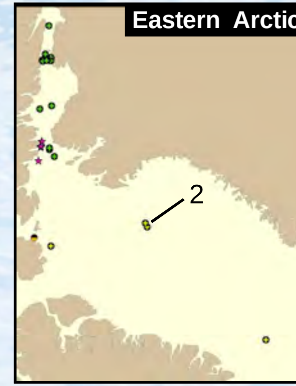
Multi-year ice

26 July

74°40'N, 66°54'W

Key identifiers:

- ☑ freeboard
- ☐ floe size
- ☐ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☑ sound when hit
- ☐ other (see comments)



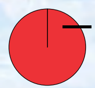
Ship response:

- ☑ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☑ Floe splitting occurred

Confidence that it's multi-year ice: 100%

Floe size: 50 m

Est. average thickness: ?

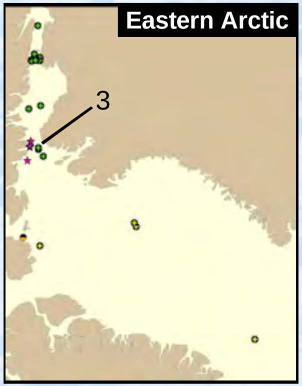


This feature is definitely multi-year ice. It floats higher than the surrounding first-year ice and its hummocked surface is eroded. Other key identifiers include its colour, ponding, thickness and the sound of the ship impact.

Multi-year ice

11 August

78°00’N, 73°54’W



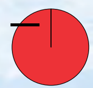
Key identifiers:

- [ ] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [ ] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)

Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

MYI (100%)



Confidence that it’s multi-year ice: 100%

Floe size: 20 m

Est. average thickness: 2.5 m

This is a multi-year ice floe because it has well-established drainage patterns and a weathered surface topography. The colour of the ice and ponds also indicates that it is multi-year ice.

4

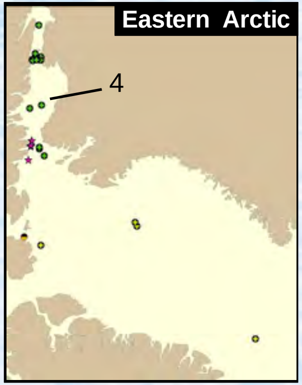
Multi-year ice

11 August

79°10'N, 70°48'W

Key identifiers:

- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☐ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☐ other (see comments)



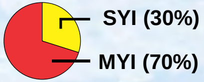
Ship response:

- ☐ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☐ Floe splitting occurred

Confidence that it's multi-year ice: 70%

Floe size: 300 m

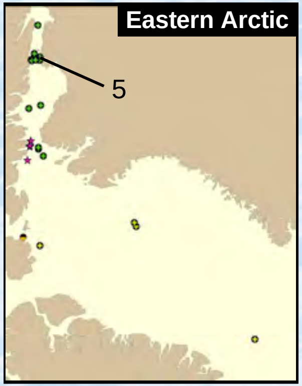
Est. average thickness: 2 m



This is probably a multi-year ice floe because it has a well-established drainage network and some surface topography. The colour of the floe also indicates multi-year ice. The ridge on this ice floe is still quite angular (not very old and weathered), which tells me that the floe is either young multi-year ice or, perhaps, second-year ice. The freeboard of this floe is estimated to be about 25 cm.

Multi-year ice

14 August
80°27'N, 67°07'W



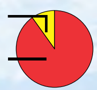
Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [x] sound when hit
- [ ] other (see comments)

Ship response:

- [x] Ship impacted ice feature
- [ ] Backing and ramming was required
- [x] Floe splitting occurred

5



Confidence that it's multi-year ice: 90%
Floe size: 1000 m
Est. average thickness: 3 m

I would call this a multi-year ice floe because it has interconnected ponds/drainage features and its topography is weathered. Other key identifiers include its freeboard, colour and thickness. The sound of the ship impact also told me that it was multi-year ice. There is some chance that it could be second-year ice, however.

6

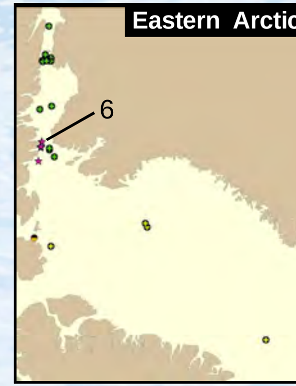
Multi-year ice

19 August

78°11'N, 74°57'W

Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)



Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

Confidence that it's multi-year ice: 60%

Floe size: 100 x 60 m

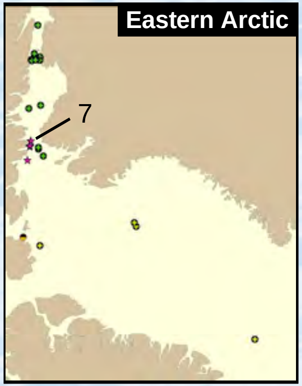
Est. average thickness: ?

The high freeboard, colour, ponding, hummocked surfaced topography and thickness definitely classify this feature as old ice, but it is very difficult to tell whether it is multi-year ice or second-year ice. I will classify it as multi-year ice with a 60% confidence. It could be second-year ice though, because its drainage network is not that well established. Many of the melt ponds had a frozen layer of ice on them and some snow covering their surface. This floe has an estimated freeboard of about 50 cm.

Multi-year ice

19 August

78°20’N, 74°25’W

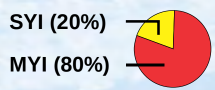


Key identifiers:

- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☐ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☐ other (see comments)

Ship response:

- ☐ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☐ Floe splitting occurred



Confidence that it’s multi-year ice: 80%

Floe size: 300 m

Est. average thickness: ?

The eroded hummocks and well-established drainage network on this floe indicate that it is very likely multi-year ice. The rubbled ice around the perimeter of the floe also tells me that it is multi-year ice (the rubble formed because this floe was harder than the ice with which it collided). Some of the floe’s characteristics, such as its level ice surface and dark coloured melt ponds, suggest that it could be second-year ice however.

8

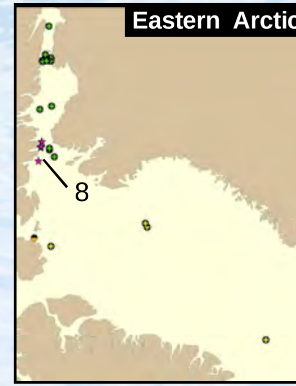
Multi-year ice

20 August

77°50'N, 75°58'W

Key identifiers:

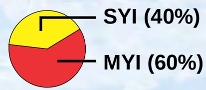
- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☐ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☐ other (see comments)



Confidence that it's multi-year ice: 60%

Floe size: 100 m

Est. average thickness: ?



Ship response:

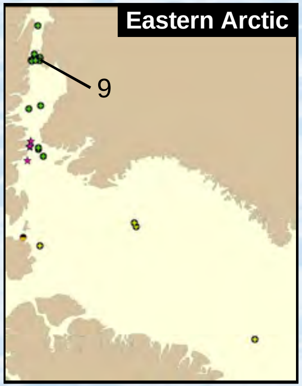
- ☐ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☐ Floe splitting occurred

It is difficult to decide whether this is second-year ice or multi-year ice. The floe has a very weathered surface and looks quite thick, which indicates multi-year ice, but its angular hummocks (about 2 to 3 m high) and limited drainage network suggest second-year ice.

Multi-year ice

24 August

80°22’N, 67°26’W



Key identifiers:

- ☑ freeboard
- ☐ floe size
- ☐ floe shape
- ☑ colour
- ☐ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☐ other (see comments)

Ship response:

- ☐ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☐ Floe splitting occurred

Confidence that it’s multi-year ice: 80%

Floe size: 20 m

Est. average thickness: 8 m

This is most likely a multi-year ice floe, given its high freeboard, thickness, colour and well-weathered surface. There is some chance that it could be second-year ice because its drainage is limited. Part of the uncertainty in determining whether it is second-year or multi-year ice is because this fragment of ice is so small (20 m across) – the Key Identifiers would be much more visible on a larger ice floe.

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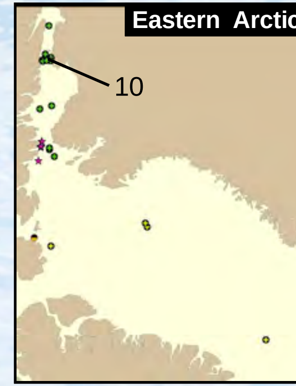
Multi-year ice

24 August

80°30’N, 68°43’W

Key identifiers:

- [x] freeboard
- [x] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)



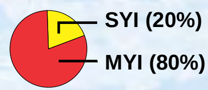
Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

Confidence that it’s multi-year ice: 80%

Floe size: 400 m

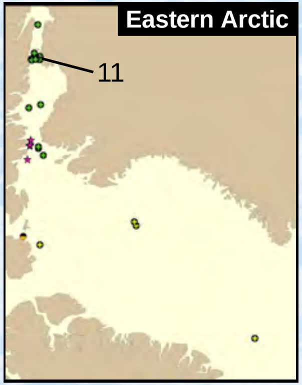
Est. average thickness: 8 m



This is very likely a multi-year ice floe because it has high freeboard, is very thick and weathered, is blue in colour and it has an extensive drainage network. Its size and relatively level surface suggest that it might be second-year ice however.

Multi-year/Second-year Matrix

25 August
80°26’N, 67°52’W

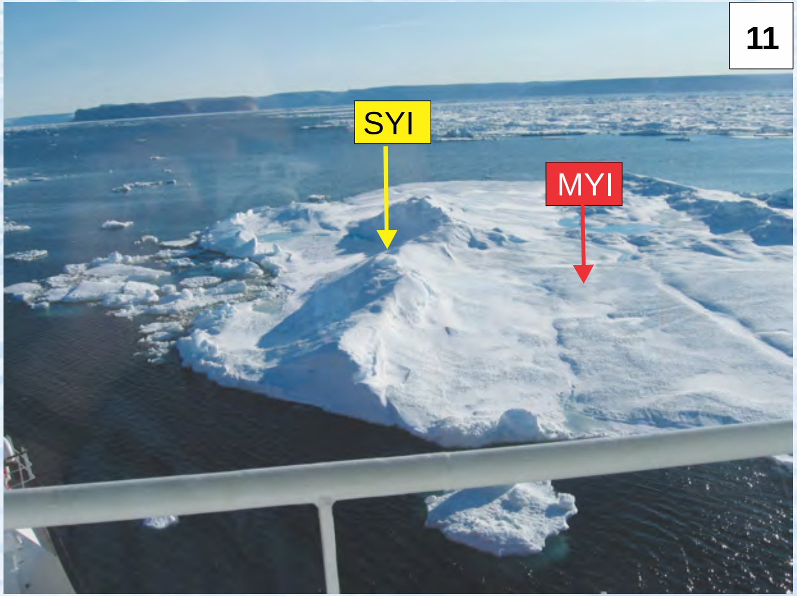


Key identifiers:

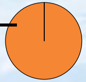
- ☑ freeboard
- ☐ floe size
- ☐ floe shape
- ☐ colour
- ☑ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☑ snow cover
- ☐ sound when hit
- ☑ other (see comments)

Ship response:

- ☐ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☐ Floe splitting occurred



MYI/SYI mix (100%)



Confidence that it’s SYI & MYI matrix: 100%

Floe size: 80 m

Est. average thickness: 3 m

This feature is only about 80 m across, but it is very interesting. The floe is comprised of both second-year and multi-year ice. The left part of the floe consists of ridged second-year ice. We know that the ridge is second-year because it is more eroded than a first-year ridge and it has consolidated over time (voids are not evident in the ridge cross section, which has been sheared off). The ridge is not at the stage of a multi-year hummock yet; we can still see rubble along its crest (not very weathered, quite “peaky”) and its faces are fairly steep. The right side of the floe looks very different than the left side of the floe because it is multi-year ice.

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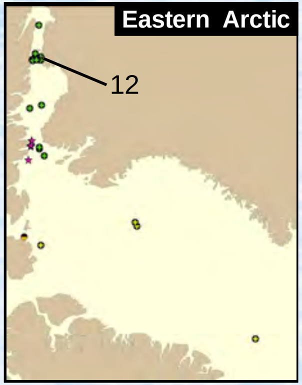
Second-year ice

25 August

80°26'N, 68°04'W

Key identifiers:

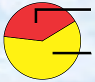
- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☐ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☐ other (see comments)



Confidence that it's second-year ice: 60%

Floe size: 2 km

Est. average thickness: 3 m



Ship response:

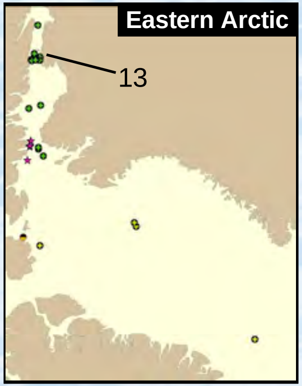
- ☐ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☐ Floe splitting occurred

The stage of weathering, the appearance of the ponds and the colour of the ice suggest this is second-year ice. Its drainage network is not very well established and its hummocks are quite angular, which also tell me it is second-year ice. However, the floe's freeboard and thickness make me wonder whether it could be multi-year ice.

Multi-year ice

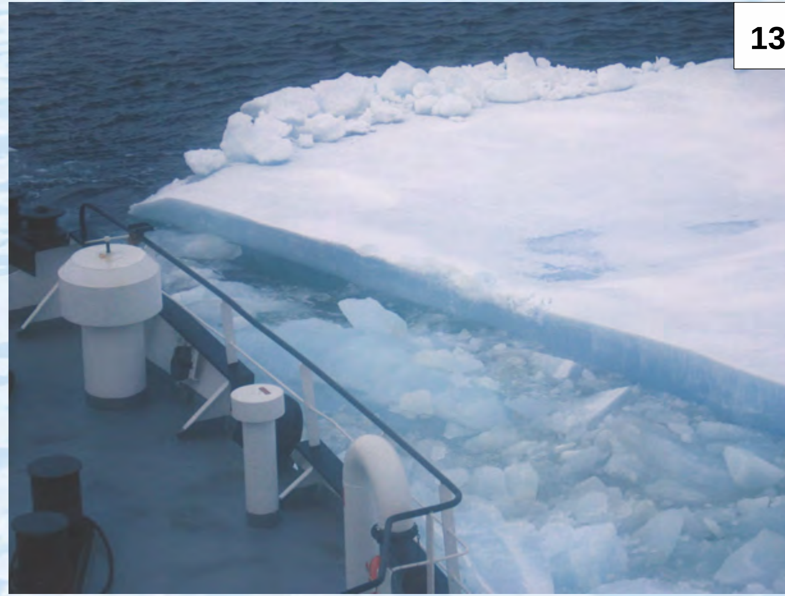
25 August

80°28’N, 68°42’W



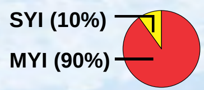
Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [ ] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)



Ship response:

- [x] Ship impacted ice feature
- [x] Backing and ramming was required
- [x] Floe splitting occurred



Confidence that it’s multi-year ice: 90%

Floe size: 20 m

Est. average thickness: 6 m

The ice freeboard and ice thickness tell me this is a multi-year floe. The colour of the ice and ponds also suggest multi-year ice. The ship needed to back and ram to get through this floe. The uncertainty in calling it multi-year ice arises only because it has a very level surface, which is more representative of second-year ice.

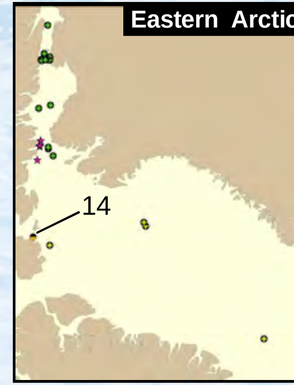
Multi-year ice

1 September

75°40'N, 80°00'W

Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [x] snow cover
- [ ] sound when hit
- [ ] other (see comments)



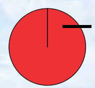
Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

Confidence that it's multi-year ice: 100%

Floe size: 20 m

Est. average thickness: ?

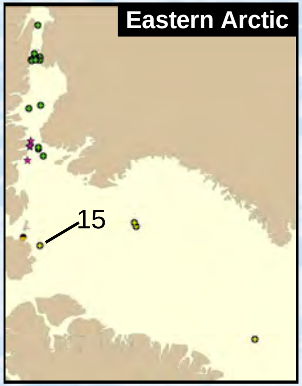


We are encountering many small multi-year ice floes in this area, each about 20 to 60 m across. They are definitely fragments of multi-year ice, given their freeboard, colour, ponding, thickness, hummocked topography and snow cover. The color of the pond on the largest piece of ice in the photo above, and its eroded hummock, indicate that it is multi-year ice. I was not sure about whether the ice fragment in the foreground of the photo also classified as multi-year, until I saw the underwater keel connecting the two pieces of ice. When the ship impacts fragments like these, they split. Backing and ramming is not needed.

Multi-year ice

12 October

75°15'N, 78°22'W



Key identifiers:

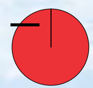
- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [ ] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

15

MYI (100%)



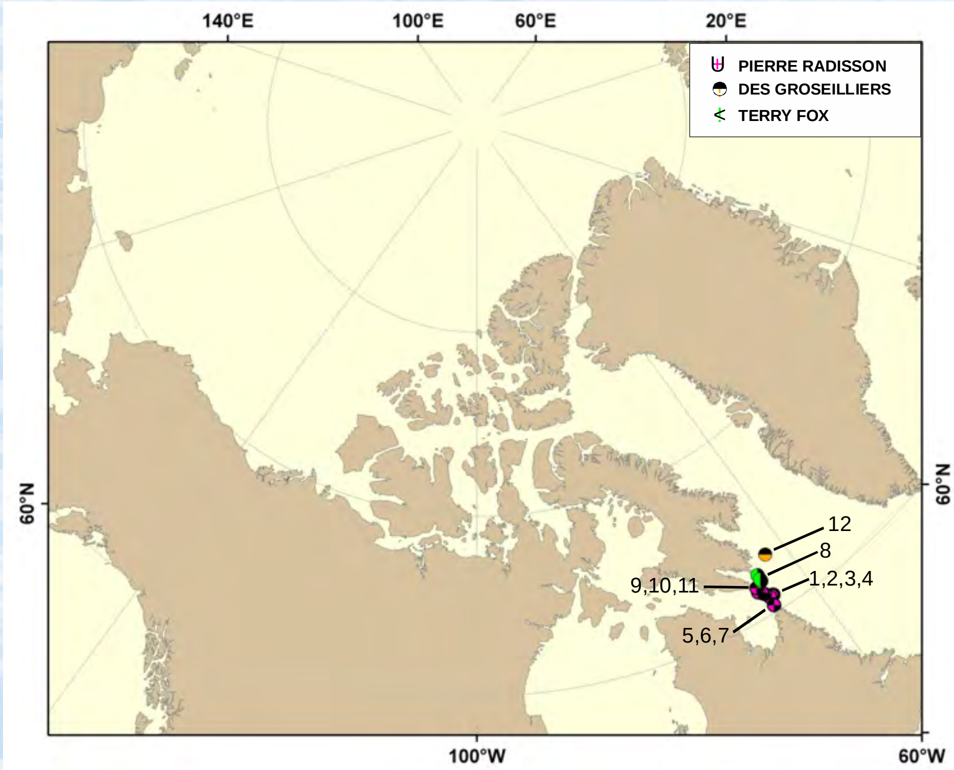
Confidence that it's multi-year ice: 100%

Floe size: 150 m

Est. average thickness: 8 m+

The freeboard and blue colour of the blocks of ice along the edges of this floe were the first indications that it was multi-year ice. The ridges are not as weathered as one usually sees on multi-year ice floes. We know that this is multi-year ice because on-ice measurements showed the ice to be more than 8 m thick at ten, randomly distributed stations on the floe. The floe's salinity and strength confirmed that it was multi-year ice. Its extremely rubbled surface (inset photo above) was likely first-year or second-year ice that overtopped the multi-year floe.

sub-Arctic

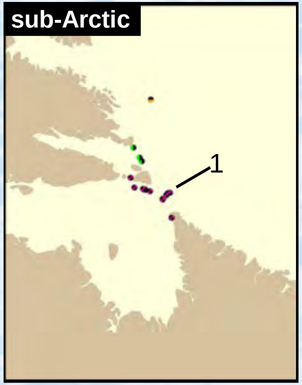


140°E
100°E
60°E
20°E
PIERRE RADISSON
DES GROSEILLIERS
TERRY FOX
60°N
60°N
12
8
1,2,3,4
9,10,11
5,6,7
100°W
60°W

Second-year ice

26 June

60°54’N, 64°17’W

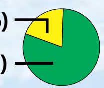


Key identifiers:

- [x] freeboard
- [x] floe size
- [ ] floe shape
- [ ] colour
- [ ] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)

Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred



Confidence that it’s second-year ice: 20%

Floe size: 100 m

Est. average thickness: 5 m

Foggy conditions made classifying this ice feature very difficult. This floe could be second-year ice because it has moderate freeboard, its hummocks are somewhat weathered and it has limited drainage patterns. But, given the area in which we are operating and my experience, I would say this feature is probably deformed first-year ice from a hummock field that has not decayed much.

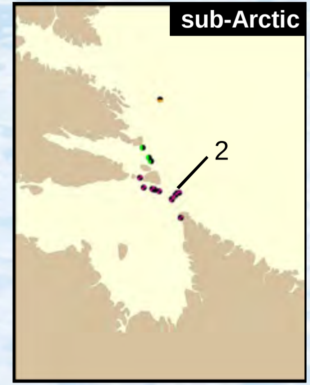
Multi-year ice

26 June

60°55'N, 64°23'W

Key identifiers:

- ☑ freeboard
- ☐ floe size
- ☐ floe shape
- ☑ colour
- ☐ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☐ other (see comments)



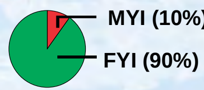
Ship response:

- ☐ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☐ Floe splitting occurred

Confidence that it's multi-year ice: 10%

Floe size: 25 m

Est. average thickness: 5 m

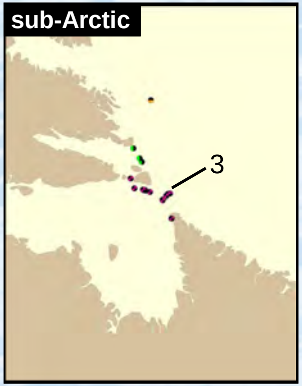


This feature is difficult to classify because it is so small (only 25 m across). It could be multi-year ice because it is weathered, dirty and thick. It could also be a small piece of ice from a bergy bit. Or it could be a fragment of first-year ice from a floeberg or hummock field. I would say that it is most likely thick, deformed first-year ice. Its maximum estimated freeboard is about 3 m.

Second-year ice

26 June

60°55’N, 64°23’W

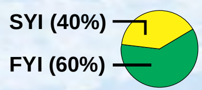


Key identifiers:

- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☐ colour
- ☐ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☐ other (see comments)

Ship response:

- ☐ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☐ Floe splitting occurred



Confidence that it’s second-year ice: 40%

Floe size: 150 m

Est. average thickness: 6 m

This floe’s thickness and hummocked features suggest second-year ice, but I can’t really tell from the ship under these foggy conditions. Given the time of year and the location, it is more likely first-year ice that hasn’t really started to decay yet.

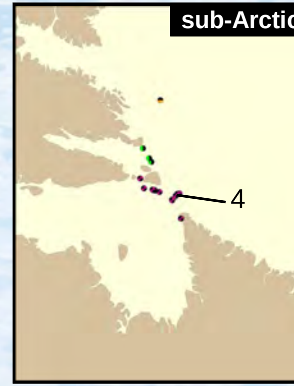
Multi-year ice

26 June

60°54'N, 64°30'W

Key identifiers:

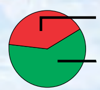
- ☑ freeboard
- ☐ floe size
- ☐ floe shape
- ☐ colour
- ☐ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☐ other (see comments)



Confidence that it's multi-year ice: 40%

Floe size: 300 m

Est. average thickness: 8 m



Ship response:

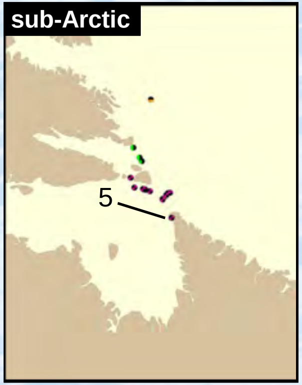
- ☐ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☐ Floe splitting occurred

This could be either multi-year ice or first-year ice. Its large, somewhat eroded ridges make me think multi-year ice, but the feature is more apt to be very deformed first-year ice that is not very weathered, since first-year hummock fields in this area can be massive. The freeboard of this ice feature is estimated to be at least 4 m.

Multi-year ice

27 June

60°23’N, 64°51’W

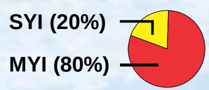


Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [ ] colour
- [ ] ponding/drainage
- [x] ice thickness
- [ ] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred



Confidence that it’s multi-year ice: 80%

Floe size: 150 m

Est. average thickness: 2.5 m

I would classify this feature as multi-year ice because its ponds are interlinked, its ridges are weathered and its freeboard is higher than the surrounding first-year ice. There is some chance that it is second-year ice, but I don’t really think so. It couldn’t be second-year ice that was originally from this area because first-year ice seldom survives the summer at this location. If the floe was imported into the area from further north, it must be multi-year ice because second-year ice probably wouldn’t have survived the journey so intact.

6

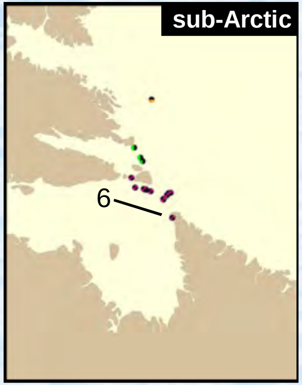
Multi-year ice

27 June

60°23'N, 64°51'W

Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)



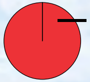
Ship response:

- [x] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

Confidence that it's multi-year ice: 100%

Floe size: 60 m

Est. average thickness: 4.5 m

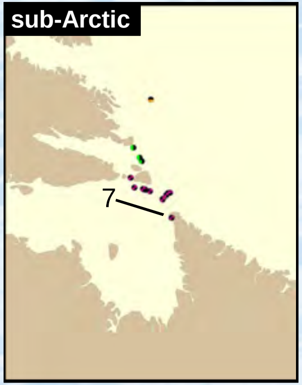


This is definitely a multi-year ice floe because it is so blue and it has considerably more freeboard than the surrounding first-year ice. The ice feature was very soft and rotten because when the floe slowly drifted into the ship, the ship's bow left a visible indentation in the ice.

Multi-year ice

28 June

60°23’N, 64°51’W



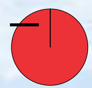
Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)

Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

MYI (100%)



Confidence that it’s multi-year ice: 100%

Floe size: 40 m

Est. average thickness: 4 m

This feature is easily recognized as multi-year ice because of its freeboard, colour, ponding, thickness and hummocked topography.

8

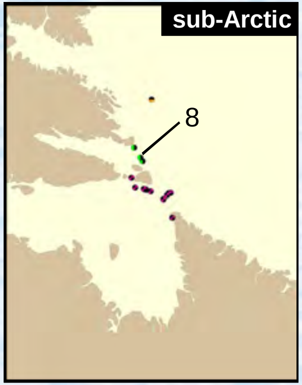
Second-year ice

2 July

61°54’N, 64°38’W

Key identifiers:

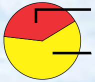
- [x] freeboard
- [x] floe size
- [ ] floe shape
- [ ] colour
- [ ] ponding/drainage
- [ ] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)



Confidence that it’s second-year ice: 60%

Floe size: 80 m

Est. average thickness: 3 m



Ship response:

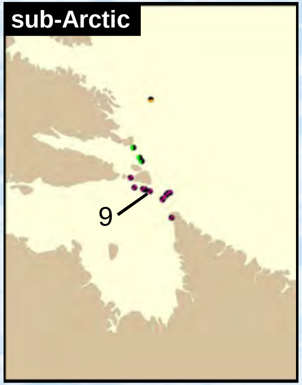
- [x] Ship impacted ice feature
- [ ] Backing and ramming was required
- [x] Floe splitting occurred

The freeboard, floe size, snow cover and recently developed hummocks suggest this is a second-year floe. However it could be multi-year ice because the ship’s speed decreased as it impacted the 80 m diameter floe. The floe split. Backing and ramming was not required.

Second-year ice

3 July

61°11’N, 65°05’W



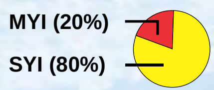
Key identifiers:

- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☐ colour
- ☑ ponding/drainage
- ☐ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☐ other (see comments)

Ship response:

- ☑ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☑ Floe splitting occurred

9



Confidence that it’s second-year ice: 80%

Floe size: 80 m

Est. average thickness: ?

This is likely a second-year ice floe because it is relatively smooth and, although it does not have much surface topography, its ridges are quite angular. The drainage features on this floe also suggest it is second-year ice (they are not as interconnected as drainage features on multi-year ice).

10

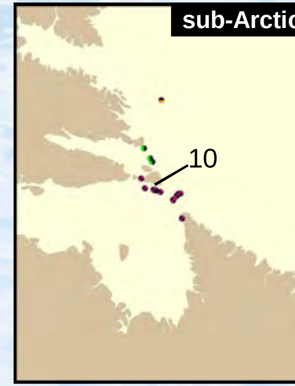
Second-year ice

3 July

61°17’N, 65°15’W

Key identifiers:

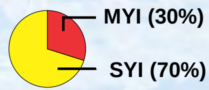
- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☐ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☐ other (see comments)



Confidence that it’s second-year ice: 70%

Floe size: 100 m

Est. average thickness: 4 m



Ship response:

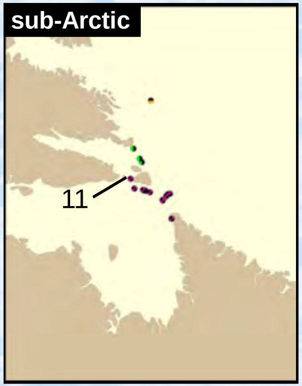
- ☐ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☐ Floe splitting occurred

I would characterize this as second-year ice because its surface features/ridges are somewhat angular. The ponds and the colour of the ice also indicate that it is second-year ice, but there is some chance that it could be multi-year ice.

Second-year ice

3 July

61°42’N, 65°34’W

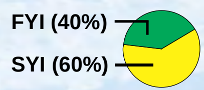


Key identifiers:

- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☐ colour
- ☐ ponding/drainage
- ☐ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☑ other (see comments)

Ship response:

- ☐ Ship impacted ice feature
- ☐ Backing and ramming was required
- ☐ Floe splitting occurred



Confidence that it’s second-year ice: 60%

Floe size: 75 m

Est. average thickness: 5 m

This might be second-year ice because its surface features/ridges are somewhat angular. Or it could be very deformed first-year ice that has not yet decayed since much of the first-year ice in this area is deformed by winds pushing it against the coast.

12

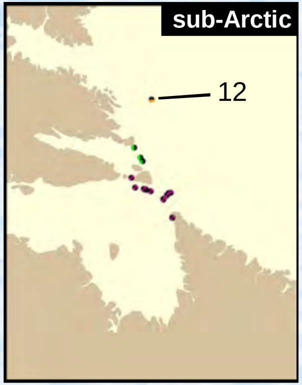
Multi-year ice

14 July

63°02’N, 62°30’W

Key identifiers:

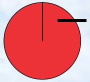
- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [ ] hummocked
- [x] snow cover
- [ ] sound when hit
- [ ] other (see comments)



Confidence that it’s multi-year ice: 100%

Floe size: 60 m

Est. average thickness: 5 to 6 m



Ship response:

- [ ] Ship impacted ice feature
- [ ] Backing and ramming was required
- [ ] Floe splitting occurred

The freeboard, colour, ponding, thickness and snow cover on this floe characterize it as multi-year ice. We often encounter similar multi-year ice floes in this area. Some of the floes, like this one, are probably remnants of multi-year ridges that have drifted south along the coast of Baffin Island.

Aerial Observations

Aerial Reconnaissance in Support of Arctic Operations

The same Key Identifiers that are used to characterize ice from a ship or structure are also appropriate for assessing the ice during aerial reconnaissance. Aircraft often provide a better perspective from which to characterize the ice than the ship's bridge or an offshore structure. Drainage or ponding – one of the most widely used Key Identifiers for discriminating ice types – is much more evident from the air. The same is true when gauging the size and shape of a floe. That is why aerial reconnaissance can be the deciding factor for determining whether a feature qualifies as first-year, second-year or multi-year ice.

Historically, aerial reconnaissance played an essential role in the preparation of Ice Charts; it provided the only means of gathering detailed information about ice conditions over large areas. The advent of onboard satellite synthetic aperture radar (SAR) sensors, which can penetrate cloud cover and darkness, decreased the importance of aerial reconnaissance. Aerial patrols of the Arctic are still conducted; one such example being the Marine Aerial Reconnaissance Team (MART), formed as a partnership between Environment Canada's Canadian Ice Service (CIS) and Transport Canada Marine Safety (TCMS). The MART was established in 2005 to conduct pollution and ice patrols in the Canadian Arctic. Aerial reconnaissance is also still used by Government and Industry, especially in spring and summer, when C-band SAR sensors have difficulty distinguishing old ice from first-year ice, as discussed in *Satellite Observations*.

Most Canadian Coast Guard icebreakers have a helicopter onboard to "look ahead" at the ice conditions – anticipating ice conditions is a necessary requirement for Coast Guard to fulfill their mandate. Many of the aerial observations in this section were obtained by ISSs during reconnaissances conducted from Canadian Coast Guard icebreakers. Aerial photographs of some of the features discussed in *On-ice Measurements* are also included. In fact, assessing floes from the air during a reconnaissance was the means by which floes were selected for on-ice measurements.

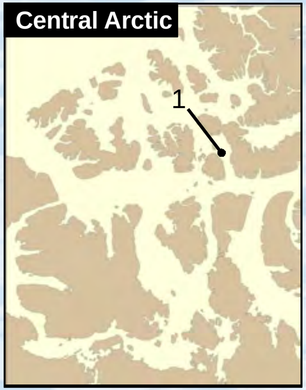
The floe thicknesses reported in this section were either obtained from on-ice measurements or were estimated from the air (based upon the floe's surface topography or freeboard). Most of the floe thicknesses estimated from the air are less than thicknesses obtained from actual drill hole measurements. That underscores the fact that the old ice can be much thicker than it looks – whether it is viewed from the air, a ship's bridge or an offshore platform.

Rotten first-year ice (mostly grey colour) sandwiched between two decayed multi-year ice floes (mostly white colour). Many Key Identifiers, such as the interconnectedness of ponds, are better seen from the air than from the ship's bridge.

Multi-year ice

24 May
75°17'N, 93°13'W

1



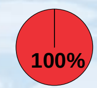
Key identifiers:

- [ ] freeboard
- [ ] floe size
- [x] floe shape
- [ ] colour
- [ ] ponding/drainage
- [x] ice thickness
- [ ] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

Confidence that it's multi-year ice: 100%

Floe size: 200 m

Average drill hole thickness: 7.2 m



This floe was part of a larger, aggregate floe that was identified in a RADARSAT image prior to arriving in the field (see *Satellite Observations,* observation #1). A relatively flat region of multi-year ice was selected for sampling ("M" in the photo). The upturned edges of this 200 m diameter floe confirmed that it was multi-year ice. Ice thickness measurements ranged from 3.2 to 15 m, with an average of 7.2 m (see *On-ice Thickness Measurements*, observation #1)

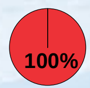
Multi-year ice

26 June
60°55’N, 64°23’W

Key identifiers:

- [ ] freeboard
- [ ] floe size
- [x] floe shape
- [ ] colour
- [ ] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

Confidence that it’s multi-year ice: 100%



Floe size: 50 m x 250 m

Average drill hole thickness: 8.1 m

This floe was in an area of multi-year ice located between Cornwallis Island and Little Cornwallis Island (see *Satellite Observations*, observation #2). The prominent 3.5 m high hummock in this photo separated two multi-year floes. The sampled floe (this side of the hummock, “M”) looked thick, had rounded edges and was estimated to be about 50 m wide and 250 m long. Thicknesses at 23 drill holes ranged from 1.9 to 16.9 m, with an average of 8.1 m (as discussed in *On-ice Thickness Measurements*, observation #2).

Multi-year ice

2 July
75°40'N, 97°10'W

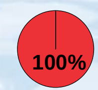
Key identifiers:

- [x] freeboard
- [ ] floe size
- [x] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

Confidence that it's multi-year ice: 100%

Floe size: 200 m

Average thickness along crest of hummock: 6.8 m



This floe was only about 200 m across. Clearly, it was multi-year ice because it floated higher, had rounded edges and turquoise blue melt ponds. The 2.5 m high hummock was also weathered, with gradually sloping sides. This floe was one of two multi-year floes visited earlier in the summer (the other floe is discussed in *Properties of a Multi-year Hummock*). The ice thicknesses at four holes drilled along the crest of the hummock were 6.21, 6.84, 7.12 and 7.24 m. Salinity and strength measurements confirmed that this was multi-year ice.

4

Multi-year ice

22 July
70°33’N, 160°49’W

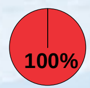
Key identifiers:

- [x] freeboard
- [ ] floe size
- [x] floe shape
- [ ] colour
- [x] ponding/drainage
- [ ] ice thickness
- [ ] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

Confidence that it’s multi-year ice: 100%

Floe size: 800 m

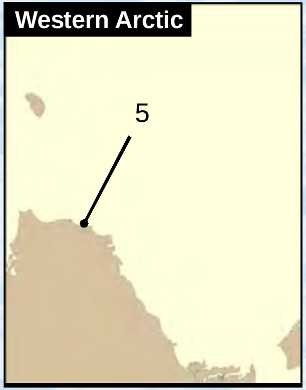
Estimated average thickness: 5 m



The first hint that this was old ice was that it was different than the surrounding ice floes. The surrounding first-year ice was very decayed, while this floe was intact. It had a smooth, weathered surface, well-established drainage patterns, high freeboard and the edges of the floe were rounded. This is an aggregate floe, comprised of multi-year ice held together by what looks like second-year ice. I am certain about the multi-year ice (100% confidence), but I am less certain calling the thinner ice holding it together second-year ice (60% confidence) because it could be first-year ice.

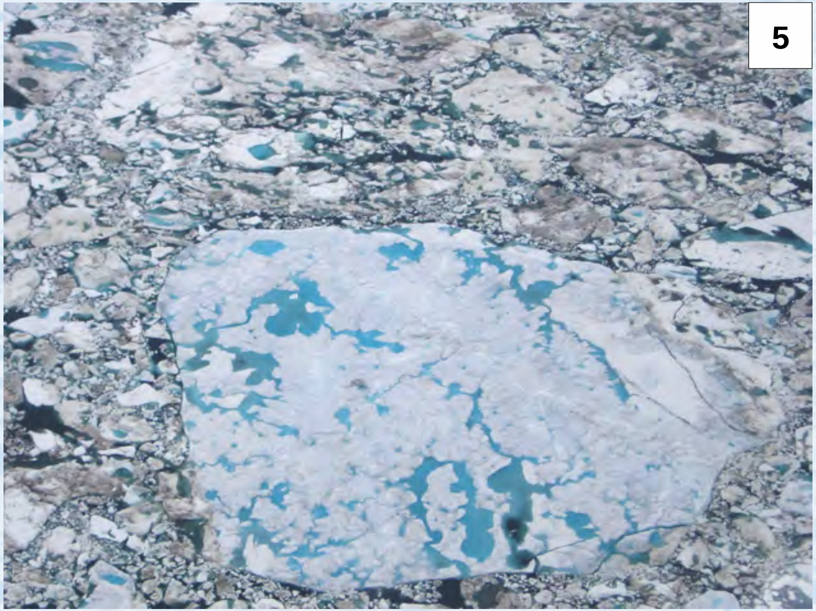
Multi-year ice

22 July
70°39'N, 160°16'W



Key identifiers:

- [x] freeboard
- [ ] floe size
- [x] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)



Confidence that it's multi-year ice: 100%

Floe size: 150 m

Estimated average thickness: 5 m

100%

This was clearly a multi-year floe because it floated higher, had blue melt ponds, was hummocked, had rounded edges and well-established drainage patterns. This multi-year ice floe was very different than the surrounding rubbled, dirty first-year ice.

6

Multi-year ice

26 July
74°32'N, 66°56'W

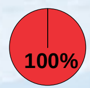
Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [ ] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)

Confidence that it's multi-year ice: 100%

Floe size: 80 m

Estimated average thickness: ?



From the air, the first signs that this is a multi-year floe include the colour of its ponds and its weathered hummocks. The well-established drainage features also identify this as multi-year ice.

Multi-year ice

30 July
70°16'N, 99°47'W

Key identifiers:

- [x] freeboard
- [x] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)

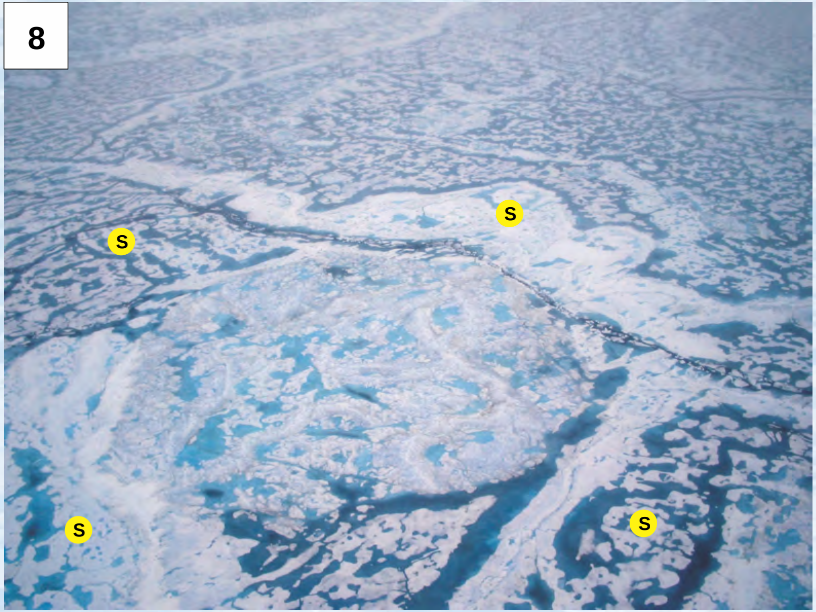
Confidence that it's multi-year ice: 100%

Floe size: 4 km

Estimated average thickness: ?

We can easily recognize the multi-year floes in this area of fast ice because of their freeboard, floe size, turquoise blue colour and their well-established drainage features. They are also very thick and have weathered hummocks. The multi-year ice floe in this photo (denoted by an "M") is about 4 km in diameter. The decayed second-year ice around it is discussed on the opposite page.

8



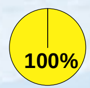
Second-year ice

30 July
70°16’N, 99°47’W

Key identifiers:

- [ ] freeboard
- [ ] floe size
- [ ] floe shape
- [ ] colour
- [ ] ponding/drainage
- [ ] ice thickness
- [ ] hummocked
- [ ] snow cover
- [x] sound when hit
- [x] other (see comments)

Confidence that it’s second-year ice: 100%



Floe size: fast ice

Estimated average thickness: 1 m

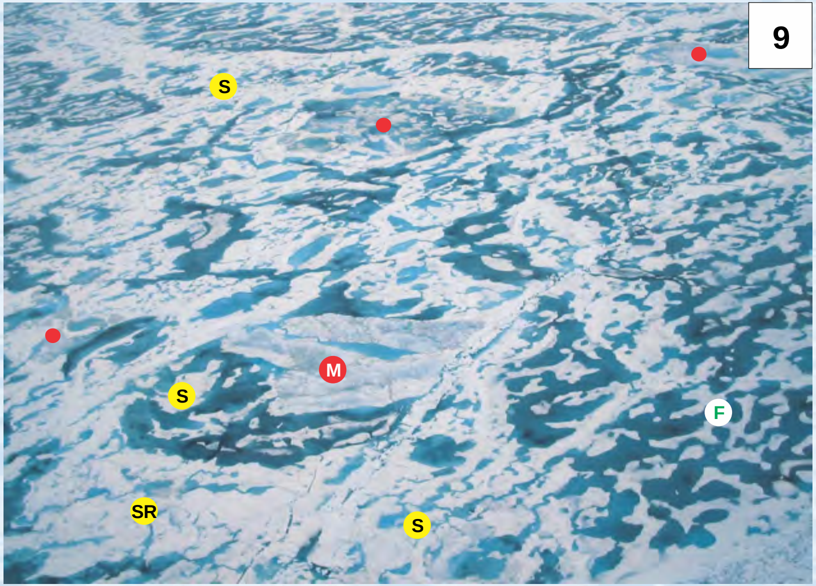
The fast ice surrounding the 4 km diameter multi-year floe (see opposite page) is only about one metre thick, but it must be second-year ice (“S” in photo) because this area of first-year ice didn’t melt last summer. The level second-year ice caused the same kind of ship response as first-year ice normally does. The ridged second-year ice was harder to transit, but it certainly wasn’t as solid as multi-year ice.

Multi-year ice

31 July
69°41'N, 99°45'W

Key identifiers:

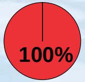
- ☑ freeboard
- ☑ floe size
- ☐ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☑ other (see comments)



Confidence that it's multi-year ice: 100%

Floe size: 300 m

Estimated average thickness: ?



This photograph includes several small and medium multi-year floes surrounded by second-year and first-year ice. It is easy to identify the multi-year floes in this area because they are dirty (red markers in photo). The multi-year floe marked "M" is about 300 m in diameter. The second-year ice is white and looks like dried ice ("S"). The first-year ice is flooded and dark grey ("F"). The ridged second-year ice in the photo ("SR") was weathered, but not as much as multi-year ice. As the ship penetrated the second-year ice, its speed slowed about 2 kn, but when the ship tried to penetrate the multi-year floe ("M") it came to a full stop. Two backing and ramming sequences were needed to split that multi-year floe.

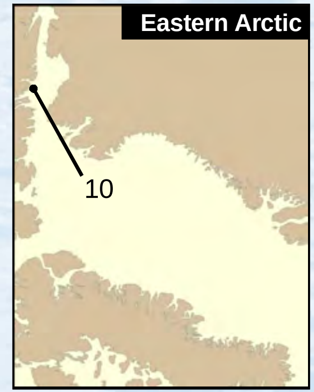
10

Multi-year ice

11 August
79°14'N, 72°45'W

Key identifiers:

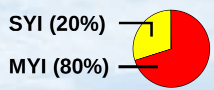
- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [ ] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [ ] other (see comments)



Confidence that it's multi-year ice: 80%

Floe size: 400 m

Estimated average thickness: 3 m



This floe is most likely multi-year ice because it floats higher in the water, is blue in colour, has well-defined drainage features and weathered hummocks. There is some chance that it could be second-year ice, however, because some of its ridges look fairly fresh.

Multi-year ice

12 August
78°38N, 73°33'W

Key identifiers:

- [x] freeboard
- [x] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

Confidence that it's multi-year ice: 100%

Floe size: 4 km

Average drill hole thickness of level ice: 4.8 m

The maze of melt ponds covering the surface of this floe provide an excellent example of the well-established drainage patterns that characterize multi-year ice. Portions of the floe were extremely level, but it also had very rough, hummocked areas of ice. Thickness at 30 drill holes in a relatively level area of ice ranged from 1.7 to 8.5 m, with an average of 4.8 m (see *On-ice Thickness Measurements*, observation #4).

Multi-year ice

11 August
79°14’N, 72°45’W

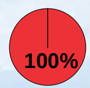
Key identifiers:

- ☑ freeboard
- ☑ floe size
- ☑ floe shape
- ☐ colour
- ☐ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☑ other (see comments)

Confidence that it’s multi-year ice: 100%

Floe size: 500 m

Average drill hole thickness of ice (hummock excepted): 10.2+ m



This floe was only about 500 m in diameter, but its 4 m high ridge promised very thick ice. This multi-year ice floe was not blue and its drainage was not that well established. Thicknesses at 19 holes ranged from 5.8 m to more than 16 m. On average, the ice was more than 10.2 m thick (see *On-ice Thickness Measurements*, observation #6).

Multi-year ice

22 August
80°40’N, 68°23’W

Key identifiers:

- [ ] freeboard
- [ ] floe size
- [ ] floe shape
- [ ] colour
- [x] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

Confidence that it’s multi-year ice: 100%

Floe size: 500 m x 200 m

Average thickness of relatively level ice: 5.2 m

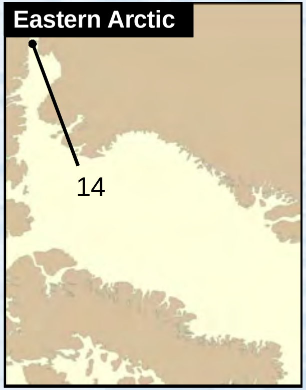
This floe was only about 500 m long and 200 m wide, but it was the largest floe that we could find this close to Ellesmere Island. The surface of the floe had the characteristic undulations of multi-year ice and a well-established drainage network. Ice thicknesses at 30 drill holes ranged from 2.1 to 8.4 m, with an average thickness of 5.2 m. Salinity and strength profiles of the ice confirmed that it was a multi-year floe (see *On-ice Thickness Measurements*, observation #7).

Multi-year ice

24 August
80°37'N, 67°42'W

Key identifiers:

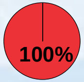
- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☑ colour
- ☑ ponding/drainage
- ☐ ice thickness
- ☑ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☑ other (see comments)



Confidence that it's multi-year ice: 100%

Floe size: 600 m

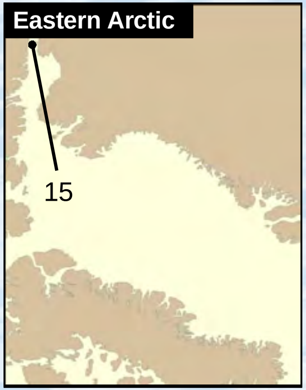
Average drill hole thickness: ?



The extensive drainage patterns, colour and smoothed topography identified this as multi-year ice. Note the very different appearance (and drainage patterns) of the decayed first-year floe just behind this multi-year floe.

Second-year ice

26 August
80°24'N, 67°37'W



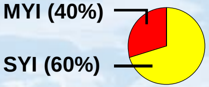
Key identifiers:

- ☐ freeboard
- ☐ floe size
- ☐ floe shape
- ☑ colour
- ☐ ponding/drainage
- ☑ ice thickness
- ☐ hummocked
- ☐ snow cover
- ☐ sound when hit
- ☑ other (see comments)

Confidence that it's second-year ice: 60%

Floe size: 200 m

Measured thickness: 3 to 4 m



It was difficult to tell whether this was very young, decayed multi-year ice or second-year ice. The colour of the ponds, drainage features, lack of surface relief and thickness all suggested second-year ice. However, the ice on the right side of the floe had a different texture, its ponds were bluer and it looked thicker – indicating perhaps, multi-year ice. The 3 to 4 m thickness (at four holes), salinity and strength indicated that the main part of the floe was likely second-year ice. This could be another example of a floe that is part second-year ice and part multi-year ice (see also *Ship-based Observations, Eastern Arctic* #11).

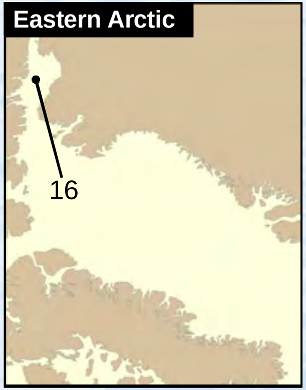
16

Multi-year ice

24 August
79°23'N, 70°46'W

Key identifiers:

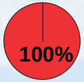
- [ ] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [x] ponding/drainage
- [ ] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)



Confidence that it's multi-year ice: 100%

Floe size: 5 km x 2.5 km

Measured thickness: 3 to 8.5 m



This 5 km long aggregate floe was comprised of many different multi-year ice floes, and probably second-year ice in between. On-ice properties were made towards the far end of the floe ("M"). Two tabular icebergs (shown by arrows) flanked the left side of this large multi-year floe. Ice thickness at three places on the floe were 3.3 m, 5.0 m and 8.5 m, with the thinnest ice being near the edge of a pond. Temperature, salinity and strength measurements confirmed this as multi-year ice. The CCGS *Henry Larsen* (circled in photo) patiently waits at the edge of the floe for the field party to return.

Multi-year ice

31 August
75°50'N, 80°05'W

Key identifiers:

- [x] freeboard
- [x] floe size
- [x] floe shape
- [ ] colour
- [ ] ponding/drainage
- [x] ice thickness
- [x] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

Confidence that it's multi-year ice: 100%

Floe size: 150 m x 200 m

Average thickness of relatively level ice: 3.6 m

This multi-year ice floe was one of the few floes in the area large enough to sample. It was only about 200 m across and drifted at an average rate of 2.1 km/hr while it was sampled over the course of the day. Other floes jostled against this floe as it drifted east in Lady Anne Strait. Its hummocked surface indicated multi-year ice, as did its blue melt ponds and drainage patterns. Ice thicknesses at 38 drill holes ranged from 2.3 to 5.0 m, with an average thickness of 3.6 m. Temperature, salinity and strength measurements confirmed that it was multi-year ice (see *On-ice Thickness Measurements*, observation #10).

18

Multi-year ice

12 October
75°14'N, 78°20'W

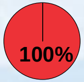
Key identifiers:

- [x] freeboard
- [ ] floe size
- [ ] floe shape
- [x] colour
- [ ] ponding/drainage
- [x] ice thickness
- [ ] hummocked
- [ ] snow cover
- [ ] sound when hit
- [x] other (see comments)

Confidence that it's multi-year ice: 100%

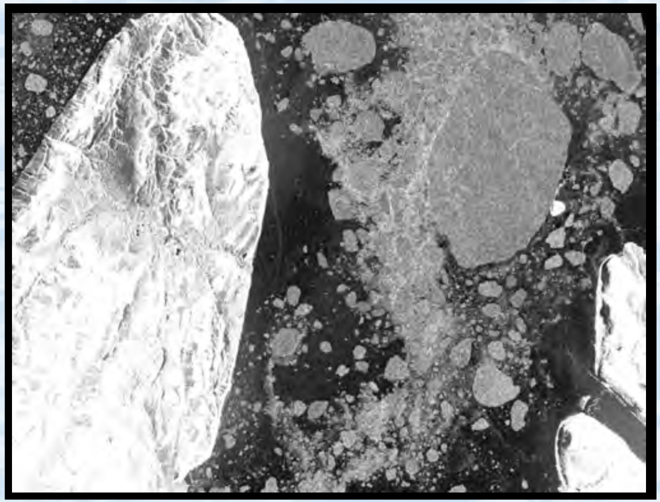
Floe size: 150 m

Measured thickness: 8+ m



This multi-year floe was surrounded by icebergs, smaller fragments of multi-year floes and newly formed first-year ice as it drifted south along the coast of Devon Island. The floe was only 150 m in diameter, but it was the largest floe that we could find in the area. It had large, blue blocks of multi-year ice piled at one end and a prominent ridge along its back edge. The jagged rubble that covered the surface of this floe made walking difficult. The ice at five drill holes (distributed across the floe) was more than 8 m thick. Ice salinity and strength profiles confirmed that this was a multi-year floe, covered by what was likely first-year rubble.

Satellite Observations



Obtaining Ice Information from Satellite Imagery

The RADARSAT-1 images included in this section show selected ice features from *On-Ice Measurements*, *Ship-based Observations* and *Aerial Observations* from the satellite perspective. Satellite imagery is used routinely by CIS Ice Service Specialists (ISS) on Coast Guard ships to support safe and efficient navigation in and around ice. The ISS integrates information from the satellite image with visual observations, to advise the bridge on optimal ship routing. CIS Operations have since transitioned to RADARSAT-2, and more recently to the RADARSAT Constellation Mission (RCM). While these newer satellites offer many capabilities for improved ice detection, the concepts outset in this section (using RADARSAT-1 imagery) remain relevant.

RADARSAT is a synthetic aperture radar (SAR) that transmits and receives electromagnetic energy in C-band (5.3 GHz), giving it the ability to penetrate cloud cover and darkness – conditions that present severe limitations to many other types of satellite technology. For the cold periods, the appearance of sea ice in RADARSAT (and other C-Band) imagery is a function of both the micro- and macro-scale roughness of sea ice, and the salinity and microstructure of the upper layers of sea ice. The penetration of C-band SAR is first determined by the salinity of the sea ice – the higher the salinity, the less penetration. As such, the SAR signature of saltier new ice, young ice and first-year ice is dominated by strong surface scattering. If the surface is smooth, the ice appears dark in imagery as most of the energy is reflected away from the sensor. If the surface is rough, e.g. ridged FYI or pancake floe edges, the ice returns a brighter signature. C-band SAR penetrates further into the normally less saline multi-year ice, interacting with its air bubbles/inclusions. This promotes volume scattering which results in a strong return and a brighter appearance in the imagery – often much brighter than seasonal ice. That is partly why cold first-year ice appears grey (low return) in a SAR image, and cold multi-year ice appears white (high return). The reader is referred to Shokr and Sinha (2015) for a discussion how ice microstructure affects the microwave signature of first-year and old ice.

RADARSAT's C-banÇ frequency allows for good separation of first-year ice and multi-year ice in fall, winter and early spring, when the ice surface is sufficiently cold and dry. When warm temperatures increase the amount of water in the snow layer which typically covers seasonal and multi-year ice, C-band SAR has difficulty penetrating to the underlying ice. The resultant signature is dominated by scattering and absorption in the snowpack and as such, it becomes more difficult to distinguish between the underlying ice types. Ice typing continues to be difficult after the snow volume fully melts and ponds dominate the sea ice surface. Even skilled interpreters have difficulty separating first-year ice from water during the spring/summer melt period – or, more importantly, discriminating old ice from first-year ice.

RADARSAT can collect imagery at a variety of resolutions (3 to 100 m) over a wide range of swath widths (25 to 500 km). ScanSAR Wide is the preferred RADARSAT mode for ice surveillance. ScanSAR provides the best balance between resolution (100 m nominal resolution) and coverage (500 km swath) for operational ice monitoring, however the following pages show that it is not usually possible to identify small (<500 m) multi-year ice floes in ScanSAR imagery. On the other hand, several examples of RADARSAT Standard imagery (25 m nominal resolution) are used to illustrate that superior image quality comes at the expense of coverage (100 km).

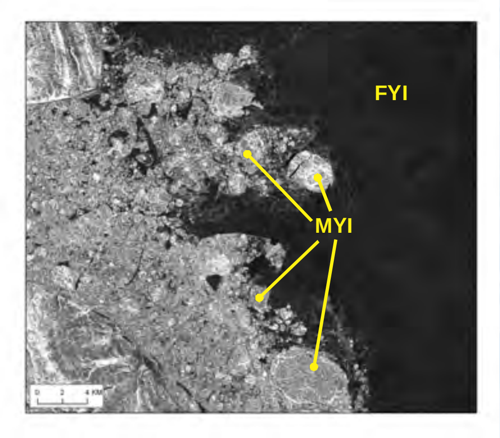
New sensors such as PALSAR (L-band) have been, and will continue to be, developed. A concerted effort is underway to understand if and how these sensors can improve sea ice detection and monitoring. It is hoped that they will improve ice detection during the warm periods, but until then, the observer must use visual observation as her/his primary means of detection.

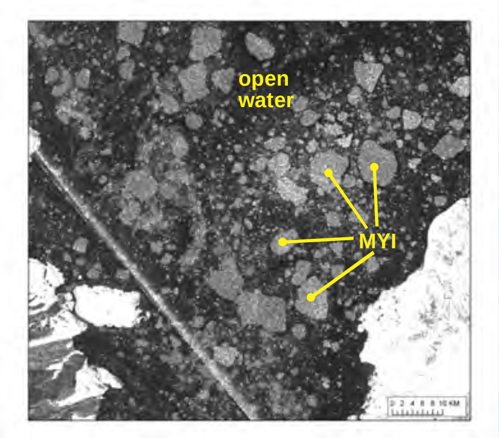
Obtaining Ice Information from Satellite Imagery

Experienced interpreters can reliably ‘type’, or classify, different stages of first-year ice (see *Growth and Ageing of First-year Ice*) in satellite imagery because they each have a characteristic microwave signature. That is how the relative thickness of the different stages of first-year ice is obtained from SAR imagery. However, once sea ice reaches the stage of second-year or multi-year ice, it is generally called “old ice”, regardless of how thick it is. That is unfortunate, but it stems from the fact that second-year and multi-year ice usually appear very similar iå satellite imagery, although exceptions do apply.

It is not yet possible to measure ice thickness directly (and accurately) from space because satellite SARs cannot penetrate through the full thickness of ice. At present, no satellite sensor gives reliable ice thickness data at resolutions required for operational work. Ice thickness estimates from satellite-based sensors necessitate continued validation (Kwok et al., 2007; Laxon et al., 2013; Kwok, 2015), yet the spatial averaging effect of those sensors make validating their thickness estimates difficult. The observations in this Guide show that ice freeboard varies a great deal for the same floe, for different floes, and that it depends upon the time of year (see also Johnston 2019-a). The same is true for ice density (Timco and Frederking, 1996), which is an important consideration when relating ice draft or ice freeboard to ice thickness.

Until technology provides a means of reliably differentiating first-year, second-year and multi-year ice throughout the year, the operator must use visual observations as his/her primary means of identification. Nevertheless, the examples in this section demonstrate that satellite imagery can be a very useful ‘tool’ for ensuring safe and effective operations in ice-covered waters.





RADARSAT-1 images of multi-year ice and first-year ice in May, Wellington Channel (*near right*) and multi-year floes drifting in open water in August, Kane Basin (*far right*). Multi-year ice appears light grey or white in both images, whereas first-year ice and open water appear dark grey.

Image of Wellington Channel was acquired in Standard mode. Image of Kane Basin was acquired in ScanSAR mode.

Multi-year ice

24 May

75°17’N, 93°13’W

Key identifiers:

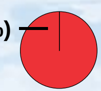
- ☑ floe shape
- ☑ ice thickness
- ☑ other (see observation #1, *On-ice Thickness Measurements*)

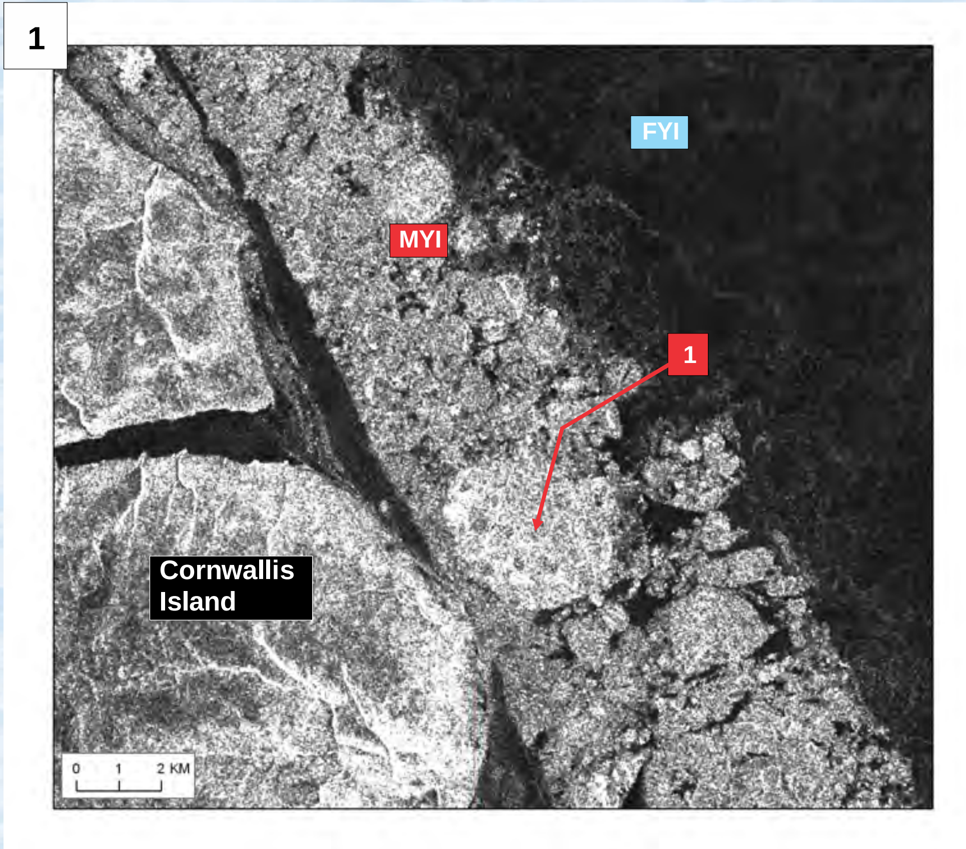
1

Confidence that it’s multi-year ice: 100%

Floe size: 200 m

Average thickness from drill hole measurements: 7.2 m





Multi-year ice

24 May

75°17’N, 93°13’W

Type of image:
RADARSAT Standard

Observation date/time:
13 May (23:17UTC)

Date/time of image:
24 May (12:00UTC)

In this RADARSAT Standard image, the east coast of Cornwallis Island is shown by the thin red line. The white-looking ice along the coastline is multi-year ice. The uniformly dark grey ice in the right side of the image is mostly level first-yÉar ice. This image was acquired several weeks before arriving in the field. Since all of the ice in this image was landfast, conditions in the image acquired on 13 May are exactly as seen in the field on 24 May.

The sampled 200 m diameter multi-year floe was part of a 3.8 km diameter aggregate floe. The Standard image shows the aggregate floe quite well, but it is difficult to see the outline of the 200 m diameter multi-year floe on which thickness measurements were made.

Multi-year ice

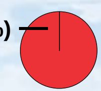
27 May
75°32’N, 95°50’W

Central Arctic

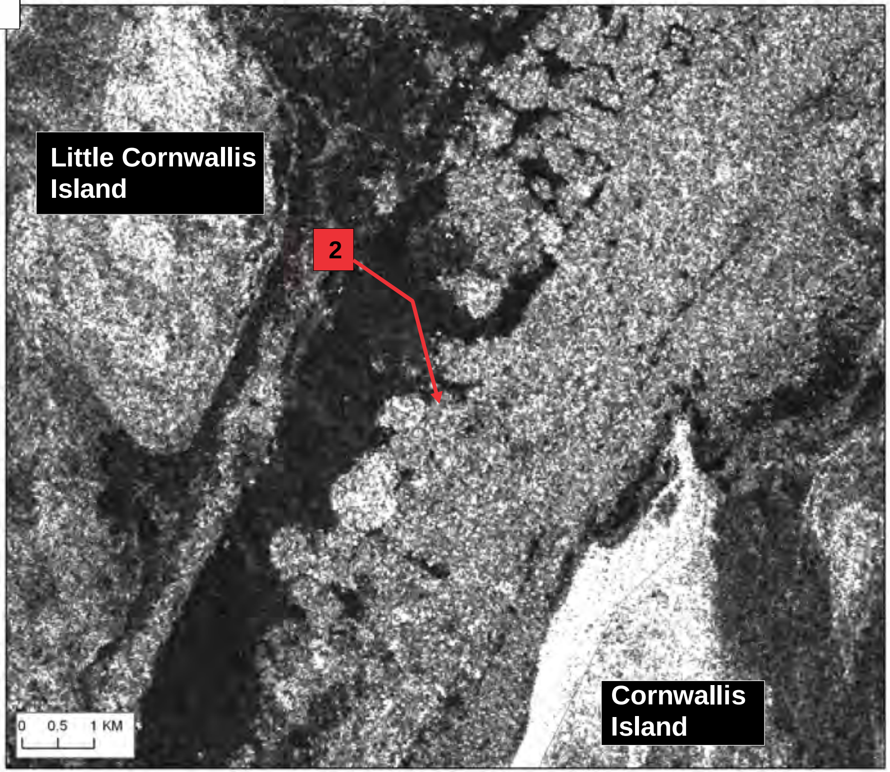
Key identifiers:

- ☑ floe shape
- ☑ ice thickness
- ☑ hummocked
- ☑ other (see observation #2, *On-ice Thickness Measurements*)

Confidence that it’s multi-year ice: 100%
Floe size: 50 m x 250 m
Average thickness from drill hole measurements: 8.1 m



2



Multi-year ice

27 May

75°32'N, 95°50'W

Type of image:
RADARSAT Standard

Observation date/time:
13 May (23:17UTC)

Date/time of image:
27 May (12:00UTC)

This RADARSAT Standard image shows a strip of landfast multi-year ice (about 3.5 km wide) between Little Cornwallis Island and Cornwallis Island. It is not possible to identify the multi-year floe on which ice thickness measurements were made. However, the GPS coordinates and the flight pattern used to circle the floe indicated that the 50 x 250 m floe was near the kidney-shaped region shown by the arrow.

Multi-year ice

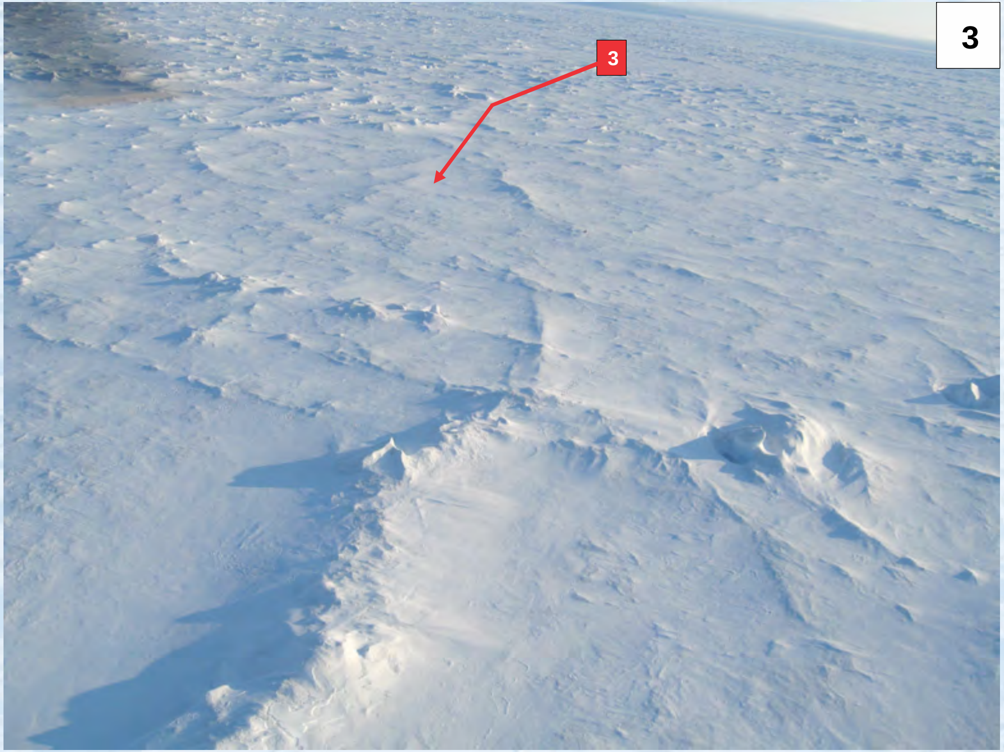
30 May

75°41'N, 93°41'W

Key identifiers:

- ☑ floe shape
- ☑ ice thickness
- ☑ hummocked
- ☑ other (see comments in *On-ice Thickness Measurements*, observation #3)

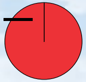
3



Confidence that it's multi-year ice: 100%

Floe size: 300 m

Average thickness from drill hole measurements: 8.6 m



Multi-year ice

30 May
75°41'N, 93°41'W

Type of image:
RADARSAT Standard

Observation date/time:
13 May (23:17UTC)

Date/time of image:
30 May (12:00UTC)

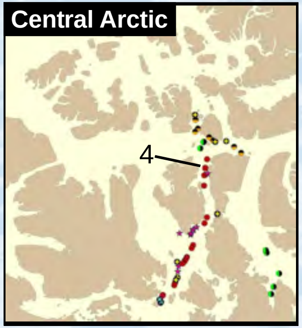
The 300 m diameter floe on which ice thickness measurements were made was part of an aggregate landfast floe (3.6 km in diameter). The satellite image clearly shows the aggregate floe. A re-frozen lead (dark grey line) formed at the north end of the floe, evidently when the floe pulled apart earlier in the season. The Twin Otter used that lead as a landing strip. The lead was no more than 100 m across.

The GPS coordinates and flight trajectory made it possible to identify the 300 m diameter floe on which measurements were made (arrow). The pair of similarly shaped floes (see previous page) are oriented NW-SE in the image, and were separated by ridged ice (linear white feature).

Second-year ice

19 July

73°26'N, 96°09'W



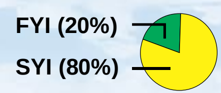
Key identifiers:

- ✔ freeboard
- ✔ floe size
- ✔ colour
- ✔ ponding/drainage
- ✔ ice thickness
- ✔ hummocked
- ✔ sound when hit
- ✔ other (see ship-based observation #1, *Central Arctic*)

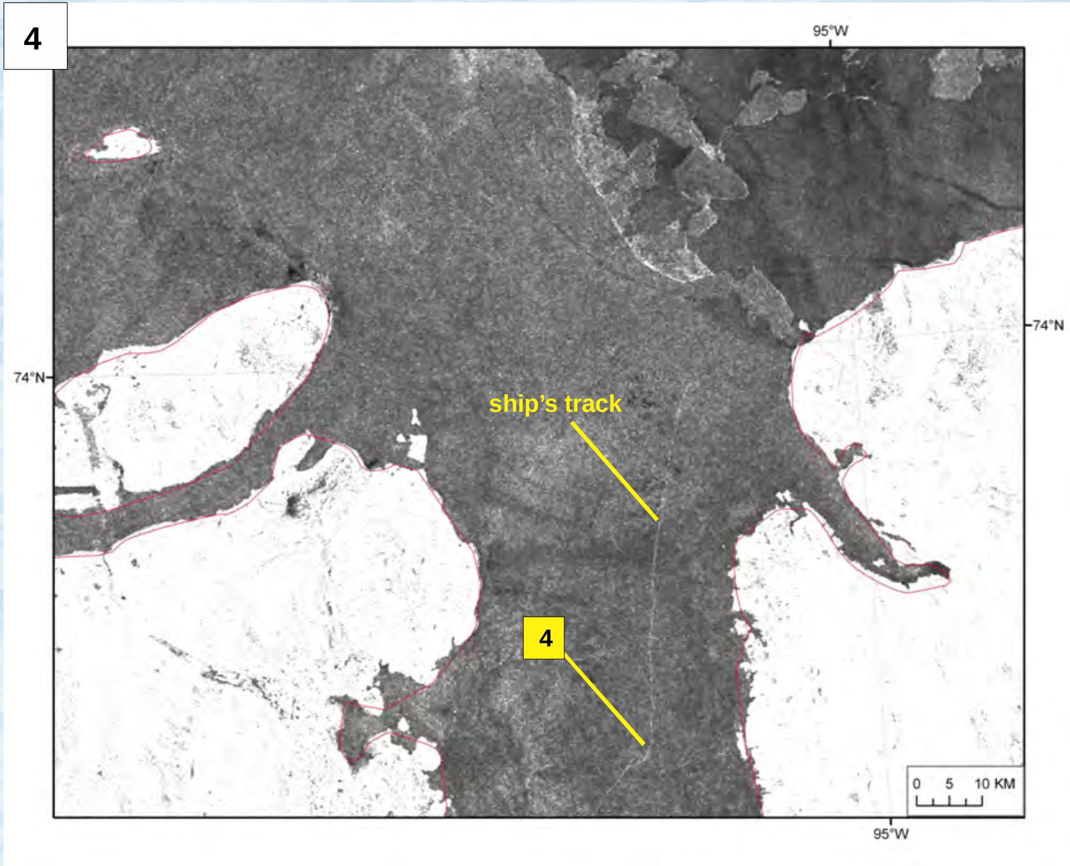
Confidence that it's second-year ice: 80%

Floe size: 10 km+

Est. average thickness: ?



4



Second-year ice

19 July
73°26'N, 96°09'W

Type of image:
RADARSAT ScanSAR

Observation date/time:
19 July (13:15UTC)

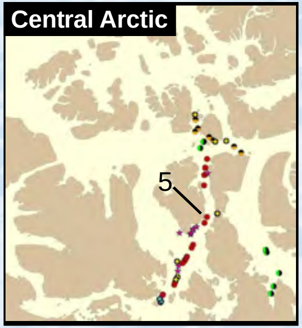
Date/time of image:
19 July (23:29UTC)

The ship's track is visible passing through the landfast ice in Peel Sound but the outline of the 10 km+ diameter second-year floe cannot be seen in this RADARSAT ScanSAR image. Since the image was acquired after the ship encountered the giant second-year floe, the ship's track can be seen passing south of the floe.

Multi-year ice

20 July

71°52’N, 96°13’W



Key identifiers:

- ✔ colour
- ✔ hummocked
- ✔ snow cover
- ✔ other (see ship-based observation #3, *Central Arctic*)

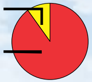
Confidence that it’s multi-year ice: 90%

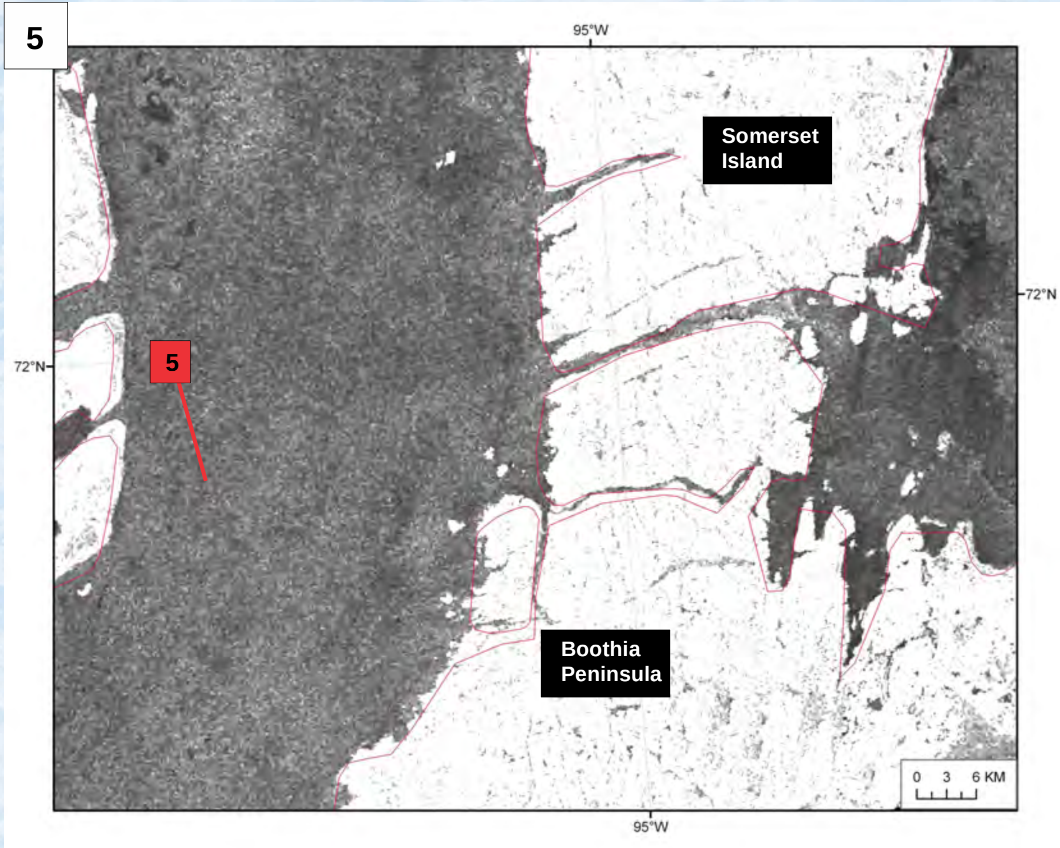
Floe size: 150 to 200 m

Est. average thickness: 7 m

SYI (10%)

MYI (90%)





Multi-year ice

20 July

71°52'N, 96°13'W

Type of image:
RADARSAT ScanSAR

Observation date/time:
20 July (20:10UTC)

Date/time of image:
19 July (23:29UTC)

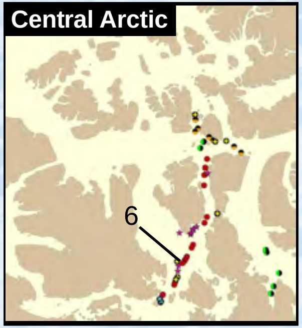
The 150 to 200 m diameter landfast multi-year floe is not visible in this RADARSAT ScanSAR image.

The ship's track is not visible in the image because the image was acquired the day before the ship passed through the region.

Multi-year ice

22 July

70°17’N, 98°56’W



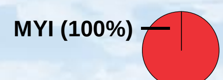
Key identifiers:

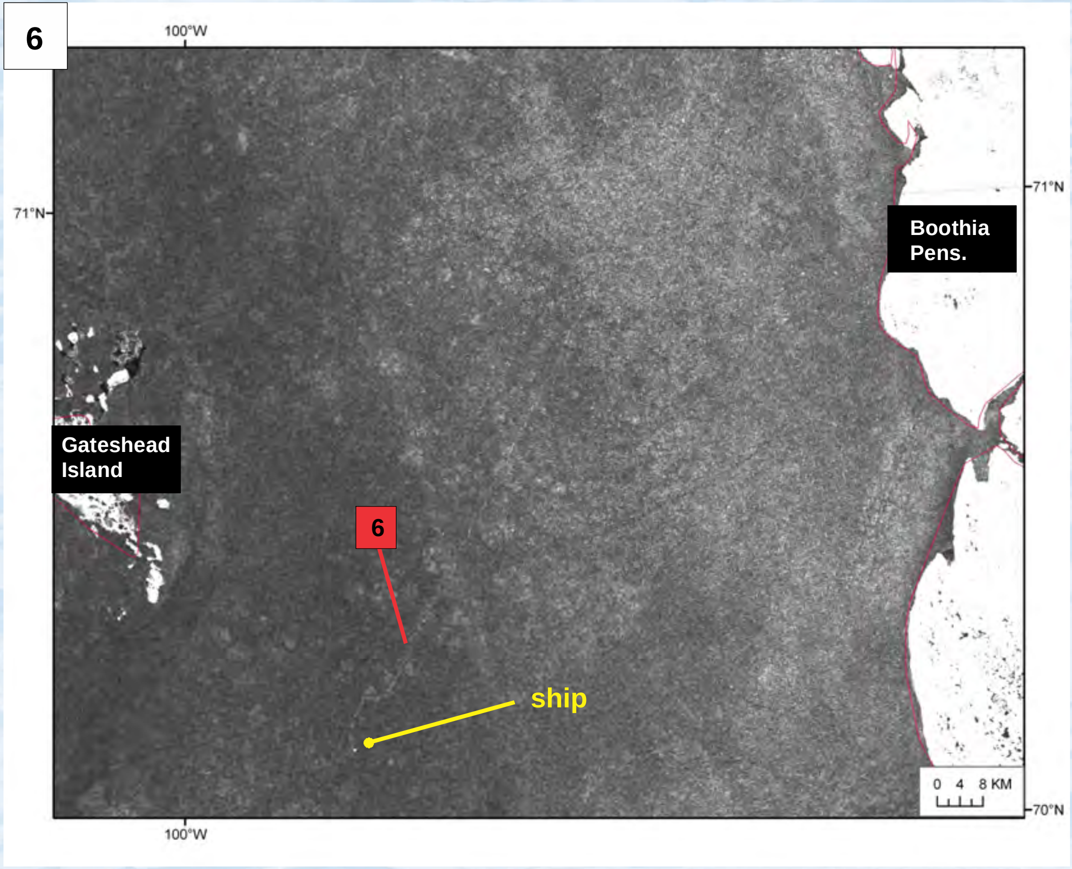
- ✔ freeboard
- ✔ floe size
- ✔ ponding/drainage
- ✔ ice thickness
- ✔ hummocked
- ✔ sound when hit
- ✔ other (see ship-based observation #6, *Central Arctic*)

Confidence that it’s multi-year ice: 100%

Floe size: 4 km+

Est. average thickness: 5 m





Multi-year ice

22 July

70°17'N, 98°56'W

Type of image:
RADARSAT ScanSAR

Observation date/time:
22 July (19:35UTC)

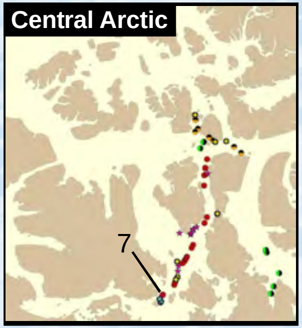
Date/time of image:
22 July (23:40UTC)

The 4 km+ diameter landfast, multi-year floe cannot be seen in the RADARSAT ScanSAR image. The ship's track is visible, as is the ship (bright white dot). Judging by the dog-legged shape of the track, the ship changed course when it encountered difficult ice south of Floe 6.

Multi-year ice

24 July

69°02’N, 101°15’W



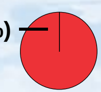
Key identifiers:

- ✔ floe size
- ✔ colour
- ✔ ponding/drainage
- ✔ hummocked
- ✔ sound when hit
- ✔ other (see ship-based observation #7, *Central Arctic*)

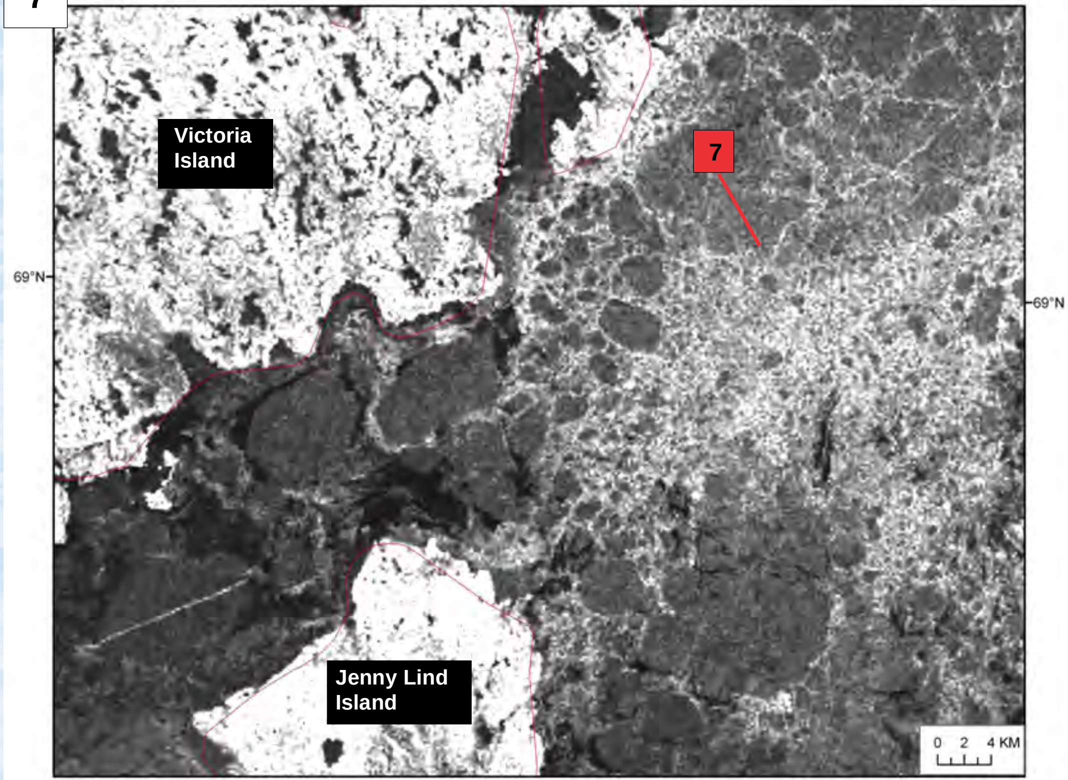
Confidence that it’s multi-year ice: 100%

Floe size: 200 to 400 m

Est. average thickness: ?



7



Multi-year ice

24 July

69°02'N, 101°15'W

Type of image:
RADARSAT ScanSAR

Observation date/time:
24 July (18:10UTC)

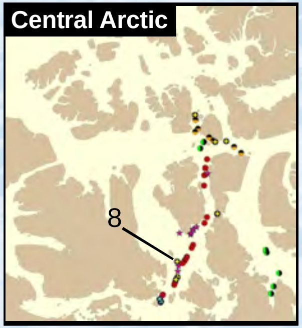
Date/time of image:
25 July (00:22UTC)

The 200 to 400 m diameter, landfast floe is too small to be clearly identified in the RADARSAT ScanSAR image.

Multi-year ice

30 July

70°16’N, 99°47’W



Key identifiers:

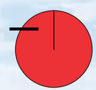
- ✔ freeboard
- ✔ floe size
- ✔ colour
- ✔ ice thickness
- ✔ hummocked
- ✔ other (see observation #7, *Aerial Observations*)

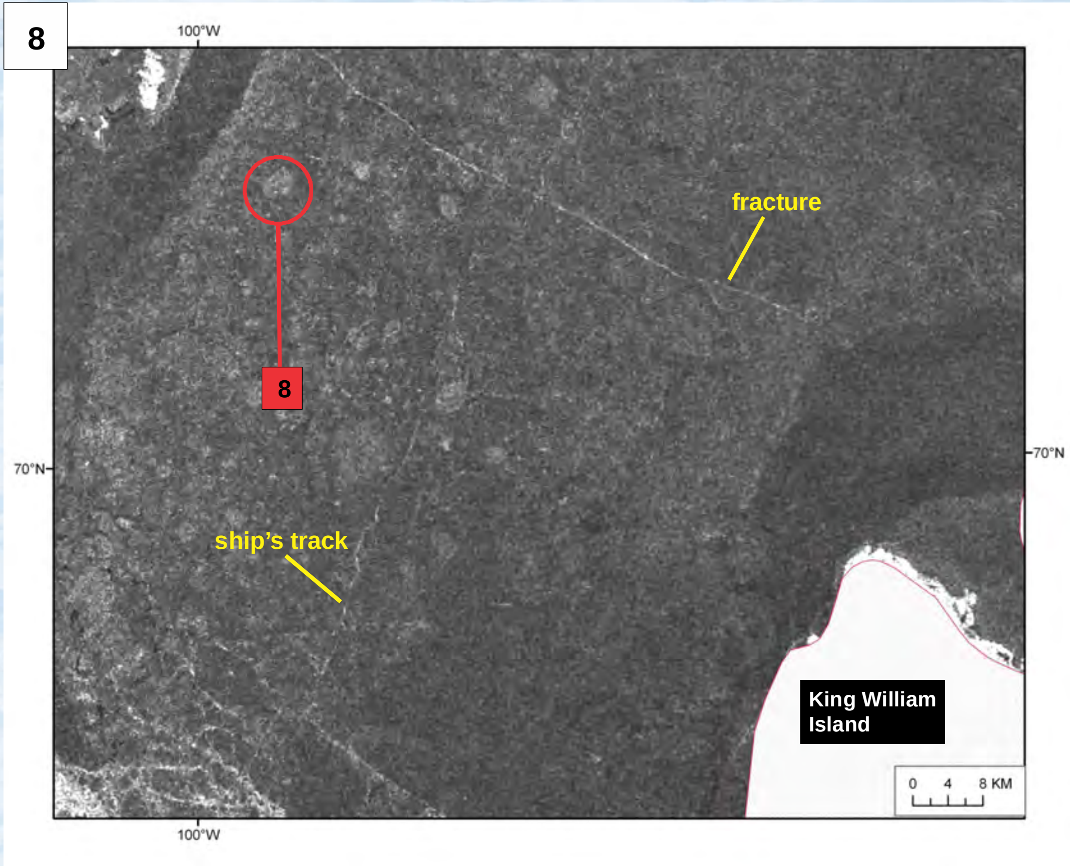
Confidence that it’s multi-year ice: 100%

Floe size: 4 km

Est. average thickness: ?

MYI (100%)





Multi-year ice

30 July

70°16'N, 99°47'W

Type of image:
RADARSAT ScanSAR

Observation date/time:
30 July (13:38UTC)

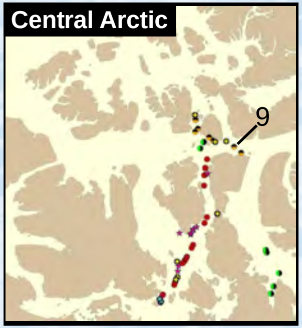
Date/time of image:
30 July (13:13UTC)

This RADARSAT image shows a multi-year ice floe (about 4 km across) embedded in the landfast ice of Larsen Sound. Based upon the screen capture from the ship's computer monitor, that circled floe is believed to be the one shown in the aerial photo on the previous page.

The ship's track is visible in this image extending NE-SW. The ship's track does not intersect the floe because this ice feature was observed during an aerial reconnaissance. Note the linear fracture extending across Larsen Sound, north of Floe 8.

Multi-year ice

4 August
74°21’N, 92°02’W

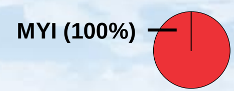


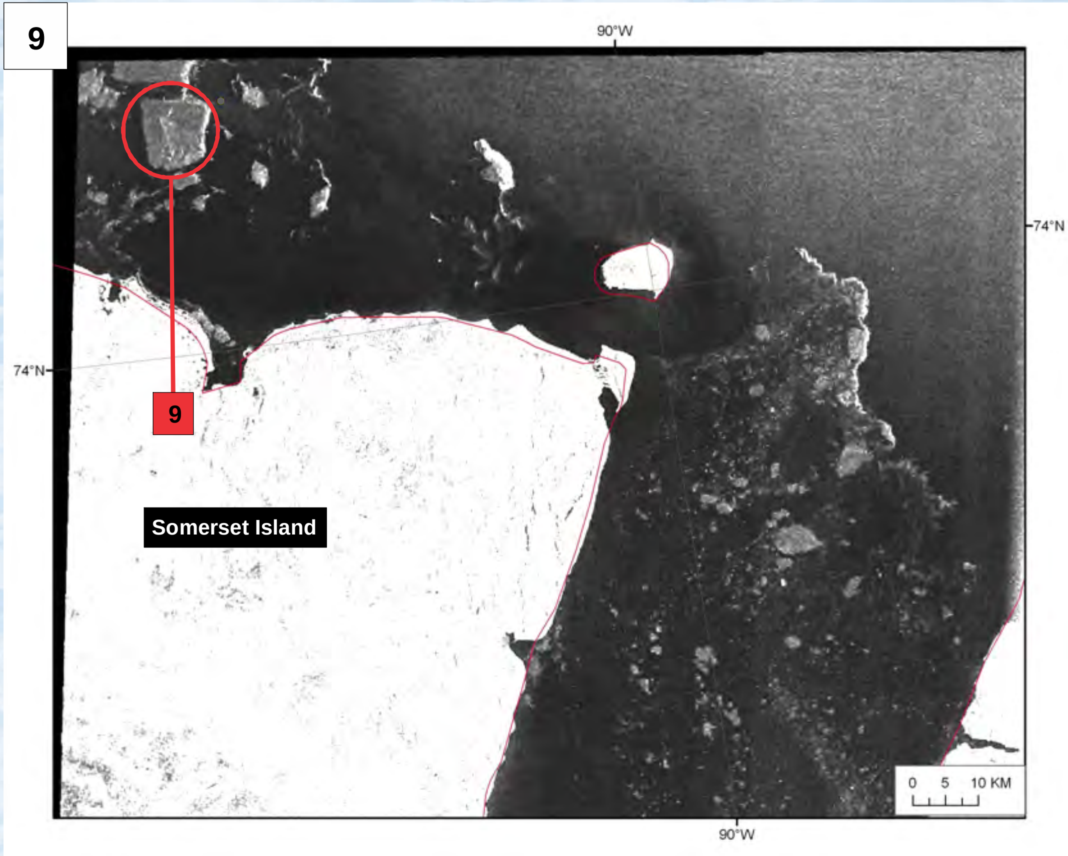
Key identifiers:

- ✔ colour
- ✔ ponding/drainage
- ✔ ice thickness
- ✔ hummocked
- ✔ other (see ship-based observation #10, *Central Arctic*)

9

Confidence that it’s multi-year ice: 100%
Floe size: 500 to 1000 m
Est. average thickness: 2 to 4 m





Multi-year ice

4 August

74°21'N, 92°02'W

Type of image:
RADARSAT ScanSAR

Observation date/time:
4 August (00:49UTC)

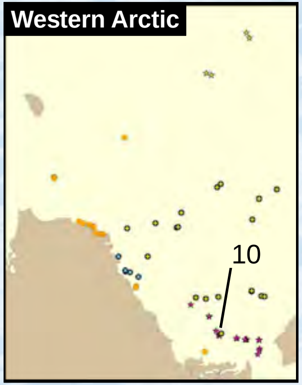
Date/time of image:
4 August (12:26UTC)

A giant first-year ice floe, about 12 km across, is circled in this RADARSAT ScanSAR image. This first-year floe contained 2 to 3/10ths concentration of multi-year ice. The photo on the previous page shows one of the embedded multi-year floes. This 500 to 1000 m diameter floe cannot be distinguished from the surrounding first-year ice in the ScanSAR image.

Multi-year ice

4 August

71°12’N, 133°38’W



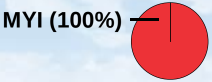
Key identifiers:

- ☑ freeboard
- ☑ floe size
- ☑ ice thickness
- ☑ hummocked
- ☑ other (see ship-based observation #11, *Western Arctic*)

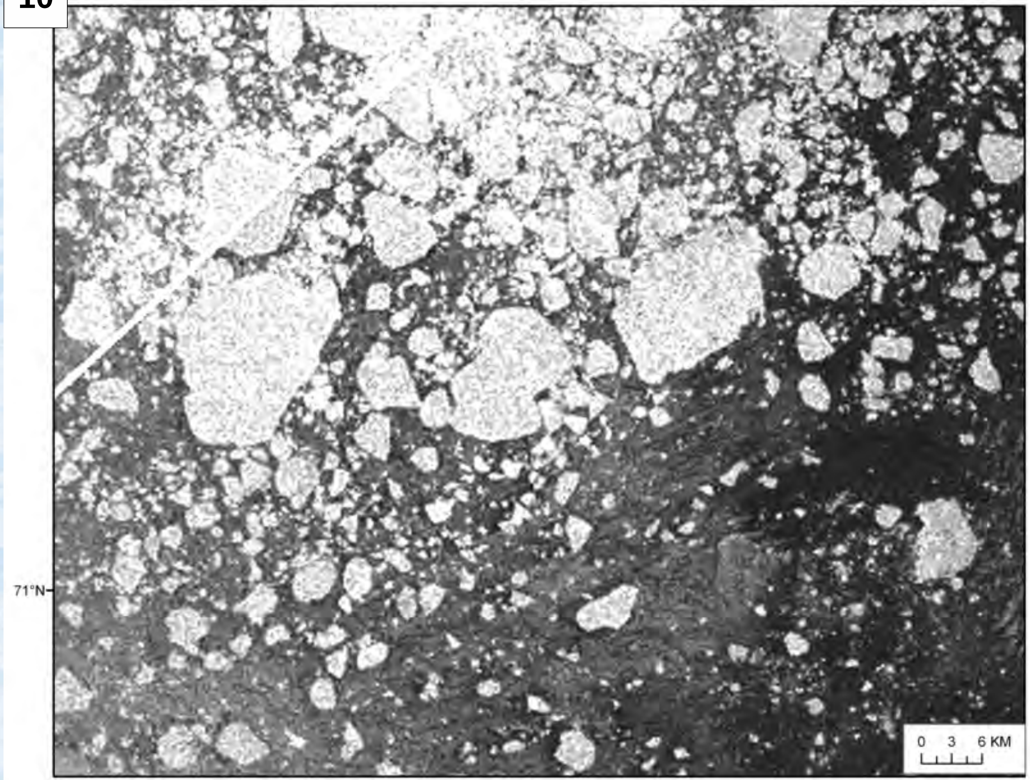
Confidence that it’s multi-year ice: 100%

Floe size: 300 m

Est. average thickness: 2 m



10



Multi-year ice

4 August

71°12’N, 133°38’W

Type of image:
RADARSAT ScanSAR

Observation date/time:
4 August (? UTC)

Date/time of image:
4 August (15:49UTC)

The RADARSAT ScanSAR image shows hundreds of drifting old ice floes surrounded by open water and decaying first-year ice. The 300 m diameter multi-year floe on the previous page cannot be seen in the image because it is too small.

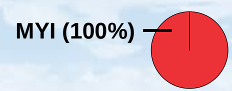
Multi-year ice

12 August
78°38’N, 73°33’W

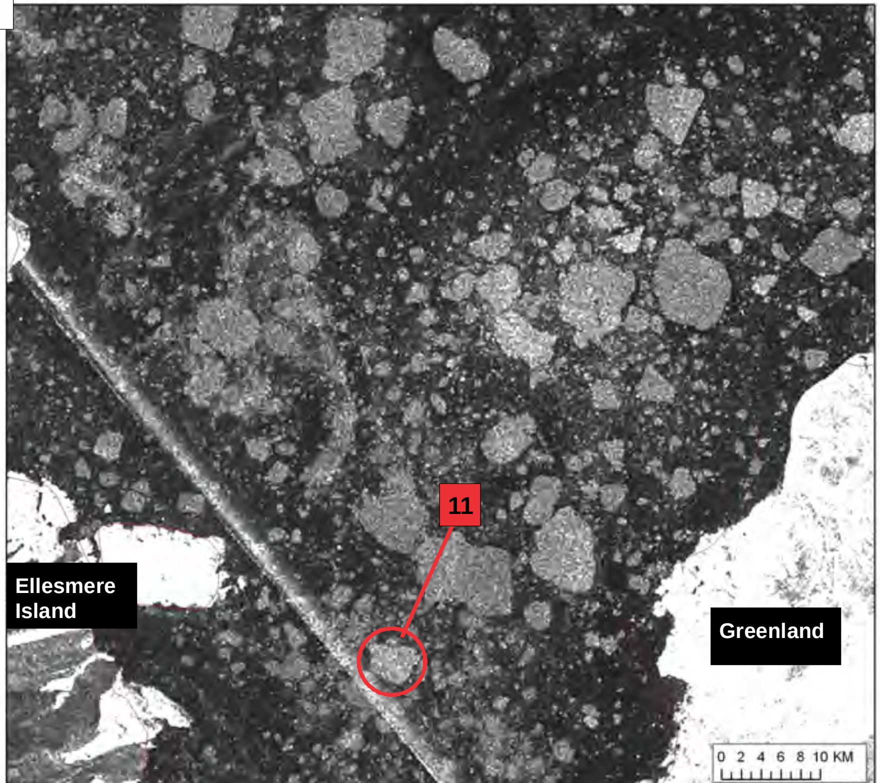
Key identifiers:

- ☑ freeboard
- ☑ floe size
- ☑ colour
- ☑ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☑ other (see observation #4, *On-ice Thickness Measurements*)

Confidence that it’s multi-year ice: 100%
Floe size: 4 km
Average thickness from drill hole measurements: 4.8 m



11



Multi-year ice

12 August

78°38’N, 73°33’W

Type of image:
RADARSAT ScanSAR

Observation date/time:
12 August (20:54 UTC)

Date/time of image:
12 August (21:57UTC)

This multi-year ice floe was drifting south in Kane Basin, towards Smith Sound. The floe is easily identified in the RADARSAT Standard image, as are hundreds of other old ice floes drifting in what is mostly open water.

The white band cutting across the image is an artifact in the image.

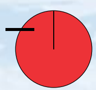
Multi-year ice

13 August
79°50’N, 70°38’W

Key identifiers:

- ☑ freeboard
- ☑ floe size
- ☑ colour
- ☑ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☑ other (see observation #5, *On-ice Thickness Measurements*)

Confidence that it’s multi-year ice: 100%
Floe size: 5 km
Average thickness from drill hole measurements: 5.8 m



12

Multi-year ice

13 August

79°50'N, 70°38'W

Type of image:
RADARSAT Standard

Observation date/time:
13 August (13:14 UTC)

Date/time of image:
13 August (11:29UTC)

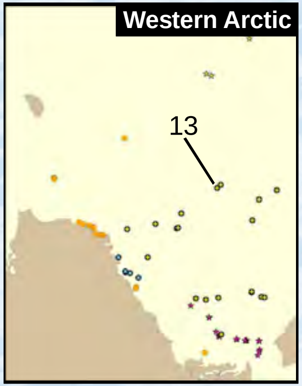
This multi-year ice floe was sampled in the north part of Kane Basin on 13 August. It was an aggregate floe consisting of many smaller old ice floes.

The aggregate floe is evident in the RADARSAT Standard imagery, but the smaller floes that comprise it are not.

Multi-year ice

13 August

76°44’N, 149°56’W



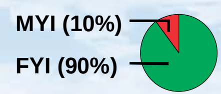
Key identifiers:

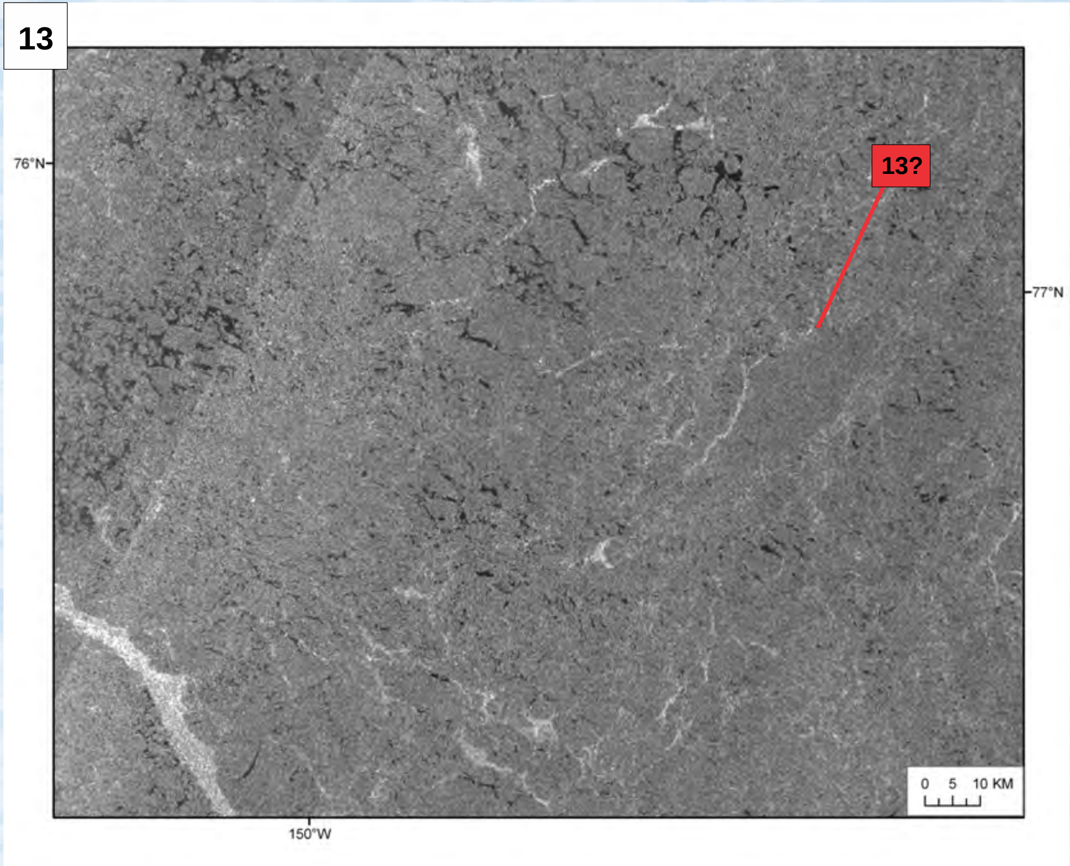
- ☑ other (see ship-based observation #14, *Western Arctic*)

Confidence that it’s multi-year ice: 10%

Floe size: 100 to 500 m

Est. average thickness: less than 1 m





Multi-year ice

13 August

76°44'N, 149°56'W

Type of image:
RADARSAT ScanSAR

Observation date/time:
13 Aug (17:00UTC)

Date/time of image:
13 Aug (02:51UTC)

The RADARSAT ScanSAR image shows what is generally drifting, decayed second-year and multi-year ice in the Beaufort Sea. The floe on the previous page resembled decaying first-year ice, rather than old ice.

It is not possible to distinguish the 100 to 500 m diameter multi-year floe in this satellite image.

Multi-year ice

22 August
80°40’N, 68°23’W

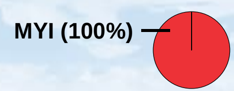
Key identifiers:

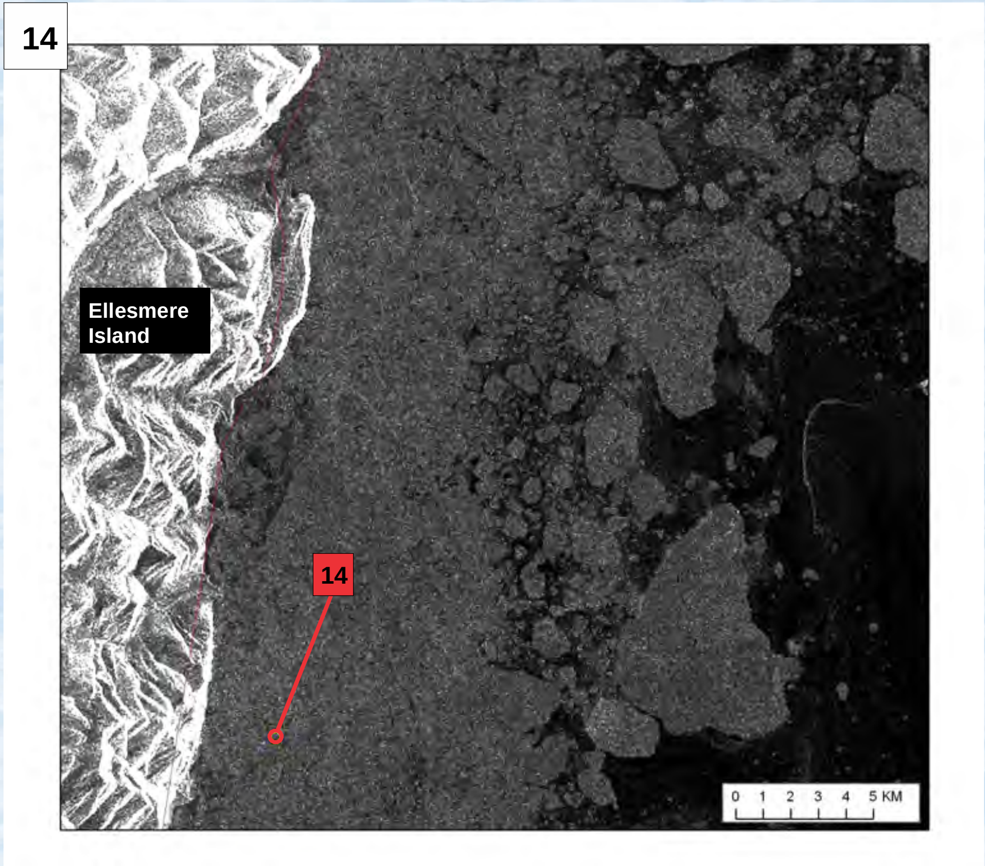
- ☑ freeboard
- ☑ floe size
- ☑ colour
- ☑ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☑ other (see observation #7, *On-ice Thickness Measurements*)

Confidence that it’s multi-year ice: 100%

Floe size: 500 m x 200 m

Average thickness from drill hole measurements: 5.2 m





Multi-year ice

22 August

80°40’N, 68°23’W

Type of image:
RADARSAT Standard

Observation date/time:
22 August (13:06 UTC)

Date/time of image:
23 August (12:07UTC)

This floe was visited on 22 August drifting south along the coast of Ellesmere Island. The floe was a small, about 500 m long and 200 m wide.

This floe is not visible in the RADARSAT Standard imagery. There was no need for the ship to break a track through the ice because the floe was accessed by helicopter.

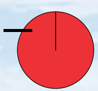
Multi-year ice

24 August
80°36’N, 68°04’W

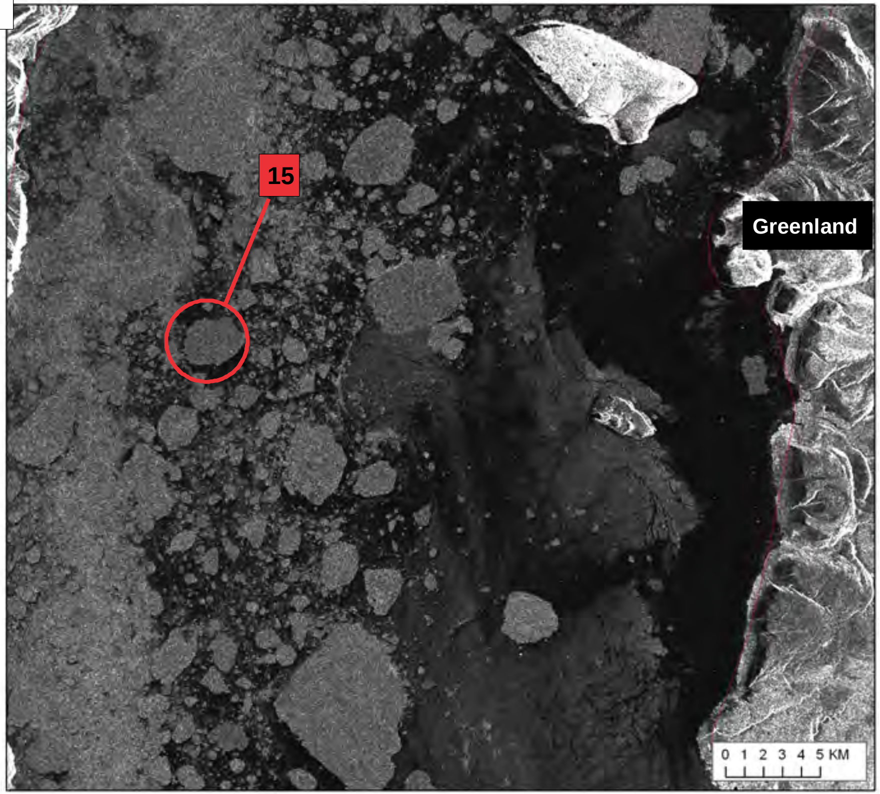
Key identifiers:

- ☑ freeboard
- ☑ floe size
- ☑ colour
- ☑ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☑ other (see observation #8, *On-ice Thickness Measurements*)

Confidence that it’s multi-year ice: 100%
Floe size: 3 km
Average thickness from drill hole measurements: 9.3 m+



15



Multi-year ice

24 August

80°36'N, 68°04'W

Type of image:
RADARSAT Standard

Observation date/time:
24 August (13:13 UTC)

Date/time of image:
24 August (12:49UTC)

The 3 km diameter multi-year floe on the previous page is clearly evident in this RADARSAT Standard image. The satellite image does not capture details about the floe's hummocked topography.

Multi-year ice

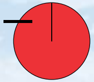
29 August
76°56'N, 91°41'W

Central Arctic

Key identifiers:

- ☑ freeboard
- ☑ floe size
- ☑ colour
- ☑ ponding/drainage
- ☑ ice thickness
- ☑ hummocked
- ☑ other (see observation #9, *On-ice Thickness Measurements*)

Confidence that it's multi-year ice: 100%
Floe size: 5 km
Average thickness from drill hole measurements: 11.3 m+



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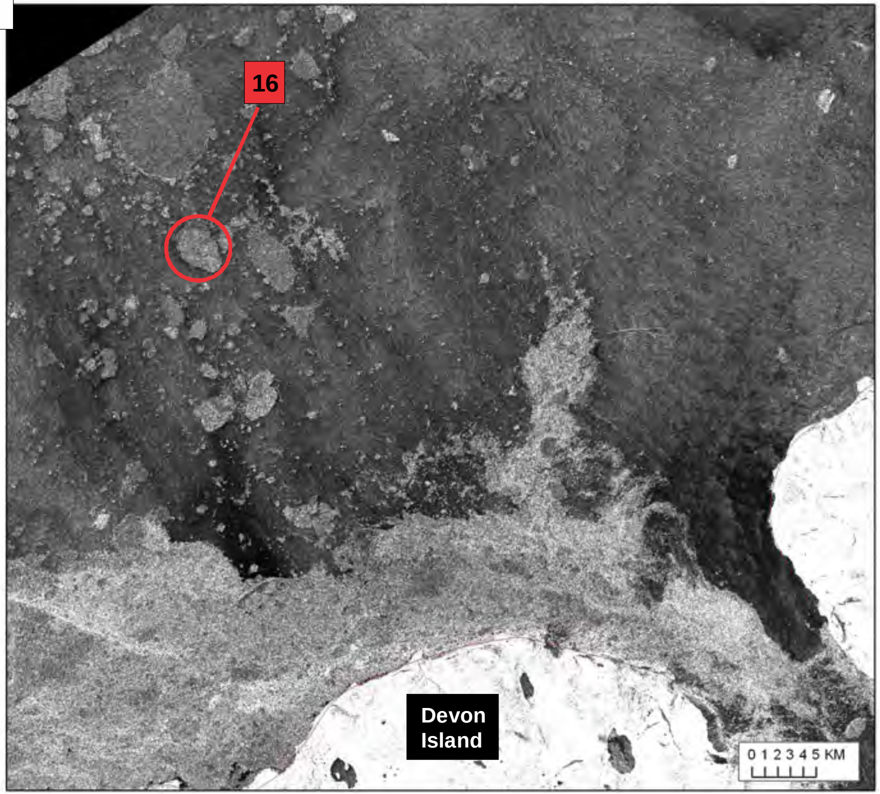


Multi-year ice

29 August

76°56’N, 91°41’W

Type of image:
RADARSAT Standard

Observation date/time:
29 August (21:29 UTC)

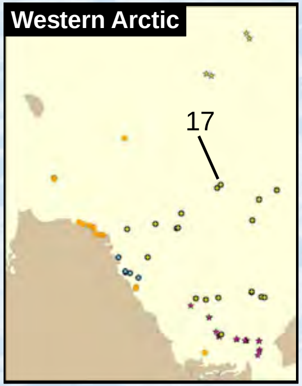
Date/time of image:
28 August (22:31UTC)

The 5 km diameter drifting multi-year ice floe on the previous page was sampled in Norwegian Bay on 29 August. The satellite image was acquired the day before the floe was sampled. The floe was identified in the image using the floe’s trajectory while being sampled, two days worth of satellite imagery and aerial photographs. The floe is visible here, but the image reveals little information about the floe’s hummocked surface and its extensive drainage patterns.

Second-year ice

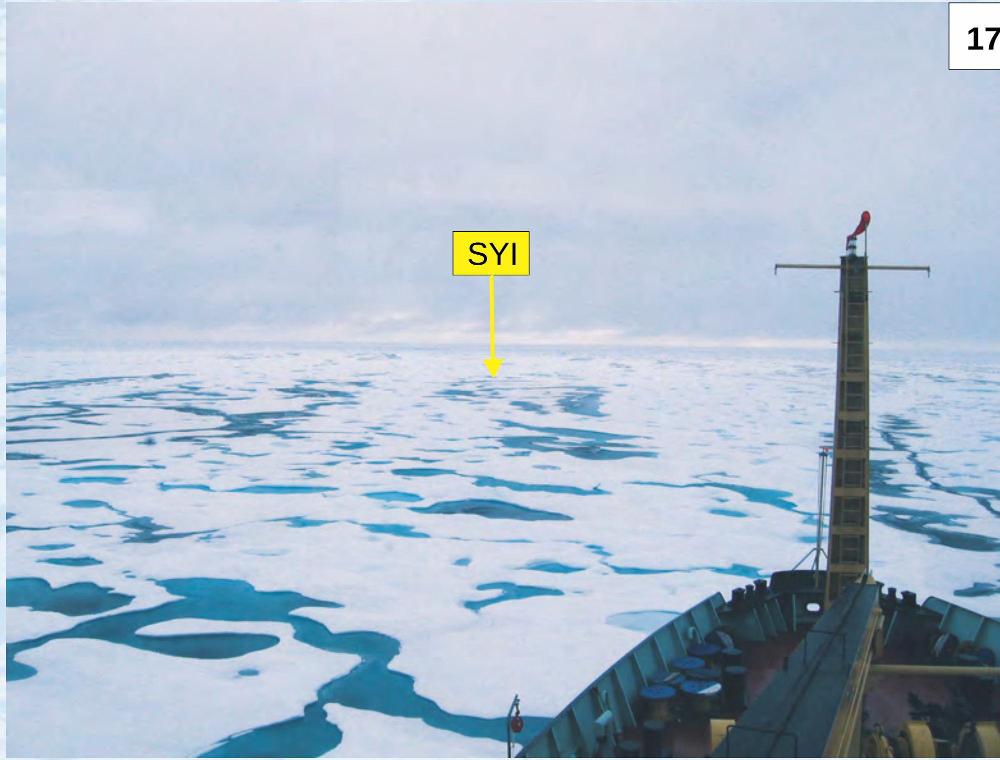
29 August

76°58'N, 149°53'W



Key identifiers:

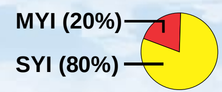
- ☑ freeboard
- ☑ colour
- ☑ ponding/drainage
- ☑ ice thickness
- ☑ other (see ship-based observation #21, *Western Arctic*)



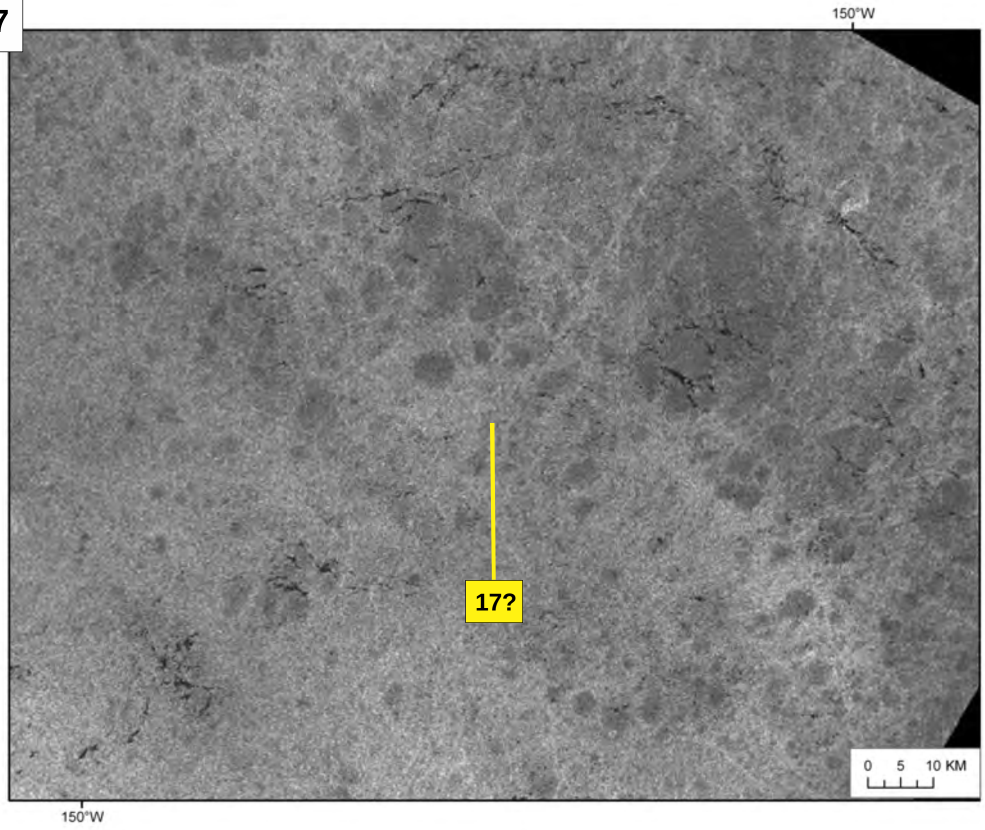
Confidence that it's second-year ice: 80%

Floe size: 200 to 400 m

Est. average thickness: 1 to 2 m



17



Second-year ice

29 August

79°58'N, 149°53'W

Type of image:
RADARSAT ScanSAR

Observation date/time:
29 Aug (19:00UTC)

Date/time of image:
28 Aug (03:08UTC)

It is not possible to distinguish the 200 to 400 m diameter, drifting second-year floe in this RADARSAT ScanSAR image.

Afterword

Natural resources have been, and will continue to be, one of the most significant drivers of economic activity and prosperity in the North. With it comes opportunities for Northern communities, but it also places increased pressure on Northern lifestyles and limited infrastructure in the Arctic. Renewed interest in Arctic resources is not a direct result of the decreased sea ice extent that has occurred over the past few decades, but it is certainly beneficial.

Changing ice conditions have resulted in a longer shipping season (ships enter the Arctic earlier in the season and stay longer), an increase in cruise ship and pleasure craft traffic, newly-introduced systems for evaluating the risk of navigating ice-covered waters, amongst other things. One natural outcome of the increased activity has been a greater demand for experienced operators. But there is a shortage of personnel with first-hand knowledge about operating in the unique ice conditions of the Arctic. There are also too few ice observers with years of experience to draw from. It is only logical then, that less experienced people will venture into the Arctic in the future. That brings us to one of the most important objectives of this Guide: to familiarize less experienced operators with the types of hazardous ice they will encounter in the Arctic and sub-Arctic, today and in the foreseeable future. This objective is particularly important, given the commonly cited decreases in sea ice extent and diminishing ice thickness - and the false sense of security that they instill in new-comers to the Arctic.

Understanding and Identifying Old Ice in Summer is not only a comprehensive collection of photographs to document the many facets of old ice, it offers insight about why first-year, second-year and multi-year ice present different levels of risk for a ship or structure – thickness being just one of their many differences. However, the Guide contains ample evidence that even very experienced personnel can have limited confidence distinguishing multi-year ice from second-year, or first-year ice. That is especially true in the sub-Arctic, where pieces of hazardous old ice are frequently too small to positively identify. It may also become more common in the Arctic, in future years. All operators will encounter situations where they cannot reliably identify an ice feature. In those cases, the only approach would be to assume the feature is multi-year ice, and avoid it when possible. Therein lies the extreme importance of always using due caution and diligence to transit ice-covered waters in the Arctic and sub-Arctic.

In closing, it is hoped that the *e-Guide to Understanding and Identifying Old Ice in Summer* will continue to be a useful tool for mariners not familiar with operating in the Arctic, as well as the more seasoned mariner.

We look forward to receiving your feedback about the e-Guide. Please direct your questions and comments to Dr. M. Johnston (michelle.johnston@nrc-cnrc.gc.ca) or NRC.ContactOCRE-ContactezGOCF.CNRC@nrc-cnrc.gc.ca

Acknowledgements

This Guide, having been four years in the making, was initially intended to be a pictorial booklet about old ice as seen from the ship-based, aerial and satellite perspectives. While drafting the Guide, the authors realized there wasn't much sense in helping mariners discriminate multi-year and second-year ice from first-year ice, without explaining why the three ice types differ. Therefore, a 'primer on old ice' was added, along with recently conducted on-ice measurements to illustrate the extreme thicknesses of some multi-year floes. Publication of the e-Guide allowed for this material to be updated to reflect our better state of knowledge today.

The list of acknowledgements for this publication is long. First, the e-Guide was developed with funding from the NRC Arctic Program, with the impetus being supplied by Mr. John Falkingham. Despite having requests for an electronic format for many years, it was John's prodding that led us to finally make it happen. Thanks to M. Proulx and R. Forrest of NRC Communications for getting the hardcopy version into electronic format. We would like to thank the Canadian Government for their financial support through the Canadian Climate Change Technology and Innovation Initiative (CCTII) Arctic Transportation Project, which provided funding for collecting and compiling the three years of ship-based observations. Additional funding for the work was provided by Transport Canada and the Program for Energy Research and Development (PERD). The Canadian Ice Service contributed to the Guide in many ways: enlisting the participation of their Ice Service Specialists (ISS), providing the imagery and much of the introductory text to the satellite section and undertaking the translation of the original hardcopy Guide. Captain J. Vanthiel, Captain N. Thomas and Captain G. Tremblay graciously participated in the program from three foreign vessels, for which we also acknowledge the in-kind support of the Swedish Maritime Administration, the US Coast Guard and Hapag-Lloyd. The assistance of A. Collins (NRC-CHC) is also much appreciated, for compiling three years of observations and lending her keen eye in reviewing the original Guide's complete text. The artistic talent of D. Sudom (NRC-CHC) was enlisted to sketch an ideal second-year floe and multi-year floe, which has been a great success. A considerable amount of time and patience was required of NRC's Reprographic Services, particularly S. Moor, while working with the authors to format the hundreds of pictures in the Guide and to ensure a high-quality publication.

The past 15 years of on-ice measurements would not have been possible without the long-standing support of Transport Canada and the Program for Energy Research and Development (PERD). We especially thank Transport Canada's V. Santos-Pedro for recognizing the importance of, and enthusiastically supporting, on-ice measurements. The logistical support of the Polar Continental Shelf Project (PCSP) and the Canadian Coast Guard has been absolutely essential to the success of our field programs. In addition, some of the folks at PCSP and the crew of several CCGS icebreakers actively participated in the back-breaking measurements on multi-year ice. Much of our first-class field equipment was designed and built by NRC's Design and Fabrication Services, or early-on was borrowed from N.K. Sinha (NRC), T. Prowse (NHRI) and/or Sandwell, Inc.

Thanks to the CCGS headquarters in Sarnia, particularly our contact J. Ouellet, because they allowed us to conduct many field programs from icebreakers and to update Coast Guard on our work at their annual meetings. The Centre for Earth Observation Science (CEOS) of the University of Manitoba provided in-kind support for the first-year ice measurements at Truro Island and B.J. Hwang participated in the ship-based observation program from the CCGS *Amundsen*. R. DeAbreu of the Canadian Ice Service generously arranged for satellite imagery each year, greatly contributing to the success of our fieldwork. The Nunavut Research Institute provided scientific permits to conduct this work across the Arctic. We are also thankful to the Hunter's and Trappers Association, Resolute for providing important linkages to the community and allowing the field programs to take place. B. Simard (CIS) provided extremely valuable comments concerning the ship-based observations.

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We have attempted to include most of the people who contributed to this Guide but, due to space limitations, some will escape un-named. For that, we do apologize.

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Sea Ice Nomenclature

Aged ridge – ridge that has undergone considerable weathering. These ridges are best described as undulations on the ice surface.

Bergy bit – a large piece of floating glacier ice, generally showing from 1 m to less than 5 m above sea-level and normally about 100 to 300 m² in area.

Concentration – the ratio usually expressed in tenths describing the amount of the sea surface covered by ice as a fraction of the whole area being considered.

Consolidated ridge – ridge in which the base has frozen together.

Deformed ice – a general term for ice which has been squeezed together and in places forced upwards (and downwards).

Dried ice – sea ice from the surface of which meltwater has disappeared after the formation of cracks and thaw holes. During period of drying, the surface whitens.

Fast ice – sea ice which forms and remains fast along the coast, where it is attached to the shore, to an ice wall, to an ice front, between shoals or grounded icebergs. Fast ice may be more than one year old, and may be prefixed with either old, second-year or multi-year.

First-year ice – sea ice of not more than one winter's growth, developing from young ice; thickness 30 cm to 2.0 m.

Floe – any relatively flat piece of sea ice 20 m or more across. Floes are subdivided based upon their diameter as: giant (10 km+), vast (2 to 10 km), big (500 to 2000 m), medium (100 to 500 m) and small (20 to 100 m).

Floeberg – a massive piece of sea ice composed of a hummock, or a group of hummocks frozen together, and separated from any ice surroundings. It may protrude up to 5 m above sea-level.

Freeboard – is defined as how high the ice floats above the water. The freeboard can be used to estimate the ice thickness in spring and early summer, when the ice has not yet become saturated with water and is still relatively void-free. Pore spaces are filled with mostly air and, to a lesser extent, brine.

Glacial ice – Ice in, or originating from, a glacier, whether on land or floating on the sea as icebergs, bergy bits and growlers.

Grey ice – young sea ice that is 15 to 30 cm thick. It is more likely to ridge under pressure, than raft.

Grey-white ice – young sea ice that is 10 to 15 cm thick and is less elastic than nilas. It often breaks from swells and usually rafts under pressure.

Hillock – raised areas of the ice surface that give a floe an undulating topography. Hillocks form from the natural weathering process.

Hummock – area of uneven surface of broken ice that has been forced upwards by pressure. May be fresh or weathered.

Hummocked ice – sea ice piled haphazardly one piece over another to form an uneven surface. When weathered, has the appearance of smooth hillocks.

Hummocking – the pressure process by which sea ice is formed into hummocks.

Sea Ice Nomenclature (cont.)

Keel – the submerged volume of broken ice under a ridge, forced downwards by pressure.

Medium first-year ice – sea ice that is 70 to 120 cm thick.

Multi-year ice – old ice that is typically more than 3 m thick which has survived at least two summers' melt. Hummocks are even smoother than second-year ice, and the ice is less saline than either first-year or second-year ice. Melt pattern consists of large interconnecting irregular puddles and a well-developed drainage system. Color, where bare, is usually blue.

New ridge – ridge newly formed with sharp peaks and slope of sides usually 40°. Fragments are visible from the air at low altitude.

Nilas – a thin elastic crust of floating ice that is less than 10 cm thick and easily bends from waves and swells. Nilas has a matte surface appearance.

Pack ice – term used in wide sense to include any area of sea ice, other than fast ice, no matter what form it takes or how it is disposed.

Pond/puddle – describes the accumulation of meltwater on the ice, mainly due to melting snow, but in the more advanced stages also to the melting of ice. Summer melting produces a regular pattern of numerous small puddles on second-year ice, whereas the melt pattern on multi-year ice consists of large interconnecting irregular puddles and a well-developed drainage system.

Rafting – the pressure process whereby one piece of ice overrides another. Most common in new and young ice.

Ridge – a line or wall of ice forced up by pressure. May be fresh or weathered.

Ridging – the pressure process by which sea ice is forced into ridges.

Rotten ice – sea ice which has become honeycombed and which is in an advanced state of disintegration.

Sea ice – any form of ice found at sea which has originated from the freezing of water.

Second-year ice – old ice which has survived only one summer's melt; typical thickness up to 2.5 m and sometimes more. Because it is thicker than first-year ice, it stands higher out of the water. In contrast to multi-year ice, summer melting produces a regular pattern of numerous small puddles. Bare patches and puddles are usually greenish blue.

Thaw holes – vertical holes in sea ice formed when surface puddles melt through to the underlying water.

Thick first-year ice – sea ice that is greater than 120 cm thick.

Thin first-year ice/white ice – sea ice that is 30 to 70 cm thick. Thin first-year ice may be sub-divided into the first stage, 30 to 50 cm thick and the second stage, 50 to 70 cm thick.

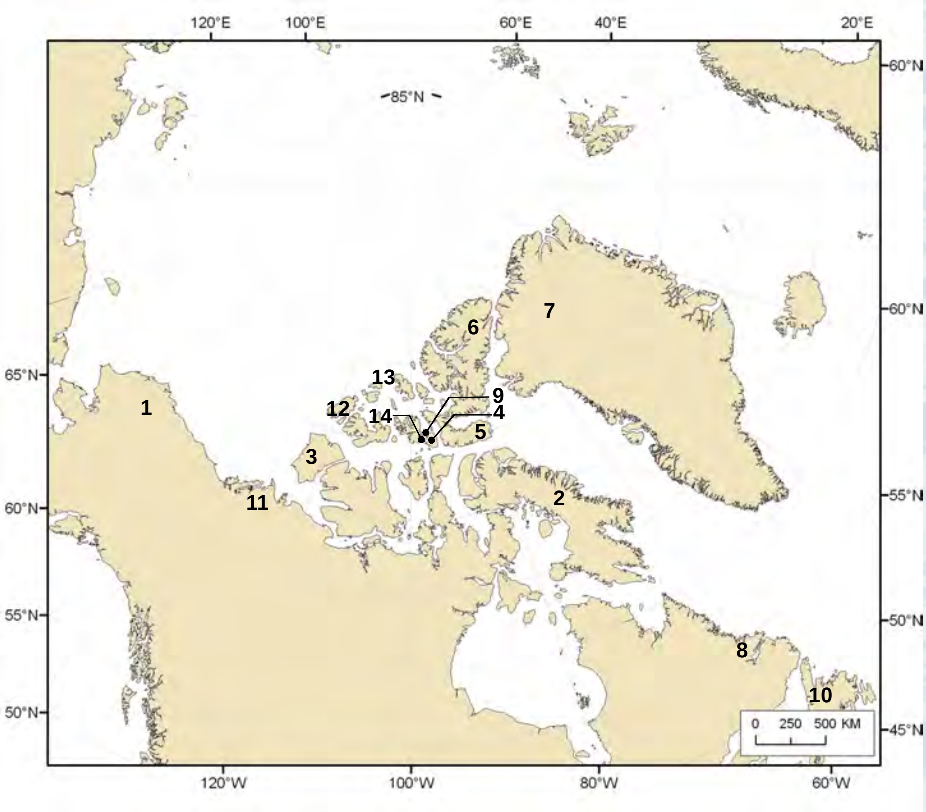
Sea Ice Nomenclature (cont.)

Very weathered ridge – ridge with peaks very rounded, slope of sides usually 20° to 30°.

Weathered ridge – ridge with peaks slightly rounded and slope of sides usually 30° to 40°. Individual fragments are not discernable.

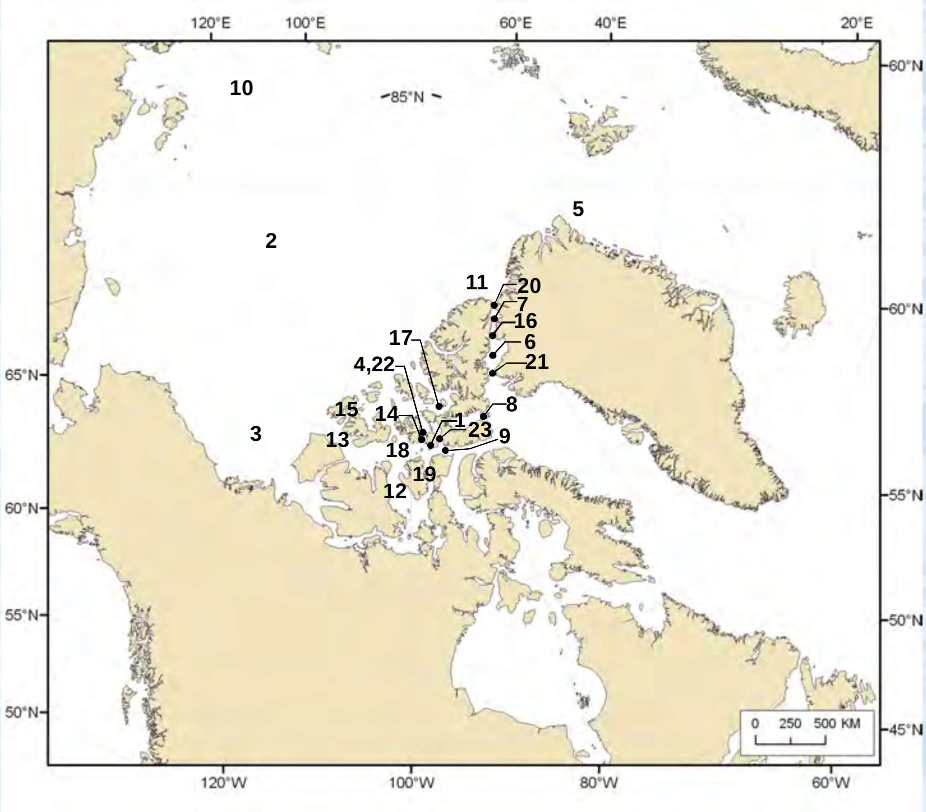
Weathering – processes of ablation and accumulation which gradually eliminate irregularities in an ice surface.

Reference Map (Islands)



1 Alaska
2 Baffin Island
3 Banks Island
4 Cornwallis Island
5 Devon Island
6 Ellesmere Island
7 Greenland
8 Labrador
9 Little Cornwallis Island
10 Newfoundland
11 Northwest Territories
12 Prince Patrick Island
13 Queen Elizabeth Islands
14 Truro Island

Reference Map (Oceanographic)



1 Allen Bay
2 Arctic Basin
3 Beaufort Sea
4 Crozier Strait
5 Fram Strait
6 Kane Basin
7 Kennedy Channel
8 Lady Anne Strait
9 Lancaster Sound
10 Laptev Sea
11 Lincoln Sea
12 M'Clintock Channel
13 M'Clure Strait
14 McDougall Sound
15 Mould Bay
16 Nares Strait
17 Norwegian Bay
18 Parry Channel
19 Peel Sound
20 Robeson Channel
21 Smith Sound
22 Templeton Bay
23 Wellington Channel

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