ARCTIC ICE ISLAND AND ICE SHELF STUDIES

Part II

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In Part I of this article (Crary 1958) the thicknesses, surface and subsurface features of the Ellesmere ice shelf* near Ward Hunt Island and the ice island T-3 were outlined. The purpose of Part II is to discuss the possible conditions at high latitudes (north of about 80°N.) under which thick floating ice can form, and to outline the possible history of these two thick remnants of arctic ice. A further purpose is to explain their general surface features and to discuss briefly the possible future of these ice masses.

T-3 consists, away from the edges, of two general types of ice: the upper part with innumerable dirt layers and the lower part without these dirt layers. Marshall (1955) and Weeks (*in* Crary 1958) have both examined petrographic evidence from the upper part of the lower ice and have reached the conclusion that this is not sea ice. However, the lack of any traces of dirt in the lower ice (when all ice that has obviously accumulated from the top shows many dirt layers) and its salinity indicate natural growth from below by freezing, perhaps of brackish or fresh run-off waters of coastal streams. The presence of well-preserved shells found above sea-level along the northern shores of Ellesmere Island, which pre-date pieces of driftwood located back of the present shelf and therefore pre-date the shelf, make it appear most improbable that glacier ice forms the base of the main shelf feature. Local glacier ice does, however, play a part in the formation of some ice shelves and this has been discussed by Marshall (1955).

Growth of floating ice sheets in Arctic Ocean areas

The growth of perennial ice can take place either at its top surface by the accumulation of snow or at its lower boundary by the freezing of sea water. The upward flow of heat from the lower boundary is caused by the average difference in temperature between the ice surface and the water and removes the latent heat released by the freezing of the sea water. The amount of growth is limited by the amount of surface ablation and by any additional heat that may be supplied by the ocean waters.

* Since this article was written the Canadian Board on Geographical Names has adopted several new names and name changes for northern Ellesmere Island. They have been used in the illustrations, but not in the text.

For our considerations only net annual changes in high arctic areas will be considered. It will also be assumed that the heat flow through the ice can by calculated using the average annual surface temperature. The annual heat flow per cm.^{2}, Q, through an ice sheet H cm. thick is given by

$$Q = \frac{K \triangle T}{H} t \qquad (1)$$

where K is the thermal conductivity, $\triangle T$ the difference between the average annual surface temperature and water temperature, and t the time, 1 year or 3.1×10^7 sec.

The thermal conductivity of fresh-water ice is 0.0053 (in C.G.S. units). Malmgren (1927), from observations made on sea ice from the *Maud,* reported values varying from 0.0015 near the surface to 0.0045 near the bottom.

The indirect Schmidt approximation method *(see* Ingersoll *et al.* 1954, p. 209-11) has been used to check these thermal constants for shelf and floe ice from known changes in ice temperatures. By using a time interval of 1 day and an arbitrary depth interval varying from 30 cm. to 70 cm. the value of diffusivity dependent on these time and depth intervals was made to vary as widely as necessary. Fixed upper and lower levels were chosen where temperatures were measured, and these were varied in the calculations according to the observed data. Interpolations from measured temperature-depth values were used for the initial boundary conditions, and after calculations the theoretical and observed temperature-depth curves were compared. Fig. 1 shows these comparisons for the two cases computed: (1) fresh ice in the upper part of the Ellesmere ice shelf, (2) a 2.5-metre sea-ice floe that was studied by Iakovlev (Somov 1955) during the drift of Station NP 2. In the ice shelf study the best fit is obtained using a diffusivity of 0.0121 (in C.G.S. units), which gives, using 0.9 for the density and 0.5 for the specific heat, a value of 0.0054 for the thermal conductivity. In the ice floe study a good fit is obtained with a diffusivity value of 0.0096. Using again 0.9 for the density and 0.6 for the specific heat for ice of this salinity and temperature, the thermal conductivity would be 0.0052 (in C.G.S. units). A value of 0.0053 is used here for the calculations of ice shelf growth.

The value of $\triangle T$ will be taken as 15.2°C., the difference between -17°C., the average annual surface temperature and -1.8°C., the freezing point of the surface water of the Arctic Ocean. The general solution can be written as follows:

$$\frac{dH}{dt} = S + \left[\frac{K \triangle T}{H} - A \right] \frac{1}{\rho L} \qquad (2)$$

where S represents the surface change, either positive as accumulation or negative as ablation, A represents the heat furnished by the ocean waters, ρ the density or 0.9, and L represents the latent heat released in freezing.

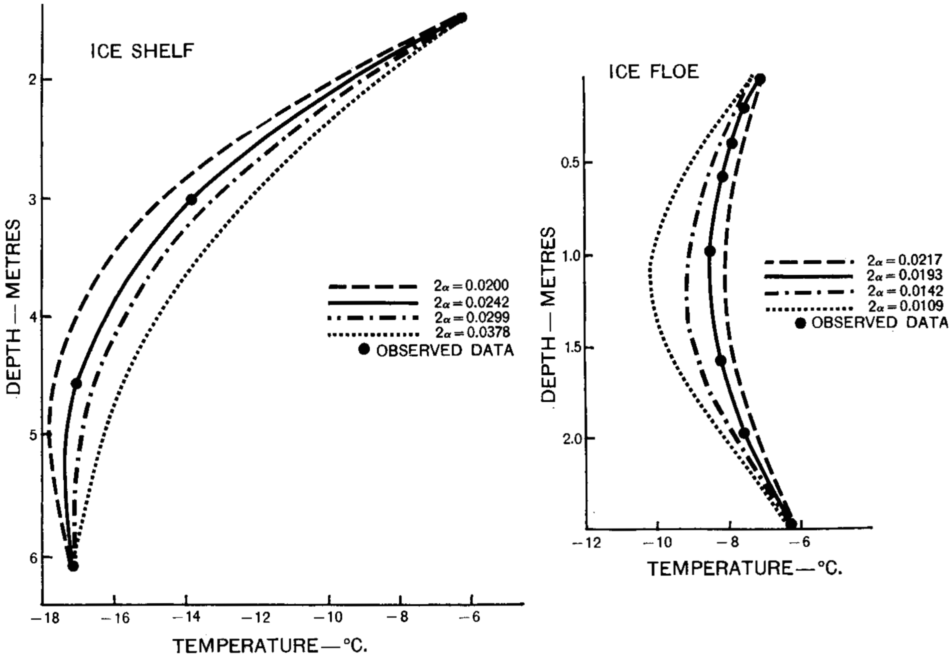

Fig. 1. Temperature-depth curves based on Schmidt approximation.

This equation can be simplified to:

$$\frac{dH}{dt} = \frac{a}{H} + C \qquad (3)$$

where $a = K \triangle T/\rho L = 0.0011$ and $C = S - A/\rho L$. The solution of this equation assuming that $H = O$ when $t = O$, is

$$t = \frac{H}{C} - \frac{a}{C^2} \ln \frac{a + CH}{a}. \qquad (4)$$

This gives the time, t, necessary to form ice of thickness H.
When $C = O$, the solution of equation (3) is

$$t = H^2/2a \qquad (5)$$

an approximate formula widely used for ice growth.

Fig. 2 shows graphically the time in years necessary to grow ice of various thicknesses with different annual values of C. It can be seen that 50 metres of ice could be built up in 360 years and 100 metres in 1440 years without net change at the surface and without heat supplied by the sea water. With an accretion of 5 centimetres per year a thickness of 50 metres would be reached in 245 years and a thickness of 100 metres in 760 years.

Equation (3) shows that no growth of ice can take place if $C \leq -a/H$. This determines the combinations of surface conditions and heat from the ocean waters that limit the ice thickness. Fig. 3 shows the maximum or

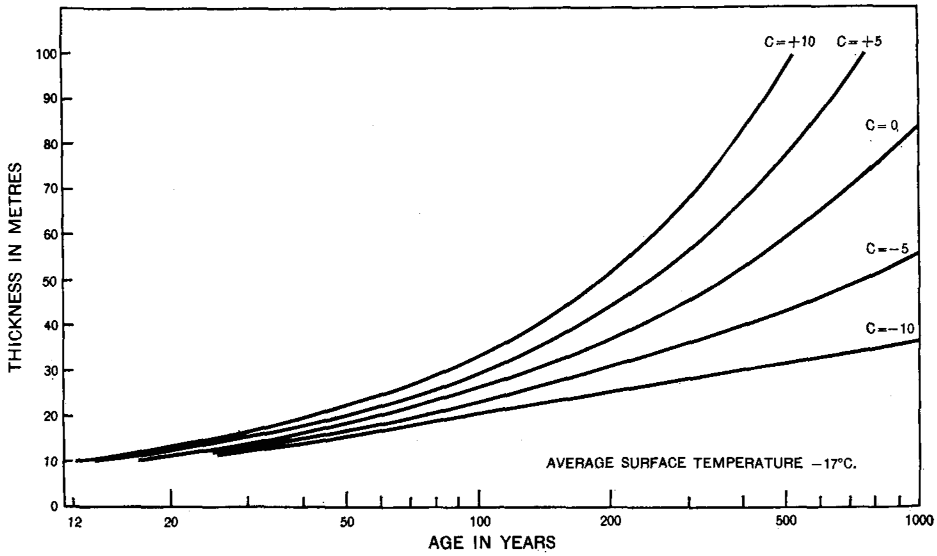

Fig. 2. Time necessary to graw ice of varying thicknesses with various values of C.

equilibrium values of ice thicknesses associated with various values of surface ablation and heat contributed by the ocean waters. The time required to establish equilibrium is sufficiently long for minor climatic changes to occur. Thus, if C is not generally constant but varies over the years consequent variations in ice thickness may be expected.

Fig. 4 gives the accumulation and ablation observed on T-3 at latitudes 83° to 89°N. and on the ice shelf at 82°N. during the years 1952 to 1955. The high arctic areas are relatively arid and the small accumulation figures at T-3 are substantiated by the data given in Table 1. When the summer melt water remains on the surface of the floating ice and by freezing adds to its growth then there is a partial lowering of the surface temperature and a corresponding decrease of the average annual temperature difference between the upper and lower ice boundaries. Although in the years 1952 to 1955 there was a net ablation of the ice surface, the ice shelves and sea-level ice fields in high arctic areas indicate that the average surface change over many centuries has not been great.

Little information is available on the role played by various factors in the thermal budget of the ice surface of the Arctic Ocean. Iakovlev *(in* Timofeev 1958) has computed the heat balance of the ice cover at the NP 2 Station over a period of a year, finding the radiative balance of the surface to be + 2.9 kcal./cm.^{2}, turbulent heat exchange between ice and air + 1.5, heat of melting — 2.9, heat flux from water + 5.5, and evaporation — 7.0, this last figure being obtained as a residual value. At the IGY drifting station Alpha a little farther north Untersteiner (1958) found by direct measurement of the summer thermal budget that the maximum evaporation loss over a period of 12 hours was only 30 cal./cm.^{2}. Untersteiner

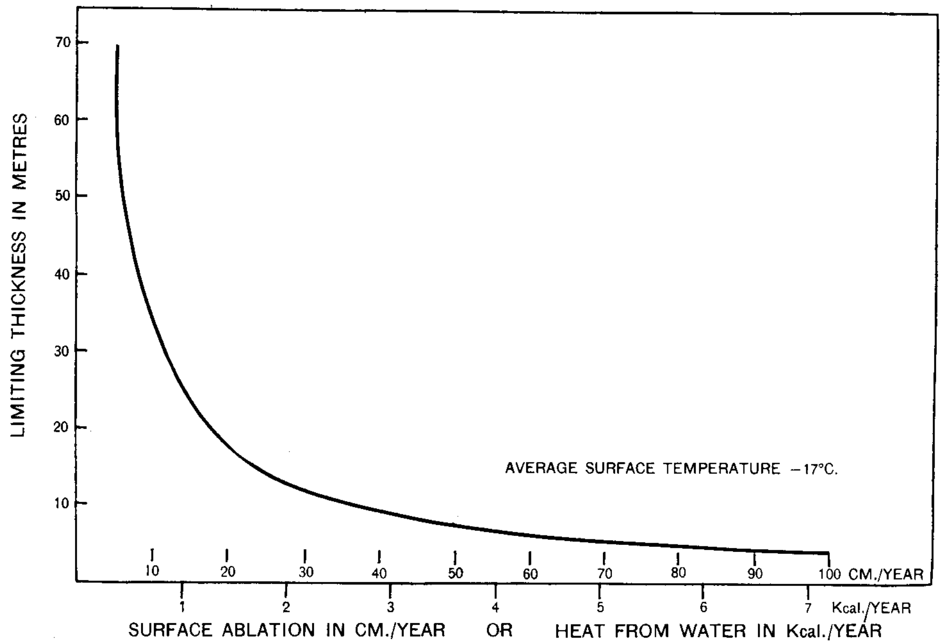

Fig. 3. Limiting values of ice thickness associated with varying values of surface ablation or heat contributed by the ocean waters.

expects that further analysis of his data will show that radiative heat is the most important element in the summer thermal budget. Fritz (1958), analysing incoming radiation data taken on T-3 in the summer of 1953, suggests that upward heat transfer by turbulence may be a large factor in accounting for small amounts lost in melting. Of particular importance in studies of the thermal budget in the Arctic are the effects of the cloud cover, which is characteristic of the summer in the high Arctic.

As noted above, the heat contributed by arctic waters also limits the growth of arctic ice. This heat is supplied by the Atlantic waters entering the Arctic through the Greenland Sea. Although oceanographic stations are still scarce, observations on ice-floe and ice-island stations in recent years have increased the knowledge of these Atlantic waters considerably. Timofeev in recent articles (1957, 1958) has given figures for water budget, Atlantic water circulation, and heat budget. Both Timofeev and Worthington (1953), though their conjectures of circulation in the Beaufort Sea areas differ, have shown an outflow of Atlantic waters in the western part of the Greenland Sea. Nansen (1902), Sverdrup (1956), and Shirshov (1944) originally considered the Atlantic flow only a compensating current for the excess of loss of surface ice and water in the Greenland Sea over contributions from Pacific waters and continental run-off.

Timofeev's values for the annual heat budget balance of the waters of the arctic basin, based on observations at many of the recent drifting

Table 1. Mean snow depth at stations in the Canadian Arctic Archipelago. (Data from Meteorological Branch, Canada Department of Transport).

Station	*Location*	*Years of record*	*Snow depth in cm.*											
			Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Alert	82°30′N. 62°20′W.	5	36.3	38.6	37.3	32.5	27.2	13.2	1.3	2.8	14.7	26.7	30.0	33.0
Eureka	80°00′N. 85°56′W.	8	14.5	15.7	17.8	19.8	19.6	9.6	0.5	0.0	2.3	5.8	9.1	12.7
Isachsen	78°47′N. 103°32′W.	7	18.8	18.3	18.8	21.6	21.8	11.7	1.3	0.5	4.8	11.2	15.0	17.0
Mould Bay	76°16′N. 119°28′W.	7	15.5	17.0	19.3	22.1	22.6	12.2	1.3	0.5	4.3	9.1	11.7	13.7
Resolute	74°41′N. 94°54′W.	8	21.1	23.4	24.8	26.9	31.2	18.8	1.5	0.2	4.5	13.0	18.5	19.6

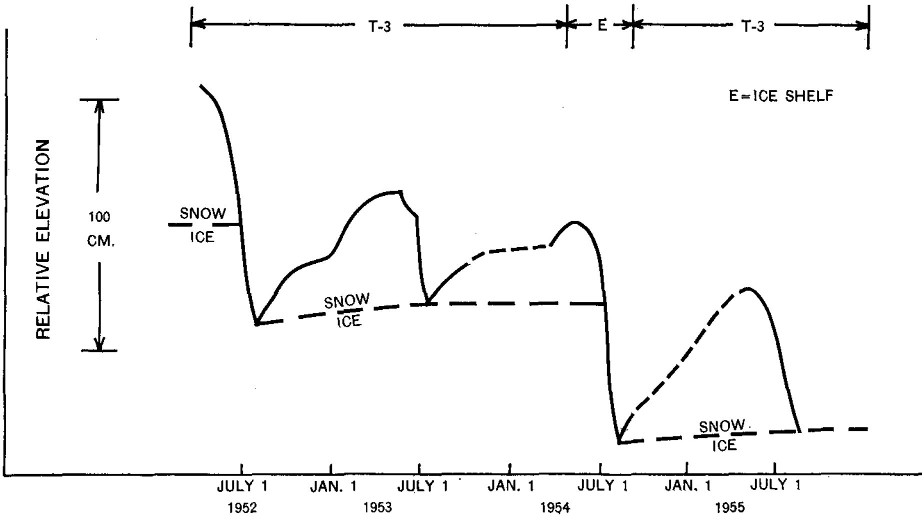

Fig. 4. Accumulation and ablation on T-3 and the Ward Hunt Ice Shelf.

stations, are given in Table 2. Although these figures are very speculative they probably represent as good an estimate as is possible at this time.

If the heat expended in the central arctic basin were distributed evenly over the approximately five million square kilometres of the arctic basin, each square centimetre would receive about 3400 calories annually, which, without surface changes, would restrict ice thickness to about 7 metres (*see* Fig. 3).

Fig. 5, constructed from Timofeev's values (Timofeev 1957), with added information obtained at T-3, shows the total heat above 0°C. in a vertical column of water of 1 cm.^{2} cross section and illustrates how the supply of heat decreases with increasing distance from the source. From this chart the annual heat loss in a given area could be estimated if the speed of the Atlantic water current were known.

Table 2. Annual heat balance of arctic basin waters. (from Timofeev 1958).

	Incoming heat (*kcal.*)
Atlantic waters (98,082 km.^{3})	214,357 x 10^{12}
Freezing of ice (3,108 km.^{3})	248,640 x 10^{12}
Pacific waters (36,000 km.^{3})	33,490 x 10^{12}
Continental run-off (2,377 km.^{3})	10,987 x 10^{12}
	507,474 x 10^{12}
	Outgoing heat (*kcal.*)
Atlantic waters	72,881 x 10^{12}
Lost to atmosphere in peripheral seas (assumed)	263,070 x 10^{12}
Lost to atmosphere in central basin	171,523 x 10^{12}

Standard methods of obtaining velocity by calculation of dynamic heights are not yet applicable in the arctic basin because of the scarcity of synoptic information. The T-3 data are of little use as the ice island apparently moved along flow lines providing no areal distribution of data from which velocities could be calculated.

Timofeev (1957) has calculated the average life of Atlantic waters to be 5.9 years by using the ratio of total kcal. (above 0°C.) in the arctic basin to the heat brought in annually. It would seem more logical to use the ratio of volumes, when, using Timofeev's figures, the life would be 28.1 years.

From known rates of ice drift it would take about 4 years for surface ice and water to move from the Alaskan coast to the Greenland Sea. The approximate time for the Atlantic waters to make this trip in the reverse direction should depend on this time and the ratio of volumes of water involved. If as Shirshov believes (Shirshov 1944) the lower boundary of the upper waters can be taken at the level of maximum vertical stability, where maximum increase in salinity is found, the surface ice and water

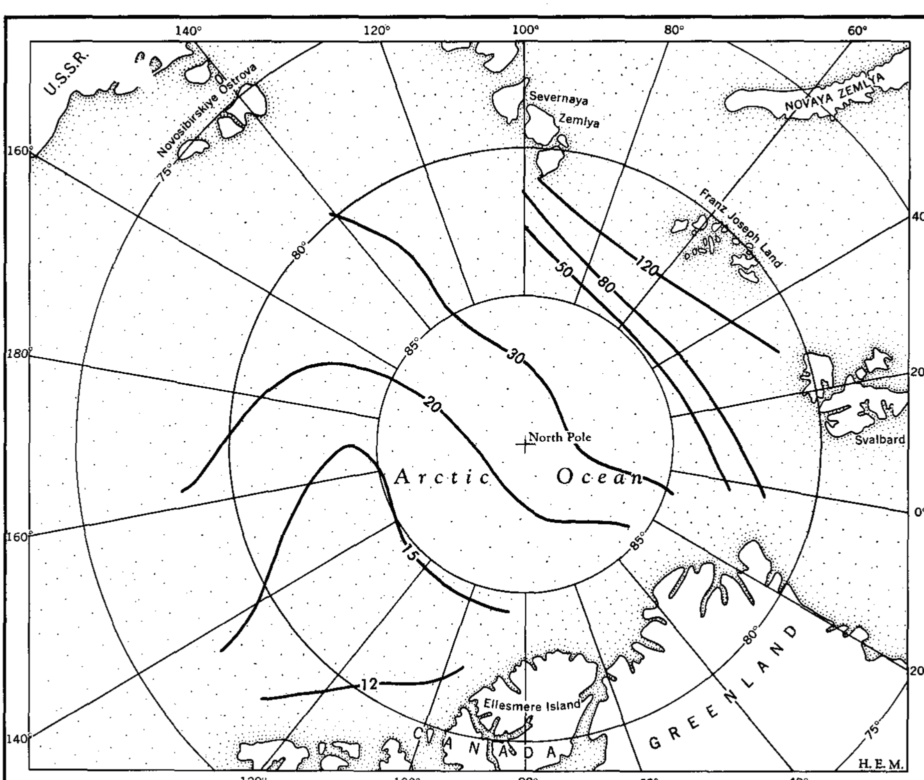

Fig. 5. Lines of equal heat. Values are total heat, in Kcal., above 0°C. in a vertical column one centimetre square.

would extend to 75 metres. If the Atlantic waters, on the basis of temperatures, occur from 200 to 600 metres the movement of Atlantic waters across the arctic basin should take about 20 years.

In an attempt to determine the age of Atlantic waters a sample taken at 400 metres at 82° 45'N., 98°30'W. was analyzed for tritium content by Giletti and Kulp (1959) and estimated to be less than 3 years old. The author speculated that the source of this water may have been the Canadian Archipelago, but Barnes and Coachman (1959) consider this unlikely and that results are too sketchy to serve as a basis for determining water circulation. The importance of analyzing further samples for tritium concentration is very apparent.

The above arguments mainly indicate how little is known of arctic water circulation. If the total life of Atlantic waters were 20 years, velocities would average about 150 km./year. According to Fig. 5 this would mean a loss of 2.0 kcal./year/cm.^{2} from Atlantic waters. If this heat flow were all lost through the ice it would restrict the ice growth to 12 metres according to Fig. 3.

It is difficult to estimate the differences, if any, between the factors governing the growth of ice in the Arctic Ocean and along the northern shores of Ellesmere Island and Greenland. As noted in the Ellesmere Island studies (Crary 1956) Atlantic waters were found off the ice shelf and also in Disraeli Bay. In Fig. 5 it can be seen, however, that the Atlantic waters have lost much of their heat before arriving at the shores of the western part of the Arctic.

A possible deterrent to the growth of thick ice near the shores might be the summer run-off, but this is not extensive in northern Ellesmere Island. At present the melt water does not extend to ice shelf depths and appears to expend its small amount of heat in melting the thin ice on the "moat" along the landward edge of the shelf.

The dissipation of heat of the Atlantic water upward must be quite variable both in time and space and dependent on factors influencing the eddy conductivity at depth. In this respect the movement of pack ice along the edge of the ice shelves in northern Ellesmere Island and the flow of tides in and out of the bays should have some effect on increasing the eddy conductivity values, which would normally be quite low in the ice-covered Arctic Ocean as compared with other oceans.

One of the most important factors in the continual growth of thick ice is its drift. The main arctic pack ice is constantly drifting, with a maximum life expectancy of about 4 years for any ice floe in the eastern arctic basin. The drift rate of T-3 indicates that ice formed in the seas north of Alaska or near the Canadian islands can survive much longer, but under present drift patterns thawing in the more southern waters during the cycle would probably prevent growth of abnormally thick ice.

The evidence from T-3, the Ellesmere ice shelves, and the ice fields near the ice shelves shows that as much as 30 or 40 metres of ice has been built up at the upper surface some time in the past. The evidence from the T-3 dirt layers shows that this was a slow process with many periods in which the summers must have been quite similar to that of 1955. The heavy dirt layers below this accumulated ice may represent surface material consolidated after other long periods of ice accumulation. From whatever meteorological cause, this condition must have been representative of all high latitude areas of the Arctic Ocean. As the ice becomes thicker its breaking strength increases and hummocking decreases. The movement will become less on account of decreased wind stresses and increased Coriolis effect from added thickness. It will also deviate more to the right of the wind (Browne and Crary 1958). This condition would again be reversed by changing atmospheric factors. Landfast ice along the northern coasts of Ellesmere Island and Greenland, retained by protecting bays and other coastline configurations, can have an indefinite growth period.

Probable history of ice shelves

Collections of material for age determinations by the carbon-14 method from T-3 and Ellesmere Island included dirt layers, driftwood, and marine shells. As was mentioned in Part I the dirt layers on T-3 showed minute amounts of carbon material, mainly plant remains, under microscopic examination. To obtain the necessary amount of carbon for age determination 2 or 3 kilograms of the dirt material were needed. All samples were analyzed by Broeckner, Kulp, and Tucek (1956). Information on the various samples from T-3 is given below.

(1) Sample 192B. Surface dirt from Area A (Part I, Fig. 6), collected early in 1952. Two different countings of this sample gave 5720 $\pm$ 250 years and 5830 $\pm$ 200 years. This may not represent an average age of all dirt.

(2) Sample 192A. This was laboriously collected along the shallow drilling section A (Part I, Fig. 19), from a lower dirt layer. About 10 cubic metres of ice were excavated, giving 365 grams of dirt and only about 1 gram of carbon, considerably less than needed for an accurate age determination. The ages that were obtained in two different counts were 4370 $\pm$ 200 years and 4480 $\pm$ 200 years. Although this sample should represent a very definite depositional period in the island's history, the evidence is open to some doubt since 38 separate meltings of about 3 to 4 hours each were required to melt the ice, which could have easily been contaminated by the soot from the diesel fuel used in the stoves.

(3) Sample 192E was collected in 1952 in Area B (Part I, Fig. 6), and consisted of small pieces of plant material. The age was determined as 450 $\pm$ 150 years. This is not necessarily representative of the top dirt layer as the material was probably washed down on the island from a nearby land mass. However, it does represent a maximum for the time since the island broke away from land.

(4) Sample 213D. After Marshall had located the surface outcropping of the deep heavy dirt layer found in the camp-site drill holes in 1953 a pit excavation was made in Area C and 3 to 4 kilograms of material obtained.

This layer seems identical with the layer at the camp site, but as it was obtained about a half metre below the top layer it may or may not include intervening dirt layers that were found at the camp site. Age figures on two counts were 3050 ± 150 years and 3100 ± 180 years.

(5) Sample 298B. In 1955 a further excavation was made to the heavy bottom layer in Area A where it was separated from the top layer by only about half a metre. The age of this sample was 3000 ± 200 years, a very good check on 213D from the opposite end of the island.

(6) Sample 298A. In the area of 298B the dirt from the top layer was also obtained. The age for this sample was 3500 years.

The information given by these age determinations is quite conflicting. Generally the top surface dirt layer is older than the bottom layers, although 192E may perhaps be discounted because of possible contamination and shortage of carbon material. The carbon available has been shown to be of microscopic size and it might be questioned whether this wind-blown material has an age contemporary with the period at which it was blown on the ice. The most reliable samples, and those least susceptible to contamination are the bottom layers 213D and 298B.

During 1953 and 1954 considerable material, mainly pieces of driftwood, was collected by Hattersley-Smith and members of his Ellesmere Island Expeditions and ages were determined by carbon-14 analysis. The sources of the samples are shown in Fig. 6 and the data are summarized in Table 3.

The pelecypod and mollusc shells noted in Table 3 were found at 38 metres and at 60 metres above sea-level respectively, giving an average rate of the rise of land with respect to sea-level of about 0.5 and 0.8 metres per century. The presence of these shells also indicates the absence of any major glacial advance in the past 7200 years in this area.

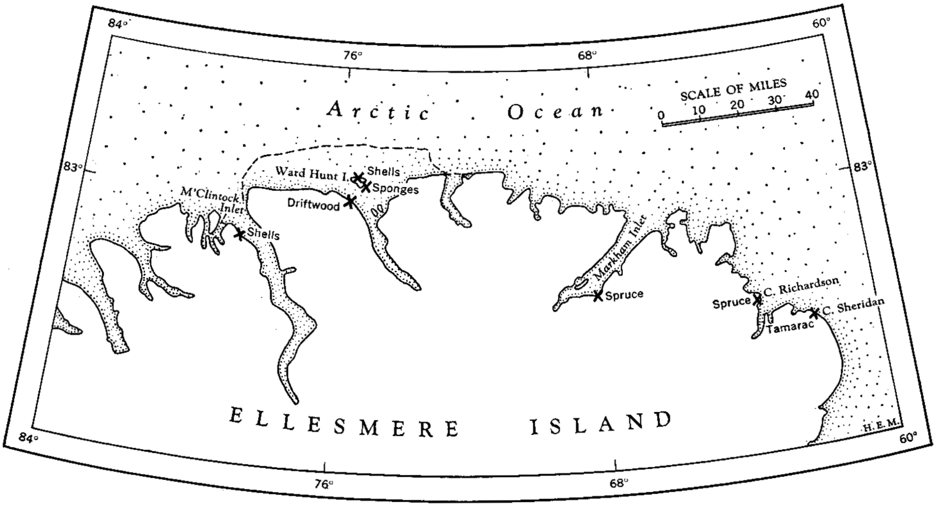

Fig. 6. Map showing locations where samples were obtained for radiocarbon dating.

Table 3. Natural radiocarbon measurements.

Sample No.	*Description*	*Apparent age (radiocarbon years)*
L261A	large fragment of spruce found south of Cape Richardson in mudbank above stream, 6 metres above sea-level	980±100
L261B	small fragment of spruce from low point on east side of Markham Inlet found in glacial outwash and raised beach material, 7 metres above sea-level	2190±150
L261C	small fragments of tamarack (?) from raised beach above river valley at Cape Sheridan 30 metres above sea-level	6050±200
L254A	wood from northern shore of Ellesmere Island, inland from ice shelf, not more than 3 metres above sea-level	3400±150
L254B	more wood from same general area as L254A	5740±200
L254C	more wood from same general area as L254A	6120±150
L254D	more wood from same general area as L254A	3000±200
L248A	pelecypod shells from raised beach on north side of Ward Hunt Island, 38 metres above sea-level (surveyed by theodolite)	7200±200
L248B	mollusk shells from west side of M'Clintock Bay among undisturbed marine deposits near glacier face, approximately 60 metres above sea-level	7200±250
L284	sponge found on surface of ice shelf near east end of Ward Hunt Island	400±150

Sample 284 was a large sponge found on the ice surface near Ward Hunt Island. Apparently the ice has thickened or the land has risen sufficiently in the last 400 years to ground the ice and by surface thawing and bottom freezing, in the manner described by Debenham (1954), the sponge was brought to the surface. This would require a net ablation in the last 400 years of an amount at least equivalent to the ice thickness in that area.

The driftwood pieces located back of the present Ellesmere ice shelf with ages varying from 3000 to 6120 years could not have arrived at their positions in the presence of the ice shelf and therefore give a maximum age for the beginning of the ice shelf. Although this driftwood could most easily have been brought in during a period of an open or nearly open Arctic Ocean, sample 261A with an age of only 980 years was most likely deposited when the Arctic Ocean was ice-covered.

No direct evidence for the minimum age of the ice shelf is available. On T-3 the best indications of minimum age come from the complexity and amounts of the dirt layers. The smallest ones, presumably the result of a single melt season, consist generally of scattered grains or very thin layers, which could not easily be weighed. The majority of layers showed evidence of having experienced several years of melting at the surface and though they could generally be followed for short distances in a section, it was necessary to core holes half a metre apart in order to trace many of them. The layers in the deep holes, all drilled in the same general area, could not be correlated, except for the heavy bottom layers. An age determination based on the evidence of probable annual deposition and total dirt would be several thousand years.

Further evidence leading to an estimated age is the uplift of the land areas. The outcropping of a heavy dirt layer on the edges of T-3, 10 to 15 metres higher than its location at the camp site on T-3 and the steep dip of the ice layers south of the Ward Hunt ice rise (Marshall 1955) are best explained by a rising of land areas. The old strand cracks found at an elevation of more than 20 metres above the present active ones on the south side of the Ward Hunt ice rise are difficult to explain except by uplift of the land. Using the carbon-14 age of the marine shell samples, which give an uplift of about 0.5 metres per century, a minimum age of a few thousand years could be expected for both ice island and ice shelf.

At two sites near the edge of T-3 outcrops of the heavy dirt layer are attributed to the uplift of land along the coast of northern Ellesmere Island, where these parts of the island were attached to the shore originally. At Rocky Point much morainal material, rocks, and some glacier ice were found. At Colby Bay considerable plant and animal material was obtained, including fish remains and *Serpula* tubes, which must have been picked up from the bottom of the water by the freezing ice. From geological evidence the most likely sites for the origin of T-3 appear to be Cape Bourne or Yelverton Bay. An original location deep in Yelverton Bay, as shown in Fig. 7, would account for the uplift at the two opposite ends and for the material found in the Colby Bay area.

Even though the general structures of T-3 and the present ice shelf in the Ward Hunt Island area are similar, the evidence of several age determinations indicates that the two may not be contemporaneous, and that T-3 may be older than the ice shelf in the Ward Hunt Island area. If we accept the ages of the ice shelf and ice island as greater than that of the driftwood samples L261A and L261B (980 and 2190 years, respectively), found a considerable distance east of the ice shelf, then these samples must have been brought in during periods of an ice-covered Arctic Ocean not unlike the present, as the ice shelf could hardly have existed in the presence of an open Arctic Ocean. Similarly, at an earlier period, when the T-3 ice island was in Yelverton Bay, but prior to the growth of the present ice shelf, driftwood could have been deposited on the mainland south of Ward Hunt Island by moving pack ice. However, if the age of the ice island can be shown from future evidence to be less than that of the driftwood, the possibility of an open Arctic Ocean during deposition of the samples south of Ward Hunt Island, and thus before the growth of the shelf, would be increased.

From evidence on T-3 and assuming that the wind-blown dirt particles were deposited uniformly with time, the last 7 per cent have been deposited during an ablation period and about 22 per cent before that were deposited

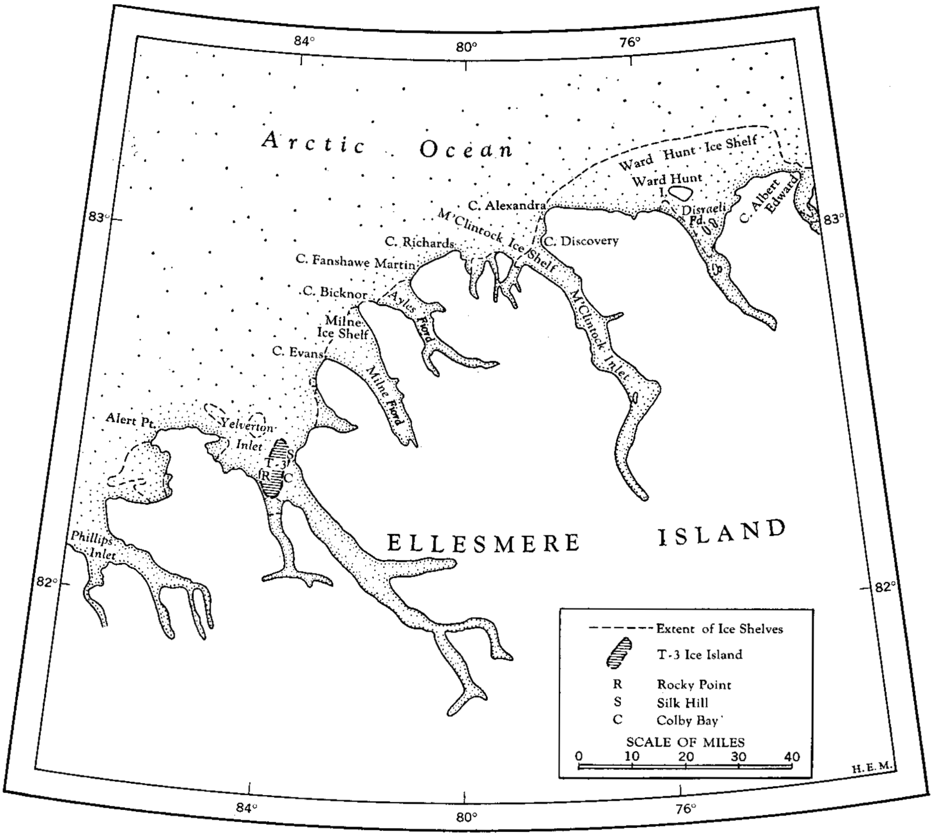

Fig. 7. Map showing possible source location of T-3 in Yelverton Inlet.

during a general accumulation period in which the island may have grown by about 20 to 30 metres. Any evidence of accumulation of snow older than the main dirt layer has been lost by later ablation. If an average age for the lower dirt layer is taken as 3000 years, this would give about 5500 years for the oldest dirt in this layer. Assuming that the ice of the island started to build up about 5500 years ago, the last accumulation period would have begun about 1600 years ago and continued until about 385 years ago, when the present ablation period started.

An ablation period starting about 400 years ago is substantiated by the sponge found on the ice surface, with an age of 400 years, and by the plant material, Sample 192E, 450 years old, also located on the surface. Surprisingly, evidence for this ablation period was found only in a few localities near the Ward Hunt ice rise, where old strand cracks existed mainly on the grounded ice and are believed to have resulted from uplift of the land. Where the underlying land is dipping very gently, horizontal changes in locations of strandlines would be greatest. The air photographs of the Ellesmere ice shelf very plainly show evidence of older, more extensive grounded ice in the northwestern part of the Ward Hunt Island ice rise.

The historical evidence that pertains to climatic changes and that has resulted from the study of the ice islands and ice shelves can be stated briefly:

(1) From carbon-14 dates of the dirt from T-3 and the driftwood on the landward side of the Ellesmere ice shelf it can be concluded that these features are definitely later than the end of the Wisconsin ice age some 11,000 years ago.

(2) Thick growths of ice, of which T-3 is a remnant, probably began in Yelverton Bay about 5500 years ago, and in the vicinity of Ward Hunt Island about 3000 years ago. As part of the inner ice in Yelverton Bay, T-3 was protected from the movement of arctic pack ice.

(3) Along the shores of northern Ellesmere Island the deposits of marine shells indicate that there has been no general advance of the glaciers in the area for at least 7200 years, and that the land has risen 38 to 60 metres with respect to sea-level in this time.

(4) Evidence from T-3 dirt layers and from material that worked up through the ice indicates that the present ablation period has been going on for about 400 years and that it was preceded by an accumulation period about three times as long.

Discussion of surface features

The major surface features that characterize the ice shelves of the Arctic are ridge and trough systems of quite uniform wave-length. Along the survey line on the ice shelf near Ward Hunt Island the average distance between ridges is 235 metres, and measurements from T-3 (Fig. 2, Part I) give values varying from 230 to 260 metres. This is a close agreement considering that the ice island T-3, as discussed above, probably had its origin about 200 kilometres southwest of the shelf. Depths of the troughs vary from a fraction of a metre to 6 metres. The cause of the uniformity in wave-length must be a factor that is itself uniform in high arctic areas.

Examples of the effect of stresses on floating ice shelves can be found in both arctic and antarctic areas. On newly formed sea ice a few centimetres thick that is subjected to shearing stresses insufficient to buckle the ice completely, *en échelon* systems of anticlines will occur at approximately 45° to the direction of the stresses. However, these are quite exceptional and anticlinal systems on arctic ice floes subjected to almost continuous stresses are significantly absent. In Antarctica many types of deformation features are formed by stresses in floating ice. Best known are those in the Ross Ice Shelf caused by the movement of ice around Roosevelt Island. Compressional forces north of the island causing the "Gould" anticlines have been studied by Zumberge (1958). Valleys and rifts are common in the tension areas along the front of the Ross Ice Shelf

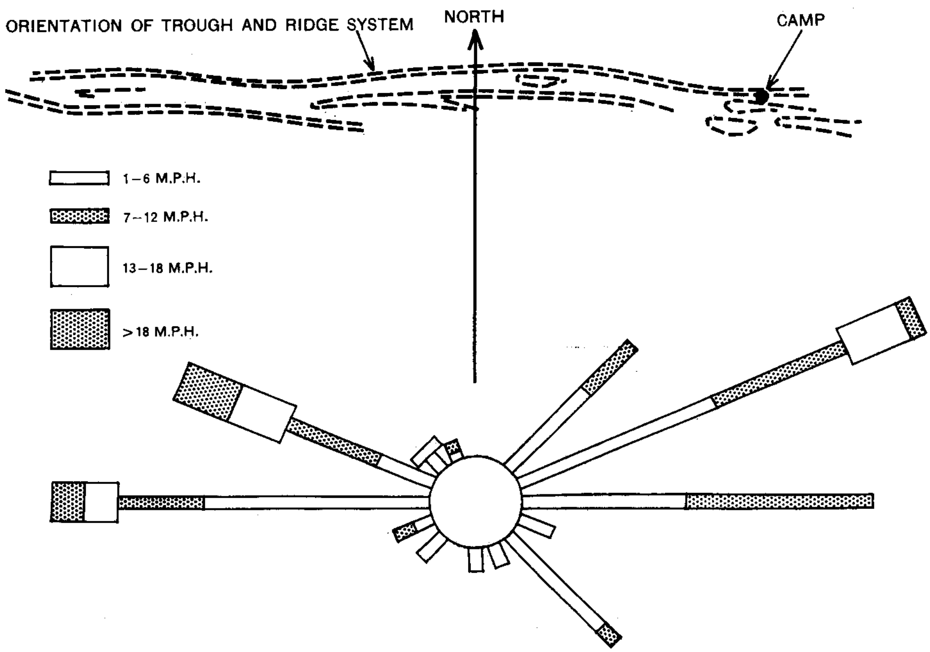

Fig. 8. Sketch showing orientation of ridge-and-trough system compared with wind rose.

on either side of Roosevelt Island. In both cases they are the result of the slow steady forces of moving ice, factors now absent in the shelf ice of northern Ellesmere Island. Despite the presence of Ward Hunt Island and other submerged islands no deformation features such as would be expected if the ice were moving can be found. In particular, if glaciers from land areas were a major factor in the formation of the shelves, it would be expected that some surface evidence of glacier action would remain, but except for features at opposite ends of T-3 they are absent. Any possibility that the ridges may have developed by grounding along submerged features of the shore must be discarded because of lack of uniform water depths and seaward motion.

It is believed, as suggested by Hattersley-Smith (1957), that the ridge and trough systems are the result of the action of strong summer winds on melt-water lakes and ponds. Fig. 8 shows that the prevailing surface winds during the 1954 expedition to northern Ellesmere Island were parallel to the ridge and trough systems. Fresh water on ice is a very efficient medium for ablating the ice because of its lower albedo and the convection processes below 4°C. High surface winds pile up water downwind and at the same time speed up these convection currents. Any series of randomly scattered ponds should in time form elongated lake systems under the influence of a system of prevailing winds. These elongated lakes would become deeper in time, although from evidence on both T-3 and the ice shelves, the melt-water lakes appear to be seldom deeper than 1.5 metres, a limit imposed probably by the decrease in convective currents in deeper water.

The second factor that could cause the formation of systems of elongated melt-water lakes would be surface slope. Although favoured accumulation areas could occur locally, particularly in the immediate vicinity of land, the slight slopes seen on the shelf and ice island are probably caused by the increased surface ablation on the downwind ends of melt-water lakes. Inside the fiord or inlets, such as Disraeli Bay, wind systems are complicated by surface topography and complicated ridge and trough patterns develop.

If the troughs are the product of the influence of wind systems on melt-water lakes, then the wave-lengths should depend primarily on the amount of summer melting. The problem would be much the same as that associated with the preferred size and spacing of randomly located melt-water lakes on flat arctic ice floes. Large lakes would generally be favoured as they would be more effective in causing additional melting. The sizes, however, are limited by the tendency of the ponds to grow mainly in the direction of the prevailing winds, and also by the effects of the local topography. In Fig. 3 of Part I it is shown that on many of the wide ridges of the ice shelf individual ponds are formed that should eventually grow to either elongated lakes or tributaries of larger systems. Distances between lakes should generally be comparable to lake widths.

That the trough systems migrate horizontally with time is apparent from the results of drilling on T-3 during 1955 (*see* Fig. 26, Part I), but it appears that this is a very slow process. Normally on the Ellesmere ice shelves lateral migration of ridge and trough systems might be expected from increased melting on the southern slopes of the ridges. T-3, formed in a bay area, must have been subject to other factors such as differential snow accumulation or differential melt-water flow from land.

Discussion of ice islands

As is now well known the floating ice islands are parts of the vast ice shelf areas of northern Ellesmere Island and Greenland that have broken loose under the action of meteorological or oceanographic factors. Although the term "ice island" is not wholly suitable and would certainly not find favour in Antarctica, where huge tabular floes are commonplace, the usage has found general acceptance in the Arctic Ocean, where icebergs or parts of ice shelves are rare.

Discussions of many aspects of the ice islands, their locations and probable numbers followed soon after the original discovery (Koenig *et al.* 1952, Montgomery 1952). Although over 80 have been located, most of these have been in the bays and inlets of the Canadian Arctic Archipelago, and many have undoubtedly been grounded there for gradual melting. As far as their recent history is known, only T-1, T-2, T-3, and NP 6 have been followed for any length of time in the arctic basin. The largest, T-1, may still be in the Arctic, although its last sighting was at 80°45′N. 4.0°E. Though it is not expected that more than a few ice islands are now in the arctic basin, no thorough search has been made since 1951, when J. O. Fletcher directed systematic flights over the western half of the Arctic before the occupation of T-3.

As seen from the general circulation pattern of the surface waters in the western part of the arctic basin (Browne and Crary 1958) tracks of the known islands from northern Ellesmere Island are gyral, swinging south to the Beaufort Sea, then westward and north along approximately the 180th meridian. Of the four known ice islands two have continued past the Pole to escape from the Arctic Ocean into the Greenland Sea, and two have continued to another circuit of the western arctic basin. As far as can be estimated the possibilities of an ice island leaving the Arctic or continuing in the gyral pattern are about equal. The chance of being caught in the Canadian Arctic Archipelago must be rather greater on the first round than on the succeeding ones. A lifetime of more than 30 years in the arctic basin would be improbable under present circulation patterns. Polunin (1955a, 1955b) has estimated from comparison of growth rings of arctic willow from T-3 and Ward Hunt Island, and from observations of the moss *Hygrohypnum polare,* found on T-3, that T-3 left its original site not earlier than 1935. The difference noted between the outline of the ice shelf near Ward Hunt Island as given by Marvin in 1906 (Bushnell 1956) and that found in 1954 indicates that several parts of this shelf have broken off in the intervening period. T-1, T-2, T-3, NP 6 and possibly several other ice islands, as Crocker Land (Peary 1910) and Bradley Land (Cook 1911), represent sizeable portions of the shelf that have broken loose in the later part of the ablation period discussed above. This is rather surprising in view of the indicated age of the shelf and island. It would appear that we are indeed approaching a period when the ice shelves might very well become extinct. It can be inferred from this that at present the arctic areas must be as open and the ice as thin as at any time in the last 3000 years.

References

Barnes, C. A. and L. K. Coachman. 1959. Oceanographic phenomena in the arctic basin. Science 129:901-3.

Broecker, W. S., J. L. Kulp, and C. S. Tucek. 1956. Lamont natural radiocarbon measurements III. Science 124:154-65.

Browne, I. M. and A. P. Crary. 1958. The movement of ice in the Arctic Ocean. *In* Arctic sea ice. Natl. Acad. Sci. Pub. 598, pp. 191-208.

Bushnell, V. C. 1956. Marvin's ice shelf journey, 1906. Arctic 9:166-77.

Cook, F. A. 1911. My attainment of the Pole. New York: Polar Pub. Co., 604 pp.

Crary, A. P. 1956. Geophysical studies along northern Ellesmere Island. Arctic 9:155-65.

——————1958. Arctic ice island and ice shelf studies, Part I. Arctic 11:2-42.

Debenham, F. 1954. The ice islands of the Arctic: a hypothesis. Geog. Rev. 44:495-507.

Fritz, S. 1958. Solar radiation measurements in the Arctic Ocean. Polar Atmosph. Symp. Pt. 1 Meteor. AGARDograph No. 29:159-66.

Giletti, B. J. and J. L. Kulp. 1959. Tritium tracer in arctic problems. Science 129:901-3.

Hattersley-Smith, G. 1957. The rolls on the Ellesmere ice shelf. Arctic 10:32-44.

Ingersoll, L. R., O. J. Zobel, and A. C. Ingersoll. 1954. Heat conduction, with engineering, geological, and other applications. Madison: University of Wisconsin Press, pp. 209-11.

Koenig, S. L., E. R. Greenaway, and M. Dunbar. 1952. Arctic ice islands. Arctic 5:68-95.

Malmgren, F. 1927. On the properties of sea ice. *In* Norwegian North Polar Expedition with the *Maud*, 1918-1925, Sci. Results. Vol. 1, No. 5.

Marshall, E. W. 1955. Structural and stratigraphic studies of the northern Ellesmere ice shelf. Arctic 8:109-14.

Montgomery, Margaret R. 1952. Further notes on ice islands in the Canadian Arctic. Arctic 5:183-7.

Nansen, F. 1902. The oceanography of the North Polar Basin. Norwegian North Polar Expedition, 1893-1896, Sci. Results. Vol. 3, 427 pp.

Peary, R. E. 1910. The North Pole. London: Hedder and Stoughton, 326 pp.; New York: F. A. Stokes Co., 373 pp.

Polunin, N. 1955a. Attempted dendrochronological dating of ice island T-3. Science 122:1184-6.

————1955b. Long-distance plant dispersal in the north polar regions. Nature 176:22-5.

Shirshov, P. P. 1944. Scientific results of the drift station "North Pole". Akad. Nauk SSSR. Obshchee sobranie, Feb. 1944, pp. 110-40 (Translated for AFCRC by Am. Meteor. Soc. on contract AF19(604)-1364).

Somov, M. M. *Ed.* 1955. Observational data of the scientific research drifting station of 1950-1951, Vol. 2. (Translated for AFCRC by Am. Meteor. Soc. on contract AF19(604)-1364).

Sverdrup, H. U. 1956. Oceanography of the Arctic. *In* The Dynamic North, Book I, No. V. U. S. Navy, Chief of Naval Operations.

Timofeev, V. T. 1957. Atlantic water in the arctic basin. Problemy Arktiki No. 2:41-51. (Translated for AFCRC by Am. Meteor. Soc. on contract AF19(604)-1936).

————1958. An approximate determination of the heat balance of arctic basin waters. Problemy Arktiki, No. 4:23-8. (Translated for AFCRC by Am. Meteor. Soc. on contract AF19(604)-1936).

Untersteiner, N. 1958. Arctic sea ice studies. Trans. Am. Geophys. Union 39:601-5.

Worthington, L. V. 1953. Oceanographic results of Project Skijump I and Skijump II in the polar sea, 1951-1952. Trans. Am. Geophys. Union 34:543-51.

Zumberge, J. H. 1958. Ross Ice Shelf deformation project, 1957-58. Trans. Am. Geophys. Union 39:794-9.