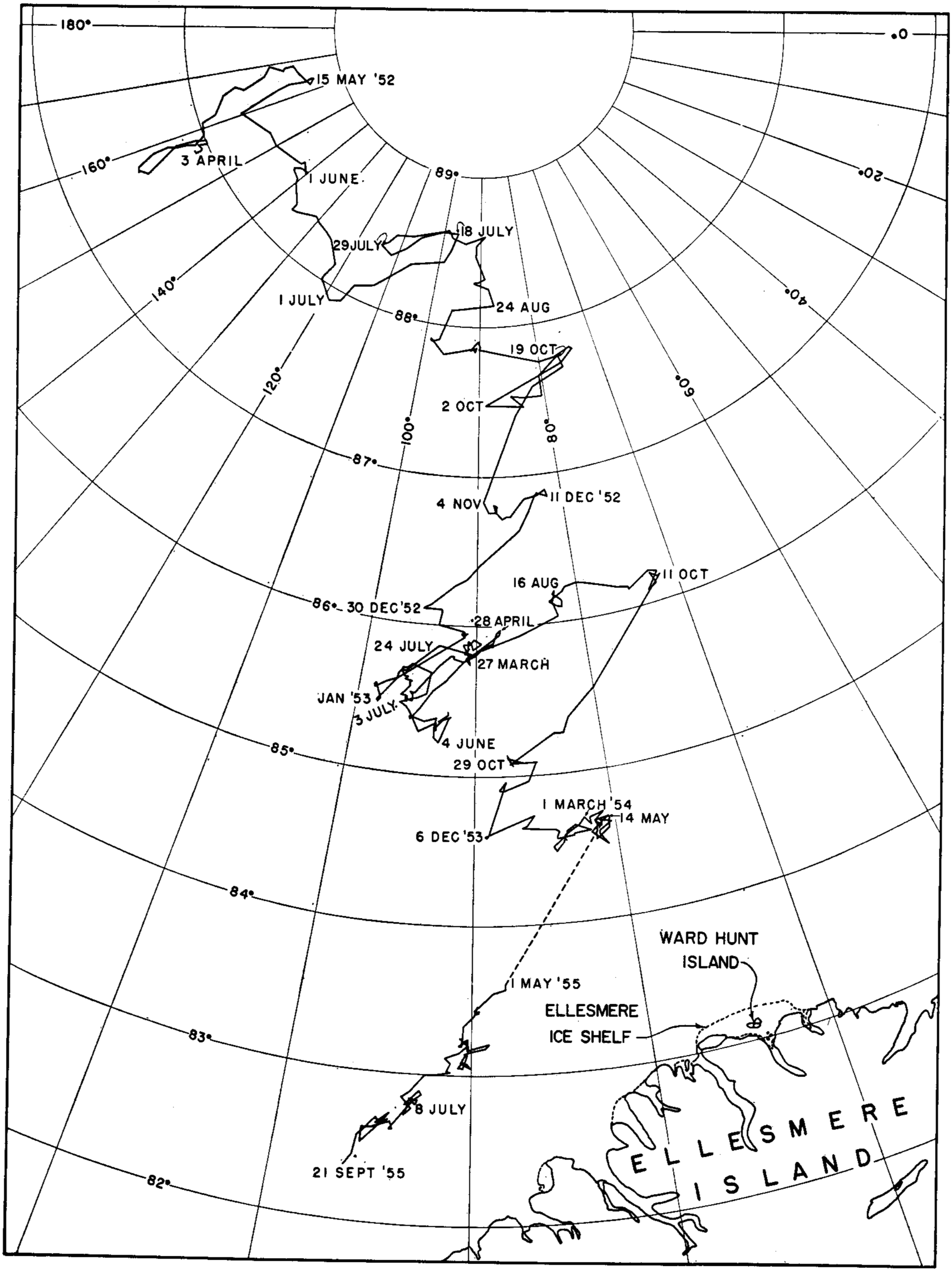

**Fig. 1.** Path of ice island T-3 during its period of occupancy shown in relation to the north coast of Ellesmere Island.

# ARCTIC ICE ISLAND AND ICE SHELF STUDIES

## Part I

A. P. Crary*

## Introduction

In March 1952, in what was termed Project ICICLE, under the leadership of Lt. Col. Joseph O. Fletcher, the Alaskan Air Command of the United States Air Force landed a small party of men about 150 miles from the North Pole on T-3, one of three floating ice islands whose movements in the Arctic Ocean had been followed since the first sighting in 1946. Soon after the initial landings meteorological upper air observations were started by the Air Weather Service, and geophysical studies were begun by the Air Force Cambridge Research Center. The upper air weather station continued in operation for a total of 22 months until in 1954 at 84°40′N., 81°W. operations were abandoned. During this period of occupation various scientific studies were carried out periodically by personnel from the Air Force Cambridge Research Center, from the University of Southern California under contract to the Arctic Aeromedical Laboratory, from Woods Hole Oceanographic Institute under contract to the Office of Naval Research, and from SIPRE (Snow, Ice, and Permafrost Research Establishment). A small group of scientists reoccupied the island from April to September 1955 when it was in the general area of 83°N., 90°W.

In an attempt to correlate the character of the ice island with that of the Ellesmere Ice Shelf, the presumed source of T-3, two expeditions led by Geoffrey Hattersley-Smith of the Defence Research Board of Canada explored the northern shores of Ellesmere Island in the summers of 1953 and 1954 from the weather station Alert to Lands Lokk, with the main efforts being concentrated near Ward Hunt Island in 1954. Each expedition was accompanied by a geologist of the Geological Survey of Canada, and in the second expedition United States personnel from the Air Force Cambridge Research Center and from SIPRE also participated. Fig. 1 shows the track of T-3 during its period of occupancy and also shows the location of the northern Ellesmere Ice Shelf. In May 1952 a small party from T-3 briefly visited T-1, one of the largest of the known floating ice islands, when it was about 40 miles offshore from Ellesmere Island.

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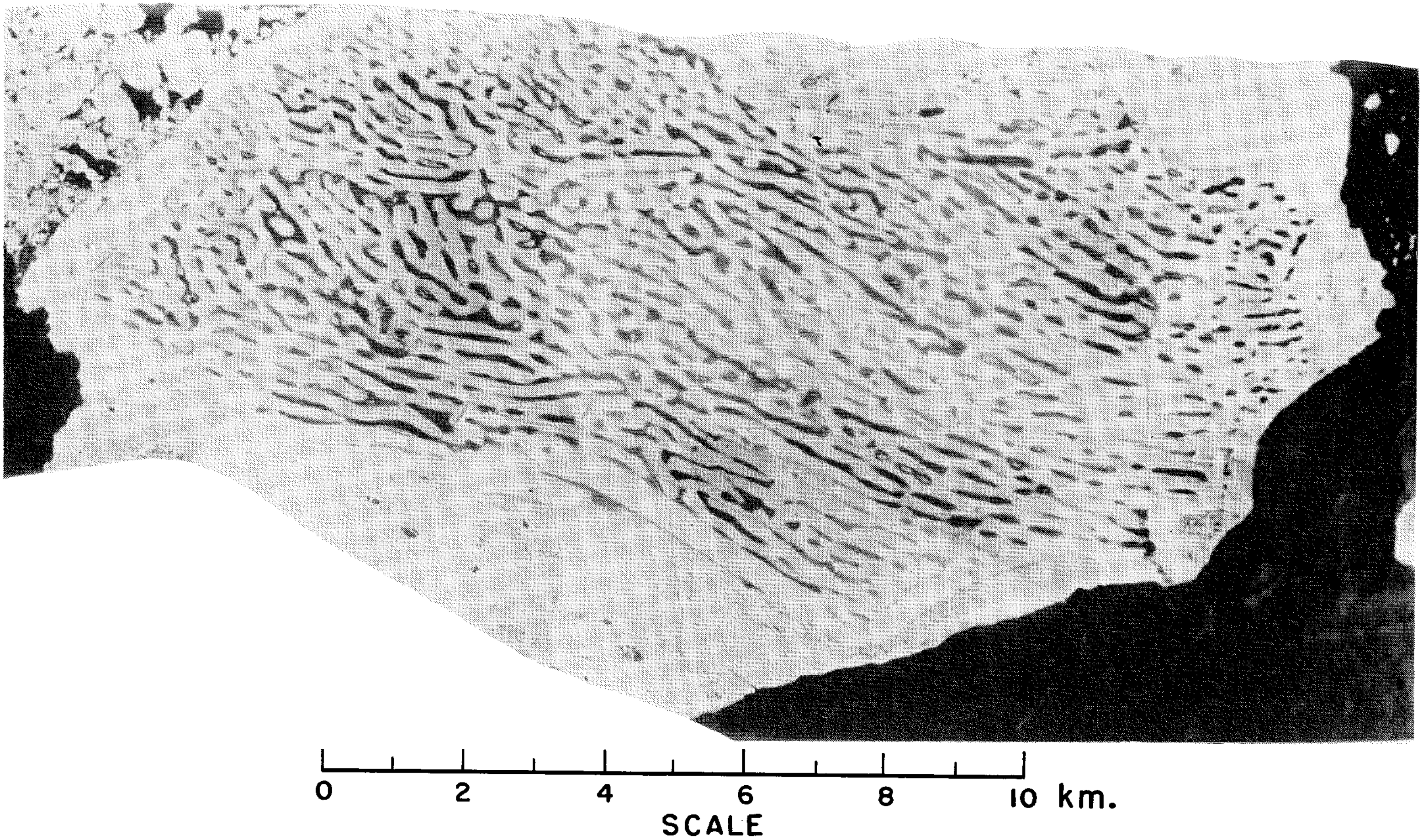


**Fig. 2.** Photo mosaic of ice island T-3. (By courtesy of U.S. Air Force).

The early history of the discovery of the arctic ice islands and the correlation with the ice shelf is given by Koenig *et al.* (1952). Résumés of the Air Force occupation and the early scientific programmes are given by Fletcher (1953) and Crary *et al.* (1952). Hattersley-Smith (1955) and Marshall (1955) have since described the general Ellesmere Ice Shelf programme.

The scientific operations in the ice island and ice shelf programmes fall into two major groups: the study of the arctic areas involved, their oceanography, geology, meteorology, etc., and the study of the ice island and ice shelf character. It is the intention to summarize in this article some general physical characteristics of the ice island and the ice shelf.

*Photo:* R.C.A.F.

**Fig. 3.** Aerial photo of Ellesmere ice shelf showing Ward Hunt Island.

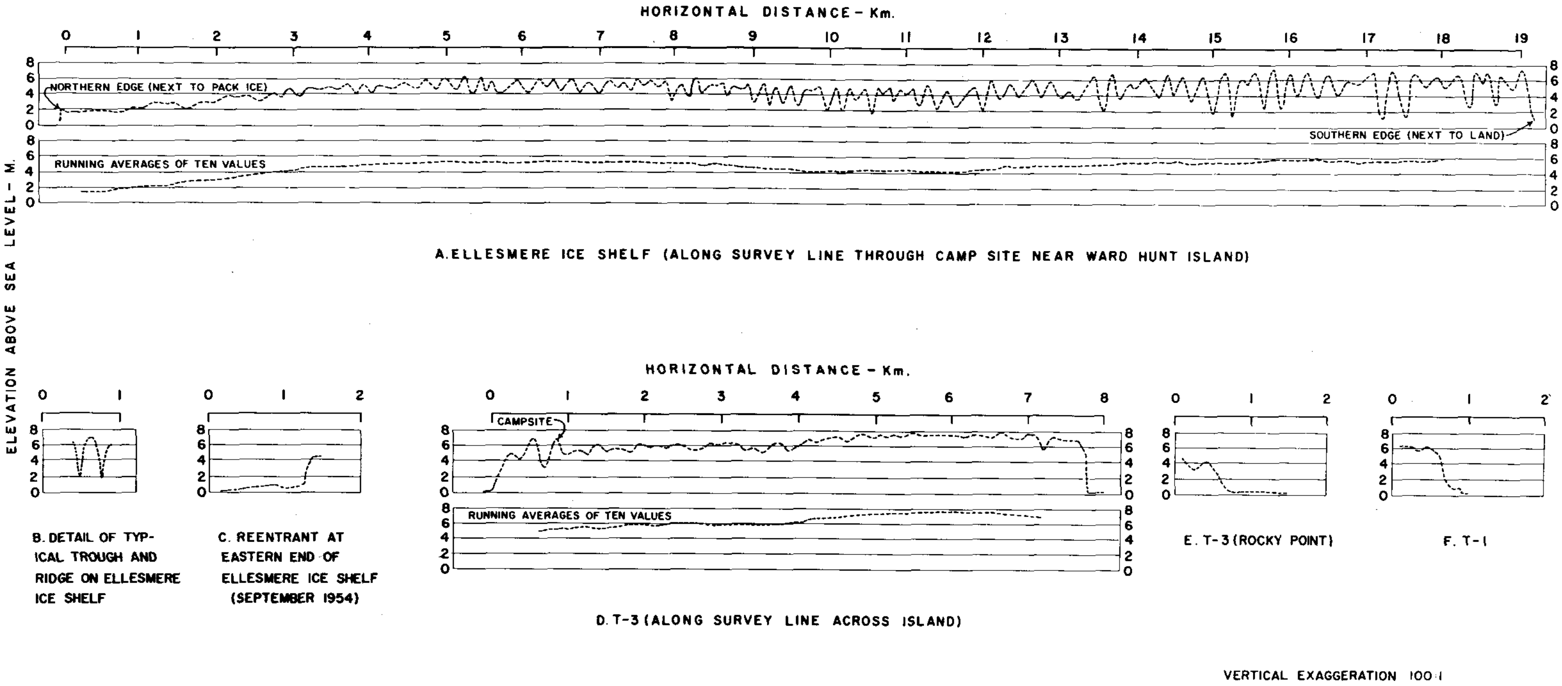


**Fig. 4.** Surface elevations of the northern Ellesmere ice shelf and of the ice islands T-1 and T-3

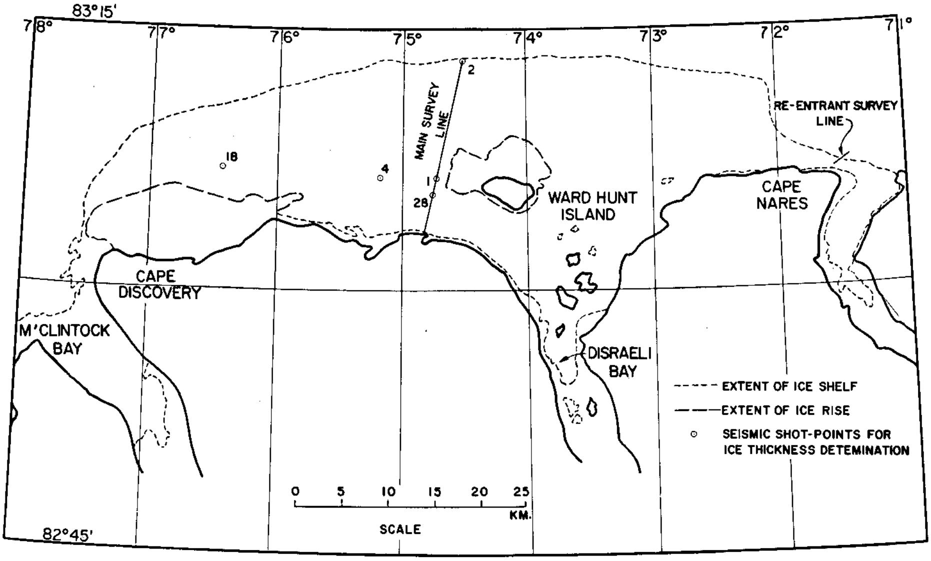


**Fig. 5.** Map of Ellesmere ice shelf showing the locations of survey lines and points where ice thickness was determined.

## General configuration of ice island and ice shelf

Air photographs of the surface features of T-3, Fig. 2, and the Ellesmere Ice Shelf, Fig. 3, show island and shelf with similar ridge and trough features which are very evident in summer, when the troughs are filled with melt-water. Some of these features, both of the island and the present shelf, are seen to be regular; others, especially in the protected bays of the shelf, are quite irregular. The collective areal extent of the many known floating ice islands is about 2,500 square kilometres, somewhat more than the extent of the present ice shelf along northern Ellesmere. Most of the floating islands appear to have found the end or near-end of their journey in the Canadian Arctic Archipelago, while a few are still adrift in the perennial pack ice of the Arctic Ocean. It is believed that the process of ice shelf building is continuous, as many ice features are noted in aerial photographs, which appear less massive but have surface characteristics similar to the Ward Hunt Ice Shelf.

## Surface elevations

Fig. 4 shows the results of transit level surveys across various parts of the ice shelf and island and Figs. 5 and 6 show the locations of these surveys. Values were taken to the hard ice surface under the snow cover.

The main survey across the Ellesmere Ice Shelf (Fig. 4A) shows the well developed ridge and trough systems on the inshore portion. The exact over-all extent of the area of little relief is not known though it is present along the entire extent of the west, north, and northeast edges.

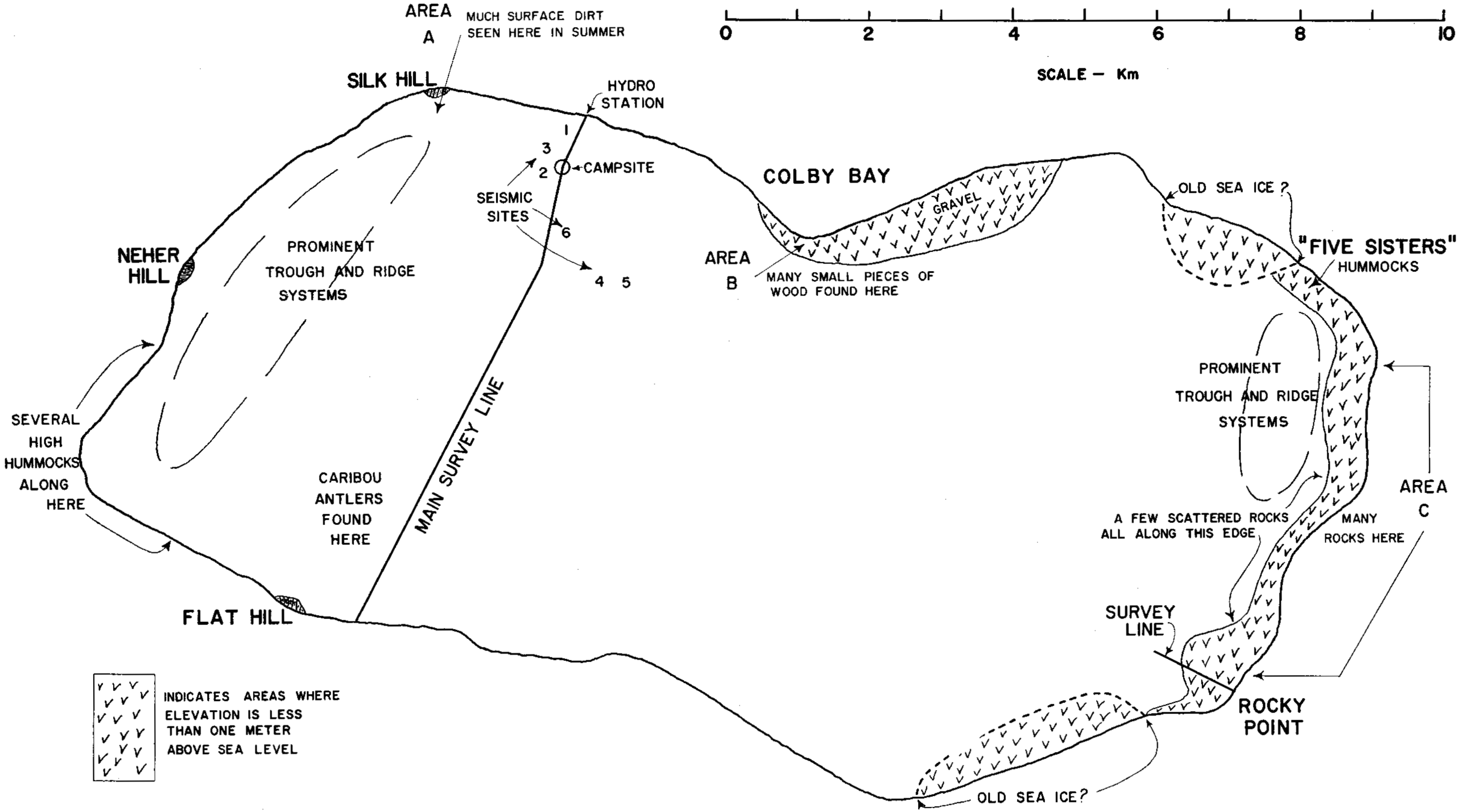


**Fig. 6.** Map of T-3 showing location of survey line and other points of interest.

There is also a low "moat" at approximately sea-level along some shore areas where warm drainage water from land collects during the summer. The ice shelf is obviously afloat throughout, with the exception of the small buried "islands" near the mouth of Disraeli Bay. The junctions of the ice shelf with the ice rises or buried islands are marked by obvious tidal or strand crack systems.

Fig. 4B shows in detail the elevations of a typical ridge with adjoining trough system. It should be noted that the ridge is much wider than the troughs, and in the calculation of average elevations this must be considered. The average elevations shown in Fig. 4A were obtained using five adjoining trough and ridge system elevations, allowing double weight for all ridge figures.

Figure 4C shows the elevations of an area north of Cape Nares immediately off the edge of the shelf. This area is of interest because it was here that a large piece of ice shelf broke loose about 1946 (Koenig *et al.*, 1952). The elevations were taken after the summer melt, and do not conform with estimated thicknesses, as will be discussed later.

Figures 4D and 4E are surveys made of the T-3 surface. The ridge and trough systems are not apparent on the main survey although the aerial picture shows the melt lakes very plainly. Figure 6 shows the approximate regions on T-3 where the ridge and trough systems are prominent, also the areas in which the elevations were probably less than 1 metre above sea-level. Elevations of one of these low lying areas are shown in Fig. 4E.

On T-1 the brief reconnaissance revealed no apparent ridge and trough systems. From aerial examination the surface of this large island is believed to have very little relief (Koenig *et al.*, 1952).

## Thickness and average density

Crary (1954) has described various seismic methods of measuring island thickness, three of which are dependent on plate waves. These three methods average the ice thickness over a distance of a kilometre or more. The fourth involves travel-time comparisons of seismic waves reflected from the ocean bottom in an area of uniform depths. In 1955 an additional thickness determination was made on T-3, using the horizontally polarized shear wave, (SH), reflected from the ice-water interface.

Attempts to obtain ice thickness on the Ellesmere Ice Shelf in 1954 were limited to six sites on the thick ice and one on the newer ice north of Cape Nares. On the ice shelf itself, at five sites, the SH shear wave was produced by a blow on a piton driven horizontally in the side of a pit. Detectors were located in a horizontal orientation and parallel to the force of the blow. Figure 7 shows a sample record in which four reflections of this SH wave to and from the top and bottom of the ice shelf are noted. The SH shear wave is not propagated in a fluid nor modified at the lower boundary into other wave types (Press and Ewing, 1951), and hence its total energy is reflected back from the bottom of the ice.

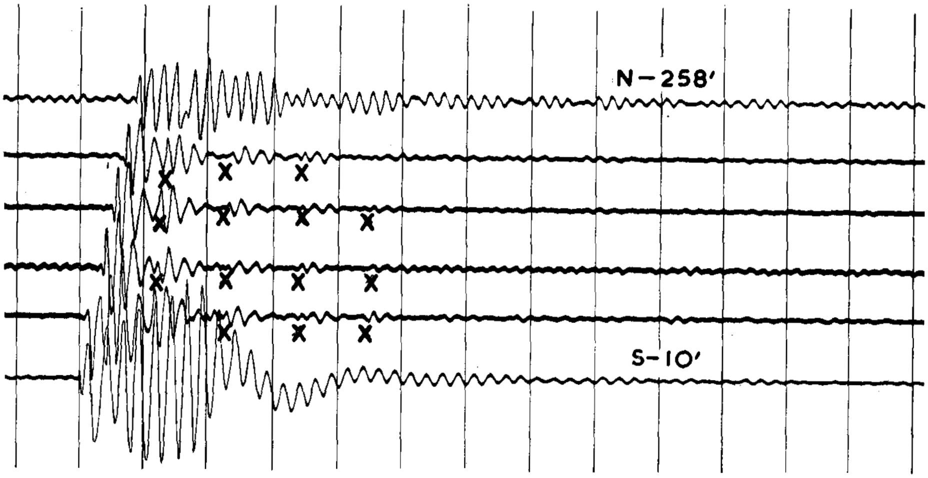


**Fig. 7.** Sample seismic record showing SH wave with four reflections.

In the calculations of thickness by this method, a slight modification of the reflection formulas was used. Repeated reflections between the bottom and top of the ice layer are described by the formula:

$$V^2 \; T^2 = 4n^2 \, H^2 + X^2,$$

where V is the shear wave velocity in ice, T the travel time, n the number of reflections from the bottom, H the thickness, and X the distance between the source of energy and the detector.

Although the reflection energies are quite evident, the initial impulse cannot be accurately timed except in a few cases. However, some identical phase of the several reflections can always be identified, and if we let the time difference between this part of the reflection and the actual beginning be e, the formula then becomes:

$$V^2(T - e)^2 = 4n^2 \, H^2 + X^2,$$

where T now represents time to the identified part of the reflection. Comparing any two arrivals, with m and n number of reflections from the bottom occurring at the same distance, X, we get, by eliminating e:

$$H^2 = \frac{V^2 \; TmTn(Tn - Tm) + X^2(Tn - Tm)}{4(n^2Tm - m^2Tn)}$$

In addition to the SH reflections the multiple reflected SV shear wave which had proved successful in the ice island thickness studies was used at one site on the Ellesmere Ice Shelf.

In order to obtain thickness values by these methods, it is necessary to know the velocity of shear waves in shelf ice. Figure 8 shows the time-distance refraction curve obtained from mechanical impulses, from which a velocity of 1,880 metres per second was obtained. Table 1 summarizes the various thickness determinations for the locations shown on the maps in Figs. 5 and 6.

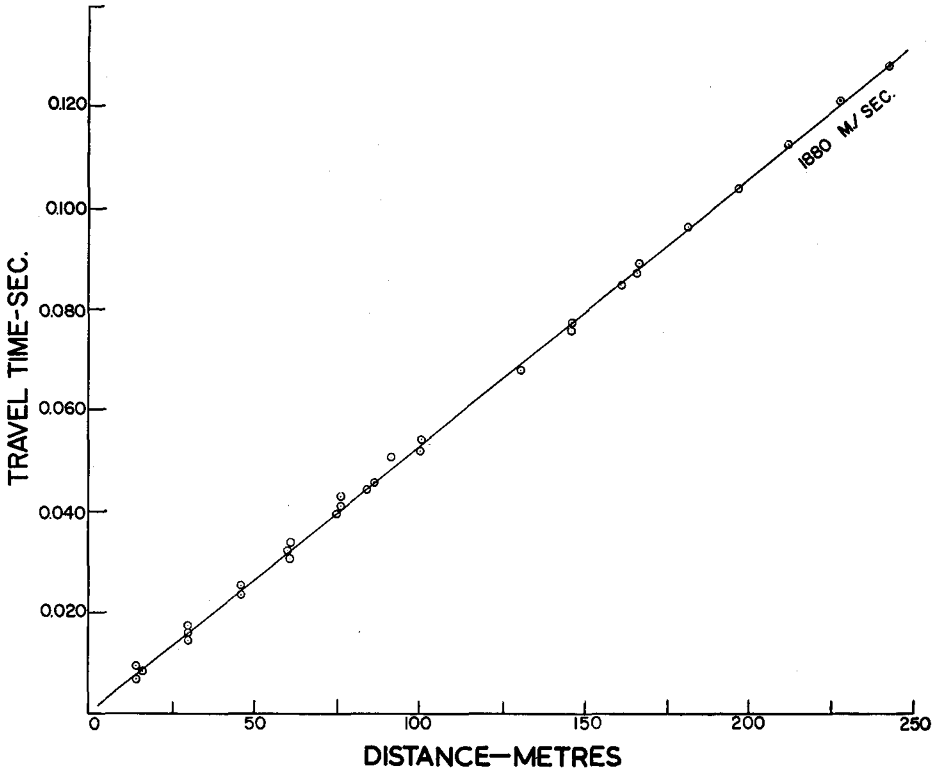


**Fig. 8.** Time-distance refraction curve giving velocity of shear waves in shelf ice.

**Table 1.** Values of ice thickness as determined by seismic means.

| *Location* | *Seismic method used* | *Elevation (metres)* | *Thickness (metres)* |
|---|---|---|---|
| Ellesmere Ice Shelf | | | |
| Shot point No. 1 | First SH reflection | 4.5 | 45 |
| " " No. 1 | SH reflections | 4.5 | 43 |
| " " No. 3 | " " | >4.6 | 51 |
| " " No. 4 | " " | >4.6 | 51 |
| " " No. 18 | " " | >4.6 | 53 |
| " " No. 28 | " " | 6.5 | 52 |
| " " No. 28 | SV wave | 6.5 | 54 |
| Ice island T-3 | | | |
| Site 1 | Ocean bottom reflections | 4.6 | 40 |
| " 2 | " " " | 5.1 | 47 |
| " 3 | SH reflection | — | 46 |
| " 4 | Flexural wave | — | 50 |
| " 5 | Air-coupled wave | — | 51 |
| " 6 | SV multiple wave | — | 53 |

In 1952 densities of 29 ice samples, from the surface to a depth of 16 metres on T-3, were obtained by the immersion method and are given in Fig. 9. Average density value is 0.905 gm./cm.$^3$. Using this value the ratio of total ice thickness to elevation above sea-level should be about 9:1 for T-3 when the water density is 1.024 gm./cm.$^3$, and from 9:1 to 10.5:1 for the Ellesmere Ice Shelf where water densities may vary from 1.0 to 1.024 gm./cm.$^3$. For the locations in Table 1 for which both thickness and elevation figures are available, a multiplication factor of from 8 to 10 is obtained. For the highest elevations found in the level surveys a maximum thickness of about 68 metres for T-3, and 60 metres for the Ellesmere Ice Shelf is indicated.

The problem of determining the thickness of the fringe areas on T-3 and on the ice shelf by elevations and densities is complicated by the lack of equilibrium where the thin and thick ice are essentially held together. The area along the northern part of the Ellesmere Ice Shelf must certainly be thin, 9 to 12 metres as determined by elevations and densities. However,

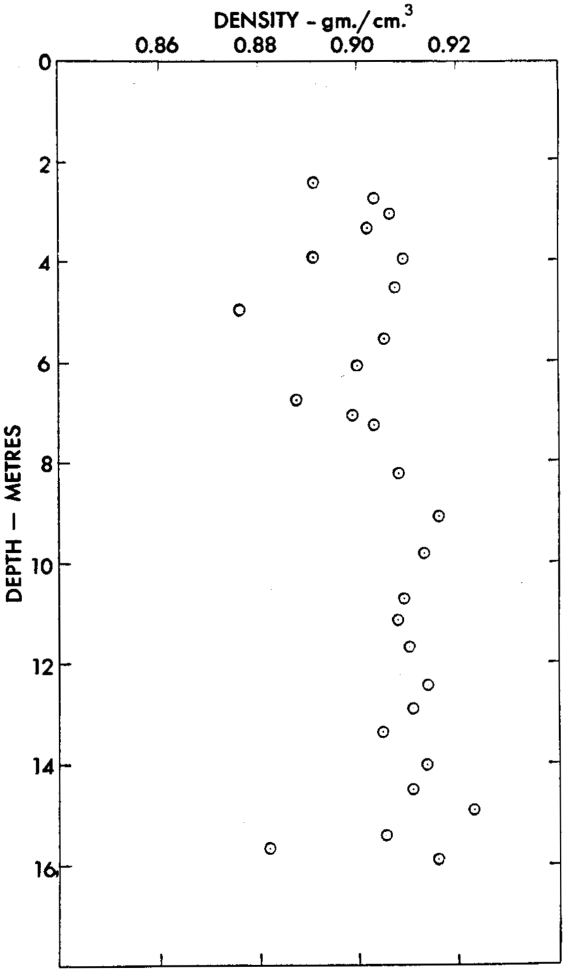


**Fig. 9.** Observed values of ice density in ice island T-3.

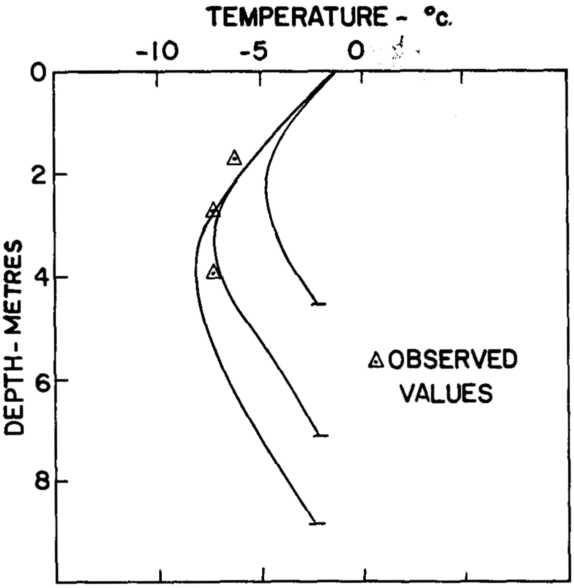


**Fig. 10.** Fit of theoretical temperature curves for ice of varying thicknesses to observed ice temperature values.

low elevation areas like those on T-3, which are much less extensive, may be considerably thicker. Because of abnormal amounts of foreign material, these areas have a low albedo and may have ablated to a lower surface elevation without any great change in the thickness below sea-level. On a smaller scale the same phenomenon is presented by the melt-water lakes where these are restricted in area. The surfaces of melt-water lakes of many of the troughs inside Disraeli Bay are at sea-level.

An unsuccessful attempt was made in September 1954 to determine the ice thickness by using seismic flexural waves in the area where a portion of shelf had broken off in 1946 north of Cape Nares. It is believed that the failure was due to the variations in ice thickness caused by the melt-water streams. Holes were drilled to a depth of 6 metres, where salt water infiltration prevented further deepening. An attempt was made to determine the thickness from observed below-surface ice temperatures, using an assumed value for surface temperature variations. Fig. 10 shows three theoretical temperature curves computed for depths of 4.5, 7.0, and 8.9 metres. A depth of 7 metres shows the best fit to the observed temperature values. With consideration of known values of the average temperature range, thermal coefficients of the ice, and the validity of the assumption of negligible surface change, an ice thickness of 7 metres is approximately the value for the growth during 7 years.

## Surface features and surface deposits

### Surface dirt layer

One of the most obvious surface features of the ice island and ice shelf is the thin layer of dirt near the surface. This dirt was not distributed uniformly but collected in small holes generally from a few millimetres to about 2 centimetres in width and up to 10 centimetres below the ice surface. The small collections of dirt, by absorbing more radiation than the ice, have melted out the small deposit holes and caused continued melting ahead of the ice surface. Some individual grains of dirt remained on the surface to give it a darkish appearance after summer melting had removed the snow cover.

The amount of this "surface" dirt layer was determined in two instances in shallow pits approximately 1 square metre in area near the campsite at T-3. Values obtained were 114 and 122 gm./m.$^2$. At the campsite location on the ice shelf in northern Ellesmere a similar determination gave a value of 45 gm./m.$^2$. If evenly spaced, the T-3 dirt layer would be only of the order of 1/20 of a millimetre thick. It is difficult to estimate the fraction of this dirt that may be lost by drainage during summer melting but ordinarily the dirt is protected by its location in the small holes. An exception to this was noted during a very heavy rainstorm on the northern Ellesmere Ice Shelf in mid-August 1954, when the dirt in many places was literally flushed from its protecting beds. The dirt layer did not seem to vary in appearance anywhere on the high areas of the ice island, but on the ice shelf it was less noticeable on the seaward edge than it was over the shoreward areas of the shelf. At T-1 there was the same type of dirt layer in the area visited, though perhaps not as heavy as on T-3.

Examination of the mineral content of the dirt on T-3 has been made by Stoiber, Lyons, Elberty, and McCrehan of Dartmouth College (1956). They report the following estimated percentages of minerals in the surface dirt: 60% lithic fragments (fine-grained altered volcanics), 5% quartz, 10% plagioclase, 5% muscovite, 10% biotite, 5% K-feldspar, with small amounts of hornblende, chlorite, sphene, calcite, garnet, etc. They found "no essential mineralogical difference between the surface dusts of T-3, T-1, and the dusts from within the ice of T-3. It is also evident that the dusts are mineralogically identical with the rocks collected at the surface of T-3." They appear to have been derived from a land mass underlain partly by volcanic rocks and partly by metamorphic and plutonic types. The low percentage of heavy minerals in the dust makes it probable that it was wind-deposited. It was noted that the low-lying hills adjacent to the coast near the Ellesmere Ice Shelf were snow free from mid-June until about mid-August. Prevailing coastwise winds in that area would account for the decrease in the amount of the deposited layer toward the seaward edge of the shelf.

This surface dust also contains some organic material. Dr. Barghoorn of Harvard University (personal communication) has kindly given the following description for one of the samples. "Organic residues in the sample consist of a considerable range of microfossils. These include threads of fungus hyphae, algal (?) spores, fungus spores, and fairly numerous fragments of woody tissues of higher plants, commonly infested with fungus hyphae; resinous bodies and a very few pollen grains." However, he found that "other samples collected in the summer of 1955 exhibit a very low proportion of organic matter and a high proportion of acid

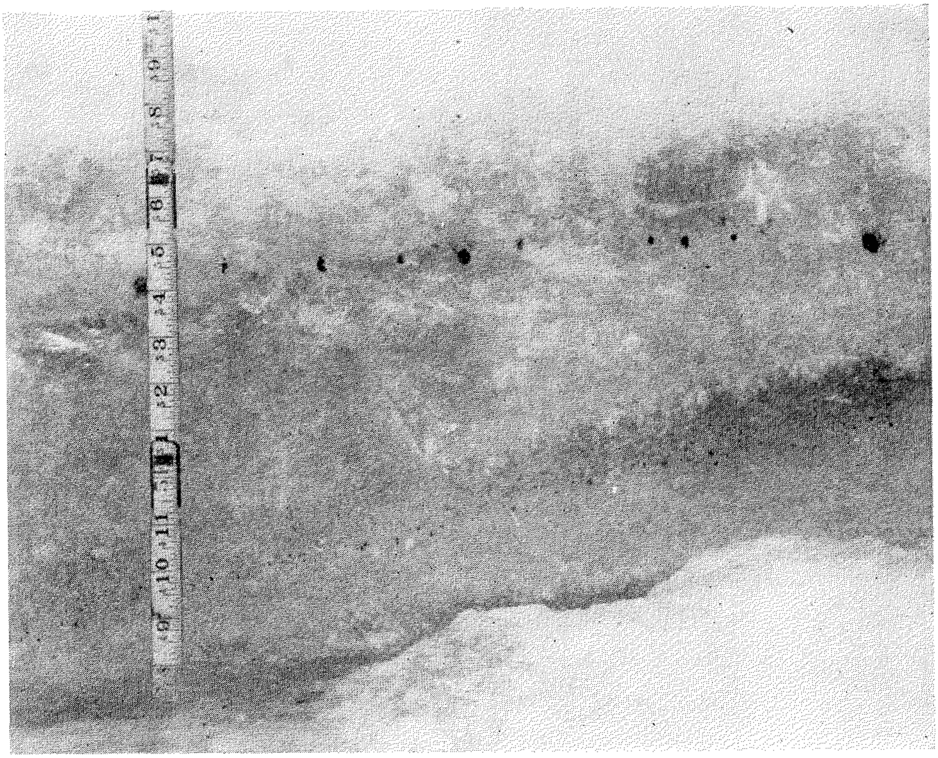


Fig. 11. Section of T-3 ice showing heavy top dirt layer and one lower layer.

insoluble minerals. Standard procedures for extraction of pollen and spores yielded negative results and the only organic constituents found were amorphous, finely divided fragments of particulate organic matter. A few discrete cells of probable algal origin were observed."

Very soon after the occupation of T-3, as excavations were made into the ice, it was noted that in addition to the top surface dirt layer there were other, much lighter layers in the interior of the ice. Fig. 11 shows the dirt in the top layer, and one of the heavier of the lower dirt layers. Some of these layers were extremely light, so that the grains were actually separated. It was quite apparent that the top layer must represent a long period of collection either by continual melting into the ice surface or by the surface remaining virtually unchanged for many years. In no locations were there thin dirt layers buried in the accumulated snow or ice above this heavy layer. Therefore it must have been many years since snow had accumulated in the area of its origin. On the Ellesmere shelf during the summer of 1954, which was an exceptionally long summer, the dust deposited was not noticeable. It is very unlikely also that more than one light layer could be deposited annually since the low-lying hills are bare for only about two months. Summer snowfall heavy enough to cover the ice would also cover these hills and the melting in one area would be closely paralleled by melting in the other.

### Plant and animal specimens

During the period in which T-3 has been occupied, about one-half of the island surface has been examined. This was possible only during the late summer period after the snow cover had melted. Although the entire surface of T-3 was characterized by a honeycombed appearance with the small aggregations of dirt of the top layer at the bottom of the holes, there were several areas of particular interest as indicated in Fig. 6. In the area "A", about 2 to 3 square kilometres in size, lying at or near sea-level, very large amounts of surface dirt were present; they were several times larger than those of the normal surface layer, and in many areas the dirt completely covered the ice as a thin mantle. In this heavy dirt layer were found a few fragments of plants, some lemming remains, and caribou excrement. Following the island edge clockwise, two fish skeletons were found about 2 metres above sea-level. These had broken apart and were dispersed in holes in the honeycombed ice. It was seen that in most of the shore areas along this part of the island where elevations change to sea-level gradually rather than dropping off abruptly, the holes containing the dirt layers were much larger, in many cases up to 30 or 40 centimetres in diameter.

In area "B" large amounts of plant material were located. Dr. Polunin (1955) made a thorough examination of this material and the following information is obtained from his report. "Plant materials collected during 1952, 1953, and 1955 at or near the surface of the ice island T-3 belong mainly to arctic willow, *Salix arctica,* (531 items, mostly pieces of stems or roots up to 15 centimetres long), purple saxifrage, *Saxifraga oppositifolia* (164 items, including tussocks up to 12 centimetres in diameter), low spear grass, *Poa abbreviata* (20 partial specimens, including a tussock 9 centimetres in diameter), and tufted saxifrage, *Saxifraga caespitosa* (7 small rosettes, etc.). In addition, there were determined various leaves, roots, and faeces; also four species of lichens and fairly numerous mosses and liverworts of which some were represented by sizeable tussocks. All were dead except a circular mat 24 centimetres in diameter of the moss *Hygrohypnum polare,* which proved to be still alive. Gathered during the protracted drift of the ice island in the Polar Basin, and in many cases in the vicinity of the North Pole, these land-grown botanical items with a few understandable exceptions strongly suggest very high-arctic origin, and it is supposed that they were washed (or possibly in some cases blown) on to the surface of T-3 when it formed part of the shelf-ice attached most likely to the north coast of Ellesmere Island. So far as this last region has been investigated, available data would seem to support this suggestion." Most of the area "B" was near sea-level and also had an unusually large amount of surface dirt. Near the far end of area "B" some gravel deposits were located. A thorough examination of this area was planned for 1955 but for the first time during the occupation the snow never completely melted and surface studies were not possible.

**Fig. 12.** Large rock near area C on T-3 (length approximately 3 feet).

## Geological specimens

Starting with an isolated specimen about 2 kilometres from Area C and continuing around that end of T-3, erratic rocks and gravels were common. The isolated specimen shown in Fig. 12, which is about 3 feet long, was perhaps one of the largest. Others were located in long morainal features over 1 kilometre in length. A petrographic analysis of twelve rock samples collected in 1952 was done by Shorey (1953). He found "four gneissoid rocks of granitic composition, two amphibolite gneisses, an actinolite granite gneiss, a granite micropegmatite, an aplite, two felsites, and a diabase. The gneissoid rocks appear to be of metasomatic origin with the mafics delineating the relict bedding planes. Banding was not prominent in any of the specimens and in only two of the samples was foliation outstanding. The minerals found in the gneisses are all only of medium grade."

A total of 153 rocks from T-3 was examined by Stoiber *et al.* (1956). Of these, "a representative group of 38 was studied in thin section and the remainder were examined in hand specimens. . . . The rocks with few exceptions may be divided into several categories according to their petrography. The general subdivisions are schists, gneisses, more or less altered extrusives, intrusives, (and) graywackes. . . . The most abundant rock type represented in the suite is altered volcanics. . . . It is noted that the following rock types are not present: slates, chlorite schists, and other low-grade metamorphic rocks; limestones and other sedimentary rocks, except for two graywacke specimens."

From a comparison of these rock specimens with those collected by Christie in his study of northern Ellesmere shore areas (Christie, 1957), Stoiber *et al.* (1956) conclude that "of the land bordering the Arctic Ocean, areas on the north and northwest coast of Ellesmere Island such as Yelverton Bay and Cape Bourne are the most likely sources of the rock material on T-3." On the basis of available evidence it is impossible to fix the precise location of origin.

In 1955 in the general rocky terrain of Area C on T-3, a dead lichen specimen was collected by Norman Goldstein from one of the larger rocks. This was examined by Dr. I. M. Lamb of Harvard University (Polunin, 1955), who identified it as *Caloplaca elegans* (Link) Th. Fr.

In most of Area C, as in Area A, the surface dirt layer was many times heavier than had been noted at the campsite and on other parts of the island. There was also some animal material found among the rocks. This included a small fish about 10 centimetres long and some bones thought to be from a polar bear. Area C, however, has not had a thorough searching during the period in which the snow was completely gone.

## Strand cracks

At the junction between floating and grounded ice on the Ward Hunt Ice Shelf occur obvious strand cracks, usually ½ metre or less in width

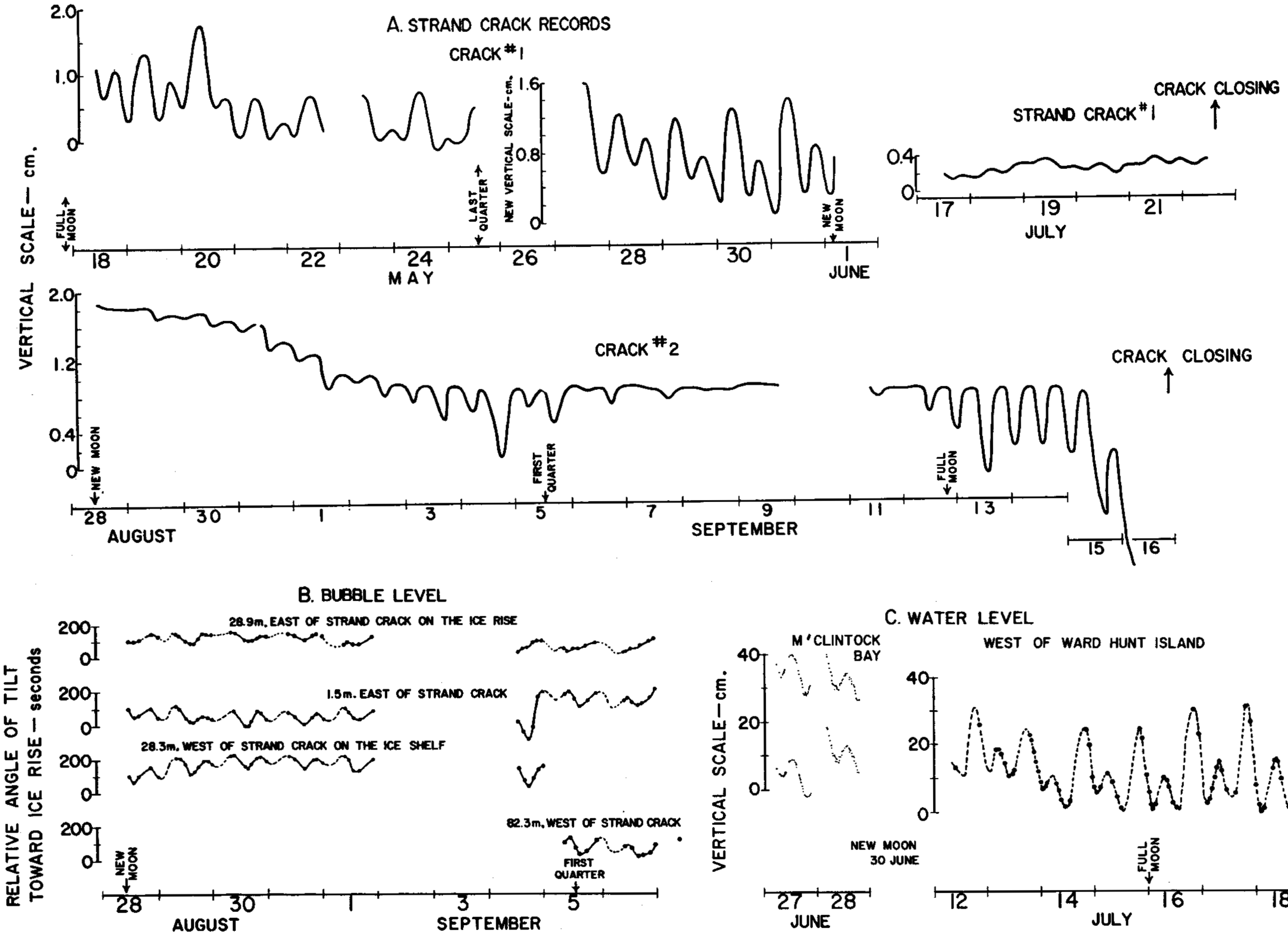


**Fig. 13.** Recorded amplitudes of strand crack opening and closing; water-level observations; and bubble level readings (Ellesmere 1954).

and 2 to 8 metres deep. These cracks were not continuous along the outer fringe of the grounded zone but often occurred in "en echelon" formations. These were found around all buried islands, ice rises, and shore areas bordering the ice shelf, and were not observed elsewhere. These cracks, as will be shown, are the surface expression of strains produced by ocean tides.

In June and July 1954 close observations of actual tide levels were taken by R. L. Christie of the Geological Survey of Canada to whom the author is indebted for this information. His figures were obtained in open water in M'Clintock Bay and near Ward Hunt Island and are shown in Fig. 13C. The maximum tidal range appears to be about 30 centimetres and the diurnal tides show considerable inequality of range. The tide character appears generally similar to that at Resolute Bay and Isaachsen as given by Rae (Manning and Rae, 1950).

Observations were made of the opening and closing of the strand cracks in the western section of the Ward Hunt Island ice rise. This was done by freezing lever arms in the ice which operated a pencil over a spring-driven clock drum. In Fig. 13A are shown observations made during May, July, and again in late August and September. During the summer months when the shelf surface temperature is higher, the ice apparently can undergo considerable bending without fracture. The renewal of larger tide motion in the crack zone, shown in September, coincided with the appearance of a new small surface-crack entirely independent of the previous one which had filled with water and frozen. This new crack, though running closely to the older one, alternately was on one side and then the other and fortunately crossed the old crack underneath the recording mechanism. Comparisons of the opening and closing of the strand cracks with tidal observations during mid-July, when these observations are available in the same vicinity, show that the cracks tend to close at high tide as would be expected. The maximum amount of horizontal movement occurred during late May with a value of about 1 centimetre. Since the ice shelf thickness is about 40 metres in this vicinity, this would represent a surface tilt difference of about 100 seconds across the strand crack, if equal strains take place on the upper and lower ice surfaces.

To get further information of this ice tilt that is taking place near the grounded zone, bubble levels of 30 and 60 seconds resolution were frozen in the ice on either side of the stand crack. Figure 13B shows the results, which were obtained only for a few days of late August and early September, at a time when strand crack opening and closing was about a quarter to a third of that observed in May. Though an average range of 100 seconds was obtained, no particular difference was noted on opposite sides of the crack during the observational period. An appreciable tilt probably occurs as far back as 1000 metres from the grounded area, since no difference in tilt was observed over a distance of 100 metres.

Figure 14 shows the western half of the Ward Hunt ice rise. Along the western edge of the ice rise the fracture zone lies mainly on the seaward

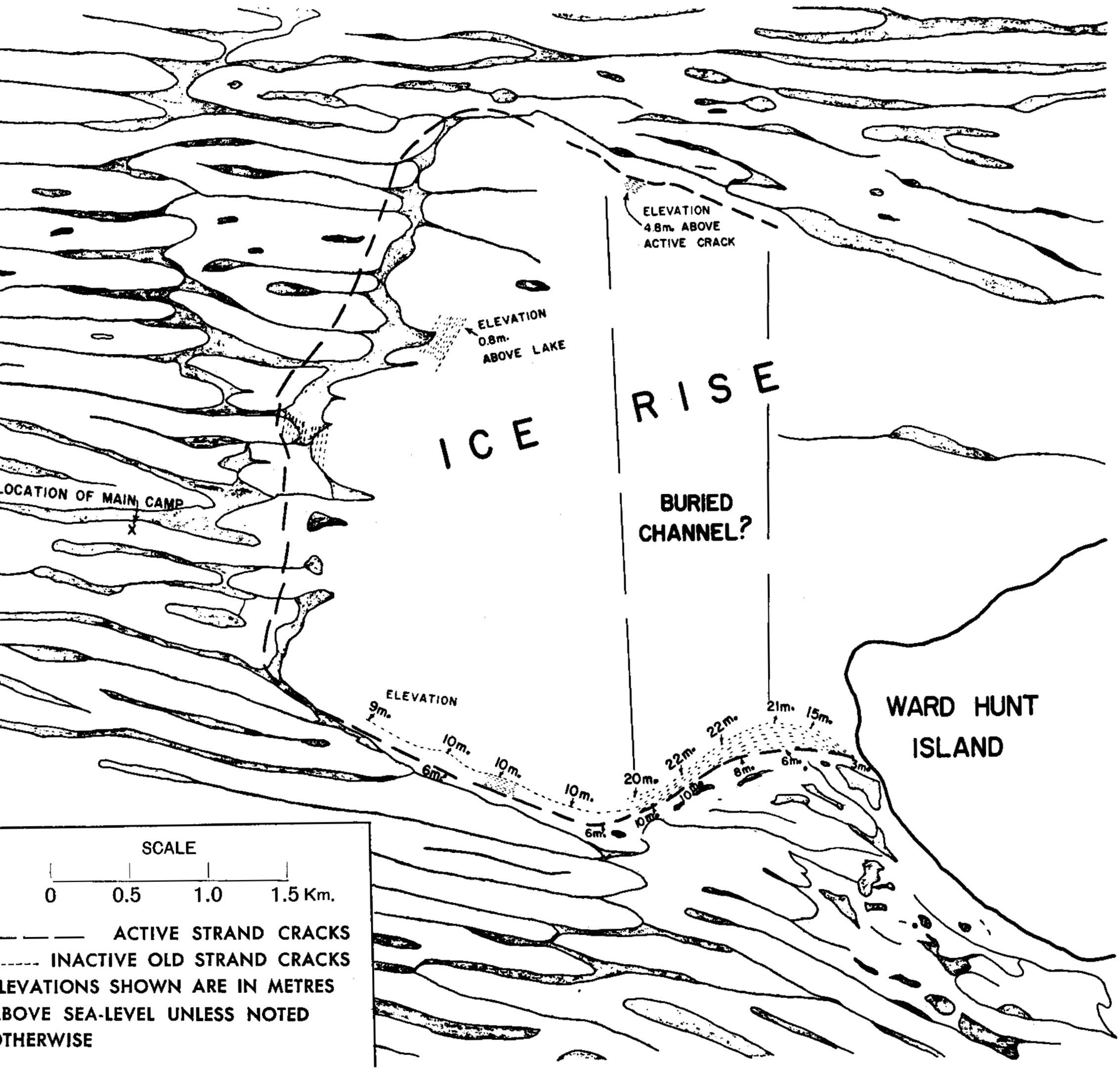


**Fig. 14.** Western portion of Ward Hunt ice rise and surrounding shelf ice. Location of the main active strand crack is shown, as well as many of the old inactive ones.

side of the lower elevation drainage lakes, while on the northern and southern edges it lies inshore and parallel to the lakes, in places rising up on the slopes of the ice rise. The elevation of the fracture zone above sea-level will necessarily be an indication of the thickness of the ice which is balanced on the bottom, hence the changes in elevation will be an indication of the sub-ice topography except where the strand cracks occur in narrow deep channels, lakes, or other minor surface drainage features.

Figure 15 shows the approximate elevations above sea-elevel of the strand crack south of the ice rise and elevations relative to lake level of

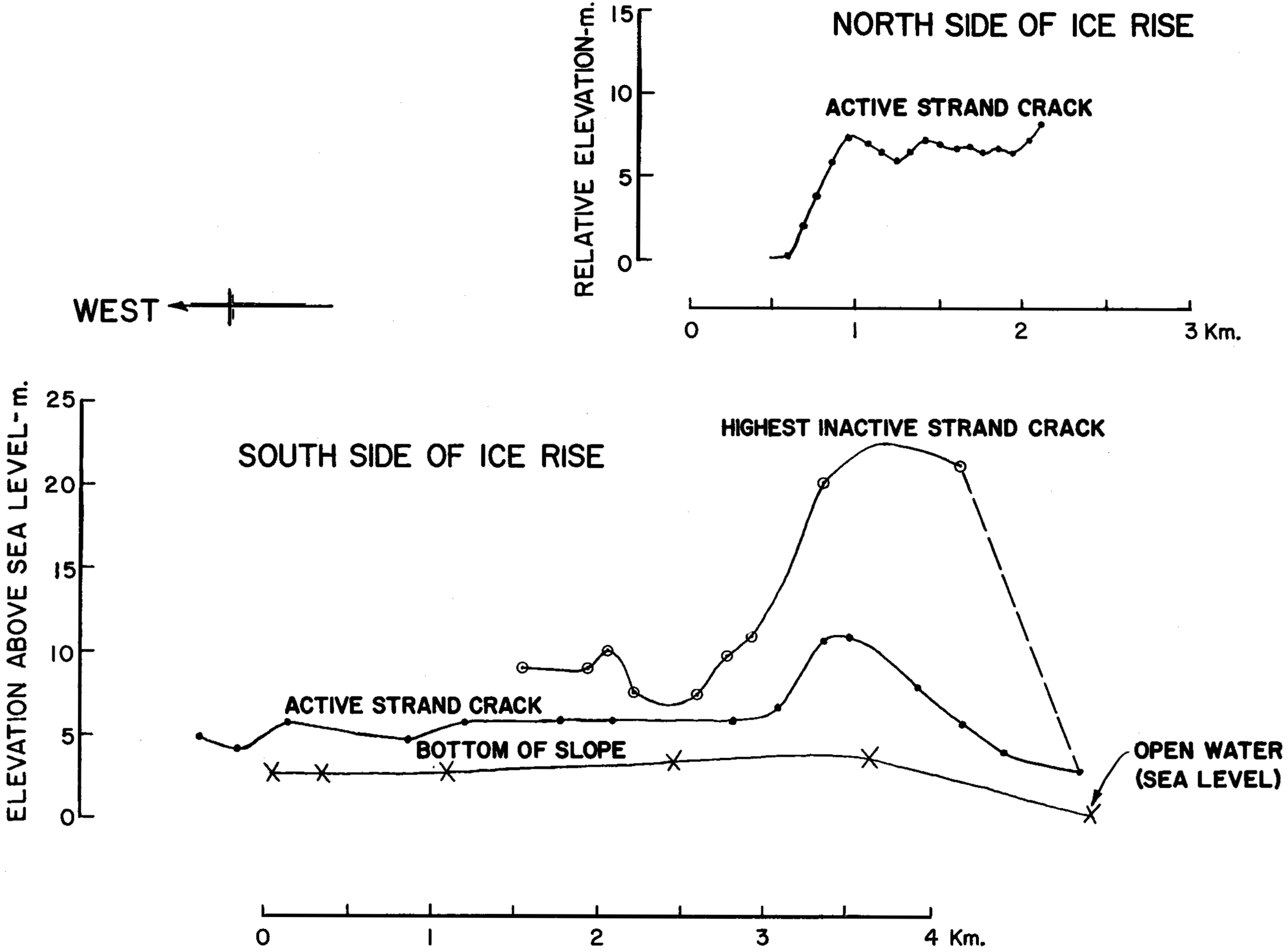


**Fig. 15.** Elevations of strand cracks on ice rise west of Ward Hunt Island.

the crack to the north. Sea-level elevations were obtained from the north-south line through the campsite (see Fig. 5) and checked at the open water southwest of Ward Hunt Island. An interesting feature is a possible channel under the ice rise. This is suggested by the higher elevations of the strand cracks, as indicated. This channel, perhaps over 60 metres below sea-level, may be responsible for the pronounced saddle in the ice rise surface immediately west of Ward Hunt Island. At another smaller ice rise south of the ice shelf and immediately off shore just west of Disraeli Bay, the presence of a channel is also suggested by strand crack elevations. This is supported to some extent by bathymetric information, as seen in Fig. 16. This channel is immediately off shore from a small stream now diverted eastward to the edge of the ice rise.

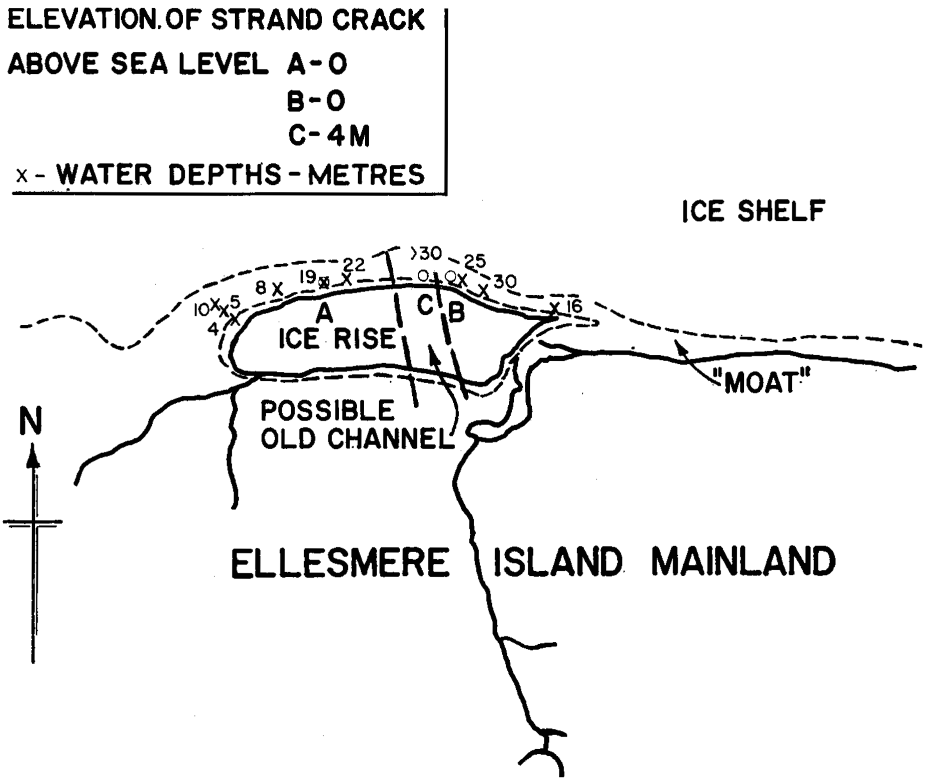


**Fig. 16.** Water depths and strand crack elevations at small ice rise west of Disraeli Bay.

Of more importance in a historical study of the ice shelf and ice island are the old scars left by strand cracks of previous periods. Fortunately, the 1954 summer was quite prolonged and allowed studies after the snow melt was complete. As noted above, the strand cracks are considered as expressions of strains in a zone that must increase in width with a smaller angle of dip of the ground surface under the ice. During the summer seasons strand cracks fill with drainage water which freezes before lower surface temperatures start another fracturing cycle. However, through the years many factors influence the fracture-zone location: increase or decrease of the thickness of the floating ice, changes in sea-level, or rise and fall of land areas due to isostatic adjustment. Hence, the older fracture scars that are no longer in the tidal adjustment zone are evidences of past history. Fortunately, the ice frozen in these strand cracks differs sufficiently in character from the normal ice of the shelf formed from accumulated snow so that they are quite evident, as shown in Fig. 17. Figure 14 shows the general areas of old strand cracks. Figure 15 shows elevations of the highest inactive fracture on the southern edge of the ice rise. In some locations these older fractures were as high as 10 to 15 metres above the present zones and in all but a few cases they were on the ice that is grounded at present.

Considering the possible causes of variations in strand crack location, accumulation or ablation from the surface causing a change in the ice thickness would move the balance zone seaward or landward respectively. These cracks would always develop at the floating ice surface, so that the elevations of the cracks would vary only by about one-ninth of the total change in ice thickness. Also, general accumulation and ablation to a marked degree would bury or erase by thawing old strand crack evidence. A recent, relatively short thawing period could explain the very few areas of fracturing seaward of the present active cracks. The absence of extensive fractures seaward, however, may be the result of the simultaneous rising of land areas that would nullify the effects of the thinning of the ice. Another possible change, which must be considered, is the building up of ice from below. Build-up from below without surface change would move the active crack seaward and at the same time raise the elevation of the fractures by one-ninth of the total thickness. This may explain the presence of the lower elevation drainage lake systems along the western part of the Ward Hunt ice rise on the land side of the present strand crack system.

For an explanation of the higher elevations of the older systems on the north and south side of the ice rise, it seems most likely that an isostatic rise of the Ward Hunt Island group has taken place. This is confirmed by the presence of marine shells on the raised beach of Ward Hunt Island, for which carbon-14 studies give an age of 7200 years.

## Subsurface observations

### Shallow sections

In August 1952 ice cores averaging 1 metre long were obtained by drilling along several different sections in the vicinity of the campsite at T-3. These sections were located over the ridges only, since drilling was difficult through the water in the troughs. The purpose of obtaining these shallow sections was to learn more about the light dirt layers; their con-

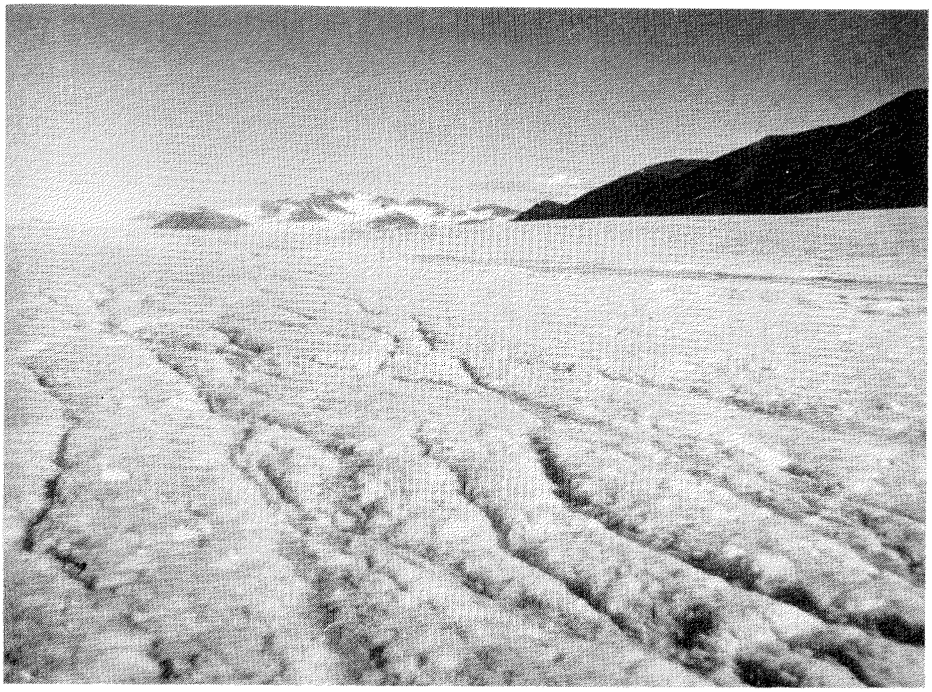


**Fig. 17.** Systems of old strand cracks in the ice shelf near the Ellesmere mainland.

tinuity, consistency, and attitude with respect to the heavy dirt layer immediately at the surface. Figure 18 shows the locations and Figure 19 shows the profiles. No studies were made of the ice character of these cores. It is noted that although there is general continuity to the dirt layers it is by no means evident in all cases. In many of the profiles, holes had to be bored 1 metre apart to establish correlation. The deformation of these dirt layers can be attributed only to a nearly stagnant ice body existing over a long period of time. The second noticeable feature is that there is a very definite discontinuity in all profiles between the top heavy dirt layer and the lower ones, which are themselves generally conformable. Figure 18 shows possible surface changes between the present time and the time in which the lighter layers underneath were deposited. This migration is not uniform, however, either in direction or distance. In general the main outlines of the ridges are not significantly different from those of the present.

As noted above, the amount of dirt in the top layer was greater by a factor of about ten, than that of any of the lower dirt layers noticed near the surface. The lighter layers also varied widely. Their weight per square metre ranged from about 12 grams for the lower one illustrated in Fig. 11, to less than 1 gram per square metre, which could not be easily measured, for many others. In many of the lower layers the same features as found in the top layer were noted on a smaller scale. Very fine dust,

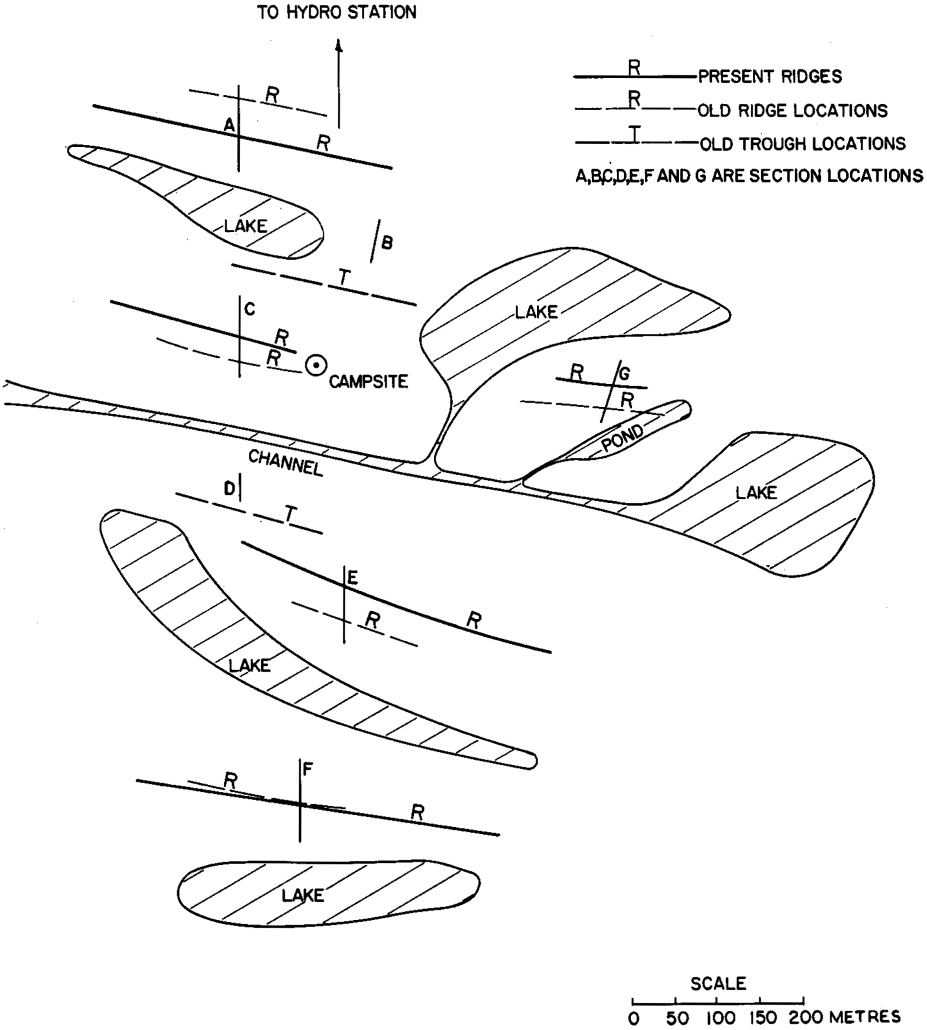


**Fig. 18.** T-3 campsite area showing locations of shallow profiles; inferred change in trough and ridge locations is indicated.

visible usually as discoloration, was followed within less than 1 centimetre by the masses collected in symmetrical holes, which had filled with melt water and frozen. Some grading was also noticeable, the larger masses being lower in the ice. Such layers must represent the result of many years' accumulation. The sections shown in Fig. 19 represent only the obvious dirt layers, those that were noticeable when the solid core was laid on the snow and washed with water. Later more careful examinations of cores taken in the vicinity of Section A revealed a few other, very much lighter layers that had been overlooked.

On the right-hand side of Sections C, E, and G, in Fig. 19, it was noted that the dirt particles were not in regular layers but scattered through

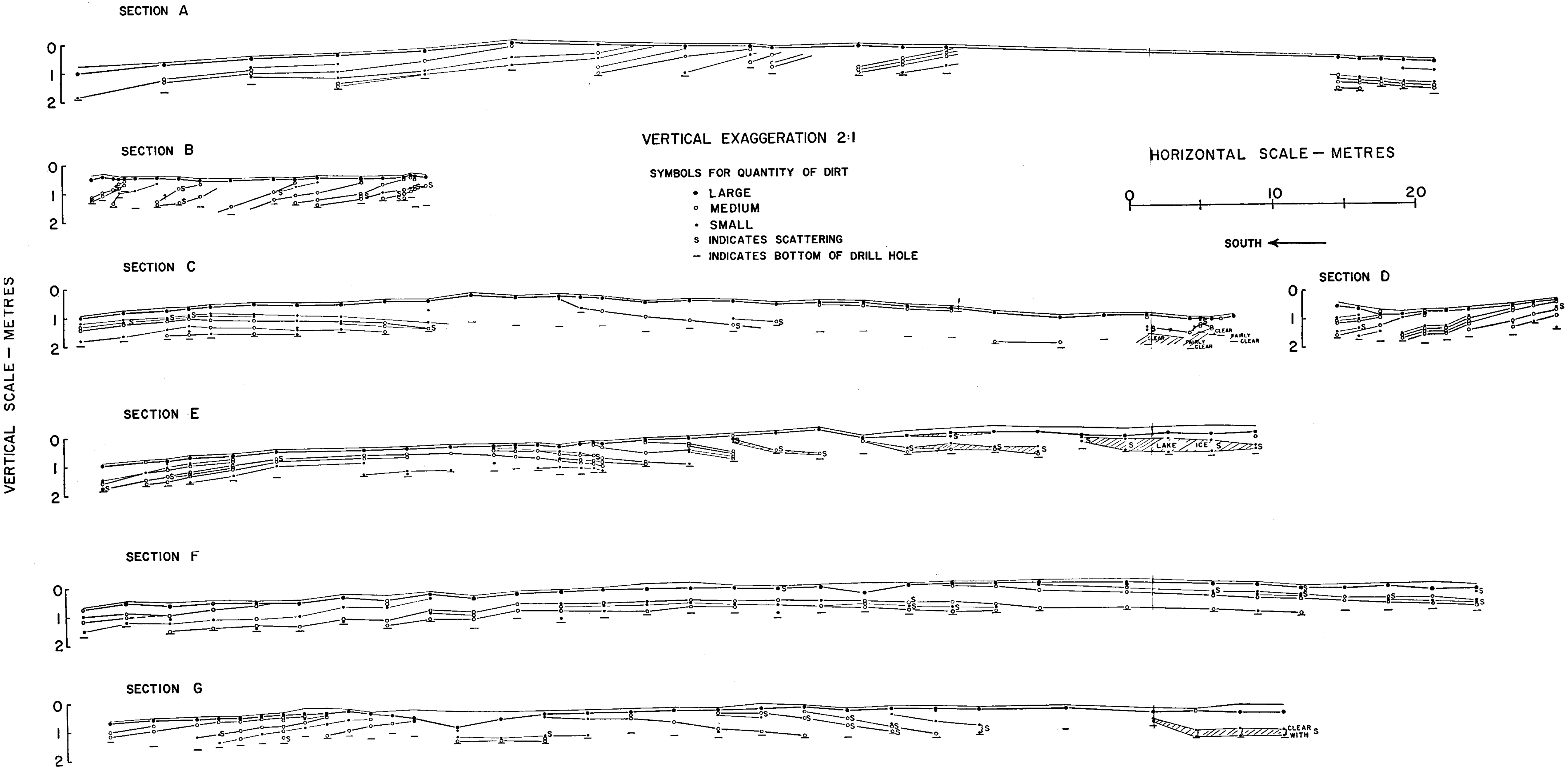


**Fig. 19.** T-3 profiles based on shallow drilling.

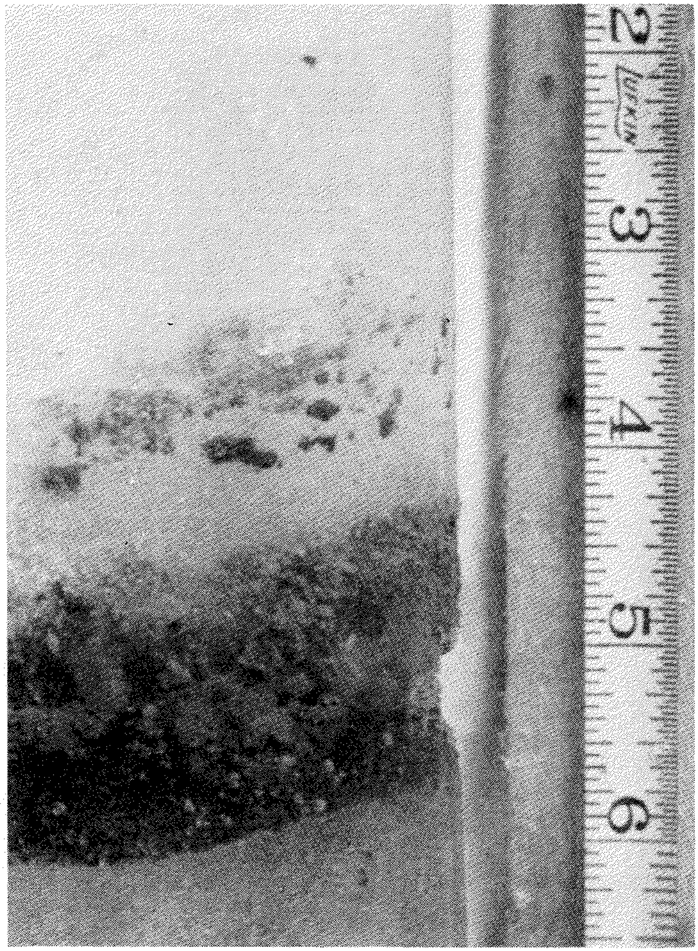


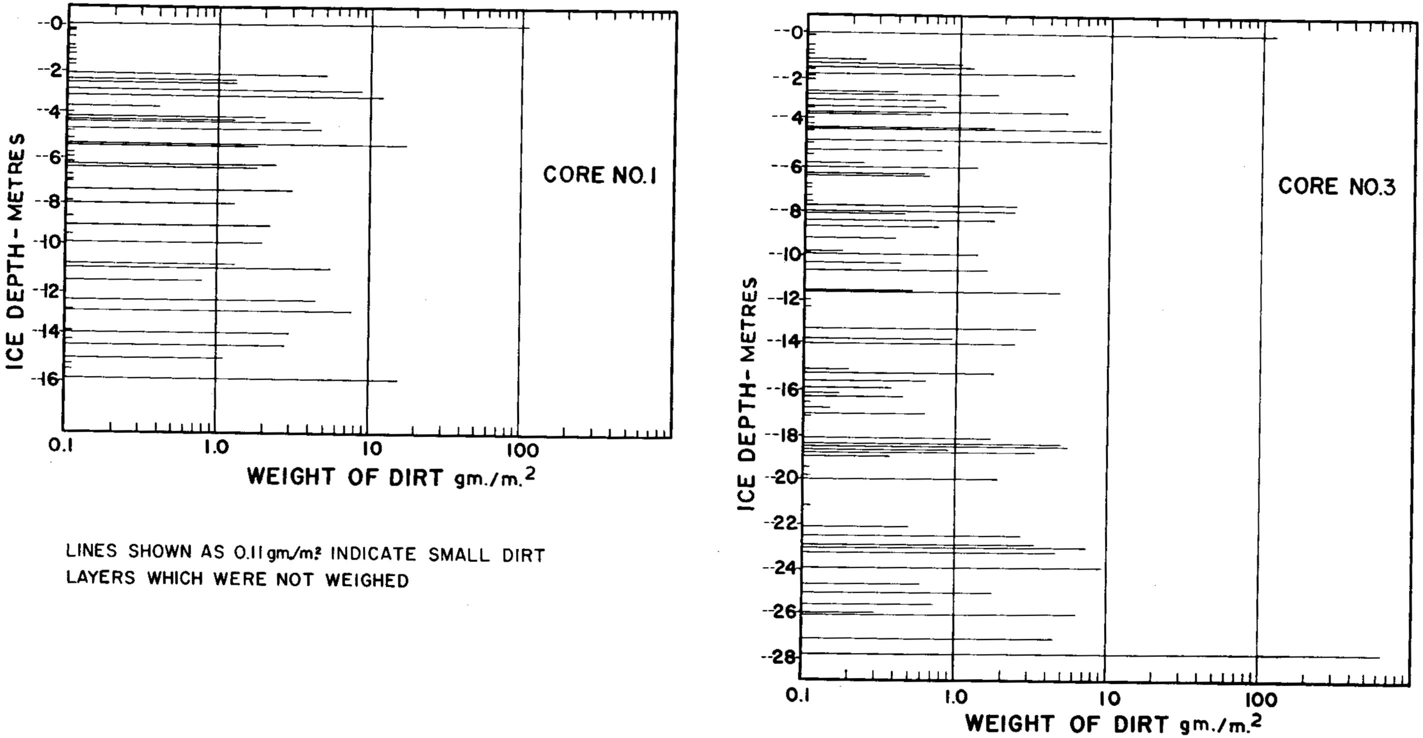
**Fig. 20.** Section of T-3 ice core showing heavy bottom dirt layer.

the ice or in many cases arranged in short, vertical lines. It is believed that this is the result of deposits on lake ice where crystals are usually elongated vertically. When thawing progresses on such ice, crystal boundaries melt first, allowing the dirt particles to penetrate between the crystals. Such conditions were observed at the surface of the ice shelf in northern Ellesmere in 1954 and were interpreted as indicating locations of former lakes or ponds.

It is noted that some migration of trough and ridge systems appears to have taken place since the lower dirt layers were deposited.

## Deep drilling

*Dirt layers.* A total of nine deep holes for study of the dirt layers and ice character was drilled on T-3 on the campsite ridge and across the intervening trough to the adjacent ridge between Sections A and B, Fig. 18. The first deep hole was drilled in August 1952 to 15.8 metres. Throughout this length of core continuous dirt bands were encountered, totalling nearly



LINES SHOWN AS 0.11 gm./m.² INDICATE SMALL DIRT LAYERS WHICH WERE NOT WEIGHED

Fig. 21. Depths and weights of dirt layers as determined by two T-3 cores.

50. In all cases, however, none were nearly as heavy as the layer at the surface. In 1953 two other deep holes were drilled, Hole 2 on the same campsite ridge as Hole 1, and Hole 3 on the opposite ridge at the site of Section A. Hole 2 was used for ice petrographic study (Marshall, 1955) and was drilled to 32.5 metres. Dirt layers were noted down to 25.4 metres where a very heavy layer was encountered. Figure 20 illustrates this heavy layer. Below this in the remaining 7.1 metres of the hole, the ice was completely free of any dirt particles. In August 1953 Hole 3 was drilled to 28 metres in order to obtain the weights of the dirt layers. The heavier dirt layer was encountered at 27.8 metres, and 0.2 metre was cored into the dirt-free ice below. The weights of the heaviest of the dirt layers, extrapolated from the 8-centimetre-diameter core to 1 square metre, are given in Fig. 21 for Holes 1 and 3. As in the shallow sections, there was a lack of correlation between the cores as regards the heavier of the intermediate layers, which should themselves represent ablation periods of many tens or perhaps hundreds of years. The lower part of Hole 3 below approximately 20 metres consisted mainly of what has been defined above as lake ice according to the manner in which the dirt had collected, usually in vertical lines or individual masses instead of lying in layers such as had been found above.

Soon after Hole 2, which showed the extremely heavy bottom dirt layer followed by dirt-free ice, had been drilled, Marshall located outcrops where this layer had combined with the surface layer near the shore at Area A and later at Area C, Fig. 6. In these areas, this heavy layer was identical both in appearance and in lack of underlying dirt layers to that found in the deep holes. Thus, the heavy surface layer in those areas represented the full amount found in the total column at the campsite. Near these outcrops it was possible to obtain an average weight over a fairly large area of several square metres, and a value of 614 grams per square metre was obtained. Assuming uniform annual deposition this would represent about five times the melt period of the top surface dirt layers; and also from an assumption that the lightest dirt layers represent an annual accumulation, the conclusion is drawn that the outcrop deposition must have taken at least a span of time of the order of several thousand years.

In 1955, before the melt season had begun, a series of six deep holes was drilled across the valley between the ridges where the first three holes had been located. Figure 22 shows the results of this section and of the previous drilling. The heavy dirt layer located at depths 25 and 28 metres under the ridges was unexpectedly encountered at shallow depths in the 1955 drilling. Thus a complete migration of trough and ridge appeared to have taken place, though it is not evident if the distances between ridges were different though they cannot have been smaller, and appear not to have been much greater.

A third fairly heavy dirt layer was located immediately above the heavy bottom one in several holes along the top of the buried ridge. The

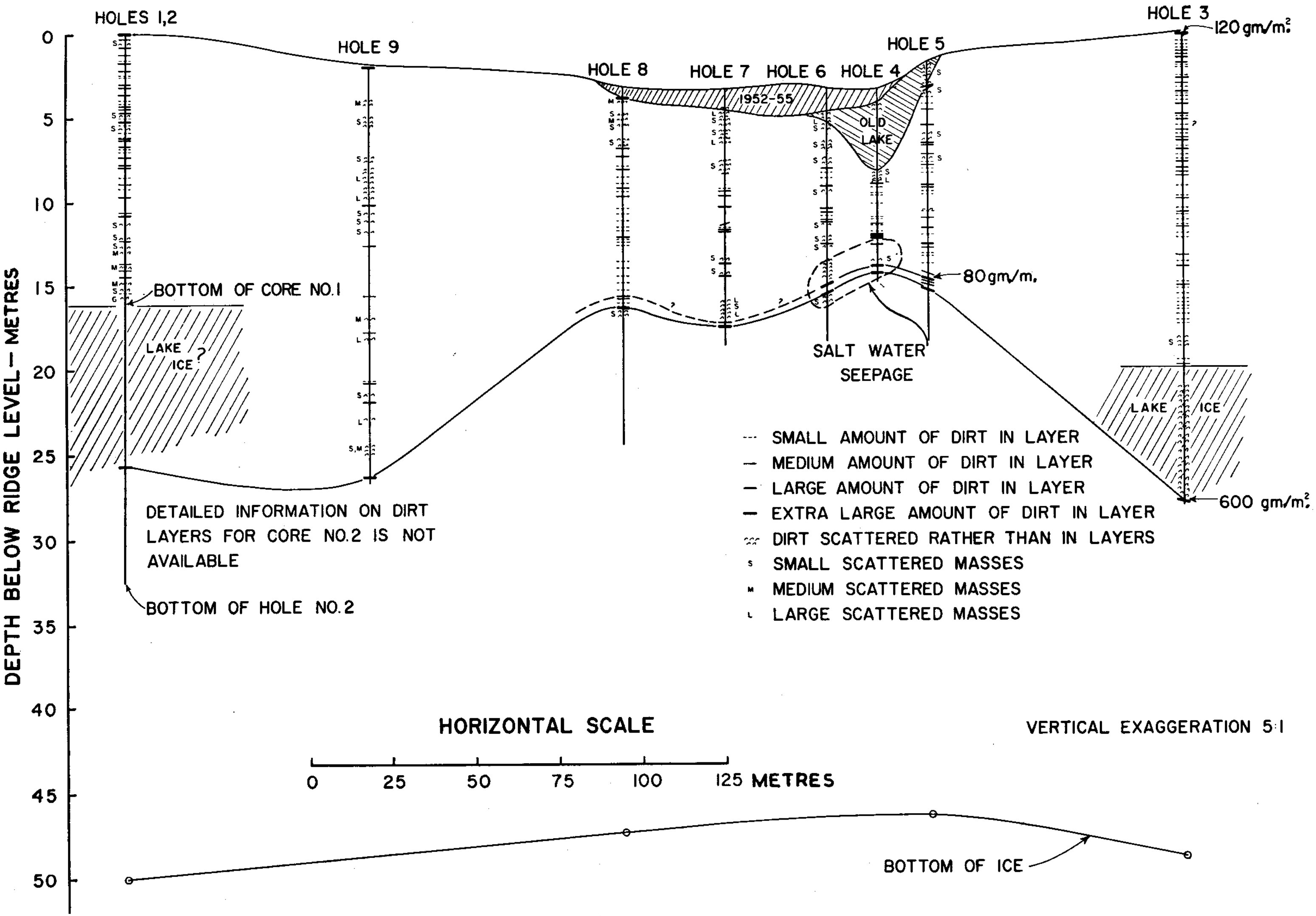


**Fig. 22.** Cross section based on deep drilling on T-3.

weights in two cases gave about 80 grams per square metre for this layer, not too different from that of the top one, and hence must represent another long period of ablation. The accumulative weights from the bottom dust layer to the top layer are shown in Fig. 23 for the cores of the present trough and ridge. The horizontal axis is in effect a time scale, providing dust was uniformly deposited. Previous periods of ice accumulation such as have formed the top part of T-3 probably existed prior to the ablation periods in which the dirt of the two lower layers was collected.

A comparison of the lower dirt layers including the heavy bottom layer was made by Stoiber *et al.* (1956) and showed that no differences whatever existed as regards the mineralogical content, grain size, or percentage of heavy minerals between any of the dirt layers encountered.

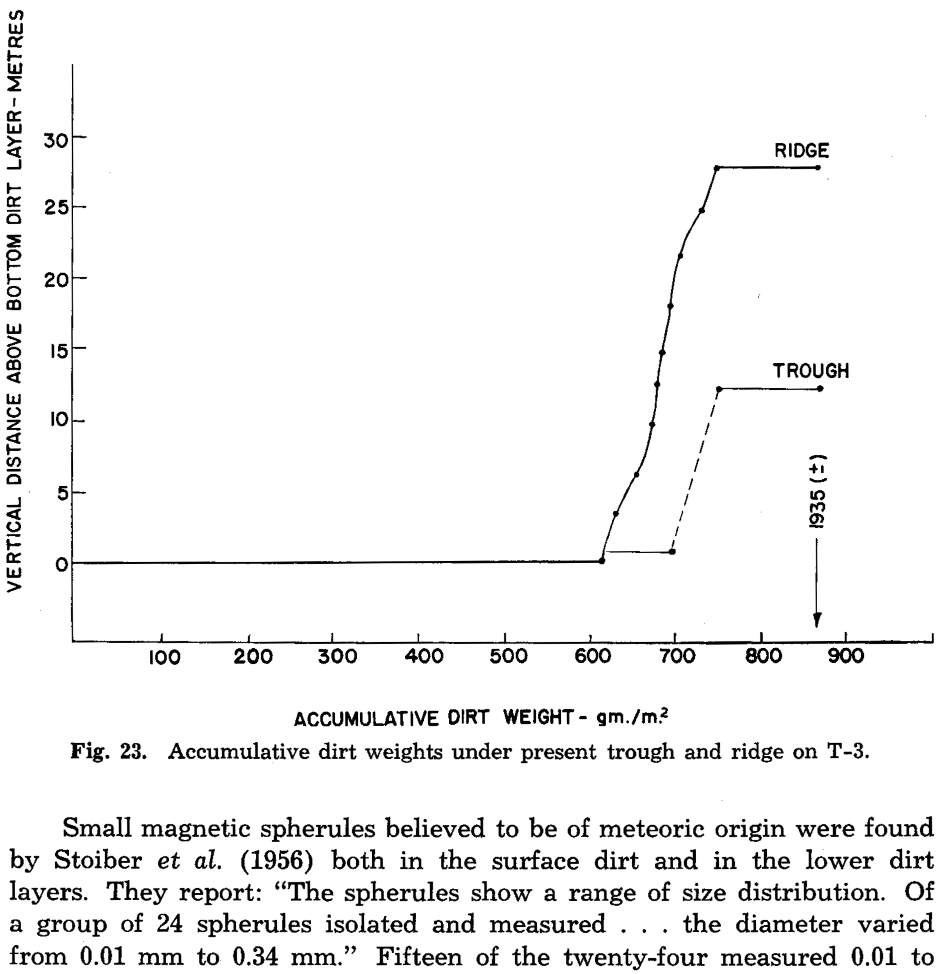


**Fig. 23.** Accumulative dirt weights under present trough and ridge on T-3.

Small magnetic spherules believed to be of meteoric origin were found by Stoiber *et al.* (1956) both in the surface dirt and in the lower dirt layers. They report: "The spherules show a range of size distribution. Of a group of 24 spherules isolated and measured . . . the diameter varied from 0.01 mm to 0.34 mm." Fifteen of the twenty-four measured 0.01 to 0.02 mm. "Smaller spherules were seen, but were difficult to identify with certainty and to isolate. . . . Characteristically, the micrometeoritic spherules are black, with either a striated or pitted surface. A few show concave surface indentations analogous to those described in spherules from deep-sea cores. Very rarely they show a protuberance which appears to be a small bubble attached to the smaller sphere. A few of them are hollow. . . . Several methods were used to determine the composition of the magnetic spherules. All are magnetic. Some dissolve in aqua regia. Others do not. All dissolve in hydrobromic acid. They yield a positive microchemical test for iron, and a few of them gave questionable reactions for nickel. Although several attempts at spectrochemical analysis were made, no positive results were obtained because of the small amount of available material. On the other hand, X-ray powder analysis indicates that magnetite is a common constituent of many of the spherules and that olivine is present in some. Optical examination indicates that most of the spherules consist chiefly of a glass of mean refractive index of approximately 1.550 in which there is disseminated black opaque material (magnetite?) and some minor amounts of birefracting material (olivine?). Silicate glasses of this refractive index correspond to rocks of andesitic or basaltic composition with silica content of 50-60%. Our conclusion therefore is that most of the T-3 spherules which we have examined consist of silicate glass of the approximate chemical composition of a basalt or andesite and that in the glass there is disseminated magnetite and olivine. Compared with the large classes of meteorites, the T-3 spherules would be grouped with the aerolites."

"Several negative conclusions are of interest. The siliceous meteoritic tektites have glasses of lower refractive index than the T-3 spherulites. No spherulite from T-3 was found to be metallic, nor have we identified either native iron or iron carbides in the X-ray patterns. We have had no positive chemical determination of any element except iron. Nickel is questionable. Many tests were inconclusive because of the small amounts of material with which we were forced to experiment."

In an attempt to determine the age of T-3 by the number of spherules found in the dirt of the ice cores, a brief review of recent literature on the rates of infall was undertaken. This showed "extreme discrepancies in the present estimates, the higher values exceeding the lower by factors of approximately 500,000. The fact that meteoritic showers vary in intensity with locality on the earth's surface, that there may be considerable unrecognized industrial contaminant in many of the samples counted, and that the methods used to recover the spherules vary enormously in efficiency, makes some of the discrepancies understandable." However, from an analysis of these various reports, Stoiber *et al.* are of the opinion that the spherules found on T-3 are "far less abundant than one should expect had they been accumulating over a period of several thousand years." Obviously the uncertainties concerning the rate of accumulation and the percentage of recovery prevent any definite conclusions.

*Salinity.* Observations were made of the salinity of many of the lower sections of the ice cores, particularly those below the heaviest dirt layer. This was done by chloride titration methods with results shown in Fig. 24.

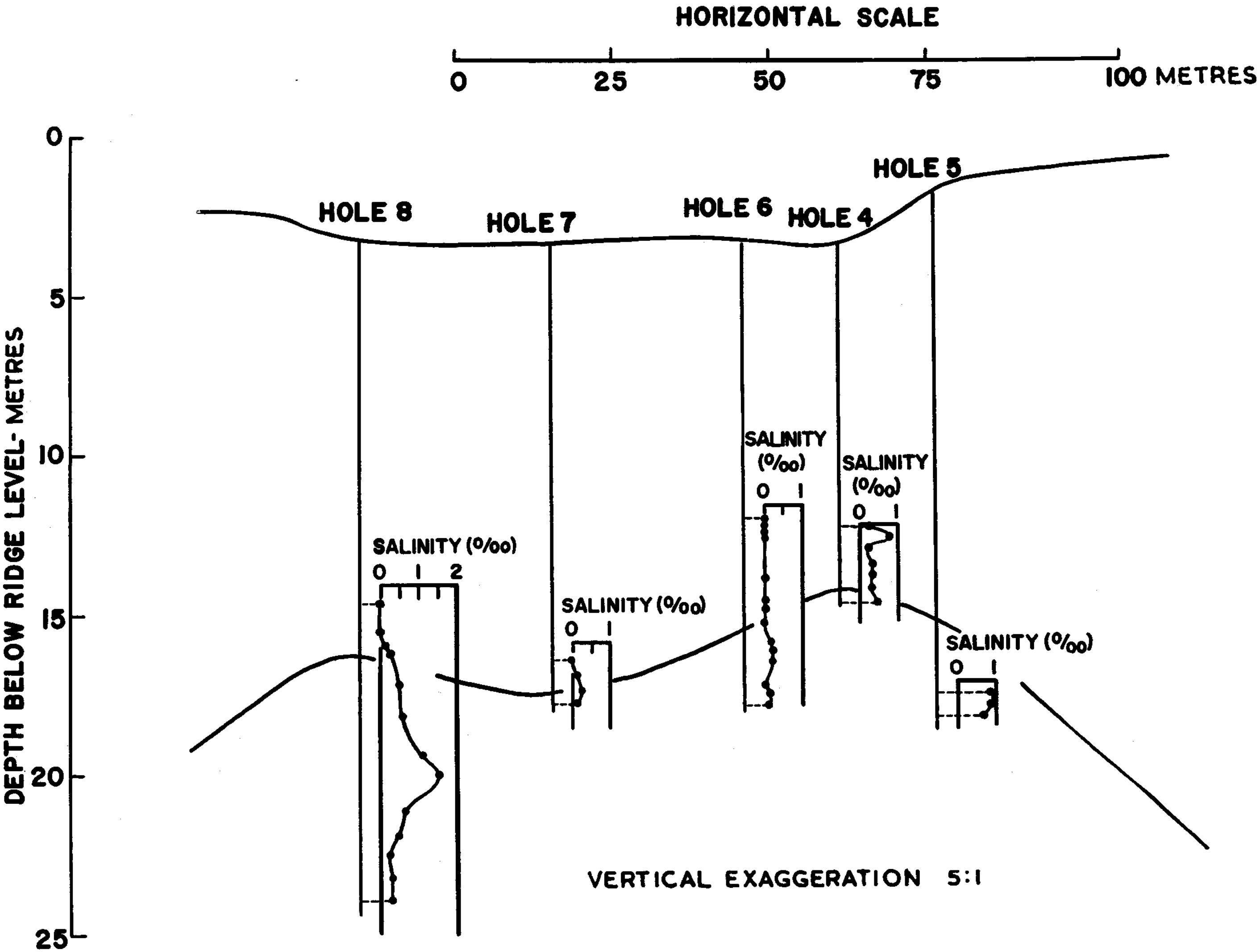
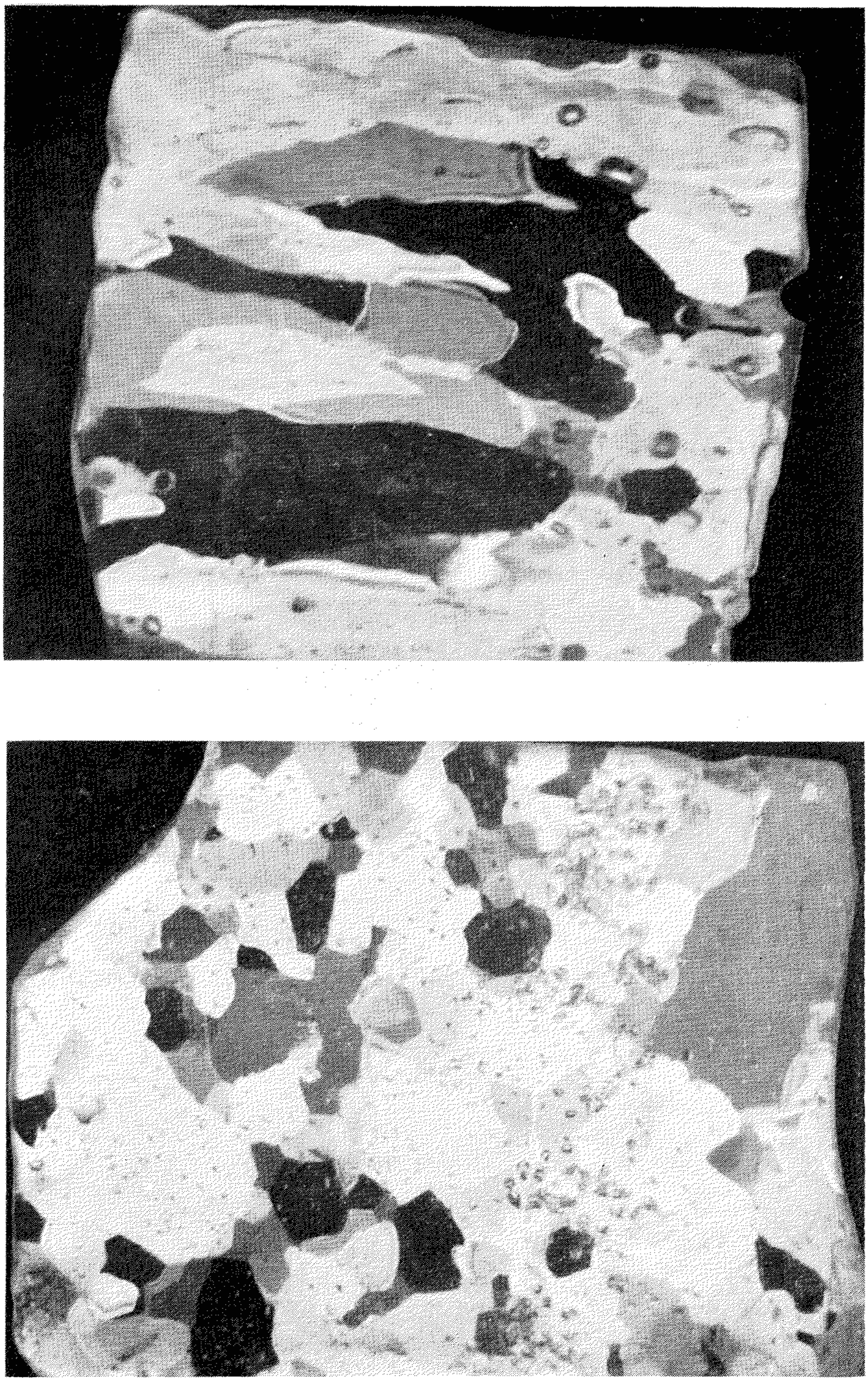


Fig. 24. Salinity of T-3 ice in regions of bottom dirt layer and below.



ICED FIRN

LAKE ICE

**Fig. 25.** Typical thin sections of T-3 ice cores (magnification appr. X 1.2).

The salinities were all very low and usually zero above the heavy dirt layer, while only one observation of zero salinity was made below the heavy dirt layers. It would appear both from the dirt-free character, and the salinity, that the ice below the heavy dirt layer was ice growth accumulated from the bottom but, as noted later, observations of crystal character do not completely confirm this.

In the first deep hole drilled on the Ellesmere Ice Shelf in 1954 by Marshall, salt water encroachment occurred at about 24.5 metres and in a few days about 1 metre of salt water stood in the hole. This was also encountered on T-3 in Holes 4 and 6 near the top of the buried ridge. Here the damp ice persisted only for a fraction of a metre and then dry ice was encountered below. However, within a week about 2 metres of salt water had collected, which showed a salinity value of 54 parts per 1000, corresponding to the temperature of about —3°C prevalent at that depth. This salt water near the heavy dirt layer may be due to previous melting of salt ice layers, or it may have been collected from salt water which actually washed over the ice at an early date.

*Crystal structure.* On the basis of petrographic studies made in 1953 on the ice island and in 1954 on the Ellesmere Ice Shelf, Marshall (1955) has identified the upper ice as belonging to four types: iced firn, glacier ice, lake ice, and sea ice.

During the ice island program in 1955, photographs of thin sections of many of the ice cores were taken through crossed polaroids. Examples of these are shown in Fig. 25. W. F. Weeks (personal communication) has examined these data and has made a tentative separation of the ice into two types: (1) iced firn, which is semi-equigranular, has an average grain size of 1 centimetre and has regular, smooth, intergrain contacts and (2) lake ice, which shows a pronounced elongation of the crystals perpendicular to the freezing surface and more irregular, sutured, intergrain contacts in horizontal sections. None of the thin sections or rubbings were identified as either sea or glacier ice. It is possible that some of the material identified as lake ice could have originally been sea ice. This is considered doubtful however since Weeks was not able to observe any of the substructures so typical of sea ice. Weeks' identification of the ice types in the 1955 cores is shown in Fig. 26.

It is interesting to note that the ice below the heavy dirt layer does not conform to the sea ice type, though usually showing the presence of salt. Further work is needed on this lower ice and also on the type of ice that is formed from brackish waters of low salinity such as may be found in the shore areas where the islands originated.

## Internal ice temperatures

Copper-constantan thermocouples were located in six of the deep 8-cm-diameter holes drilled for petrographic and dirt layer studies; four of these were on the ice island, one on the Ellesmere Ice Shelf and one on the

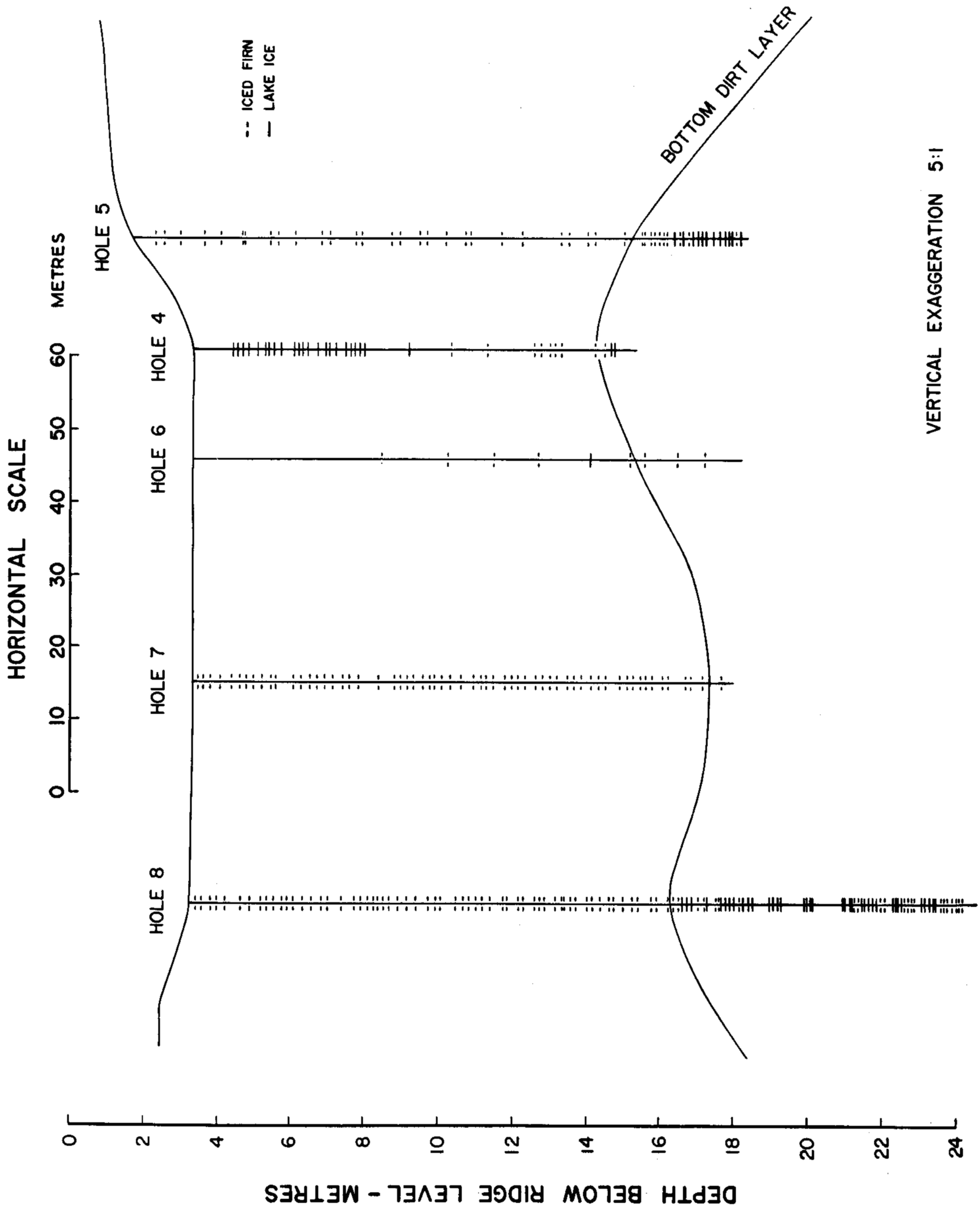


**Fig. 26.** Section showing 1955 drilling on T-3 with the ice types identified.

Ward Hunt ice rise. These thermocouples were frozen in the holes and are still usable, serving also as long-term surface ablation indicators. Locations and depths below the ice surface at which thermocouples were originally installed are given in Table 2. Unfortunately the readings taken at T-3

**Table 2.** Locations and depths of thermocouples.

| *Location* | *Depths (metres)* | | | | | *Date installed* |
|---|---|---|---|---|---|---|
| T-3 Ice Island, No. 1 - Ridge | 3.0 | 9.1 | 15.2 | | | Nov. 1952 |
| T-3 Ice Island, No. 3 - Ridge | 5.2 | 12.8 | 20.4 | 28.0 | | Sept. 1953 |
| T-3 Ice Island, No. 7 - Trough | 8.4 | 14.5 | | | | May 1955 |
| T-3 Ice Island, No. 9 - Midway between Trough and Ridge | 24.7 | | | | | July 1955 |
| Ellesmere Ice Shelf - Trough | 0.3 | 1.5 | 3.0 | 4.6 | 6.1 | |
| | 7.6 | 9.1 | 12.2 | 15.2 | 21.3 | May 1954 |
| Ward Hunt Ice Rise | 1.5 | 3.0 | 6.1 | 12.2 | 18.0 | Sept. 1954 |

Hole 1 are not considered normal since very soon after the installation of the thermocouples, new camp buildings were erected near the site, with the consequence that abnormal drifting of snow occurred in the immediate area.

*Shallow-depth temperatures.* The best records of shallow-depth temperature variations were obtained in a ridge hole on the Ellesmere Ice Shelf between May and September 1954. They are shown in Fig. 27. Temperatures at greater depth were obtained at both Ellesmere and on the ice island and are shown in Fig. 28.

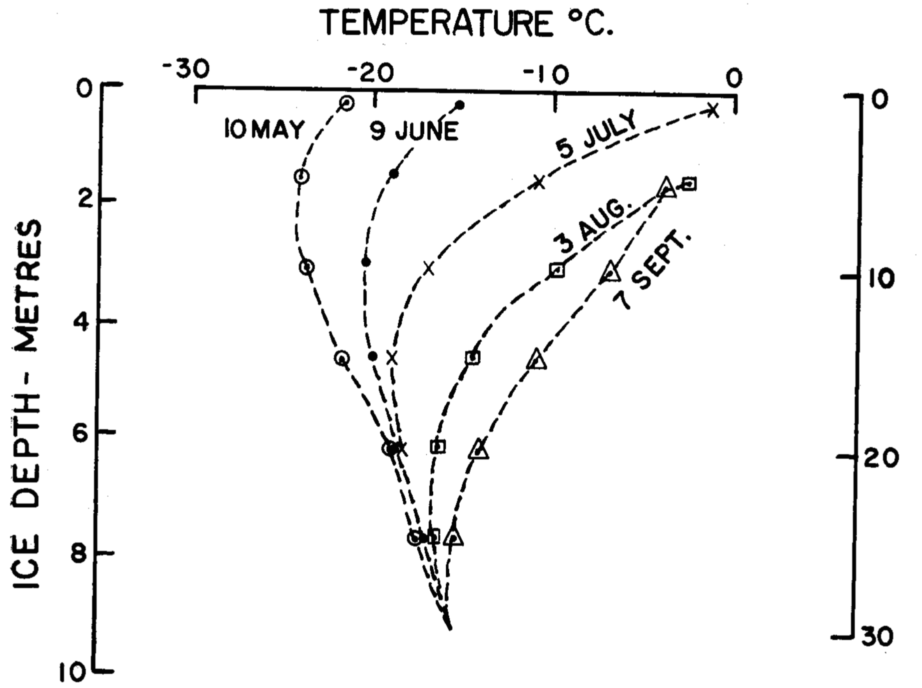


Fig. 27. Temperatures in a deep hole in the Ellesmere ice shelf, 1954.

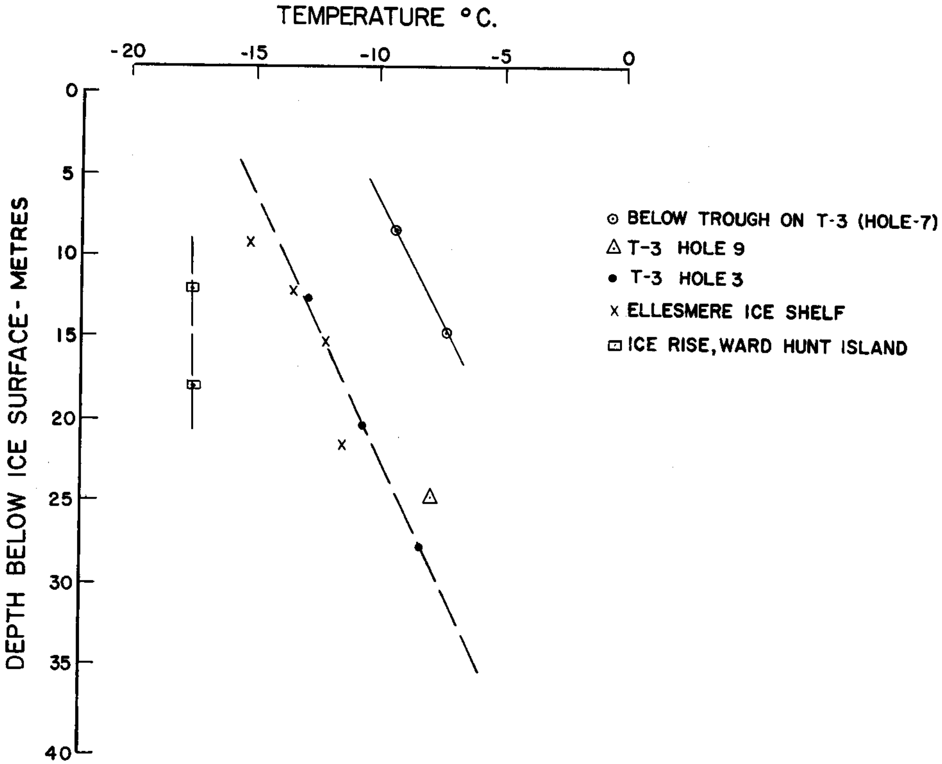


**Fig. 28.** Temperatures at depths below annual change, Ellesmere ice shelf and T-3.

The temperatures in the interior of the ice depend on the temperatures at the upper and lower boundaries of the ice and the thermal constants of the ice. The temperature of the lower ice surface may be taken as the freezing point of the water, which can be considered as a constant, though variation of as much as 2°C may be expected in coastal areas where there is an abundance of freshwater run-off under the ice.

Table 3 lists the monthly air temperature averages from the ice island T-3 and other high-latitude areas. The low T-3 values may be for abnormal years or areas but may also be explained by the very small upward flow

**Table 3.** Average monthly surface temperature (°C)

| | *Jan.* | *Feb.* | *Mar.* | *Apr.* | *May* | *June* | *July* | *Aug.* | *Sept.* | *Oct.* | *Nov.* | *Dec.* | *No. of years recorded* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SEDOV | -28 | -31 | -31 | -23 | -12 | -4 | -2 | -3 | -8 | -16 | -21 | — | 1 |
| FRAM | -36 | -36 | -31 | -23 | -11 | -2 | 0 | -2 | -9 | -22 | -29 | -32 | 3 |
| T-3 | -35 | -37 | -39 | -24 | -8 | -2 | 0 | -3 | -11 | -21 | -27 | -32 | 2 |
| NP-2* | -37 | -34 | -28 | -23 | -10 | -2 | -1 | -2 | -8 | -17 | -28 | -35 | 1 |
| NP-3* | -34 | -35 | -29 | -20 | -11 | -2 | 0 | -2 | -9 | -14 | -28 | -30 | 1 |
| NP-4* | -32 | -37 | -31 | -26 | -13 | -2 | 0 | -1 | -9 | -18 | -31 | -33 | 1 |

* Russian "North Pole" drift stations

of heat through the thick ice, compared to that of normal pack ice of 3 or 4 metres thickness. In Fig. 29 are shown average ice island air temperatures and most probable ice-surface temperatures. These latter are based on thermocouple or direct thermometer readings at various sites, but complete data are lacking, particularly in late winter months. It is noted that the curves are not sinusoidal, since the coldest and warmest months are March and July respectively. A theoretical fit to this type of curve is given by the equation:

$$T = A + B \sin \frac{2\pi t}{P} + C \sin \frac{4\pi t}{P}$$

where P = period, one year, t = time, T = mean monthly temperature, with the constant B about four times the numerical value of C. This curve is also shown in Fig. 29, where $A = -17.75$, $B = 17.48$, and $C = 4.07$.

The solution of the heat-flow equation in floating ice has been given by Malmgren (1927) for sinusoidal surface temperatures. It includes an additional term to the normal solution for a semi-infinite solid which is of equal value and opposite sign at the lower ice-surface boundary and decreases exponentially upward. This equation is given below.

$$T = T_1 + (T_2 - T_1)\frac{x}{l} + T'e^{-ax}\sin(nt - ax) - T'e^{-a(2l-x)}\sin[nt - a(2l-x)]$$

where $T$ = mean monthly temperature
$T_1$ = mean annual temperature at the surface
$T_2$ = temperature at lower ice boundary
$l$ = total ice thickness
$x$ = depth
$t$ = time
$T'$ = amplitude
$a = \sqrt{\frac{n}{2\alpha}}$
$n = \frac{2\pi}{P}$, $P$ = period
$\alpha$ = thermal diffusivity

With thermal constants of freshwater ice, the standard solutions for a semi-infinite solid can be used at depths below 10 metres with the addition of a linear term. For the equation of arctic ice surface temperatures given above, each term of the equation can be handled separately.

In Fig. 30 are shown the observed values of temperature at 4.6 metres in the Ellesmere Ice Shelf compared with theoretical values. Small variations are to be expected in different areas and different years.

*Temperatures below depth of annual change.* Temperatures obtained at the ice rises near Ward Hunt Island of —17.7°C at 12.2 metres and —17.3°C at 18.0 metres (Fig. 28) should be the average annual temperature at the surface of the ice. The differences occurring during the course of the year between the monthly average temperature of the ice surface and that of the air, as recorded at the normal height of 2 metres at surface weather

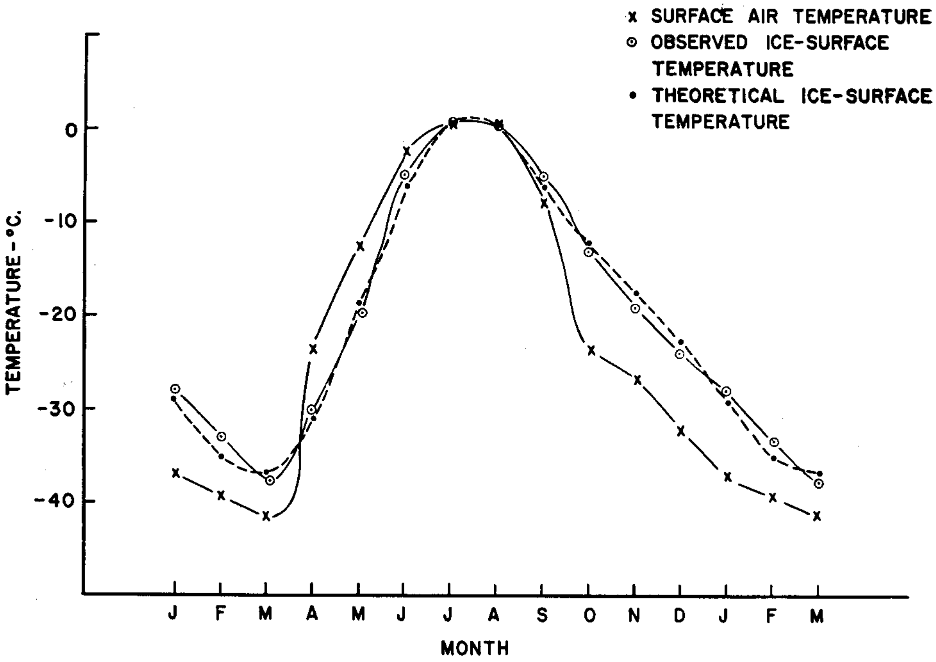


**Fig. 29.** Average ice island temperatures and most probable ice surface temperatures.

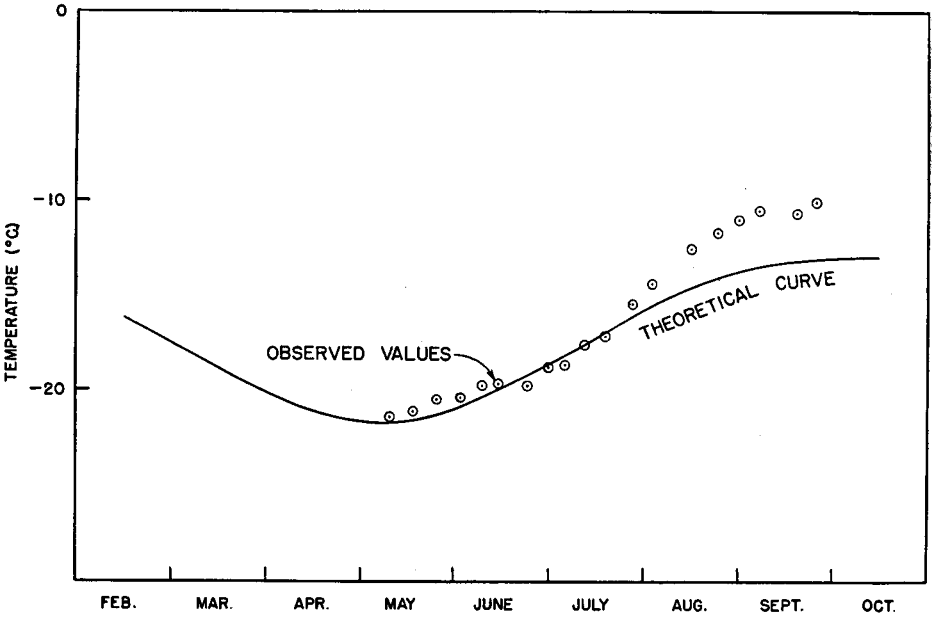


**Fig. 30.** Observed values of temperatures at 4.6 metres in the Ellesmere Ice Shelf compared with theoretical values.

stations, may not be very large, as is indicated in Fig. 29, despite the effects of snow cover and long-wave radiation from the ice surface. The annual average air temperatures at the weather stations Alert and Eureka, the two nearest to Ward Hunt Island, are —16.8°C and —19.1°C respectively, taken over a period of 3 years.

The linearity of the temperatures under the ridges, between surface average and the temperature of freezing water, shows that the ice shelf and island must consist of ice of apparently uniform thermal conductivity. Underneath the troughs temperatures are somewhat higher, as would be expected, considering that the drainage lakes remain after summer melting has ceased. At the bottom of the lakes of average depth the temperature would be 0°C for four to six months and a linear relation would be established between the resulting higher annual average and the sea water temperatures. Directly under the troughs, therefore, the gradient in the bottom part of the ice would be less than that under the ridges, which could tend to build up less ice there. This effect may be decreased somewhat in the areas near land if fresh melt-water is present in sufficient quantities to extend under the shelf. The lighter, less saline waters with higher freezing temperatures would be found under the shallow part of the shelf and this should tend to offset the influence of the smaller gradient.

In 1952 a freshwater lake under considerable pressure was located in the trough area adjacent to the campsite on T-3 (see Fig. 31). Two dirt layers were found in the 2.5 metres of ice above this lake, so that it was believed at least two melt seasons had occurred since the lake had formed.

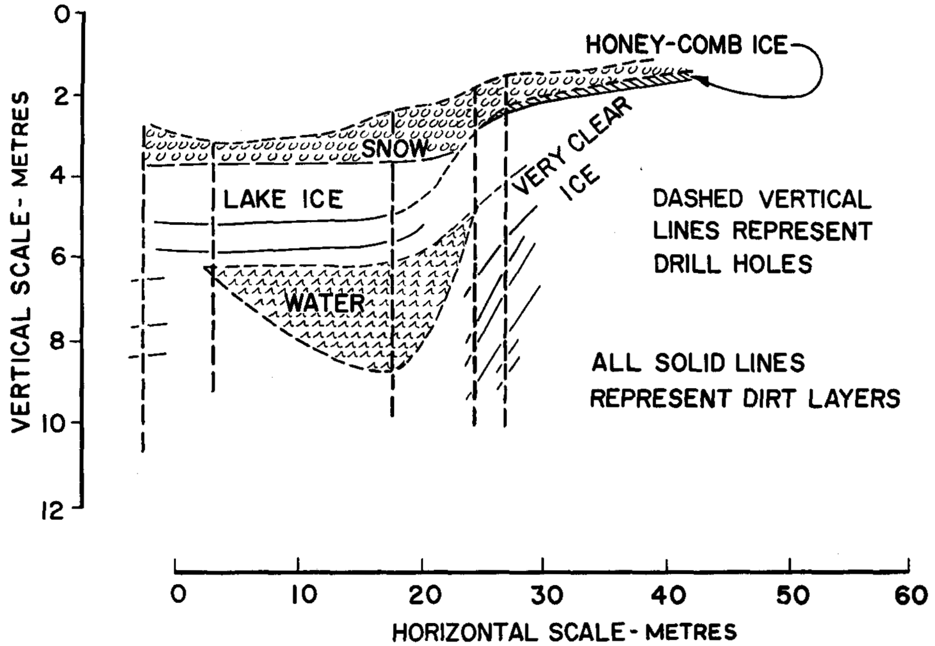


**Fig. 31.** Buried lake found on T-3 in 1952.

In 1953 at the same location there were 3 metres of ice over this lake. It was also noticed that clear ice with very large crystals was characteristic of the surroundings of this lake, presumably caused by the high pressures due to expansion during freezing. In 1955 (see Fig. 22) this lake was entirely frozen. It is presumed that this lake was formed in the summer of 1949 or 1950 when the ice island was at the most southerly part of its track.

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