The Thermal and Compositional Structure of the Koettlitz Ice Tongue, McMurdo Sound, Antarctica

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Abstract

The floating tongue has attracted attention of glaciologists since Debenham had found remains of fish, corals, sponges, and other remains of sea creatures at the surface of the tongue near the Dailey Islands, McMurdo Sound, Antarctica. To explain the presence of the sea remains at the surface a hypothesis was suggested about freezing of sea water at the bottom of the tongue and ablation at the surface, and as the result of lifting the remians had been caught by freezing at the bottom of the tongue. Gow had explained the existence of the remains at the surface differently but in spite of that the question about the possibility of freezing at the bottom of the tongue has not been answered.

A hole about 20 m deep had been drilled in the tongue near the Dailey Islands in October 1965 to find out, what kind of processes occurred within the tongue.

Temperatures had been measured and cores had been taken throughout the hole. The theoretical analysis had shown that the measured temperatures corresponded with the moving upwards of the ice within the glacier, *i.e.* there is ablation at the surface and freezing at the bottom of the tongue. The intensity of the ablation at the surface has been estimated as about 1.5 m of ice per year, freezing at the bottom—about 0.5 m per year. It was shown that freezing of that kind can take place, if there was a water layer with lower salinity between the bottom of the tongue and the sea water below this layer.

An analysis of the structure and composition of the cores has shown that deeper layers of the ice consist of ice formed from sea water.

I. Introduction

The floating shelf like tongue of the Koettlitz Glacier has attracted the attention of many scientists mainly because of the fish and other marine animals found on its ablating surface. The surface of the glacier is incised by an intricate system of melt streams and all evidence points to an intensive ablation of the surface. The extent of this ablation was first fully appreciated by Debenham (1920) who postulated that the animal remains found on top of the ice were originally frozen in at the bottom and were then subsequently transferred to the surface as a result of the combined process of surface ablation and bottom freezing. Recent studies by Gow and others (1965) have shown that the fish and fossiliferous moraines tend to be concentrated on certain parts of the shelf, particularly in the vicinity of the Dailey Islands and that the ice on which they lie is fresh water ice, not sea ice. Nevertheless evidence is forthcoming that much of the Koettlitz Glacier tongue has been reconstituted by bottom freezing as originally hypothesized by Debenham.

The object of the present study has been to investigate the englacial temperature and composition of the ice in the immediate vicinity of the Dailey Islands (Figs. 1–2) in order to obtain additional data on this process of reconstitution. The temperature analysis and interpretations are due almost entirely to Zotikov. Gow contributed the work on core studies.

II. Thermal Regime of a Glacier

It has been shown by Robin (1955), that there is a strong correlation between the temperature distribution in a glacier and the vertical movement of the ice particles. Temperatures within a one dimensional glacier of constant density and with a stable heat regime can be described by the following equation:

$$\frac{\mathrm{d}^2 T}{\mathrm{d} X^2} - \frac{W(X)}{A} \frac{\mathrm{d} T}{\mathrm{d} X} = 0, \qquad (1)$$

where

T is the temperature at a distance X from the bottom of the glacier,

W is the vertical component of velocity of the ice movement, and

A is the coefficient of emperature conductivity of the ice.

The distribution of temperature in a glacier described by eq. (1) is

$$\frac{T - T_\mathrm{b}}{T_\mathrm{s} - T_\mathrm{b}} = \frac{\int_0^X \left[\exp \int_0^X \frac{W(X)}{A} \, \mathrm{d} X \right] \mathrm{d} X}{\int_0^H \left[\exp \int_0^X \frac{W(X)}{A} \, \mathrm{d} X \right] \mathrm{d} X}, \qquad (2)$$

where H is the thickness of the ice and T_s and T_b are the temperatures at the surface and the bottom of the glacier. In floating ice where the vertical velocity of movement varies linearly with depth the distribution of temperature in the glacier described by eq. (2) can be written as a composite of several tabulated integrals. Where there is no vertical movement the temperature in the ice will vary linearly with depth. If the glacier is ablating on the top and freezing

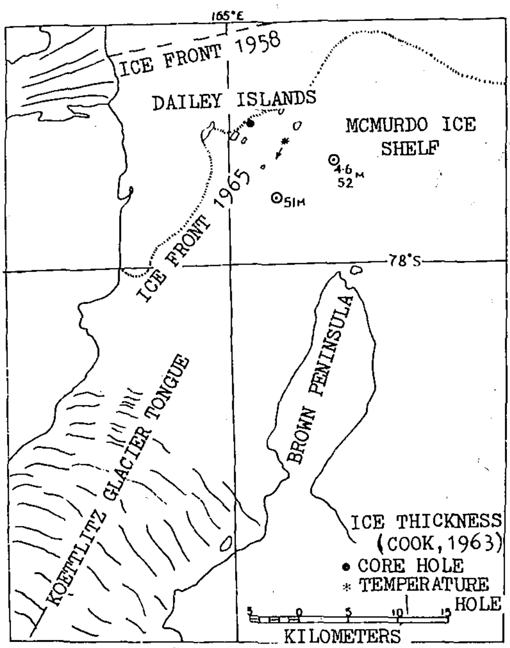


Fig. 1. Sketch map of Koettlitz Glacier tongue and Dailey Islands, McMurdo Sound, showing locations of drill holes and ice thickness measurements

on the bottom the englacial temperatures will be warmer than those at corresponding depths in the glacier where there is no vertical movement. Conversely if there is accumulation at the surface and melting at the bottom temperatures will be colder. By measuring temperatures and comparing them with theoretical distributions it should be possible to determine whether the ice is moving up or down and at what rate.

III. Core Studies and Temperature Measurements

Drilling was carried out during September and October 1965 at the two locations indicated in Figs. 1 and 2. At the location marked with a star in Fig. 2 an attempt was made to bore the hole with a thermal drill. Unfortunately a broken water pump 7 m

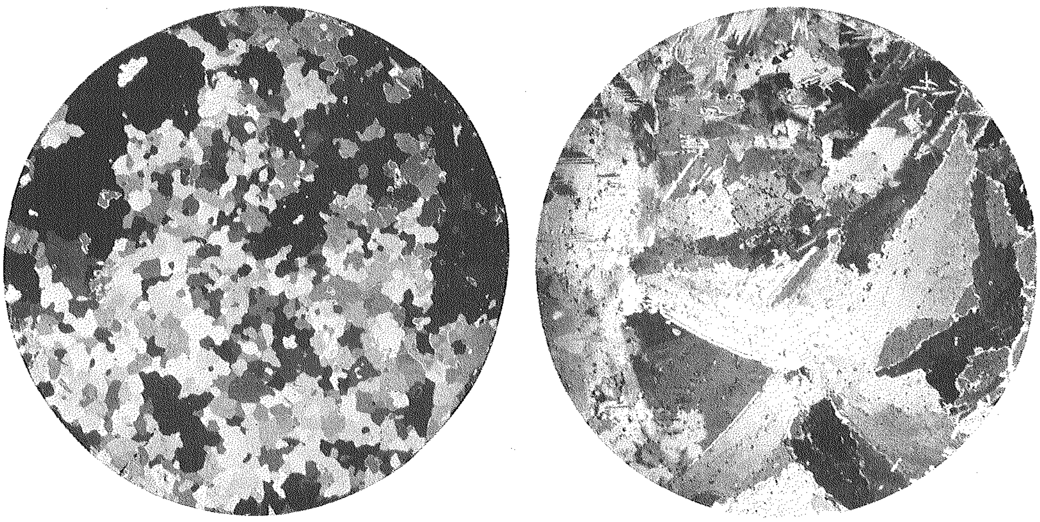
Fig. 2. Aerial trimetrogon photograph of Dailey Islands and Koettlitz Glacier tongue looking west. Locations of the drill holes are indicated by the star and solid circle. Temperatures were measured at the former location. (Photograph by U.S. Navy for U.S. Geological Survey)

below the surface prevented any further drilling with this device and the remainder of the drilling was accomplished with a SIPRE coring auger. Drilling was finally discontinued at a depth of 17.5 m. Very concentrated brine was encountered below 7 m depth. This brine continued seeping into a hole at a rate of approximately 0.5 liters per hour and it was necessary to keep bailing out the brine before attempting to make temperature measurements.

Ice cores from this hole possessed an opaque appearance and lacked all form of stratification, and they appeared also to be completely free of dirt. However, a small amount of light fluffy material was observed to settle out from a number of samples melted for conductivity measurements. This material is probably of algal or diatomaceous origin but was not positively identified as such. Results of conductivity measurements together with their corresponding salinities are presented in Table 1. These measurements were made with a glass pipette cell connected to a Type RC conductivity bridge with a read out accuracy of better than ±1%. It was found that all samples except the near surface sample contained appreciable quantities of salt, indicating that this part of the ice tongue has been reconstituted by freezing of sea water. This view was subsequently confirmed when several thin sections of cores were examined between crossed polaroids (see Fig. 3). Ice from near the surface was much finer grained than other sections and possessed a texture simulating that of

Table 1. Conductivities and salinities of ice cores from hole drilled for temperature measurements. Salinities were calculated on the assumption that the rations of salts in the ice are the same as in sea water. Data corrected to 25°C

Depth m	Conductance $\mu\mho$/cm	Salinity ‰
0.10	7	0.004
7.5	2 200	1.28
12.0	2 000	1.16
14.0	2 400	1.39
(Brine)	200 000	111.6



Depth : 0.1 m Depth : 14 m

Fig. 3. Thin sections of ice cores from the hole drilled for temperature measurements. Sections were photographed between crossed polariods. ×0.944

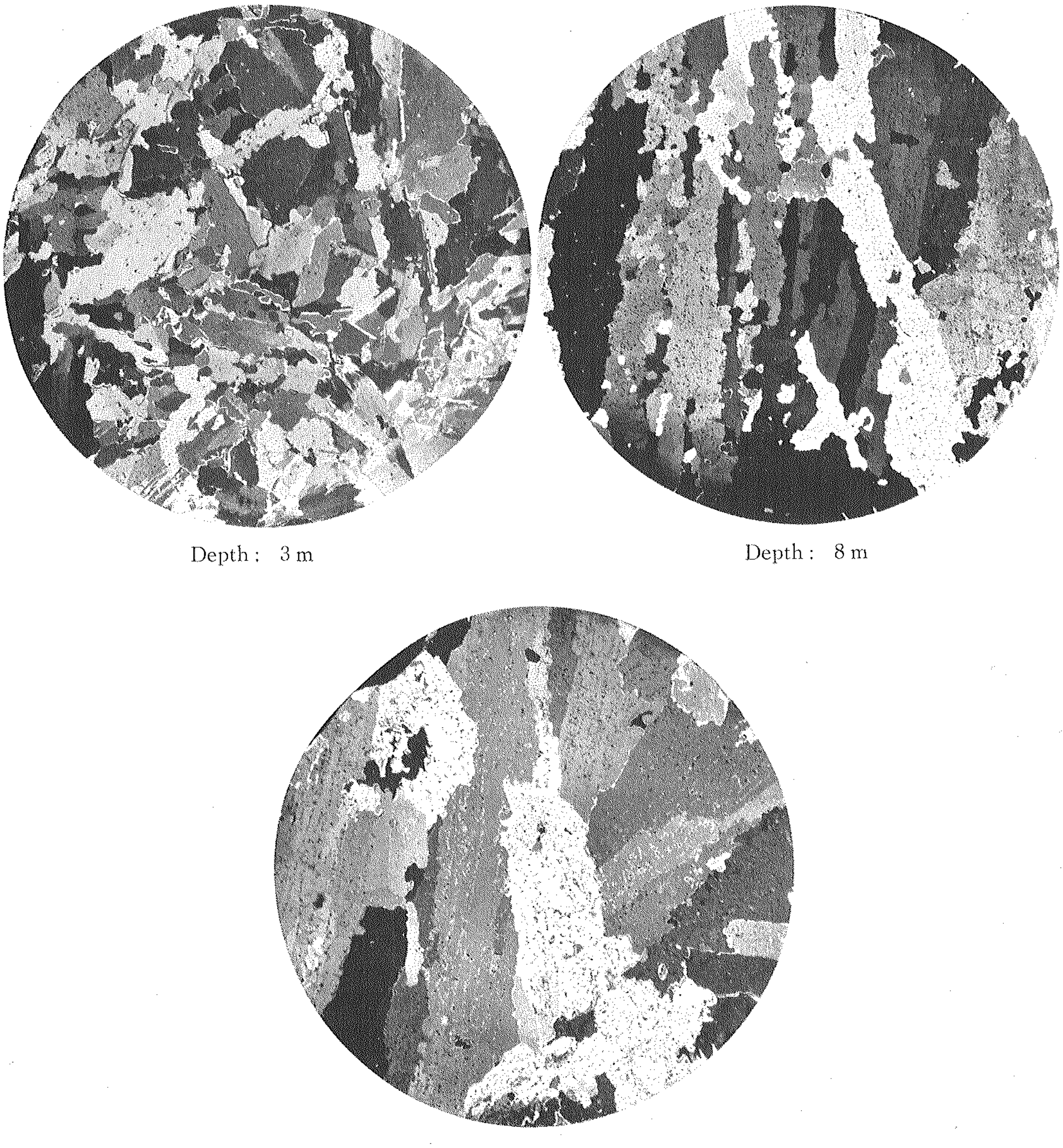


Fig. 4. Thin section photographs of saline ice from second drill hole. Note the brine pockets and platelet structures in all three thin sections. ×0.944

superimposed ice. This ice was most probably formed at the surface by freezing of relatively fresh water. Ice from 14 m depth possessed a totally different texture. The crystals are much larger and the texture can be said to be inter-penetrating, and platelet structures and brine pockets are clearly discernible in thin section. These latter structures are even more clearly demonstrated in thin sections (Fig. 4) of cores from a second hole located approximately 3 km further north near the ice front (the location of this hole is marked by a solid circle in Fig. 2). Ice salinities at this second hole averaged close to

2.0% increasing to nearly 5% within a few centimeters of the bottom. Cores were completely devoid of dirt.

The salty nature of the ice at both these locations is in striking contrast with the composition of the ice from the immediate area of the tide crack in front of the easternmost Dailey Islands where core drilling in November 1963 revealed the existence of dirt-ridden fresh water ice only. Apparently the fresh water ice is confined to these areas where surface run-off can make its way down under the ice, *e.g.*, tide cracks, and can subsequently freeze onto the bottom. Elsewhere however, it would appear that it is sea water (or at least highly brackish water) that is freezing to the bottom of the ice tongue.

Temperatures (made at the first hole only) were measured every 2 to 3 m with a thermistor probe coupled to a sensitive Wheatstone bridge. The thermistor was calibrated both before and after taking measurements and all temperatures are considered to be accurate to within at least ±0.1°C. At each level of measurement the probe was lowered to the bottom of the drill hole where it was left in contact with the ice for two hours while temperatures were recorded five or six times. Temperatures taken in the ice cores immediately after their removal from the core barrel never exceeded by more than ±0.1°C temperature measured at the bottom of the hole. Results of these measurements are given in Table 2 and Fig. 5.

Table 2. Temperature values from drill hole near Dailey Islands. (Location of hole indicated by star in Fig. 2)

Depth	m	1.0	3.5	5.5	7.5	8.5	9.5	12	15	17.5
Temperature	−°C	18	20.8	18.3	15.5	12.7	10.7	8.7	7.8	7.0

Temperatures in the ice depend upon temperatures at the upper and lower surfaces and the thermal properties of the ice itself. In a floating ice sheet the temperature at the bottom can be taken as the freezing point of the water. In this paper a temperature of −1.8°C, the freezing point of sea water, was used in the calculations. The mean annual surface temperature at the drill hole has not been determined but it is probably very similar to temperatures recorded in other parts of McMurdo Sound. According to Simpson (1921) mean annual surface air temperatures at Hut Point, Cape Royds and Cape Evans for the 5 year period 1902, 1903, 1908–1909, 1911 and 1912 averaged −17.4°C which agrees very closely with the value of 17.7°C reported by Nichols and Ball (1964) from 7 years continuous measurements (1957–1963) at Hut Point. The temperature of the surface can be assumed to be equal to that of the air except during months of December and January when for much of the time the ice is at the melting point. Taking this factor into account a value of −17°C for the mean annual surface temperature of the ice was finally adopted for the calculations. In the upper 12 m or so temperatures will of course vary with the seasons but in deeper ice the temperature at any particular level can be assumed to vary by less than 0.1°C the whole year around.

Since the drill hole did not penetrate to the bottom of the ice tongue some estimate of its thickness is necessary. The brine that seeped into the hole was so saline that at the end of a week it was still unfrozen at a depth of 6.2 m below the ice surface. From a consideration of ice density (the average for several pieces of core was 0.90 $g \cdot cm^{-3}$)

and the final level of brine in the drill hole the ice thickness at this location is probably 45 m or more. Results of later drillings up the middle of the ice tongue showed that the ice was submerged only 6/7~7/8 of its thickness, indicating that the ice tongue is tiding "high" in the water. If the same ratios are applied to the temperature hole (assuming that the top of the brine is at sea level) then the thickness of ice should lie between 43 and 50 m. This value would accord well the seismic measurements of Cook (1963) which indicated thicknesses of 40 to 50 m a few kilometers to the rear of the drill hole (See Fig. 1 for locations of soundings and recorded thicknesses). Surface leveling measurements in the direction of the arrow in Fig. 1 also showed that the ice surface was essentially horizontal. In the analysis that follows an ice thickness of 40 m has been assumed.

IV. Temperature Analysis and Interpretation

Where there is no vertical movement of ice the temperature profile of the glacier simply follows the straight line connecting the average annual temperature of the surface with the temperature at the bottom of the glacier. An examination of temperatures below 12 m in the drill hole near the eastern-most Dailey Islands shows that they are

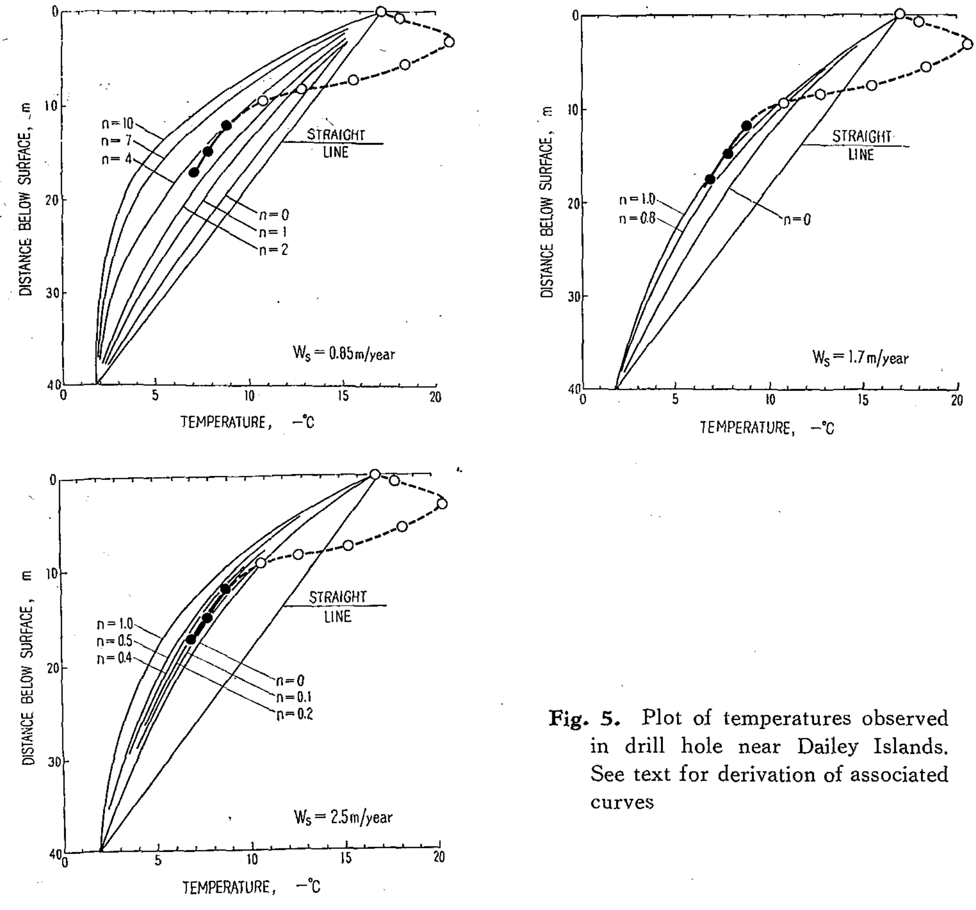


Fig. 5. Plot of temperatures observed in drill hole near Dailey Islands. See text for derivation of associated curves

approximately 4°C warmer than those for a glacier with no vertical movement. Any error in our estimate of ice thickness would tend to increase this difference because the thickness value actually used in the calculations (40 m) is probably too small. This 4°C difference can hardly be attributed to the effect of water in the hole because this would tend to bring temperatures into even closer alignment with those in a glacier with no vertical movement. The only other possible explanation of this temperature difference is that there is an upward movement of ice. For a constant thickness glacier this could only mean that there is ablation at the surface and freezing at the bottom.

Downfacing curves in Fig. 5, calculated on the basis of equations developed by Zotikov (1964) show the effects of different rates of bottom freezing on temperature distributions for surface ablation rates of 0.85, 1.7 and 2.5 $m \cdot yr^{-1}$ respectively. The number "n" for each curve simply represents the ratio between freezing rate and the rate of ablation, *e.g.*; when $n=0$ only ablation is taking place while when $n=1$ the rates of freezing and ablation are the same. As indicated in Fig. 5 many curves can be constructed to fit the observed data depending upon what rate of freezing is chosen. To determine which combination of ablation and freezing values best fits the observed temperatures we must make some additional assumptions concerning ice movement.

The rate of movement of the Koettlitz Glacier tongue has not been determined but it is probably of the order of 100 $m \cdot yr^{-1}$. This was the rate of flow measured by Swithinbank (1963) for the smaller glaciers discharging into the Ross Ice Shelf, *e.g.*, Live Glacier. More recently Zotikov and Paige have found that the Erebus Glacier tongue on the east side of McMurdo Sound is moving forward at about 125 $m \cdot yr^{-1}$. If the Koettlitz Glacier is discharging ice into McMurdo Sound at the rate of 100 $m \cdot yr^{-1}$ then we could expect the floating tongue of the glacier to be moving at least the same speed where the flow of ice is unrestricted. Near the ice front, however, it would appear that the ice is moving much more slowly. For example, observations of the positions of fish remains on top of the ice and fossiliferous moraines near the easternmost Dailey Islands indicate that there has been negligible movement of the ice for the past two years. Apparently the Dailey Islands are exerting a strong braking action on the flow of the glacier tongue causing it to slow down and compress.

It might be noted in Fig. 1 that the ice flowing between Brown Peninsula and the western shore of McMurdo Sound is of more or less constant width throughout. If in the first approximation we can assume that the thickness of ice between the Dailey Islands and the head of the tongue remains constant and that the properties of the ice don't change, that the distance over which the assumed discharge velocity of 100 $m \cdot yr^{-1}$ is dissipated is 50 km and that the rates of ablation and accumulation remain constant along the entire length of the glacier tongue then from continuity considerations it can be shown that surface ablation must exceed bottom freezing by about 0.5 $m \cdot yr^{-1}$. Since this difference could be larger (an increase in either the thickness or rate of flow of the glacier would cause an even greater difference) it is concluded on the basis of the calculations depicted in Fig. 5 that surface ablation cannot be less than 0.5 $m \cdot yr^{-1}$. If there was no growth of ice on the bottom of the glacier tongue then according to Fig. 5 even an ablation of 2.5 $m \cdot yr^{-1}$ would not be large enough to account for the observed temperature distribution in the ice. We can only conclude from this that there is considerable accretion of ice to the bottom of the Koettlitz Glacier tongue. An examination of Fig. 5 shows that the observed temperatures plot closest to curves with ablation rates of 1.7 and 2.5 m·yr^{-1} and corresponding n values of 1 and 0.2. There n values yield rates of freezing of 1.7 m·yr^{-1} and 0.5 m·yr^{-1} respectively.

For more precise calculations the saltiness of the ice should probably have been considered since the specific heat of ice is known to change appreciably with changes in salinity (Schwerdtfeger, 1963). In practice, however, it is generally very difficult to calculate the change in specific heat. The analysis shows that as a first approximation, it is possible to use the graphed curves for pure ice if the real speed of freezing on the bottom can be corrected. A rough calculation using the curve corresponding to 1.7 m·yr^{-1} of both ablation and bottom freezing for pure ice shows that when the observed salinity of about 1.2‰ is taken into account the value for bottom freezing could diminish by as much as 0.7 m·yr^{-1} to 1.0 m·yr^{-1}. All things considered an ablation rate at the surface of 1.7 m·yr^{-1} and an accretion of 1.0 m·yr^{-1} at the bottom would seem to represent the most likely combination of ablation and bottom freezing for the floating tongue of the Koettlitz Glacier.

V. Bottom Freezing and Composition of Water

When the temperature gradient in the ice near the bottom is analyzed it is found that the transfer of heat from the bottom is not great enough to allow more than 3 mm sea water to freeze each year. To account for the much larger rate of accretion calculated above (1.0 m·yr^{-1}) it can only be assumed that the water directly underneath the ice is considerably less saline than ordinary sea water. The fact that the salinities of the ice cores seldom exceeded 2‰, including those from near the bottom of the second drill hole, might indicate growth from brackish water rather than ordinary sea water. Using as a first approximation the heat transfer data within the water near the bottom (Wexler, 1960; Shumsky and Zotikov, 1963), it can be shown that the salinity of this water would have to be less than 15‰ (freezing point -0.7°C) in order to allow freezing to take place at the calculated rate of 1.0 m·yr^{-1}. Fresh water is known to underlie the glacier tongue near the easternmost Dailey Islands (Gow *et al.*, 1965). The formation of a layer of fresh water under the ice is due almost certainly to the drainage of surface melt down tide cracks and other fissures in the ice and any subsequent mixing with sea water would give rise to brackish water. Much the same situation has been postulated for the growth of ice on the bottom of the Ward Hunt Ice Shelf of Ellesmere Island (Crary, 1956).

After the original draft of this manuscript had been completed one of the authors (A. J. Gow) drilled a series of core holes along the mid-line of the glacier tongue. Five of those holes, spaced 5~6 km apart, pierced glacier bottom and it was discovered that for a distance of approximately 24 km back from the ice front the floating tongue was composed entirely of saline ice. The maximum thickness of ice encountered was 14.5 m which is appreciably thinner than the ice drilled to obtain the temperature measurements discussed in this paper. Glacier ice was encountered in the 6th and last hole drilled. This hole was located approximately 32 km back from the ice front which would also place it about 20 km seaward of the point where the Koettlitz Glacier discharges into McMurdo Sound. Apparently the glacier ice 32 km from the ice front becomes entirely reconstituted by the time it reaches a point 24 km from the ice front. It is suspected that much of the bottom freezing has occurred in brackish water formed from the mixing of sea water with relatively fresh water from the surface. Core samples and samples of water from directly under the ice tongue are now being analyzed for oxygen isotope content in order to determine both the degree of mixing and the freezing point of these brackish waters. More detailed results of these studies are to be published elsewhere. An array of markers was also set up in the general area of the Dailey Islands in order to measure ice movement and surface ablation near the ice front.

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