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BASEMENT ICE, WARD HUNT ICE SHELF, ELLESMERE ISLAND, CANADA

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Abstract. Oxygen-isotope and chlorinity determinations, as well as petrographic observations, indicate that the basement ice of the Ward Hunt Ice Shelf is largely composed of a unique brackish ice, which interdigitates with sea ice. Some iced firn occurs near the top of the basement ice, below an unconformity.

Stratification in brackish and sea ice represents annual increments to the bottom of the ice shelf. The *c*-axis vertical orientation and small-angle grain-boundary relations in brackish ice are explained by nucleation and floating of ice dendrites from the undercooled brackish water zone to the bottom of the ice shelf, where they attach themselves sub-parallel to the plane of the undersurface.

Ice island T-3 did not come from a break-up of the main part of the Ward Hunt Ice Shelf but probably originated in a nearby area to the west.

Résumé. *Glace de fond dans la Ward Hunt Ice Shelf, Ellesmere Island, Canada.* Des déterminations de teneur en isotopes de l'oxygène et de chlorinité, ainsi que des observations pétrographiques montrent que la glace de la base de la Ward Hunt Ice Shelf est en majorité composée d'un type unique de glace saumâtre avec intercalations de doigts de glace de mer. Il arrive que du névé passant à la glace se trouve près du sommet de la glace de base, au pied d'une irrégularité.

La stratification dans la glace saumâtre et dans la glace de mer représente l'accroissement annuel par le fond de la banquise. L'orientation verticale des axes *c* et les liaisons à angle faible aux limites de grains dans la glace saumâtre sont expliqués par la nucléation et le flottage de dendrites de glace à partir de la zone d'eau saumâtre en surfusion en dessous de la banquise, à laquelle elles se fixent à peu près parallèlement au plan de l'interface glace–eau.

L'île de glace T-3 ne vient pas d'une rupture de la partie principale de la Ward Hunt Ice Shelf mais a probablement pris naissance dans une région voisine à l'Ouest.

Zusammenfassung. *Eis an der Unterseite des Ward Hunt Ice Shelf, Ellesmere Island, Kanada.* Sauerstoffisotopen- und Chlorgehaltsbestimmungen wie auch petrographische Beobachtungen weisen darauf hin, dass das Eis an der Unterseite des Ward Hunt Ice Shelf sich weitgehend aus einem eigenartigen brackigen Eis zusammensetzt, das mit Meereis verzahnt ist. Nahe seiner oberen Grenze tritt unterhalb einer Unstetigkeit etwas vereister Firn auf.

Die Stratigraphie des Brackeises und des Meereises spiegelt den jährlichen Zuwachs an der Unterseite des Schelfeises wieder. Die vertikale Orientierung der *c*-Achsen und die kleinen Winkel zwischen den Korngrenzen im Brackeis werden durch Kernbildung und Aufschwimmen von Eisdentriten aus der unterkühlten Brackwasserzone an die Schelfeisunterseite erklärt, wo sie sich parallel zur Unterseite anheften.

Die Eisinsel T-3 ist nicht durch Abbrechen vom Hauptteil des Ward Hunt Ice Shelf entstanden, sondern stammt vermutlich aus einem westlich nahe benachbarten Gebiet.

Introduction

The ice islands of the Arctic Ocean originate from the break-up of ice shelves, such as the Ward Hunt Ice Shelf, along the northern coast of Ellesmere Island. As calculated from mean freeboard and ice-density relations, the Ward Hunt Ice Shelf has an average thickness of 44 m. It is composed of two major stratigraphic units: (1) a lower "basement" ice thought by Marshall (1960, p. 47) to be largely of glacial origin and brine-soaked, but by Nakaya and others (1962, p. 29) to be of a quite uncertain origin, and (2) an upper unit of interstratified iced firn and lake ice lying with angular unconformity (Marshall, 1960; Lyons and Leavitt, 1961) upon the basement ice. The unconformity is easily mapped at the surface or is recognized in drill cores because it is marked by a heavy concentration of aeolian dust developed during an ablation cycle which separates the times of formation of the lower and upper shelf stratigraphic units (Fig. 1).

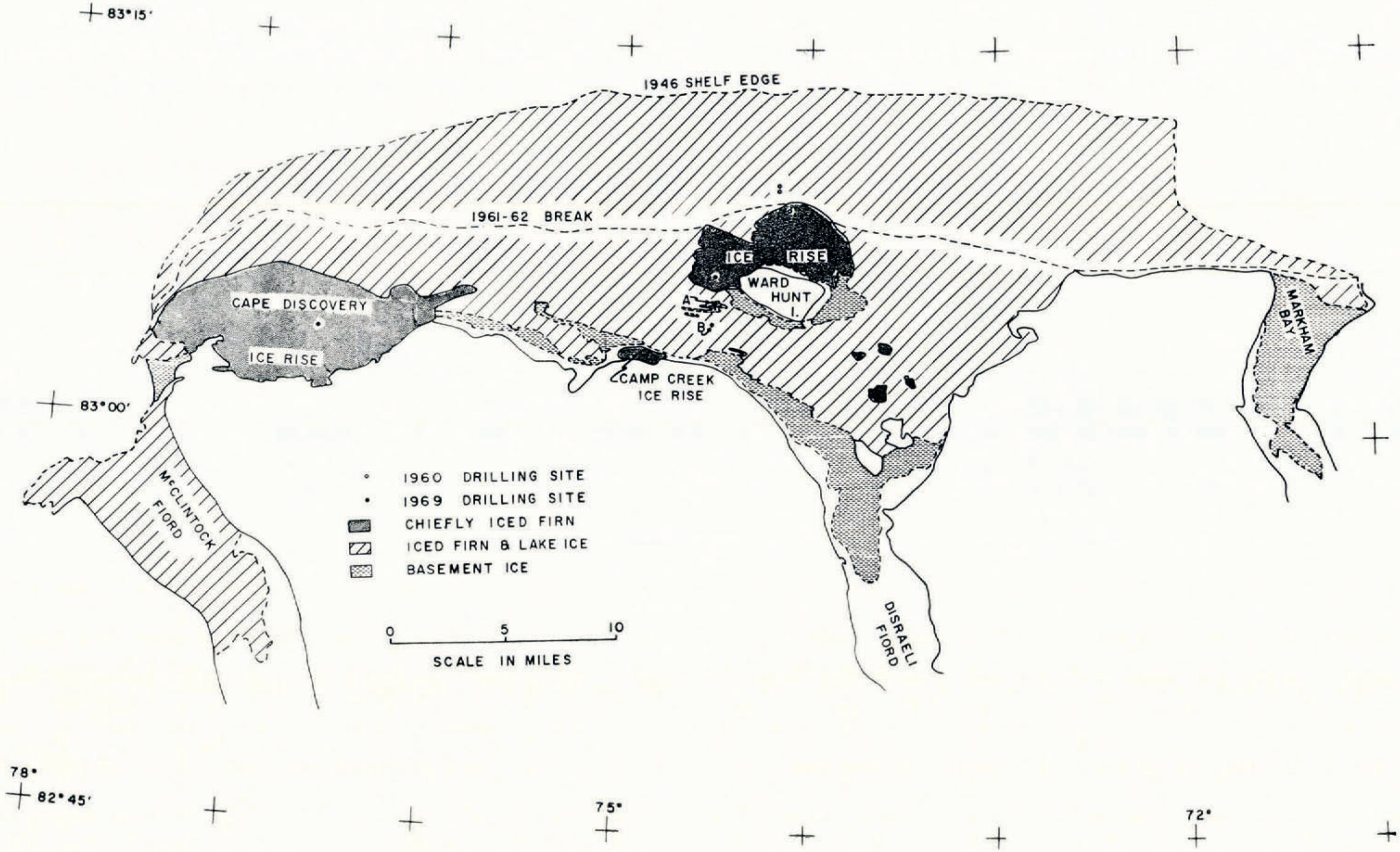

Fig. 1. Map of Ward Hunt Ice Shelf and adjacent ice rises. Ice types identified partly by field and laboratory study, and partly by aerial photography.

This picture of the stratigraphy of the Ward Hunt Ice Shelf is, to some extent, an over-simplification. Radio echo-sounding (Evans and others, 1969; Hattersley-Smith and others, 1969) suggests that the ice shelf may have a total range in thickness of from 25 to 80 m. Cores from the northern edge of the Ward Hunt ice rise and from the shelf north-east of the ice rise (Ragle and others, 1964) show no heavy dust layer nor any basement ice; instead, the lower 20–25 m consist of sea ice. Thus the outer part of the ice shelf, a large part of which calved off in 1961–62 (Hattersley-Smith, 1963; Nutt, 1966), has a sea-ice basement which differs significantly from the inner basement ice described originally by Marshall (1960) for the Ward Hunt Ice Shelf, and by Nakaya and others (1962) on ice island T-3. The petrographic recognition of a difference in the nature of the ice of the lower part of the Ward Hunt Ice Shelf in its inner and outer parts is also consistent with Crowley's (1961) seismic studies of the ice shelf which showed acoustic differences in the basement ice in these two places. It is the inner basement ice which is the chief subject of the present communication.

PETROGRAPHY OF BASEMENT ICE

Most of the inner basement ice, where exposed, shows a remarkably well-developed stratification (Fig. 2) reflecting cyclic variations in the abundance of entrapped gases and average grain-size of the ice. On both T-3, where it constitutes a major part of the ice island, and on the Ward Hunt Ice Shelf, the strata are 20–25 cm in average thickness, and are locally warped into a series of folds with wavelengths of the order of 100 m, and dips on the limbs of as high as 90° (Lyons and Leavitt, 1961, p. 14–19; Nakaya and others, 1962, p. 12). Texturally, much of the stratified ice is characterized by what appear to be very large columnar crystals with indistinct grain diameters of up to 120 cm. The large crystals, however, consist of mosaics of smaller sub-columnar grains showing a sub-parallel orientation of their *c*-axes normal to the stratification planes, and small-angle grain-boundary relations to one another (Nakaya and others, 1962, p. 13). Salinity in stratified basement ice is extremely low (Table I; Nakaya and others 1962, fig. 28). This fact, as well as the optic orientation (*c*-axis vertical

Fig. 2. Stratified basement ice, Ward Hunt Ice Shelf.

rather than horizontal) and the lack of a characteristic platelet substructure, effectively rule out the possibility that the stratified ice could be sea ice recrystallized *in situ*. Similar petrographic arguments may be marshalled against iced firn, glacial ice or lake ice as possible prototypes of the stratified basement ice.

Not all of the basement ice is of the stratified type. Iced firn has been identified in the upper basement ice of both the Ward Hunt Ice Shelf and T-3 by Lyons and Leavitt (1961, p. 8) and by Nakaya and others (1962, p. 20), respectively. The latter investigators also identified 2 m of sea ice at the bottom of T-3. In holes drilled into Ward Hunt basement ice during the 1969 field season (cf. Fig. 1) at locations 1.6 and 2.6 km south-west of the south-western tip of the island, stratified basement ice and sea ice alternated in the core samples in the manner shown in Figure 3. Identification of ice types was based upon petrographic criteria in the field and was confirmed in the laboratory by chemical tests (Table I).

TABLE I. $\delta^{18}O$ AND CHLORINITY DETERMINATION ON ICE AND WATER SAMPLES, NORTHERN ELLESMERE ISLAND

Sample number	*Depth* m	*Petrographic description*	$\delta^{18}O$ *(relative to SMOW standard)*	*Number of analyses*	*Average deviation*	*Chlorinity* ‰
2	6	Stratified basement ice	−21.56	3	0.07	0.16
3	15	Stratified basement ice	−13.22	3	0.23	0.19
4	18	Sea ice	−0.63	2	0.11	1.25
5	21	Basement ice, transition type	−17.47	2	0.04	0.13
6	5	Fresh water, Disraeli Fiord	−27.15	3	0.15	<0.01
7	43	Brackish water, Disraeli Fiord	−4.66	2	0.02	16.25
8	300	Salt water, Disraeli Fiord	+0.41	2	0.03	17.65
9	2	Fresh water, Ward Hunt Lake	−24.06	3	0.15	<0.01
12	14	Iced firn, Camp Creek ice rise	−30.60	3	0.06	<0.01
13	1	Iced firn, Ward Hunt ice rise	−27.29	3	0.08	<0.01

^{18}O analyses by S. M. Savin. Cl analyses by L. M. Banos.

OCEANOGRAPHIC OBSERVATIONS

Along the north, east and south sides of Ward Hunt Island, and along the north shore of Ellesmere Island, fresh-water moats open up during the summer melt season. In the moat between Ellesmere Island and the Ward Hunt Ice Shelf (Lyons and Leavitt, 1961, fig. 4), fresh water extends to a depth of 48±3 m, which is a few meters below the bottom of the ice shelf. In the adjoining Disraeli fiord, Keys and others (1969) have shown that the upper part of the fiord is filled with fresh water to a depth of 44 m. Between 44 and 45 m is a brackish water zone, below which is Arctic Ocean sea-water with a salinity of 32‰. The ice shelf apparently acts as a dam for the surface melt waters draining from northern Ellesmere Island, but interchange with Arctic Ocean water can occur at greater depths (Keys and others, 1969, p. 7). Today, as in the past, ice accreting below the Ward Hunt Ice Shelf could conceivably be fresh, brackish or saline ice, depending upon geographic location and climatologic factors (i.e. the depths of the fresh, brackish and oceanic zones relative to the ice-shelf bottom). Thinning of the ice shelf during an ablation cycle should increase the likelihood of accreting fresh water or brackish ice on its underside; thickening of the ice shelf during an accretionary cycle would enhance the probability for sea-ice accretion. In any case, complex inter-tonguing relations of ice types are to be expected. Schwarzacher (1959) has shown that accretion of fresh ice beneath thin sea ice is a common consequence of run-off of melt waters from the pack ice of the Arctic Ocean, and Gow and others (1965) have described a similar situation in a part of the McMurdo Ice Shelf of Antarctica.

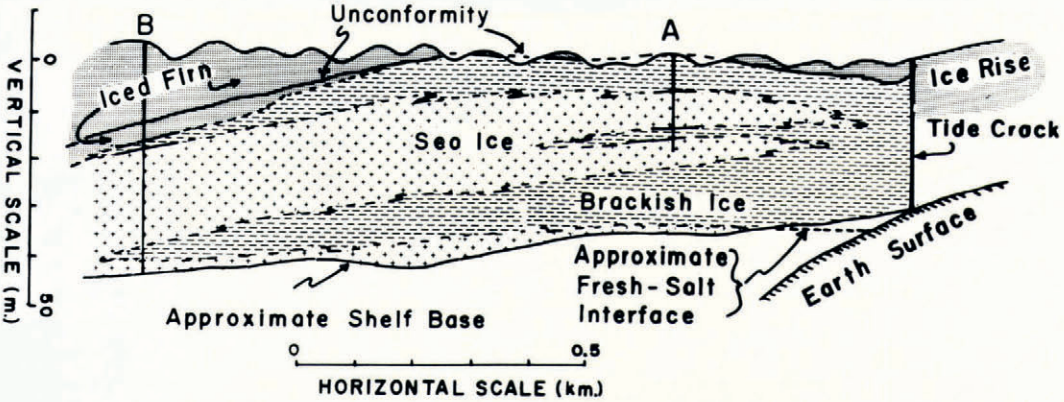

Fig. 3. Interpretation of stratigraphy of part of Ward Hunt Ice Shelf, based on drill-core and laboratory studies. See Figure 1 for location of holes A and B. Ward Hunt ice rise towards right side of section; trough of syncline between Ward Hunt and Ellesmere Islands to left of section.

OXYGEN-ISOTOPE AND CHLORINITY DATA

Table I presents oxygen-isotope and chlorinity data of ten samples collected during the 1969 field season. Three of them (Nos. 6, 7 and 8) were taken by J. Keys and H. Serson from an oceanographic station in Disraeli Fiord, and the remainder were collected by the writers. Determinations of $\delta^{18}O$ were made using techniques described by Epstein and Mayeda (1953). Chlorine was determined using ion-sensitive electrodes. The basement-ice samples come from the holes drilled 1.6 and 2.6 km south-west of the south-west edge of Ward Hunt Island (Fig. 1).

The extremely low $\delta^{18}O$ values of the ice from the Camp Creek and Ward Hunt ice rises (Nos. 12 and 13) are consistent with the petrographic and stratigraphic identification of iced firn. Because of the number of samples (two), we can draw no conclusions concerning the significance of the differences in $\delta^{18}O$ values with respect to temperature of accumulation, or other factors.

For the fresh-water samples (Nos. 6 and 9) the lower $\delta^{18}O$ value from Disraeli Fiord is consistent with the fact that it receives melt waters from elevations of up to 1 980 m, and its average $\delta^{18}O$ value should therefore be more negative than that from Ward Hunt Lake, which receives its drainage from elevations lower than 415 m. Lake ice forming from the melt water in Ward Hunt Lake should have $\delta^{18}O$ values of about -24 or more positive; that forming on the Ward Hunt Ice Shelf presumably would have values in the range of -27 to -30.

Because the ice petrographically identified as sea ice (No. 4) has a $\delta^{18}O$ value very close to 0.00, as does the Arctic Ocean water (No. 8), there seems to be little doubt that this ice type is identifiable both chemically and petrographically with considerable certainty.

The three basement ice samples (Nos. 2, 3 and 5) show $\delta^{18}O$ values more negative than the brackish water in Disraeli Fiord (No. 7) but not as negative as fresh melt water in the same fiord. The $\delta^{18}O$ and chlorinity of samples 3 and 5 imply crystallization of ice from brackish water. Sample 2 seems to have formed from water which was also brackish but its $\delta^{18}O$ value is anomalously low. This sample was taken quite close to the surface in an area from which iced firn has been ablated only recently. It is possible, though not indicated by any other criteria, that a decrease in the $\delta^{18}O$ value has occurred because of downward percolation by firn melt water. The alternative possibility is that the ice crystallized from water somewhat fresher than that represented by samples 3 and 5.

An obvious conclusion concerning samples 3 and 5, and probably sample 2 as well, is that they represent a newly recognized type of ice, best termed brackish ice, which is a unique but volumetrically significant constituent of Arctic ice shelves and ice islands. Crary (1960, p. 33) had suggested that the freezing of fresh or brackish waters on the underside of T-3 and the Ward Hunt Ice Shelf might have been important in their development. What seems surprising, as gauged by Figure 3, is that approximately half of the basement ice is of brackish origin.

Discussion

Tritium measurements in Disraeli Fiord (Keys and others, 1969, p. 4) suggest that each season's melt water sinks to the interface between the salt and fresh water where it may flow directly out of the fiord, under the ice shelf. However, because the ice shelf thins by ablation, particularly near the edges, there is the possibility that some of the melt water, brackish water, or sea-water may accrete as ice on the underside of the ice shelf. The brackish water is of interest in this regard, because its salinity lies in the range where theory predicts (Weeks and Lofgren, 1967) that ice growing in the sub-surface should have the *c*-axis horizontal orientation and platelet substructure characteristic of sea ice. Supercooling and ice-dendrite formation, as observed in the Disraeli Fiord brackish water zone (Keys and others, 1969, p. 3), provide a mechanism for explaining the *c*-axis vertical and small-angle grain-boundary texture so common in the brackish ice. Nucleation followed by floating of dendrites to the underside of the ice shelf, with consequent *c*-axis vertical preferred orientation, would seem to be an inevitable consequence of undercooling in the brackish water zone. On the other hand, there is no evidence for supercooling of the Arctic Ocean sea-water, and shelf sea ice does, predictably, have its *c*-axis horizontal.

The concentration of bubbles marking the stratification planes in the basement ice can be understood in terms of the inverse relation between air solubility and salinity in water (Dorsey, 1940, p. 534–49). If brackish ice accretes below the ice shelf, it will expel downward water more saline than the relatively pure ice which is crystallizing, and a condition will eventually be reached where exsolution of gas becomes inevitable. This gas concentrates beneath the year's annual increment of brackish ice and is partly trapped in the downward encroaching ice front. Flooding of the next summer's fresh or brackish water under the ice shelf partly dissolves the preceding winter's gases and allows the cycle to repeat itself.

If the average stratum of basement ice is 20 cm thick, and if this represents an annual increment to the basal edge of the ice shelf because of ablation at the surface, only 220 years as a minimum might be required to bring stratified ice from the bottom of the 44 m thick ice shelf to the surface. This is a surprisingly short time but not inconsistent with a radiocarbon age of 400±150 years which Crary (1960, p. 43) reported for a siliceous sponge which had passed through the basement ice south of Ward Hunt Island.

An extension of the model proposed here for the stratified basement ice is that the individual strata may, on the average, thin or wedge out completely toward the center of the ice shelf. The thickness of the average layer and its nature (brackish ice or sea ice) will depend on hydrologic factors which are, in turn, related to climatology. If the ice shelf maintains a nearly constant thickness, curling up at its edges and, over the past several hundred years, accumulating firn and lake ice in the area between Ward Hunt and Ellesmere Islands, bottom melting is also a necessity under this median part of the ice shelf (Lyons and Ragle, 1962, p. 93–94). Similarly, accretion of ice under some parts of the McMurdo and Ross Ice Shelves of the Antarctic, and ablation under others, has recently been demonstrated by Gow and others (1965) and by Swithinbank (1970).

An interesting feature of the basement ice is its age relative to the upper iced firn and lake ice of the ice shelf. Some of it, immediately below the dust-marked unconformity, must be older than the superjacent iced firn and lake ice, but the lowermost basement ice must be younger than the unconformity. Hattersley-Smith and Serson (1970) have shown that the mass balance of the Ward Hunt Ice Shelf and ice rise has been negative over the past decade, so the present surface is working its way downward into older iced firn and lake ice. In the ice shelf as a whole, therefore, the age increases both from the top downward, and from the bottom upward.

Our interpretation of the stratigraphic-structural relations of the basement ice of the Ward Hunt Ice Shelf is shown in Figure 3. Beneath the heavy-dust ablation unconformity, the basement is gently warped into a broad syncline between Ward Hunt and Ellesmere Islands (cf. Fig. 1). Where the basement ice re-appears at the surface near Ellesmere Island, it is deformed into anticlines and synclines, probably because of stresses exerted on this edge of the ice shelf by glaciers advancing from Ellesmere Island at a time prior to the major ablation cycle during which the heavy-dust layer was concentrated. Crary's (1960, p. 44–46) estimate of the age of the ablation cycle, based upon somewhat conflicting radiocarbon dates is 1 600 years. However, the oxygen-isotope data of Dansgaard and others (1969) from Camp Century, Greenland, suggest that a major ablation cycle in northern latitudes terminated as recently as 850 years ago.

Finally, the distribution and structure of the ice types comprising the Ward Hunt Ice Shelf (Fig. 1) make it clear that T-3 could not have originated from the area between McClintock Fiord and Markham Bay. McClintock Fiord itself, however, or one of the bays to the west such as Yelverton Bay remain likely sites for its point of origin (cf. Stoiber and others, 1960).

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